



Quantum Information Technology: Entanglement, Teleportation and Quantum Memory

January 30, 2003

Presentation to the CMI Workshop on
Quantum Information Processing

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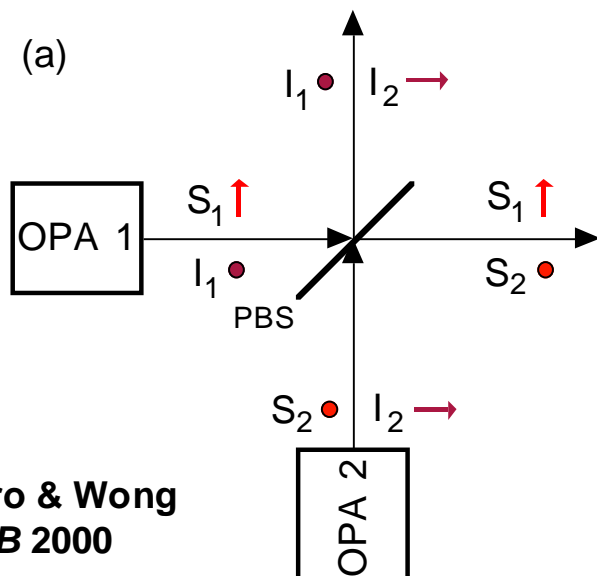
Long-Distance Qubit Teleportation: MIT/NU Communication Architecture

Long-Distance Quantum Communication System

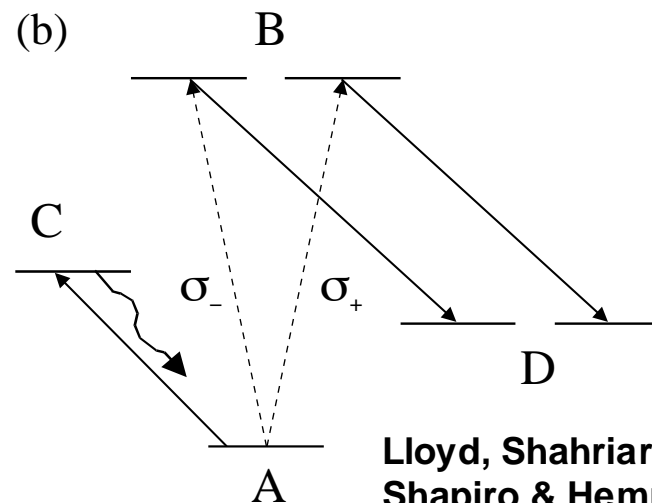


Shapiro
QCMC 2000,
NJP 2002

- P = Ultrabright, narrowband polarization-entanglement source (a)
- $L = L$ km of standard telecommunication fiber
- M = Trapped rubidium atom quantum memory (b)



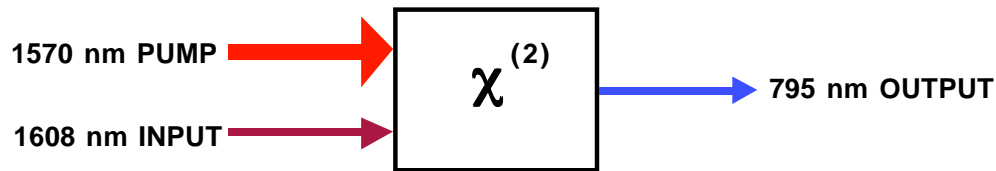
Shapiro & Wong
J Opt B 2000



Lloyd, Shahriar,
Shapiro & Hemmer
PRL 2001

Long-Distance Qubit Teleportation: MIT/NU Communication Architecture

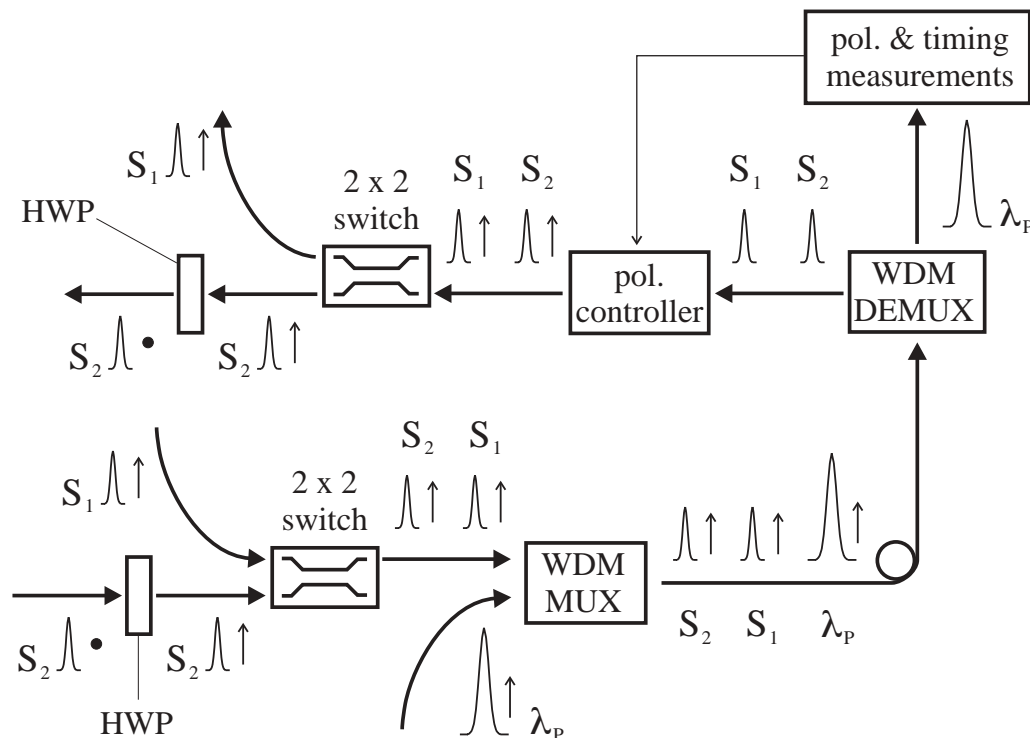
Quantum Transmission over Standard Telecom Fiber



Quantum-State
Frequency
Conversion

Huang & Kumar
PRL 1992

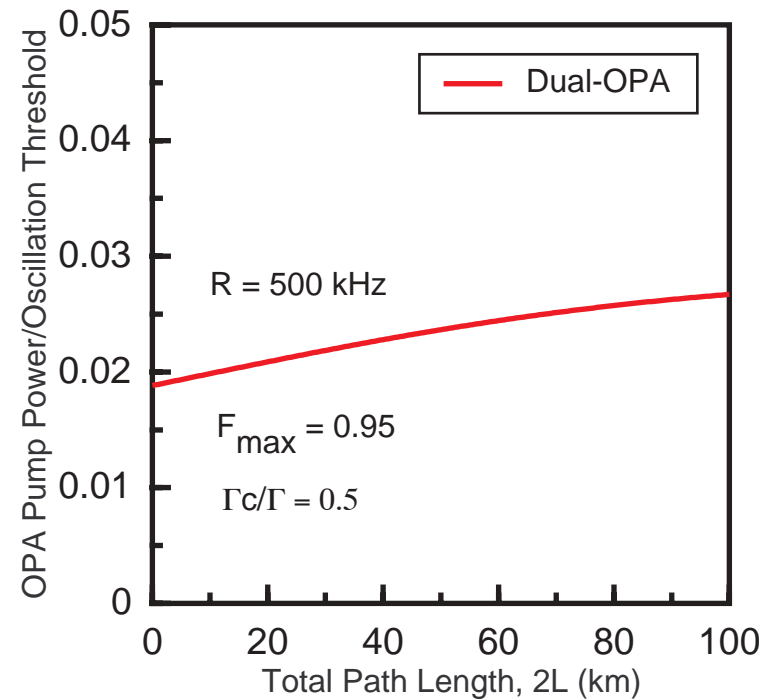
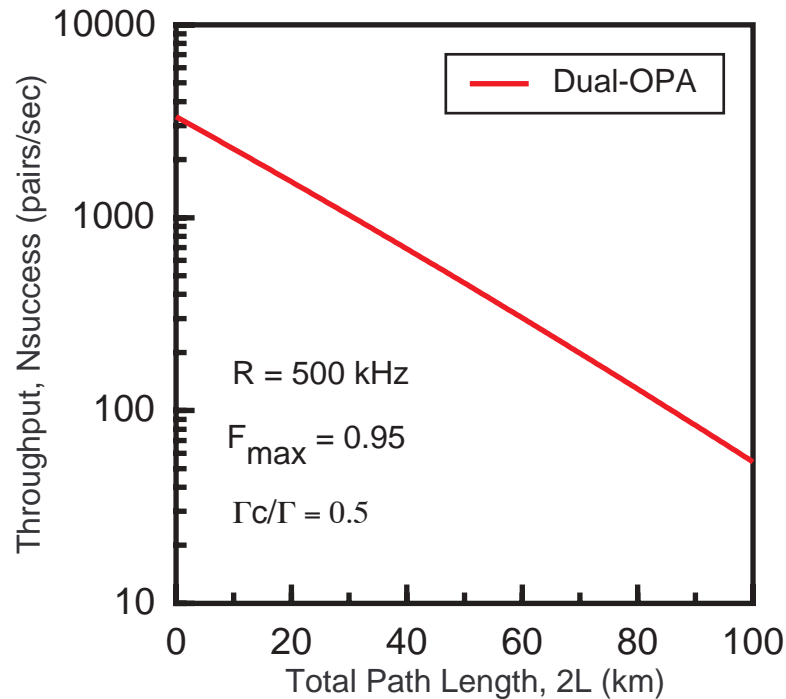
Time-Division
Multiplexing for
Polarization
Restoration



cf. Bergman et al. *Opt Lett* 1993

Long-Distance Qubit Teleportation: MIT/NU Communication Architecture

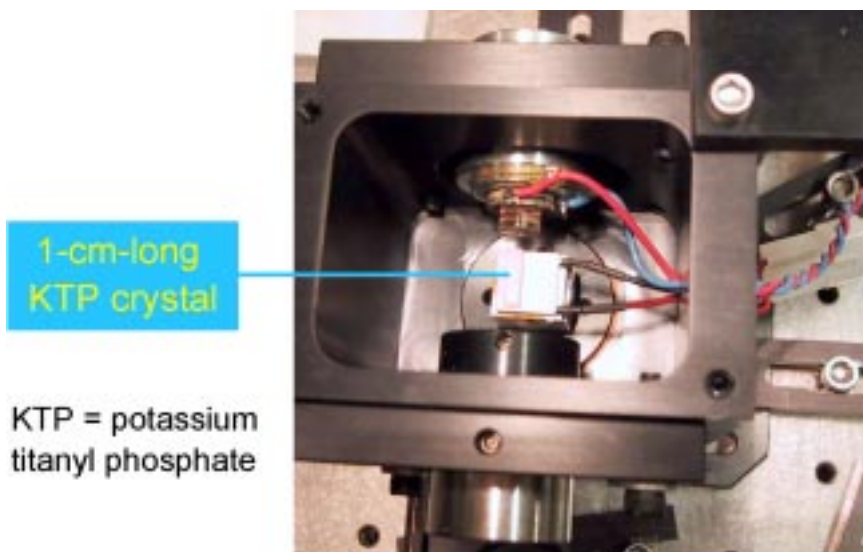
Quantum Transmission over Standard Telecom Fiber



Fixed Loss = 5 dB per P -to- M path; Fiber Loss = 0.2 dB/km

Shapiro *NJP* 2002

Doubly-Resonant Optical Parametric Amplifier: Triplet-State Generation Experiment

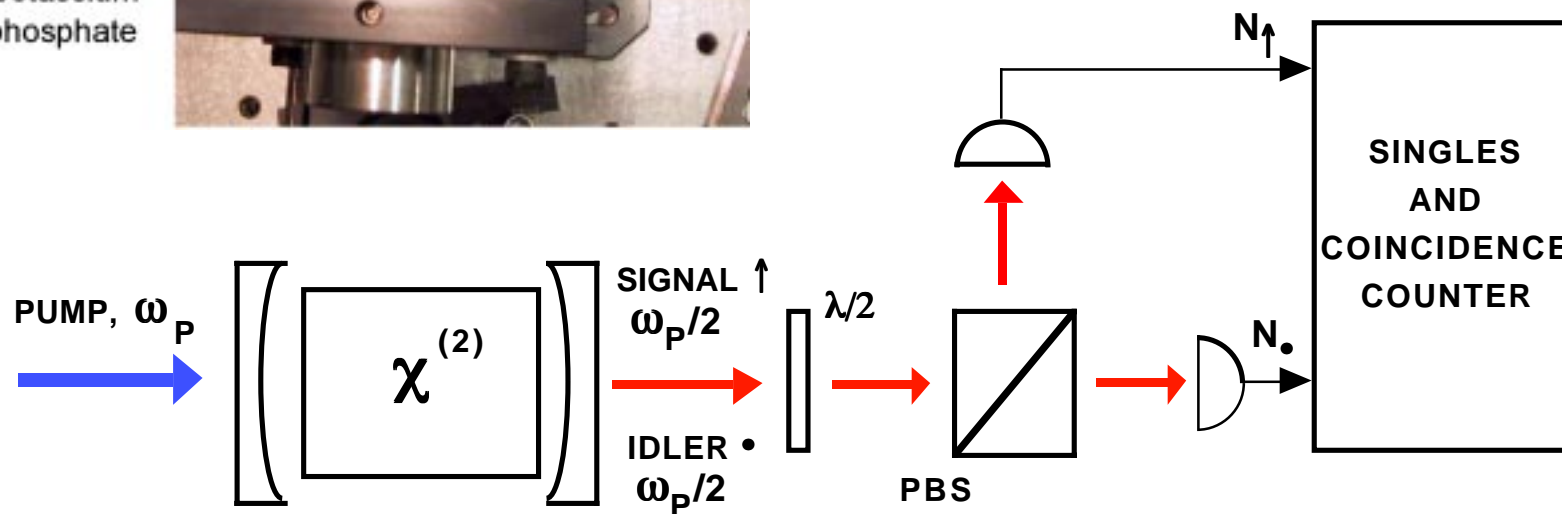


Without polarization mixing:

- coincidence counts verify pairs generation

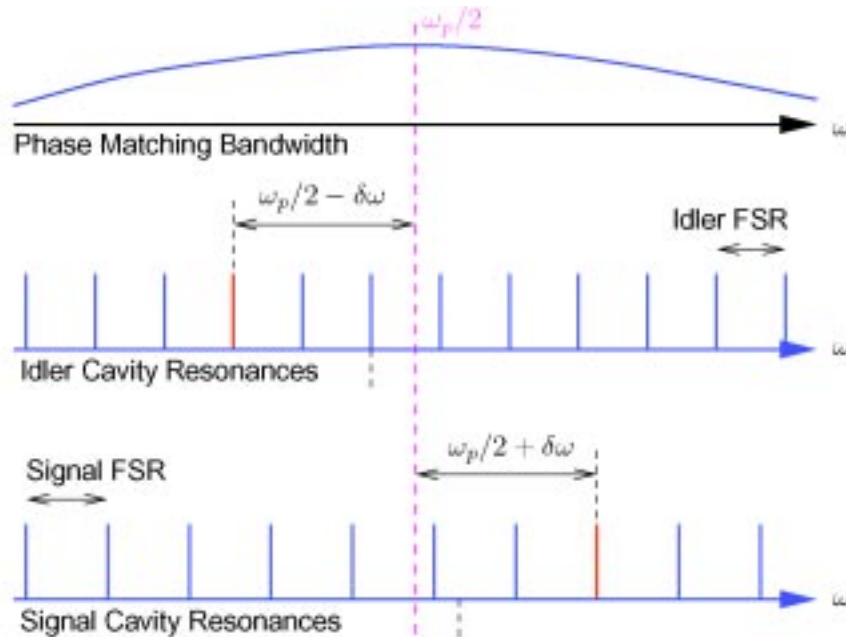
With polarization mixing:

- coincidence-count dip verifies triplet generation



Kuklewicz, Keskiner, Wong & Shapiro
J Opt B 2002

Doubly-Resonant Optical Parametric Amplifier: Triplet-State Generation Experiment



OPA output contains three types of modes:

- non-resonant, singly- and doubly-resonant

Only nonresonant modes were degenerate:

- quantum interference is incomplete

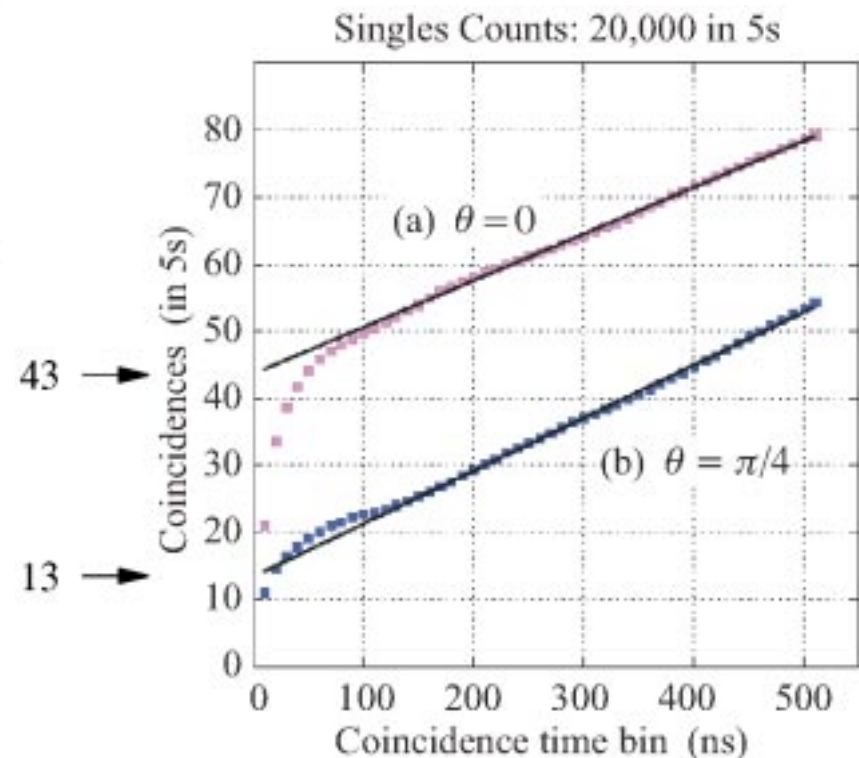
Ultrabright pair generation:

- 5.3×10^4 pairs/s/GHz/mW

Ultrabright triplet generation:

- 6×10^6 triplets/s/mW in 320 GHz

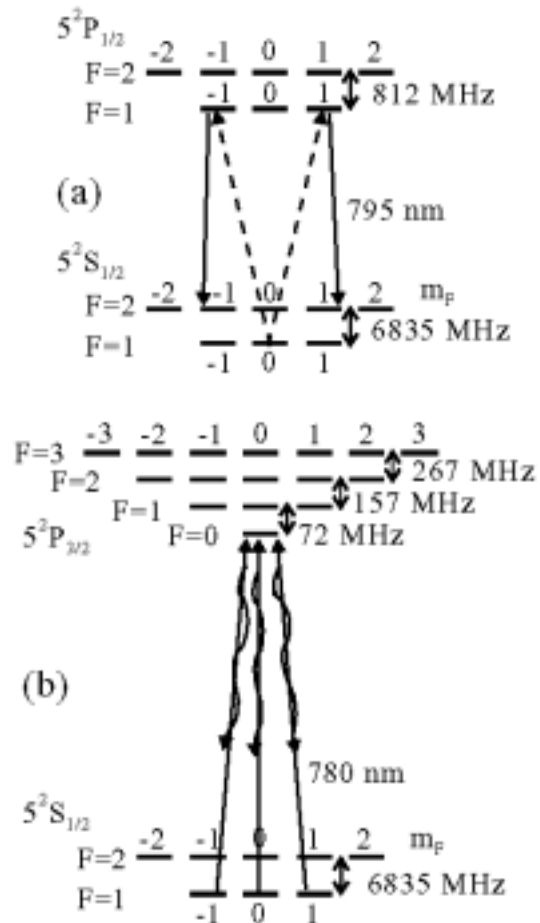
Kuklewicz, Keskiner, Wong & Shapiro
J Opt B 2002



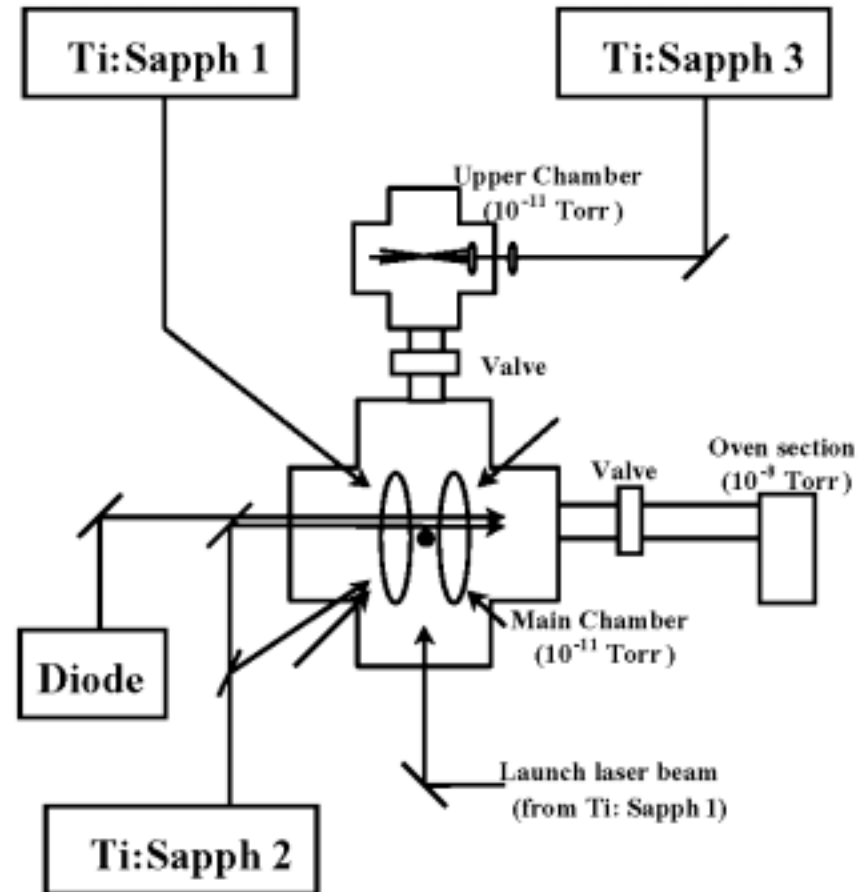
Trapped-Atom Quantum Memory

Energy levels in ^{87}Rb for:

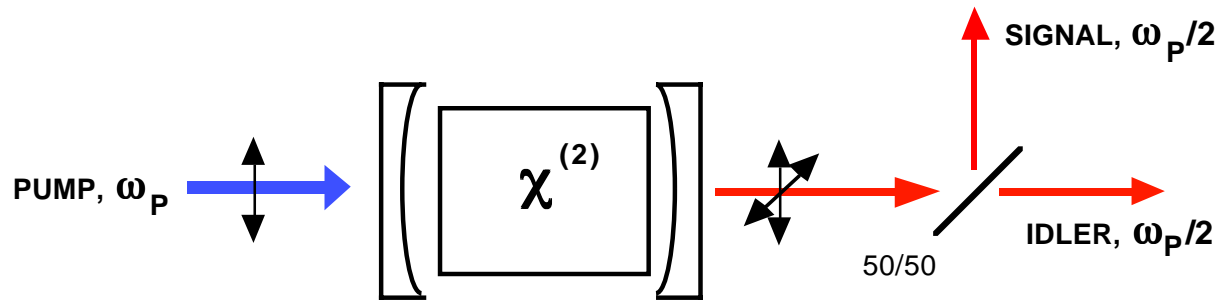
- qubit storage (a), load verification (b)



Magneto-optic trap design



Long-Distance Qubit Teleportation: DPA Source for MIT/NU Architecture

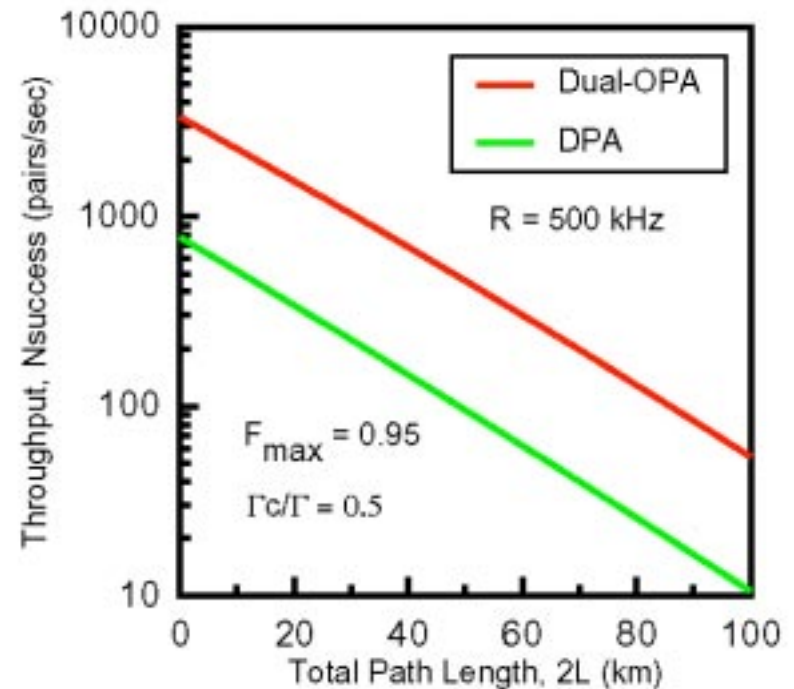


Degenerate
Parametric
Amplifier
(DPA)

$$|\psi^+\rangle_{SI} = \left(|1\rangle_{S_x} |1\rangle_{I_y} |0\rangle_{S_y} |0\rangle_{I_x} + |0\rangle_{S_x} |0\rangle_{I_y} |1\rangle_{S_y} |1\rangle_{I_x} \right) / \sqrt{2}$$

Fixed Loss = 5 dB per *P*-to-*M* path
Fiber Loss = 0.2 dB/km

Shapiro *NJP* 2002

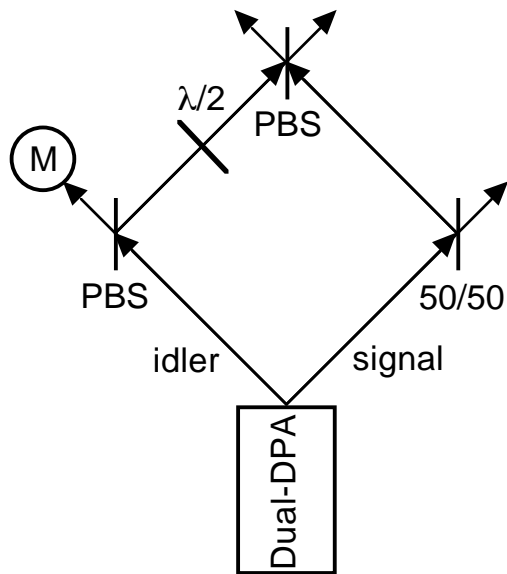


Multi-Party Entanglement: MIT/NU Architecture for GHZ-State Communication

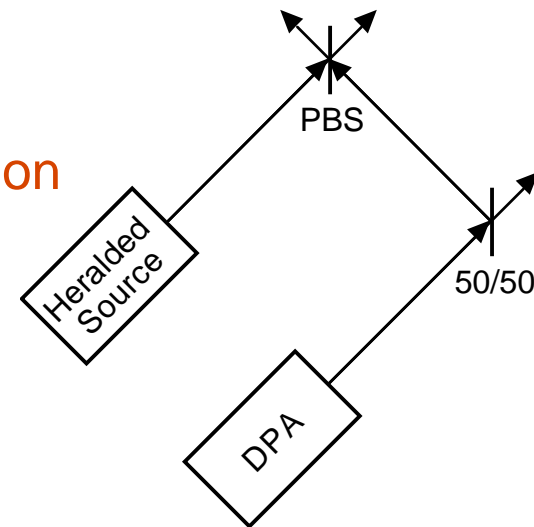
Greenberger-Horne-Zeilinger State

$$|\psi\rangle_{GHZ} = (|\uparrow\rangle|\uparrow\rangle|\bullet\rangle + |\bullet\rangle|\bullet\rangle|\uparrow\rangle) / \sqrt{2}$$

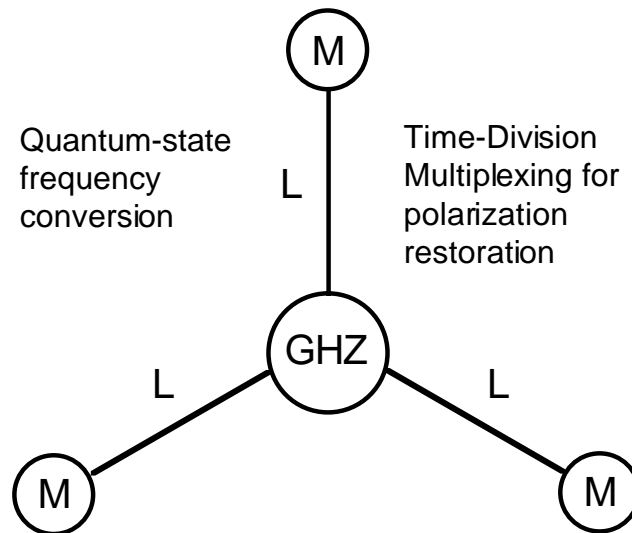
Dual-DPA
source



DPA+heralded
source



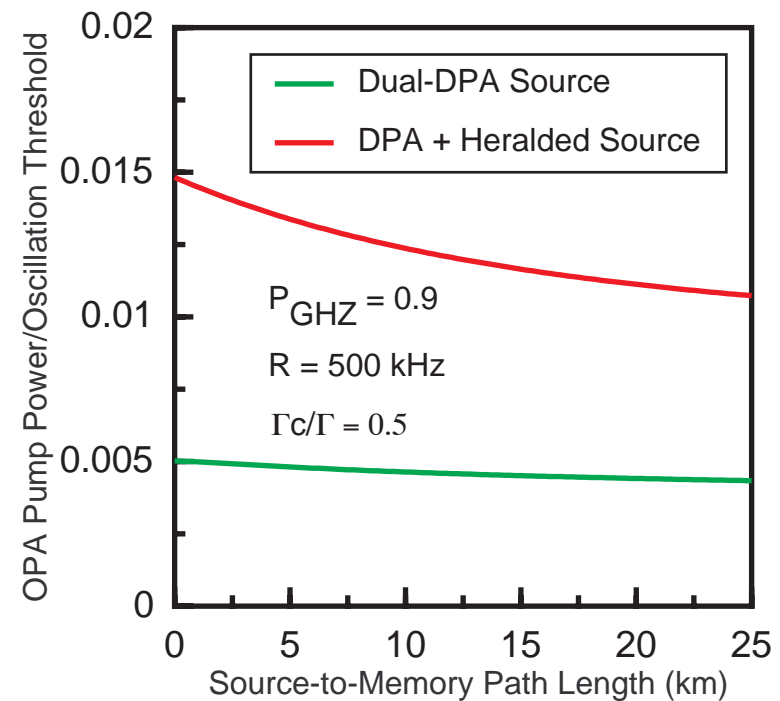
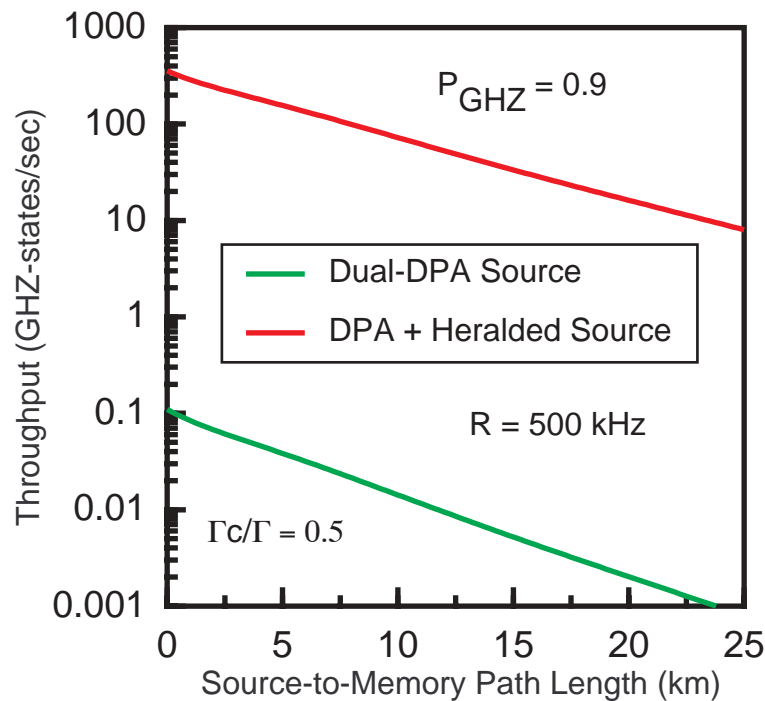
Long-Distance Transmission



Shapiro *NJP* 2002

Multi-Party Entanglement: MIT/NU Architecture for GHZ-State Communication

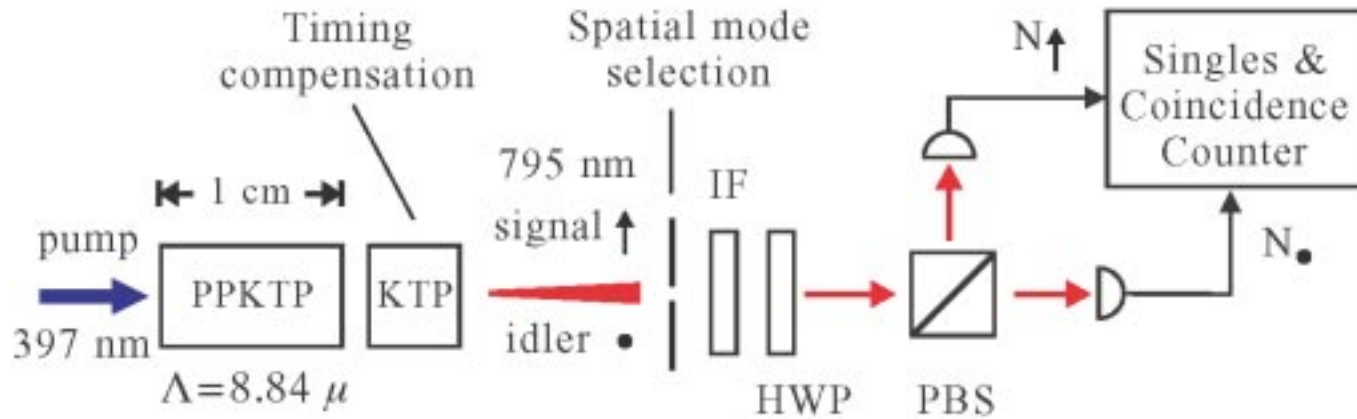
Quantum Transmission over Standard Telecom Fiber



Fixed Loss = 0 dB; Fiber Loss = 0.2 dB/km

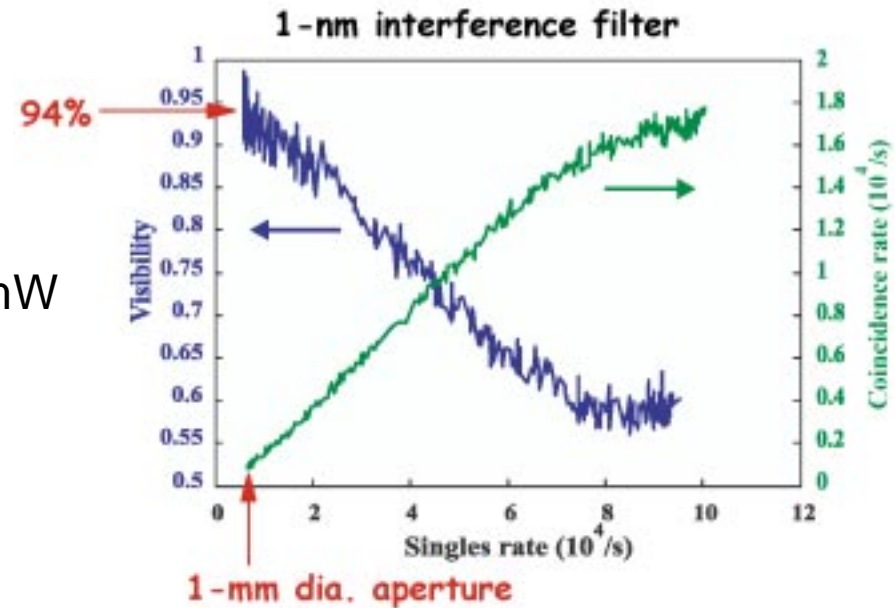
Shapiro *NJP* 2002

PPKTP Parametric Downconverter: Triplet-State Generation at 795 nm

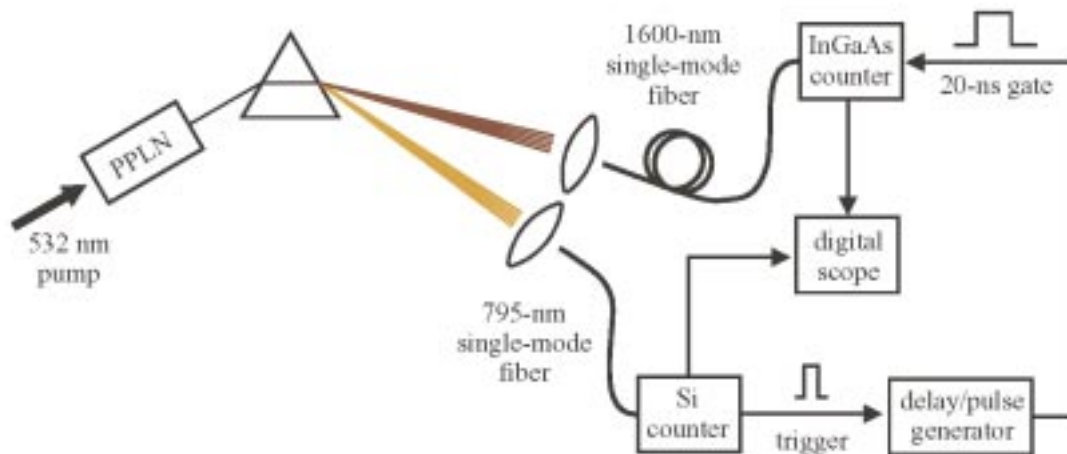


- 10^5 /s detected pair coincidences with 5 mW pump
- Inferred production rate $\sim 3 \times 10^5$ /s/mW
- Overall quantum efficiency 20-25%

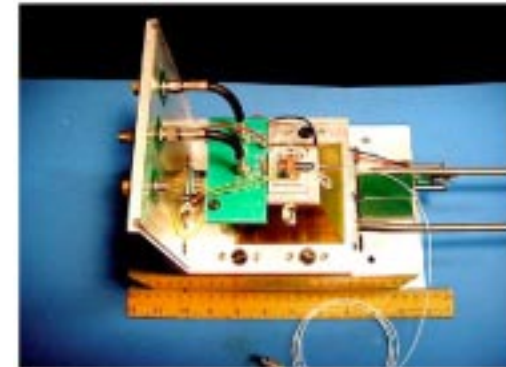
Albota, König, Kuklewicz, Mason,
Messin, Shapiro & Wong
NLO 2002



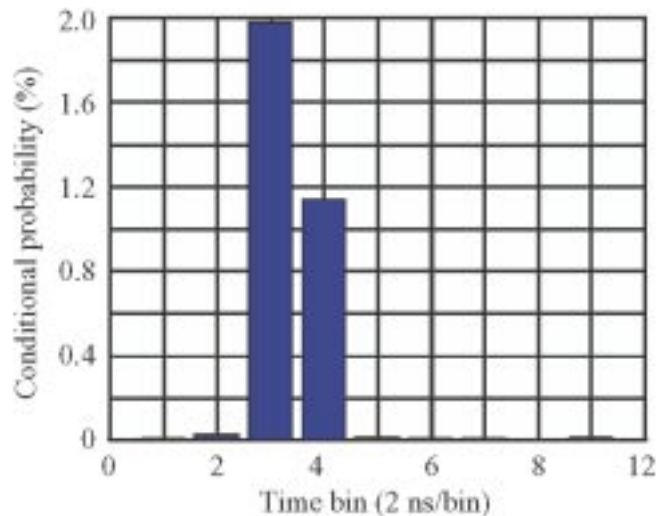
PPLN Parametric Downconverter: Non-degenerate Pair Generation



JDS Uniphase EM239
InGaAs APD in Geiger mode



Gated Signal-Conditioned Idler Detections



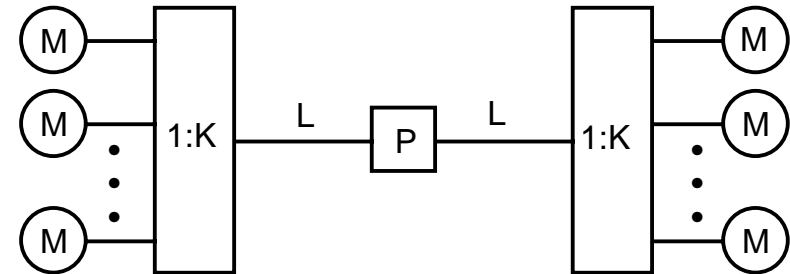
- Time coincidence within a 4-ns time bin
- High SNR (>100)
- Conditional detection probability 3.1%
 - detector quantum efficiency ~20%
 - propagation ~85%
 - fiber coupling ~50%
 - mode matching 36%
- 930 pairs/s/mW detected coincidences

Mason, Albota, König & Wong
Opt Lett 2002

Long-Distance Qubit Teleportation: Single-Photon Error Model and Error Mitigation

K memories at each end of teleportation link

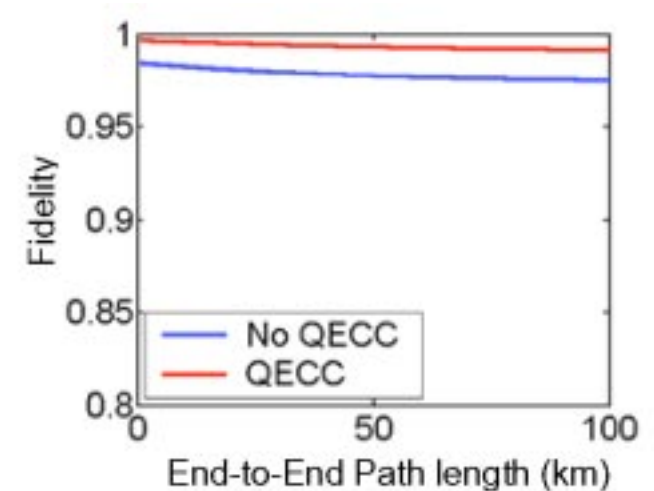
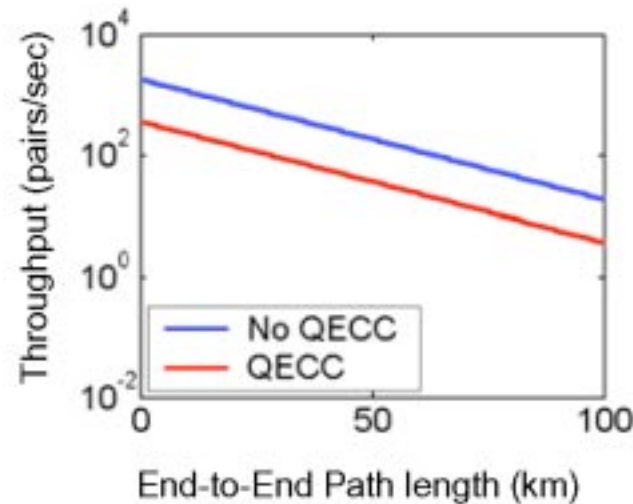
Werner state conditional density operator



$$\hat{\rho} = P_{\text{success}} |\psi^-\rangle_{TR TR} \langle \psi^-| + P_{\text{error}} \left(|\psi^+\rangle_{TR TR} \langle \psi^+| + |\phi^+\rangle_{TR TR} \langle \phi^+| + |\phi^-\rangle_{TR TR} \langle \phi^-| \right) / 3$$

Fidelity improvement vs. throughput loss with 5-qubit quantum error correcting code [Laflamme et al. (PRL 1997)]

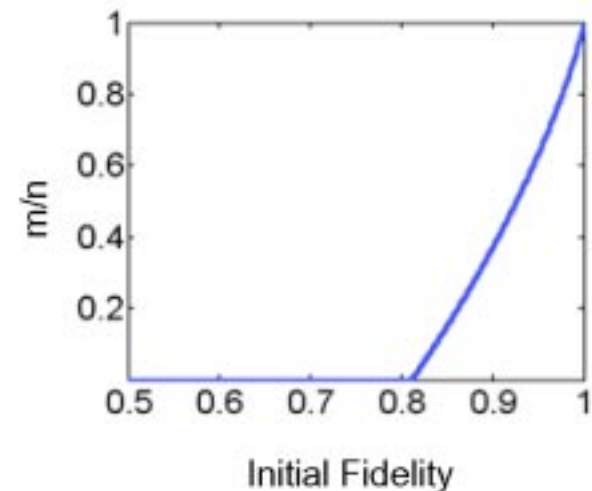
Shapiro, Aung & Yen
Feynman Festival 2002



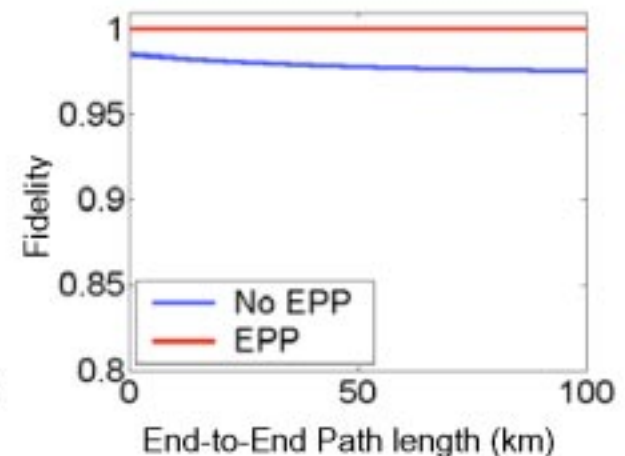
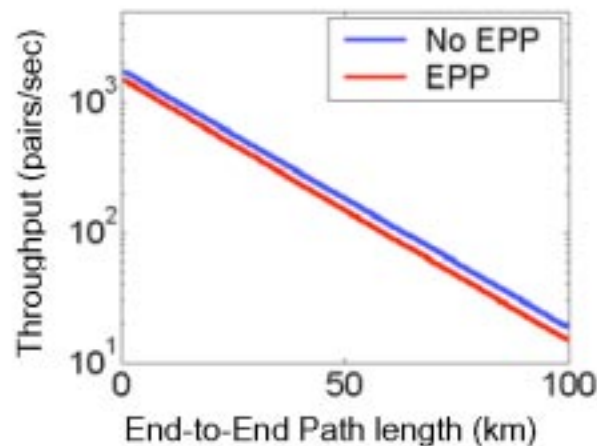
Long-Distance Qubit Teleportation: Error Mitigation via Entanglement Purification

Entanglement purification protocols:

- start with n entangled pairs
- sacrifice $n-m$ pairs to increase fidelity of remaining m pairs
- Bennett et al. one-way hashing (*PRA* 1996)
 - distills m perfect singlets for $n \rightarrow \infty$
 - m/n approaches $1 + \text{tr}[\hat{\rho} \log_2(\hat{\rho})]$ for $n \rightarrow \infty$



Fidelity improvement
vs. throughput loss
with one-way hashing
protocol



Shapiro, Aung & Yen
Feynman Festival 2002

Bi-Photon State with Coincident Frequencies: $M = 2, N = 1$ State for Quantum Position Sensing

Twin-beam state from continuous-wave downconversion

$$|\text{TB}\rangle = \int \frac{d\omega}{2\pi} \frac{\sin(2\pi\omega / \Omega_f)}{2\pi\omega / \Omega_f} |\omega_P / 2 + \omega\rangle_S |\omega_P / 2 - \omega\rangle_I$$

Difference-beam state: $M = 2$ state for quantum positioning

$$|\text{DB}\rangle = \int \frac{d\omega}{2\pi} \alpha(\omega_P + 2\omega) |\omega_P / 2 + \omega\rangle_S |\omega_P / 2 + \omega\rangle_I$$

Type-II pulsed downconversion with extended phase matching

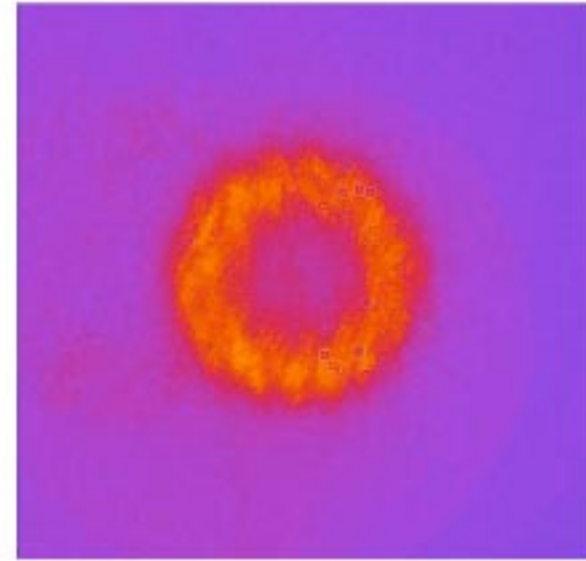
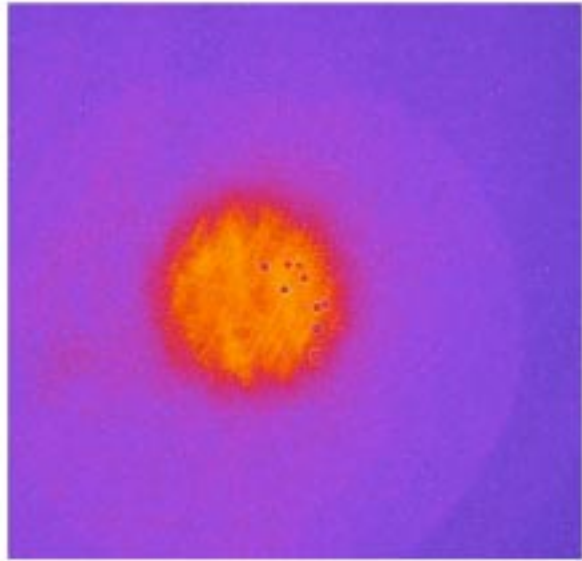
$$n_P(\omega_P) = [n_S(\omega_P / 2) + n_I(\omega_P / 2)] / 2$$

$$k'_P(\omega_P) = [k'_S(\omega_P / 2) + k'_I(\omega_P / 2)] / 2$$

in a long crystal produces the DB state

Giovannetti, Maccone, Shapiro & Wong
PRL 2002

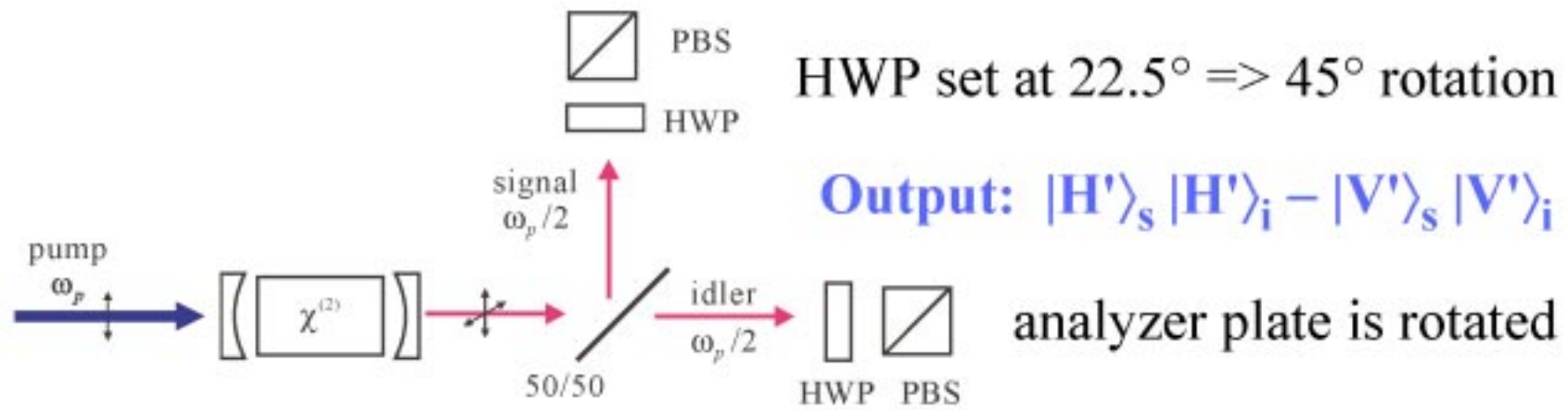
Images of PPKTP Downconverter Outputs



H-polarization Nearly-degenerate outputs V-polarization

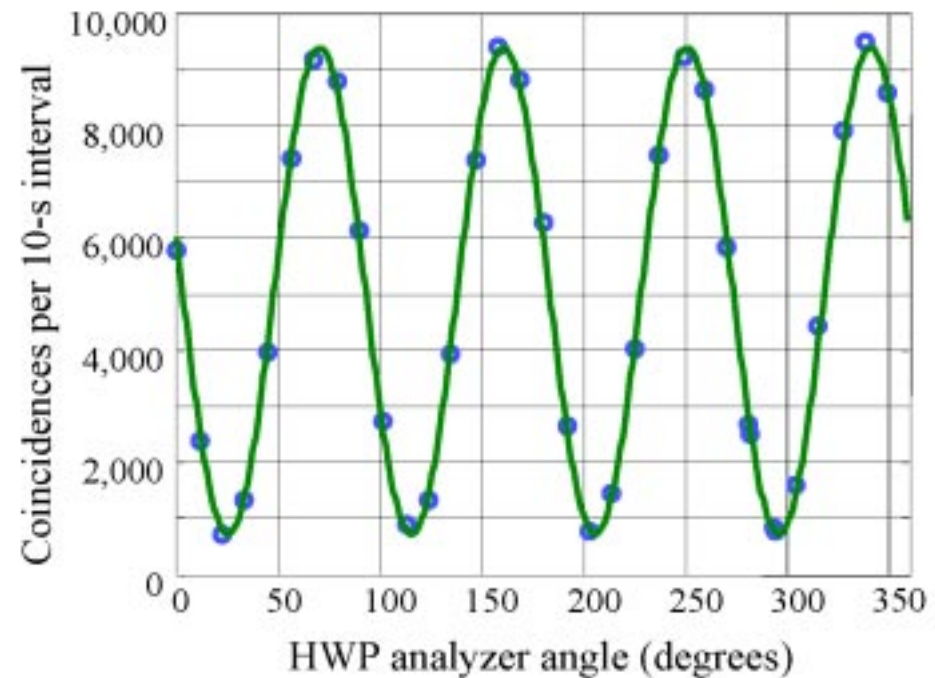
- Degenerate outputs: collinear propagation in a collapsed cone
- Truly collinear only in the small central region
- Nondegenerate outputs: usual cone of outputs can be observed
- Pinholes and interference filters are essential to control the outputs

Bell's Inequality Measurement



Visibility = 86%

max $V = 93.5\%$



Conclusions and Related Work

- MIT-NU collaboration on long-distance quantum teleportation
 - MIT effort on quantum communication architecture
 - MIT effort on ultrabright narrowband entanglement source
 - MIT effort on quantum-state frequency conversion
- Entanglement engineering
 - DB state generation via extended phase-matching
 - Coincidence dips and revivals from a parametric amplifier
- Quantum information theory
 - Quantum multiple-access channel