Time-reversal interferometry with classical light for reproducing quantum optical phenomena

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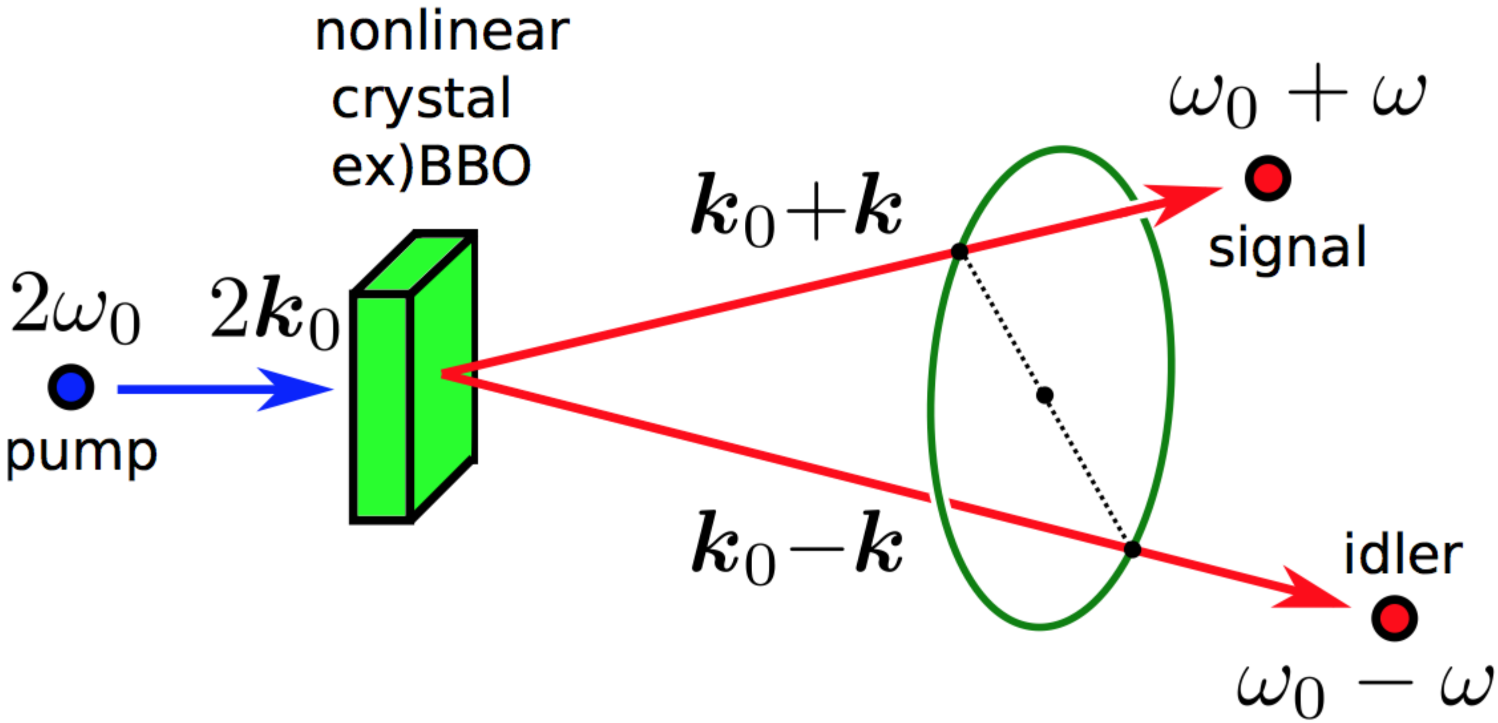
Background : Parametric down conversion

1980 : Generation of entangled photons by
spontaneous parametric down conversion (SPDC)



Energy conservation

$$\hbar\omega_{\mathrm{p}} = \hbar\omega_{\mathrm{s}} + \hbar\omega_{\mathrm{i}}$$

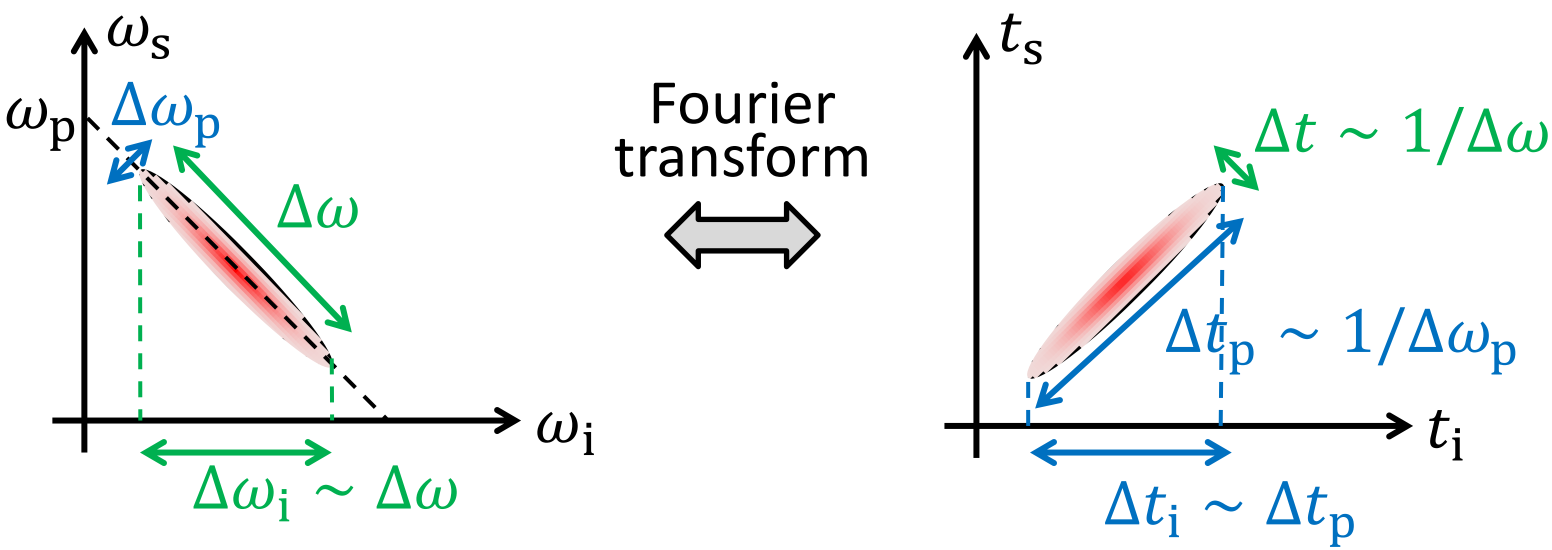
Momentum conservation

$$\hbar\boldsymbol{k}_{\mathrm{p}} = \hbar\boldsymbol{k}_{\mathrm{s}} + \hbar\boldsymbol{k}_{\mathrm{i}}$$

Quantum correlation (Entanglement)

$\Delta\omega_{\mathrm{p}}, \Delta t_{\mathrm{p}}$: Frequency and time width of pump photon

$\Delta\omega_{\mathrm{i}}, \Delta t_{\mathrm{i}}$: Frequency and time width of idler photon



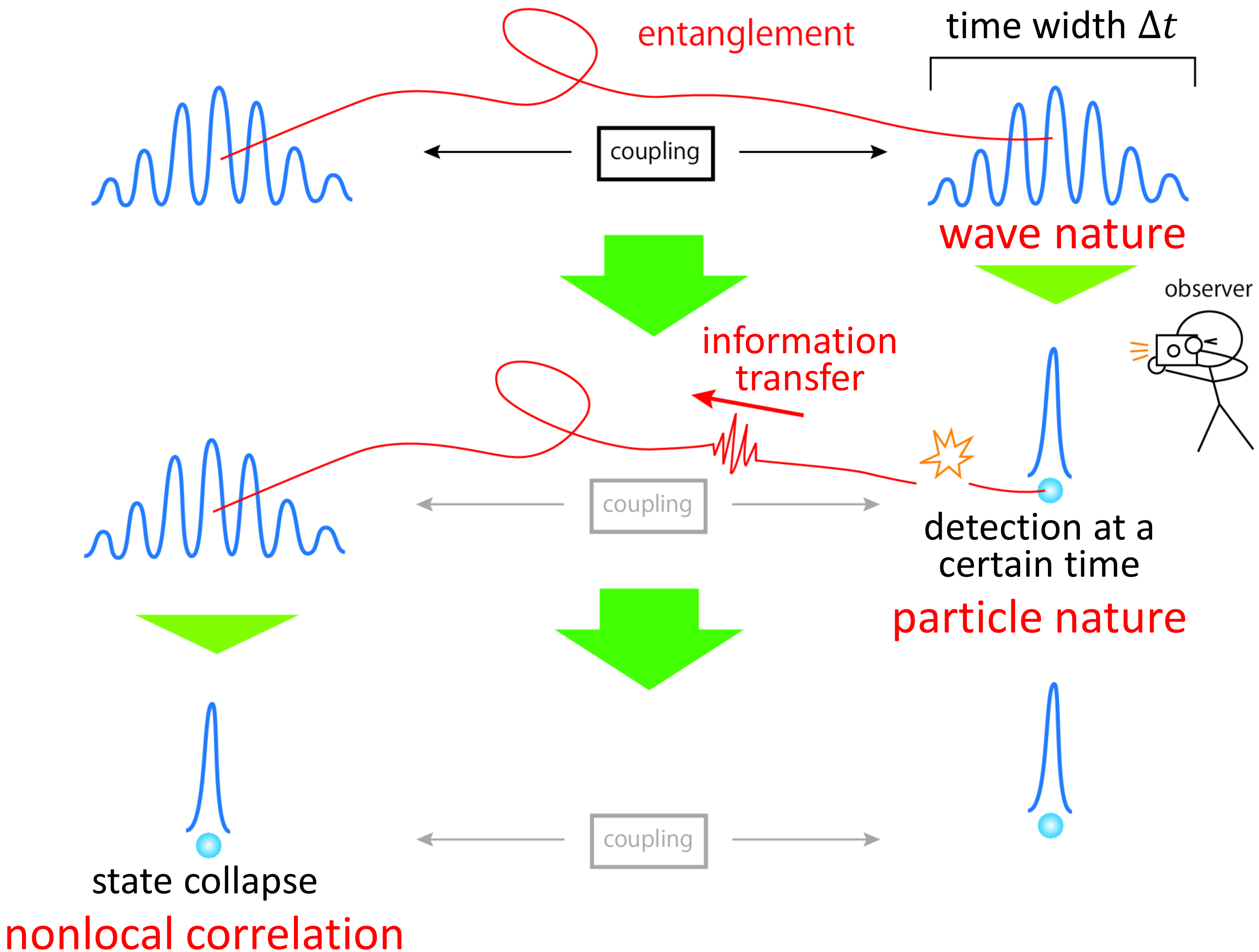
Energy conservation

$$\hbar\omega_{\mathrm{p}} = \hbar\omega_{\mathrm{s}} + \hbar\omega_{\mathrm{i}}$$

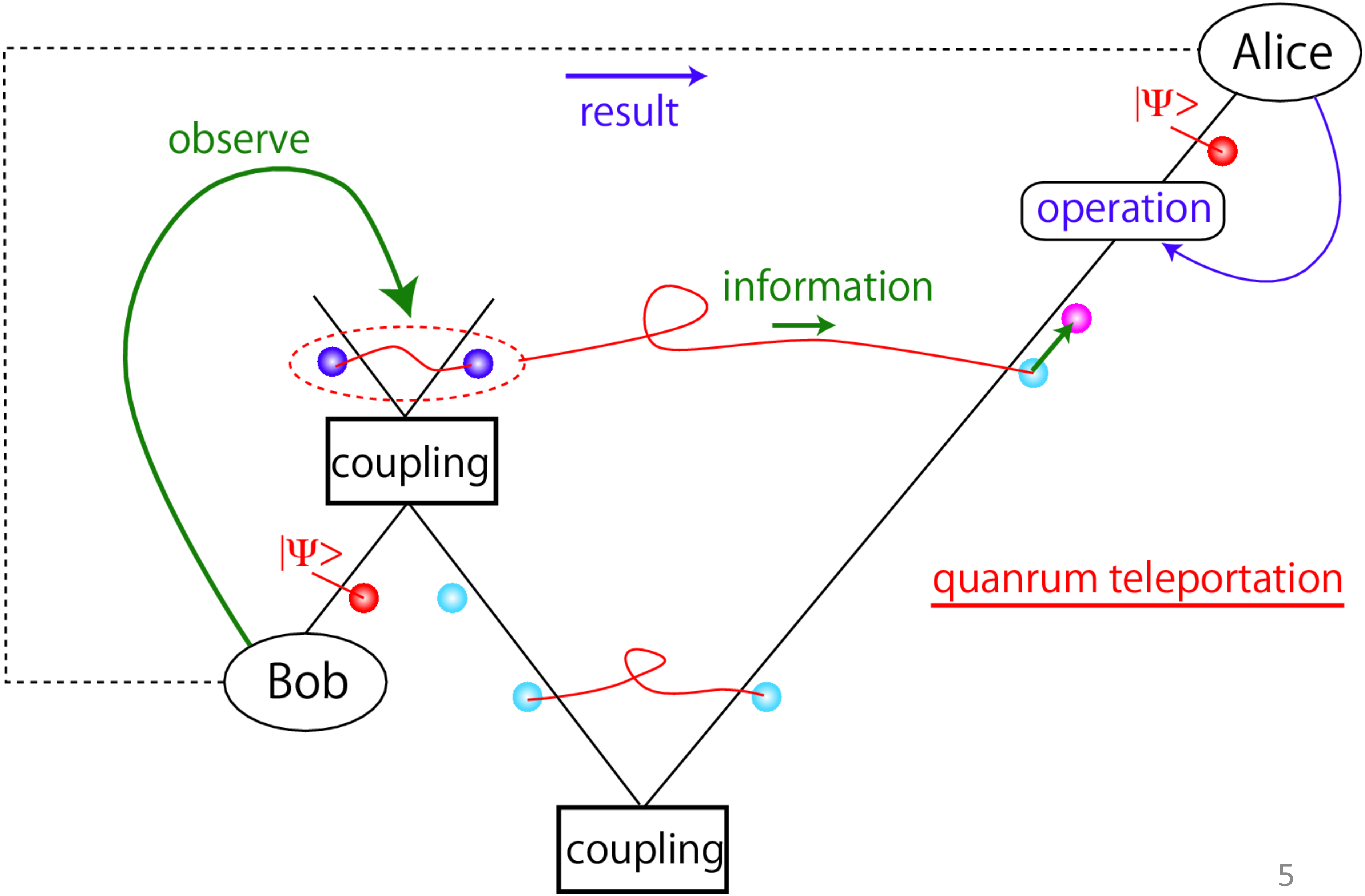
$$t_{\mathrm{i}} \simeq t_{s}$$

Simultaneous generation of two photons within Δt

Non-local quantum correlation

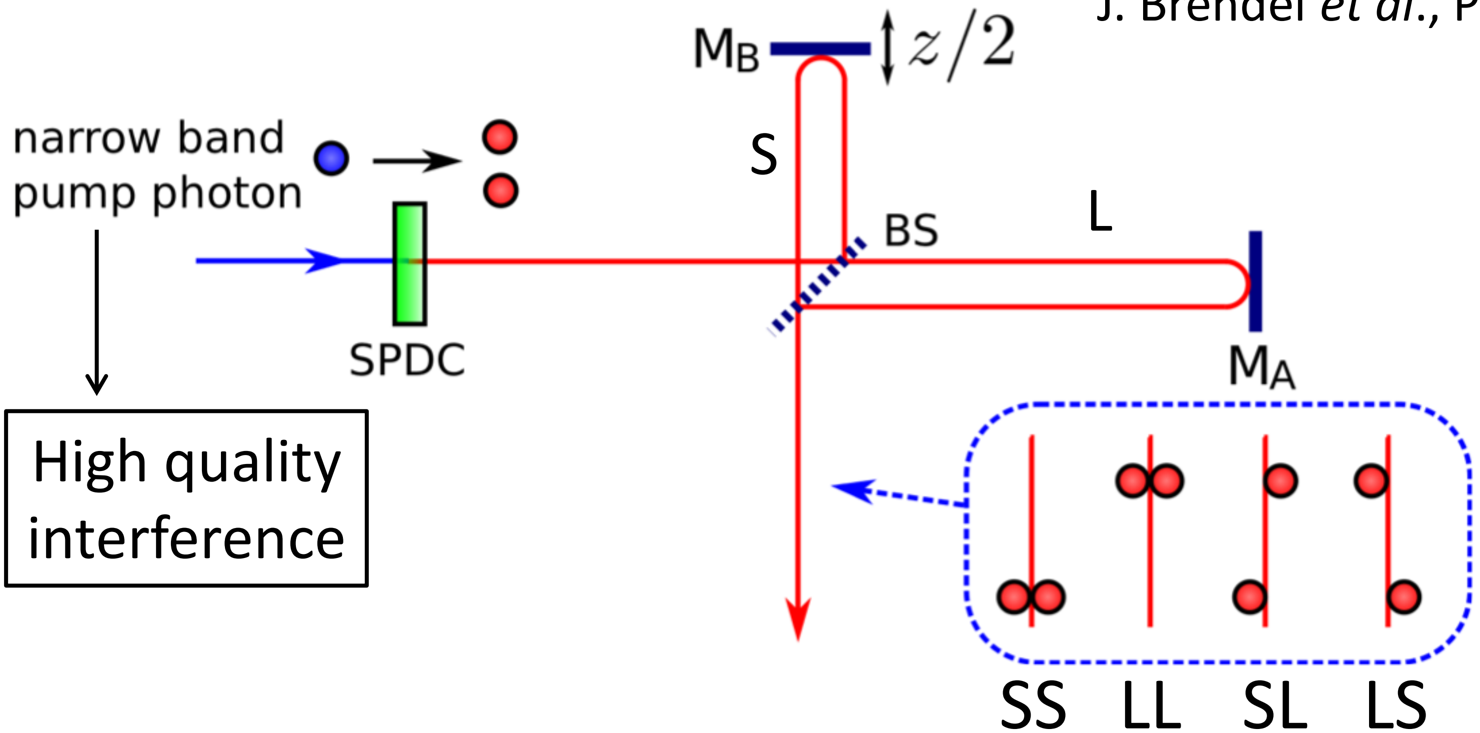


Quantum teleportation



Two-photon interference

J. Brendel *et al.*, PRL **66**, 1142 (1991)

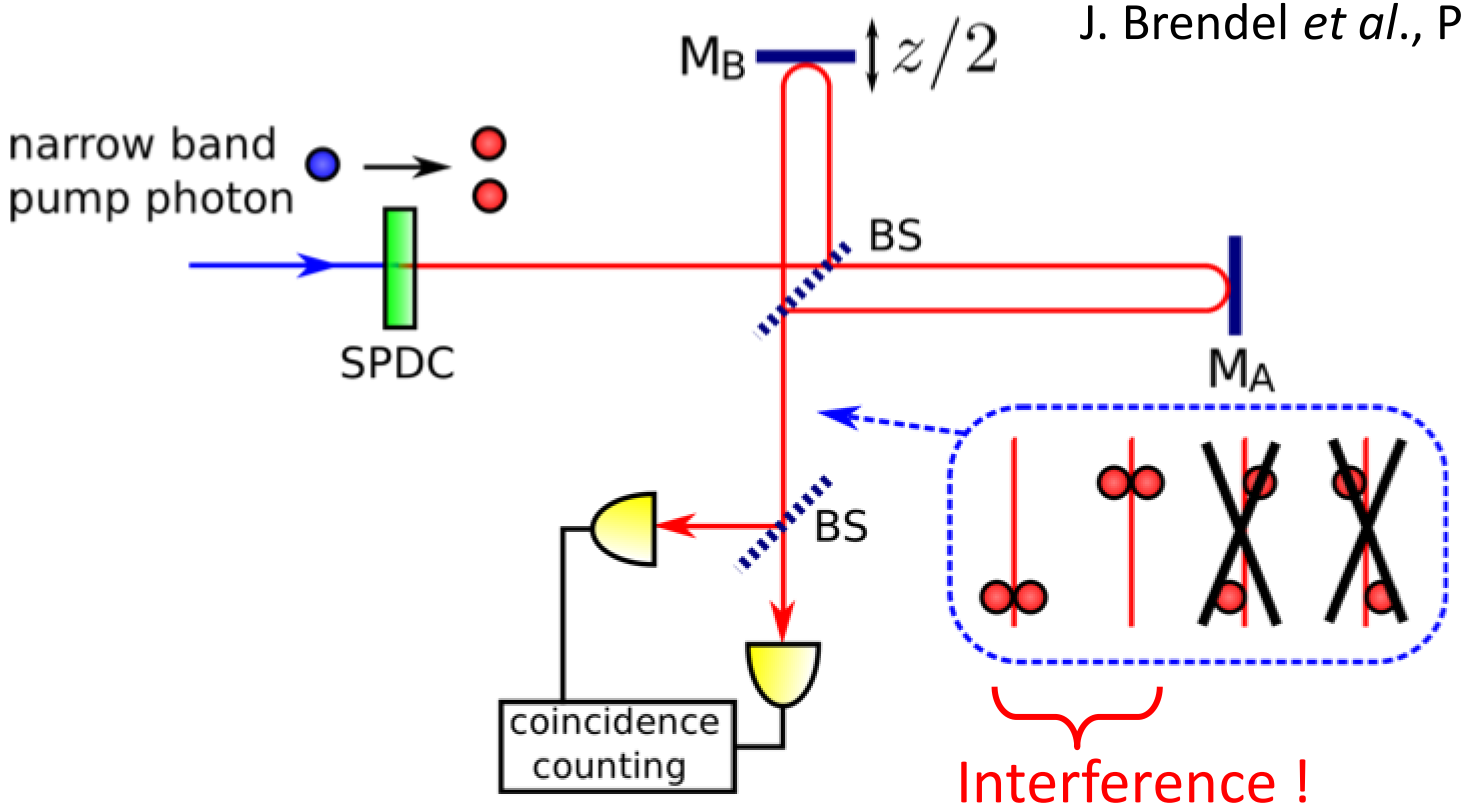


✓ Unbalanced Michelson interferometer

✓ Output = LL + SS + LS + SL

Two-photon interference

J. Brendel *et al.*, PRL **66**, 1142 (1991)



- ✓ Unbalanced Michelson interferometer
- ✓ Output = LL + SS + ~~LS + SL~~
- ✓ Coincidence counting eliminates LS and SL

Two-photon interference

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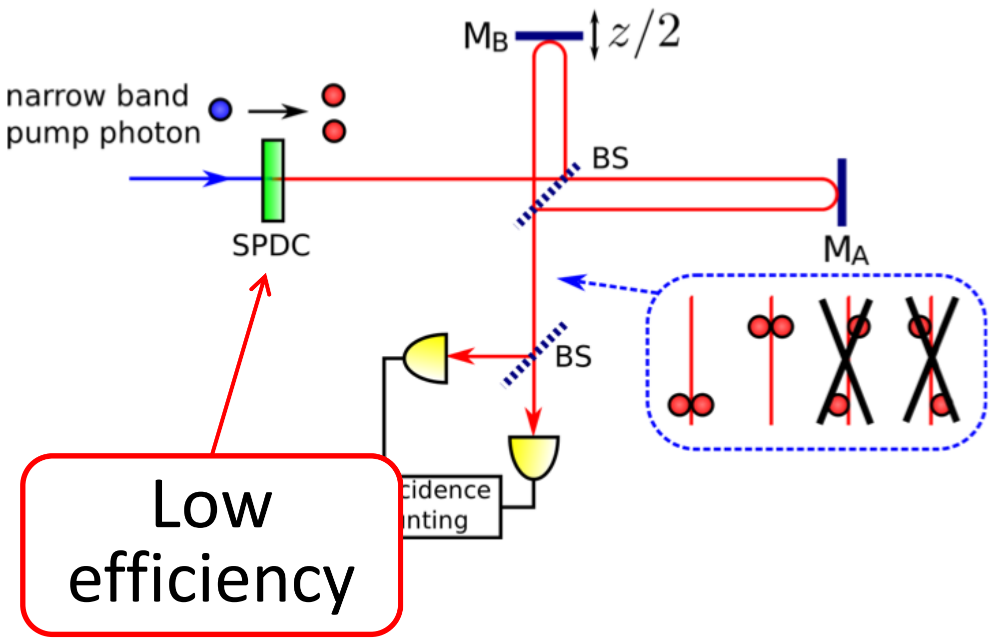
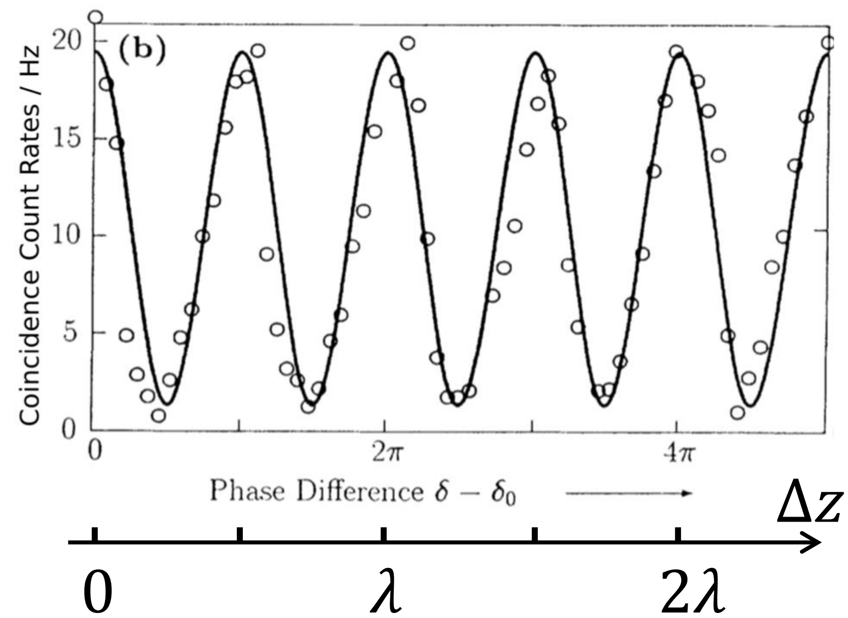


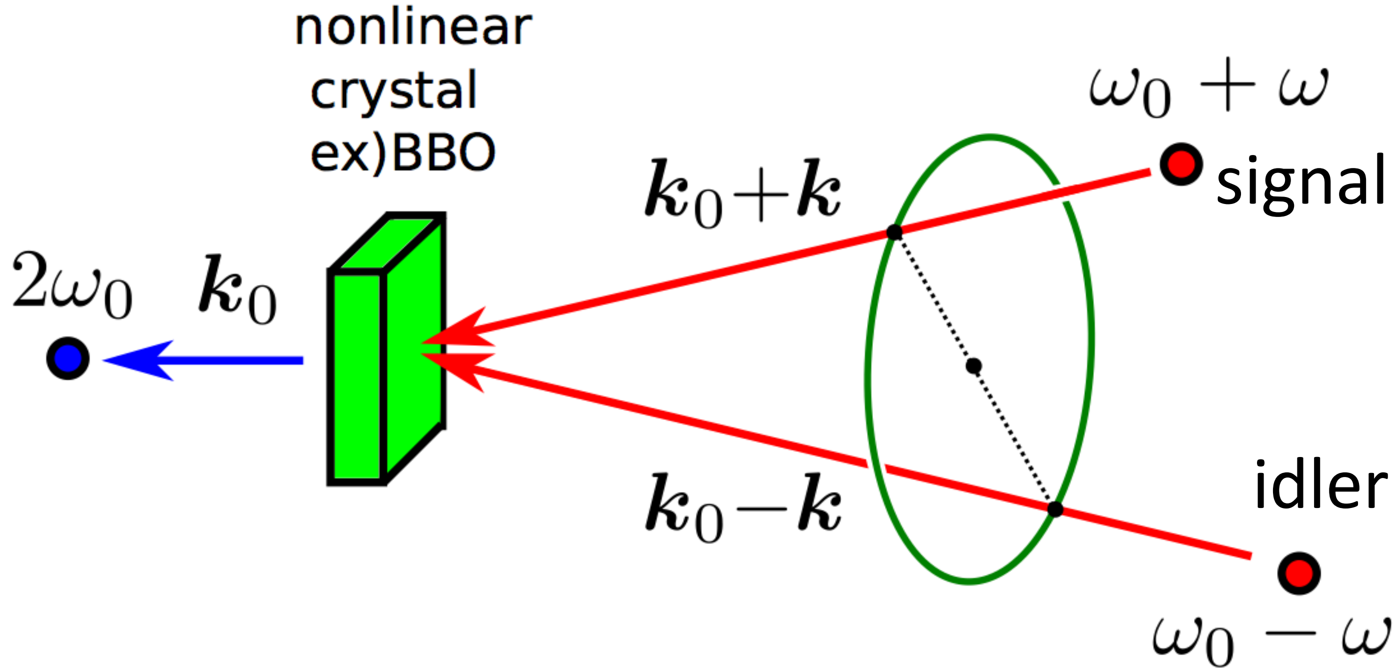


- ✓ Unbalanced Michelson interferometer
- ✓ Output = LL + SS + LS + SL
- ✓ Coincidence counting eliminates LS and SL
- ✓ Fringe cycle = $\lambda/2$ （Two-photon interference）
  → Quantum lithography

Sum frequency generation (SFG)

SFG = Reverse process of SPDC

(Coincident two photons → one photon)



Energy conservation

$$\hbar\omega_{\mathrm{s}} + \hbar\omega_{\mathrm{i}} = \hbar\omega_{\mathrm{p}}$$

Momentum conservation

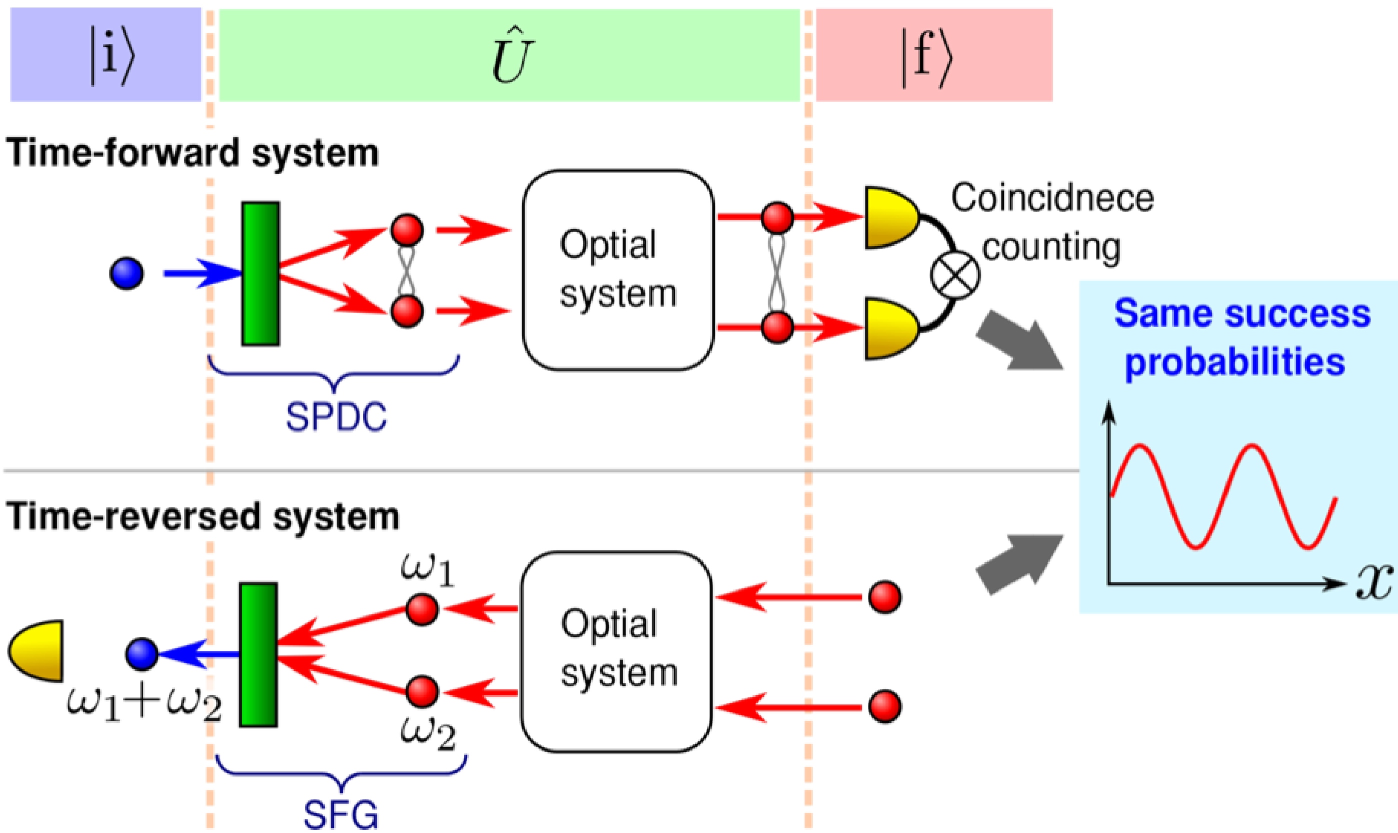
$$\hbar\boldsymbol{k}_{\mathrm{s}} + \hbar\boldsymbol{k}_{\mathrm{i}} = \hbar\boldsymbol{k}_{\mathrm{p}}$$

Time-reversal symmetry of quantum mechanics

$$\left|\langle \mathrm{f}|\hat{U}|\mathrm{i}\rangle\right|^2 = \langle \mathrm{i}|\hat{U}^\dagger|\mathrm{f}\rangle\langle \mathrm{f}|\hat{U}|\mathrm{i}\rangle = \left|\langle \mathrm{i}|\hat{U}^\dagger|\mathrm{f}\rangle\right|^2$$

$$\left|\langle \mathrm{f}|\hat{U}|\mathrm{i}\rangle\right|^2$$

$$\left|\langle \mathrm{i}|\hat{U}^\dagger|\mathrm{f}\rangle\right|^2$$

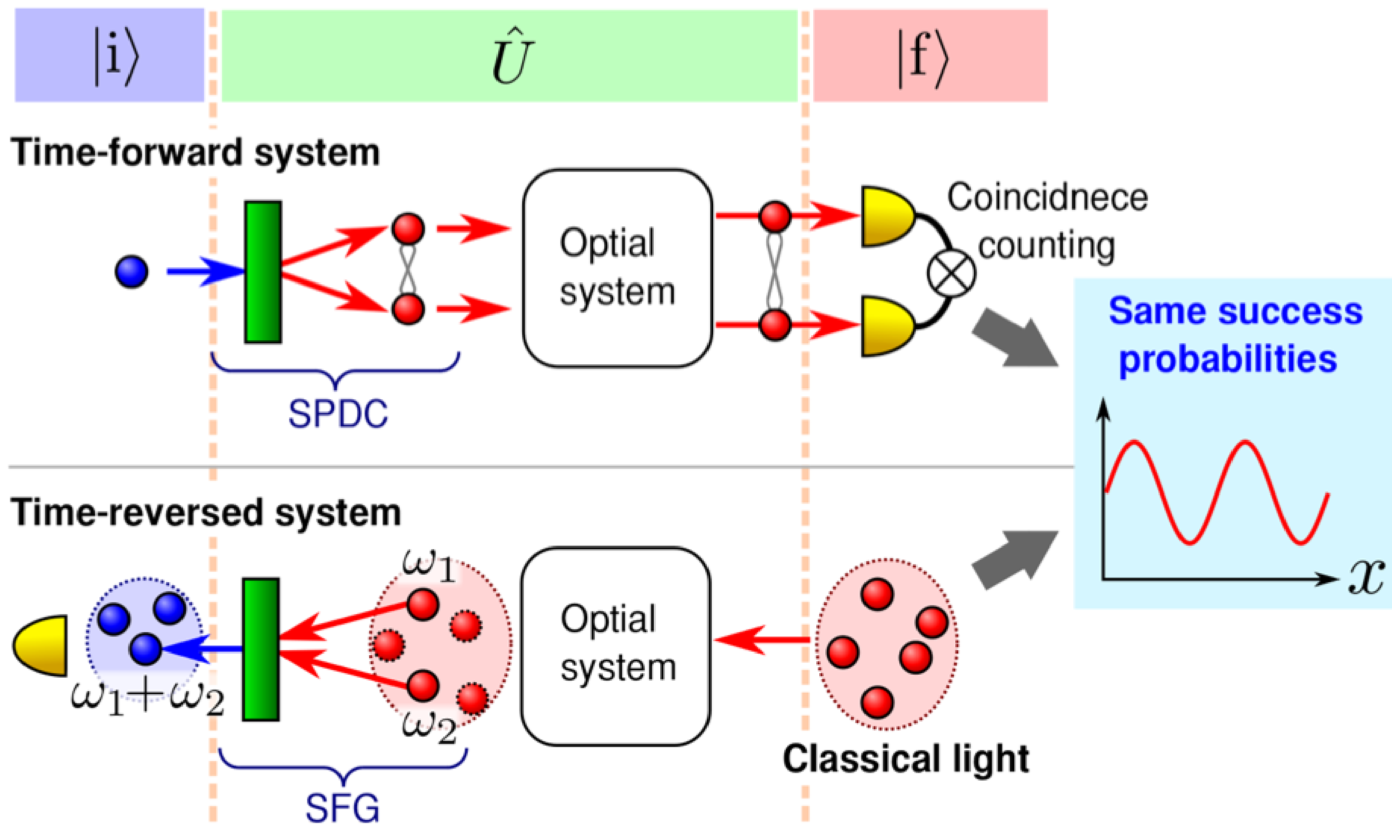


Can we replace two photons to classical light?

Answer : Yes !

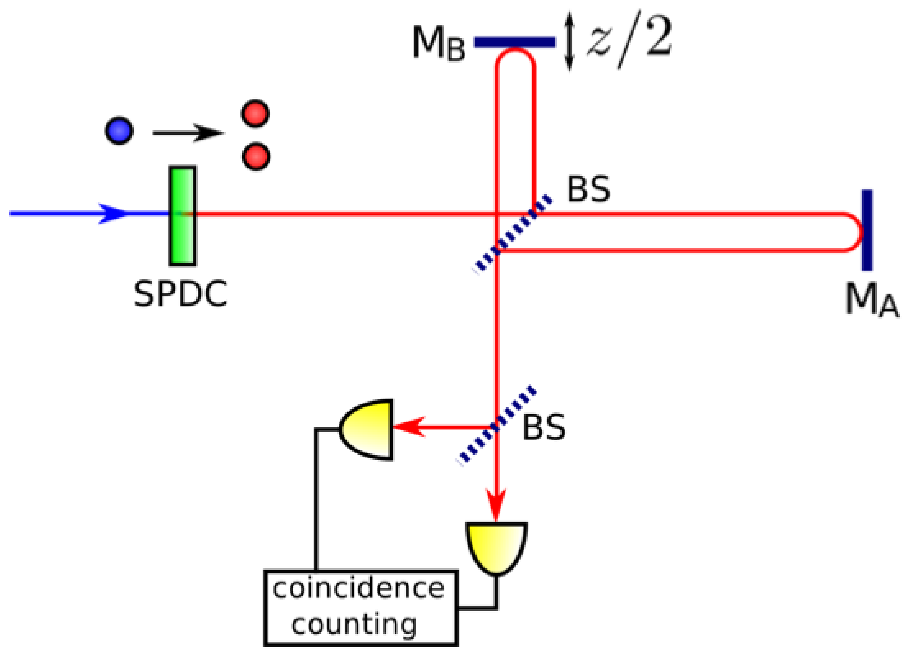
$$|\langle f|\hat{U}|i\rangle|^2$$

$$|\langle i|\hat{U}^\dagger|f\rangle|^2$$

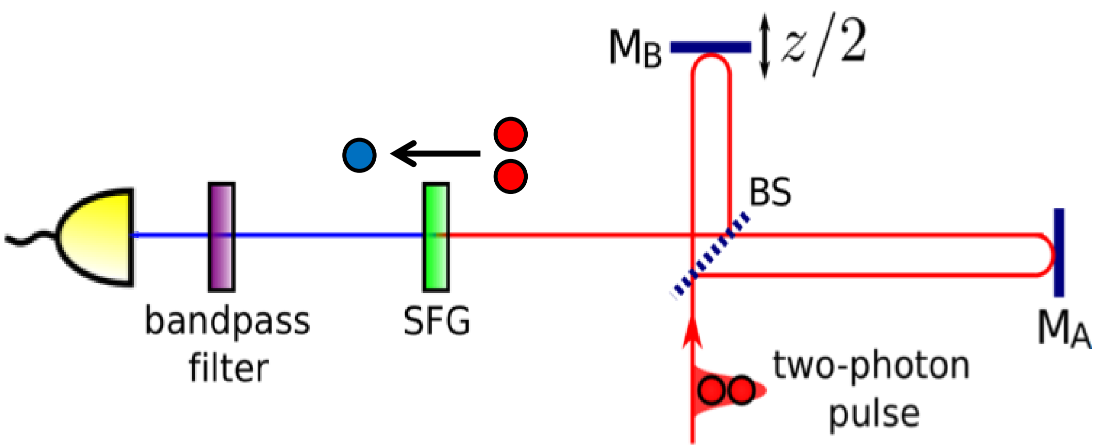


Time-reversed system for two-photon interference

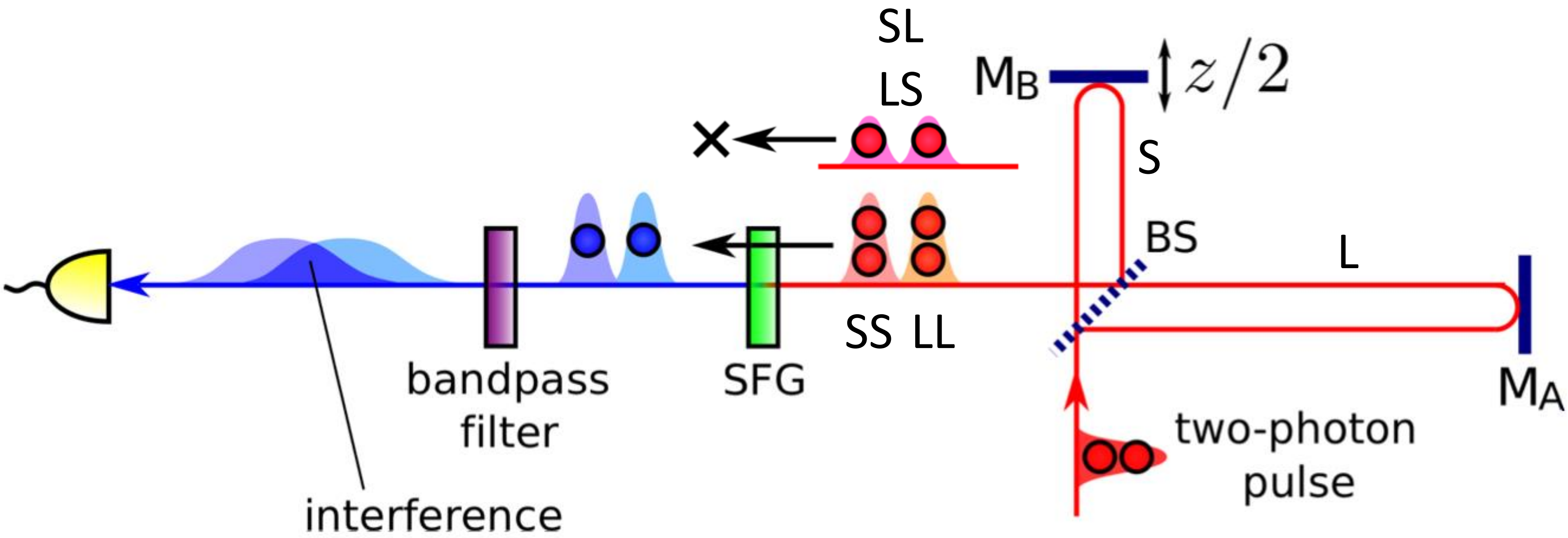
Time-forward System



Time-Reversed System

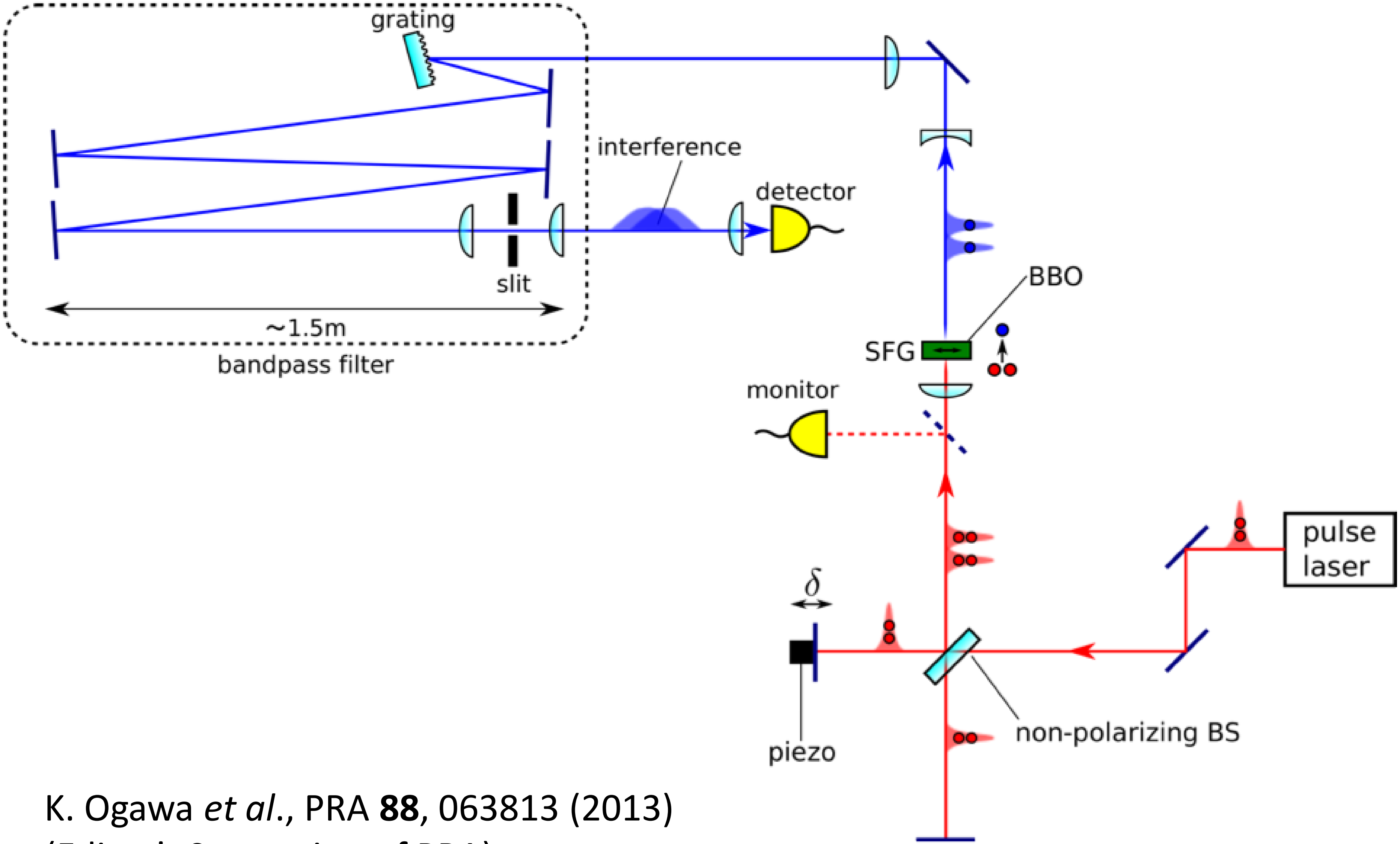


Can we replace two photons to classical light?



- ✓ Unbalanced Michelson interferometer
- ✓ Output = LL + SS + ~~LS + SL~~
- ✓ SFG eliminates LS and SL
- ✓ Fringe cycle = $\lambda/2$ （＝Two-photon interference）

Experimental setup



K. Ogawa *et al.*, PRA **88**, 063813 (2013)
(Editor's Suggestion of PRA)

Experimental result

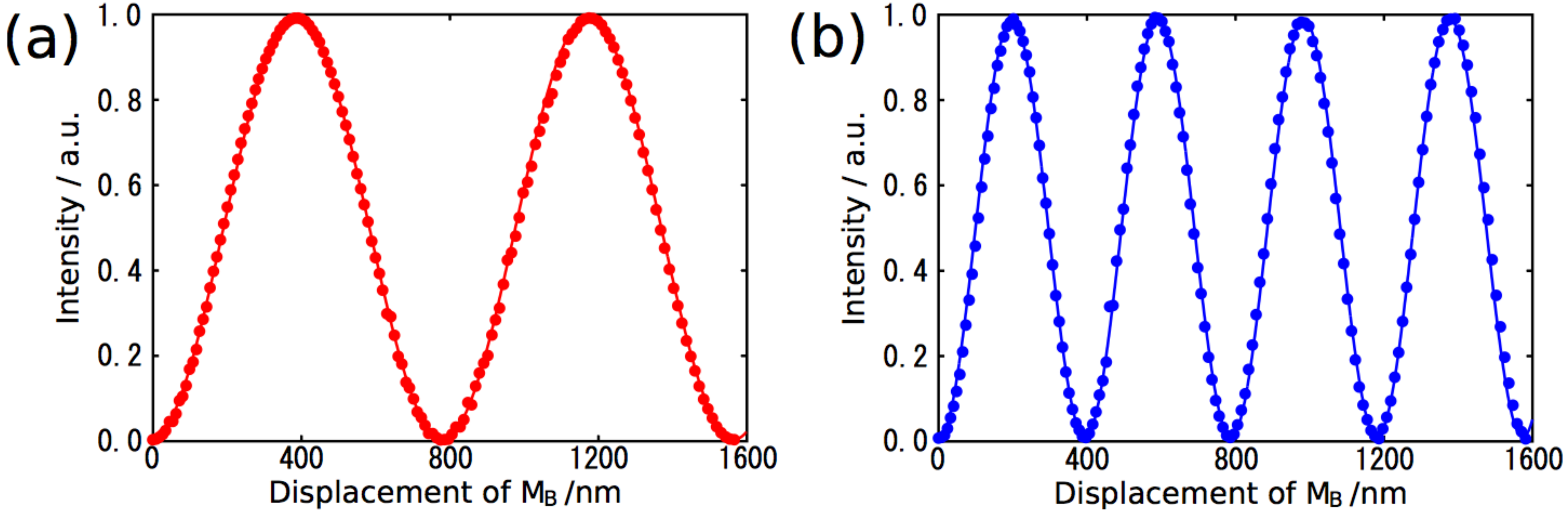
Wavelength $\lambda = 780\ (\mathrm{nm})$

(a) One-photon interference

Fringe cycle = 780 nm , Visibility = 99.1 %

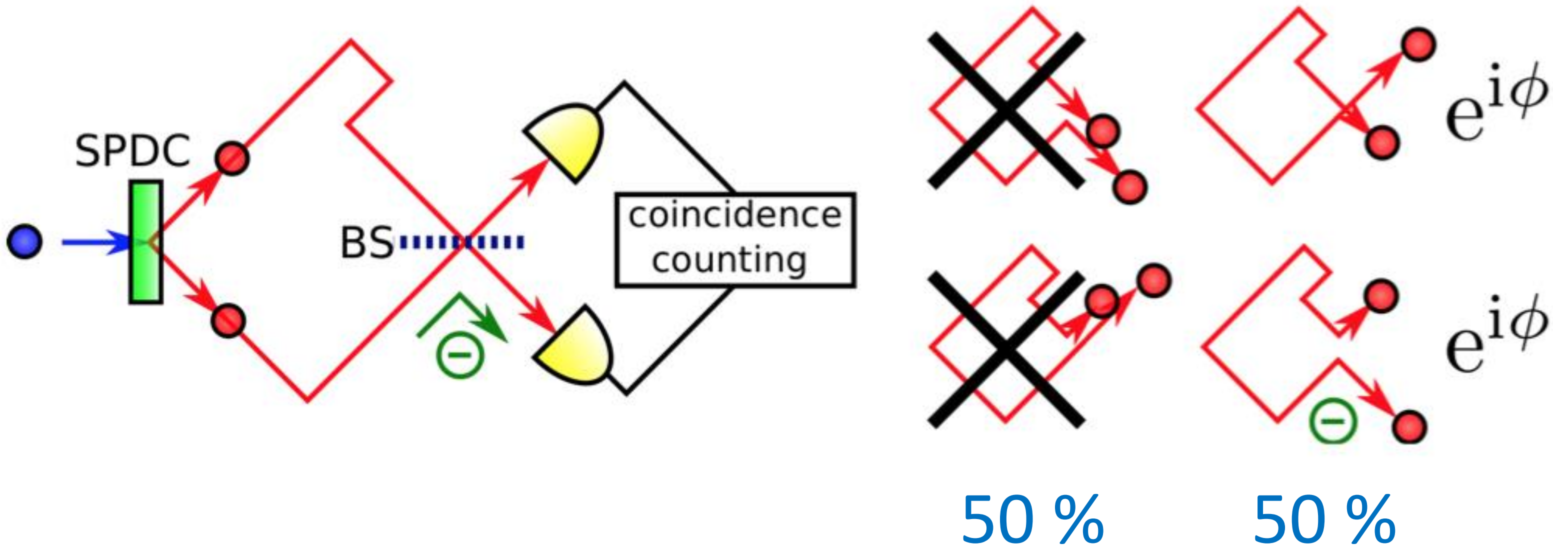
(a) Two-photon interference

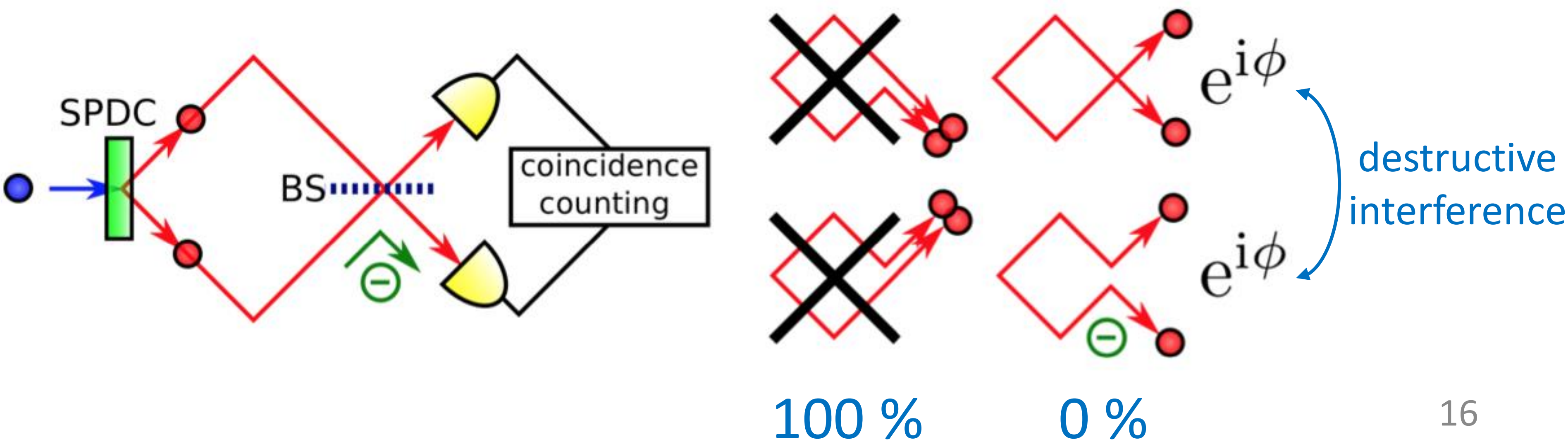
Fringe cycle = 390 nm , Visibility = 97.9 %



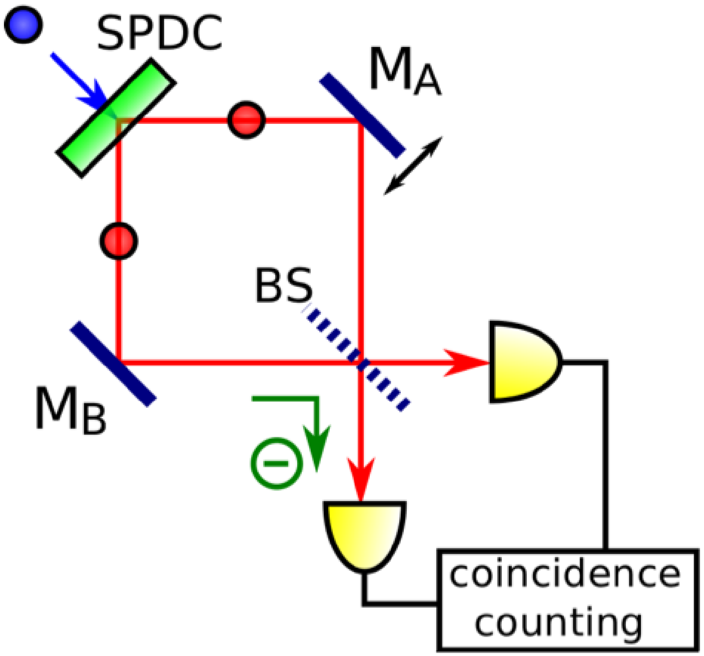
Hong-Ou-Mandel (HOM) interference

C. K. Hong *et al.*, PRL **59**, 18 (1987)





Hong-Ou-Mandel (HOM) interference



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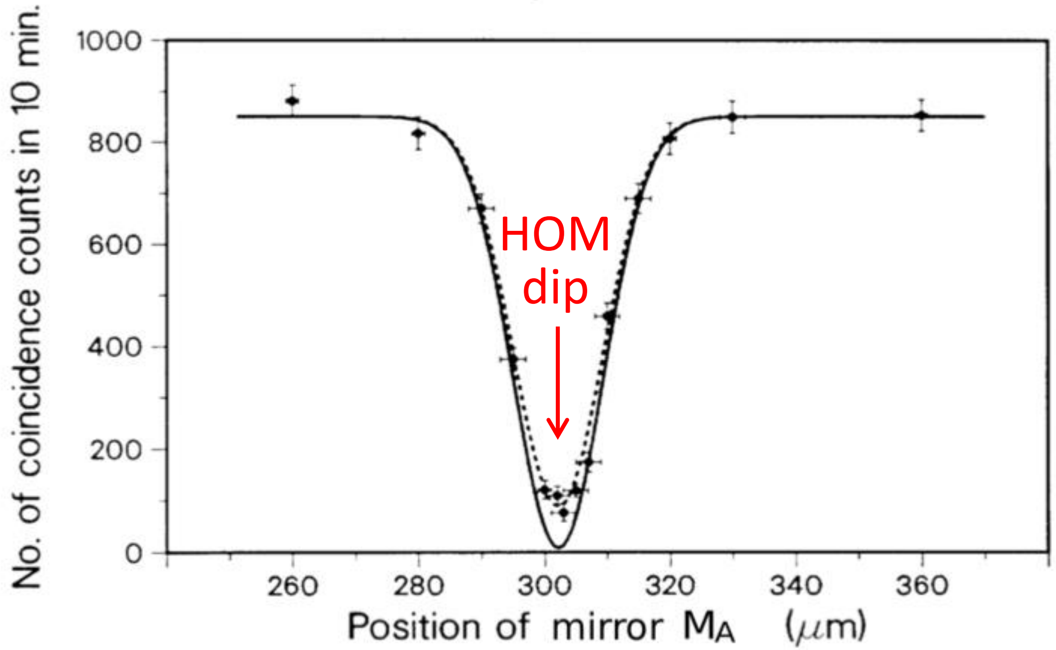
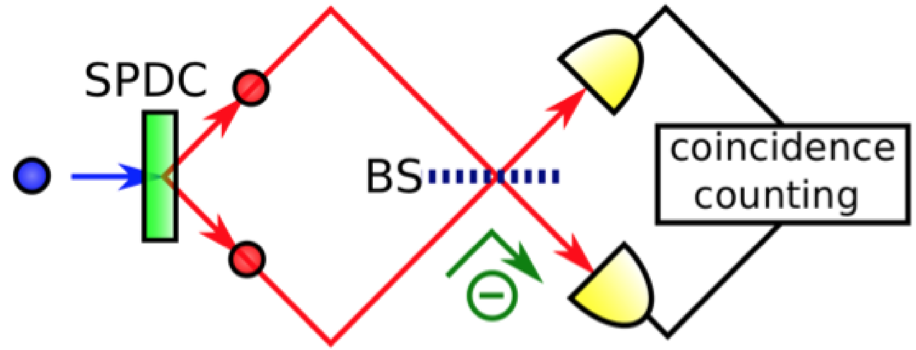


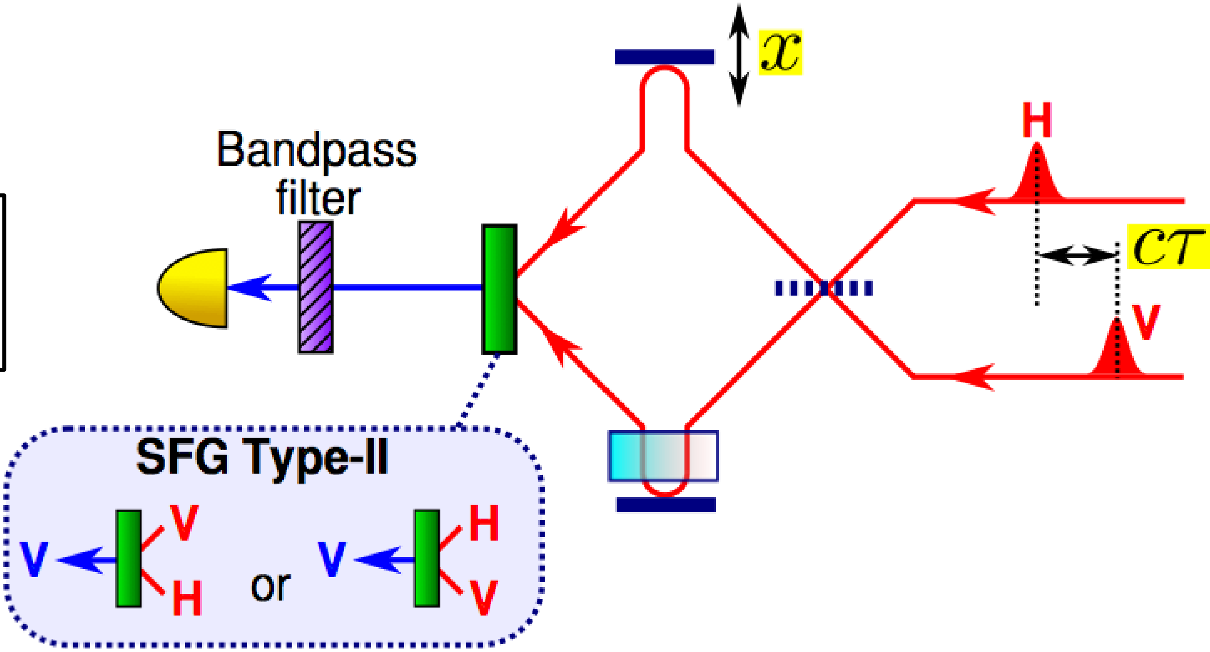
- ✓ When $\mathrm{M_A} \neq \mathrm{M_B}$, coincidence count is possible
- ✓ When $\mathrm{M_A} = \mathrm{M_B}$, destructive interference makes "HOM dip"

Time-reversed system of HOM interferometer

Time-forward System

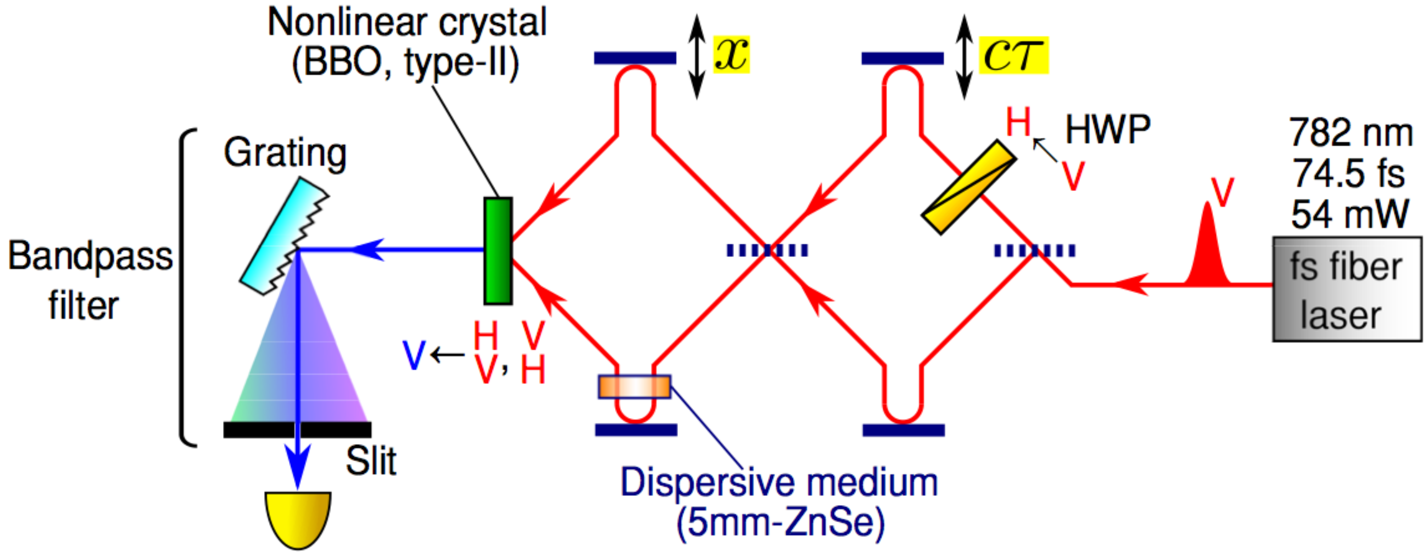


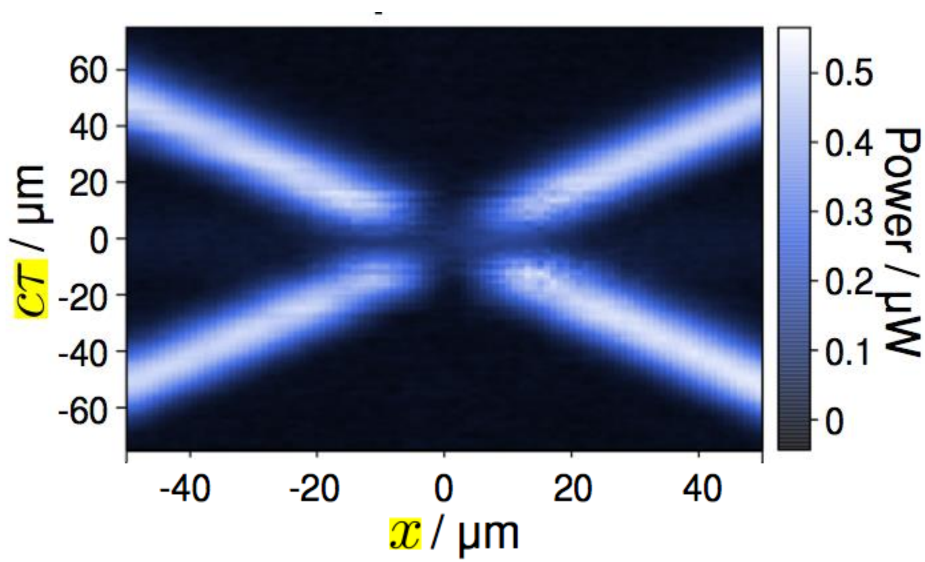
Time-Reversed System

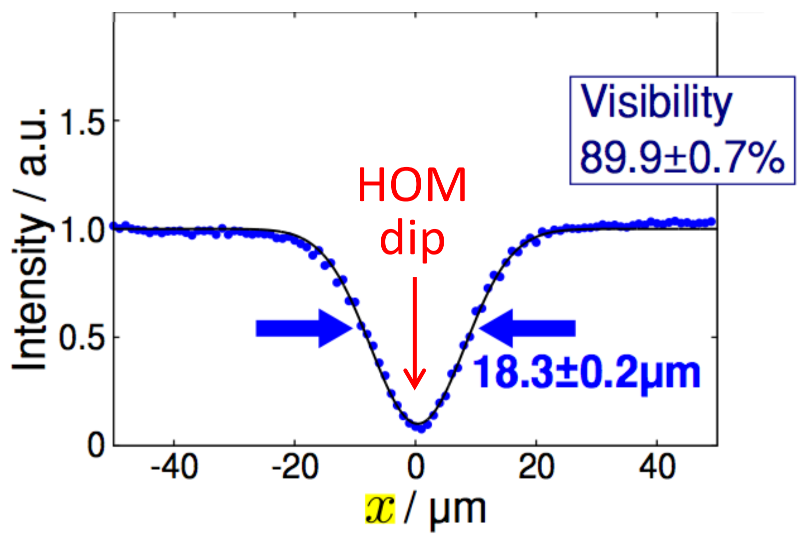


Experimental setup and results

K. Ogawa *et al.*, PRA **91**, 013846 (2015)







Conclusion

$$\left|\langle \mathrm{f}|\hat{U}|\mathrm{i}\rangle\right|^2 = \left|\langle \mathrm{i}|\hat{U}^\dagger|\mathrm{f}\rangle\right|^2$$

- ✓ Time-forward and time-reversed system provide the same probability distribution
- ✓ Because of strong intensity, time-reversed system often has advantage of easy observation and high quality results
- ✓ Quantum interference of two photons can be reproduced by classical pulsed light with time-reversed system

- ✓ But… nonlocal correlation is not realized by classical light