# Highly efficient entanglement swapping for long-distance quantum communication


## Rui-Bo Jin

*Researcher*

*National Institute of Information and Communications Technology (NICT), Tokyo, Japan*



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# Highly efficient entanglement swapping for long-distance quantum communication

Rui-Bo Jin[1], Masahiro Takeoka[1], Utako Takagi[1,2], Ryosuke Shimizu[3], Masahide Sasaki[1]

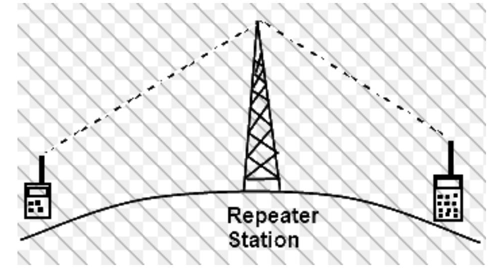
*[1]National Institute of Information and Communications Technology (NICT), Tokyo, Japan*
*[2]Tokyo University of Science, Tokyo, Japan*
*[3]University of Electro-Communication (UEC), Tokyo, Japan*

1. **Motivation**
2. **Introduction (entangled sources; SNSPD detectors)**
3. **Experiment**
4. **Result (4-fold HOM interference; teleportation; swapping)**
5. **Discussion**
6. **Conclusion**

# 1. Motivation

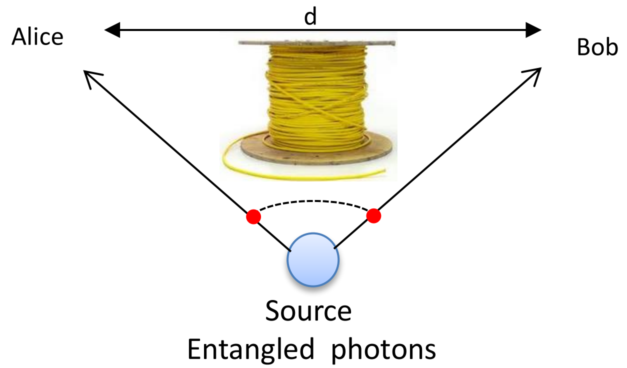
## The scenario of quantum repeaters

**Global quantum communication requires quantum repeaters**
**Quantum repeaters need entanglement swapping**

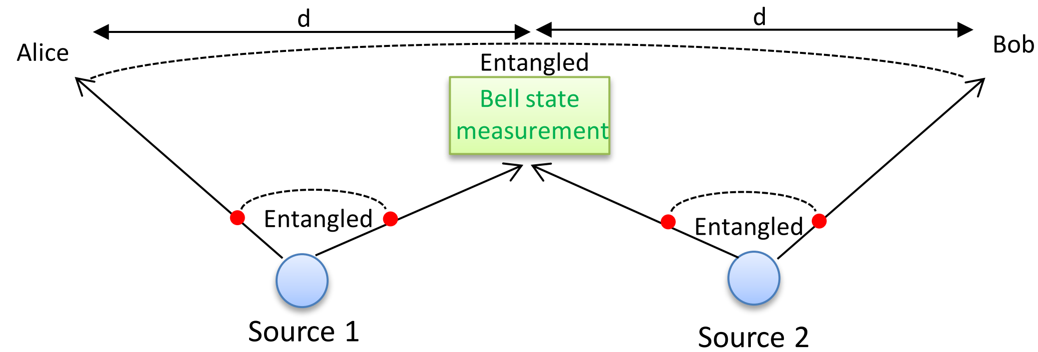


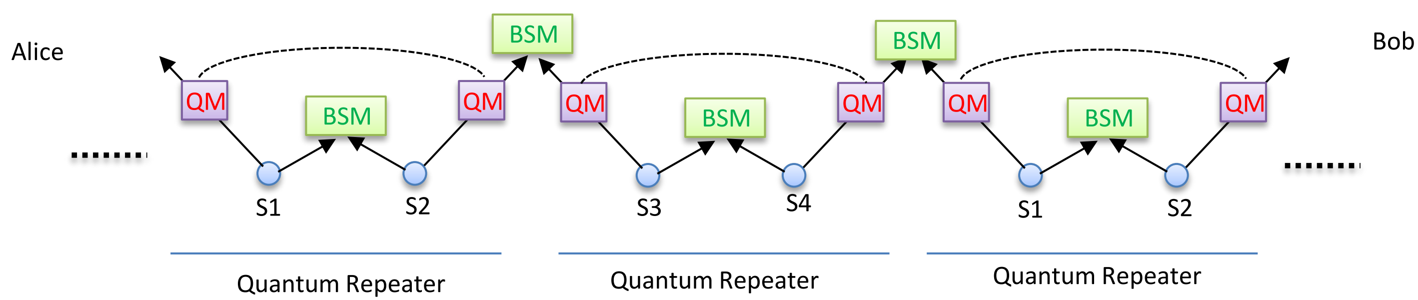

Classical repeater

QC in fibers ~300-500 km, due to the losses, 0.2dB/km




Quantum repeater




QM=quantum memory

Global quantum communication network

Rev. Mod. Phys. **83**, 33(2011)
Nature **453**, 1023(2008)

# 2. Introduction (1)

**Previous work on entanglement swapping**

**1. The first entanglement swapping experiment was demonstrated at ~800nm**

**Pan, *et al*, PRL. 80, 3891(1998)**

**2. The previous entanglement swapping experiments at telecom wavelengths**

| Ref | Material | Wavelength | 4-fold coincidence | visibility | application |
|---|---|---|---|---|---|
| 1. Marcikic2003 | LBO | 1310nm | 0.05cps | 70% | teleportation |
| 2. Riedmatten2005 | LBO | 1310nm | 0.004cps | 80% | swapping |
| 3. Halder2007 | PPLN-WG | 1560nm | 0.0003cps | 77% | swapping |
| 4. Takesue2009 | fiber | 1551nm | 0.038cps | 64% | swapping |
| 5. Xue2012 | DSF (fiber) | 1550nm | 0.016cps | 75% | swapping |
| 6. Wu2013 | PPLN WG | 1550nm | 0.08cps | 92% | swapping |

**The low count rates :**
long accumulation time to obtain reliable data → big obstacle for quantum communication.

**Two reasons :** low-efficiency entangled sources + low-efficiency detectors.

# 2. Introduction (2)

## Photon sources from PPKTP crystal

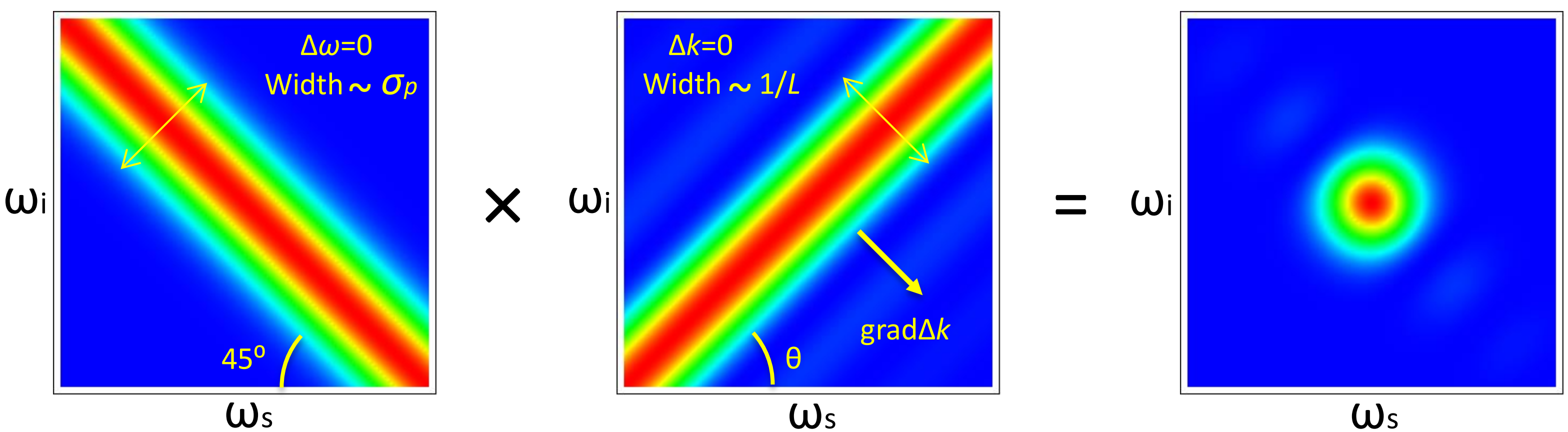
In type II SPDC in PPKTP crystal, the group velocities are matched around 1584nm

$$V_g^{-1}(\omega_s) + V_g^{-1}(\omega_i) = V_g^{-1}(\omega_p)$$

**GVM condition:**
**Grice, *et al*, PRA 56, 1627 (1997).**
**Konig, *et al*, APL 84, 1644 (2004).**
**Eckstein, *et al*, PRL 106, 013603 (2011).**

**Jin, *et al,* Opt. Express 21, 10659 (2013)**

(a) Pump envelop intensity (b) Phase matching intensity (c) Joint spectral intensity




$$|\alpha(\omega_s,\omega_i)|^2 = \exp[-\left(\frac{\omega_s+\omega_i-\omega_p}{\sigma}\right)^2]$$

$$|\phi(\omega_s,\omega_i)|^2 = (Sinc[\frac{\Delta kL}{2}])^2$$

$$|f(\omega_s,\omega_i)|^2 = |\alpha(\omega_s,\omega_i)|^2 \, |\phi(\omega_s,\omega_i)|^2$$

Group velocity matched → High spectral purity → no need for narrow band pass filters

# 2. Introduction (3)

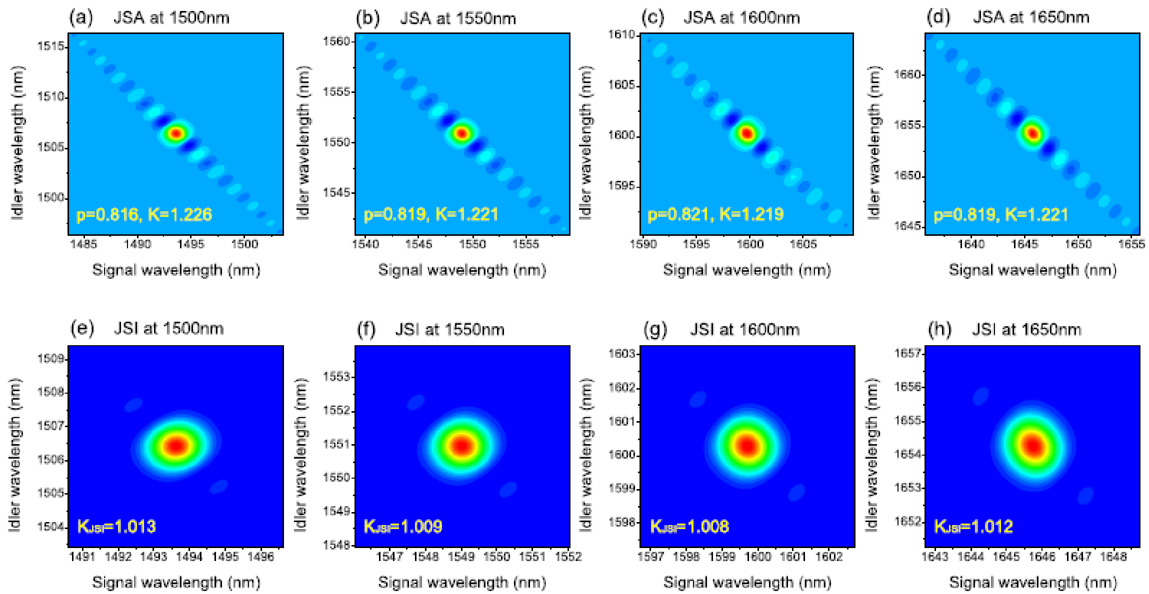
## GVM-PPKTP photon source

### High spectral purity and wide tunability

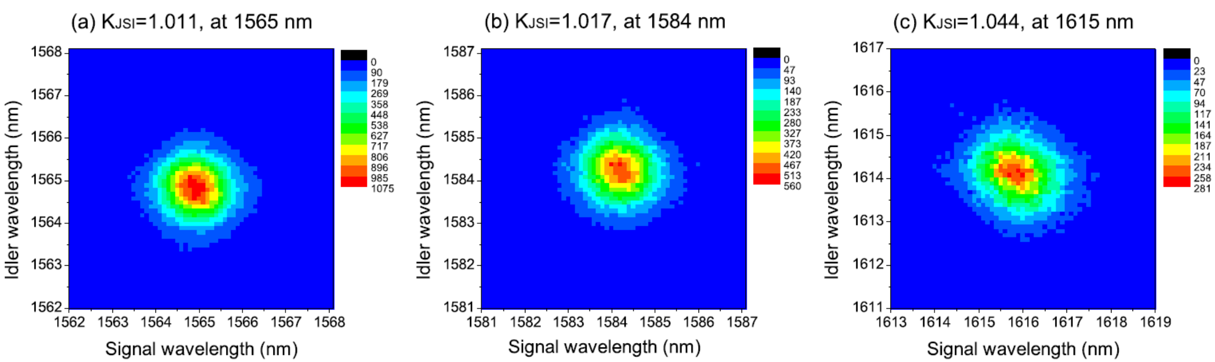
## Simulation data

**Joint spectral amplitude**

**Joint spectral intensity**




## Experimentally measured data

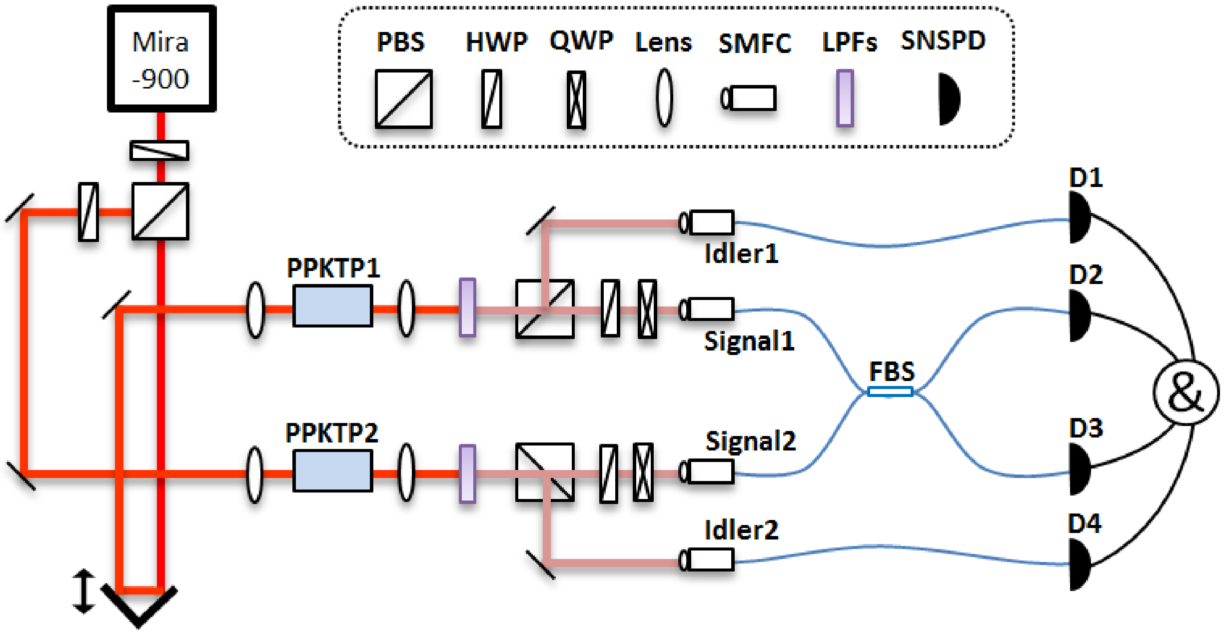



Jin, *et al,* Opt. Express 21, 10659 (2013)

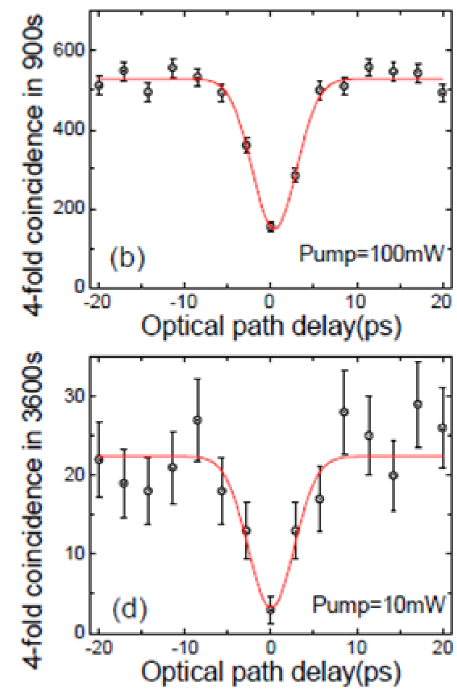
# 2. Introduction (4)

**Spectral purity is important for multi-photon interference**

**Jin, *et al*, PRA 87, 063801 (2013)**




4-fold HOM interference




High visibility of 85.5+-8% was achieved without using any BPF.
Because the intrinsic spectral purity is high.

**Hong-Ou-Mandel interference**

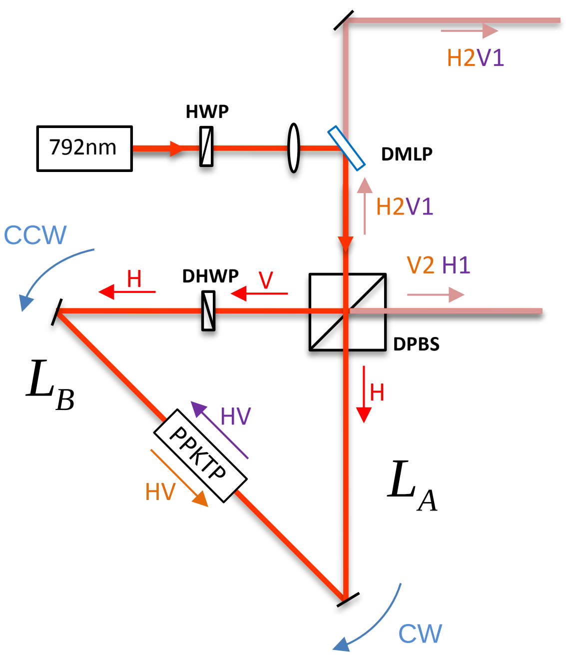
**Hong *et al*, PRL 59, 2044 (1987)**

# 2. Introduction (5)

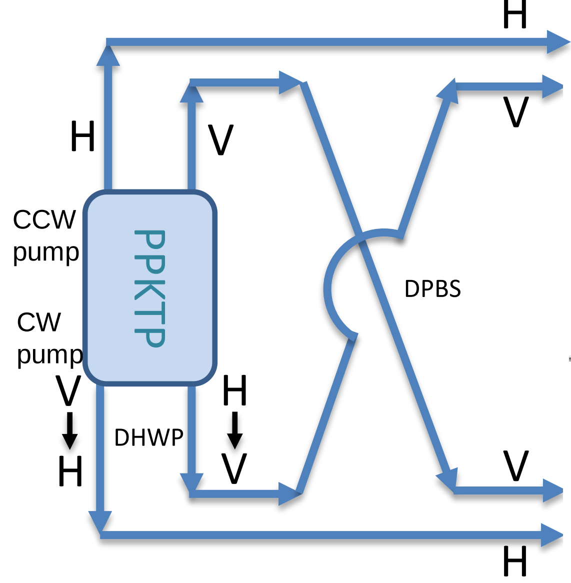
## From single photon source to entangled photon source

### Sagnac-GVM-PPKTP entangled source

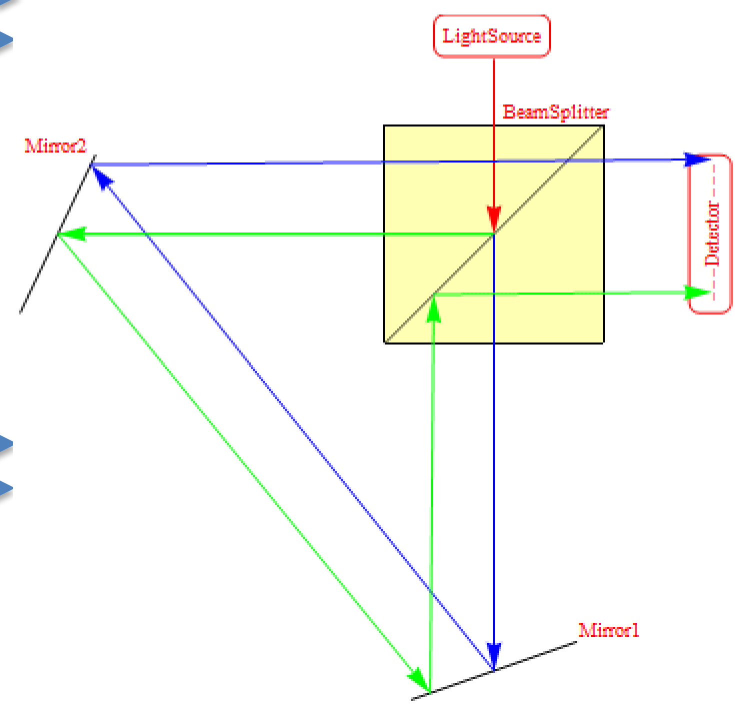
**Sagnac interferometer → Highly stable; no temporal walk-off**




**The model**




**Alignment**





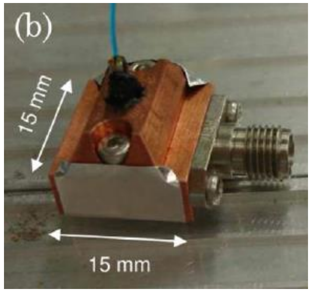
Kim, *et al,* PRA 73, 012316 (2006)
Wong, *et al,* Laser Physics 16, 1517(2006)
Jin, *et al,* Opt. Express 22, 11498 (2014)
Takeoka, *et al,* will submit soon (2014)

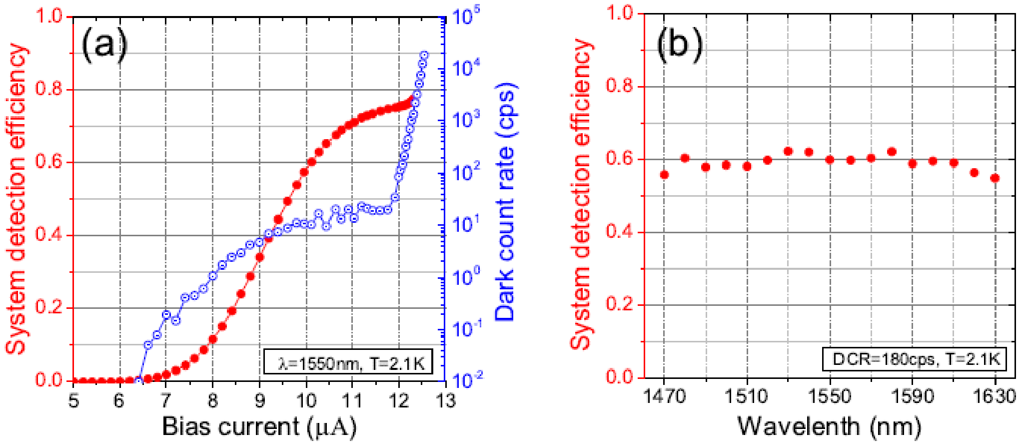

http://demonstrations.wolfram.com/SagnacInterferometer/ (open source)
https://www.youtube.com/watch?v=Ju-Ca3iT5ns

# 2. Introduction (6)

**We have good detectors：Superconducting nanowire single photon detectors (SNSPD)**

**High efficiency: detecting efficiency > 70% dark counts ~ 1 kcps**
**recovery time = 40 ns, time jitter = 68 ps**
**spectral range: 1470-1630nm**

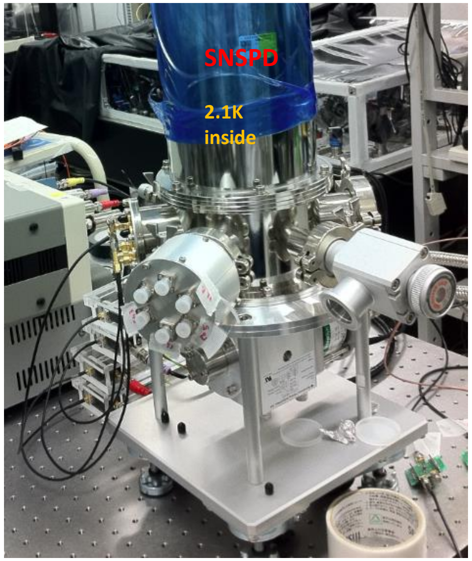



**Miki, *et al,* Opt. Express 21, 10208 (2013)**
**Yamashita, *et al,* Opt. Express 21, 27177 (2013)**
**Miki, *et al, IEEE Trans. Appl. Sc. 17, 285 (2007)***

Test with single photon source

**Single counts=5.23Mcps**
**Coincidence=1.17Mcps**
**at 400mW pump**
**the highest ever reported at telecom wavelengths**

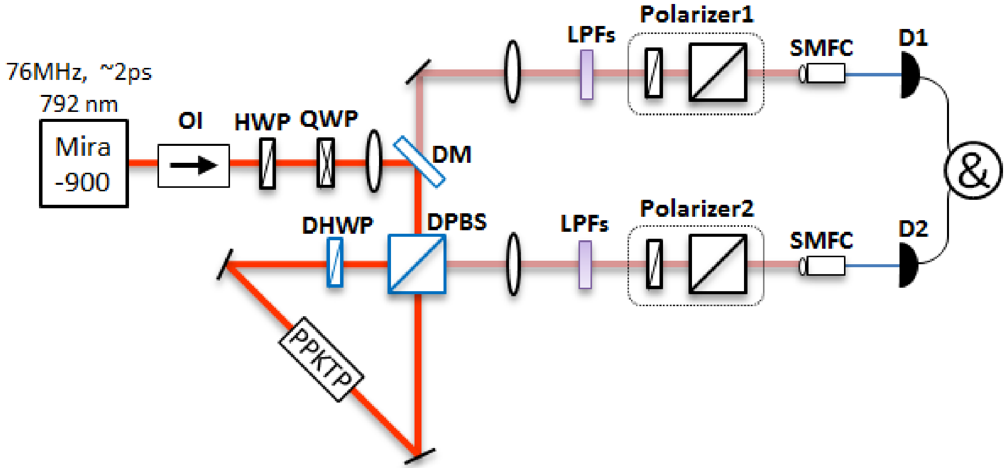


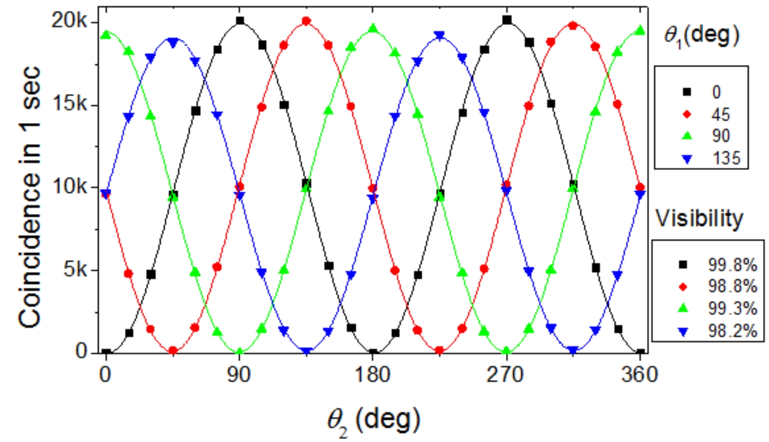

**Jin, *et al*, arXiv：1309.1221**

# 2. Introduction (7)

## Performance of our entangled source

Jin, *et al*, Opt. Express 22, 11498 (2014)



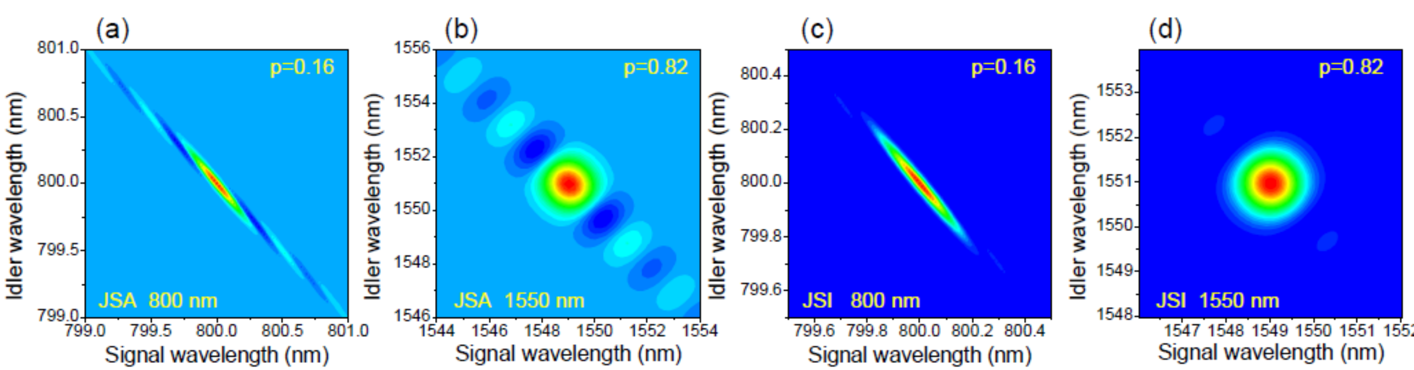

**Beam waist= 45 um**
**PPKTP=30mm, type II**
**@1584nm**

**SNSPD efficiency=0.7**
**Coupling efficiency= 0.5**
**Overall efficiency=0.2**

**Coincidence=40 kcps @ 10mW**
**Visibility>98% for all bases**
**Spectral purity=0.82**

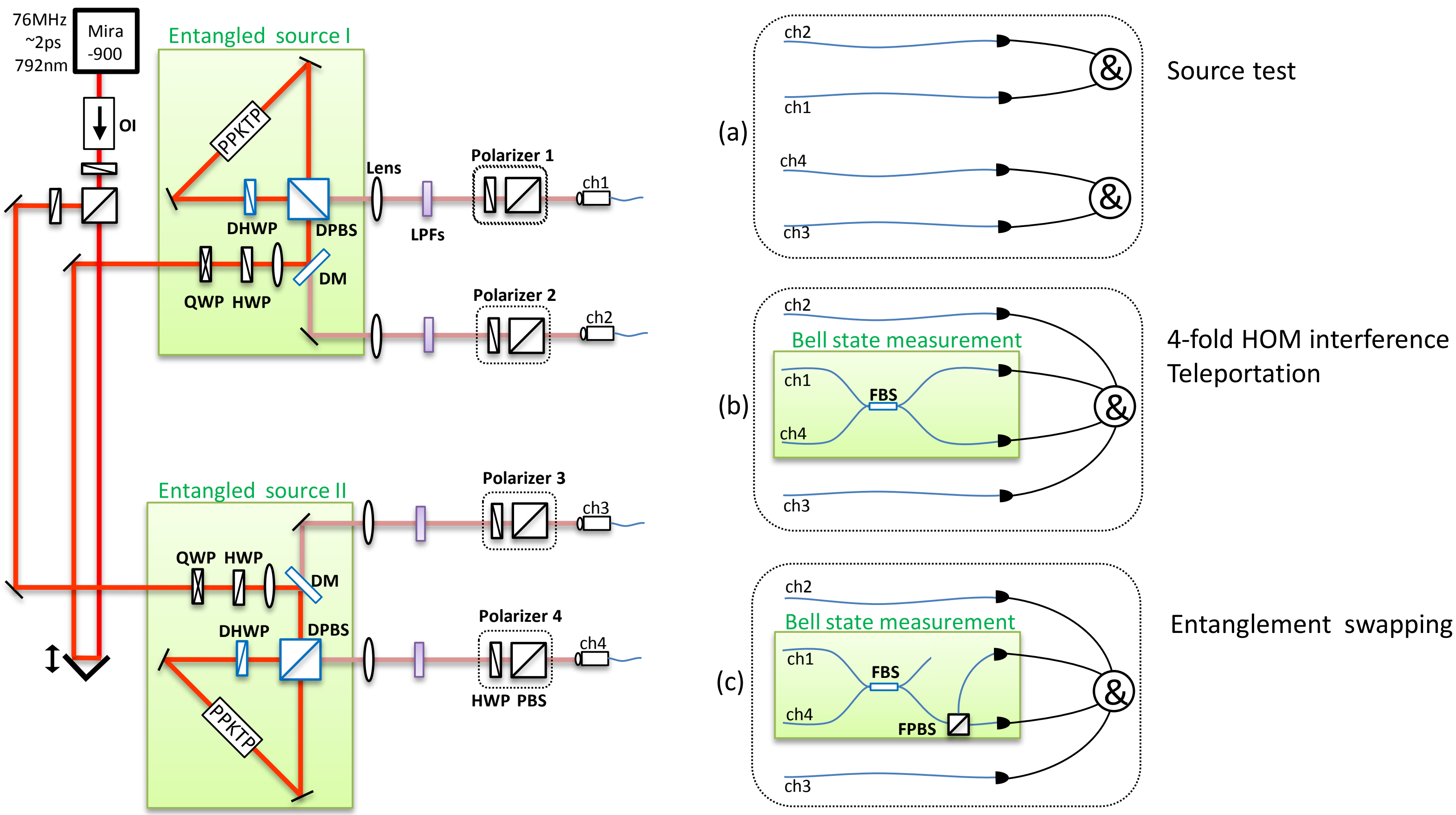
**Advantages of our entangled source: Stable; intrinsically high purity; telecom wavelength**

**Joint spectral amplitude (JSA)** **Joint spectral intensity (JSI)**



# 3. Experiment (1)

## Experimental setup

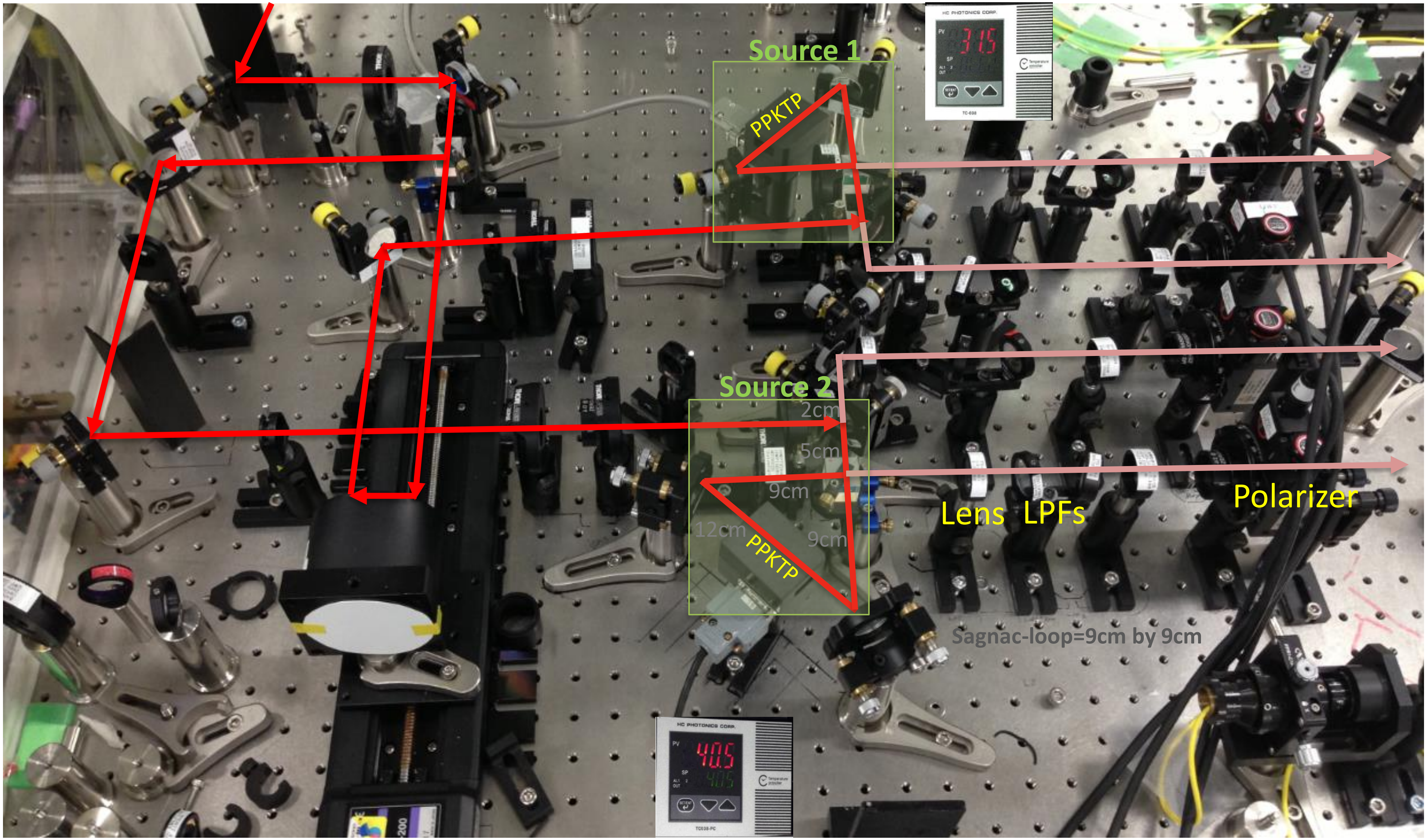



PPKTP: 30-mm-long , poling period = 46.1 $\mu$m,
type-II group-velocity-matched SPDC, degenerate.
The temperature for PPKTP=31.0/40.5 ◦C

80mW—Source I 85mW—Source II
Average photon numbers per pulse ~0.1

# 3. Experiment (2)

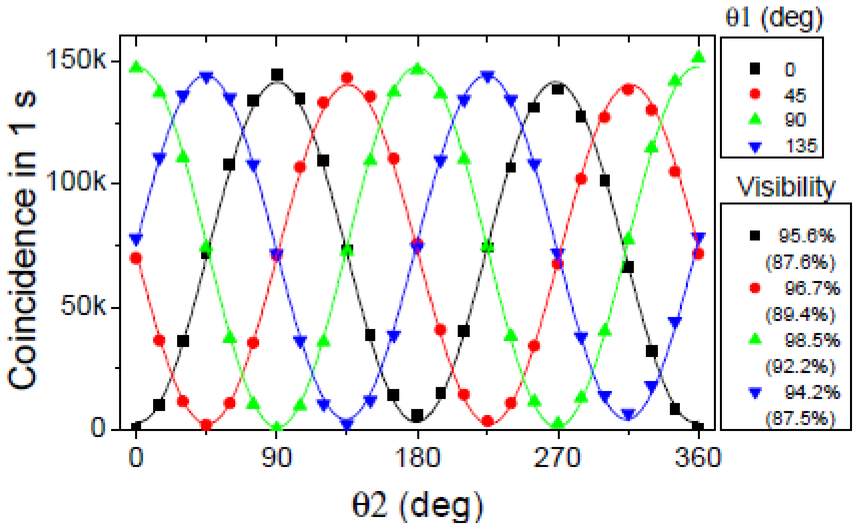
## Experimental setup



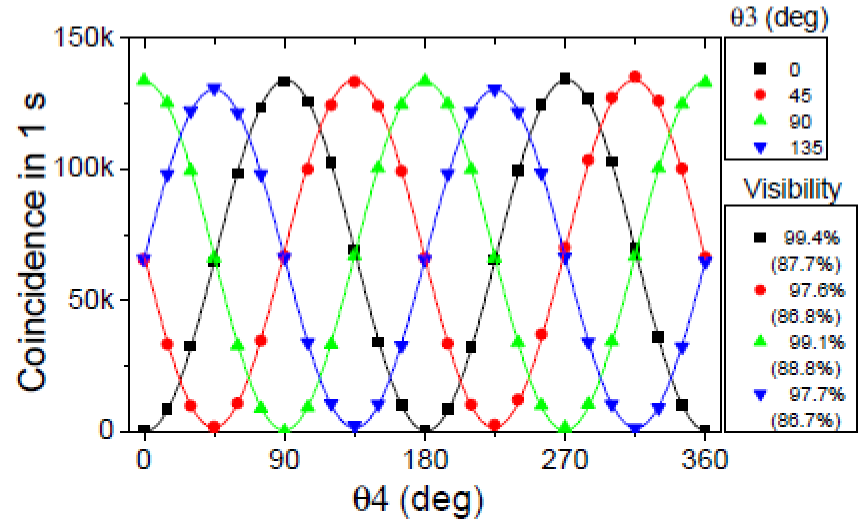
# 4. Result (1)

## Polarization correlation measurement (EPR interference)

(a) Source I $|\psi^-\rangle$



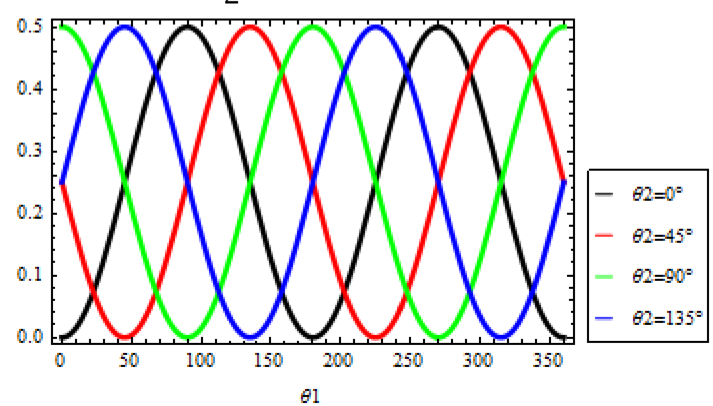

(b) Source II $|\psi^-\rangle$




Pump: 80/85mW, accumulate in 1 sec, coincidence counts~150 kcps
net V~97%, raw V~87%, Average photon numbers per pulse~0.1

Net visibility
(Raw visibility)

$$I = \frac{1}{2}[\sin(\theta_2 - \theta_1)]^2$$




Theory calculation

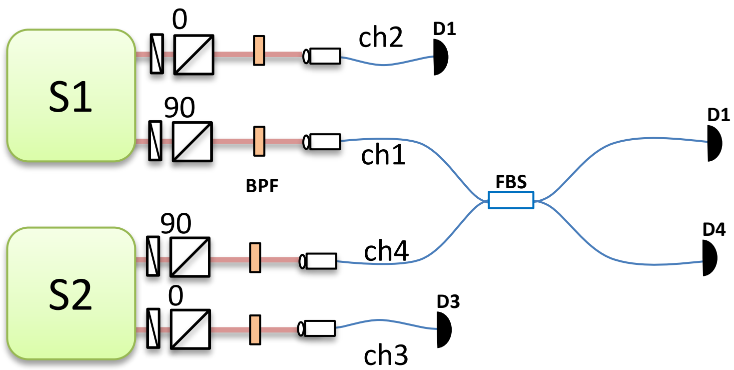
$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle - |V_1H_2\rangle) \qquad I = \frac{1}{2}[\sin(\theta_2 - \theta_1)]^2$$

$$|\theta_1\rangle = \cos\theta_1 |H_1\rangle + \sin\theta_1 |V_1\rangle \quad (with \quad HWP_1 = \theta_1/2), \quad |\theta_2\rangle = \cos\theta_2 |H_2\rangle + \sin\theta_2 |V_2\rangle$$

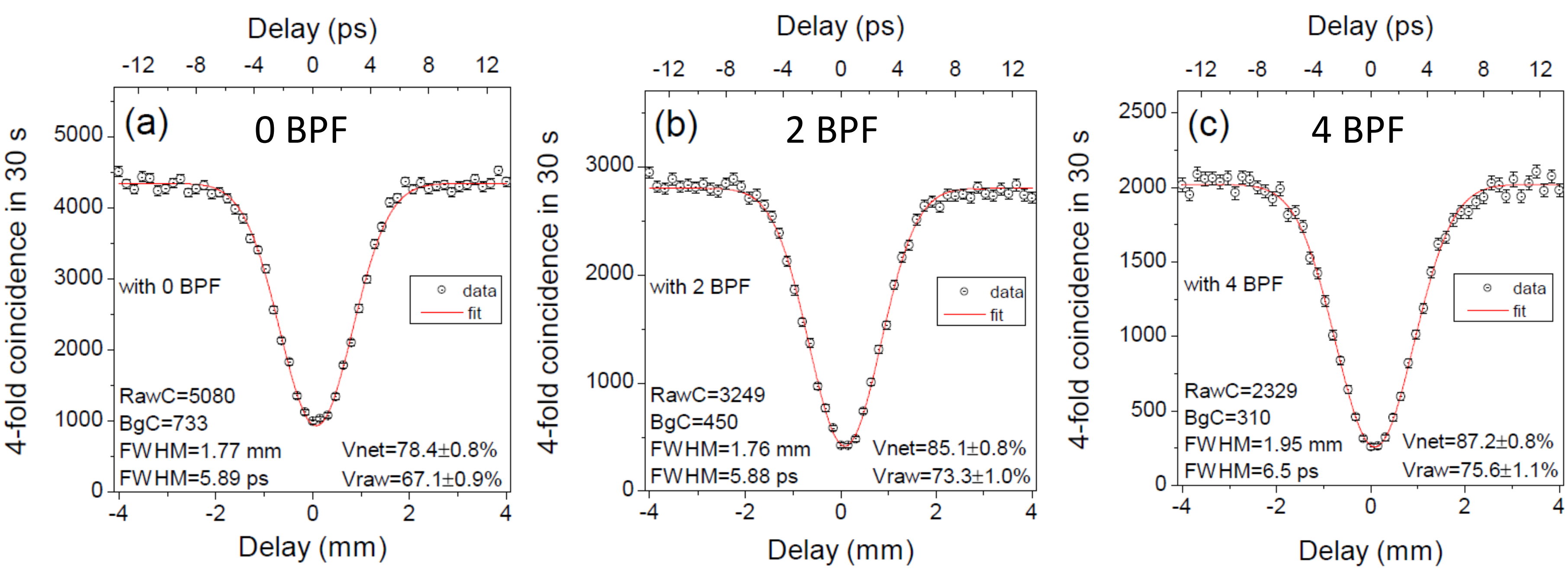
$$\langle\theta_2|\langle\theta_1|\psi^-\rangle = \frac{1}{\sqrt{2}}[\sin\theta_2\cos\theta_1 - \cos\theta_2\sin\theta_1] = \frac{1}{\sqrt{2}}\sin(\theta_2 - \theta_1)$$

# 4. Result (2)

## 4-fold Hong-Ou-Mandel (HOM) interference

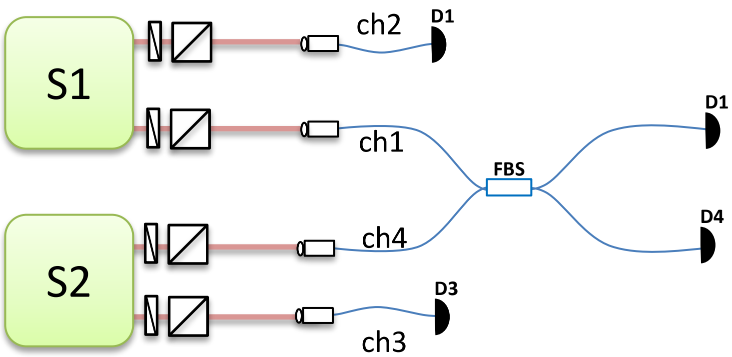



| Number | No BPF | 2BPF | 4BPFs |
|---|---|---|---|
| Raw visibility | 67.1% | 73.3% | 75.6% |
| Net visibility | 78.4% | 85.1% | 87.2% |
| 4-fold coincidence | 169cps | 108cps | 78cps |
| background | 24cps | 15cps | 10cps |



# 4. Result (3)

## How to subtract background in 4-fold HOM interference




| Number | No BPF | 2BPF | 4BPFs |
| --- | --- | --- | --- |
| Raw visibility | 67.1% | 73.3% | 75.6% |
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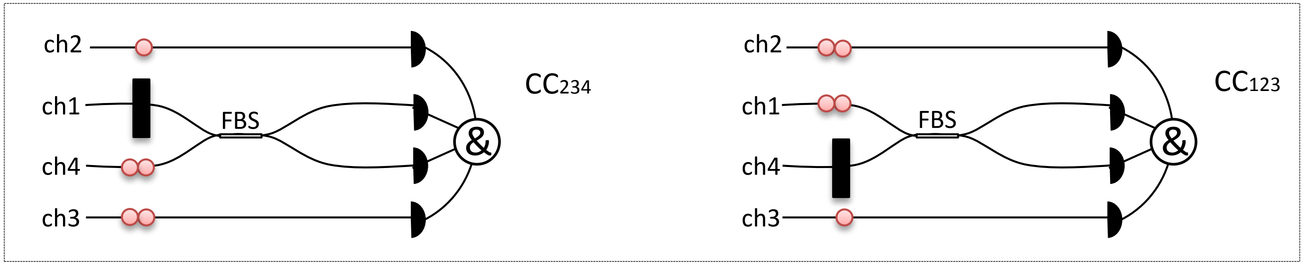



Background counts= $CC_{234}+CC_{123}$ Contributed by multi-photon emission

**Soller, *et al*, PRA 83, 031806 (2011)**
**Jin , *et al*, PRA 87, 063801 (2013)**

# 4. Result (4)

## Visibility is determined by spectral purity

Purity of source1, source 2

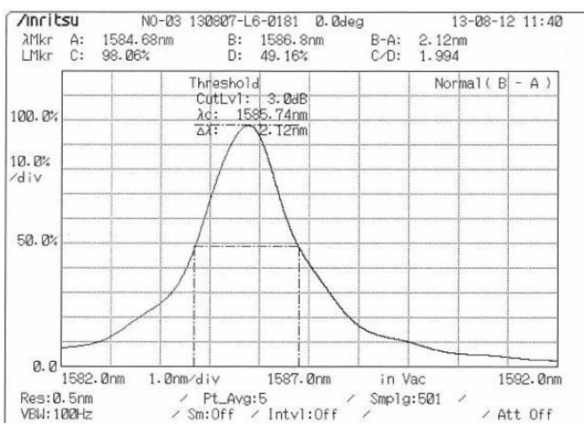
$$V = \mathrm{Tr}[\rho_1 \rho_2] = \frac{\mathrm{Tr}[\rho_1^2] + \mathrm{Tr}[\rho_2^2] - \|\rho_1 - \rho_2\|^2}{2}$$

visibility

Indistinguishability of source1 and 2

**Jin, *et. al*, PRA 87, 063801 (2013)**
Osorio, *et. al*, J Phys. B **46**,055501 (2013).
Mosley *et. al*, PRL **100**, 133601 (2008).
Lee, *et. al*, PRL **91** 087902(2003)

Coarse BPF

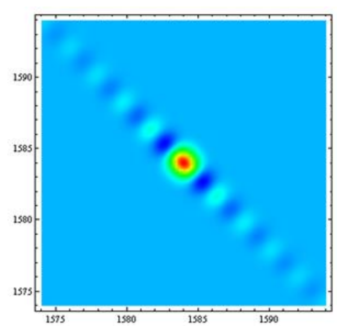



Peak Transmission=93%
FWHM=2.1nm
Overall transmission=77%

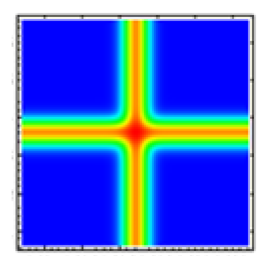
FWHM of the BPF=2.1nm
FWHM of the source=1.1nm
FWHM after filter=1.0nm

With small loss we can improve the purity from 0.82 to 0.99

**Purity=0.82**

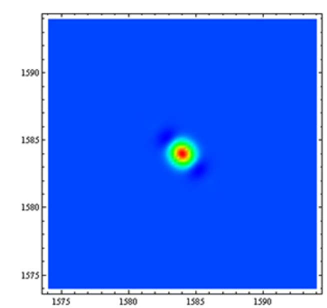



BPF of 2.1nm



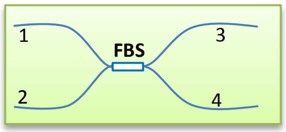
Cut side lobes

**Purity=0.99**



# 4. Result (5) Teleportation: Bell state measurement-1

Bell state analyzer
Rev. Mod. Phys. **84**,777(2012)




$BS:$

$\hat{a}_1 = (\hat{a}_3 + \hat{a}_4)/\sqrt{2}$

$\hat{a}_2 = (\hat{a}_3 - \hat{a}_4)/\sqrt{2}$

If the input sate is

$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle - |V_1H_2\rangle)$$

$$H_1 = \frac{1}{\sqrt{2}}(H_3 + H_4) \quad H_2 = \frac{1}{\sqrt{2}}(H_3 - H_4) \quad V_1 = \frac{1}{\sqrt{2}}(V_3 + V_4) \quad V_2 = \frac{1}{\sqrt{2}}(V_3 - V_4)$$

$$H_1V_2 = \frac{1}{2}(H_3 + H_4)(V_3 - V_4) = \frac{1}{2}(H_3V_3 - H_4V_4 - H_3V_4 + H_4V_3)$$

$$V_1H_2 = \frac{1}{2}(V_3 + V_4)(H_3 - H_4) = \frac{1}{2}(H_3V_3 - H_4V_4 + H_3V_4 - H_4V_3)$$

$$H_1V_2 - V_1H_2 = H_4V_3 - H_3V_4 \qquad H_1V_2 + V_1H_2 = H_3V_3 - H_4V$$

$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle - |V_1H_2\rangle) \xrightarrow{BS} \frac{1}{\sqrt{2}}(|H_3V_4\rangle - |V_3H_4\rangle)$$

$$|\psi^+\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle + |V_1H_2\rangle) \xrightarrow{BS} \frac{1}{\sqrt{2}}(|H_3V_3\rangle - |V_4H_4\rangle)$$

$$|\phi^+\rangle = \frac{1}{\sqrt{2}}(|H_1H_2\rangle + |V_1V_2\rangle) \xrightarrow{BS} \frac{1}{2}[(|H_3H_3\rangle - |H_4H_4\rangle) + (|V_3V_3\rangle - |V_4V_4\rangle)]$$

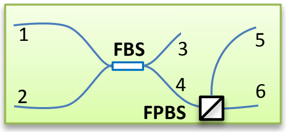
$$|\phi^-\rangle = \frac{1}{\sqrt{2}}(|H_1H_2\rangle - |V_1V_2\rangle) \xrightarrow{BS} \frac{1}{2}[(|H_3H_3\rangle - |H_4H_4\rangle) - (|V_3V_3\rangle - |V_4V_4\rangle)]$$

Conclusion： only when $|\psi^-\rangle$ state inputs, CC exists.
So, a CC means the $|\psi^-\rangle$ state is detected

Partial Bell state measurement

# 4. Result (6) Teleportation: Bell state measurement-2

Bell state analyzer
Rev. Mod. Phys. **84**,777(2012)




$PBS:$

$\hat{a}_{4H} = \hat{a}_{6H} \qquad \hat{a}_{4V} = \hat{a}_{5V}$

$BS + PBS:$

$$\hat{a}_{1H} = (\hat{a}_{3H} + \hat{a}_{4H}) / \sqrt{2} = \hat{a}_{6H} / \sqrt{2}$$
$$\hat{a}_{1V} = (\hat{a}_{3V} + \hat{a}_{4V}) / \sqrt{2} = \hat{a}_{5V} / \sqrt{2}$$
$$\hat{a}_{2H} = (\hat{a}_{3H} - \hat{a}_{4H}) / \sqrt{2} = -\hat{a}_{6H} / \sqrt{2}$$
$$\hat{a}_{2V} = (\hat{a}_{3V} - \hat{a}_{4V}) / \sqrt{2} = -\hat{a}_{5V} / \sqrt{2}$$

If the input sate is

$$|\psi^-\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle - |V_1H_2\rangle) \xrightarrow{BS} \frac{1}{\sqrt{2}}(|H_3V_4\rangle - |V_3H_4\rangle)$$ There is no CC at port 5/6

$$|\psi^+\rangle = \frac{1}{\sqrt{2}}(|H_1V_2\rangle + |V_1H_2\rangle) \xrightarrow{BS} \frac{1}{\sqrt{2}}(|H_3V_3\rangle - |V_4H_4\rangle)$$ There is CC at port 5/6

$$|\phi^+\rangle = \frac{1}{\sqrt{2}}(|H_1H_2\rangle + |V_1V_2\rangle) \xrightarrow{BS} \frac{1}{2}[(|H_3H_3\rangle - |H_4H_4\rangle) + (|V_3V_3\rangle - |V_4V_4\rangle)]$$

$$|\phi^-\rangle = \frac{1}{\sqrt{2}}(|H_1H_2\rangle - |V_1V_2\rangle) \xrightarrow{BS} \frac{1}{2}[(|H_3H_3\rangle - |H_4H_4\rangle) - (|V_3V_3\rangle - |V_4V_4\rangle)]$$

There is no CC at port 5/6

Conclusion： A CC detection means the $|\psi^+\rangle$ state is detected

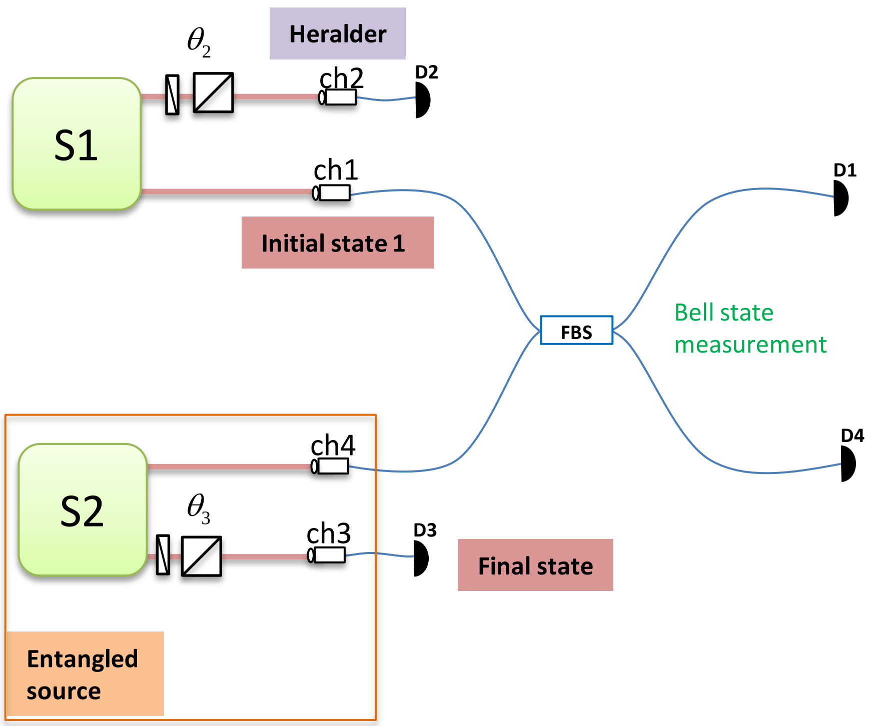
# 4. Result (7)

## The principle of teleportation

$$|\psi^-\rangle_{34} \otimes |i\rangle_1 = \frac{1}{\sqrt{2}}(|HV\rangle - |VH\rangle)_{34}\underline{(\alpha|H\rangle + \beta|V\rangle)_1}$$

$$\equiv \frac{1}{2}[|\psi^+\rangle_{41}(-\alpha|H\rangle + \beta|V\rangle)_3 + |\psi^-\rangle_{41}\underline{(\alpha|H\rangle + \beta|V\rangle)_3} + |\phi^+\rangle_{41}(\alpha|V\rangle - \beta|H\rangle)_3 + |\phi^-\rangle_{41}(\alpha|V\rangle + \beta|H\rangle)_3]$$

$$|\psi^-\rangle_{34} \otimes (\alpha|H\rangle_1 + \beta|V\rangle_1) \xrightarrow{BSM} \frac{1}{2}|\psi^-\rangle_{14}(\alpha|H\rangle_3 + \beta|V\rangle_3)$$




$$ch_1 \xrightarrow{teleport} ch_3$$

e.g. 1

$$Ch2:(|V\rangle) \xrightarrow{Herald} Ch1:(|H\rangle) \xrightarrow{BSM\ \ select} Ch3:(|H\rangle)$$

$$\Rightarrow Ch3{=}0^\circ \to CC\ \ exist \to no\ \ HOM\ \ dip\ \ (\theta_2/\theta_3 = 90^\circ/0^\circ)$$

$$Ch3{=}90^\circ \to no\ \ CC \to\ \ HOM\ \ dip\ \ (\theta_2/\theta_3 = 90^\circ/90^\circ)$$

e.g. 2

$$Ch2:(|H\rangle + |V\rangle) \xrightarrow{Herald} Ch1:(|H\rangle - |V\rangle) \xrightarrow{BSM\ \ select} Ch3:(|H\rangle - |V\rangle)$$

$$\Rightarrow Ch3{=}45^\circ \to no\ \ CC \to HOM\ \ dip\ \ (\theta_2/\theta_3 = 45^\circ/45^\circ)$$

$$Ch3{=}135^\circ \to\ \ CC \to no\ \ HOM\ \ dip\ \ (\theta_2/\theta_3 = 45^\circ/135^\circ)$$

# 4. Result (8) Teleportation Result

e.g. 1

$$Ch2:(|V\rangle)\xrightarrow{Herald}Ch1:(|H\rangle)\xrightarrow{BSM\ \ select}Ch3:(|H\rangle)$$

$$\Rightarrow Ch3{=}0^{\circ}\rightarrow CC\quad exist\rightarrow no\quad HOM\quad dip\quad (\theta_2/\theta_3=90^{\circ}/0^{\circ})$$

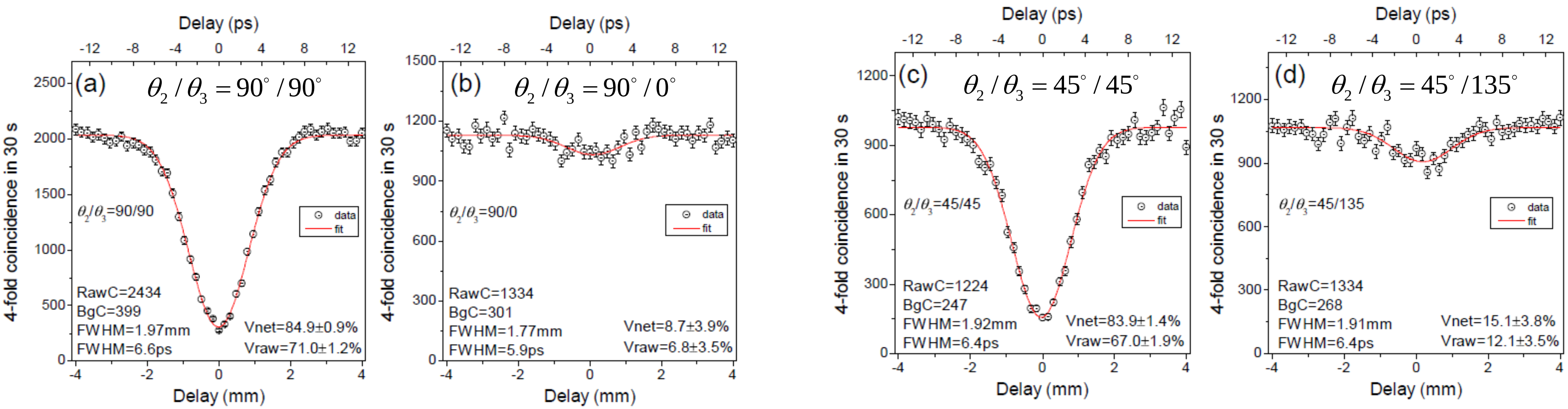
$$Ch3{=}90^{\circ}\rightarrow no\quad CC\rightarrow\quad HOM\quad dip\quad (\theta_2/\theta_3=90^{\circ}/90^{\circ})$$

e.g. 2

$$Ch2:(|H\rangle+|V\rangle)\xrightarrow{Herald}Ch1:(|H\rangle-|V\rangle)\xrightarrow{BSM\ \ select}Ch3:(|H\rangle-|V\rangle)$$

$$\Rightarrow Ch3{=}45^{\circ}\rightarrow no\quad CC\rightarrow HOM\quad dip\quad (\theta_2/\theta_3=45^{\circ}/45^{\circ})$$

$$Ch3{=}135^{\circ}\rightarrow\quad CC\rightarrow no\quad HOM\quad dip\quad dip\quad (\theta_2/\theta_3=45^{\circ}/135^{\circ})$$

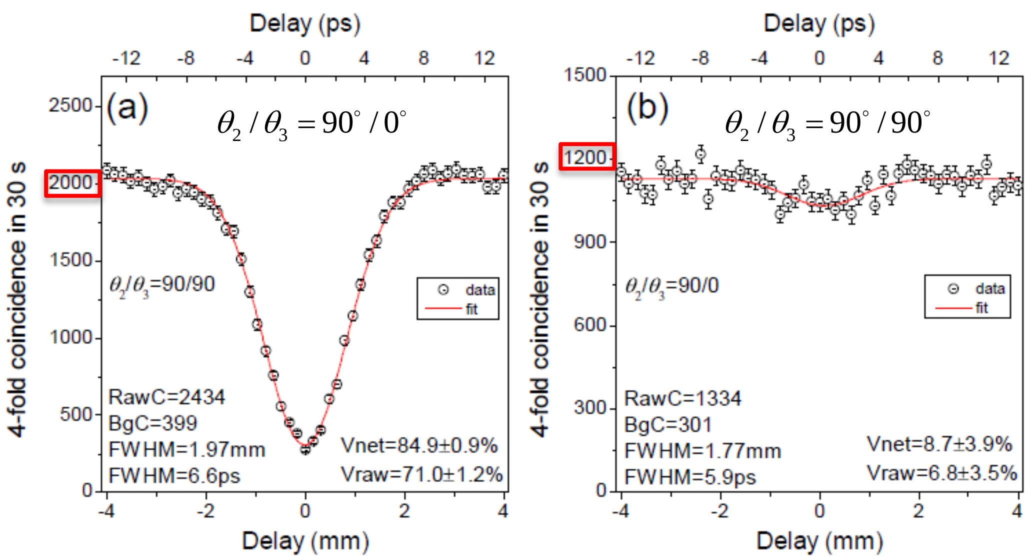



## Teleportation at other angles

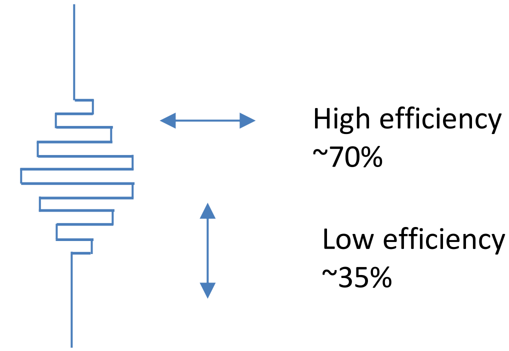
| $\theta_2/\theta_3$ | Raw Visibility | Net Visibility | Ideal | | $\theta_2/\theta_3$ | Raw Visibility | Net Visibility | Ideal |
|---|---|---|---|---|---|---|---|---|
| 0/0 | 56% | 75.8% | 100% | | 45/45 | 66.9% | 83.9% | 100% |
| 0/90 | 11.4% | 14.2% | 0% | | 45/135 | 12.0% | 15.1% | 0% |
| 90/0 | 6.8% | 8.7% | 0% | | 135/45 | 13.2% | 16.9% | 0% |
| 90/90 | 71% | 84.9% | 100% | | 135/135 | 65.9% | 81.9% | 100% |

# 4. Result (9)

## Polarization dependency of SNSPD's efficiency



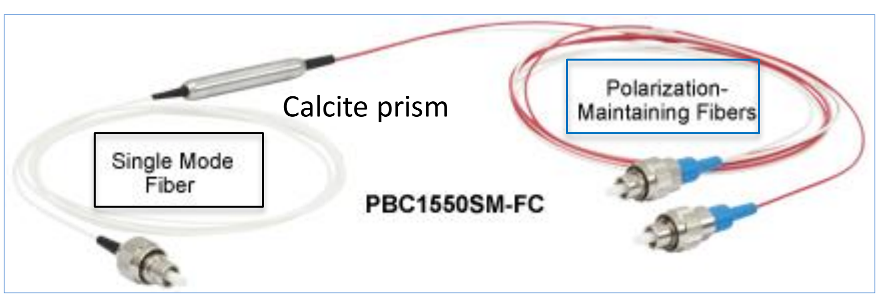

SNSPD

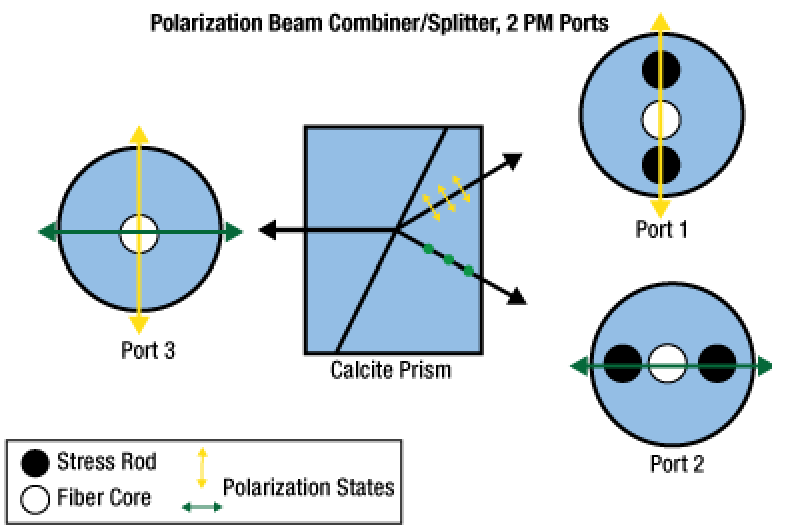



D1: 250/120=2.0
D2: 560/230=2.4
D3: 590/400=1.5
D4: 335/200=1.7

How to overcome this problem?

Fiber-PBS



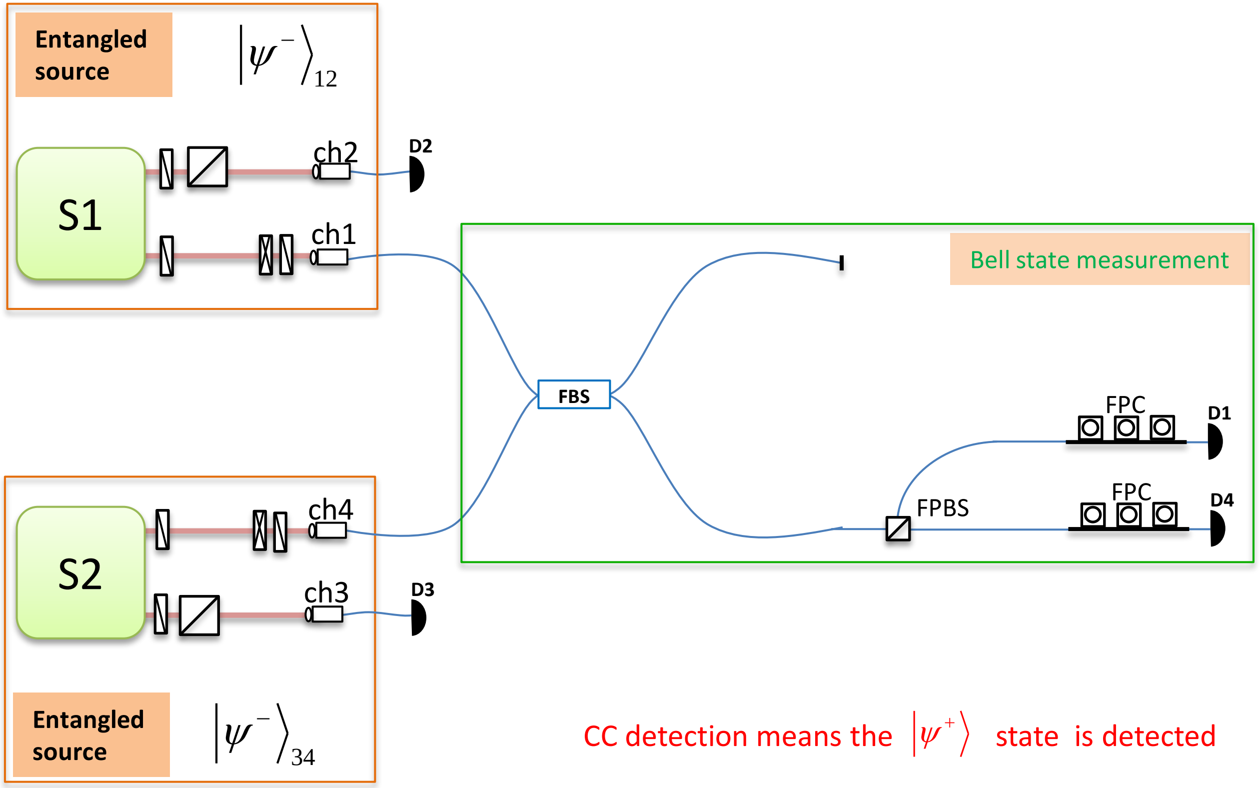




Extinction ratio>1000/1

# 4. Result (10) The principle of entanglement swapping

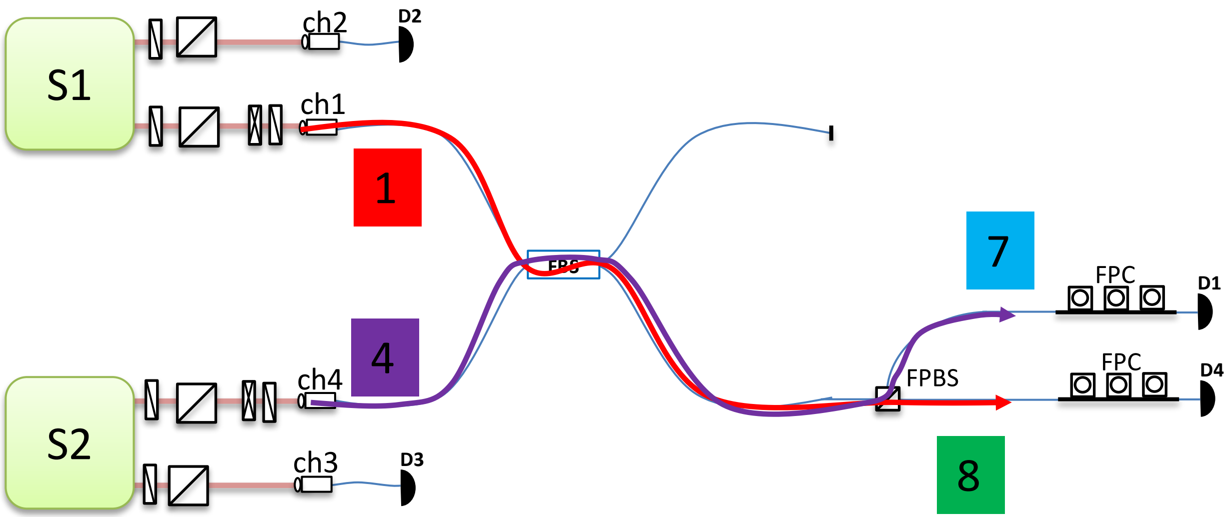
$$|\psi^-\rangle_{12} \otimes |\psi^-\rangle_{34} \equiv \frac{1}{2}(|\psi^+\rangle_{14} \otimes |\psi^+\rangle_{23} - |\psi^-\rangle_{14} \otimes |\psi^-\rangle_{23} - |\phi^+\rangle_{14} \otimes |\phi^+\rangle_{23} + |\phi^-\rangle_{14} \otimes |\phi^-\rangle_{23})$$

$$|\psi^-\rangle_{12} \otimes |\psi^-\rangle_{34} \xrightarrow{BSM} |\psi^+\rangle_{14} \otimes |\psi^+\rangle_{23}$$




CC detection means the $|\psi^+\rangle$ state is detected

# 4. Result (11) Entanglement swapping Calibration




$$H_1 \rightarrow 8 \quad H_4 \rightarrow 7$$

$$H_1 \xrightarrow{HWPQWP} H_1$$

$$H_4 \xrightarrow{HWPQWP} V_4$$

$$|\psi^\pm\rangle_{14} \xleftrightarrow{HWPQWP} |\phi^\pm\rangle_{14}$$

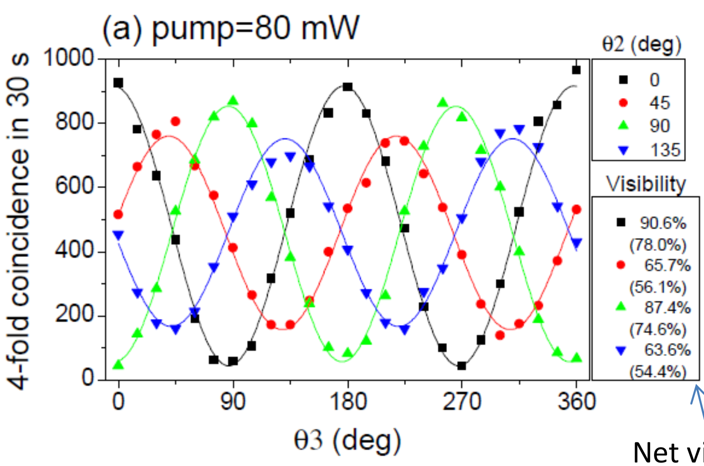
$$|\psi^-\rangle_{12} \otimes |\psi^-\rangle_{34} \equiv \frac{1}{2}(|\psi^+\rangle_{14} \otimes |\psi^+\rangle_{23} - |\psi^-\rangle_{14} \otimes |\psi^-\rangle_{23} - |\phi^+\rangle_{14} \otimes |\phi^+\rangle_{23} + |\phi^-\rangle_{14} \otimes |\phi^-\rangle_{23})$$

$$|\psi^-\rangle_{12} \otimes |\psi^-\rangle_{34} \rightarrow \frac{1}{2}(|\phi^+\rangle_{14} \otimes |\psi^+\rangle_{23} - |\phi^-\rangle_{14} \otimes |\psi^-\rangle_{23} \underline{- |\psi^+\rangle_{14} \otimes |\phi^+\rangle_{23}} + |\psi^-\rangle_{14} \otimes |\phi^-\rangle_{23})$$

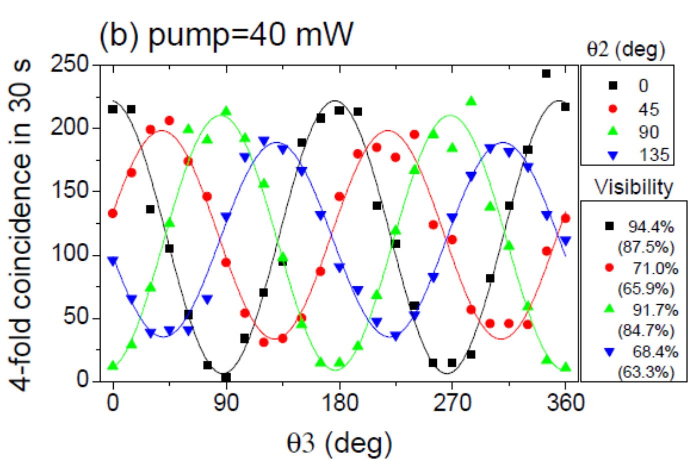
# 4. Result (12) Entanglement swapping

$$\left|\psi^-\right\rangle_{12}\otimes\left|\psi^-\right\rangle_{34}\rightarrow\frac{1}{2}\left(\left|\phi^+\right\rangle_{14}\otimes\left|\psi^+\right\rangle_{23}-\left|\phi^-\right\rangle_{14}\otimes\left|\psi^-\right\rangle_{23}-\left|\psi^+\right\rangle_{14}\otimes\left|\phi^+\right\rangle_{23}+\left|\psi^-\right\rangle_{14}\otimes\left|\phi^-\right\rangle_{23}\right)$$

$$\left|\psi^-\right\rangle_{12}\otimes\left|\psi^-\right\rangle_{34}\xrightarrow{HWPQWP+BSM}\left|\psi^+\right\rangle_{14}\otimes\left|\phi^+\right\rangle_{23}$$




Net visibility
(Raw visibility)




V improved by 7%

## Theory calculation

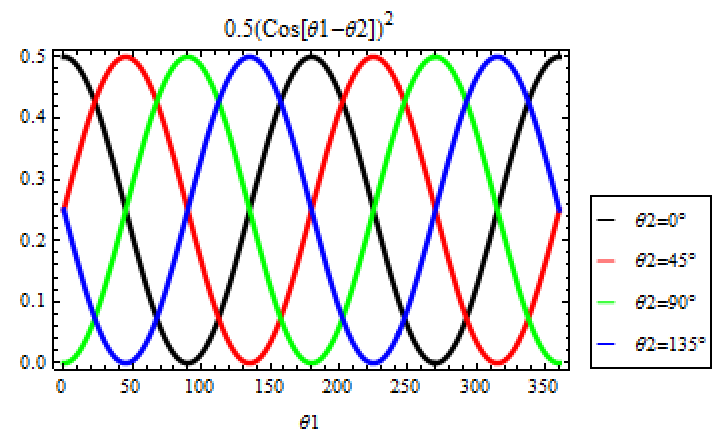
$$\left|\phi^+\right\rangle=\frac{1}{\sqrt{2}}\left(\left|H_1H_2\right\rangle+\left|V_1V_2\right\rangle\right)$$

$$\left|\theta_1\right\rangle=\cos\theta_1\left|H_1\right\rangle+\sin\theta_1\left|V_1\right\rangle\quad(with\quad HWP_1=\theta_1/2),$$

$$\left|\theta_2\right\rangle=\cos\theta_2\left|H_2\right\rangle+\sin\theta_2\left|V_2\right\rangle$$

$$\left\langle\theta_2\right|\left\langle\theta_1\right|\psi^-\rangle=\frac{1}{\sqrt{2}}[\cos\theta_2\cos\theta_1+\sin\theta_2\sin\theta_1]=\frac{1}{\sqrt{2}}\cos(\theta_2-\theta_1)$$

$$I=\frac{1}{2}[\cos(\theta_2-\theta_1)]^2$$



# 5. Discussion (1)

## Comparison of the 4-fold coincidence counts

With the previous experiments at ~1550nm

| Ref | Material | Wavelength | 4-fold coincidence | HOM visibility | application |
|---|---|---|---|---|---|
| [1]. Marcikic2003 | LBO | 1310nm | 0.05cps | 70% | teleportation |
| [2]. Riedmatten2005 | LBO | 1310nm | 0.004cps | 80% | swapping |
| [3]. Halder2007 | PPLN-WG | 1560nm | 0.0003cps | 77% | swapping |
| [4]. Takesue2009 | fiber | 1551nm | 0.038cps | 64% | swapping |
| [5]. Xue2012 | DSF (fiber) | 1550nm | 0.016cps | 75% | swapping |
| [6]. Wu2013 | PPLN WG | 1550nm | 0.08cps | 92% | swapping |
| **This work** | **PPKTP** | **1584nm** | **108cps** | **78%** | **swap./telep.** |

**Our count rate is 3 orders higher than the previous schemes**

**Highly bright sources + highly efficient detectors**


[1] Marcikic, *et al*, Nature 421, 509 (2003).
[2] Riedmatten, *et al*, PRA. 71, 050302 (2005).
[3] Halder, *et al*, Nat. Phys. 3, 629 (2007).
[4] Takesue , *et al*, Opt. Express 17, 10748 (2009)
[5] Xue, *et al*, PRA. 85, 032337(2012)
[6] Wu , *et al*, J. Phys.B 46, 235503 (2013)

# 5. Discussion (2)

## Comparison with the best performance at ～800 nm

| Ref | Material | Wavelength | 2-fold coincidence | HOM Visibility | application |
|---|---|---|---|---|---|
| [1]. Herbst2014 | BBO | 808nm | $C_2$=130kcps | 60% | Swap. 143km |
| [2]. Yin2012 | BBO | 808nm | $C_2$=440kcps | 60% | Telep. 100km |
| [3]. Yao2012 | BBO | 780nm | $C_2$=310kcps | 76% | **8-photon entangled state** |
| [4]. Huang2011 | BBO | 780nm | $C_2$=220kcps | 82% | **8-photon entangled state** |
| **This work** | **PPKTP** | **1584nm** | **$C_2$=150kcps** | **78%(raw)** | **Swap./Telep.** |

**Future application**

- **Free space test of teleportation/swapping at telecom wavelengths**
- **6,8,10-photon entangled state generation at telecom wavelengths**

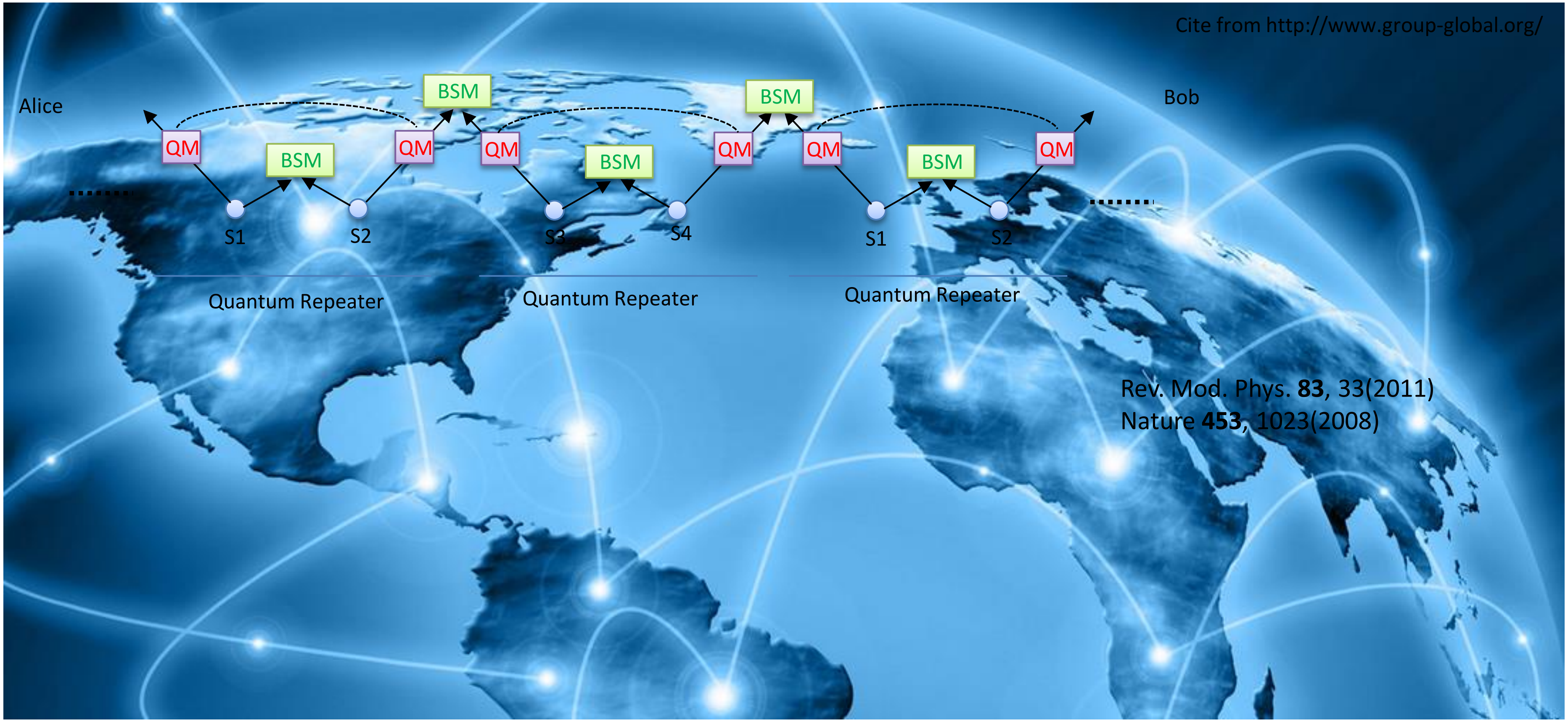
The brightness of the source is ready.
The efficiency of the SNSPD is ready.


[1] Herbst, *et al*, arXiv:1403.0009.
[2] Yin, *et al*, Nature 488, 185 (2012).
[3] Yao, *et al*, Nat. Photon. 6, 225 (2012).
[4] Huang , *et al*, Nat. Commun. 2, 546 (2011).

# 5. Discussion (3)

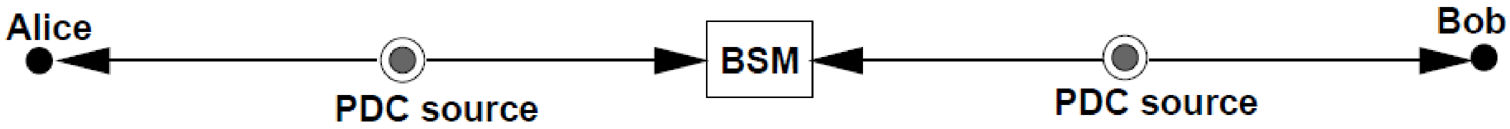
## Application for the future quantum repeater

Global quantum communication network with quantum repeaters



# 5. Discussion (4)

## Application for entanglement swapping based QKD




Ref: Artur Scherer, *et al*, Opt. Express **19**, 3004 (2011).

To demonstrate ES-QKD
Lowest requirement:

1. Four-fold coincidence count rate > 10cps
2. All visibility>71% to violate the Bell Inequality

Compare with decoy-state-QKD

Advantage: Long distance
Disadvantage: Low count rate

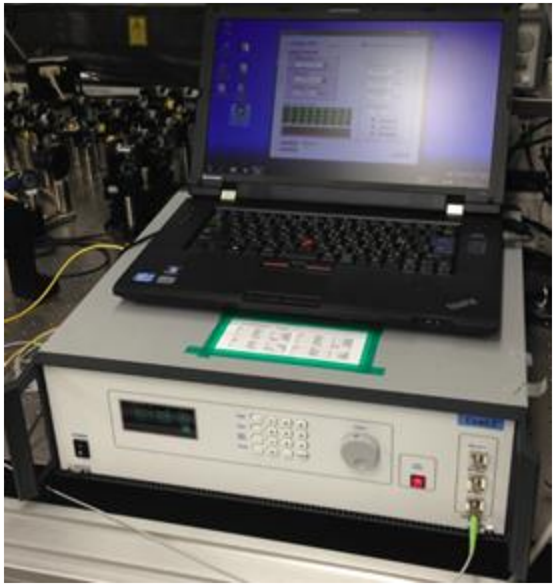
It is scientifically meaningful to demonstrate ES-QKD…

# 5. Discussion (5)

## How to decrease the multi-pair emission

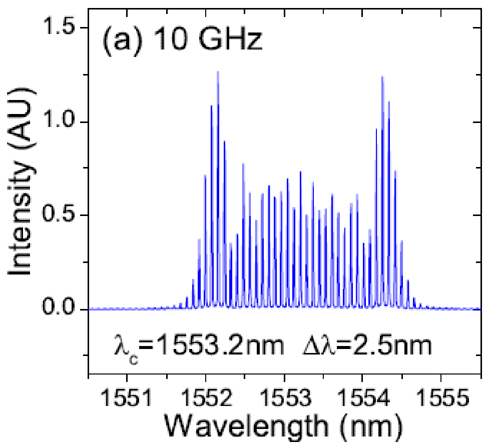
### Using high repetition rate laser

Low average power per pulse → low multi-pair emission
high repetition rate → high count rate

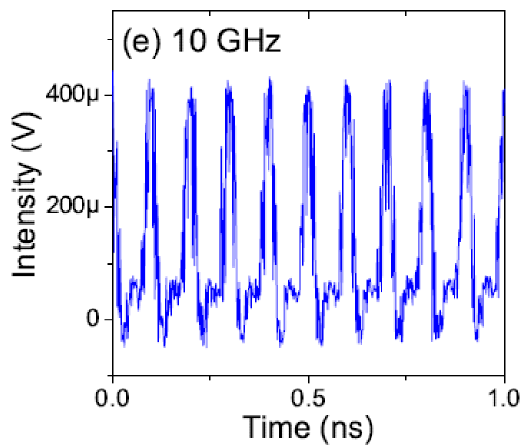


**10 GHz repetition-rate comb laser**

**Spectrum**




**Time sequence**




**Efficient generation of twin photons at telecom wavelengths with 10 GHz repetition-rate-tunable comb laser**
**Jin, *et al,* submitted (2014)**

# 6. Conclusion

✓ **1. The setup of our entanglement swapping and teleportation experiments**

GVM-PPKTP-Sagnac + SNSPDs

✓ **2. The performance of our entanglement swapping**

HOM interference visibility: raw 73%, net 85%

4-fold Coincidence: 108cps

Teleportation visibility: 84.9%

Entanglement swapping visibility: 68.4% to 94.4%

✓ **3. Future application**

Field test of entanglement swapping/ teleportation

6 photon Entangled state generation at telecom wavelength

Quantum repeater

Entanglement swapping based QKD

**arXiv：1409.XXXX, will submit soon**
**Jin, *et al*, Opt. Express 22, 11498 (2014)**
**Jin, *et al*, arXiv：1309.1221**
**Jin, *et al*, Opt. Express 21, 10659 (2013)**
**Jin, *et al*, PRA 87, 063801 (2013)**

# Thank you !