

Quantum information:

from the optics laboratory to the "real" world

Kevin Resch

IQC, Dept. of Physics

University of Waterloo

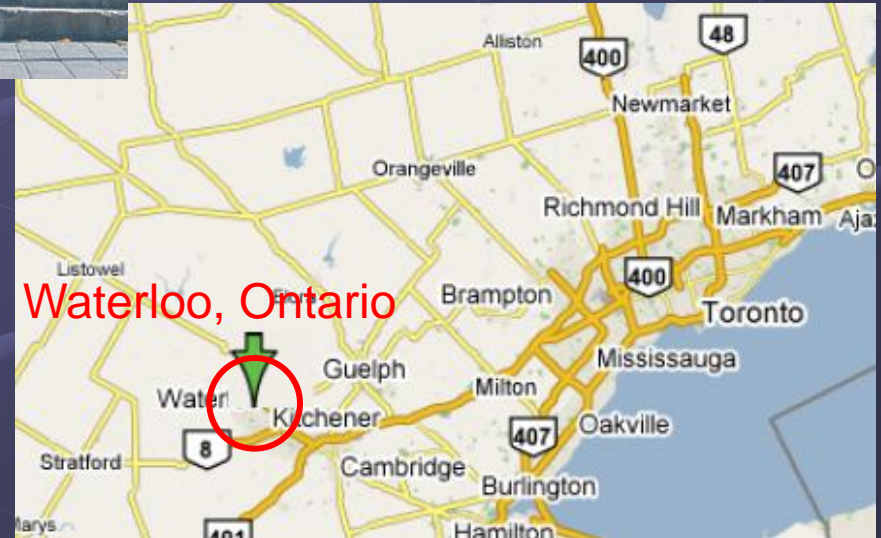


Institute for Quantum Computing

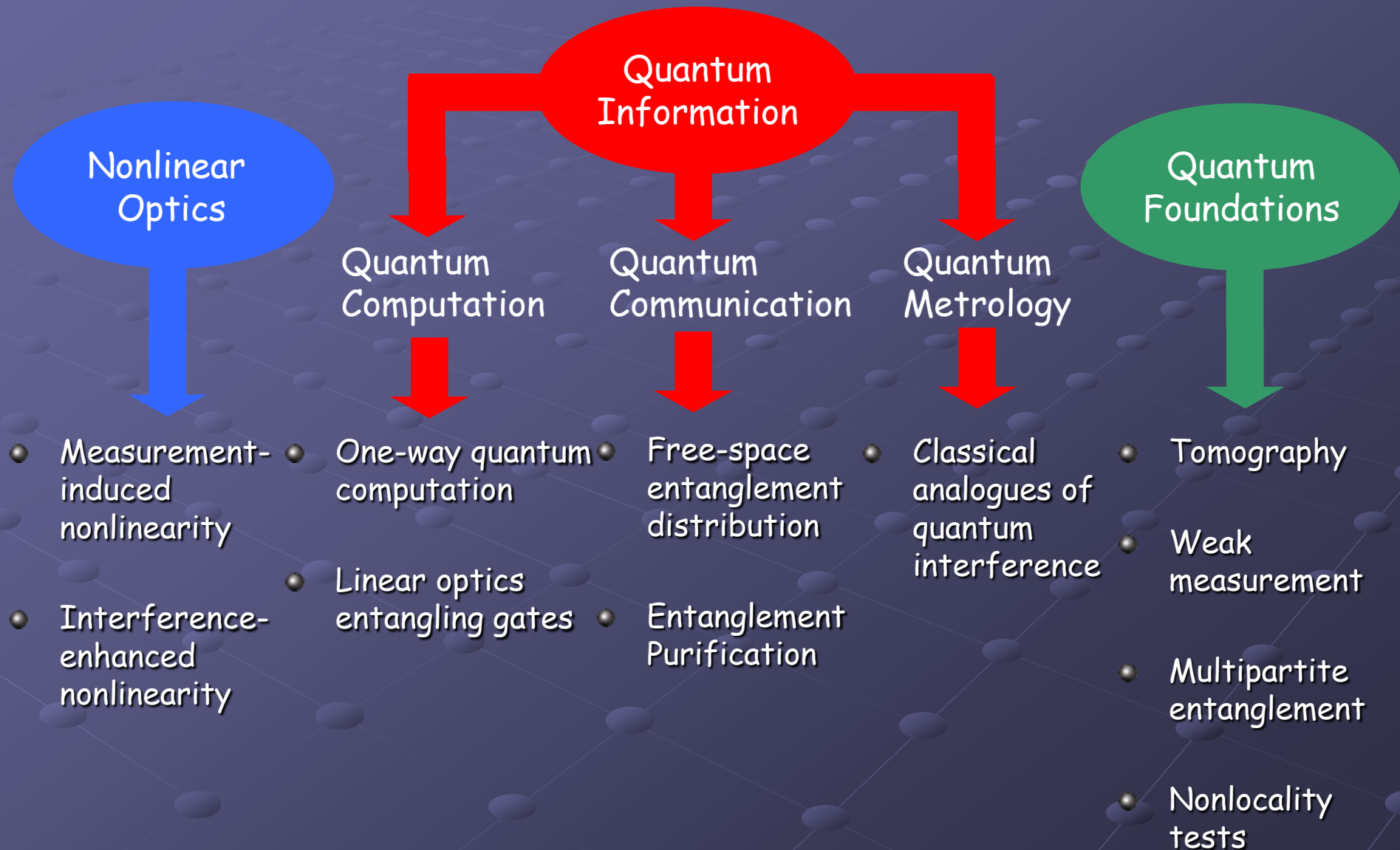


- Founded 2001 at University of Waterloo

- 14 faculty
 - 6 post-docs
 - ~50 students
- Always looking for more!



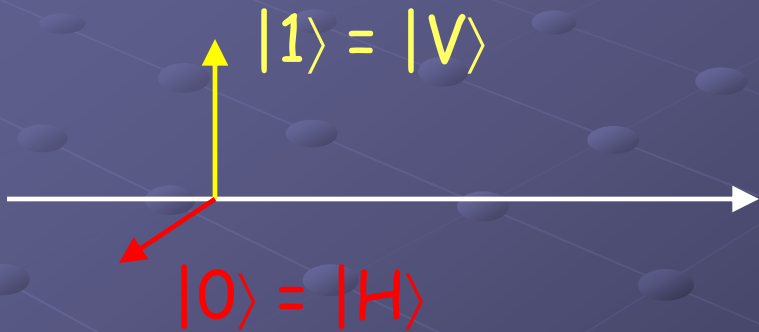
Optical Quantum Information



Quantum information

Quantum bits can be 0 or 1 but also superpositions

bit: 0 or 1
qubit: $\alpha|0\rangle + \beta|1\rangle$



Photon Polarization



Atomic Levels

Familiar quantum features

- Uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Position

Momentum



W. Heisenberg

- No-cloning theorem

$$|\psi\rangle|0\rangle \xrightarrow{\text{NOPE}} |\psi\rangle|\psi\rangle$$



Wooters



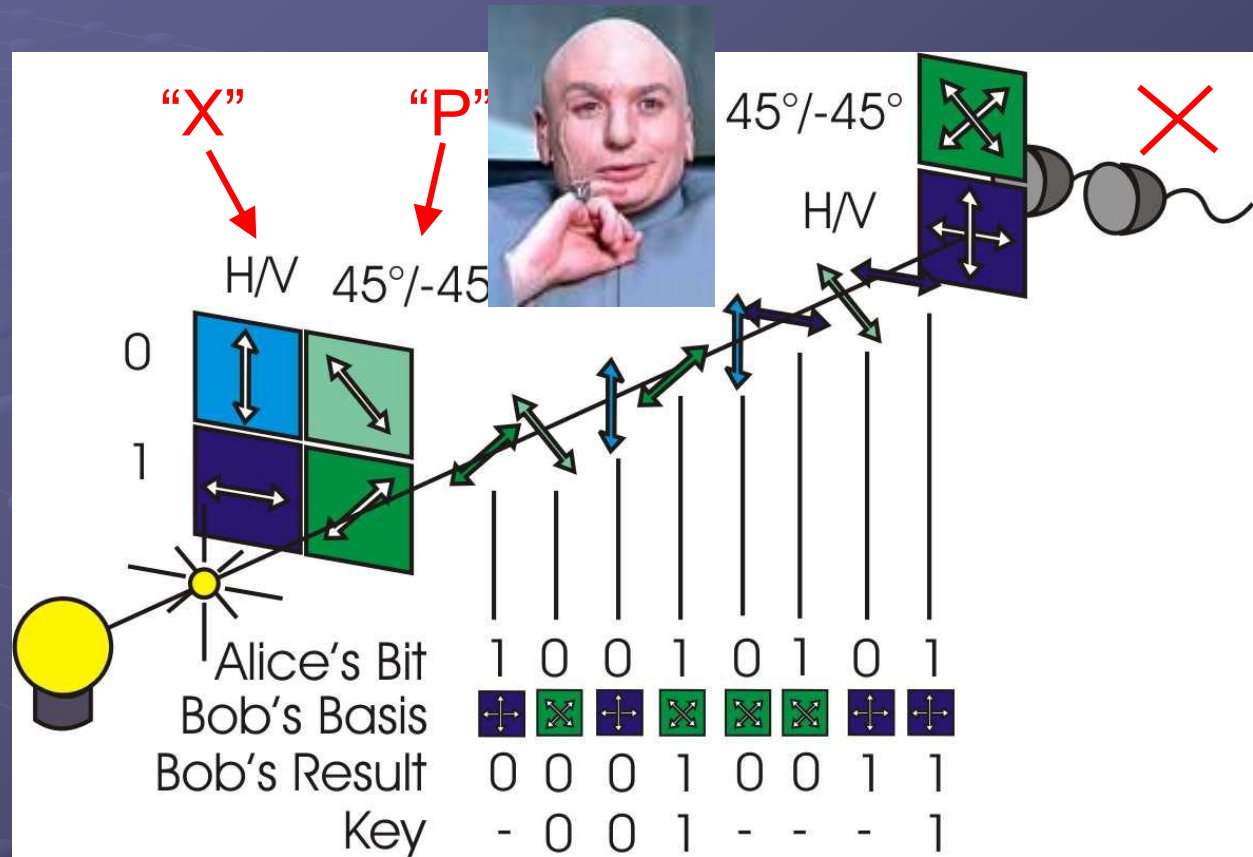
Zurek



Dieks

...leads to ultimate cryptosystem

Attempting to copy a quantum state without disturbing it (no-cloning) is a strategy with inherent errors. In the absence of a detection signal, one might think that copying can be done without disturbance (HUP).



C. Bennett, G. Brassard 1984

...leads to ultimate cryptosystem

Attempting either strategy will lead to errors in the detected signal

Single photons are sent in one of two noncommuting basis states

An eavesdropper must make measurements to learn about the state, but cannot do so without disturbance (HUP)

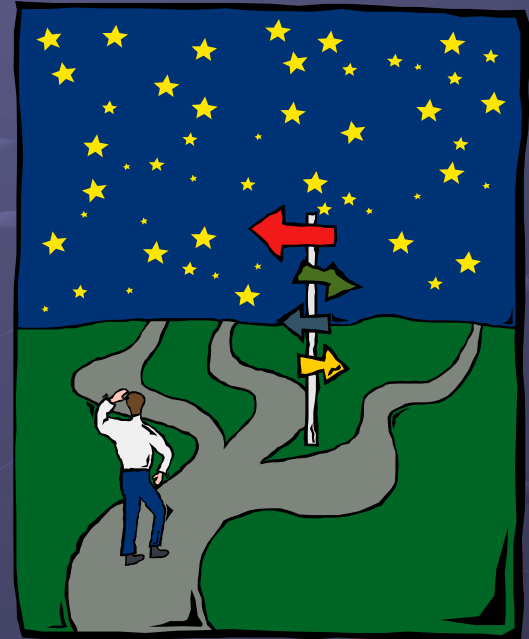
Nor can the eavesdropper make identical copies of the state and make measurements on them (no-cloning)

More quantum features

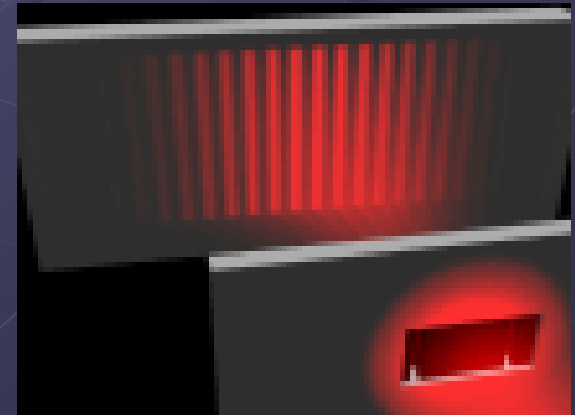
● Superposition

- A quantum system can be in many states at the same time

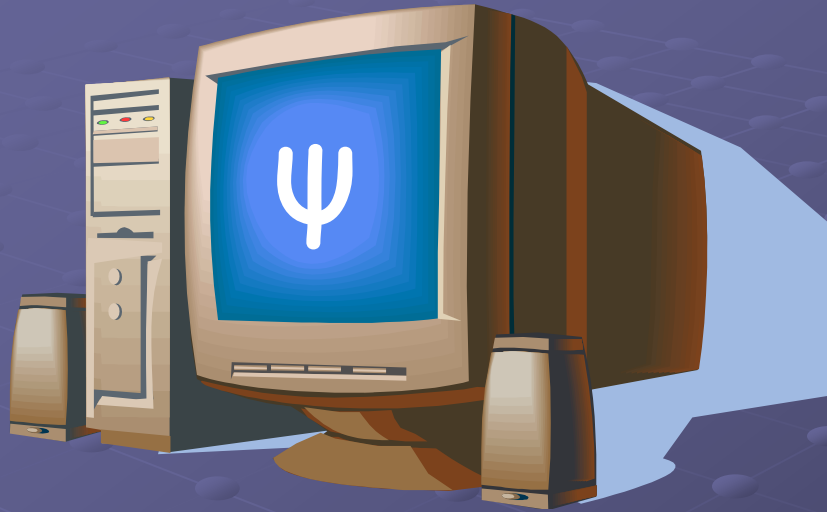
$$|\Psi\rangle = \frac{1}{\sqrt{N}} (|\psi\rangle_1 + |\psi\rangle_2 + |\psi\rangle_3 + \dots)$$



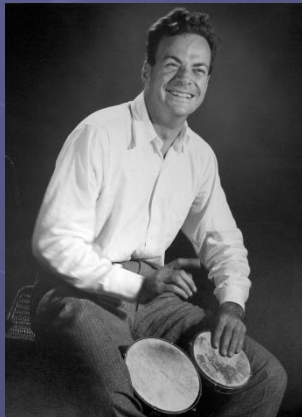
● Interference



...more powerful computers



Measurement results are like a random sequence of bits, except that if you interfere (i.e. revert to a classical algorithm) you can reduce wrong answer states



Feynman



Deutsch

Entanglement

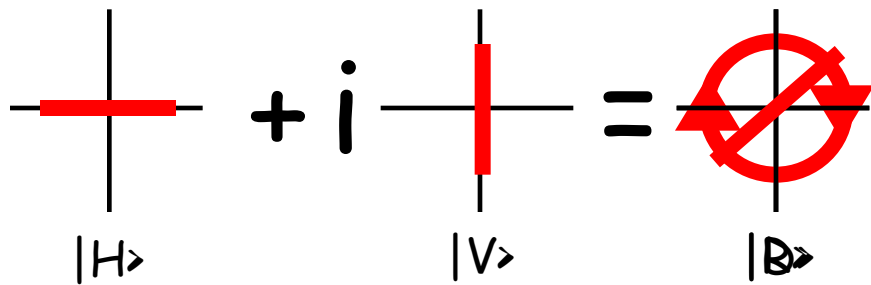
- An entangled state (not entangled)

$$\begin{aligned} |\psi\rangle_{12} &= \frac{1}{\sqrt{2}} (|0\rangle_1 \otimes |0\rangle_2 + |1\rangle_1 \otimes |1\rangle_2) \\ &= |00\rangle + |11\rangle \quad \text{"Bell state"} \end{aligned}$$

- Foundation for most quantum information protocols

Optical photons as qubits

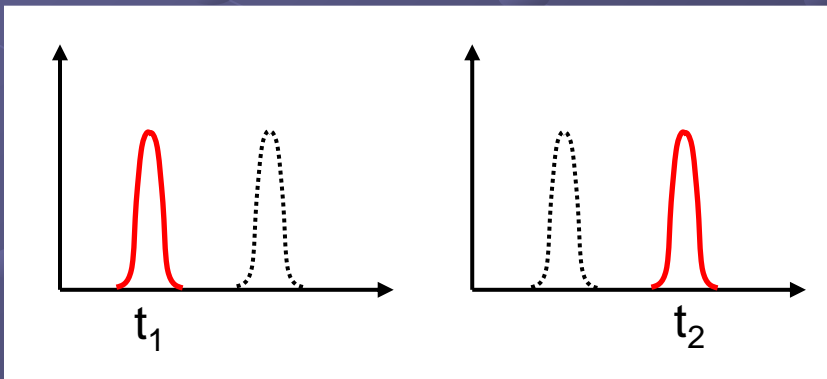
● Polarization



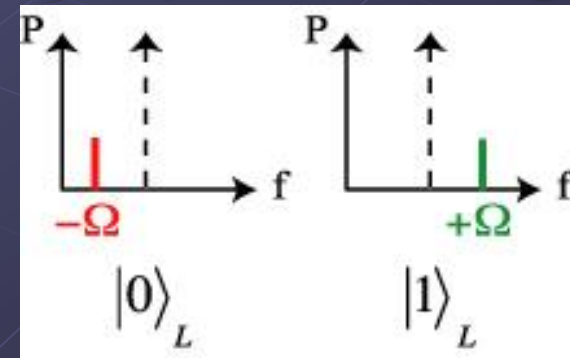
● Spatial modes



● Time-bin



● Freq. encoding



Optical photons as qubits

The Good

- Single-qubit operations
- Low decoherence
- High speed
- Perfect carriers of quantum information

The Bad

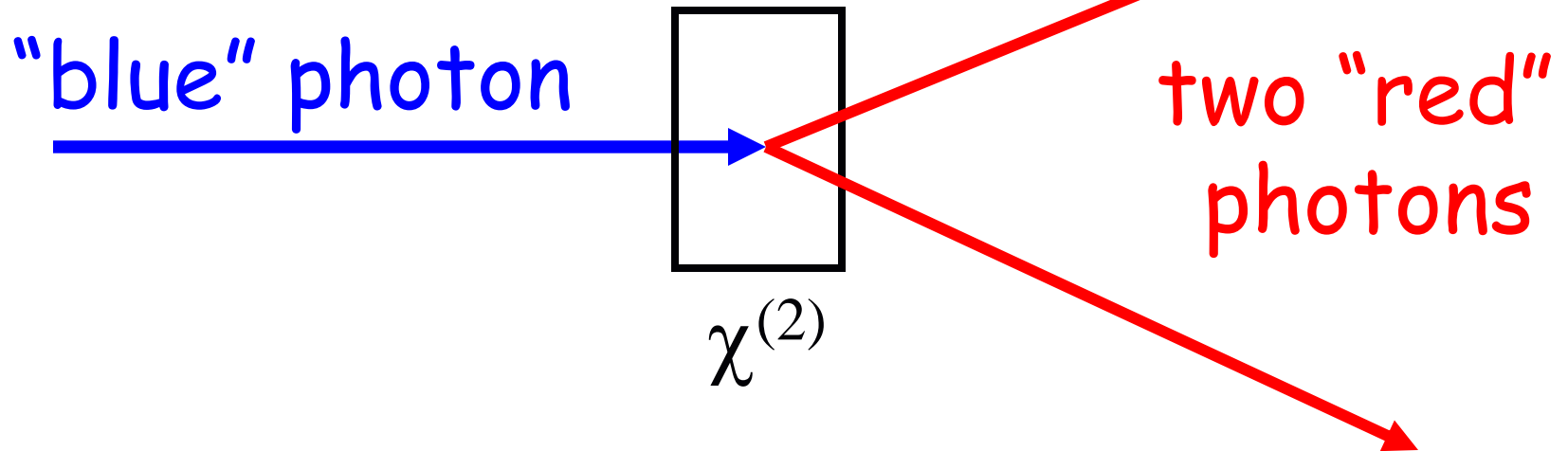
- Easy to lose a photon
- No natural interactions/weak nonlinearities means 2-qubit operations are hard

The Ugly

- Linear optics proposals for scalable quantum computing are extremely complicated (~50-1000s of ancillas/elements per CNOT)

Entangled Photon Source

Parametric Down-conversion



Phase matching:

$$\omega_{\text{pump}} = \omega_s + \omega_i$$

$$\vec{k}_{\text{pump}} = \vec{k}_s + \vec{k}_i$$

Type-II Down-conversion

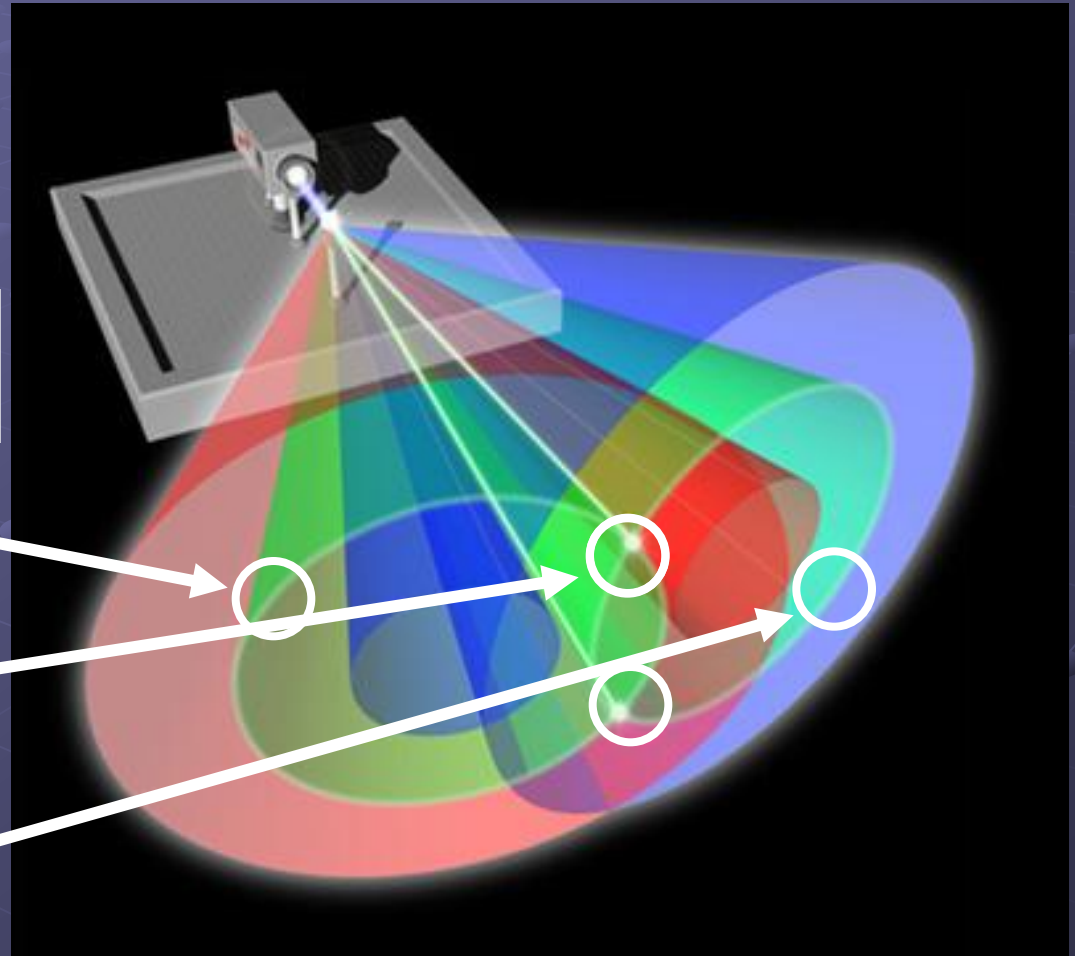
Entangled Pair

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_1 |V\rangle_2 - |V\rangle_1 |H\rangle_2)$$

H-Photon

Confused

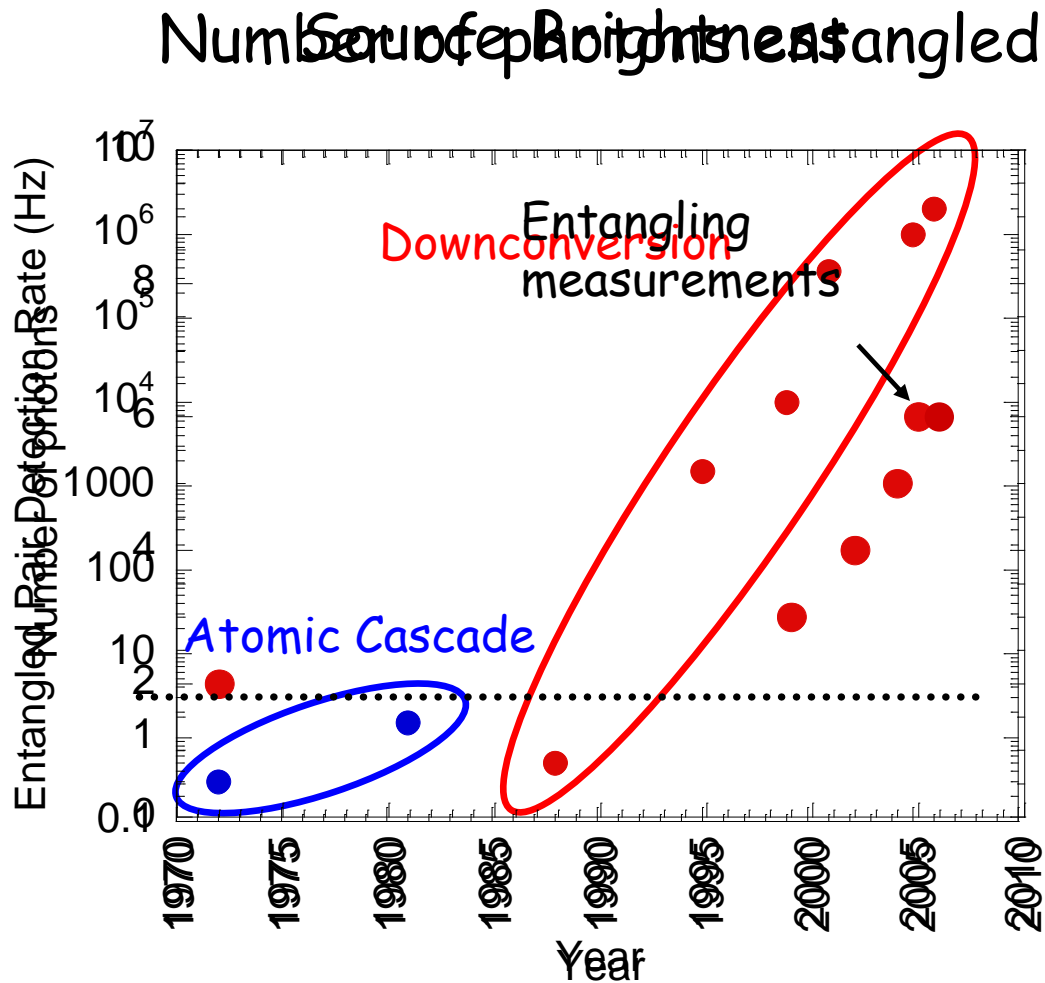
Correlated V-Photon



Recent source advancements

- High-power UV laser diodes (cheap, easy to use -> UG lab!)
- Efficient single-mode coupling (long-distance, low divergence, free-space)
- 4-, 5-, and 6-photon entanglement
 - Controllable entanglement - fundamental tests and quantum computing

State of the art





Long-distance Entanglement distribution



Quantum source

Zeilinger Group



Not Pictured here:

FS1&2: Michael Taraba

FS2: Bibiane Blauensteiner, Alessandro Fedrizzi, Christian Kurtsiefer,
Tobias Schmitt-Manderbach, Henning Weier, Harald Weinfurter

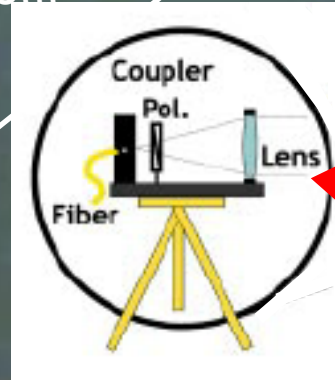
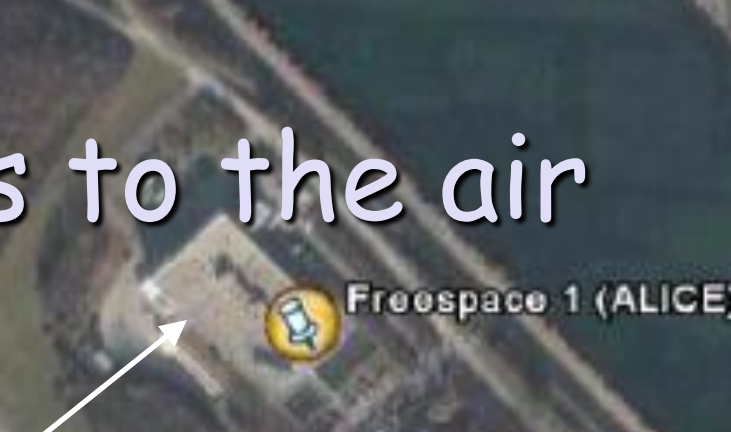
Distributing Entanglement

- Photons are the ideal carriers
- Practical quantum communication needs shared entanglement over long distances
- Challenges: High efficiency (no cloning) and high background rejection (single photons)

Entanglement takes to the air



500m



Freospace 1 (SOURCE)

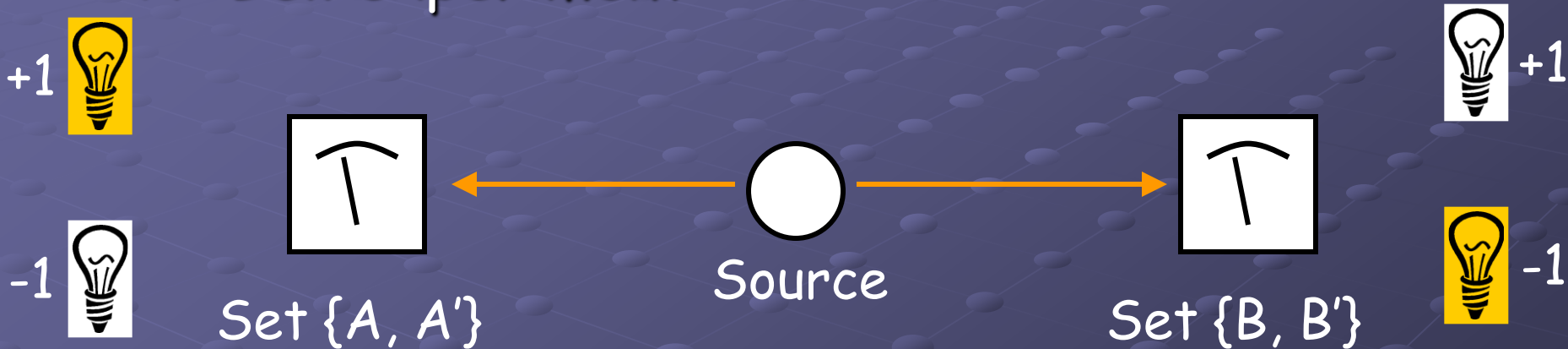
150m

Freospace 1 (BOB)



Quantum correlations

- A "Bell experiment"



- ~~● Local properties (ex. $A=+1, A'=-1, B=+1, B'=+1$)~~

$$\del A(B+B') + A'(B-B') = \pm 2$$

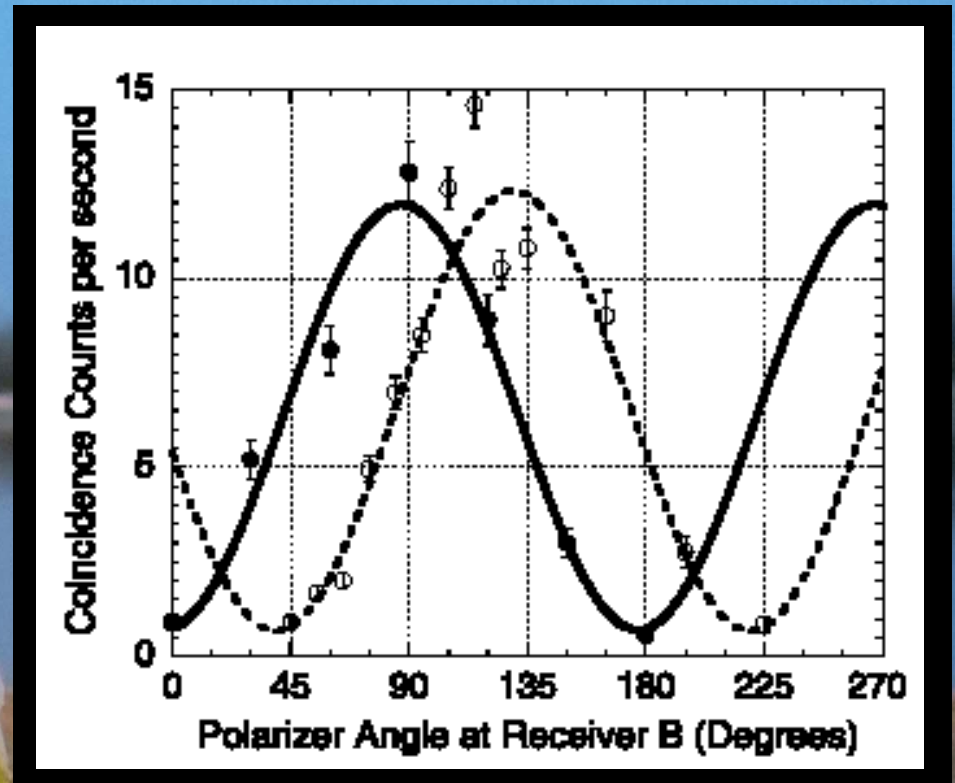
- CHSH-Bell inequality (req. 16 measurements)

$$S = |\langle AB + AB' + A'B - A'B' \rangle| \leq 2$$

- QM allows $S = 2\sqrt{2} = 2.83$

Freespace 1 Results

- Measured $S = 2.4 \pm 0.1$ (larger than 2 indicates entanglement)
- Two links 500m & 100m
- ~10 coincidences/s
- SMF-SMF coupling
- Time-stable channel



Polarization correlations

Science (2003)

The next step

- 500m to 7.8km (the atmosphere straight up is 7.3km thick)
- No more cable
- Light passed over a city - likely real-world scenario

Source telescope



15cm

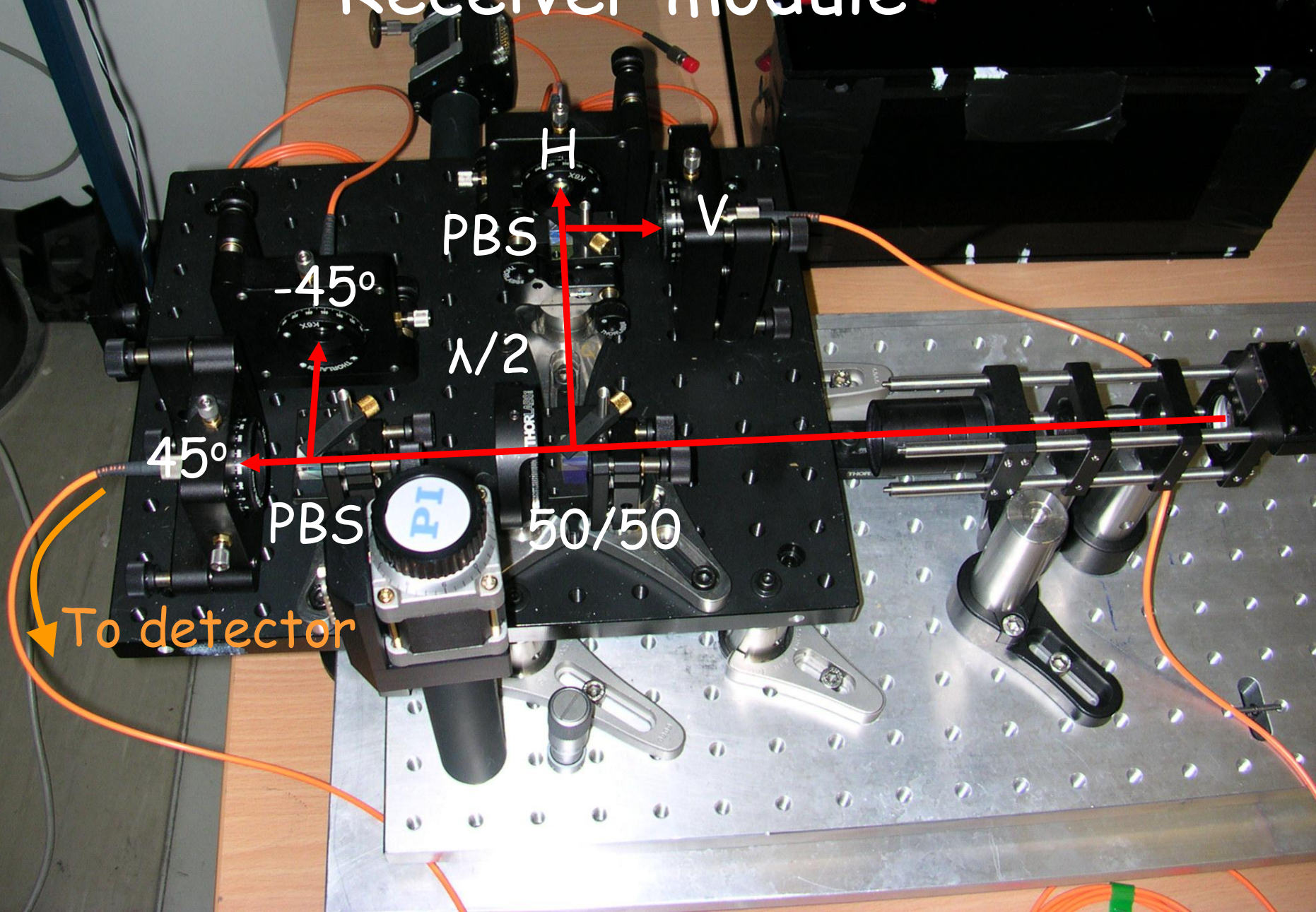


From Source

Atmospheric fluctuations

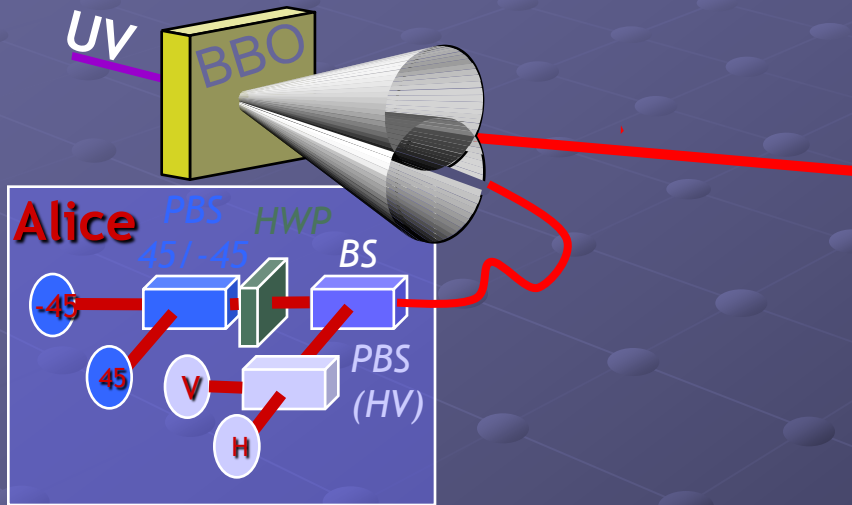


Receiver module



Practicalities

- Absence of good single-photon sources
- Can use quantum randomness to select state:



$$\begin{aligned} &|HH\rangle + |VV\rangle \\ &= |45,45\rangle + |-45,-45\rangle \end{aligned}$$

- Triggered single photons, reduced "empty" pulses $|0\rangle$ and double photons $|2\rangle$
- Laser frequency monitoring unnecessary

Entanglement takes to the air - again!



Freempace 2

Test Range (Receiver)

Test Range (Laser Source)

Millennium City (BOB)

7.8km

Inst. f. Experimental Physik

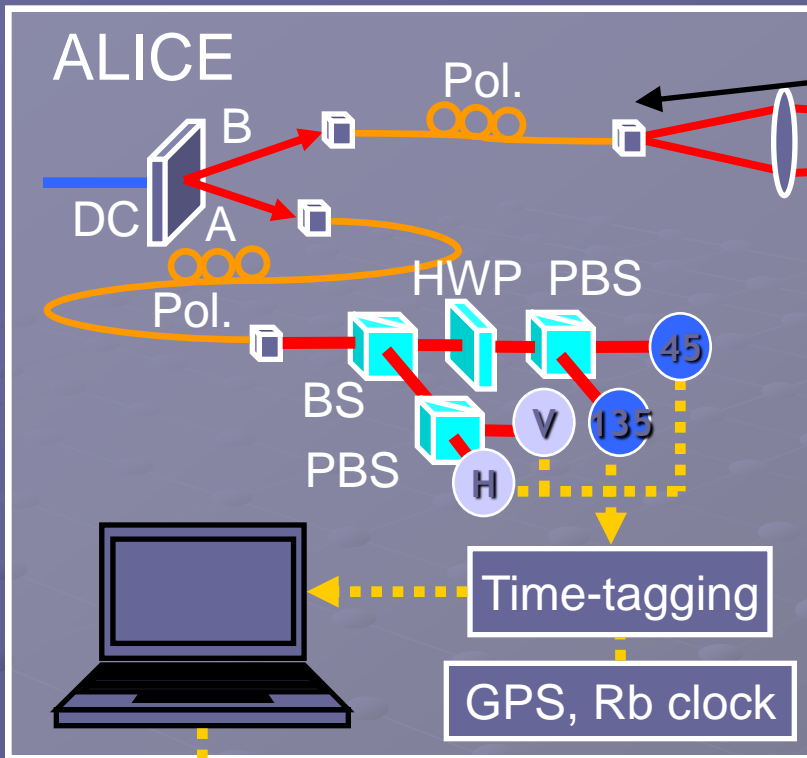
Freempace 2 (ALICE)

Vienna

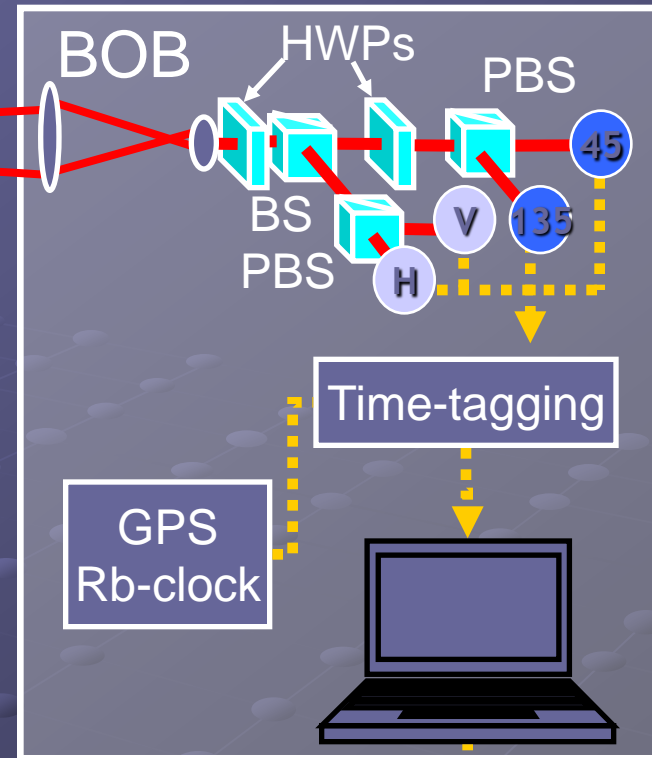
Freempace 1 (ALICE)

Freempace 1 (SOURCE)

Freempace 1 (BOB)



Free-space
(Quantum
Channel)



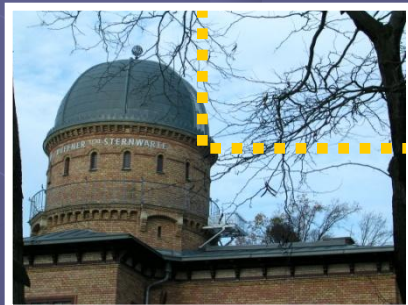
Public Internet (Classical Channel)

VIENNA

ALICE

7.8km

BOB





Freespace 2 Results

		Millenium Tower (Bob)			
		22.5°	112.5°	67.5°	157.5°
Kuffner Sternwarte (Alice)	0°	1469	5763	6500	1067
	90°	4015	1305	1483	2959
	45°	2171	9103	2633	6357
	135°	5373	1701	6889	1090



$$S = 2.27 \pm 0.019 > 2$$

Quantum Correlations!

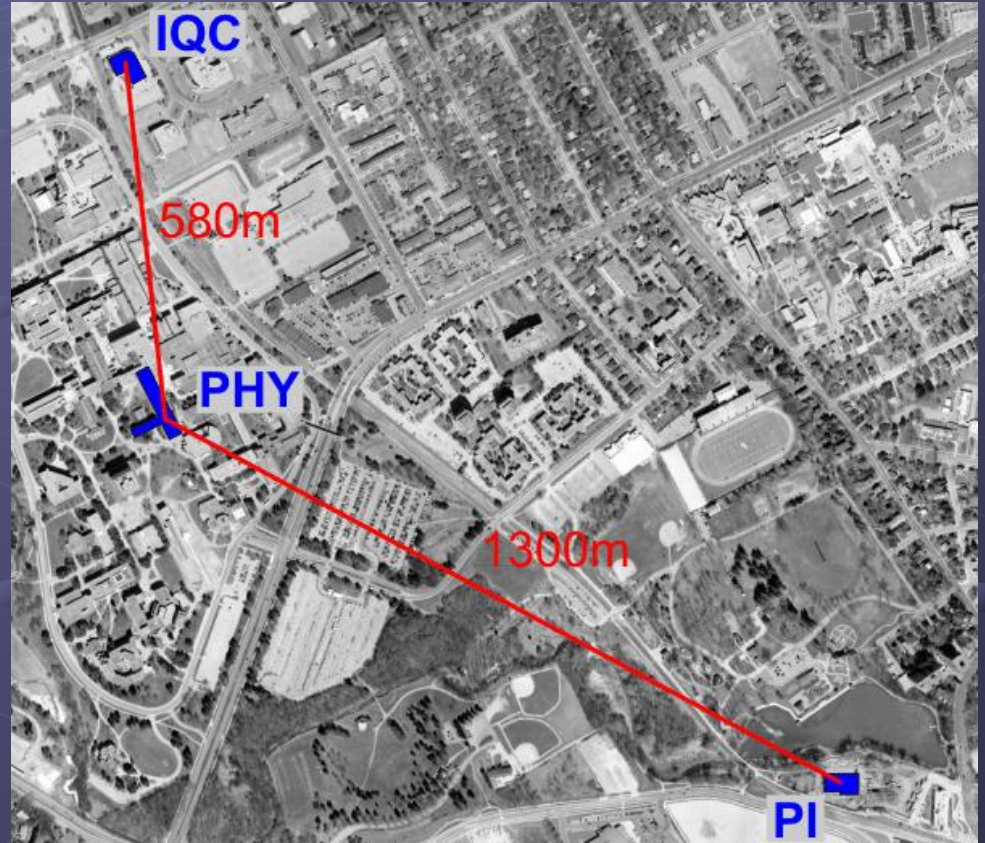
- Two links 7.8 km and 10⁻⁴km
- 25 ccps found over time tags/internet
- Single-mode fibre to spatial-filter coupling
- 14- σ Bell violation, all 16 meas. taken simultaneously

Remaining challenges

- Longer distances, Higher bit rates
- Active components to compensate atmosphere
- Long-distance quantum interference (repeaters)
- Full cryptography, different protocols
- Moving targets (satellites, airplanes)

IQC free-space experiment

- Gregor Weihs
- Raymond Laflamme
- Chris Erven



A hand is shown holding a single nut, with three other nuts lined up on a surface below. The scene is lit with warm, golden light. The text is overlaid on the image.

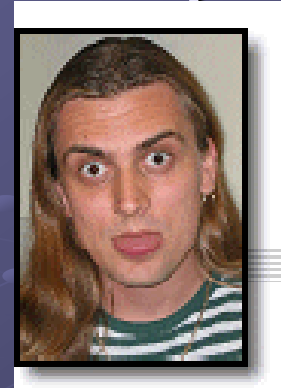
One-way quantum computation with a multi-photon cluster state

"1"



Photonic one-way quantum computation

- Philip Walther (Vienna→Harvard)



- Terry Rudolph (Imperial)

- Emmanuel Schenck (Vienna→ENS)



- Vlatko Vedral (Leeds)

- Markus Aspelmeyer (Vienna)

- Harald Weinfurter (LMU, Munich)

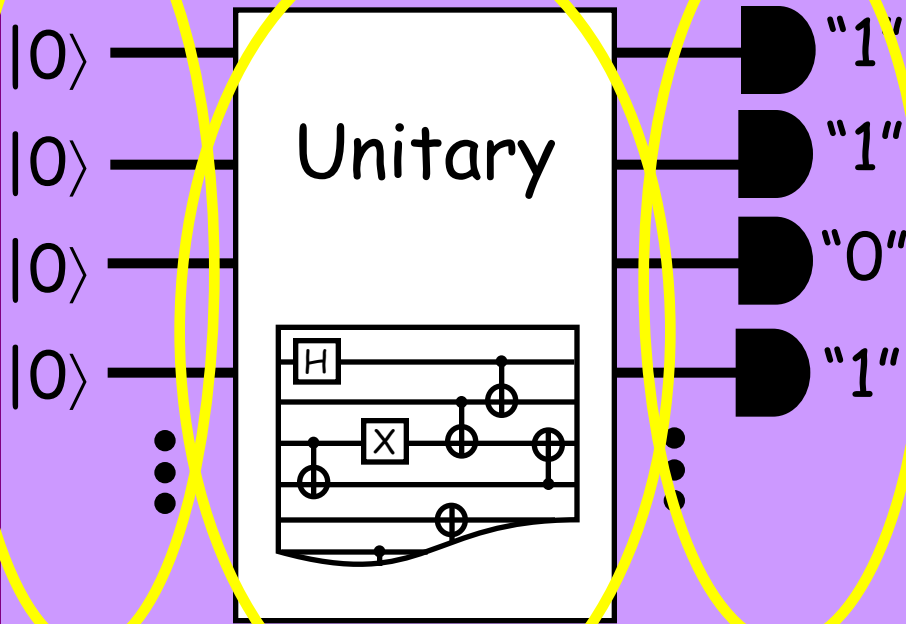


- Anton Zeilinger (Vienna)



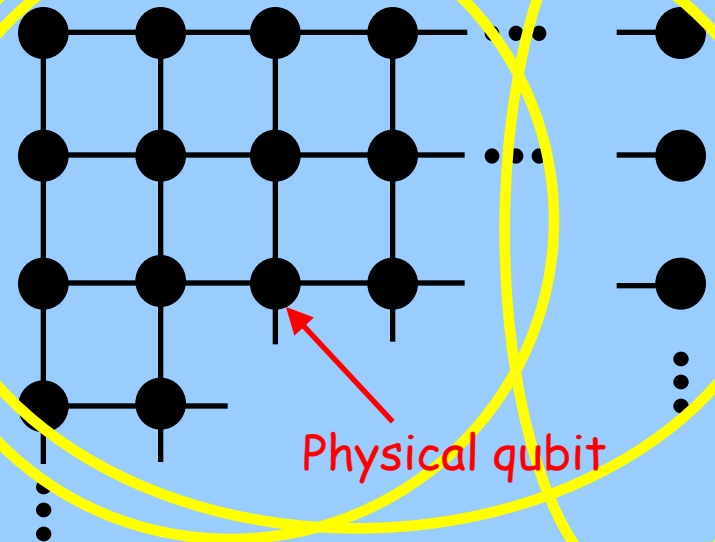
QC - Circuit vs. One-way model

Circuit Model



Initial state ($|0\rangle$)
 Algorithm (dynamics)
 Readout (classical bits)

One-way model

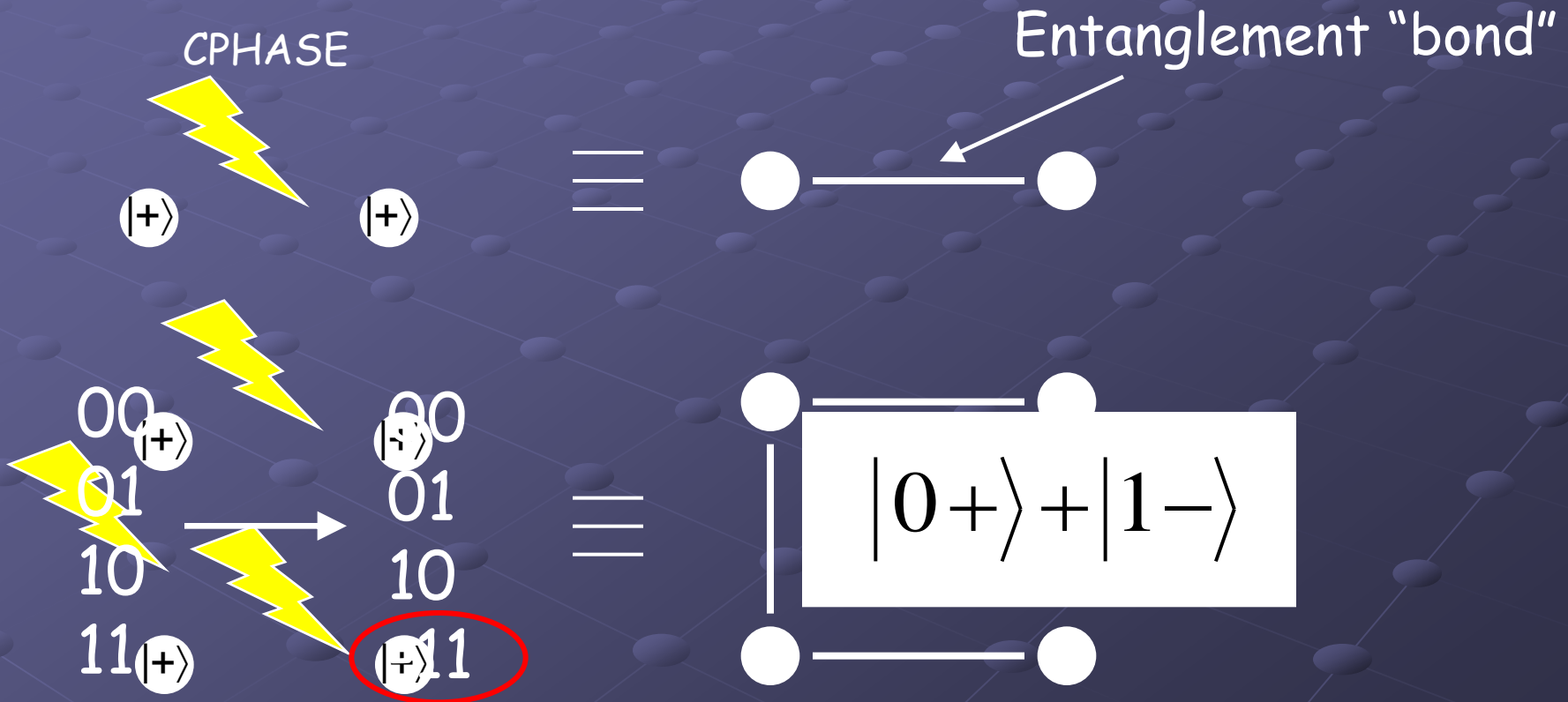


Initialization (single qubit state)
 Algorithm (preparation of cluster state)
 Readout (single qubit measurements)

Raussendorff & Briegel, PRL 86, 5188 (2001)
 Optics: Neilsen; Browne/Rudolph

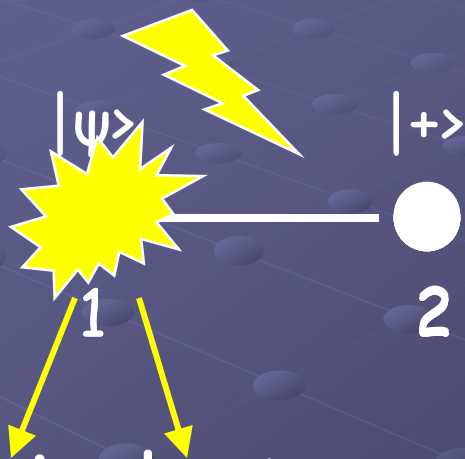
One-way quantum computing

- Cluster states can be represented by graphs



Processing encoded information

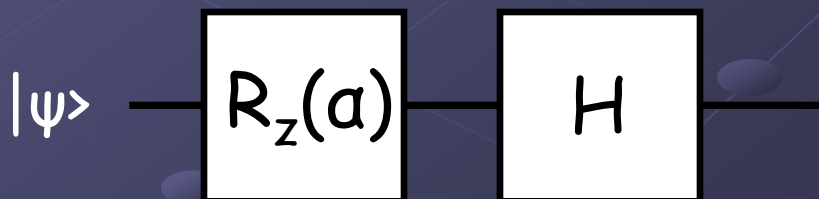
- How measurement can compute



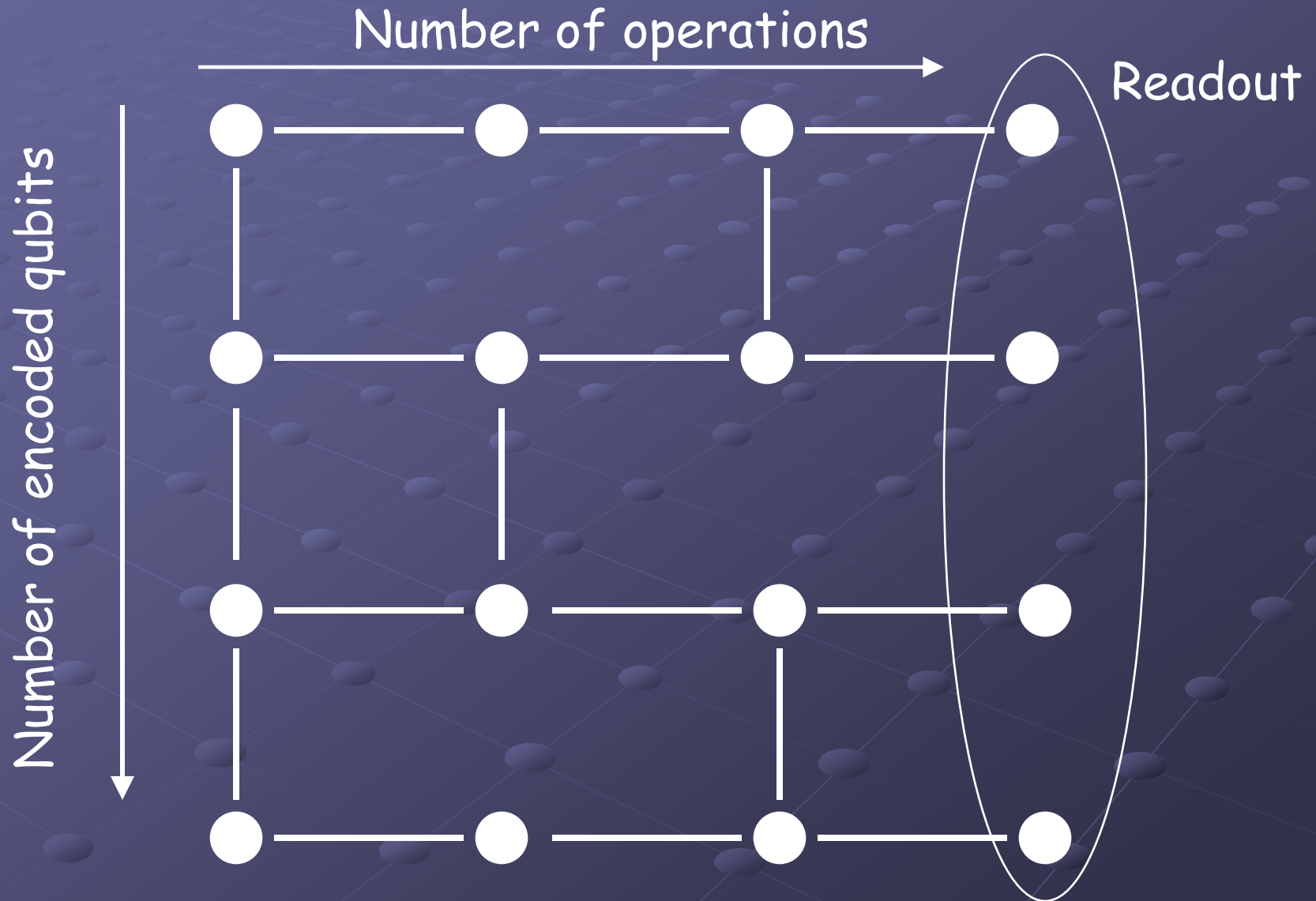
- $R_z(a) = \exp(-i\alpha\sigma_z)$
- 2 $B(a) = \{ \text{apply } R_z(a), \text{ flip } |1\rangle \}$

This is an example of Feed-forward

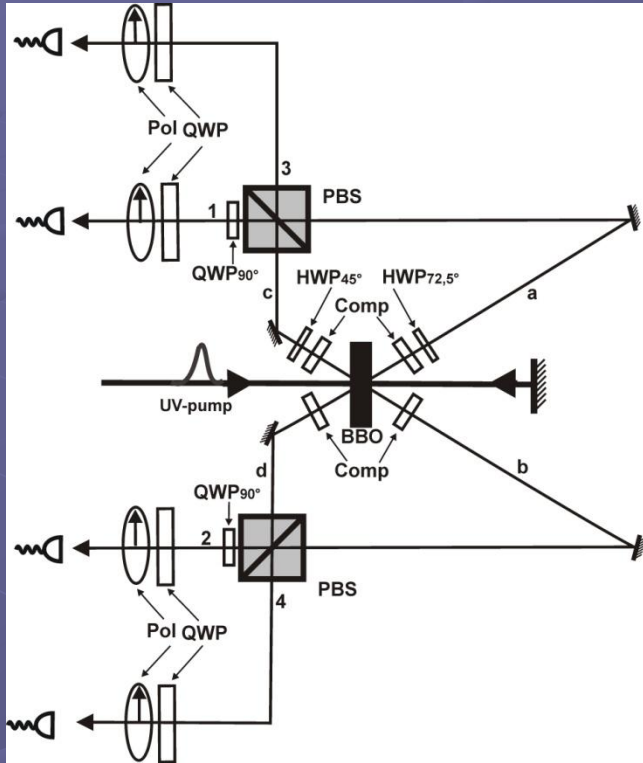
- Equivalent quantum circuit



More general computations



Making cluster states

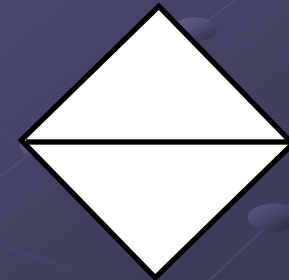
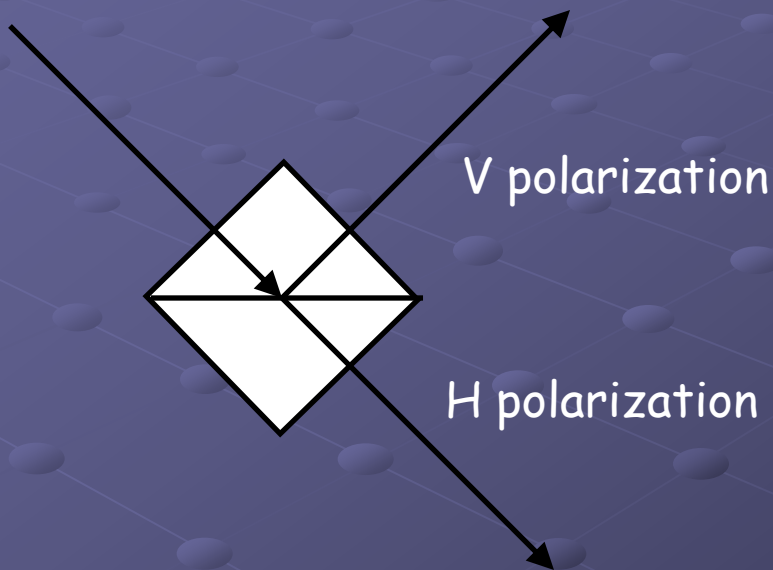


$$|\psi\rangle = |HHHH\rangle + |HHVV\rangle + |VVHH\rangle - |VVVV\rangle$$

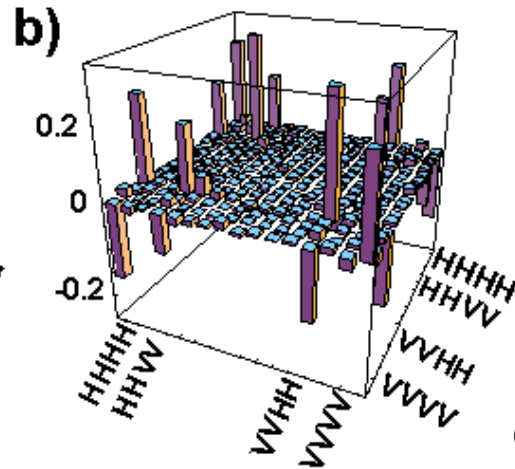
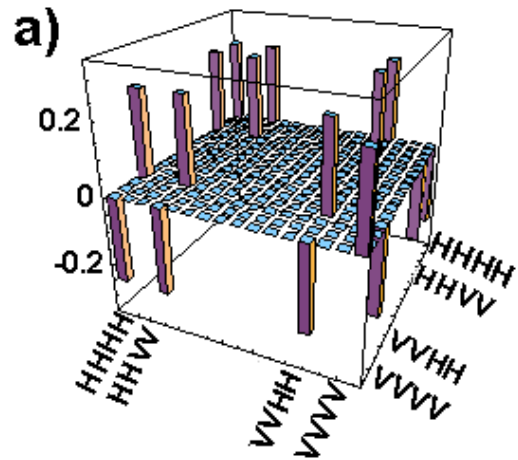


Polarizing Beam-splitter

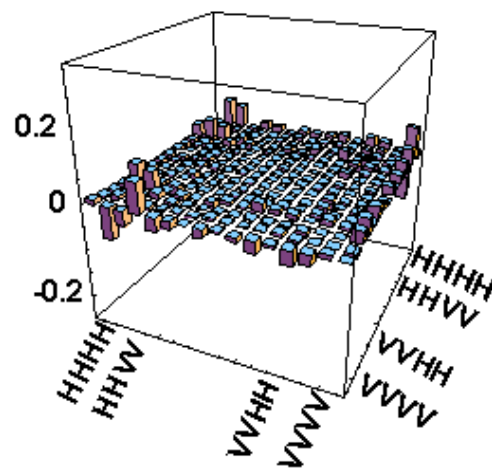
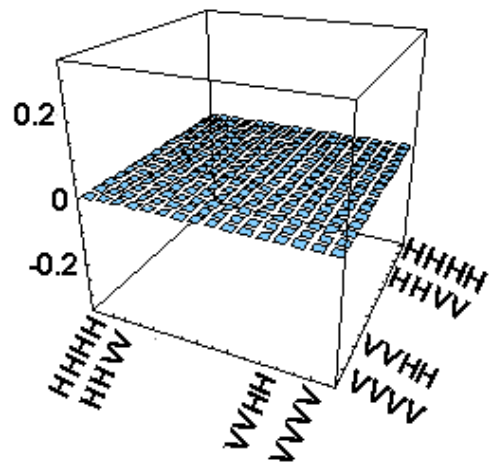
- Quantum "parity check"



The four-photon cluster



Quantum state tomography
Reconstructed density matrix



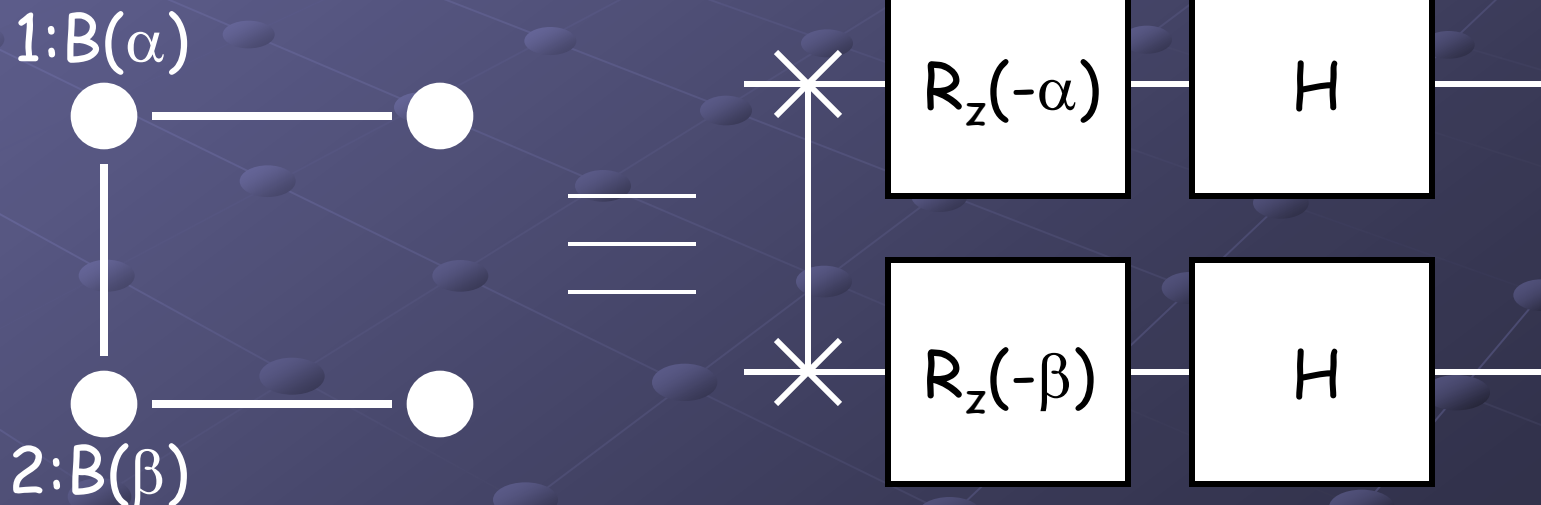
Fidelity = 63%

Clusters to circuits

- Horizontal bond:

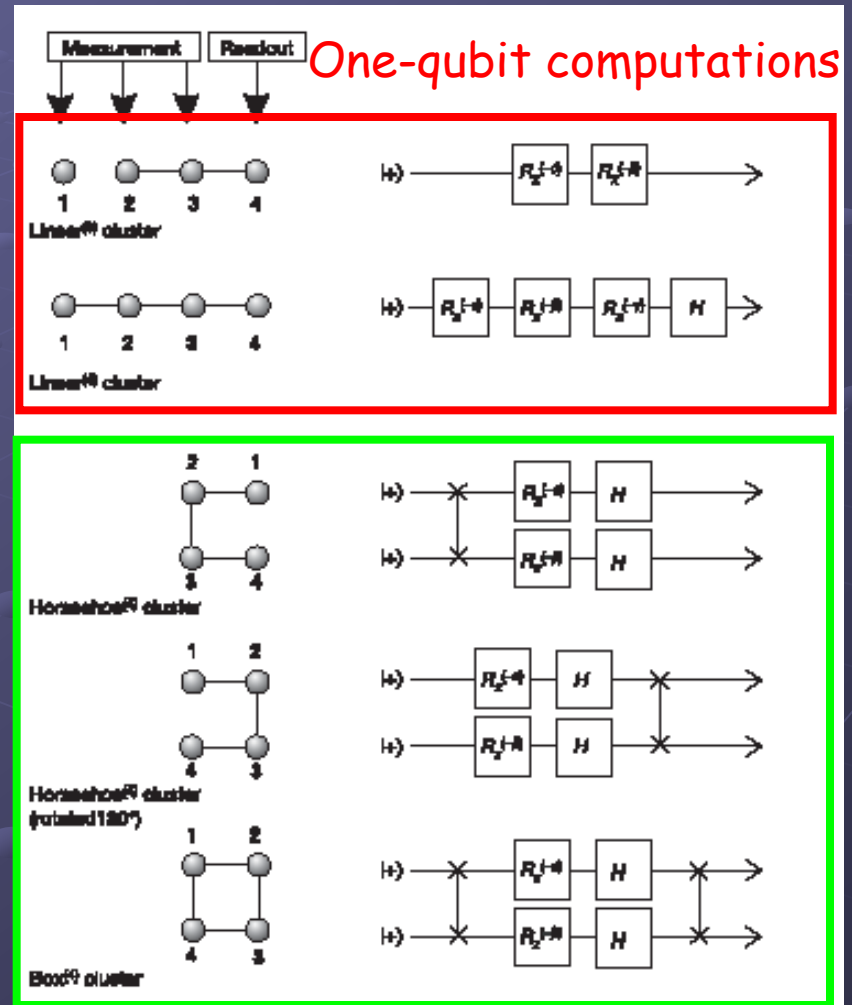


- Vertical bond:



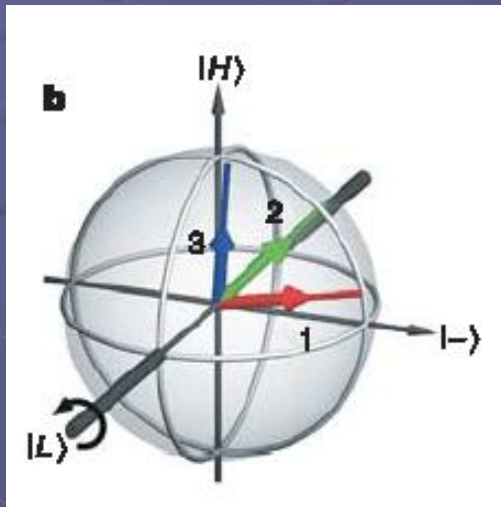
Clusters to circuits

- Multiple circuits using a single cluster
- Different order of measurements



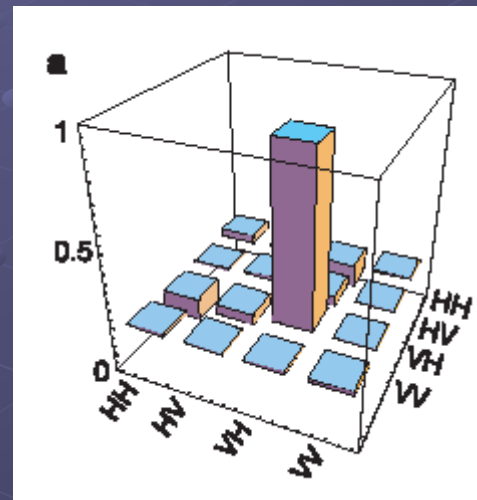
Single & two-qubit operation

Single-qubit rotations



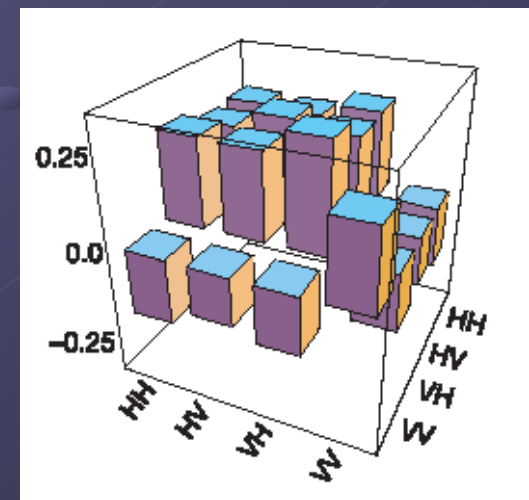
Fid \sim 83-86%

Two-qubit operations



Separable

Fid = 93%
Tangle = 0



Entangled

Fid = 84%
Tangle = 0.65

Grover's Algorithm

R P 104HidoryDrNmgln.....	3886 8565	Grow K M 62DrydaleGrnBkRd.....	3574 4764
R T & L M 124Wellington		Growth	
Omnia.....	3821 6440	D L 16SandraGiang.....	3263 4739
S & C 272KangarooGallyRd		G A 52PowerWayeHts.....	3266 1120
Belbire.....	3202 9789	L G 96StressadDrivMcGwl.....	3353 4918
S F 12MoorecraeCtphl.....	3378 2115	R J & Fernis E M 45BellfieldPI	
S J 34EwingRdWrdge.....	3299 1824	Wstke.....	3376 9545
S J & L F 9CartanderPI FnsLk.....	3372 4895	R & M 12TaraCphas.....	3823 5236
Mobile Service.....	0412 484 594	Growden E K NewbarnStHilcrest	
S & S 10MahoniaBelwarr.....	3202 7159	Mobile Service.....	0412 937 441
William 43FembergRdPadd.....	3369 3676	Growler	
Grower		C R 83ClawleyCreca.....	3379 2038
A 27PalmerGrupa.....	3342 0510	P W & F E 25FolnavenKerwa.....	3720 1137
Geof & Joan 37CairnsRdHI.....	3368 1958	S A 43ReubenKoflPK.....	3397 2700
Mobile Service.....	0412 449 811	Greaz J J 15ReadingRdStls	
W & M 155Woolf Rd.....	3371 4319	Grozdasic P 355MainKPI.....	
K 111MerstyrRdNF.....	3254 2612	Grozdasicovic	
M J 32EdnaAldry.....	3356 9675	B 38IvanovDybekHts.....	3344 1194
R & C 6GowanCrtKng.....	3886 1141	H 12NormanCrsNormPk.....	3395 6272
M.....	0402 154 034	K 62DorseyHillMoorka.....	3840 4167
Groves		V & M 45WickillMcGr.....	3343 5370
280E Sedeth.....	3321 4517	Grozdansovska E 21Evgene	
A 35LowaraMarfield.....		BromPne.....	3806 8512
Mobile Service.....	0417 772 969	Grozdansov V 37ThistleKegnsPk	
A M 1345StationCtDrp.....	3378 5381	Grozler A 4LightLchrdt.....	
B J 4MannopI Crna.....	3390 1428	Grozinger	
B J 3MauriceDrivEagle.....	3807 9978	K 5WintonPI Selgh.....	3807 0103
B S 21PysareRacew.....	3281 9958	P J 155TozerEagls.....	3807 3709
C 477RavennockRdAsly.....	3263 1694	P & T 96InlnterrocrtLoganholme	
C 29DareCrtScarbrgh.....	3885 8906	Mobile Service.....	0412 273 744
C D 3PakiLaYally.....	3255 8940	Grtfllis L 41ArhysRdAshg.....	
C S 92-98DunspareDrvGmbrk.....	3200 0957	Gruar E K 40McAureyRdCl.....	
D 11MacLayCrtTngpa.....	3390 4415	Grubae S 170 OldClevelandRd	
D B & N G 42AshburtonCtphl.....	3378 5182	Crete.....	3394 3594
D J & K J 318BanksideAveAshg.....	3366 0084	Grubanovich M & L 151Yabba	
D & M 15BockolombaCrsFrsLk.....	3879 7538	Asst.....	3262 8890
D M 167HaroldgrawRdWestEd.....	3846 7552	Grubb	
Dm & Jr 24TamarlaAveBrayPk.....	3881 0414	B J 17EwinstakTngpa.....	3390 4055
D M & R M 78WendellHend.....	3216 4360	Brnce.....	
Mobile Service.....	0417 793 691	22TansereCrtEasonsHil.....	0412 772 822
E P 1083LiseCowanStHil.....		Mobile Service.....	0413 247 822
McGral.....	3349 8732	B S 176EwingRdWrdge.....	3808 4230
E M 9305ympieRdCherm.....	3359 6339	B S & R E 60ParramattaRd	
F M 79ParkRdStacksCk.....	3299 3243	Unbrd.....	3209 2445
G 13DouglasGmlpa.....	3394 2008	D J 31GartionWesbr.....	3857 0229
G 109AndrewWys.....	3393 3239	E P & D J 45JacksonRd	
G C & J A 6MacArthurVicPl.....	3207 4577	SnytskHts.....	3345 5524
G J & H C 121EwlynGrme.....	3156 3126	G K C 24ParramattneBrk.....	3408 6327
G T & S G 2Pierplek.....	3303 0541	J 155TaraBelwarr.....	3399 5570
J 228ottAshg.....	3840 3179	Grover	
J 92FegesDrvMoorka.....	3840 3179	Mobile Service.....	0417 635 093
J 648estamPdWyn.....	3293 4609	40YathongCrtAnswHlts.....	0417 635 095

Easy

Sorted database

R P 104HidoryDrNmgln.....	3886 8565	Grow K M 62DrydaleGrnBkRd.....	3574 4764
R T & L M 124Wellington		Growth	
Omnia.....	3821 6440	D L 16SandraGiang.....	3263 4739
S & C 272KangarooGallyRd		G A 52PowerWayeHts.....	3266 1120
Belbire.....	3202 9789	L G 96StressadDrivMcGwl.....	3353 4918
S F 12MoorecraeCtphl.....	3378 2115	R J & Fernis E M 45BellfieldPI	
S J 34EwingRdWrdge.....	3299 1824	Wstke.....	3376 9545
S J & L F 9CartanderPI FnsLk.....	3372 4895	R & M 12TaraCphas.....	3823 5236
Mobile Service.....	0412 484 594	Growden E K NewbarnStHilcrest	
S & S 10MahoniaBelwarr.....	3202 7159	Mobile Service.....	0412 937 441
William 43FembergRdPadd.....	3369 3676	Growler	
A 27PalmerGrupa.....	3342 0510	C R 83ClawleyCreca.....	3379 2038
Geof & Joan 37CairnsRdHI.....	3368 1958	P W & F E 25FolnavenKerwa.....	3720 1137
Mobile Service.....	0412 449 811	S A 43ReubenKoflPK.....	3397 2700
W & M 155Woolf Rd.....	3371 4319	Greaz J J 15ReadingRdStls	
K 111MerstyrRdNF.....	3254 2612	Grozdasic P 355MainKPI.....	
M J 32EdnaAldry.....	3356 9675	Grozdasicovic	
R & C 6GowanCrtKng.....	3886 1141	B 38IvanovDybekHts.....	3344 1194
M.....	0402 154 034	H 12NormanCrsNormPk.....	3395 6272
Groves		K 62DorseyHillMoorka.....	3840 4167
280E Sedeth.....	3321 4517	V & M 45WickillMcGr.....	3343 5370
A 35LowaraMarfield.....		Grozdansovska E 21Evgene	
Mobile Service.....	0417 772 969	BromPne.....	3806 8512
A M 1345StationCtDrp.....	3378 5381	Grozdansov V 37ThistleKegnsPk	
B J 4MannopI Crna.....	3390 1428	Grozler A 4LightLchrdt.....	
B J 3MauriceDrivEagle.....	3807 9978	Grozinger	
B S 21PysareRacew.....	3281 9958	K 5WintonPI Selgh.....	3807 0103
C 477RavennockRdAsly.....	3263 1694	P J 155TozerEagls.....	3807 3709
C 29DareCrtScarbrgh.....	3885 8906	P & T 96InlnterrocrtLoganholme	
C D 3PakiLaYally.....	3255 8940	Mobile Service.....	0412 273 744
C S 92-98DunspareDrvGmbrk.....	3200 0957	Grtfllis L 41ArhysRdAshg.....	
D 11MacLayCrtTngpa.....	3390 4415	Gruar E K 40McAureyRdCl.....	
D B & N G 42AshburtonCtphl.....	3378 5182	Grubae S 170 OldClevelandRd	
D J & K J 318BanksideAveAshg.....	3366 0084	Crete.....	3394 3594
D & M 15BockolombaCrsFrsLk.....	3879 7538	Grubanovich M & L 151Yabba	
D M 167HaroldgrawRdWestEd.....	3846 7552	Asst.....	3262 8890
Dm & Jr 24TamarlaAveBrayPk.....	3881 0414	Grubb	
D M & R M 78WendellHend.....	3216 4360	B J 17EwinstakTngpa.....	3390 4055
Mobile Service.....	0417 793 691	Brnce.....	
E P 1083LiseCowanStHil.....		22TansereCrtEasonsHil.....	0412 772 822
McGral.....	3349 8732	Mobile Service.....	0413 247 822
E M 9305ympieRdCherm.....	3359 6339	B S 176EwingRdWrdge.....	3808 4230
F M 79ParkRdStacksCk.....	3299 3243	B S & R E 60ParramattaRd	
G 13DouglasGmlpa.....	3394 2008	Unbrd.....	3209 2445
G 109AndrewWys.....	3393 3239	D J 31GartionWesbr.....	3857 0229
G C & J A 6MacArthurVicPl.....	3207 4577	E P & D J 45JacksonRd	
G J & H C 121EwlynGrme.....	3156 3126	SnytskHts.....	3345 5524
G T & S G 2Pierplek.....	3303 0541	G K C 24ParramattneBrk.....	3408 6327
J 228ottAshg.....	3840 3179	J 155TaraBelwarr.....	3399 5570
J 92FegesDrvMoorka.....	3840 3179	Grover	
J 648estamPdWyn.....	3293 4609	Mobile Service.....	0417 635 093
		40YathongCrtAnswHlts.....	0417 635 095

Hard

Best Classical: $O(N)$ queries
Quantum: $O(\sqrt{N})$ queries

Unsorted database

Conclusions and Future directions

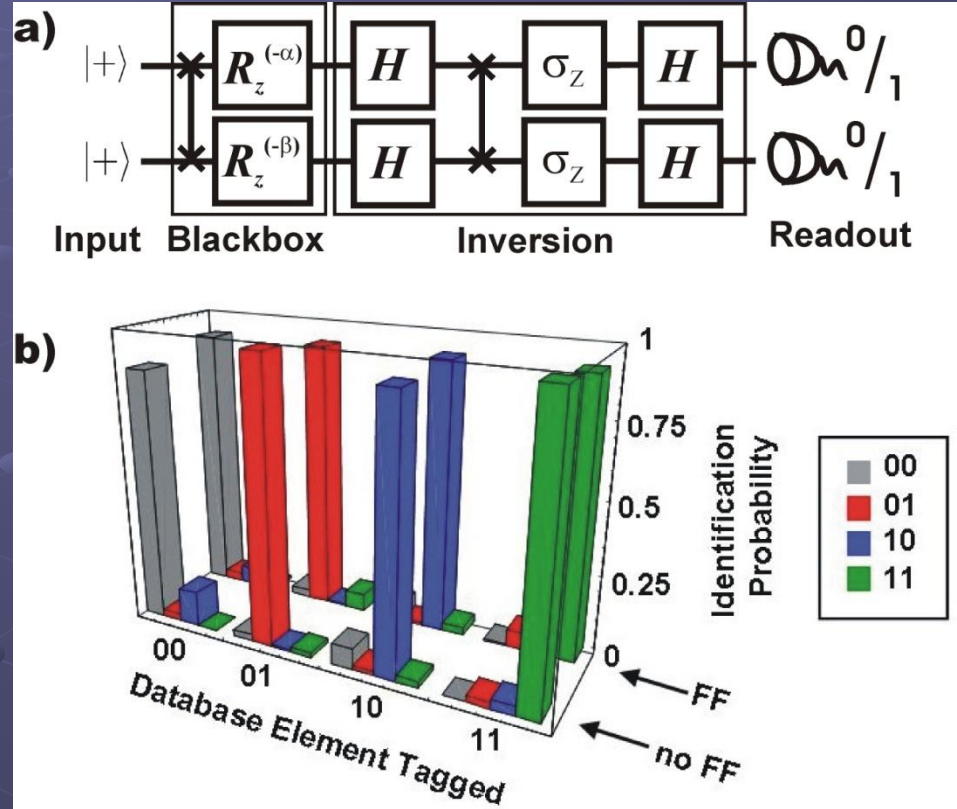
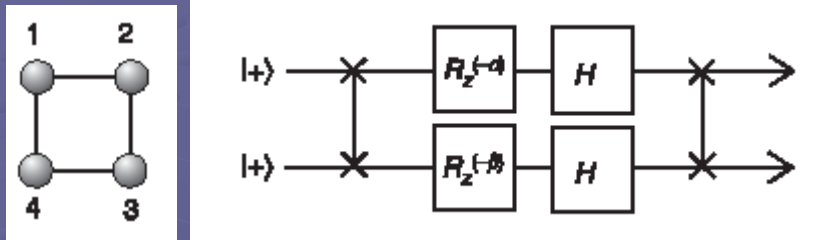
- First demonstration of one-way quantum computation using cluster states
- Experimental
 - Larger cluster states = more complex circuits
 - Feed-forward - two types - easy and hard
- Theoretical
 - Different geometries and measurements
 - Higher dimensions

Summary

- “Real” world
 - First experiments demonstrating free-space entanglement distribution
- Ideal world
 - First demonstration of Cluster State Quantum Computing - including the first algorithm



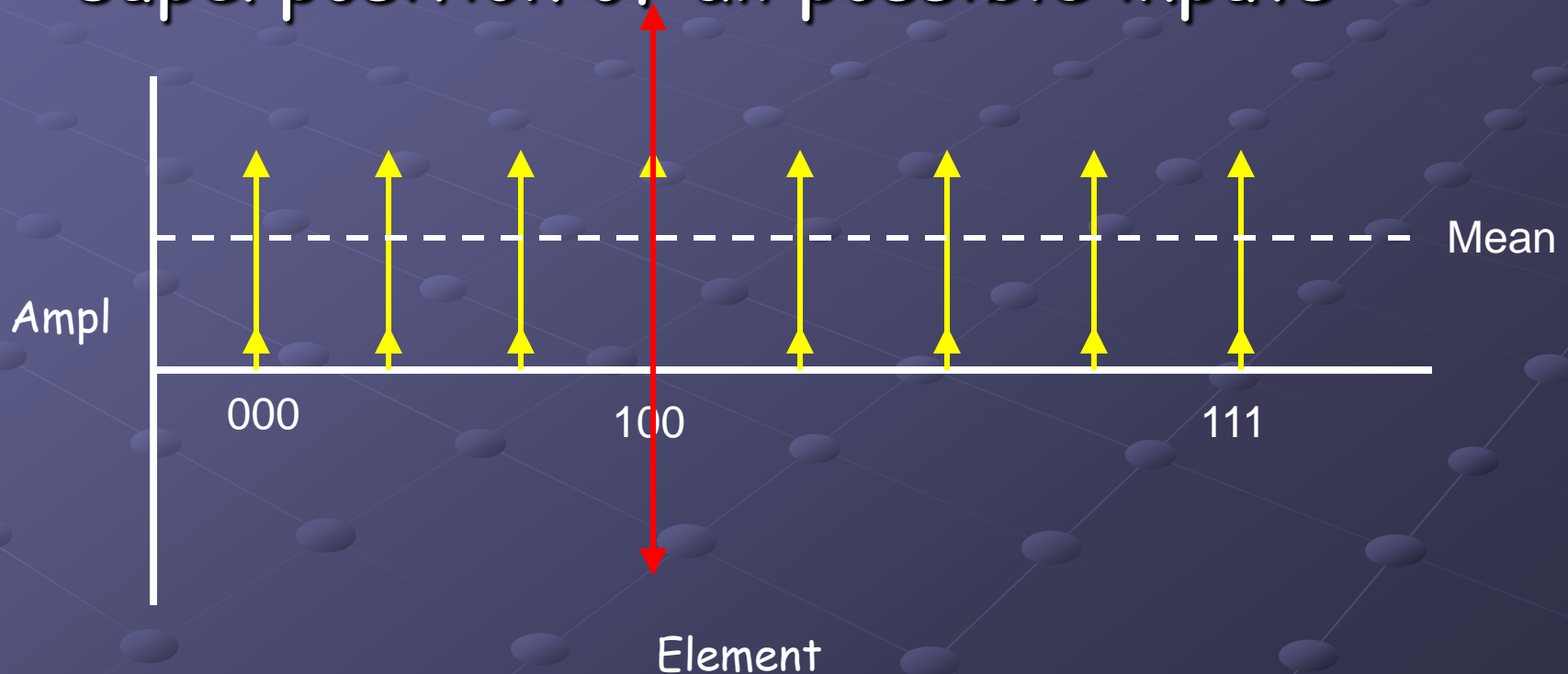
Clusters/Grover's Algorithm



- 90% correct computational output
- First algorithm in the cluster model

Grover's algorithm

- Quantum parallelism
- GA initializes the qubits to equal superposition of all possible inputs



- Interference
- "Inversion about the mean" amplifies the correct element and reduces the others
- On a query to the black box (quantum database/phonebook), the sign of the amplitude of the special element is flipped

THANK YOU!

