A Compact Source of Narrowband Biphotons

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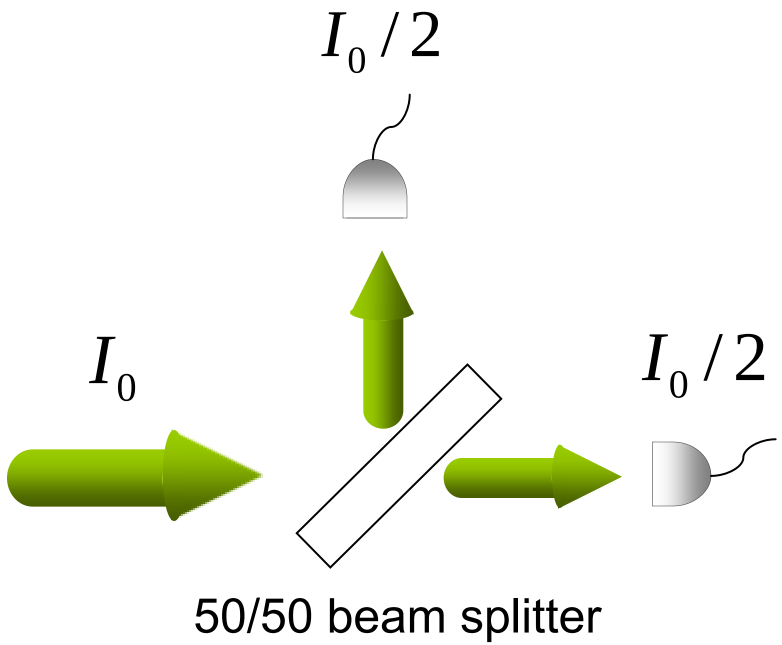
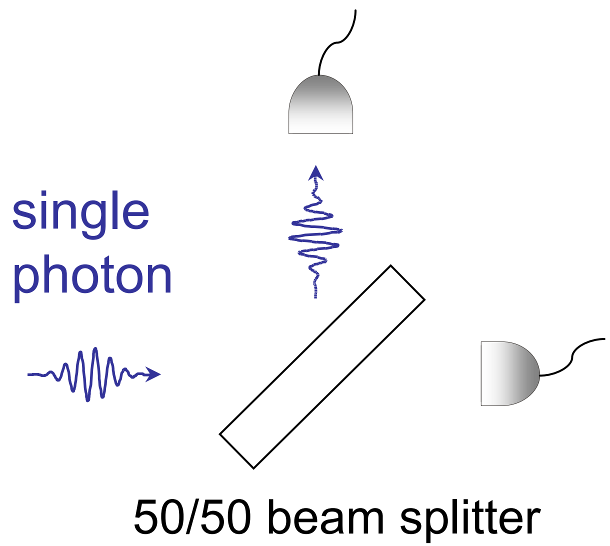
NTHU AMO Seminar 2012

Outline

- Single photons, biphotons
- Motivation: quantum communication
- Generation of narrowband biphotons
- Our proposed method
- Summary

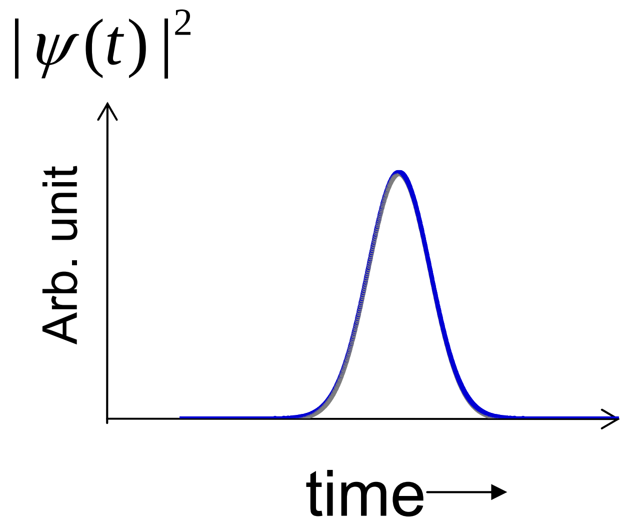
Single Photons



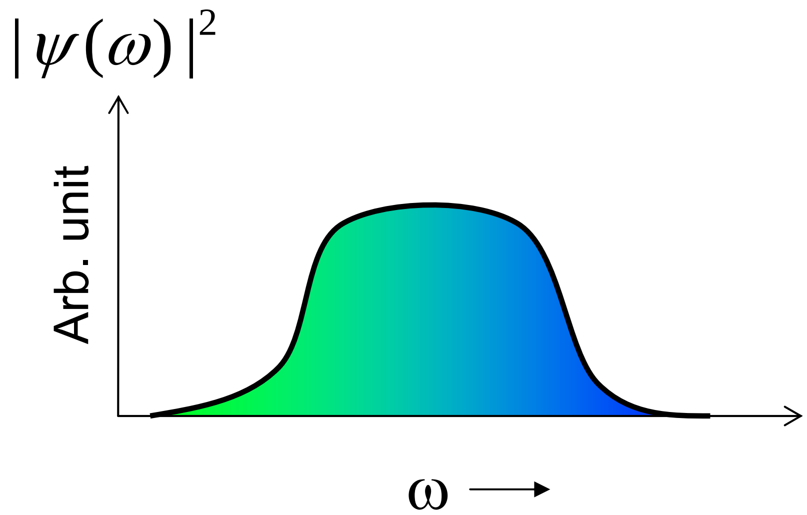


Single Photons: Wavepackets

wavepacket

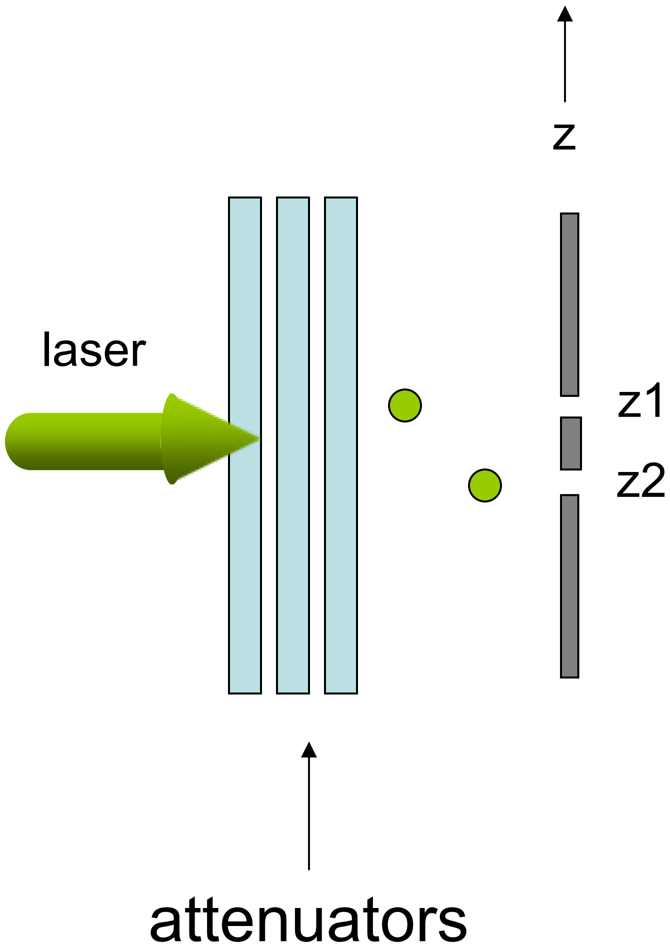


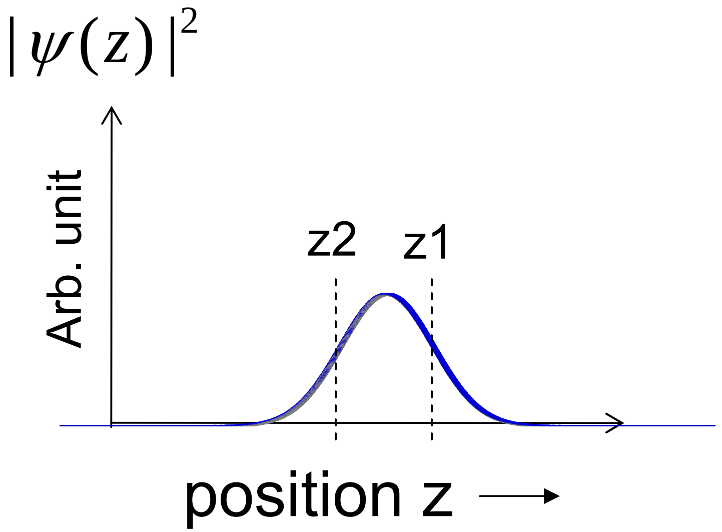
spectrum



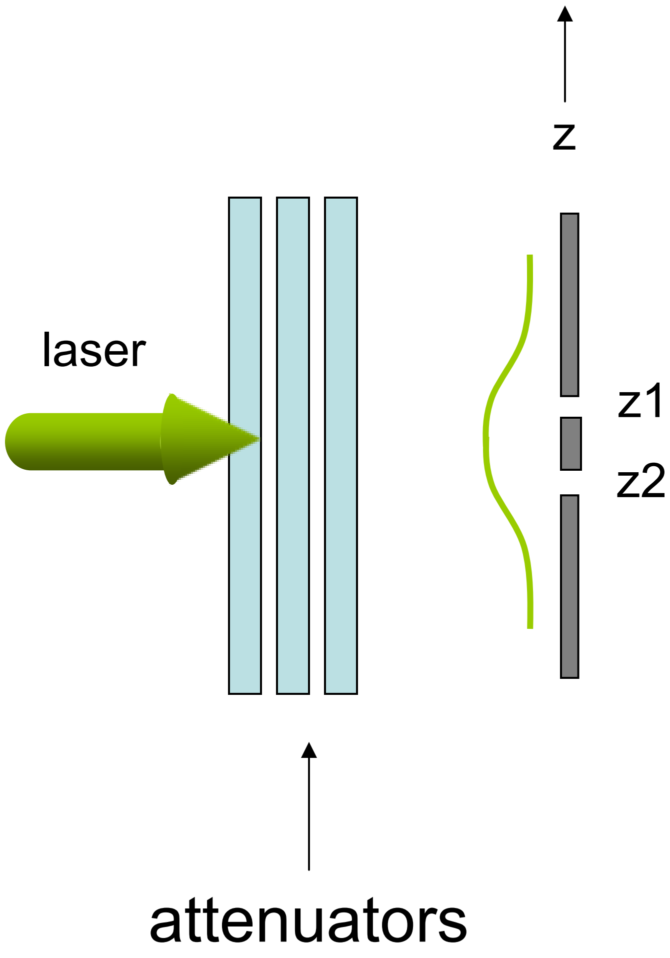
Δω Δt ≥ 1

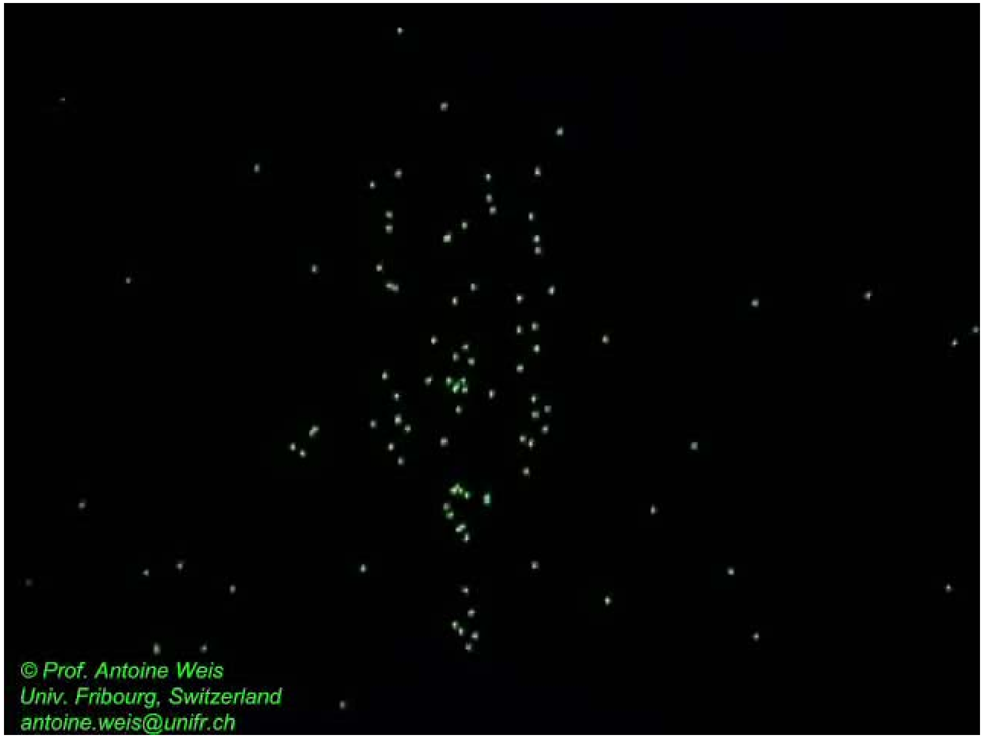
Single Photons: Wavepackets



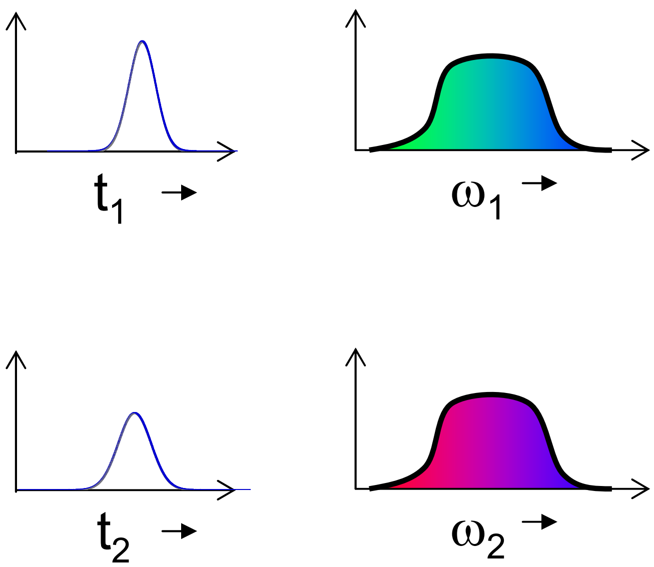


Single Photons: Wavepackets





Two Uncorrelated Single Photons



$$\Delta\omega_1 \, \Delta t_1 \geq 1$$

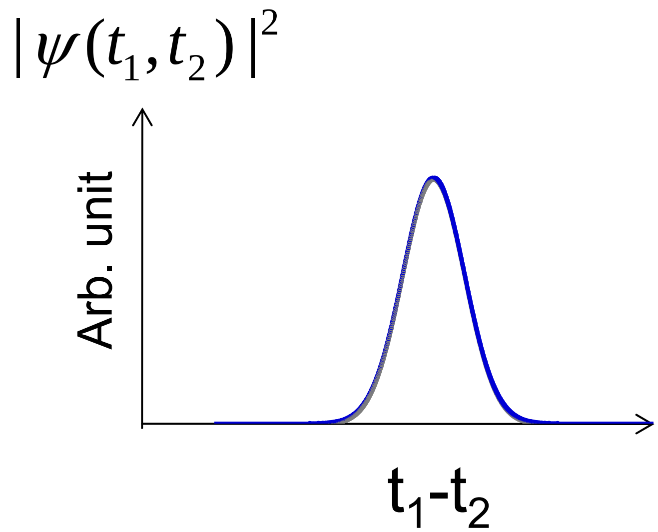
$$\Delta\omega_2 \, \Delta t_2 \geq 1$$

$$\Delta(\omega_1 + \omega_2) \, \Delta(t_1 - t_2) \geq 1$$

Mancini et. al. PRL **88**, 120401 (2002).

Biphotons: Time-Energy Entangled Photon Pair

wavepacket



$\Delta\omega_1 \, \Delta t_1 \geq 1$

$\Delta\omega_2 \, \Delta t_2 \geq 1$

$\Delta(\omega_1 + \omega_2) \, \Delta(t_1 - t_2) \geq 0$

Mancini et. al. PRL **88**, 120401 (2002).

$$|\leftrightarrow\rangle_1 |\leftrightarrow\rangle_2 - |\updownarrow\rangle_1 |\updownarrow\rangle_2$$

polarization entanglement

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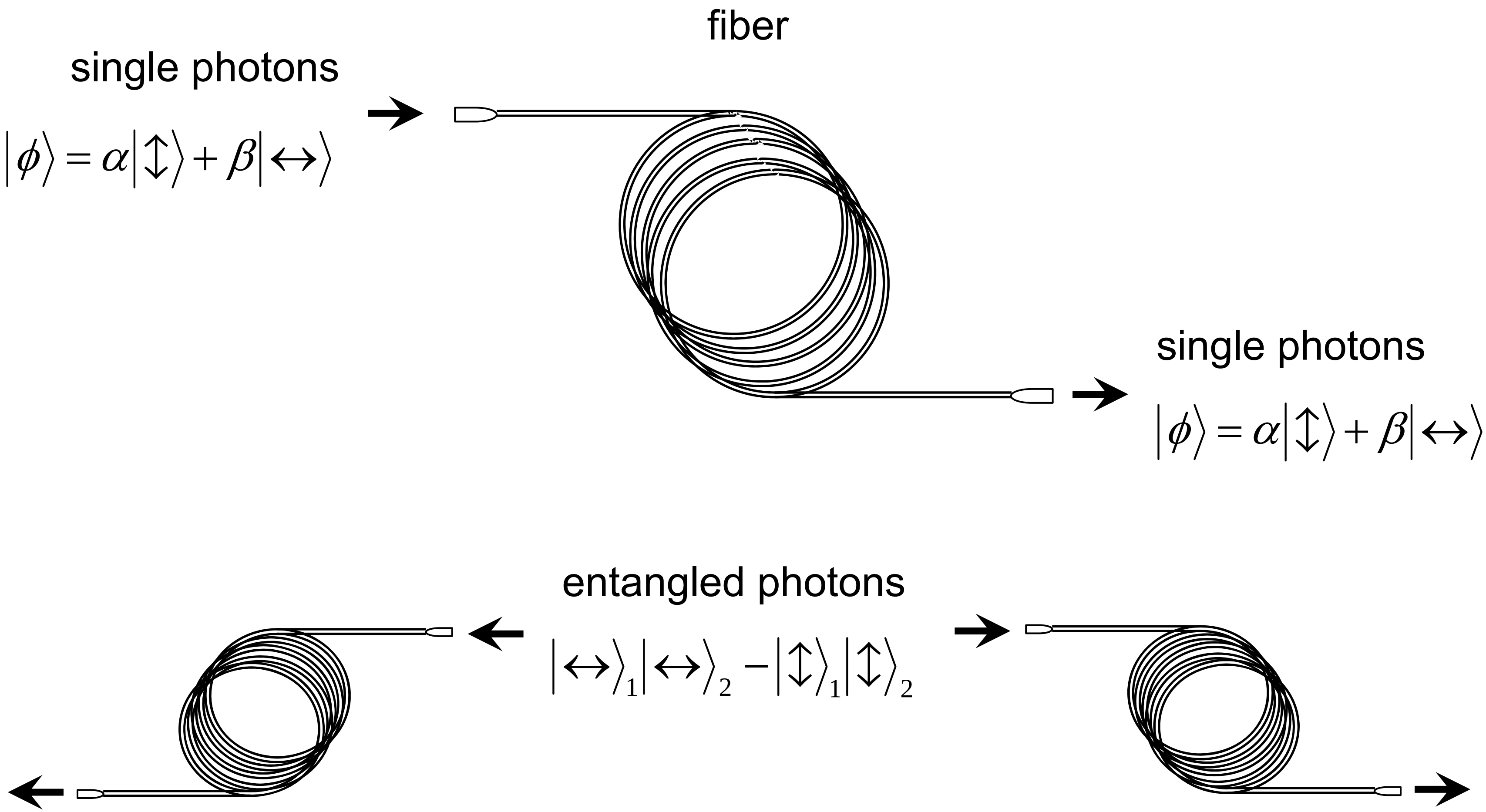
Distribution of Quantum States Over Distances



Quantum Key Distribution

$$\left|\leftrightarrow\right\rangle_1\left|\leftrightarrow\right\rangle_2 - \left|\updownarrow\right\rangle_1\left|\updownarrow\right\rangle_2$$

1

2

Measurement basis (1)			
$+$	$\times$	$\times$	$+$

Measurement basis (2)			
$+$	$+$	$\times$	$\times$

Measurement basis

Measurement results (1)			
↔	⤢	⤢	↕

Measurement results (2)			
↔	↕	⤢	⤡

Measurement results

0		1	

0		1	

Keys

↔ ⤡ = 0

↕ ⤢ = 1

Quantum Teleportation

1

$$|\varphi\rangle_{12} = |\updownarrow\rangle_1 |\leftrightarrow\rangle_2 - |\leftrightarrow\rangle_1 |\updownarrow\rangle_2$$

2

$$|\varphi\rangle_3 = \alpha|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_3$$

3

$$\begin{aligned}|123\rangle = |\varphi\rangle_{12}|\varphi\rangle_3 = &\left(\alpha|\updownarrow\rangle_2 + \beta|\leftrightarrow\rangle_2\right)\left(|\updownarrow\rangle_1|\leftrightarrow\rangle_3 + |\updownarrow\rangle_1|\leftrightarrow\rangle_3\right) + \\ &\left(-\alpha|\updownarrow\rangle_2 - \beta|\leftrightarrow\rangle_2\right)\left(|\updownarrow\rangle_1|\leftrightarrow\rangle_3 - |\updownarrow\rangle_1|\leftrightarrow\rangle_3\right) + \\ &\left(\alpha|\updownarrow\rangle_2 - \beta|\leftrightarrow\rangle_2\right)\left(|\updownarrow\rangle_1|\updownarrow\rangle_3 + |\leftrightarrow\rangle_1|\leftrightarrow\rangle_3\right) + \\ &\left(-\alpha|\updownarrow\rangle_2 + \beta|\leftrightarrow\rangle_2\right)\left(|\updownarrow\rangle_1|\updownarrow\rangle_3 - |\leftrightarrow\rangle_1|\leftrightarrow\rangle_3\right) +\end{aligned}$$

Quantum Teleportation

1

$$|\varphi\rangle_{12} = |\updownarrow\rangle_1 |\leftrightarrow\rangle_2 - |\leftrightarrow\rangle_1 |\updownarrow\rangle_2$$

2

$$|\varphi\rangle_3 = \alpha|\leftrightarrow\rangle_3 + \beta|\updownarrow\rangle_3$$ 3

$$\begin{aligned}
|123\rangle = |\varphi\rangle_{12}|\varphi\rangle_3 = &\left(\alpha|\updownarrow\rangle_2 + \beta|\leftrightarrow\rangle_2\right)\left(|\updownarrow\rangle_1|\leftrightarrow\rangle_3 + |\updownarrow\rangle_1|\leftrightarrow\rangle_3\right) + \\
&\left(-\alpha|\updownarrow\rangle_2 - \beta|\leftrightarrow\rangle_2\right)\left(|\updownarrow\rangle_1|\leftrightarrow\rangle_3 - |\updownarrow\rangle_1|\leftrightarrow\rangle_3\right) + \\
&\left(\alpha|\updownarrow\rangle_2 - \beta|\leftrightarrow\rangle_2\right)\left(|\updownarrow\rangle_1|\updownarrow\rangle_3 + |\leftrightarrow\rangle_1|\leftrightarrow\rangle_3\right) + \\
&\left(-\alpha|\updownarrow\rangle_2 + \beta|\leftrightarrow\rangle_2\right)\left(|\updownarrow\rangle_1|\updownarrow\rangle_3 - |\leftrightarrow\rangle_1|\leftrightarrow\rangle_3\right) +
\end{aligned}$$

Bell states

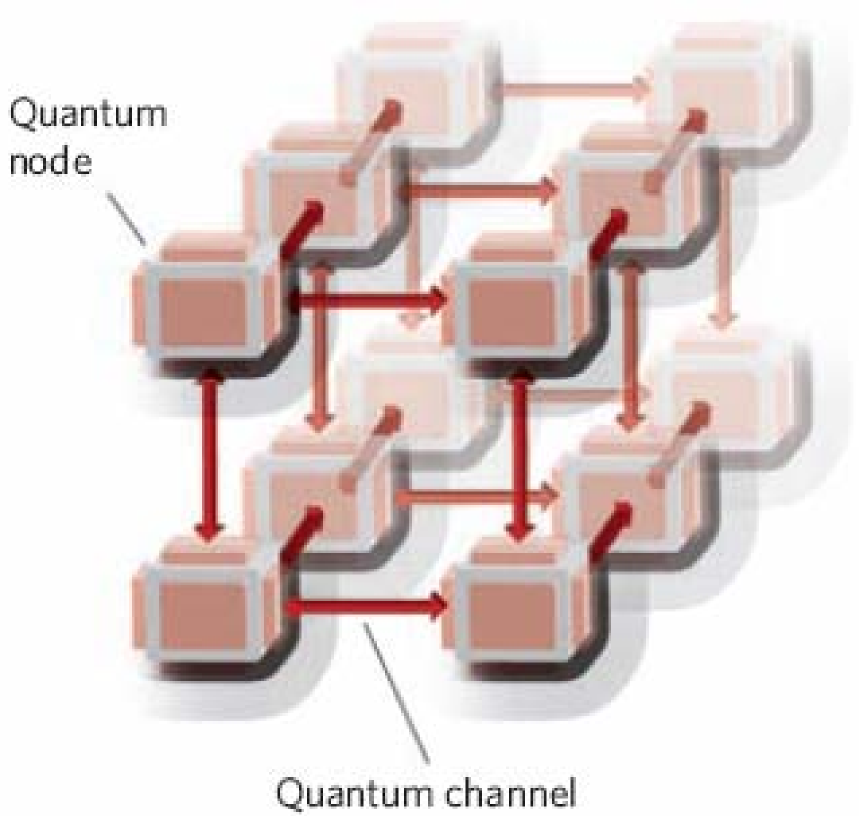
Quantum Teleportation of a “Person”
(impossible in practice)

Space shuttle

Station on the moon

Zeilinger, Scientific American, 50 (April 2000)

Quantum Networks

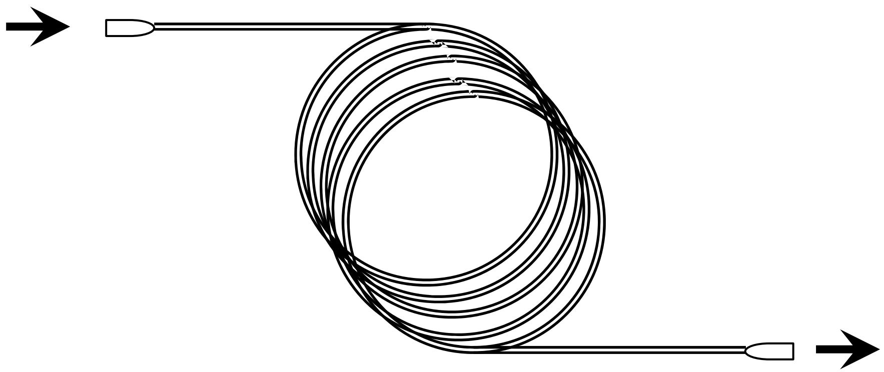


Kimble, Nature 53 1023 (2008)

Photon Loss in Quantum Channels

fiber, 0.2 dB/km

10^{10} photons/s



1 photon/s (500 km)
10^{-10} photons/s (1000 km)

Transmission probability for a qubit: $p(l) = e^{-l/l_0}, \quad l_0 = 21.7 \text{ km}$

Average number of required repetition: $n(l) = \dfrac{1}{p(l)} = e^{l/l_0}$

$$n(500\text{km}) = 10^{10}$$

No-Cloning Theorem

A perfect amplifier:

$$\left|\updownarrow\right\rangle\left|0\right\rangle \rightarrow \left|\updownarrow\right\rangle\left|\updownarrow\right\rangle$$
$$\left|\leftrightarrow\right\rangle\left|0\right\rangle \rightarrow \left|\leftrightarrow\right\rangle\left|\leftrightarrow\right\rangle$$

For $\left|\phi\right\rangle = \alpha\left|\updownarrow\right\rangle + \beta\left|\leftrightarrow\right\rangle$,

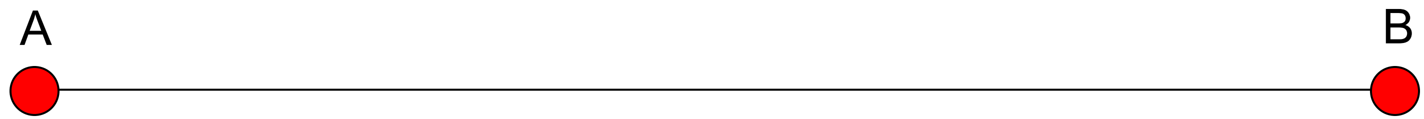
$$\begin{aligned}\left|\phi\right\rangle\left|0\right\rangle \rightarrow \left|\phi\right\rangle\left|\phi\right\rangle &= \left(\alpha\left|\updownarrow\right\rangle + \beta\left|\leftrightarrow\right\rangle\right)\left(\alpha\left|\updownarrow\right\rangle + \beta\left|\leftrightarrow\right\rangle\right)\\ &= \alpha^2\left|\updownarrow\right\rangle\left|\updownarrow\right\rangle + 2\alpha\beta\left|\updownarrow\right\rangle\left|\leftrightarrow\right\rangle + \beta^2\left|\leftrightarrow\right\rangle\left|\leftrightarrow\right\rangle\end{aligned}$$

But

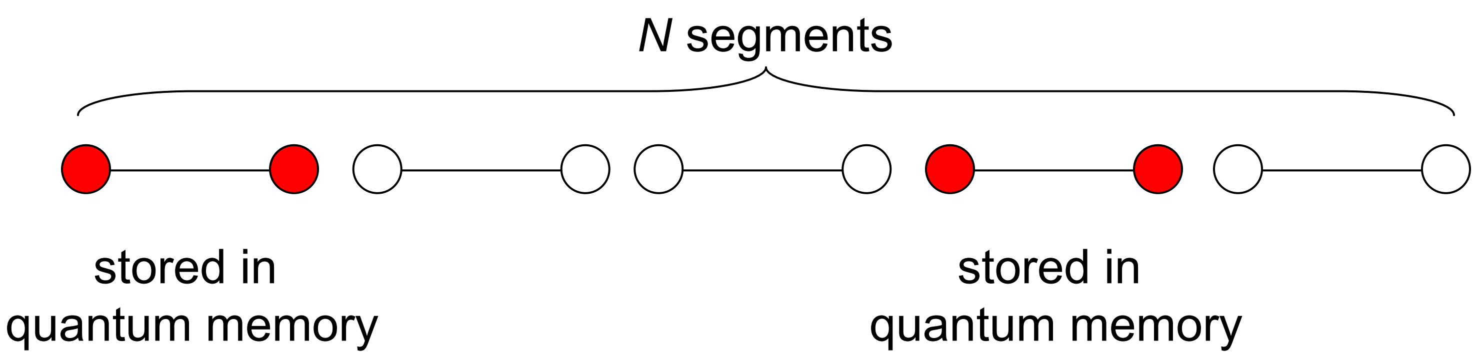
$$\left|\phi\right\rangle\left|0\right\rangle = \left(\alpha\left|\updownarrow\right\rangle + \beta\left|\leftrightarrow\right\rangle\right)\left|0\right\rangle \rightarrow \alpha^2\left|\updownarrow\right\rangle\left|\updownarrow\right\rangle + \beta^2\left|\leftrightarrow\right\rangle\left|\leftrightarrow\right\rangle$$

Therefore there cannot exist such a amplifier for unknown quantum state.

Quantum Repeater



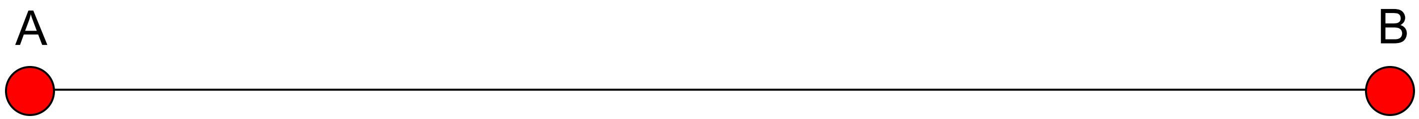
Number of required repetition for direct transmission: $n(l) = e^{l/l_0}$



Number of required repetition for each segment: $n(l/N) = e^{l/Nl_0}$

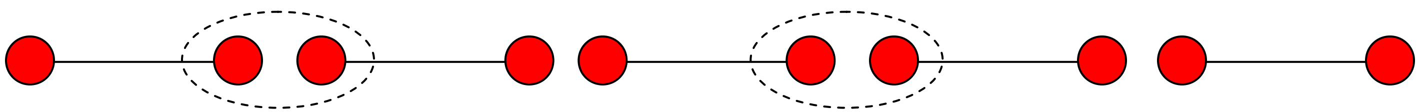
Total number of required repetition: $N \times n(l/N) = Ne^{l/Nl_0}$

Quantum Repeater



Number of required repetition for direct transmission: $n(l) = e^{l/l_0}$

Entanglement swapping



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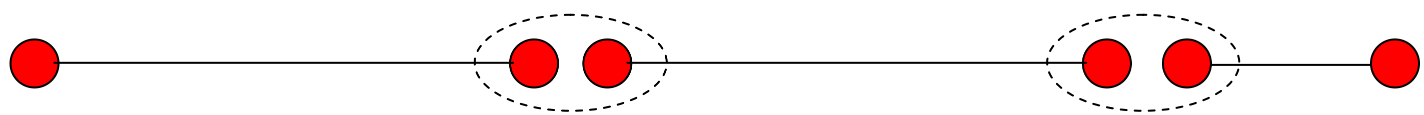
Quantum Repeater

Number of required repetition for direct transmission: $n(l) = e^{l/l_0}$

Entanglement swapping



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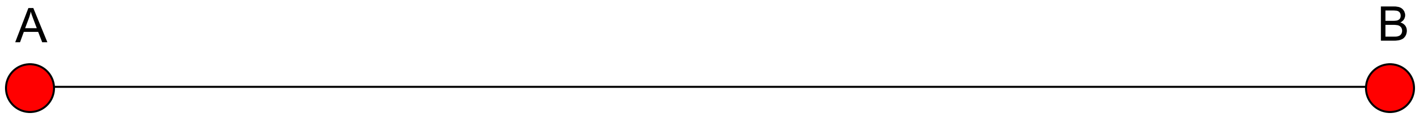
Quantum Repeater



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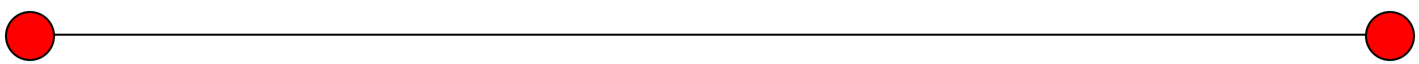
Entanglement swapping



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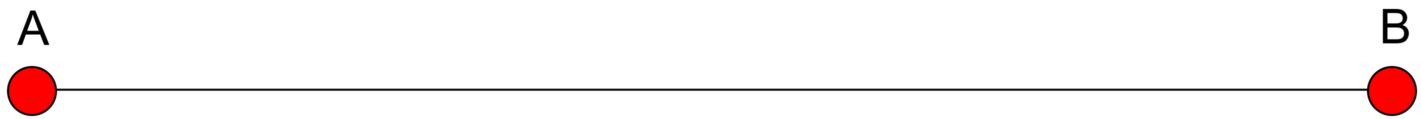
Quantum Repeater



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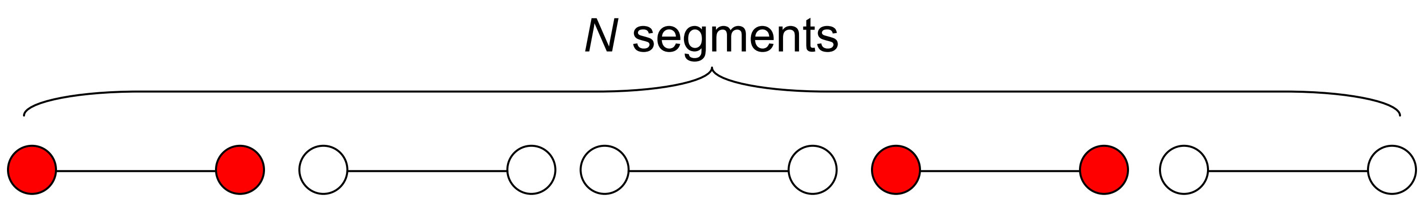
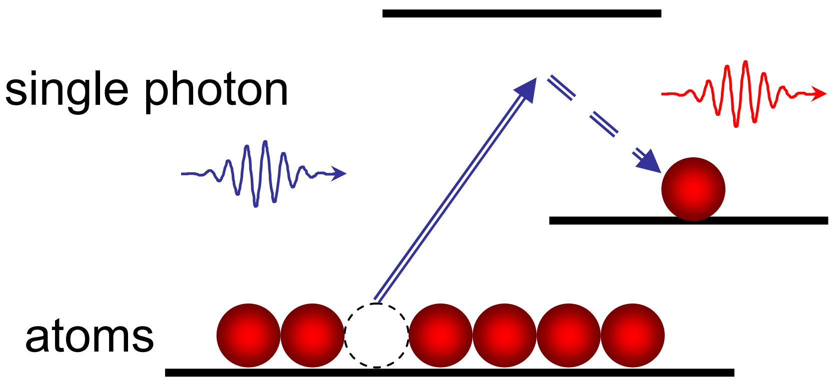


Number of required repetition for each segment: $n(l/N) = e^{l/Nl_0}$

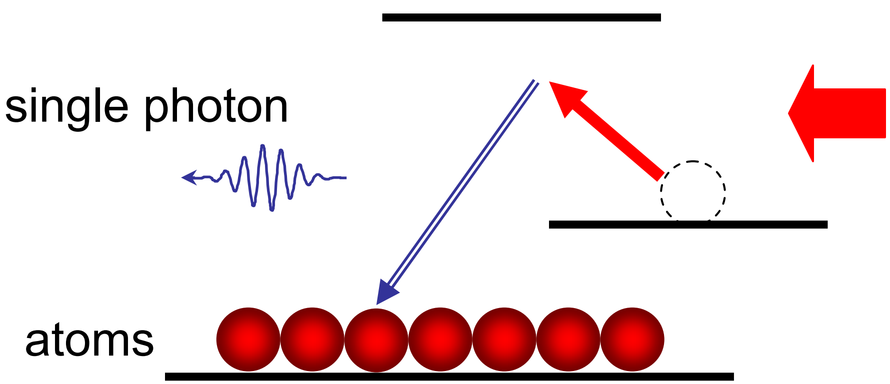
Total number of required repetition: $N \times n(l/N) = Ne^{l/Nl_0}$

For $N = l/l_0$, $n_{\min} = l\,(e/l_0)$

Quantum Memory



Storage



Readout

Narrowband photons interact with atoms more efficiently.

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- ❑ Single photons, biphotons
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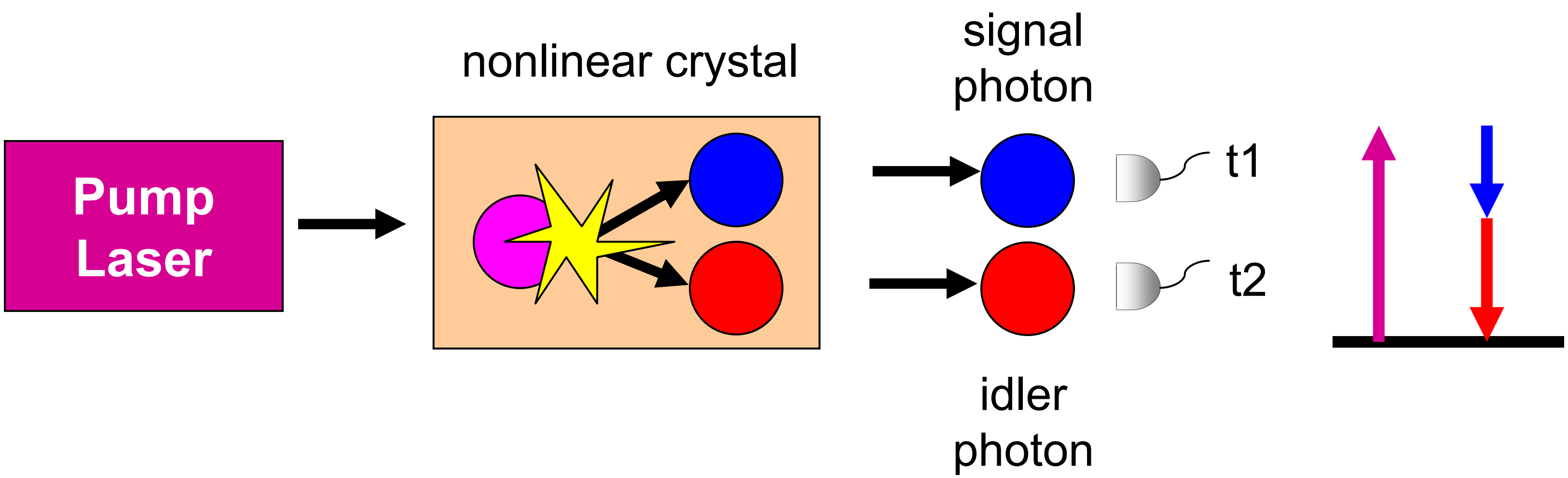
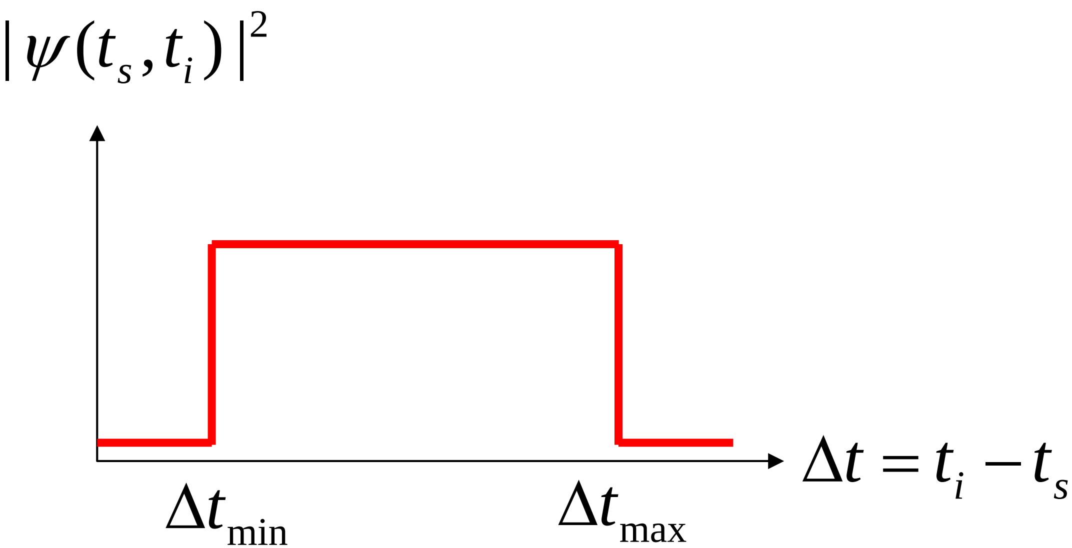
Spontaneous Parametric Down-Conversion (SPDC)





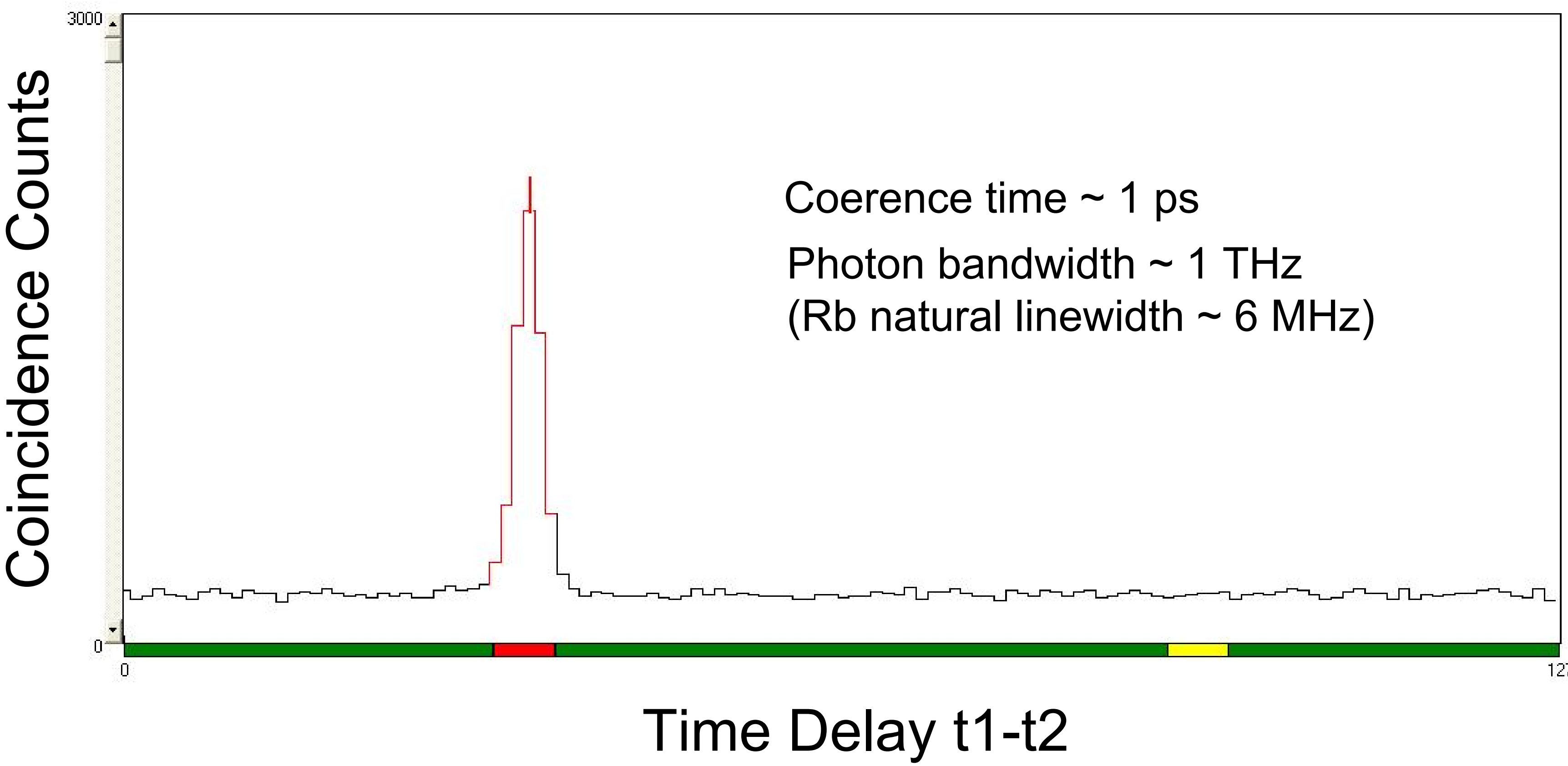
$$\Delta t_{\min} = 0$$

$$\Delta t_{\max} = L / v_i - L / v_s$$

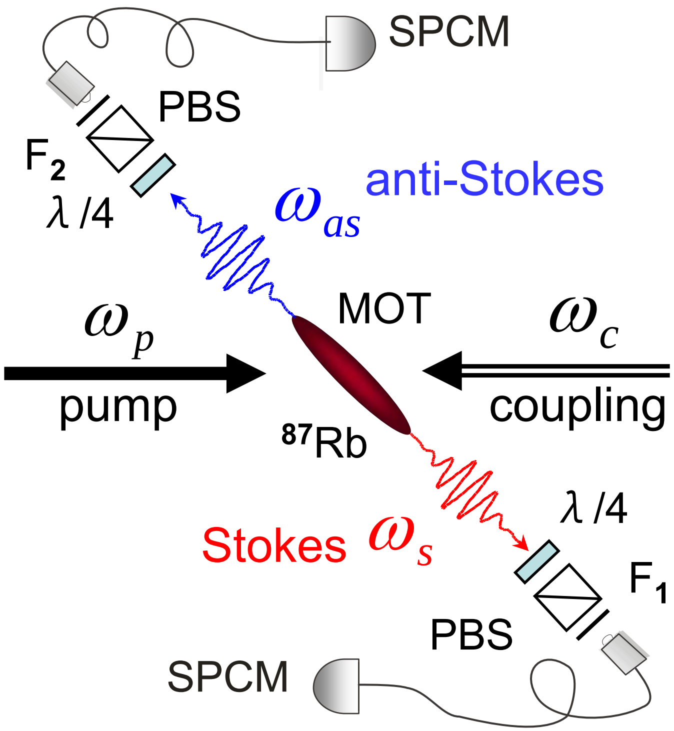
Biphoton coherence time

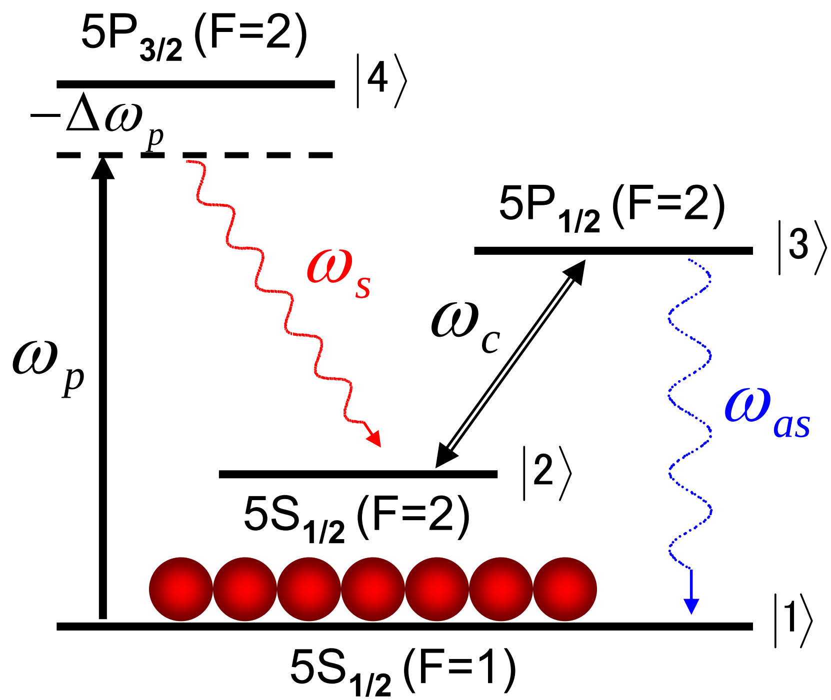
$$T = \Delta t_{\max} - \Delta t_{\min}$$
$$= L\left(v_i^{-1} - v_s^{-1}\right)$$

Spontaneous Parametric Down-Conversion (SPDC)



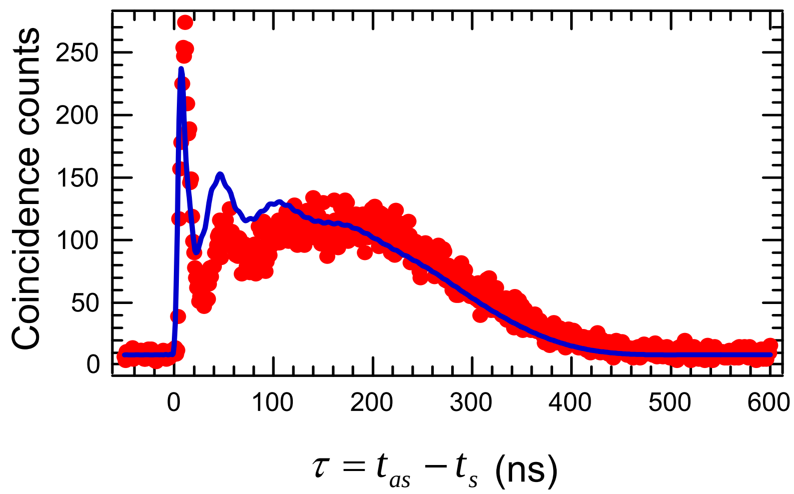
4-Wave Mixing and Slow Light in Cold Atoms

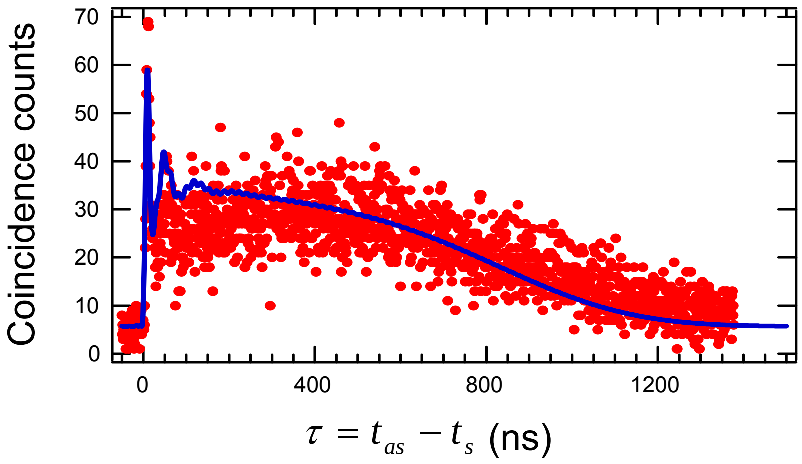


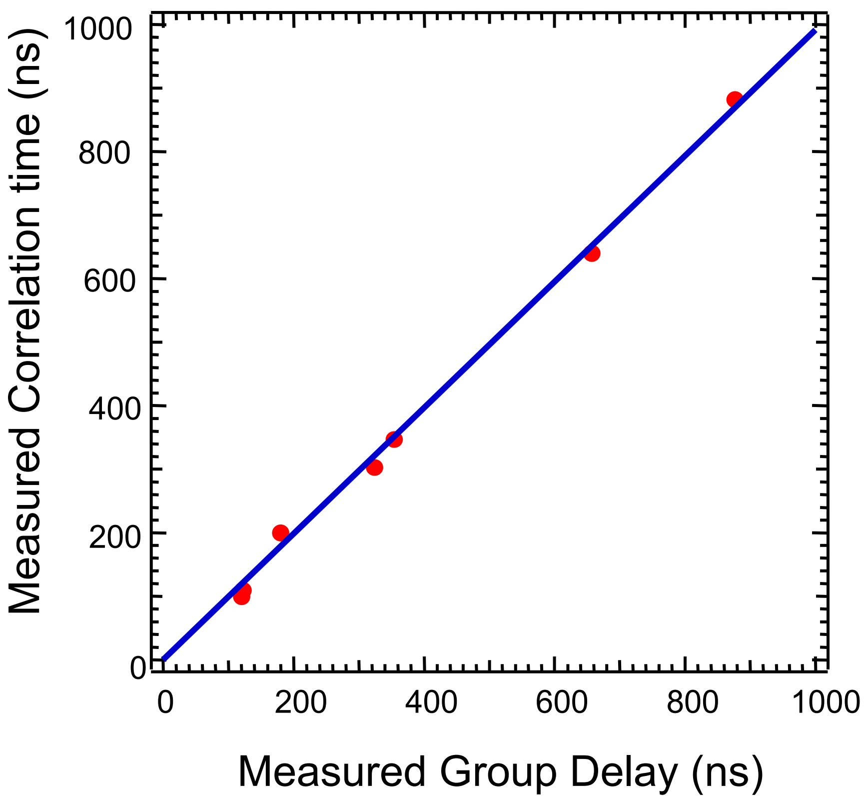


$$T = L\left(v_i^{-1} - v_s^{-1}\right)$$

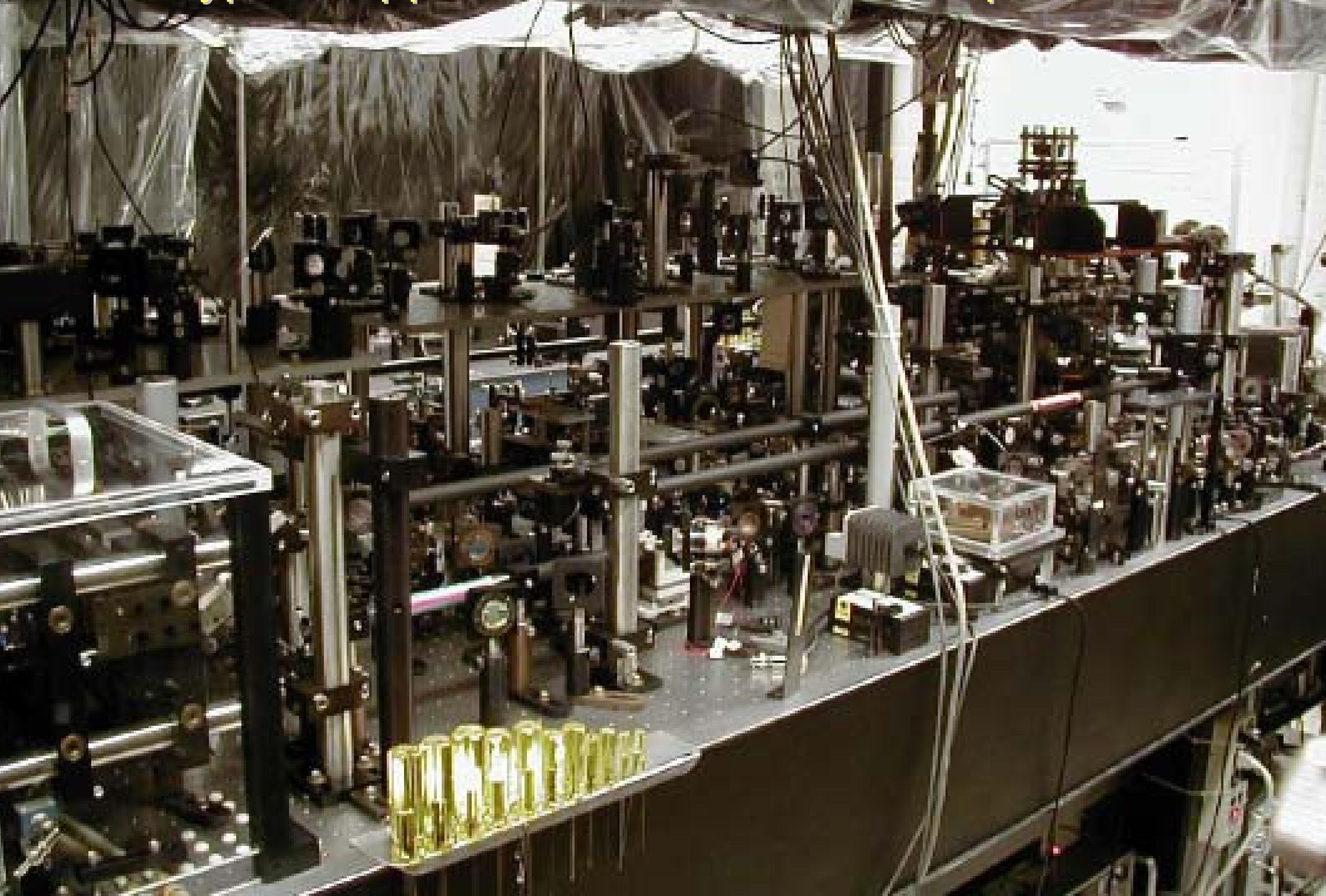
4-Wave Mixing and Slow Light in Cold Atoms



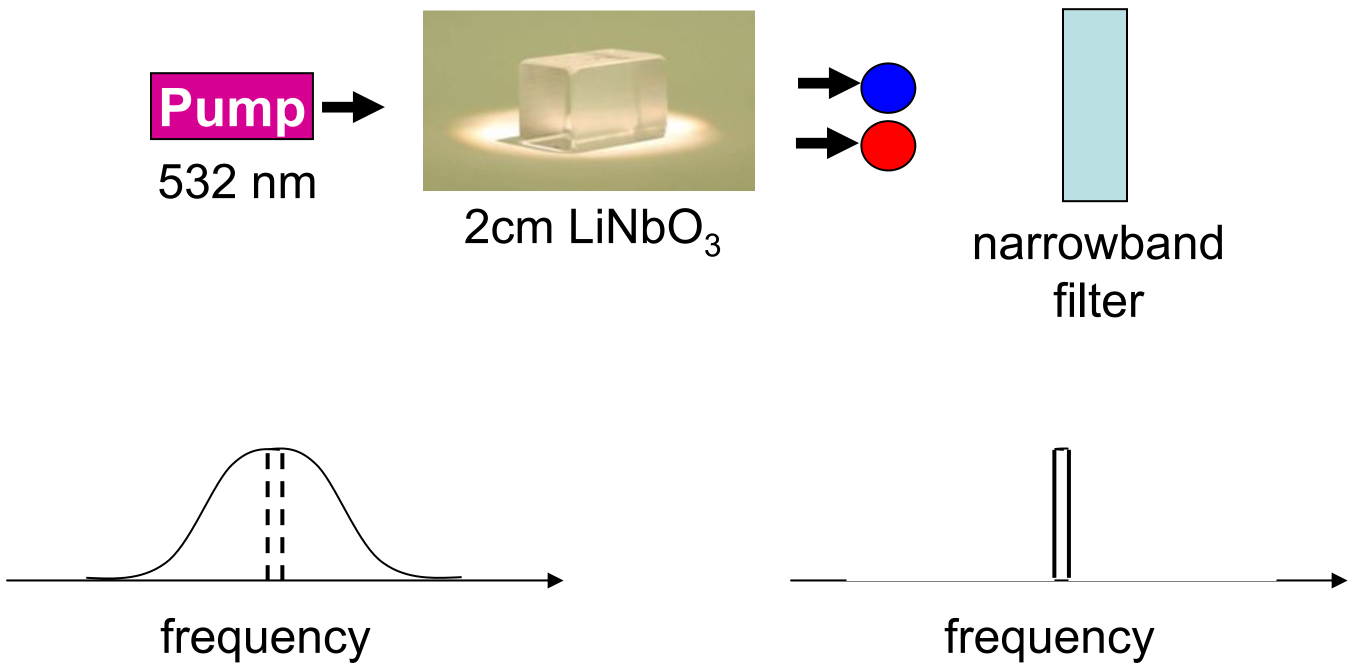




Typical Apparatus for Cold Atom Experiments

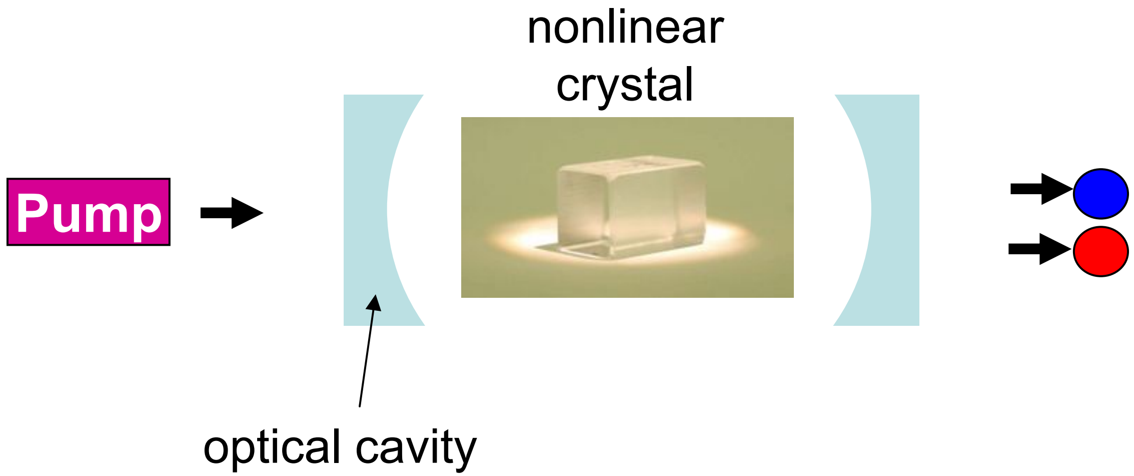


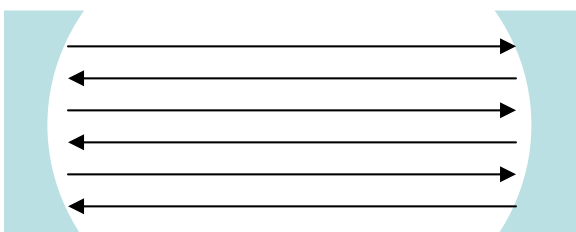
SPDC with Spectral Filtering

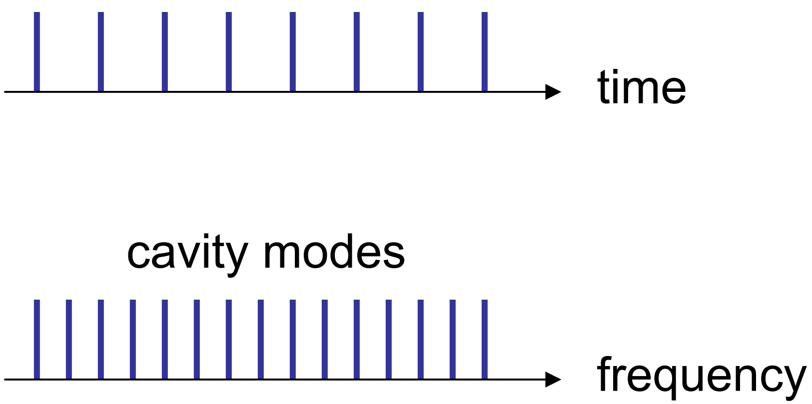


$$\frac{6\,\text{MHz}}{1\,\text{THz}} = 6 \times 10^{-6}$$

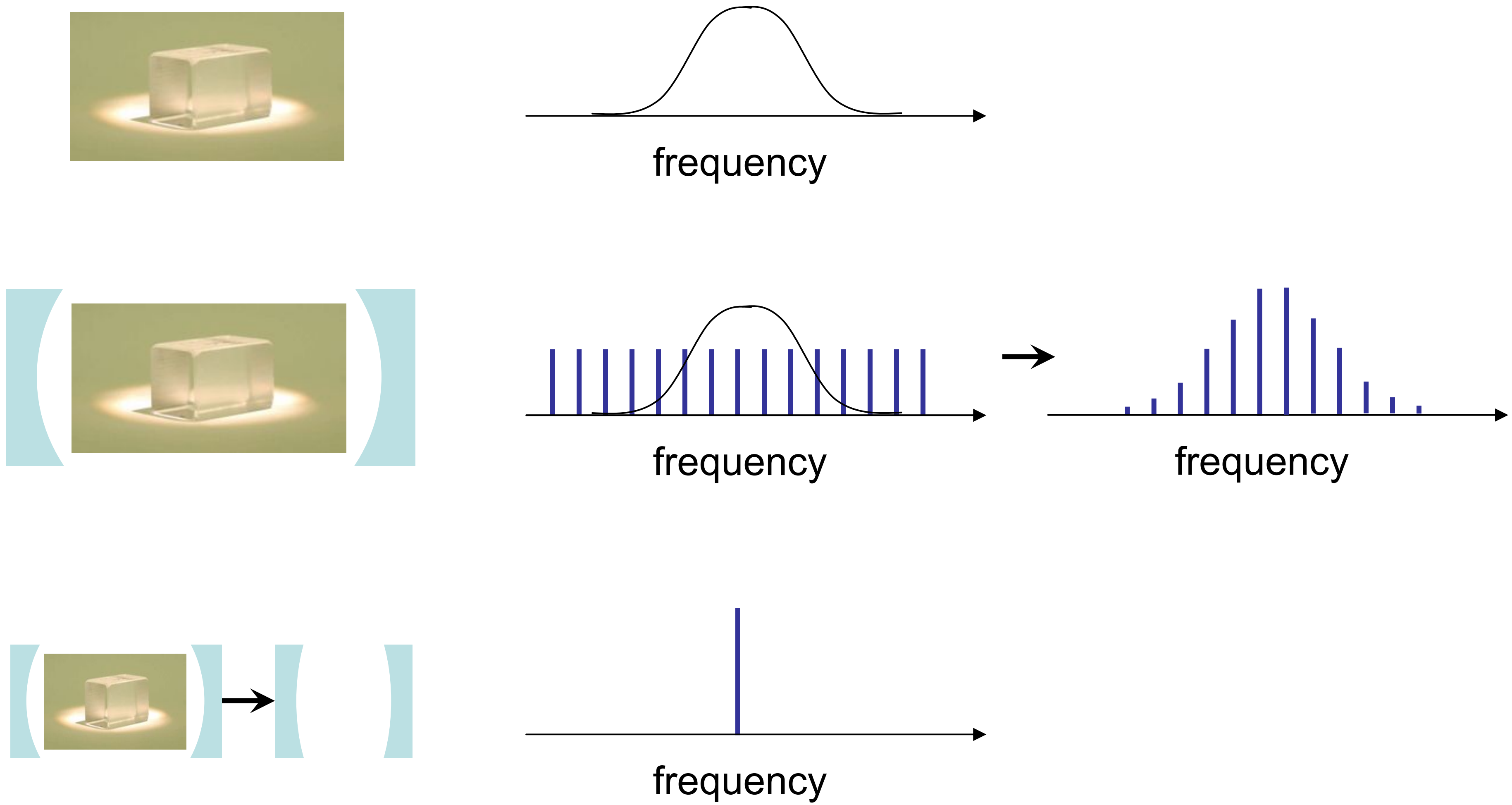
SPDC in a Resonant Cavity



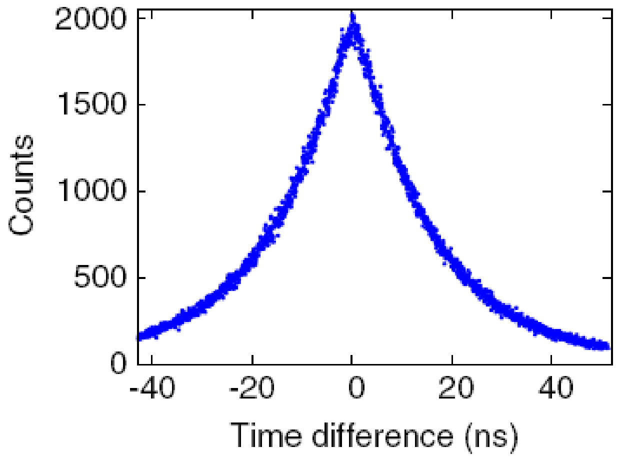




SPDC in a Resonant Cavity

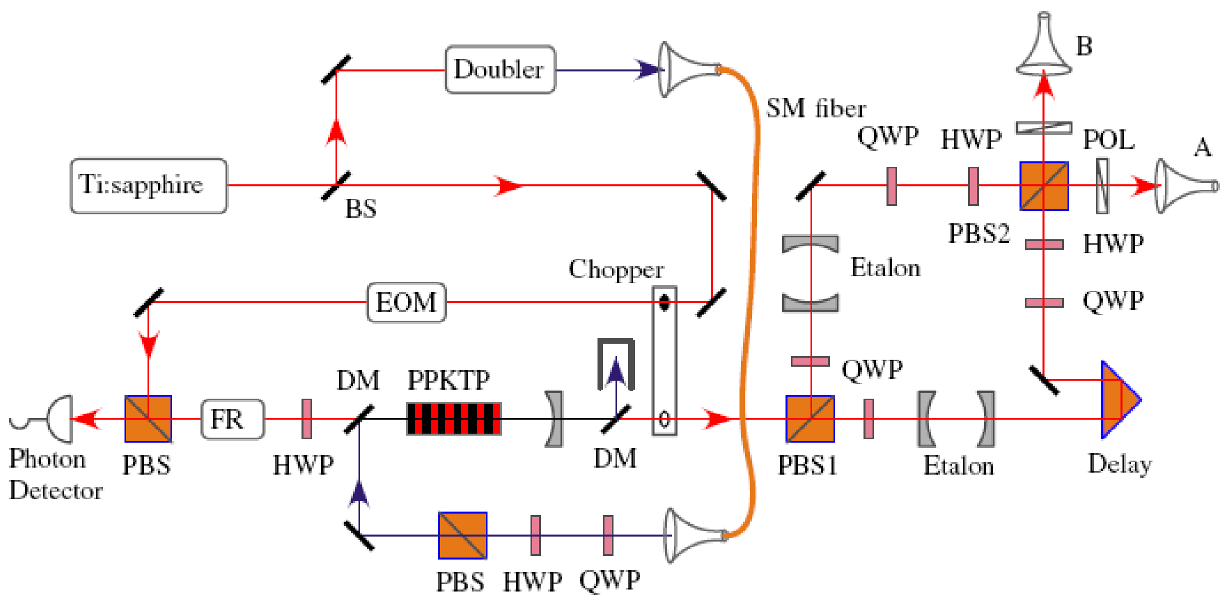


SPDC with Spectral Filtering



Coherence time ~ 30 ns
Bandwidth ~ 10 MHz
Number of cavity modes ~ 20

Bao et al., PRL 101, 190501 (2008)



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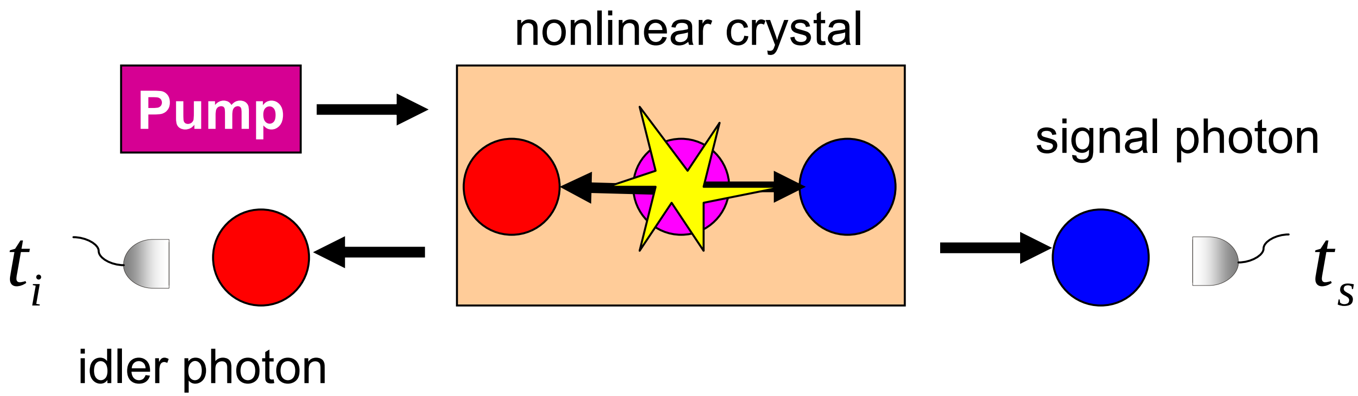
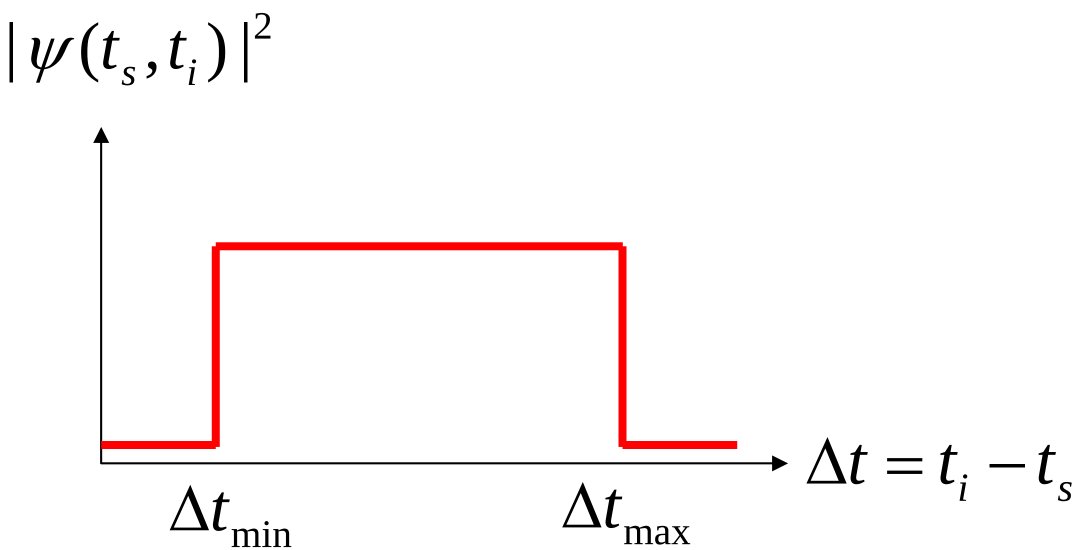
Backward-wave SPDC





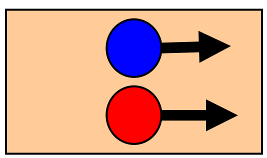
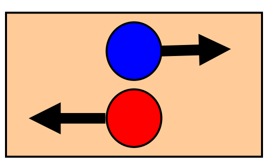
$$\Delta t_{\min} = -L/v_i$$

$$\Delta t_{\max} = L/v_s$$

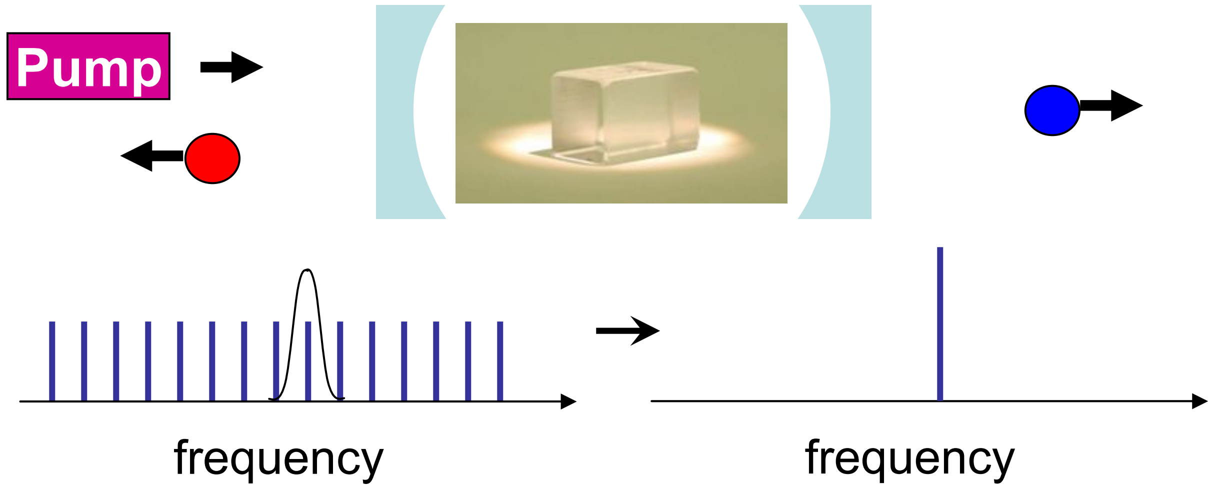
Biphoton coherence time

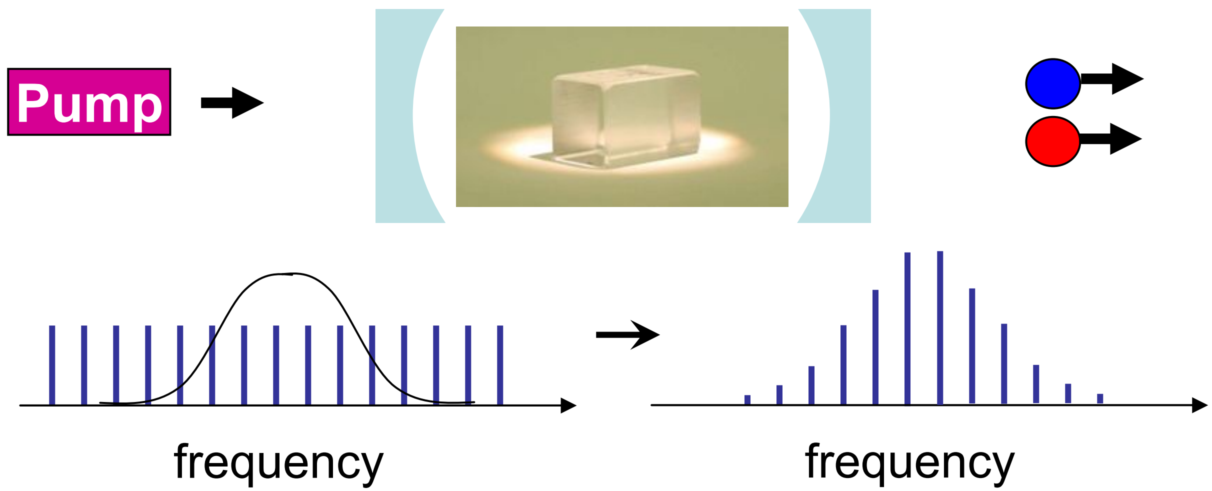
$$T = \Delta t_{\max} - \Delta t_{\min}$$
$$= L\left(v_i^{-1} + v_s^{-1}\right)$$

Backward-wave SPDC v.s. Forward-wave SPDC

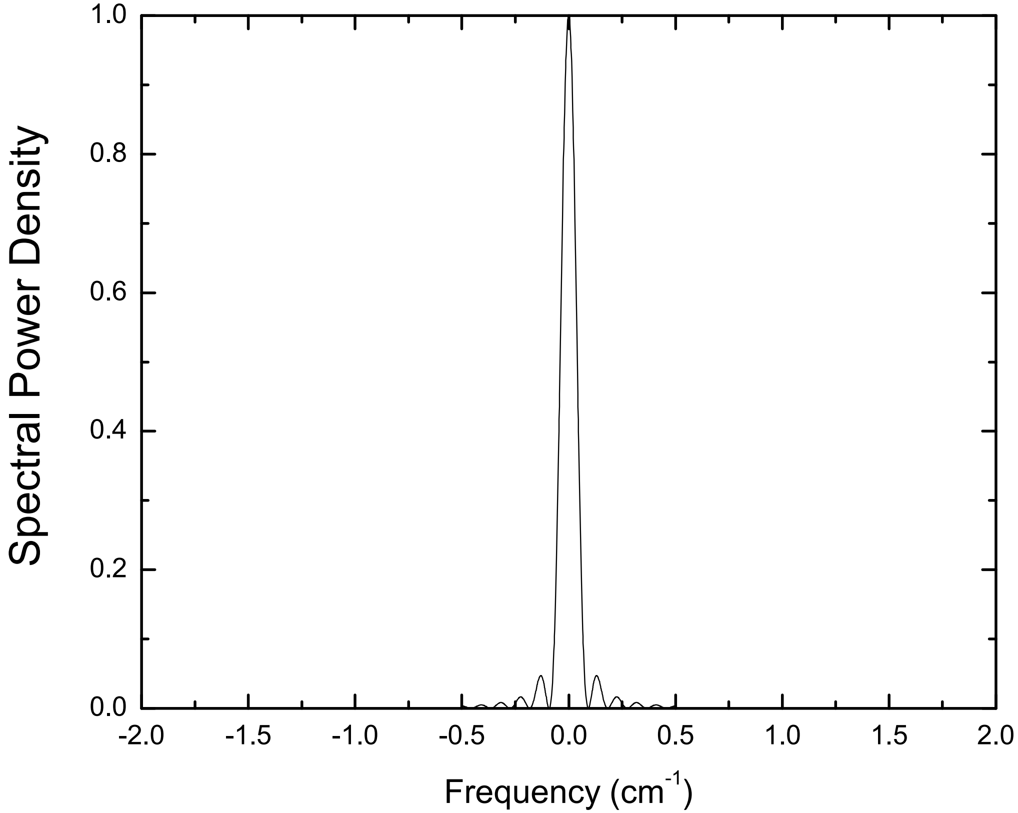
	Coherence Time	Gain Linewidth
Forward-wave 	$L\left(v_i^{-1} - v_s^{-1}\right)$	$\dfrac{1.77\pi}{L\left(v_i^{-1} - v_s^{-1}\right)}$
Backward-wave 	$L\left(v_i^{-1} + v_s^{-1}\right)$	$\dfrac{1.77\pi}{L\left(v_i^{-1} + v_s^{-1}\right)}$

Backward-wave SPDC v.s. Forward-wave SPDC





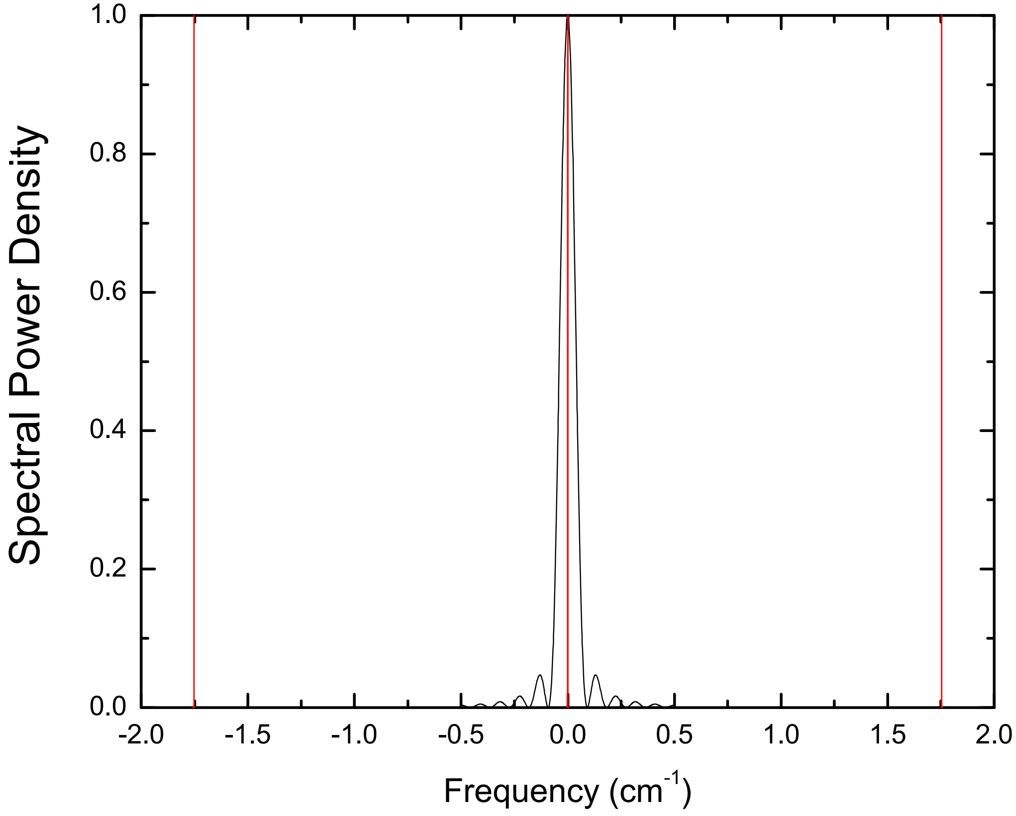
Backward-wave Biphoton Source



Gain Profile

30-mm long PPKTP crystals
Pump λ = 532nm
Signal, idler λ = 1064 nm
Gain linewidth = 0.08 cm^{-1}

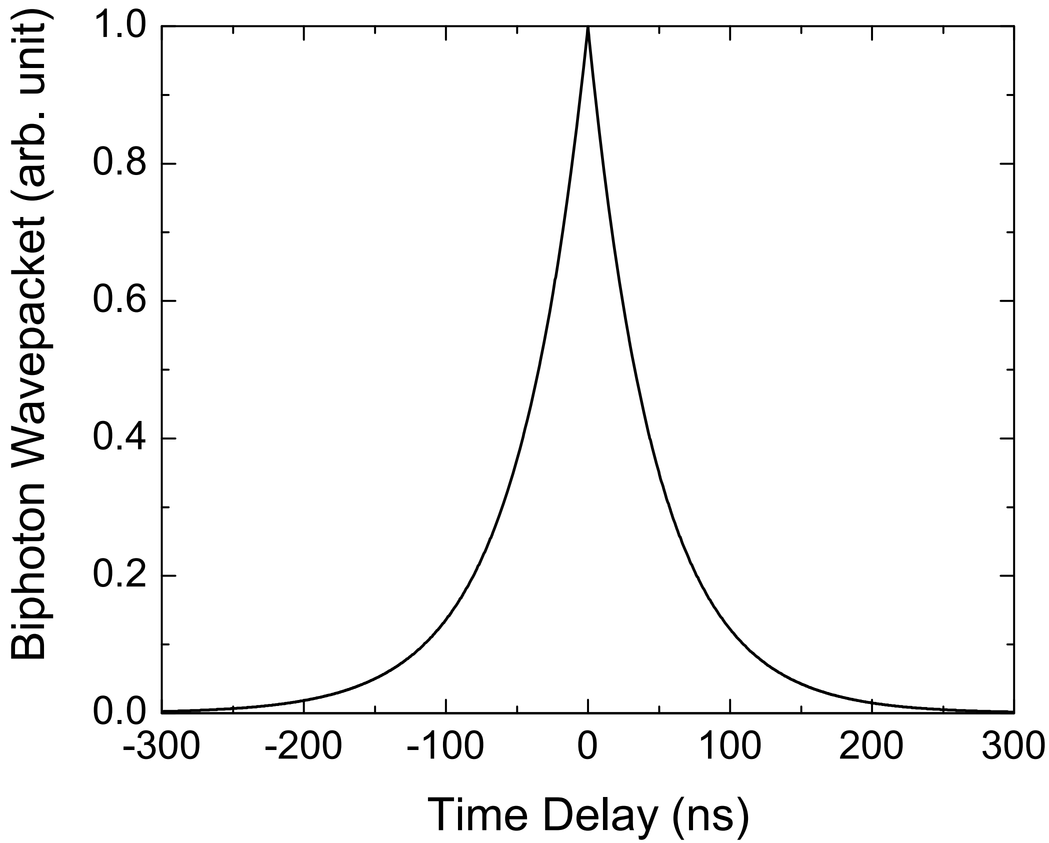
Backward-wave Biphoton Source



Cavity Modes

30-mm long PPKTP crystals
Pump λ = 532nm
Signal, idler λ = 1064 nm
Gain linewidth = 0.08 cm^{-1}
Cavity finesse = 1000
Mode spacing = 1.75 cm-1
Cavity bandwidth = 3MHz

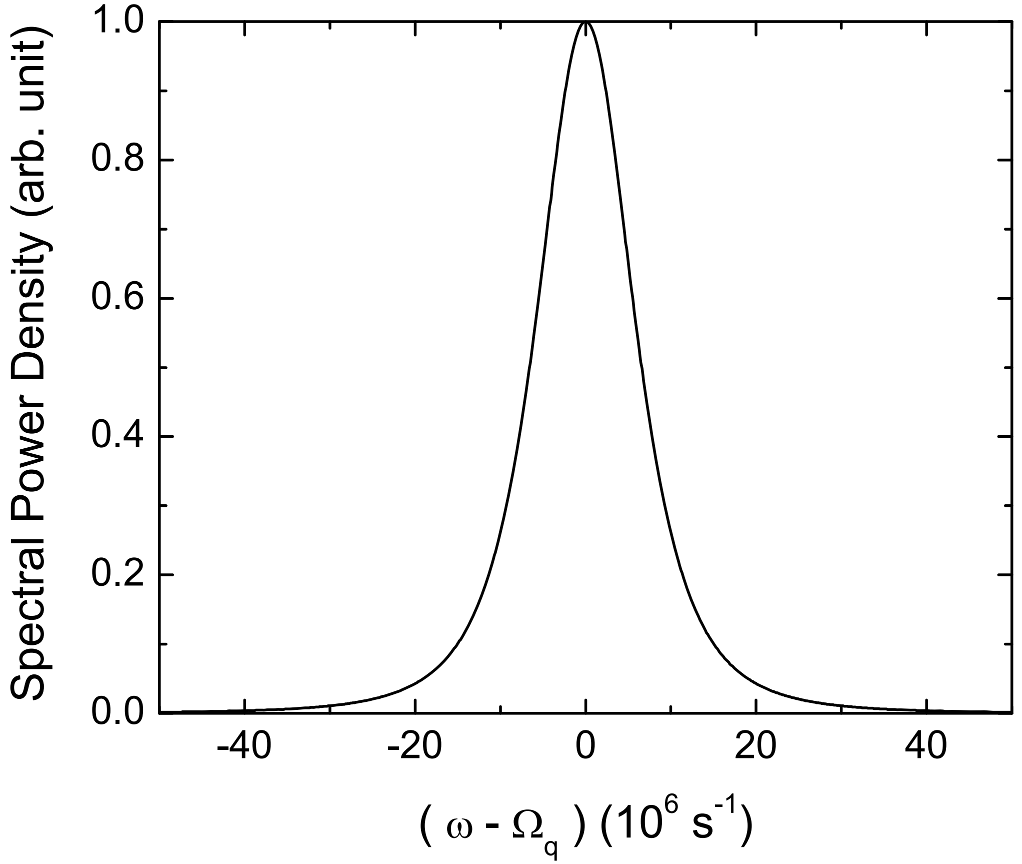
Backward-wave Biphoton Source



Wavepacket

30-mm long PPKTP crystals
Pump λ = 532nm
Signal, idler λ = 1064 nm
Gain linewidth = 0.08 cm^{-1}
Cavity finesse = 1000
Mode spacing = 1.75 cm^{-1}
Coherence time = 68 ns

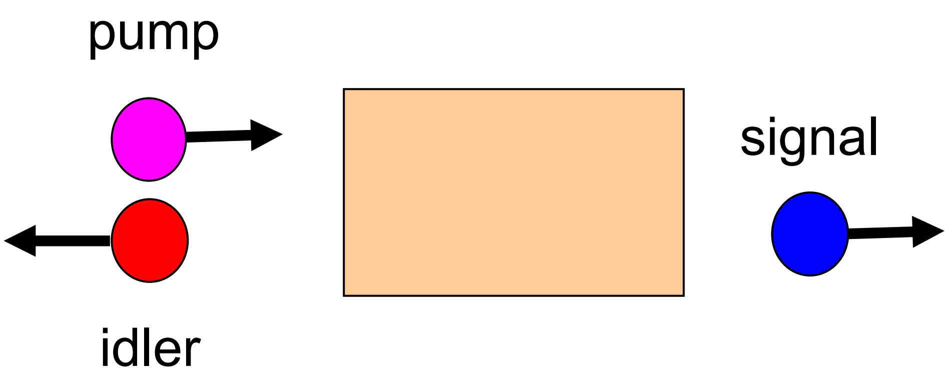
Backward-wave Biphoton Source



Spectrum

30-mm long PPKTP crystals
Pump λ = 532nm
Signal, idler λ = 1064 nm
Gain linewidth = 0.08 cm^{-1}
Cavity finesse = 1000
Mode spacing = 1.75 cm^{-1}
Coherence time = 68 ns
Bandwidth = 3 MHz

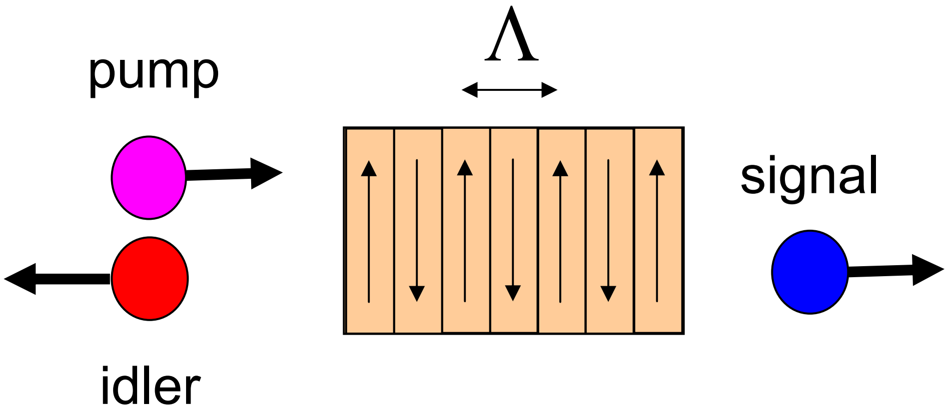
Phase Matching in Backward-wave SPDC



$$\omega_p = \omega_s + \omega_i$$

$$k_p \neq k_s - k_i$$

Quasi-Phase Matching

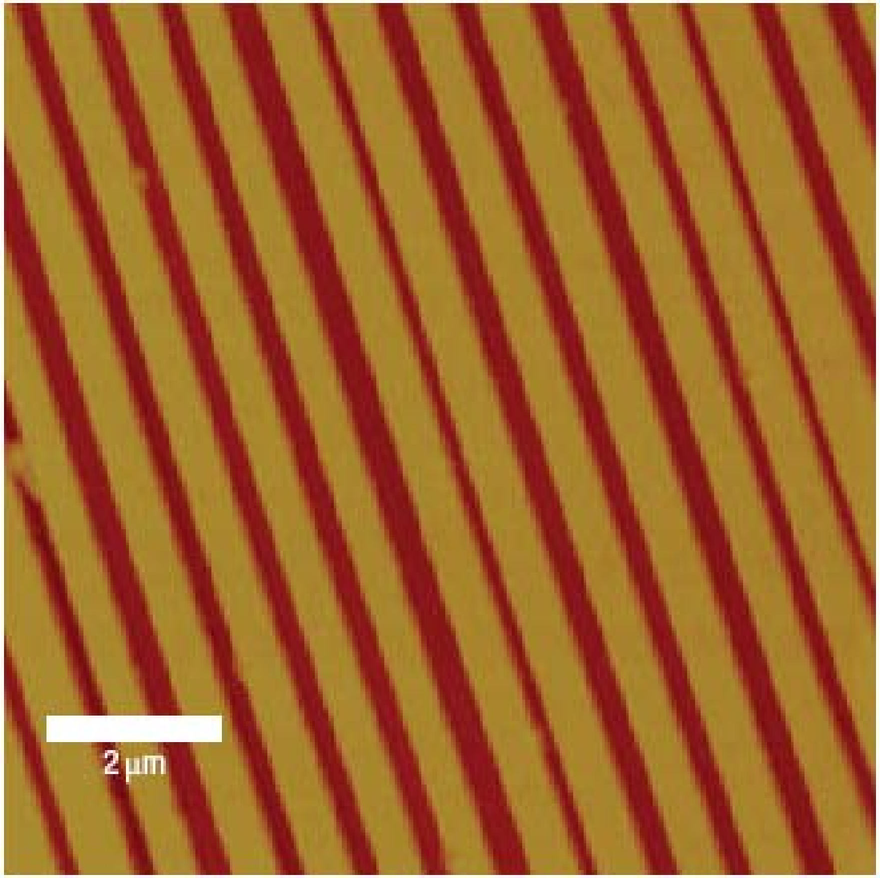


$$\omega_p = \omega_s + \omega_i$$

$$k_p = k_s - k_i + K$$

$$K = \frac{2\pi m}{\Lambda}, \quad \Lambda \leq 1\,\mu\mathrm{m}$$

Sub-micron Periodic Poling



Canalias and Pasiskevicius, Sweden

Key Features of Resonant Backward-wave SPDC

- ❑ Compact design

  no need of additional filter for single-mode biphotons

- ❑ Higher brightness (photons/MHz/mW)

  80000 times higher than nonresonant forward-wave SPDC source

- ❑ Wavelength tunability

$$k_p = k_s - k_i + 2\pi m / \Lambda$$

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