Computación e Información Cuántica con Fotones

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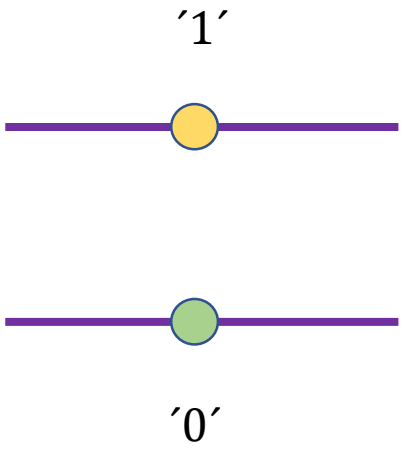
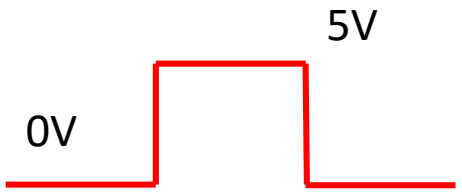
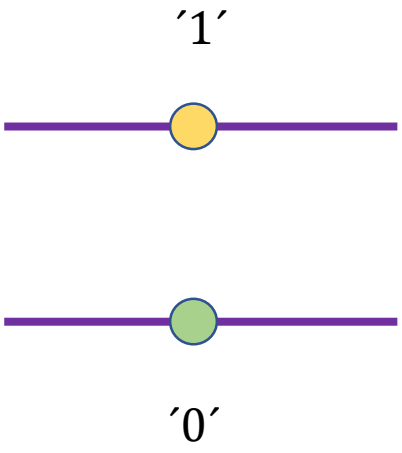
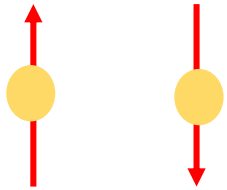
Ejemplo: dos niveles de voltaje

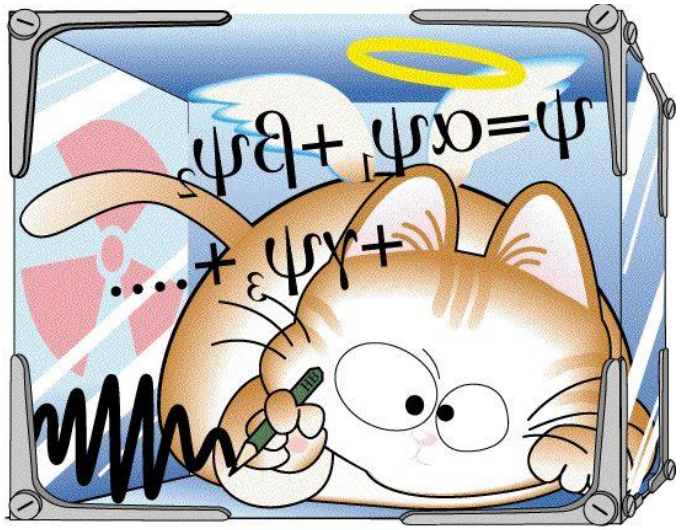




Ejemplo: espín electrónico







Superposición cuántica

$$\langle 0|1\rangle = 0$$

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

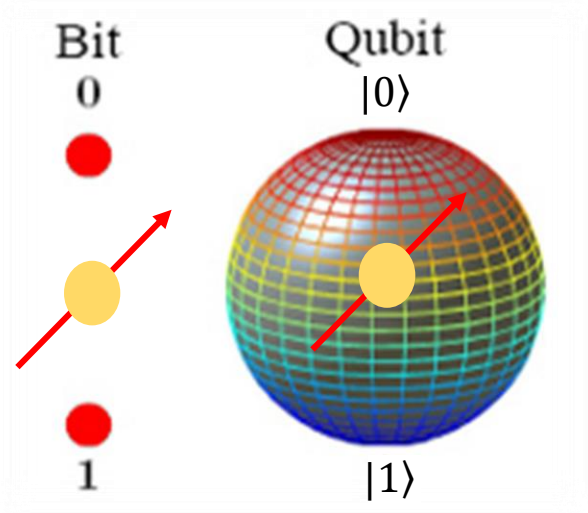
$$\langle\psi|\psi\rangle = 1 \rightarrow |\alpha|^2 + |\beta|^2 = 1$$

$$|\psi\rangle \rightarrow |\psi'\rangle = \mathcal{U}|\psi\rangle$$

$$\mathcal{U}^{\dagger}\mathcal{U}=1$$

$´0´ \rightarrow |0\rangle$

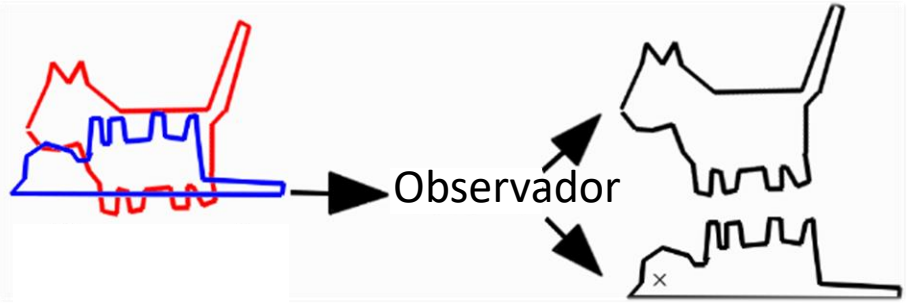
$´1´ \rightarrow |1\rangle$



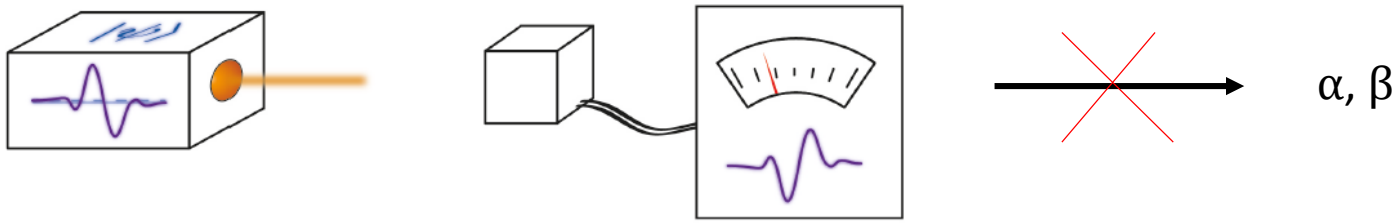
Error

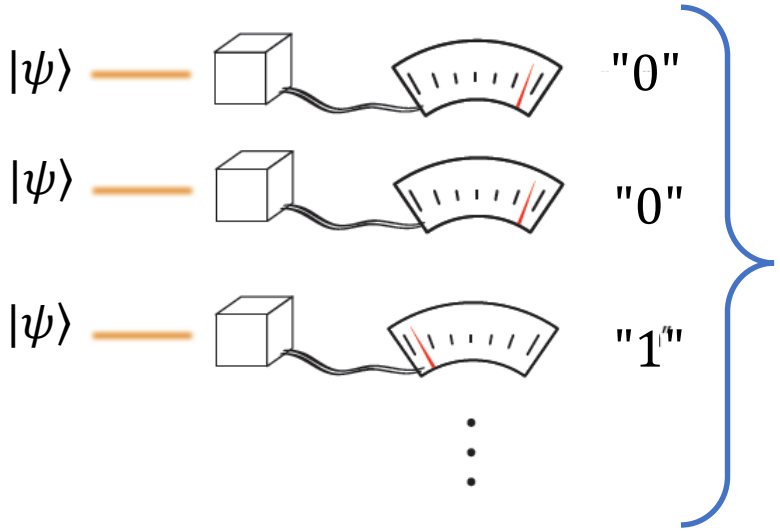
Válido

Medida



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





Análisis de datos

↓

$|\alpha|^2, |\beta|^2$

Copias

Sup. $|\psi\rangle, |\phi\rangle$ estados *no ortogonales desconocidos*

$$\langle\psi|\phi\rangle = c \neq 0$$

$$|a\rangle|\phi\rangle \xrightarrow{\mathcal{U}} |\phi\rangle|\phi\rangle$$

$$|a\rangle|\psi\rangle \xrightarrow{\mathcal{U}} |\psi\rangle|\psi\rangle$$

$$\langle\psi|\langle a|a\rangle|\phi\rangle = \langle\psi|\phi\rangle = c$$

$$\langle\psi|\langle\psi|\phi\rangle|\phi\rangle = \langle\psi|\phi\rangle\langle\phi|\psi\rangle = |\langle\psi|\phi\rangle|^2 = c^2$$

$$\rightarrow c = 0, 1$$

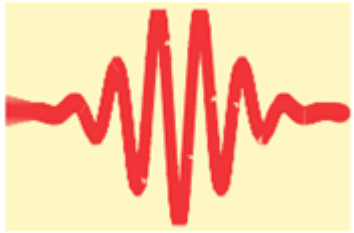
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$$\langle\psi|\psi\rangle = 1 \rightarrow |\alpha|^2 + |\beta|^2 = 1$$

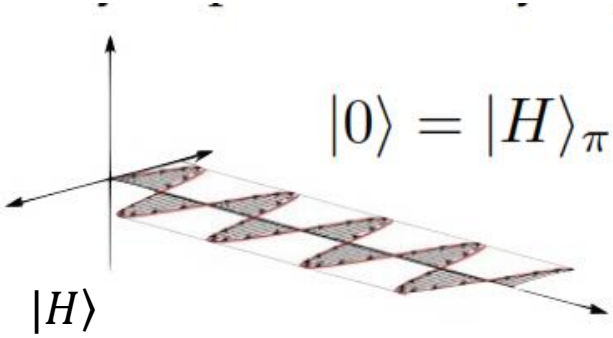
$$|\psi\rangle \rightarrow |\psi'\rangle = \mathcal{U}|\psi\rangle$$

$$\mathcal{U}^\dagger\mathcal{U}=1$$

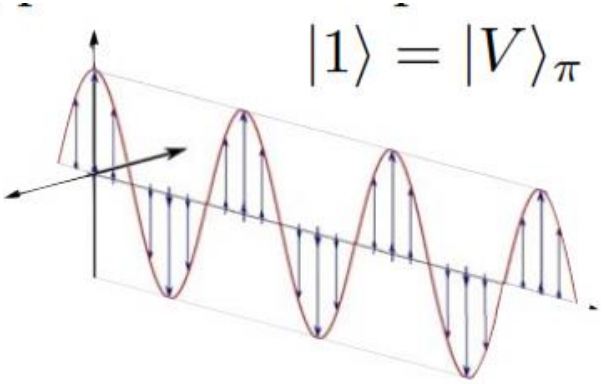
Codificando información

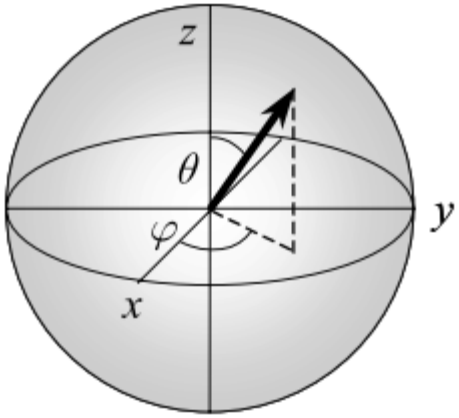


Polarización



$|H\rangle$

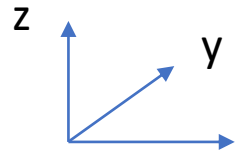




$|V\rangle$

Operaciones unitarias

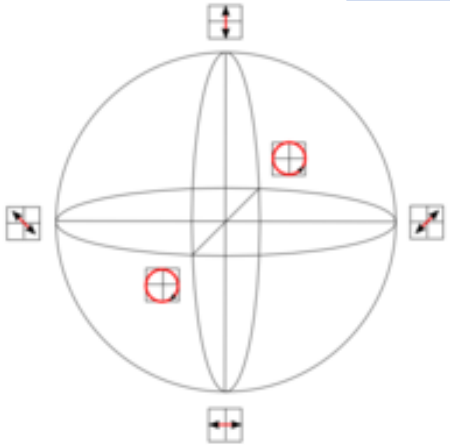
$$|\psi\rangle = \cos\frac{\theta}{2}|H\rangle + e^{i\varphi}\,\mathrm{sen}\,\frac{\theta}{2}|V\rangle$$



$\{|H\rangle, |V\rangle\}$

$$\left\{\frac{|H\rangle + |V\rangle}{\sqrt{2}}, \frac{|H\rangle - |V\rangle}{\sqrt{2}}\right\}$$

$$\left\{\frac{|H\rangle + i|V\rangle}{\sqrt{2}}, \frac{|H\rangle - i|V\rangle}{\sqrt{2}}\right\}$$



Operaciones unitarias

$$|H\rangle = \begin{pmatrix}1\\0\end{pmatrix}, |V\rangle = \begin{pmatrix}0\\1\end{pmatrix}$$

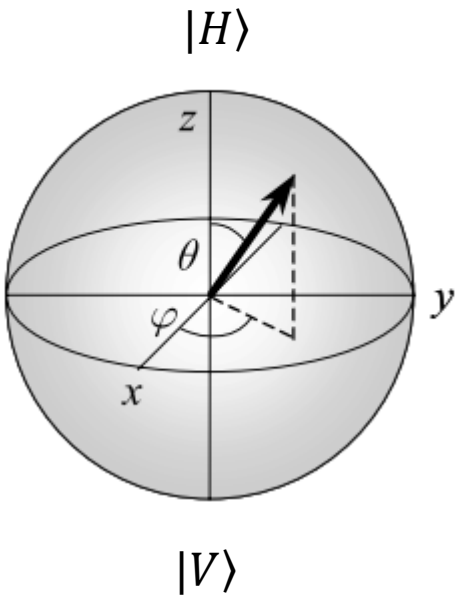


Lámina de media onda ($\lambda/2$):

$$U_{HWP}(\theta) = \begin{pmatrix}\cos 2\theta & \text{sen } 2\theta\\ \text{sen } 2\theta & -\cos 2\theta\end{pmatrix} \longrightarrow$$

Rotación en torno al eje y

$$U_X = U_{HWP}(\pi/4) = \begin{pmatrix}0 & 1\\1 & 0\end{pmatrix} \equiv X \longrightarrow U_X|H\rangle = |V\rangle,\ U_X|V\rangle = |H\rangle$$

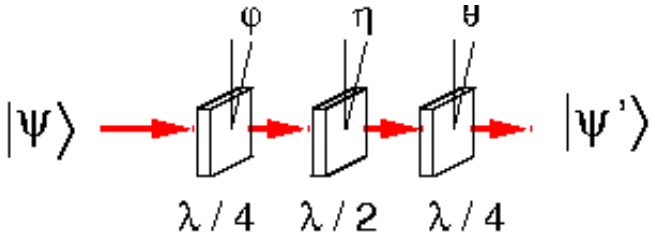
Lámina de cuarto de onda ($\lambda/4$):

$$U_Z = \begin{pmatrix}1 & 0\\0 & i\end{pmatrix} \equiv Z \longrightarrow U_Z|D\rangle = \frac{1}{\sqrt{2}} U_Z \begin{pmatrix}1\\1\end{pmatrix} = \frac{1}{\sqrt{2}}(|H\rangle + i|V\rangle) = |L\rangle,$$

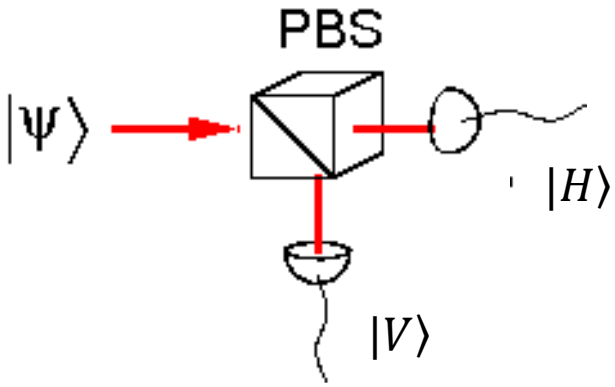
$$U_Z|R\rangle = \frac{1}{\sqrt{2}} U_Z(|H\rangle - i|V\rangle) = |D\rangle$$

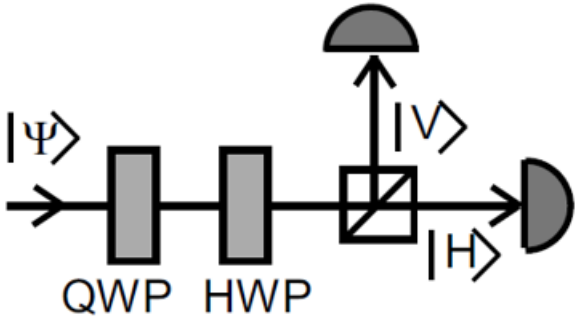
Rotación en torno al eje z

Operación arbitraria 1 qubit



Medidas





Base de medición	HWP	QWP
X (σ_x)	22.5°	0°
Y (σ_y)	0°	45°
Z (σ_z)	0°	0°

Algunas aplicaciones

Criptografía

$$\text{´0´} \rightarrow |H\rangle, \frac{|H\rangle + |V\rangle}{\sqrt{2}}$$

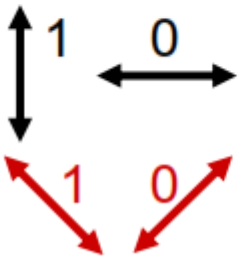
$$\text{´1´} \rightarrow |V\rangle, \frac{|H\rangle - |V\rangle}{\sqrt{2}}$$

Eve espía

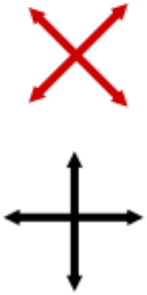
- Al medir perturba el estado
- No puede copiar los estados

Eve

Alice



Canal cuántico

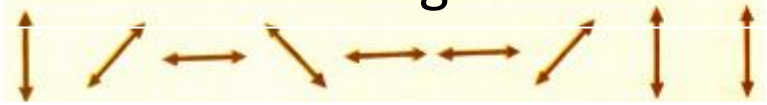


Bob

Canal clásico público

Protocolo BB84

- Alice envía fotones (qubits) a Bob aleatoriamente polarizados en alguno de los 4 estados

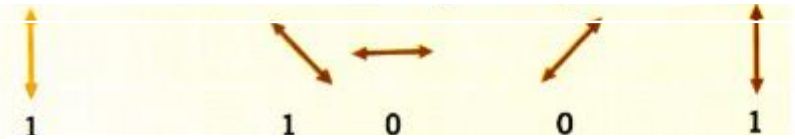


- Bob mide aleatoriamente en la base vertical o diagonal

- Bob mantiene en secreto los resultados de la medida

- Bob anuncia públicamente sus bases de medida (no los resultados) y Alice le comunica si es la base correcta.

- Alice y Bob mantienen los resultados de en las bases comunes



- Alice y Bob comparten una clave aleatoria: 1 1 0 0 1 ...

Comunicación

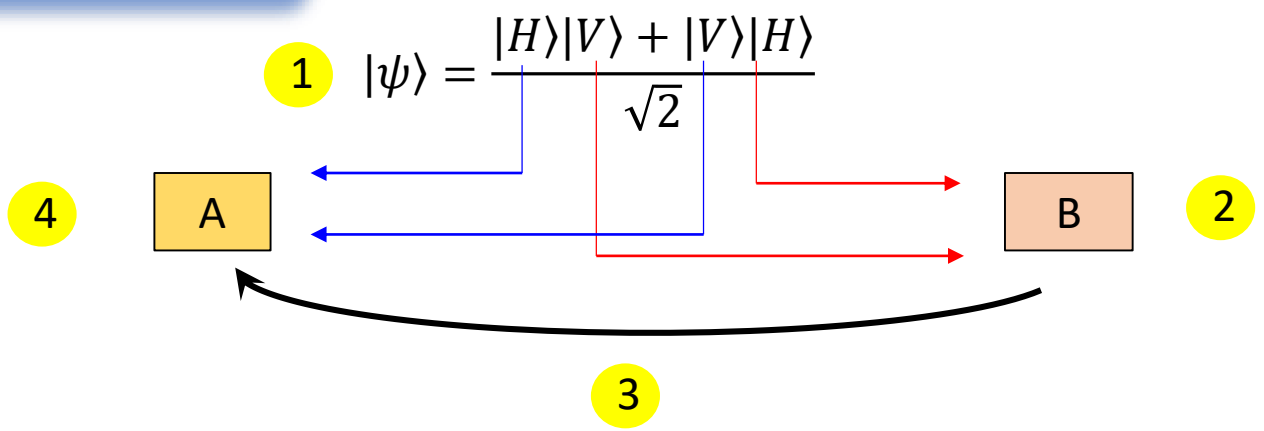
2 bits → ´00´, ´01´, ´10´, ´11´

¿Cuántos qubits necesito enviar para transmitir dos bits de información?

2 qubits → Base: $\{|H\rangle|H\rangle, |H\rangle|V\rangle, |V\rangle|H\rangle, |V\rangle|V\rangle\}$

$$|\psi\rangle = c_1|H\rangle|H\rangle + c_2|H\rangle|V\rangle + c_3|V\rangle|H\rangle + c_4|V\rangle|V\rangle \qquad \sum_{i=1}^{4}|c_i|^2 = 1$$

Entrelazamiento

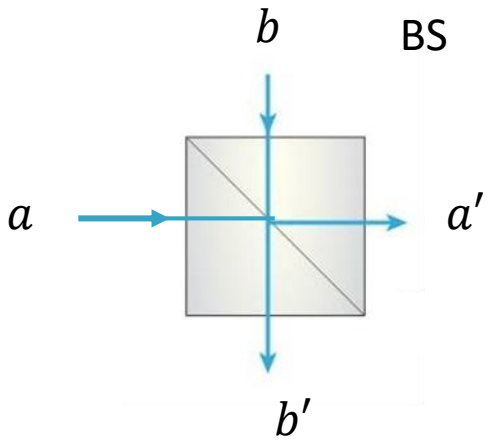


Superdense coding

1. Alice y Bob comparten un par de qubits estrelazados
2. Bob realiza una operación cuántica sobre su qubit dependiendo del bit que quiere comunicar
3. Bob envía su qubit a Alice
4. Alice mide el par entrelazado.

Bits a transferir	Operación de Bob (Unitaria)	Estado final (Bell)	Alice mide (medida de Bell)
00	I_2	$\frac{\|H\rangle\|V\rangle + \|V\rangle\|H\rangle}{\sqrt{2}}$	$\|\Psi^+\rangle$
01	X_2	$\frac{\|H\rangle\|H\rangle + \|V\rangle\|V\rangle}{\sqrt{2}}$	$\|\Phi^+\rangle$
10	Z_2	$\frac{\|H\rangle\|V\rangle - \|V\rangle\|H\rangle}{\sqrt{2}}$	$\|\Psi^-\rangle$
11	$X_2 Z_2$	$\frac{\|H\rangle\|H\rangle - \|V\rangle\|V\rangle}{\sqrt{2}}$	$\|\Phi^-\rangle$

La física del "Beamsplitter"



$$\begin{pmatrix} t_1 & r_2 \\ r_1 & t_2 \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} a' \\ b' \end{pmatrix}$$

$$\begin{pmatrix} t_1 & r_2 \\ r_1 & t_2 \end{pmatrix} \mathrm{X} \begin{pmatrix} t_1 & r_1^* \\ r_2^* & t_2 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

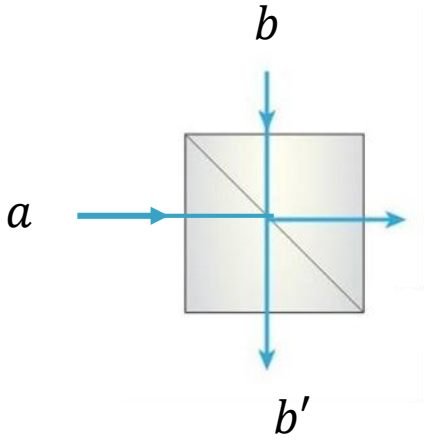
Si *t=r :*

BS $\rightarrow \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$

$$|a'\rangle = \frac{1}{\sqrt{2}}(|a\rangle + |b\rangle) \ , |b'\rangle = \frac{1}{\sqrt{2}}(|a\rangle - |b\rangle)$$

$$|a\rangle = \frac{1}{\sqrt{2}}(|a'\rangle + |b'\rangle) \ , |b\rangle = \frac{1}{\sqrt{2}}(|a'\rangle - |b'\rangle)$$

La física del "Beamsplitter"



$$|a\rangle = \frac{1}{\sqrt{2}}(|a'\rangle + |b'\rangle) \ , |b\rangle = \frac{1}{\sqrt{2}}(|a'\rangle - |b'\rangle)$$

dos fotones entrando al BS: 50/50

$$|\Psi^{\pm}\rangle = \frac{|H\rangle|V\rangle \pm |V\rangle|H\rangle}{\sqrt{2}}$$

$$|\Phi^{\pm}\rangle = \frac{|H\rangle|H\rangle \pm |V\rangle|V\rangle}{\sqrt{2}}$$

Función de onda total simétrica respecto del intercambio de partículas

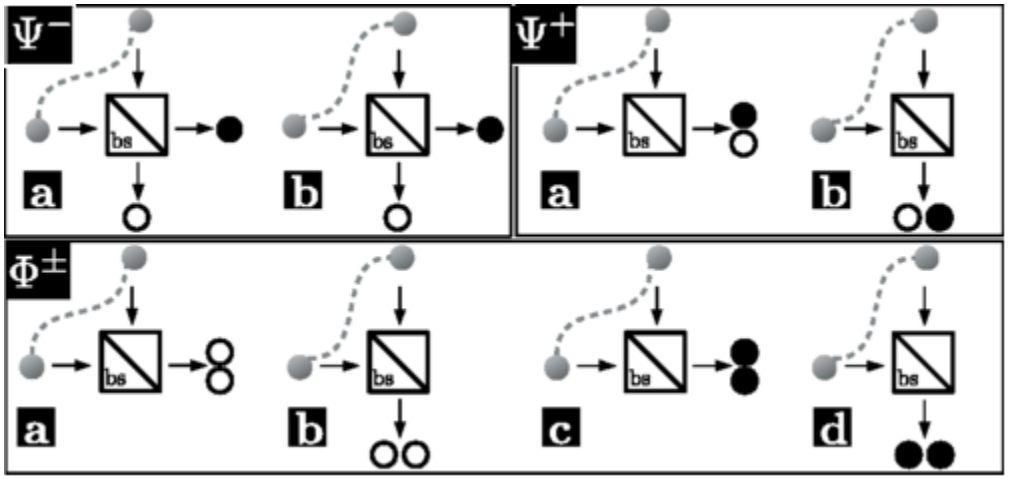
ej: $\longrightarrow$ $|\Psi^{\pm}\rangle = \left(\frac{|H\rangle|V\rangle \pm |V\rangle|H\rangle}{\sqrt{2}}\right)\left(\frac{|a\rangle|b\rangle \pm |b\rangle|a\rangle}{\sqrt{2}}\right)$

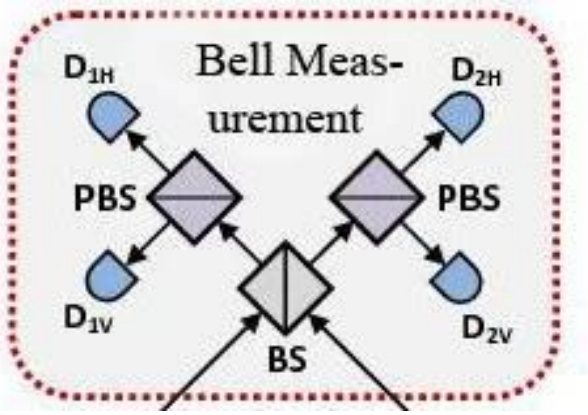
$(|a\rangle|b\rangle \pm |b\rangle|a\rangle)$ $\xrightarrow{BS}$ $\frac{1}{2}(|a'\rangle + |b'\rangle)(|a'\rangle - |b'\rangle) \pm \frac{1}{2}(|a'\rangle - |b'\rangle)(|a'\rangle + |b'\rangle)$

$|\Psi^{+}\rangle, |\Phi^{\pm}\rangle \longrightarrow |a'\rangle|a'\rangle - |b'\rangle|b'\rangle$

$|\Psi^{-}\rangle \longrightarrow |b'\rangle|a'\rangle - |a'\rangle|b'\rangle$

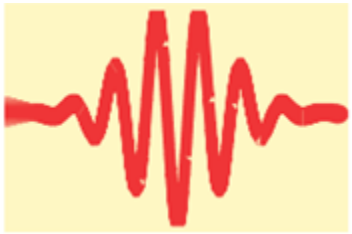
Medida de Bell





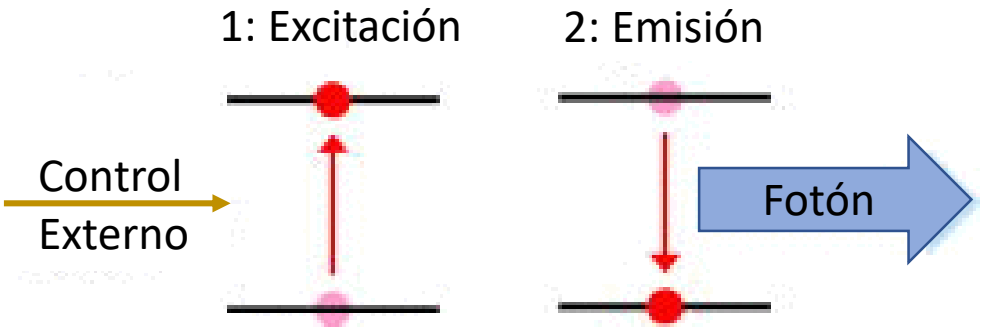
$|Bell\rangle$

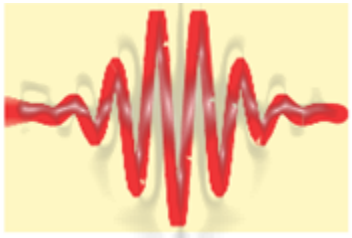
Fuentes de fotones individuales



Ideal

- Determinista (a demanda)
- $\mathcal{P}(1_f)$ =1 , $\mathcal{P}(>1_f)$ =0
- Velocidad de repetición

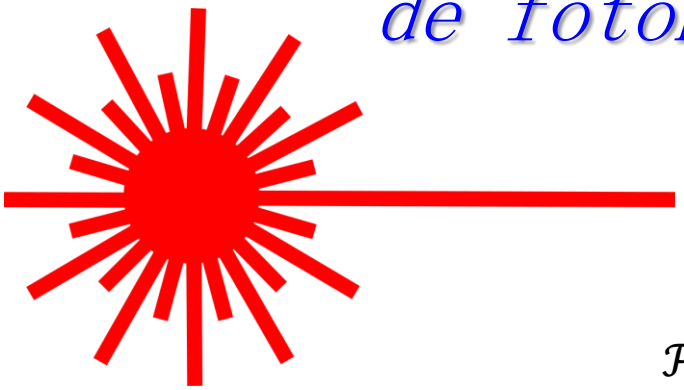




Real

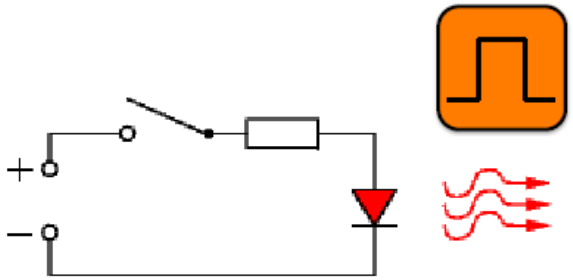
Source type	Prob. or Deter.	Temp. (K)	Wave-length range general	Wave-length tunability specific	Inherent bandwidth	Emission efficiency	Output spatial mode	$g^{(2)}(0)$	Refs.
Faint laser	P	300	vis-IR	nm	GHz	1	Single	1	
Two photon (heralded)									
Atomic cascade	P	...	Atomic line	MHz	10 MHz	0.0001	Multi	...	122
PDC									
Bulk	P	300	vis-IR	nm	nm	0.6	Multi	0.0014	123–125
Periodically poled	P	300–400	vis-IR	nm	nm	0.85	Multi[a]	...	126
Waveguide (periodically poled)	P	300–400	vis-IR	nm	nm	0.07	Single	0.0007	127
Gated	D	300	vis-IR	nm	nm	0.27	Single	0.02	128, 129, 368
Multiplexed	D	300	vis-IR	nm	nm	0.1	Single	0.08	130
FWM									
DSF	P	4–300	IR	nm	nm	0.02	Single	...	131
BSMF	P	300	vis-IR	nm	nm	0.26	Single	0.022	132
PCF	P	300	vis-IR	10 nm	nm	0.18	Single	0.01	133
SOI waveguide	P	300	IR	10 nm	nm	0.17	Single	...	134
Laser-PDC hybrid	P	300	vis-IR	nm	nm	...	Single	0.37	120
Isolated system									
Single molecule	D	300	500–750 nm	30 nm	30 nm	0.04	Multi	0.09	135–137
Color center (NV)	D	300	640–800 nm	nm	nm	0.022	Multi	0.07	138
QD (GaN)	D	200	340–370 nm	nm	nm	...	Multi	0.4	106
QD (CdSe/ZnS)	D	300	500–900 nm	nm	15 nm	0.05	Multi	0.003	139
QD (InAs) in cavity	D	5	920–950 nm	10 GHz	1 GHz	0.1	Single	0.02	140
Single ion in cavity	D	≈0	Atomic line	MHz	5 MHz	0.08	Single	0.015	141
Single atom in cavity	D	≈0	Atomic line	MHz	10 MHz	0.05	Single	0.06	142, 143
Ensemble									
Rb, Cs	D	10^{-4}	Atomic line	MHz	10 MHz	0.2	Single	0.25	144, 145

“Speudo” fuente de fotones individuales



$$|\alpha\rangle = e^{-\alpha^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{(n!)^{1/2}} |n\rangle$$

$$\mathcal{P}(n) = e^{-\alpha^2} \frac{\alpha^{2n}}{n!} \qquad \langle n \rangle = |\alpha|^2$$



Diodo laser

Atenuación

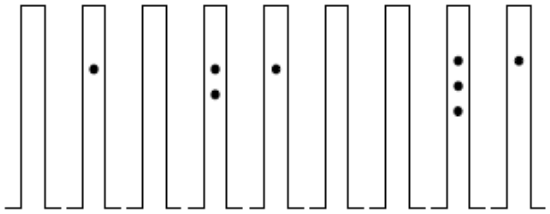
Para $\langle n \rangle = 0.1$

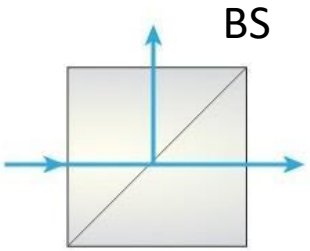
$\mathcal{P}(0) = 0.9048$

$\mathcal{P}(1) = 0.0905$

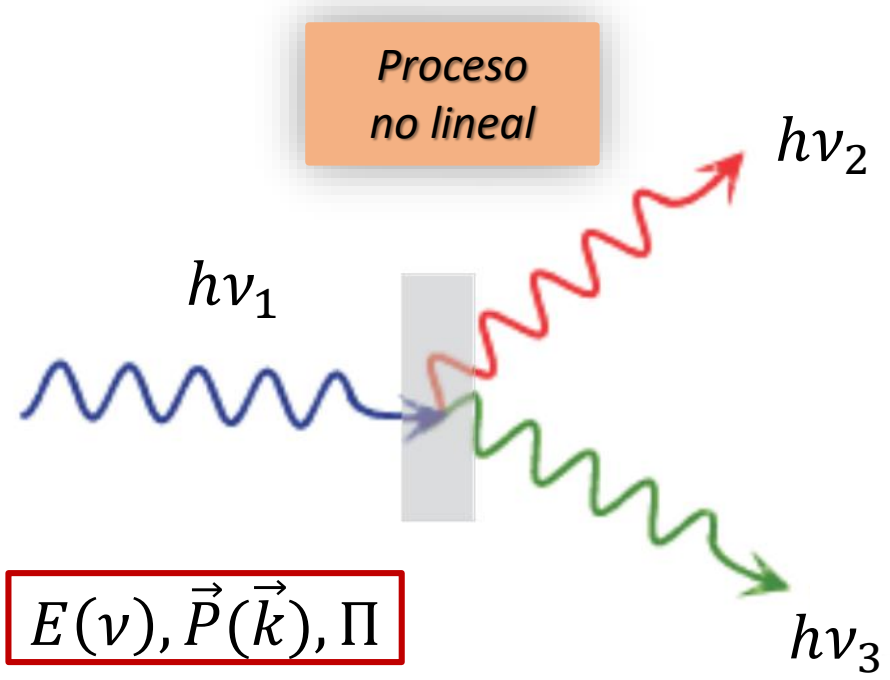
$\mathcal{P}(>1) = 0.0047$

Potencialmente inseguro





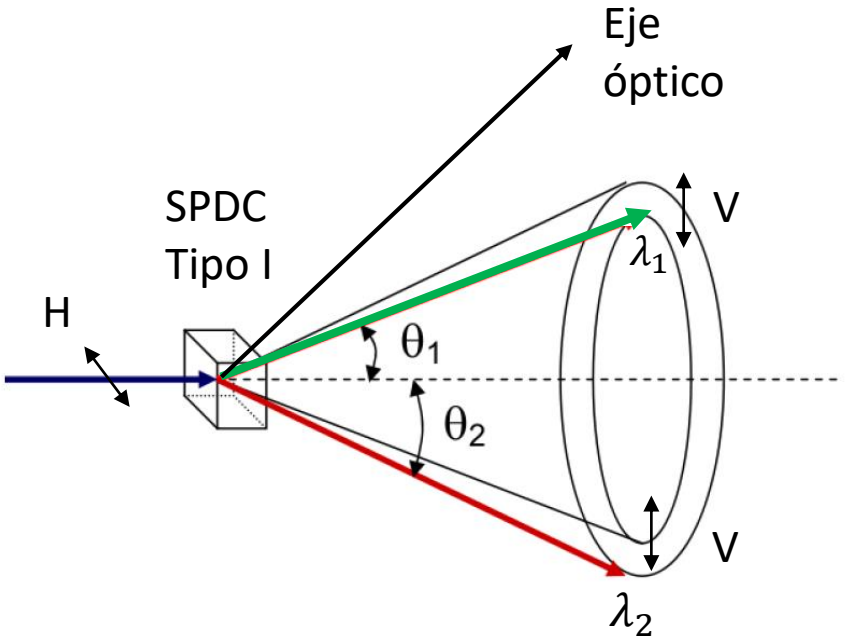
Conversión Paramétrica Espontánea Descendente - SPDC

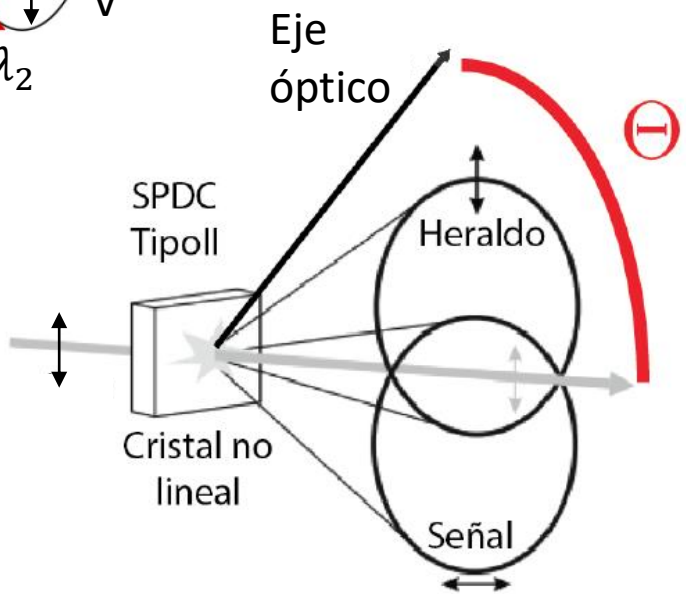


$$h\nu_1 = h\nu_2 + h\nu_3$$

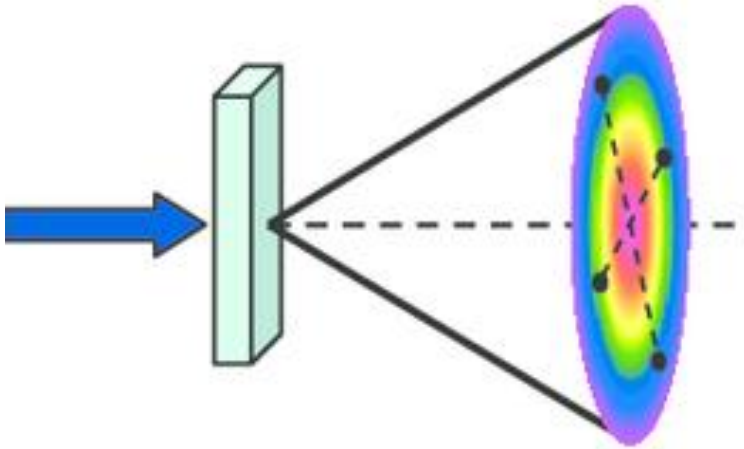
$$\overrightarrow{k_1} = \overrightarrow{k_2} + \overrightarrow{k_3}$$

SPDC en cristales birrefringentes

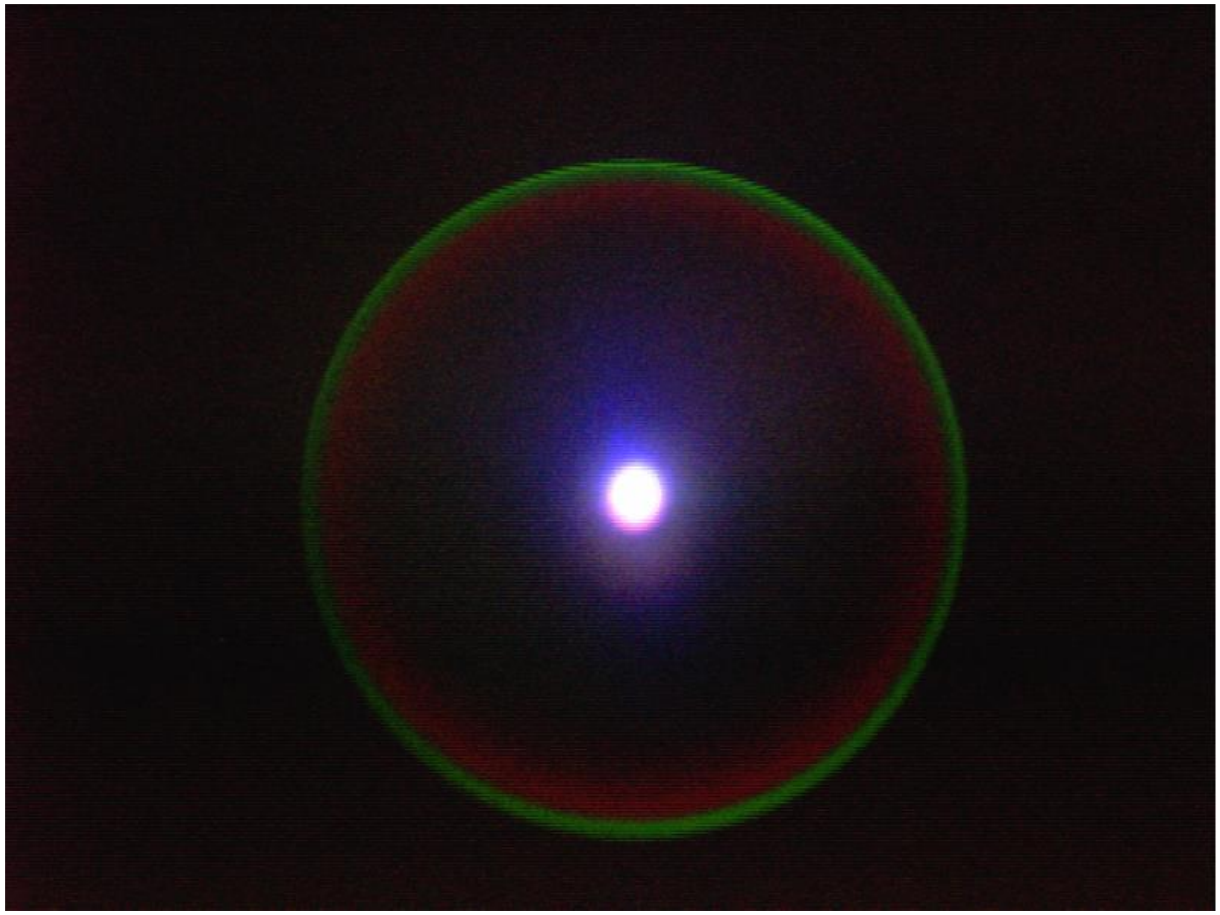




SPDC - Phase Matching Tipo I



SPDC - Phase Matching Tipo I



L. Rebón, E. Martínez
Laboratorio de Procesado de Imágenes, 2010

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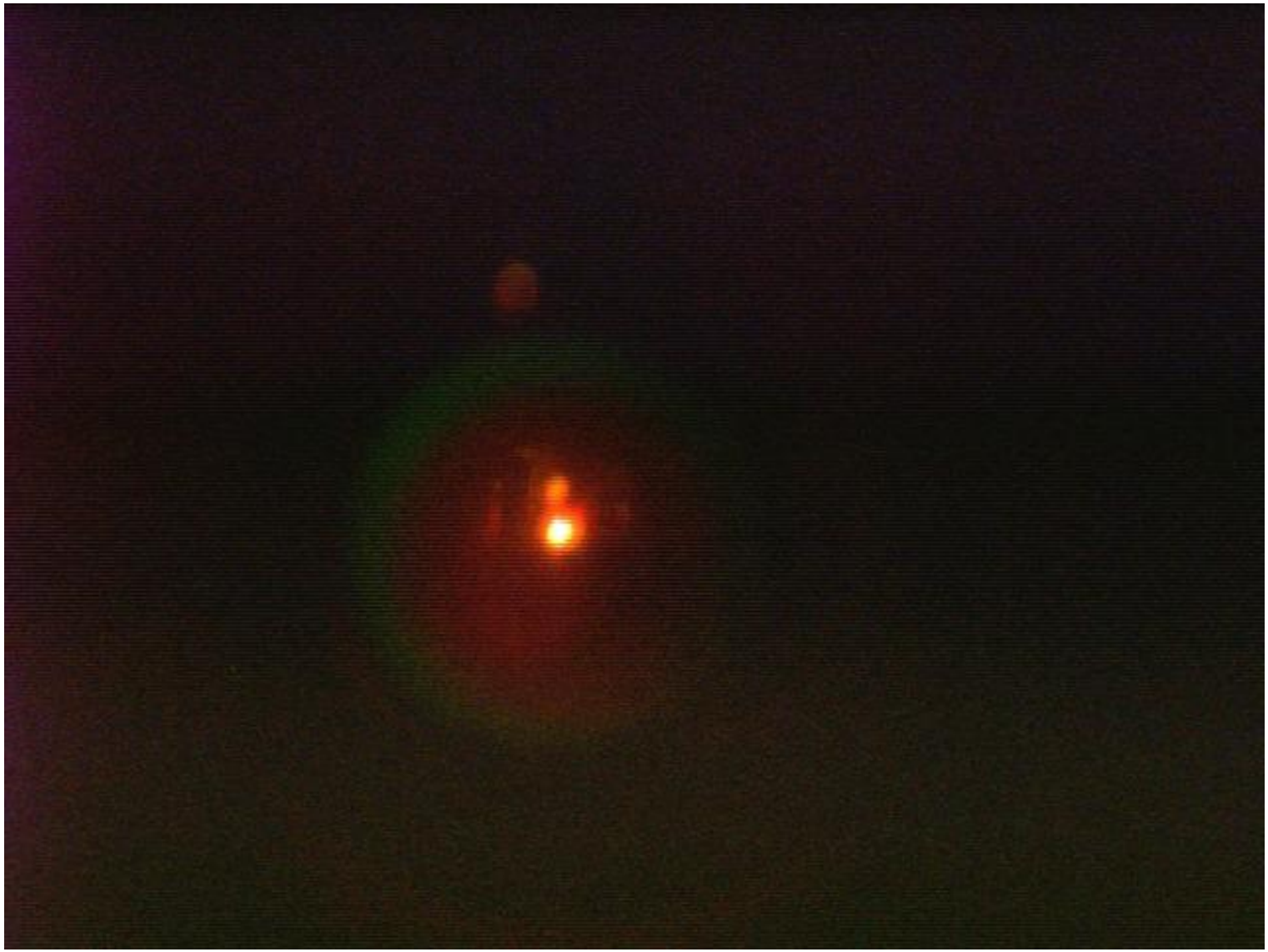
Laboratorio de Procesado de Imágenes, 2010



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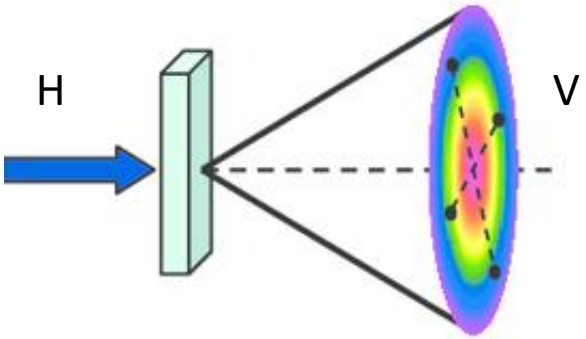
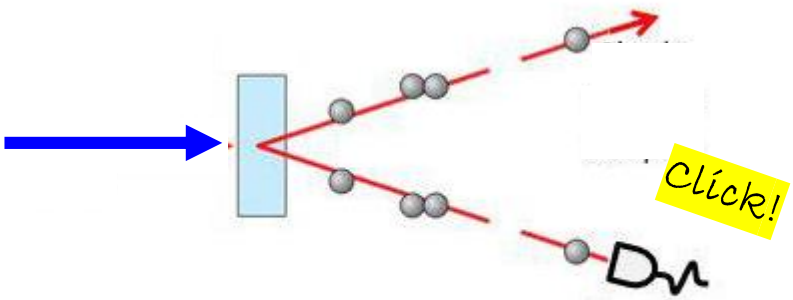
Laboratorio de Procesado de Imágenes, 2010



$$|\psi\rangle = |0\rangle|0\rangle + \chi^2|1\rangle|1\rangle + \frac{\chi^4}{2}|2\rangle|2\rangle + \cdots$$

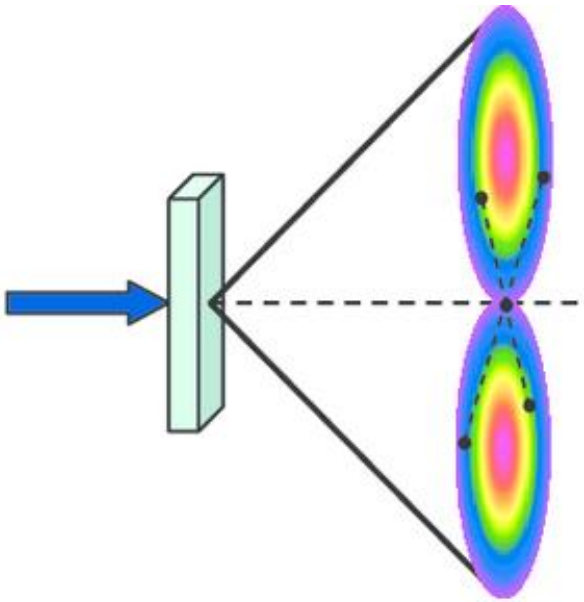
$$|\psi\rangle \approx |V\rangle|V\rangle$$

$$|\psi\rangle = |1\rangle$$

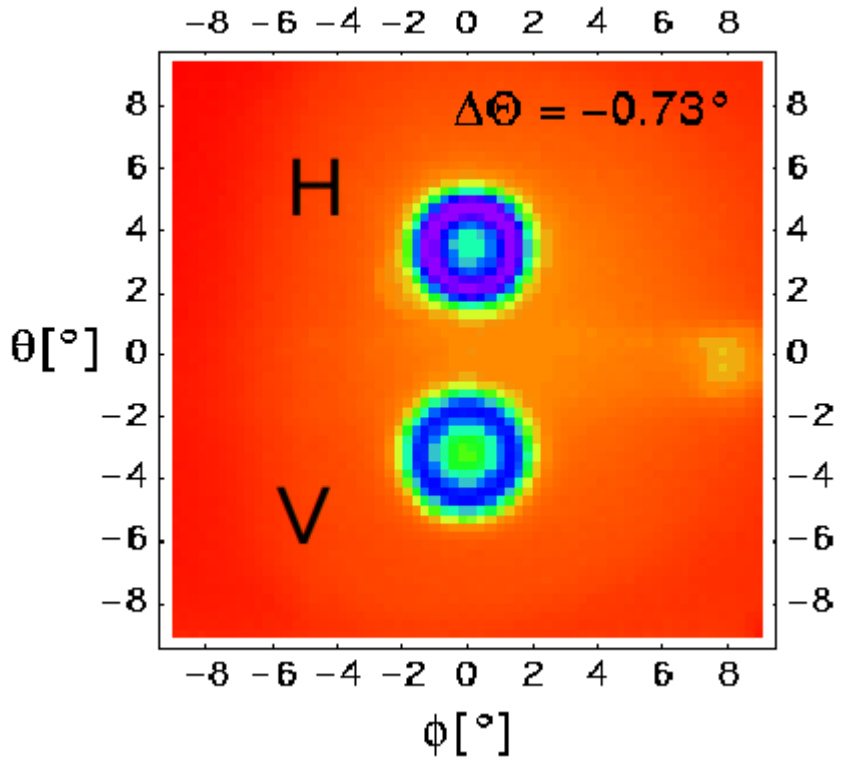


Fuente de un fotón probabilística

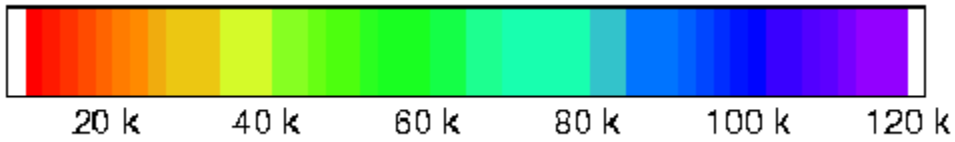
SPDC - Phase Matching Tipo II



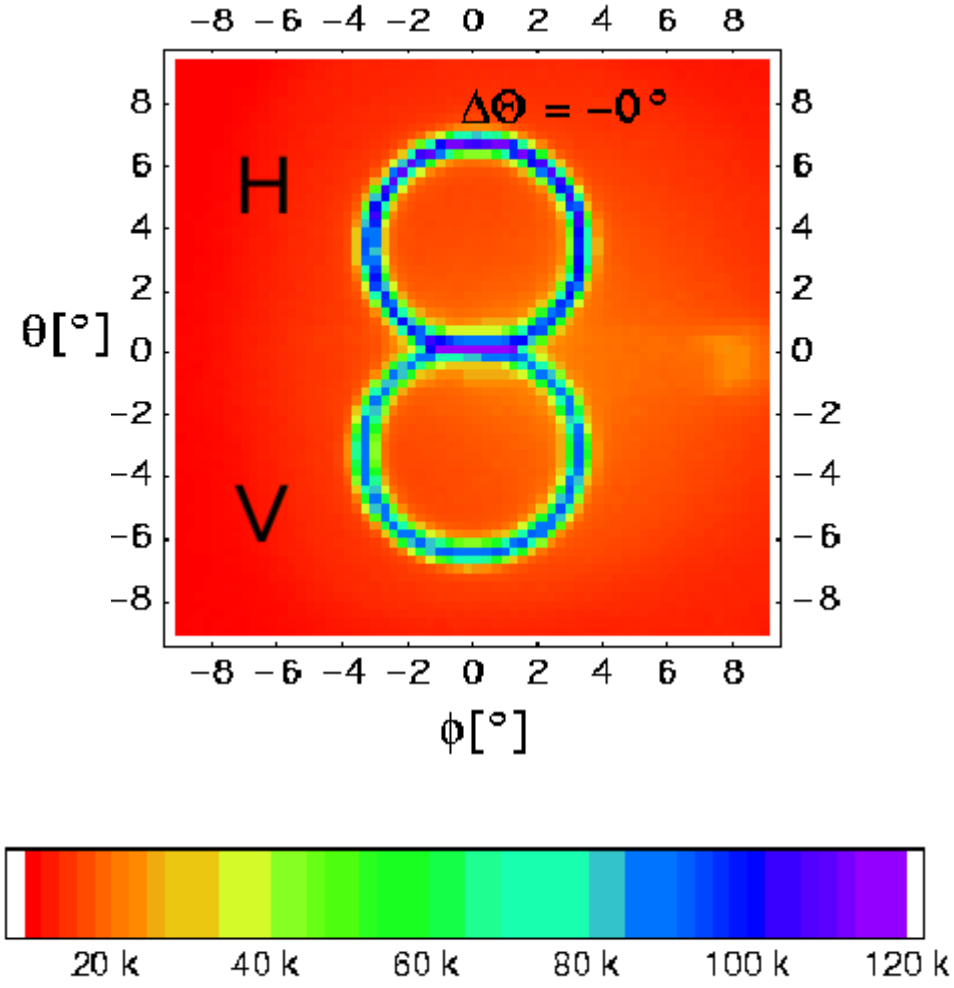
Phase Matching Tipo II



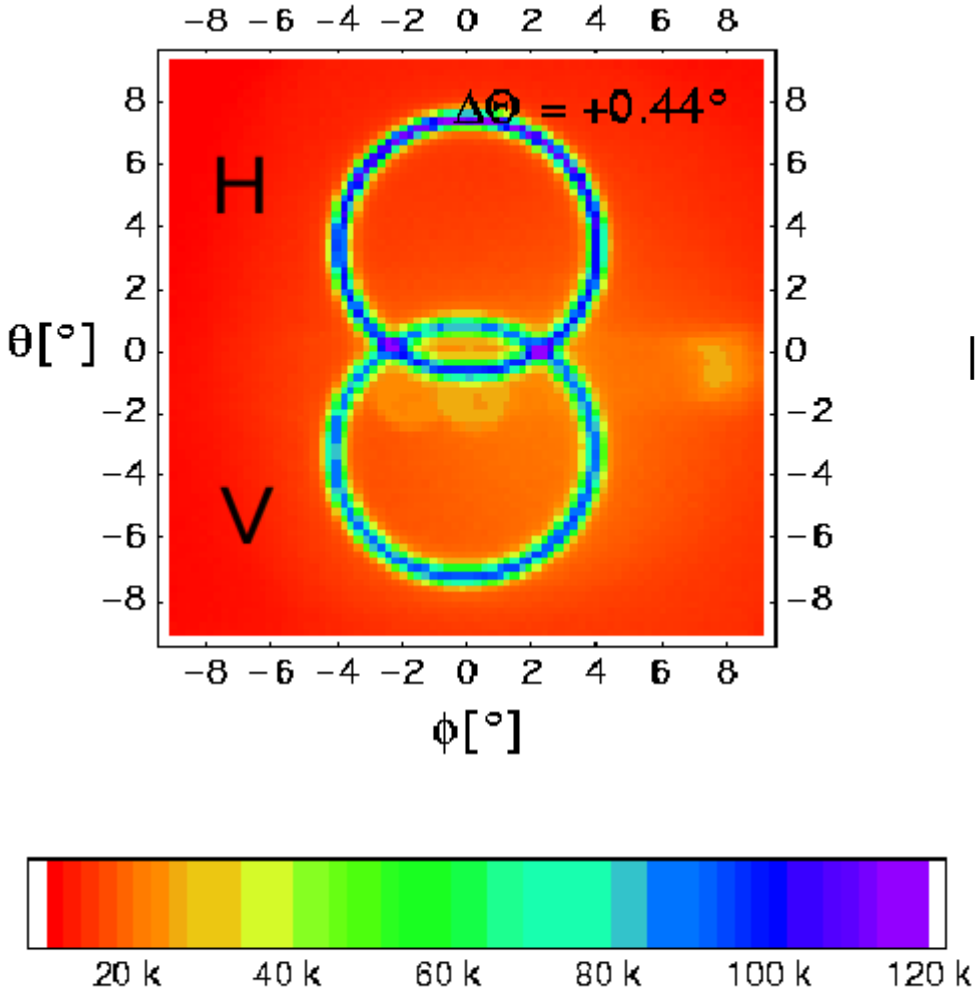
$$|\psi\rangle = |H\rangle|V\rangle$$



Phase Matching Tipo II

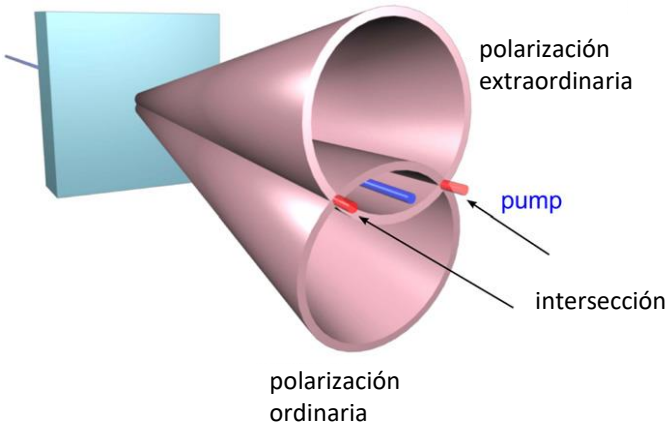


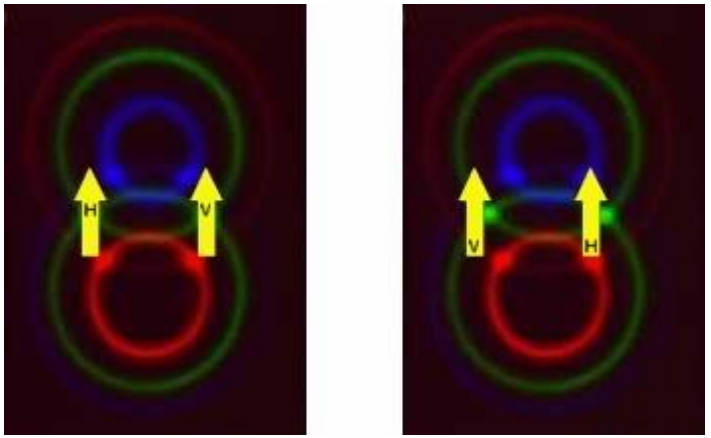
Phase Matching Tipo II



$$|\psi\rangle = \frac{|H\rangle|V\rangle + |V\rangle|H\rangle}{\sqrt{2}}$$

Entrelazamiento en polarización





Kwiat Quantum Information Group - web page

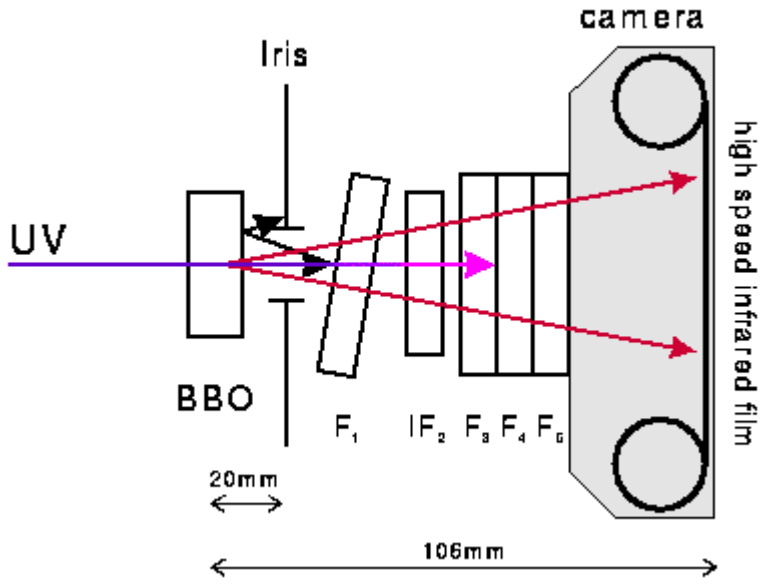
Indistinguibles

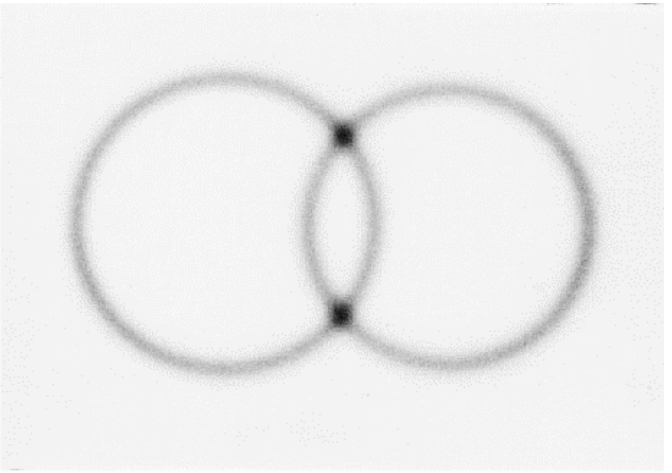
$$|\psi\rangle = \frac{|H\rangle|V\rangle + e^{i\varphi}\,|V\rangle|H\rangle}{\sqrt{2}}$$

Distinguibles

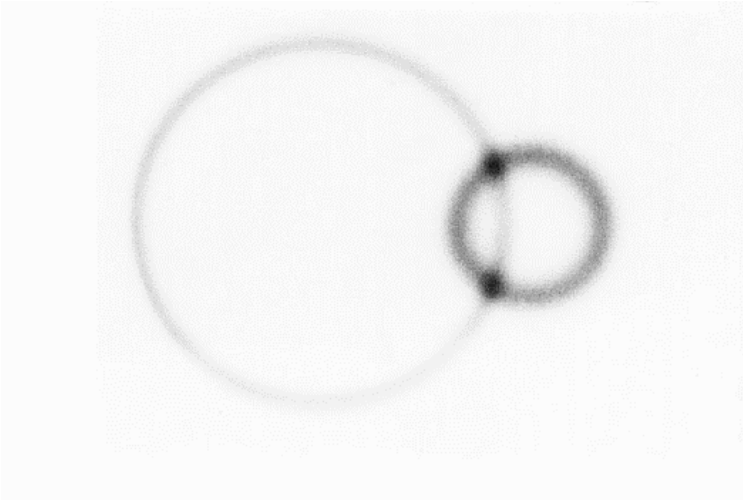
$$|\psi\rangle \neq \frac{|H\rangle|V\rangle + e^{i\varphi}|V\rangle|H\rangle}{\sqrt{2}}$$

Imagen infrarroja original





Michael Reck. Ph.D.Thesis at the Institut für Experimentalphysik, Universität Innsbruck, 1996.



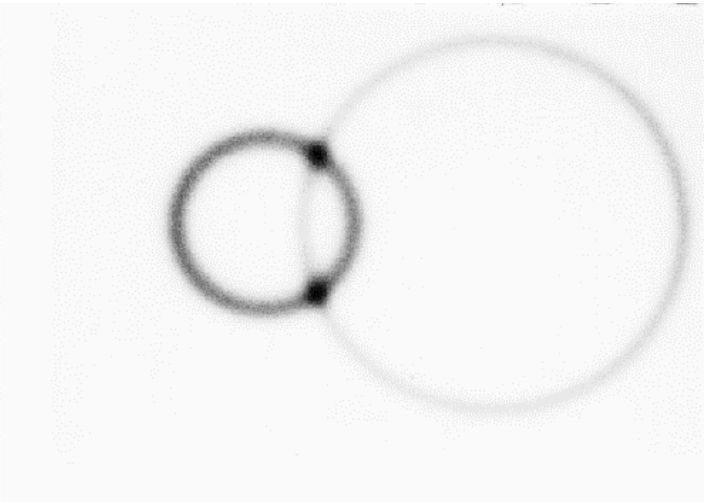
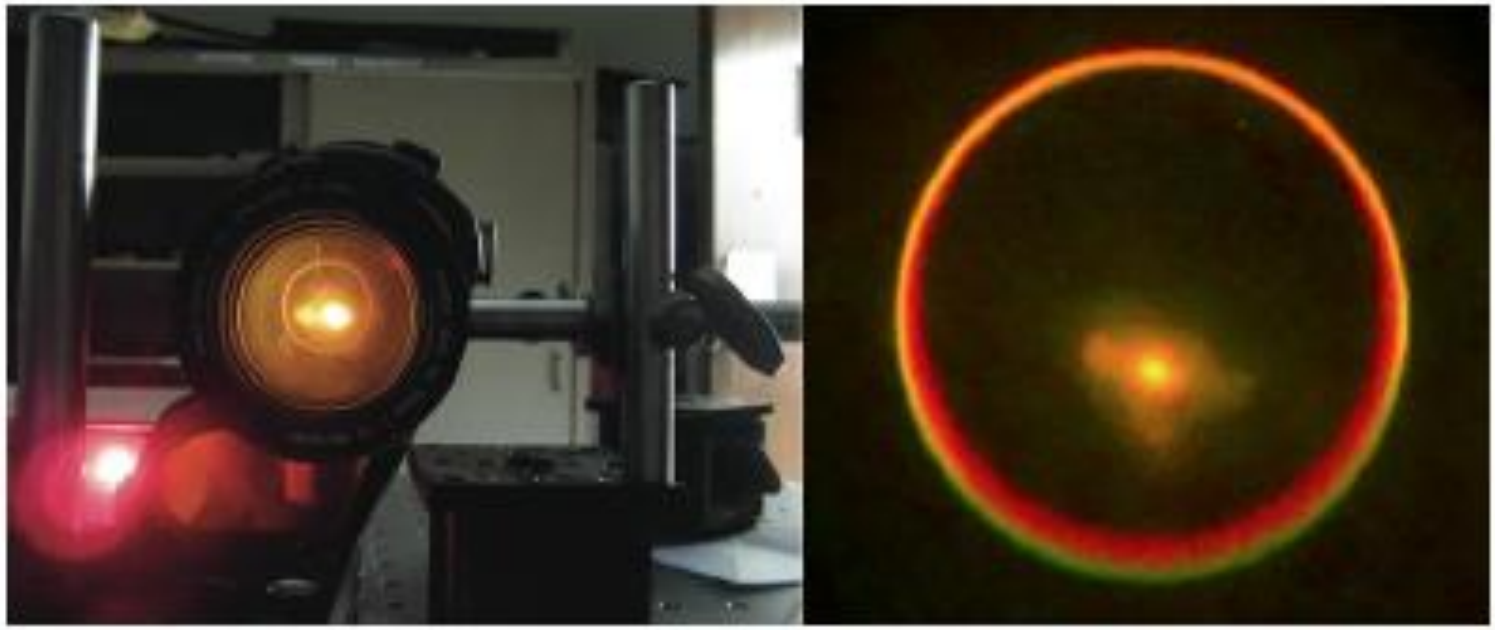
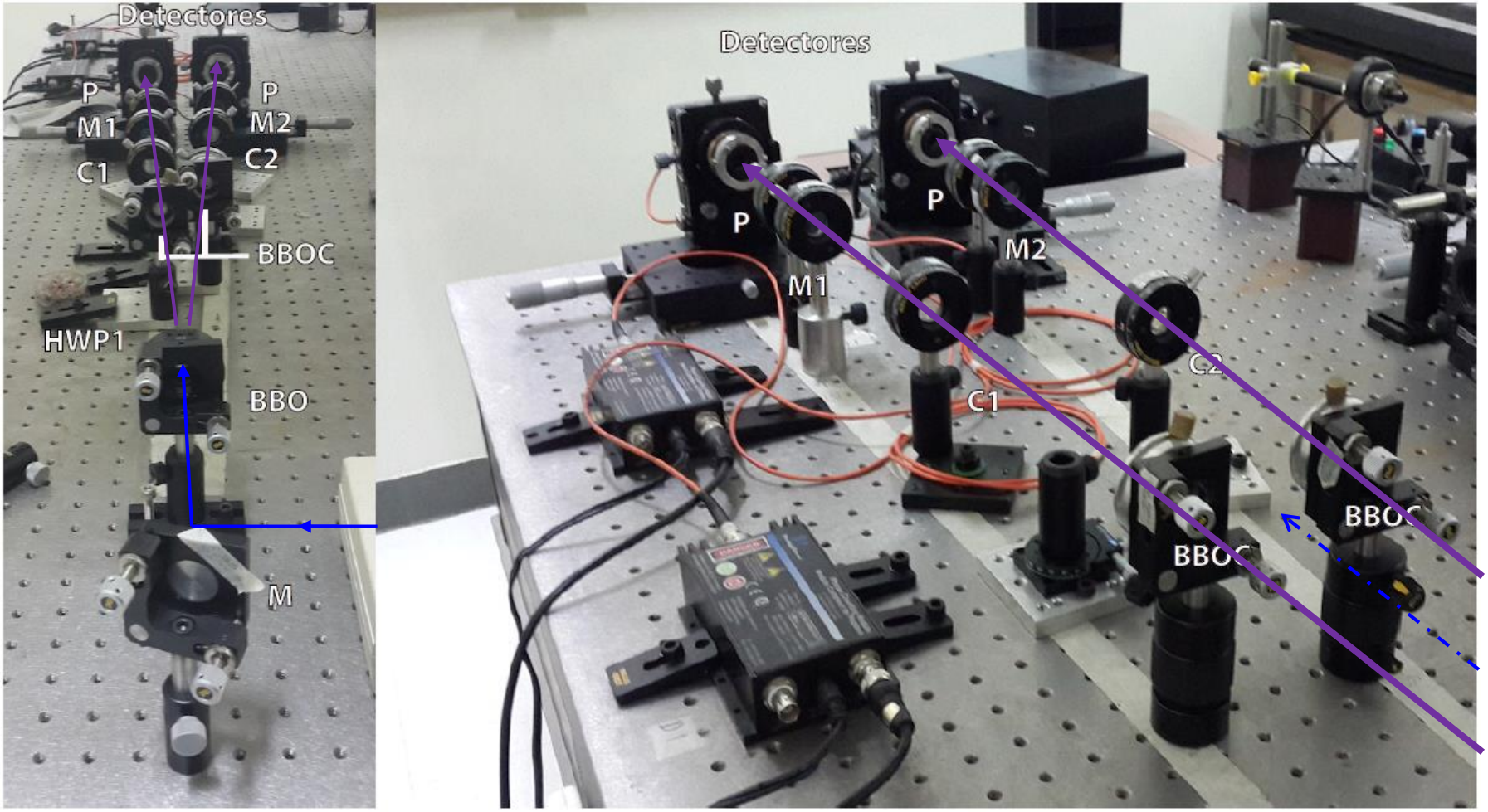


Imagen en el visible

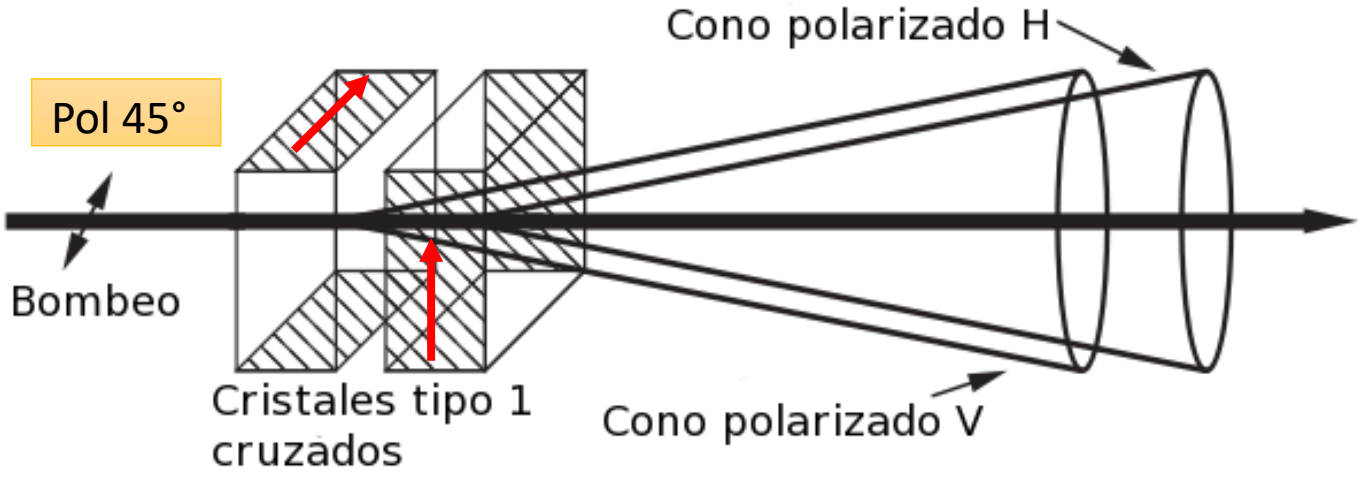


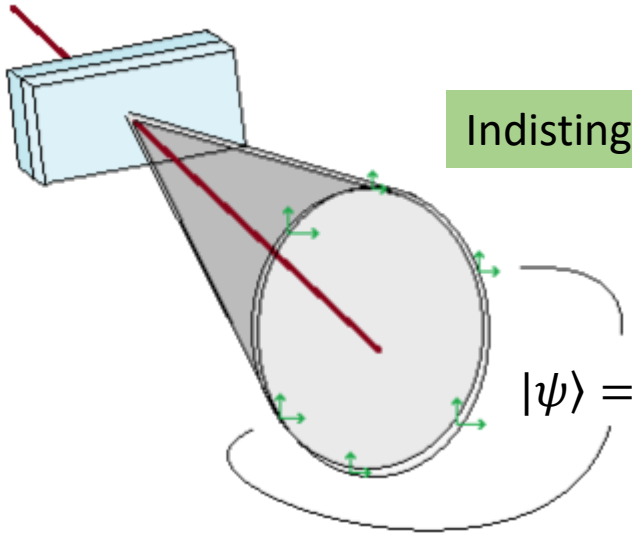
R. Cortiñas, Tesis de Licenciatura
Laboratorio de Procesado de Imágenes, 2015



R. Cortiñas, Tesis de Licenciatura
Laboratorio de Procesado de Imágenes, 2015

Fuente de fotones entrelazados

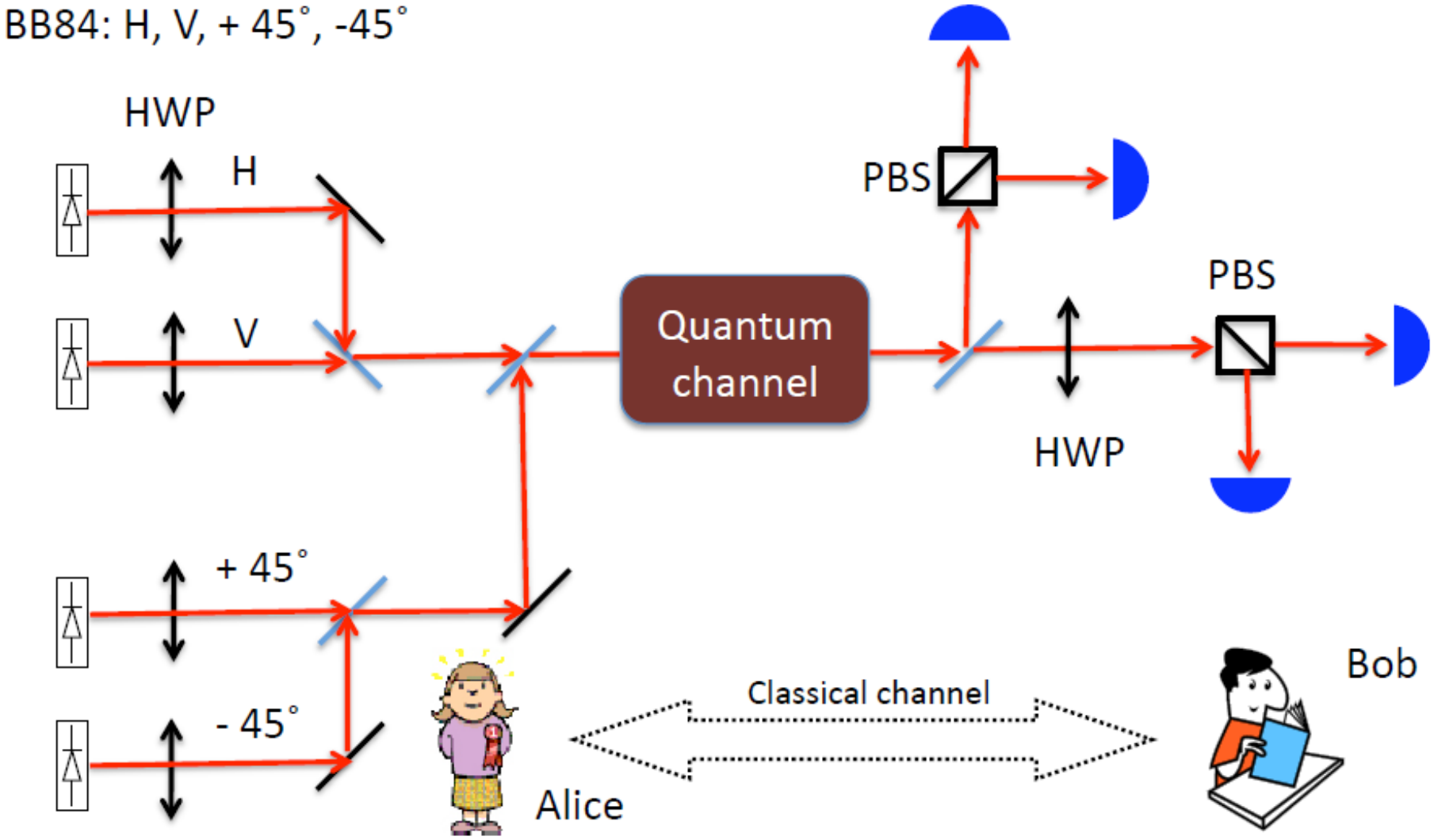




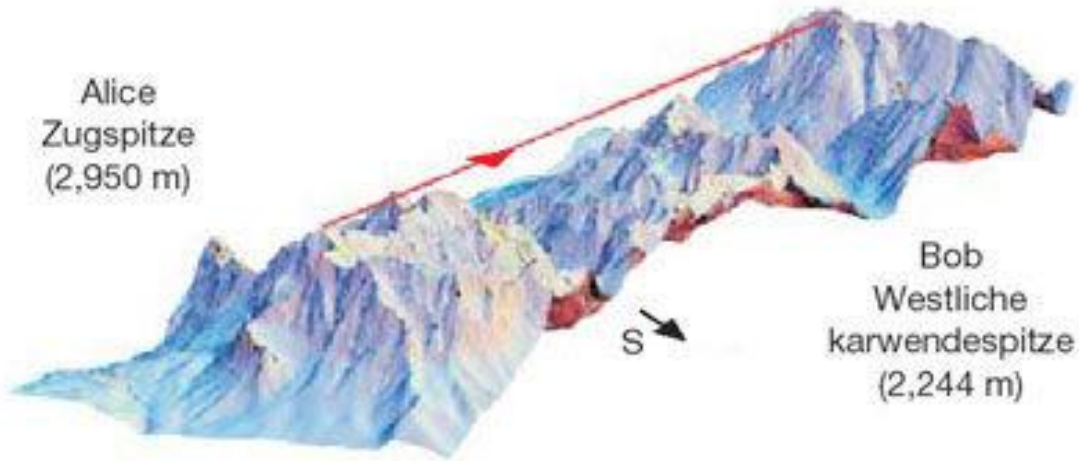
Indistinguibles

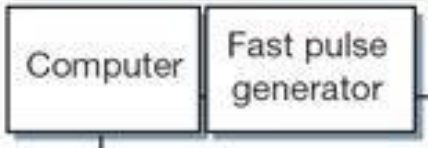
$$|\psi\rangle = \frac{|H\rangle|H\rangle + e^{i\varphi}|V\rangle|V\rangle}{\sqrt{2}}$$

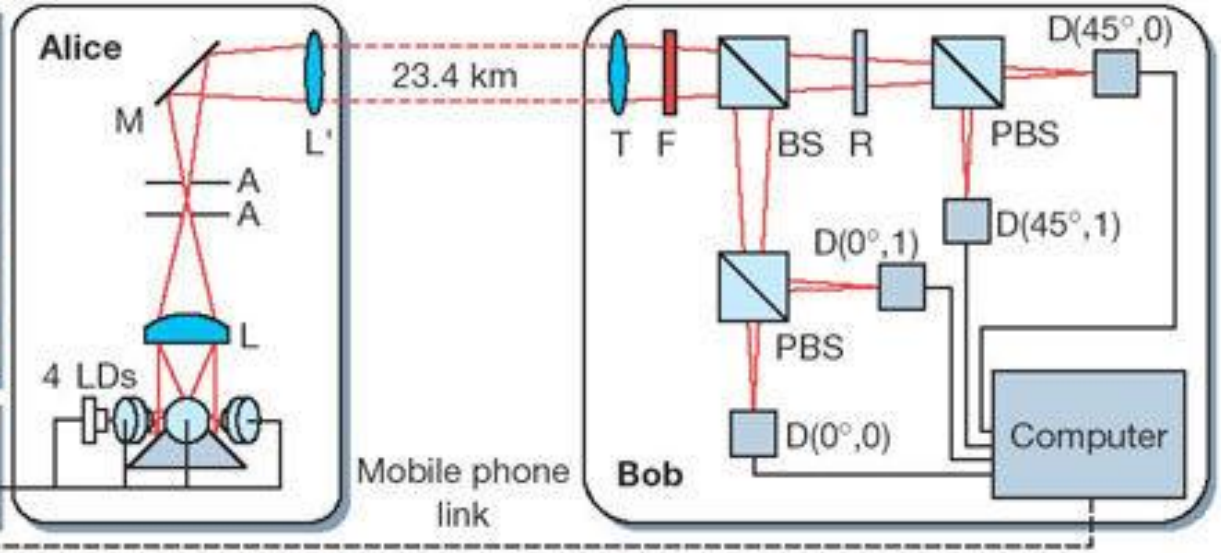
Volviendo…


BB84: H, V, + 45˚, -45˚
HWP
H
V
+ 45˚
- 45˚
Quantum channel
PBS
PBS
HWP
Alice
Classical channel
Bob

BB84 a 23.4 km

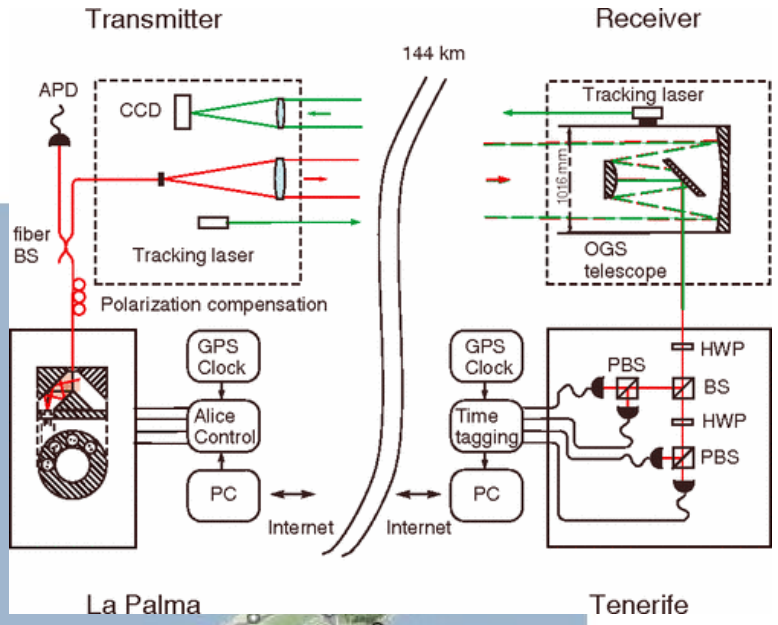


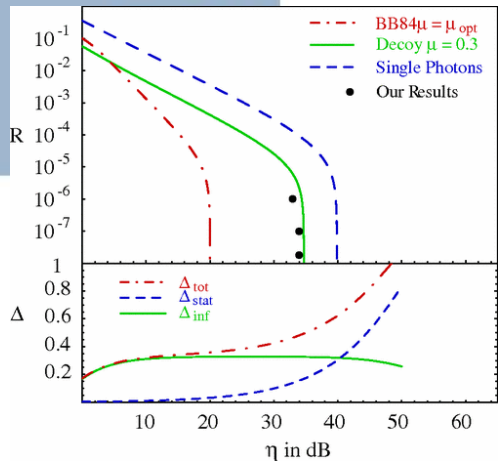




Zarda et al, Nature 419, 450 (2002)

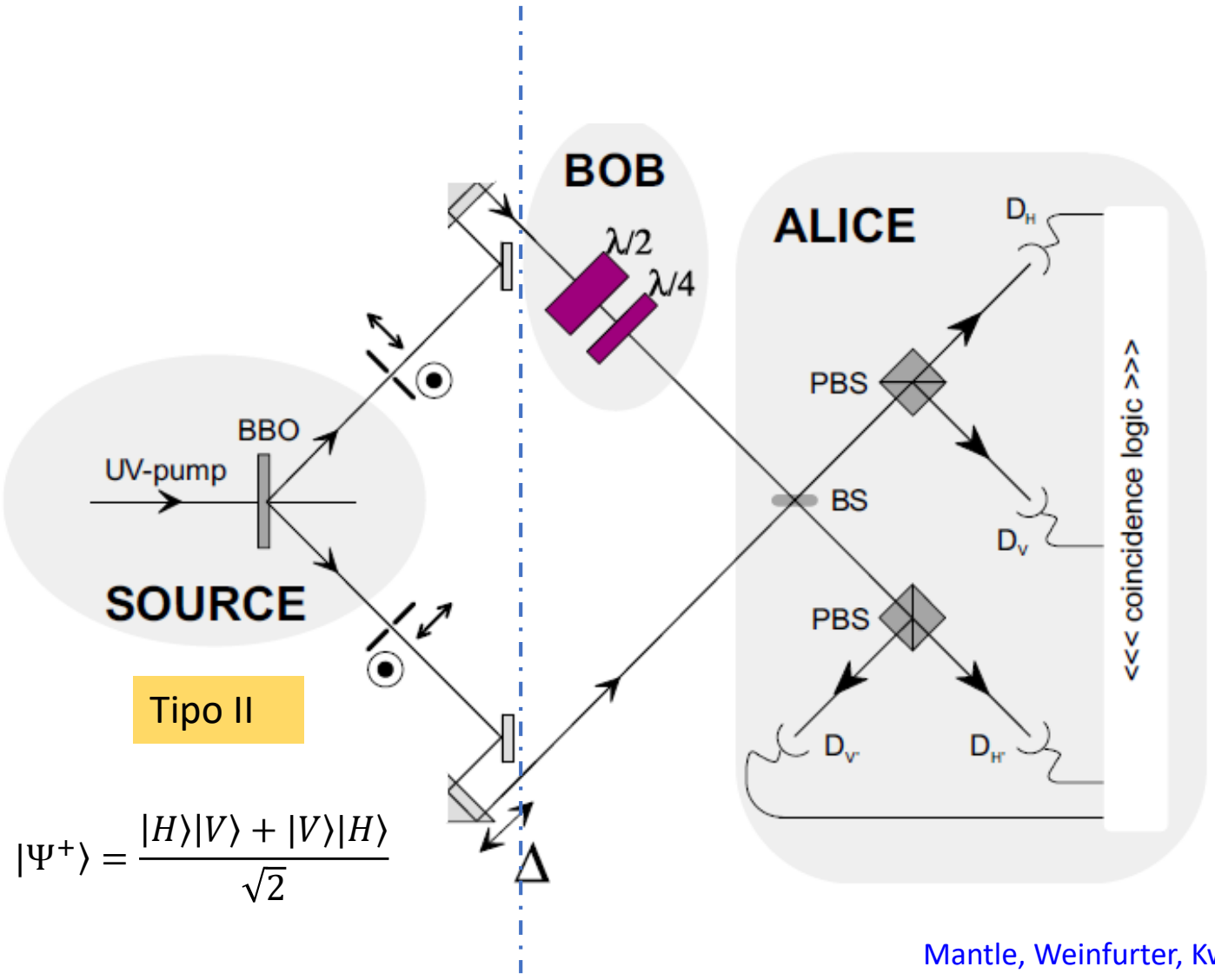
BB84 a 144 km





T. Shmitt-Manderbach et. al, PhysRevLett 98, 010504 (2007)

Superdense coding



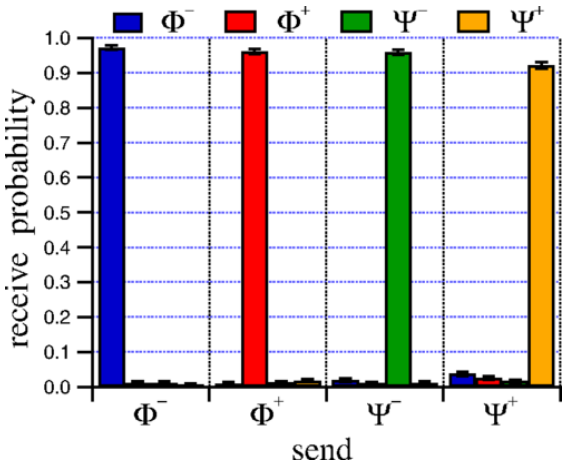
Tipo II

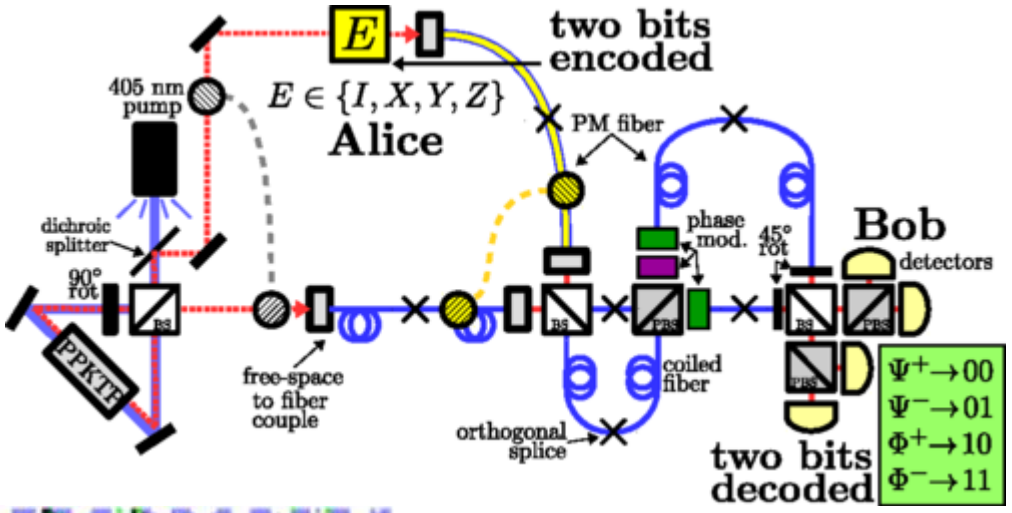
$$|\Psi^+\rangle = \frac{|H\rangle|V\rangle + |V\rangle|H\rangle}{\sqrt{2}}$$

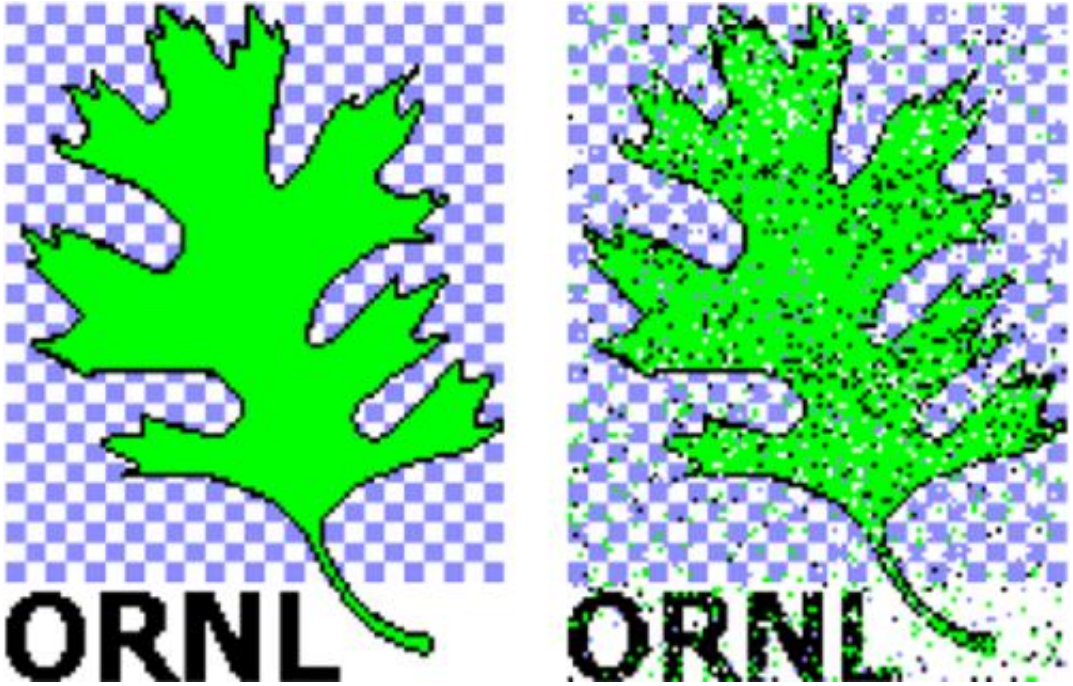
Mantle, Weinfurter, Kwiat, Zeilinger
Phys. Rev. Lett, 76, (**1996)**

Superdense coding

FIG. 4: The conditional probabilities $p(y|x)$ of receiving state y given the sent state x using our apparatus gives the highest channel capacity to date, 1.665±0.018, utilizing a single-qubit and linear optics.







BP Williams, RJ Sadlier, TS Humble - Phys. Rev. Lett, 118, 050501 **2017**

FIG. 5: (Left): The original 4-color 100x136 pixel 3.4kB image. (Right): The image received using superdense coding. The calculated fidelity was 87%.

Cuantos

1ER TALLER ARGENTINO DE CUÁNTICA – CUANTOS 2018

25 - 27 ABRIL 2018
FACULTAD DE MATEMÁTICA ASTRONOMÍA, FÍSICA Y COMPUTACIÓN
CÓRDOBA - ARGENTINA

THORLABS

CONICET UNC Universidad Nacional de Córdoba
I F E G

UNC

FAMAF Facultad de Matemática, Astronomía, Física y Computación

TUTORIALES

Experimentos con Fotones Entrelazados

RESUMEN

Gabriela Barreto Lemos
International Institute of Physics - UFRN - Brasil

Teoría de Floquet para sistemas forzados en materia condensada

RESUMEN

Luis Foa Torres
Universidad de Chile - Chile

No localidad Cuántica

RESUMEN

Ariel Bendersky
ICC-CONICET y UBA - Argentina