国立交通大學
National Chiao Tung University

# Beamlike photo-pair generation by femtosecond pulse laser

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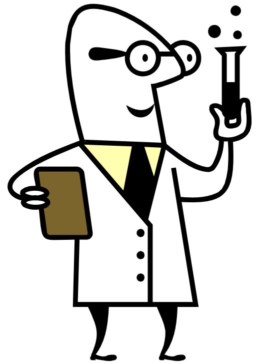
# Acknowledgements

- Taiwan National Science Council

Mr. Hsin-Pin Lo

Prof. Yabushita

Prof. Kobayashi

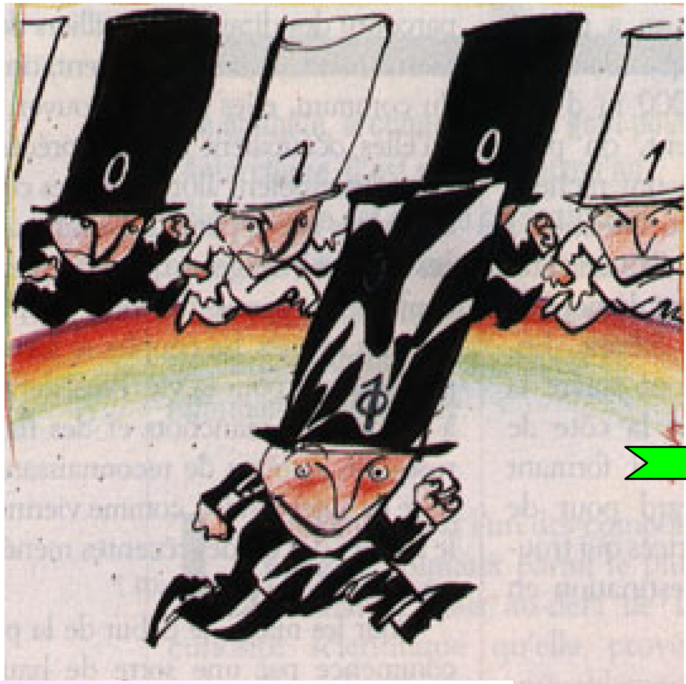


Prof. Chen

# Outline

1. Introduction — quantum information
2. Introduction — femtosecond (fs) laser pulses
3. Down conversion principle
4. Beamlike photon-pair generation

# Introduction – Quantum information



→ 1001101…..

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

*** Superposition**

**1. Speed**
**2. Density**
**3. Communication**

cf. : http://www.qubit.org/library/intros/comp/comp.html

# Introduction – Quantum information

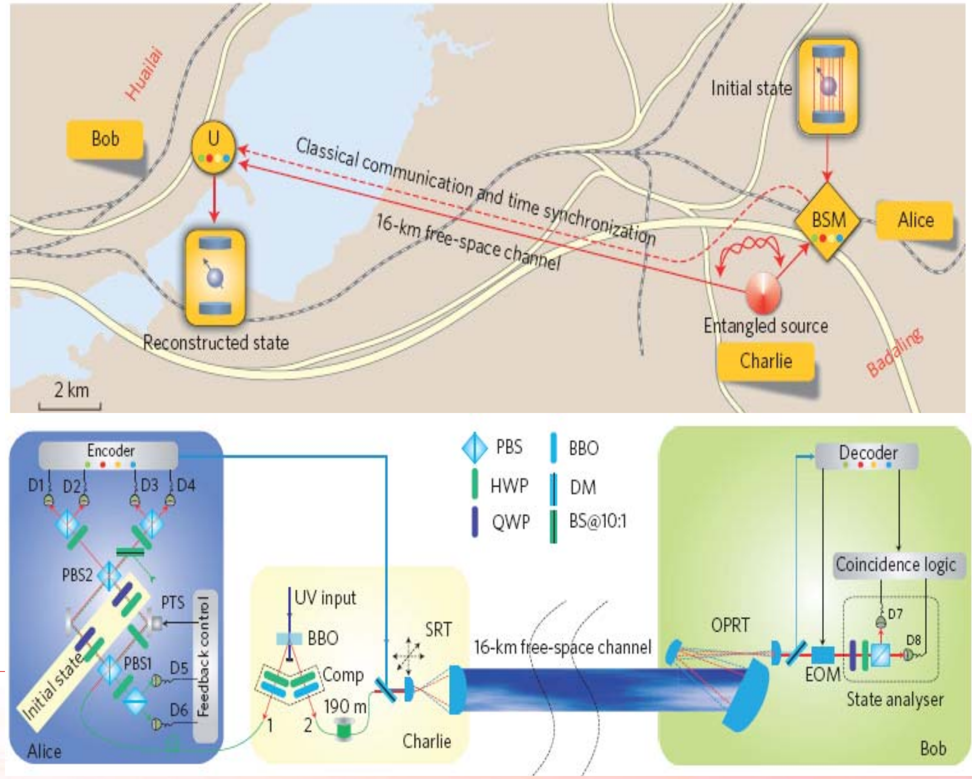
## Beam Us Up!

Teleportation doesn't work for humans yet — but it works over long distances!

Star Trek

LETTERS
PUBLISHED ONLINE: 16 MAY 2010 | DOI: 10.1038/NPHOTON.2010.87
nature photonics

**Free-space implementation of quantum teleportation over 16 km.**




Ref.: X. M. Jin, et al, Nature Photonics 4, 376 (2010).

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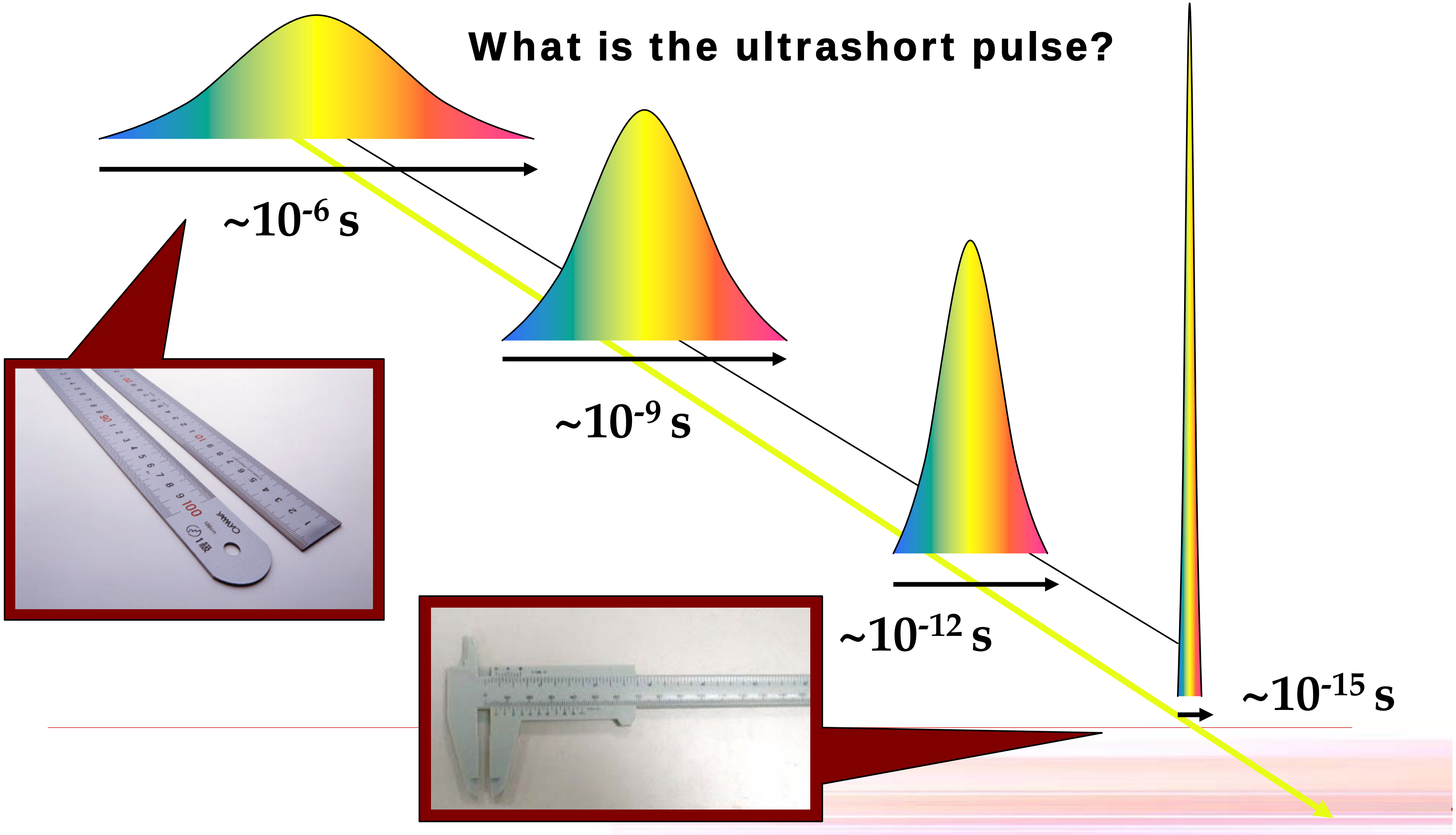
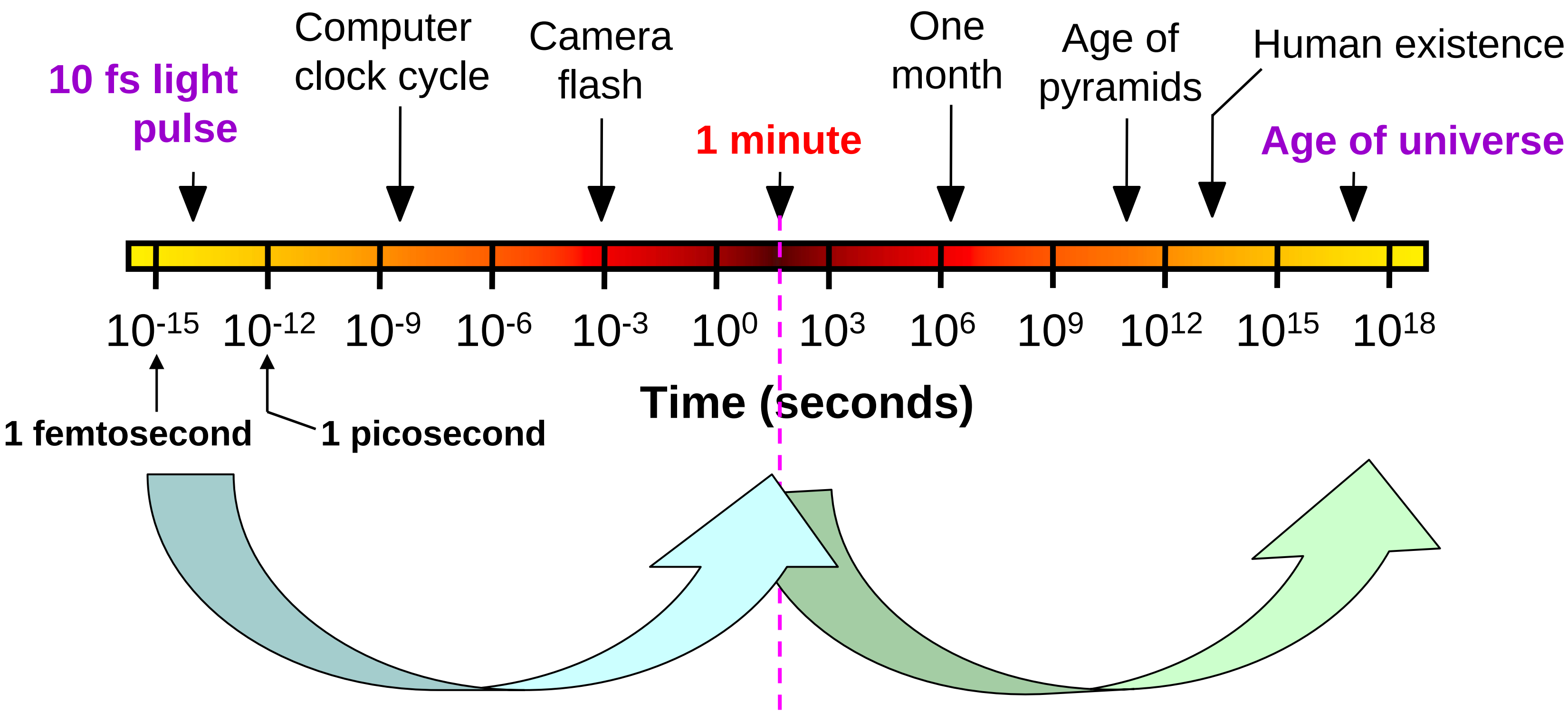
# Introduction – fs laser pulses

**What is the ultrashort pulse?**



# Introduction – fs laser pulses

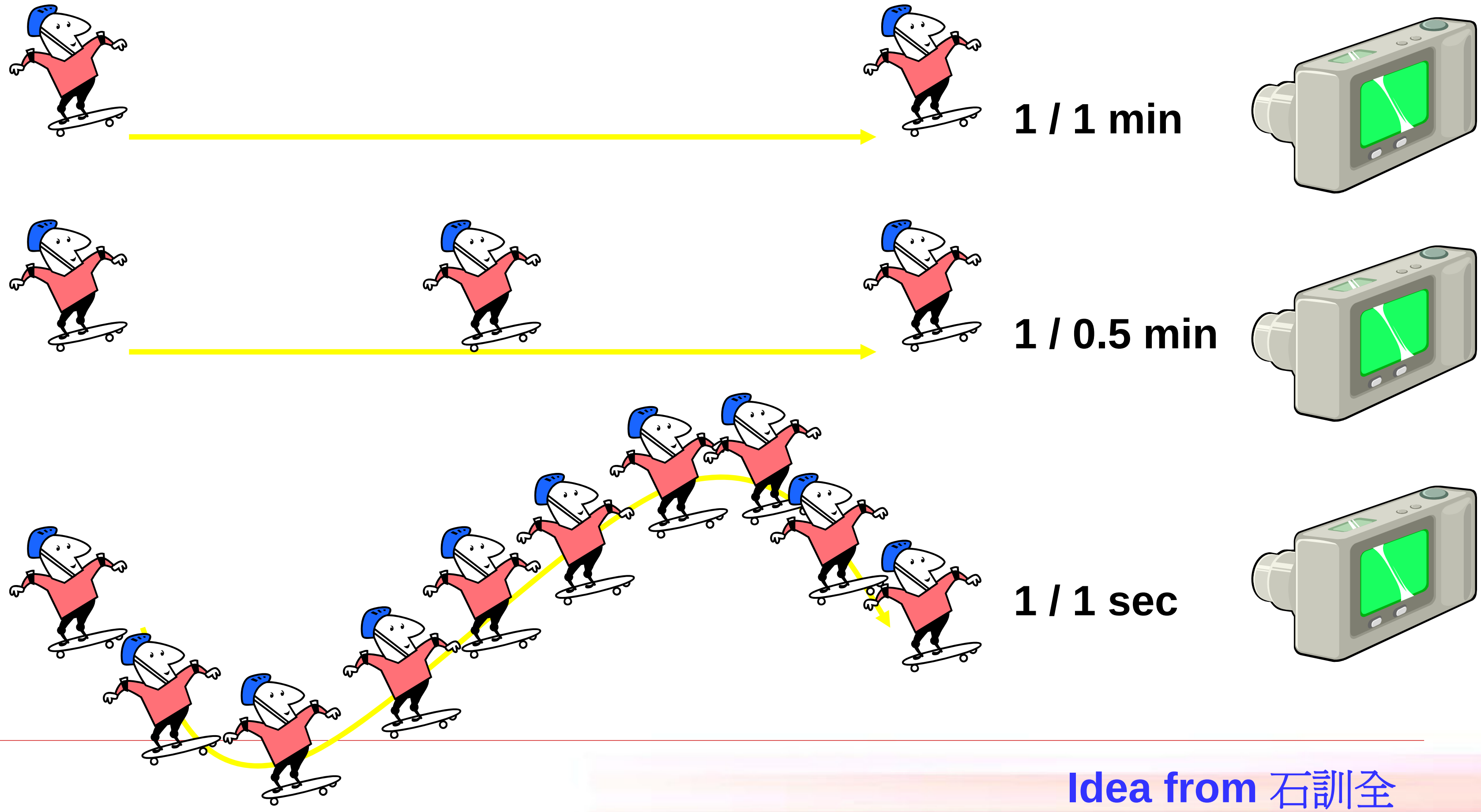
## Timescales




**a pulse : 1 minute ~ 1 minute : age of universe**

# Introduction – fs laser pulses

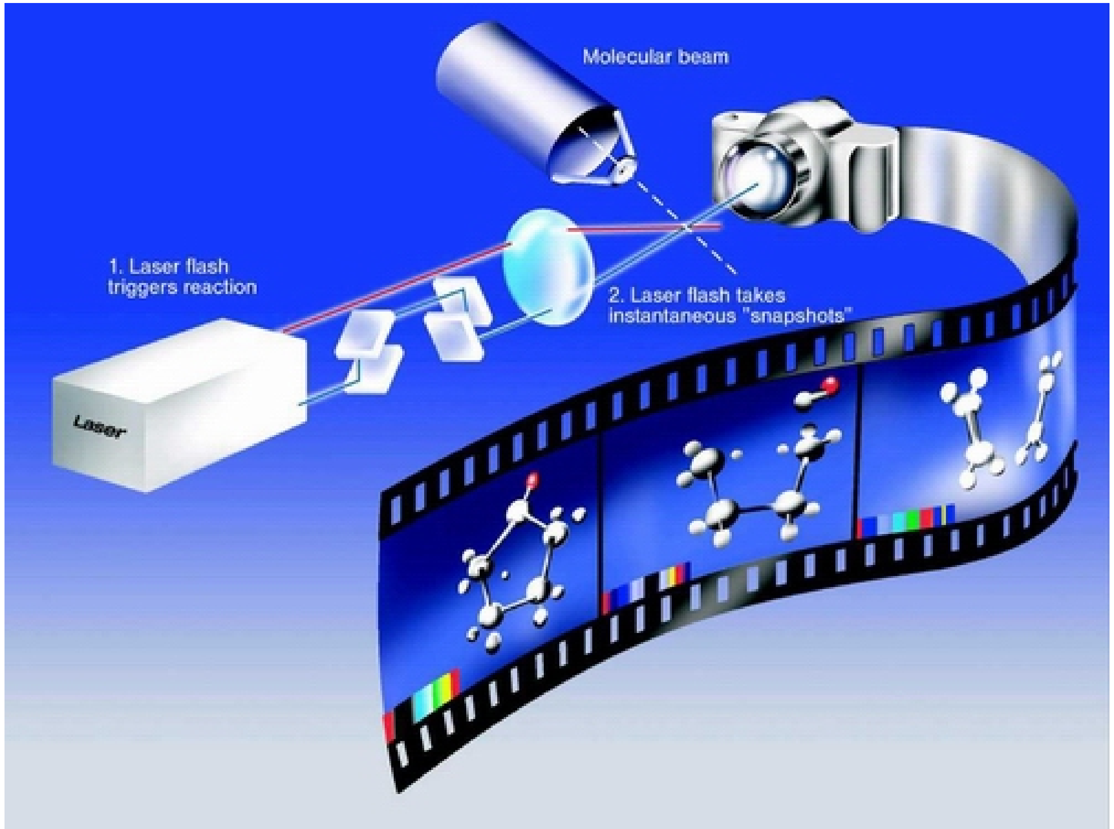
**Which one is true?**




Idea from 石訓全

# Introduction－fs laser pulses

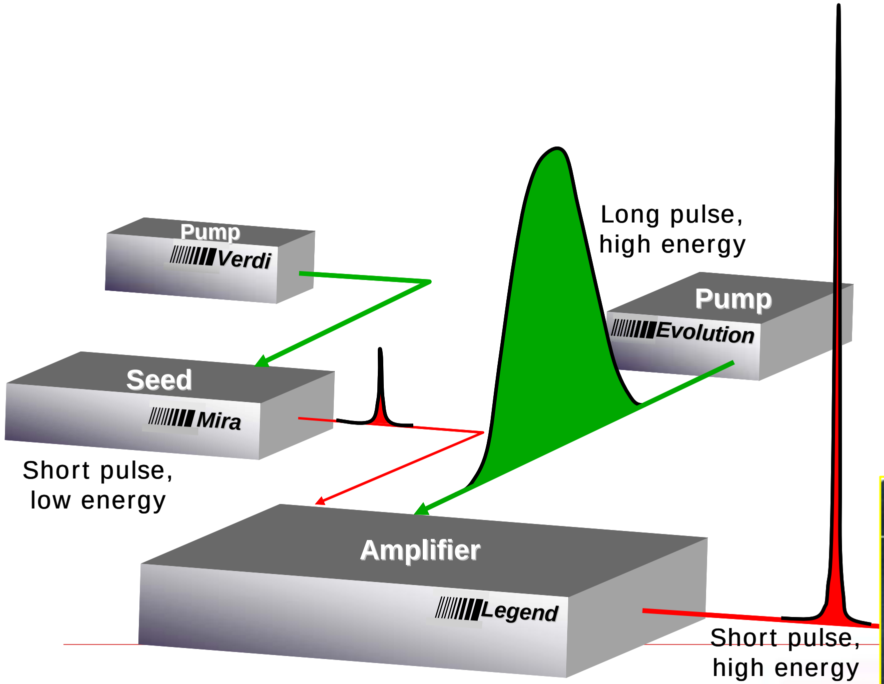
Ultrafast camera!!

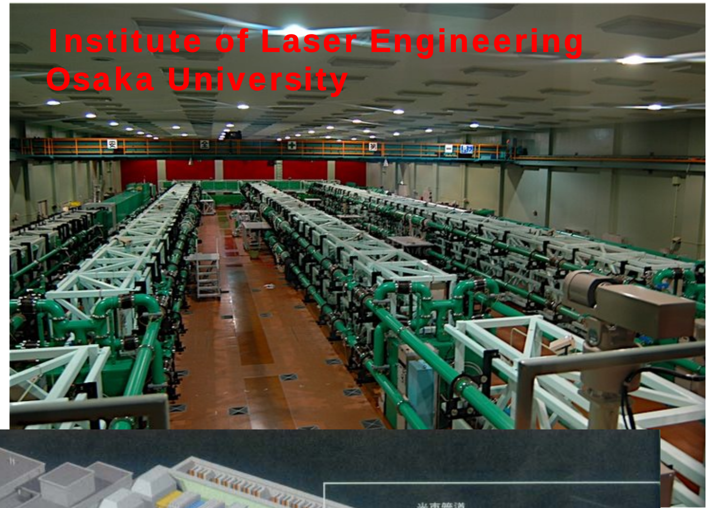


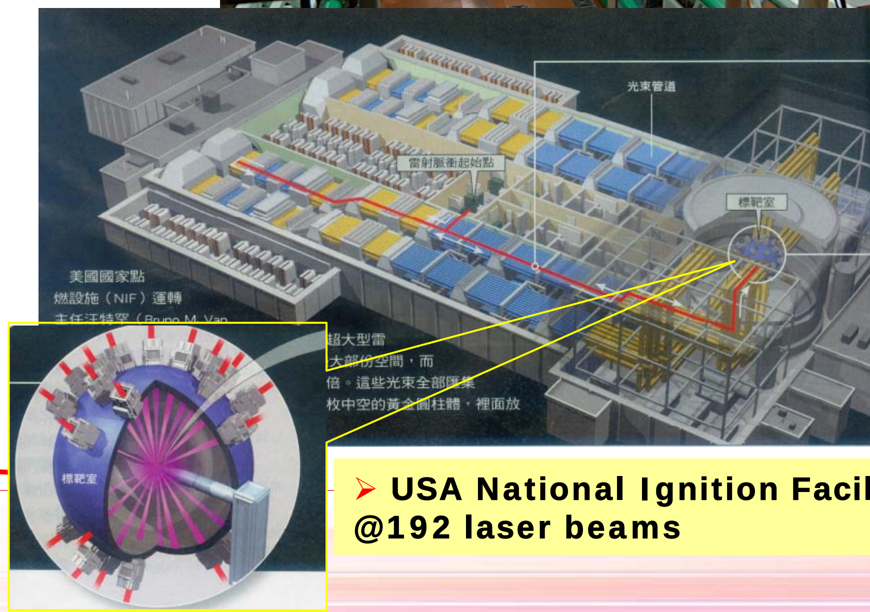
# Introduction – fs laser pulses

**The possibility for nuclear fusion!**

- Short pulse = intense peak power
  - →100 mJ, 100 fs = 1 TW
  - →$10^{18}$ W/cm$^2$ @ $\phi$ = 10 $\mu$m ($10^{10}$ V/cm)



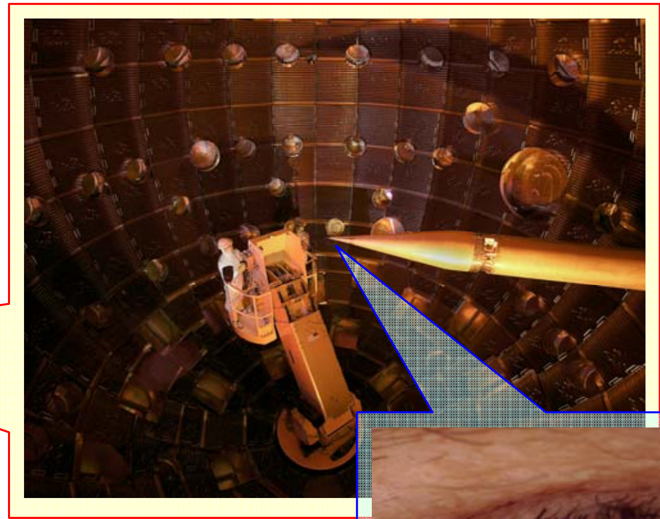



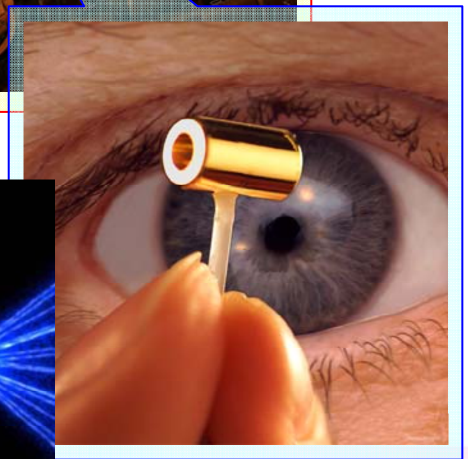



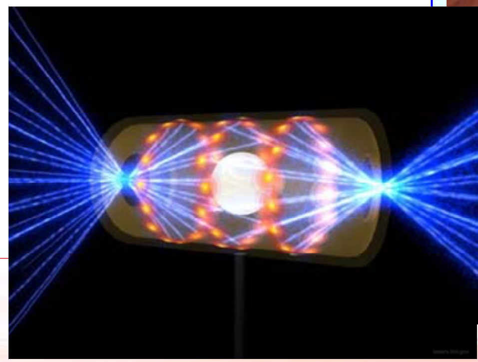
➢ **USA National Ignition Facility @192 laser beams**

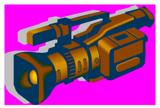
# Introduction – fs laser pulses

**USA National Ignition Facility**









- **Output power ~ 300 TW**

# Outline

1. Introduction — quantum information

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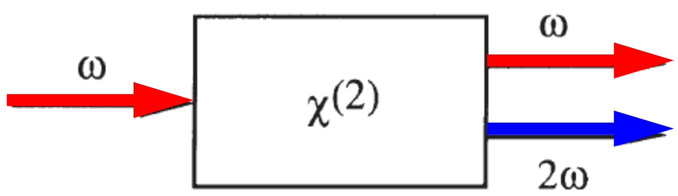
3. Down conversion principle

4. Beamlike photon-pair generation

# Down conversion principle

## Second-order susceptibility – the first nonlinear optical effect

$$\mathbf{P} = \varepsilon_0 \left( \chi^{(1)}\mathbf{E} + \chi^{(2)}\mathbf{EE} + \chi^{(3)}\mathbf{EEE} + \cdots \right)$$




- The polarization of a material can be written as

$$\Rightarrow P_i(2\omega) = \varepsilon_0 \sum_{j,k} \chi_{ijk}^{(2)} E_j(\omega) E_k(\omega)$$

$$\Rightarrow \begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{pmatrix} \begin{pmatrix} E_x^2 \\ E_y^2 \\ E_z^2 \\ 2E_zE_y \\ 2E_zE_x \\ 2E_xE_y \end{pmatrix}$$

- In a centrosymmetric (inverse sym.) crystal → $d_{ijk}=0$ → no SHG
- In non-centrosymmetric (no inverse-sym.) crystal → $d_{ijk} \neq 0$ → SHG

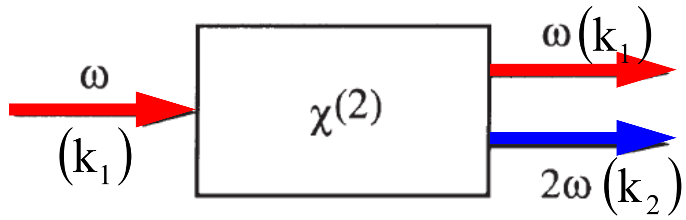
# Down conversion principle

## Second-order susceptibility

**The energy conservation** $\hbar(2\omega) = \hbar\omega + \hbar\omega$

**The momentum conservation**

$$k_2 = k_1 + k_1 = 2k_1 \Rightarrow \Delta k = k_2 - 2k_1 = 0$$



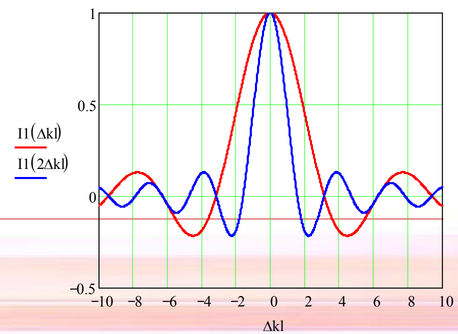

After propagation over a distance *l* in the medium,

$\Delta k l = (k_2 - 2k_1) l = 0$ The two contributions add constructively

$\Delta k l = (k_2 - 2k_1) l \neq 0$ The two interfere destructively

If it satisfies above conditions, the intensity of SHG can be calculated by

$$I(2\omega) = \frac{2^7 \pi^3 \omega^2 \chi_{eff}^2 l^2}{n^3 c^3} I^2(\omega) \left( \frac{\sin(\Delta kl/2)}{\Delta kl/2} \right)$$




Dephasing must be overcome for SHG!!

# Down conversion principle

## Second-order susceptibility

**Phase matching condition**

$$\Delta k = k^{(2\omega)} - 2k^{(\omega)} = \frac{2\omega}{c}\left(n^{2\omega} - 2n^{\omega}\right) = 0$$

⇨ Get maximum signal of SHG

**Coherent length** $$l_c = \frac{2\pi}{\Delta k} = \frac{2\pi}{k^{(2\omega)} - 2k^{(\omega)}} = \frac{\lambda}{c\left(n^{2\omega} - 2n^{\omega}\right)}$$

Index-of-refraction dispersion data on $KH_2PO_4$

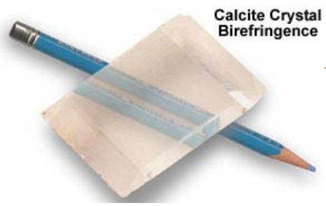
| Wavelength, μm | Index: $n_o$ (ordinary ray) | Index: $n_e$ (extraordinary ray) |
|---|---|---|
| 0.2000 | 1.622630 | 1.563913 |
| 0.3000 | 1.545570 | 1.498153 |
| 0.4000 | 1.524481 | 1.480244 |
| 0.5000 | 1.514928 | 1.472486 |
| 0.6000 | 1.509274 | 1.468267 |
| 0.7000 | 1.505235 | 1.465601 |
| 0.8000 | 1.501924 | 1.463708 |
| 0.9000 | 1.498930 | 1.462234 |
| 1.0000 | 1.496044 | 1.460993 |
| 1.1000 | 1.493147 | 1.459884 |
| 1.2000 | 1.490169 | 1.458845 |
| 1.3000 | 1.487064 | 1.457838 |
| 1.4000 | 1.483803 | 1.456838 |
| 1.5000 | 1.480363 | 1.455829 |
| 1.6000 | 1.476729 | 1.454797 |
| 1.7000 | 1.472890 | 1.453735 |
| 1.8000 | 1.468834 | 1.452636 |
| 1.9000 | 1.464555 | 1.451495 |
| 2.0000 | 1.460044 | 1.450308 |

If $\lambda = 1\ \mu m$ and $n^{2\omega} - n^{\omega} \sim 0.01 \rightarrow l_c \sim 100\ \mu m$

⇨ **$(n^{2\omega} - n^{\omega}) \rightarrow 0$, $l_c \rightarrow \infty$, $I(2\omega) \rightarrow \infty$**

In normally dispersive materials the index of refraction increases with $\omega$. This makes it **impossible** to satisfy phase matching when both the $\omega$ and $2\omega$ beams are of the same type.

**For birefringent crystal, $n_e^{\omega} \neq n_o^{\omega}$** ⇨ **Can satisfy the phase matching condition**

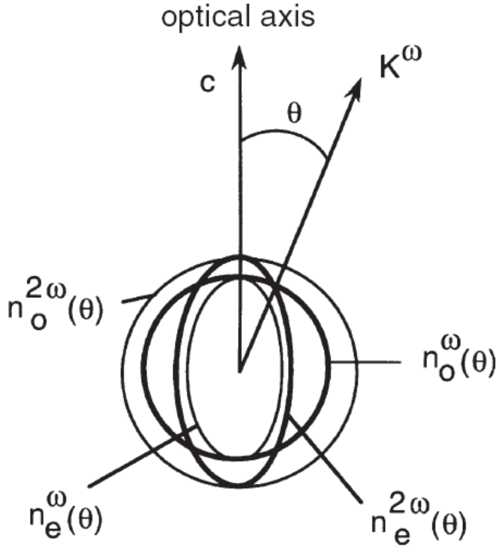


# Down conversion principle

## Second-order susceptibility

### Birefringent crystal

- Positive birefringence ($n_e > n_o$): Quartz
- Negative birefringence ($n_e < n_o$): Calcite




Calculate the phase-matching angle $\theta$ between the propagation direction and the optical axis

$$\left(\frac{1}{n_e^{2\omega}(\theta)}\right)^2 = \frac{\sin^2\theta}{\left(n_e^{2\omega}\right)^2} + \frac{\cos^2\theta}{\left(n_o^{2\omega}\right)^2} = \left(\frac{1}{n_o^{\omega}(\theta)}\right)^2$$

$$\Rightarrow \quad \theta = \sin^{-1}\left[\sqrt{\frac{\left(n_o^{\omega}\right)^{-2} - \left(n_o^{2\omega}\right)^{-2}}{\left(n_e^{2\omega}\right)^{-2} - \left(n_o^{2\omega}\right)^{-2}}}\right]$$

**For negative birefringent crystal, the polarization should be**

$$\text{Type I}: \mathbf{E}_\omega // \mathbf{E}_\omega \Rightarrow n_o^{\omega} + n_o^{\omega} = 2n_e^{2\omega}(\theta)$$

$$\text{Type II}: \mathbf{E}_\omega \perp \mathbf{E}_\omega \Rightarrow n_e^{\omega}(\theta) + n_o^{\omega} = 2n_e^{2\omega}(\theta)$$

**Bandwidth of SHG**

$$d\lambda_{2\omega} = \frac{\pm 1.39\lambda_\omega}{2\pi l}\left(\frac{\partial n_o^{\omega}}{\partial \lambda_\omega} - \frac{1}{2}\frac{\partial n_e^{2\omega}}{\partial \lambda_{2\omega}}\right)$$

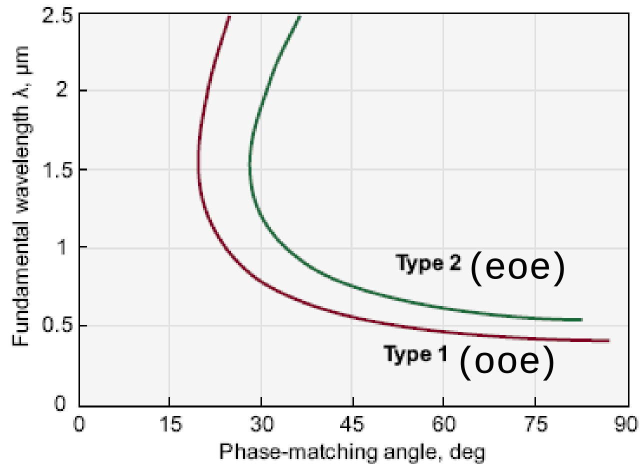
Limit by crystal thickness [30 $\mu$m KDP($KH_2PO_4$) @ 6fs]

# Down conversion principle

## Second-order susceptibility

### Ex. BBO ( β -Barium Borate, $BaB_2O_4$)

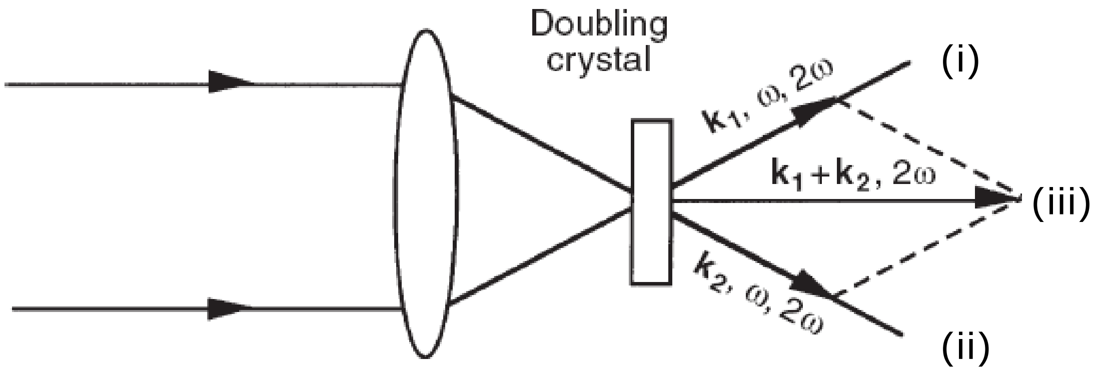
| | | |
|---|---|---|
| Crystal structure | trigonal, 3m | |
| Optical symmetry | Negative Uniaxial ($n_o > n_e$) | |
| Space group | R3c | |
| Density | 3.85 g/cm³ | |
| Mohs hardness | 5 | |
| Optical homogeneity | $\partial n = 10^{-6}$ cm$^{-1}$ | |
| Transparency region at "0" transmittance level | 189 – 3500 nm | |
| Linear absorption coefficient at 1064 nm | < 0.1% cm$^{-1}$ | |
| Refractive indices | $n_o$ | $n_e$ |
| at 1064 nm | 1.6551 | 1.5426 |
| at 532 nm | 1.6750 | 1.5555 |
| at 355 nm | 1.7055 | 1.5775 |
| at 266 nm | 1.7571 | 1.6139 |
| at 213 nm | 1.8465 | 1.6742 |
| Sellmeier equations (λ, μm) | $n_o^2 = 2.7405 + 0.0184 / (\lambda^2 - 0.0179) - 0.0155\ \lambda^2$ | |
| | $n_e^2 = 2.3730 + 0.0128 / (\lambda^2 - 0.0156) - 0.0044\ \lambda^2$ | |
| Phase matching range Type 1 SHG | 410 – 3300 nm | |
| Phase matching range Type 2 SHG | 530 – 3300 nm | |
| Walk-off angle | 55.9 mrad (Type 1 SHG 1064 nm) | |
| Angular acceptance | 1.2 mrad × cm (Type 1 SHG 1064 nm) | |
| Thermal acceptance | 70 K × cm (Type 1 SHG 1064 nm) | |
| Nonlinearity coefficients | $d_{22} = \pm(2.22 \pm 0.09)$ pm/V | |
| | $d_{31} = \pm(0.16 \pm 0.08)$ pm/V | |
| Effective nonlinearity expressions | $d_{ooe} = d_{31} \sin\theta - d_{22} \cos\theta \sin 3\varphi$ | |
| | $d_{eoe} = d_{oee} = d_{22} \cos^2\theta \cos 3\varphi$ | |
| Damage threshold for $TEM_{00}$ 1064 nm | > 0.5 GW/cm² at 10 ns | |
| | ~ 50 GW/cm² at 1 ps | |




| Code | Size, mm | θ | φ | Coating | Application |
|---|---|---|---|---|---|
| BBO-601 | 6x6x0.1 | 29.2 | 90 | P/P @ 400-800 nm | SHG @ 800 nm |
| BBO-602 | 6x6x0.2 | 29.2 | 90 | P/P @ 400-800 nm | SHG @ 800 nm |
| BBO-603 | 6x6x0.5 | 29.2 | 90 | P/P @ 400-800 nm | SHG @ 800 nm |

# Down conversion principle

The energy & momentum conservation in frequency mixing





(i) $\hbar(2\omega)=\hbar\omega_1+\hbar\omega_1, \quad k_{2\omega}=k_1+k_1$

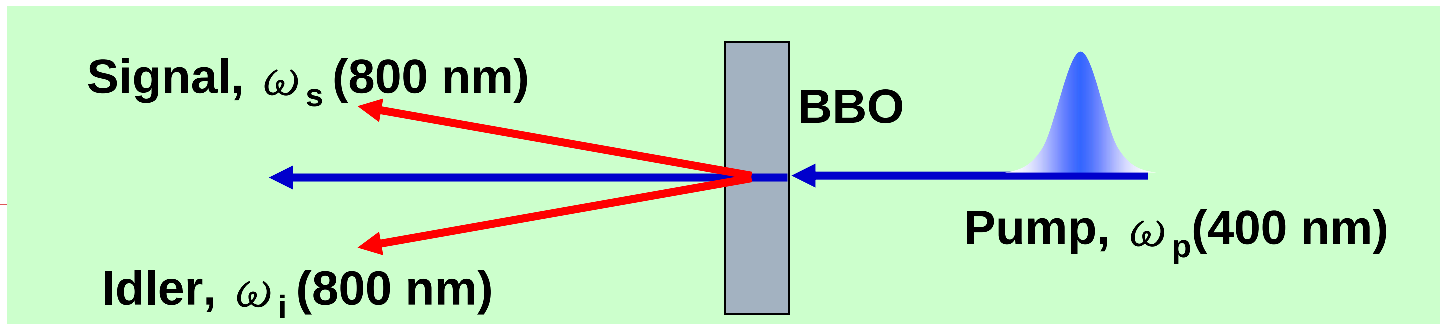
(ii) $\hbar(2\omega)=\hbar\omega_2+\hbar\omega_2, \quad k_{2\omega}=k_2+k_2$

(iii) $\hbar(2\omega)=\hbar\omega_1+\hbar\omega_2, \quad k_{2\omega}=k_1+k_2$

Type I : $\mathbf{E}_{800} // \mathbf{E}_{800}$

Type II : $\mathbf{E}_{800} \perp \mathbf{E}_{800}$

## Spontaneous Parametric Down-Conversion (SPDC)



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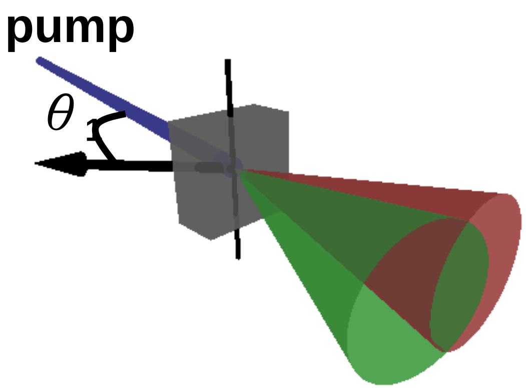
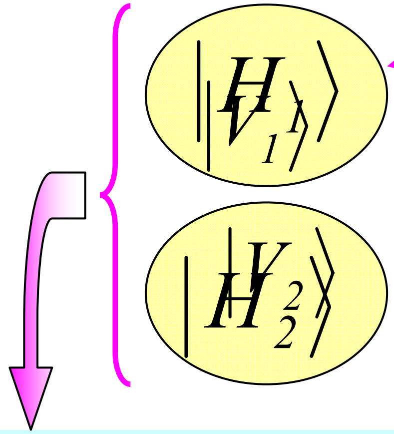
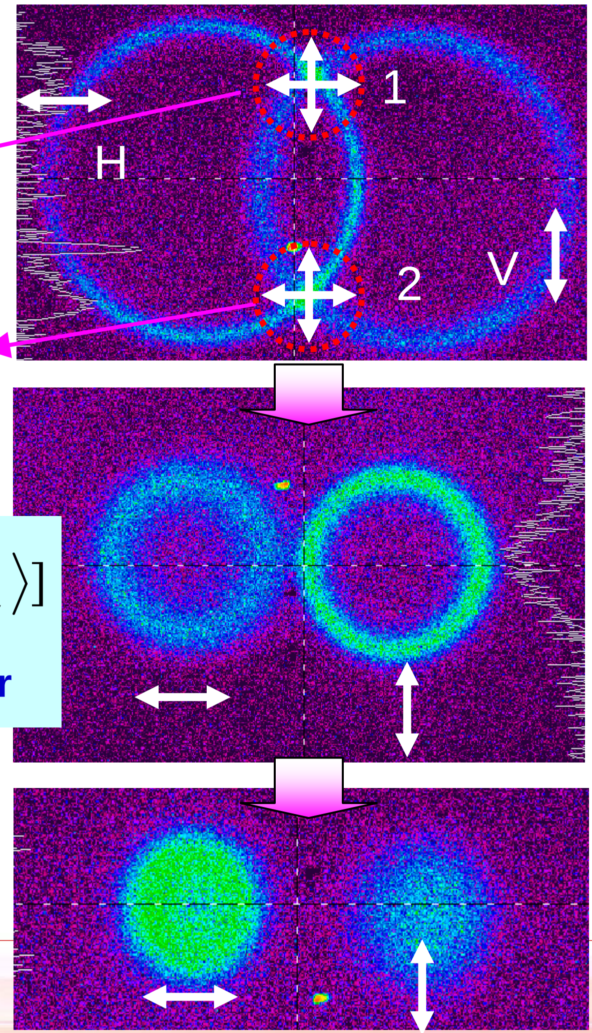
# Beamlike photon-pair generation

## SPDC photon generation

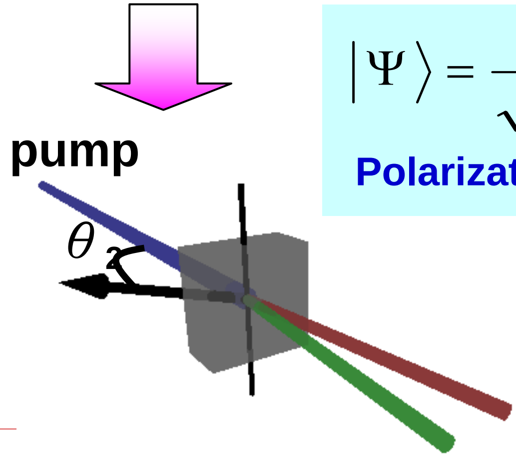





$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|H_1\rangle|V_2\rangle + |V_1\rangle|H_2\rangle]$$

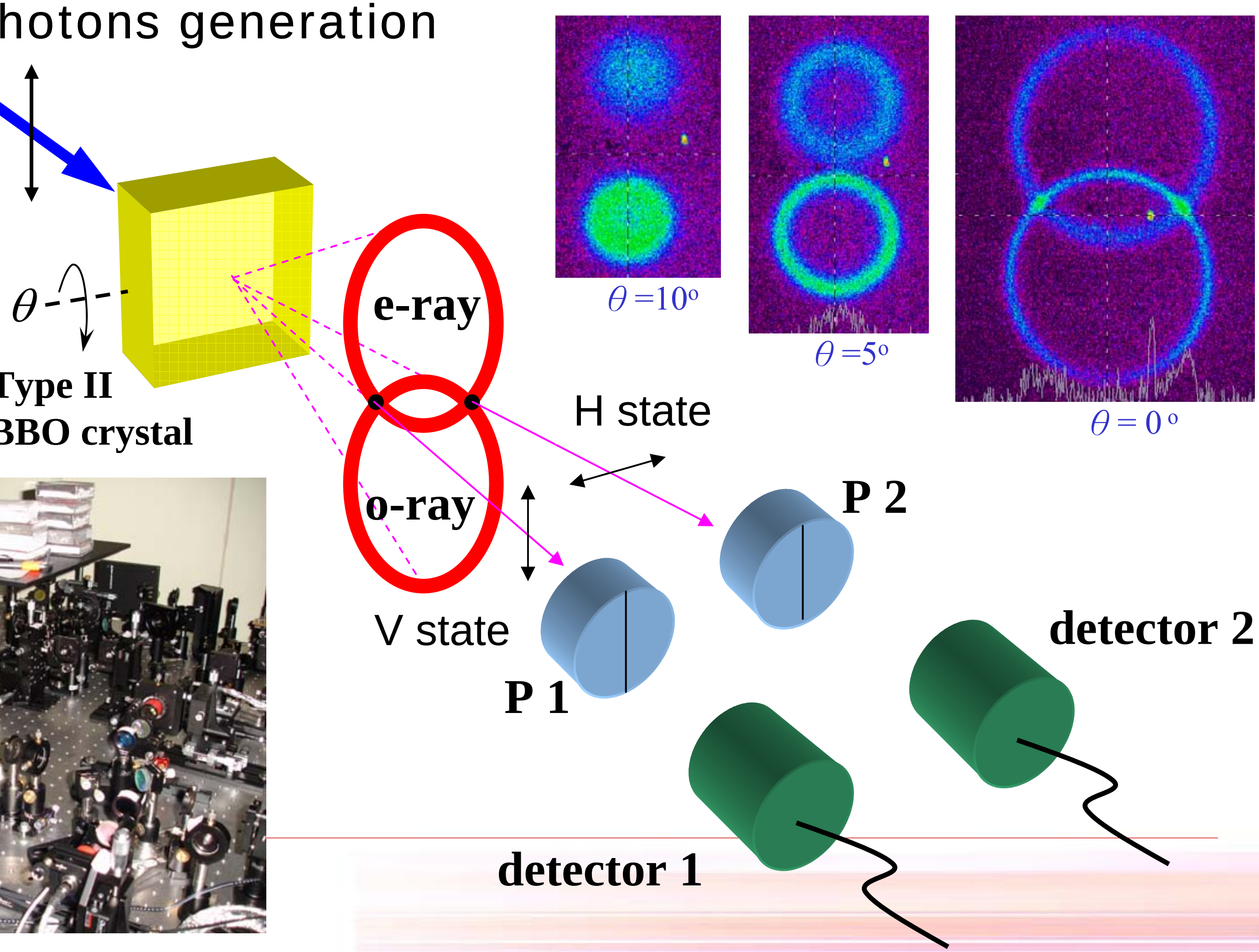
**Polarization Entangled photon pair**

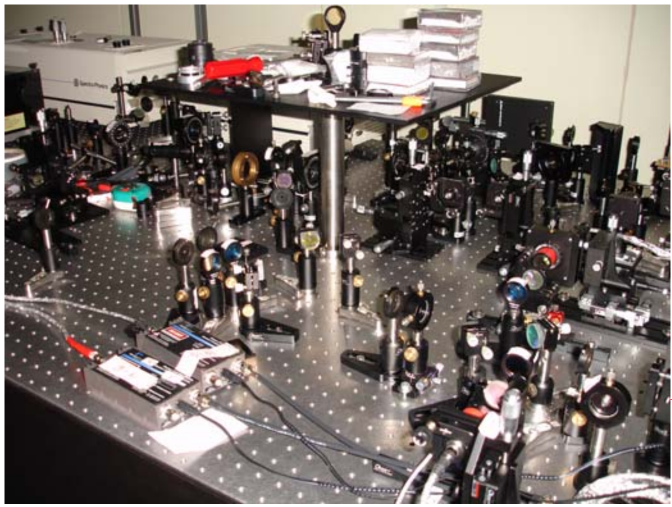



H. P. Lo, A. Yabushita, C. W. Luo, P. C. Chen,
T. Kobayashi, PRA **83**, 022313 (2011)

# Beamlike photon-pair generation

Entangled photons generation



# Beamlike photon-pair generation

PHYSICAL REVIEW LETTERS

VOLUME 75 | 11 DECEMBER 1995 | NUMBER 24

**New High-Intensity Source of Polarization-Entangled Photon Pairs**

Paul G. Kwiat,* Klaus Mattle, Harald Weinfurter, and Anton Zeilinger
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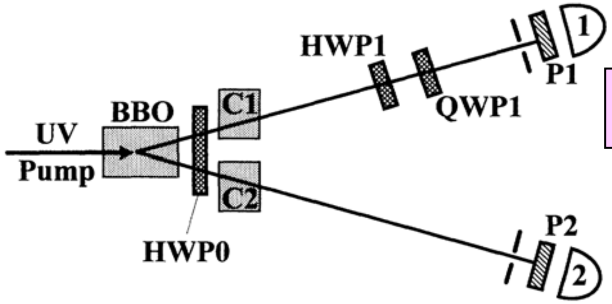
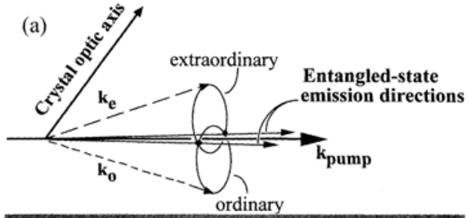
Alexander V. Sergienko and Yanhua Shih
*Department of Physics, University of Maryland Baltimore County, Baltimore, Maryland 21228*
(Received 5 July 1995)

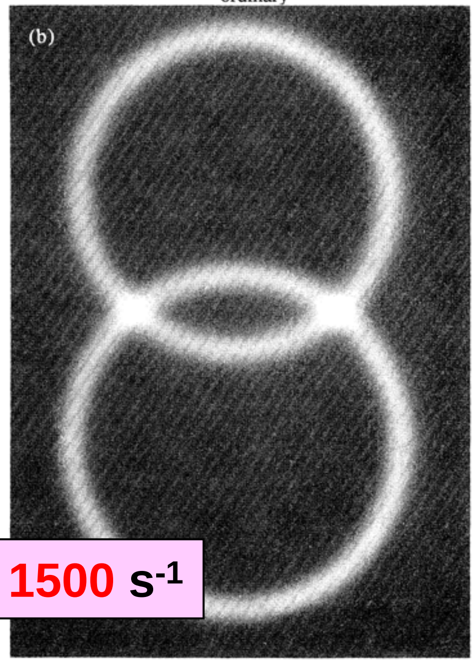
EPR-Bell states

$$|\psi^{\pm}\rangle = (|H_1, V_2\rangle \pm |V_1, H_2\rangle)/\sqrt{2},$$

$$|\phi^{\pm}\rangle = (|H_1, H_2\rangle \pm |V_1, V_2\rangle)/\sqrt{2},$$




**Generation rate ~ 1500 s$^{-1}$**

FIG. 1. (a) Spontaneous down-conversion cones present with type-II phase matching. Correlated photons lie on opposite sides of the pump beam. (b) A photograph of the down-conversion photons, through an interference filter at 702 nm (5 nm FWHM). The infrared film was located 11 cm from the crystal, with no imaging lens. (Photograph by M. Reck.)

# Beamlike photon-pair generation

968 OPTICS LETTERS / Vol. 33, No. 9 / May 1, 2008

## Beamlike high-brightness source of polarization-entangled photon pairs

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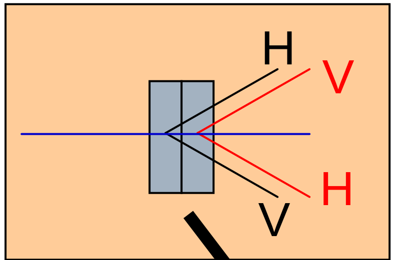
**Corresponding author: zou@osa.org*

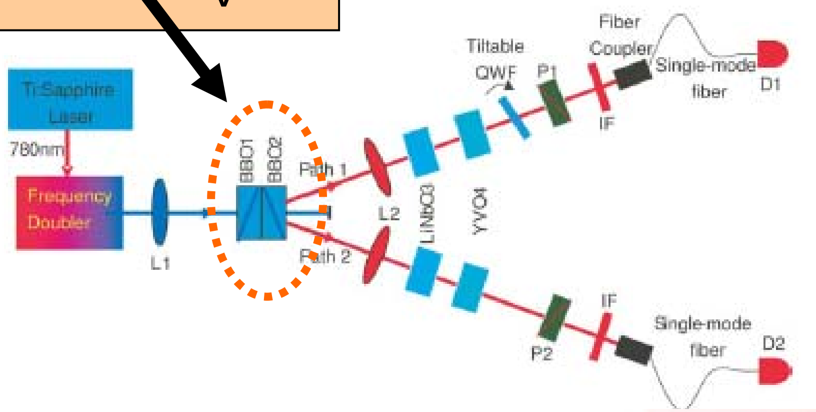
**Table 1. Results of Quantum State Tomography Measurement[a]**

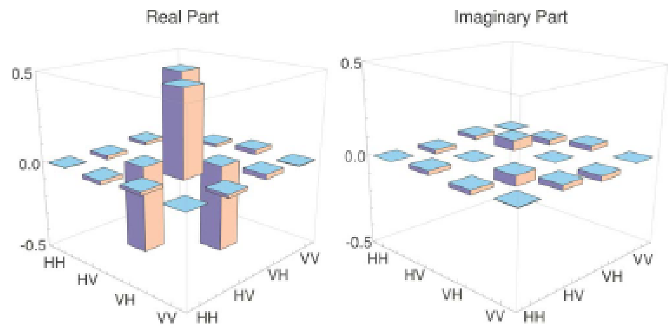
| P1, P2 Settings | Coincidence Counts (1 s) | P1, P2 Settings | Coincidence Counts (1 s) |
|---|---|---|---|
| HH | 79 | DD | 788 |
| HV | 31,851 | RD | 16,487 |
| VH | 30,885 | RL | 29,134 |
| VV | 34 | DR | 18,585 |
| HD | 15,965 | DV | 18,949 |
| HL | 14,749 | RV | 17,201 |
| DH | 13,833 | VD | 14,945 |
| [illegible] | [illegible] | [illegible] | 14,713 |

[illegible] $i|V\rangle)/\sqrt{2}$.

**Generation rate ~ 32,000 s$^{-1}$**



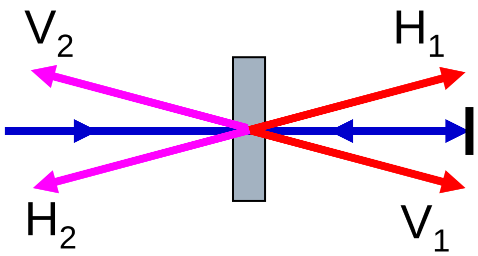



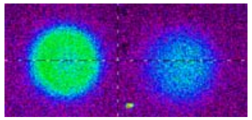

(a) (b)

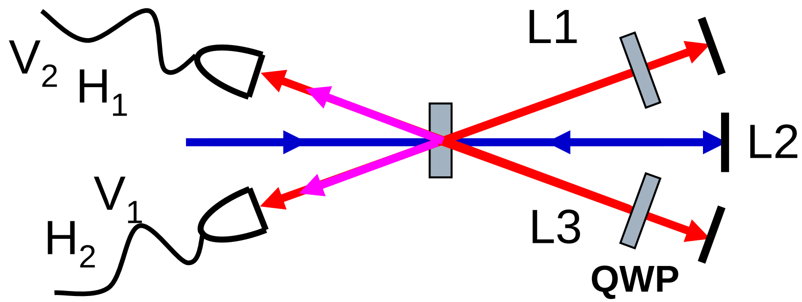
Fig. 3. (Color online) Real and imaginary parts of density matrix reconstructed from the coincidence data in Table 1.

# Beamlike photon-pair generation

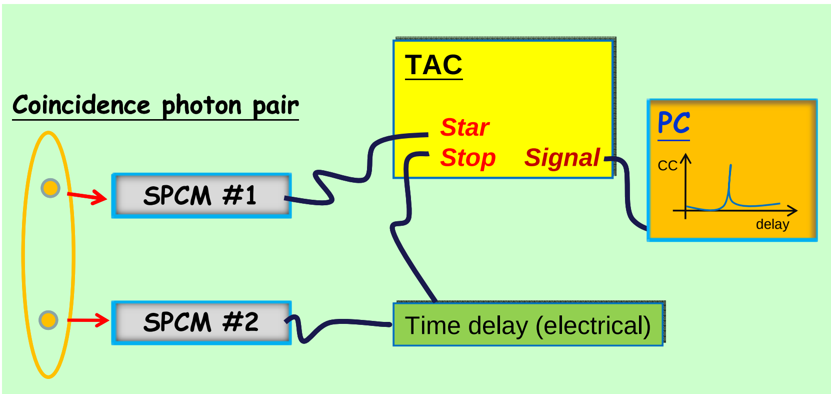
## Our idea






### Coincidence measurement



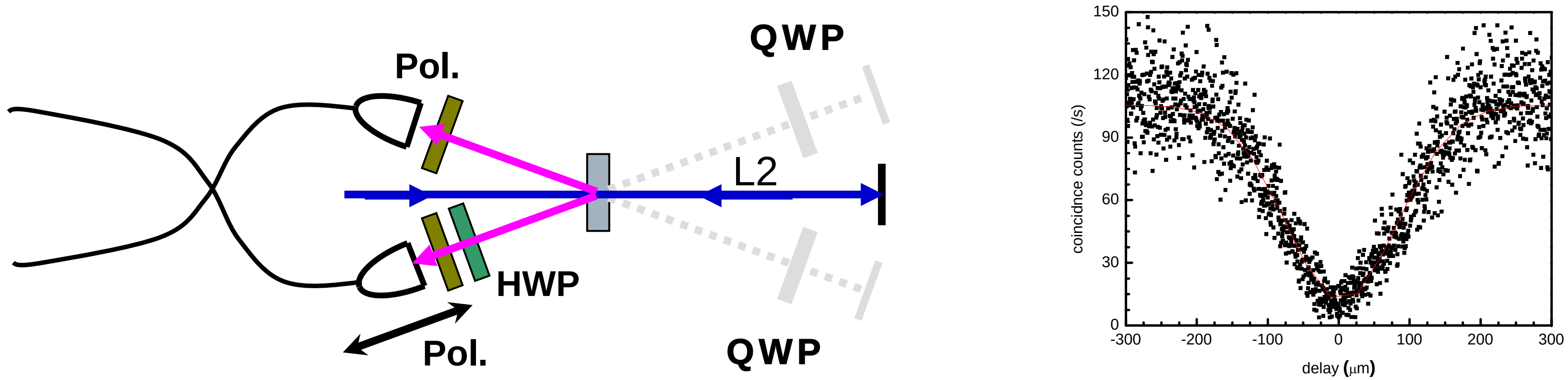

$$|\Psi\rangle = \frac{1}{\sqrt{2}} e^{i\phi}[|H_1\rangle|V_2\rangle + (e^{i\varphi}|V_1\rangle)|H_2\rangle]$$

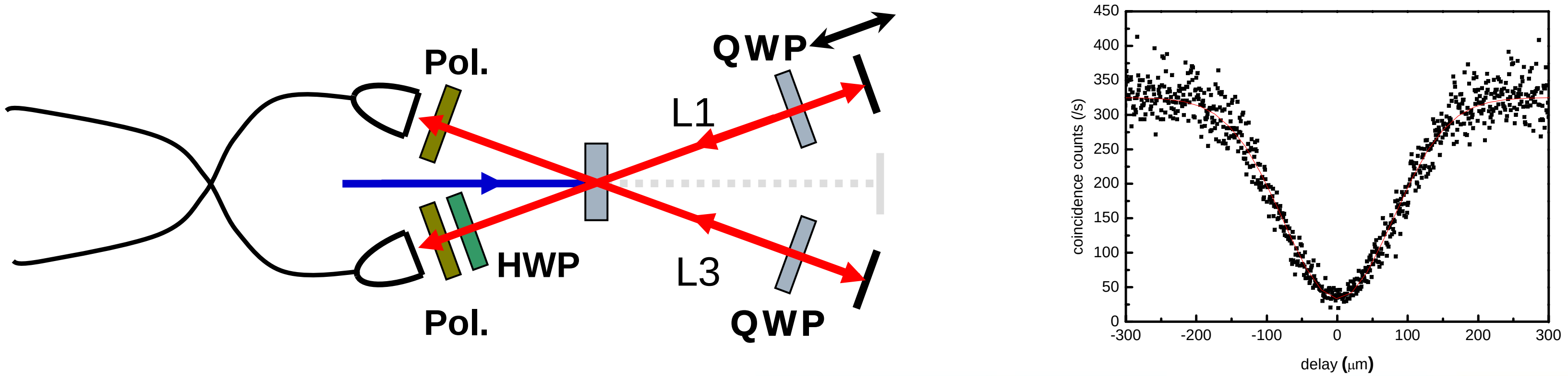
If L1=L2=L3

$$|\Psi\rangle = \frac{1}{\sqrt{2}}[|H_1\rangle|V_2\rangle - |V_1\rangle|H_2\rangle]$$

# Beamlike photon-pair generation

Hong-Ou-Mandel(HOM) dip interference measurement for light path adjustment

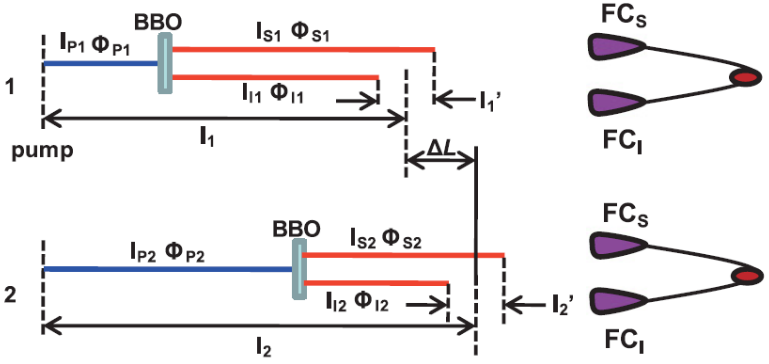


# Beamlike photon-pair generation

The coincidence count rate of the photon pairs $R_C$ can be calculated as

$$R_C \propto 1 + \gamma(\Delta L)\gamma'(\Delta L') \times \cos\left[k_{P0}\Delta L + \left(\frac{k_{S0} - k_{I0}}{2}\right)\Delta L' + \Delta\phi\right]$$




$$\begin{cases} l_i = \dfrac{l_{Si} + l_{Ii}}{2} \\ l_i' = l_{Si} - l_{Ii} \end{cases} \qquad \begin{cases} \Delta L \equiv l_1 - l_2 = \left(\dfrac{l_{S1} + l_{I1}}{2} + l_{P1}\right) - \left(\dfrac{l_{S2} + l_{I2}}{2} + l_{P2}\right) \\ \Delta L' \equiv l_1' - l_2' = (l_{S1} - l_{I1}) - (l_{S2} - l_{I2}) \\ \Delta\phi \equiv (\phi_{S1} + \phi_{I1} + \phi_{P1}) - (\phi_{S2} + \phi_{I2} + \phi_{P2}) \end{cases}$$

The normalized correlation functions of the pump and the signal-idler fields

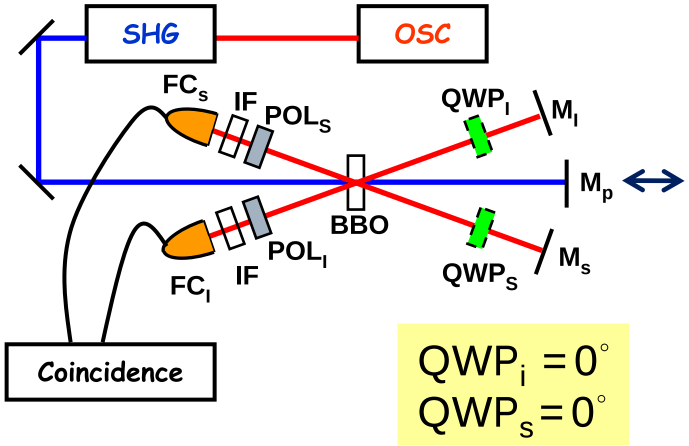
$$\gamma(\Delta L) = \exp\left[-\frac{1}{2}\left(\Delta L / l_{coh}^{p}\right)^2\right] \qquad \gamma(\Delta L') = \exp\left[-\frac{1}{2}\left(\Delta L' / l_{coh}\right)^2\right]$$

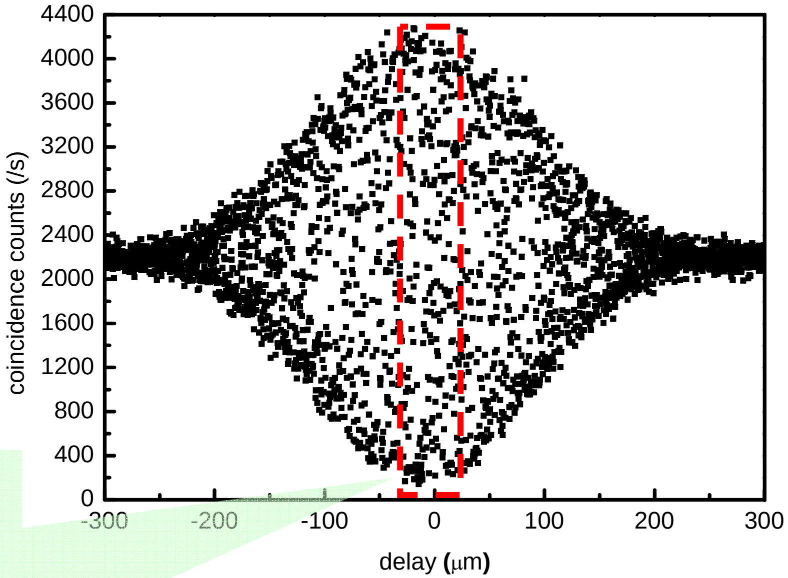
If $\Delta L' = 0$ ⇨ $R_C \propto 1 + \gamma(\Delta L)\cos[k_{P0}\Delta L + \Delta\phi]$

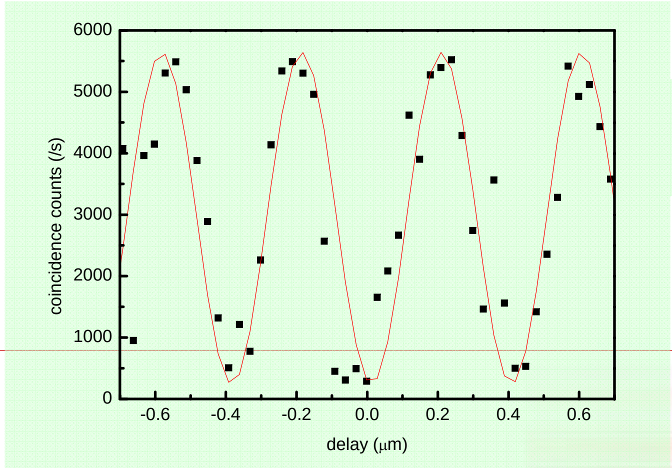
Ref.: R. W. Boyd, PRA 77, 021801(R) (2008).

# Beamlike photon-pair generation

## Two-photon interference of beamlike photon pairs

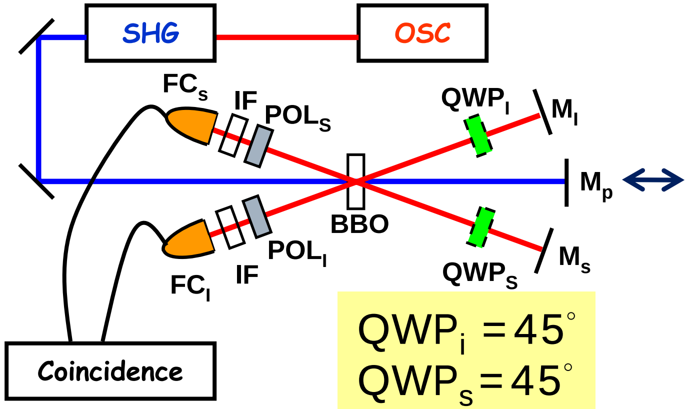


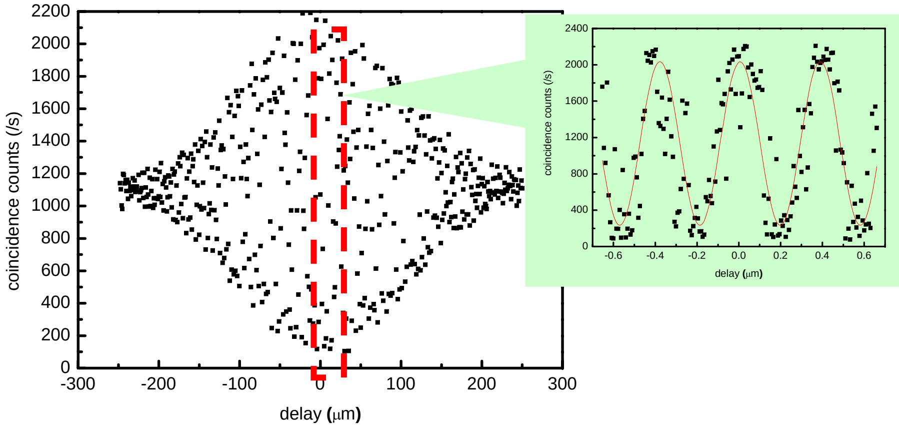



# Beamlike photon-pair generation

## Polarization entanglement of beamlike photon pairs




$\mathrm{QWP_i} = 45^\circ$
$\mathrm{QWP_s} = 45^\circ$




$$|\Psi\rangle = |V\rangle_S |H\rangle_I + \exp\left\{ i \left[ k_{P0}\Delta L + \left( \frac{k_{S0} - k_{I0}}{2} \right) \Delta L' + \Delta\Phi \right] \right\} |H\rangle_S |V\rangle_I$$

$$\because |+\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle), |-\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle), \ \Phi = k_{P0}\Delta L + \left( \frac{k_{S0} - k_{I0}}{2} \right) \Delta L' + \Delta\Phi$$

$$\Rightarrow |\Psi\rangle = \frac{1}{2}(1 + e^{i\Phi})(|+\rangle_S |+\rangle_I - |-\rangle_S |-\rangle_I) + \frac{1}{2}(1 - e^{i\Phi})(|+\rangle_S |-\rangle_I - |-\rangle_S |+\rangle_I)$$

The coincidence count rate of the photon pairs

$$\Rightarrow R_{+-} \propto \left| \langle \Psi | + \rangle_S | + \rangle_I \right|^2 = \left| 1 - e^{i\Phi} \right|^2 = 2(1 - \cos\Phi)$$

**Entanglement**

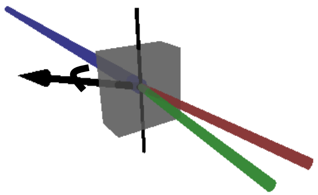
$$E(\Psi) = h\left( \frac{1 + \sqrt{1 - C^2}}{2} \right)$$

where
$$\begin{cases} h(x) = -x\log_2 x - (1-x)\log_2(1-x) \\ C(\Psi) = |\langle \Psi | (\sigma_y \otimes \sigma_y) | \Psi^* \rangle| \\ \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \end{cases}$$

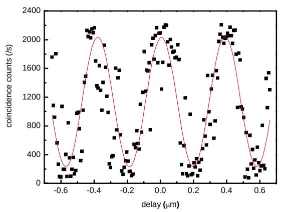
⇒ **The concurrence was calculated to be 0.9±0.05**

Ref.: W. K. Wootters, PRL 80, 2245 (1998).

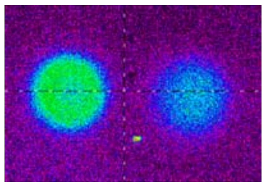
# Summary



- **In this study, we proved the new idea can generate the beamlike photon for the two-photon interference and polarization entanglement.**




- **The concurrence of the pair was calculated to be 0.90 ± 0.05, *which defines the degree of entanglement* of the generated photon pairs.**



- **This confirms that the generated beamlike photon pair is highly entangled in its polarization.**

H. P. Lo, A. Yabushita, C. W. Luo, P. C. Chen, T. Kobayashi, PRA **83**, 022313 (2011)

# Acknowledgements

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