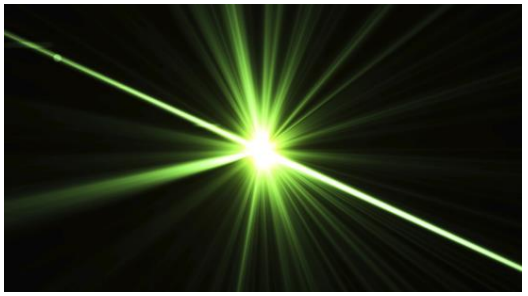
Quantum Computation, Communication, and Internet with Light

Institut für Physik,
Johannes Gutenberg-Universität Mainz

Peter van Loock

Quantum Information with (Laser) Light



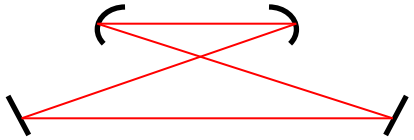
Physics

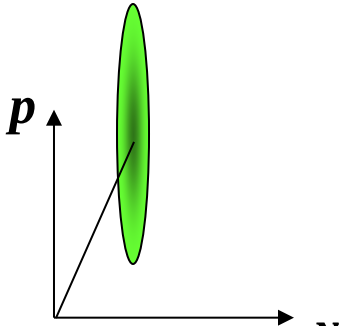
Optics

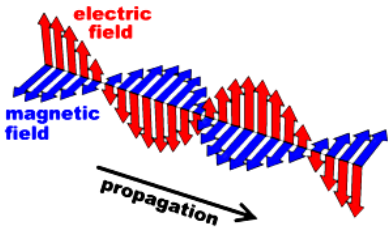
Geo-
metrical
Optics

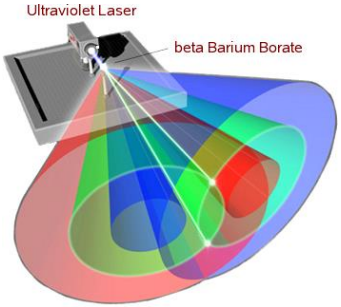
Wave
Optics

Quantum
Optics

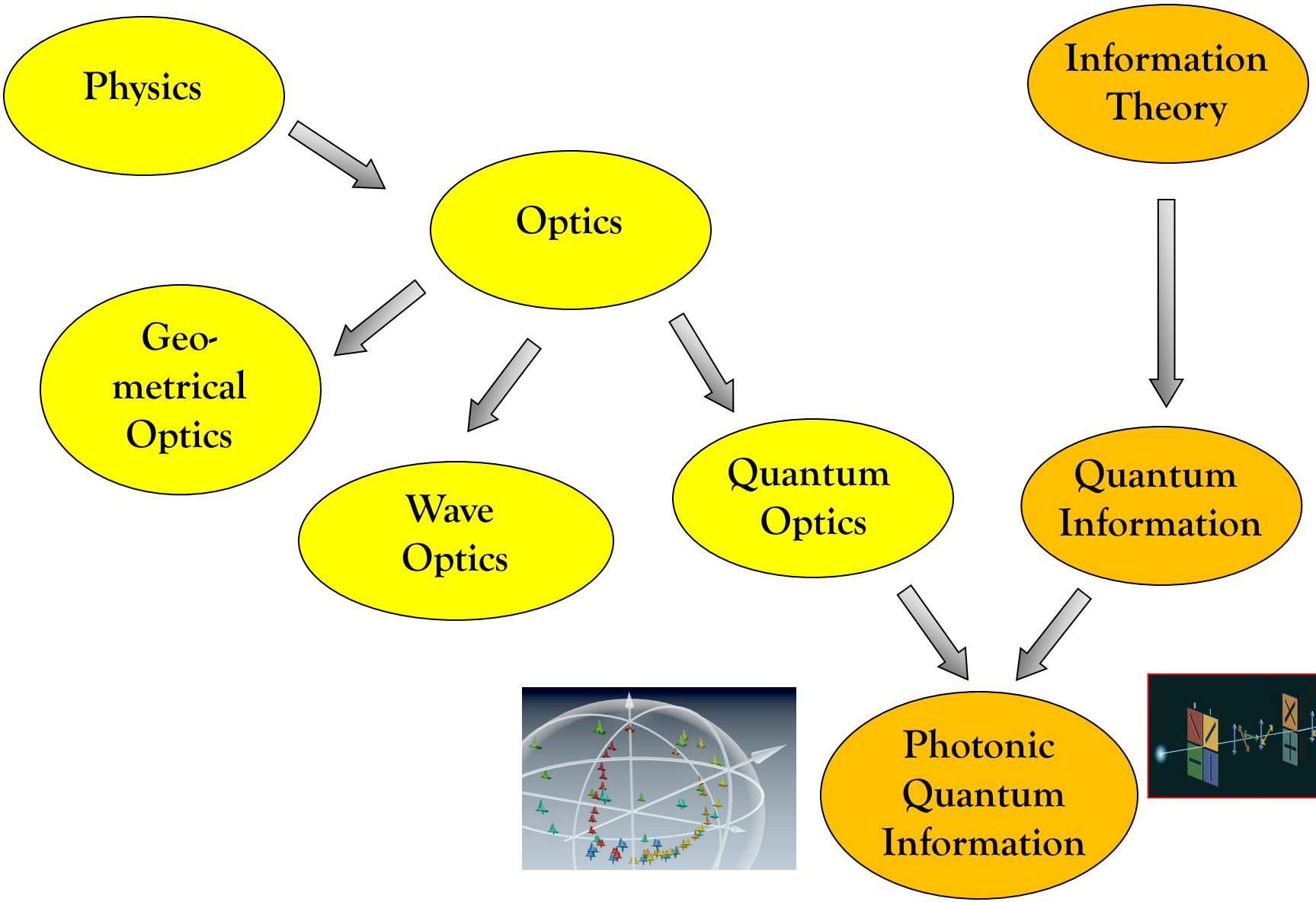








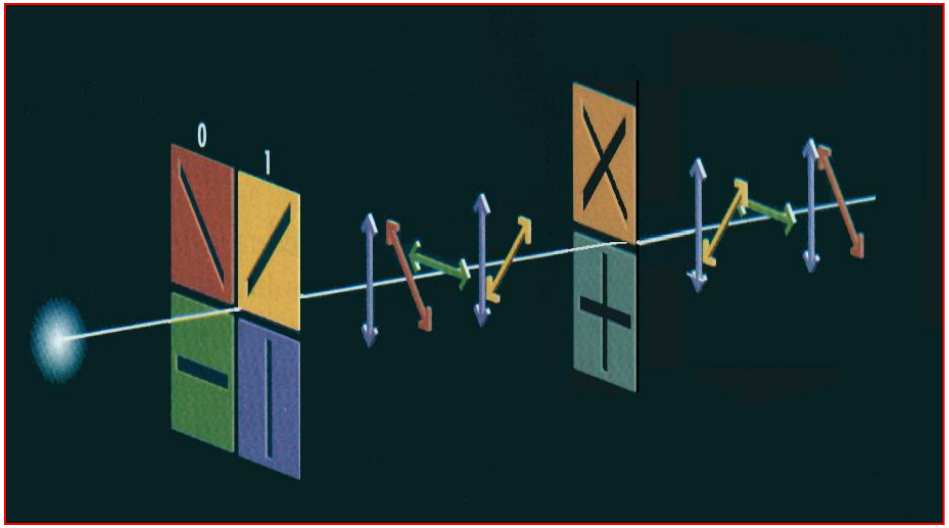
Quantum Information with (Laser) Light



Quantum Information with (Laser) Light

Quantum Information

Photonic Quantum Information



J. S. Neergaard-Nielsen *et al.*, PRL **105**, 053602 (2010)

Quantum Information with (Laser) Light

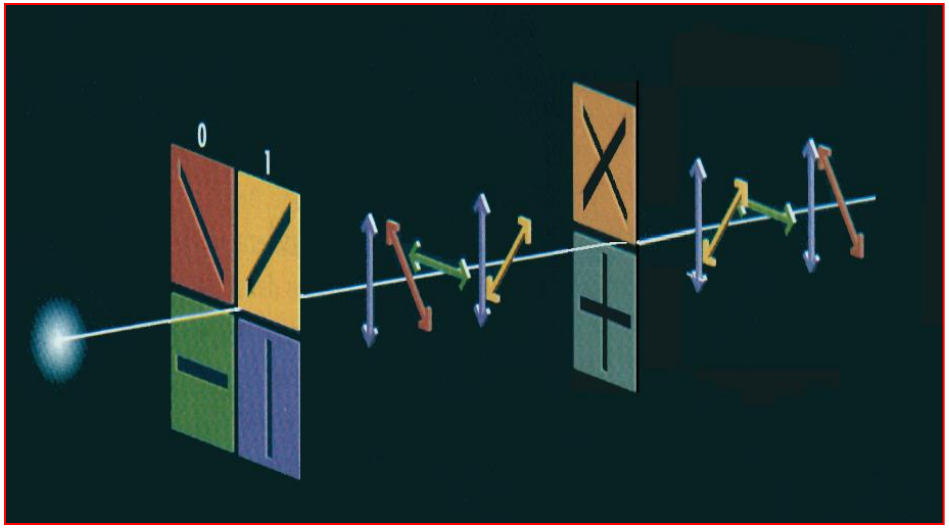
Quantum Information

Photonic Quantum Information

Bosonic / Photonic Code:
"Qubit in Quantum Oscillator"

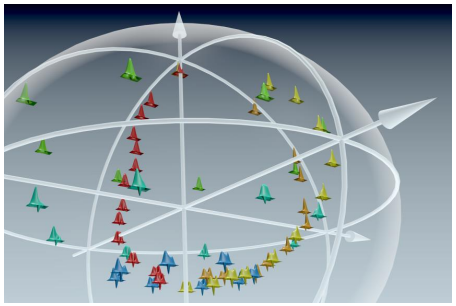
J. S. Neergaard-Nielsen *et al.*, PRL **105**, 053602 (2010)

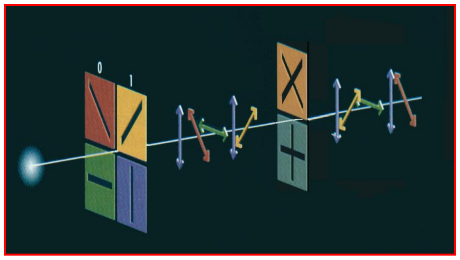
Bosonic / Photonic Qubit



Quantum Hardware

Laser Light



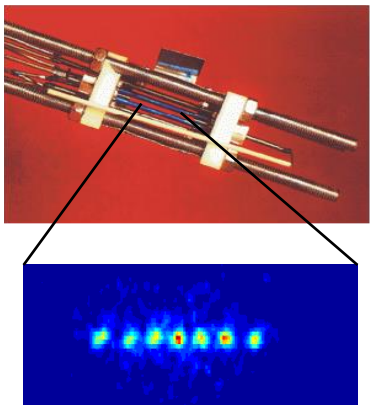


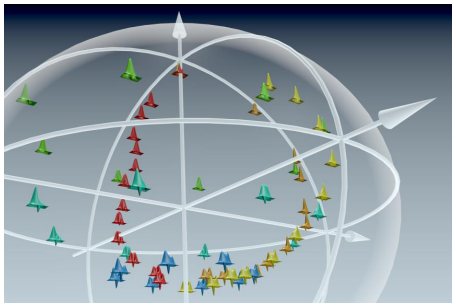
Photons

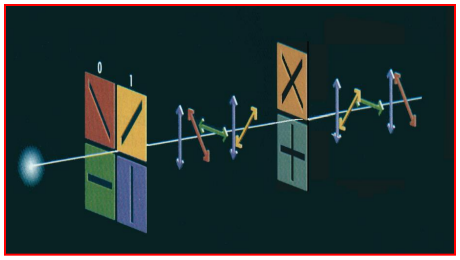
Quantum Information Processing

Quantum Hardware

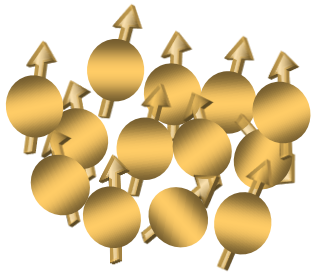
Laser Light





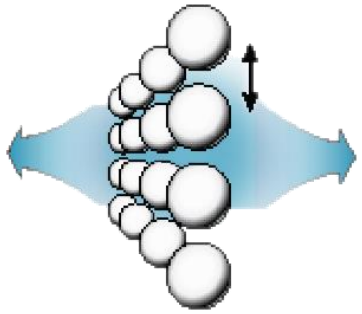


Photons



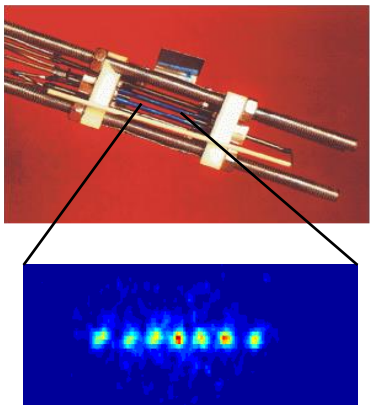
Atoms/Ions

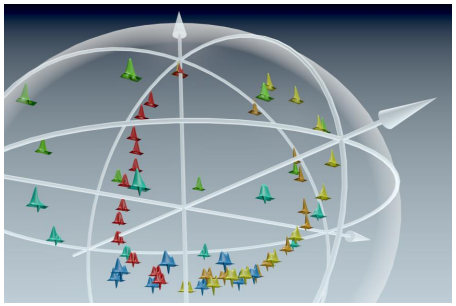
Quantum Information Processing

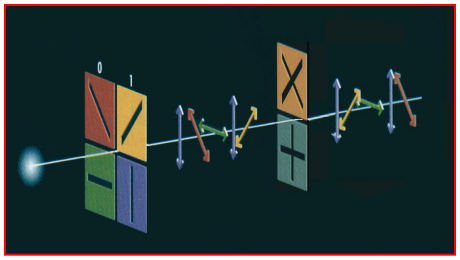


Quantum Hardware

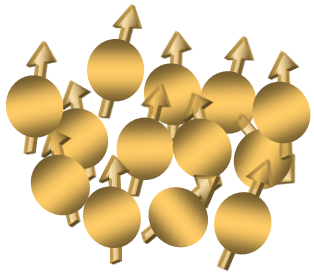
Laser Light

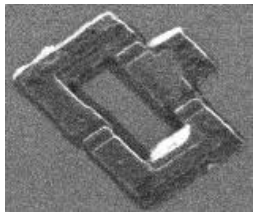


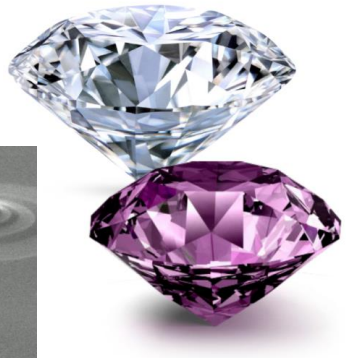


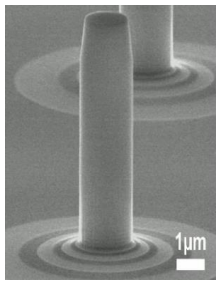


Photons





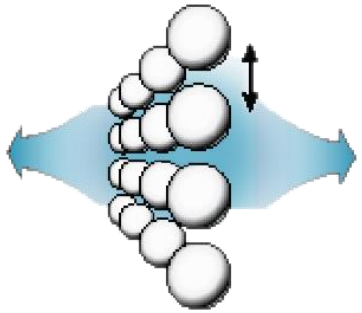




Solid State

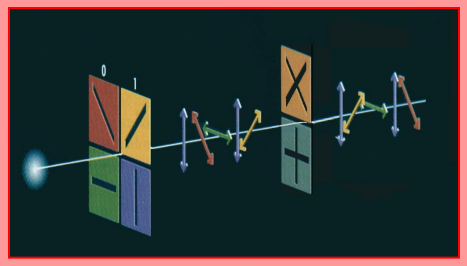
Quantum Information Processing

Atoms/Ions

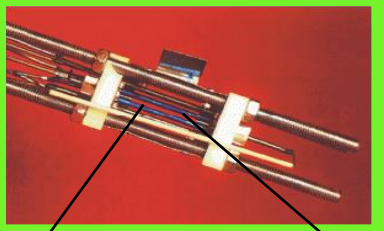


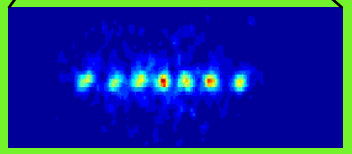
Flying vs. Stationary Quantum Information

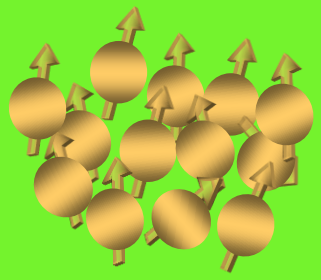
Laser Light



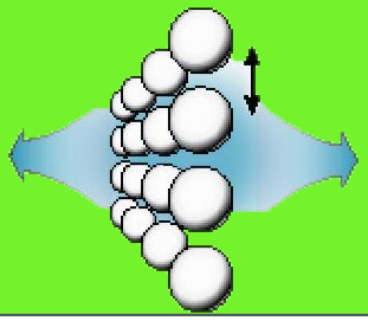
Photons



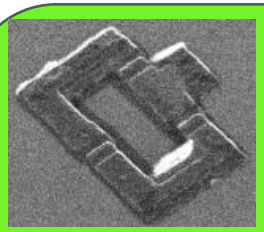


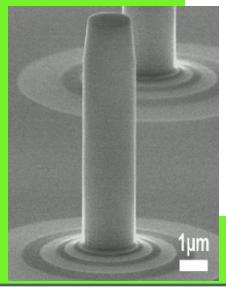


Atoms/Ions



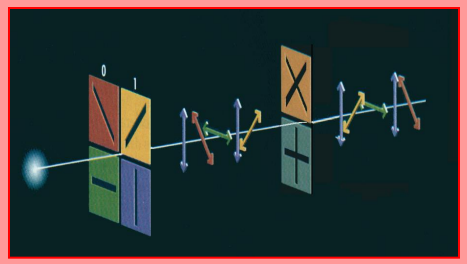
Quantum Information Processing





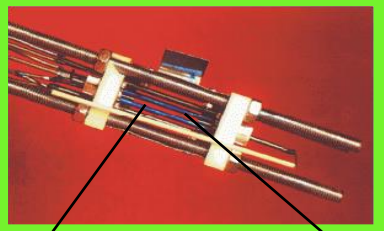
Solid State

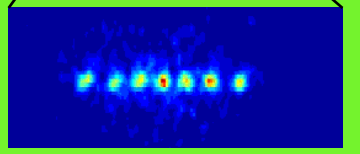
Flying vs. Stationary Quantum Information

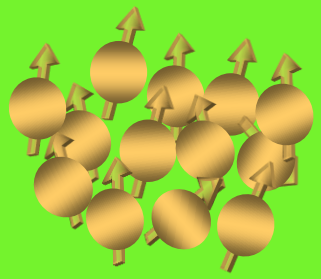


Photons

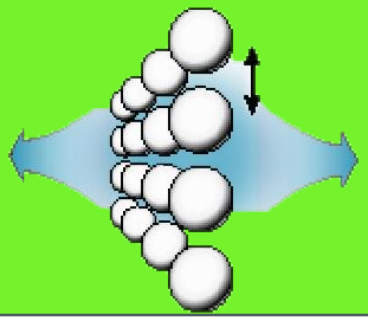
Laser/
Quantum
Light

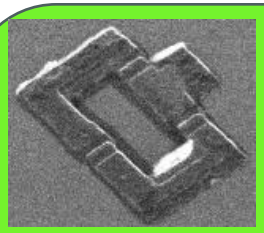


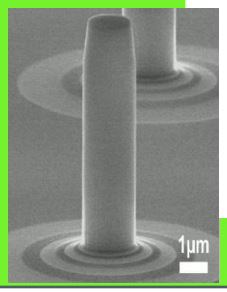




Atoms/Ions



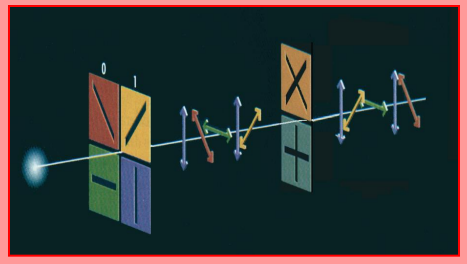




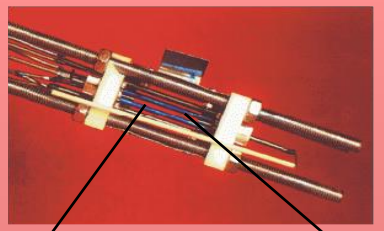
Solid State

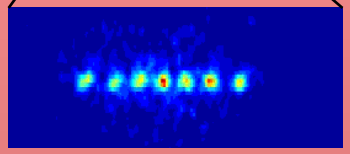
Quantum Information Processing

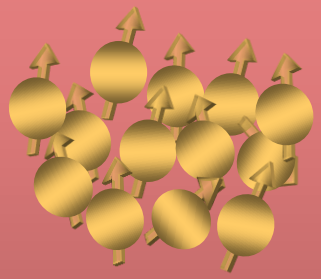
Hot vs. Cold Quantum Information

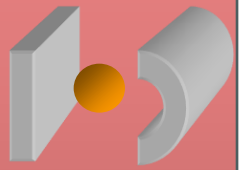


Photons

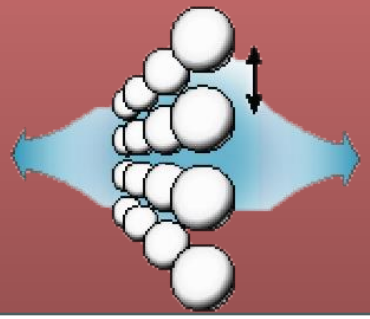




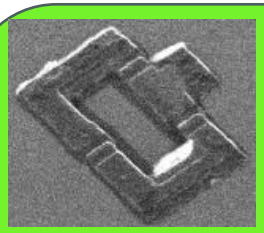


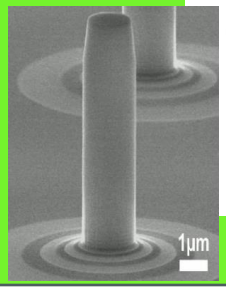


Atoms/Ions



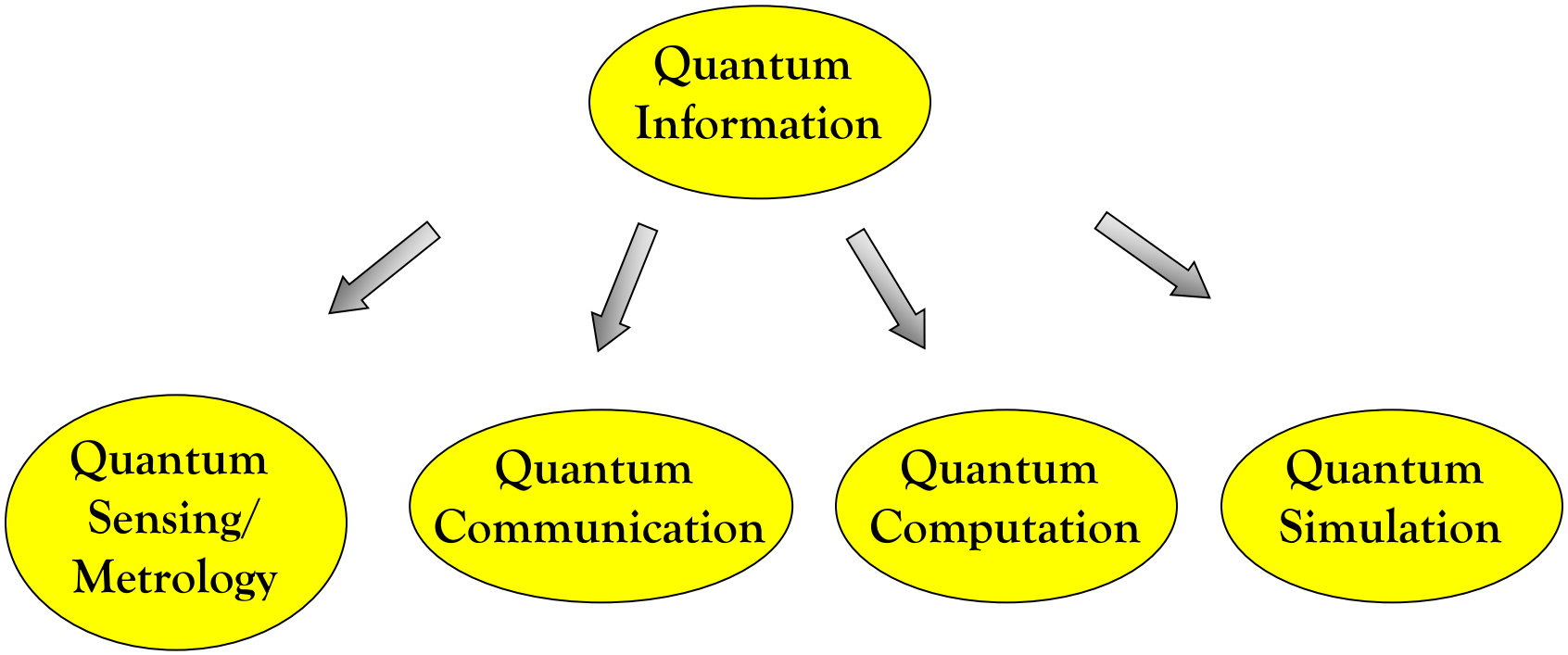
Quantum Information Processing





Solid State

Quantum Information

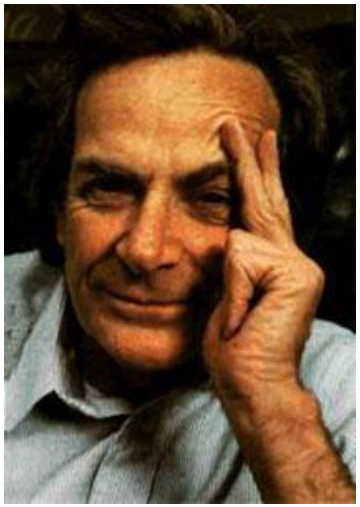


Quantum Simulation

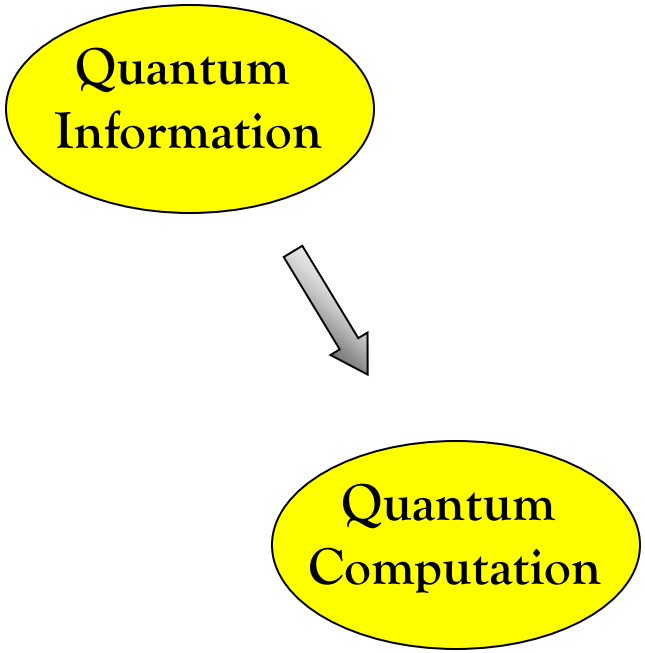
Quantum Information

Quantum Simulation

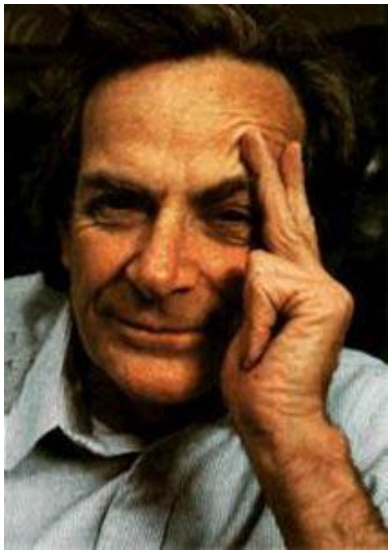
Quantum Chemistry,
Simulating Quantum Field Theories,
Noisy Intermediate-Scale Quantum (NISQ) Devices,
No Quantum Error Correction/Detection,
No Fault Tolerance
…



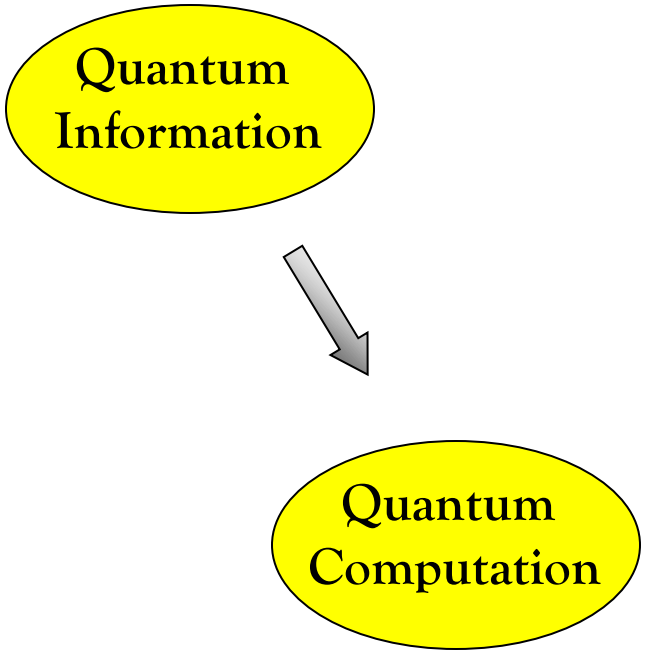
Quantum Computer



Quantum Computer

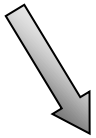


There's Plenty of Room at the Bottom
Feynman 1959

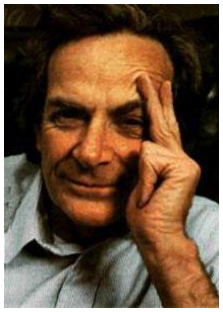


Quantum Computer

Quantum Information



Quantum Computation



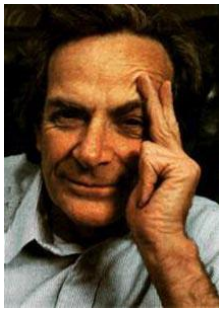
There's Plenty of Room at the Bottom
Feynman 1959

Quantum Turing Machine, Universal Quantum Computer
Deutsch 1985

Quantum Computer

Q. Turing Machine, Universal Q. Computer
Deutsch 1985

Quantum Information



There's Plenty of Room at the Bottom
Feynman 1959

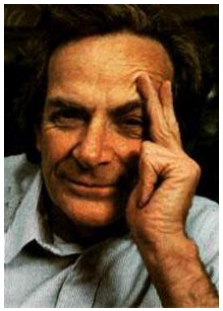
Quantum Computation

Quantum Algorithms and Codes
Shor 1994, 1995

Quantum Computer

Quantum Information

Q. Turing Machine,
Universal Q. Computer
Deutsch 1985



There's Plenty of Room at the Bottom
Feynman 1959

Quantum Computation

Quantum Speedup, Quantum Parallelism,
Quantum Algorithms,
Universal Models, Scalability, Fault Tolerance,
Quantum Error Correction
...

Q. Algorithms and Codes
Shor 1994, 1995

“Quantum Parallelism”

10 Qubits

$$2^{10}$$

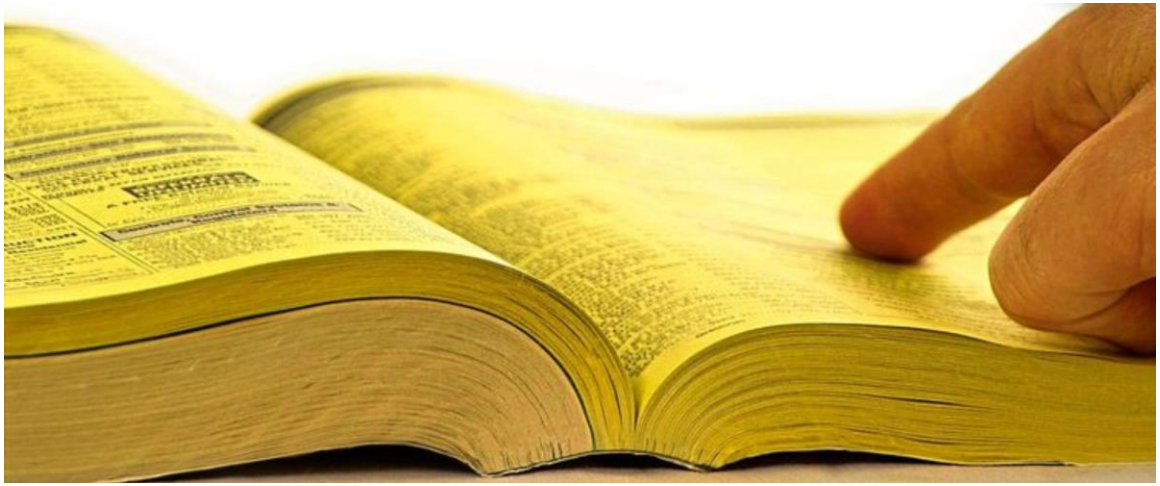
$$= 2 \times 2 \times 2 \ldots \times 2$$

$$= 1024$$

Parallel Bit Combinations

Quantum Software

Grover Algorithm



Shor Algorithm

$$15 = 5 \times 3$$

Shor Factorisation with Faulty Qubits

The estimation is that for a
2048-bit-number (number with 617 digits)
10 - 100 million qubits
will be needed
(in the ideal error-free case, it would be only a few thousand)

Quantum Computer: IBM, Google …

nature

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nature › articles › article

Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, Ryan Babbush, Dave Bacon, Joseph C. Bardin, Rami Barends, Rupak Biswas, Sergio Boixo, Fernando G. S. L. Brandao, David A. Buell, Brian Burkett, Yu Chen, Zijun Chen, Ben Chiaro, Roberto Collins, William Courtney, Andrew Dunsworth, Edward Farhi, Brooks Foxen, Austin Fowler, Craig Gidney, Marissa Giustina, Rob Graff, Keith Guerin, … John M. Martinis + Show authors

Nature **574**, 505–510 (2019) | C

Google Quantum AI Software ⌄ Hardware ⌄ Research ⌄ Education Team ⌄ Search

Research

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Qiskit

What is Quantum Volume?

Quantum volume (QV) is a single-number metric used to measure the power of a for near-term devices with a modest number of qubits, and measures the largest and depth that can be reliably run.

Visual demo

Click through these slides for a quick overview on quantum volume.

Featured publications

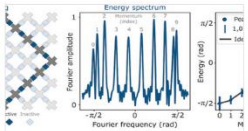
View all publications

Quantum Supremacy Using a Programmable Superconducting Processor

On Oct 23, 2019, Google announced it performed a calculation on a quantum

Topological Quantum States

We experimentally explore topologically ordered quantum states, including simulating the braiding of elusive anyons and encoding logical qubit states we



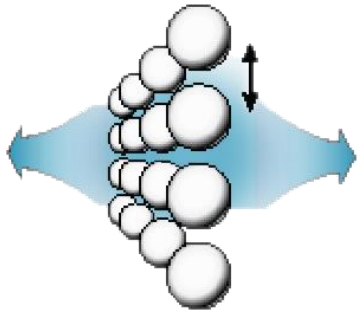
Achieving Precision in Quantum Material Simulations

We outline a blueprint for achieving record levels of precision for the task of simulating quantum materials.

Demonstrating the Fundamentals of Quantum Error Correction

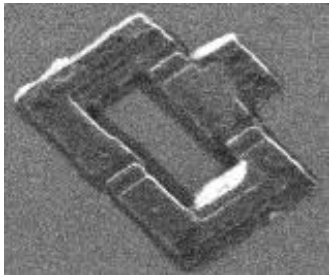
We outline in this paper how we use quantum repetition codes to demonstrate a new technique for

Status 2024: logical vs. physical qubits

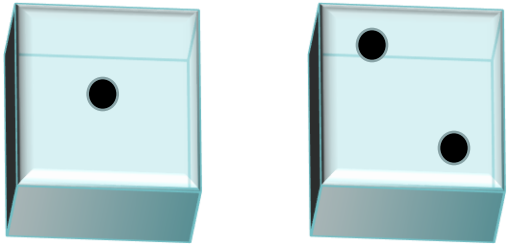


Harvard: ~ 10 logical qubits with atoms
(for 280 physical qubits)
https://www.nature.com/articles/s41586-023-06927-3

IBM: physical superconducting qubits ~ 1000:
https://www.newscientist.com/article/

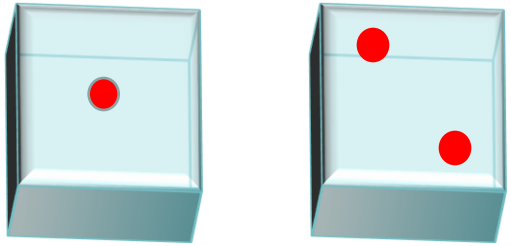


Classical Bit

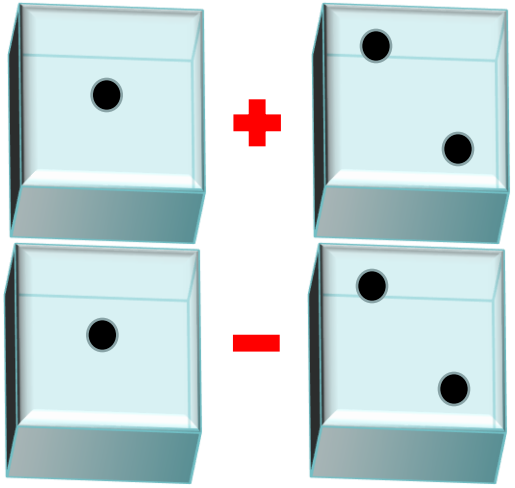


Quantum Bit, "Qubit"

2 States („computational basis")



2 States (complementary basis)

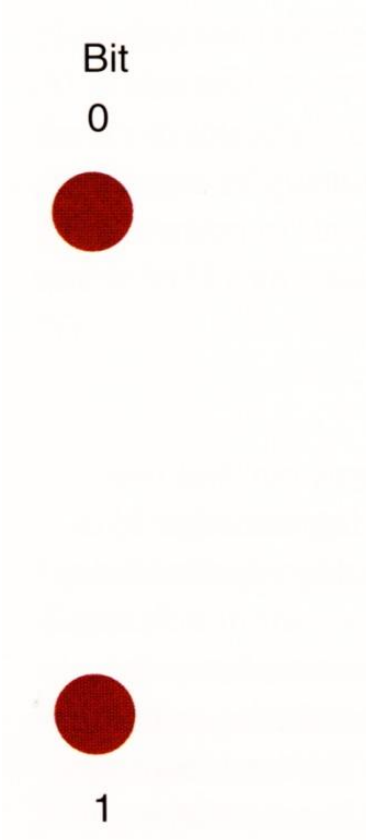


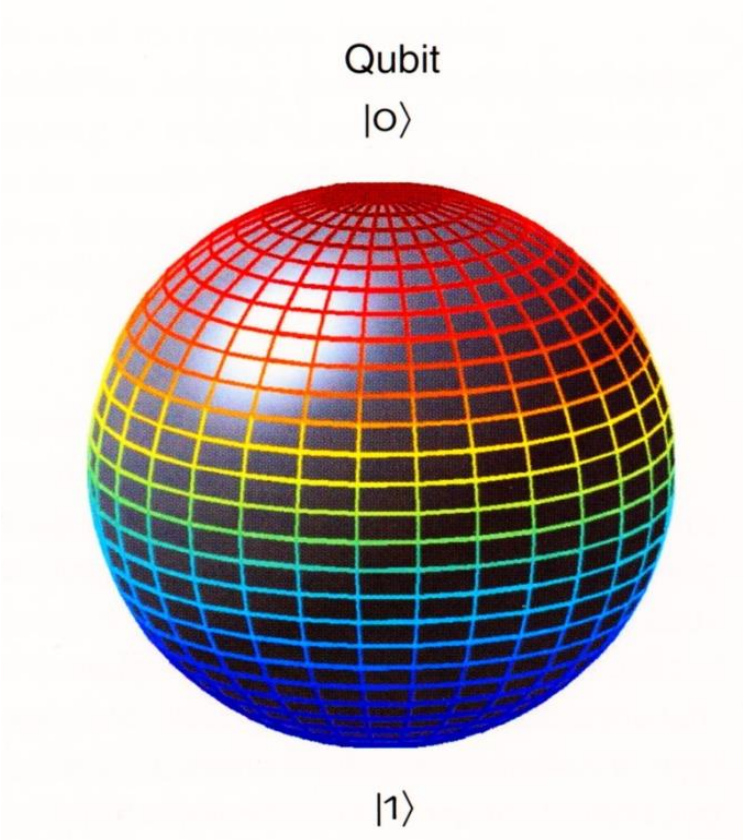
Quantum Bit, “Qubit”

Classical Bits, Quantum Bits

0 or 1

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$





Qubit in Dirac Notation

$$\alpha |0\rangle + \beta |1\rangle$$

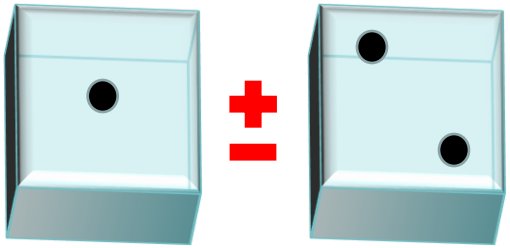
$$\alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \alpha \\ \beta \end{pmatrix}$$

Qubit in Dirac Notation: Vektor Basis

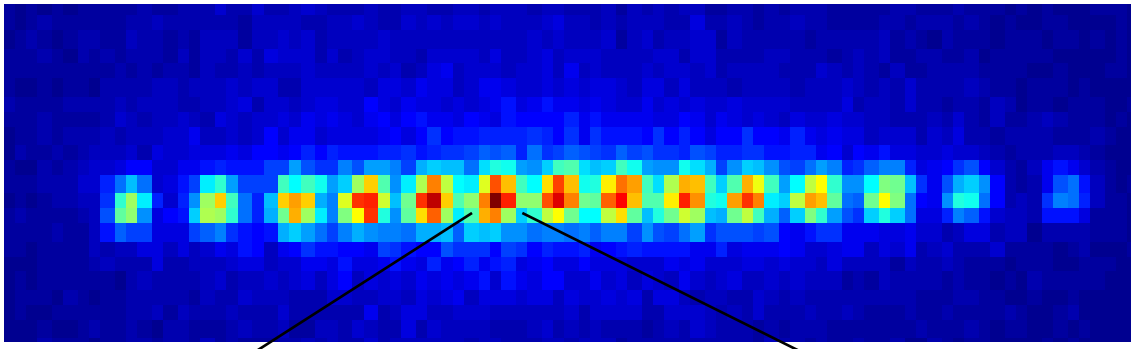
$$\begin{pmatrix} 1 & 0 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ 1 \end{pmatrix} \Rightarrow \langle 0|1 \rangle$$

“Pauli-X” Basis (Eigen-)States

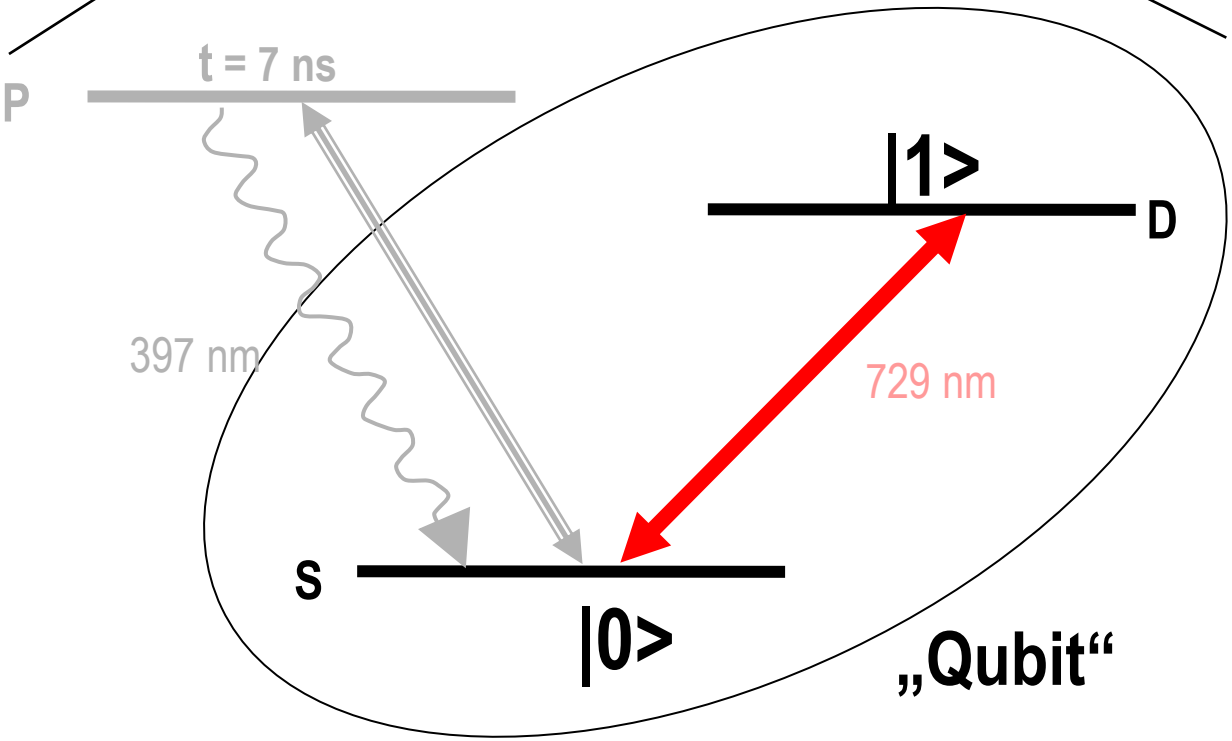
$$|0\rangle \pm |1\rangle$$



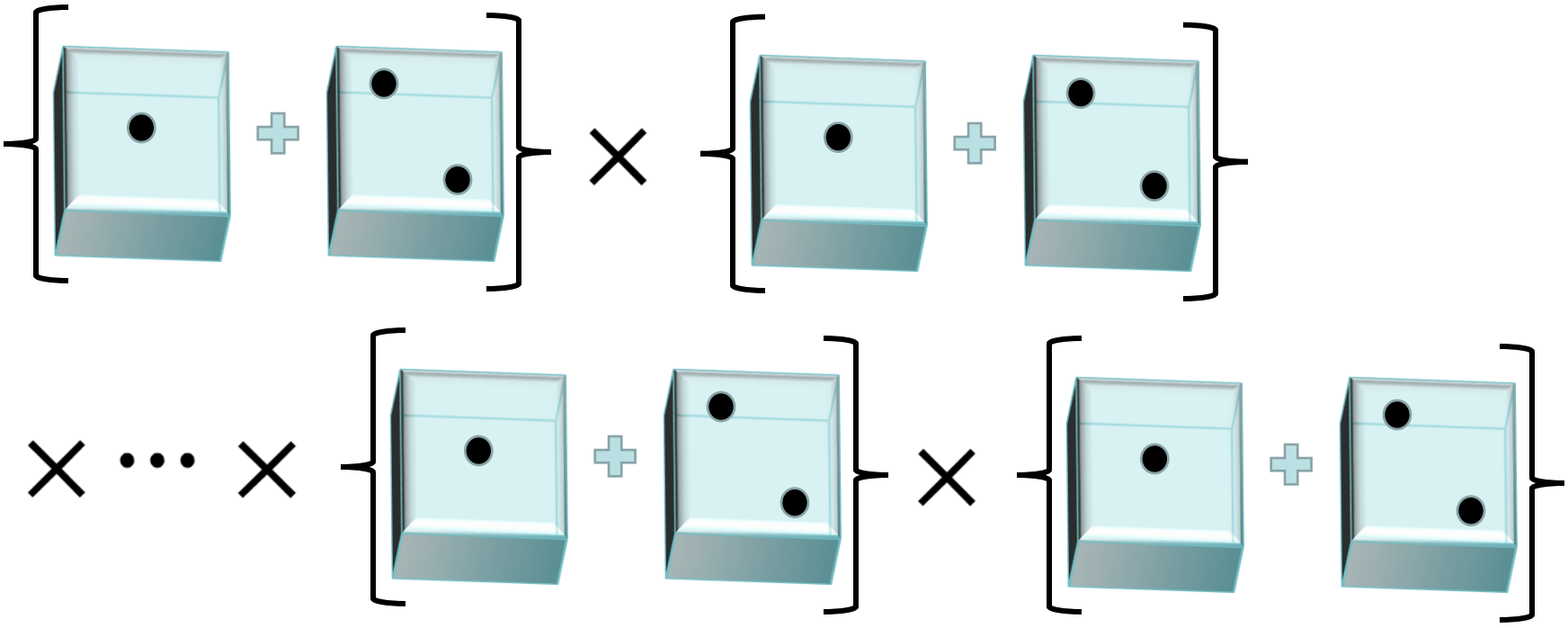
Ion Qubit



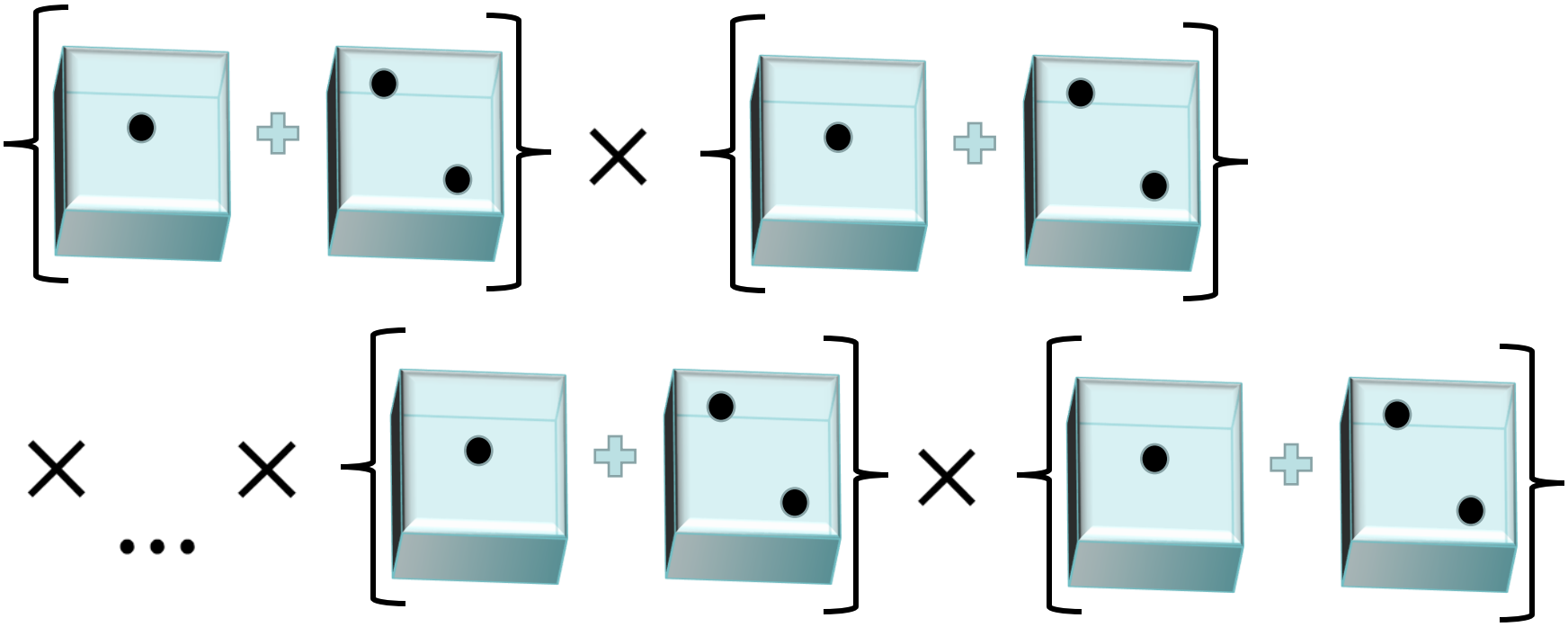
Ferdinand
Schmidt-Kaler
Group
in Mainz



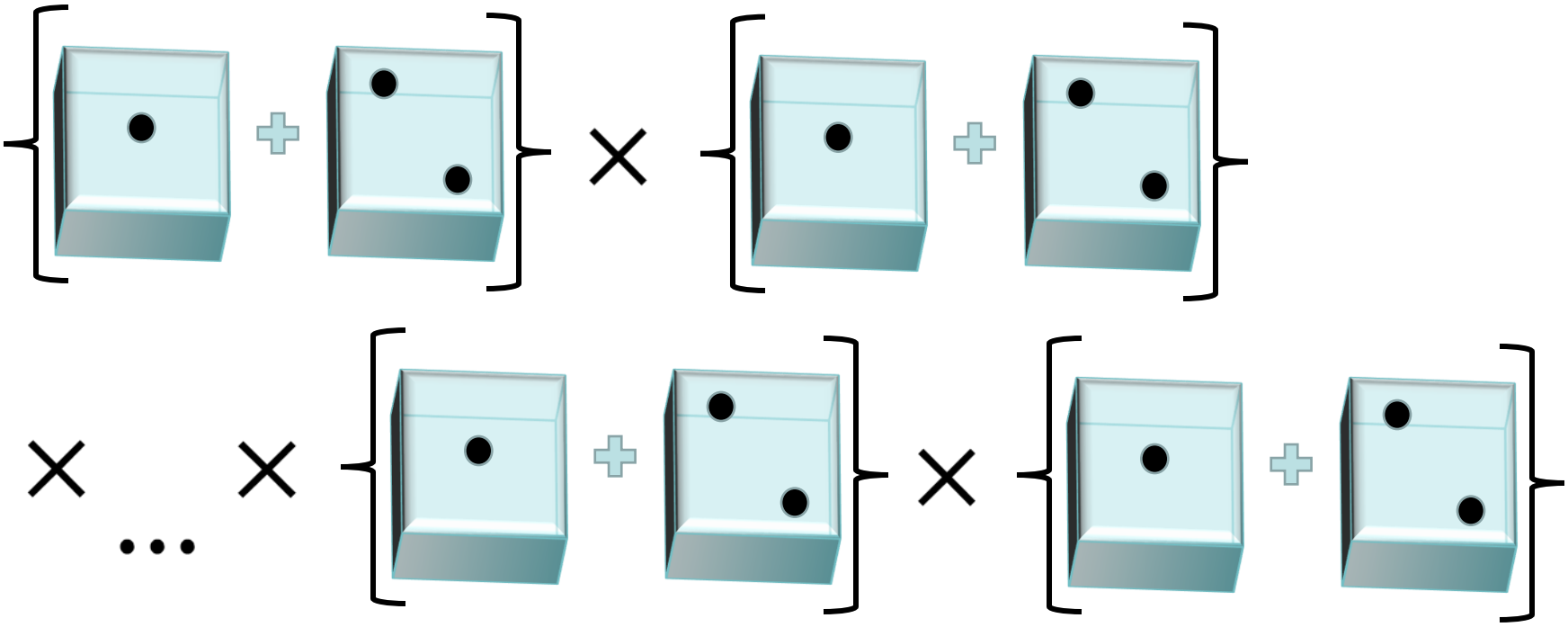
Quantum Algorithms: Input



Quantum Algorithms: Input



Quantum Algorithms: Input



$$= |000\ldots0\rangle$$

$$+|100\ldots0\rangle + \ldots$$

Quantum Error Correction: Shor Code

THIRD SERIES, VOLUME 52, NUMBER 4 OCTOBER 1995

RAPID COMMUNICATIONS

The Rapid Communications section is intended for the accelerated publication of important new results. Since manuscripts submitted to this section are given priority treatment both in the editorial office and in production, authors should explain in their submittal letter why the work justifies this special handling. A Rapid Communication should be no langer than 4 printed pages and must be accompanied by an abstract. Page proofs are sent to authors.

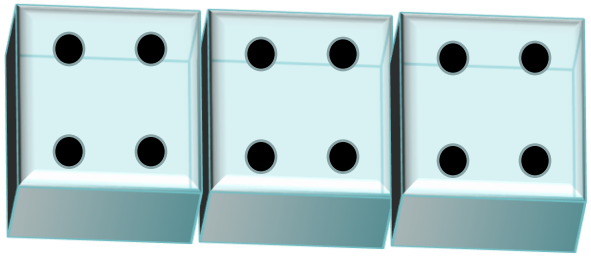
Scheme for reducing decoherence in quantum computer memory

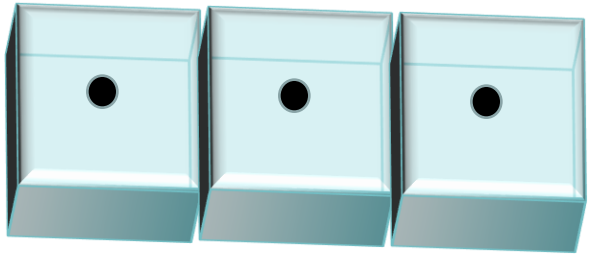
Peter W. Shor*
AT&T Bell l.Aboratories, Room 2D-149, 600 Mountain Avenue, Murray Hill, New Jersey 07974
(Received 17 May 1995)

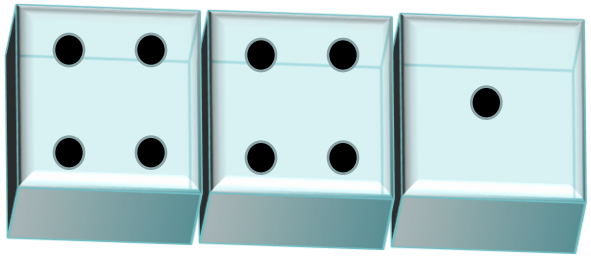
Recently, it was realized that use of the properties of quantum mechanics might speed up certain computa tions dramatically. Interest has since been growing in the area of quantum computation. One of the main difficulties of quantum computation is that decoherence destroys the information in a superposition of states contained in a quantum computer, thus making long computations impossible. lt is shown how to reduce the effects of decoherence for information stored in quantum memory, assuming that the decoherence process acts independently on each of the bits stored in memory. This involves the use of a quantum analog of error correcting codes.

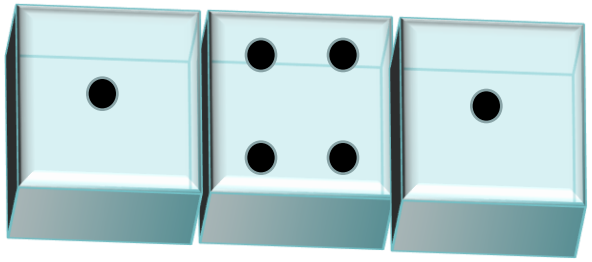
PACS number(s): 03.65.Bz, 89.70.+c

Classical Error Correction: “Redundancy”

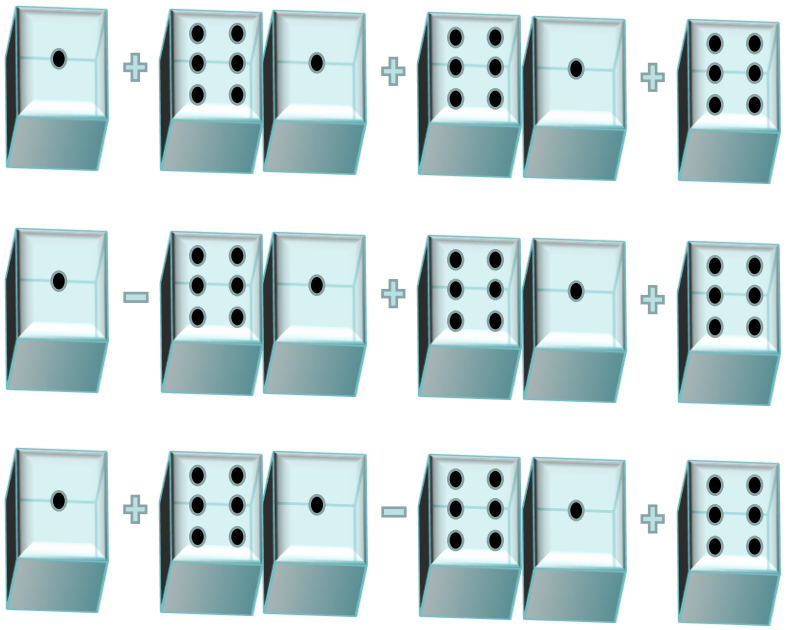








Quantum Error Correction



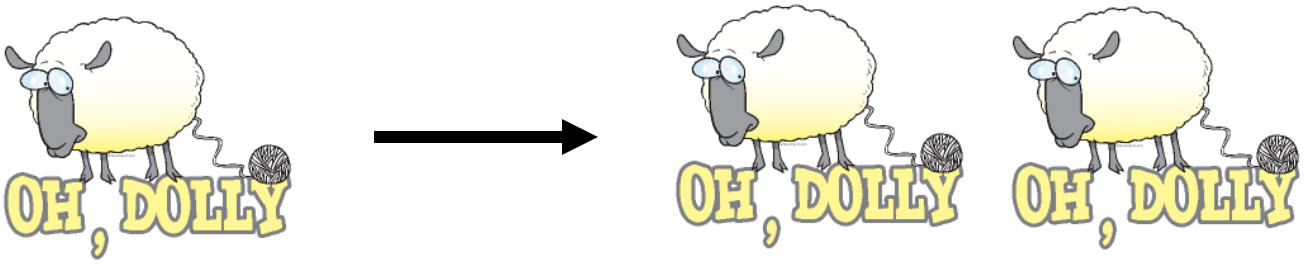
Shor's Quantum Error Correction Code

$$\alpha\left|+++\right\rangle+\beta\left|---\right\rangle$$

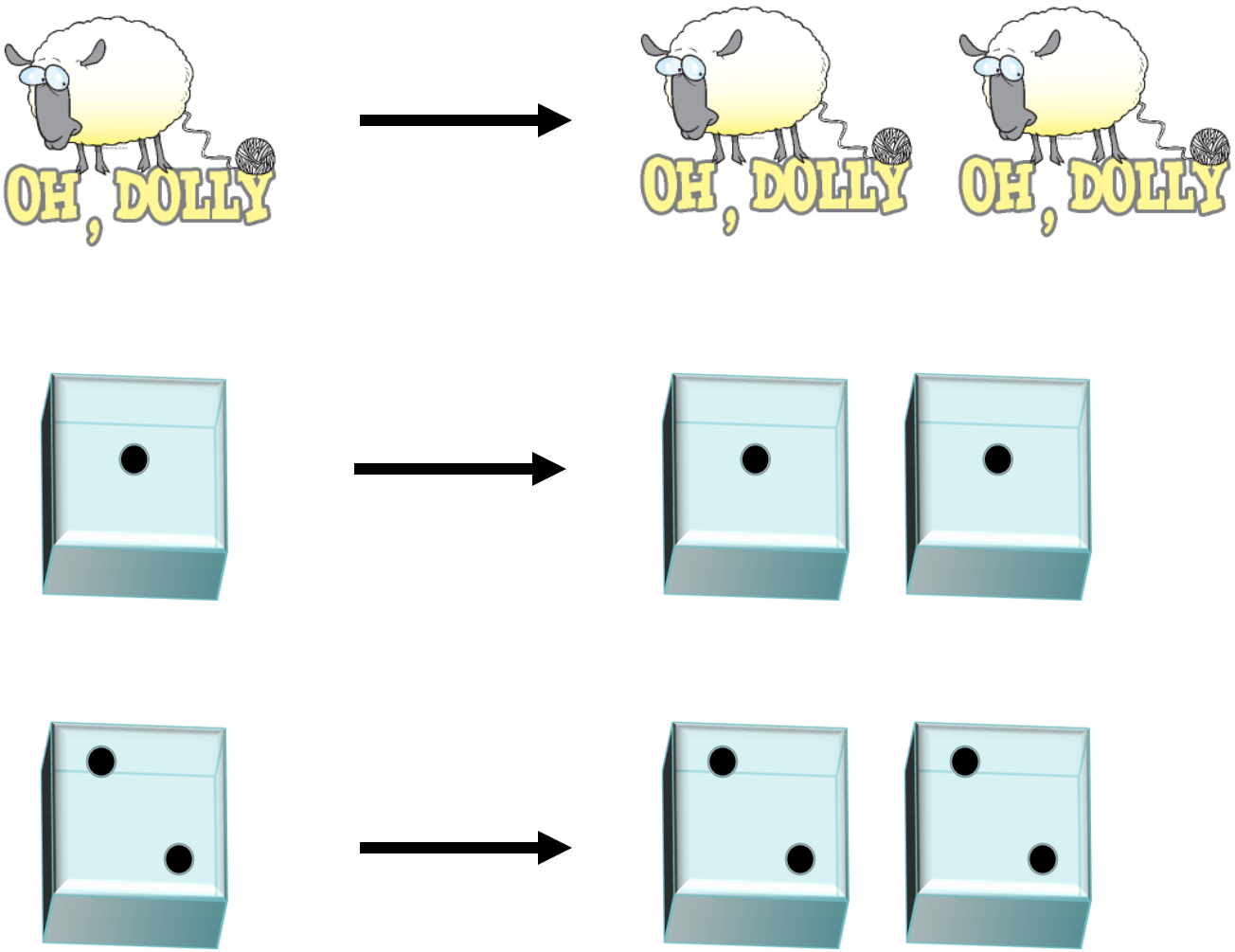
with

$$\left|\pm\right\rangle=\left(\left|000\right\rangle\pm\left|111\right\rangle\right)/\sqrt{2}$$

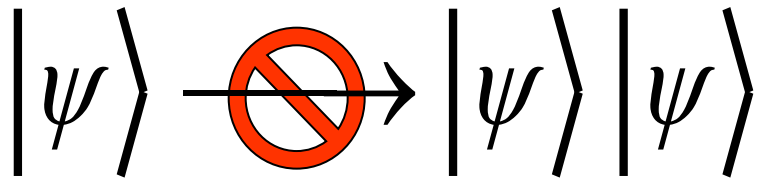
Cloning



Cloning



No-Cloning Theorem



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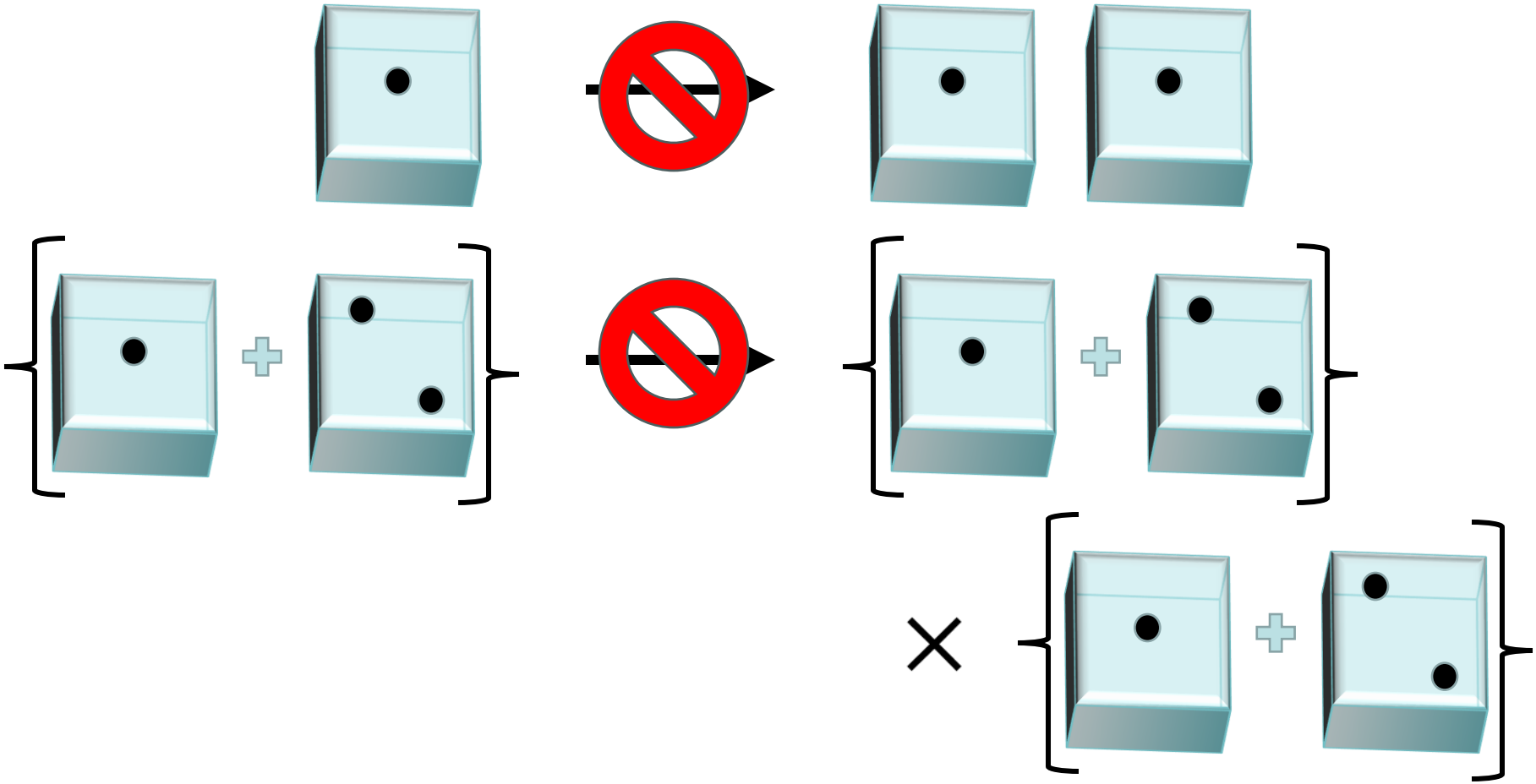
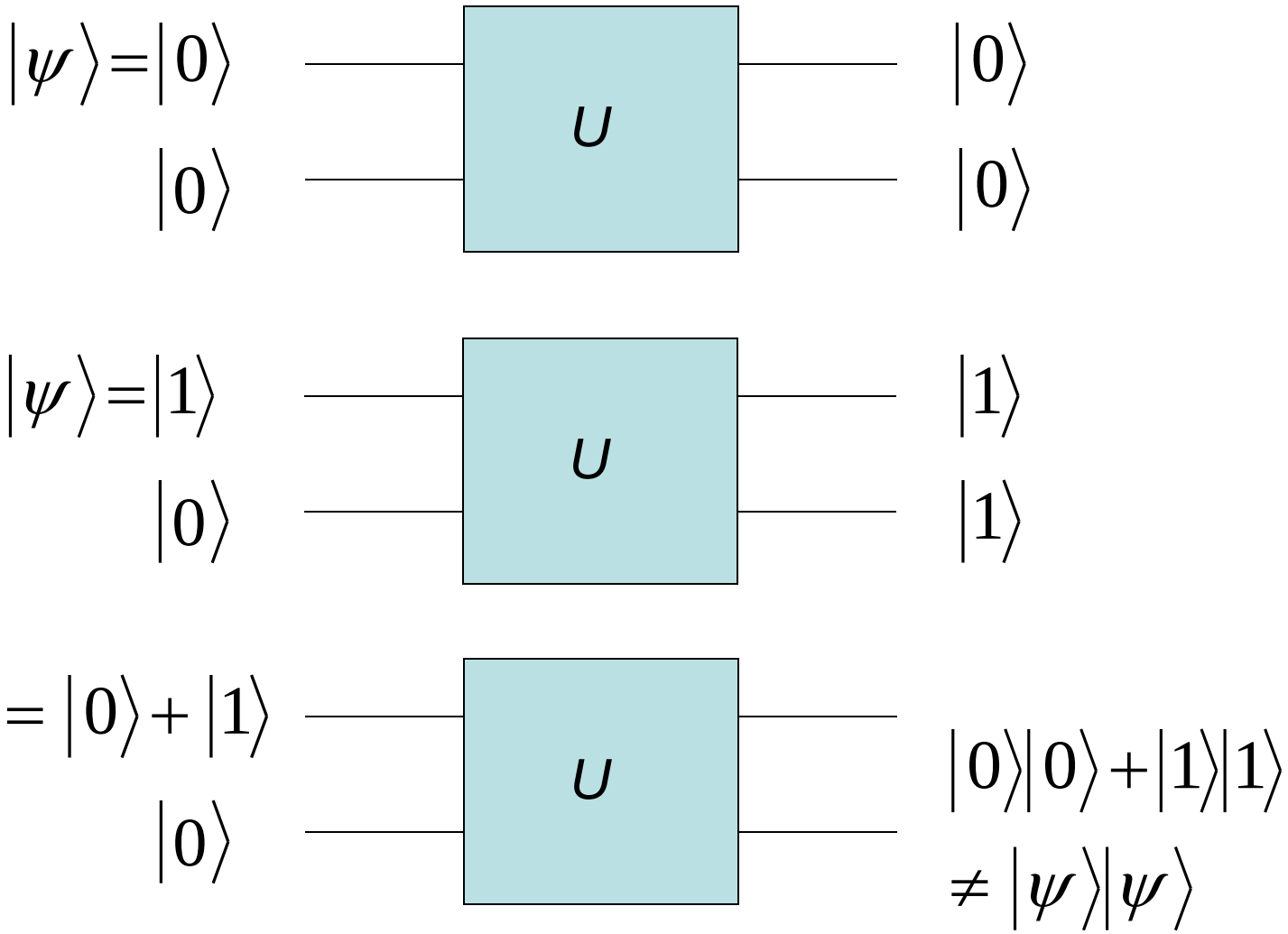
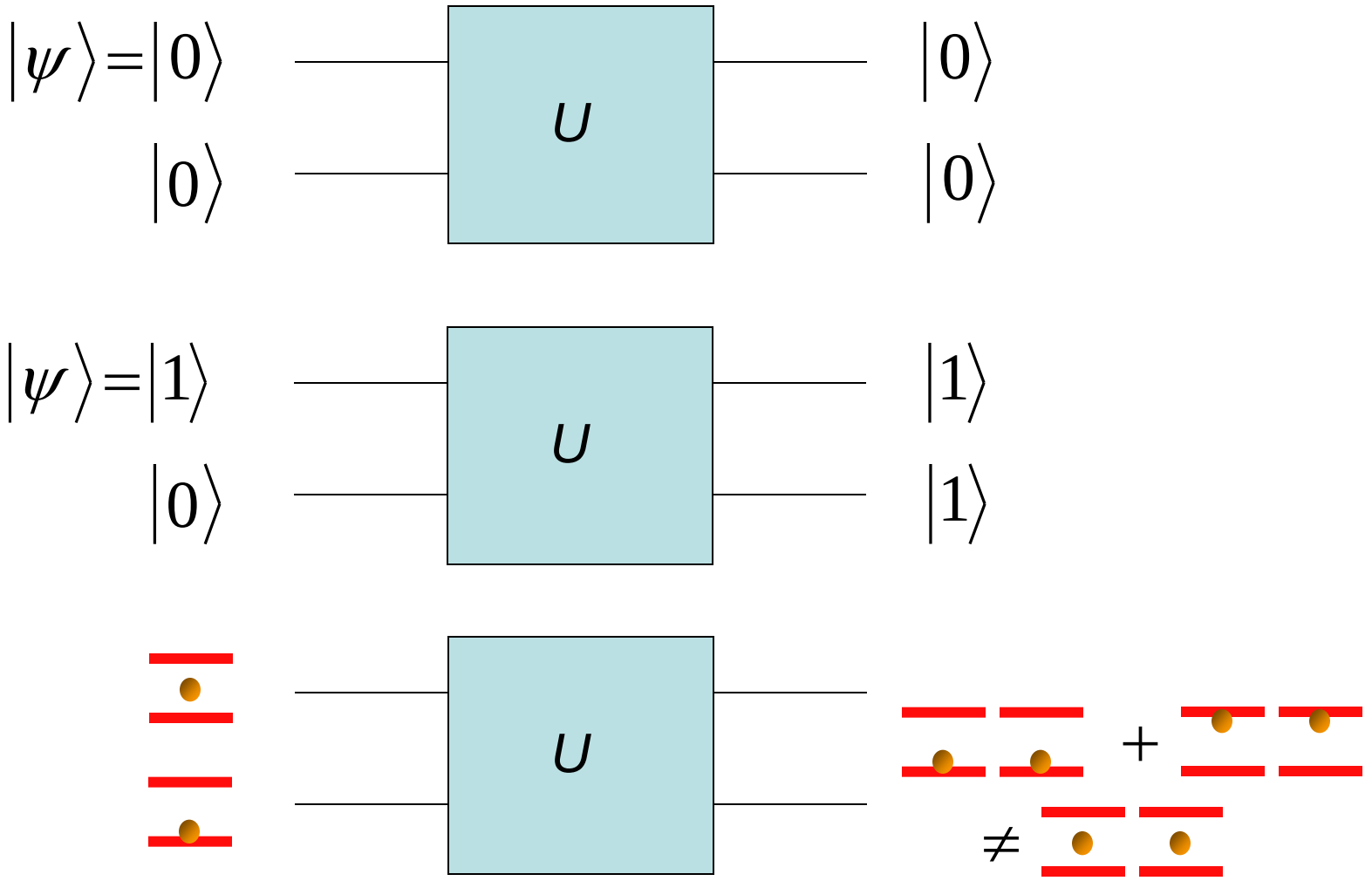


No-Cloning



Wootters and Zurek, Dieks, 1982

No-Cloning


$|\psi\rangle = |0\rangle$
$|0\rangle$
U
$|0\rangle$
$|0\rangle$
$|\psi\rangle = |1\rangle$
$|0\rangle$
U
$|1\rangle$
$|1\rangle$
U
$+$
$\neq$

Photonic QComputer: PsiQuantum,Xanadu

XANADU Products Pricing Photonics Comm

// Quantum Hardware

Quantum computational advantage on Xanadu Cloud

Forbes

FORBES > INNOVATION > CLOUD

PsiQuantum Has A Goal For Its Million Qubit Photonic Quantum Computer To Outperform Every Supercomputer On The Planet

Paul Smith-Goodson Contributor
Moor Insights and Strategy Contributor Group

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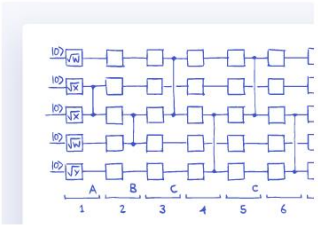
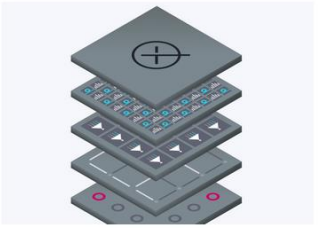


```
import pennylane as qml
from pennylane import numpy as np

# create a quantum device
dev = qml.device("default.qubit", wires

# a quantum node
@qml.qnode(dev)
def circuit(phi1, phi2):
    qml.RX(phi1, wires=0)
    qml.RY(phi2, wires=0)
```



Build

Software services for Strawberry Fields & PennyLane

Experiment

Leverage high performance simulators

Execute

Exclusive access to photonic quantum computers

PsiQuantum Home About News Careers Resources

Building the first useful quantum computer

It takes 1,000,000+ qubits.
It takes error correction.
It takes fault tolerance.
It takes photons.

Photonic Qubit

Single-Rail Qubit:

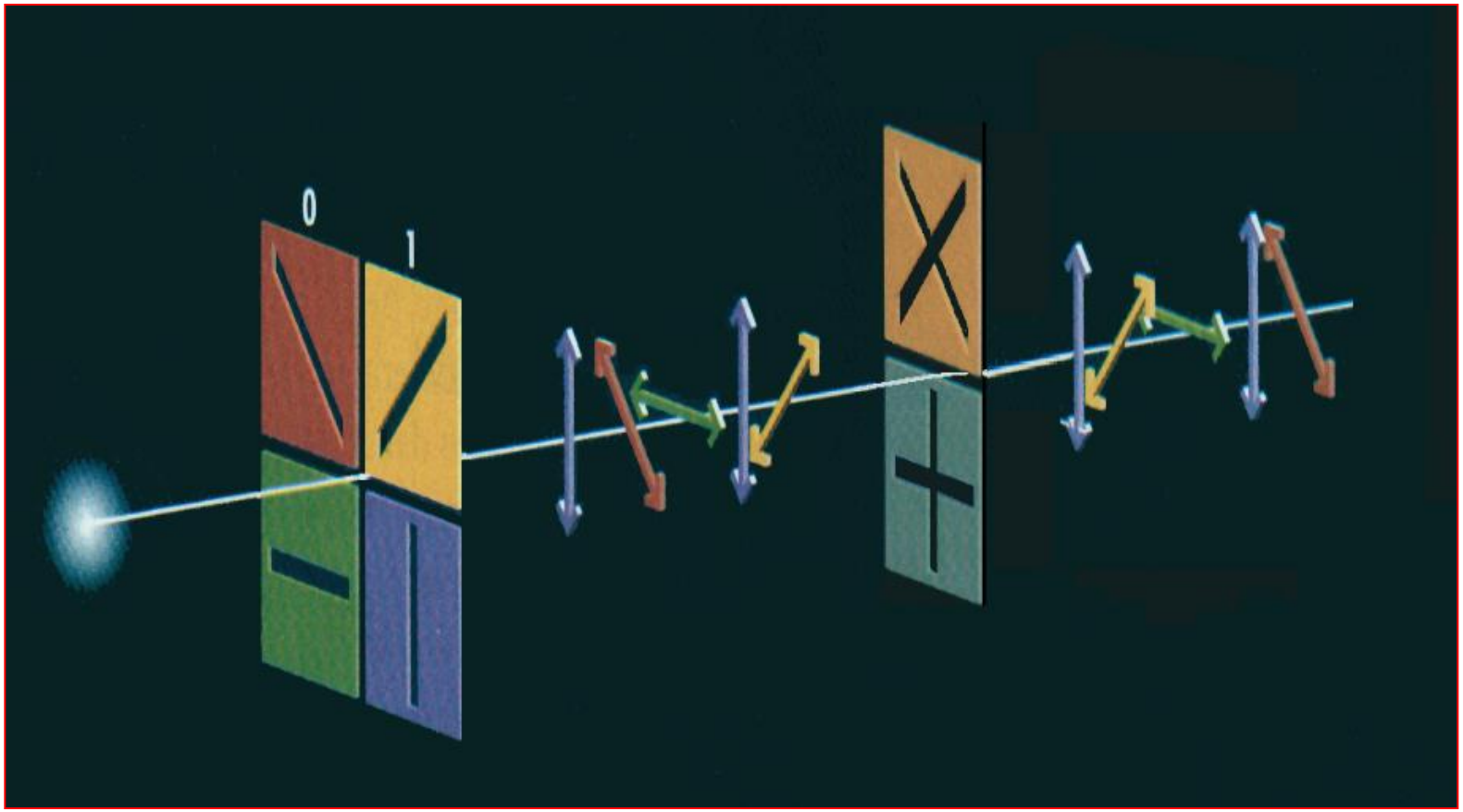
$$\alpha|0\rangle + \beta|1\rangle$$

Dual-Rail Qubit:

$$\alpha|10\rangle + \beta|01\rangle$$

PsiQuantum's Photonic Qubit

$$\alpha \left| \leftrightarrow \right\rangle + \beta \left| \updownarrow \right\rangle$$



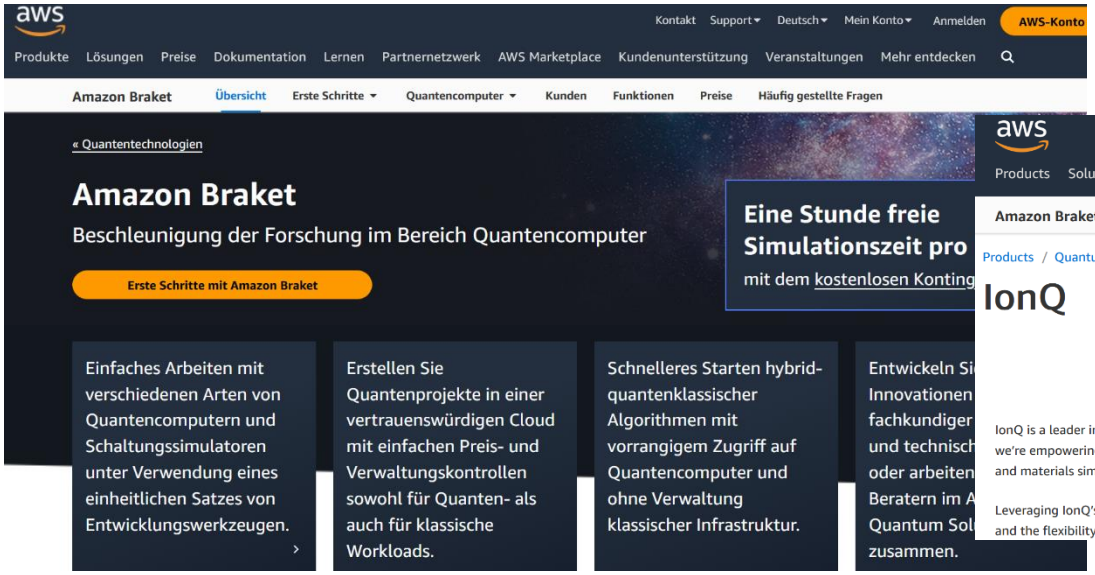
Quantum Communication

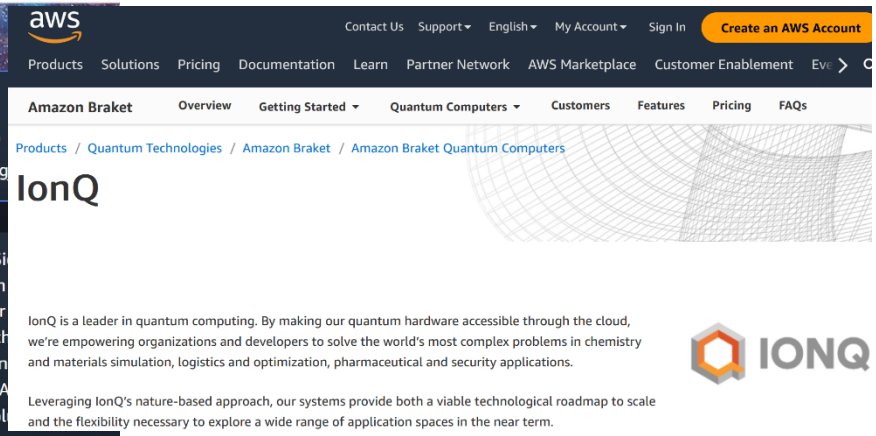
Quantum Information

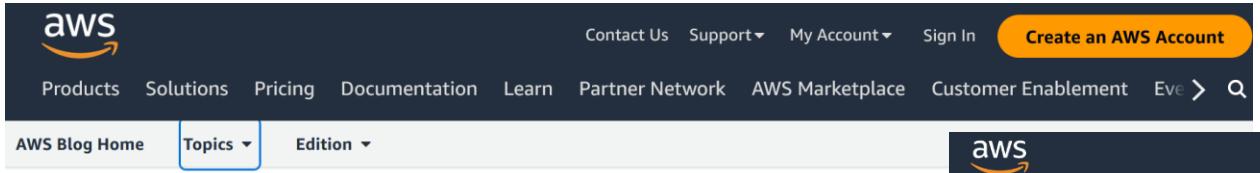
Quantum Communication

"The Art To Transfer Quantum States",
Quantum Cryptography (QKD), Quantum Networks,
Entanglement-Assisted Data Transfer,
Distributed Quantum Computing,
Quantum Internet,
Quantum Error Detection/Correction
...

Quantum Networks: Amazon …





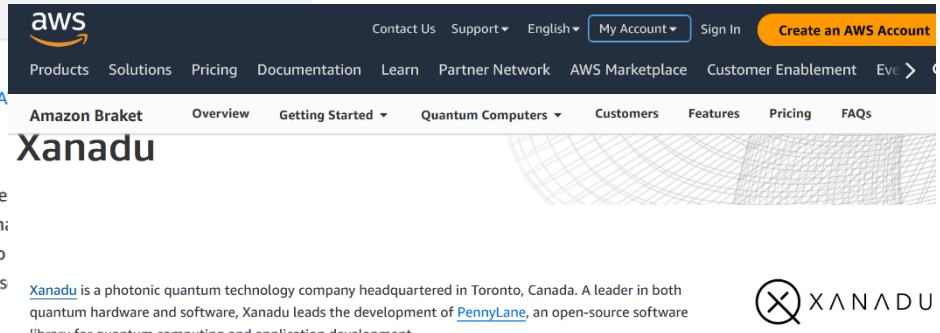


Announcing the AWS Center for Quantum Networking

by Denis Sukachev and Mihir Bhaskar | on 21 JUN 2022 | in Amazon Quantum Solutions Lab, Announcements, A
Quantum Technologies | Permalink | Share

Over the last decade, governments and technology companies have invested heavily in research and developme
the potential to revolutionize science and technology. While there is still a long way ahead, these investments ha
computers: They have evolved from delicate laboratory systems accessible to only a few research institutions to
commercial machines available to researchers, developers, and even quantum enthusiasts worldwide via cloud s

While quantum computing continues to be a major area of investment and progress for academic and industry r
component of a broader class of quantum technologies. To unlock the full potential of quantum devices, they n
quantum network, similar to the way today's devices are connected via the internet. Despite not receiving the sa
computers, quantum networks have fascinating possible applications. One of them is enabling global communic
distribution with privacy and security levels not achievable using conventional encryption techniques. Quantum
and secure cloud quantum servers by connecting together and amplifying the capabilities of individual quantum processors.



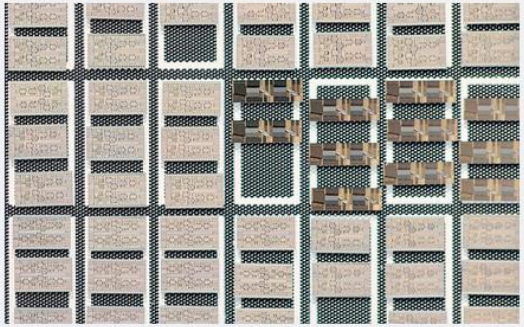
Photon-Based QTechnology: Why Light?

XANADU Products Pricing Photonics Community Company

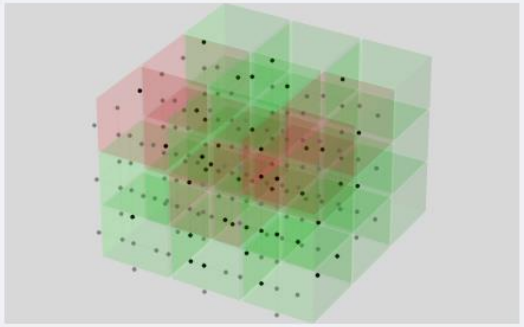
// Why Photonics

The unique advantages of Photonics

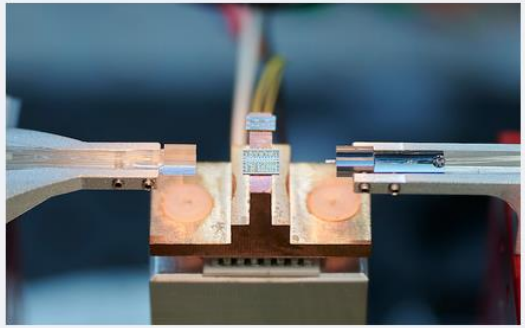
Room temperature computation



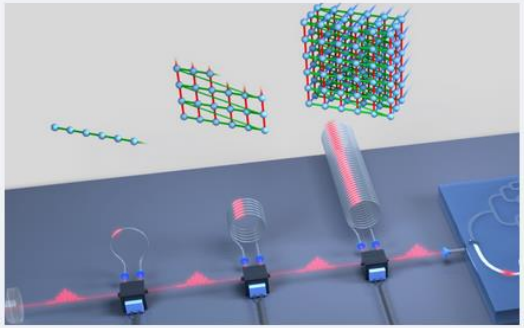
Manufacturability



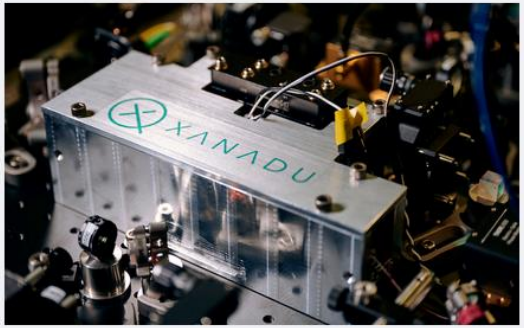
Error correction flexibility



Modular and networkable



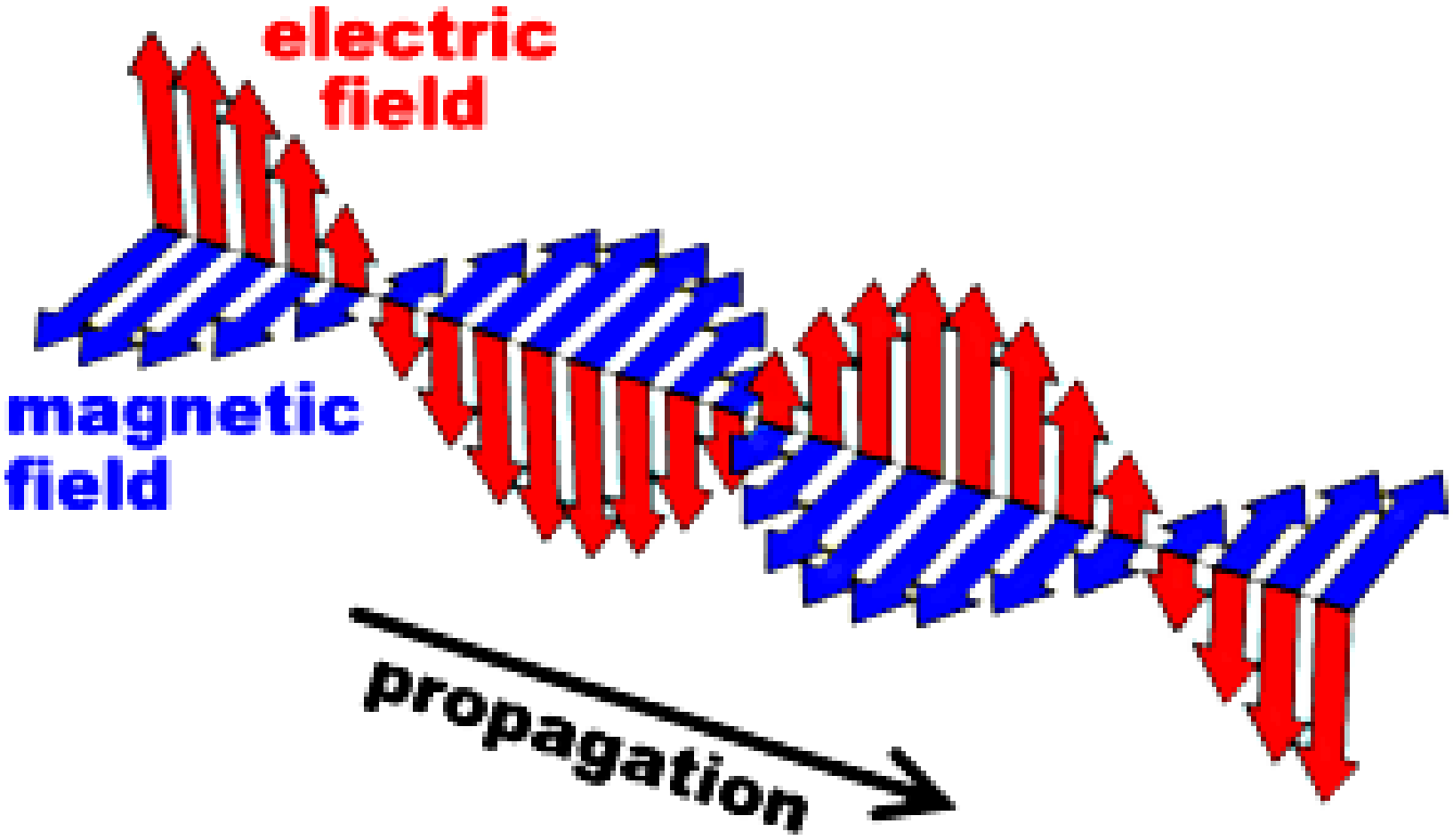
Fast clock speeds



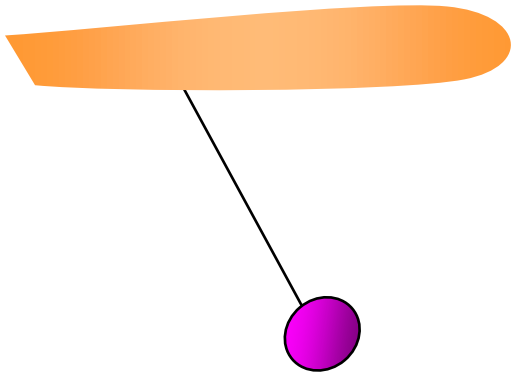
Telecom compatibility

Quantum Optics, Quantum Light

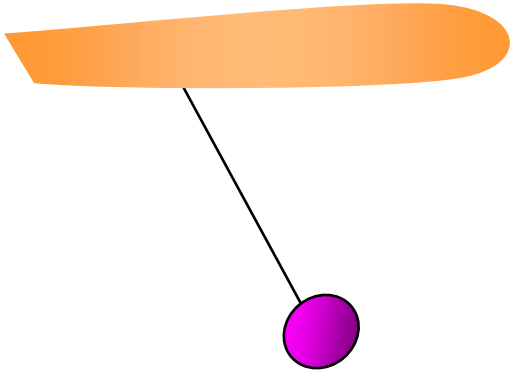
Electromagnetic Light Wave

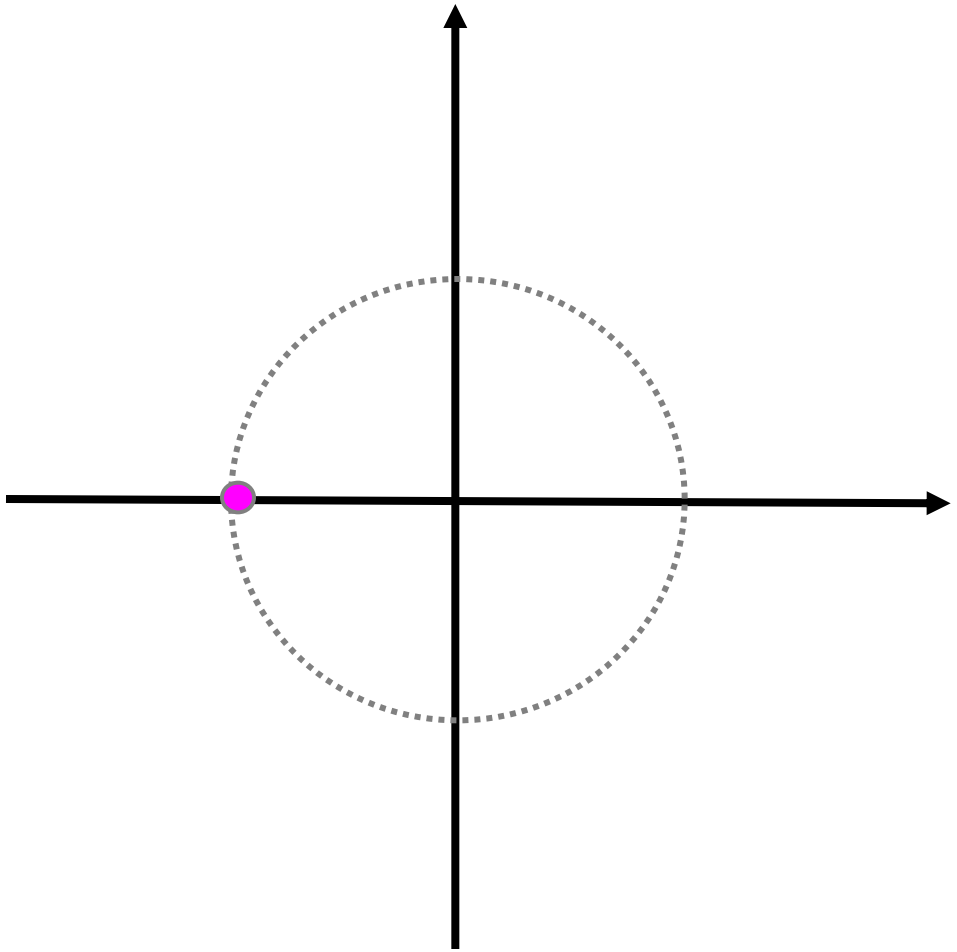


Light Wave is like a Pendulum

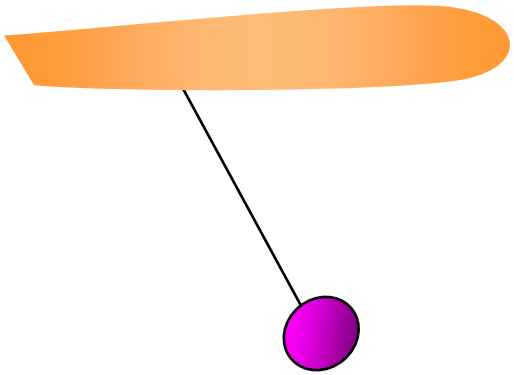


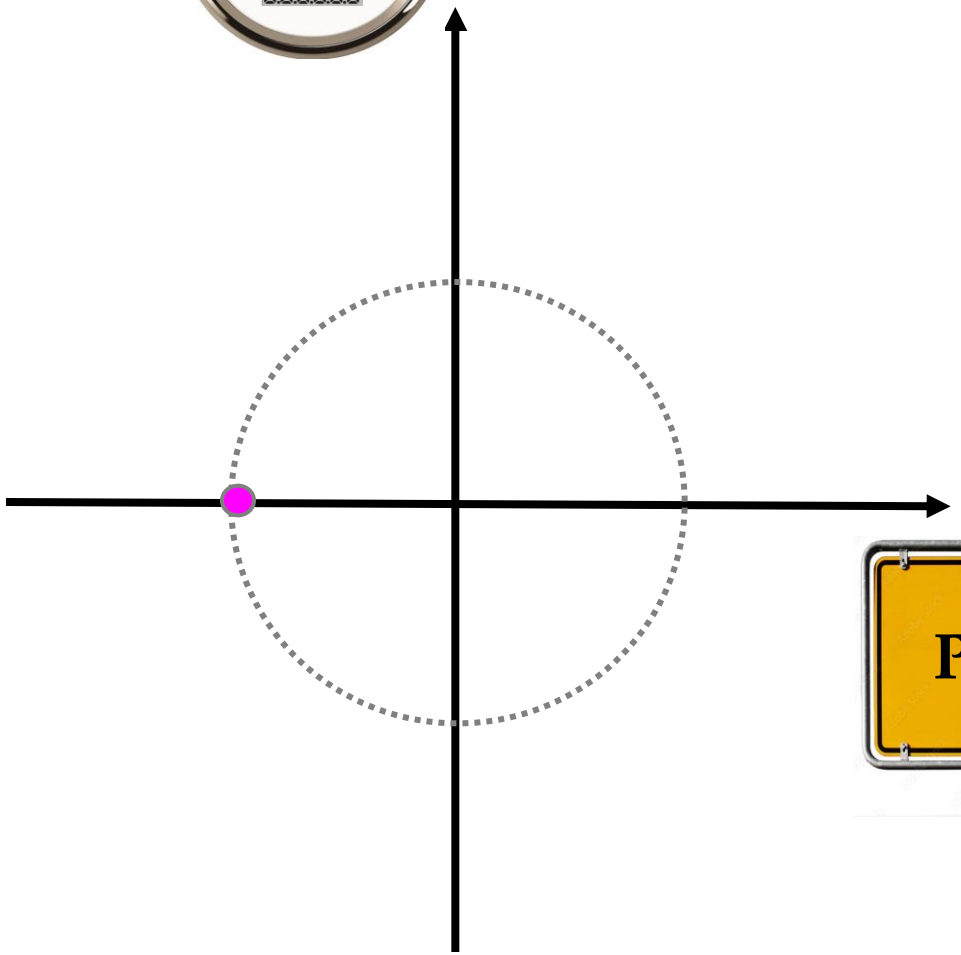
Light Wave is like a Pendulum



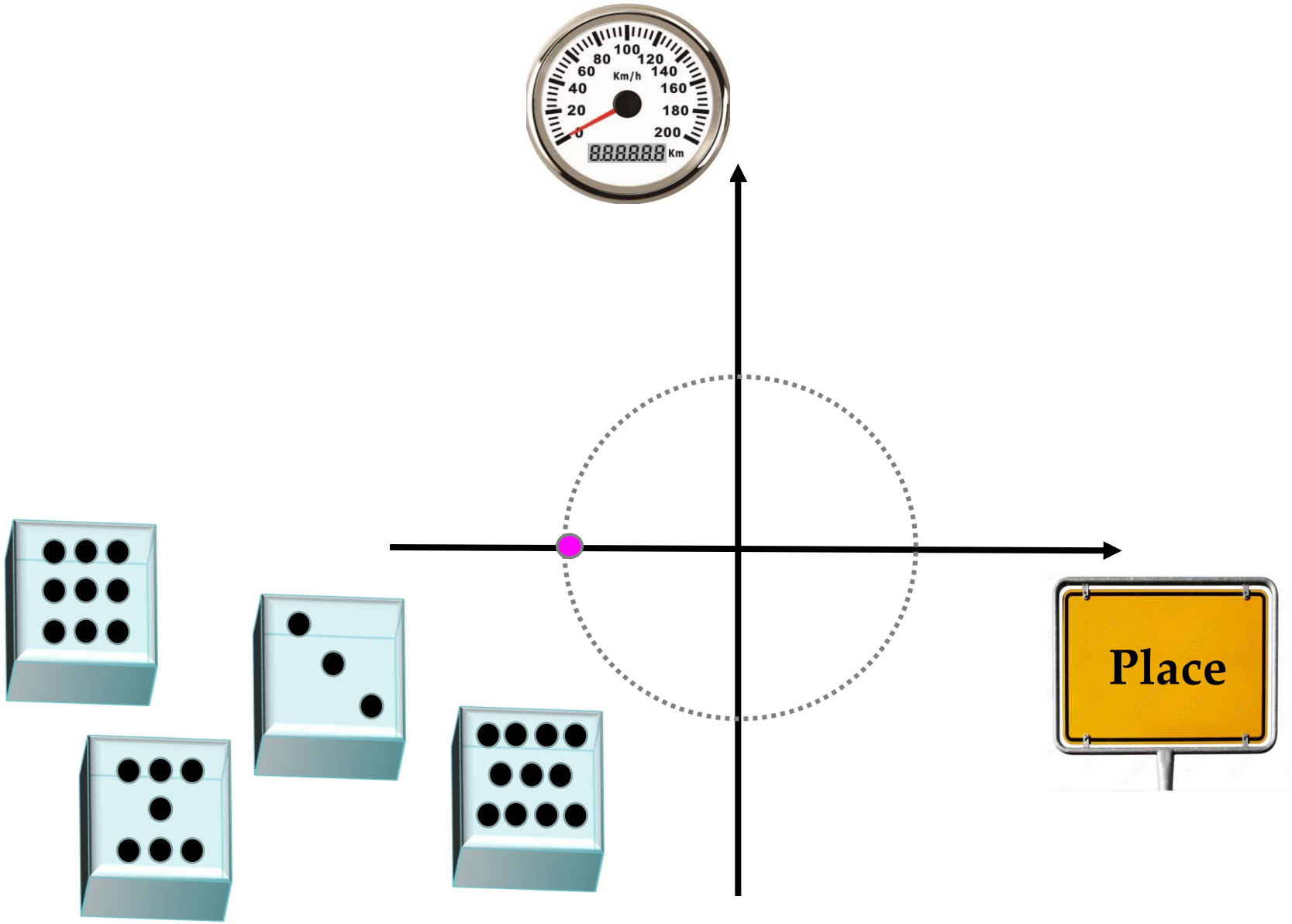


Light Wave is like a Pendulum

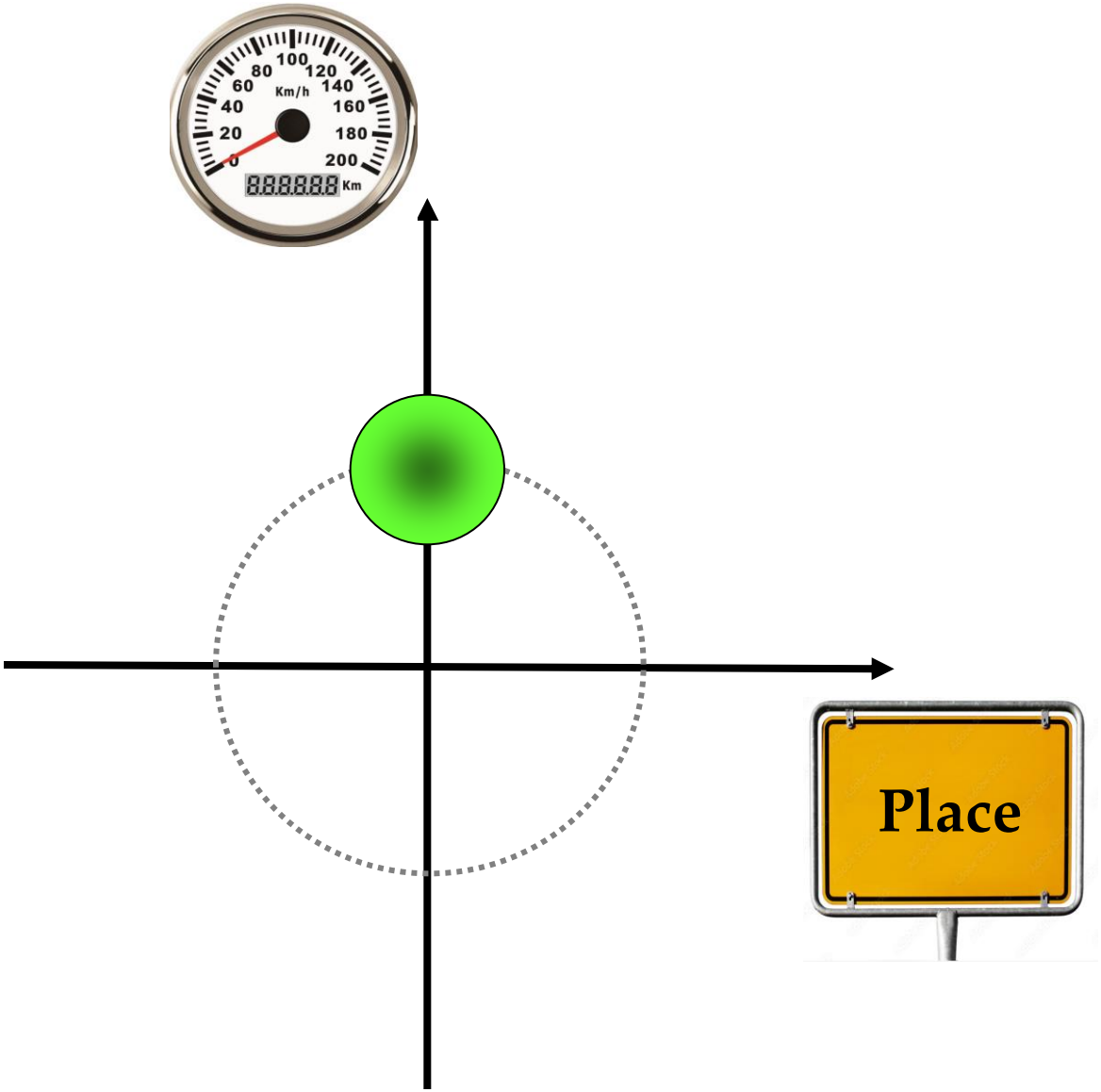




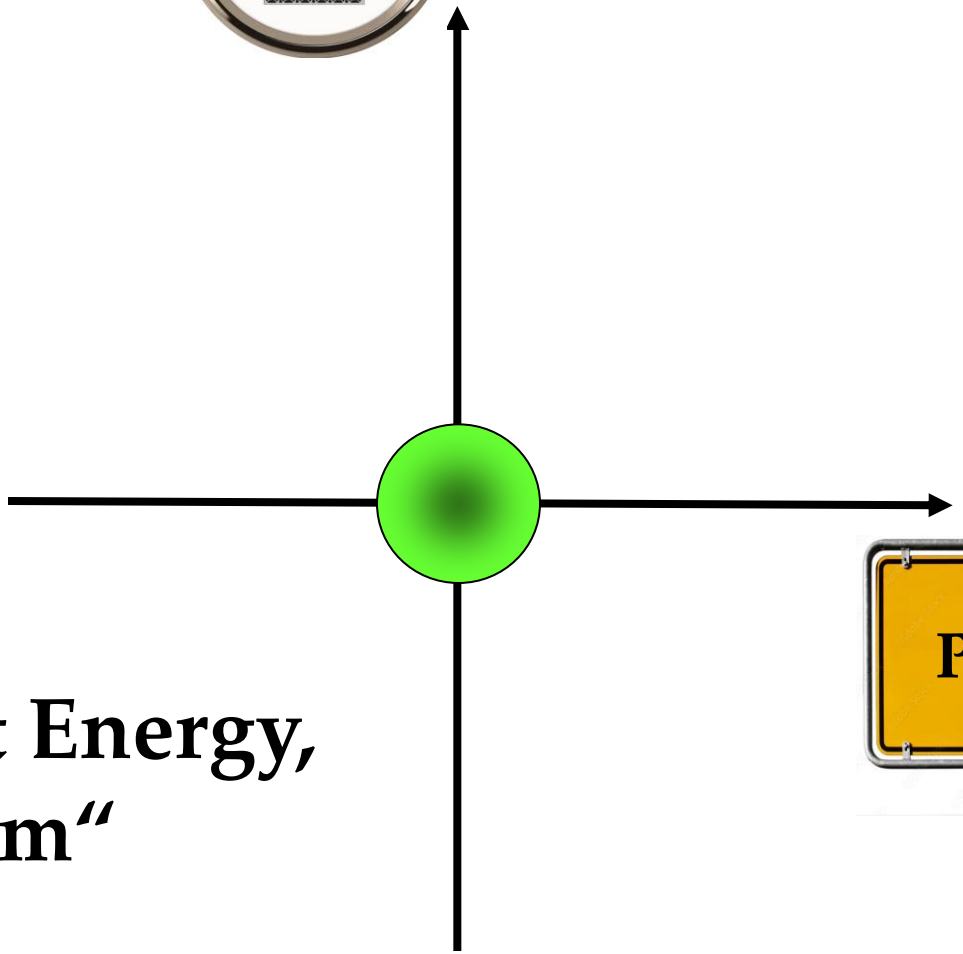
Quantum Light Wave: Quantum Pendulum



Quantum Light Wave: Quantum Pendulum

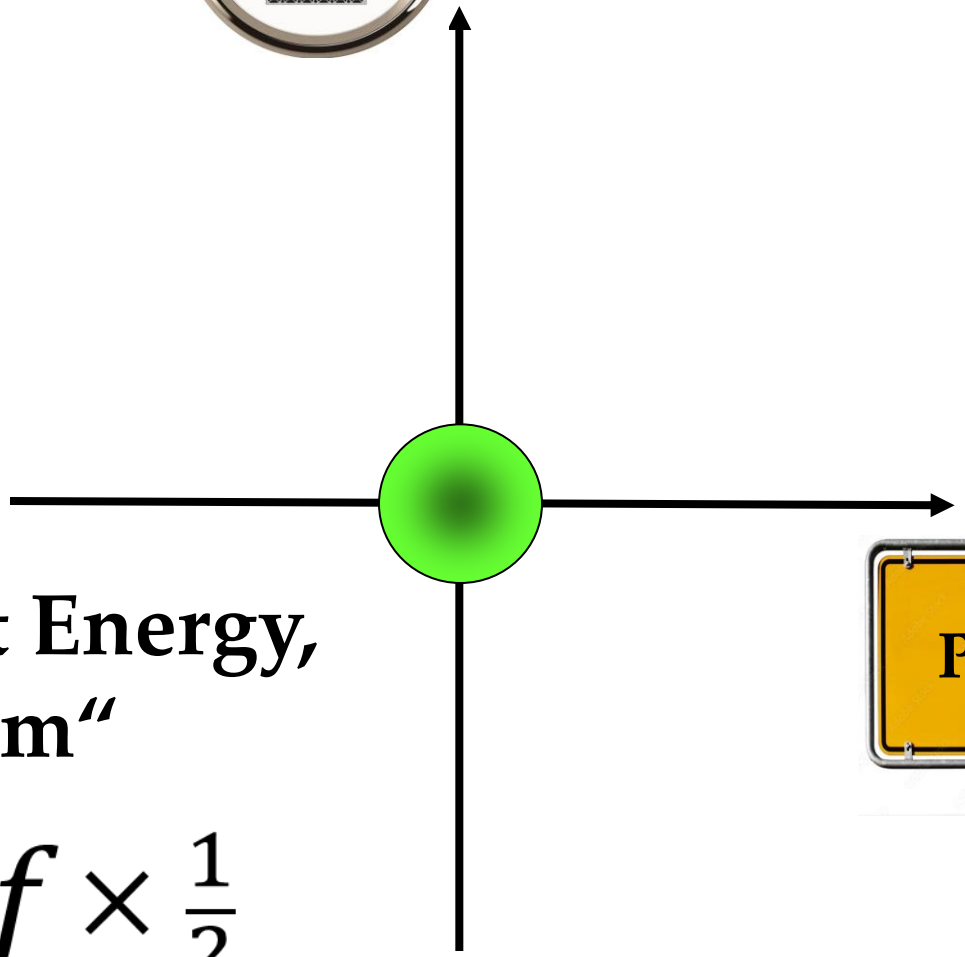


Minimal Uncertainty



„Zero Point Energy, Vacuum“

Minimal Uncertainty



„Zero Point Energy, Vacuum“

$$E = hf \times \frac{1}{2}$$

Quantum Optics

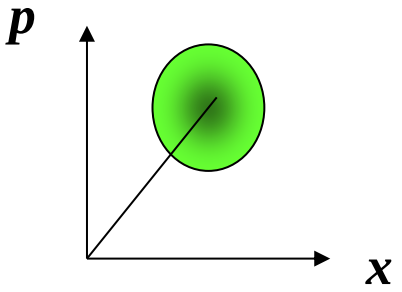
$$\hat{a} = \hat{x} + i\hat{p}$$

$$[\hat{x}, \hat{p}] = i/2$$

$$\Delta\hat{x}\Delta\hat{p} \geq 1/16$$

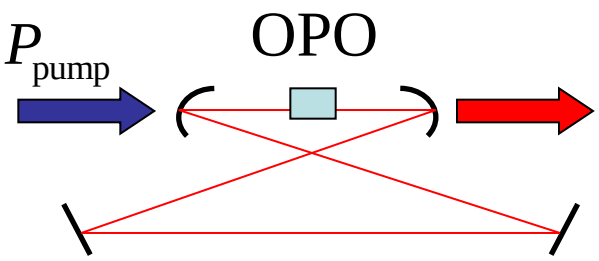
$$\hat{a}\,|\alpha\rangle = \alpha\,|\alpha\rangle$$

$$|\alpha\rangle = \hat{D}(\alpha)\,|0\rangle$$

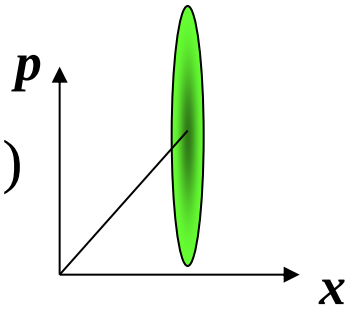


$$|\alpha\rangle = \exp(-|\alpha|^2/2)\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}|n\rangle$$

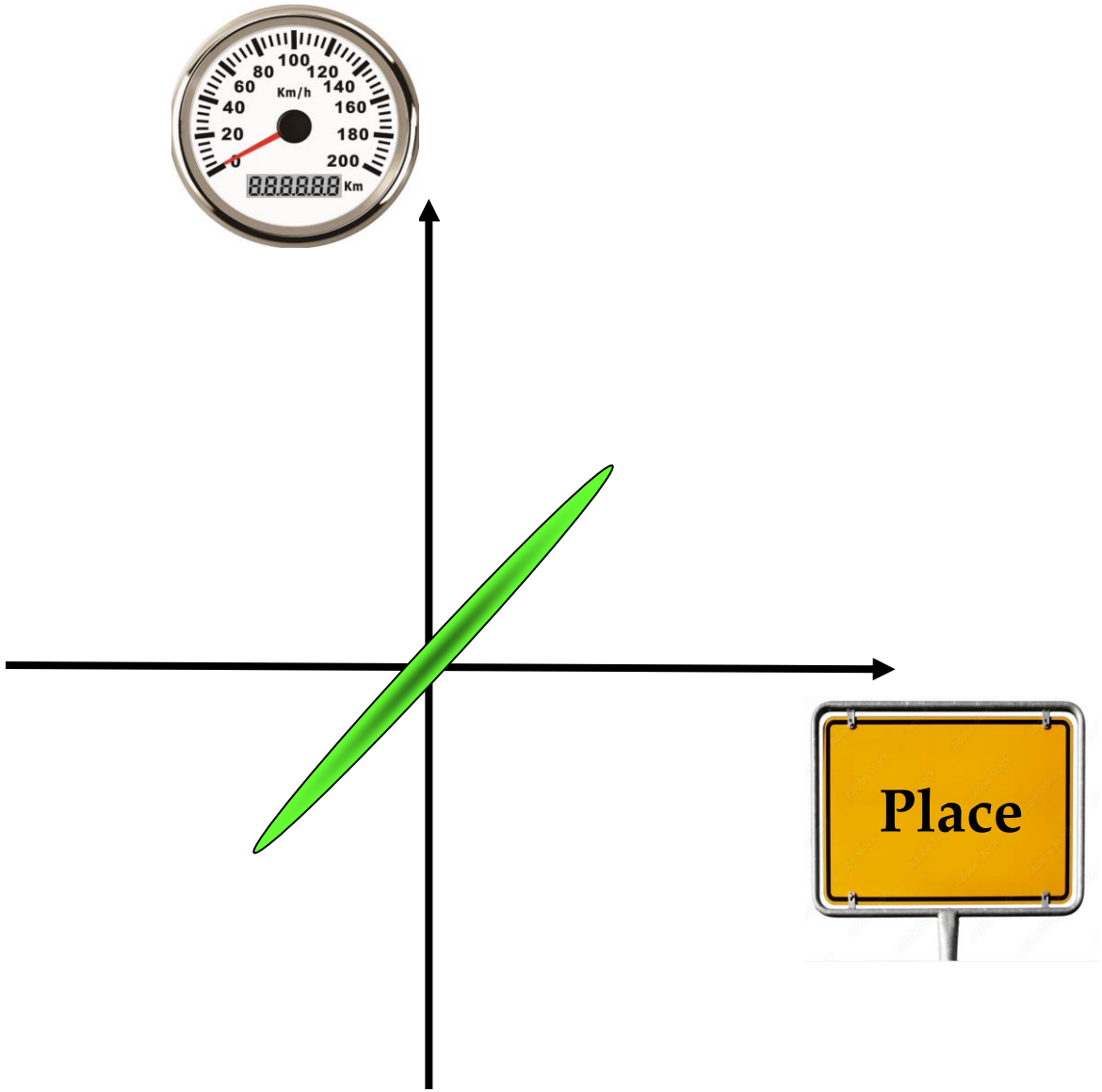
Squeezed States:



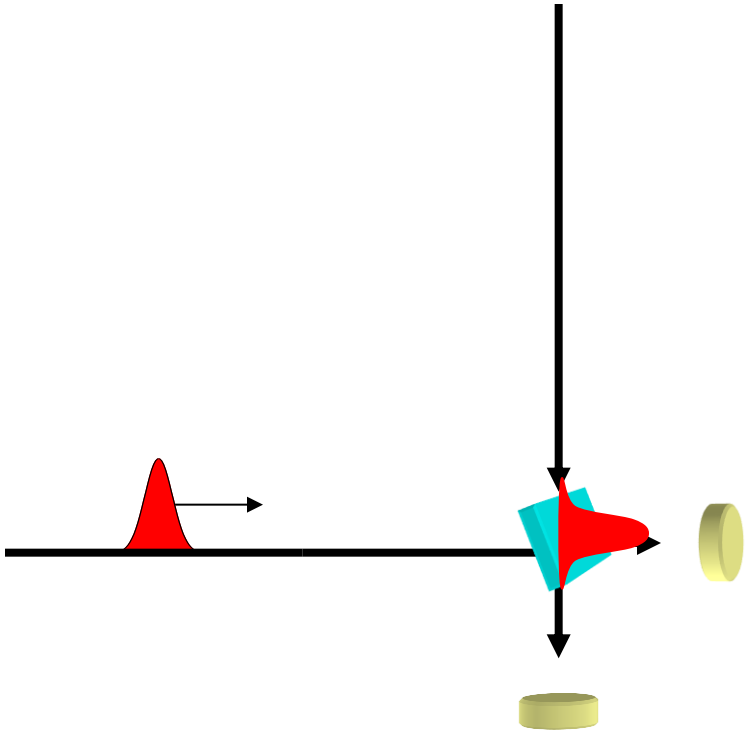
$$\hat{x} = e^{-r}\,\hat{x}^{(0)}\,, \quad \hat{p} = e^{+r}\,\hat{p}^{(0)}$$



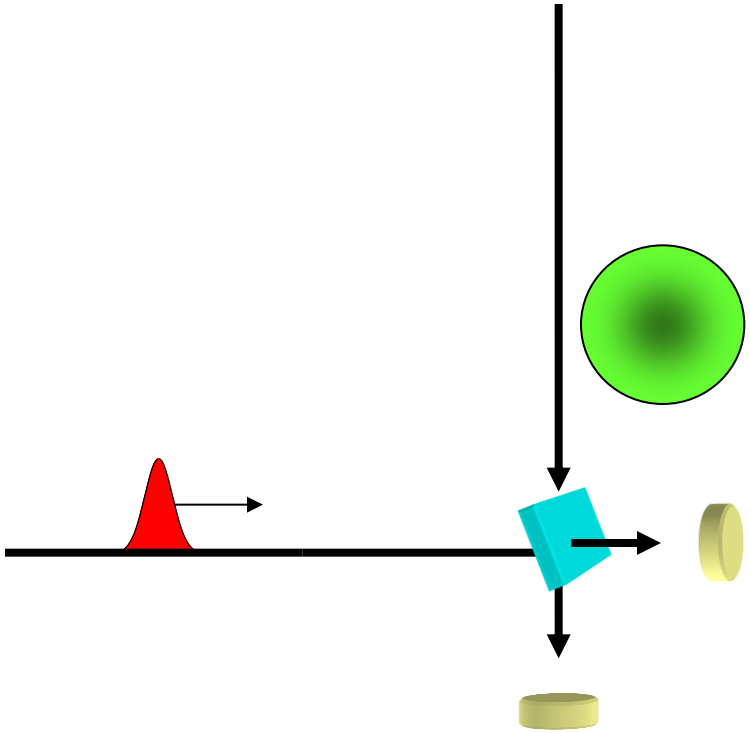
Squeezed Vacuum



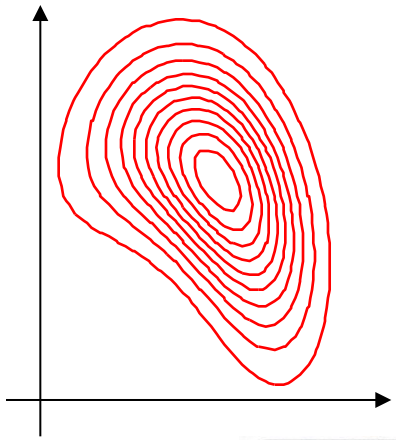
Quantum Beam Splitter

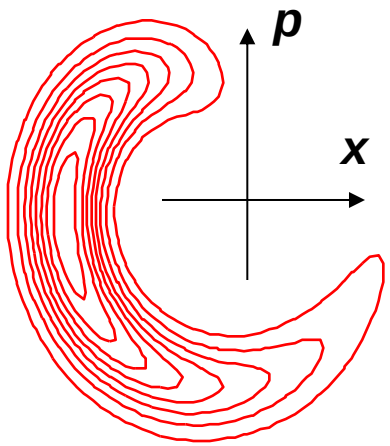


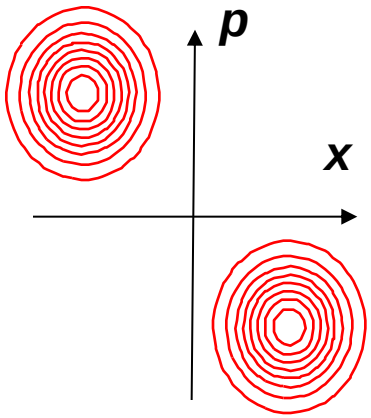
Quantum Beam Splitter: There's no Nothing



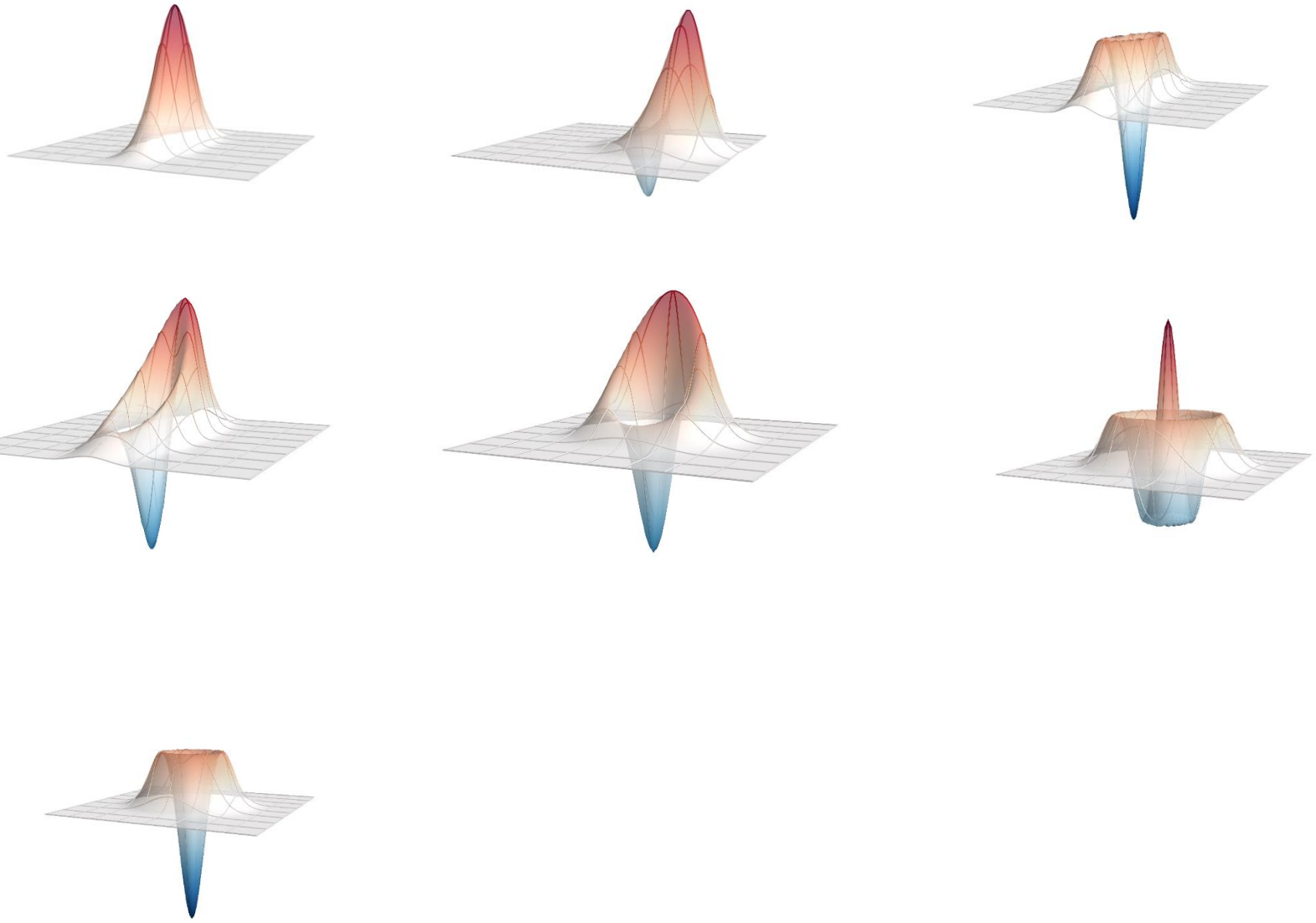
More Exotic/Non-Classical, Non-Gaussian



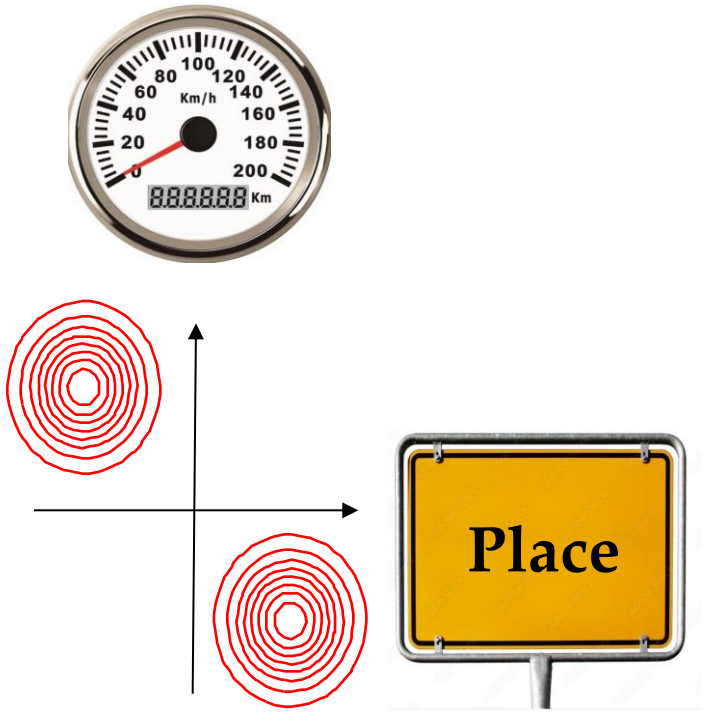




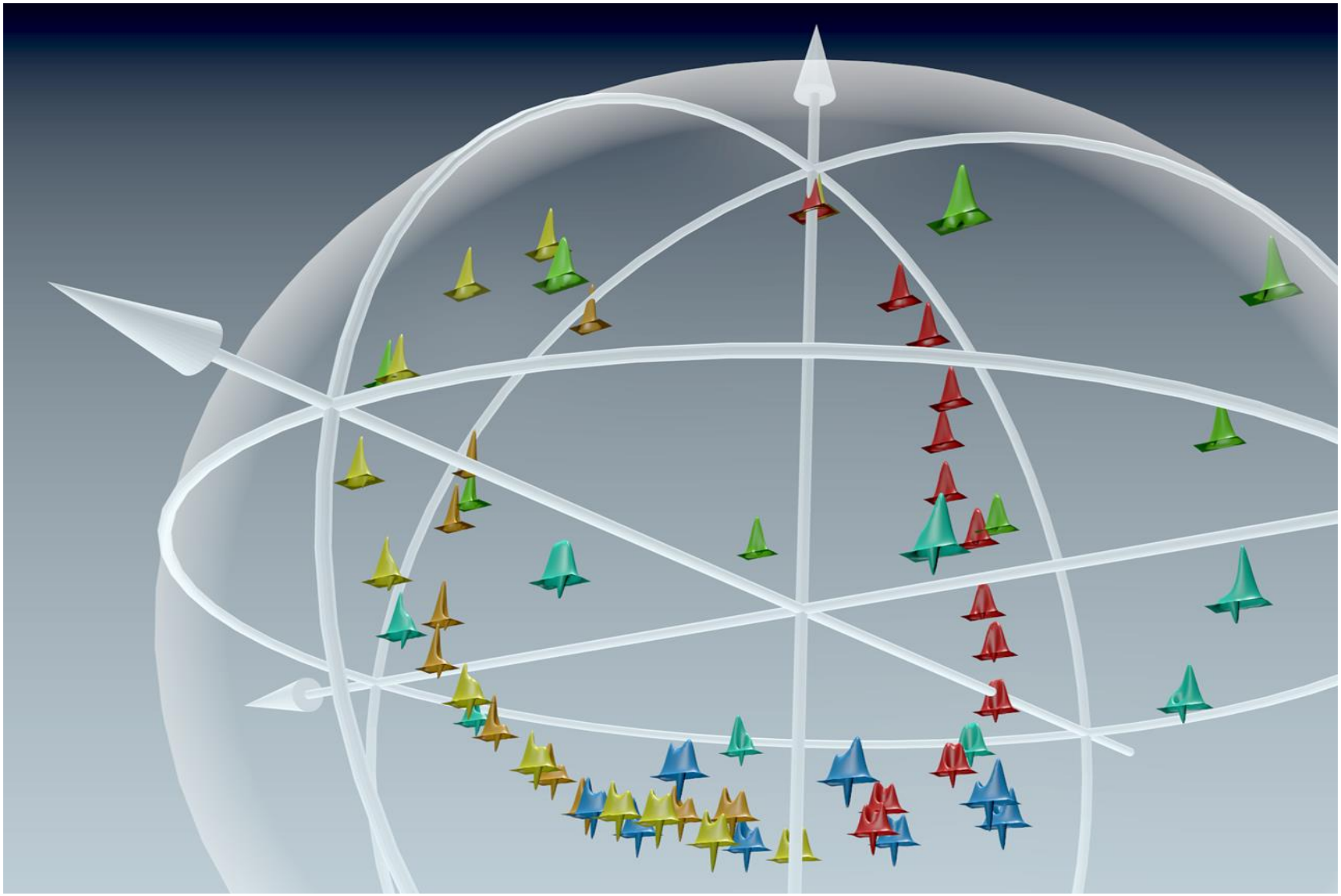
Non-Gaussian Quantum States,"Side View"



Schrödinger Cat State

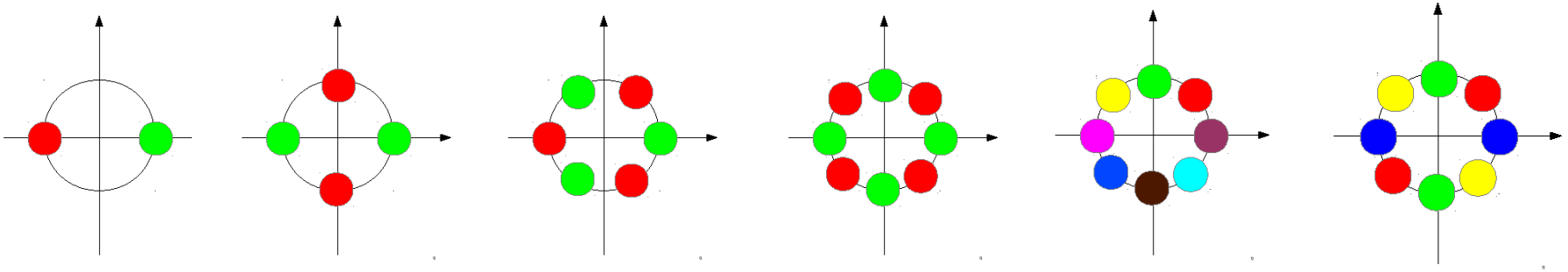


“Encoding a qubit in an oscillator”

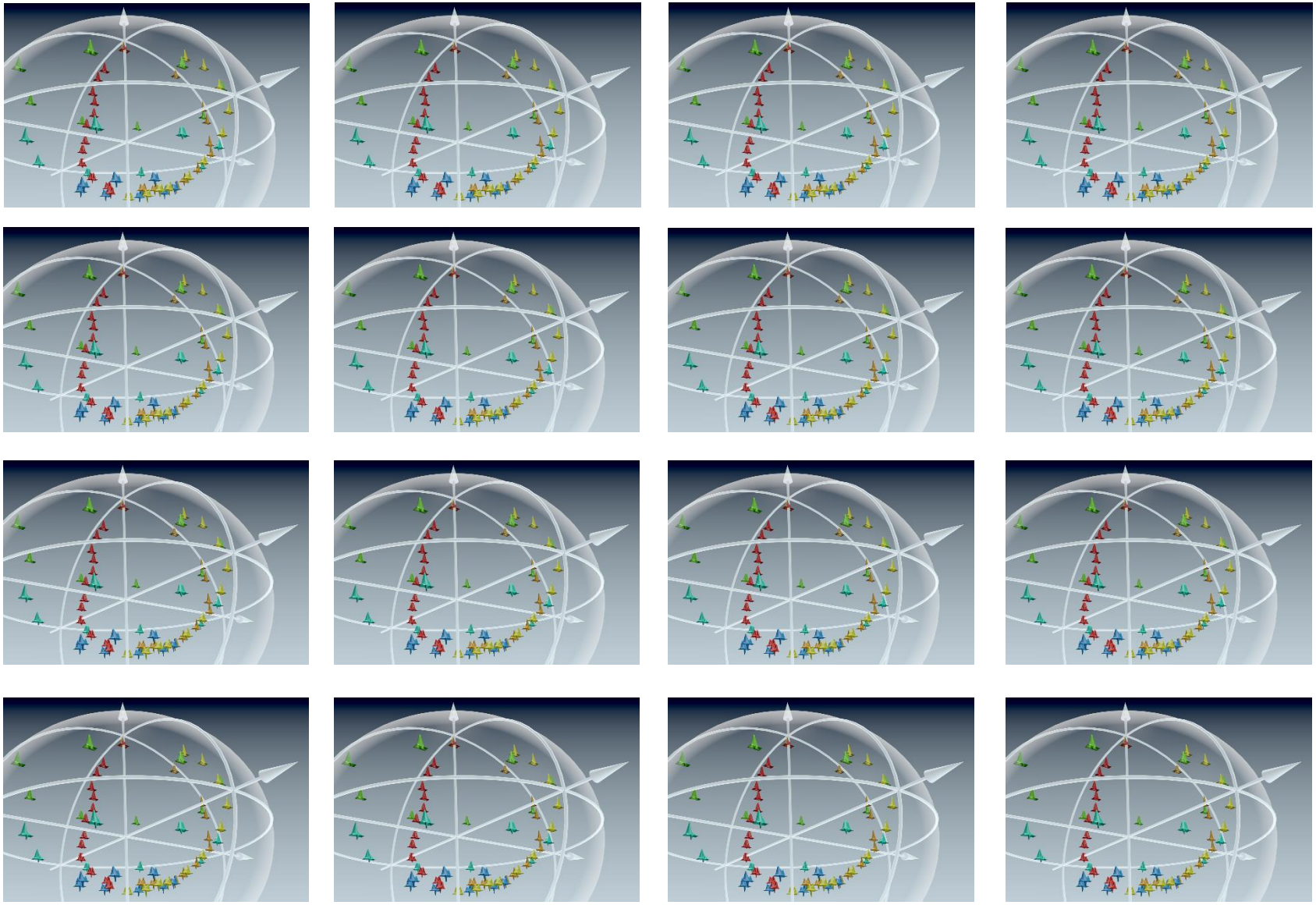


J. S. Neergaard-Nielsen *et al.*, PRL **105**, 053602 (2010)

“Cat Code”

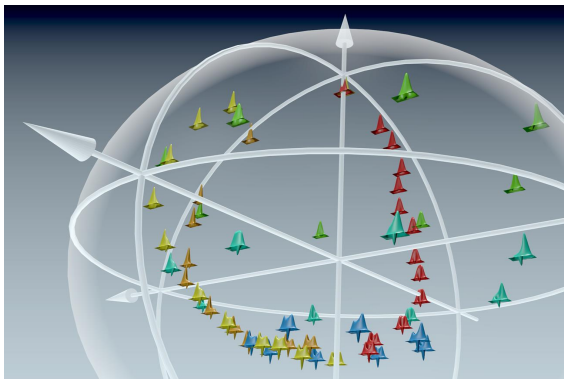
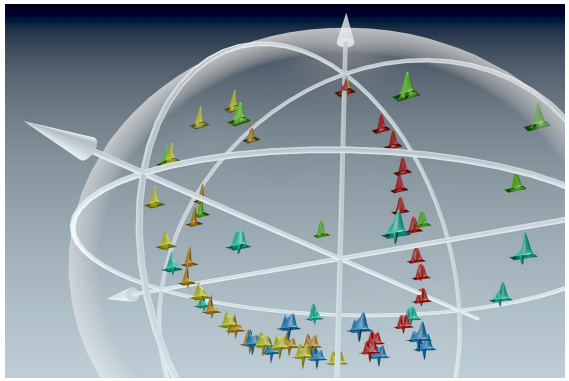
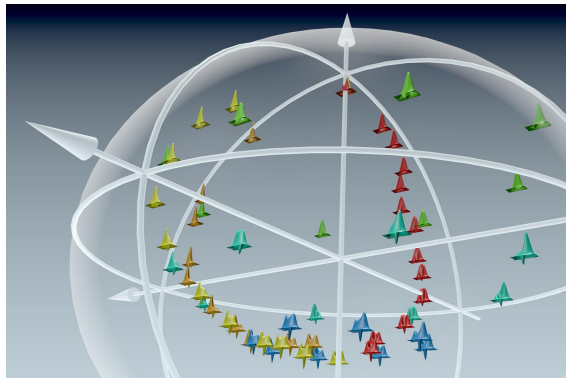


“Encoding many qubits in an oscillator”

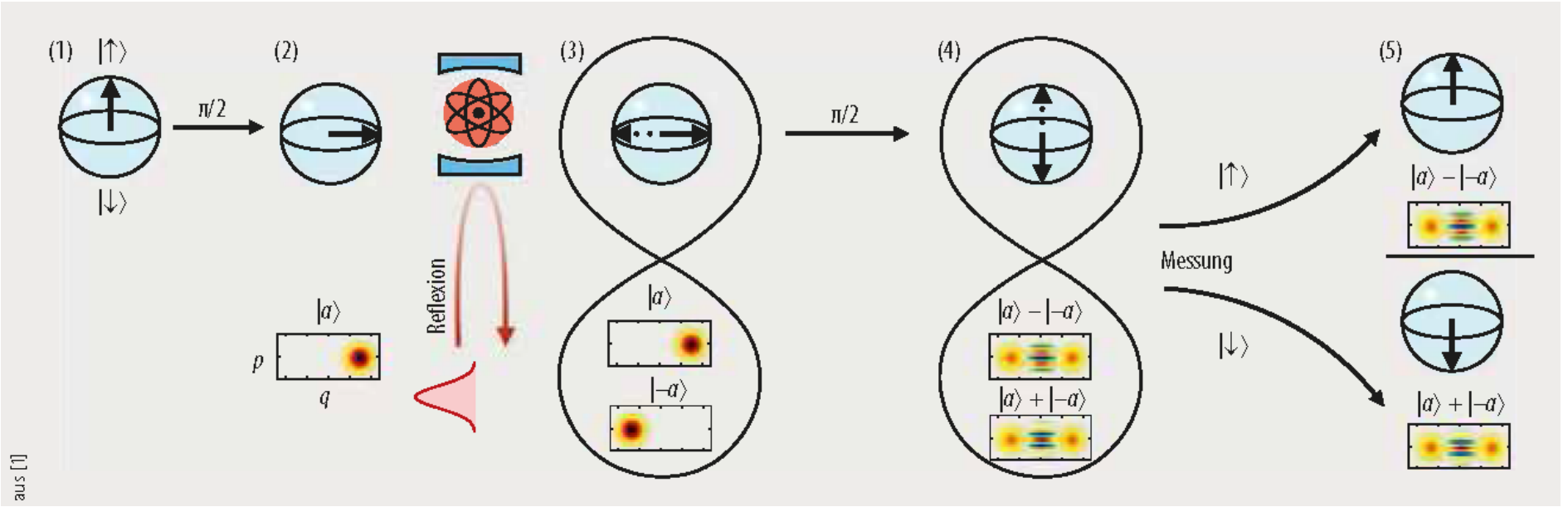


“Encoding many qubits in an oscillator”

Logical qubit
in a single
LASER light pulse !!!

Schrödinger Cat State with CQED



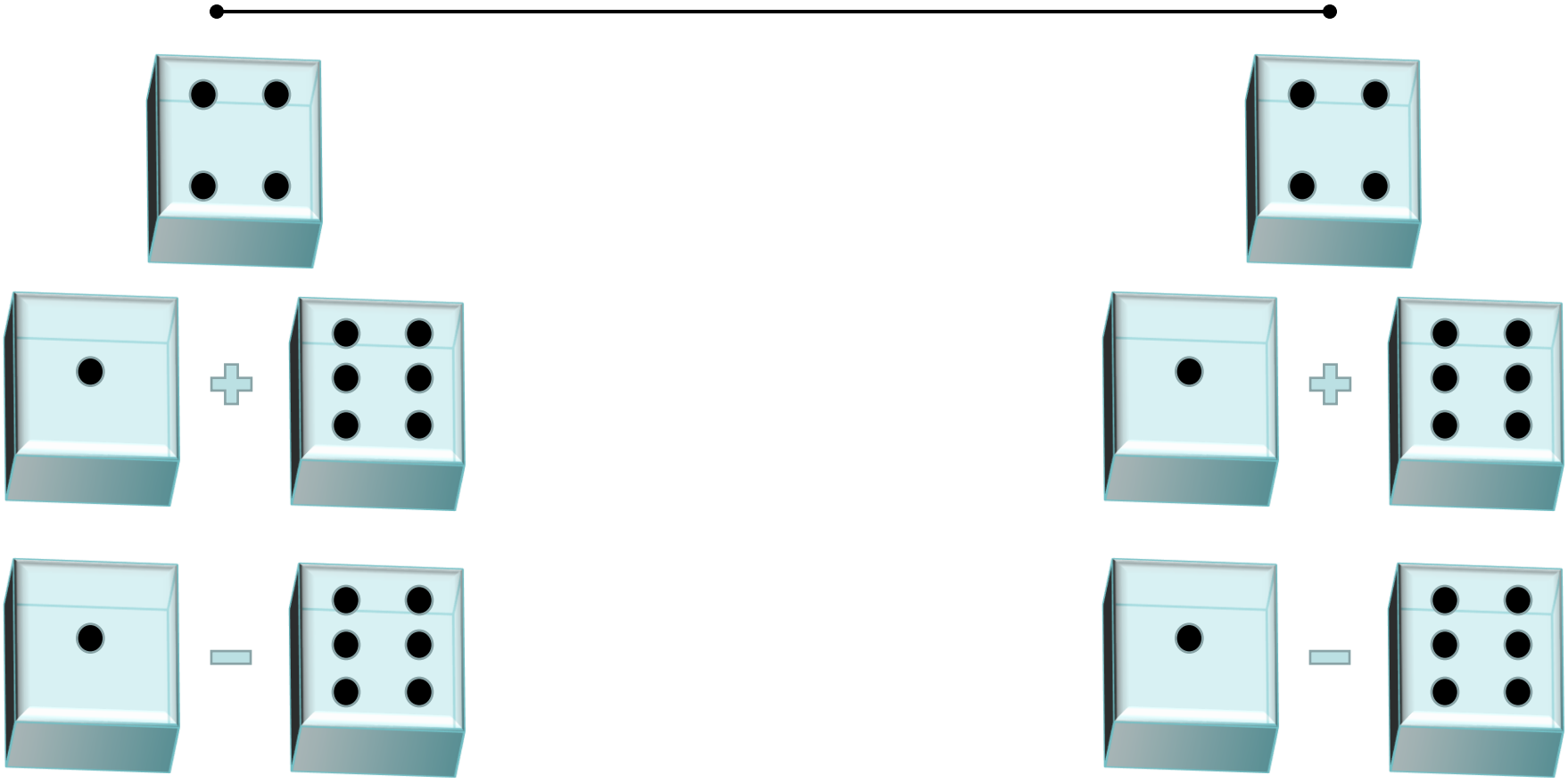
G. Rempe-Group, MPQ, Nat. Photon. (2019)

$$(|\uparrow\rangle|+\alpha\rangle + |\downarrow\rangle|-\alpha\rangle)/\sqrt{2} =$$
$$[(|\uparrow\rangle + |\downarrow\rangle)\,(|+\alpha\rangle + |-\alpha\rangle) +$$
$$(|\uparrow\rangle - |\downarrow\rangle)\,(|+\alpha\rangle - |-\alpha\rangle)]/2\sqrt{2}$$

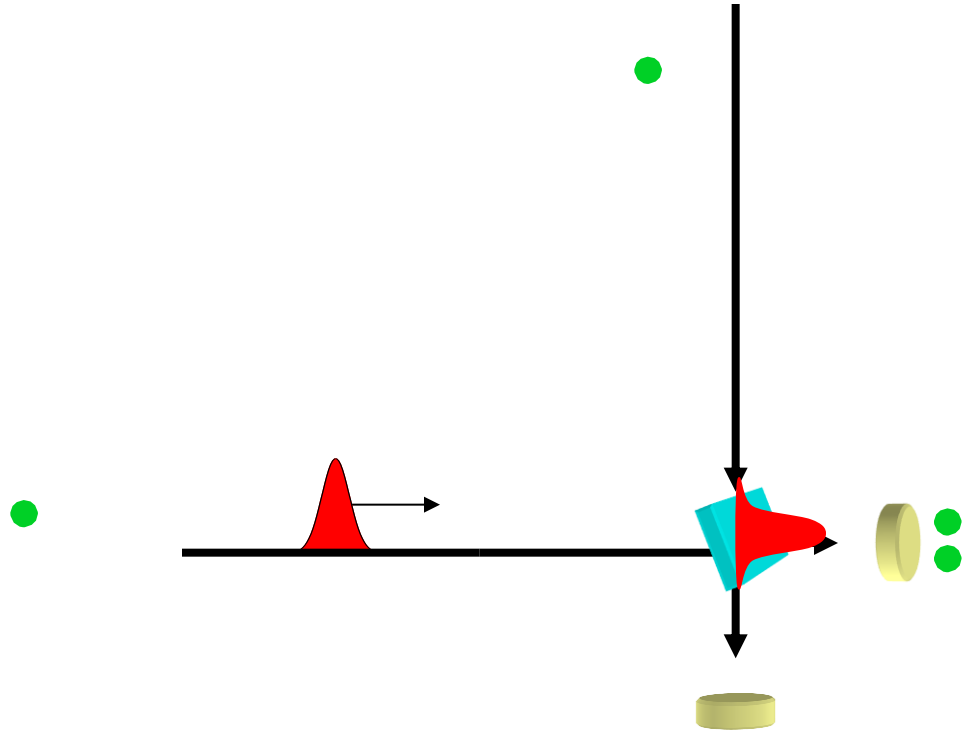
Quantum Entanglement

Classical Correlations

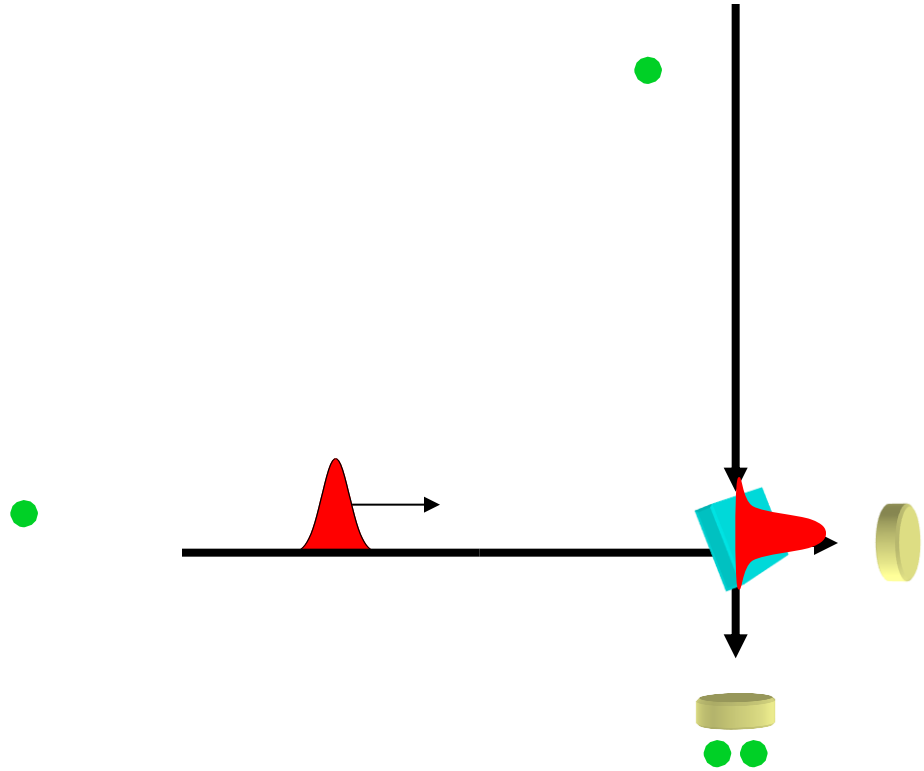
Quantum Correlations, Entanglement



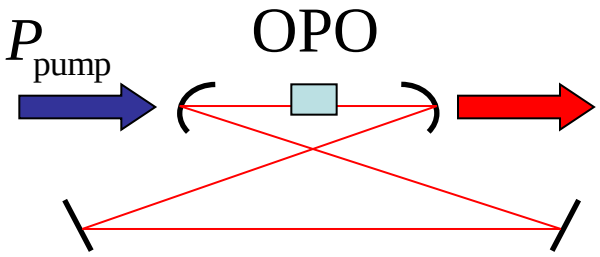
Beam Splitter: Hong-Ou-Mandel Effect

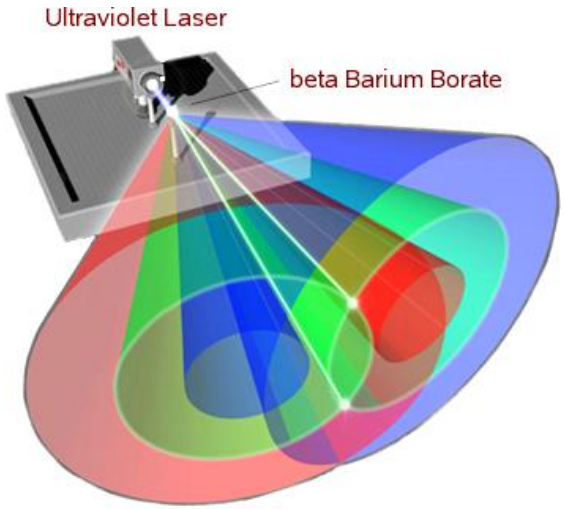


Beam Splitter: Hong-Ou-Mandel Effect

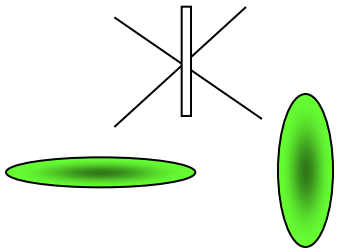


Photon Entanglement via Nonlinear Optics





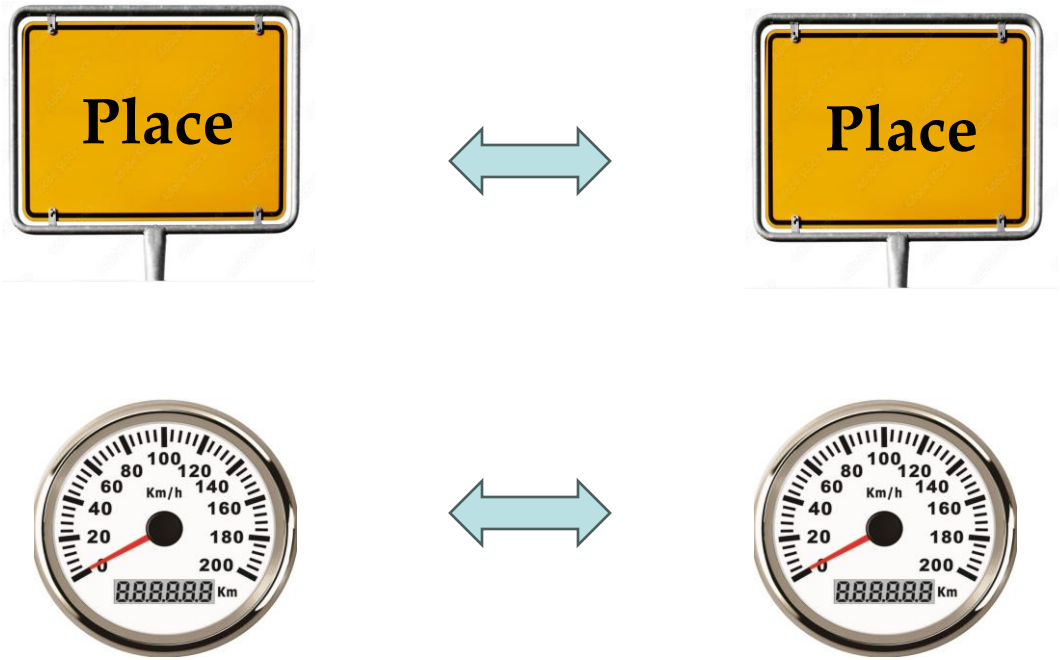
Two-Mode Squeezed State, Entanglement



$$\hat{a}_1' = \left(\hat{a}_1 + \hat{a}_2\right)/\sqrt{2}$$

$$\hat{a}_2' = \left(\hat{a}_1 - \hat{a}_2\right)/\sqrt{2}$$

Entanglement of Two Laser Light Pulses



Entanglement: ``EPR'', Schrödinger and Bell

Entanglement

$$\int dx \left| x, x-c \right\rangle$$

Continuous Variables

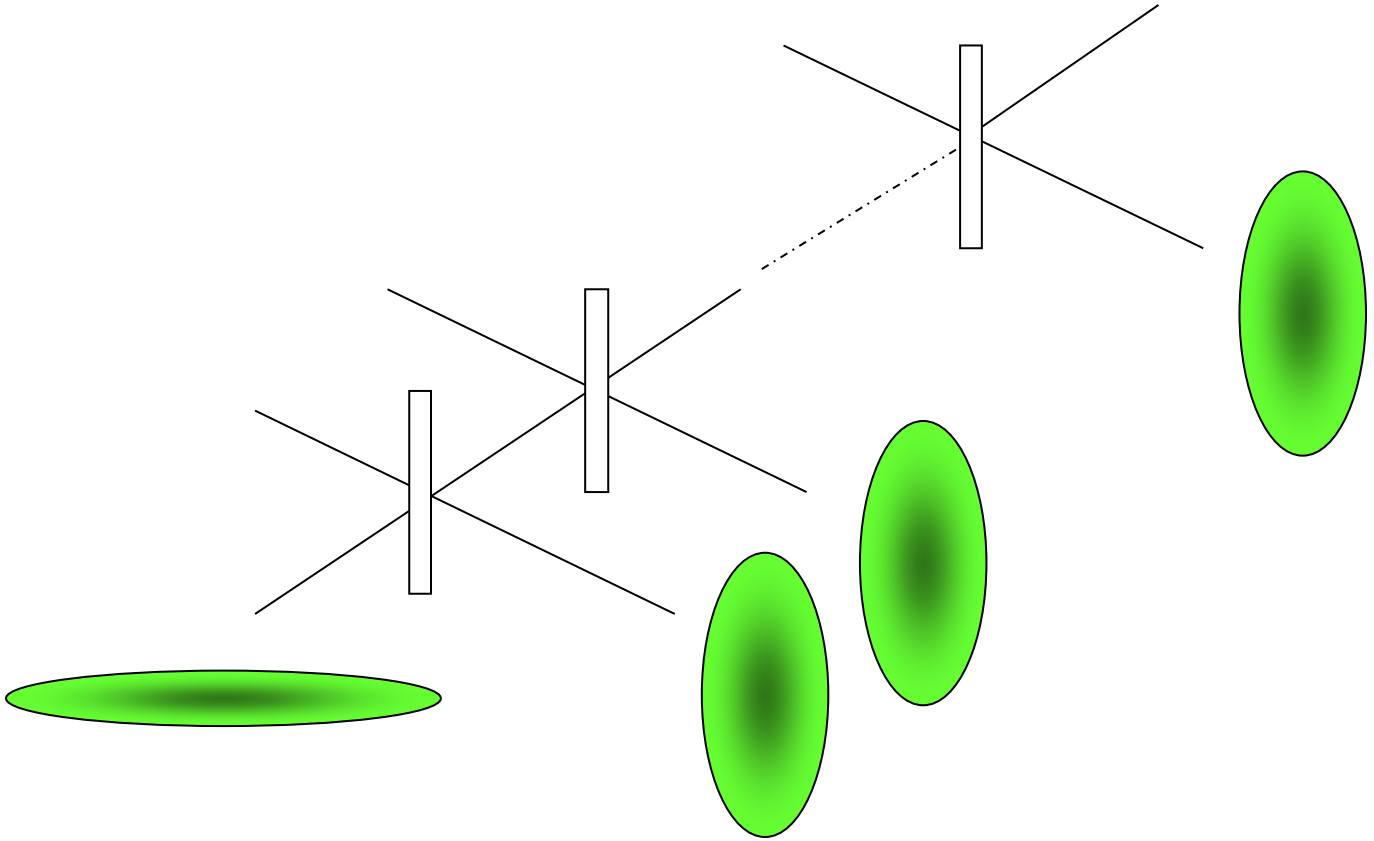
$$\left| \Psi^{+} \right\rangle = \left(\left| 01 \right\rangle + \left| 10 \right\rangle \right) / \sqrt{2}$$

Discrete Variables

Einstein, **P**odolsky, and **R**osen (1935)...

... non-locality, non-realism, or hidden variables... QM incomplete

Entanglement of Many Light Pulses




Use Laserlight, Photonic Qubits,
Entangled Photon Pairs

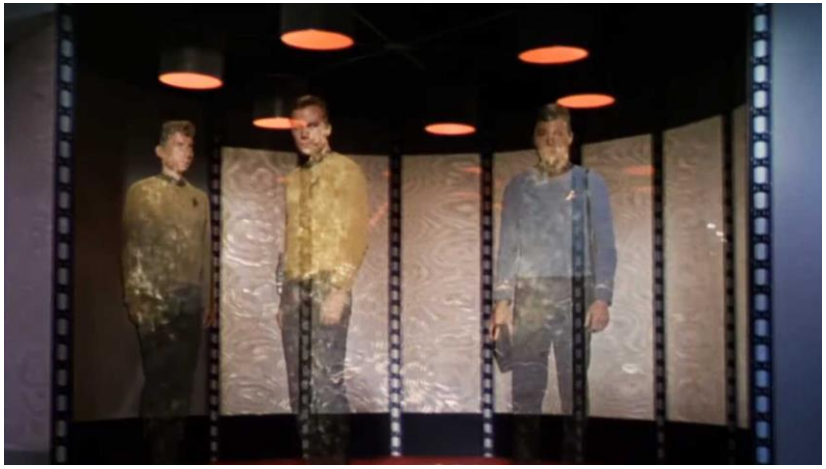
Quantum Communication

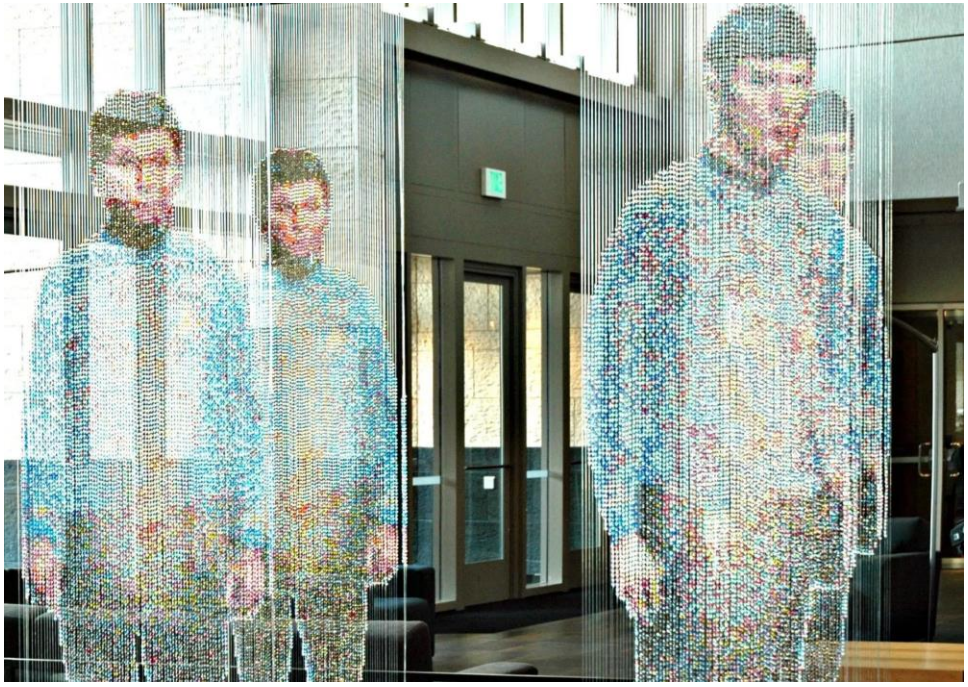
Quantum Communication

Reliable Transmission
of Quantum Information…
(Quantum **Teleportation**)

Secure Transmission
of Classical Information…
(Quantum **Cryptography**)

Teleportation





PHYSICAL REVIEW
LETTERS

(top, left) Richard Jozsa, William K. Wootters, Charles H. Bennett. (bottom, left) Gilles Brassard, Claude Crépeau, Asher Peres. Photo: André Berthiaume.

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Teleporting an Unknown Quantum State via Dual Classical and Einstein-Podolsky-Rosen Channels

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Richard Jozsa,[2] Asher Peres,[4] and William K. Wootters[5]

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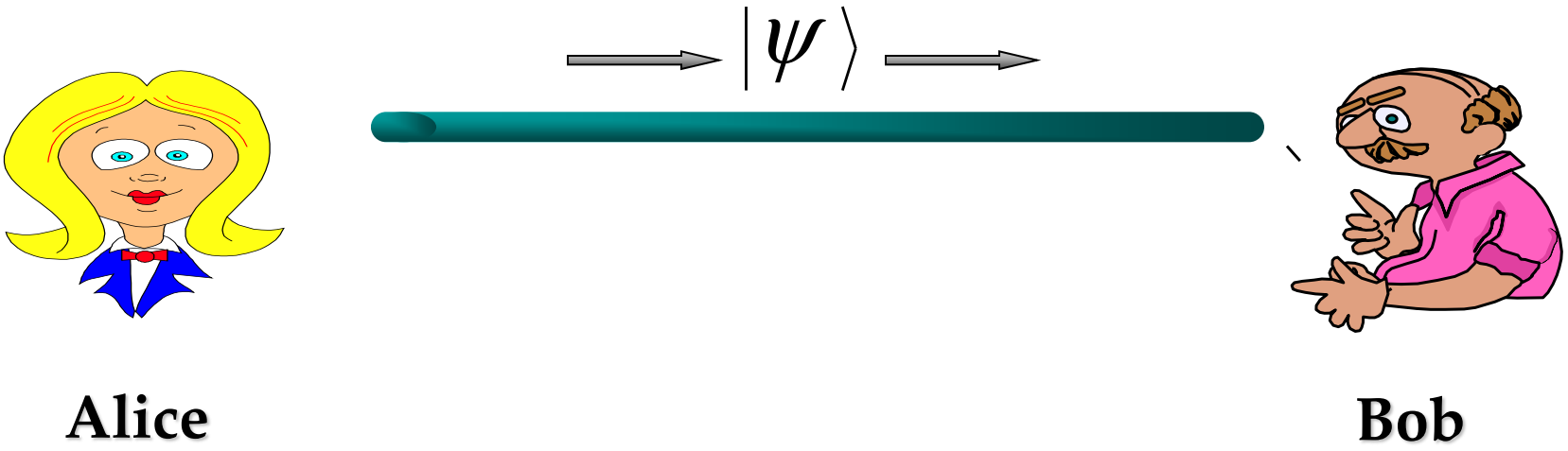
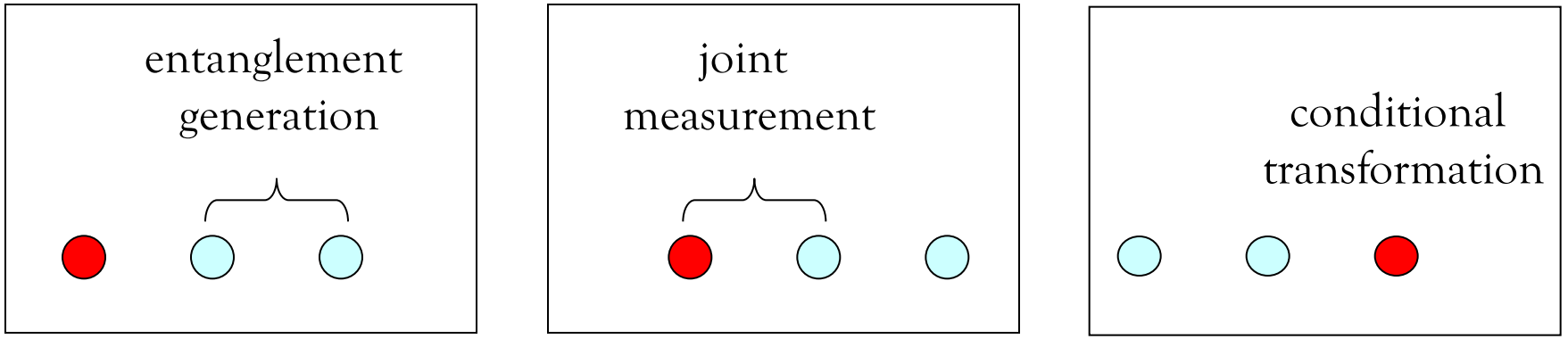
An unknown quantum state $|\phi\rangle$ can be disassembled into, then later reconstructed from, purely classical information and purely nonclassical Einstein-Podolsky-Rosen (EPR) correlations. To do so the sender, "Alice," and the receiver, "Bob," must prearrange the sharing of an EPR-correlated pair of particles. Alice makes a joint measurement on her EPR particle and the unknown quantum system, and sends Bob the classical result of this measurement. Knowing this, Bob can convert the state of his EPR particle into an exact replica of the unknown state $|\phi\rangle$ which Alice destroyed.

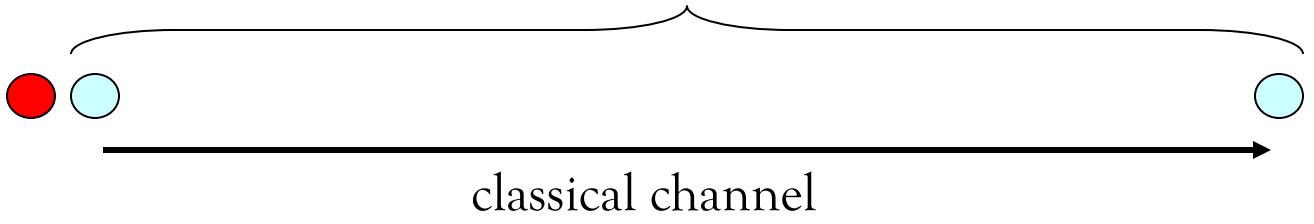
PACS numbers: 03.65.Bz, 42.50.Dv, 89.70.+c

Quantum Teleportation

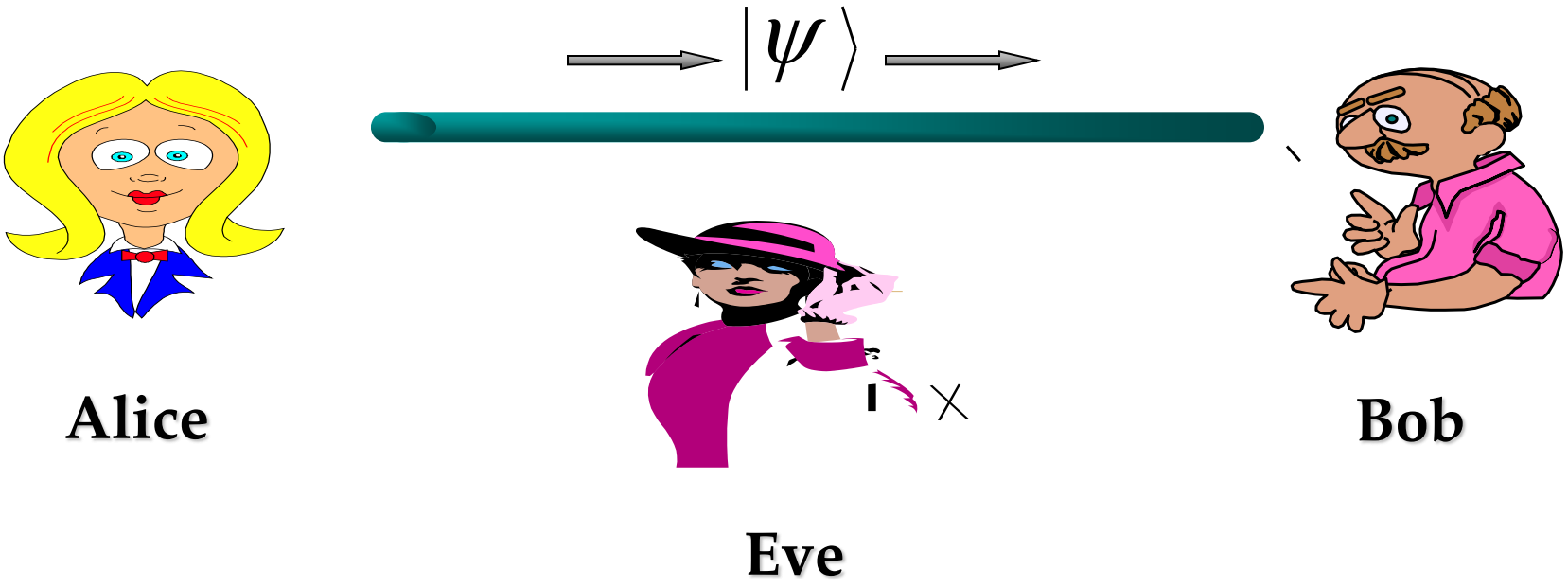


Quantum Teleportation

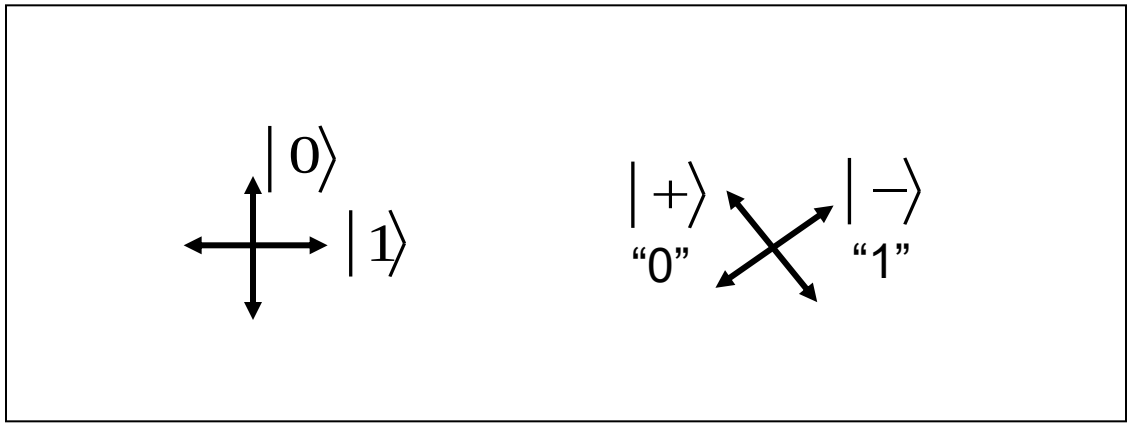




Quantum Key Distribution

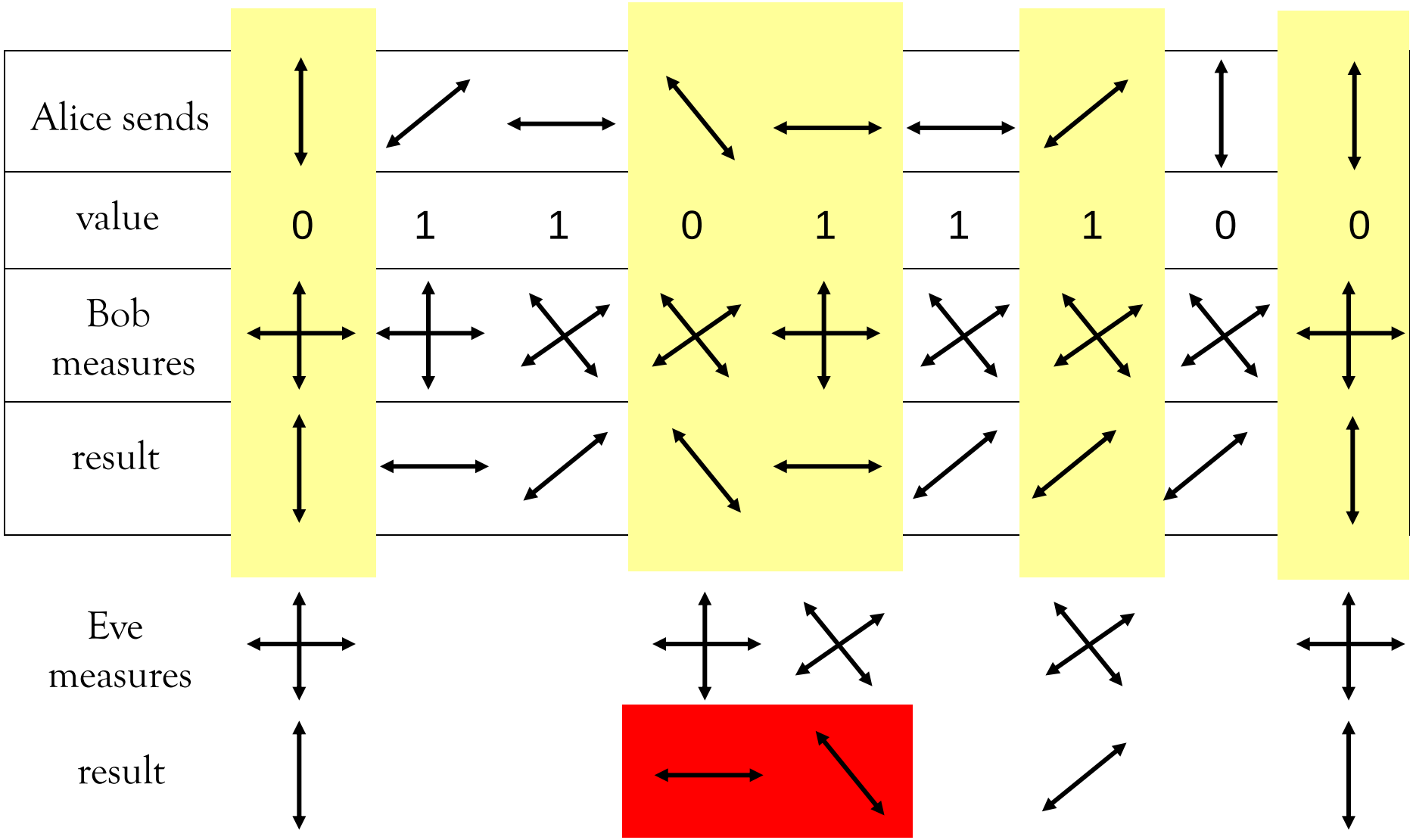


Quantum Key Distribution

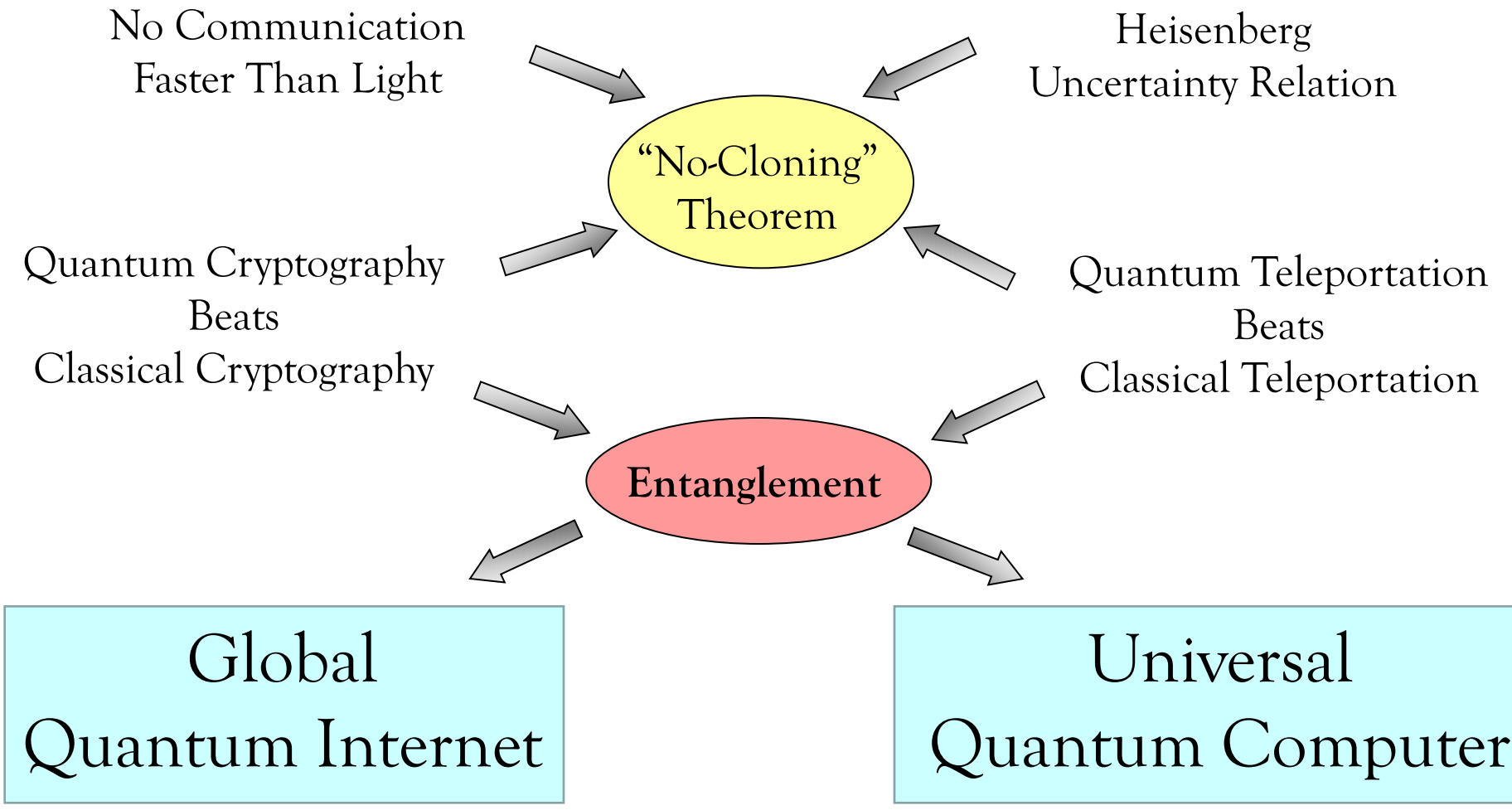


$$|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$$

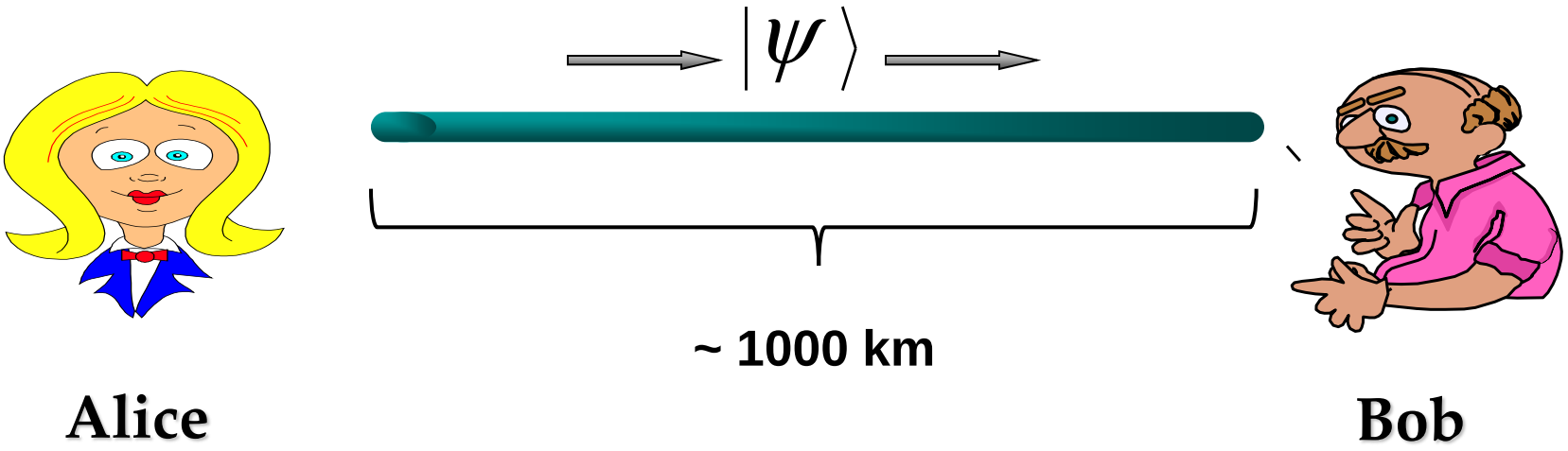
Quantum Key Distribution



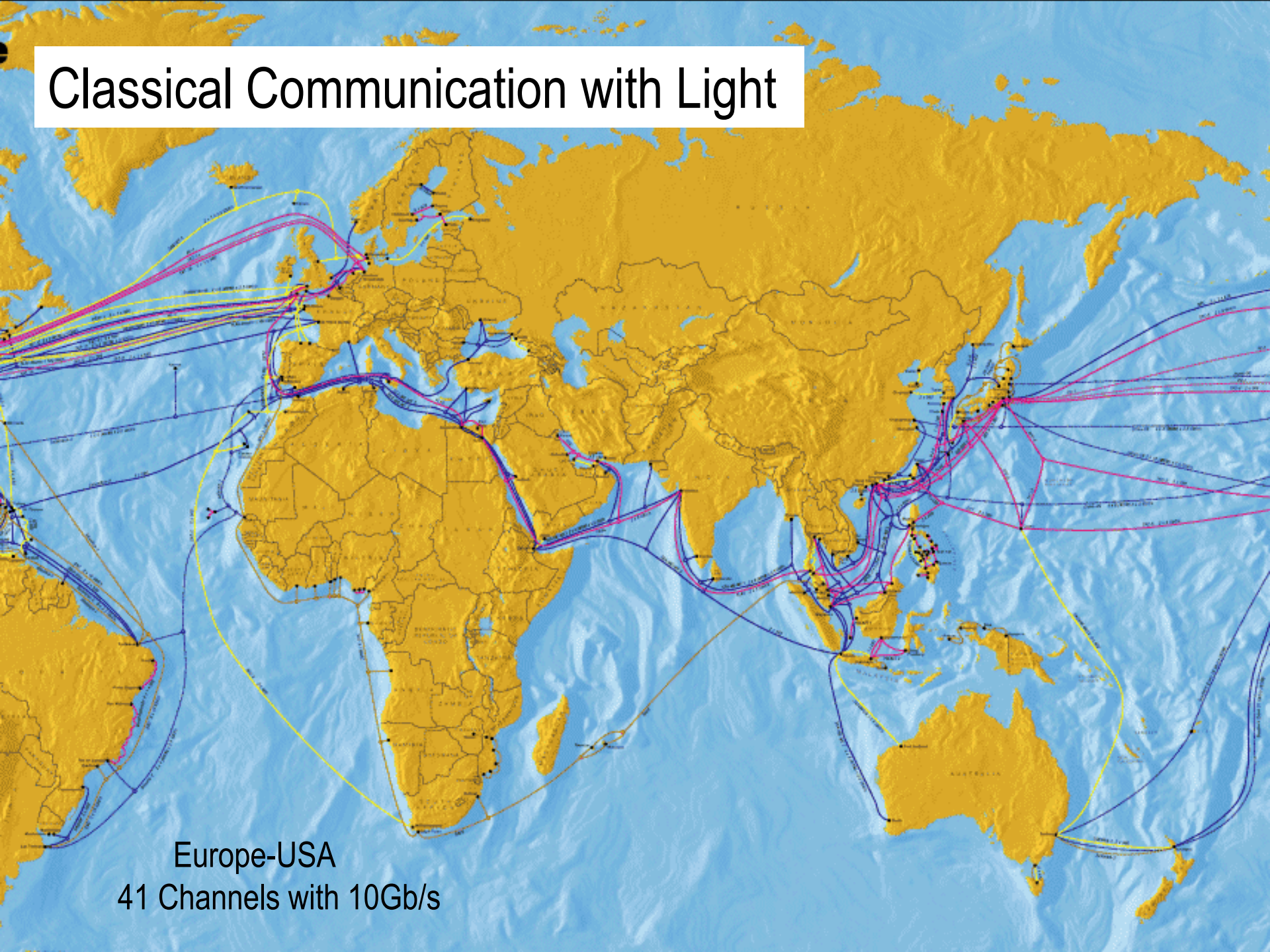
Quantum Information, Technology



Quantum Communication: Large Distances



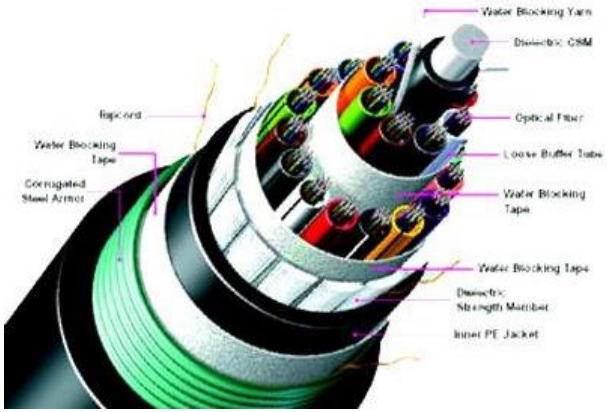
Classical Communication with Light

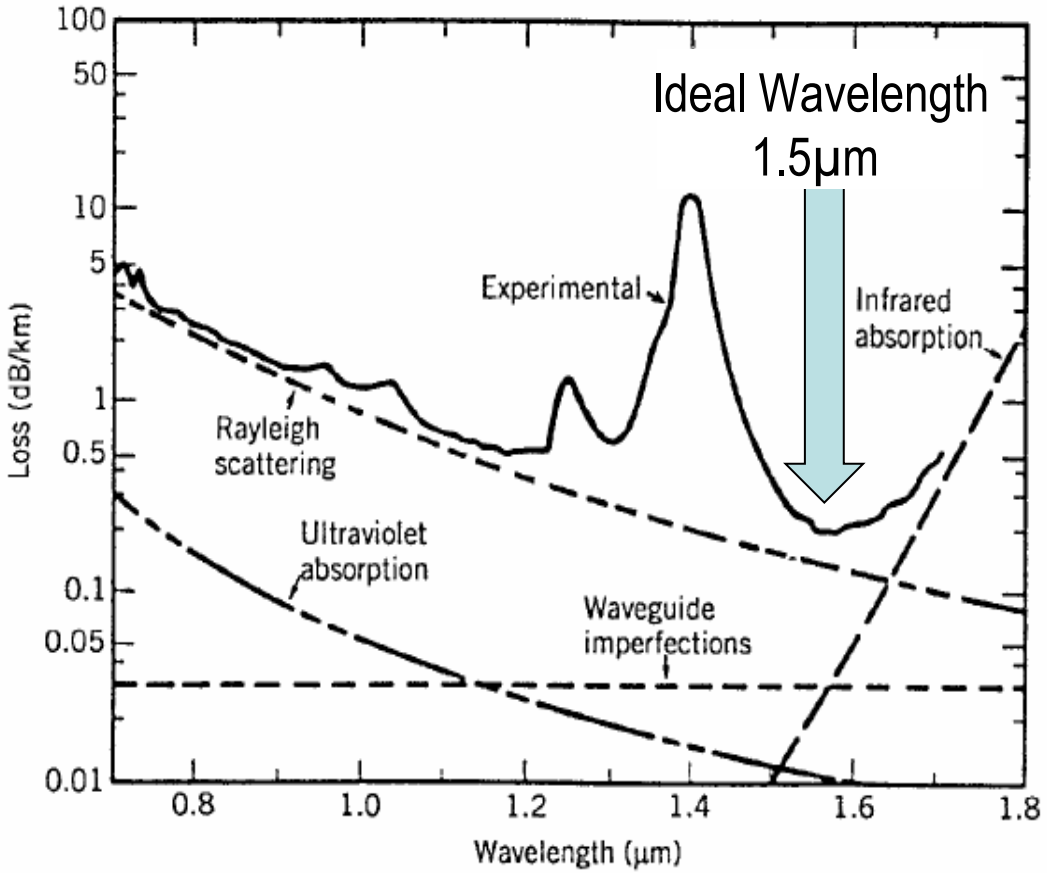


Europe-USA
41 Channels with 10Gb/s

Optical Fiber Technology

- single-mode propagation
- 0.2dB/km attenuation



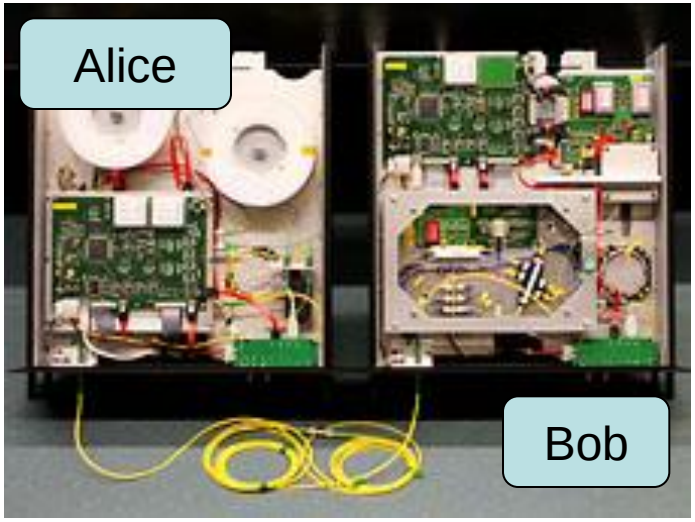


repeater stations for optical pulse recovery:

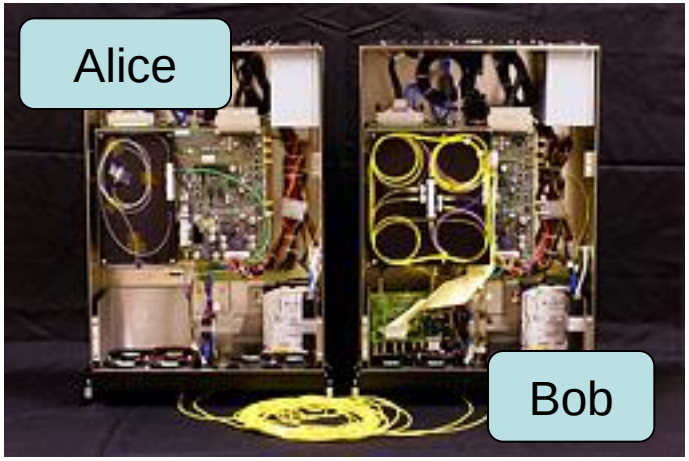
- light amplification
- compression of spreading wave packets

1mW @ 1.5μm corresponds to $7 \cdot 10^6$ photons per 0.1ns pulse
plus in- and out-coupling losses:
transmission through 300km fiber ~100 photons

Point-To-Point QKD Systems



http://www.idquantique.com



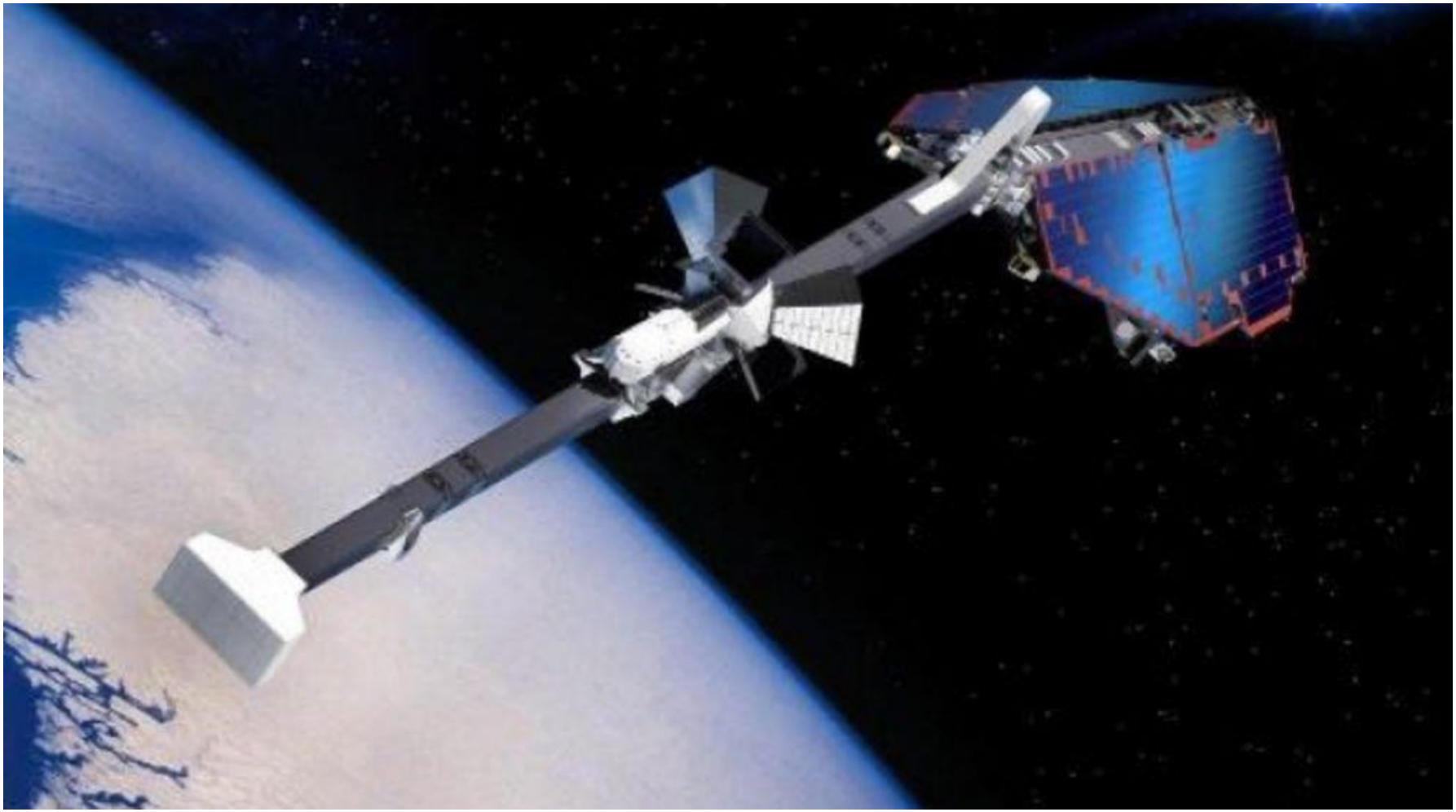
http://www.magiqtech.com

<u>Problem:</u>

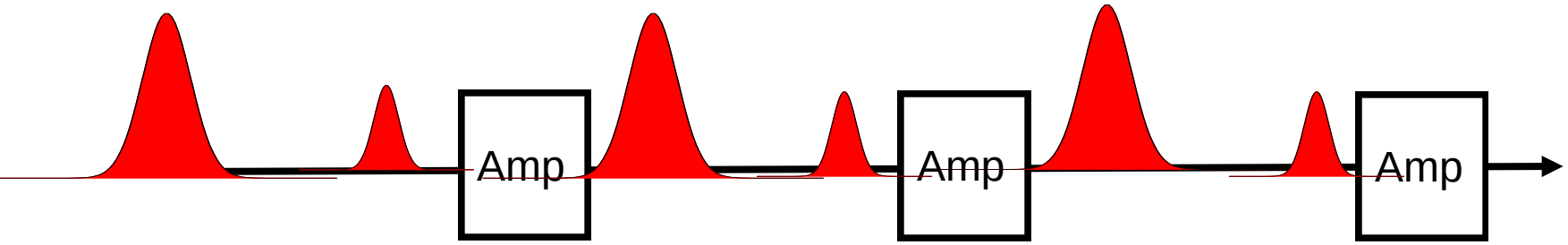
Probability to lose a photon grows exponentially in an optical fiber channel!

GHz Source, 1000km: 0.00000000002 Hz

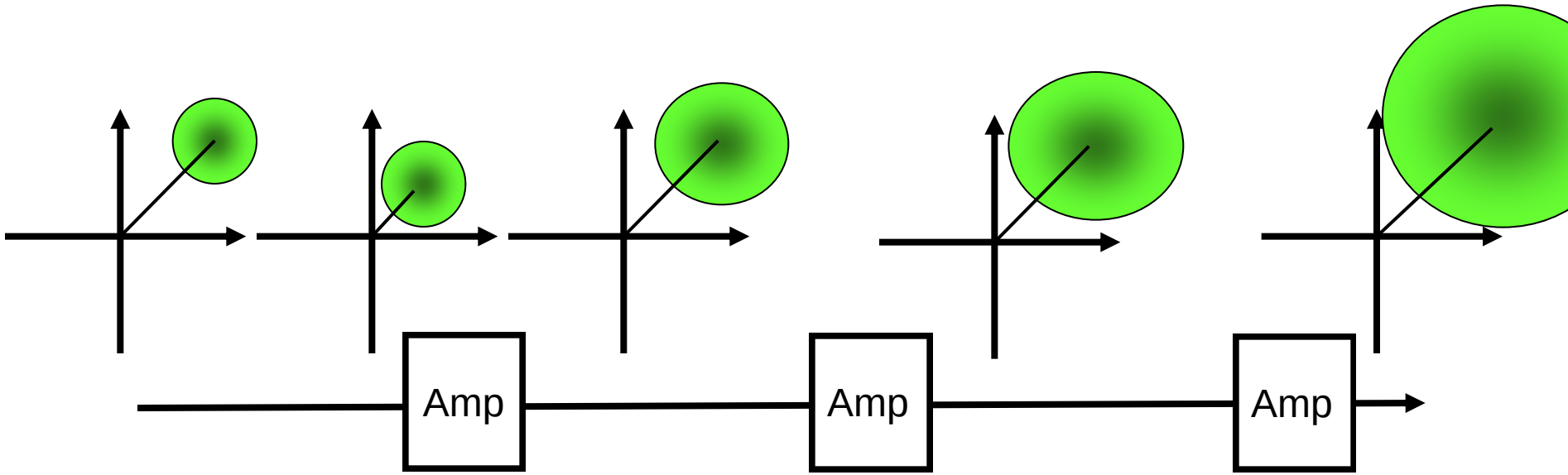
Quantum Space Satellite (QUESS)



Classical Repeater via Optical Amplifier

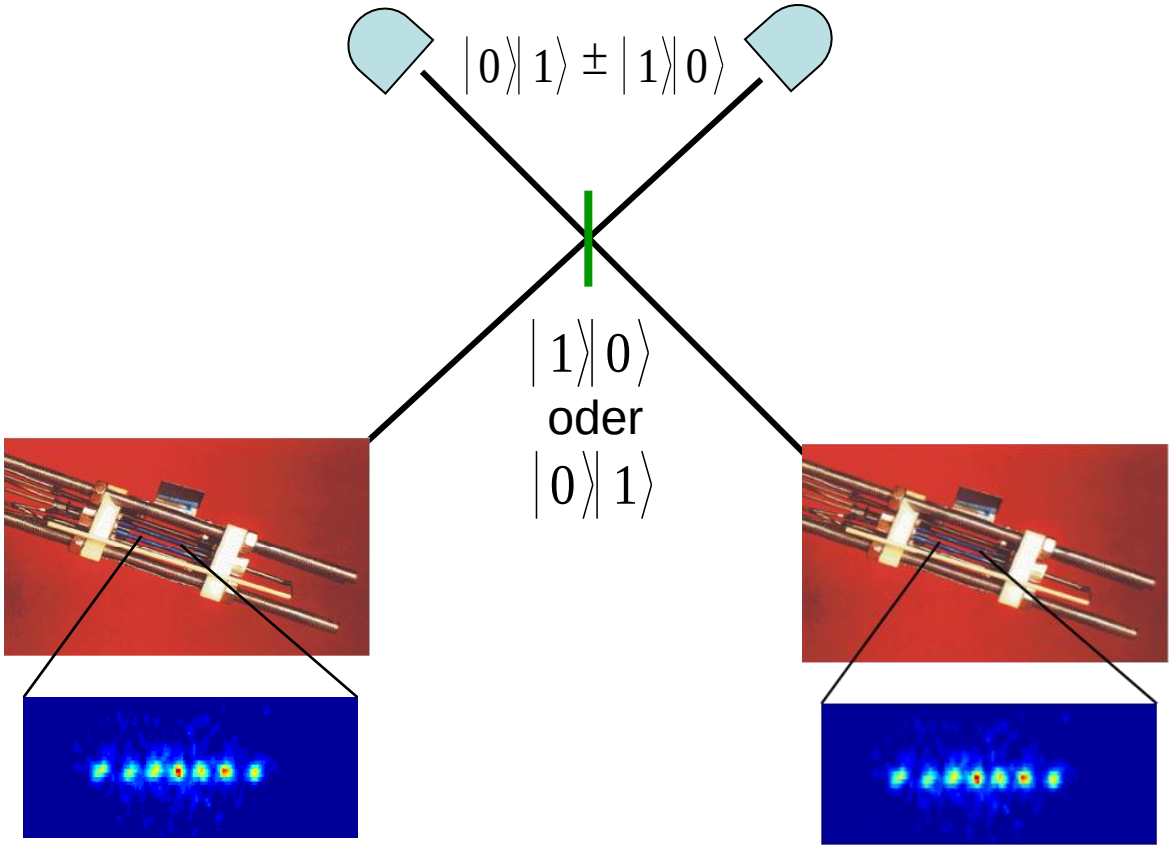


Quantum Repeater via Optical Amplifier



Quantum Repeater

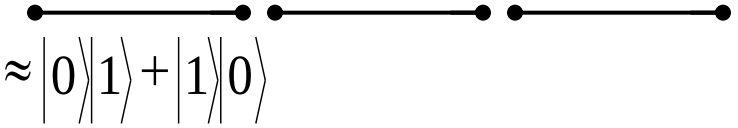
Qubit Entanglement with Ions



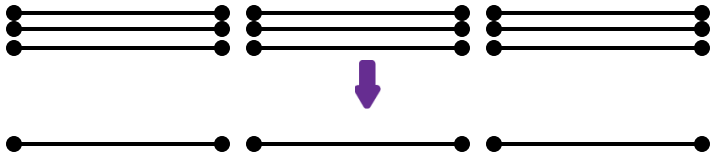
$$\left|\Psi^{\pm}\right\rangle = \left(|01\rangle \pm |10\rangle\right)/\sqrt{2}$$

Quantum Repeater

- ✓ Entanglement Distribution



- ✓ Entanglement Purification

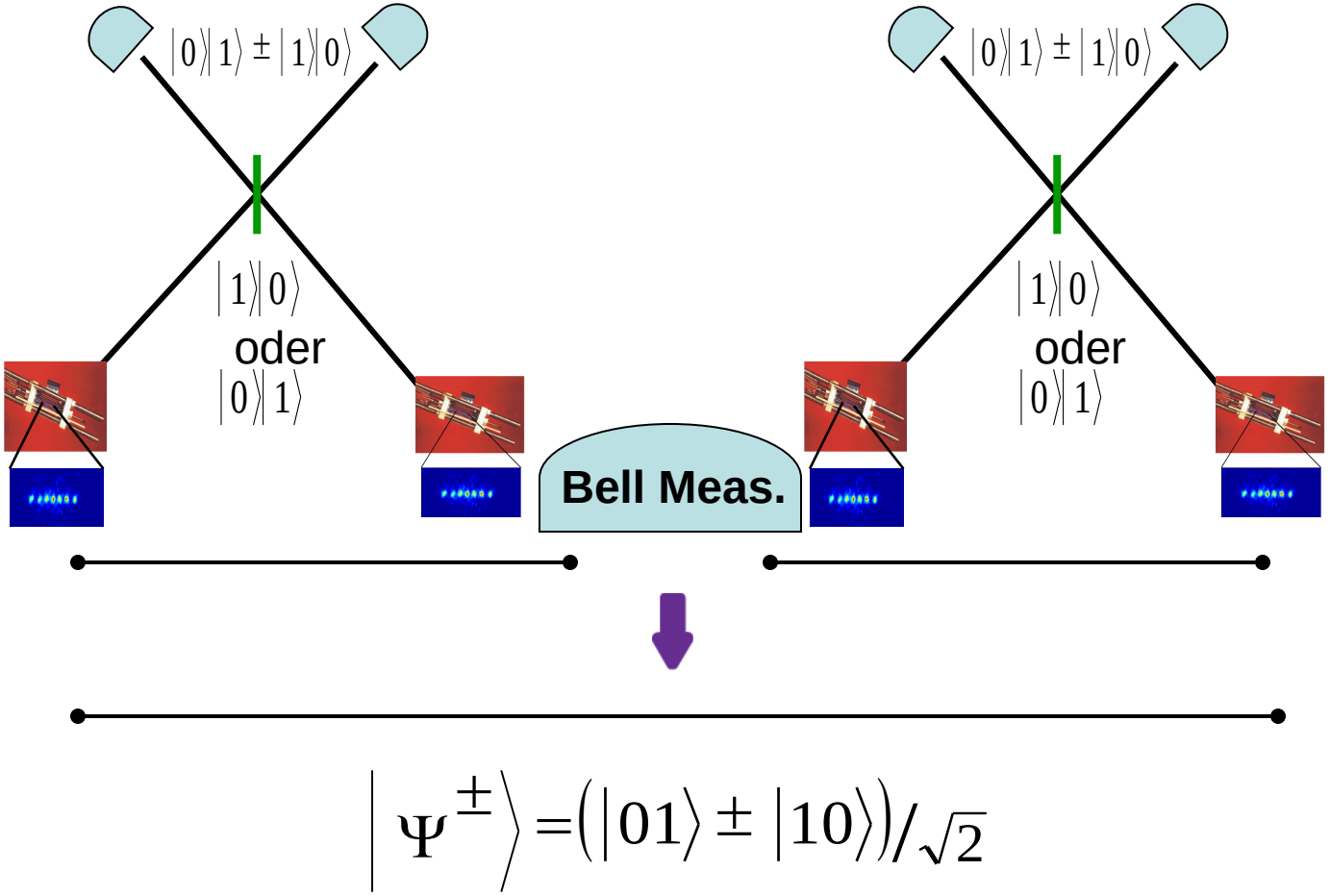


- ✓ Entanglement Swapping

- ✓ Quantum Memories

H.J. Briegel *et al.*, PRL 81, 5932 (1998)

Entanglement Swapping



$$\left|\Psi^{\pm}\right\rangle = \left(|01\rangle \pm |10\rangle\right)/\sqrt{2}$$

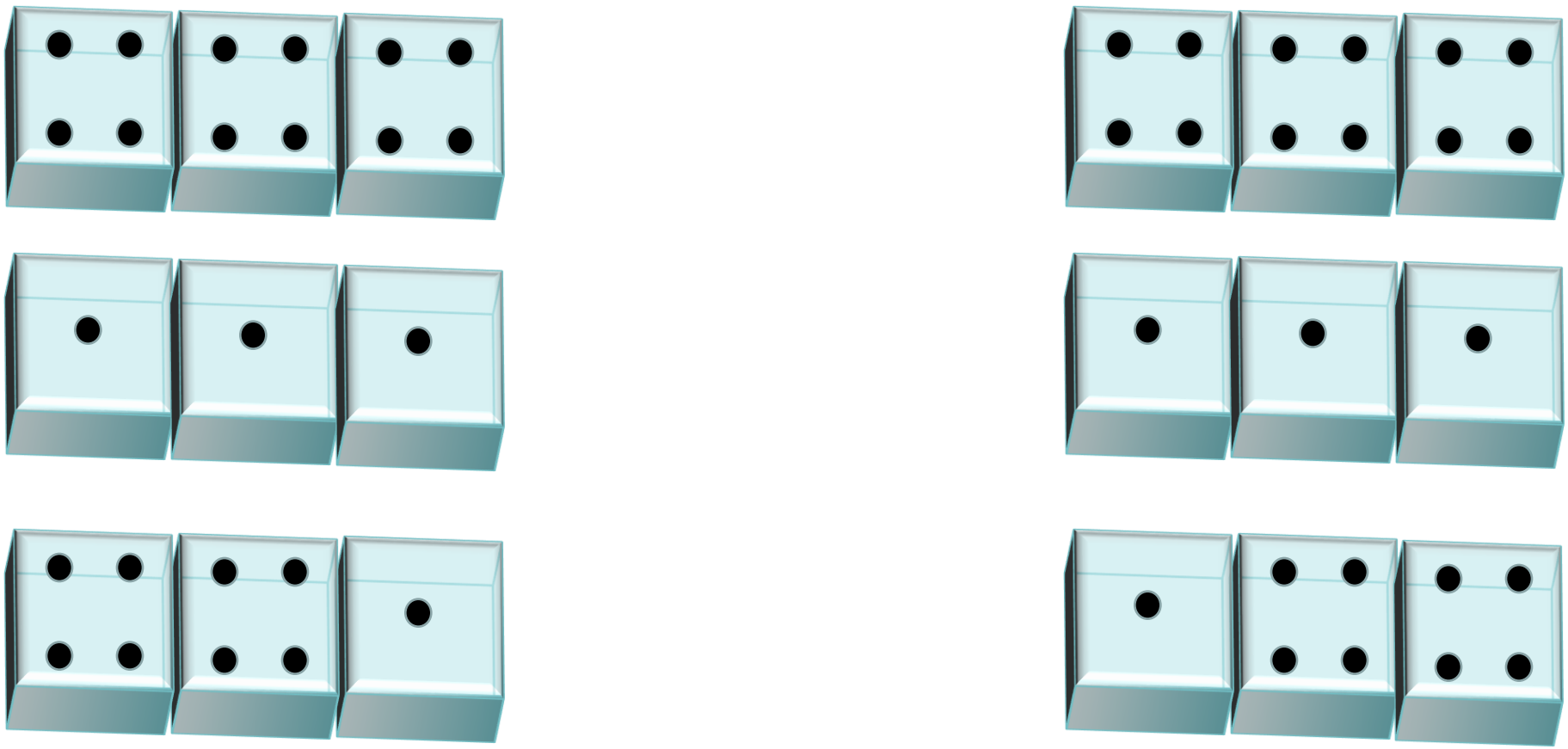
Shor's Quantum Error Corection Code

$$\alpha\left|+++\right\rangle+\beta\left|---\right\rangle$$

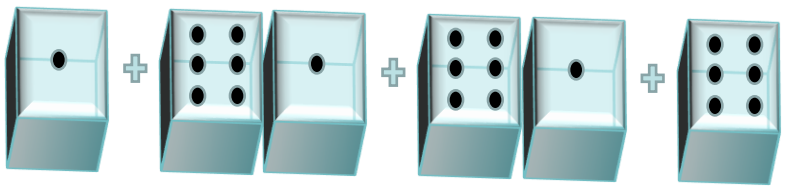
with

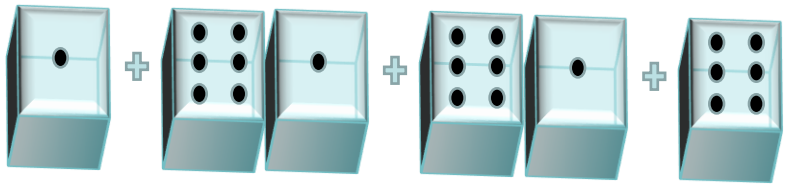
$$\left|\pm\right\rangle=\left(\left|000\right\rangle\pm\left|111\right\rangle\right)/\sqrt{2}$$

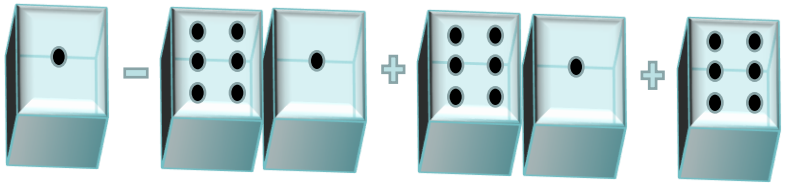
Classical Error Correction

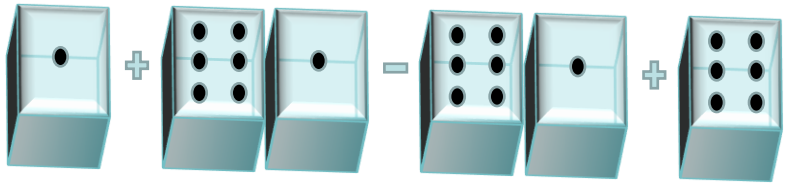


Quantum Error Correction

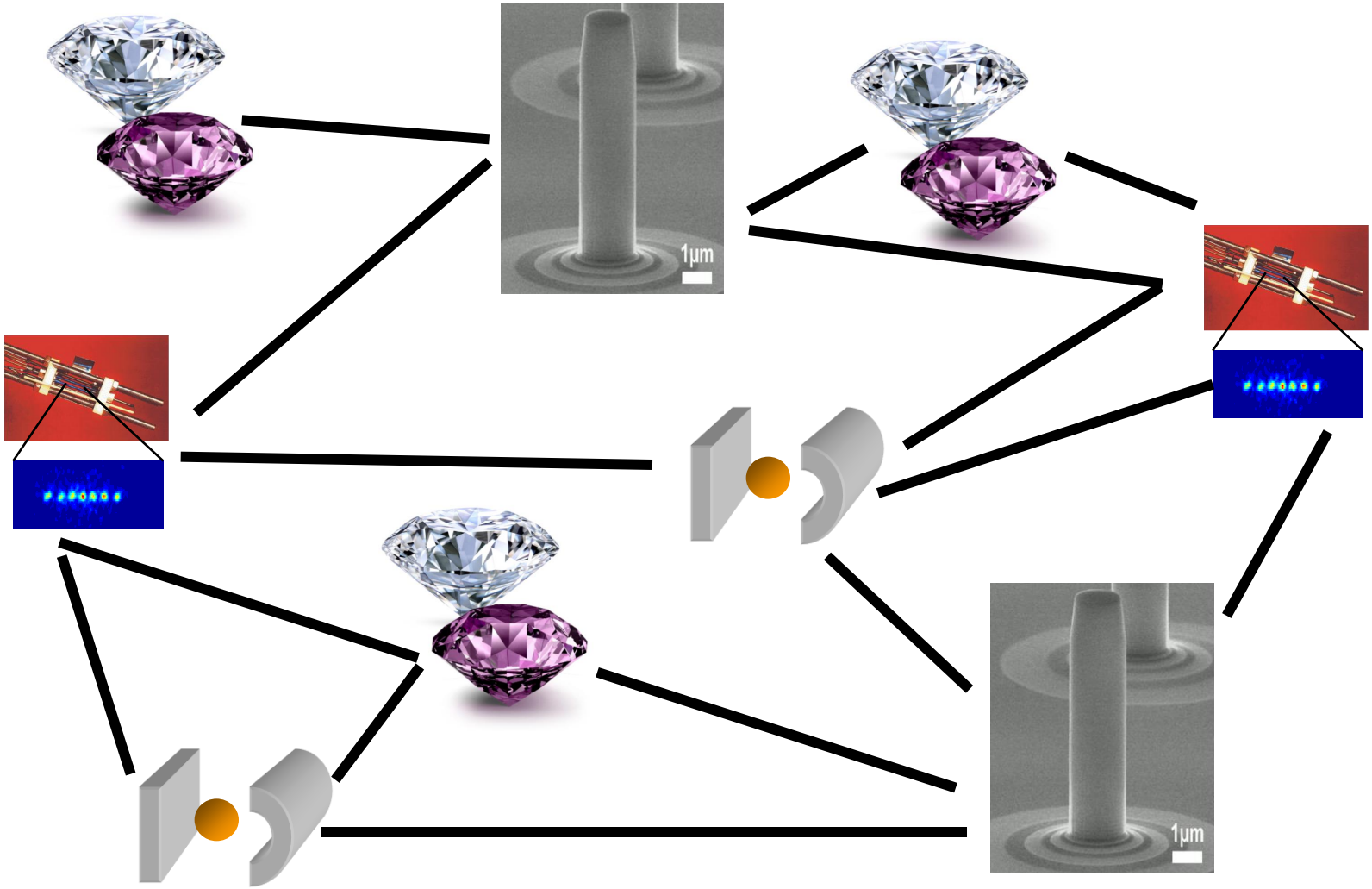




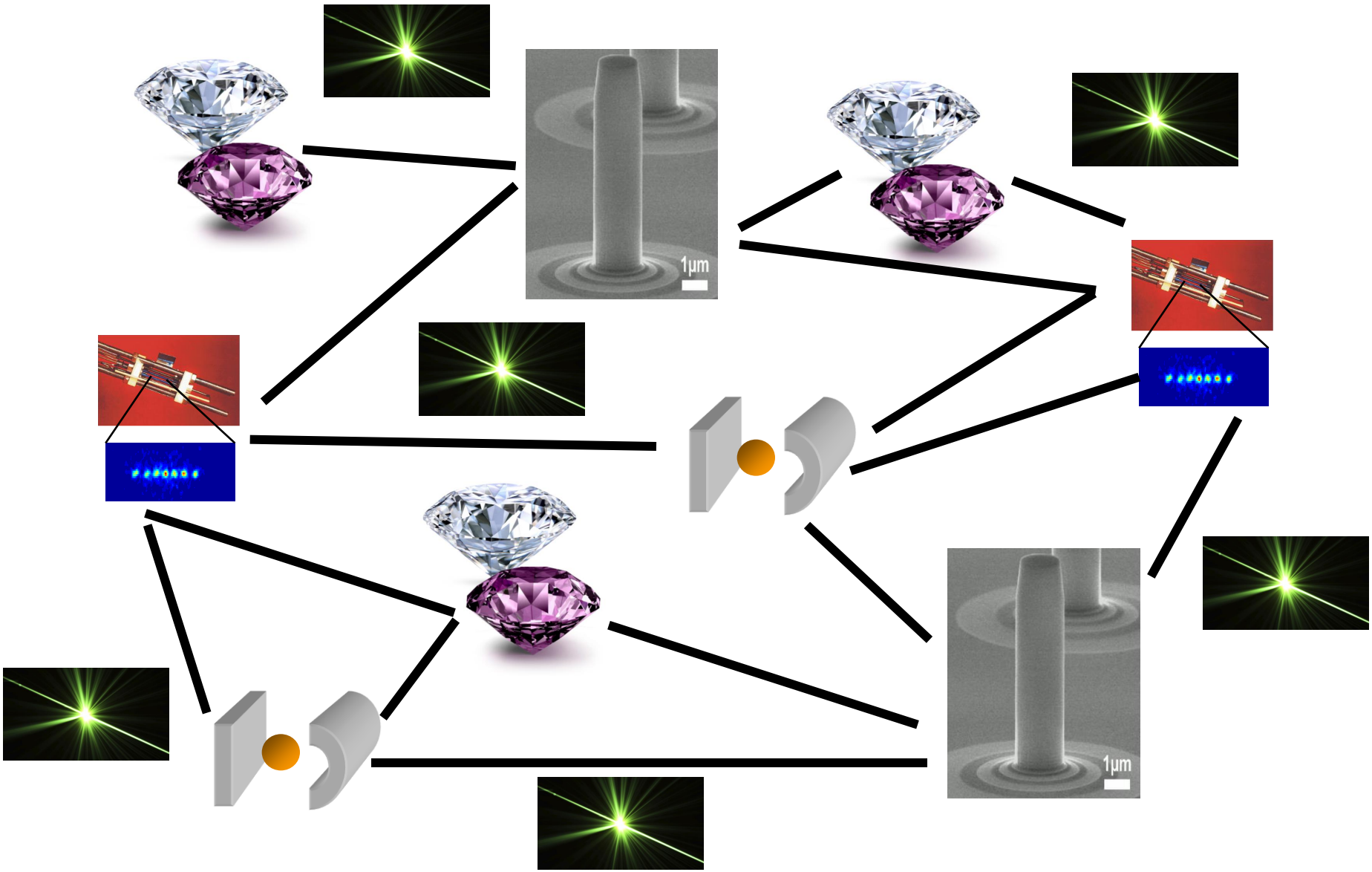




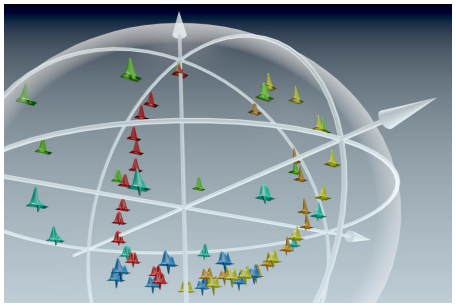
Quantum Networks

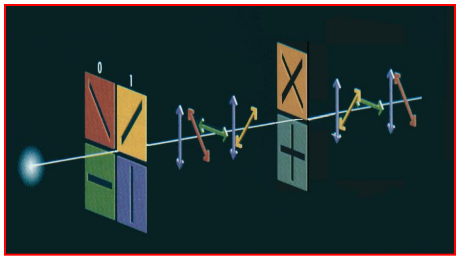


Quantum Networks



Conclusion / Bottom Line





Photons

Light is great, and indispensable for Quantum Technologies!