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Entanglement Sources for High-Speed QKD

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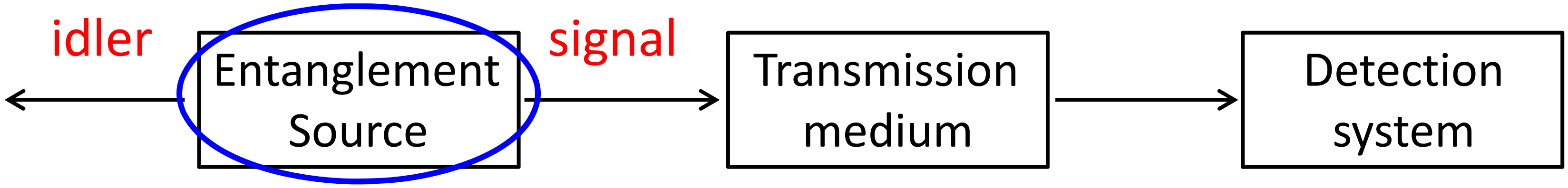
OPTICAL AND QUANTUM
COMMUNICATIONS GROUP

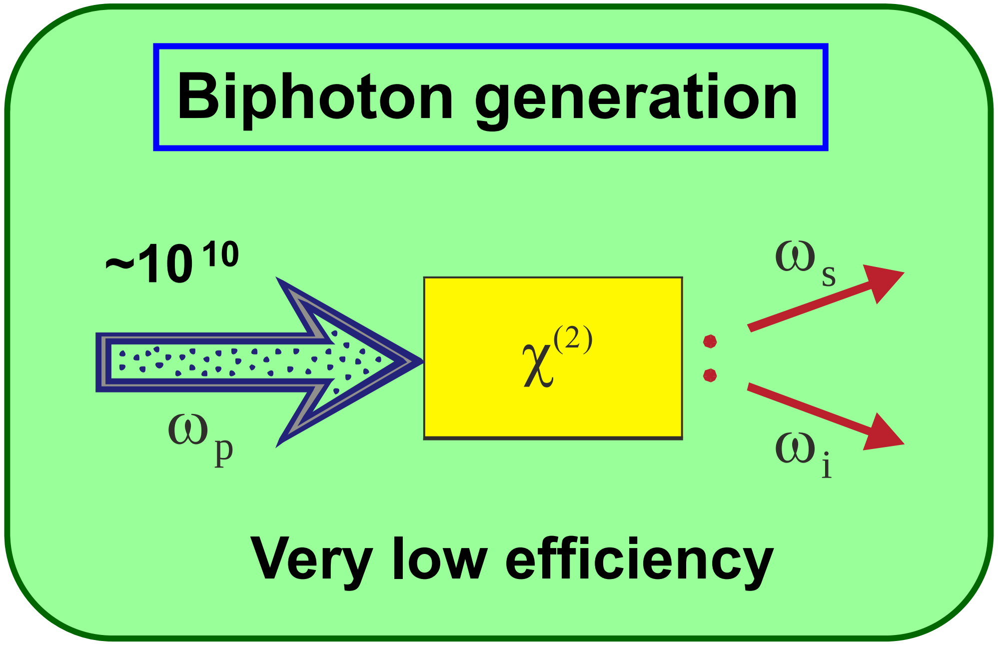
Source requirements for high-rate QKD



Transmission: free space, single-mode optical fiber
Detectors: Si APDs, InGaAs APDs, SNSPDs
Detector coupling: free-space, fiber-optic

Entanglement sources
entanglement degree of freedom: polarization, time-energy
entanglement quality: >99%
wavelength selection
pair generation efficiency; pump power
pair extraction efficiency: includes spatial and spectral filtering

Spontaneous parametric down-conversion (SPDC)



Biphoton generation

Very low efficiency

Output polarizations

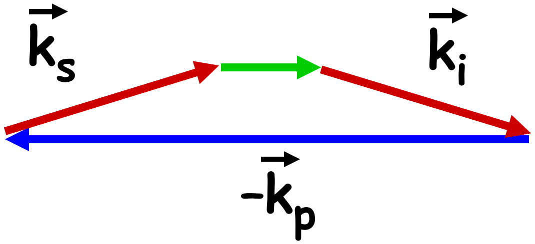
Type 0: $E_s \parallel E_i \parallel E_p$

Type I: $E_s \parallel E_i$

Type II: $E_s \perp E_i$

Energy conservation: $\omega_p = \omega_s + \omega_i$

Phase matching condition $e^{i\Delta k x}$:

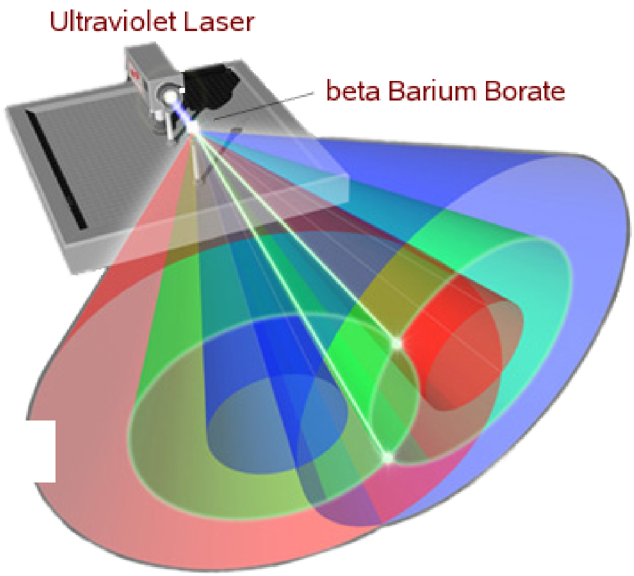


crystal grating period

(PPLN, PPKTP)

$$\Delta k = k_p - k_s - k_i + 2\pi/\Lambda = 0$$

Early crystal-based SPDC sources



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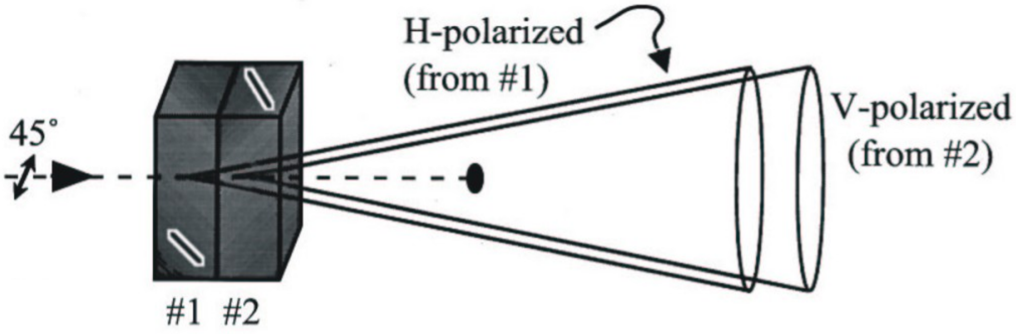
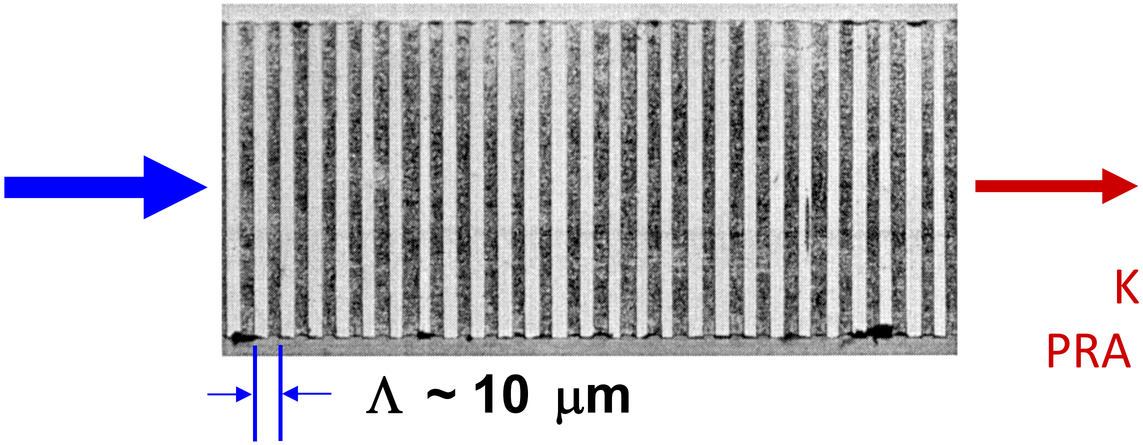


Kwiat *et al.*, PRA 60, R773 (1999)

BBO crystal(s), noncollinear geometry



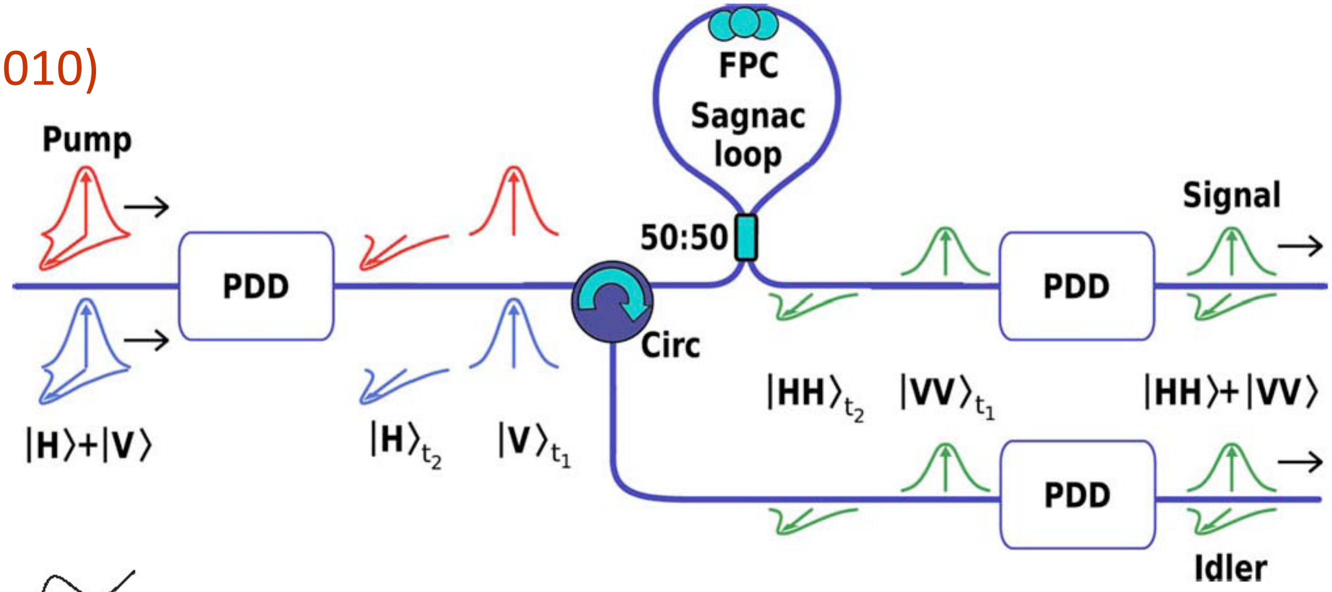
Kuklewicz *et al.*,
PRA 69, 013807 (2004)

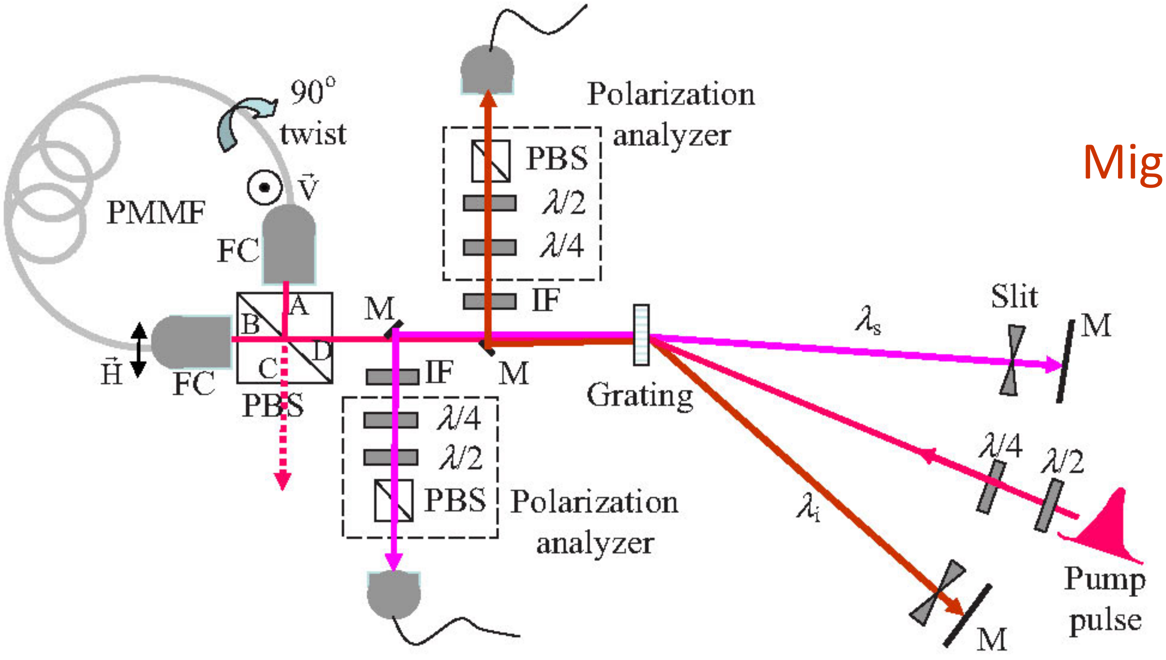
Periodically poled crystal, collinear geometry

Four-wave-mixing fiber-based sources

Kumar, OL 35, 802 (2010)

degenerate source
with SMF-28 fiber

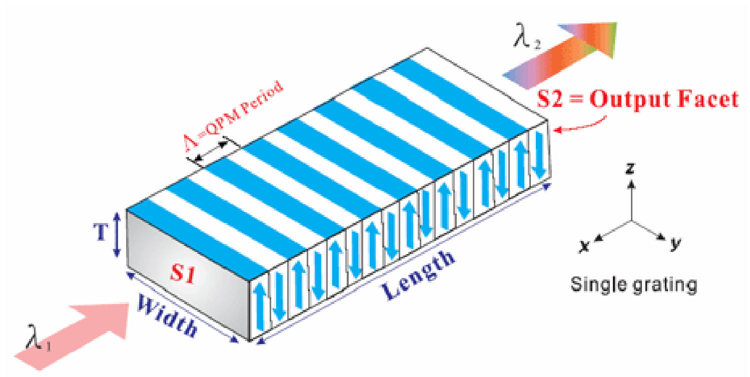


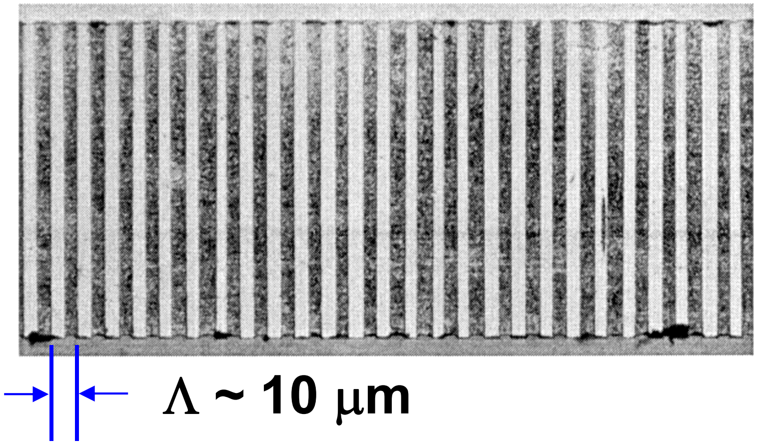


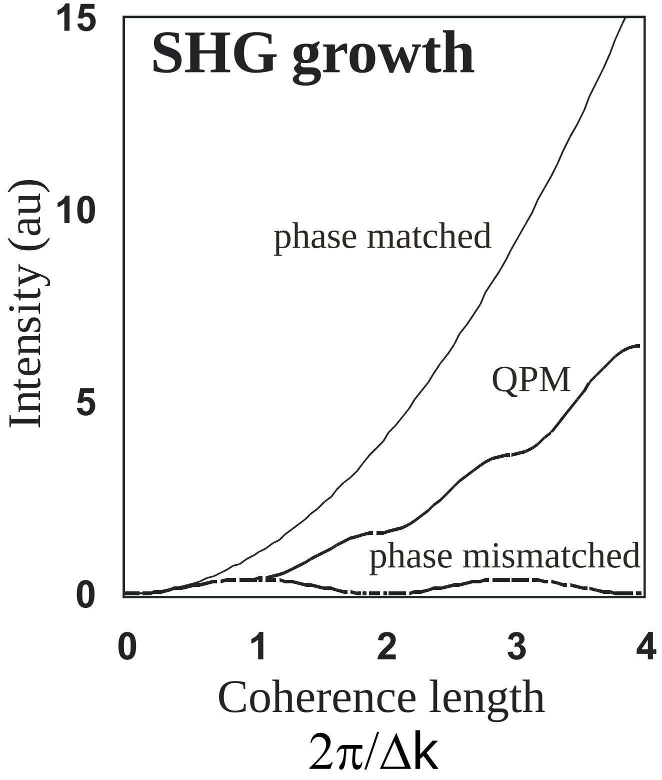
Migdall, PRA 76, 043836 (2007)

photonic crystal fiber

Quasi-phase matching in periodically poled crystals





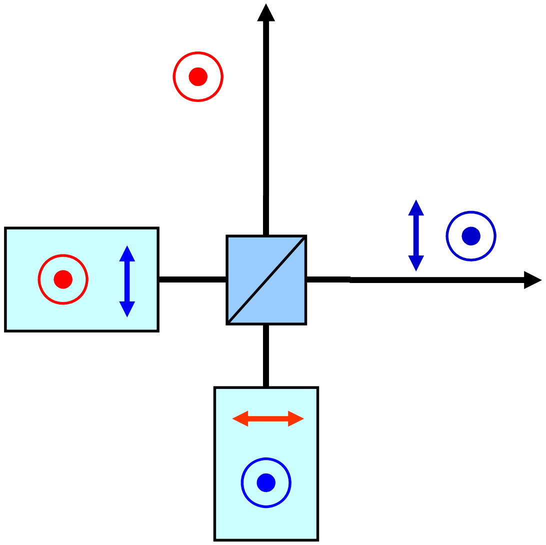


$$\Delta k = k_p - k_s - k_i + 2\pi/\Lambda$$

- Quasi-phase matching
  - efficient nonlinear generation
  - use of long nonlinear crystals
  - wide wavelength selection

- Periodic poling in ferroelectrics
  - electric-field poling
  - common crystals: PPKTP, PPLN
  - custom grating design

Interferometric combination of two SPDCs



Combine two identical sources

J. Opt. B: Quant. Semiclass. Opt. 2, L1 (2000)

- One photon in signal path and conjugate photon in idler path
- Signal and idler do not interfere: can be nondegenerate
- All photon pairs are good pairs: increased flux

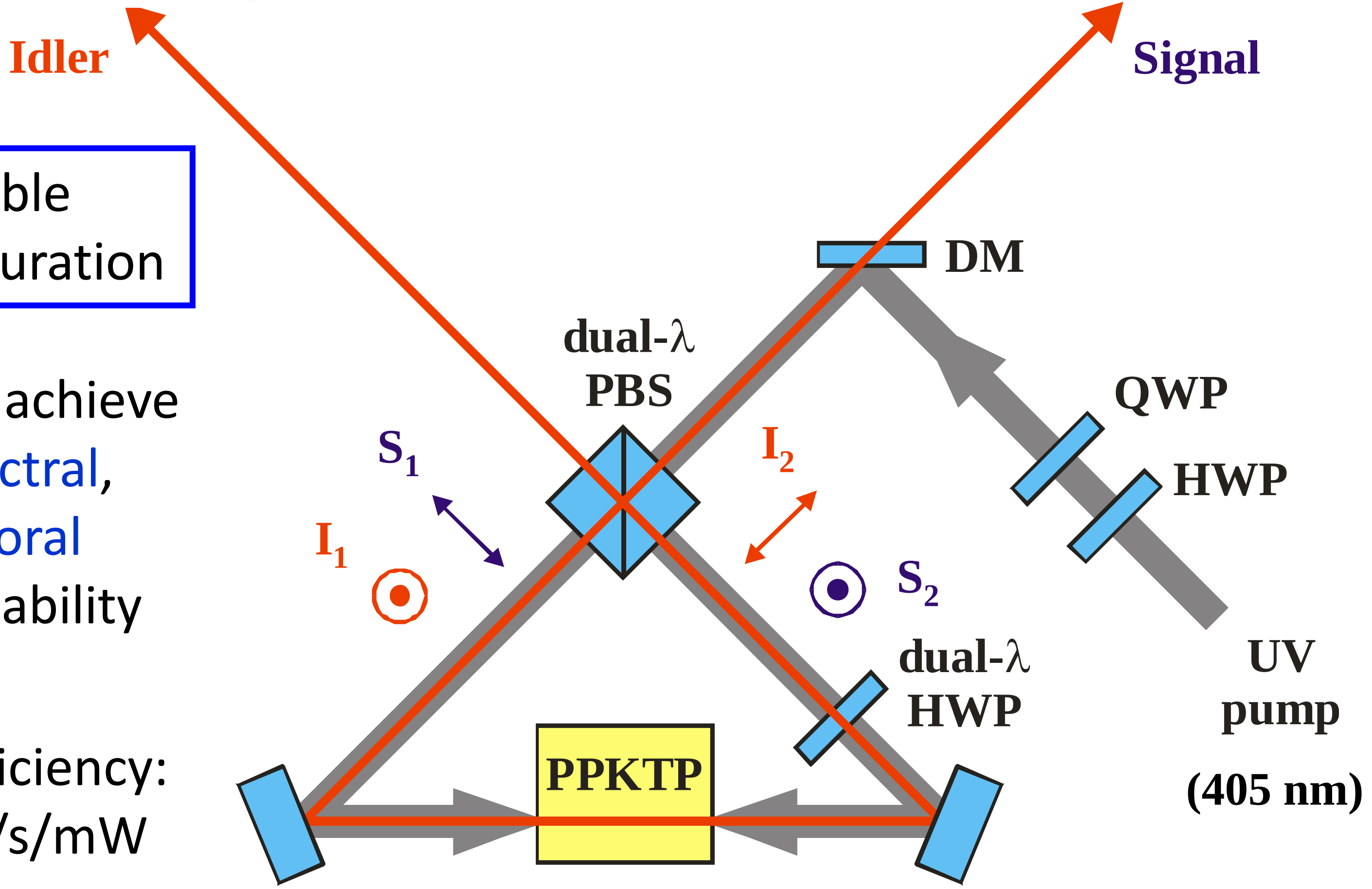
Bidirectionally pumped polarization-Sagnac SPDC

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

Phase-stable
Sagnac configuration

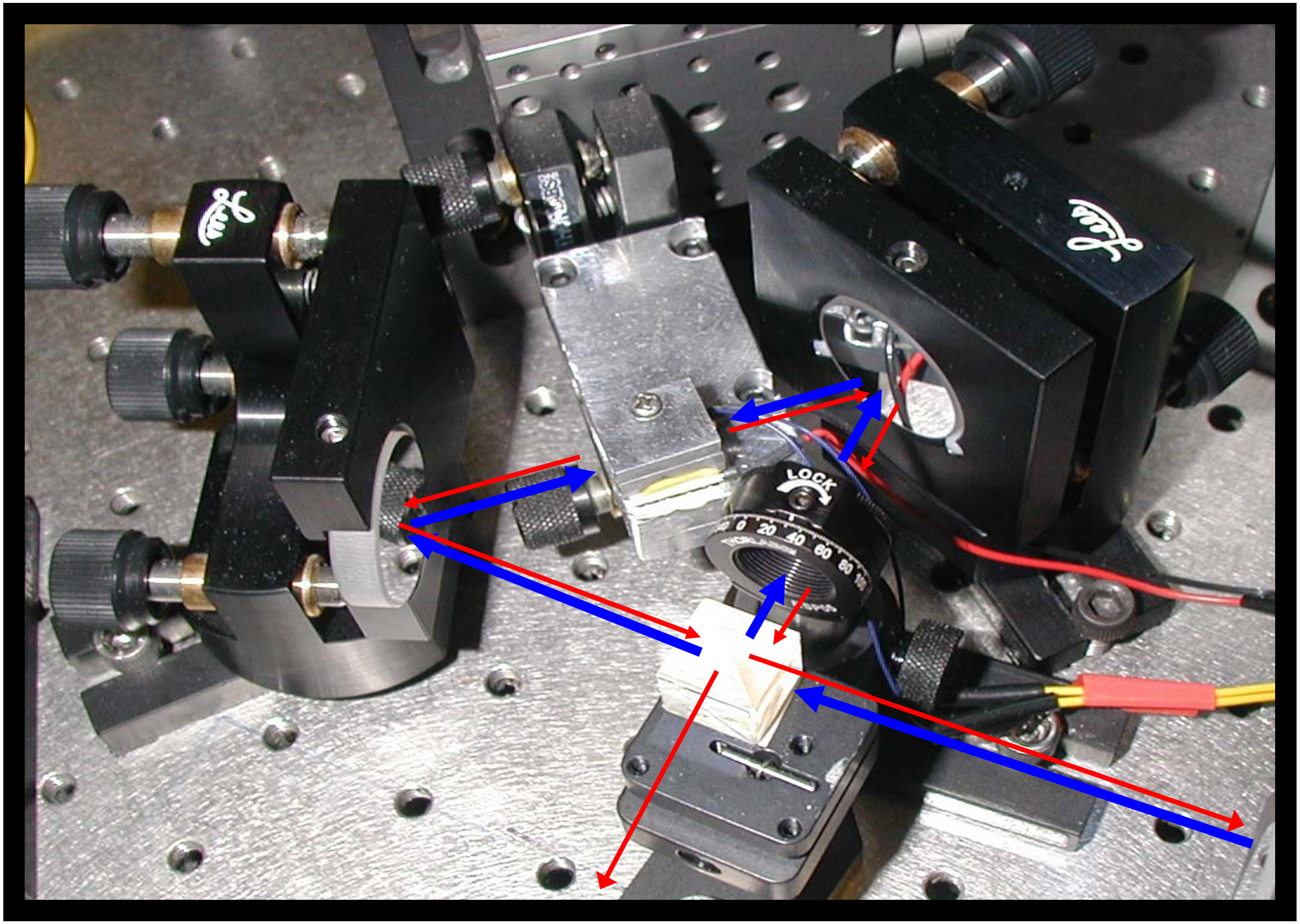
Automatically achieve spatial, spectral, and temporal indistinguishability

Generation efficiency:
0.5×10^6 pairs/s/mW

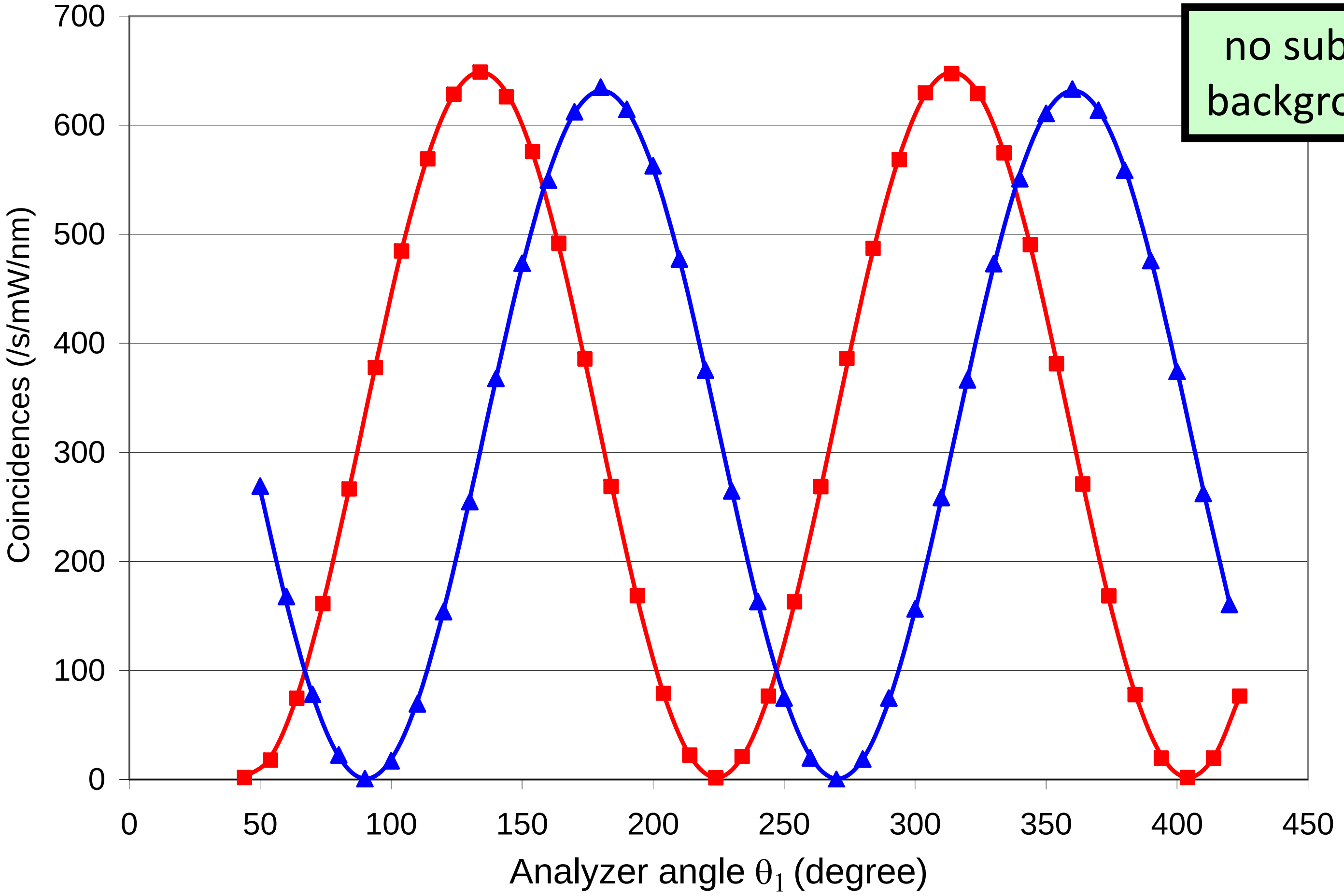


Kim *et al.*, PRA 73, 012316 (2006); Laser Phys. 16, 1517 (2006)

cw Sagnac source setup



Quantum interference visibilities (cw source)



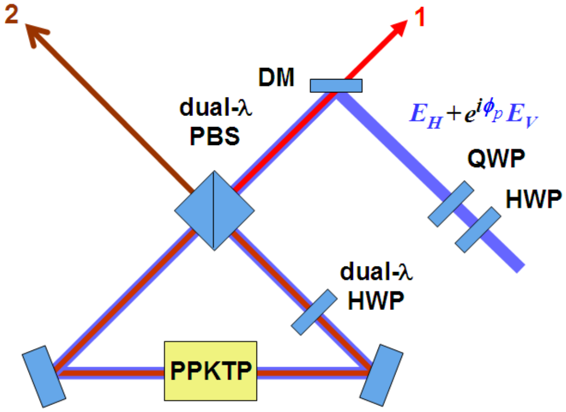
no subtraction of background counts

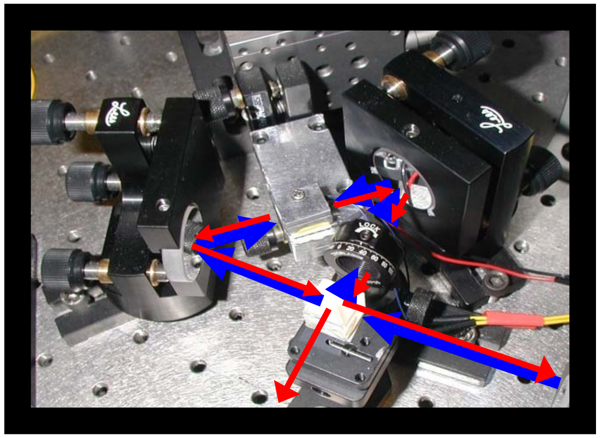
CHSH form of Bell's inequality: (quantum limit = $2\sqrt{2} \approx 2.82843$)

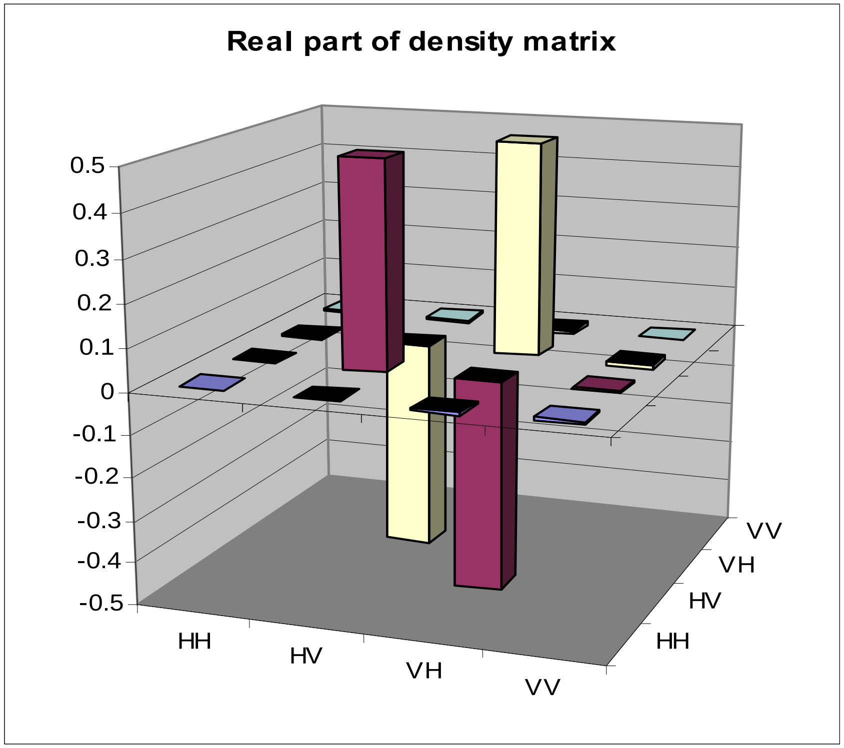
Measured S = 2.825 ± 0.015 (systematic) ± 0.0035 (statistical)

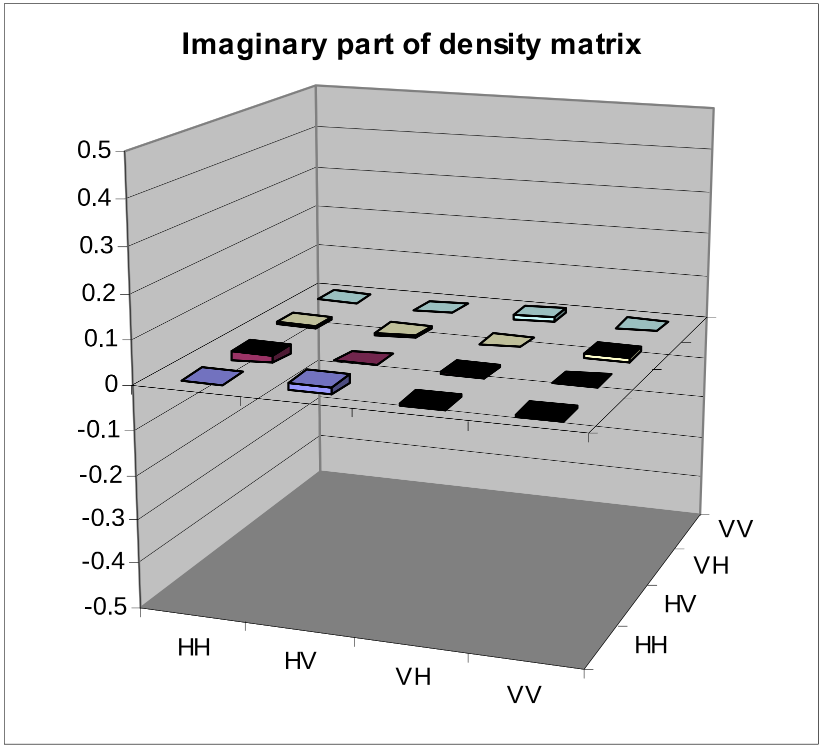
Laser Phys. 16, 1517 (2006)

Quantum state tomography of cw source

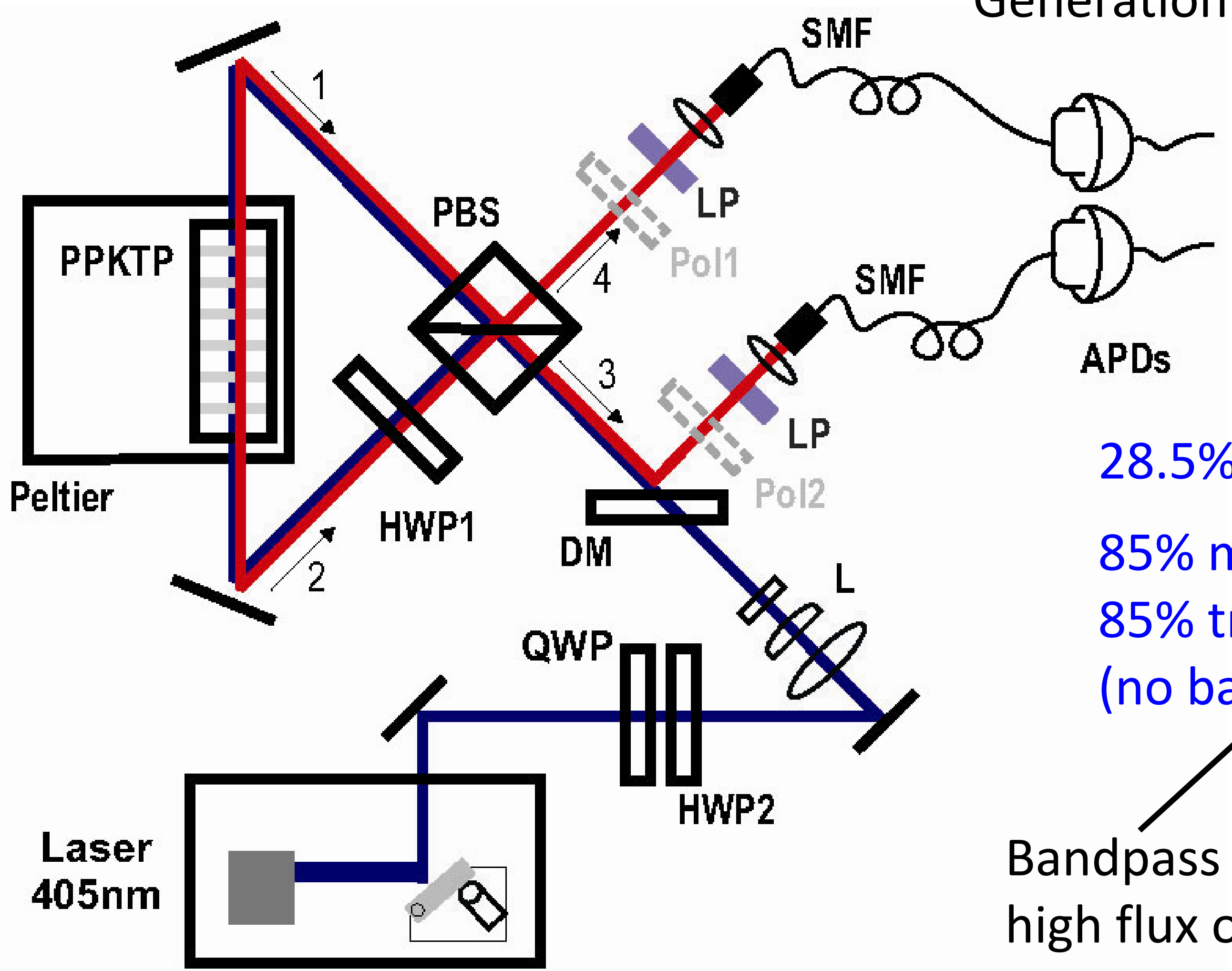








Focused-pump fiber-coupled Sagnac source



Generation rate: 10^6 pairs/s/mW

Visibility: 99.5%

Fidelity: 99.6%

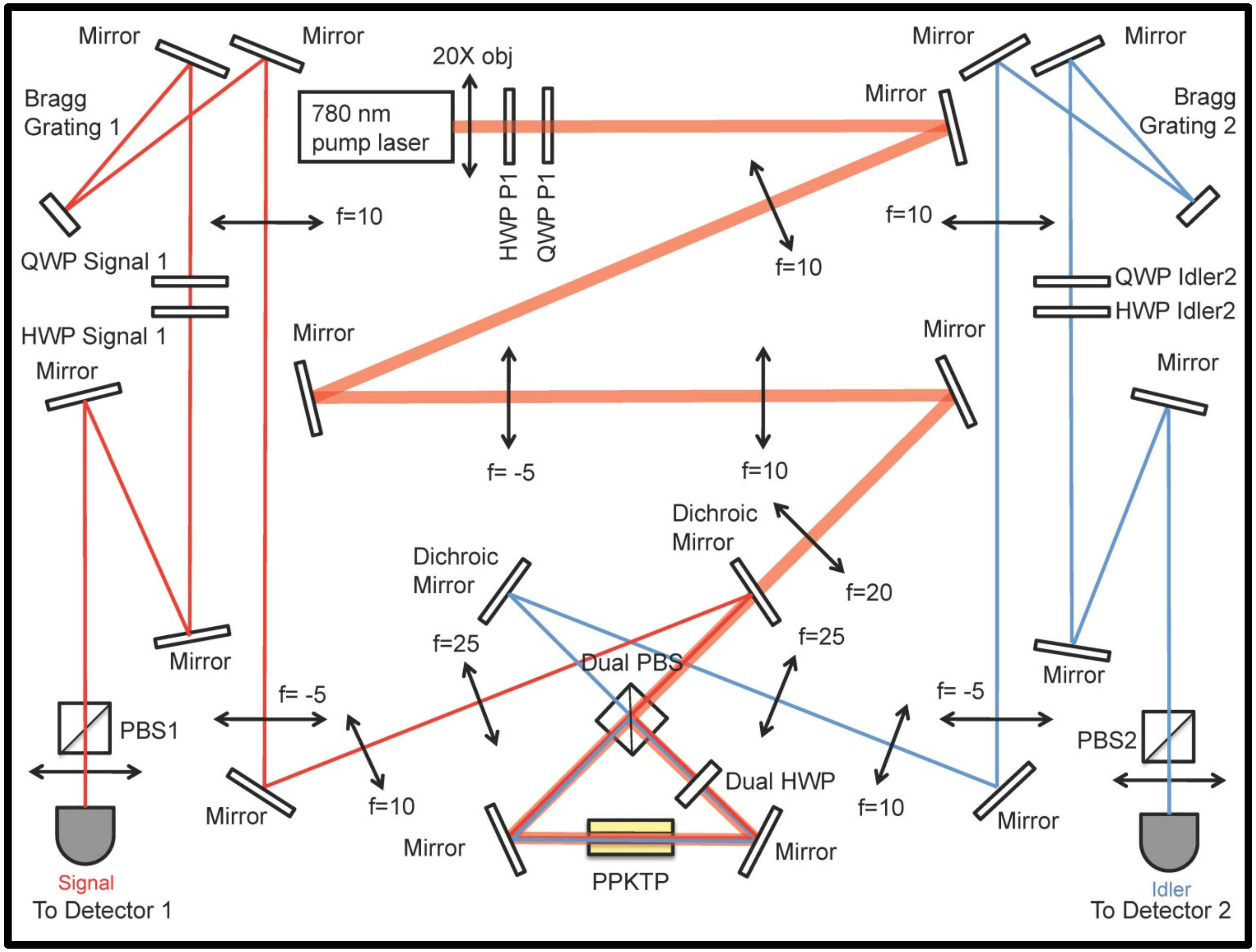
28.5% overall efficiency:

85% mode overlap
85% transmission
(no bandpass filter)

Bandpass filter is needed for high flux operation due to fluorescence

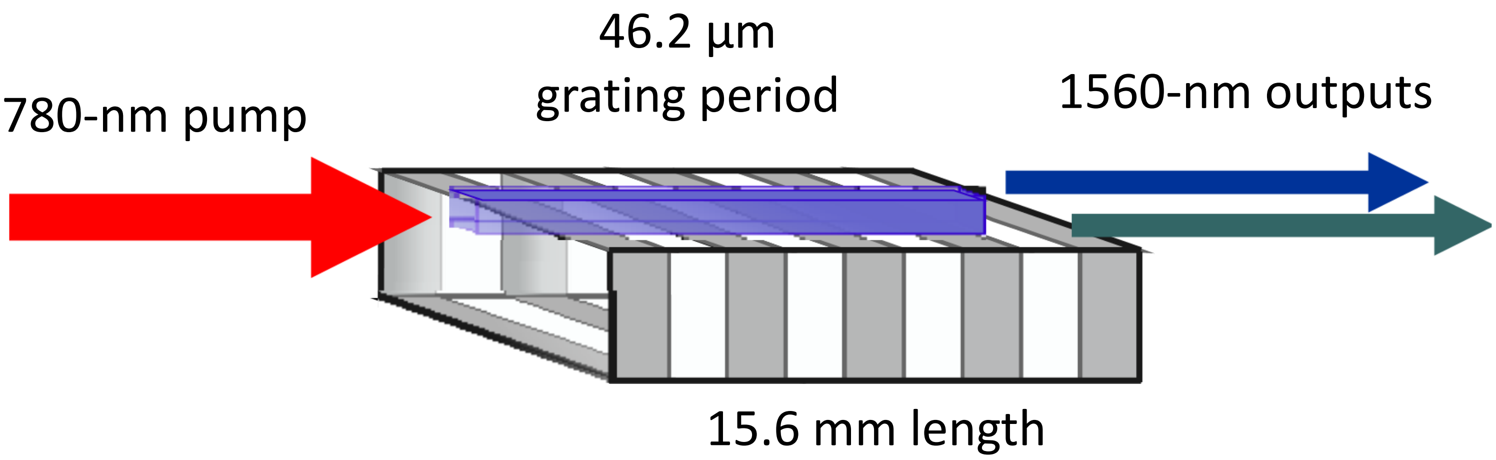
Zeilinger, OE 15, 15377 (2007)

Fiber-coupled Sagnac source at 1560 nm



- 97% efficient Bragg reflection grating filter
- Generation rate: 10^5 pairs/s/mW
- Quantum-interference visibility: 95%

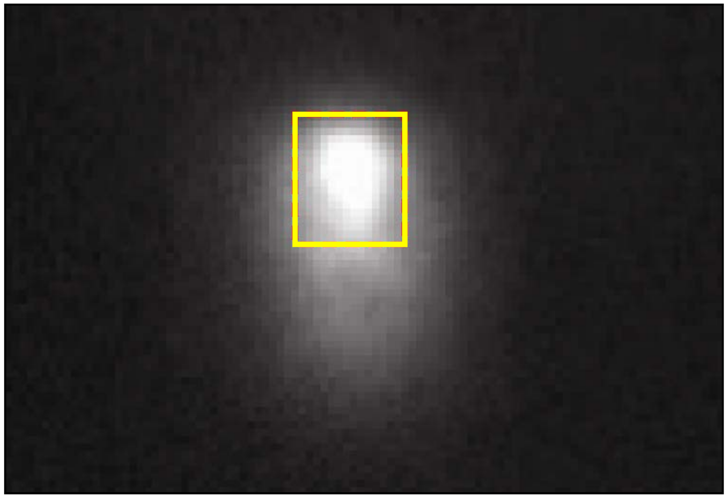
PPKTP waveguide source



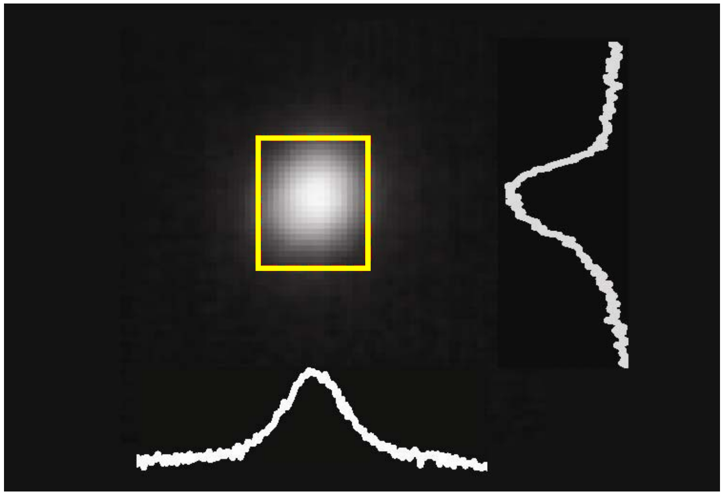
Type-II phase-matched PPKTP waveguide

- Flux enhancement (100x) due to transverse momentum matching
- Efficient generation: 10^7 pairs/s/nm/mW (1.6 nm bandwidth)
- High extraction efficiency into single-mode fibers
- Naturally time-energy entangled; very little fluorescence
- Suitable for high-rate QKD

Efficient spatial-spectral waveguide mode extraction



Multimode output
No spectral filter



Fundamental-mode output
after 99%-efficient 10-nm filter

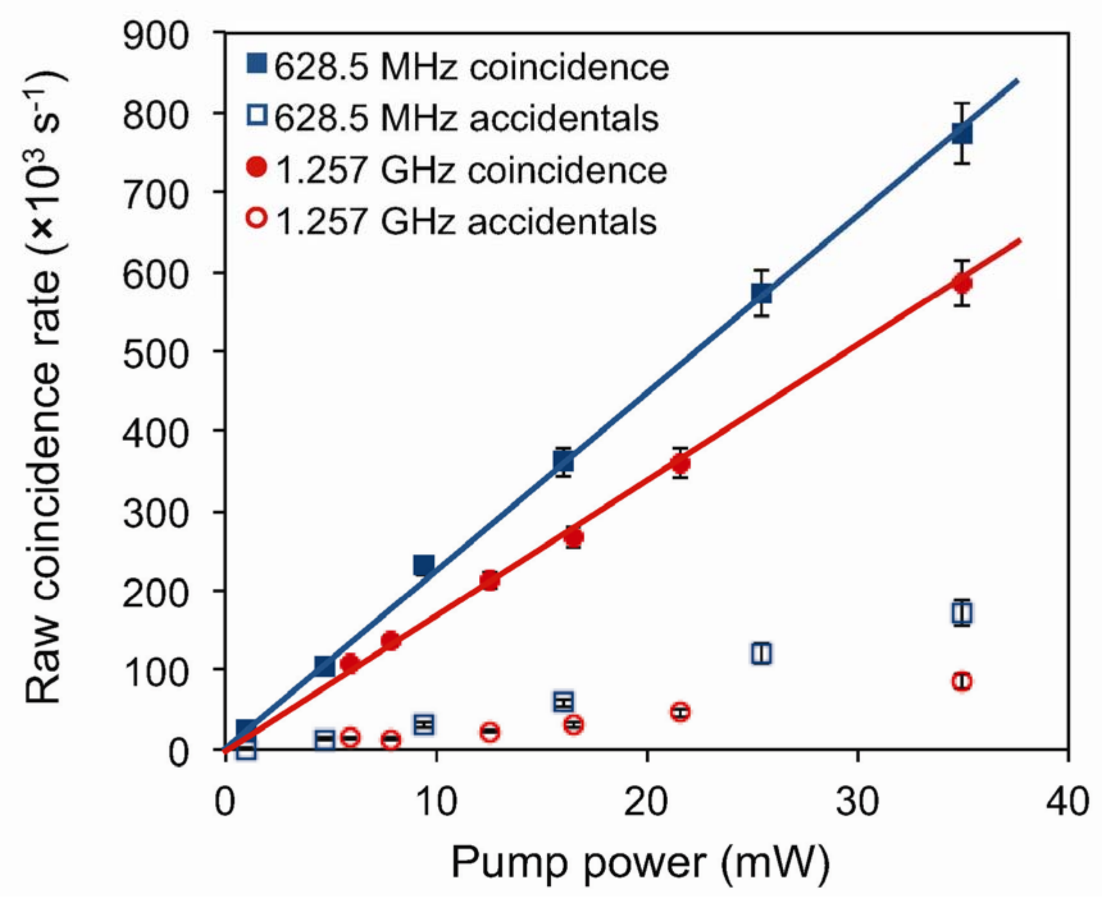
- Waveguide spatial modes are spectrally separated
- Wideband spectral filter removes higher order spatial modes
- 80% fiber coupling efficiency of fundamental waveguide mode

Future improvements:

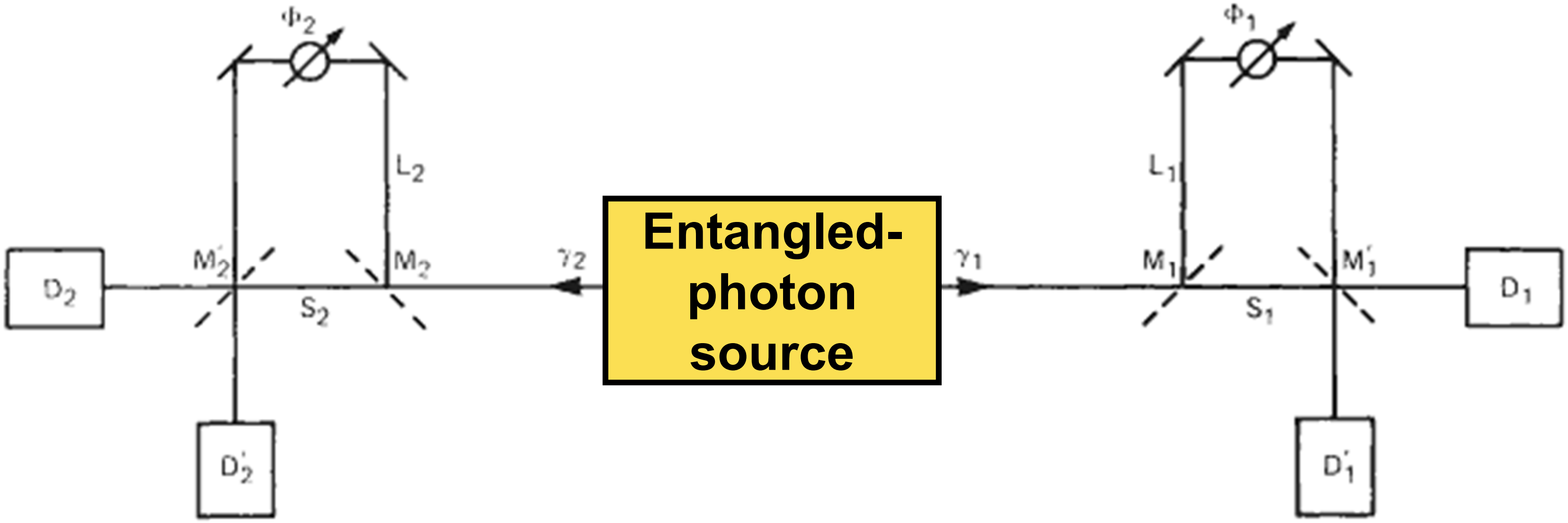
- better coupling optics
- better waveguide fabrication to reduce internal losses (~15%)

Waveguide SPDC: high-rate coincidence measurements

- InGaAs detectors with 628.5-MHz or 1.257-GHz sinusoidal gating
- System efficiency of ~10%; duty cycle: 25%
- Raw key rate >1.5 Mbit/s with 2 or 3 temporal bits/photon encoding



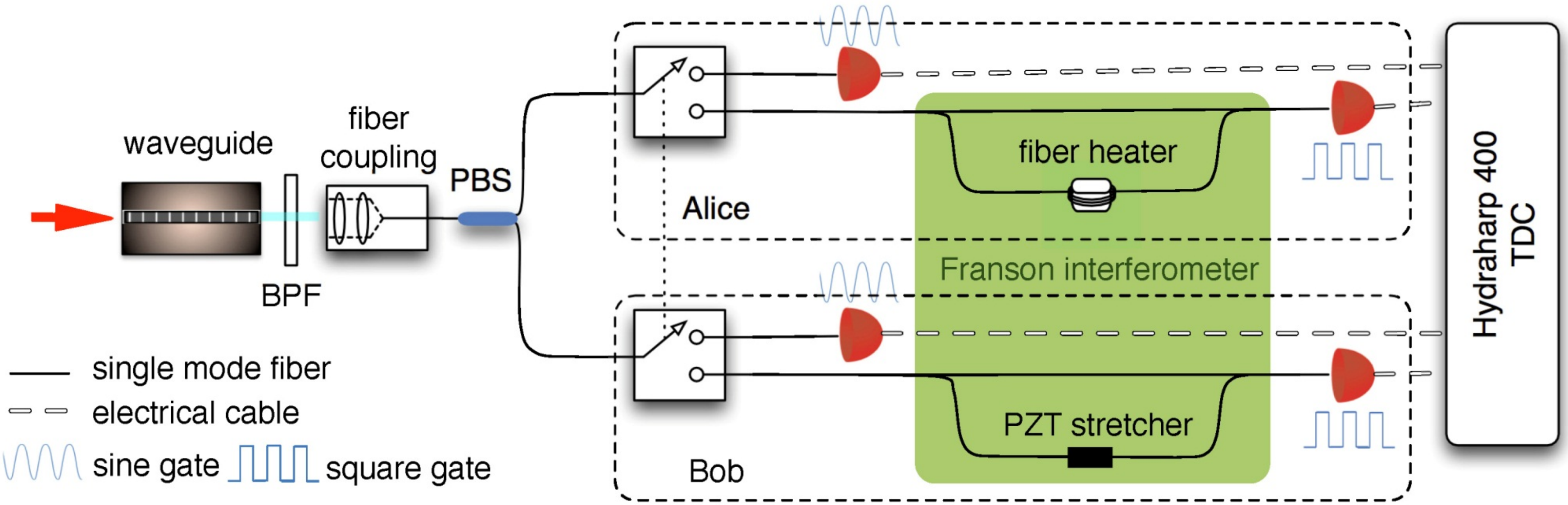
Time-energy entanglement: Franson interferometer



Franson interferometer PRL **62**, 2205 (1989)

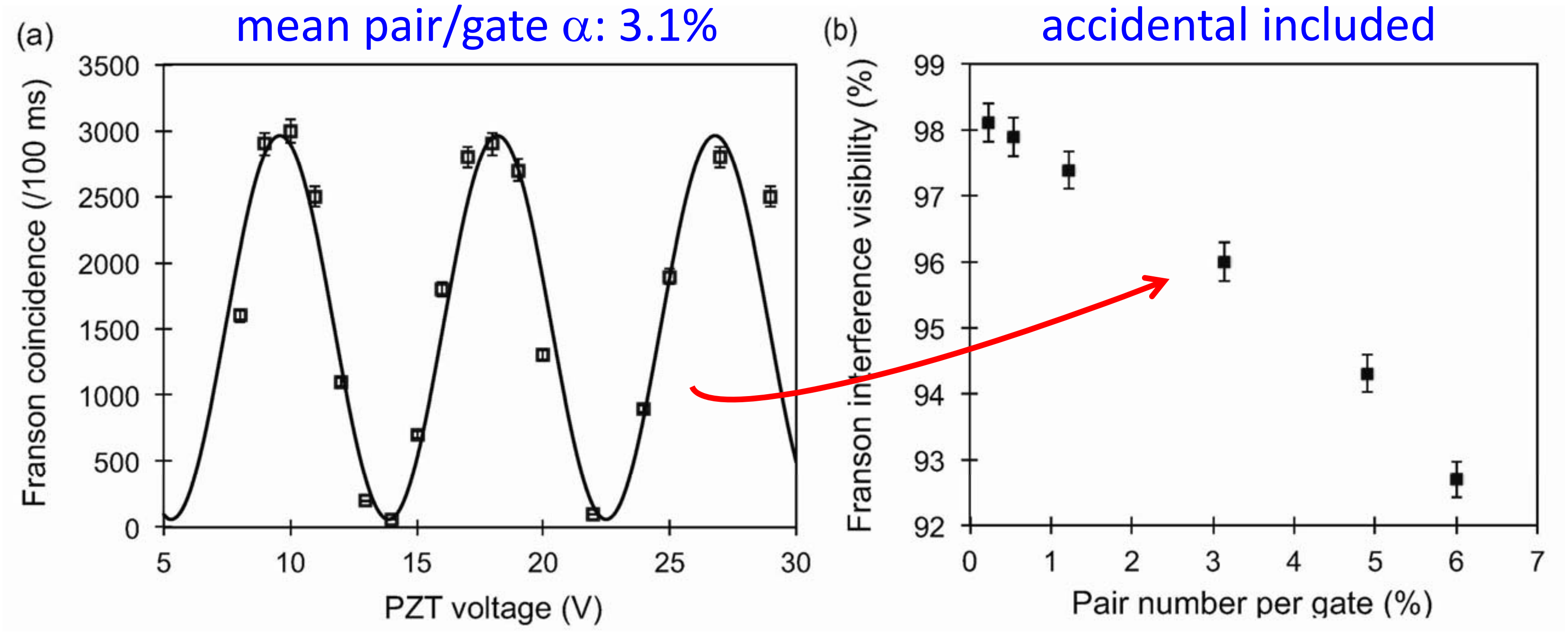
- Franson interferometer
  - measures quality of time-energy (or time-bin) entanglement
- Previous best published result shows 95.6% visibility [Tittel, PRA **81**, 052106 (2010)]
  - Why is visibility not on par with polarization entanglement (>99%)?

Time-energy entanglement



- InGaAs detectors with square gating (~100 ps window)
- Fiber-length difference: 4.8 ns = 3x gate period (for 628 MHz gating)
- Interferometer fiber-length difference matched to less than 1 biphoton coherence time (~2 ps)
- Phase control via PZT fiber stretcher

Franson interferometric measurements

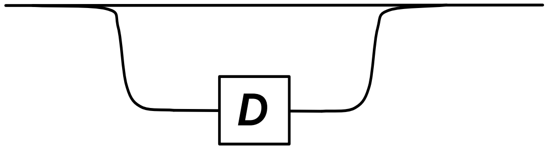

mean pair/gate α: 3.1%

accidental included

- Visibility $V = (C_{\max} - C_{\min}) / (C_{\max} + C_{\min})$
- $V = 98.2\%$ @ mean pair number per gate $\alpha = 0.24\%$
- Degradation due to multi-pair events: $V = 1 - \alpha$
- Likely source of degradation: dispersion between long and short paths
  - estimated 27 fs for 1.6 nm bandwidth, ~1 m of SMF28 fiber

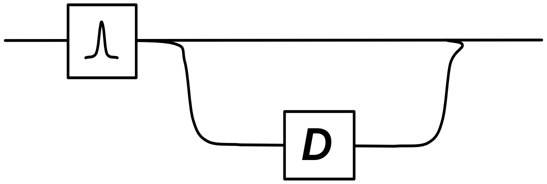
Dispersion compensated Franson interferometry

(a) no filtering
no compensation



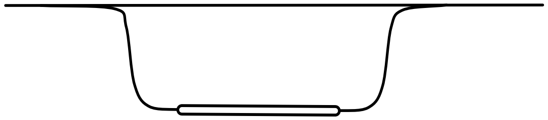
standard SMF

(b) with filtering
no compensation



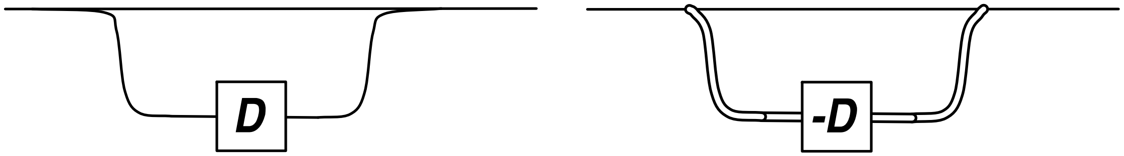
standard SMF

(c) no filtering
local compensation



LEAF fiber

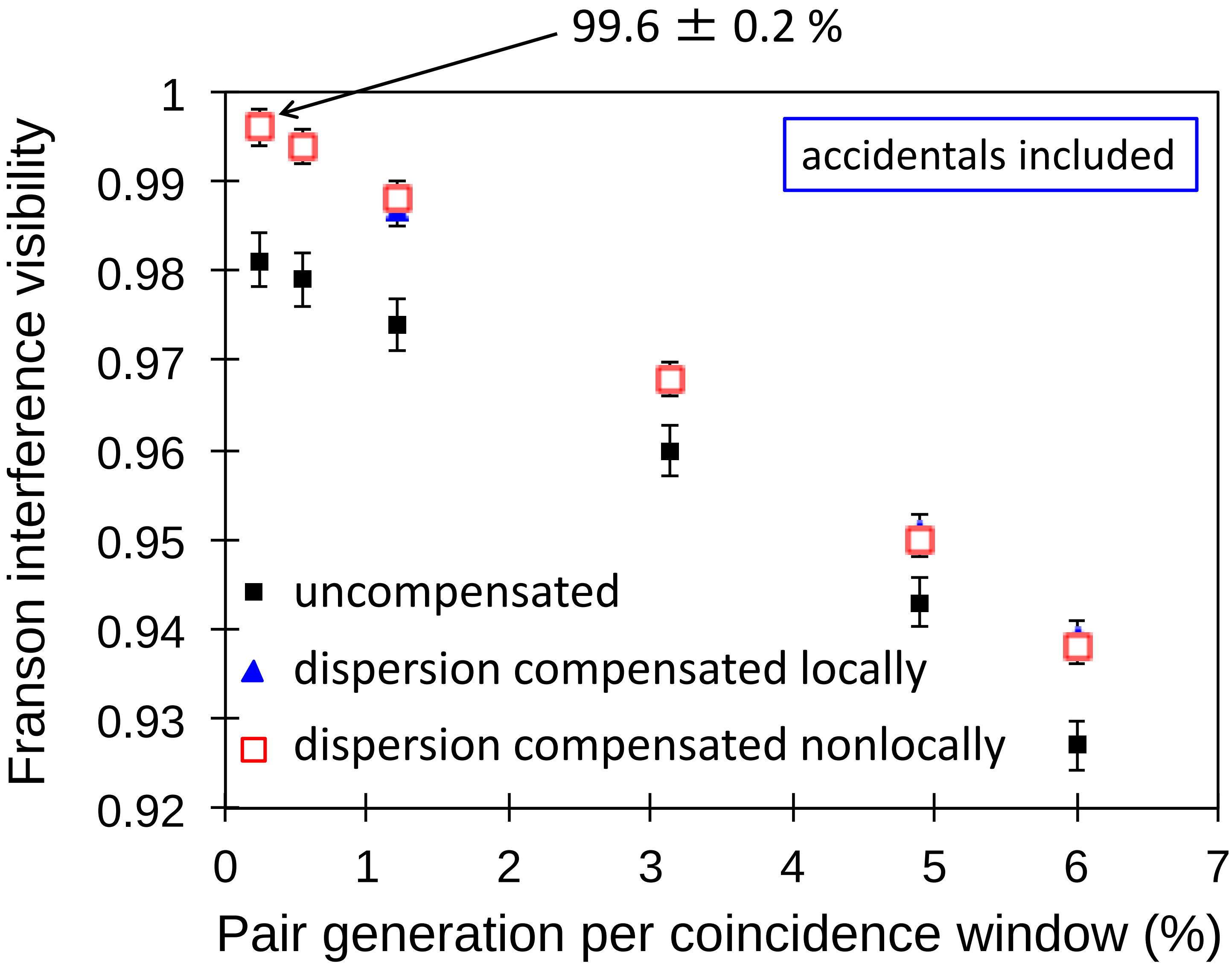
(d) no filtering
nonlocal compensation



SMF

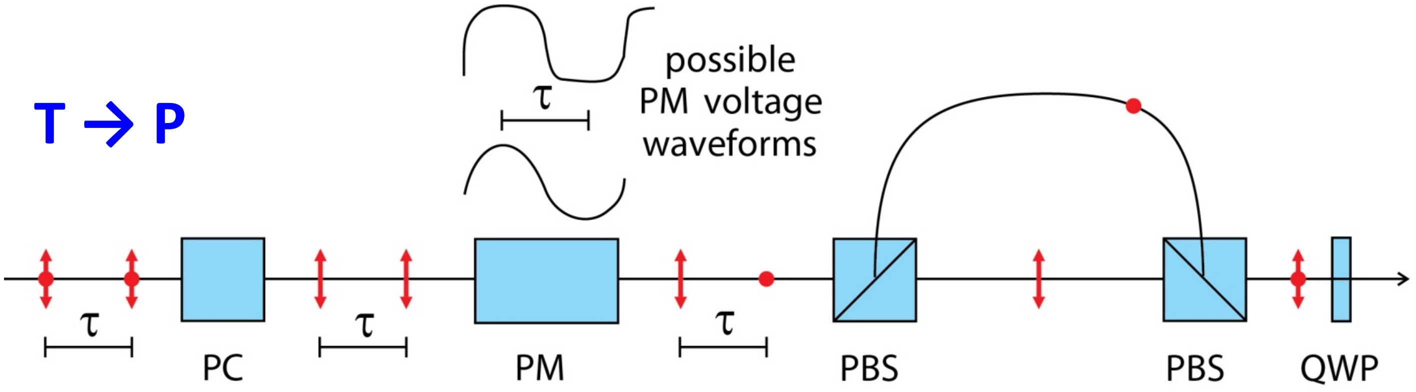
LEAF fiber

Dispersion compensated Franson interferometry



Source extension for QKD systems

- Modal conversion between polarization and time-bin qubits



  - "universal time-bin qubit analyzer" implementation by Tittel et al: PRA **81**, 052106 (2010)
- Wavelength translation by sum- or difference-frequency mixing
  - pro: unity internal conversion efficiency
  - con: background counts; filtering losses reduce system efficiency
- High-dimensional hyperentangled photon pairs
  - enlarged Hilbert space (beyond polarization) in temporal, spectral, and spatial degrees of freedom

Summary

- Sagnac source configuration
  - high polarization entanglement quality and high flux
  - use bulk crystal or waveguide

- PPKTP waveguide source
  - 100x more efficient than bulk PPKTP
  - generated >10^7 pairs/s/mW at 1560 nm (100 mW pump)
  - high single-mode extraction efficiency into single-mode fiber
  - Time-energy entanglement quality as good as polarization entanglement with local or nonlocal dispersion compensation

- Entanglement sources for high-speed QKD
  - match system features: qubit type, detectors
  - high extraction efficiency: minimize system losses such as filtering

Acknowledgments

Sagnac sources:
Taehyun Kim (now at SK Telecom), Marco Fiorentino (HP)
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PPKTP waveguide:
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Tony Roberts, Phil Battle (AdvR)

Theory:
Jeff Shapiro (MIT)

InGaAs detectors:
Alessandro Restelli, Josh Bienfang (NIST)

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