A spotlight on quantum physics

Andrew R. Cameron

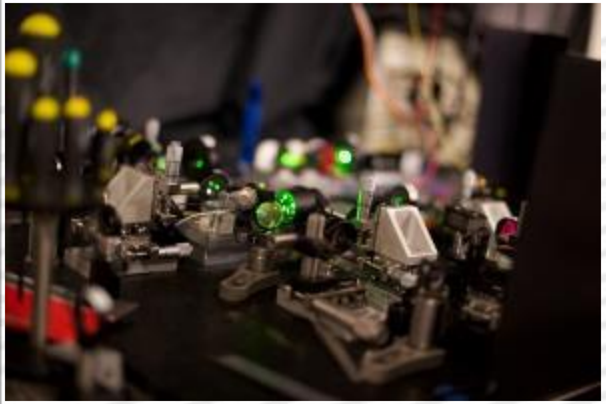
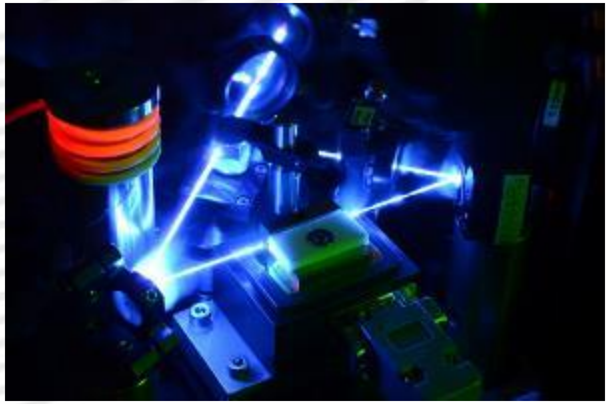
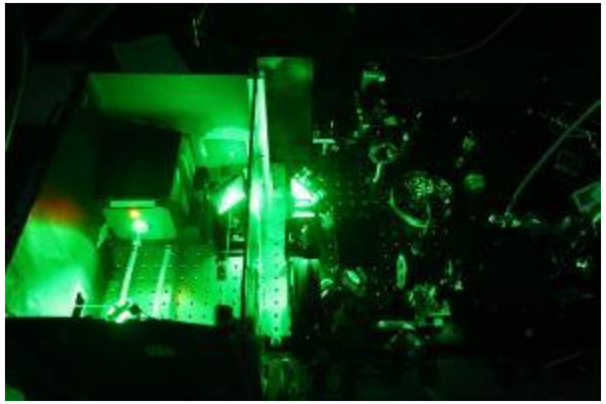
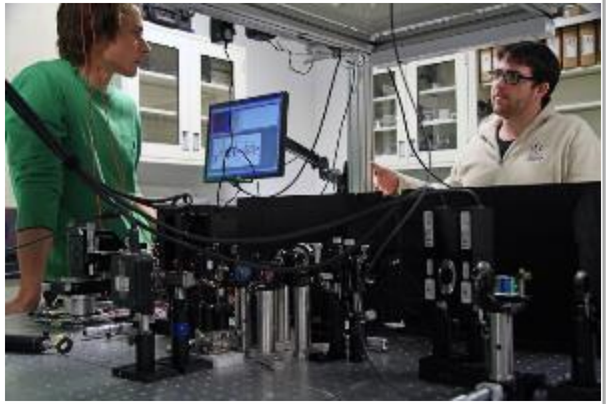
April 18th, 2026

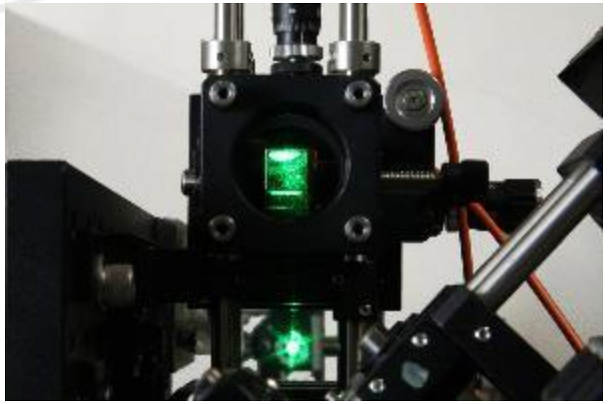
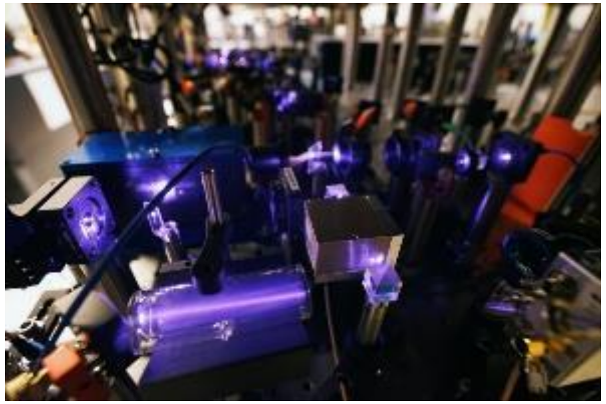
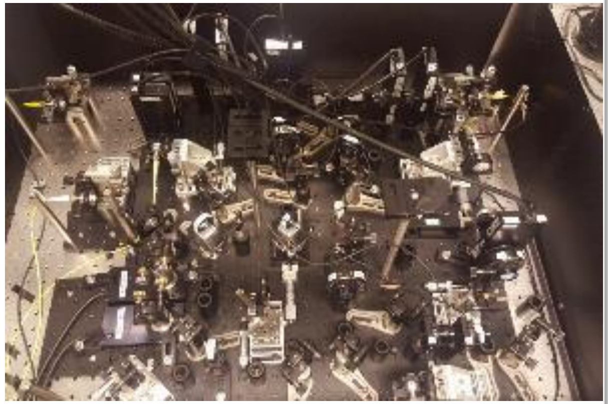
Fermilab

Based on materials developed by John Donohue at the Institute for Quantum Computing

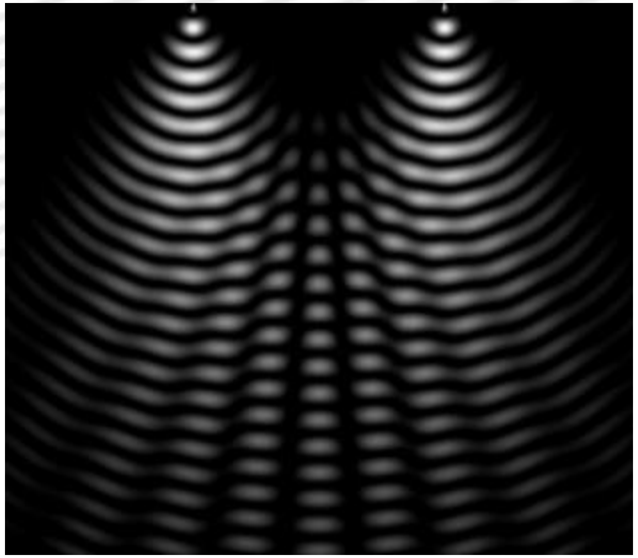
Who am I?

- Studied physics since undergrad in Prince Edward Island
- PhD in physics (Quantum information) in Waterloo
- Postdoc at Fermilab – building quantum networks
- Experimental physics – (safely) playing with lasers.

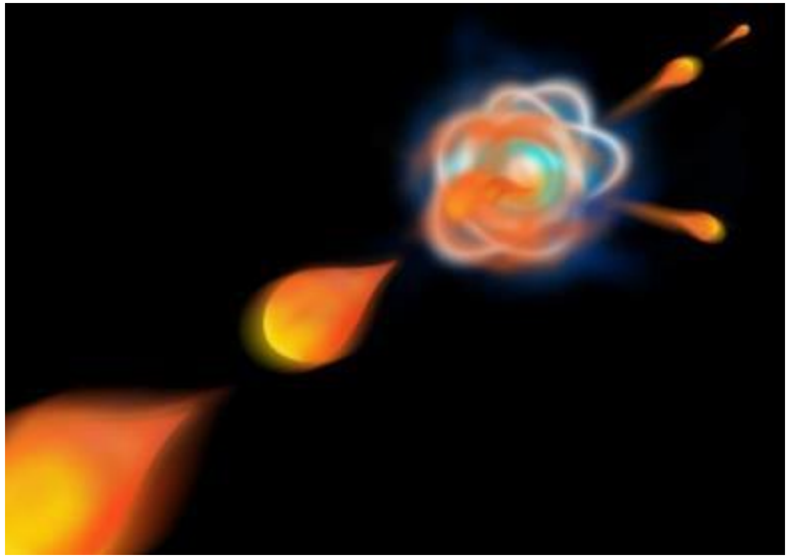





What is light?



Light is an electromagnetic wave

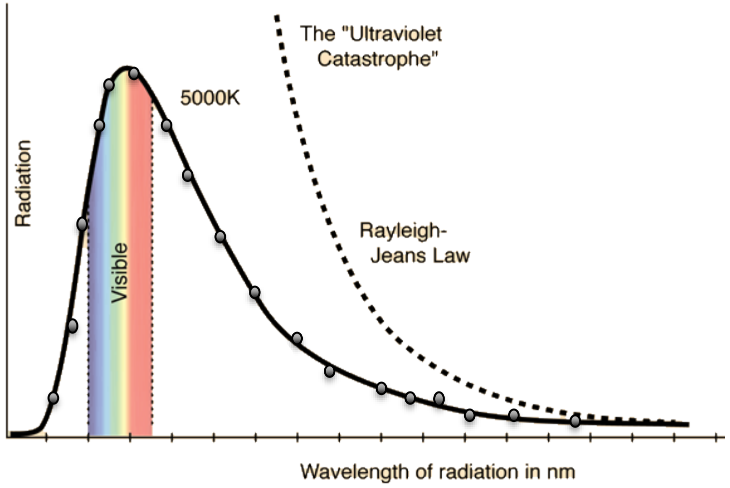


Light is made up of particles called photons

The ultraviolet catastrophe

Why do objects glow different colors at different temperatures?

Scientists knew the curves, but couldn't come up with a fundamental reason to explain them.

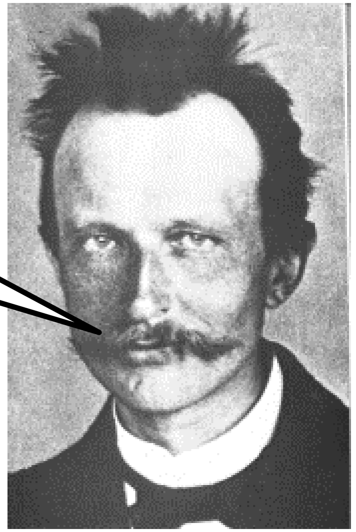


The ultraviolet catastrophe

Why do objects glow different colors at different temperatures?

Max Planck's solution:

What if light was chunky?



For more real details, read:
Max Planck: The Reluctant Revolutionary
Helge Kragh in Physics World, December 2000

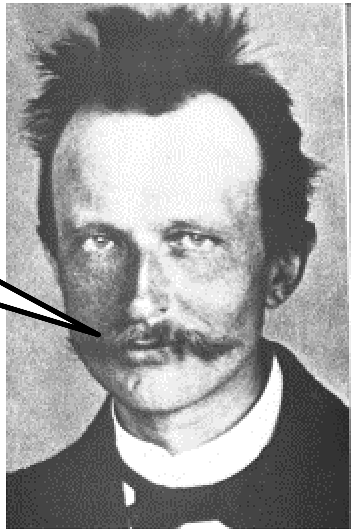
Photons

Each photon of light carries a packet energy
For visible light, each photon has about one billionth of a billionth of a joule

One Joule is about the amount of work required to lift an apple 1 meter.

$= 2 \times 10^{20}$ (20 million trillion) photons per second

What if light was chunky?



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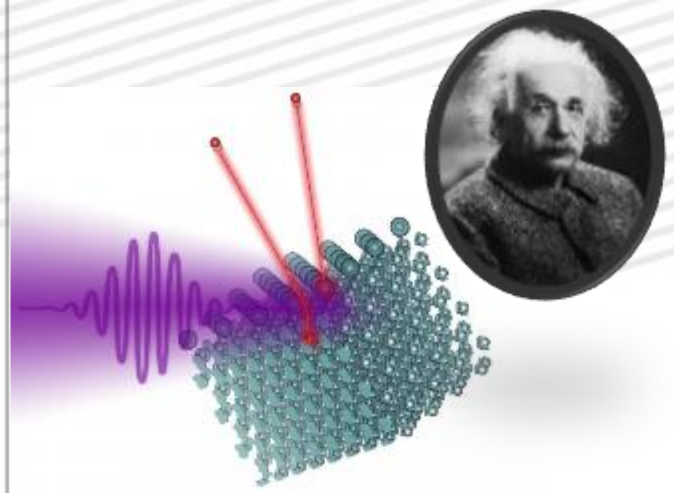
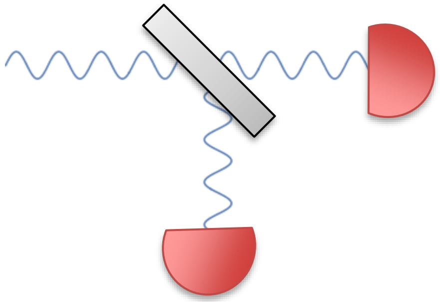
Proving photons

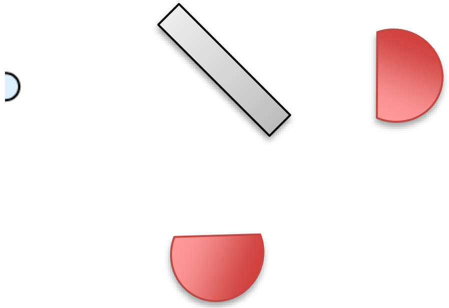


Historically,
the experimental proof
was derived from
the Photoelectric Effect
by Albert Einstein

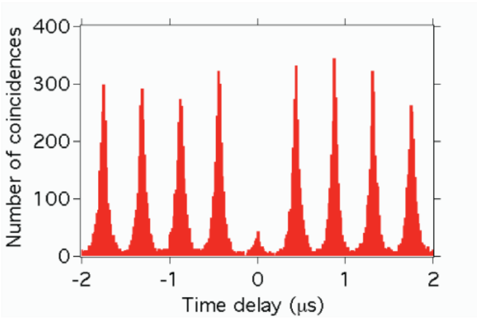
Modern experiments consider
how a photon behaves after
a 50:50 beamsplitter



Wave Picture



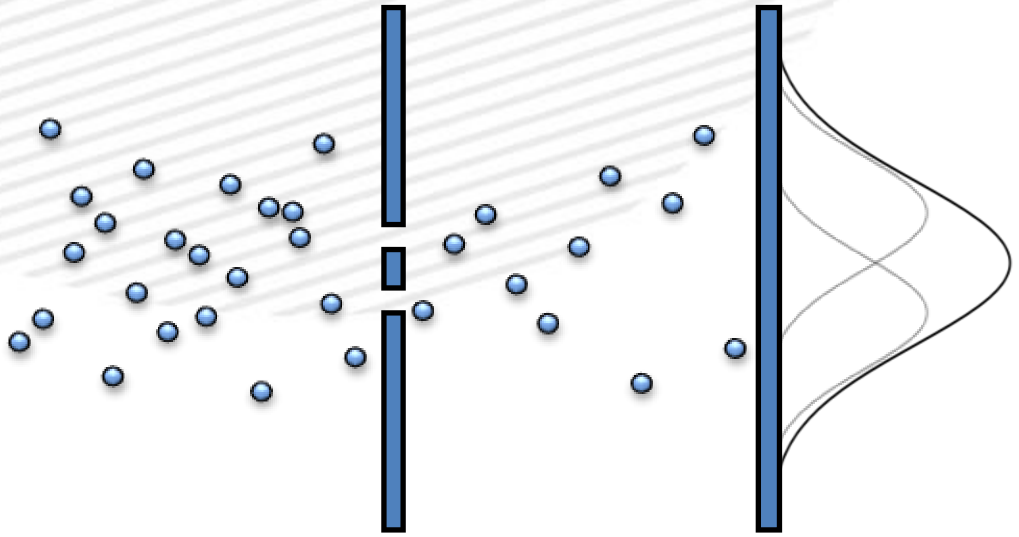
Photon Picture



We don’t see
both detectors
go off at the
same time!

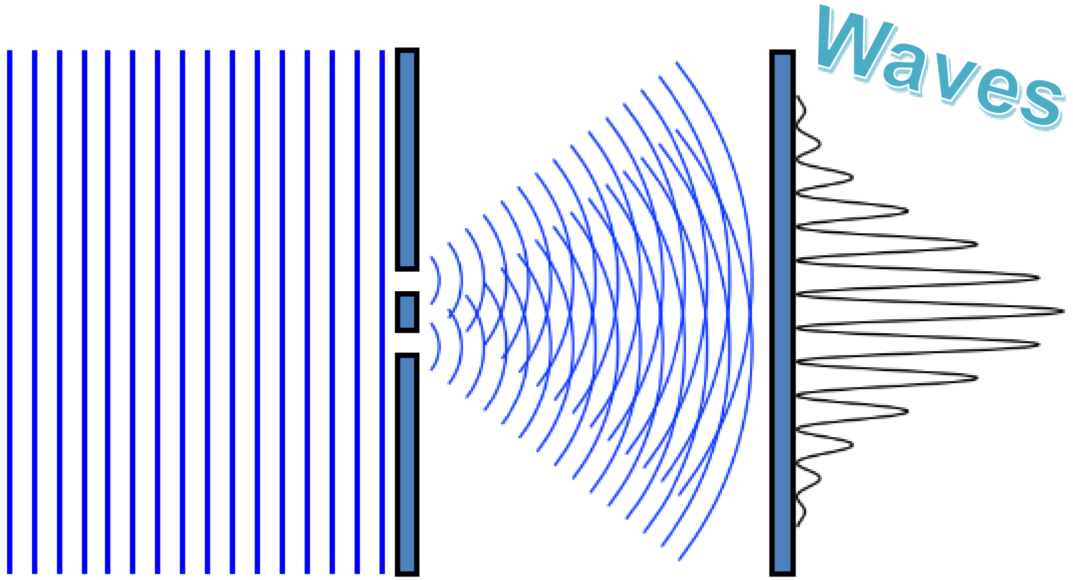
PhoTons
win!

What about the double-slit?



Particles

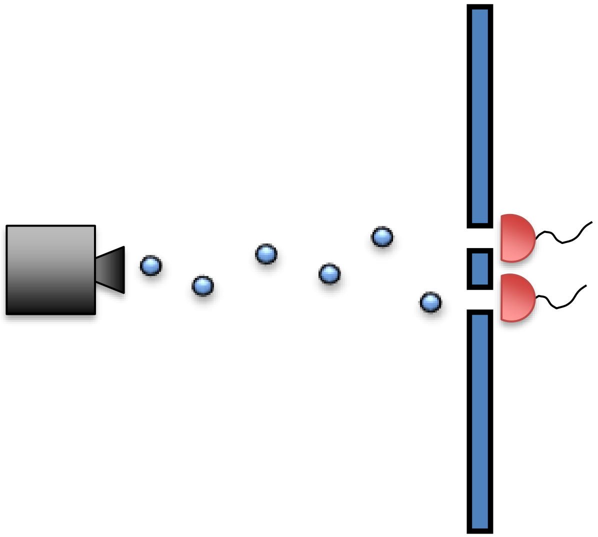
Go through one slit or the other
No pattern builds up on the screen



Waves

Wave's energy goes through both slits
Interference pattern recorded on screen

What about the double-slit?



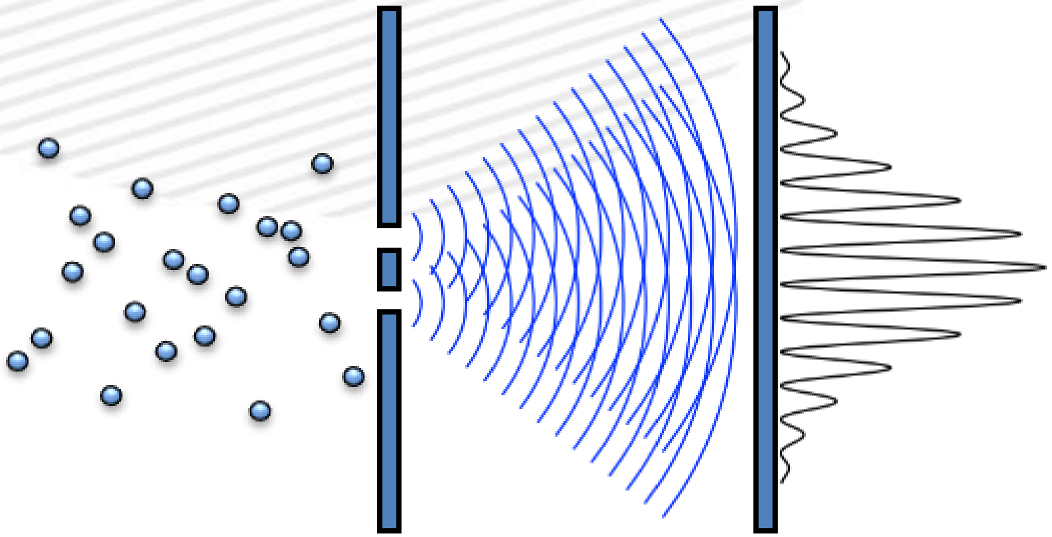
Do we still see this if we send in one photon at a time?

Wave-particle duality

This is real footage of a double-slit experiment
performed one photon at a time,
taken at the University of Waterloo.

Video Source: P. Kolenderski et al. (IQC/UWaterloo), Scientific Reports 2014; 4:4685.

So where did the photon go?



The photon went through a *superposition* of both slits.

With a 50% chance, it went to the left.

With a 50% chance, it went to the right.

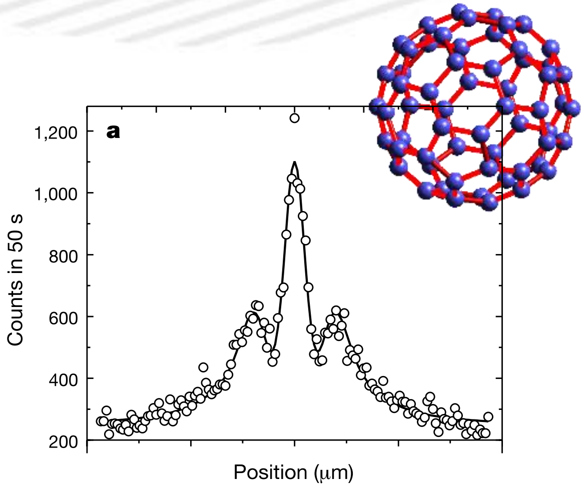
Those two possibilities interfered with each other.

But!

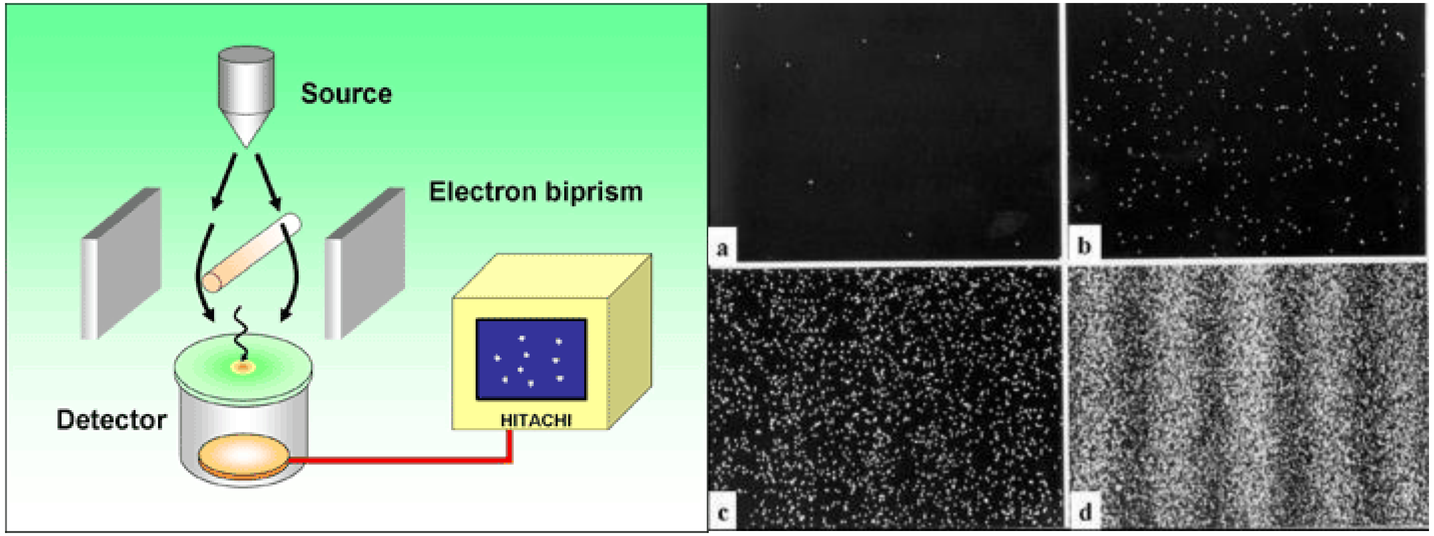
If we measure which slit the photon went through,
we'll destroy the superposition and
see no interference.

Wave-particle duality

Other “particles”,
such as electrons and molecules,
may also behave like waves



Vienna 1999 C_{60} Interference



Hitachi 1989 Electron Diffraction Experiment

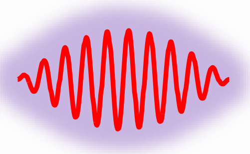
The Two Golden Rules of QM

Rule #1
Superposition

A particle can behave

as if it is both

“here” and “there”



Wave behaviour

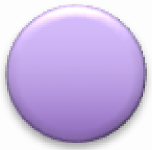
Rule #2
Measurement uncertainty

When asked where it is,

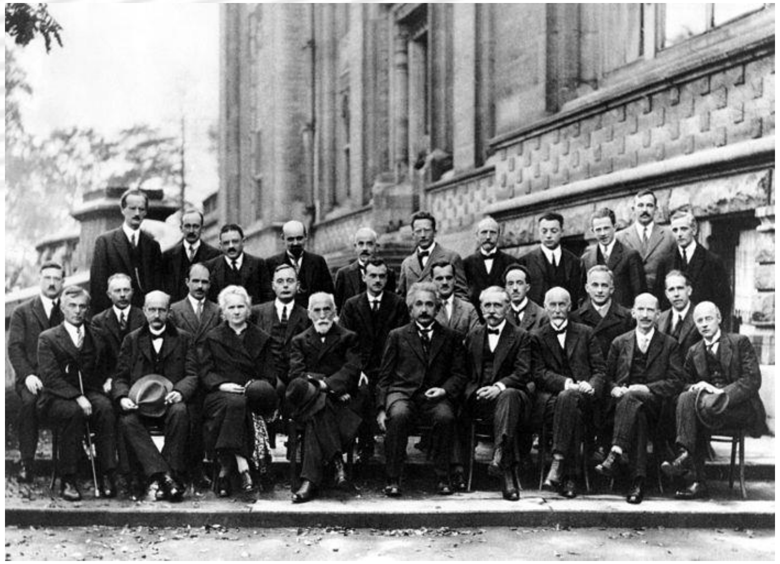
the particle will be found either

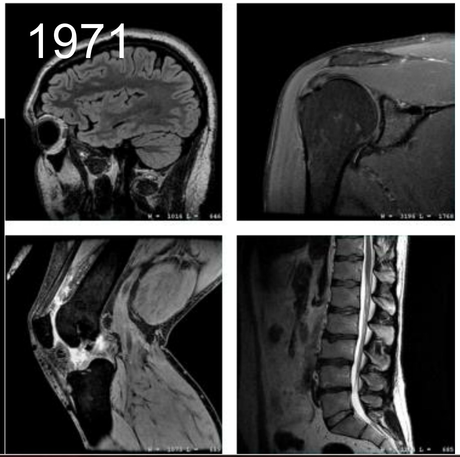
“here” or “there”

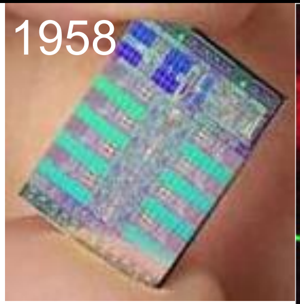
Particle behaviour



Old Hat Quantum

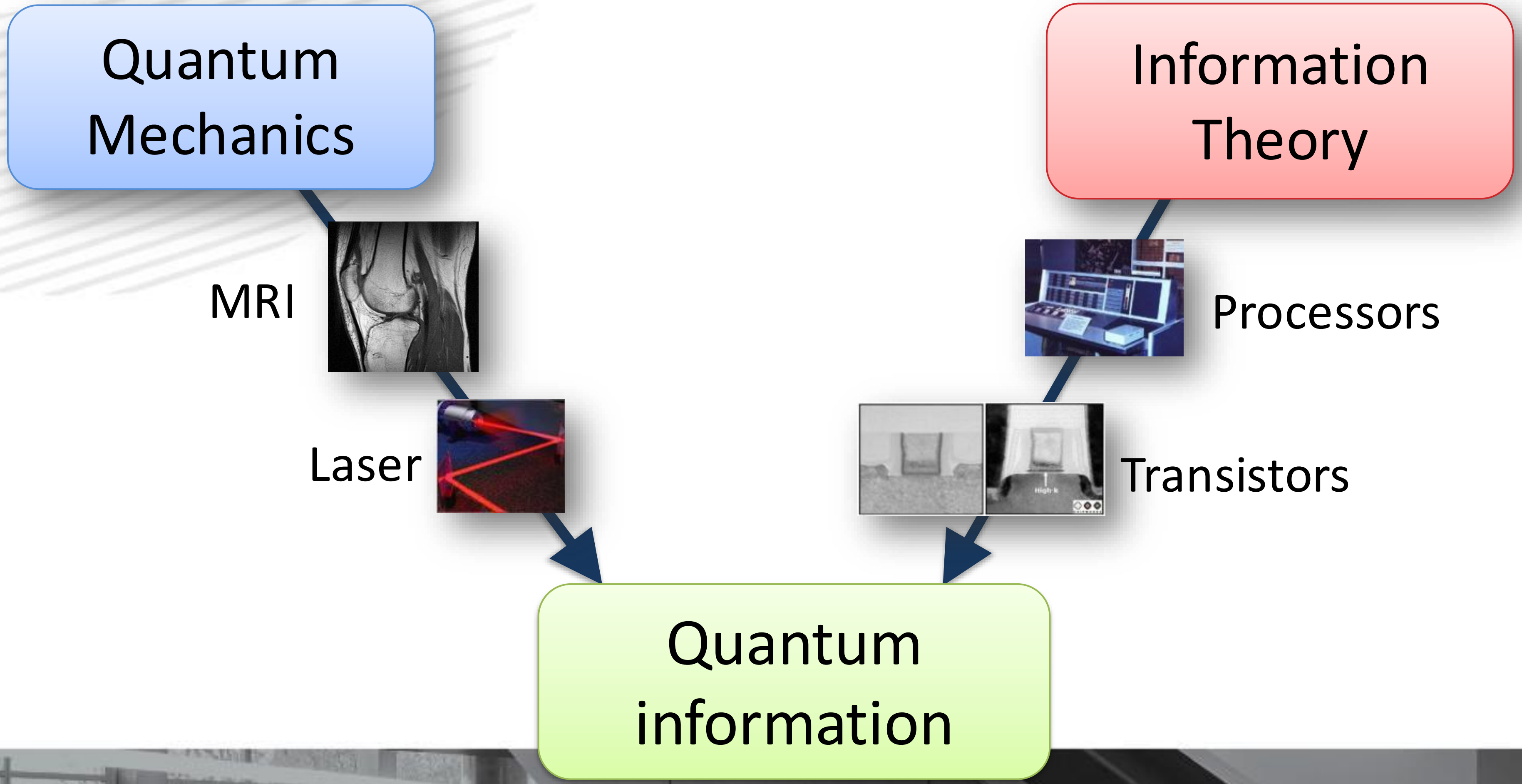




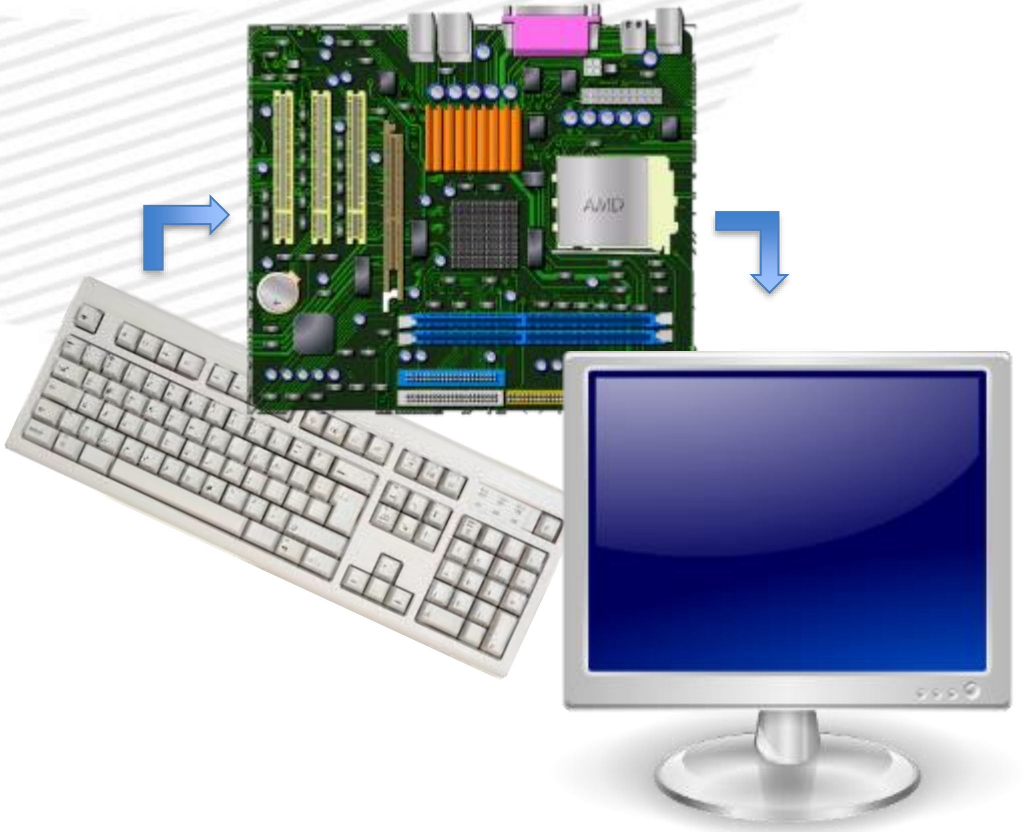


"The First Quantum Revolution"

Quantum Information



What is a computer?



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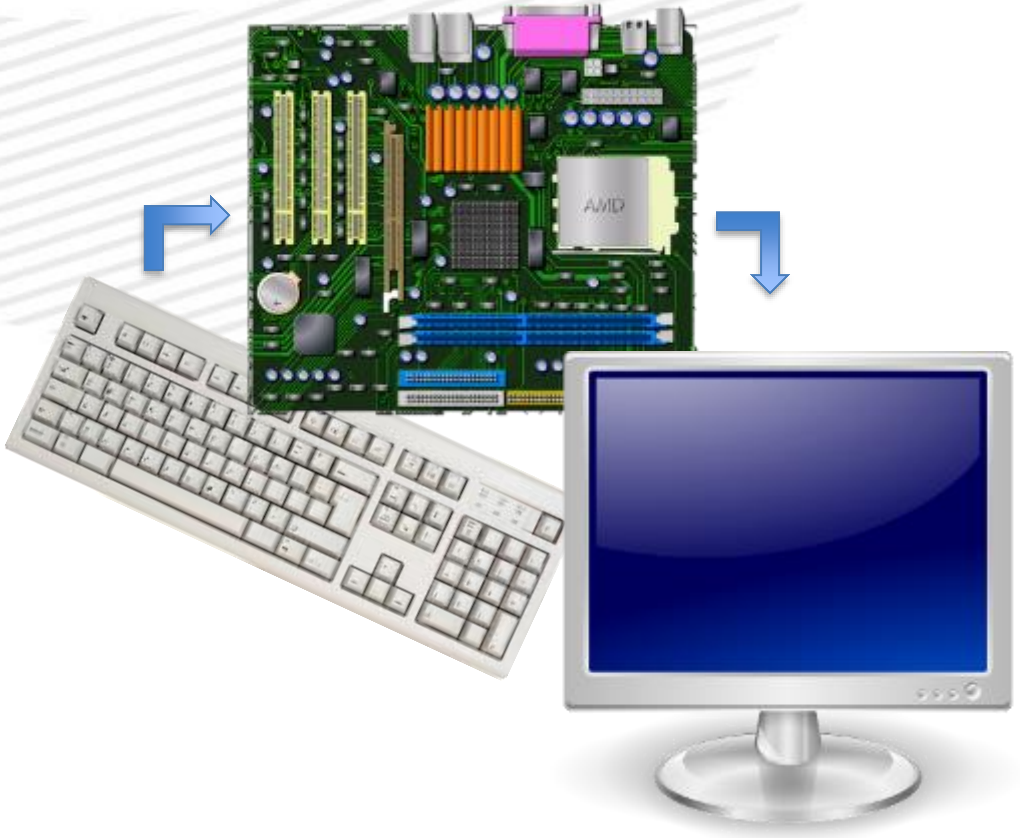

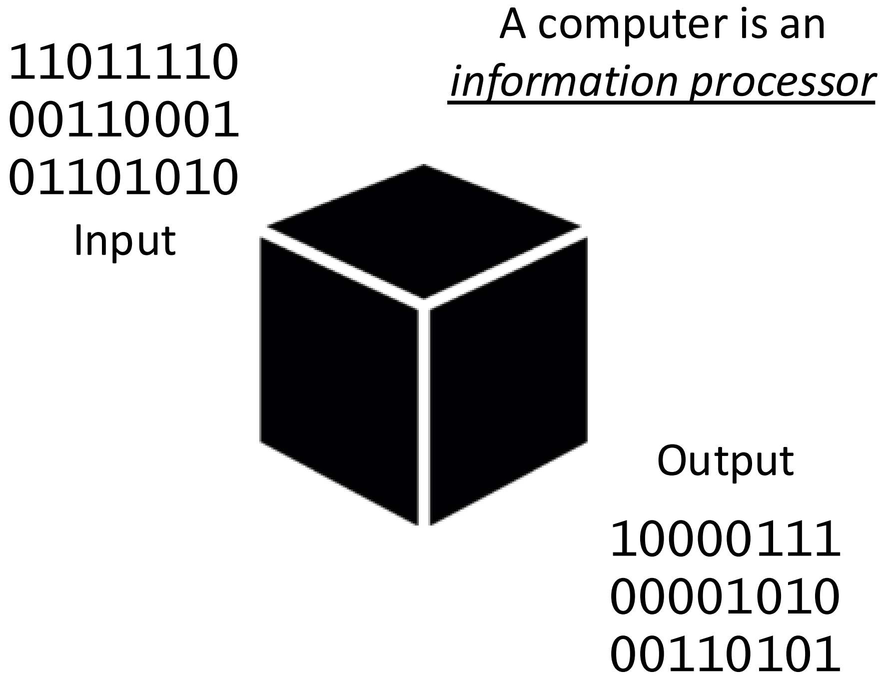

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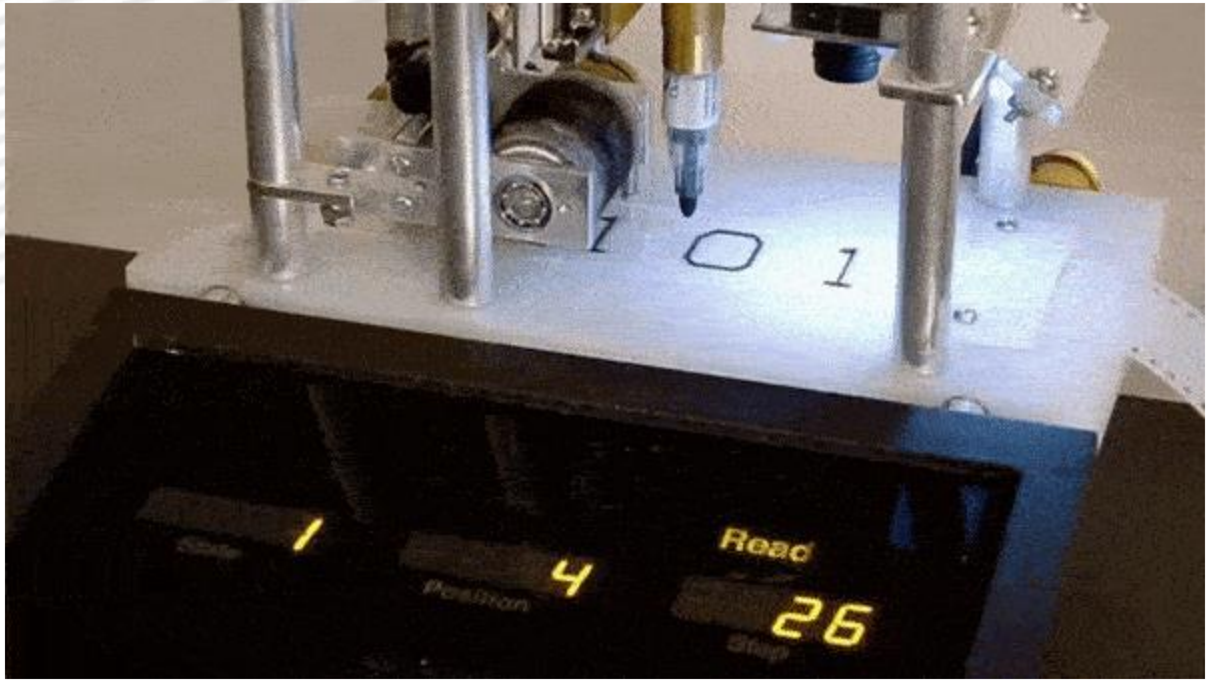


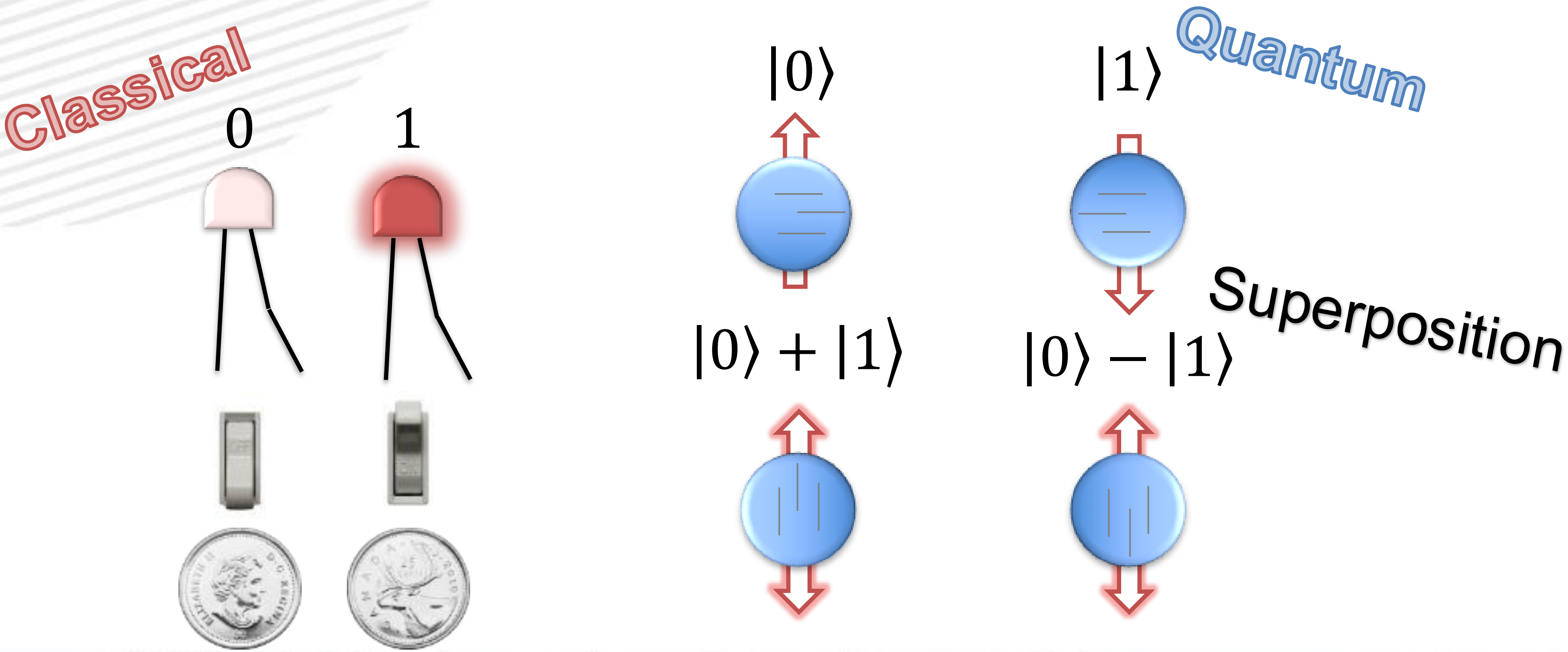
Credit: Mike Davey http://aturingmachine.com/

Traditional computing

Despite their different appearances,
all of these computers
follow the exact same rules.

From bits to qubits

What if a bit is more than just ON or OFF?



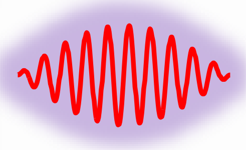
The Two Golden Rules of **QC**

Rule #1
Superposition

A **qubit** can behave

as if it is both

"**0**" and "**1**"



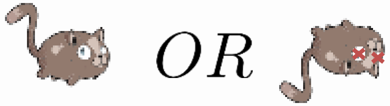
Wave behaviour

Rule #2
Measurement uncertainty

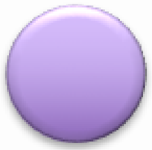
When asked where it is,

the **qubit** will be either

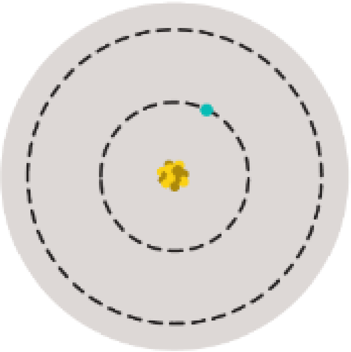
"**0**" or "**1**"



Particle behaviour

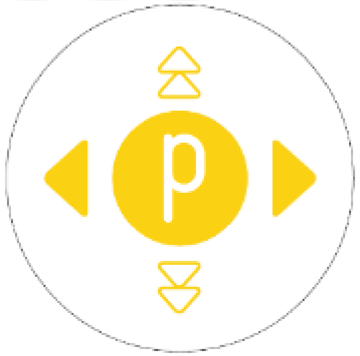


Pick Your Qubit



Atoms & Ions

Isolate a single or small number of atoms, and use their electron energy as a qubit.



Photons

Create a single photon, and encode information in its polarization or color.

Spin

Use the magnetic properties of electrons and molecules and flip them using radio waves.

Superconducting Circuits

Cool circuits to near absolute zero and measure wave properties of electrons.

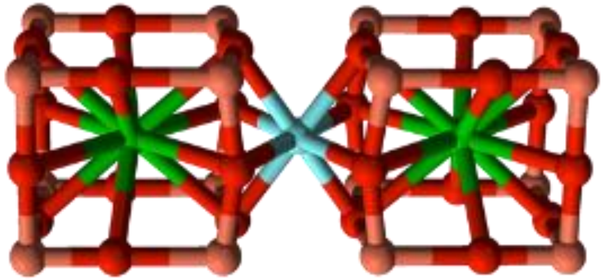
Quantum Computing

What’s it useful for?

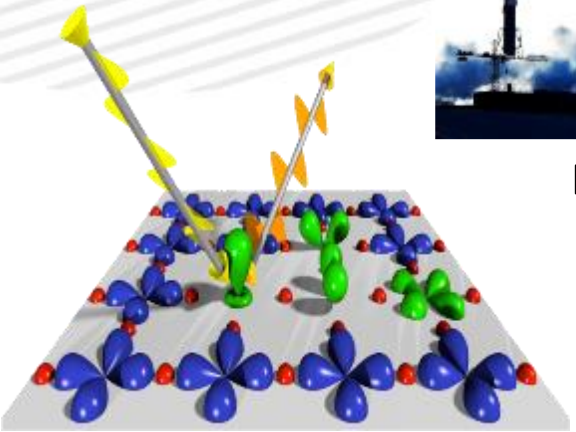
Except with some Quantum pieces

Quantum Simulation

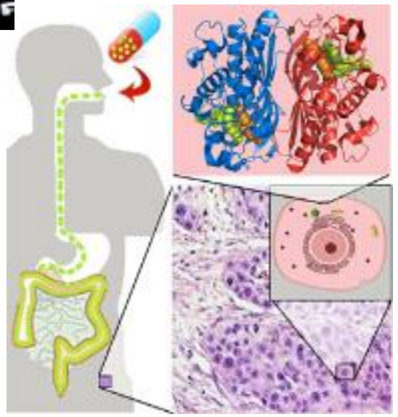
Environment



Materials



Quantum Chemistry



Biochemistry/Medicine

Factoring

$$21 = \boxed{?}$$

$$65 = \boxed{?}$$

$$56{,}153 = \boxed{?}$$

$$42{,}623{,}381 = 5{,}407 \times 7{,}883$$

$$711{,}520{,}814{,}263{,}508{,}933 = 756{,}065{,}159 \times 941{,}083{,}987$$

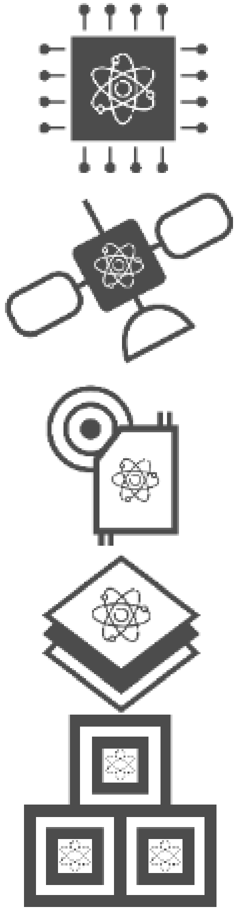
Classical Factoring Algorithms
Time ~ $10^{(\log N)^{1/2}}$

Quantum Factoring Algorithms
Time ~ $(\log N)^2$

Quantum information

Uses principles like superposition
to transform information
in new ways

A blend of physics,
chemistry, mathematics,
engineering, and computer science.



Computing

Communication

Sensors

Materials

Foundations

Slides

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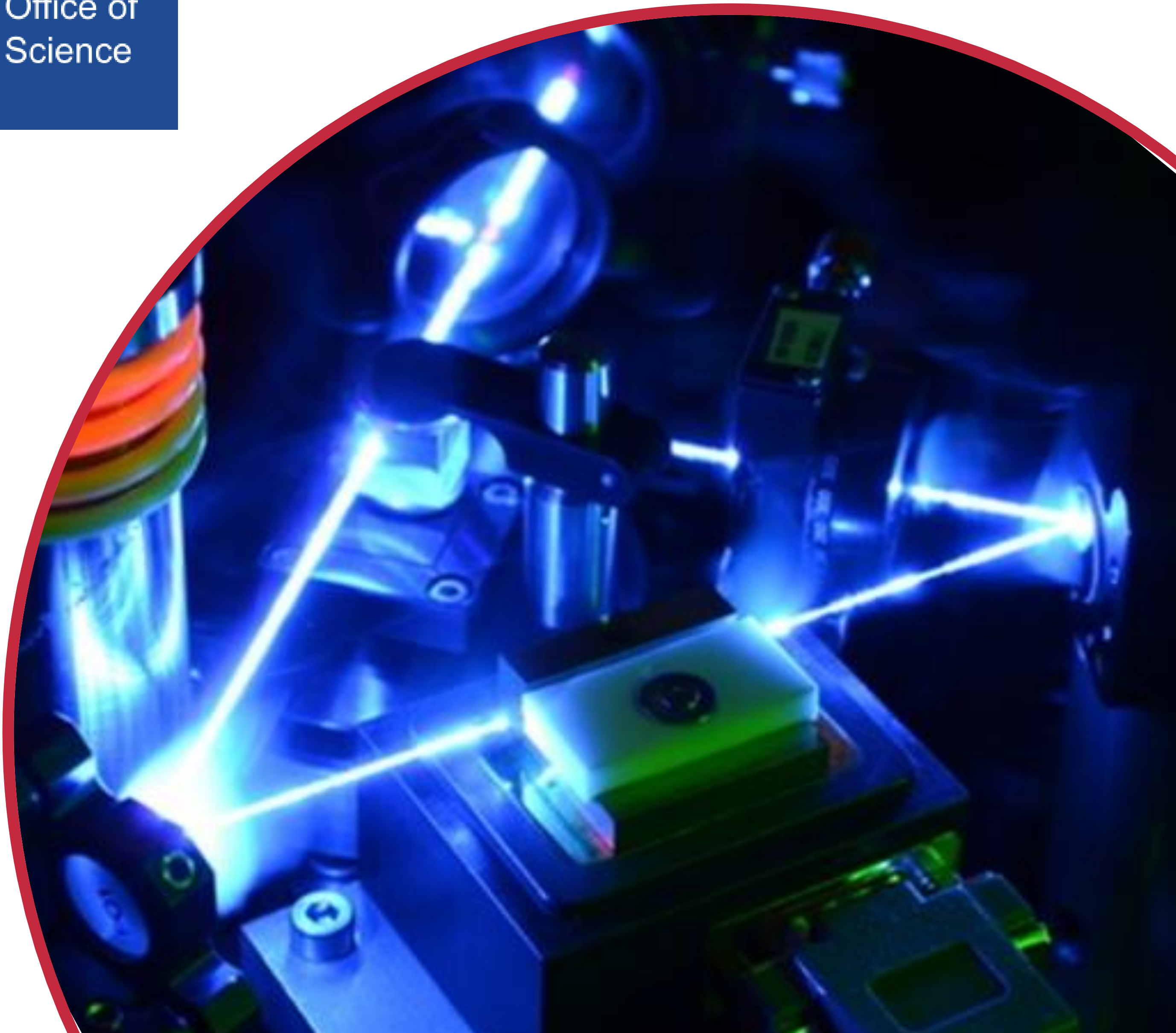
QUANTUM OPTICS

ANDREW CAMERON



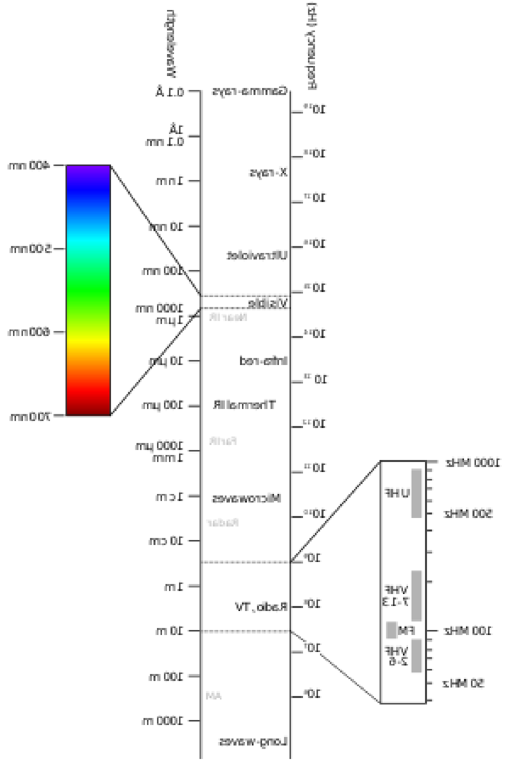
Which of the following is NOT made of photons?

A. Laser light

B. X-Rays

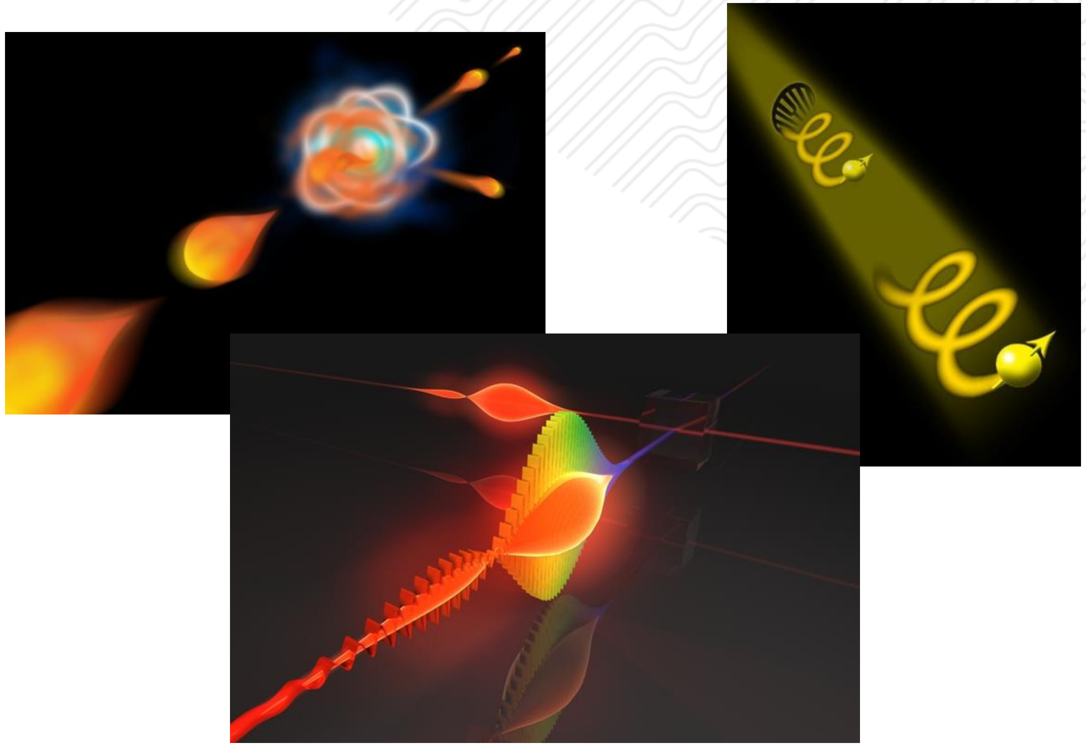
C. Gamma Rays

D. Radio Signals



E. They're all made of photons

What's a photon?



A photon is a countable unit of light

Creation Operator

Vacuum (nothing)

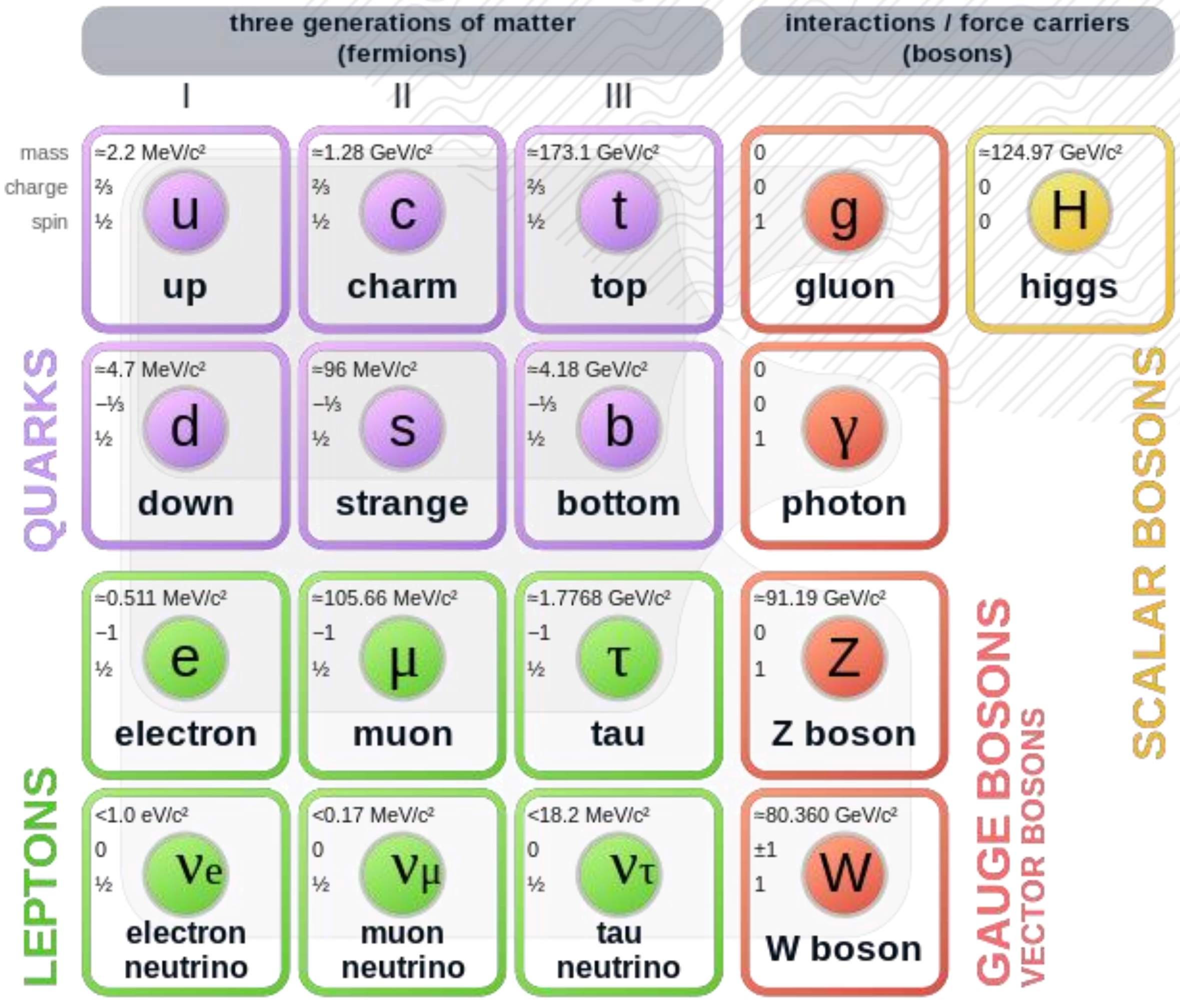
One Photon

$$\hat{a}^\dagger |\, \circ \,\rangle = |\, \bullet \,\rangle$$

$$\hat{a}^\dagger |\, \bullet \,\rangle = \boxed{\;?\;}$$

phys.org, Physics Buzz, Physics World

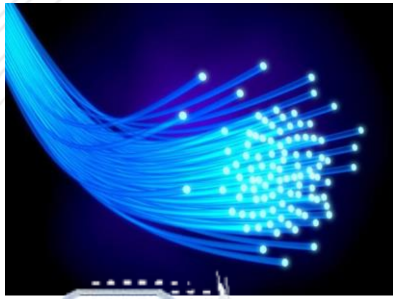
Standard model of particle physics

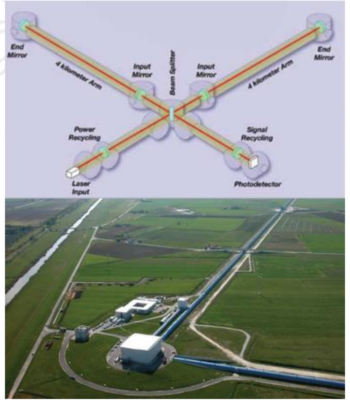


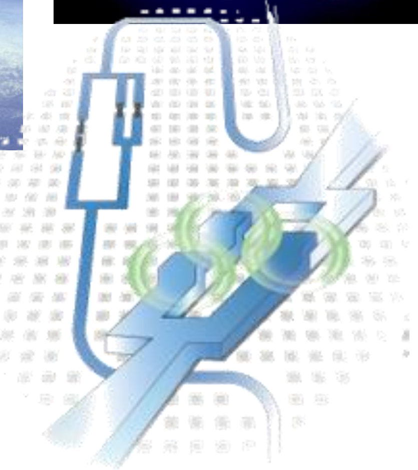
But why do we care?

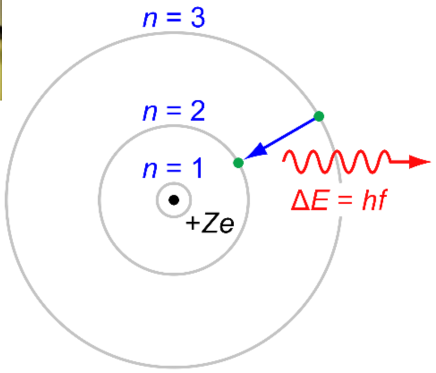
Uses of photonic qubits include:

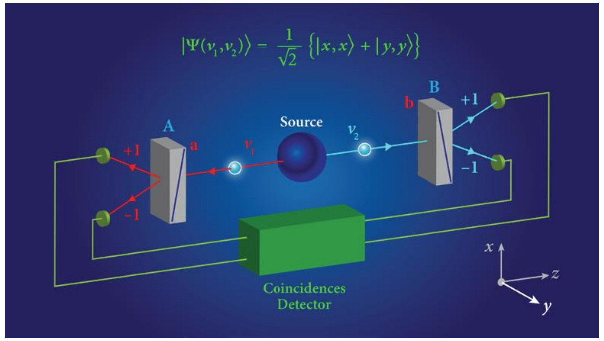
- Quantum & optical communications
- Connecting physical qubits
- Photonic quantum computing
- Quantum metrology & sensing
- Foundational physics











Quantum optics

- How do we make qubits with photons?
- How can we make photons talk to each other?
- How can we measure photons?
- How can we make photons?
- How can we verify photons?

What do we need to make a qubit?

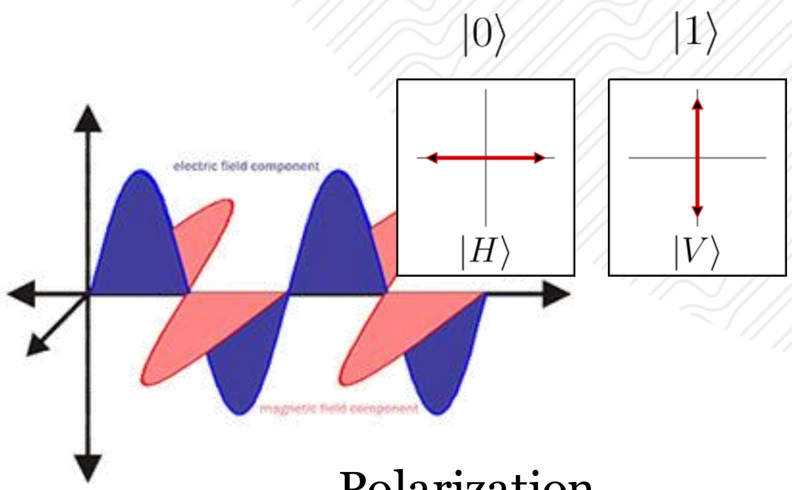
$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad |+\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \qquad |+_i\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix}$$

$$|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad |-\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -1 \end{bmatrix} \qquad |-_i\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ -i \end{bmatrix}$$

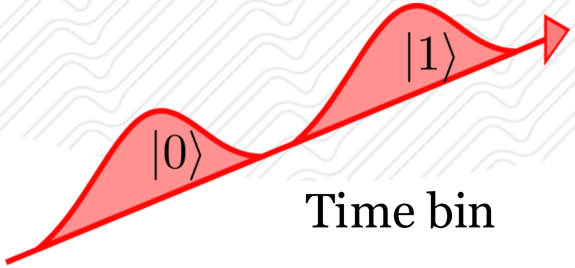
Well-defined
basis states…

…which can be controlled and measured
in coherent superpositions

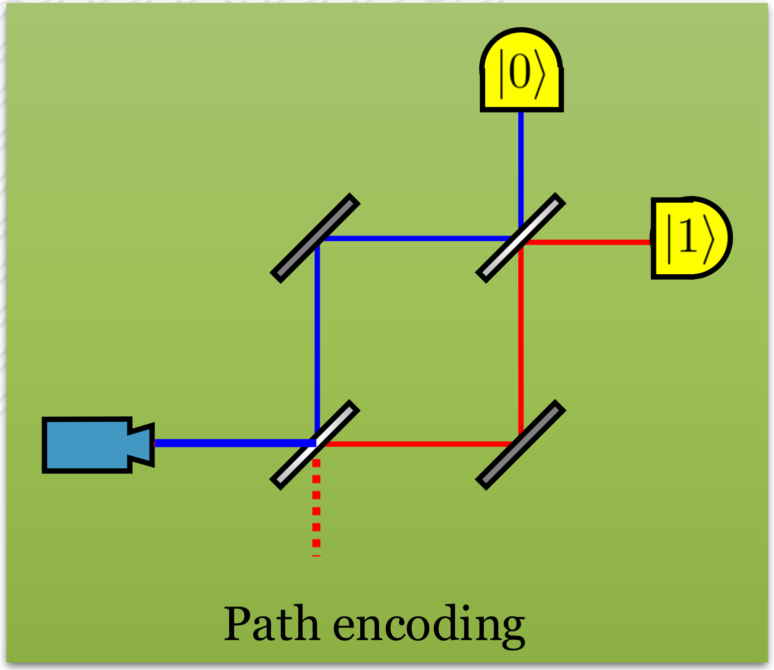
Making a qubit with photons



Polarization

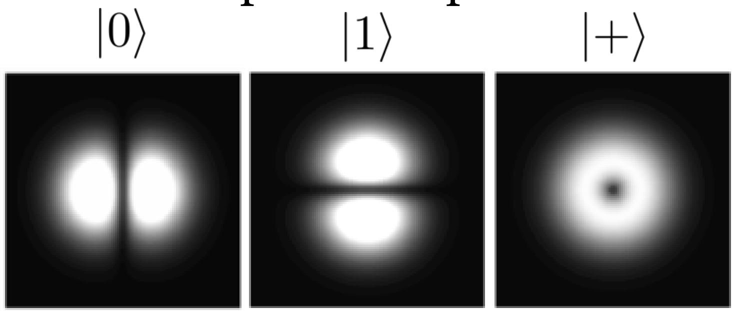


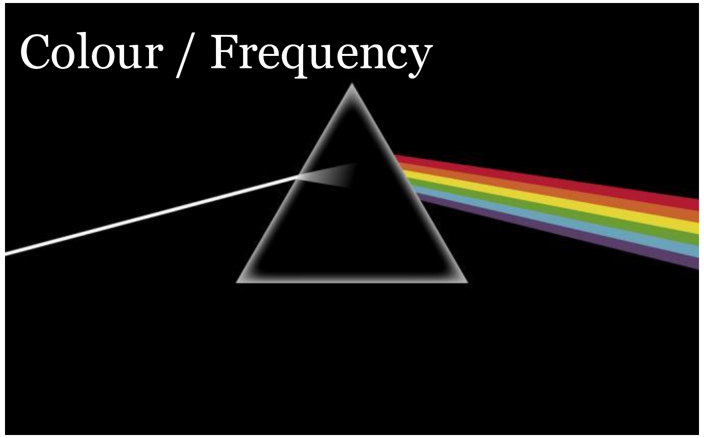
Time bin



Path encoding

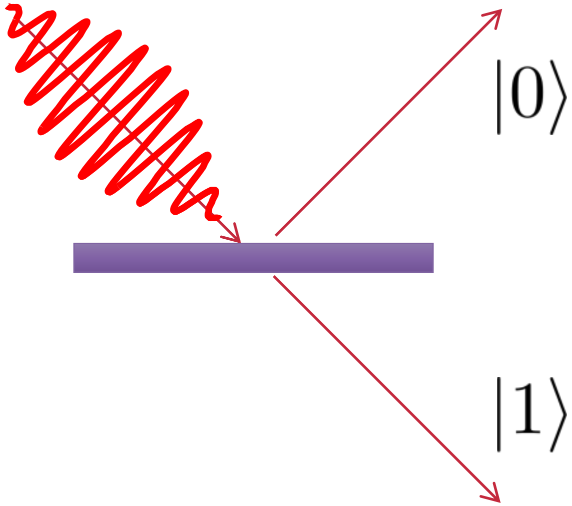
Spatial shapes




Colour / Frequency

Path encoding toolbox

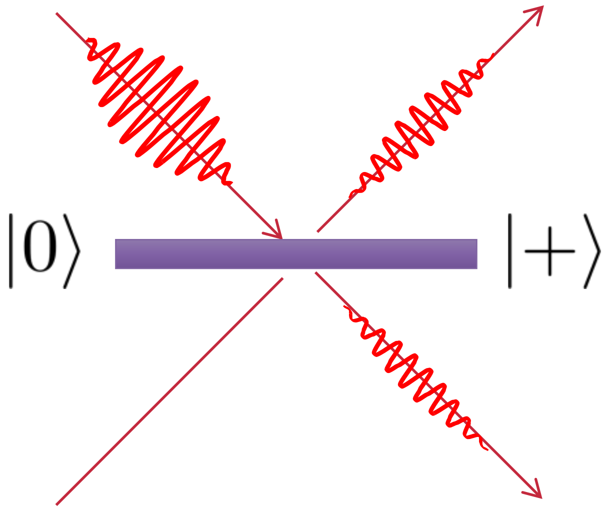
Simple “dual-rail” encoding



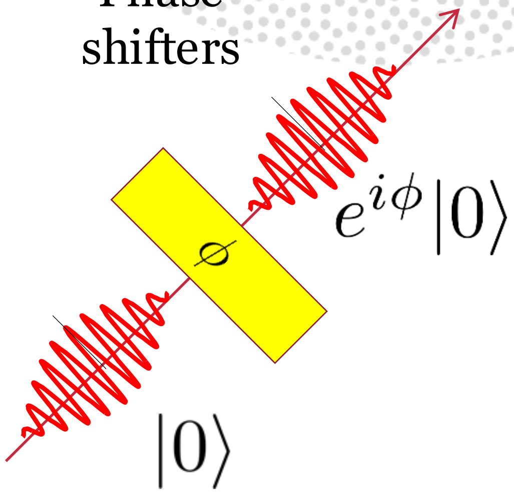
Qubit states defined by path of photon

Basic tools

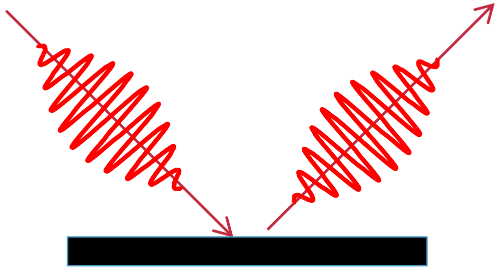
Beam splitters (Hadamard)



Phase shifters



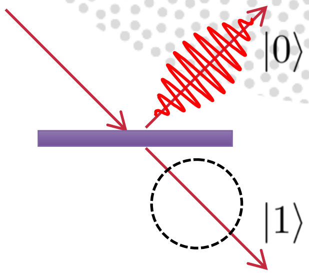
Mirrors



Path-encoded qubits

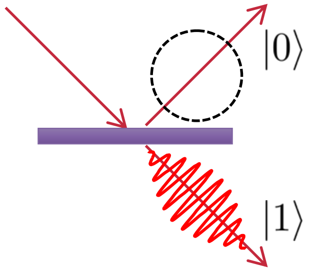
Photon here — No photon here

$$|0\rangle = \begin{bmatrix}1\\0\end{bmatrix} = \hat{a}_0^\dagger|\circ\rangle_0|\circ\rangle_1 = |\bullet\rangle_0|\circ\rangle_1$$



No photon here — Photon here

$$|1\rangle = \begin{bmatrix}0\\1\end{bmatrix} = \hat{a}_1^\dagger|\circ\rangle_0|\circ\rangle_1 = |\circ\rangle_0|\bullet\rangle_1$$

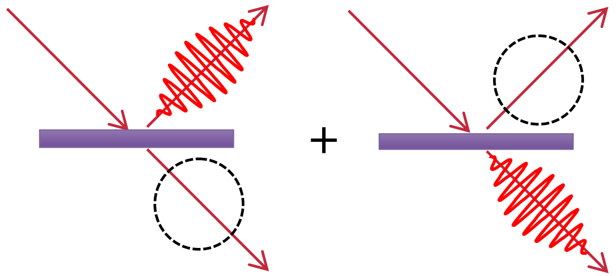


Path-encoded qubits

$$|+\rangle = \frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix} = \frac{1}{\sqrt{2}}\left(\hat{a}_0^\dagger + \hat{a}_1^\dagger\right)|\circ\rangle_0|\circ\rangle_1$$

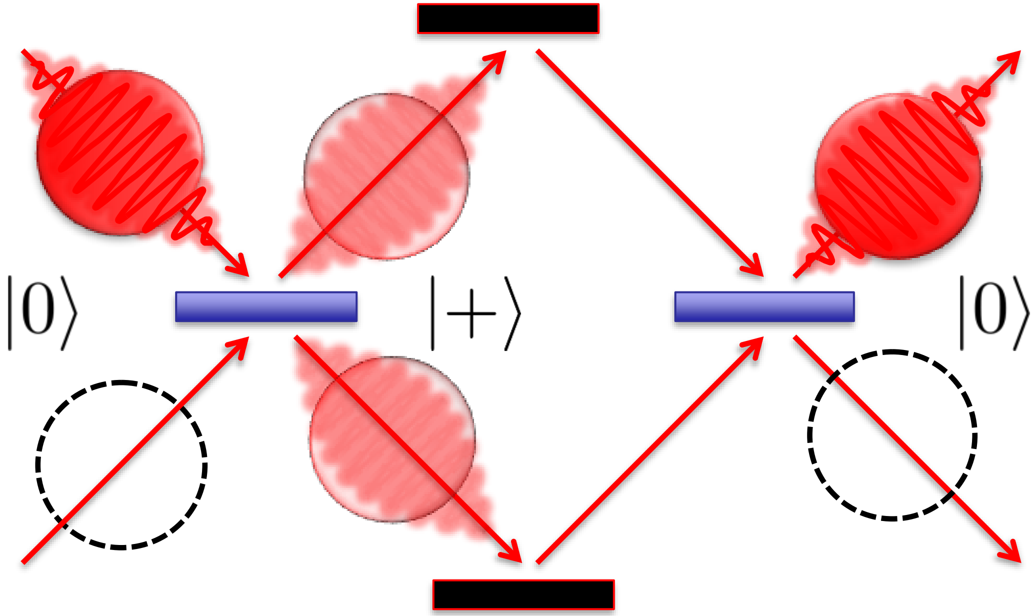
$$= \frac{1}{\sqrt{2}}\left(|\bullet\rangle_0|\circ\rangle_1 + |\circ\rangle_0|\bullet\rangle_1\right)$$

Superposition!



A **single** photon in a superposition of **two** paths

Single-photon interference



Start with a single photon in $|0\rangle$

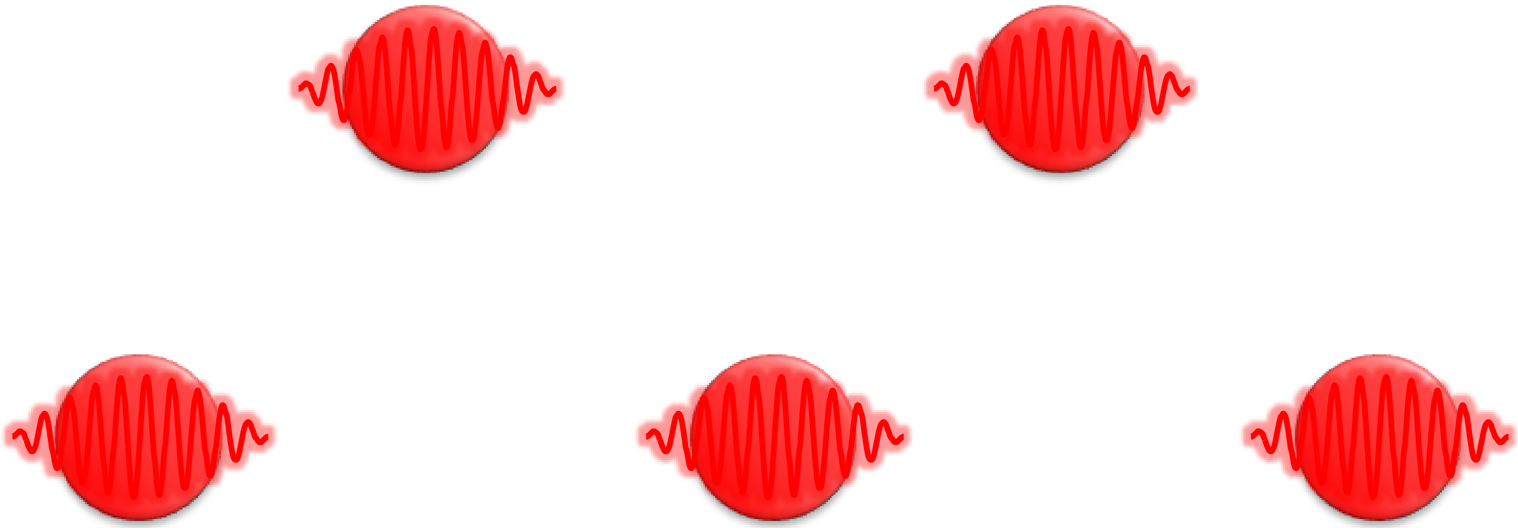
Beamsplitter puts it into superposition state $|+\rangle$

Recombine paths to state $|0\rangle$

We see the same interference for photons that we do for laser light

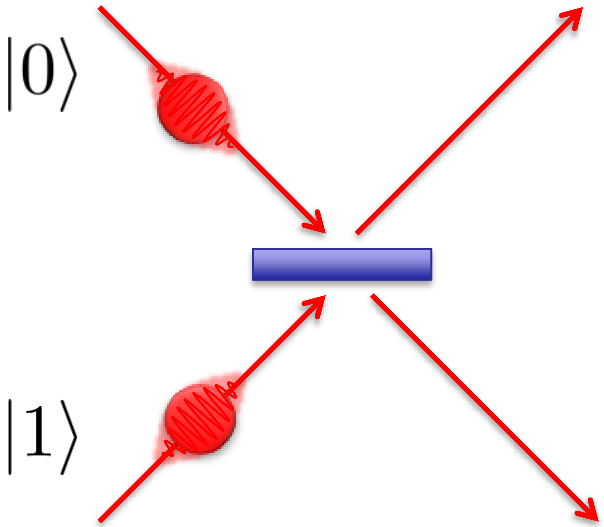
What about more photons?

We've seen that quantum light and single photons give the same interference patterns. What about multiple photons?



Let's make photons talk to each other!

Two-Photon Interference



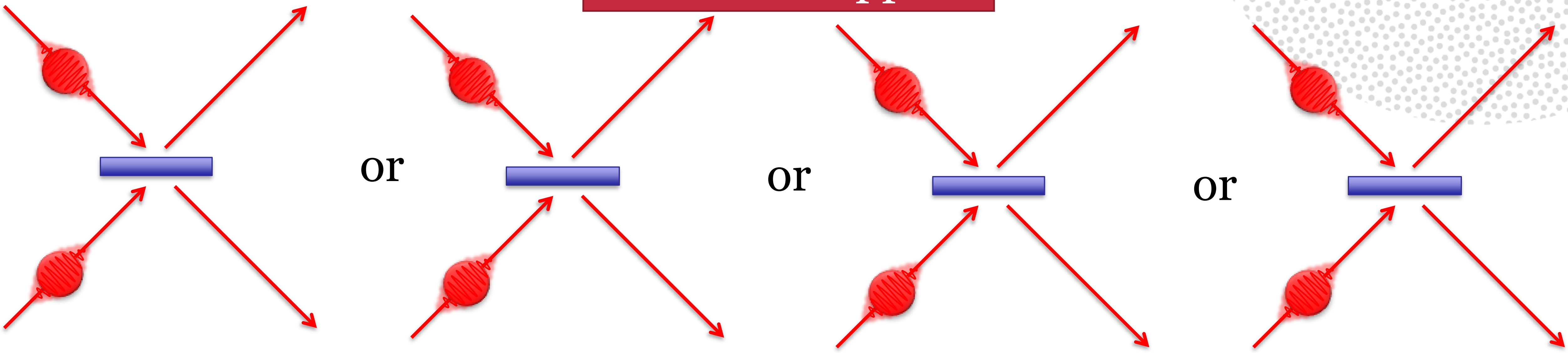
We start with
two *indistinguishable* photons
in two different paths

$$|\psi\rangle = \hat{a}_0^\dagger \hat{a}_1^\dagger |\circ\rangle_0 |\circ\rangle_1$$
$$= |\bullet\rangle_0 |\bullet\rangle_1$$

What happens at the beamsplitter?

Two-Photon Interference

What can happen?



Both pass

$|\,\bullet\,\rangle_0|\,\bullet\,\rangle_1$

One passes, one reflects

$|\,\circ\,\rangle_0|\bullet\bullet\rangle_1$ $|\bullet\bullet\rangle_0|\,\circ\,\rangle_1$

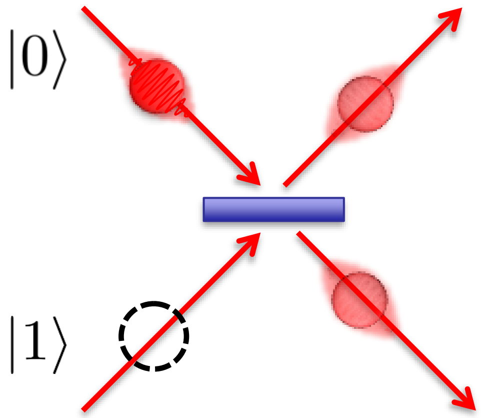
Both reflect

$|\,\bullet\,\rangle_0|\,\bullet\,\rangle_1$

What ***does*** happen?

Two-Photon Interference

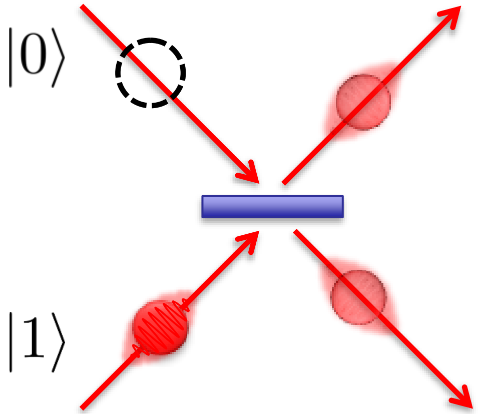
Examine what happens to each photon individually...



Qubits: $H|0\rangle = |+\rangle$

Photons: $\hat{U}_{\mathrm{BS}}|\bullet\rangle_0|\circ\rangle_1 = \frac{1}{\sqrt{2}}\left(|\bullet\rangle_0|\circ\rangle_1 + |\circ\rangle_0|\bullet\rangle_1\right)$

Operators: $\hat{U}_{\mathrm{BS}}\hat{a}_0^\dagger|\circ\rangle_0|\circ\rangle_1 = \frac{1}{\sqrt{2}}\left(\hat{a}_0^\dagger + \hat{a}_1^\dagger\right)|\circ\rangle_0|\circ\rangle_1$



Qubits: $H|1\rangle =$?

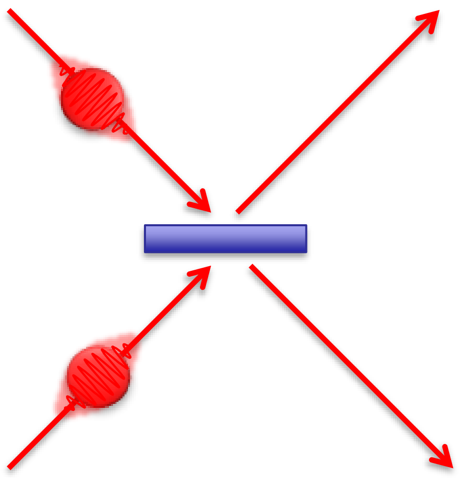
Photons: $\hat{U}_{\mathrm{BS}}|\circ\rangle_0|\bullet\rangle_1 =$?

Operators: $\hat{U}_{\mathrm{BS}}\hat{a}_1^\dagger|\circ\rangle_0|\circ\rangle_1 =$?

Two-Photon Interference

$$\hat{U}_{\mathrm{BS}}\hat{a}_0^\dagger\hat{a}_1^\dagger|\bigcirc\rangle_0|\bigcirc\rangle_1 = \frac{1}{\sqrt{2}}\left(\hat{a}_0^\dagger + \hat{a}_1^\dagger\right) \times \frac{1}{\sqrt{2}}\left(\hat{a}_0^\dagger - \hat{a}_1^\dagger\right)|\bigcirc\rangle_0|\bigcirc\rangle_1$$

Expand it out!



$$= \frac{1}{2}\left(\hat{a}_0^\dagger\hat{a}_0^\dagger + \hat{a}_0^\dagger\hat{a}_1^\dagger - \hat{a}_1^\dagger\hat{a}_0^\dagger - \hat{a}_1^\dagger\hat{a}_1^\dagger\right)|\bigcirc\rangle_0|\bigcirc\rangle_1$$

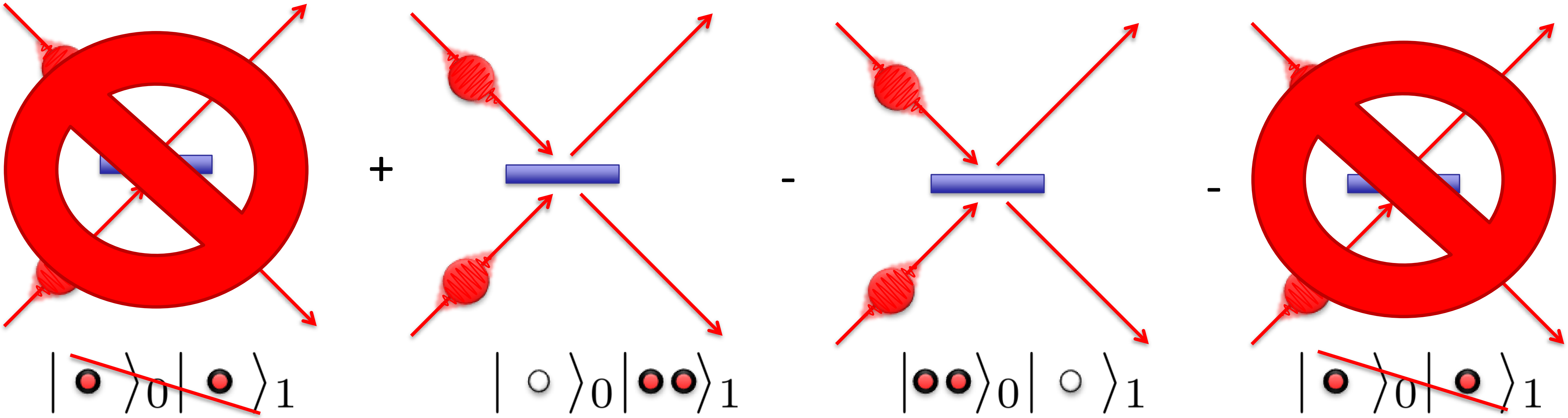
Destructive interference!

Two-Photon Interference

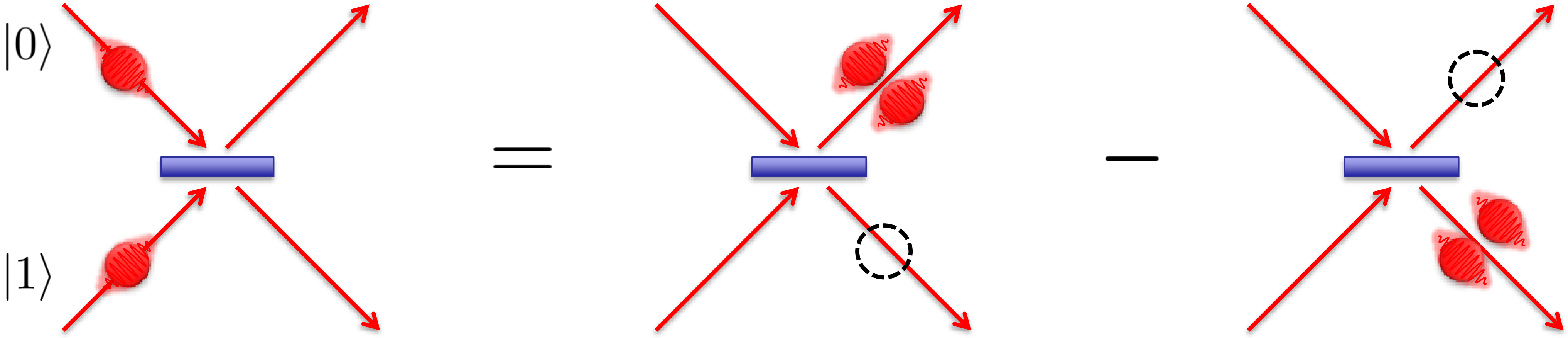
$$\hat{U}_{\mathrm{BS}}\hat{a}_0^\dagger\hat{a}_1^\dagger|\bigcirc\rangle_0|\bigcirc\rangle_1 = \frac{1}{2}\left(\hat{a}_0^\dagger\hat{a}_0^\dagger + \cancel{\hat{a}_0^\dagger\hat{a}_1^\dagger} - \cancel{\hat{a}_1^\dagger\hat{a}_0^\dagger} - \hat{a}_1^\dagger\hat{a}_1^\dagger\right)|\bigcirc\rangle_0|\bigcirc\rangle_1$$

$$= \frac{1}{2}\left(|\bigcirc\rangle_0|\bullet\bullet\rangle_1 - |\bullet\bullet\rangle_0|\bigcirc\rangle_1\right)$$

Photons always travel ***together***!



Two-Interference
(The Hong-Ou-Mandel Effect)

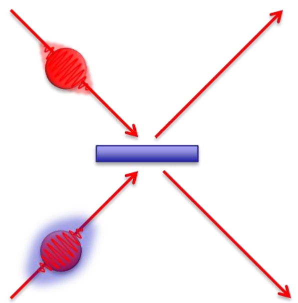


Photons always travel ***together***!

$$\hat{U}_{\mathrm{BS}}|\bullet\rangle_0|\bullet\rangle_1 = \frac{1}{\sqrt{2}}\left(|\circ\rangle_0|\bullet\bullet\rangle_1 - |\bullet\bullet\rangle_0|\circ\rangle_1\right)$$

The presence of one photon affects the path of the other
↓
Can build entangling gates

Superposition of higher photon numbers
↓
Useful for quantum metrology



What happens if the two photons have two different colours?

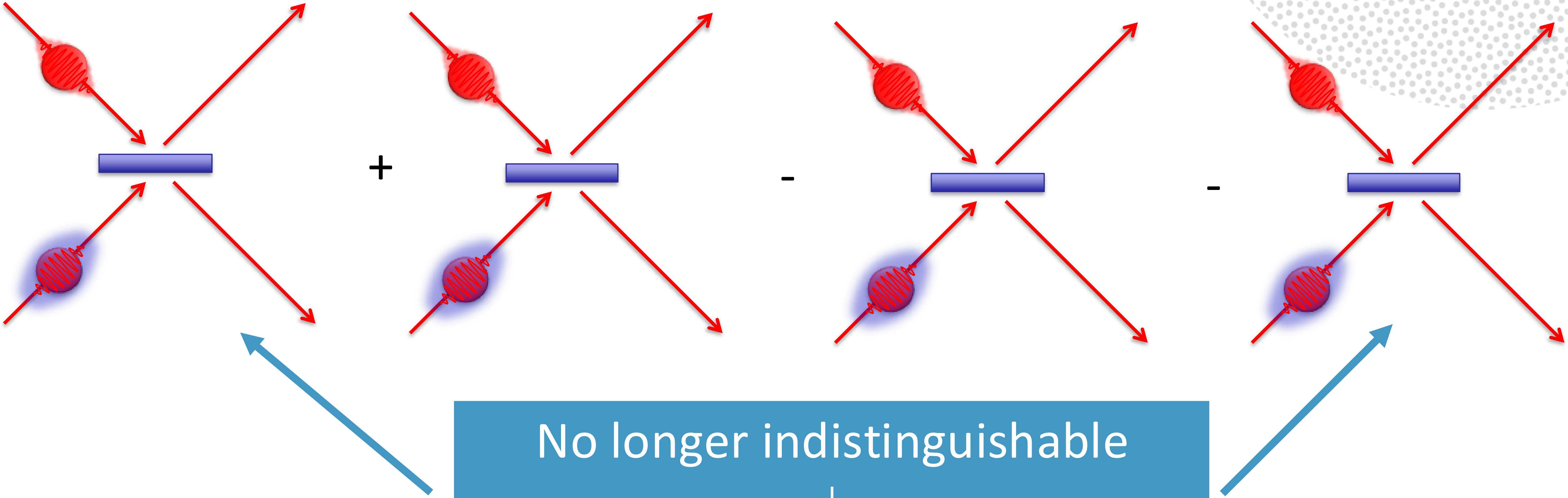
A. The still travel together

B. They go in opposite directions

C. They go in random directions (no interference)

D. They form a quantum colour

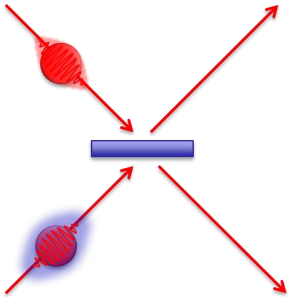
E. It’s impossible to know



No longer indistinguishable

↓

No more destructive interference



What happens if the two photons have two different colours?

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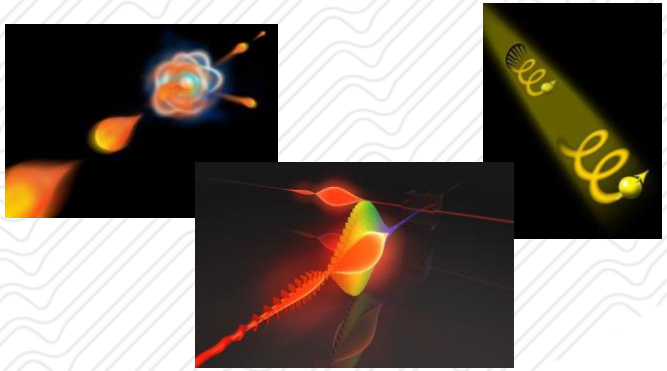
C. They go in random directions (no interference)

D. They form a quantum colour

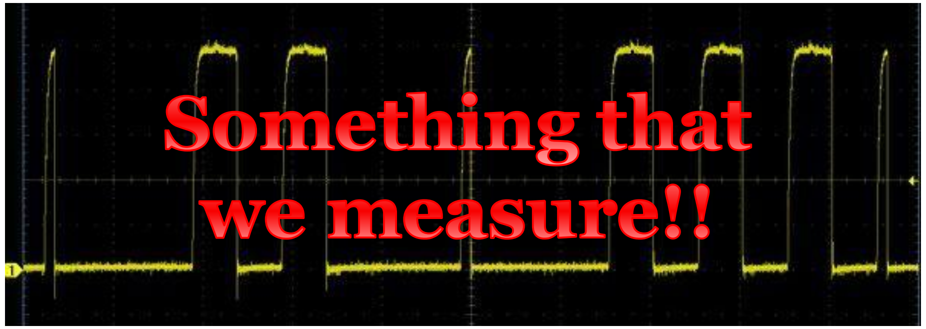
E. It's impossible to know

Question Break

What’s a photon really?



$$\hat{a}^{\dagger} | \circ \rangle = | \bullet \rangle$$

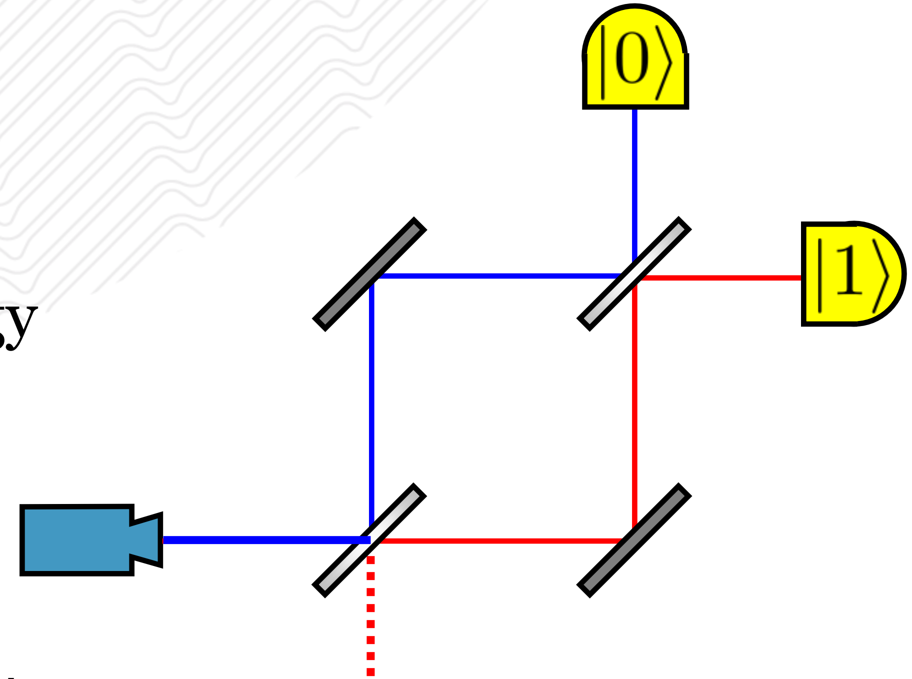


voltage

Detecting photons

A good photon detector should be:

- Sensitive!
  - It should respond to a single photon of energy
- Efficient!
  - It shouldn’t miss too many photons
- Isolated!
  - It should respond to only the interesting photons



What can detect a single photon?

PRL **112,** 213601 (2014) PHYSICAL REVIEW LETTERS week ending 30 MAY 2014

Interaction of Fixed Number of Photons with Retinal Rod Cells

Nam Mai Phan,[1,3] Mei Fun Cheng,[1] Dmitri A. Bessarab,[2] and Leonid A. Krivitsky[1,*]
[1]*Data Storage Institute, Agency for Science Technology and Research (A-STAR), 117608, Singapore*
[2]*Institute of Medical Biology, Agency for Science Technology and Research (A-STAR), 138648, Singapore*
[3]*Department of Bioengineering, National University of Singapore, 117576, Singapore*
(Received 18 December 2013; published 29 May 2014)

New tools and approaches of quantum optics offer a unique opportunity to generate light pulses carrying a precise number of photons. Accurate control over the light pulses helps to improve the characterization of photoinduced processes. Here, we study interaction of a specialized light source which provides flashes containing just one photon, with retinal rod cells of *Xenopus laevis* toads. We provide unambiguous proof of the single-photon sensitivity of rod cells without relying on the statistical modeling. We determine their quantum efficiencies without the use of any precalibrated detectors and obtain the value of $(29 \pm 4.7)\%$. Our approach provides the path for future studies and applications of quantum properties of light in phototransduction, vision, and photosynthesis.

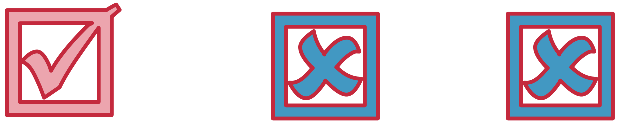
Xenopus laevis
"African clawed toad"

ARTICLE

Received 15 Jan 2016 | Accepted 7 Jun 2016 | Published 19 Jul 2016 DOI: 10.1038/ncomms12172 OPEN

Direct detection of a single photon by humans

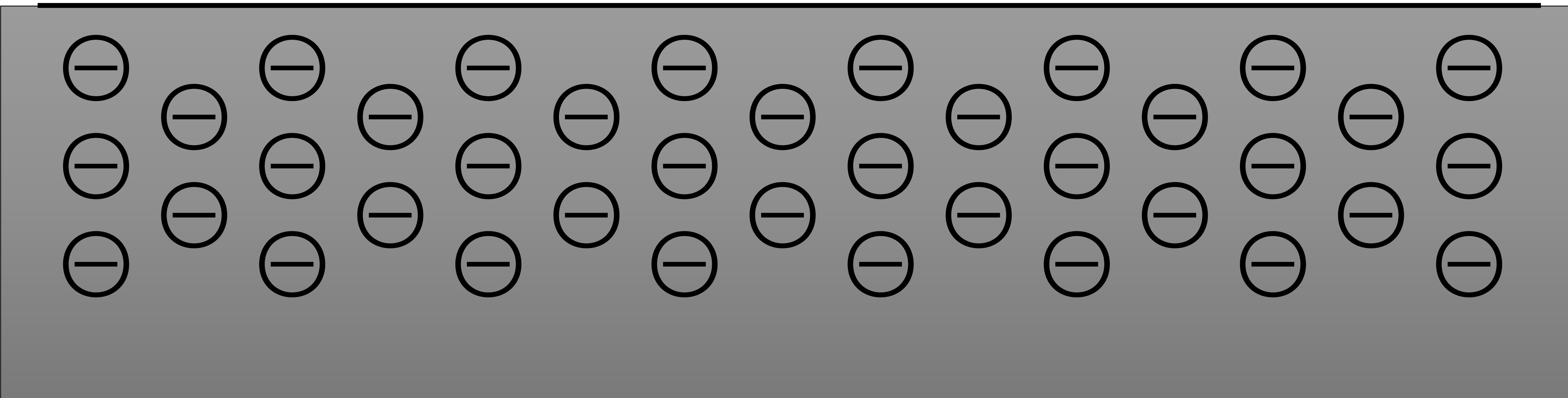
Jonathan N. Tinsley[1,2,†,*], Maxim I. Molodtsov[1,2,3,*], Robert Prevedel[1,2,3], David Wartmann[1,†], Jofre Espigulé-Pons[2,4], Mattias Lauwers[1] & Alipasha Vaziri[1,2,3,5]



Sensitivity – Efficiency - Isolation

The photoelectric effect

One photon is converted into one electron

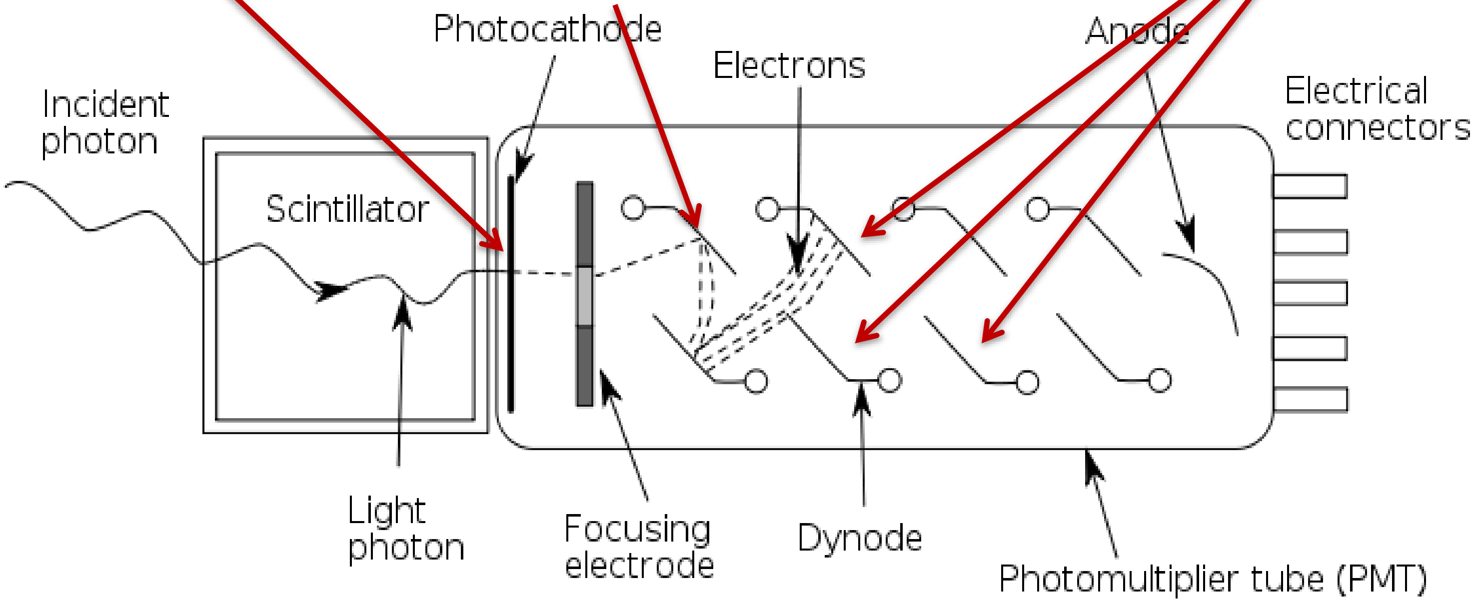


Photomultiplier Tubes

A photon knocks one electron out of photocathode.

The electron is accelerated, and crashes on next electrode, knocking out more electrons

This happens many times, until a measureable electrical signal is produced

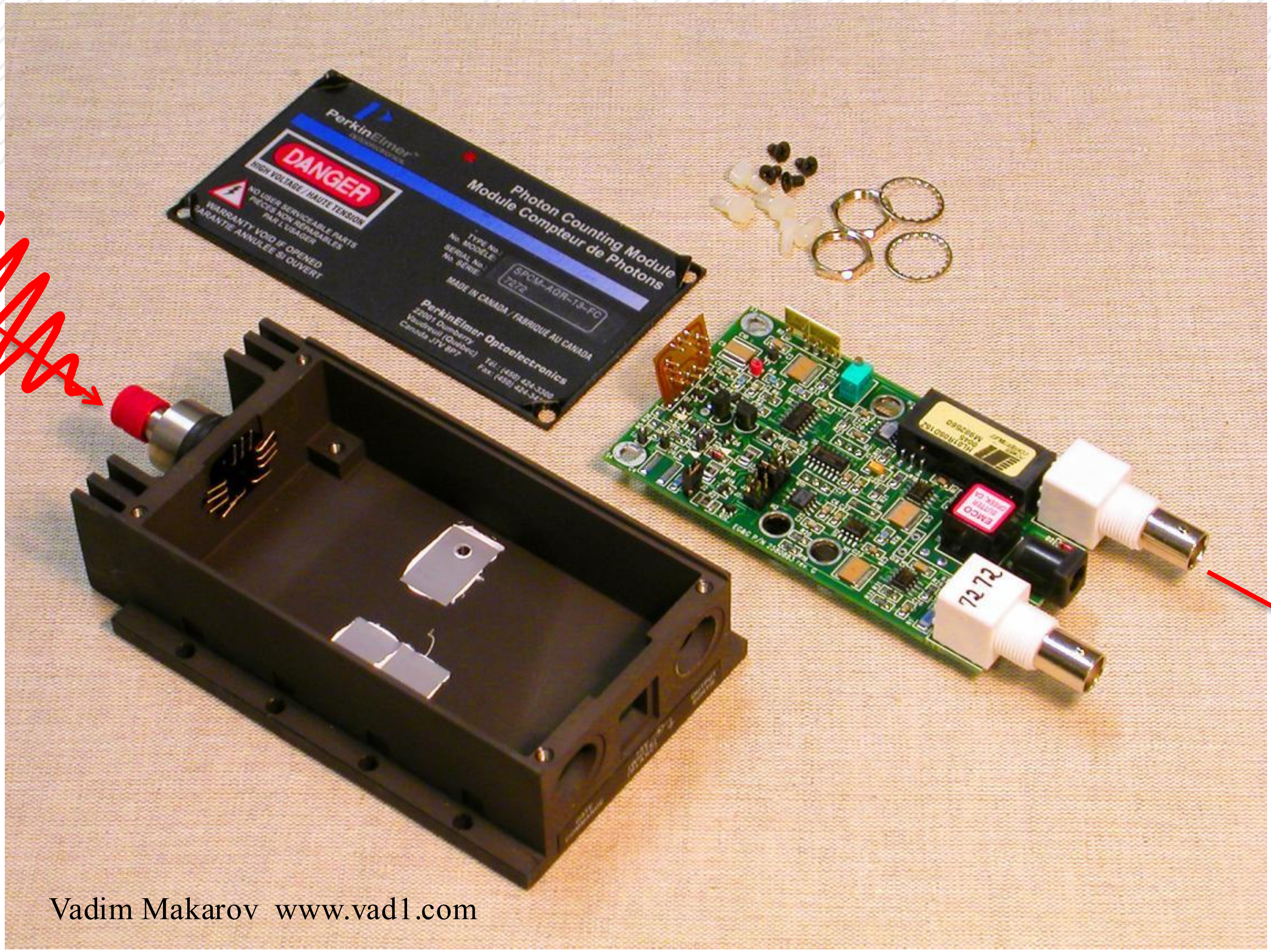


http://en.wikipedia.org/wiki/File:Photomultipliertube.svg

http://en.wikipedia.org/wiki/File:Pmside.jpg

Photon Detectors tl;dr

Photons go in

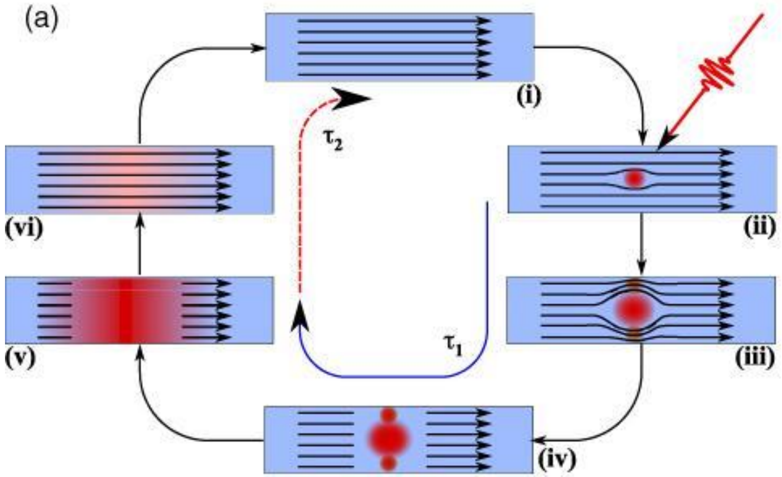


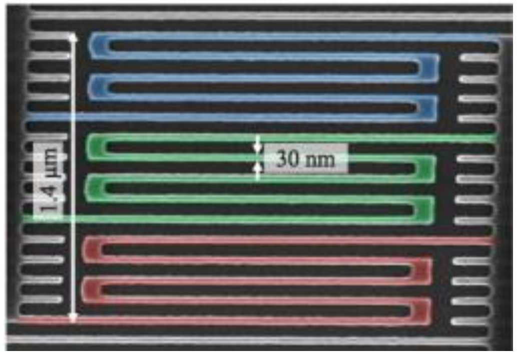
Electrical pulses come out

Superconducting Detectors

Superconductors are very sensitive to heating!

If a very thin superconductor absorbs a single photon,
it may stop superconducting.





Detect one photon
as a spike in resistance

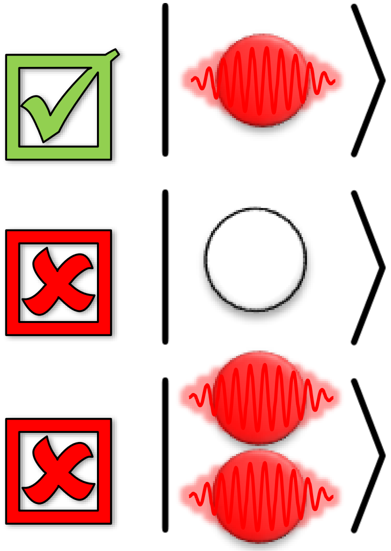
Very efficient,
but need very thin wires
(~ 50 nm)
at very low temperatures
(~ 5 K)

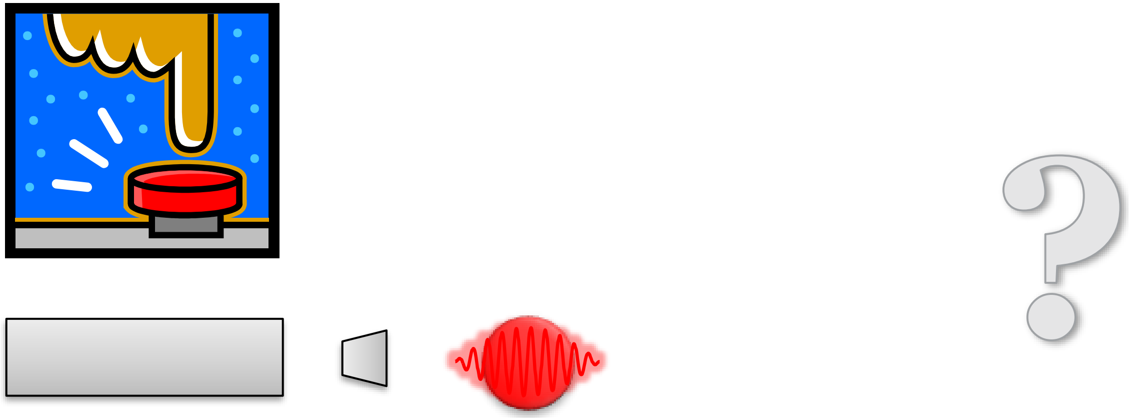
How do we <u>make</u> a photon?

We want **one and only one photon**!

We want it to **be there when we ask for it**!

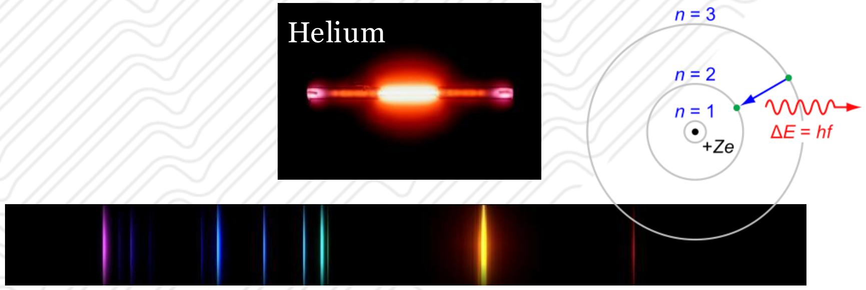
We want it to be **the right shape and color**!





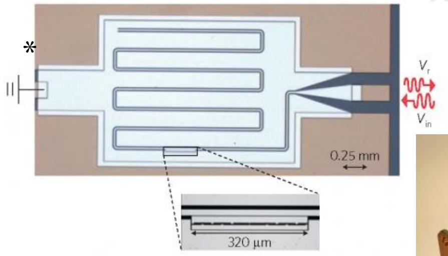
What kind of photons do we want?

We want to excite an atom
↓
It should have an exact energy,
probably visible



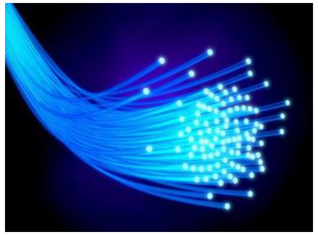
High energy

Low energy



We want to talk
to superconducting circuits
↓
It should probably be a microwave

We want to send it across a city
↓
It should probably be sent through fibre,
likely in the infrared energy region



Double-Slit with “Photons”

Proc. Camb. Philos. Soc., 15 (1909), 114–115

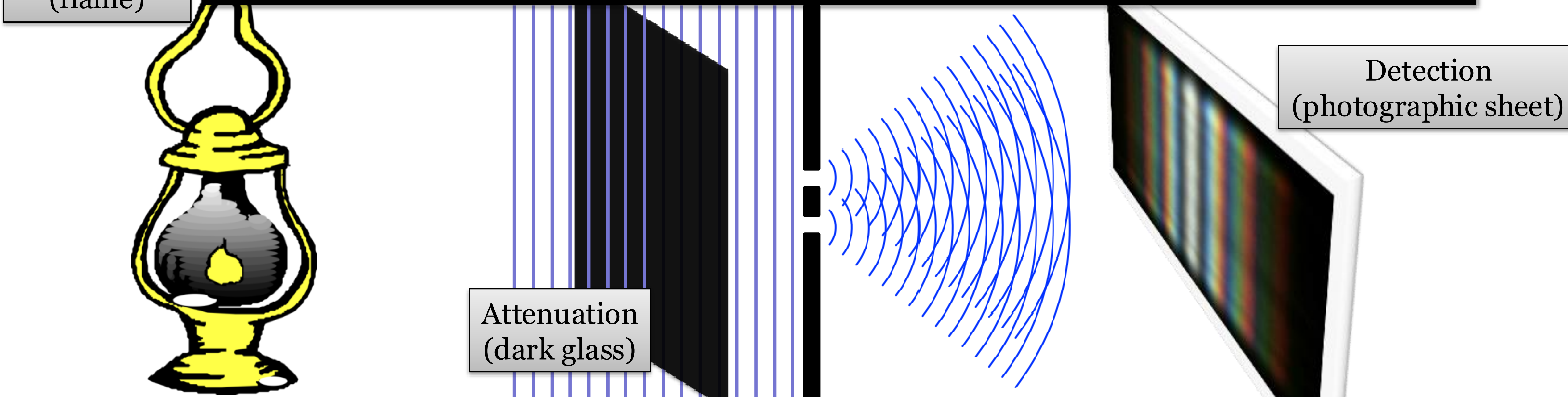
Interference Fringes with Feeble Light

G. I. TAYLOR

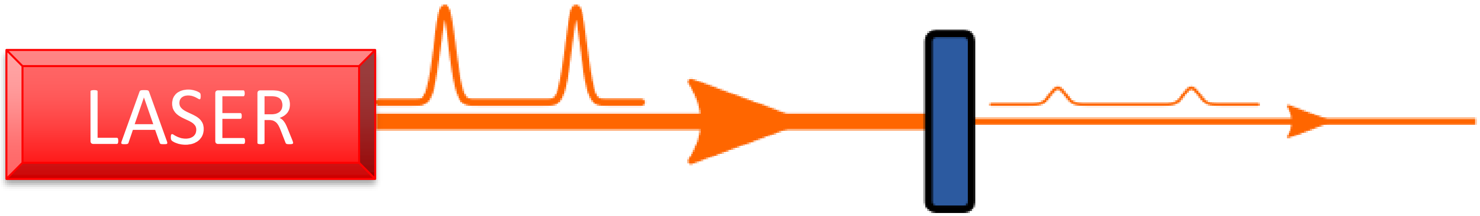
Trinity College, Cambridge, UK

Less than one photon in the experiment at a time

inverse ratio of the corresponding intensities. The longest time was 2000 hours or about 3 months. In no case was there any diminution in the sharpness of the pattern although the plates did not all reach the standard black-



Weak Coherent Light

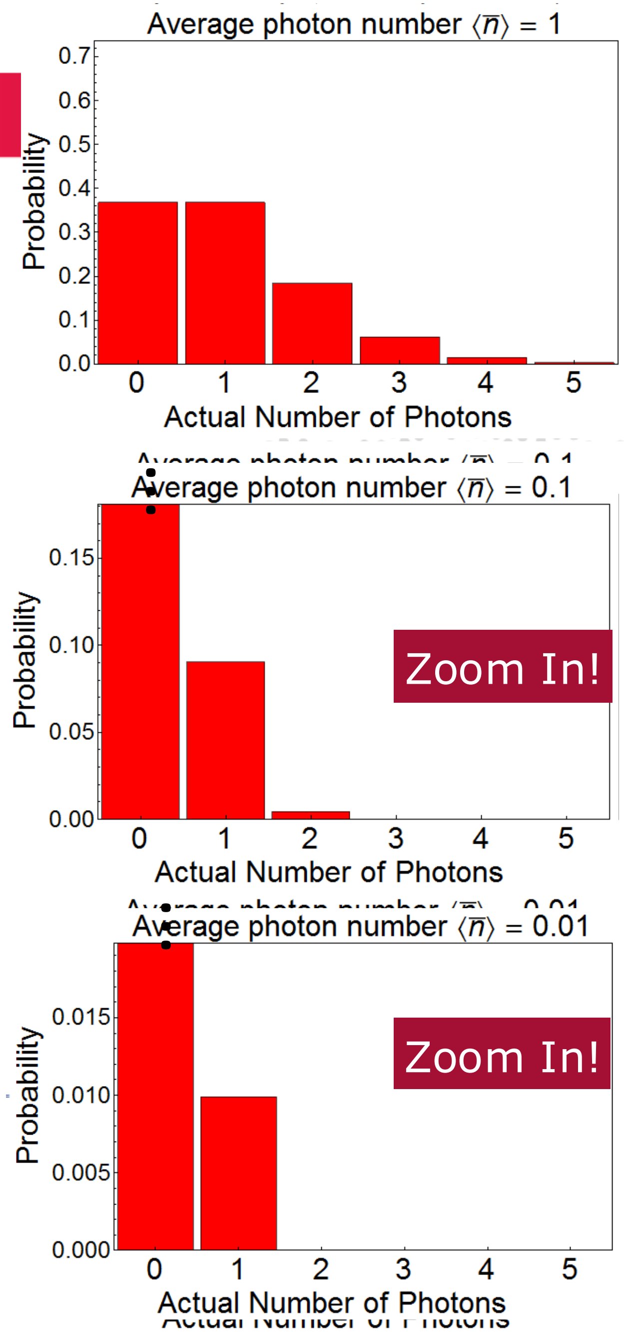


We can create “approximate” photons the same way using very weak laser pulses

Output light is weak enough that most pulses have **zero** photons

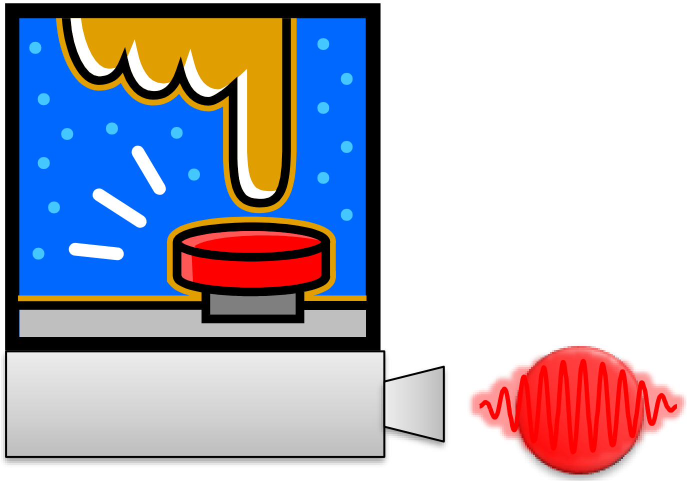
If we measure any photons, it’s unlikely that there was ever more than one

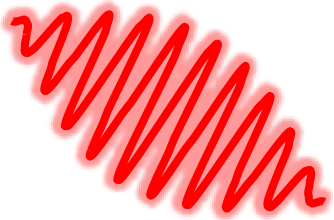
Good enough for (most) QKD!



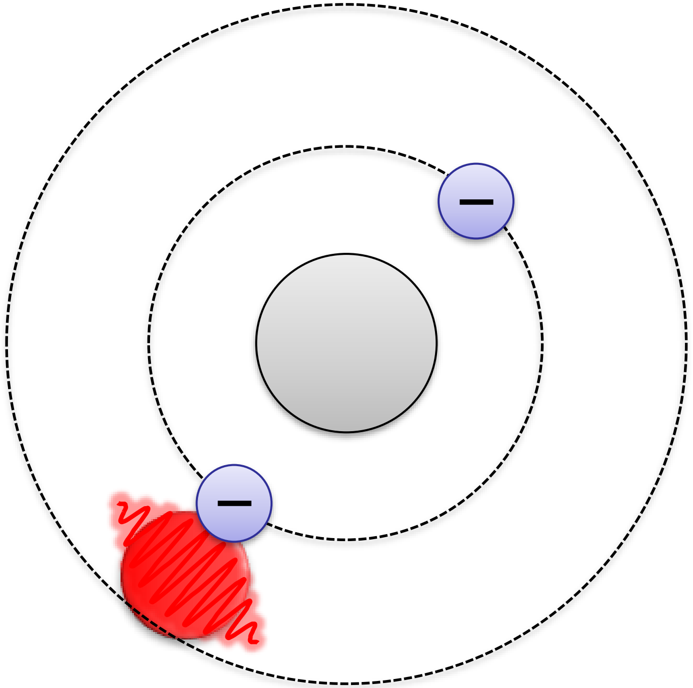
Photons on Demand

__Goal__
Push a button,
out comes a photon





__Idea__
Isolate a single atom,
excite it __only once__



__Problems__
Isolating a single atom is __hard__
Photons are emitted in every direction

Heralded Single Photons

A compromise: We don't get photons on demand…

… but know when to expect them!

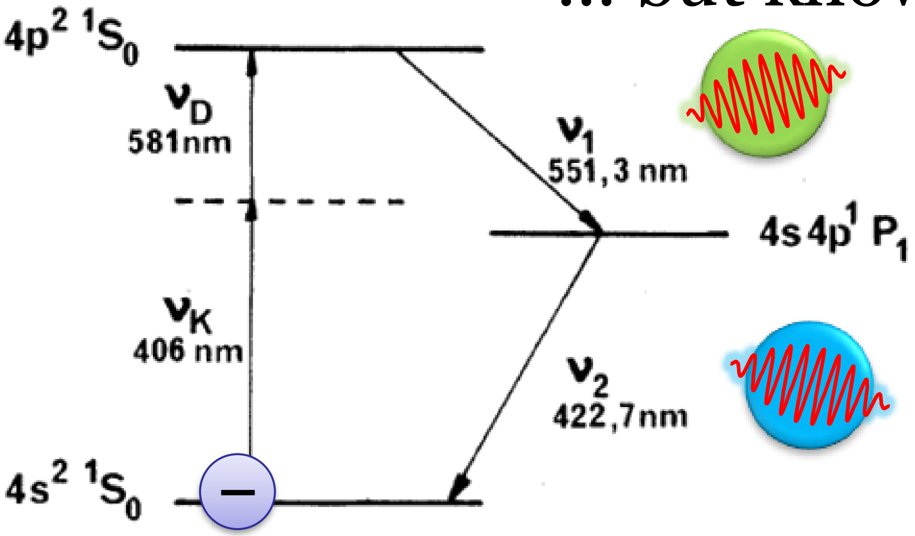


FIG. 1. Relevant levels of calcium. The atoms, selectively pumped to the upper level by the nonlinear absorption of ν_K and ν_L, emits the photons ν_1 and ν_2 correlated in polarization.

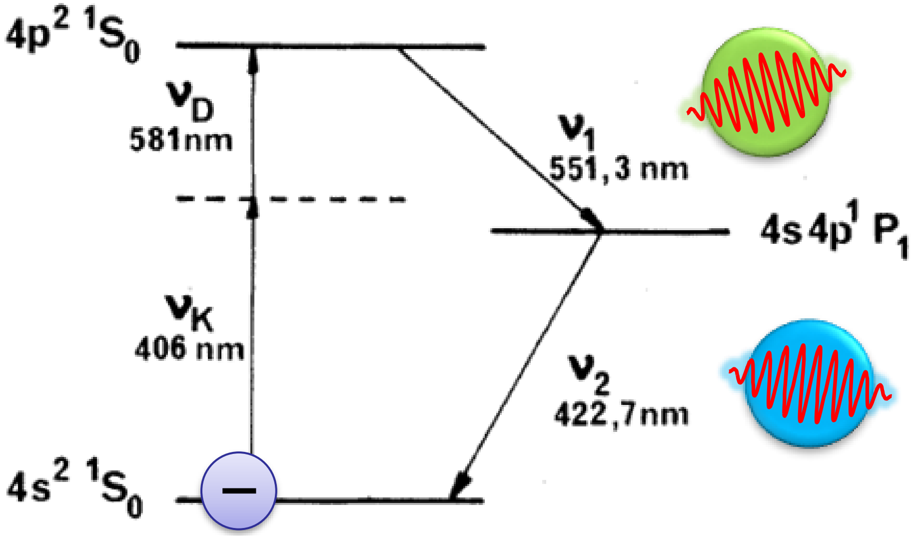
A. Aspect et al. PRL 47, 460–463 (1981)

Photons must come in **pairs**

Heralded Single Photons

A compromise: We don't get photons on demand…

… but know when to expect them!



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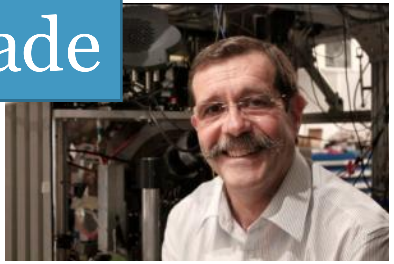
A. Aspect et al. PRL 47, 460–463 (1981)

A photon is coming!

Atomic cascade



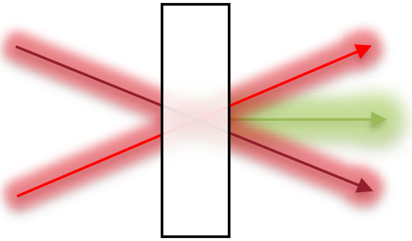
I'm ready!

Big problem:
No idea where to look!

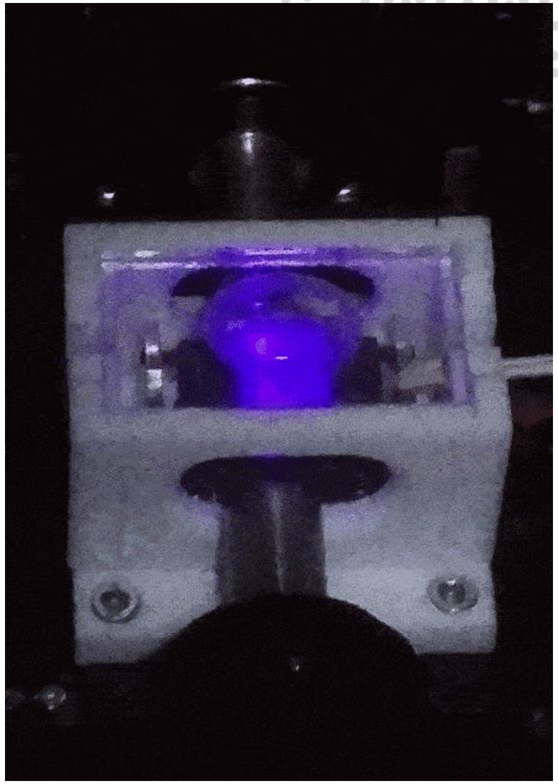
Using Nonlinear Optics

Prof. Donna Strickland
2018 Nobel Prize in Physics

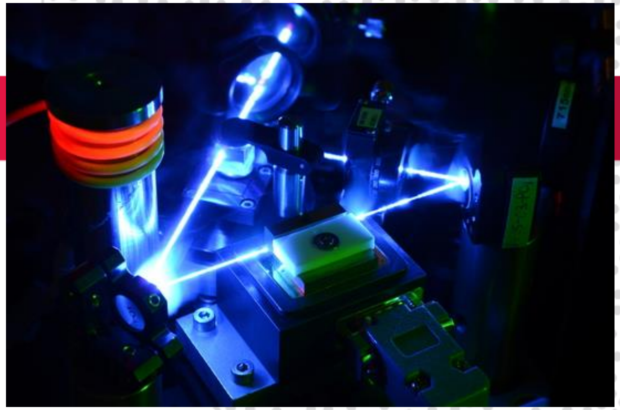
Nonlinear interactions
allow light to change color

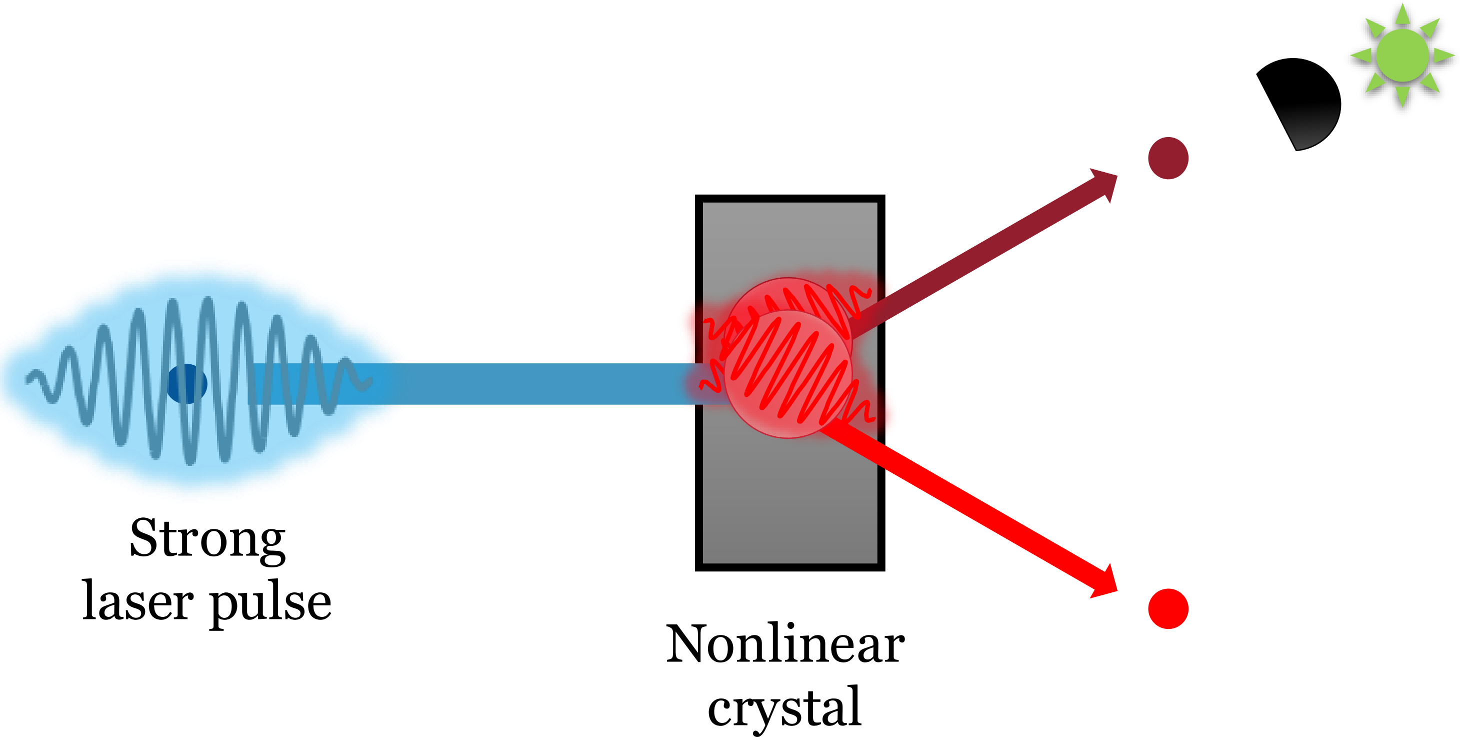


Essential for
generating and interfacing
single photons



Heralded Single Photons





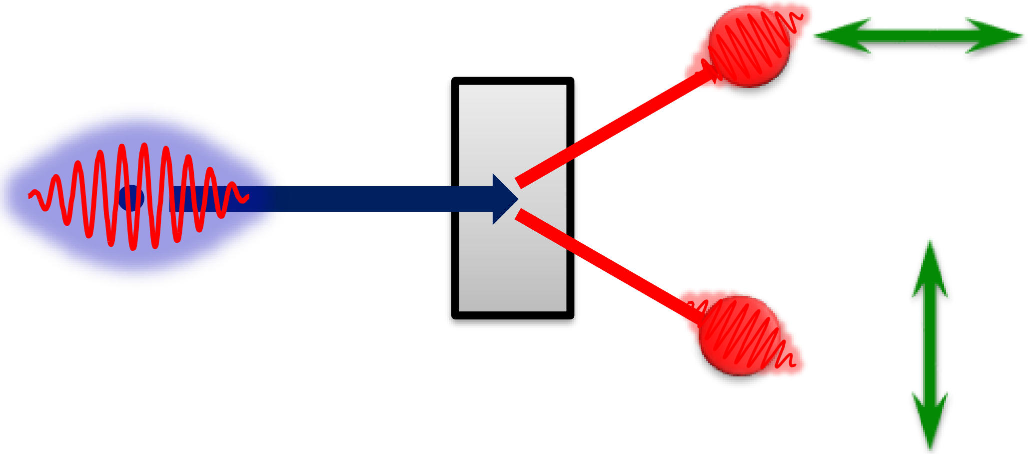
If I detect a
photon here…

Pair of
entangled
photons

…then I know
there's **one**
photon here!

Spontaneous Parametric Downconversion
(SPDC)

Polarization Entanglement



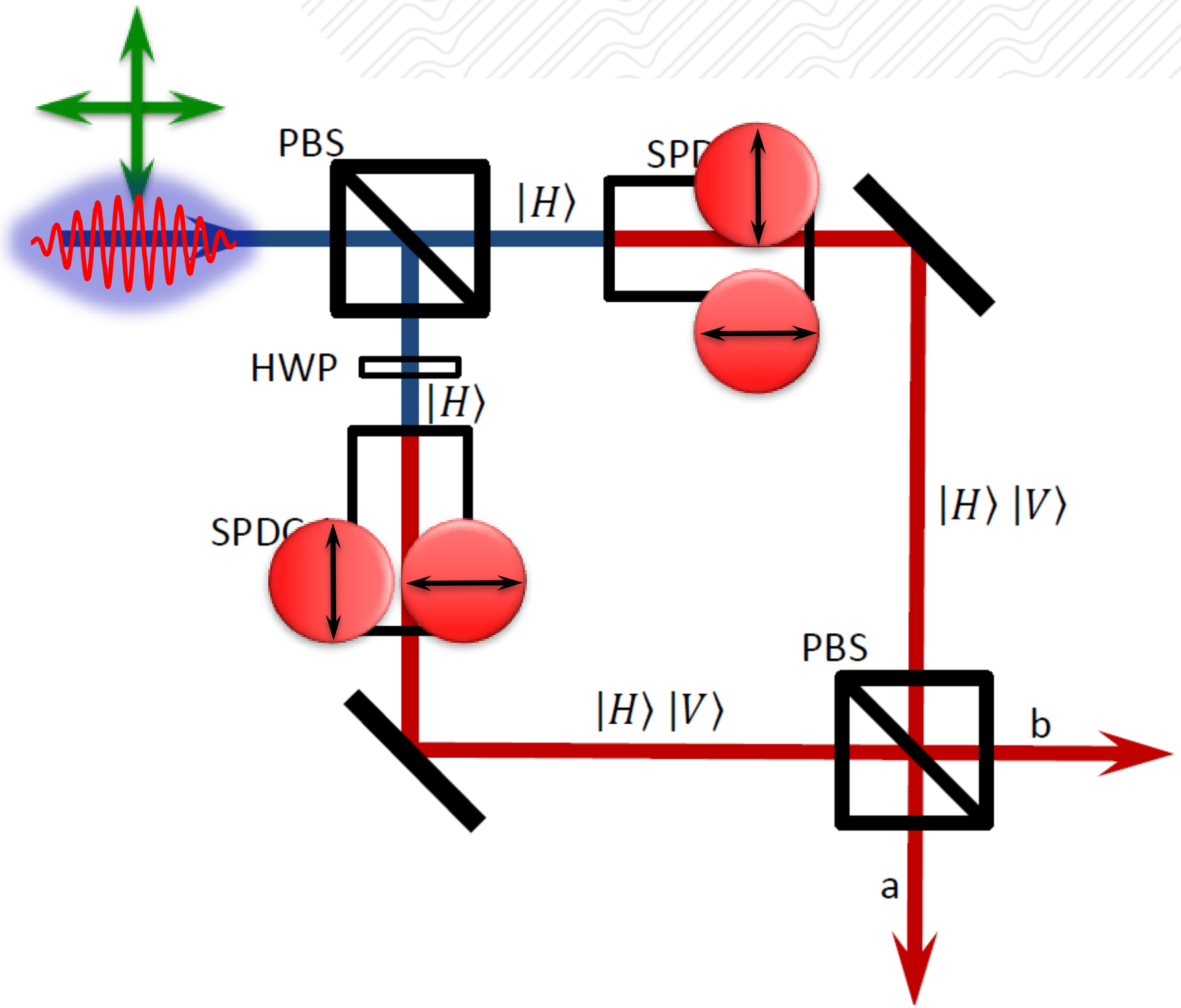
In many crystals,
the geometry ensures that both photons
are orthogonally polarized

$$|\psi\rangle = |H\rangle_s |V\rangle_i$$

The dream: $$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_s|V\rangle_i - |V\rangle_s|H\rangle_i\right)$$

Can be done by confusing the photons

Polarization Entanglement



<u>Interferometric solution</u>

Each crystal produces:

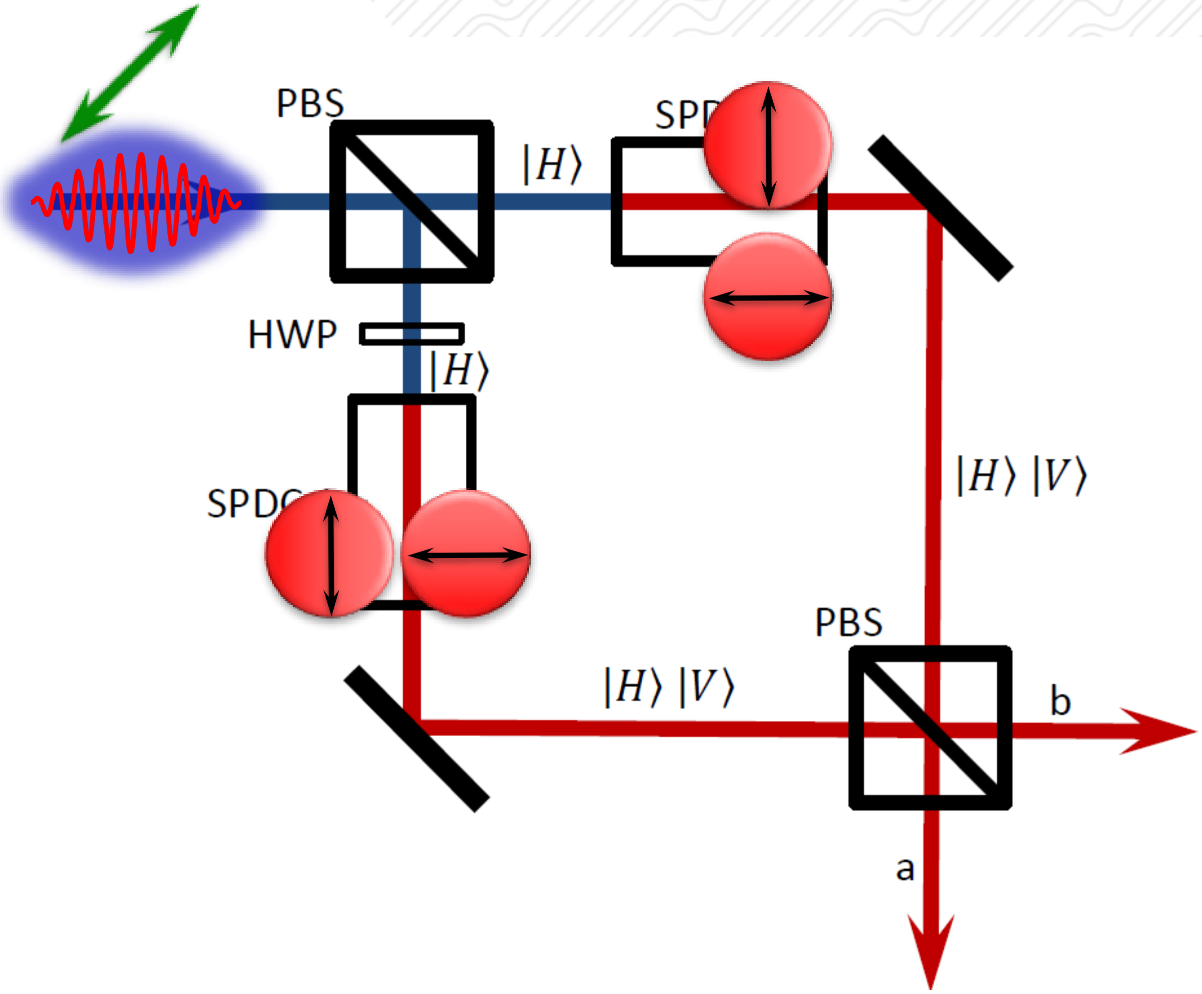
$$|\psi\rangle = |H\rangle_s|V\rangle_i$$

Assume only one downconversion happens

If SPDC 1: $|\psi\rangle = |V\rangle_a|H\rangle_b$

If SPDC 2: $|\psi\rangle = |H\rangle_a|V\rangle_b$

Polarization Entanglement



Interferometric solution

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$$|\psi\rangle = |H\rangle_s |V\rangle_i$$

Assume only one downconversion happens

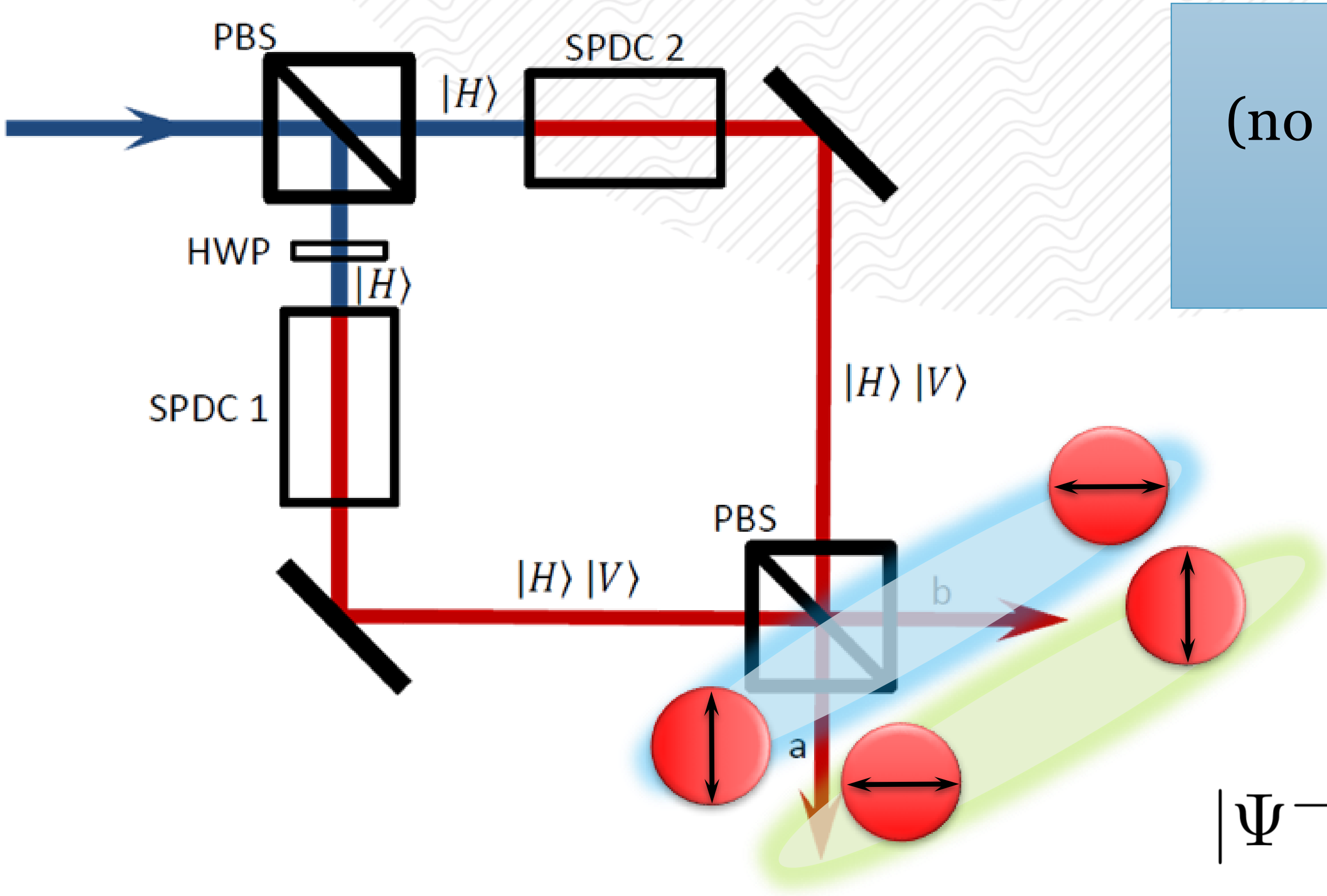
If SPDC 1: $|\psi\rangle = |V\rangle_a |H\rangle_b$

If SPDC 2: $|\psi\rangle = |H\rangle_a |V\rangle_b$

Superposition:

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

Polarization Entanglement



If events are indistinguishable
(no information exists that tells which
crystal produced photons),
we get entanglement!

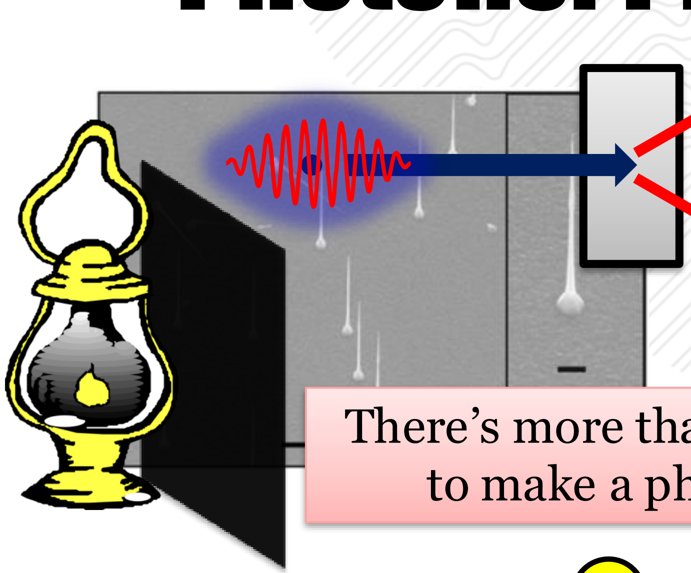
If SPDC 1: $|\psi\rangle = |V\rangle_a |H\rangle_b$

If SPDC 2: $|\psi\rangle = |H\rangle_a |V\rangle_b$

Superposition:

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

Photons! Photons! Photons!

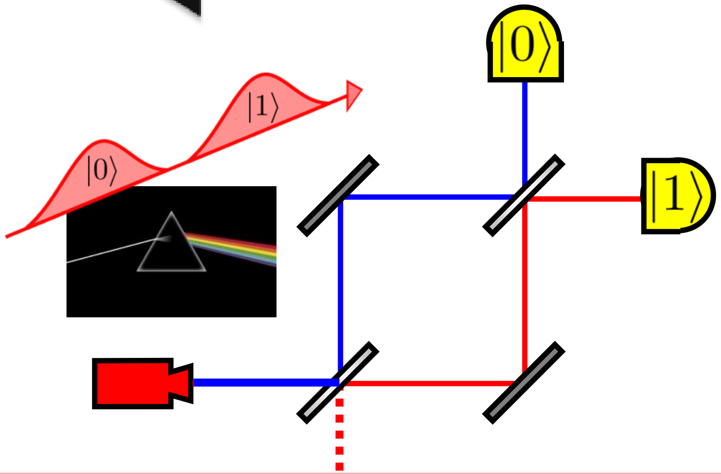


There's more than one way to make a photon...

...in many shapes and colours...

$$\hat{a}^{\dagger} | \circ \rangle = | \bullet \rangle$$

...which are mathematically defined by creation operators...



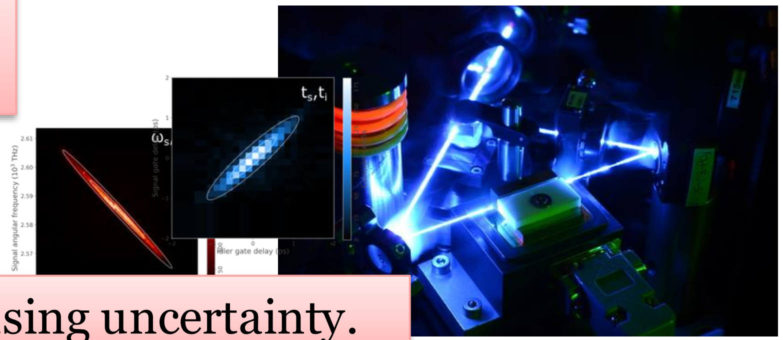
...which can be implemented in many ways...

Photon here

No photon here

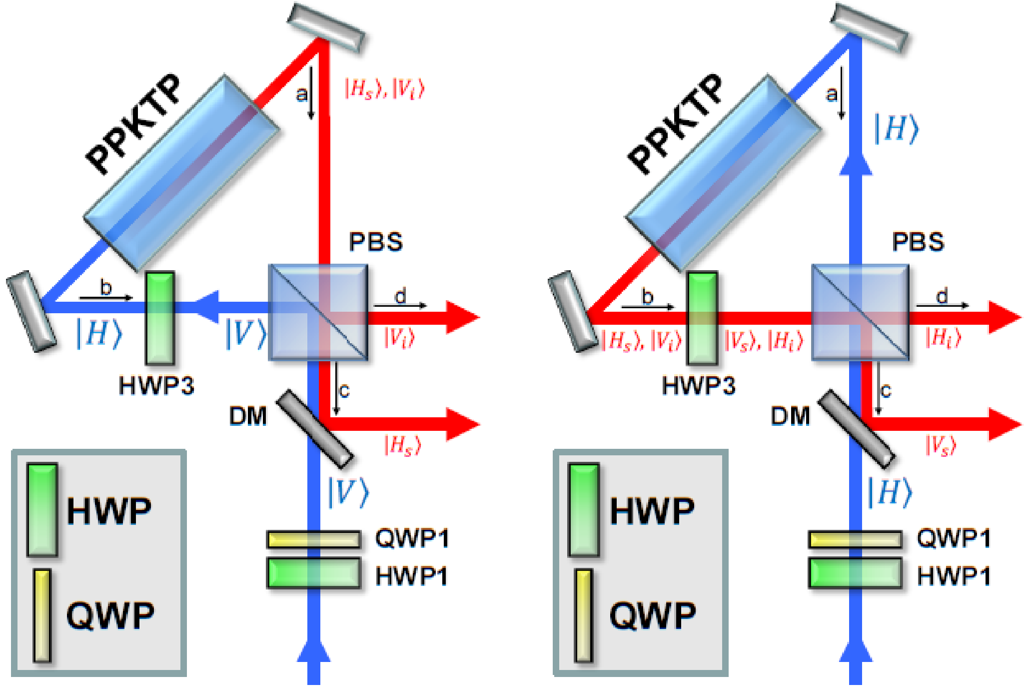
$$\hat{a}_0^{\dagger} | \circ \rangle_0 | \circ \rangle_1 = | \bullet \rangle_0 | \circ \rangle_1$$

...which can be used to define photonic qubits...

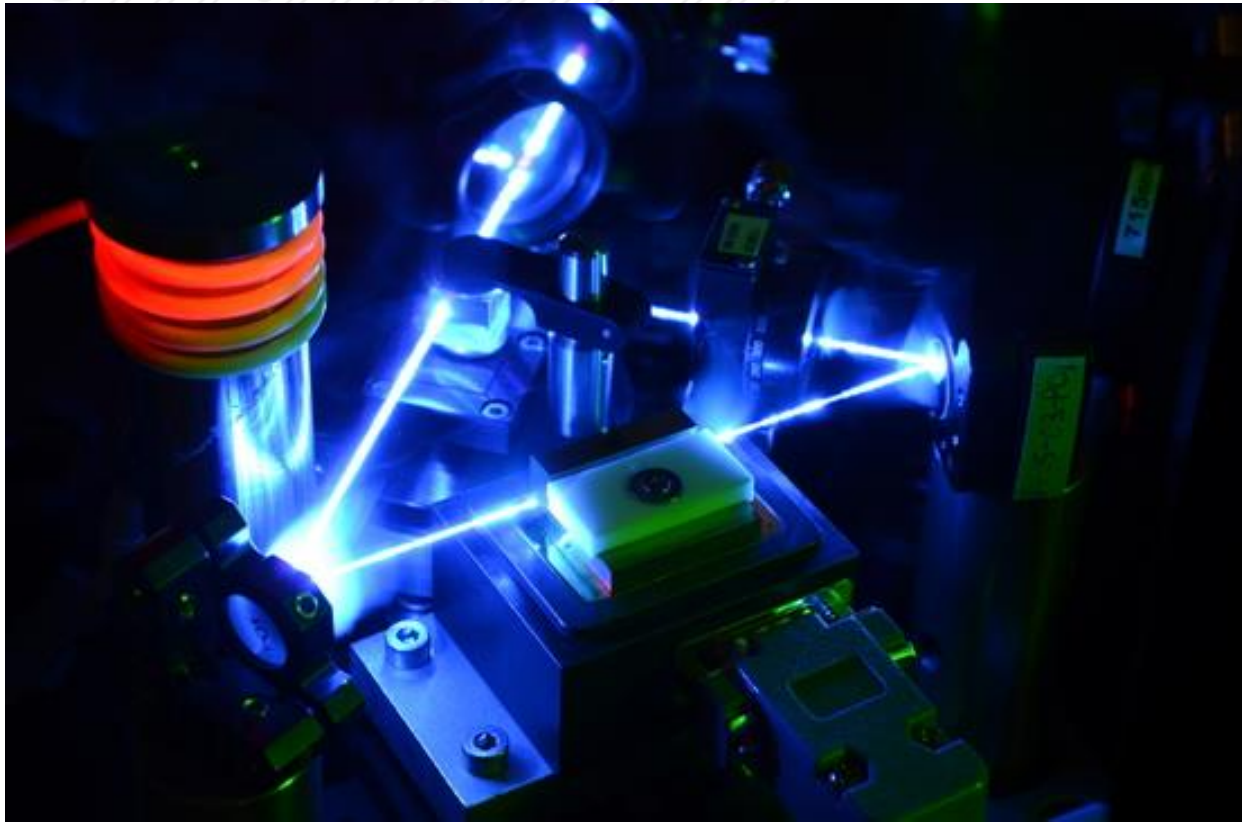


...and entangled using uncertainty.

Polarization Entanglement in the Lab



Folded for stability
(Sagnac Interferometer)



Quantum Networking in Chicago

Fermilab

California Institute of Technology

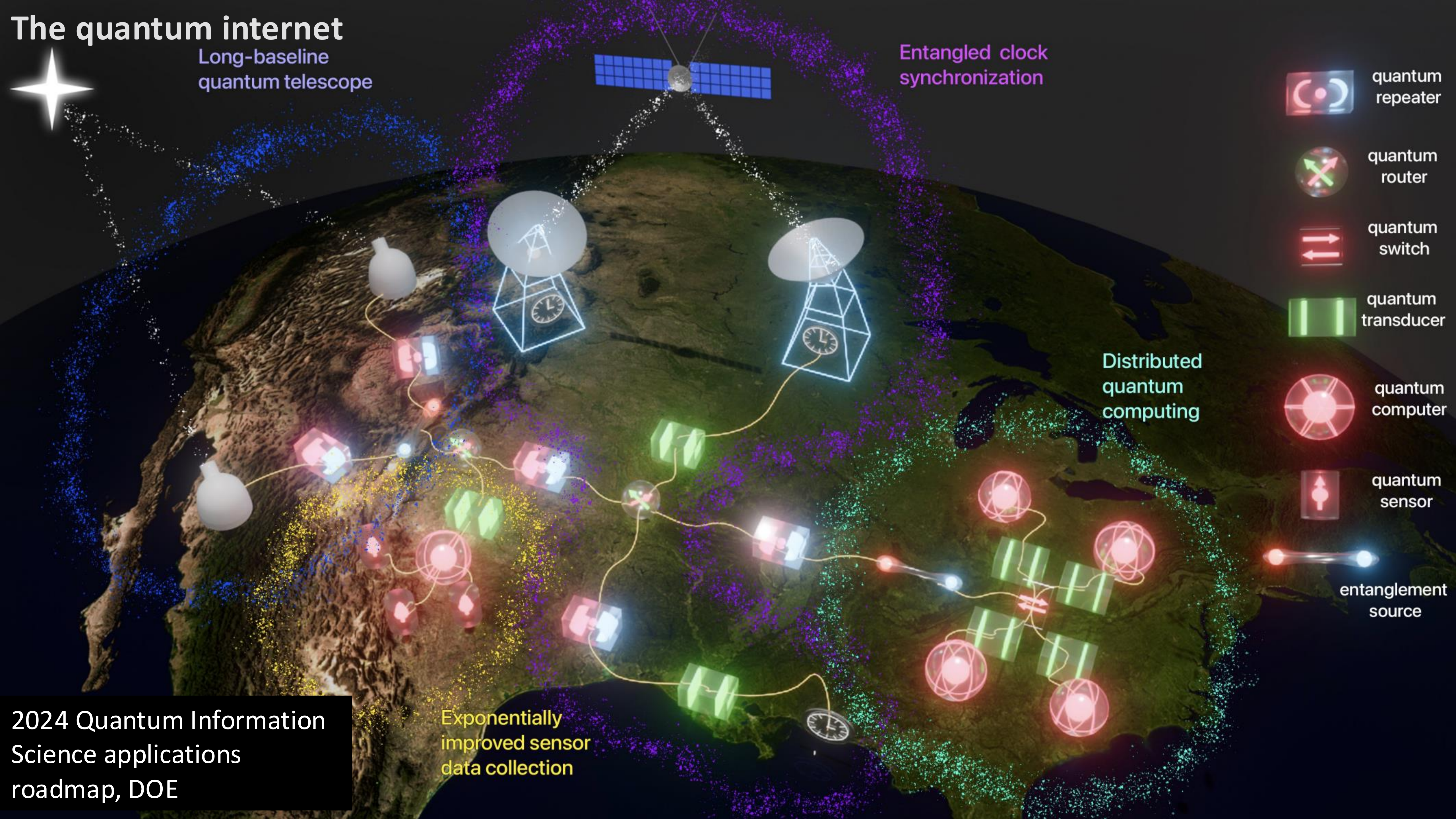
University of Illinois Urbana-Champaign

Northwestern University

JPL
Jet Propulsion Laboratory
California Institute of Technology

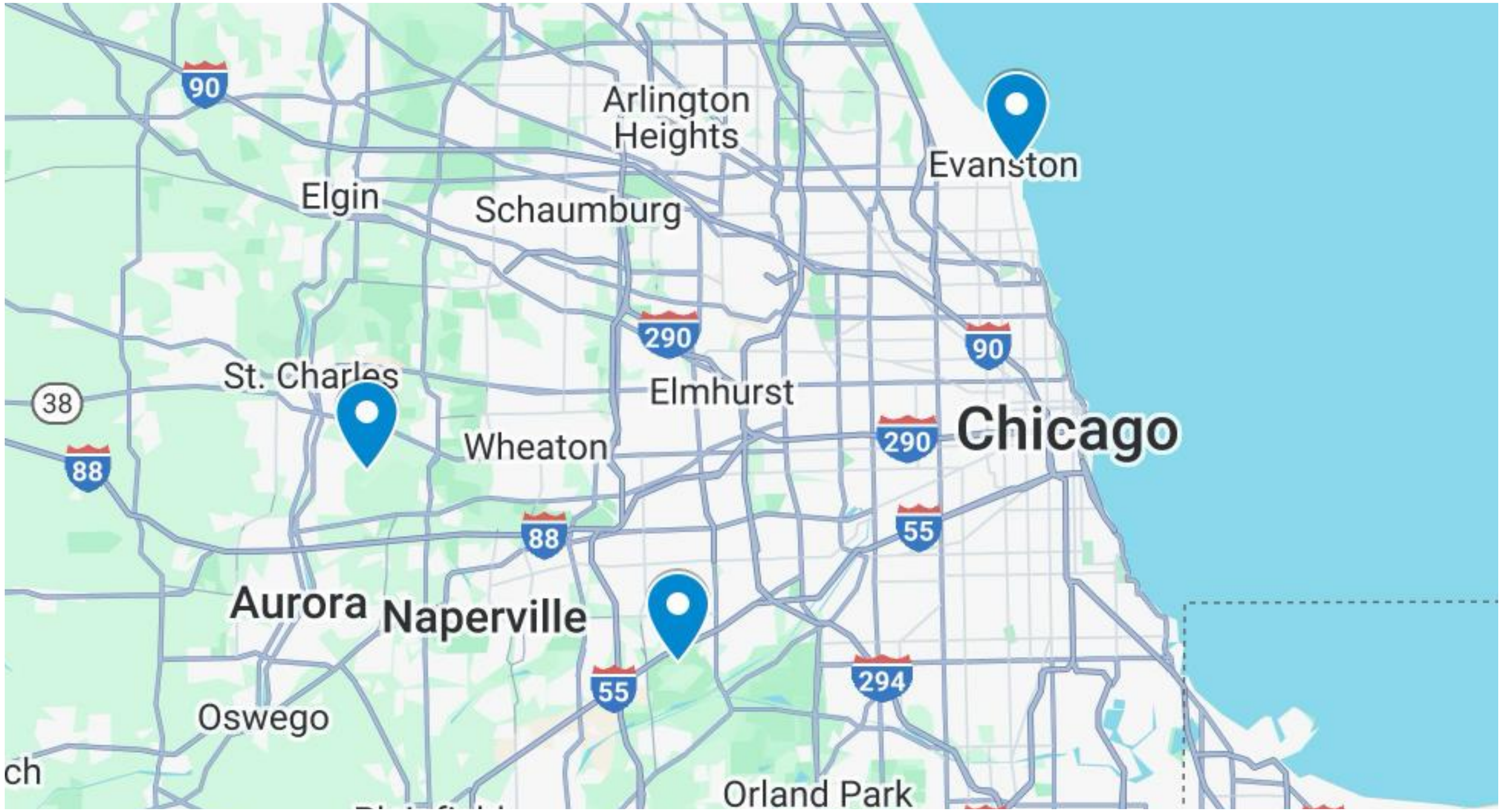
Argonne National Laboratory

The quantum internet

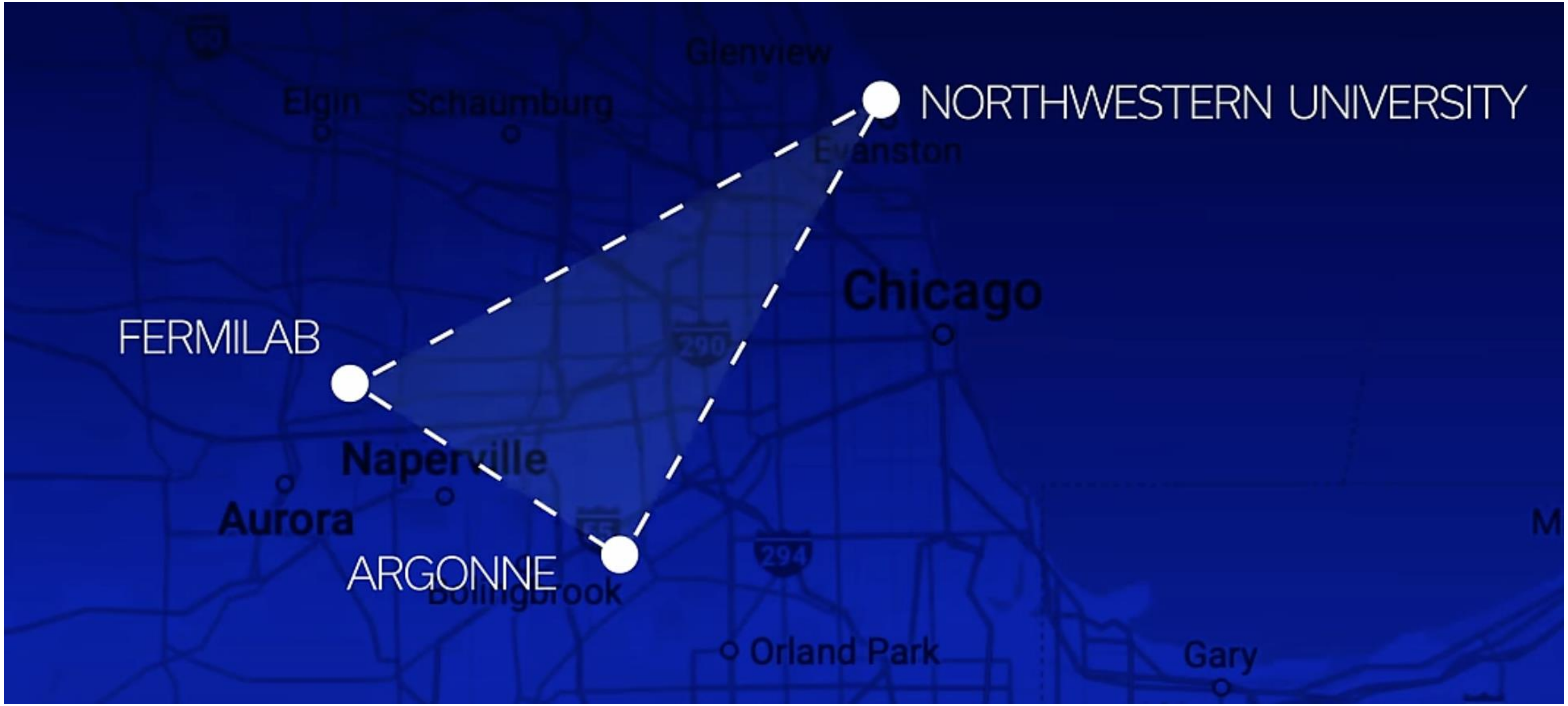


2024 Quantum Information Science applications roadmap, DOE

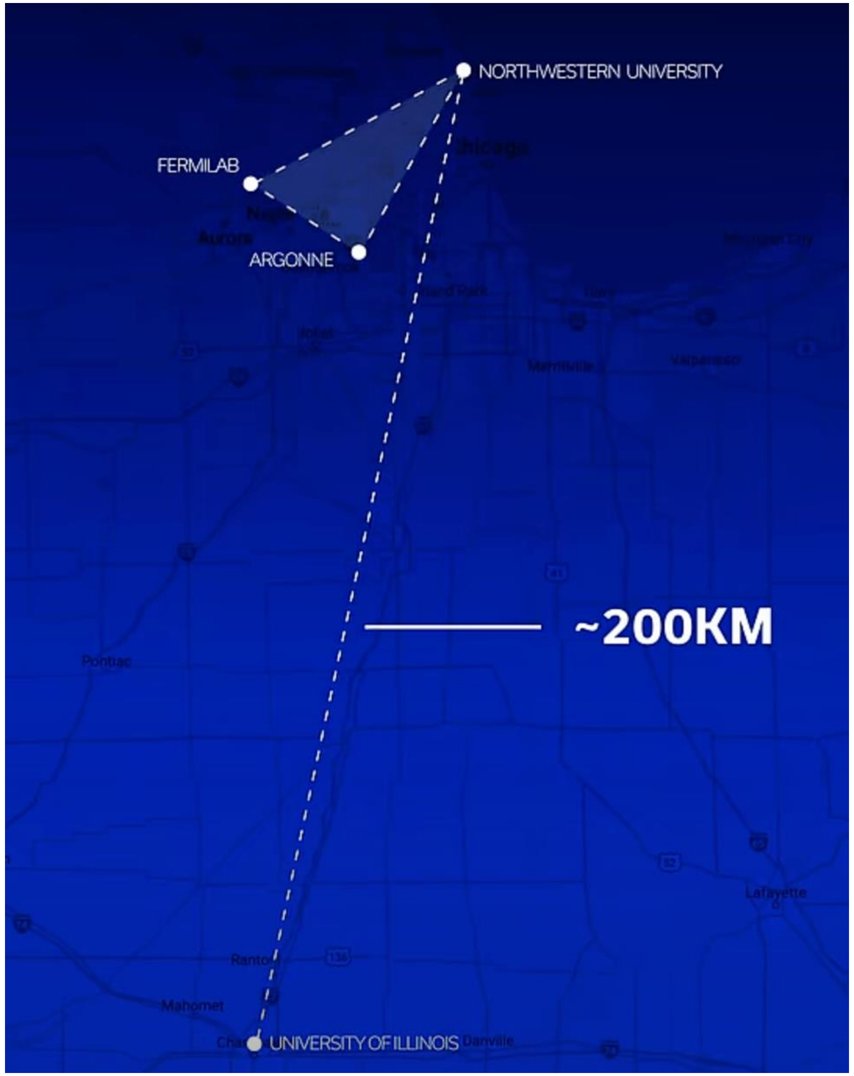
Advanced Quantum Network (AQNET)



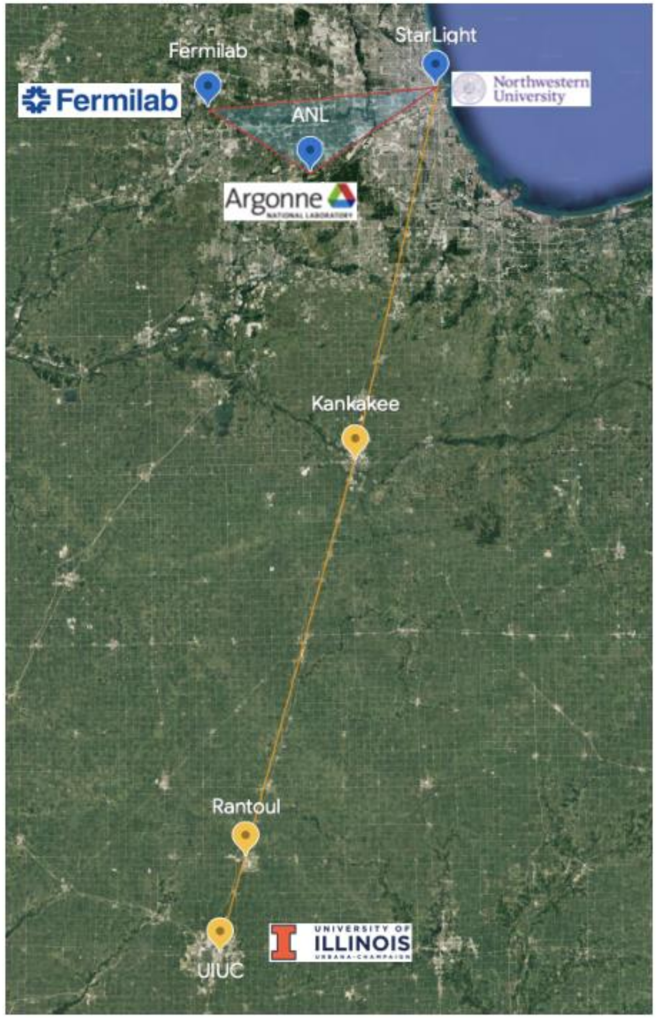
Advanced Quantum Network (AQNET)



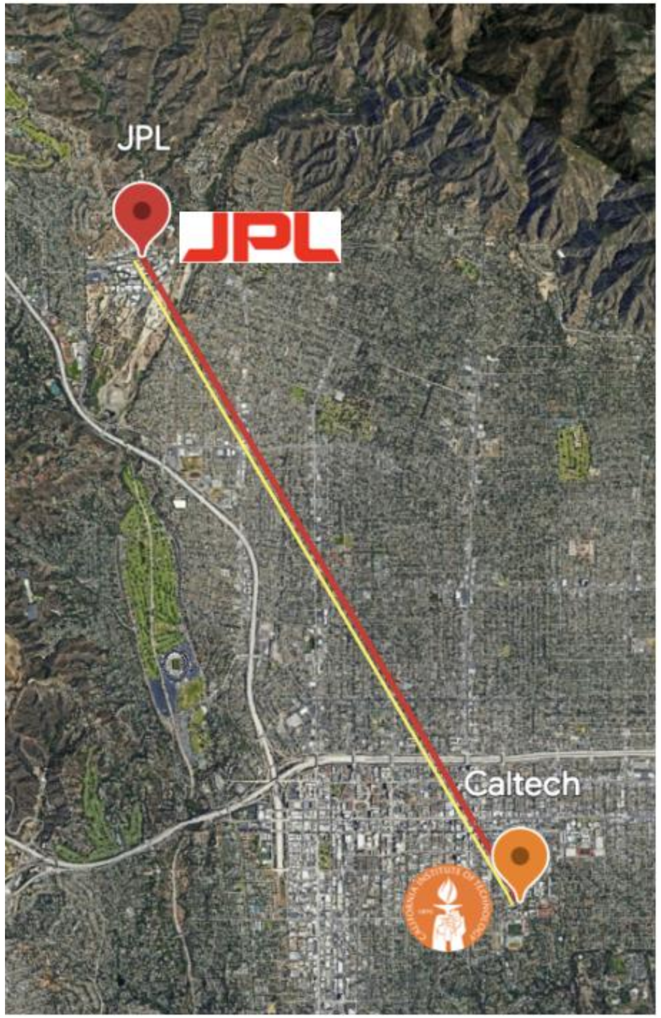
Advanced Quantum Network (AQNET)



Chicago-based Networks developed in parallel with Pasadena-based Networks

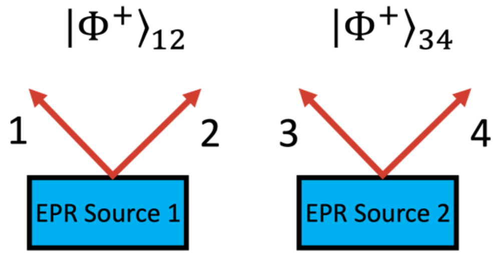


AQNET



Moving to long distance

Entanglement Swapping



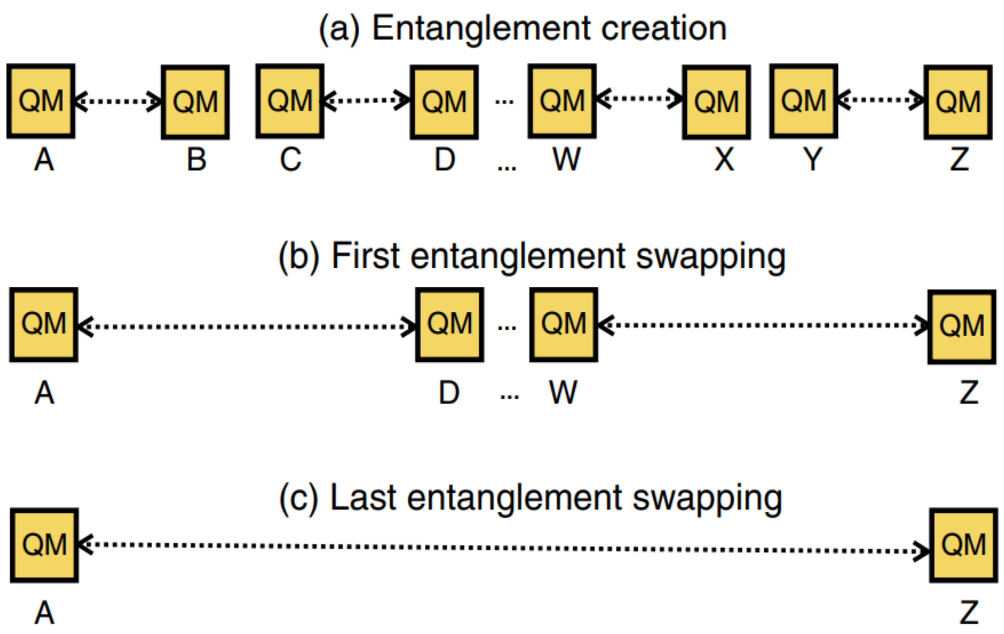
$$|\Psi\rangle_{1234} = |\Phi^+\rangle_{12} \otimes |\Phi^+\rangle_{34}$$

$$= \frac{1}{2}(|ee\rangle + |ll\rangle) \otimes (|ee\rangle + |ll\rangle)$$

$$= \frac{1}{2}|\Psi^+\rangle_{14}|\Psi^+\rangle_{23} + \frac{1}{2}|\Psi^-\rangle_{14}|\Psi^-\rangle_{23} + \frac{1}{2}|\Phi^+\rangle_{14}|\Phi^+\rangle_{23} + \frac{1}{2}|\Phi^-\rangle_{14}|\Phi^-\rangle_{23}$$

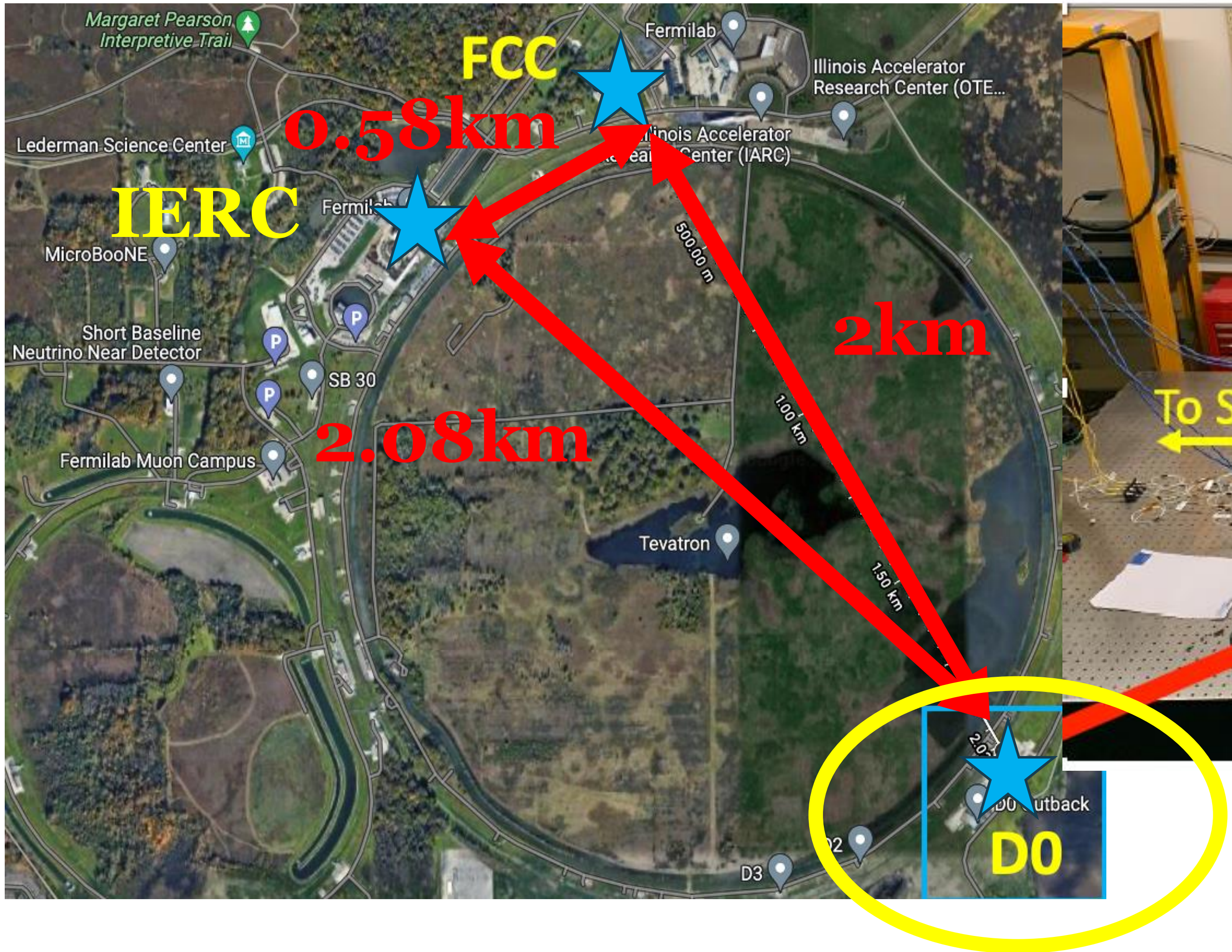
Projective measurement of photons 2 and 3 in the Bell basis entangles photons 1 and 4

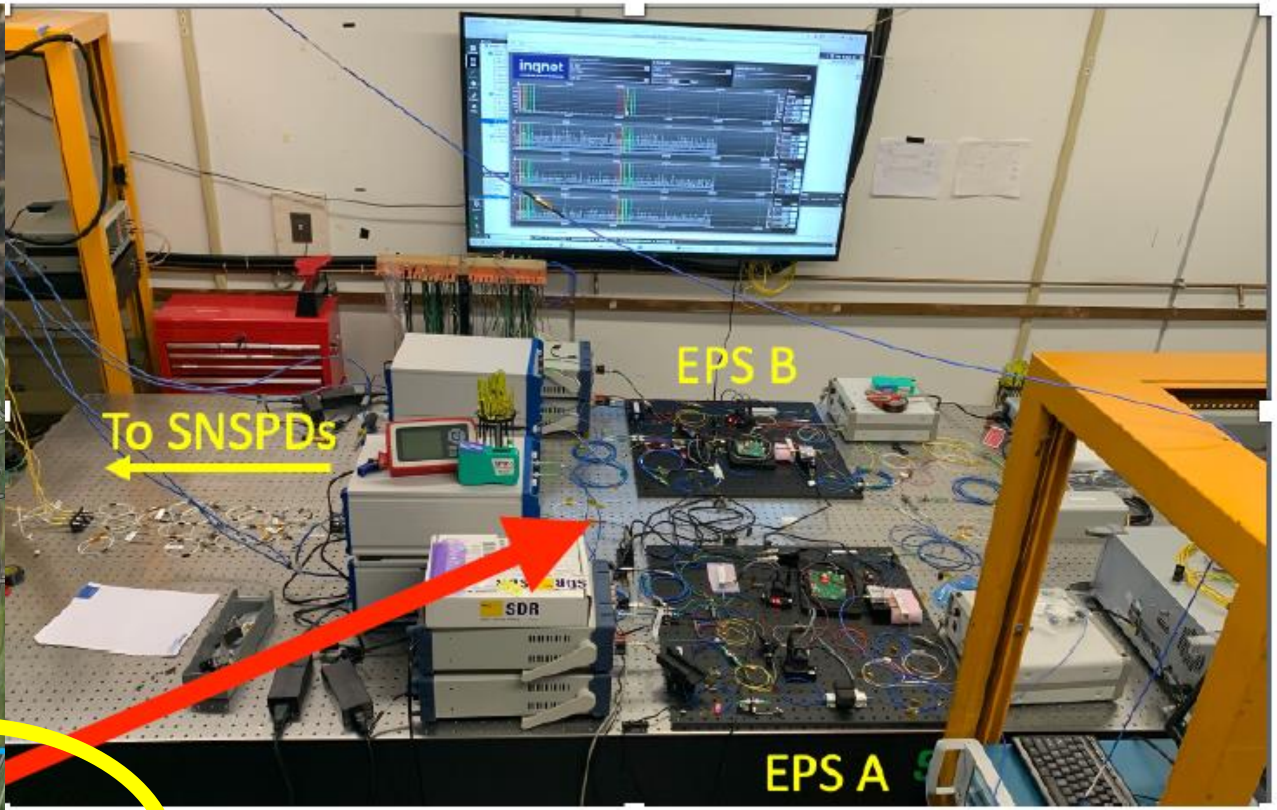
Quantum Repeater



Nicolas Sangouard, Christoph Simon, Hugues de Riedmatten, and Nicolas Gisin. *Rev. Mod. Phys.* **83**, 33 (2011).

Fermilab Quantum Network

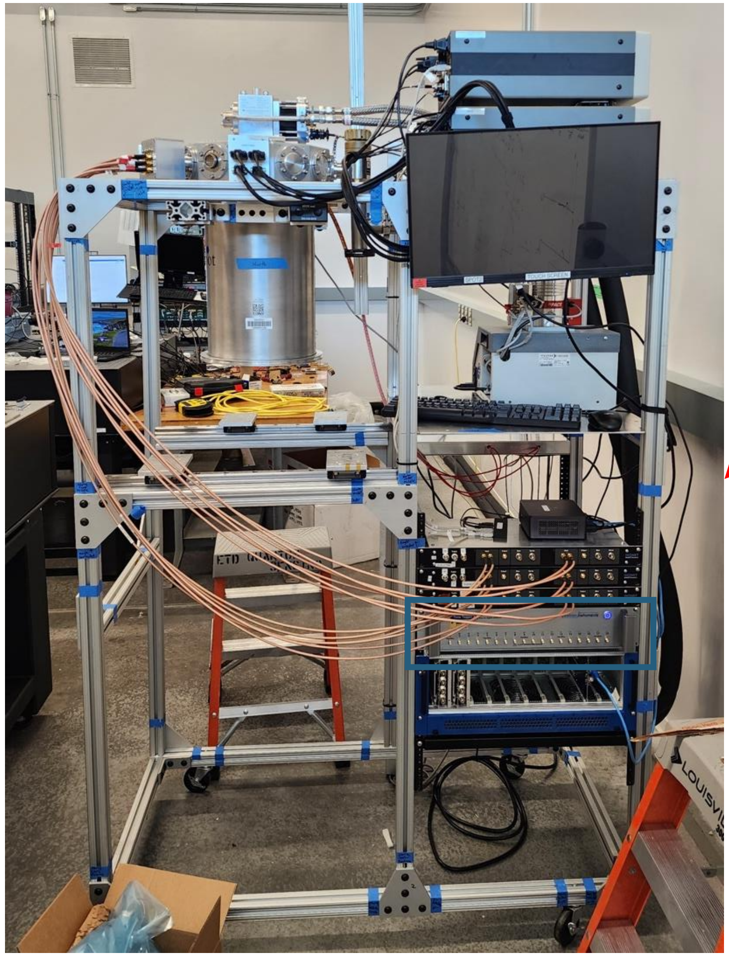


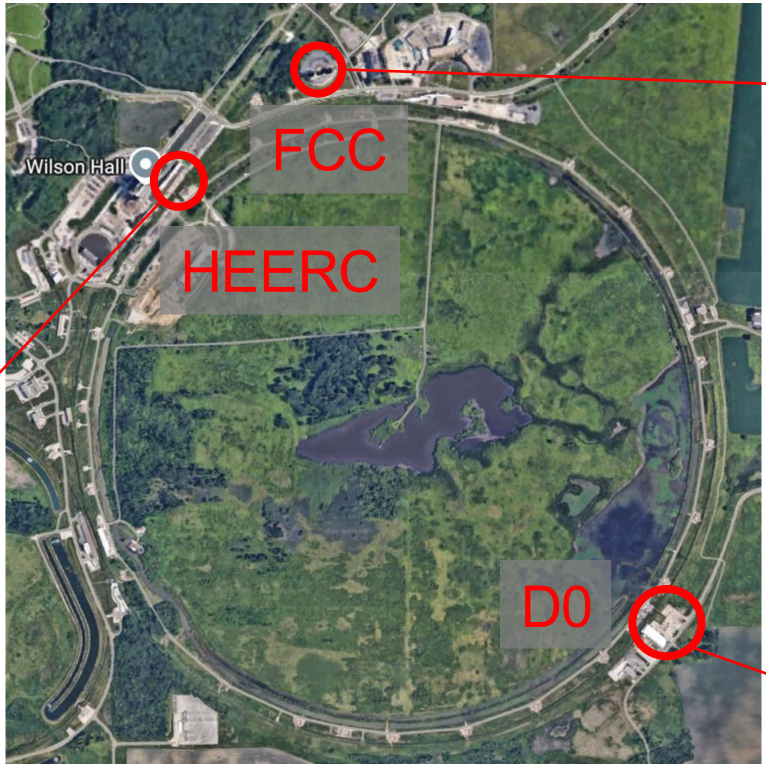


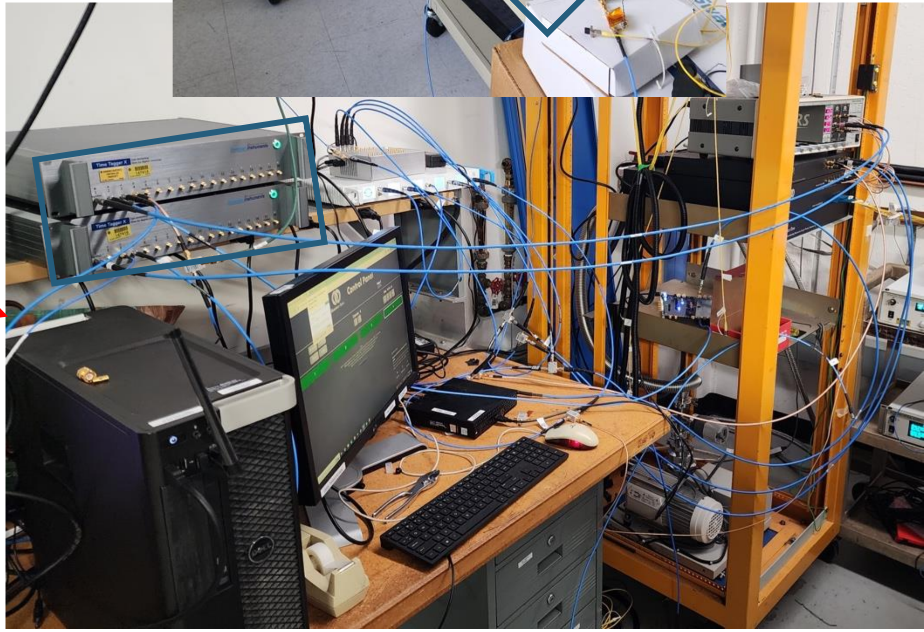
Entanglement Swapping Testbed

Fermilab

Readiness for multi-building experiments

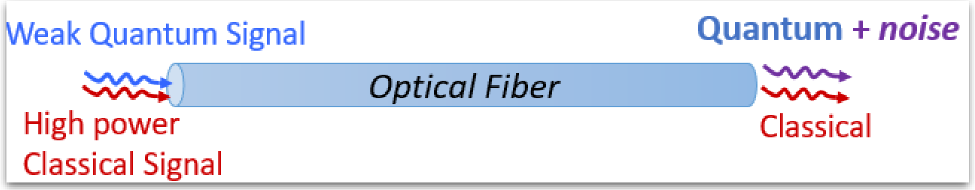




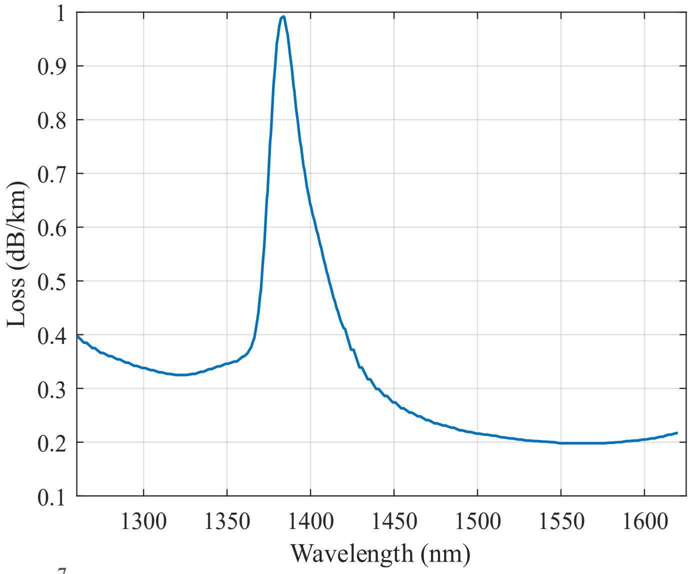


Noise Sources and Wavelength Selection

Noise photons



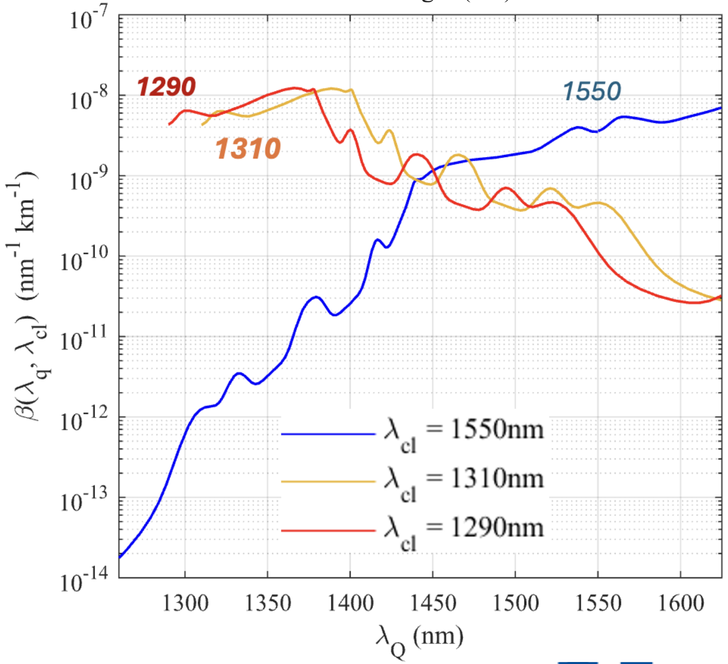
Corning SMF-28 loss spectrum



Spontaneous Raman scattering

- Broadband spectrum (>54 THz) → spanning all telecom channels for any classical channel selection

Simulated SpRS coeff spectrum



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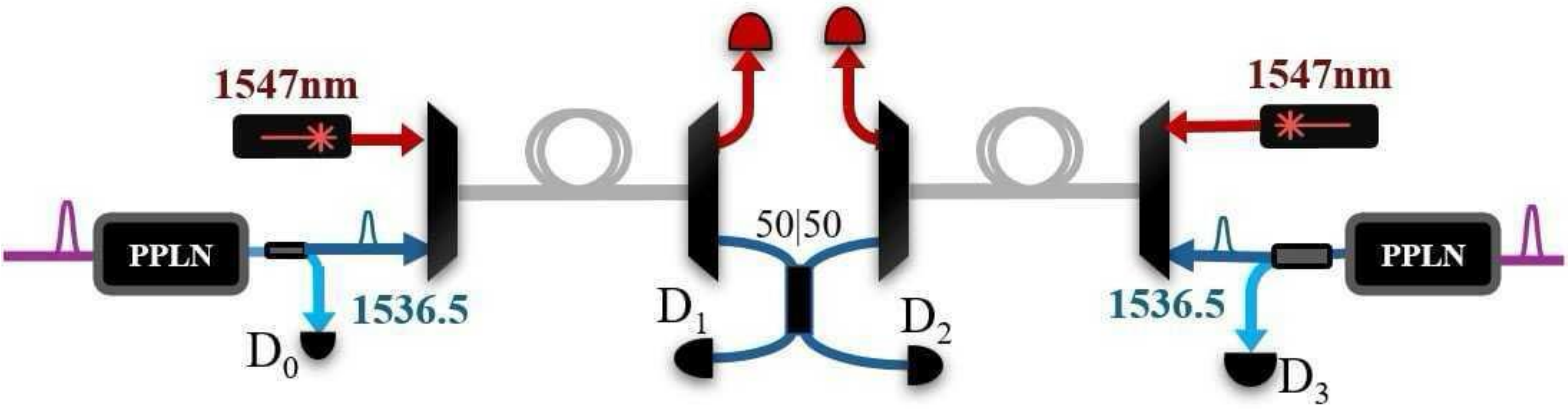
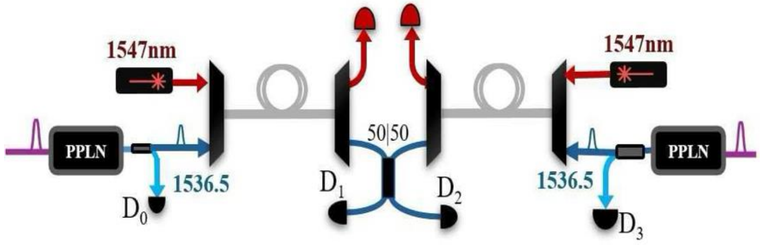
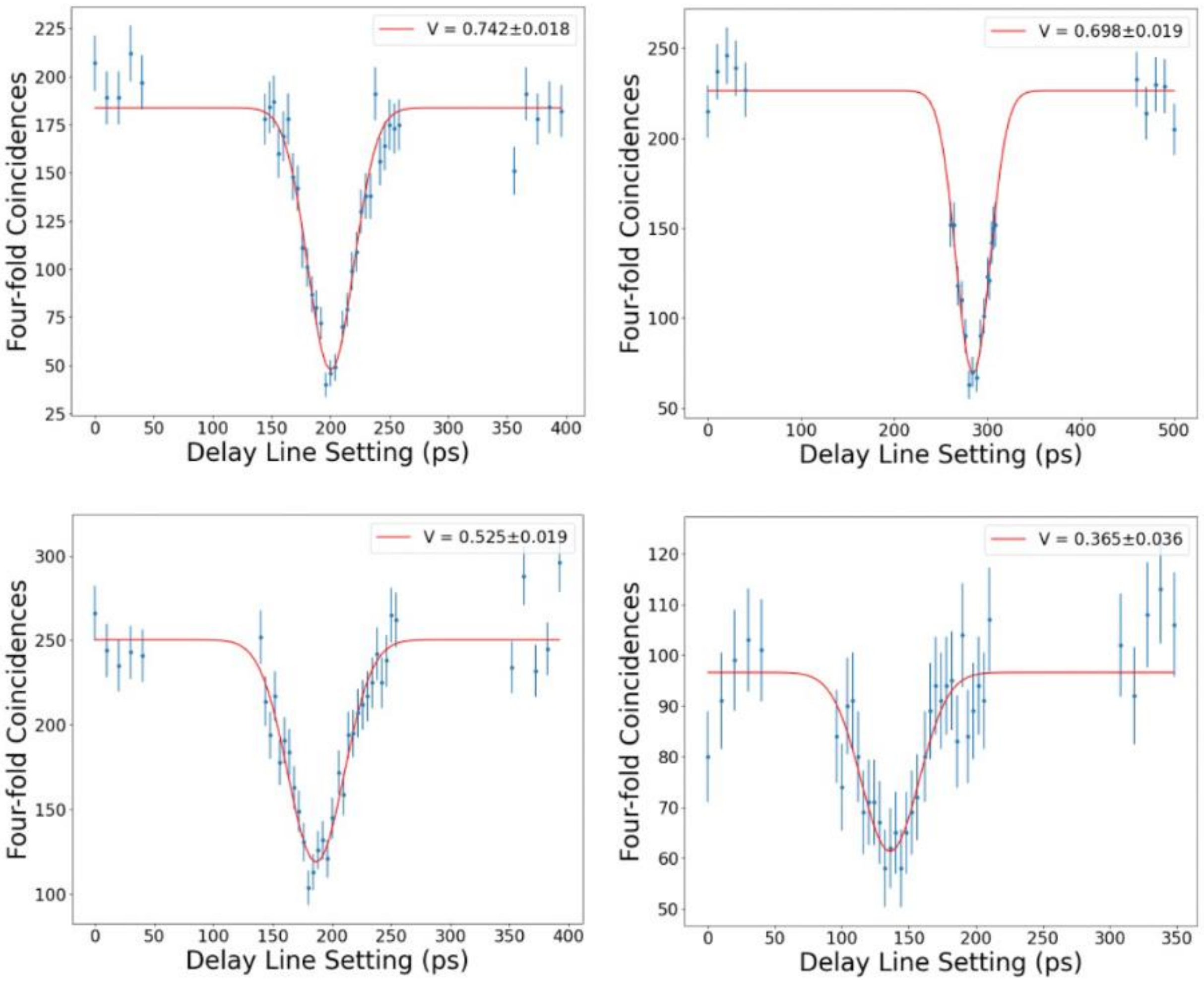
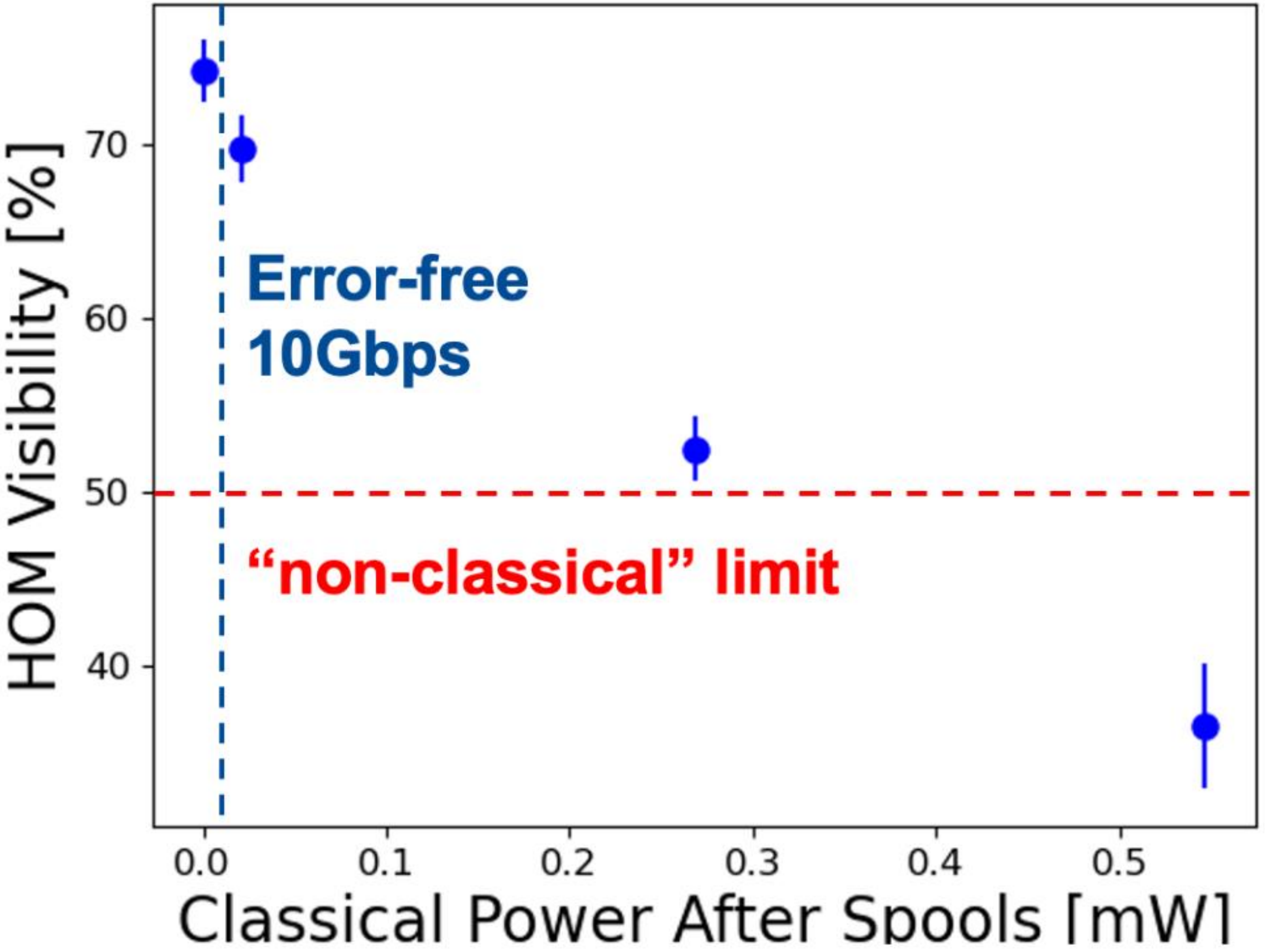
Entanglement swapping in the presence of classical communications



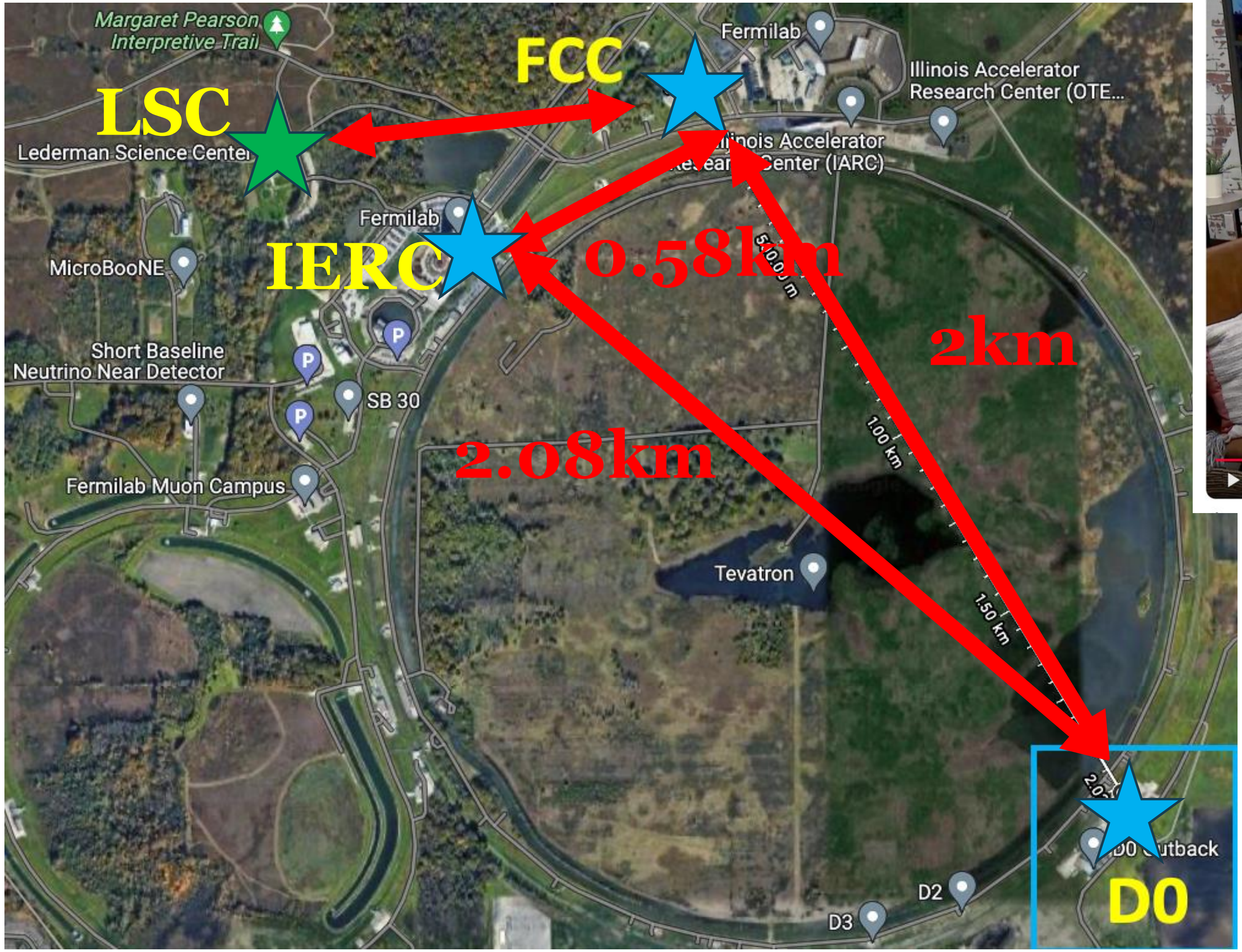
Hong-Ou-Mandel Interference with Coexistence







4th Node on Campus for the Public – Building off of UIUC success.



NEWS

U of I launches world's first public quantum network at Urbana Free Library

by: Jack Krumm
Posted: Nov 5, 2023 / 04:06 PM CST
Updated: Nov 5, 2023 / 04:06 PM CST

SHARE

URBANA, Ill. (WCIA) — The University of Illinois' Grainger College of Engineering launched the world's first public quantum network this weekend at the Urbana Free Library.

The network's link will send photons through fiber optic cables from the labs on U of I's campus to the library. The goal is to make quantum information more accessible to everybody for secure communication with quantum computers.

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