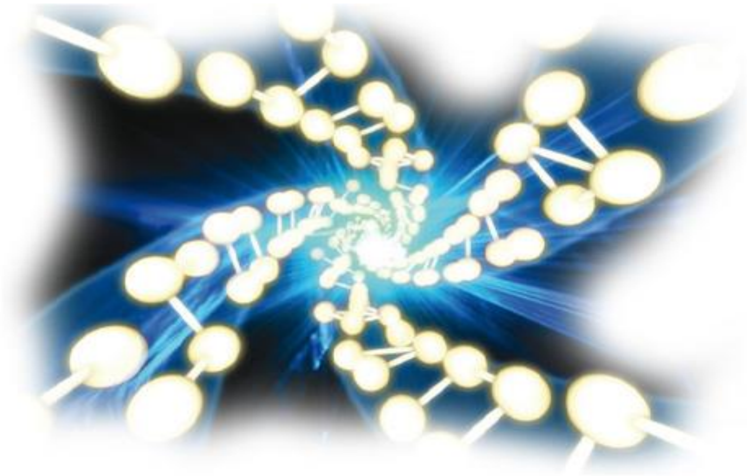

Quantum Simulation Using Photons

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University of Vienna
Austria

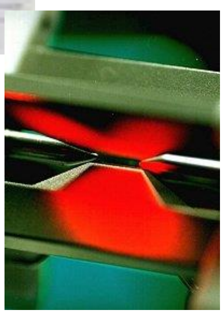
Enrico Fermi Summer School
Varenna, Italy
24-25 July 2016

Lecture I:
Quantum Photonics

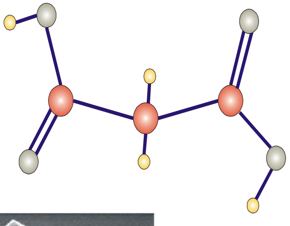
Experimental Groups doing Quantum Computation & Simulation

- **Atoms (Harvard, MIT, MPQ, Hamburg,…) :**
  - single atoms in optical lattices
  - transition superfluid → Mott insulator

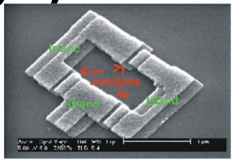
- **Trapped Ions (Innsbruck, NIST, JQI Maryland, Ulm…):**
  - quantum magnets
  - Dirac's Zitterbewegung
  - frustrated spin systems
  - open quantum systems



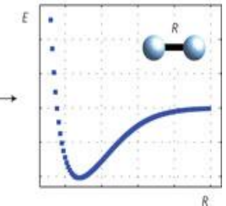
- **NMR (Rio, SaoPaulo, Waterloo, MIT, Hefei,…):**
  - simulation of quantum dynamics
  - ground state simulation of few (2-3) qubits



- **Superconducting Circuits (ETH, Yale, Santa Barbara,…):**
  - phase qudits for measuring Berry phase
  - gate operations



- **Single Photons (Queensland, Rome, Bristol, Vienna,…)**
  - simulation of H_2 potential (Nat.Chem 2, 106 (2009))
  - quantum random walks (PRL 104, 153602 (2010))
  - spin frustration



Architecture race for quantum computers

The Economist | World politics | Business & finance | Economics | Science & technology | Culture

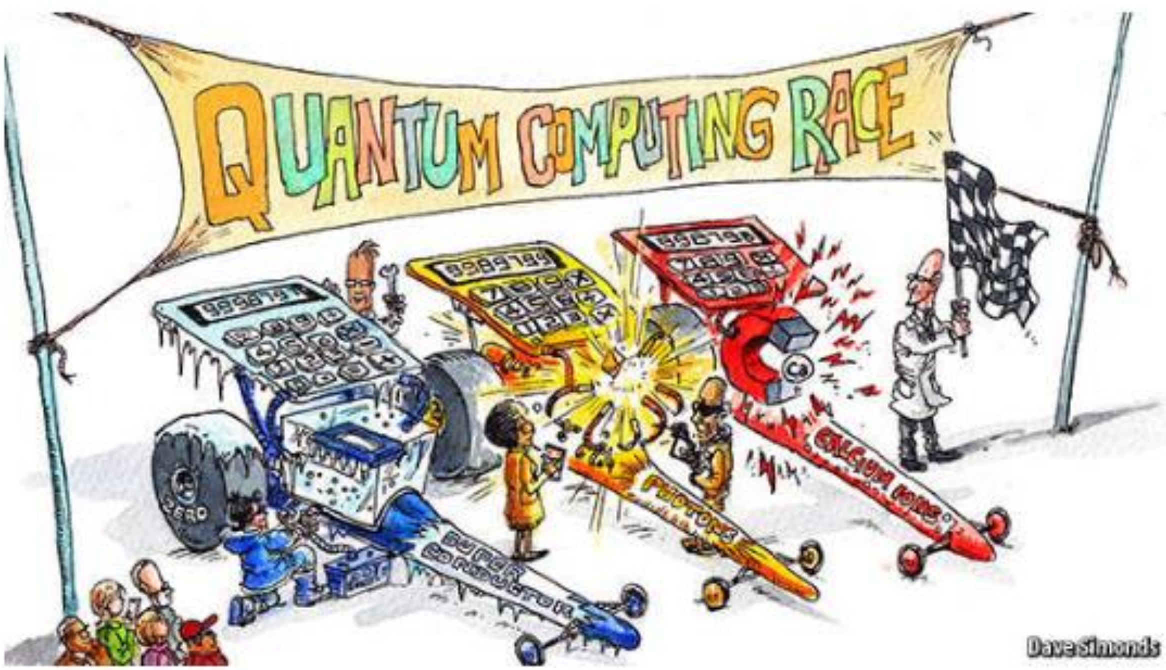
Quantum computers

A little bit, better

After decades languishing in the laboratory, quantum computers are attracting commercial interest

Jun 20th 2015 | From the print edition

Timekeeper | Like 596 | Tweet 400



D-Wave The Quantum Computing Company™

IBM®

Google

intel®

- **UK: 270 M£**
- **Netherlands: 135 M€**

Why Photons ?

- only **weak interaction** with environment (good coherence)
- **high-speed** (c), low-loss transmission (‘flying qubits”)
- good **single-qubit control** with standard optical components (waveplates, beamsplitters, mirrors,…)
- feasible **hardware requirements** (no vaccuum etc.)
- **disadvantage: weak two-photon interactions**

(requires non-linear medium -> two-qubit gates are hard)

Outlook of the Course

(1) Quantum Photonics Concepts and Technology

(2) Quantum Simulation

(3) Photonic Quantum Simulation Examples

- Analog Quantum Simulator
- Digital Quantum Simulator
- Intermediate Quantum Computation

(4) Schemes based on superposition of gate orders

Basic Elements in Photonic Quantum Computing and Quantum Simulation

Literature Suggestion

(1) Five Lectures on Optical Quantum Computing (P. Kok)

- **http://arxiv.org/abs/0705.4193v1 (2007)**

(2) Linear optical quantum computing with photonic qubits

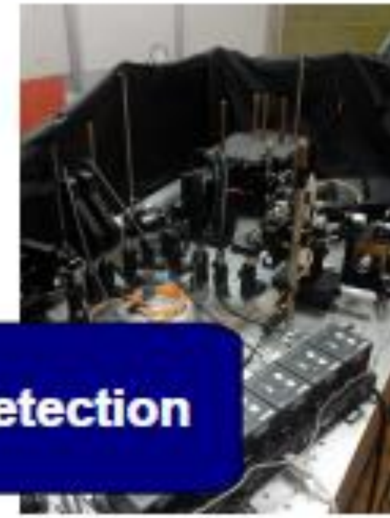
- **Rev. Mod. Phys 79, 135 (2007) (P. Kok et al.)**

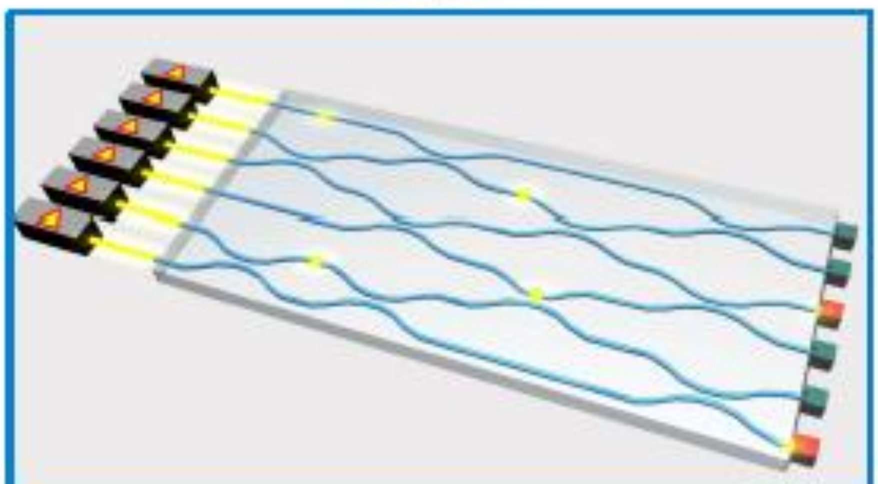
Photonic Quantum Computer Units

Preparation

Manipulation

Detection





How to encode information using photons

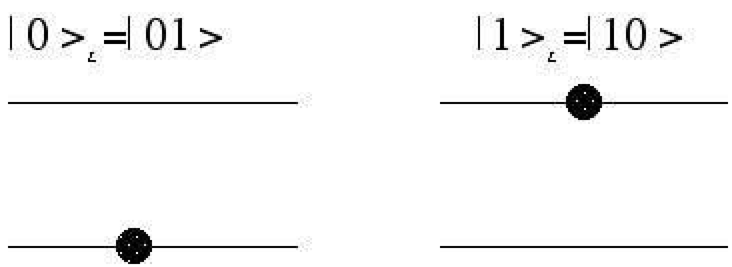
QuantumComputing@UniWien

- **Polarization**

  |0>=|H>

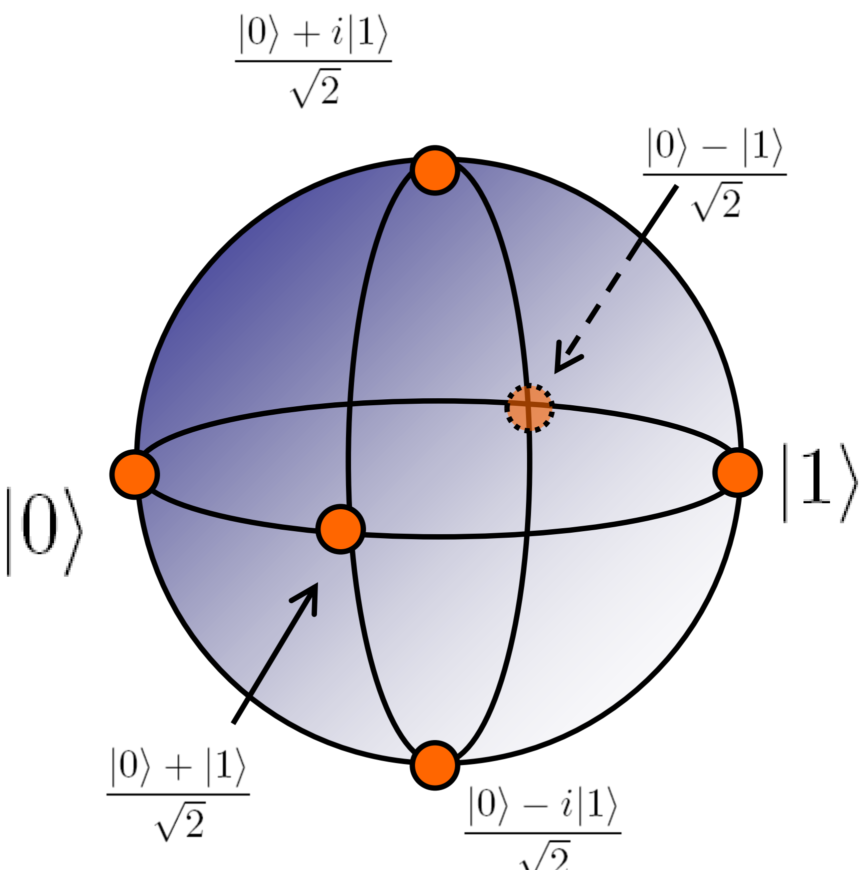
  |1>=|V>

- **Spatial Location** – dual rail representation

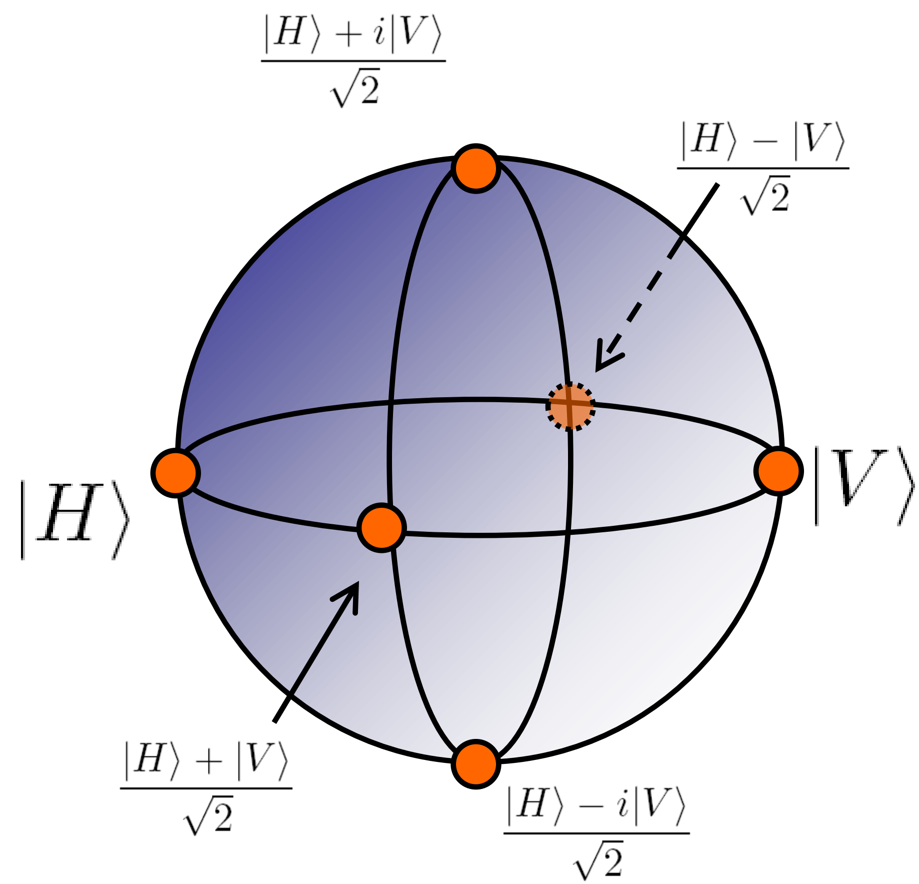


Polarization Encoding (single-rail)

- Qubit as elementary unit of (quantum) information
- Spans a 2d-Hilbert space

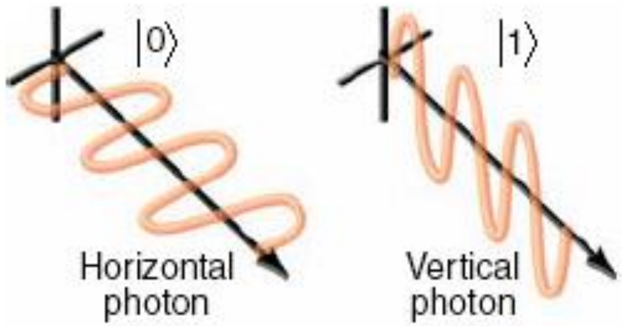


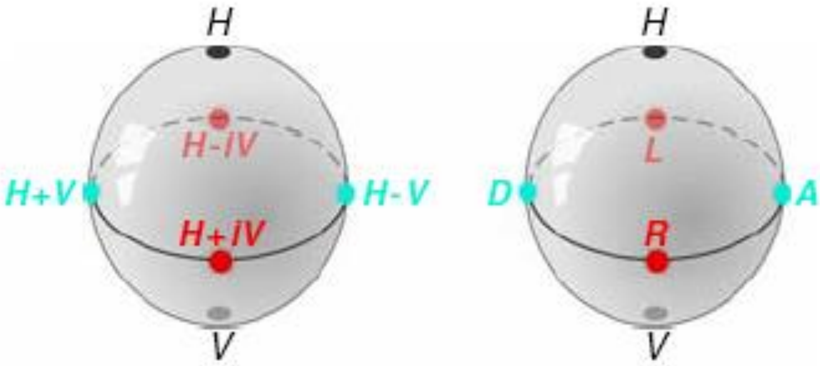
Bloch sphere

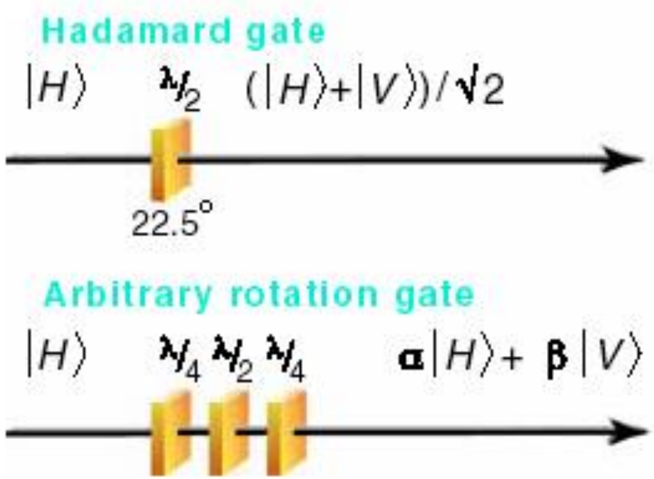


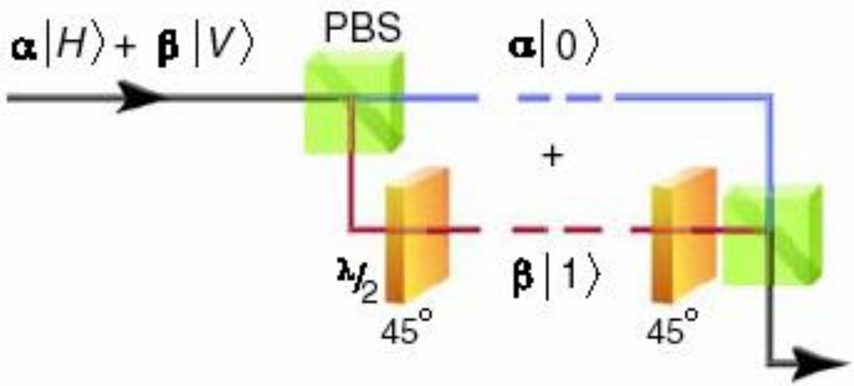
Poincare sphere

Feasible Manipulation of Polarization









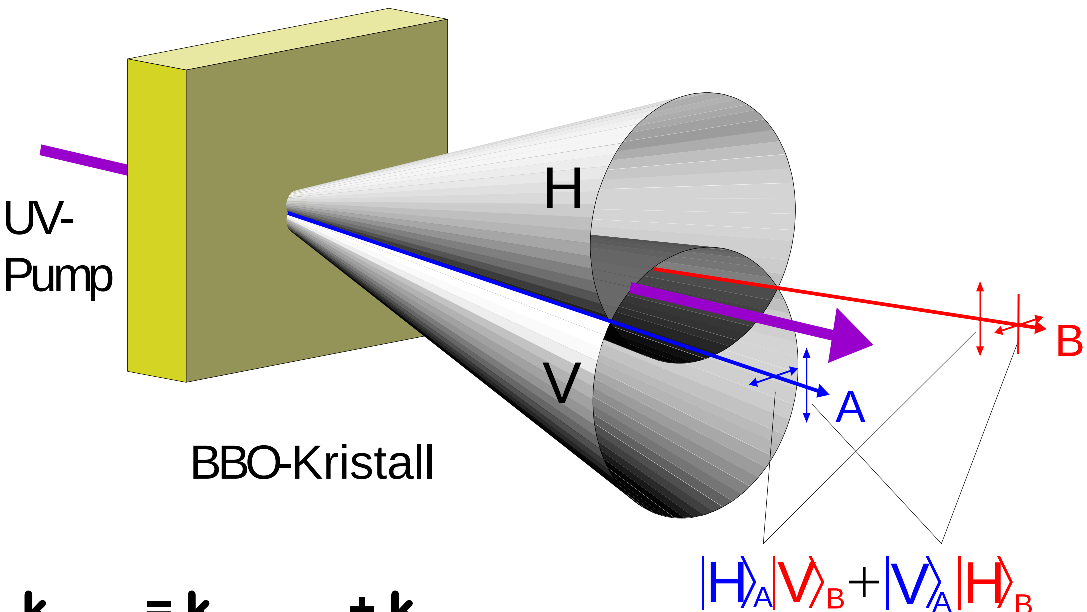
O'Brien, Science 318, 5856 (2007)

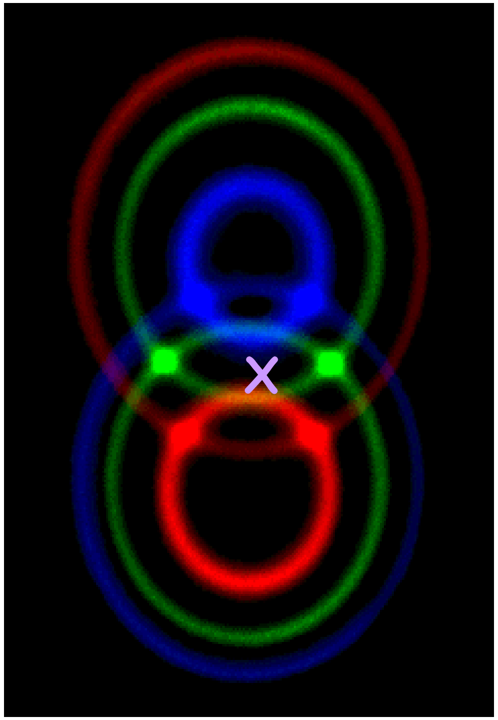
Multi-photon Sources

Two (and Multi-Photon) Generation

- Spontaneous parametric down conversion of pump field (CW or pulsed) in χ(2)-medium
- Proper mode selection leads to polarization entanglement due to indistinguishability

$$H \propto (a_A^\dagger(\omega_1, V)a_B^\dagger(\omega_2, H) - a_A^\dagger(\omega_2, H)a_B^\dagger(\omega_1, V))$$





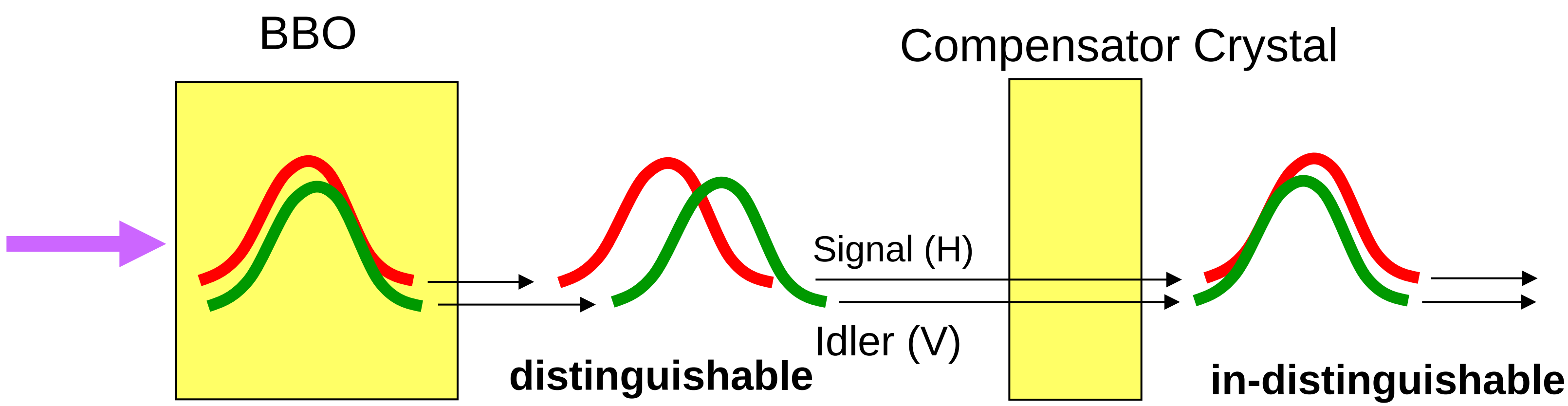
$k_{pump} = k_{photon1} + k_{photon2}$

$w_{pump} = w_{photon1} + w_{photon2}$

Entanglement on the Screen

For achieving high-quality entanglement

Erase which path information (originationg from bi-refringence):
Additional compensator crystals:

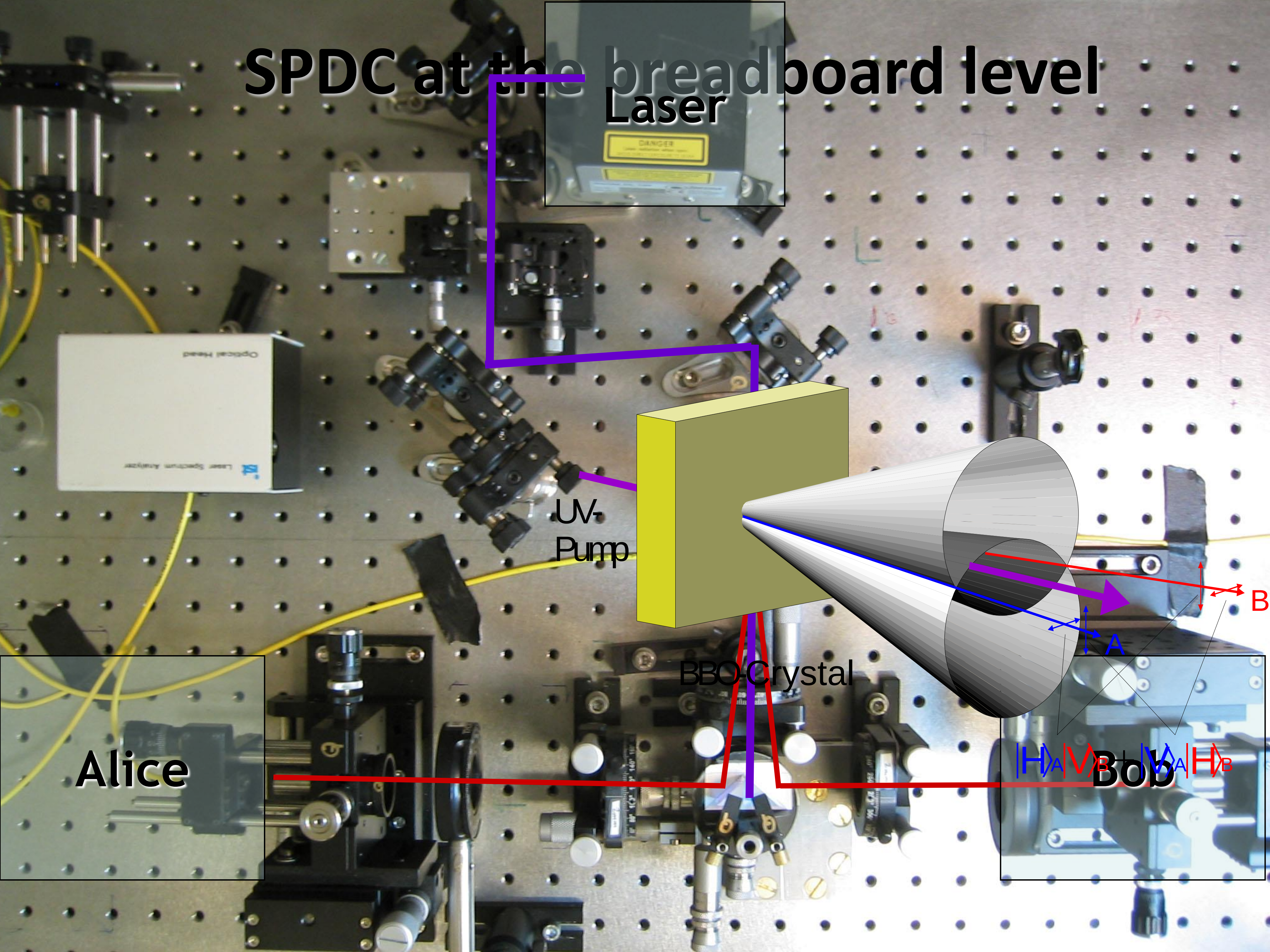


Flipping: $|H\rangle_1 |V\rangle_2$

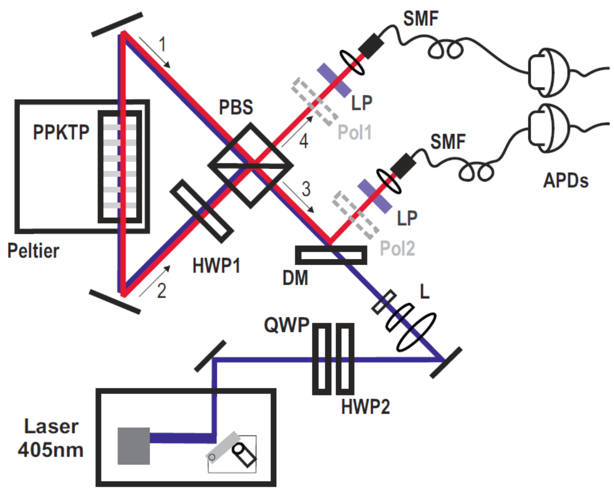
To: $|V\rangle_1 |H\rangle_2$

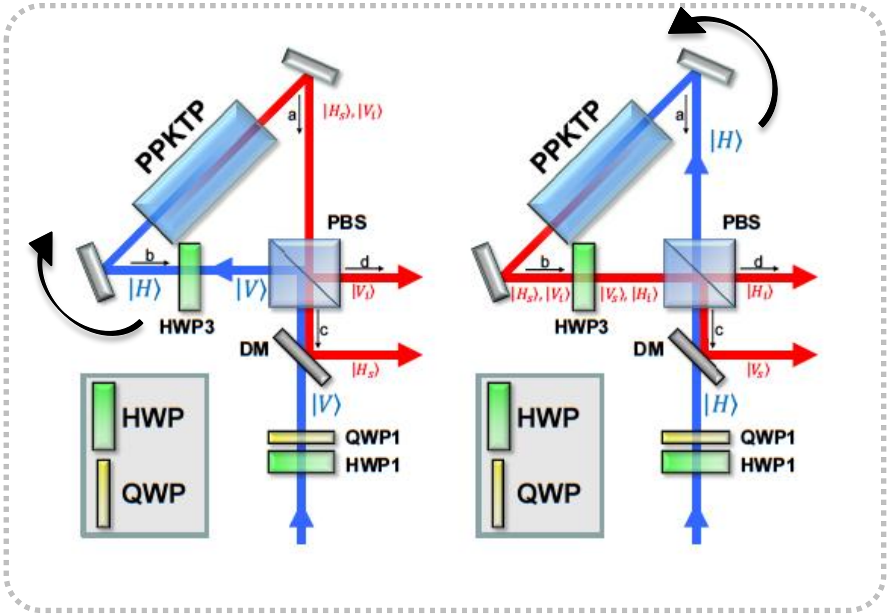
maximally entangled state: $$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1 |V\rangle_2 - e^{i\varphi}|V\rangle_1 |H\rangle_2\right) \qquad \varphi = 0, \pi$$

SPDC at the breadboard level



Sagnac interferometric configuration





Benefits: stability and high brightness

Pulse FHWM temporal width ≅ *2ps* (PPKTP crystal length of *30mm)*

Kim, Fiorentino, Wong, Phys. Rev. A 73, 012316 (2006)
Fedrizzi, Herbst, Poppe, Jennewein, Zeilinger, Opt. Express 15377 (2007)

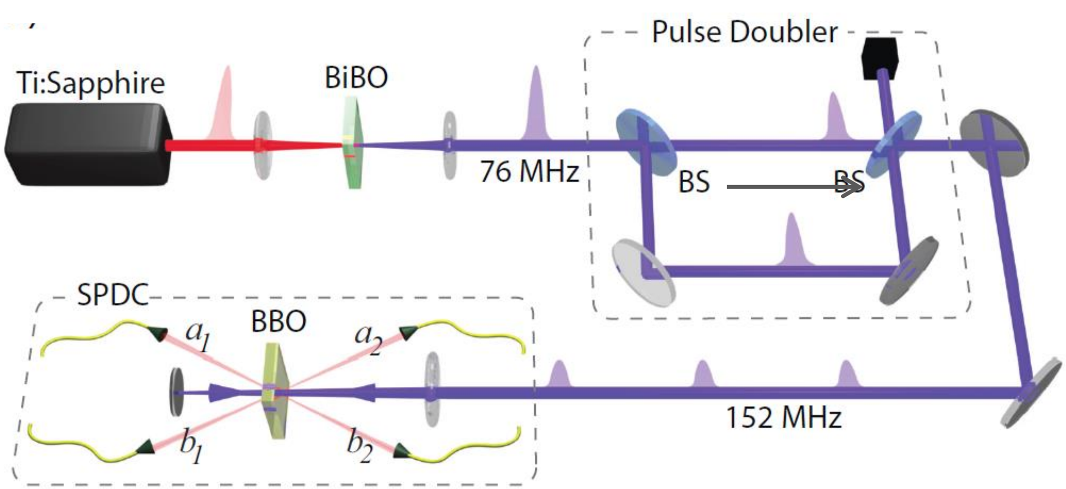
High-repetition rate pump pulses

Passive temporal multiplexing scheme:

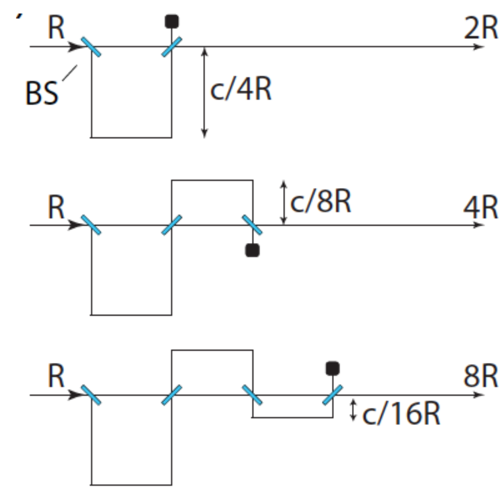
- increasing the pump laser repetition rate
- thus: reducing the energy of each pulse from the pump beam

$$C_{acc} = \frac{N_1 N_2}{f}$$ with N_i single photon rate for detector $i = 1, 2$

Doubling the pump laser repetition rate ***f*** :



Increasing 8 times ***f*** :

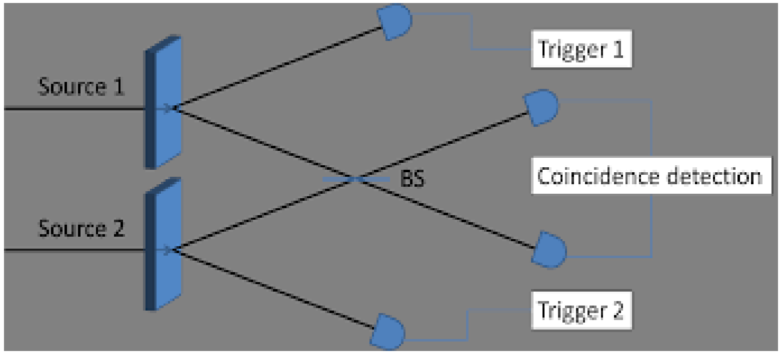


Broome, Almeida, White, Optics Express 19, 022698 (2011)

Probabilistic Single-Photon Sources

- Probabilisitc photon pair emission
  p ~ 0,02

- Probabillty that n sources emit
  p^n



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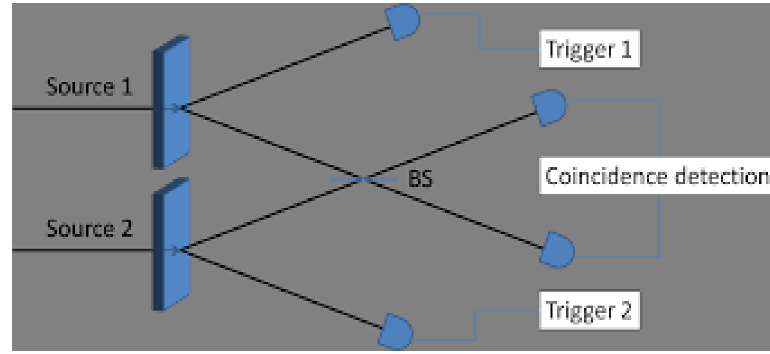

Quantum Physics

Experimental ten-photon entanglement

Xi-Lin Wang, Luo-Kan Chen, Wei Li, He-Liang Huang, Chang Liu, Chao Chen, Yi-Han Luo, Zu-En Su, Dian Wu, Zheng-Da Li, He Lu, Yi Hu, Xiao Jiang, Cheng-Zhi Peng, Li Li, Nai-Le Liu, Yu-Ao Chen, Chao-Yang Lu, Jian-Wei Pan

(Submitted on 27 May 2016)

Quantum entanglement among multiple spatially separated particles is of fundamental interest, and can serve as central resources for studies in quantum nonlocality, quantum-to-classical transition, quantum error correction, and quantum simulation. The ability of generating an increasing number of entangled particles is an important benchmark for quantum information processing. The largest entangled states were previously created with fourteen trapped ions, eight photons, and five superconducting qubits. Here, based on spontaneous parametric down-converted two-photon entanglement source with simultaneously a high brightness of ~12 MHz/W, a collection efficiency of

Probabilistic Single-Photon Sources

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- Probabillty that n sources emit
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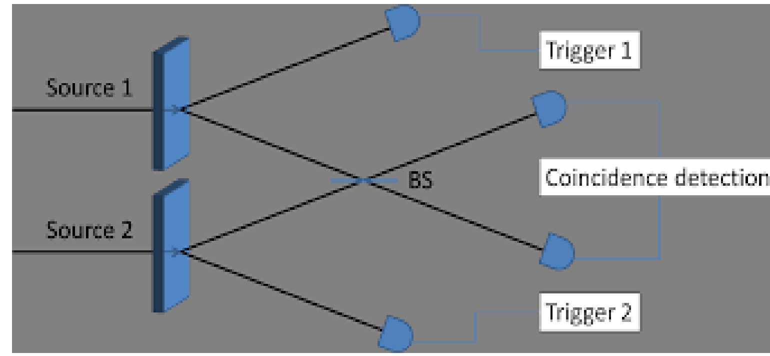


N-photon GHZ state	2 (*)	4 (*)	6 (*)	8 (*)	10 (*)	10 (**)
Fidelity	0.9720(1)	0.833(4)	0.710(16)	0.644(22)	0.573(23)	0.429(21)
Distillable entanglement, σ	5215	122.3	20.8	17.7	15.2	7.2
Genuine entanglement, σ	4334	84.6	13.3	6.5	3.1	-3.4
Count rate (Hz)	1000000	6000	39	0.2	0.0011	0.0031

* under a laser pump power of 0.57 W. ** under a laser pump power of 0.7 W.

quantum error correction, and quantum simulation. The ability of generating an increasing number of entangled particles is an important benchmark for quantum information processing. The largest entangled states were previously created with fourteen trapped ions, eight photons, and five superconducting qubits. Here, based on spontaneous parametric down-converted two-photon entanglement source with simultaneously a high brightness of ~12 MHz/W, a collection efficiency of

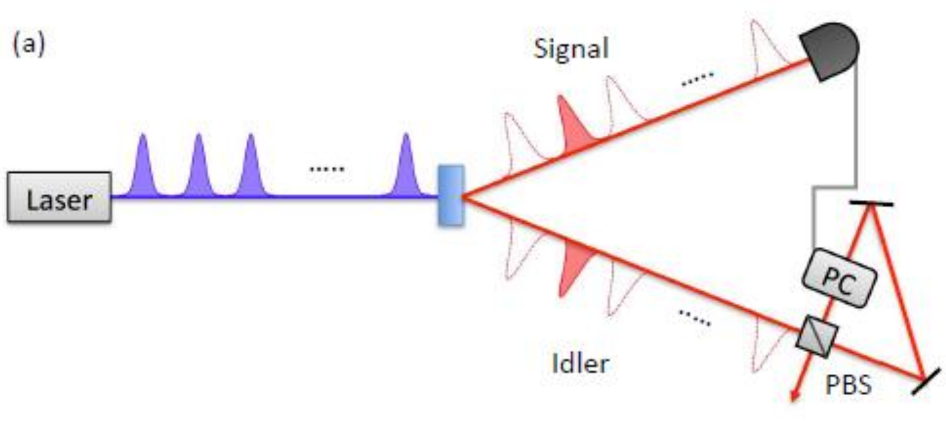
Probabilistic Single-Photon Sources

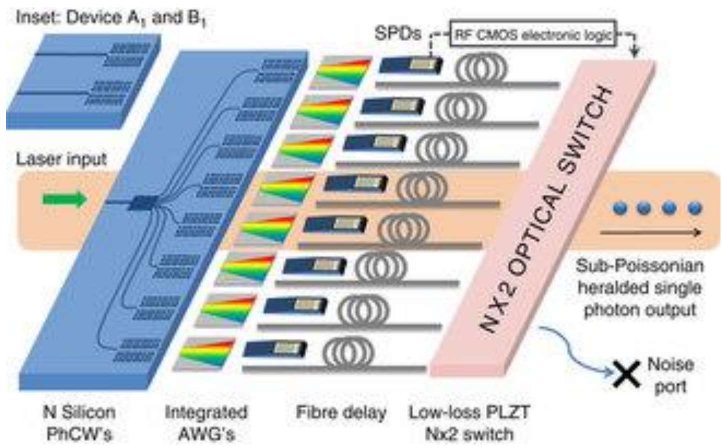
Approaches for non-exponential scaling of photon generation:

(1) Quantum Repeater (atoms, memory etc) → e.g. DLCZ scheme

(2) On-demand single-photon sources (dots, cavity-QED)

(3) Multiplexing of probabilistic sources (no atoms required)





Temporal multiplexing:
→ 6 times enhancement achieved

Spatial multiplexing:
→ 2-4 times enhancement

Kaneda et al. arXiv/quant-ph: 1507.06052 (2015)

Collins et al. Nature Communications 4, 2582 (2013)

Single-photon Detectors

Technology for Single-Photon Detection

- Probabilistic emission of down-converted photons

$$Coinc \propto \eta^N$$

N photon pair number
η system detection efficiency

N photon pair number	generated events/hour	detected events/hour
4	~33 000	~3000
6	~10	~2 × 10^{-2}
8	~4 × 10^{-3}	~9 × 10^{-6}
10	~1× 10^{-6}	~5 × 10^{-10}

- New quantum technologies open path for (probabilistic) multi-photon experiments

Detector	Detection efficiency	Maximum counting rates	Dead time	Jitter time
Current single-photon detector technologies				
Si avalanche photodiodes (APDs)	65%@650 nm	10 MHz	1 ns	400 ps
InGaAs APDs	10% @1.55 μm	10kHz	10 μs	370 ps
Emerging single-photon detector technologies				
Superconducting transition-edge sensors (TESs)	99%@1.55 μm	100kHz	1 μs	100ns
Superconducting nanowire single photon detectors (SNSPDs)	**93%@1.55 μm**	**GHz**	**100ps**	**40 ps**

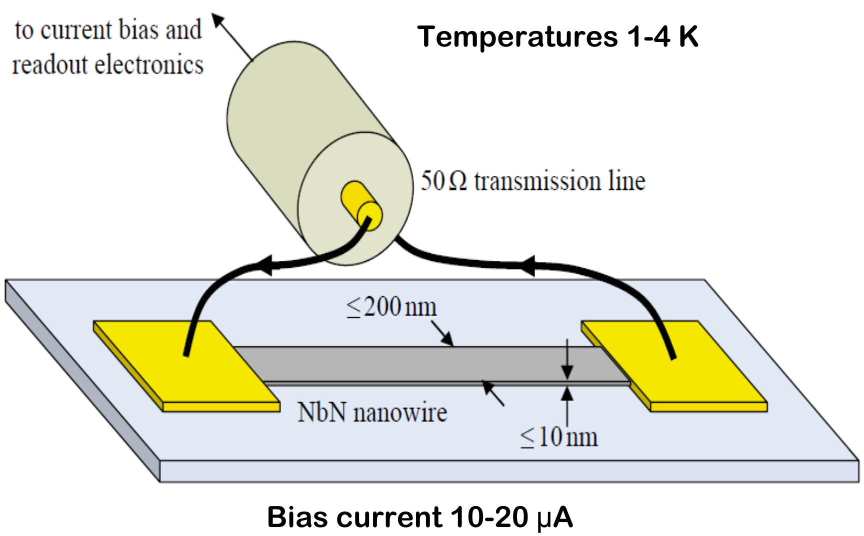
factor of 2-3 /photon
(~100x for six-photon states**)**

Marsili, Verma, Stern, Harrington, Lita, Gerrits, Vayshenker, Baek, Shaw, Mirin, Nam, Nature Photon 7, 210 (2013)

Superconducting nanowire physics

QuantumComputing@UniWien

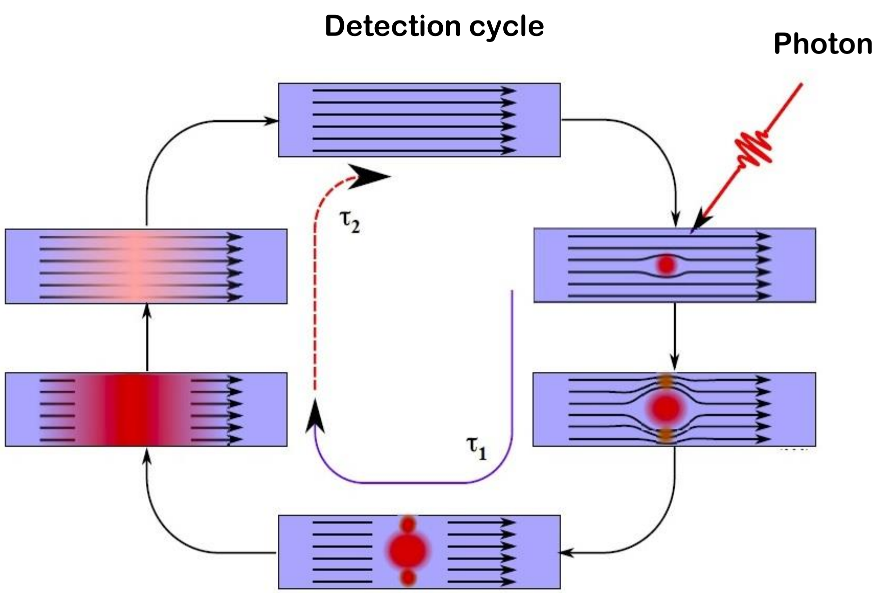
Operation



Bias current <15 μA

Temperature operation <1K

Detection cycle

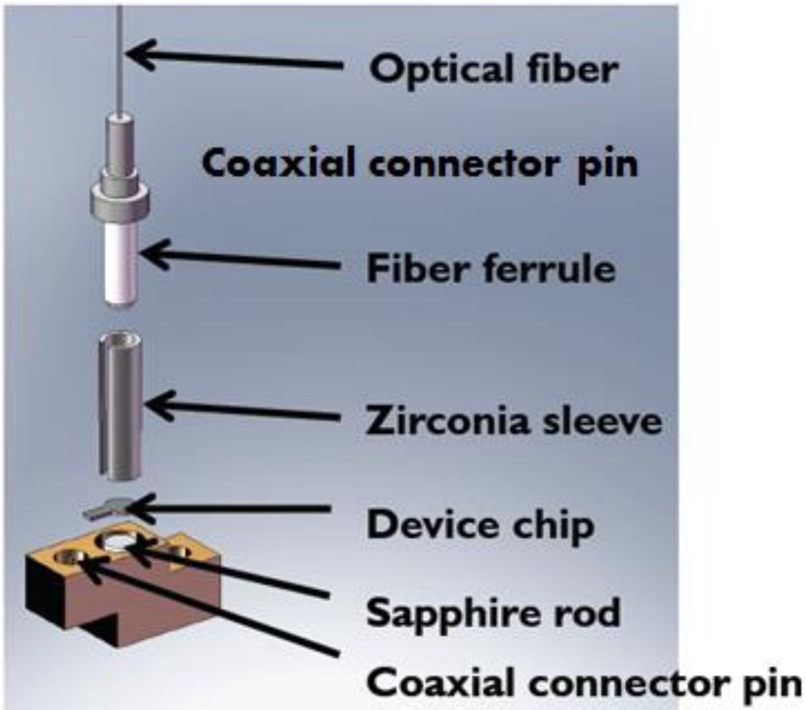


Dead times <50 ns

Jitter times <100 ps

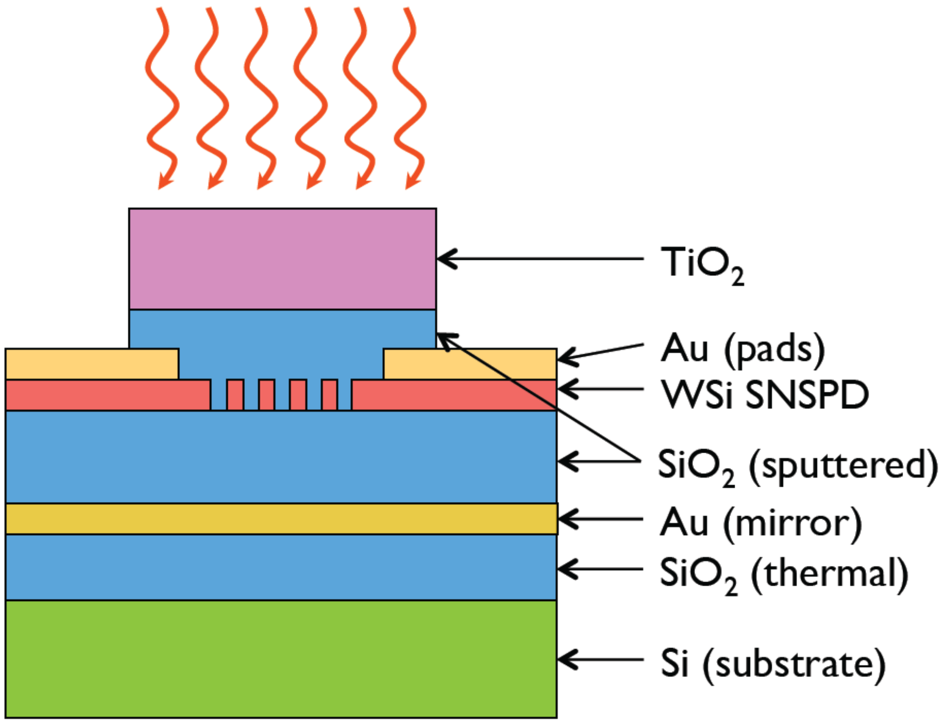
Optical alignment & Cavity design

Fiber-coupling detector



Miller et al., Opt. Express (2011)

Optical stack

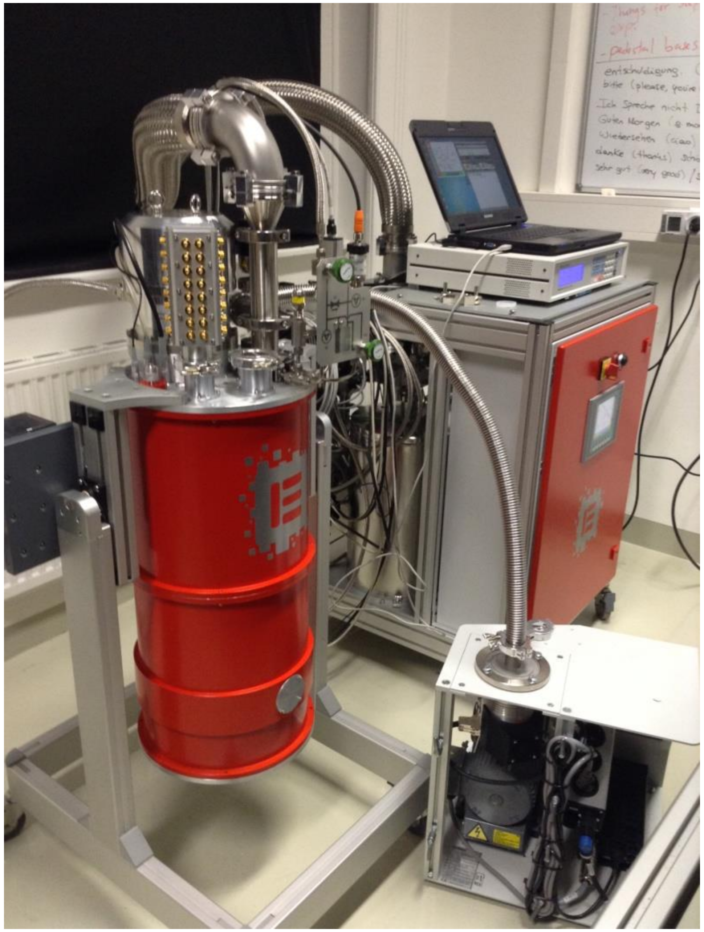


Highest coupling efficiency
Above 99%

Pseudo optical cavity (1550nm)
Above 95% absorption

System detection

Closed-cycle refrigerator

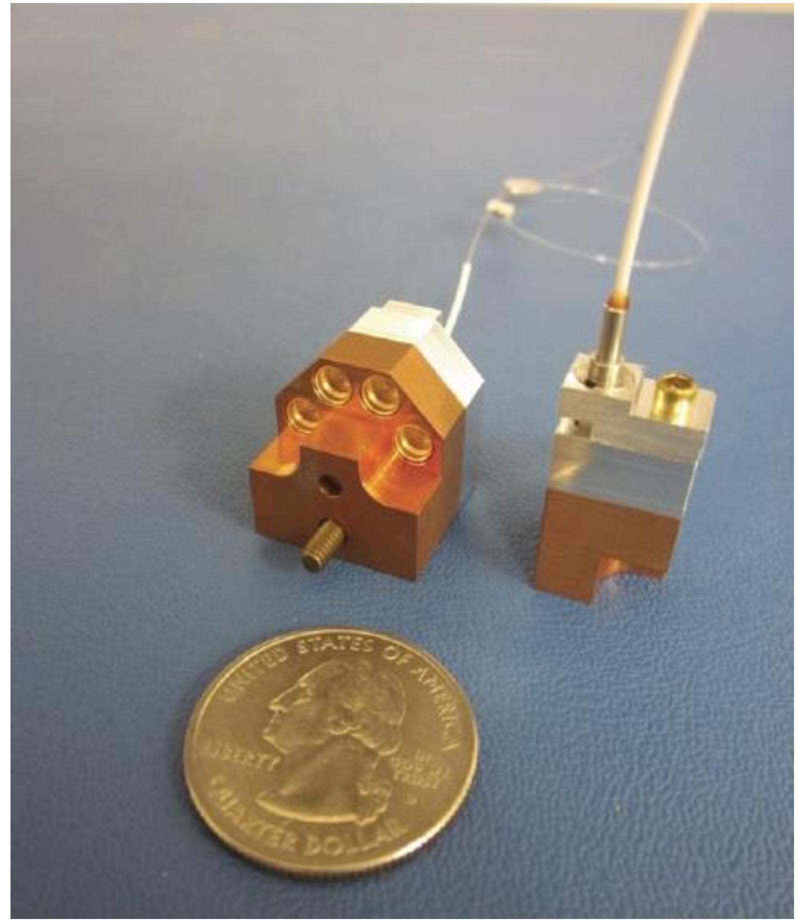


Joule-Thomson stage

Lowest temperature <0.9K

Cooling capacity > 1mW @ 1K

Four-element detector



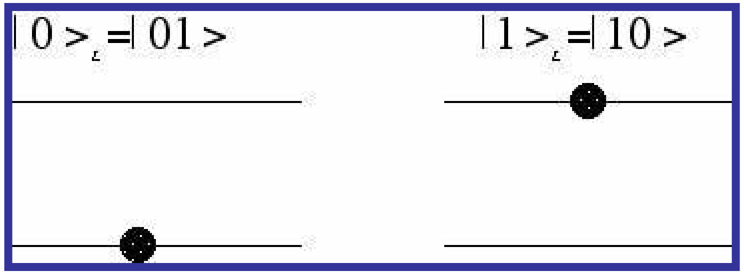
12 Four-element detector units

above 95% efficiency at telecom-wavelength

(Amorphous tungsten-silicon alloy + pseudo optical cavity)

Photonic Quantum Gates

Path-Encoding: Linear Algebra

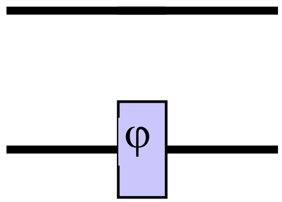


$|0\rangle$ **corresponds to** $\begin{pmatrix} 1 \\ 0 \end{pmatrix}$

$|1\rangle$ **corresponds to** $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

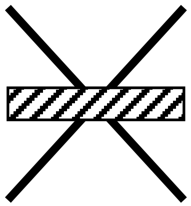
$\alpha_0|0\rangle + \alpha_1|1\rangle$ **corresponds to** $\alpha_0\begin{pmatrix} 1 \\ 0 \end{pmatrix} + \alpha_1\begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \alpha_0 \\ \alpha_1 \end{pmatrix}$

Path-Encoding: Linear Algebra



corresponds to

$$\begin{pmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{pmatrix}$$



corresponds to

$$\begin{pmatrix} \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{i}{\sqrt{2}} \end{pmatrix}$$

Hadamard:

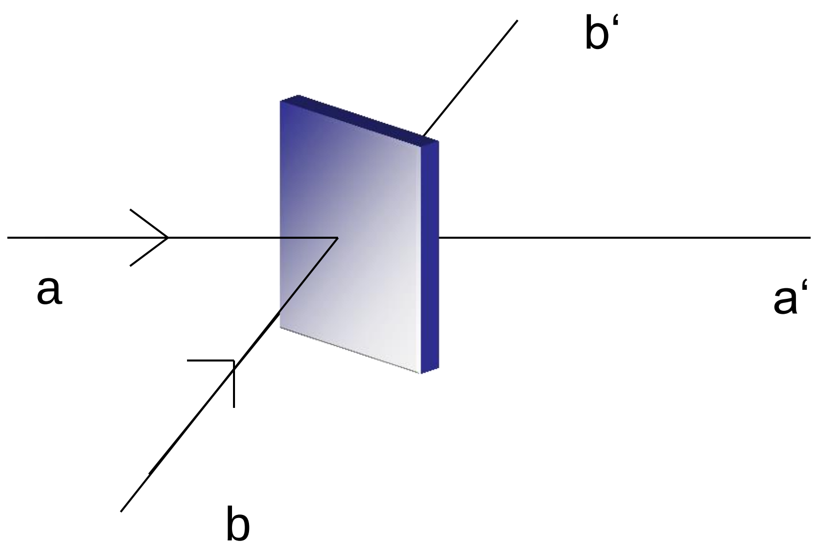
Just a 50/50 beamsplitter!

$$H = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

The (linear) ease of single photons

The whole Bloch sphere is accesible with linear optics operations (phase retardation, polarizing and non-polarizing beamsplitters)

Non-polarizing symmetric beam splitter (Hadamard gate)



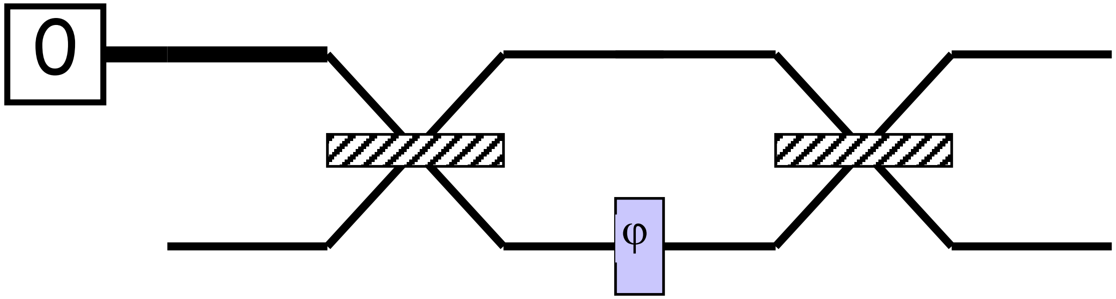
$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

$$a^{\dagger}_{H,V} \longrightarrow \frac{1}{\sqrt{2}} (a^{\dagger}_{H,V} + b^{\dagger}_{H,V})$$

$$b^{\dagger}_{H,V} \longrightarrow \frac{1}{\sqrt{2}} (a^{\dagger}_{H,V} - b^{\dagger}_{H,V})$$

$$H|10\rangle_{ab} = \frac{1}{\sqrt{2}} (|10\rangle_{ab} + |01\rangle_{ab})$$

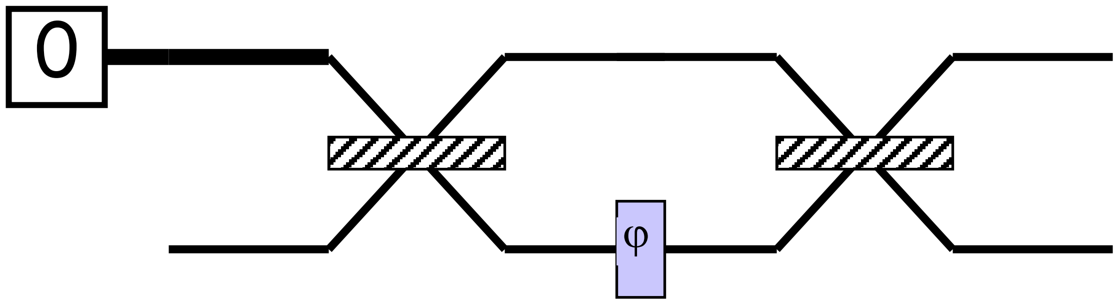
Path-Encoding: Single-Qubit Control



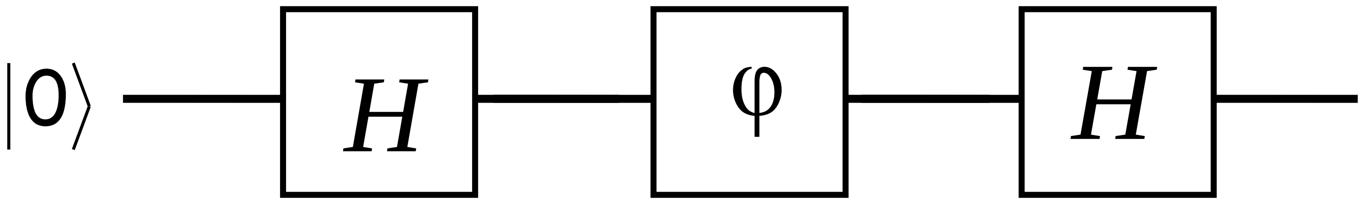
corresponds to

$$\begin{pmatrix} \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{i}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & e^{i\varphi} \end{pmatrix} \begin{pmatrix} \frac{i}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{i}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Path-Encoding: Single-Qubit Control

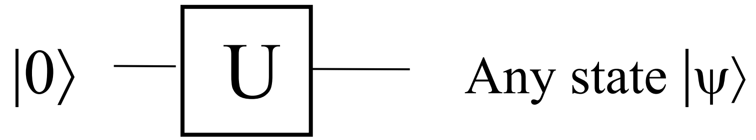


corresponds to the circuit



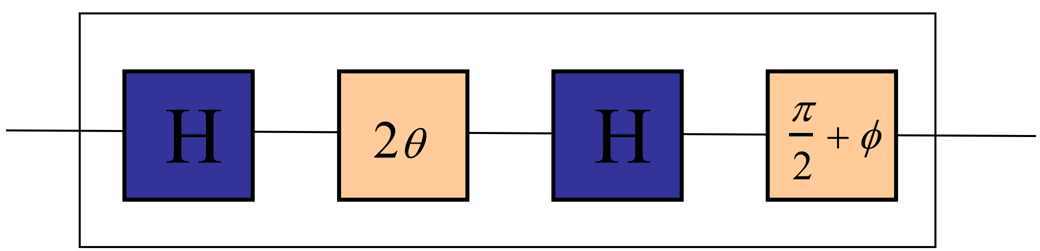
Path-Encoding: Arbitrary one-qubit Rotation

- Requirement:



- **Hadamard** and **phase-shift** gates form a universal gate set
- *Example*: The following circuit generates

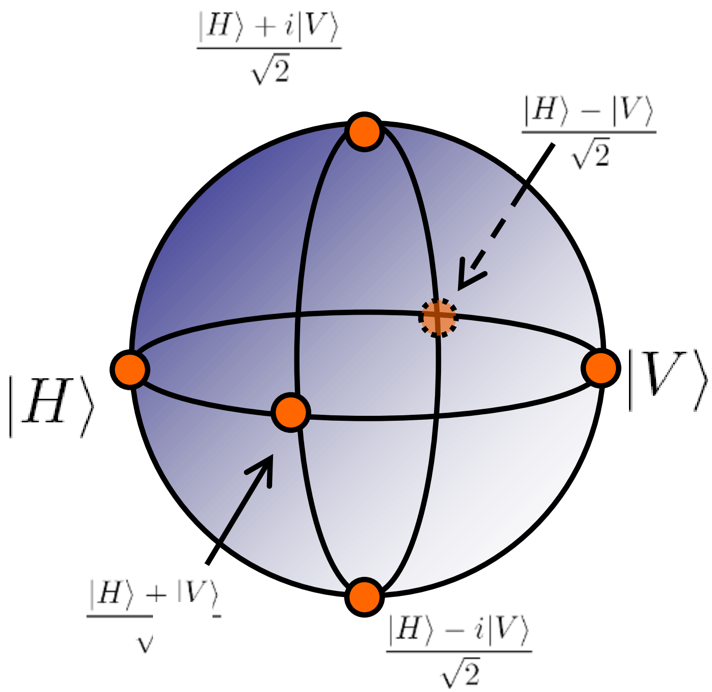
$$|\psi\rangle = \cos\theta\ |0\rangle + e^{i\phi}\sin\theta\ |1\rangle$$ up to a global factor

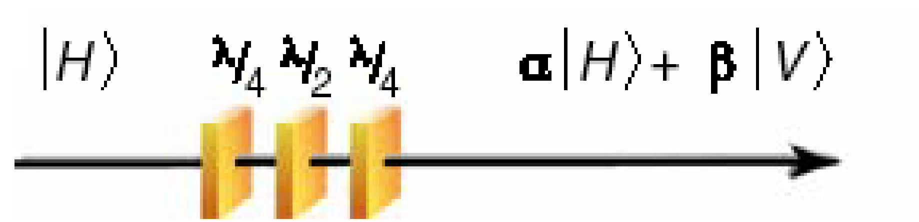


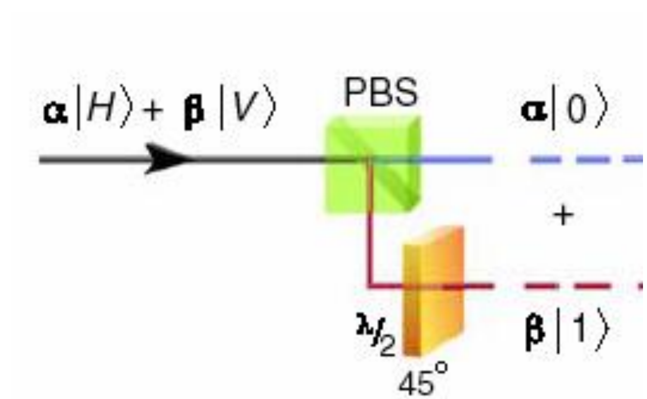
Polar.-Encoding: Arbitrary one-qubit Rotation

Requirement:

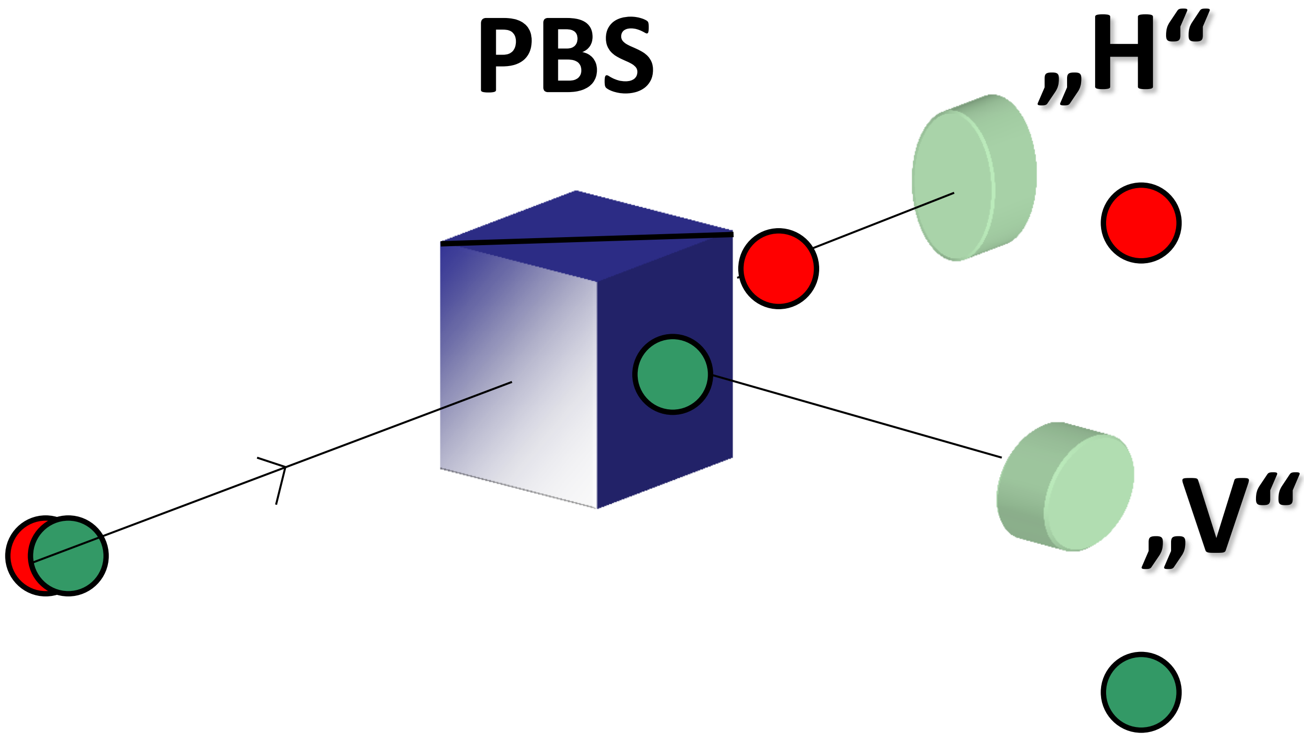
$|0\rangle$ — $\boxed{U}$ — Any state $|\psi\rangle$



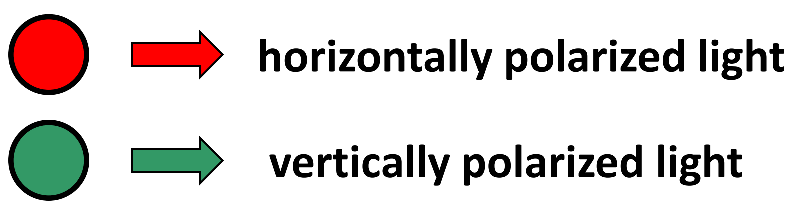




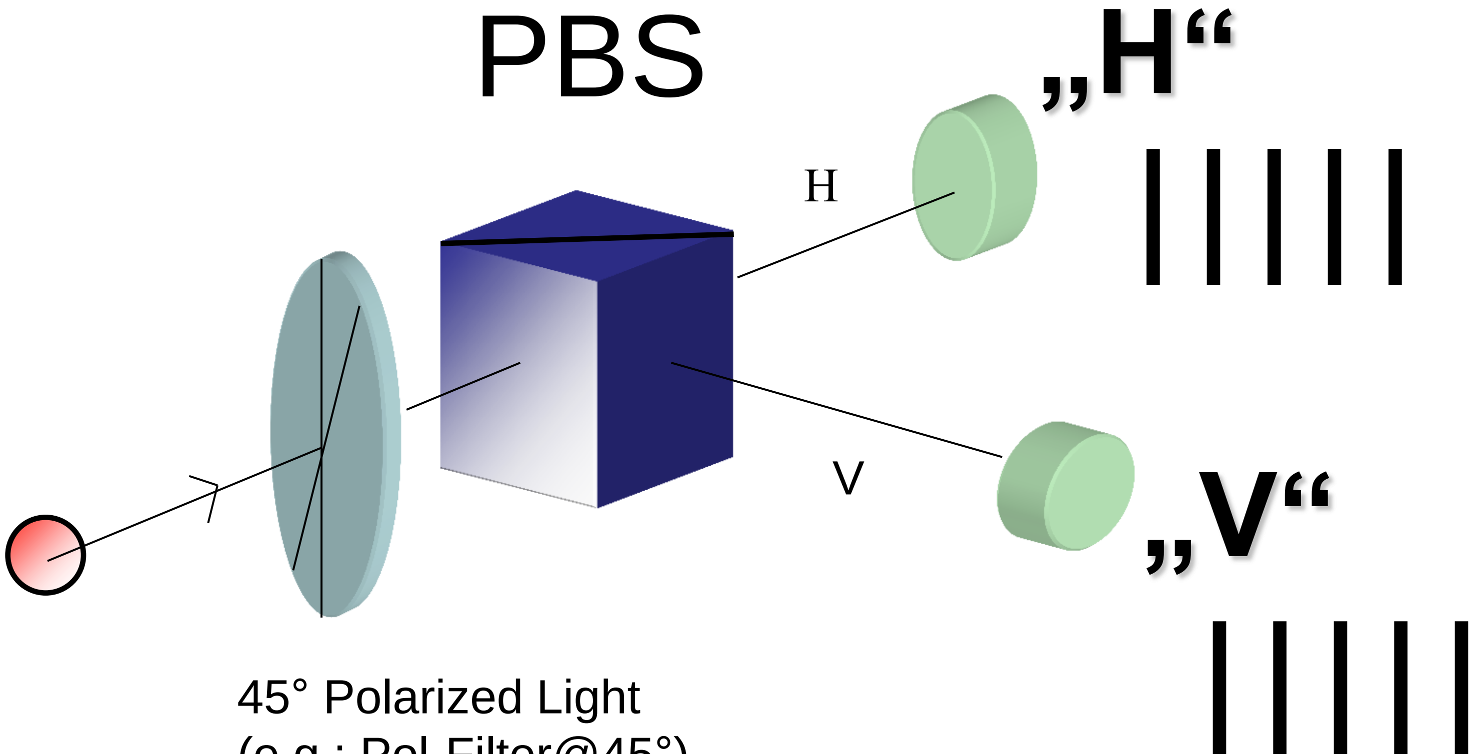
Polarizing Beamsplitter (PBS)



$$a_H^\dagger \longrightarrow a_H^\dagger$$
$$a_V^\dagger \longrightarrow b_V^\dagger$$



Hadamard via Polarizing Beamsplitters

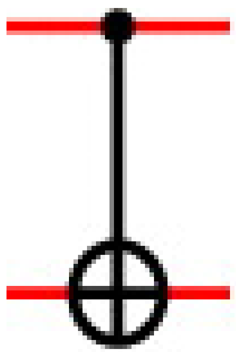


45° Polarized Light
(e.g.: Pol-Filter@45°)

2-Photon QIP
(two-qubit gates)

The challenge: photon-photon interaction

Control-NOT Gate (Control-X)



$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$\boxed{\begin{aligned} |H\rangle_C |H\rangle_T &\rightarrow |H\rangle_C |H\rangle_T \\ |H\rangle_C |V\rangle_T &\rightarrow |H\rangle_C |V\rangle_T \\ |V\rangle_C |H\rangle_T &\rightarrow |V\rangle_C |V\rangle_T \\ |V\rangle_C |V\rangle_T &\rightarrow |V\rangle_C |H\rangle_T \end{aligned}}$$

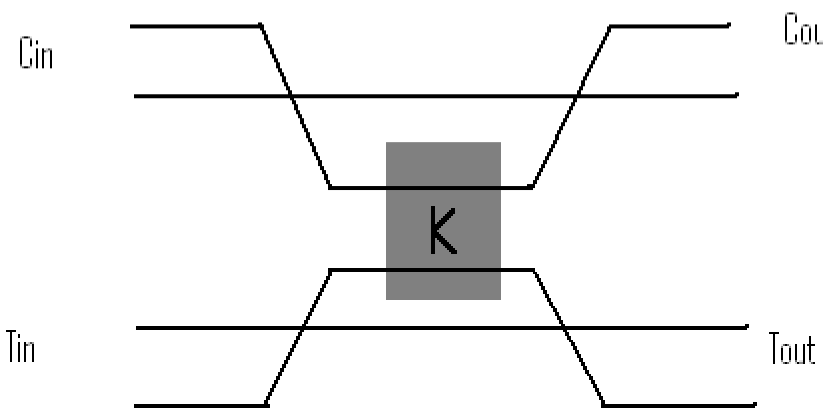
Using Nonlinearity in Medium: The Kerr effect

Control-Phase Gate

- Possible via Kerr-effect

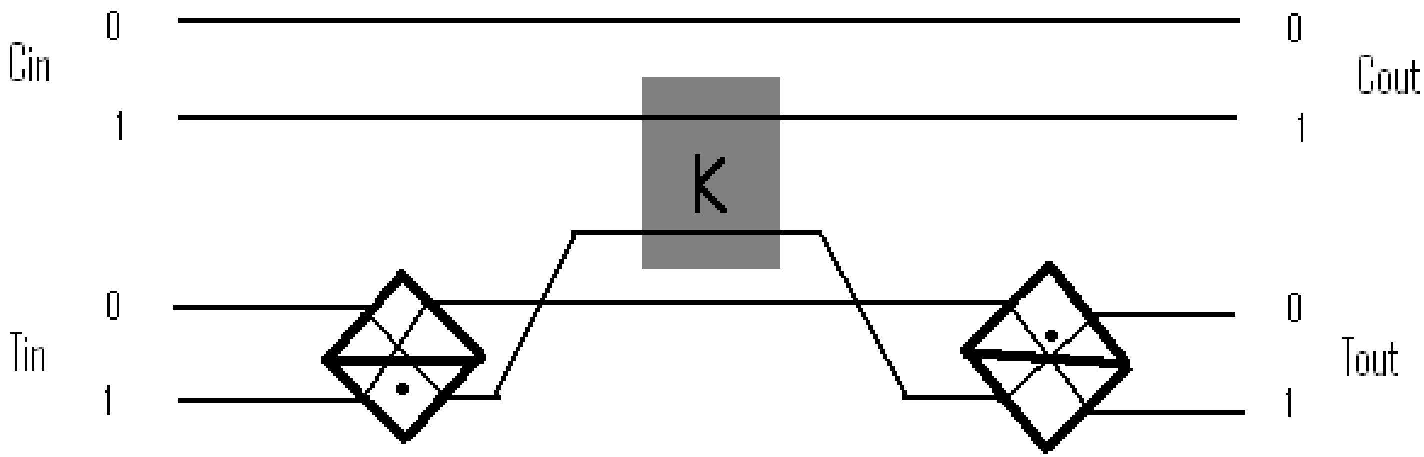
$$n_{\mathrm{Kerr}} = n_0 + \chi^{(3)} E^2$$

- But: 3rd order susceptibility is on the order of 10^{18} m^2/W
- unlikely for single photons
- Some techniques can enhance the nonlinearity significantly (~10^2) -> Cavity-QED

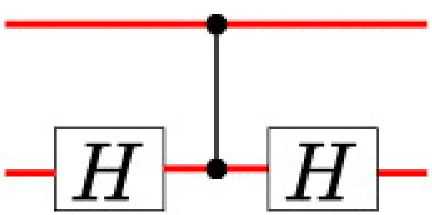


$$K = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Conversion of a C-Phase to C-NOT gate



$$K = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$



2-Photon QIP
(two-qubit gates)

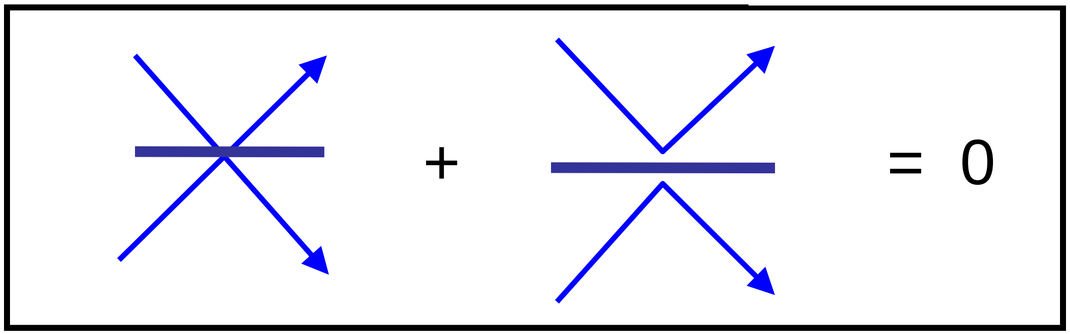
-> Effective Nonlinearity via measurement!!!

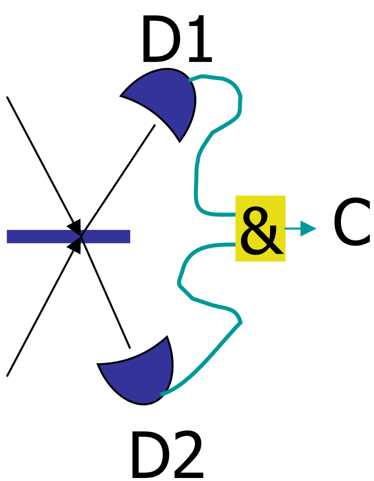
Fundamental Quantum Interference

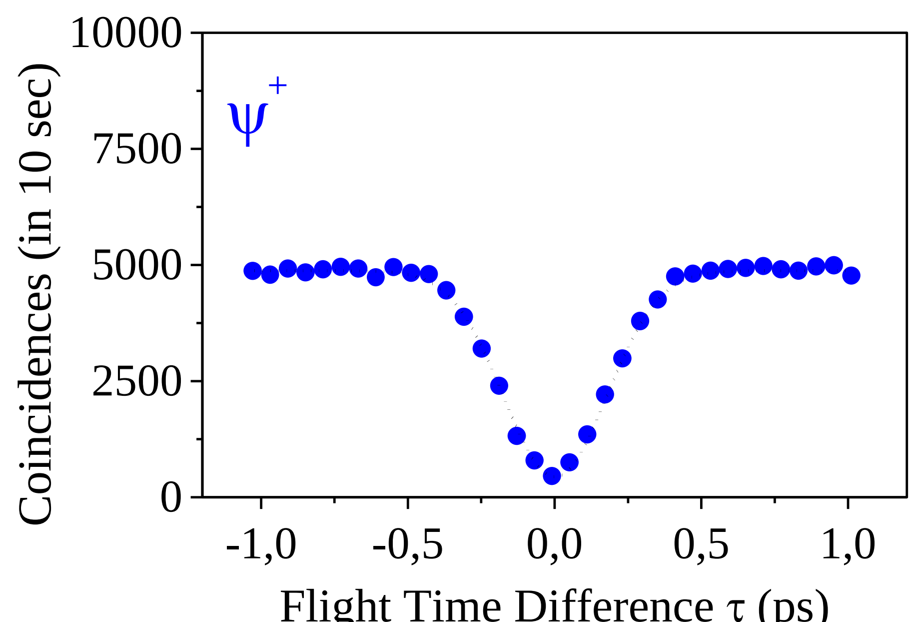
Bosonic Input → Bunching
(Hong-Ou-Mandel Effect)

$$|11\rangle_{ab} \longrightarrow H|11\rangle_{ab} = H\ a^{\dagger}b^{\dagger}\ |00\rangle_{ab}$$

Beamsplitter:
T= 50%
R=50%







Hong-Ou-Mandel type experiments

VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 10 July 1987)

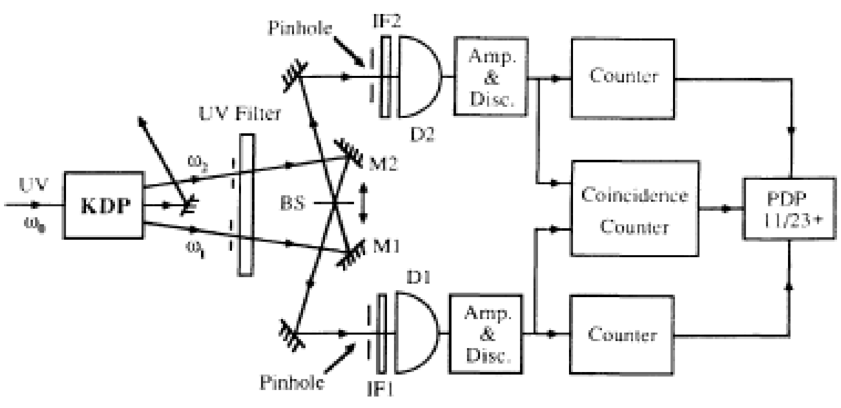
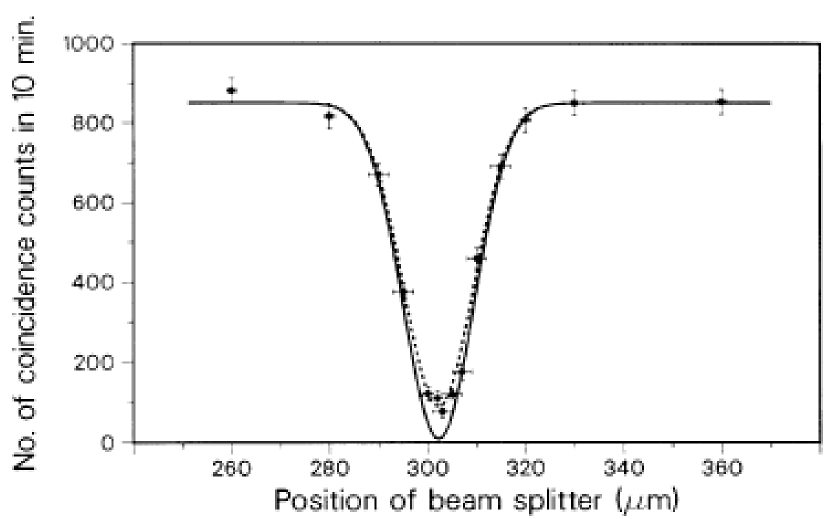


FIG. 1. Outline of the experimental setup.



How complicated you have to make it sound if you want to get it published (a joke!)

We turn now to the general case with two polarizers set at arbitrary angles θ_1 and θ_2.

$$
\begin{aligned}
P_c(0) &\approx \langle \psi | \hat{P}_{\mathrm{pol},1}(\theta_1)\hat{P}_{\mathrm{pol},2}(\theta_2)\hat{P}_{c,\mathrm{red}}{}'\hat{P}_{\mathrm{pol},2}(\theta_2)\hat{P}_{\mathrm{pol},1}(\theta_1)|\psi\rangle_{\Delta x=0} \\
&= \tfrac{1}{2}[\langle 1_1^H 1_2^{H+\phi}| - \langle 1_1^{H+\phi} 1_2^H|](|1_1^{H+\theta_1}\rangle\langle 1_1^{H+\theta_1}|)(|1_2^{H+\theta_2}\rangle\langle 1_2^{H+\theta_2}|)(\hat{a}^\dagger_{1,H}\hat{a}_{1,H}+\hat{a}^\dagger_{1,V}\hat{a}_{1,V}) \\
&\quad \times(\hat{a}^\dagger_{2,H}\hat{a}_{2,H}+\hat{a}^\dagger_{2,V}\hat{a}_{2,V})(|1_2^{H+\theta_2}\rangle\langle 1_2^{H+\theta_2}|)(|1_1^{H+\theta_1}\rangle\langle 1_1^{H+\theta_1}|)\tfrac{1}{2}[|1_1^H 1_2^{H+\phi}\rangle - |1_1^{H+\phi}1_2^H\rangle] \ .
\end{aligned}
$$

Using Eq. (A2), one can expand $|\tilde{\psi}\rangle_{\Delta x=0} = \hat{P}_{\mathrm{pol},2}(\theta_2)\hat{P}_{\mathrm{pol},1}(\theta_1)|\psi\rangle_{\Delta x=0}$. After simplifying algebra one finds

$$
\begin{aligned}
|\tilde{\psi}\rangle_{\Delta x=0} &= |1_1^H 1_2^H\rangle \cos\theta_1\cos\theta_2\sin(\theta_2-\theta_1)\sin\phi + ||1_1^V 1_2^V\rangle \sin\theta_1\sin\theta_2\sin(\theta_2-\theta_1)\sin\phi \\
&\quad + |1_1^H 1_2^V\rangle \cos\theta_1\sin\theta_2\sin(\theta_2-\theta_1)\sin\phi + |1_1^V 1_2^H\rangle \sin\theta_1\cos\theta_2\sin(\theta_2-\theta_1)\sin\phi \ .
\end{aligned}
$$

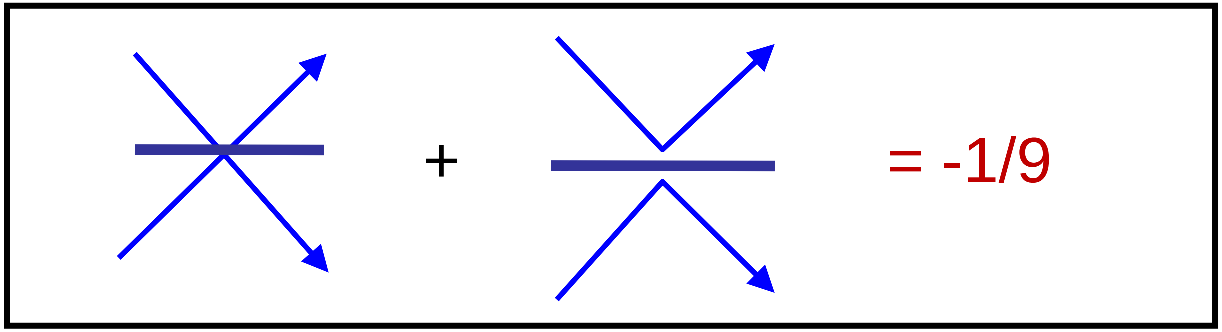
It then follows that

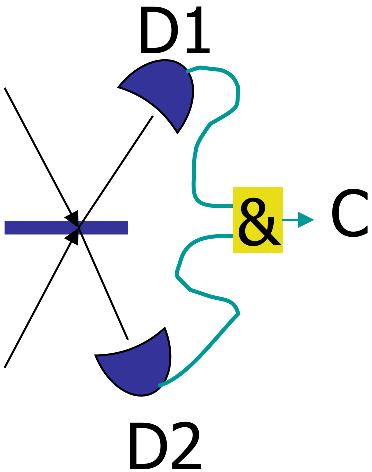
$$P_c(0) \approx \langle \tilde{\psi}|\hat{P}_{c,\mathrm{red}}{}'|\tilde{\psi}\rangle_{\Delta x=0} = \sin^2\phi\sin^2(\theta_2-\theta_1) \ ,$$

which is the more general case of Eq. (13).

Tuning Quantum Interference for 2-Photon Gates

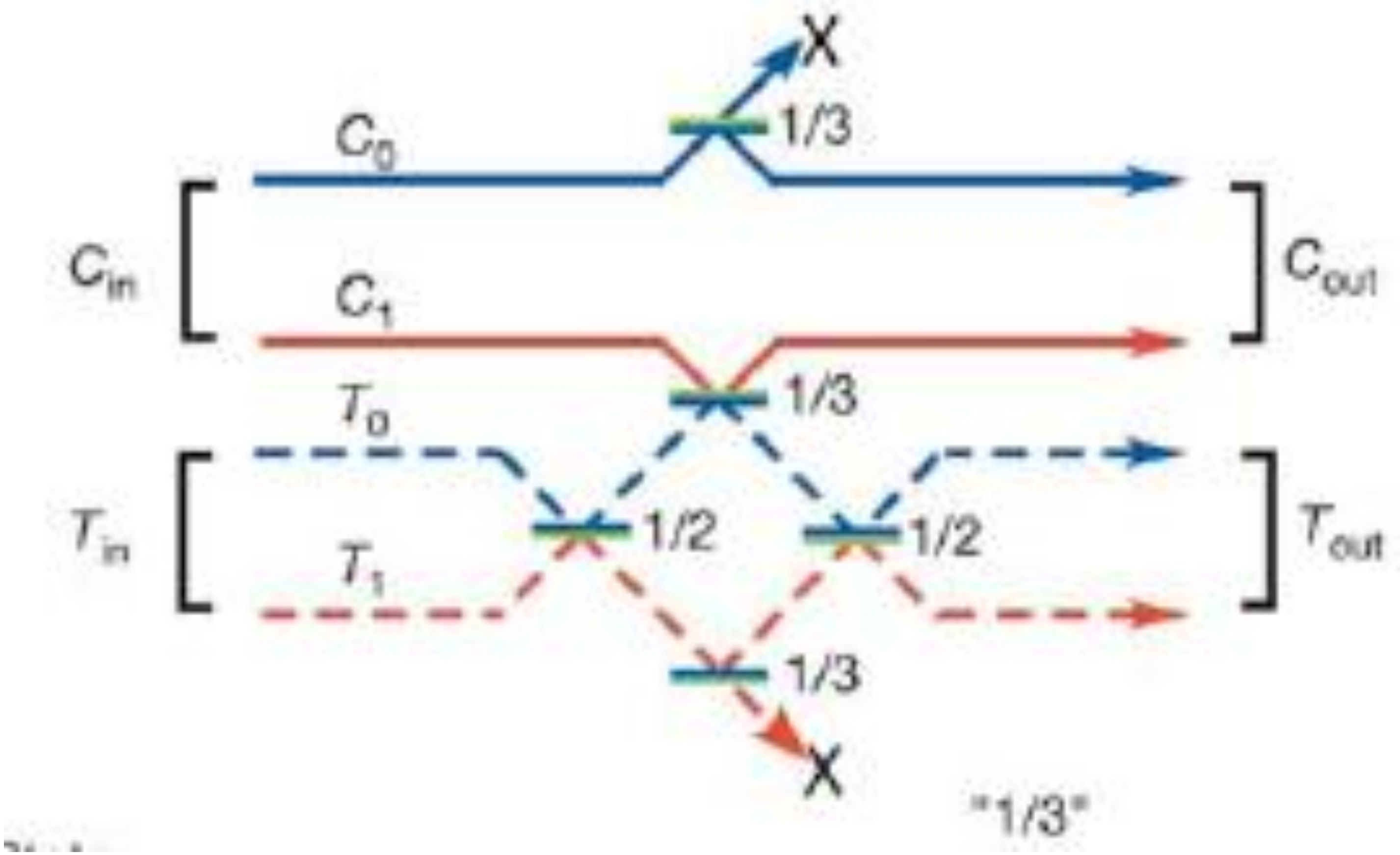
Beamsplitter:
T= 33%
R=67%





Sometimes (1/9): 2-fold-condicidences
→ these events have a (-1) phase !!!

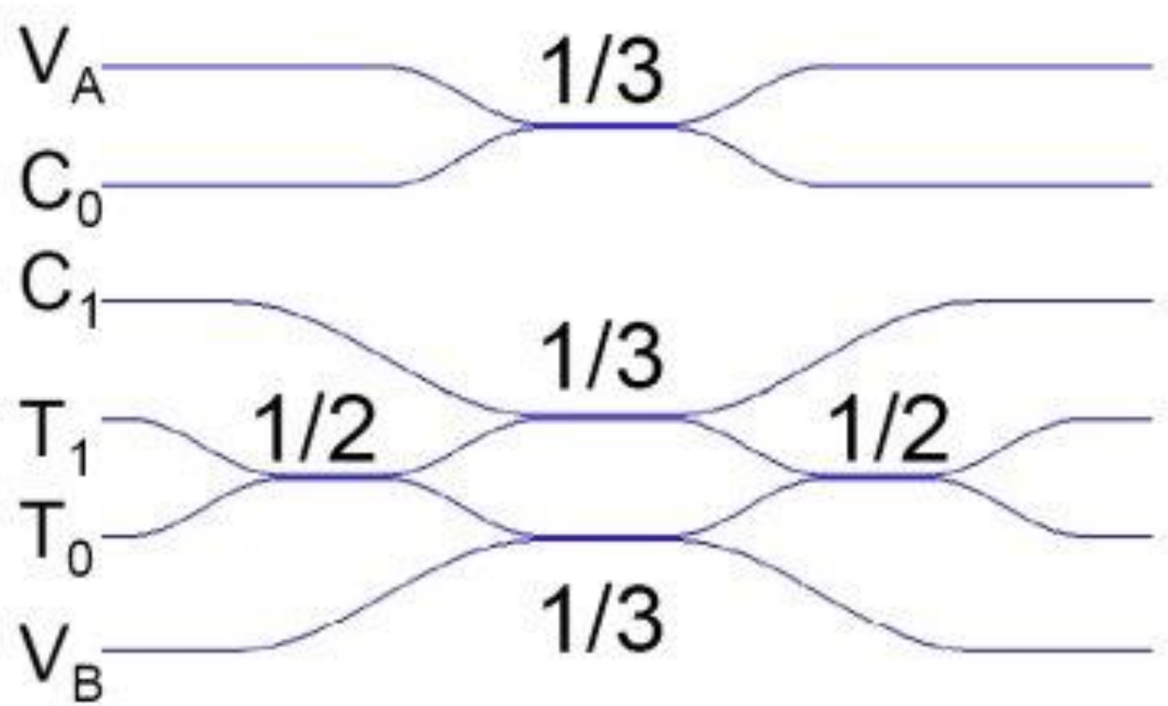
Linear-Optical C-NOT Gate (Path)

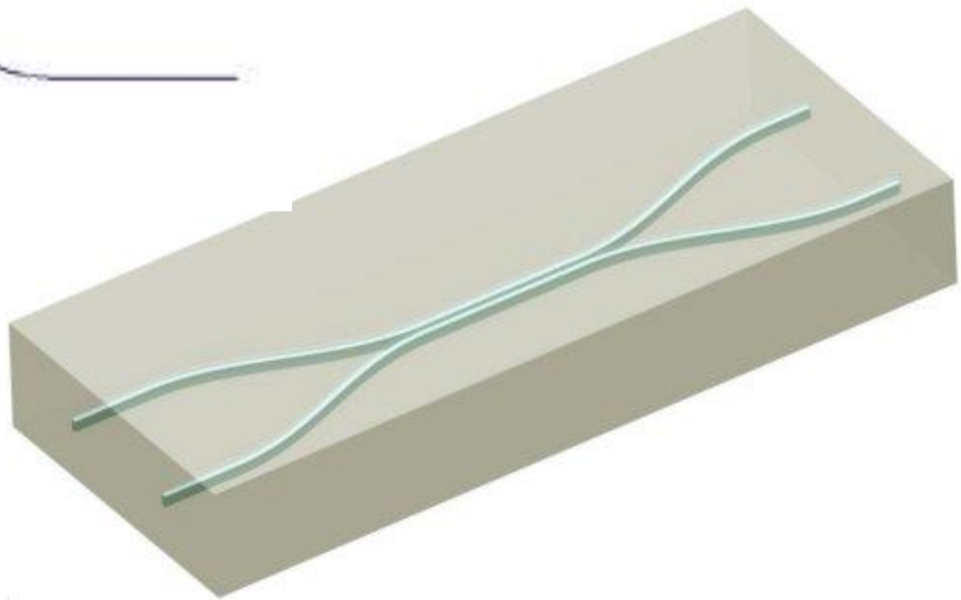


- Success probability: p=1/9
- Destructive (required to measure output)

OBrien et al., Nature 426, 264 (2003)

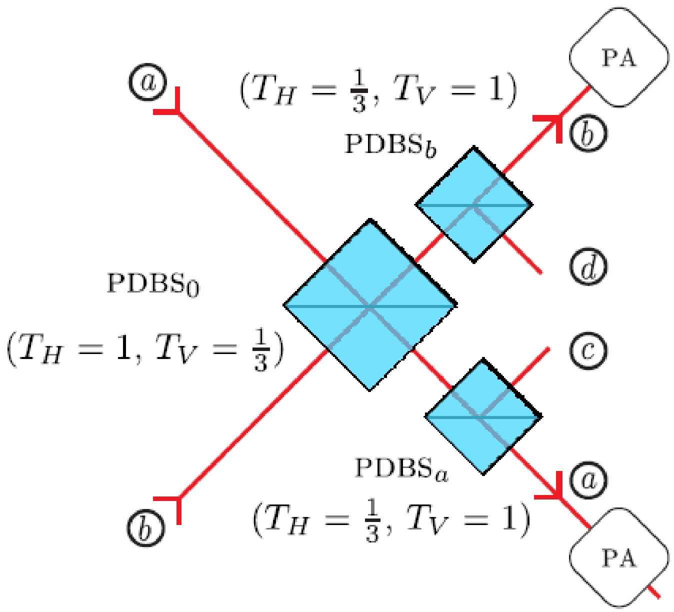
Integrated Optics for Path-Encoded C-NOT





Politi et al., Science 320, 646 (2008)

Polarization-Encoded Photons: 2-photon gate is simplified



$$\mathrm{PDBS}_0 : \begin{cases} a_H^\dagger \to a_H^\dagger \\ a_V^\dagger \to \sqrt{\frac{1}{3}}a_V^\dagger + \mathrm{i}\sqrt{\frac{2}{3}}b_V^\dagger \\ b_H^\dagger \to b_H^\dagger \\ b_V^\dagger \to \sqrt{\frac{1}{3}}b_V^\dagger + \mathrm{i}\sqrt{\frac{2}{3}}a_V^\dagger \end{cases}$$

$$\mathrm{PDBS}_a : \begin{cases} a_H^\dagger \to \sqrt{\frac{1}{3}}a_H^\dagger + \mathrm{i}\sqrt{\frac{2}{3}}c_H^\dagger \\ a_V^\dagger \to a_V^\dagger \end{cases}$$

$$\mathrm{PDBS}_b : \begin{cases} b_H^\dagger \to \sqrt{\frac{1}{3}}b_H^\dagger + \mathrm{i}\sqrt{\frac{2}{3}}d_H^\dagger \\ b_V^\dagger \to b_V^\dagger \end{cases}$$

$$a_H^\dagger b_H^\dagger \xrightarrow{\mathrm{PDBS}_0} a_H^\dagger b_H^\dagger \xrightarrow{\mathrm{PDBS}_{a,b}} \sqrt{\frac{1}{3}}a_H^\dagger\sqrt{\frac{1}{3}}b_H^\dagger = \sqrt{\frac{1}{9}}a_H^\dagger b_H^\dagger$$

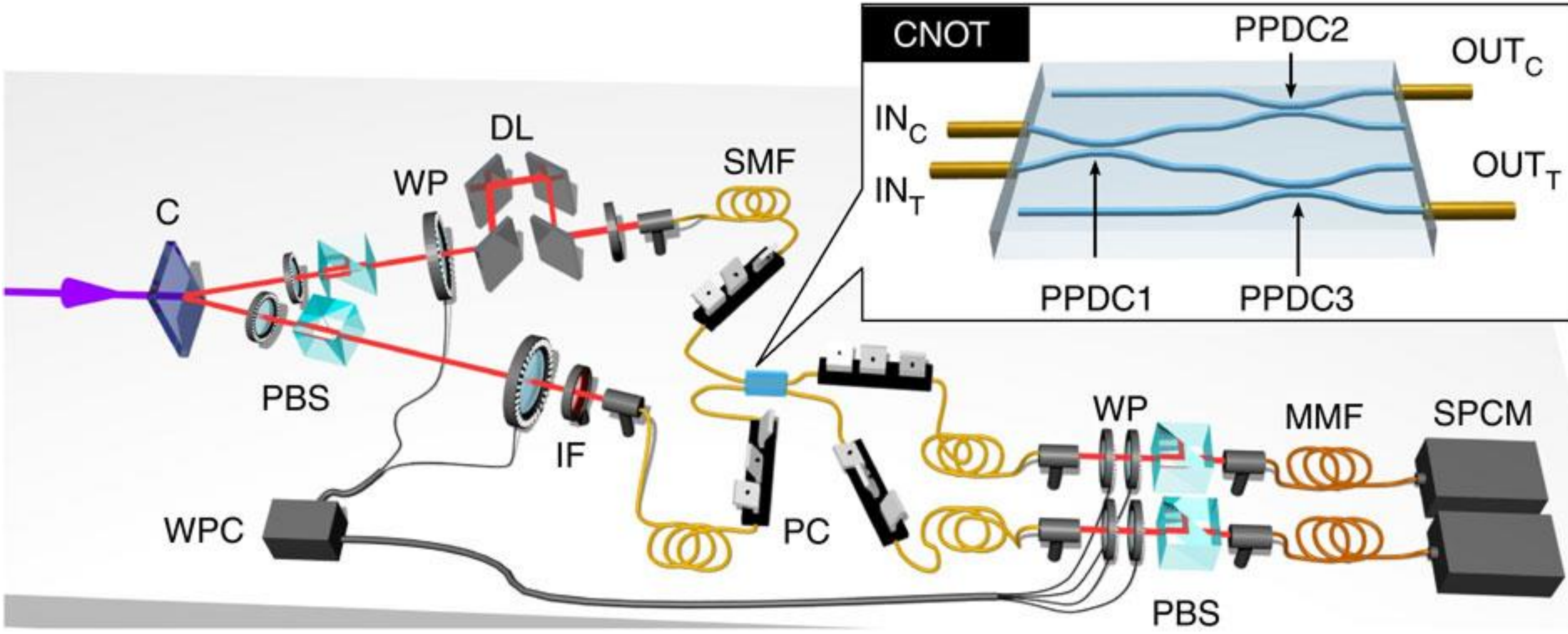
$$a_H^\dagger b_V^\dagger \xrightarrow{\mathrm{PDBS}_0} a_H^\dagger\sqrt{\frac{1}{3}}b_V^\dagger \xrightarrow{\mathrm{PDBS}_{a,b}} \sqrt{\frac{1}{3}}a_H^\dagger\sqrt{\frac{1}{3}}b_V^\dagger = \sqrt{\frac{1}{9}}a_H^\dagger b_V^\dagger$$

$$a_V^\dagger b_H^\dagger \xrightarrow{\mathrm{PDBS}_0} \sqrt{\frac{1}{3}}a_V^\dagger b_H^\dagger \xrightarrow{\mathrm{PDBS}_{a,b}} \sqrt{\frac{1}{3}}a_V^\dagger\sqrt{\frac{1}{3}}b_H^\dagger = \sqrt{\frac{1}{9}}a_V^\dagger b_H^\dagger$$

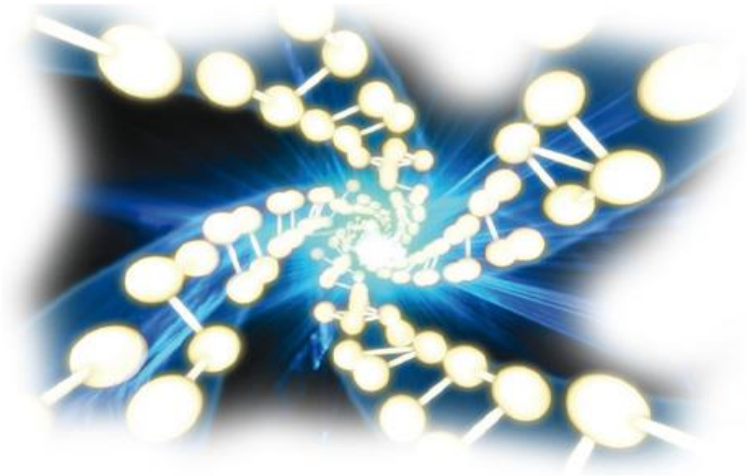
$$\boxed{a_V^\dagger b_V^\dagger \xrightarrow{\mathrm{PDBS}_0} \sqrt{\frac{1}{3}}a_V^\dagger\sqrt{\frac{1}{3}}b_V^\dagger + \mathrm{i}\sqrt{\frac{2}{3}}a_V^\dagger \mathrm{i}\sqrt{\frac{2}{3}}b_V^\dagger \xrightarrow{\mathrm{PDBS}_{a,b}} \frac{1}{3}a_V^\dagger b_V^\dagger - \frac{2}{3}a_V^\dagger b_V^\dagger = -\sqrt{\frac{1}{9}}a_V^\dagger b_V^\dagger}$$

Physical Review Letters (2005):
3 groups: Australia, Germany, Japan

Integrated C-NOT (C-Phase) Gate



Crespi et al., Nature Communications 2, 566 (2011)



Quantum Simulation Using Photons

Philip Walther

Faculty of Physics
University of Vienna
Austria

Enrico Fermi Summer School
Varenna, Italy
24-25 July 2016

PICQUE EQuaM AFOSR AIR FORCE OFFICE OF SCIENTIFIC RESEARCH universität wien SEVENTH FRAMEWORK PROGRAMME W|W|T|F VIENNA SCIENCE AND TECHNOLOGY FUND CoQuS Complex Quantum Systems FWF Der Wissenschaftsfonds. GRASP THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION HORIZON 2020

Lecture II:
Non-destructive / scalable photonic quantum gates & Photonic Quantum Simulation

Non-destructive two-qubit gates via extra (ancilla) photons

Non-Destructive C-NOT gate

$$\boxed{\begin{aligned}&|H\rangle_C |H\rangle_T \to |H\rangle_C |H\rangle_T\\&|H\rangle_C |V\rangle_T \to |H\rangle_C |V\rangle_T\\&|V\rangle_C |H\rangle_T \to |V\rangle_C |V\rangle_T\\&|V\rangle_C |V\rangle_T \to |V\rangle_C |H\rangle_T\end{aligned}}$$

$$\boxed{|H \pm V\rangle_C |H\rangle_T \to |H\rangle_C |H\rangle_T \pm |V\rangle_C |V\rangle_T}$$

- **Concept of using extra (ancilla) photons**

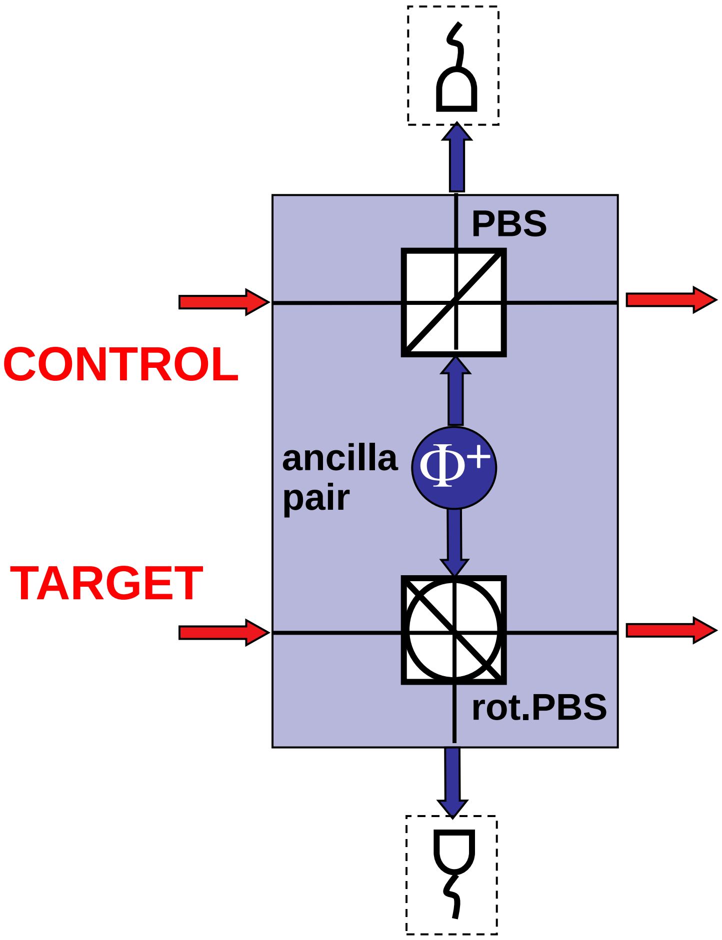
Franson, Jacobs, Pittman, PRA 70, 062302 (2004)

Non-Destructive C-NOT gate

$$|H\rangle_C|H\rangle_T \rightarrow |H\rangle_C|H\rangle_T$$
$$|H\rangle_C|V\rangle_T \rightarrow |H\rangle_C|V\rangle_T$$
$$|V\rangle_C|H\rangle_T \rightarrow |V\rangle_C|V\rangle_T$$
$$|V\rangle_C|V\rangle_T \rightarrow |V\rangle_C|H\rangle_T$$

$$|H \pm V\rangle_C|H\rangle_T \rightarrow |H\rangle_C|H\rangle_T \pm |V\rangle_C|V\rangle_T$$

- Concept of using extra (ancilla) photons
- CNOT gate works correctly if one photon exits in each mode
- probabilistic gate with 25% chance of success

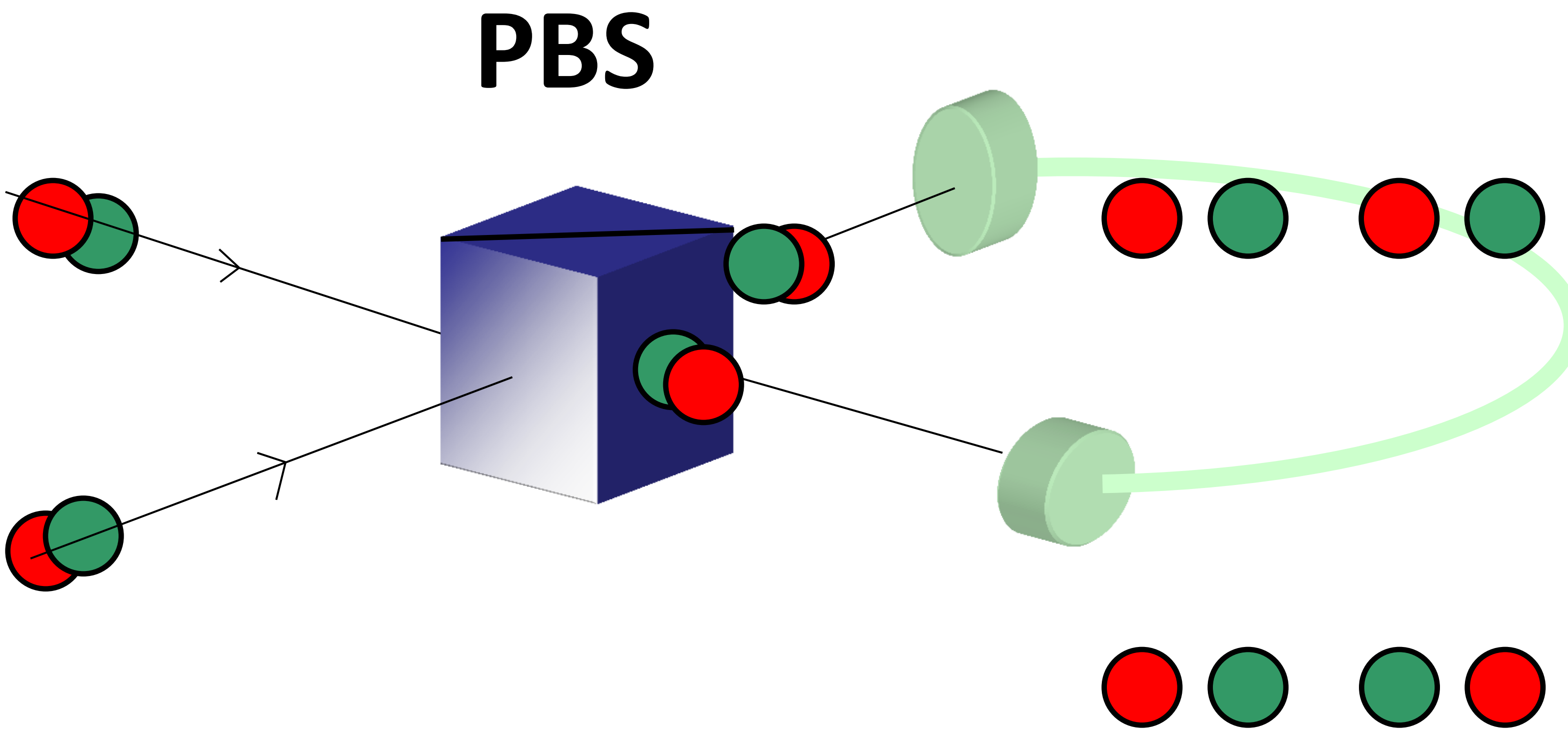


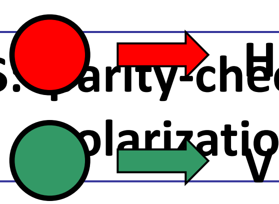
CNOT gate

Franson, Jacobs, Pittman, PRA 70, 062302 (2004)

Gasparoni, Pan, Walther, Rudolph, Zeilinger, PRL 93, 020504 (2004)

Polarizing Beamsplitter (PBS) II



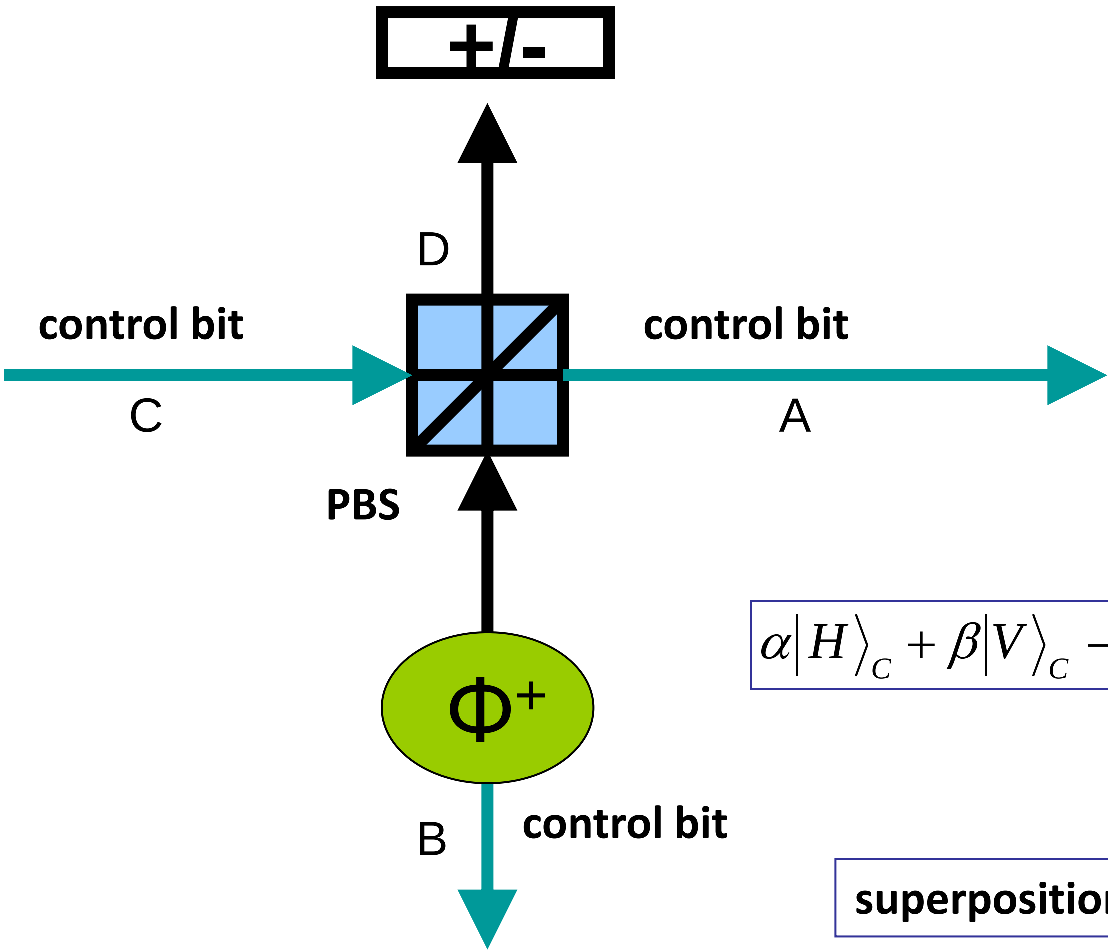


PBS: parity-check
polarization ↔ path

Quantum Encoder („duplicator“)

1AO1 Photon

P=1/2

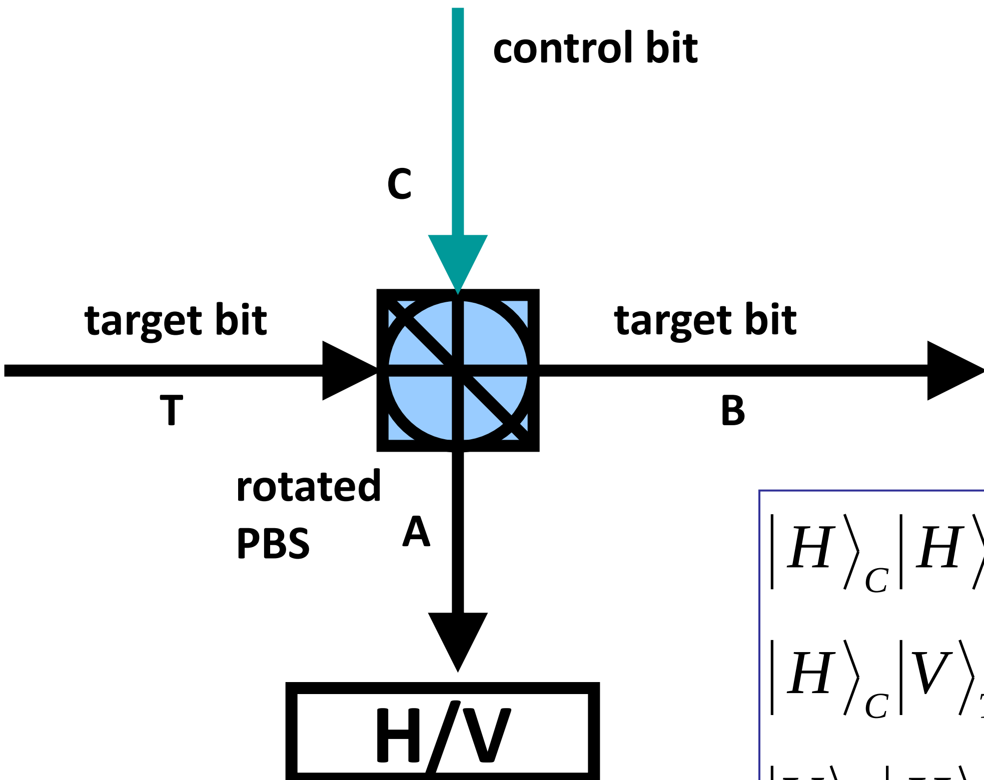


$$\alpha|H\rangle_C + \beta|V\rangle_C \rightarrow \alpha|H\rangle_A|H\rangle_B + \beta|V\rangle_A|V\rangle_B$$

superposition → entanglement

Destructive C-NOT

P=1/2



1AO1 Photon

$|H\rangle_A$

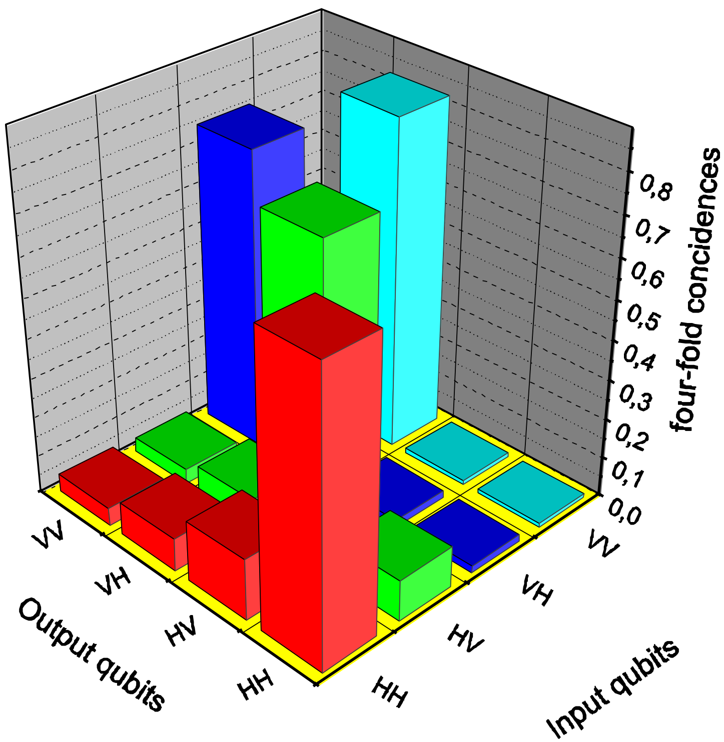
$$|H\rangle_C |H\rangle_T \rightarrow |\Phi^+\rangle_{45} \rightarrow |\Phi^+\rangle_{H/V} \Rightarrow |H\rangle_B$$

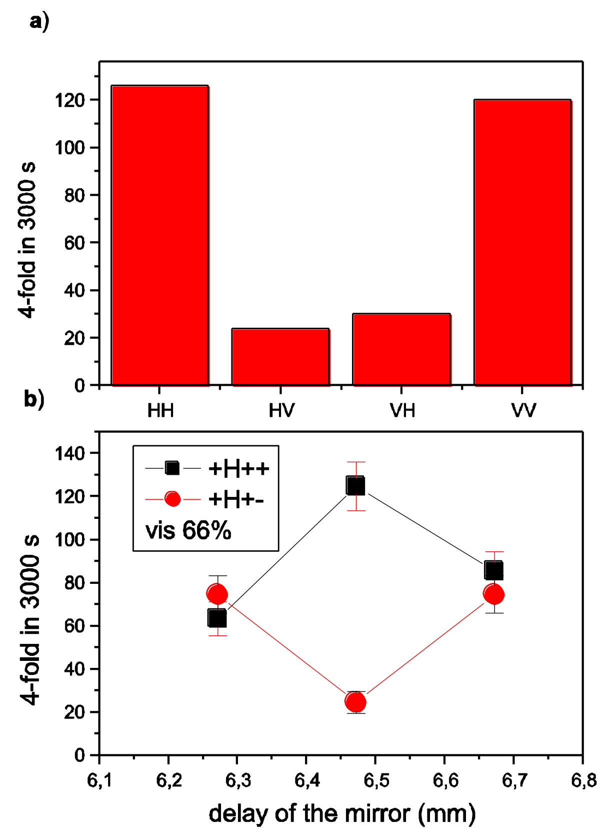
$$|H\rangle_C |V\rangle_T \rightarrow |\Phi^-\rangle_{45} \rightarrow |\Psi^+\rangle_{H/V} \Rightarrow |V\rangle_B$$

$$|V\rangle_C |H\rangle_T \rightarrow |\Phi^-\rangle_{45} \rightarrow |\Psi^+\rangle_{H/V} \Rightarrow |V\rangle_B$$

$$|V\rangle_C |V\rangle_T \rightarrow |\Phi^+\rangle_{45} \rightarrow |\Phi^+\rangle_{H/V} \Rightarrow |H\rangle_B$$

Experimental Results





16 correlation measurements:

Fidelity=81%

From separable to entangled

Fidelity=77%

Physical Review Letters 92, 020504 (2004)

Q: Great!
Measurements give me two-qubit gates.

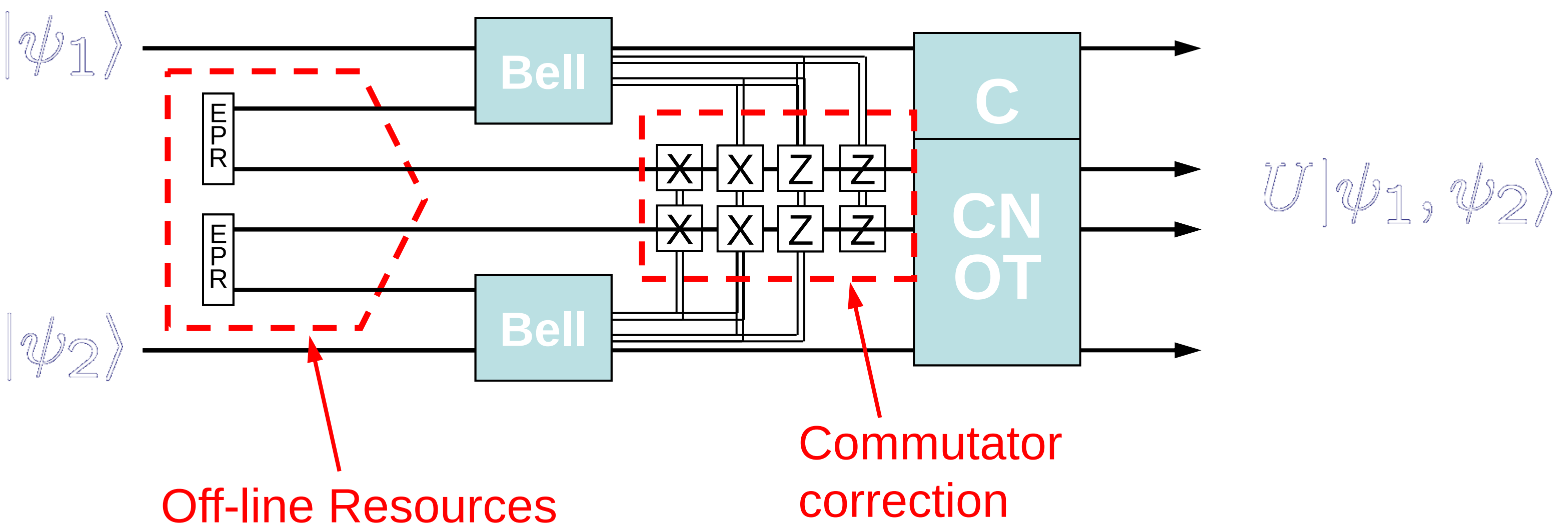
Q: But!
Isn‘t a probabilisitc gate a killer?
Just 20 gates, …and I get success rate of $(1/2)^{20}$

A: Solution is existing! Read:
1) Gottesmann & Chuang (Nature 1999) and
2) Knill, Laflamme, Milburn (Nature 2001)

A: Basically, take more photons and smart scheme to achieve deterministic gates

Teleportation Trick for achieving scalability

How can we apply probabilistic gates in a circuit without losing scalability?

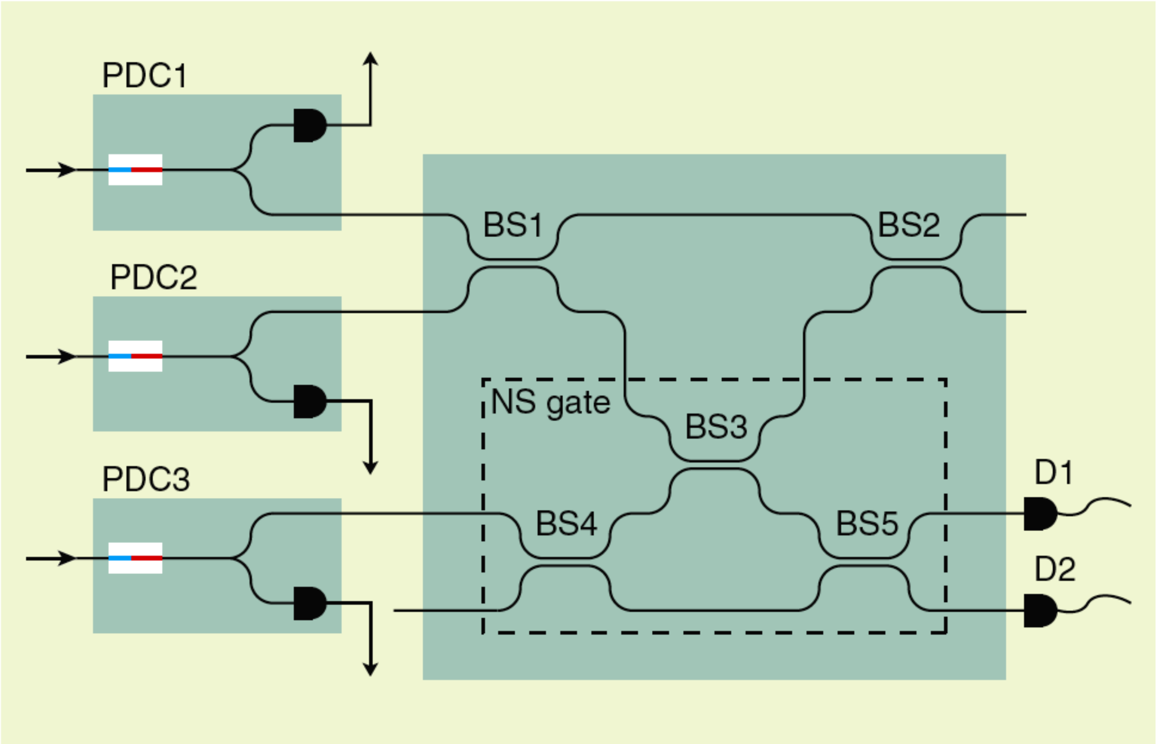


Gottesman & Chuang, Nature 402, 390 (1999).

Linear Optical Quantum Computing

Heralded photon sources

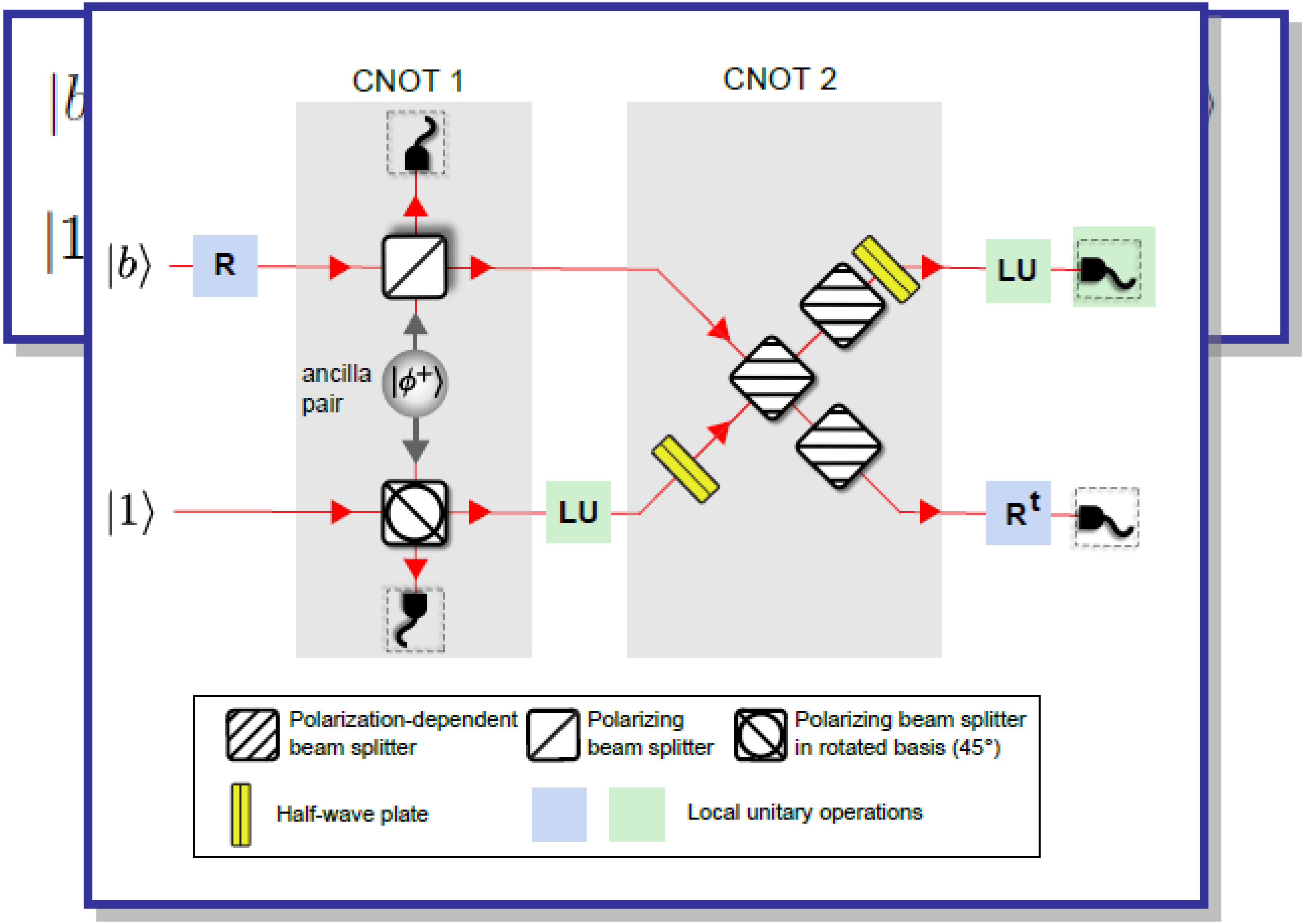
Multiphoton interference in multiple cascaded interferometers



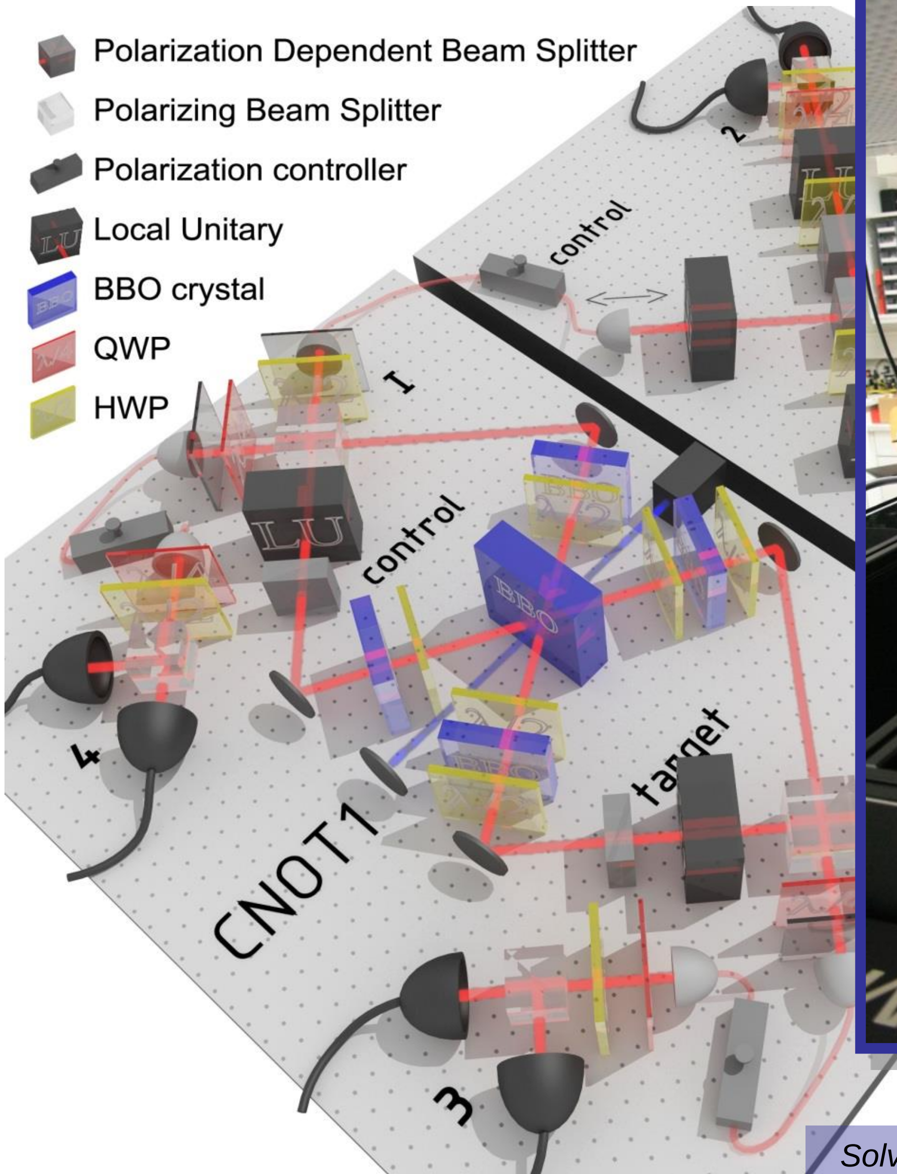
Effective non-linearities via measurement
→ $10^3 - 10^5$ extra (ancilla photons) per qubit

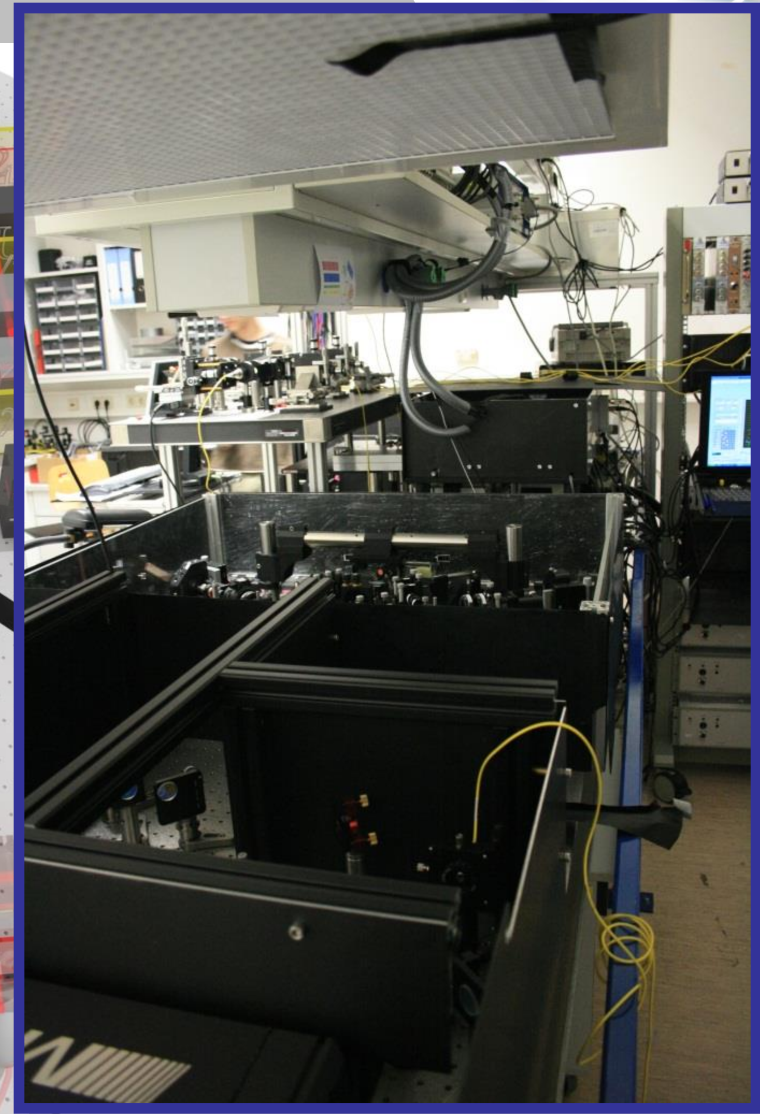
Knill, Laflamme, Milburn, Nature 409, 46 (2001)

Experimental setup for two consecutive CNOTS



Experimental setup for two consecutive CNOTS





Solving systems of linear equations on a quantum computer
Barz, Kassal, Lipp, Ringbauer, Aspuru-Guzik, Walther
Scientific Reports 4, 6115 (2014)

Show Movie !

Deterministic Photonic Quantum Gates
(some examples)

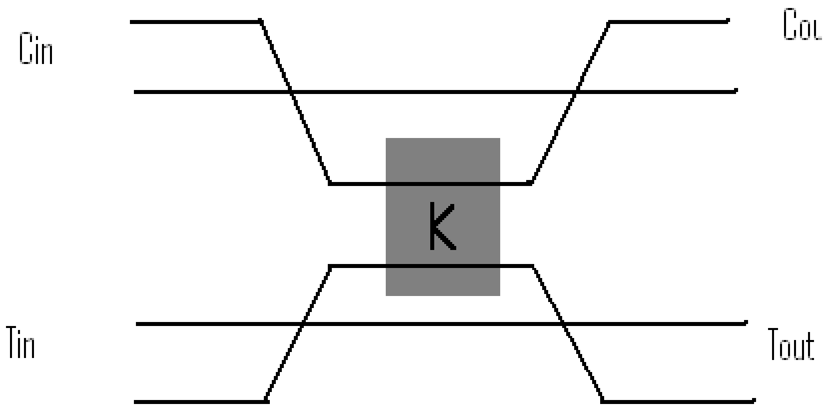
Example 1: Boosting the Kerr effect

Control-Phase Gate

- Possible via Kerr-effect

$$n_{\text{Kerr}} = n_0 + \chi^{(3)} E^2$$

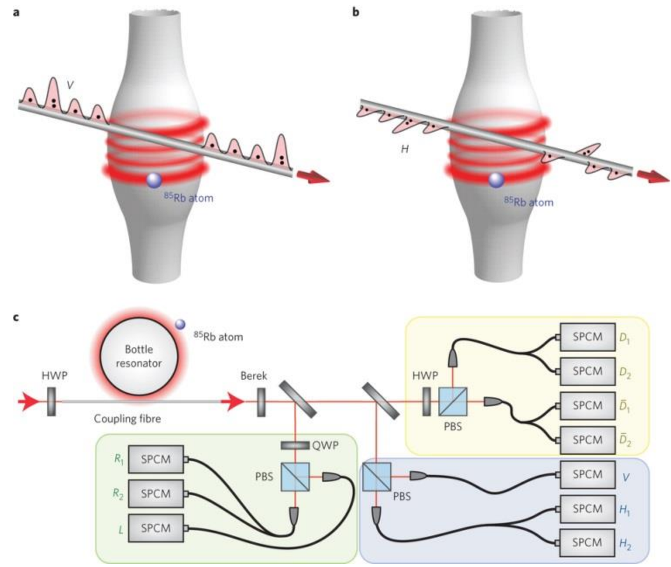
- But: 3rd order susceptibility is on the order of 10^{18} m^2/W
- unlikely for single photons
- **Some techniques can enhance the nonlinearity significantly (~10^2) -> Cavity-QED**

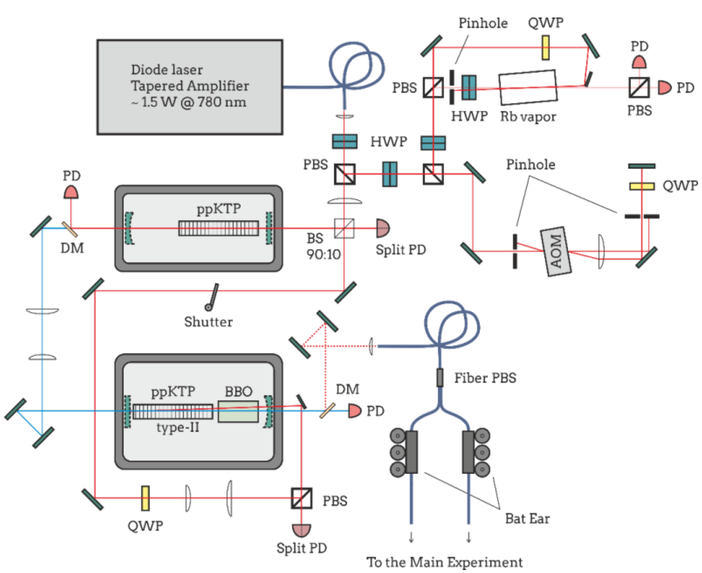


$$K = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Cavity QED for deterministic phase gates

- whispering gallery mode (WGM) resonator (Bottle resonator[1])
- ^{85}Rb atom is trapped in the evanecent field of the guide moded
- nearly lossless fiber coupling and high Q-factor (~ 10^8) tuned to an EIT ^{85}Rb atom‘s transition.





- single photons tuned to the 85Rb transition (~ 8 MHz @ 780nm)
- conditional phase-shift of π for single photons
- (phase-shifts already seen by using faint coherent light [Rauschenbeutel Group, Vienna[2]])

[1] M. Pöllinger et al., Phys. Rev. Lett. 103, 053901 (2009)

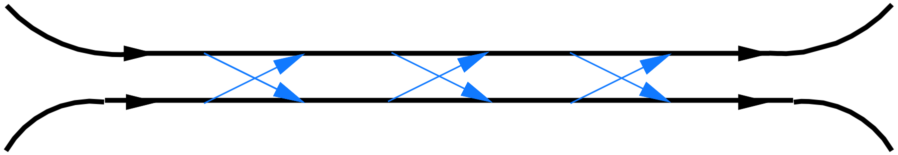
[2] J. Volz et al., Nature Photonics 8, 965–970 (2014)

Example 2: Suppression of failure events in gates

- CNOT gate works correctly if one photon exits in each mode

- All failure events are due to 2 photons leaving in the same path

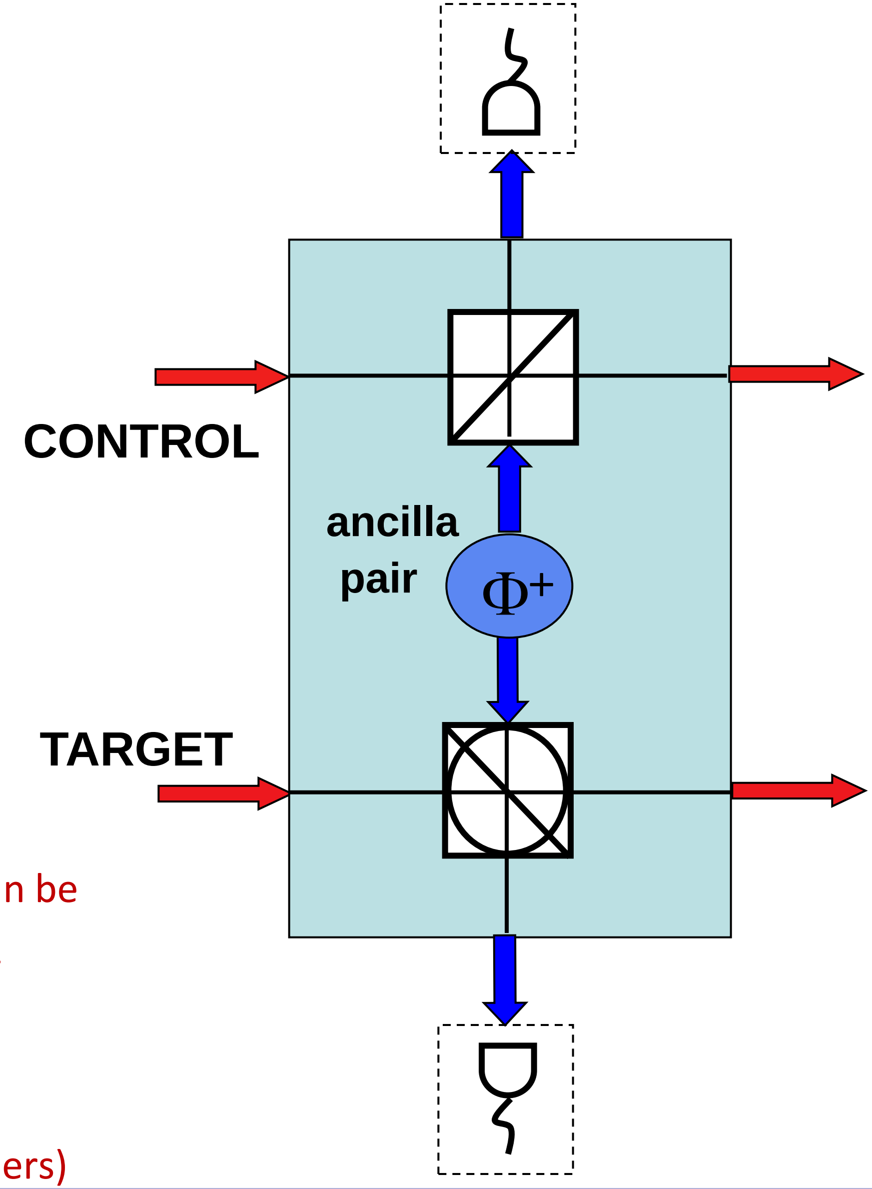
- Failure events can be suppressed by frequent observations to determine if two photons are present in the same output path → Quantum Zeno effect



- Emission of two photons into the same fiber can be inhibited by frequent measurements to see if 2 photons are there

→ 1 photon passes, but 2 photons are absorbed

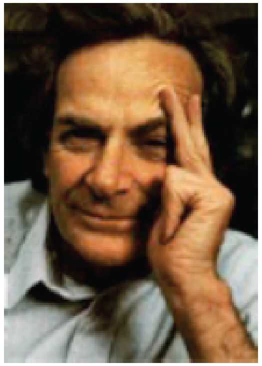
→ strong 2-photon absorption (e.g. via atoms in fibers)



Quantum computing using single photons and the Zeno effect
J.D.Franson, , B.C.Jacobs, T.B.Pittman, PRA 70, 062302 (2004)

Photonic Quantum Simulation

Experimental Quantum Simulation



Richard Feynman

The real problem is simulating *quantum mechanics*

Hopeless task on a classical computer

Let's use quantum systems as computational building blocks!

$$i\hbar \frac{d}{dt}|\psi\rangle = H|\psi\rangle$$

No. of equations $\propto$ e$^{\text{particles}}$

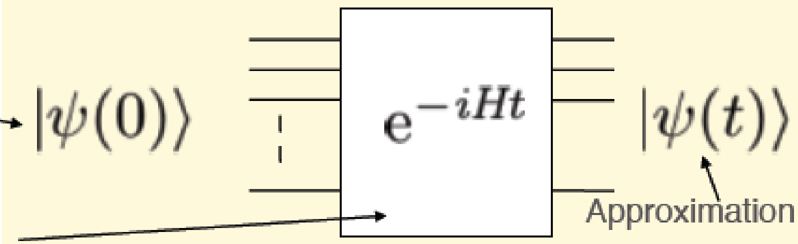
Simulating physics with computers, *Int. J. Theoretical Physics* (1982)

Seth Lloyd

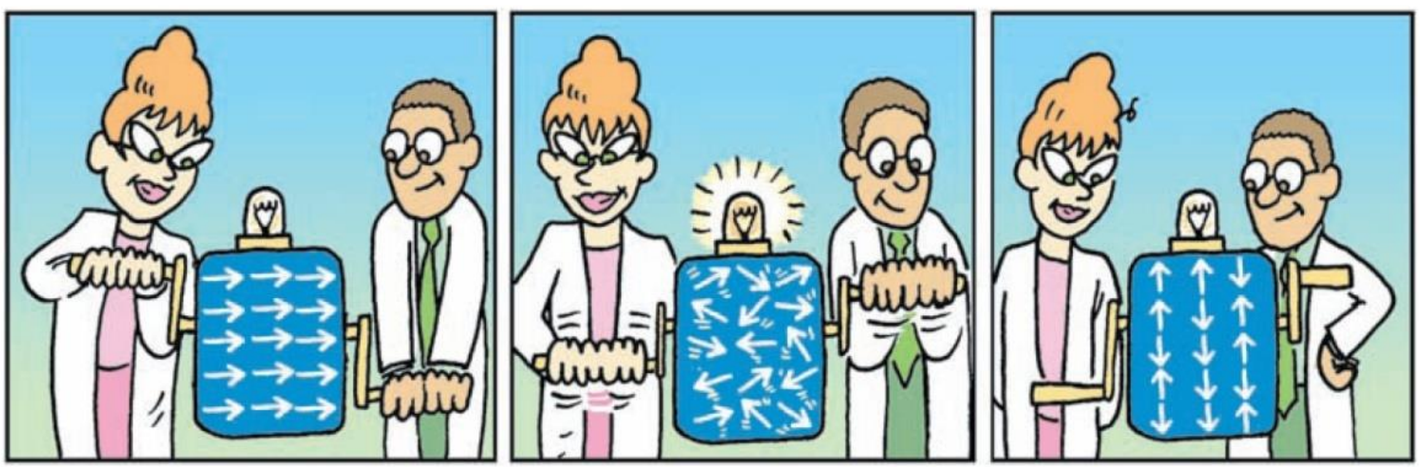
Feynman was correct, for very large class of physical quantum systems

Given initial wavefunction, No. qubits required $\propto$ poly(No. particles)

Time evolution operator, No. gates required $\propto$ poly(particles)

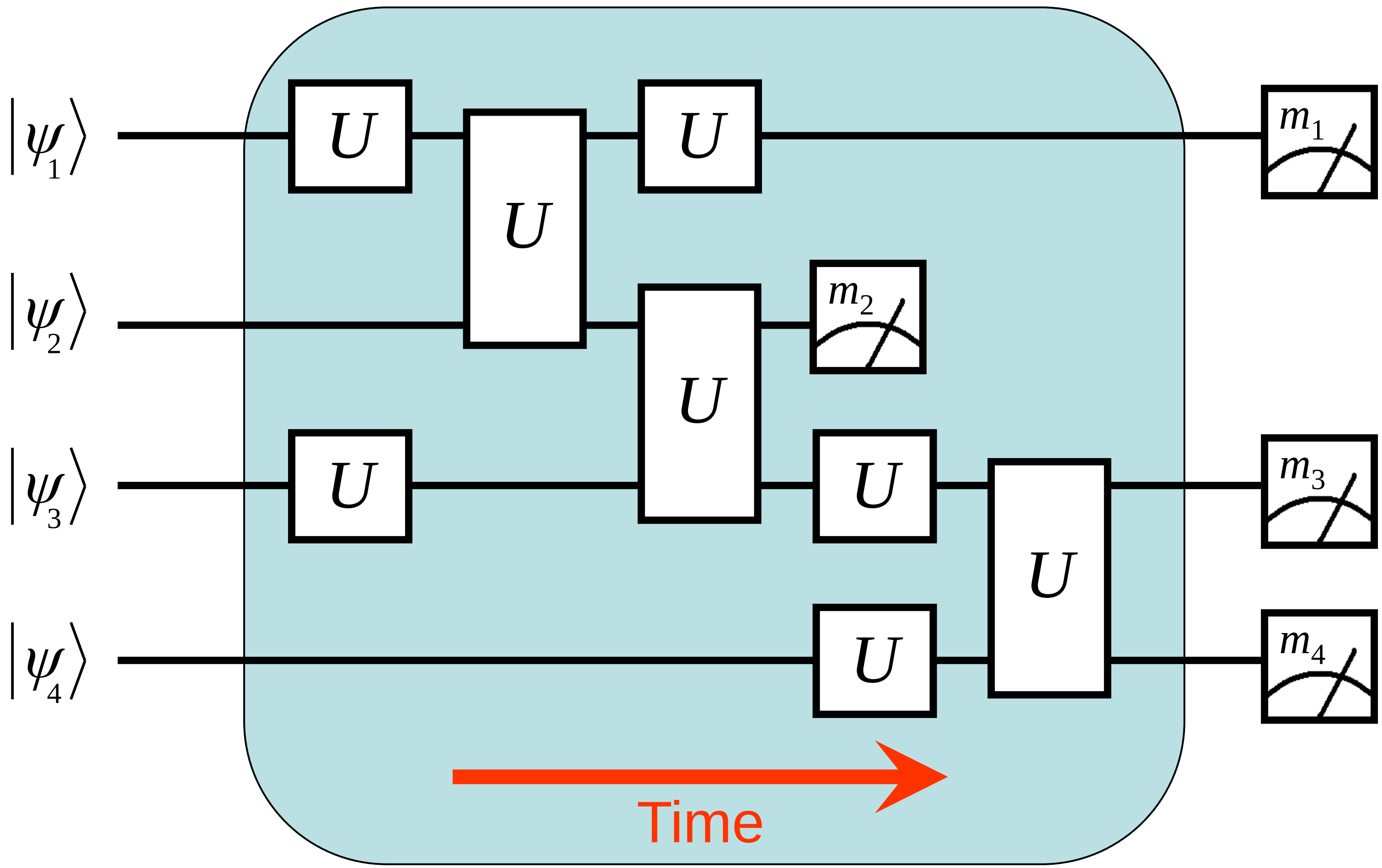


Universal quantum simulators, *Science* (1996)



Digital Quantum Simulator

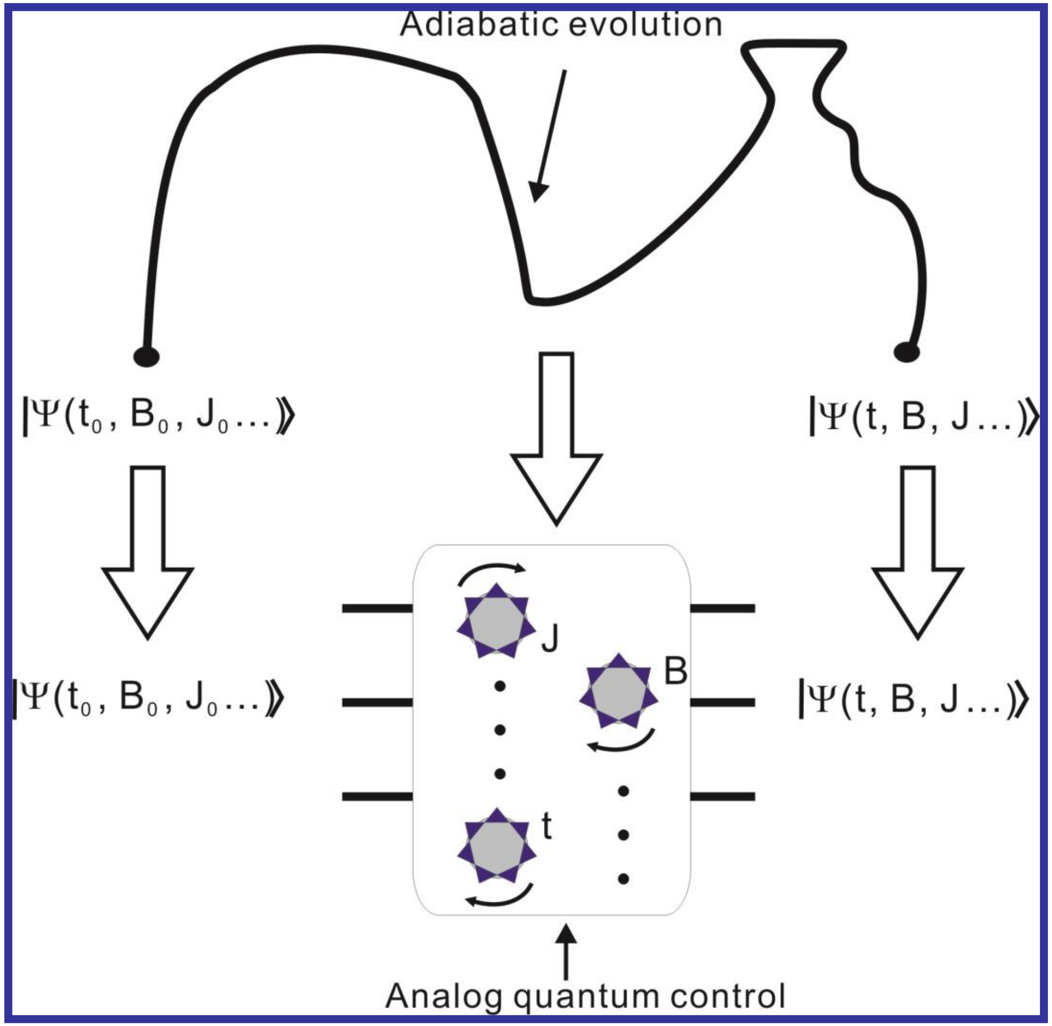
discrete gate operations



Buluta & Nori, Science 326, 108 (2009)

Analog Quantum Simulator

- same evolution as in Nature
- can be adiabatic (or not)



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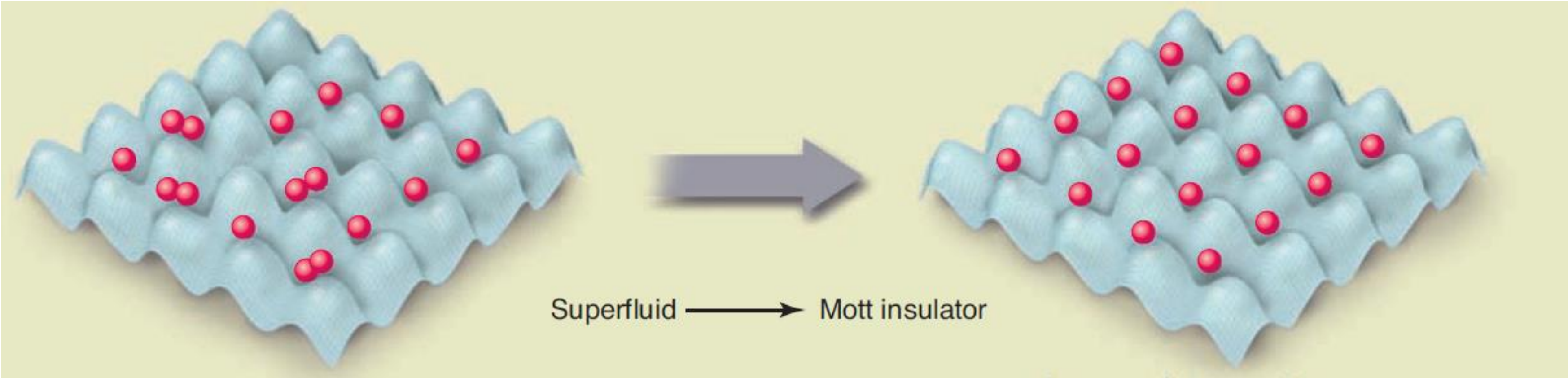
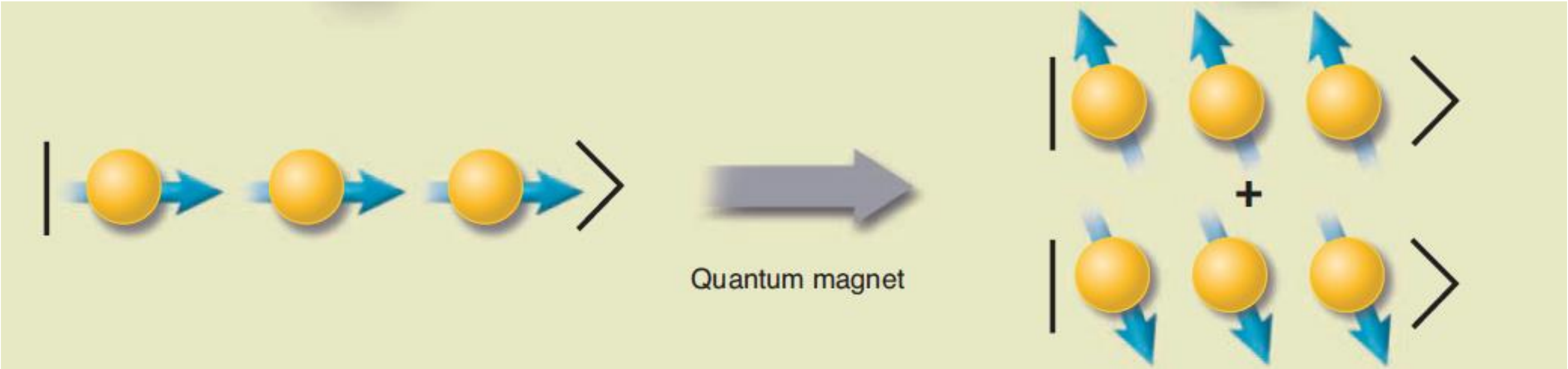




Buluta & Nori, Science 326, 108 (2009)

Quantum Simulation Architectures

Global Challenge:

to build a quantum simulator for studying other quantum systems

Benefit and Impact:

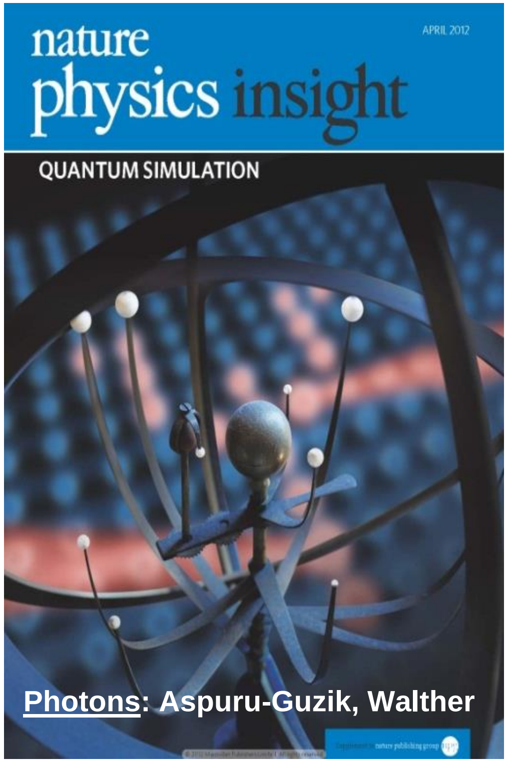
providing a means of exploring new physical phenomena in many fields

General Advantage:

Quantum simulators are less demanding ! (~40 qubits)

Advantages of Photons:

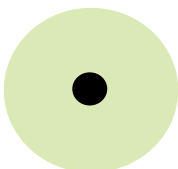
- generation of **complex multi-photon entanglement**
- use **mobility of photons** as key advantage
- **scalable processing** via light-matter interactions



Analog
Quantum Simulation
of
Heisenberg-Interacting Spins

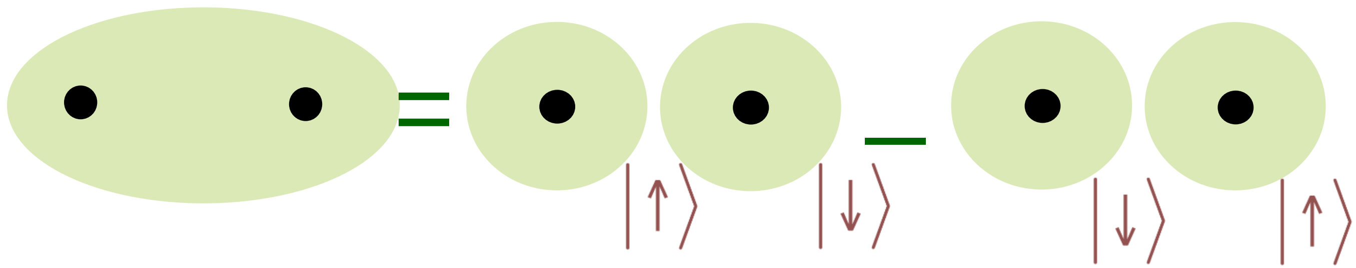
Chemical Bonds = Singlet States

Hydrogen atom:



$$|\uparrow\rangle$$

Hydrogen molecule:



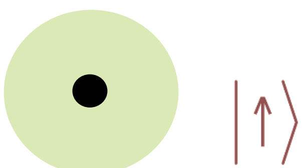
$$= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

Quantum Information in Quantum Chemistry

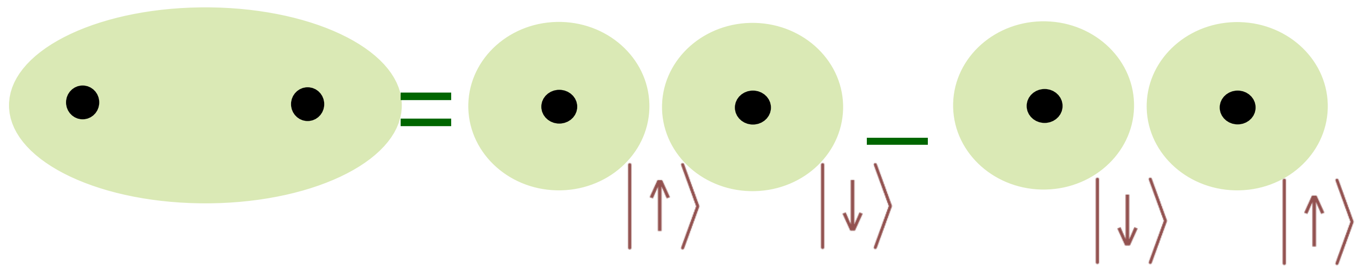
QuantumComputing@UniWien

Chemical Bonds = Singlet States

Hydrogen atom:



Hydrogen molecule:

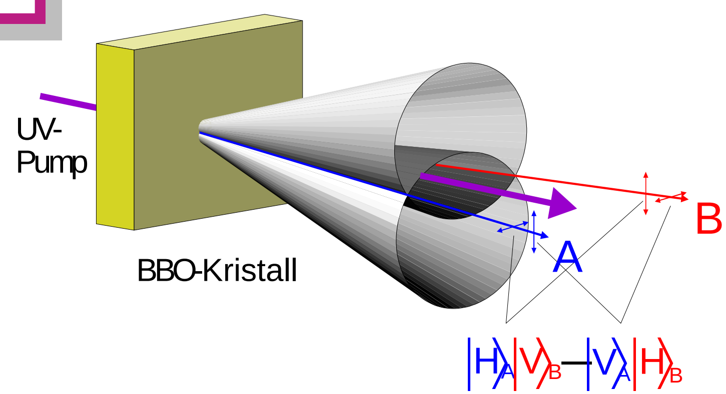


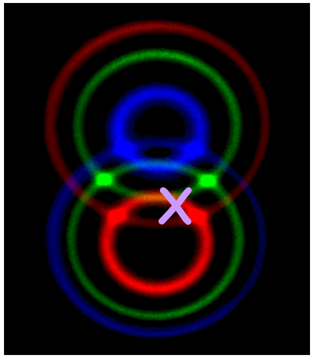
$$= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

Photonic Quantum Chemistry

$\mathbf{k}_{pump} = \mathbf{k}_{photon1} + \mathbf{k}_{photon2}$

$\mathbf{w}_{pump} = \mathbf{w}_{photon1} + \mathbf{w}_{photon2}$



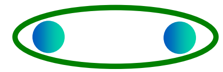


Aspuru-Guzik, Walther
Nature Physics 8, 285 (2012)

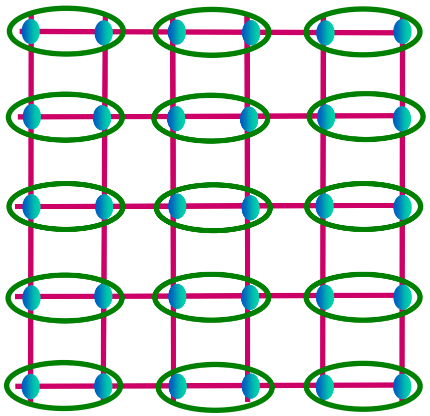
Ma, Dakic, Walther
Annu. Rev. Phys. Chem, Vol 154 (2013)

Quantum Information in Valence Bonds

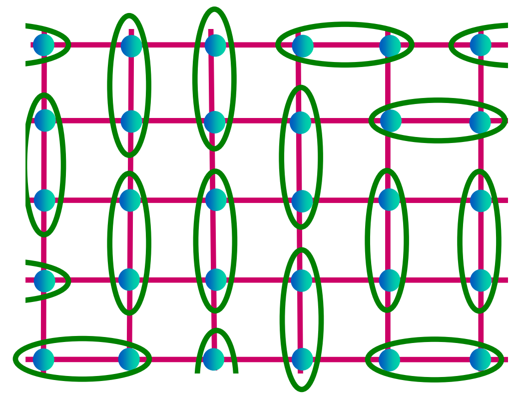
Solid State Physics

 $= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

Valence Bond Solids (VBS)



Entangled Spin Liquid:
Resonating Valence Bonds (RVB)



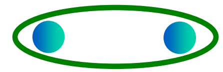
Read, Sachdev, PRL 62, 1694 (1989)

Fazekas, Anderson, Phil Mag 30, 23 (1974)

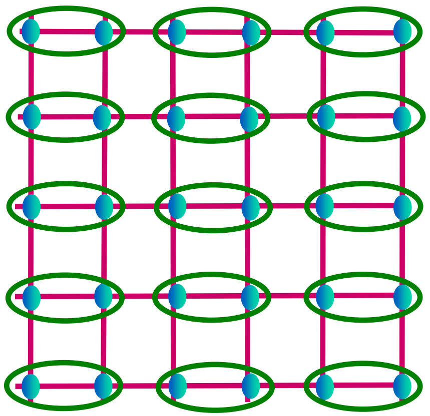
Sachdev, Science 288, 475 (2000)

Quantum Information in Valence Bonds

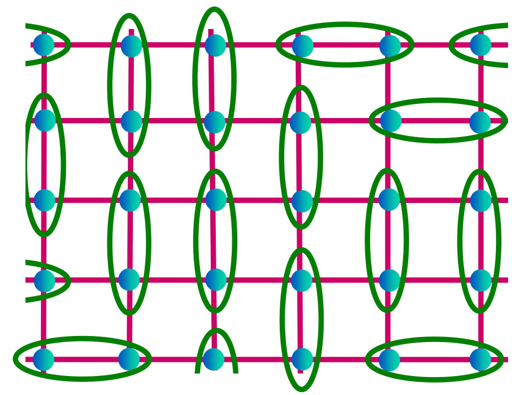
Solid State Physics

 $= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

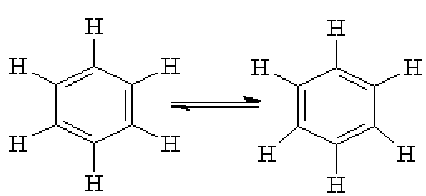
Valence Bond Solids (VBS)

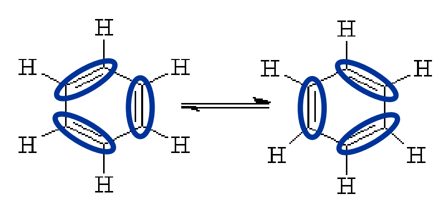


Entangled Spin Liquid: Resonating Valence Bonds (RVB)



Quantum Chemistry

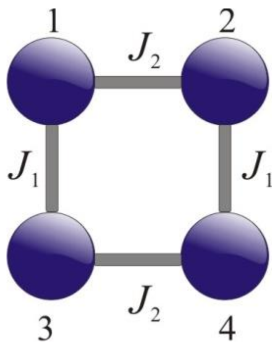




- **Resonance leads to a symmetric configuration of valence bonds (Kekulé, Pauling)**
- **aromatic systems and anti-aromatic systems (Hückel)**

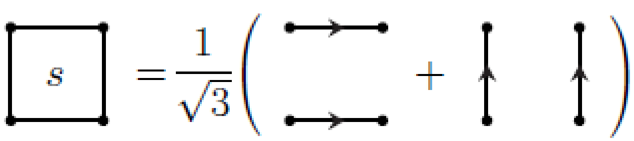
Read, Sachdev, PRL 62, 1694 (1989) **Fazekas, Anderson, Phil Mag 30, 23 (1974)** **Sachdev, Science 288, 475 (2000)**

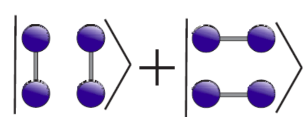
Quantum Simulation Tasks:



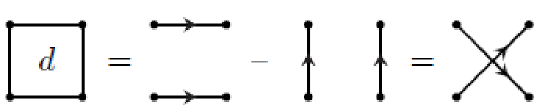
spin-1/2 tetramer or spin-1/2 plaquette

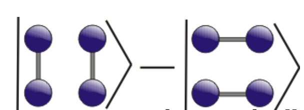
- **simulation of frustrated spin systems**
- **paired short-range singlets: insulating spin liquid ground states of Mott insulators**
- **mobile insulating states: Anderson‘s conjecture for superconductivity in cuprates**
- **simulation of s-wave pairing symmetry for valence bond states**





- **simulation of exotic d-wave pairing symmetry for valence bond states**



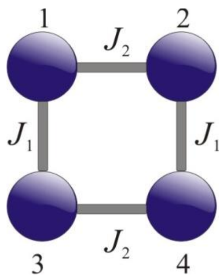


Trebst, Schollwöck, Troyer, Zoller, PRL 96, 250402 (2006)

Mambrini, Läuchli, Poilblanc, Mila, PRB 74, 144422 (2006)

Anderson, Science 235, 1196 (1987)

Ground state of a quantum anti-ferromagnet



spin-1/2 tetramer or spin-1/2 plaquette

- **absolute ground state has total spin-zero (Marhsall‘s theorem) on a bipartite lattice with nearest neighbor Heisenberg-type interactions**

- **antiferromagnetically interacting spins form spin-zero singlet states**

$|\Phi_=\rangle \equiv |\psi^-\rangle_{12}|\psi^-\rangle_{34}$ $\quad$ $|\Phi_{\|}\rangle \equiv |\psi^-\rangle_{13}|\psi^-\rangle_{24}$ $\quad$ $|\Phi_\times\rangle \equiv |\psi^-\rangle_{14}|\psi^-\rangle_{23}$

- **total spin-zero subspace is 2-dimensional → only 2 independent dimer-covering states:**

- **Static and localized dimer-covering states → valence bond solids**

- **Dimer-covering states fluctuating as superpositions → valence bond liquids**

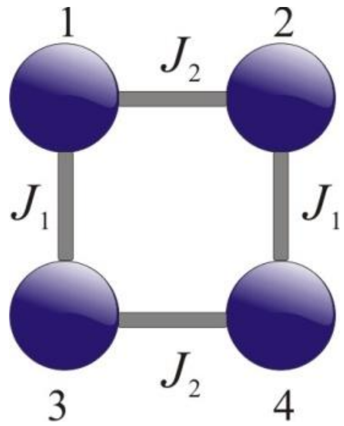
$$\boxed{|\Phi_\times\rangle = |\Phi_{\|}\rangle - |\Phi_=\rangle \qquad |\Phi_{\|}\rangle + |\Phi_=\rangle}$$

$|\Phi_=\rangle + |\Phi_\times\rangle$

Marshall, Proc. R. Soc. A 232, 48 (1955)

Trebst, Schollwöck, Troyer, Zoller, PRL 96, 250402 (2006)

Requirements for the quantum simulation of valence bond (liquid) staes



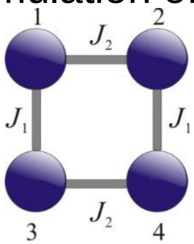
$$H = J_1\left(\vec{S}_1\vec{S}_3 + \vec{S}_2\vec{S}_4\right) + J_2\left(\vec{S}_1\vec{S}_2 + \vec{S}_3\vec{S}_4\right)$$

- **capability of preparing *arbitrary* superpostions of dimer-covering states is sufficient for simulating *any* Heisenberg-type interaction of four spin-1/2 particles on a square lattice**

- **strength of optical quantum simulators that the simulated ground states can be restricted to the spin-zero singlet subspace; e.g. by utilizing the quantum interference at a controllable beam splitter**

Photonic Analog Quantum Simulation

- Simulation of a Heisenberg spin-1/2 tetramer using a photonic AQS



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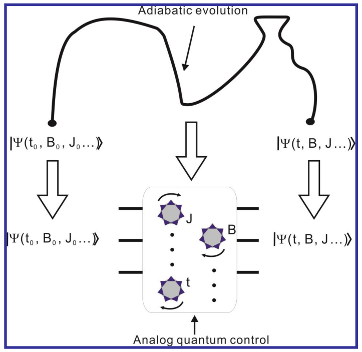

Photonic Analog Quantum Simulation

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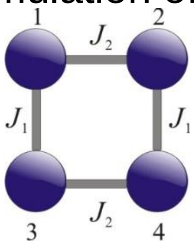

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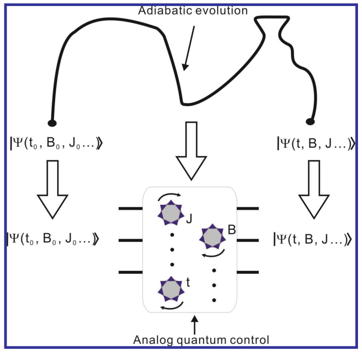
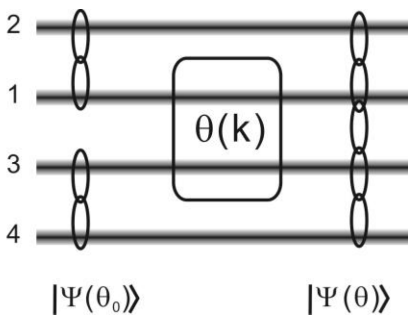
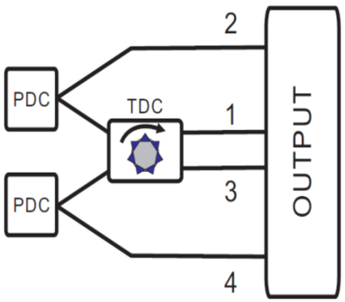


- Initial ground state: entangled photon pairs 1 & 2 and 3 & 4



$$H(\kappa) = H/J_1 = H_0 + \kappa H_1$$

$$\tan^2\theta = \kappa + \sqrt{\kappa^2 - \kappa + 1}$$



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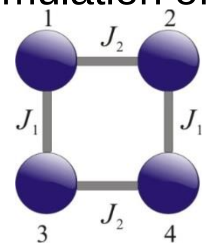
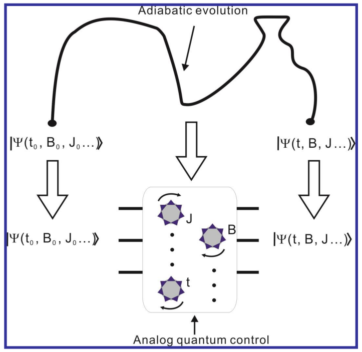


$$H = J_1\left(\vec{S}_1\vec{S}_3 + \vec{S}_2\vec{S}_4\right) + J_2\left(\vec{S}_1\vec{S}_2 + \vec{S}_3\vec{S}_4\right)$$



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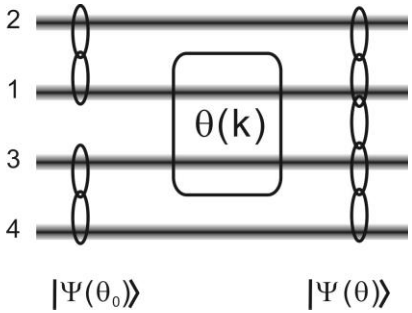

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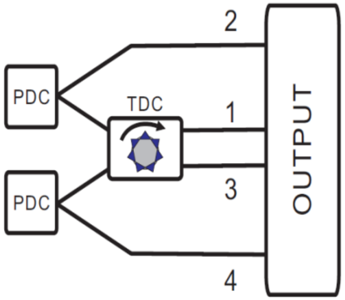
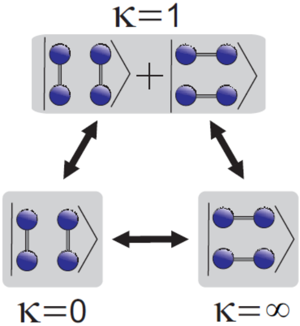


- Tunable interaction: superimposing photons 1 & 3 on a tunable beam splitter



→ **VBS states**: paired short-range singlets: insulating spin liquid ground states of Mott insulators

→ **RVB states** (Spin Liquid): mobile insulating states:, Anderson's conjecture for superconductivity in cuprates

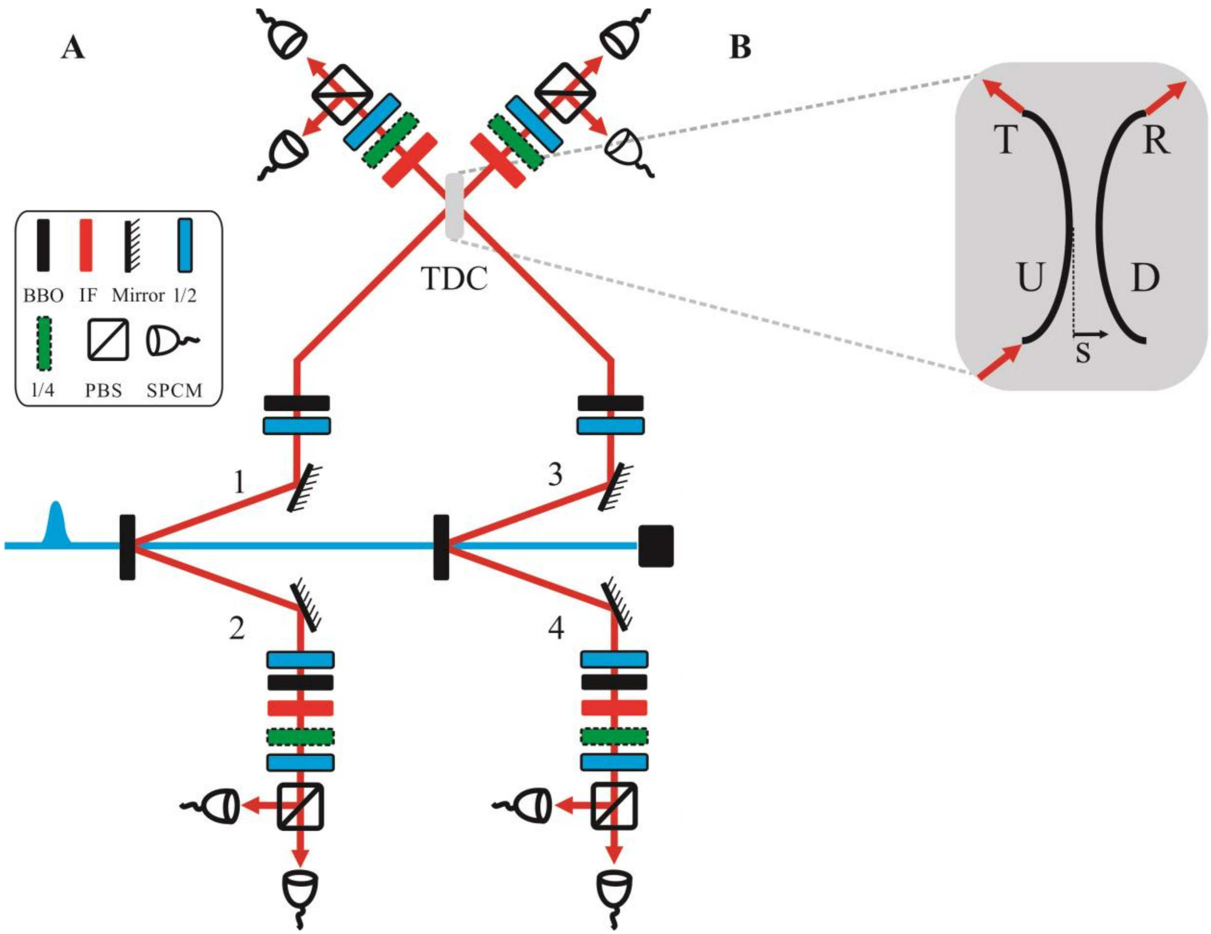
s-wave pairing

d-wave pairing

Anderson, Science 235, 1196 (1987)

Trebst, Schollwöck, Troyer, Zoller, PRL 96, 250402 (2006)

Photonic Analog Quantum Simulation



Sources:

– a pulsed ultraviolet laser : 404 nm, 180 fs, 80 MHz

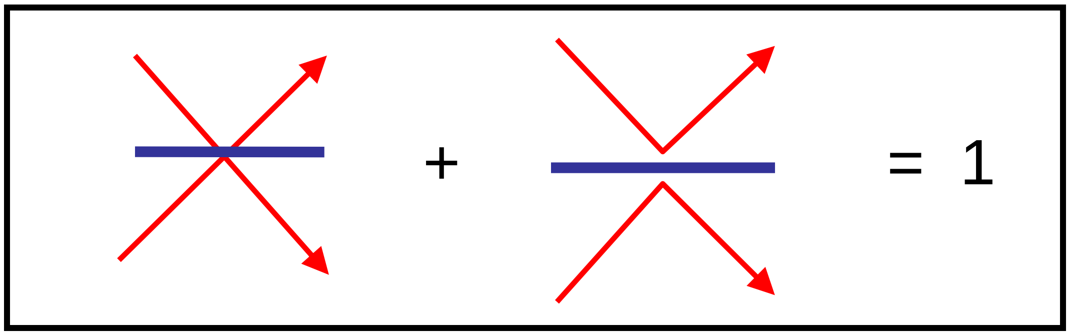
– Type-II SPDC from two BBO crystals

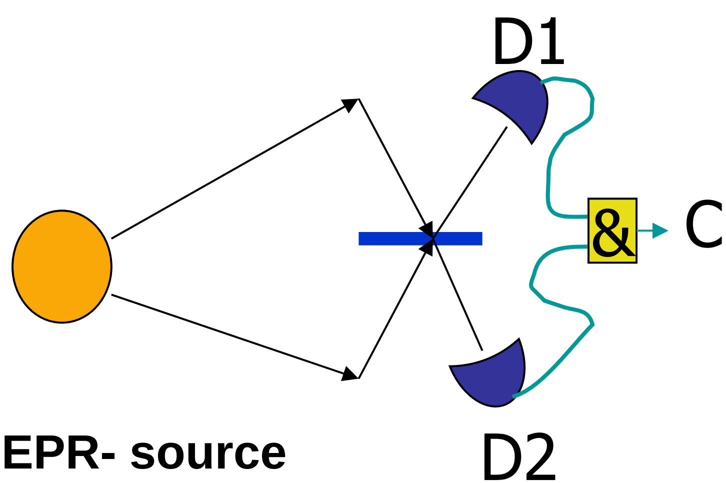
Measurement-induced interaction

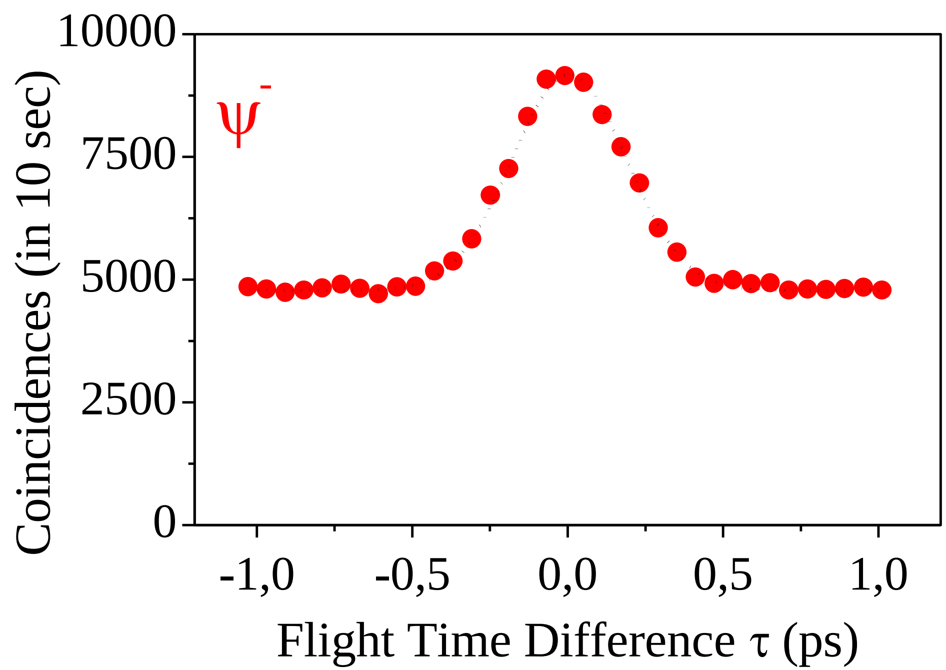
– tunable directional coupler (TDC)

Beamsplitter as Singlet-State Filter

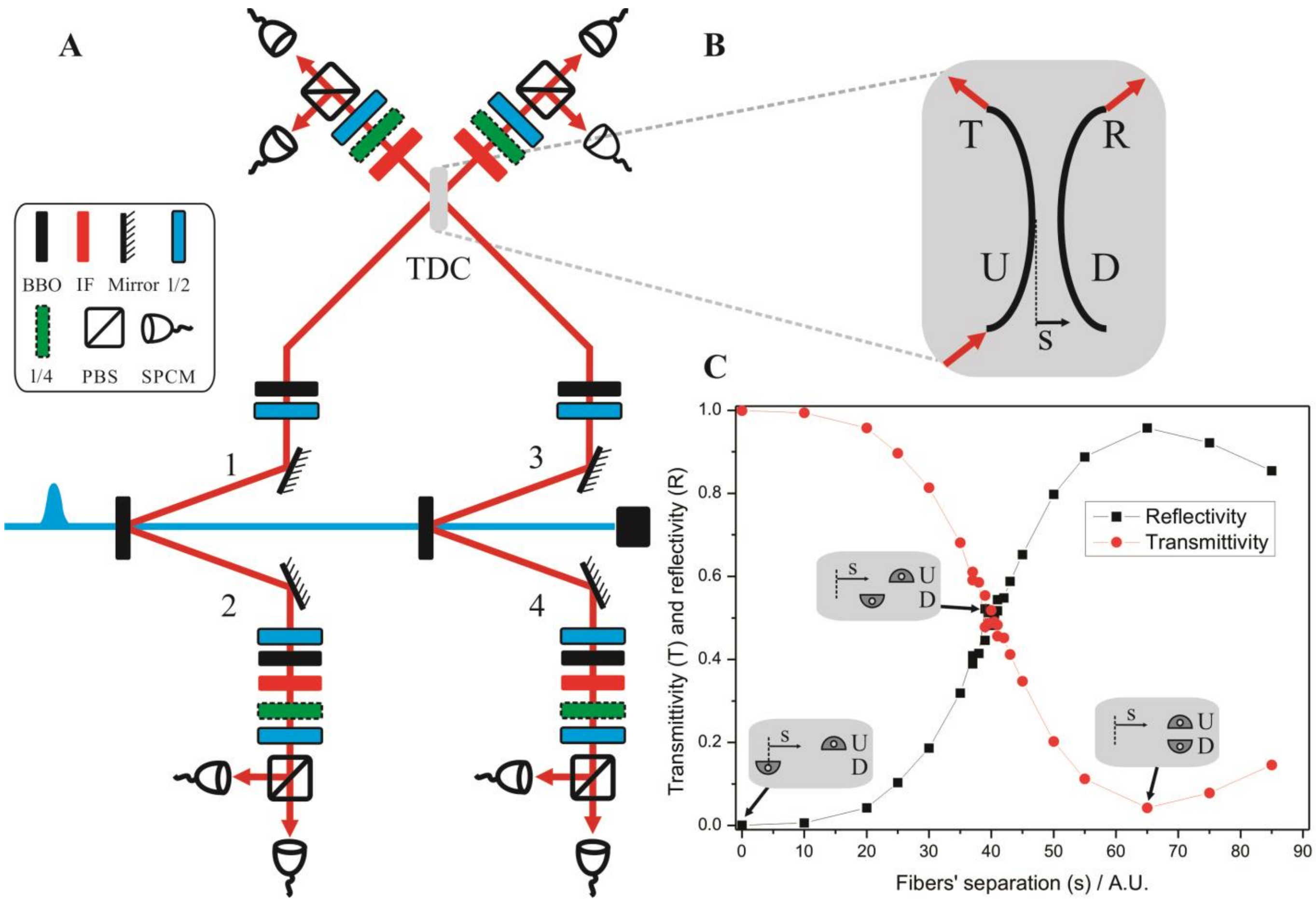
$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_1\,|V\rangle_2 - |V\rangle_1\,|H\rangle_2\right)$$







Photonics Analog Quantum Simulation

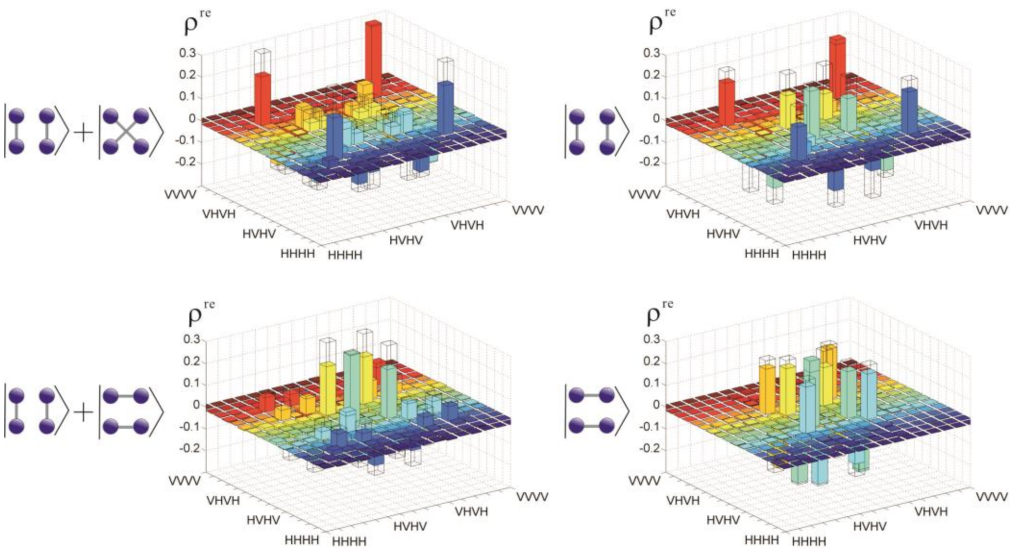


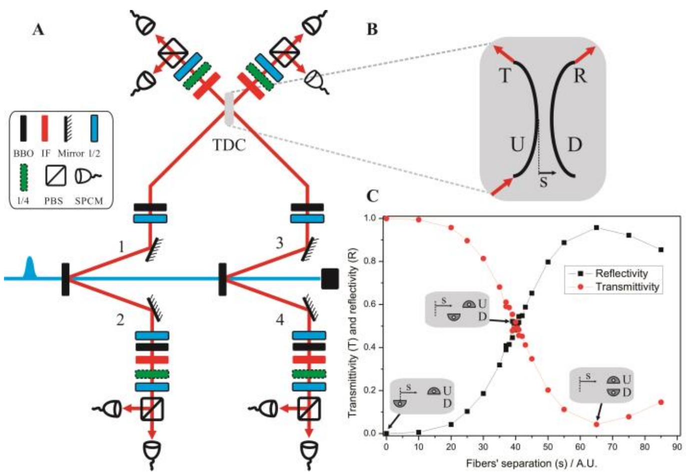
Tuning the ground state and its energy

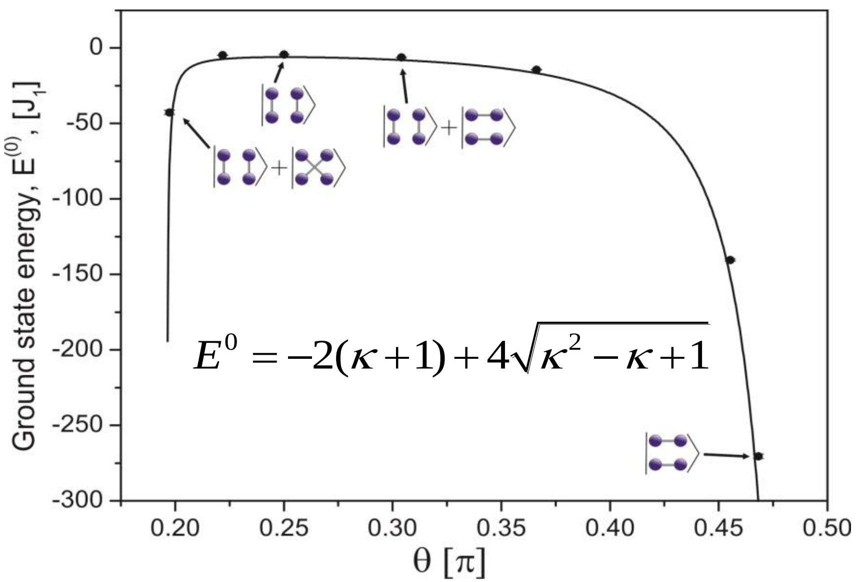
$$\left|\Psi^{0}(\theta)\right\rangle = {}^{1}\!\big/\!\sqrt{n(\theta)}\left(\cos 2\theta \left|\quad\right\rangle - \cos^{2}\theta \left|\quad\right\rangle\right)$$

Entanglement Dynamics of VB States

- tomographic reconstruction of each ground state density matrix
- eight different ground states (10.368 coincidence counts)
- high quantum-state fidelities (average of F~ 0.80)
- extraction of total energy
- extraction of pair-wise Heisenberg energy







$$|\Psi^0(\theta)\rangle = \frac{1}{\sqrt{n(\theta)}}\left(\cos 2\theta\,|\ \rangle - \cos^2\theta\,|\ \rangle\right)$$

Ma, Dakic, Naylor, Zeilinger, Walther, Nature Physics 7, 399 (2011)

And what could we learn?

Quantum Monogamy and Complementarity Relations

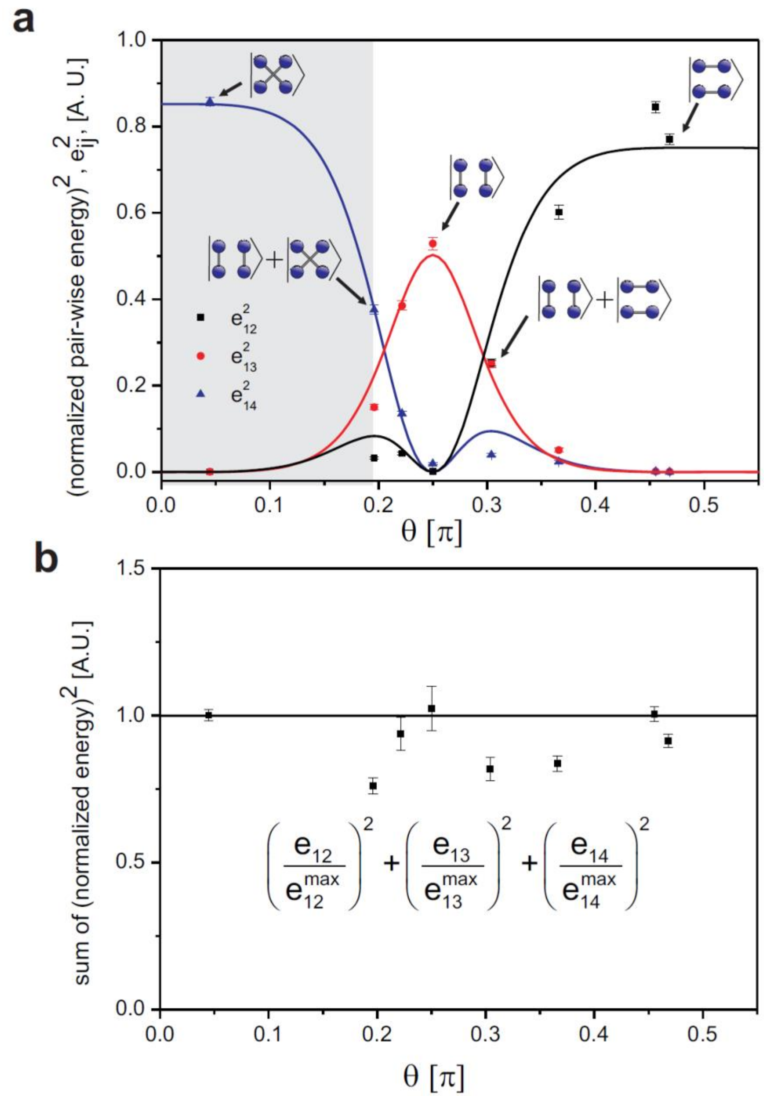
- characterization of the two-body energies and correlations

- normalized Heisenberg energy per unit of interaction

$$e_{ij} = -\tfrac{1}{3} Tr\left(\rho_{ij}\vec{S}_i\vec{S}_j\right)$$

- constraint of energy distribution through complementarity relation

$$e_{12}^2 + e_{13}^2 + e_{14}^2 = 1$$



<u>observation of quantum monogamy</u>

(1) restricts the sharability of quantum correlations among multiple parties

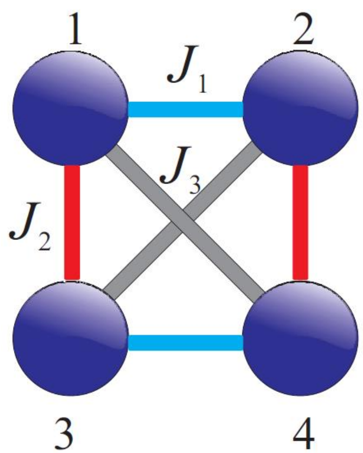
(2) leads to frustration effects in condensed-matter physics

Ma, Dakic, Naylor, Zeilinger, Walther, Nature Physics 7, 399 (2011)

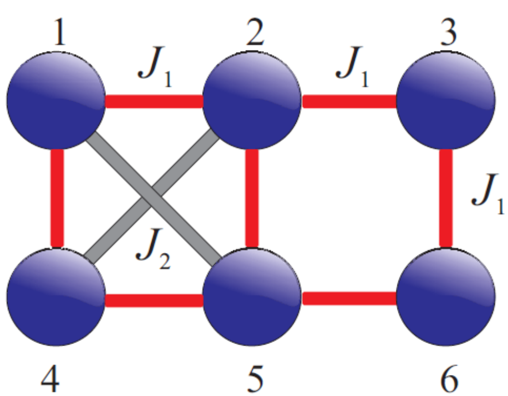
Generalized Heisenberg Interactions

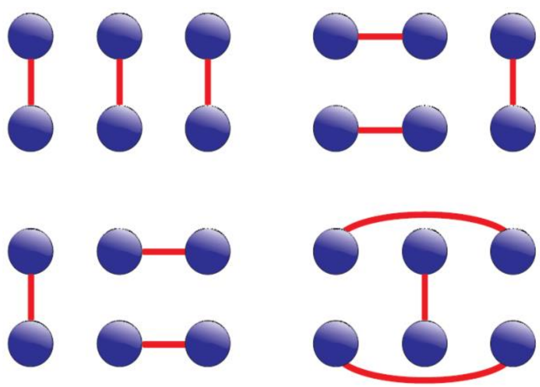
Can we get insights into ground states in the **thermodynamical limit** ?

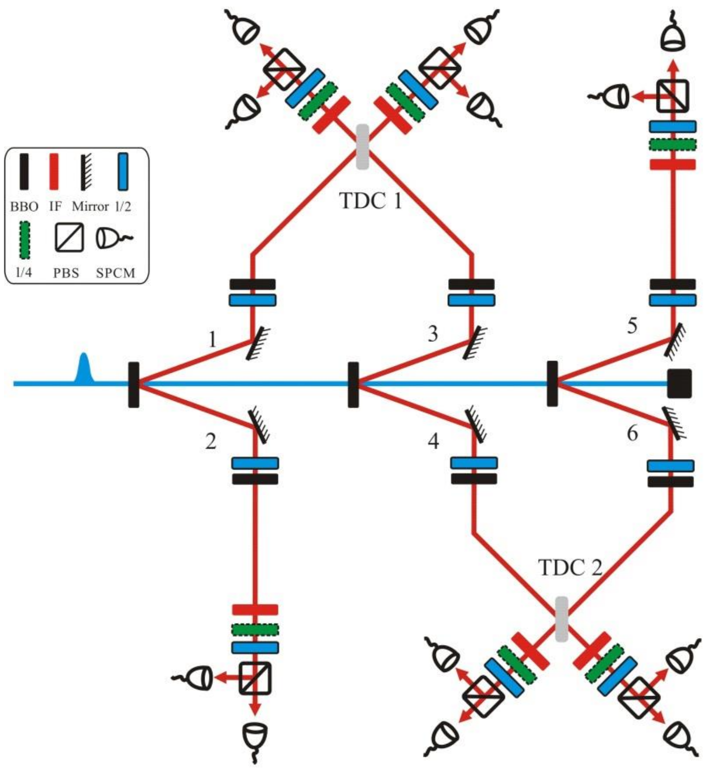
Yes !



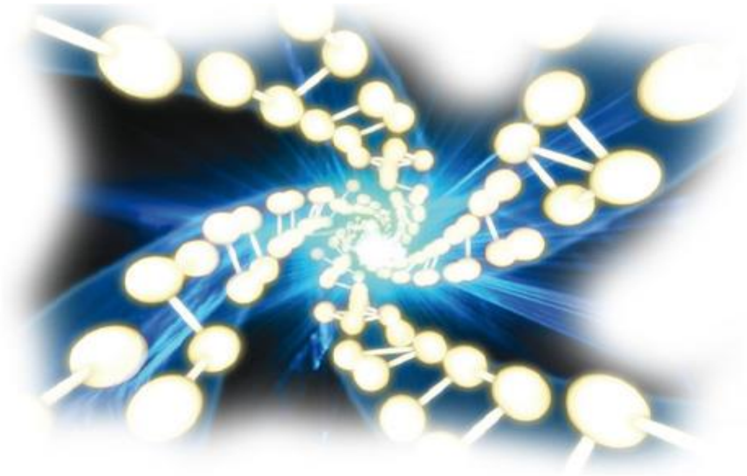
- **access to nearest and next-nearest neighbor interactions**
- **more additional tunable beamsplitters**







Ma, Dakic, Kropatschek, Naylor, Chan, Gong, Zeilinger, Duan, Walther
Scientific Reports 4, 3583 (2014)



Quantum Simulation Using Photons

Philip Walther

Faculty of Physics
University of Vienna
Austria

Enrico Fermi Summer School
Varenna, Italy
24-25 July 2016

Lecture III:
Photonic Quantum Simulation & Quantum computing exploiting the superposition of quantum gates

Digital Quantum Simulation
of
2 XY-interacting Spins

Quantum Simulation of XY-interacting Spins

- Simulation of a two-qubit XY Heisenberg Hamiltonian in a transverse magnetic field

$$H = J_x \sigma_x \otimes \sigma_x + J_y \sigma_y \otimes \sigma_y + \frac{1}{2} B (\mathbb{1} \otimes \sigma_z + \sigma_z \otimes \mathbb{1})$$

- Transformation to non-interacting particles (diagonal from) by applying *U*

$$U = \begin{pmatrix} \cos\frac{x}{2} & 0 & 0 & \sin\frac{x}{2} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\sin\frac{x}{2} & 0 & 0 & \cos\frac{x}{2} \end{pmatrix}$$

with: $\tan x = \frac{J_x - J_y}{B}$

- Allows to obtain free particle Hamiltonian

$$UHU^\dagger = \omega_1 \sigma_z \otimes \mathbb{1} + \omega_2 \mathbb{1} \otimes \sigma_z$$

free particle energy: $\omega_1 = \frac{1}{2}(E_1 - E_2)$

$\omega_2 = \frac{1}{2}(E_1 + E_2)$

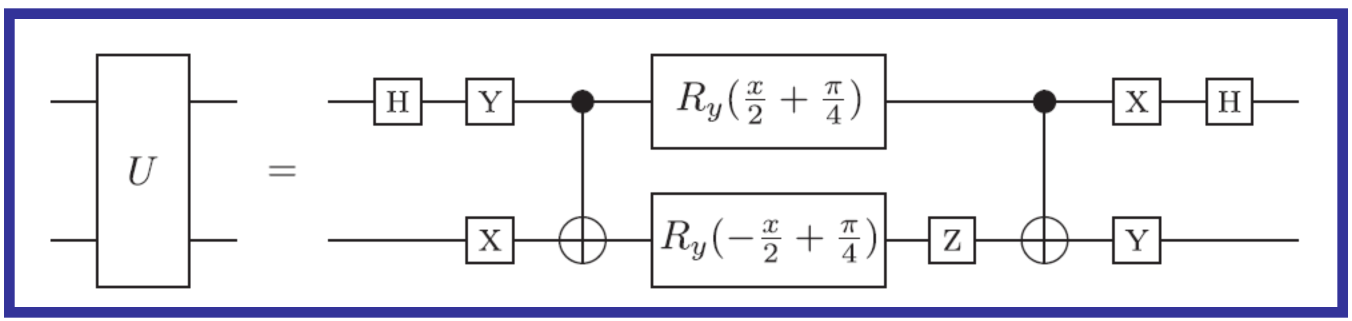
Verstraete, Cirac, Latorre, PRA 79, 032316 (2009)

Quantum Simulation of XY-interacting Spins

- With U we get access to ground and excited eigenstates of $H\,|\psi_i\rangle = E_i\,|\psi_i\rangle$

$$
\begin{aligned}
|\psi_1\rangle &= U\,|00\rangle \\
|\psi_2\rangle &= U\,|01\rangle \\
|\psi_3\rangle &= U\,|10\rangle \\
|\psi_4\rangle &= U\,|11\rangle
\end{aligned}
\quad\Longrightarrow\quad
\begin{aligned}
|\psi_1\rangle &= \cos\frac{x}{2}\,|00\rangle + \sin\frac{x}{2}\,|11\rangle\,, & E_1 &= \sqrt{B^2 + (J_x - J_y)^2} \\
|\psi_2\rangle &= \frac{1}{\sqrt{2}}\,(|01\rangle - |10\rangle)\,, & E_2 &= -J_x - J_y \\
|\psi_3\rangle &= \frac{1}{\sqrt{2}}\,(|01\rangle + |10\rangle)\,, & E_3 &= J_x + J_y \\
|\psi_4\rangle &= -\sin\frac{x}{2}\,|00\rangle + \cos\frac{x}{2}\,|11\rangle\,, & E_4 &= -\sqrt{B^2 + (J_x - J_y)^2}
\end{aligned}
$$

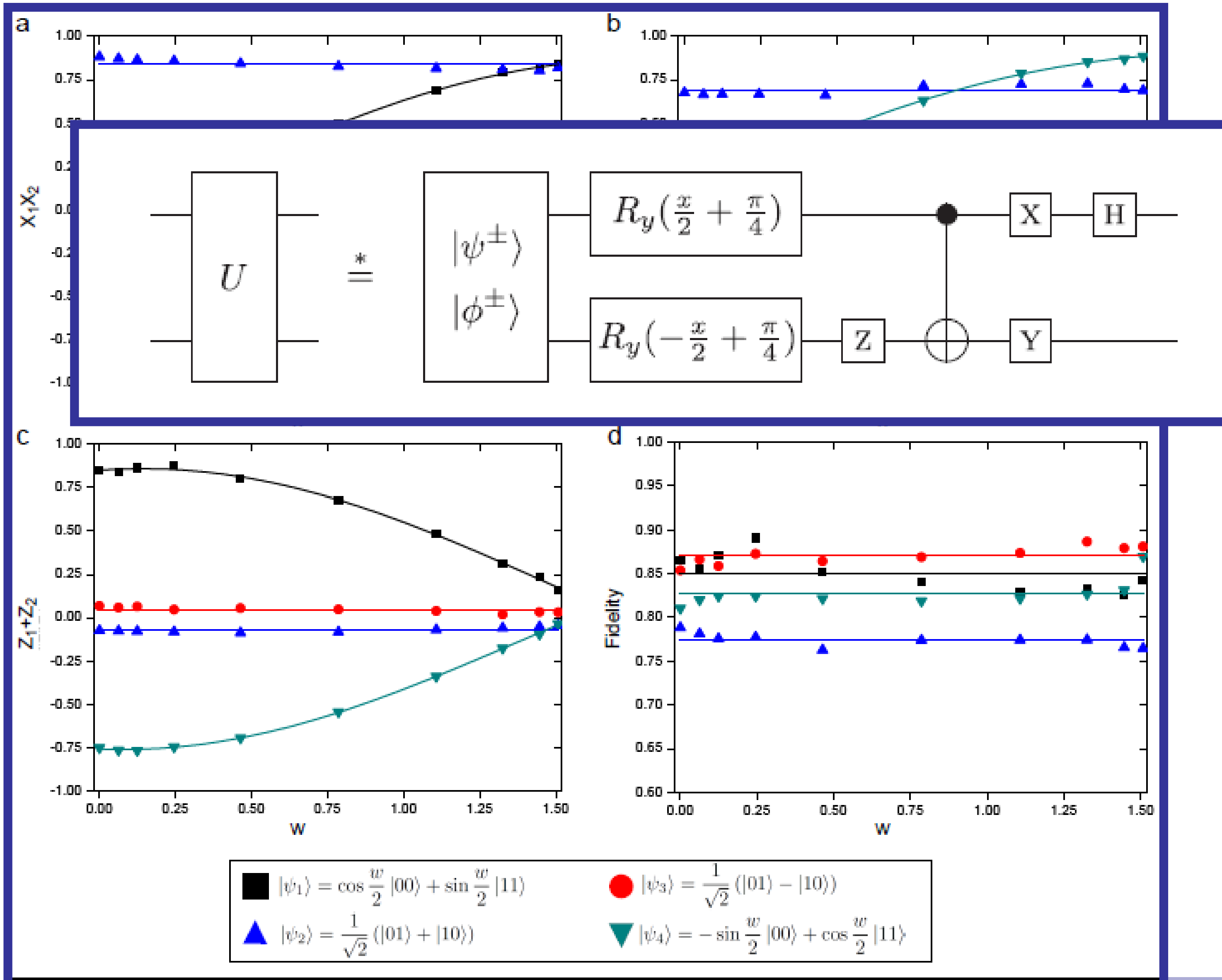
- Quantum Circuit to implement U



➡ **local Bogolubov transformations**

➡ **also for thermal states:** $\rho_{\mathrm{th}} = e^{-\frac{H}{kT}} = U\,e^{-\frac{\tilde{H}}{kT}}\,U^\dagger$

Quantum Simulation of XY-interacting Spins

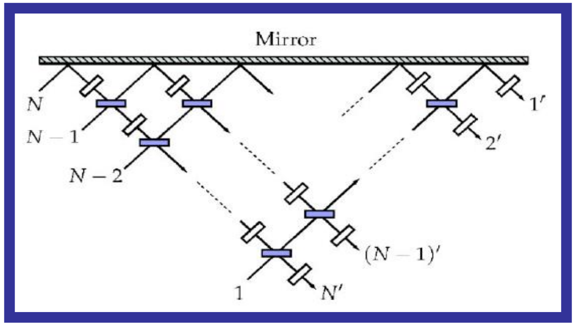


Barz, Dakic, Lipp, Verstraete, Whitfield, Walther
Physical Review X 5, 021010 (2015)

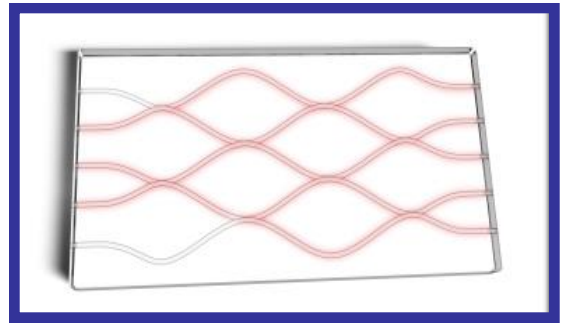
Ressource-Efficient
Intermediate Quantum Computing
(Boson Sampling)

Multi-Photon Random Walk Computation

Complex Random Walks / N-port interferometers

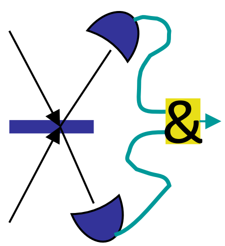


Reck, Zeilinger, Bernstein, Bertani, PRL 73, 58 (1994)

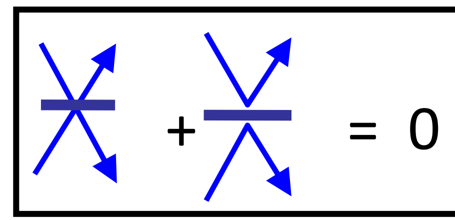


Transformation of input state to output state (for 2 photons)

$$U = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$



$$BS = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}$$



$$Perm = \begin{pmatrix} a & b \\ c & d \end{pmatrix} = (ad + cb)$$

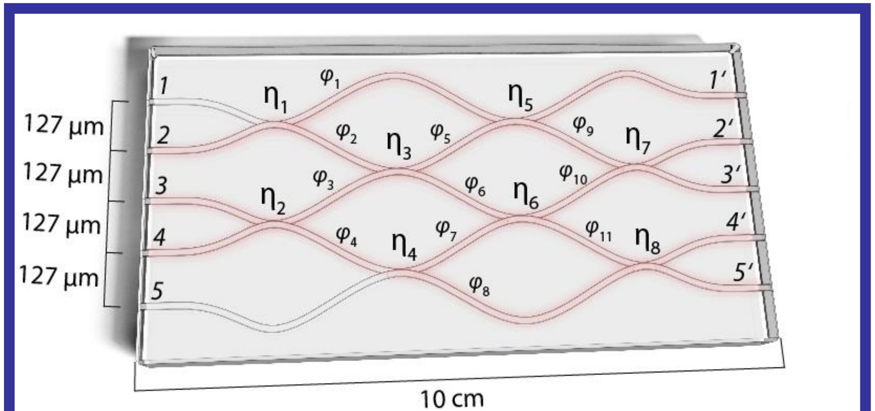
$$P = \left| Perm \begin{pmatrix} T & iR \\ iR & T \end{pmatrix} \right|^2 = \left| T^2 - R^2 \right|^2$$

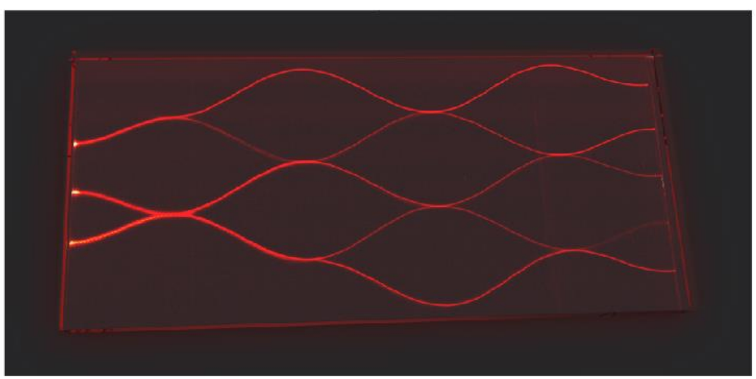
.) hard to calculate (#'P)
.) even for related operations
(e.g. sampling)

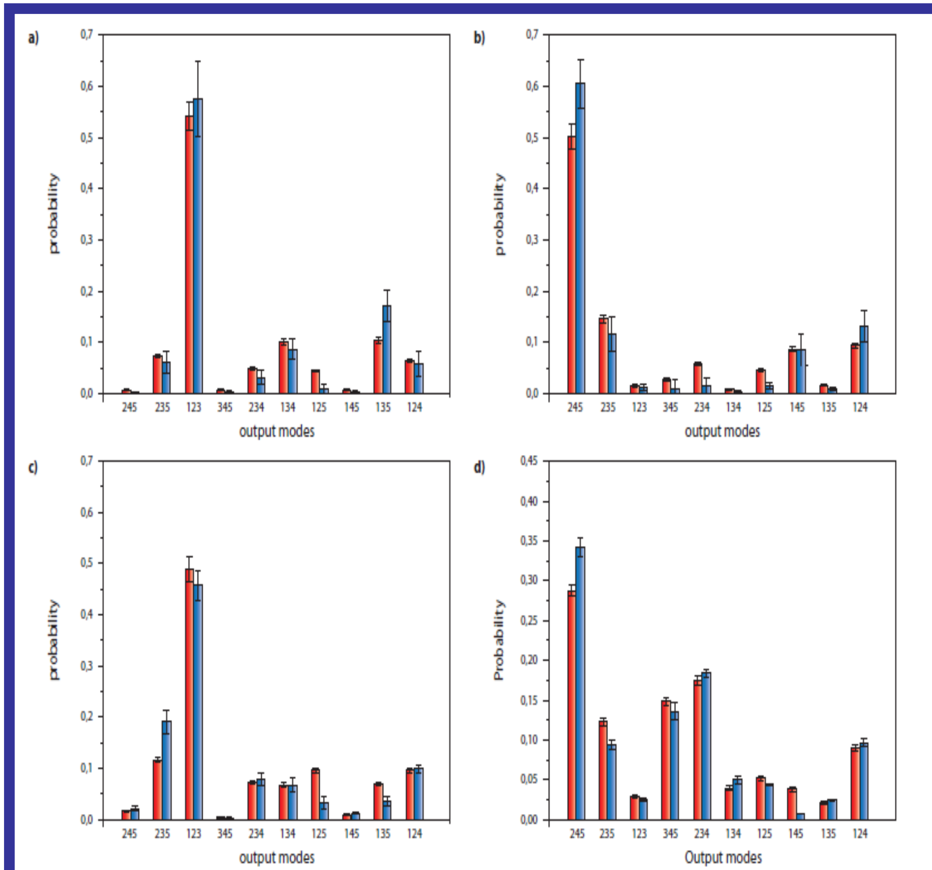
Aaronson, Arkhipov, arXiv:1011.3245v1 (2010)

Intermediate Photonic Quantum Computing

<u>Classical limit for boson sampling:</u> ~20 photons in ~400 modes **(!)**



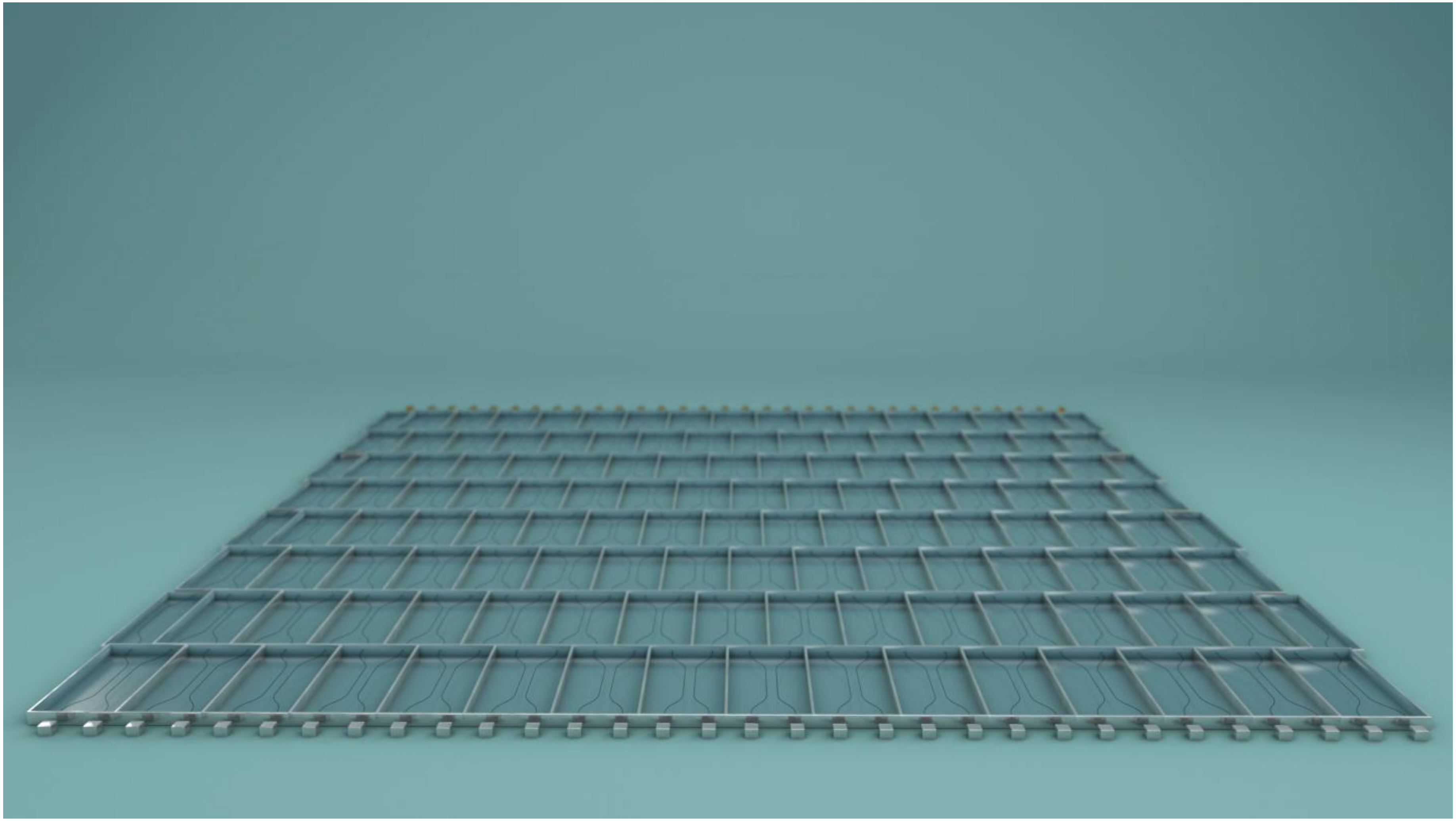




P.P. Rohde, T.C. Ralph, PRA 85, 022332 (2012)

Tillmann, Dakic, Heilmann, Nolte, Szameit, Walther,
Nature Photonics 7, 540 (2013)
<u>See also</u>: Oxford, Brisbane, Rome

Photon Interference using Waveguides



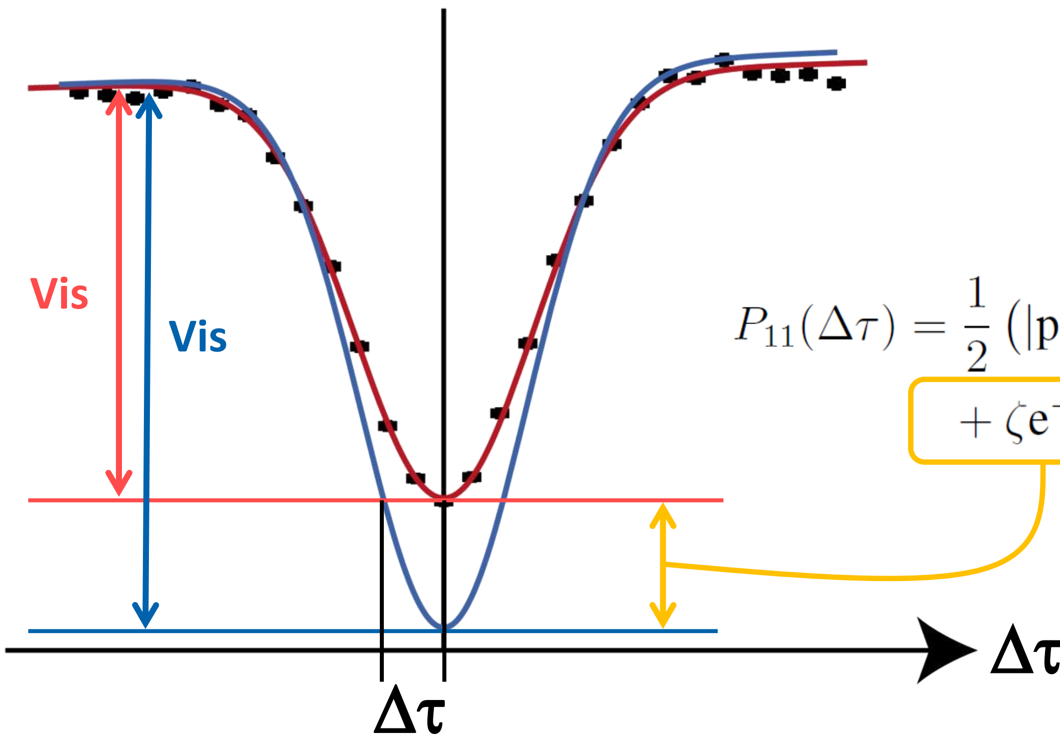
~~Intermediate~~ most-efficient Photonic Quantum Computing

<u>Classical limit for boson sampling:</u> ~20 photons in ~400 modes **(!)**

among the hottest candidates for outperforming classical computers

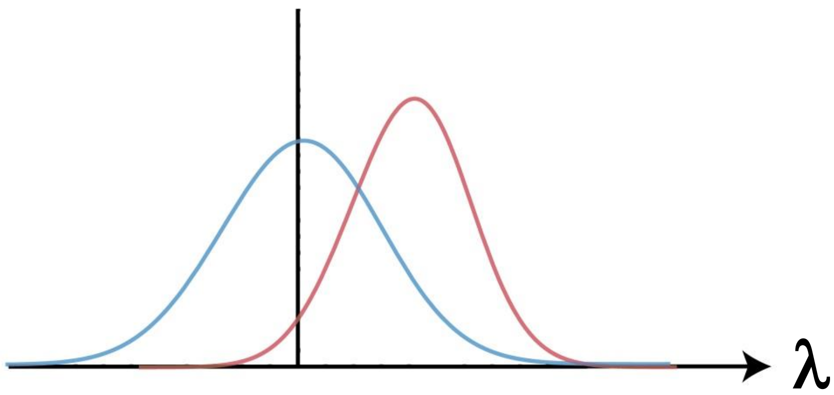
Non-ideal Boson Sampling

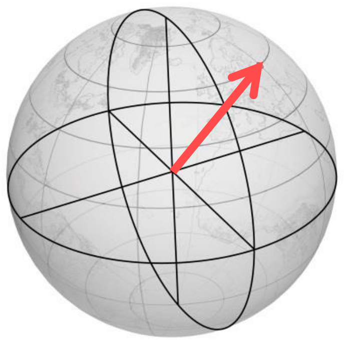
Photon Distinguishability

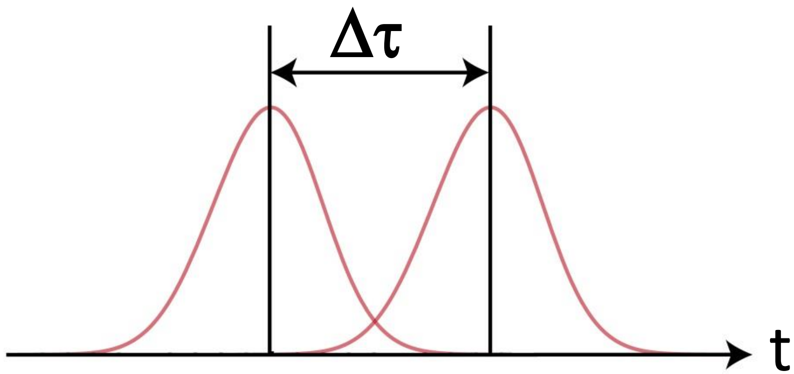


$$P_{11}(\Delta\tau) = \frac{1}{2}\left(|\mathrm{per}(B)|^2 + |\det(B)|^2\right)$$
$$\boxed{+\,\zeta e^{-\xi\Delta\tau^2}}\left(|\mathrm{per}(B)|^2 - |\det(B)|^2\right)$$

Photon Distinguishability



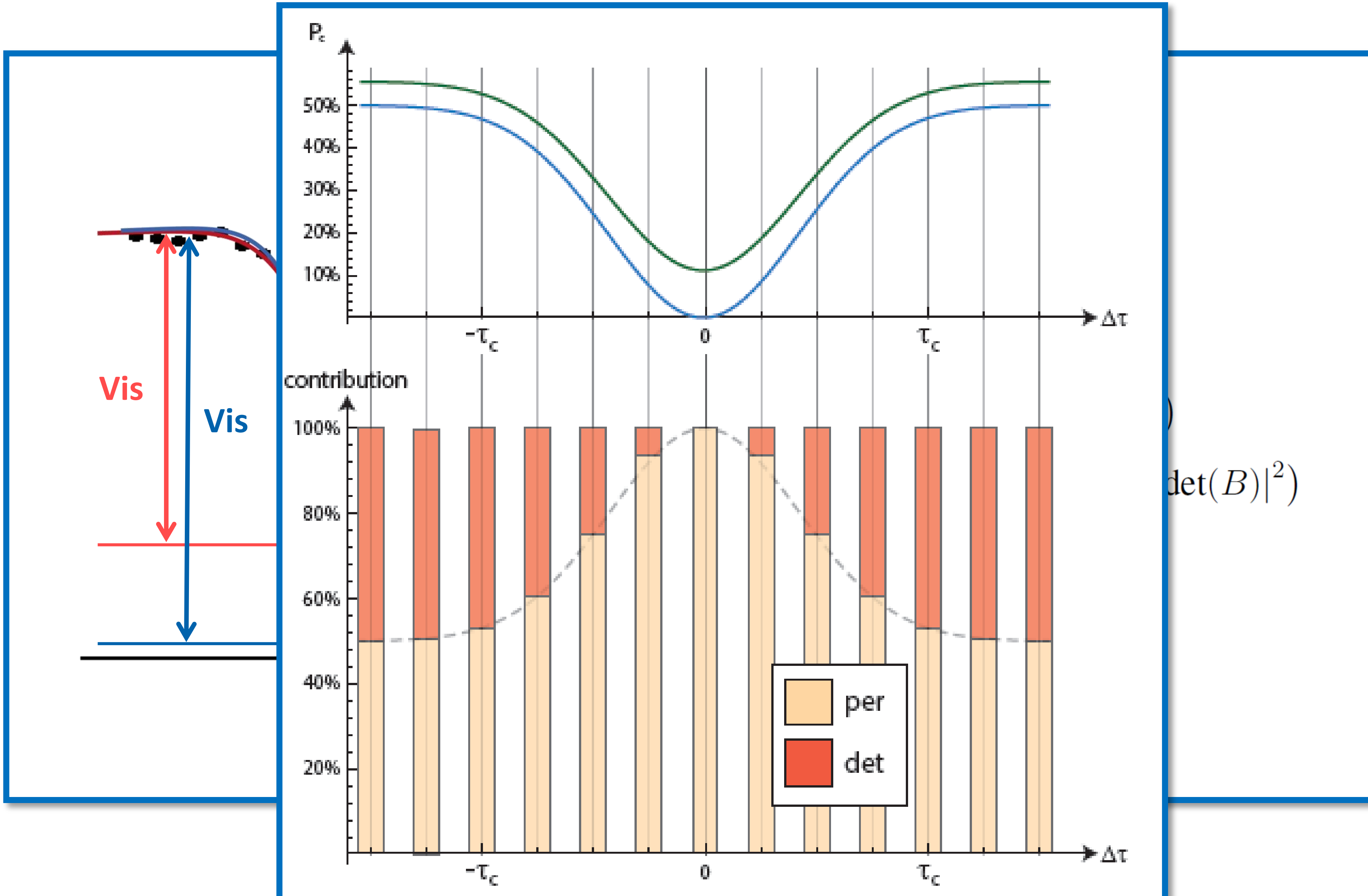




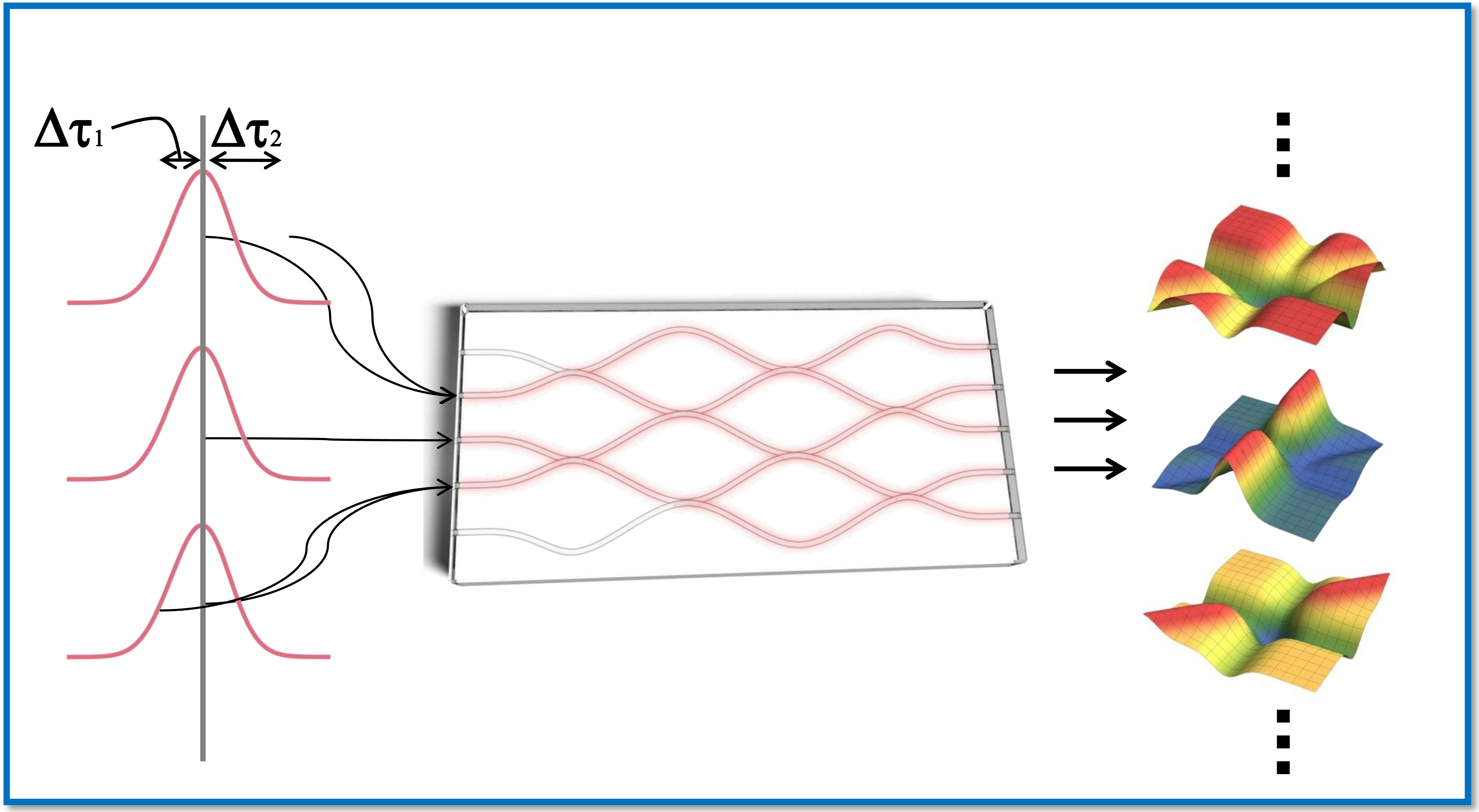
Distinguishability can always be treated as mode-mismatch

One parameter to model them all

Photon Distinguishability



Tuning of a BosonSampling Computer

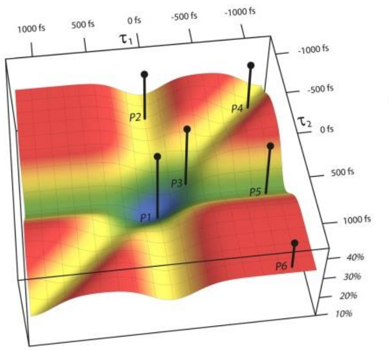


Generalized Multiphoton Quantum Interference
Tillmann, Tan, Stöckl, Sanders, de Guise, Heilmann,Nolte,Szameit,Walther
Physical Review X 5, 041015 (2015)

Theory of (in)distinguishability

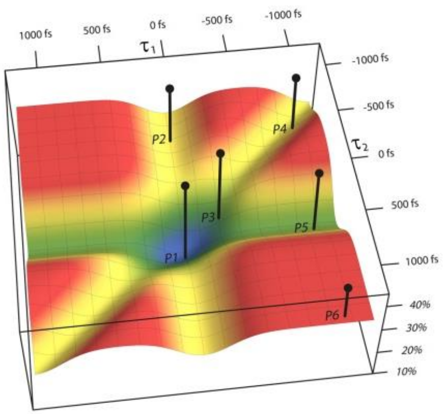
$$
\begin{aligned}
P_{111}(\Delta\tau_1,\Delta\tau_2) = &\int d\omega \int d\omega' \int d\omega'' |\,\langle 111|\,\hat{R}^\dagger a_1^\dagger(\omega) a_2^\dagger(\omega') a_3^\dagger(\omega'')\,|0\rangle\,|^2 \\
= &\frac{1}{6}|\mathrm{det}(R)|^2 + \frac{2}{9}|\mathrm{imm}(R_{132})|^2 + \frac{1}{9}\mathrm{imm}^*(R_{132})\mathrm{imm}(R_{213}) + \frac{1}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R_{213}) \\
&+ \frac{2}{9}|\mathrm{imm}(R_{213})|^2 + \frac{2}{9}|\mathrm{imm}(R_{312})|^2 + \frac{2}{9}|\mathrm{imm}(R)|^2 + \frac{1}{9}\mathrm{imm}(R_{312})\mathrm{imm}^*(R) \\
&+ \frac{1}{6}|\mathrm{per}(R)|^2 + \frac{1}{9}\mathrm{imm}(R)\mathrm{imm}^*(R_{312}) \\
&\boxed{+ \zeta_{13}\exp(-2\xi_{13}(\Delta\tau_1-\Delta\tau_2)^2}\Big(-\frac{1}{6}|\mathrm{det}(R)|^2 - \frac{2}{9}\mathrm{imm}(R)\mathrm{imm}^*(R_{132}) - \frac{1}{9}\mathrm{imm}(R)\mathrm{imm}^*(R_{213}) \\
&- \frac{1}{9}\mathrm{imm}^*(R_{132})\mathrm{imm}(R_{312}) + \frac{1}{9}\mathrm{imm}^*(R_{213})\mathrm{imm}(R_{312}) - \frac{1}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R_{312}) \\
&+ \frac{1}{9}\mathrm{imm}(R_{213})\mathrm{imm}^*(R_{312}) - \frac{2}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R) - \frac{1}{9}\mathrm{imm}(R_{213})\mathrm{imm}^*(R) + \frac{1}{6}|\mathrm{per}(R)|^2\Big) \\
&\boxed{+ \zeta_{12}\exp(-2\xi_{12}\Delta\tau_1^2)}\Big(-\frac{1}{6}|\mathrm{det}(R)|^2 + \frac{1}{9}\mathrm{imm}(R)\mathrm{imm}^*(R_{132}) + \frac{2}{9}\mathrm{imm}(R)\mathrm{imm}^*(R_{213}) \\
&+ \frac{2}{9}\mathrm{imm}^*(R_{132})\mathrm{imm}(R_{312}) + \frac{1}{9}\mathrm{imm}^*(R_{213})\mathrm{imm}(R_{312}) + \frac{2}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R_{312}) \\
&+ \frac{1}{9}\mathrm{imm}(R_{213})\mathrm{imm}^*(R_{312}) + \frac{1}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R) + \frac{2}{9}\mathrm{imm}(R_{213})\mathrm{imm}^*(R) + \frac{1}{6}|\mathrm{per}(R)|^2\Big) \\
&\boxed{+ \zeta_{23}\exp(-2\xi_{23}\Delta\tau_2^2)}\Big(-\frac{1}{6}|\mathrm{det}(R)|^2 + \frac{1}{9}\mathrm{imm}(R)\mathrm{imm}^*(R_{132}) - \frac{1}{9}\mathrm{imm}(R)\mathrm{imm}^*(R_{213}) \\
&- \frac{1}{9}\mathrm{imm}^*(R_{132})\mathrm{imm}(R_{312}) - \frac{2}{9}\mathrm{imm}^*(R_{213})\mathrm{imm}(R_{312}) - \frac{1}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R_{312}) \\
&- \frac{2}{9}\mathrm{imm}(R_{213})\mathrm{imm}^*(R_{312}) + \frac{1}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R) - \frac{1}{9}\mathrm{imm}(R_{213})\mathrm{imm}^*(R) + \frac{1}{6}|\mathrm{per}(R)|^2\Big) \\
&\boxed{+ \zeta_{123}\exp(-I_a + iI_s)}\Big(\frac{1}{6}|\mathrm{det}(R)|^2 - \frac{1}{9}|\mathrm{imm}(R_{132})|^2 - \frac{2}{9}\mathrm{imm}^*(R_{132})\mathrm{imm}(R_{213}) \\
&+ \frac{1}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R_{213}) - \frac{1}{9}|\mathrm{imm}(R_{213})|^2 + \frac{1}{9}\mathrm{imm}(R)\mathrm{imm}^*(R_{312}) - \frac{1}{9}|\mathrm{imm}(R_{312})|^2 \\
&- \frac{1}{9}|\mathrm{imm}(R)|^2 - \frac{2}{9}\mathrm{imm}(R_{312})\mathrm{imm}^*(R) + \frac{1}{6}|\mathrm{per}(R)|^2\Big) \\
&\boxed{+ \zeta_{123}\exp(-I_a - iI_s)}\Big(\frac{1}{6}|\mathrm{det}(R)|^2 - \frac{1}{9}|\mathrm{imm}(R_{132})|^2 - \frac{2}{9}\mathrm{imm}(R_{132})\mathrm{imm}^*(R_{213}) \\
&+ \frac{1}{9}\mathrm{imm}^*(R_{132})\mathrm{imm}(R_{213}) - \frac{1}{9}|\mathrm{imm}(R_{213})|^2 + \frac{1}{9}\mathrm{imm}^*(R)\mathrm{imm}(R_{312}) - \frac{1}{9}|\mathrm{imm}(R_{312})|^2 \\
&- \frac{1}{9}|\mathrm{imm}(R)|^2 - \frac{2}{9}\mathrm{imm}^*(R_{312})\mathrm{imm}(R) + \frac{1}{6}|\mathrm{per}(R)|^2\Big) \,,
\end{aligned}
$$

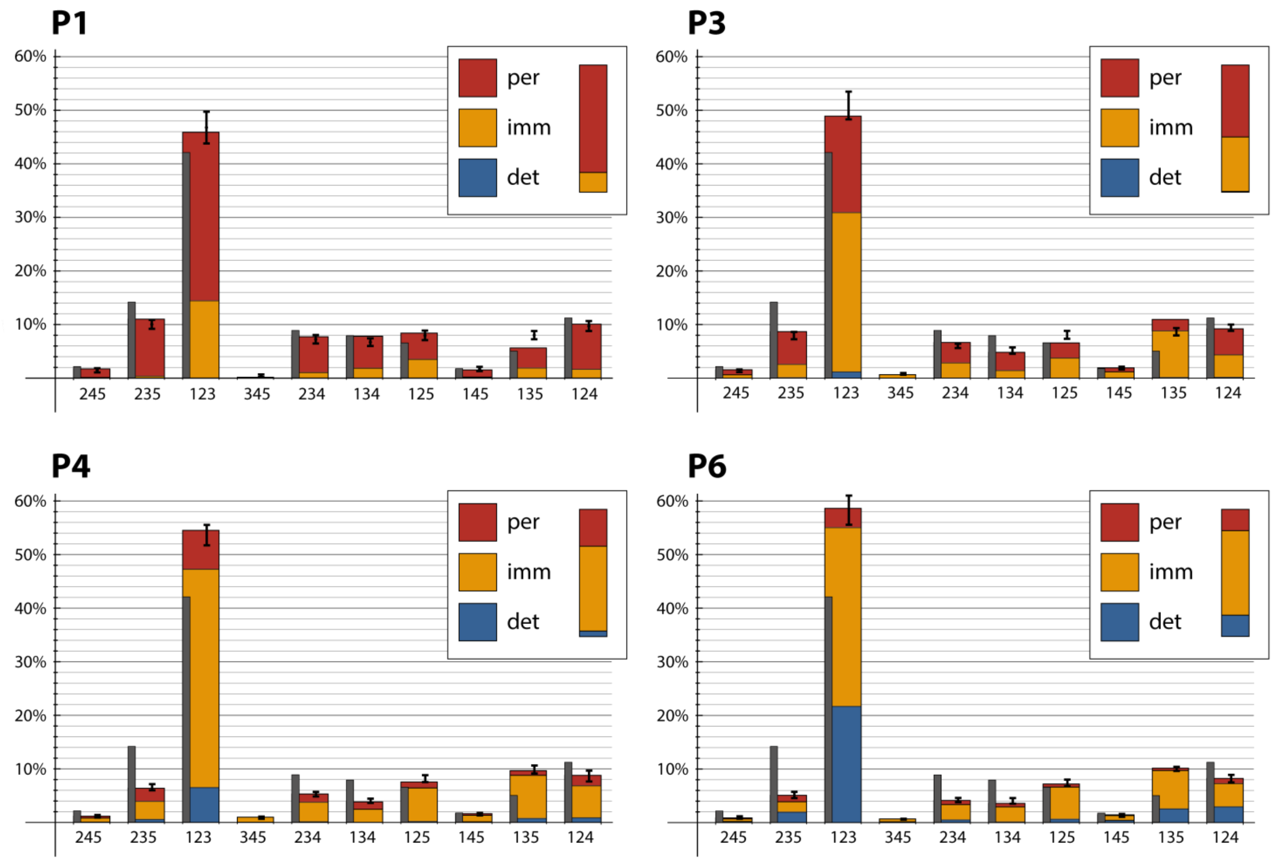
- 60 terms describe the interference of a 3-photon landscape
- Overlap-terms weight the per, det and imm
- For perfect indistinguishability this reduces to just the per



Generalized Multi-Photon Quantum Inteference

Application to larger scattering networks - BosonSampling



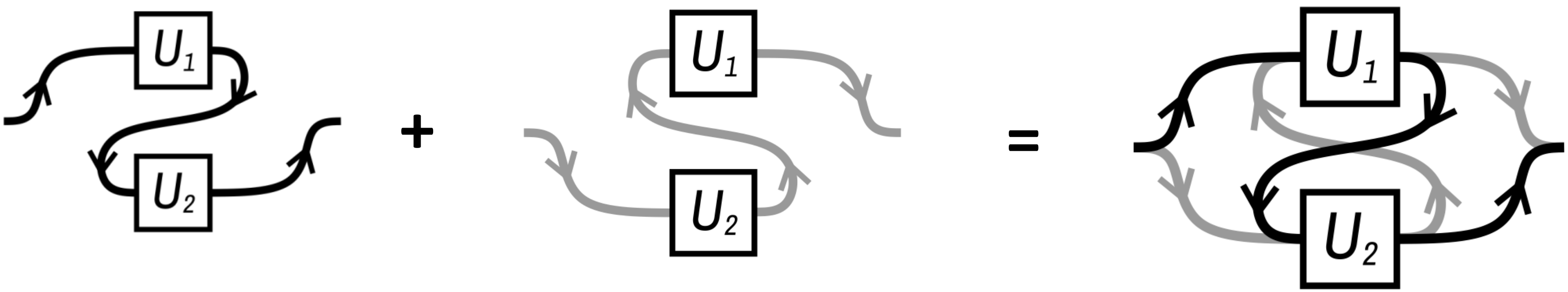


Generalized Multiphoton Quantum Interference
Tillmann, Tan, Stöckl, Sanders, de Guise, Heilmann,Nolte,Szameit,Walther
Physical Review X 5, 041015 (2015)

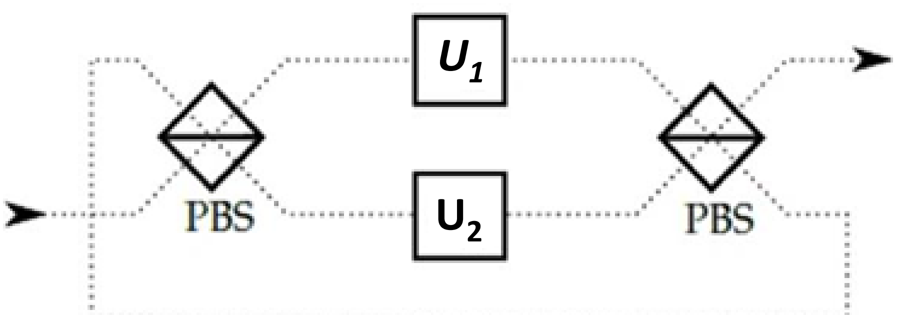
Mobility as feature for the speed-up of particular tasks for quantum computers/simulators

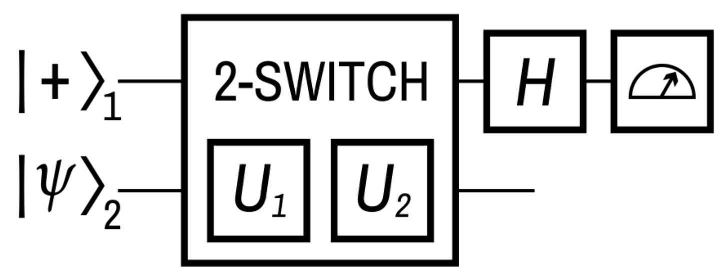
Superpostion of Quantum Circuits

Quantum switch[1]



Proposal[2]



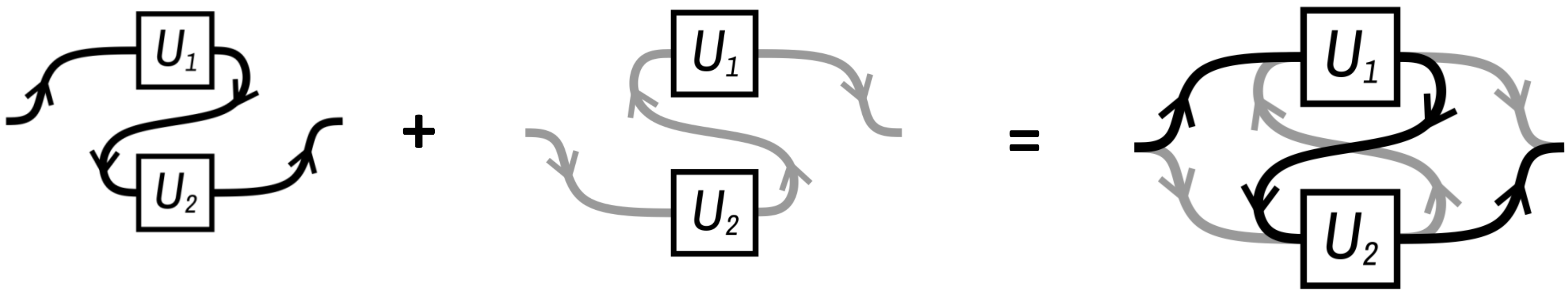


[1] Chiribella *et al,* Phy. Rev. A 88, 022318 (2013)

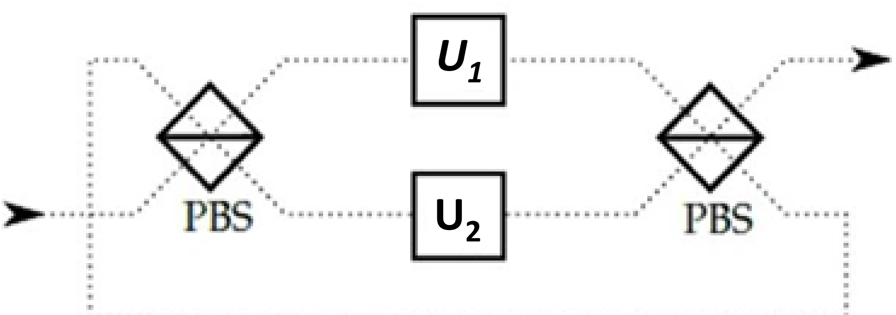
[2] Mateus Araújo, *et al* Phys. Rev. Lett. 113, 250402 (2014)

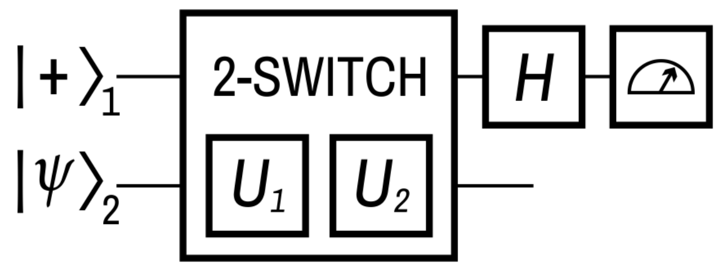
Superposition of Quantum Circuits

Quantum switch[1]



Proposal[2]





[1] Chiribella *et al,* Phy. Rev. A 88, 022318 (2013)

[2] Mateus Araújo, *et al Phys. Rev. Lett. 113, 250402 (2014)*

Superposition of Quantum Circuits

C

P

➤

Computational Benefit:

- **exponential advantage** over classical algorithms
- **linear advantage** over quantum algorithms.

Fundamental Interest:

- superpostion of **causal order**

[1] Chiribella *et al,* Phy. Rev. A 88, 022318 (2013)

[2] Mateus Araújo, *et al Phys. Rev. Lett. 113, 250402 (2014)*

A Quantum Task

The task is to distinguish whether a pair of unitary transformations ***A*** and ***B*** *commute or anti-commute.*

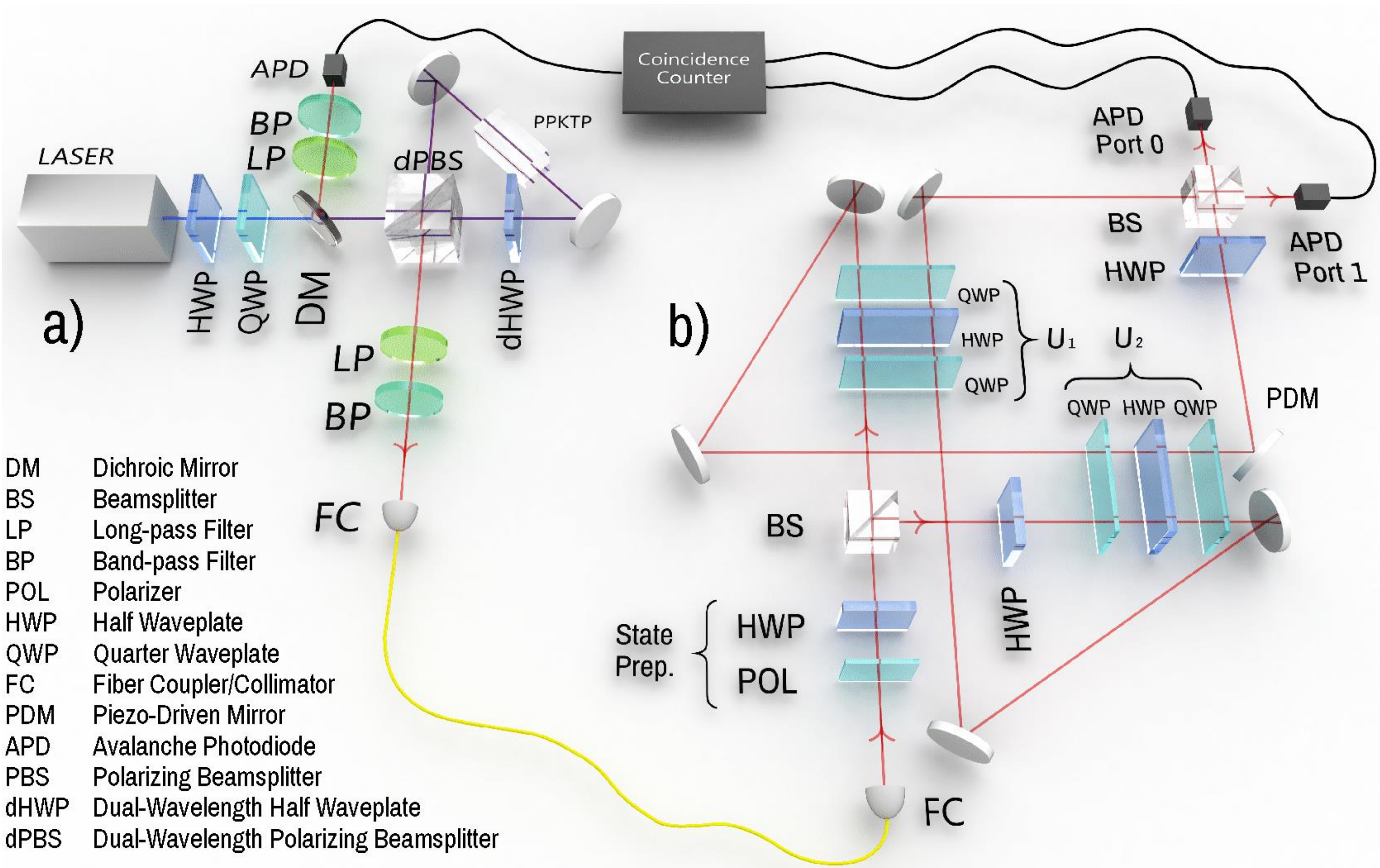
$$|\psi\rangle|H\rangle \rightarrow BA|\psi\rangle|H\rangle$$

$$|\psi\rangle|V\rangle \rightarrow AB|\psi\rangle|V\rangle$$

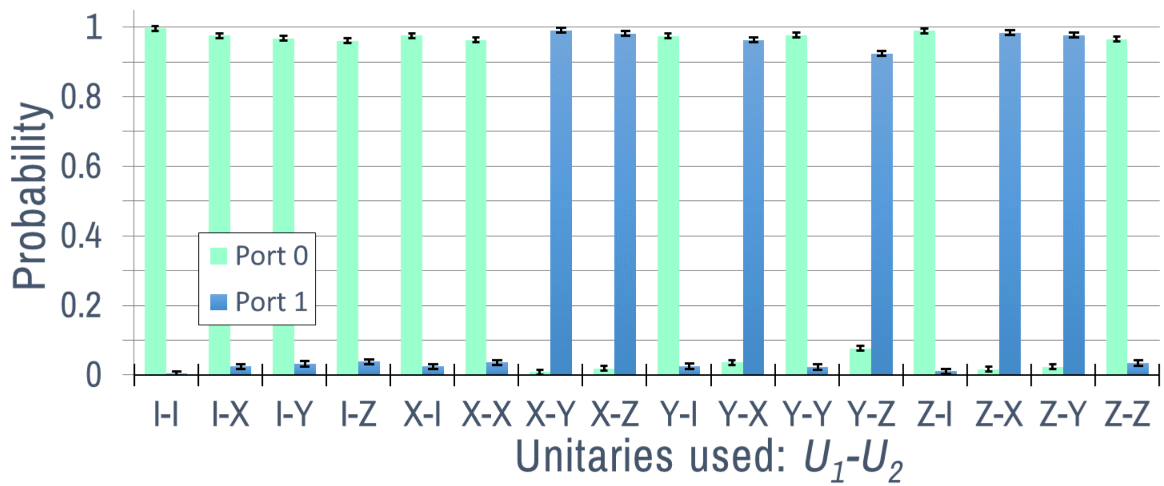
$$|\psi\rangle|D\rangle \rightarrow \frac{1}{\sqrt{2}}(BA|\psi\rangle|H\rangle + AB|\psi\rangle|V\rangle)$$

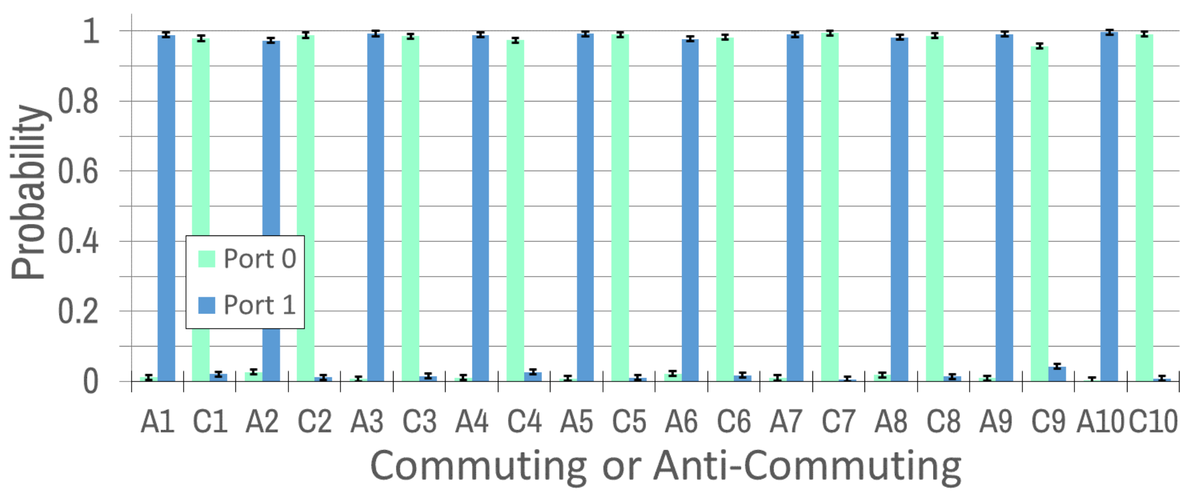
$$|\psi\rangle|D\rangle \rightarrow \frac{1}{\sqrt{2}}\left(\{A,B\}|\psi\rangle|D\rangle + [A,B]|\psi\rangle|A\rangle\right)$$

The Experimental Set-Up



Experimental Results





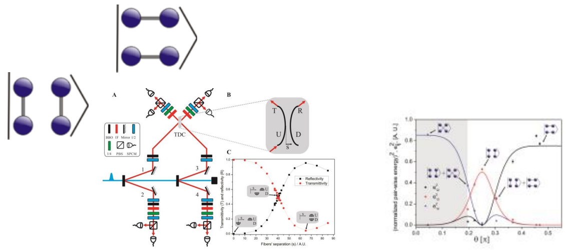
Surpassing regular QC:

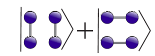
- 100 different pairs of unitary gates for determining if 2 random gates commute
- average success rate:

  0.976 ± 0015

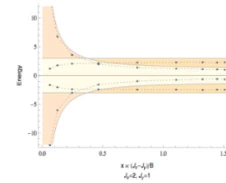
Procopio, Moqanaki, Araujo, Costa, Calafell, Dowd, Hamel,Rozema, Brukner, Walther
Nature Communication 6, 8913 (2015)

Summary & Outlook





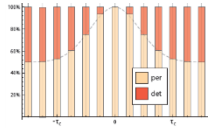
✓ **Quantum monogamy plays a key role in spin frustration**
- quantum simulation of valence-bond solids/liquids
- observation of quantum monogamy [Nature Physics 7, 399 (2011)] [Nature Physics 8, 285 (2012)]

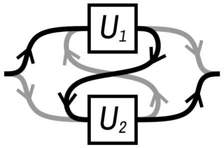


✓ **Quantum simulation of XY-interacting Spins**
- quantum simulation of level crossing [Physical Review X 5, 021010 (2015)]

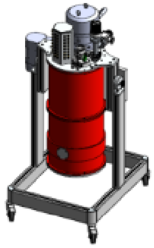
✓ **Intermediate quantum computing**
- experimental boson sampling [Nature Photonics 7, 540 (2013)]

✓ **Non-ideal intermediate quantum computing**
- experimental immanent sampling [Physical Review X 5, 041015 (2015)]

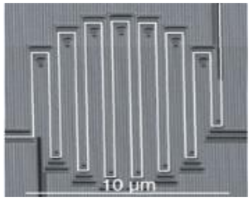


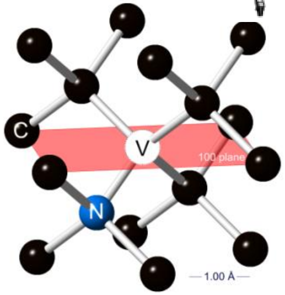


✓ **Superposition of quantum gates**
- speed-up for regular quantum computers [Nature Communications 6, 8913 (2015)]



○ **Outlook: Small-scale quantum computing (< 20 photons)**
- superconducting detectors
- low-loss waveguides
- novel nonlinear photon sources and multiplexing techniques
- entanglement in more degrees-of-freedom





○ **Outlook: Truly scalable quantum photonics**
- deterministic phase gates via light-matter quantum systems
- graphene-based photon sources
- solid-state emitters of entangled photons

Thank you for your attention !

Thank you!