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Broadband energy entangled photons and their potential for space applications

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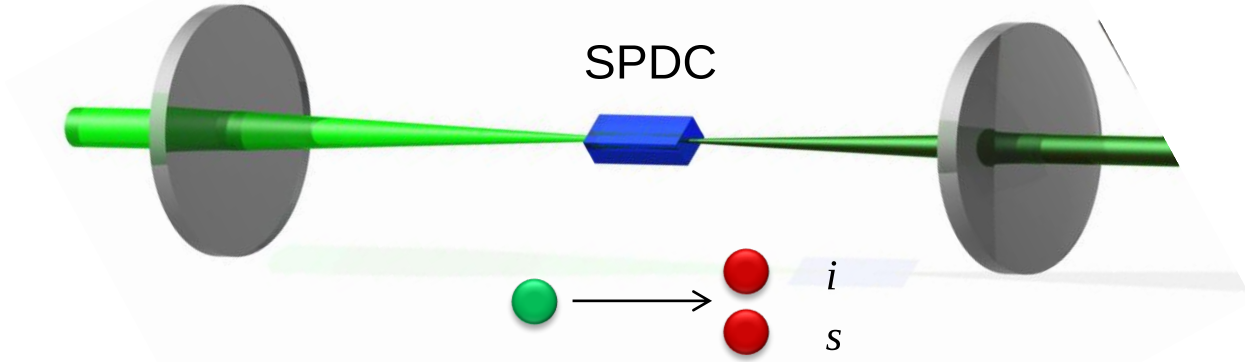
SPDC for quantum communication



Spontaneous parametric downconversion

- Easy
- High quality of states

Losses limit the maximal distance

- Increase the pair production rate
- Increase the information capacity / pair

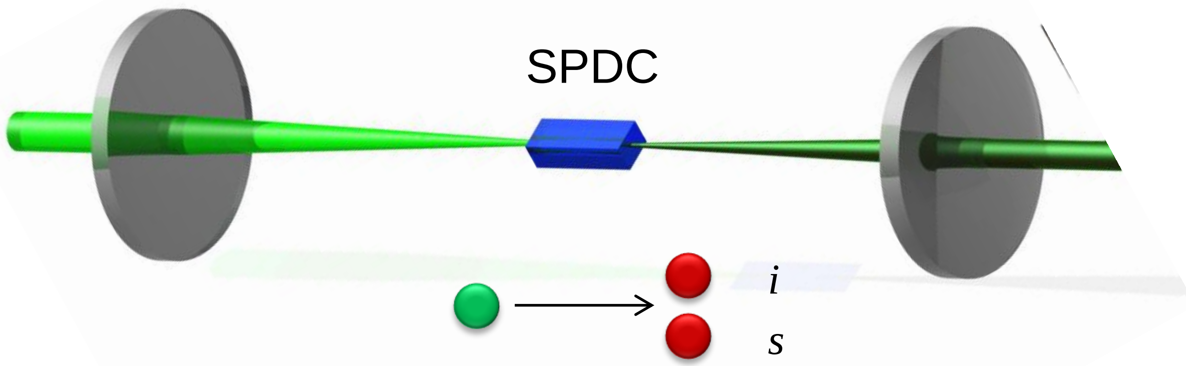
Outlook

- Energy-time photonic entanglement

- Experimental spectral manipulation
    - Quantum Information protocols, Bell Inequalities
    - Ultrafast measurements with CW light

- Conclusion, going to space

Photonic entangled qudits



- Polarization entanglement $$|\phi^+\rangle = \frac{1}{\sqrt{2}}(|H\rangle_i|H\rangle_s + |V\rangle_i|V\rangle_s)$$

- Transverse momentum $$|\psi\rangle = \int_{-\infty}^{\infty} d\mathbf{q}_i \int_{-\infty}^{\infty} d\mathbf{q}_s \, \Lambda(\mathbf{q}_i, \mathbf{q}_s)|1_{\mathbf{q}_i}\rangle_i|1_{\mathbf{q}_s}\rangle_s$$

- Energy entanglement $$|\psi\rangle = \int_{-\infty}^{\infty} d\omega_i \int_{-\infty}^{\infty} d\omega_s \, \Gamma(\omega_i, \omega_s)|1_{\omega_i}\rangle_i|1_{\omega_s}\rangle_s$$

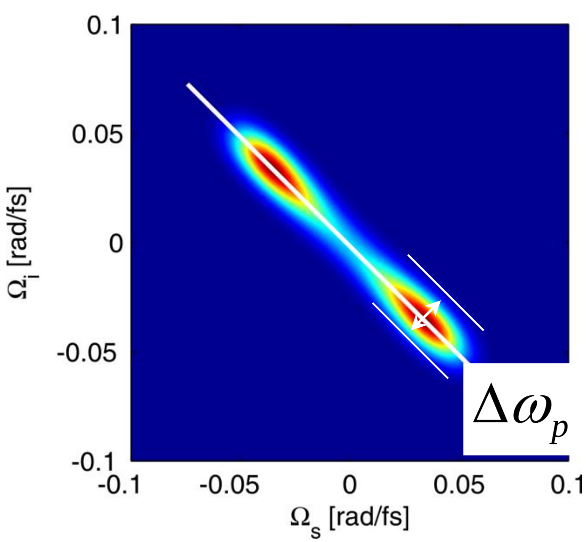
Broadband energy-entangled photons

Combine high temporal resolution with high energy resolution

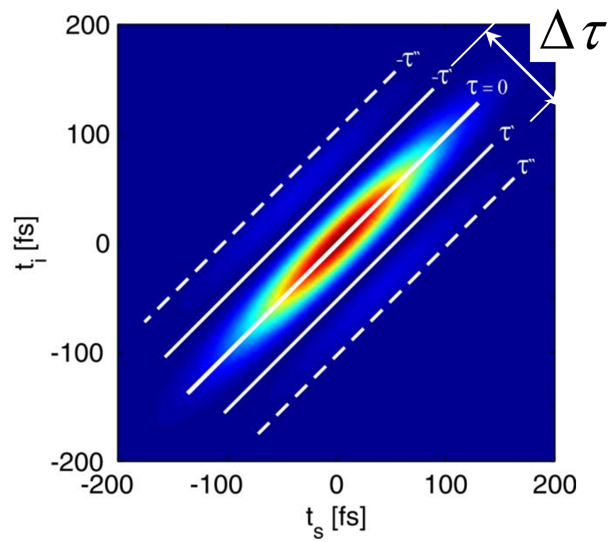
$$|\psi\rangle = \int_{-\infty}^{\infty} d\omega_i \int_{-\infty}^{\infty} d\omega_s \, \Gamma(\omega_i, \omega_s) |1_{\omega_i}\rangle_i |1_{\omega_s}\rangle_s$$

$$\boxed{\omega_p = \omega_s + \omega_i}$$

Join spectral amplitude



Join temporal amplitude

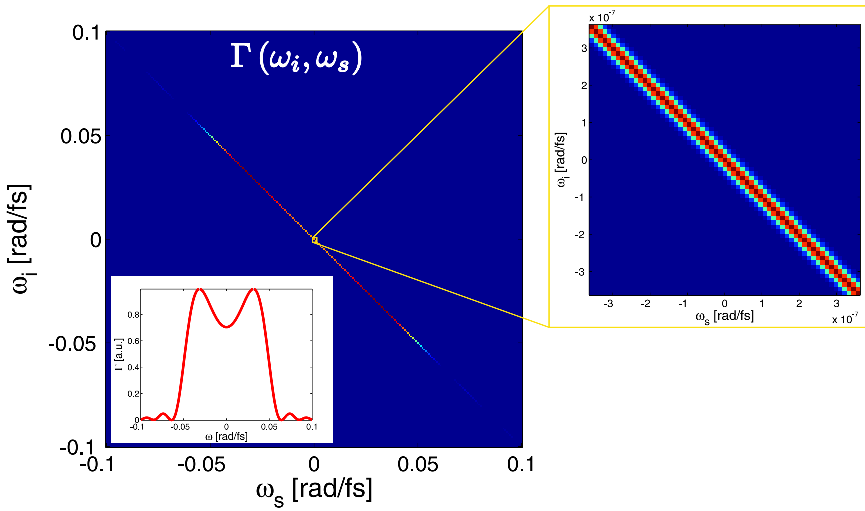


Classical light $\Delta\tau\Delta\omega > 1$

Entangled light $\Delta\tau\Delta\omega_p << 1$

Entropy of Entanglement

Quantify the entanglement of the state $\Gamma(\omega_i, \omega_s)$



Entropy of the subsystem

$$A_i(\omega_i, \omega_i') = \int_{-\infty}^{\infty} d\omega_s \, \Gamma(\omega_i, \omega_s)\Gamma(\omega_i', \omega_s)$$

$$E(\boldsymbol{A}) = -\sum_{\lambda \in \sigma(\boldsymbol{A})} \lambda \log_2(\lambda)$$

Numerical computation

CW pump field $\Longrightarrow$ large discretized matrices: $m = 72 \times 10^6$

Compute E without diagonalization of $\boldsymbol{A}$: $E(\boldsymbol{A}) = 21.1 \pm 0.2\,\text{ebits}$

$\Leftrightarrow$ maximally entangled qudit with $d = 2^E \approx 2.2 \times 10^6$

T.P. Wihler, B. Bessire, A.S. Journal of Physics A,47(24), 245201 (2014).

Outlook

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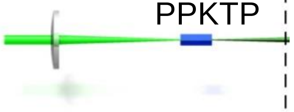
Experiment

Setup

Preparation
(SPDC)

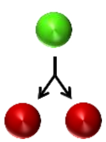
532 nm

PPKTP



$\Delta\nu_p \approx 5\ \mathrm{MHz}$

5 W pump laser



1064 nm

1 µW

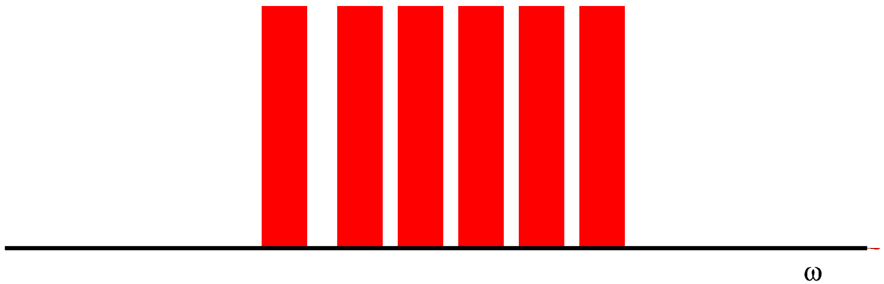
Detected signal after the SFG process:

$$S \propto \left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} d\omega_i d\omega_s \Gamma(\omega_i, \omega_s) M(\omega_i, \omega_s) \right|^2$$

$\Rightarrow$ Sensitive to a phase in the SLM transfer function $M(\omega_i, \omega_s) = M^i(\omega_i) M^s(\omega_s)$

A. Pe'er, B. Dayan, A. A. Friesem, and Y. Silberberg, Phys. Rev. Lett. **94**, 073601 (2005)

Frequency-bins



Maximally entangled qutrit $|\psi\rangle^{(d)} = 1/\sqrt{3}(|0\rangle|0+\rangle|1\rangle|1\rangle + |2\rangle|2\rangle)$

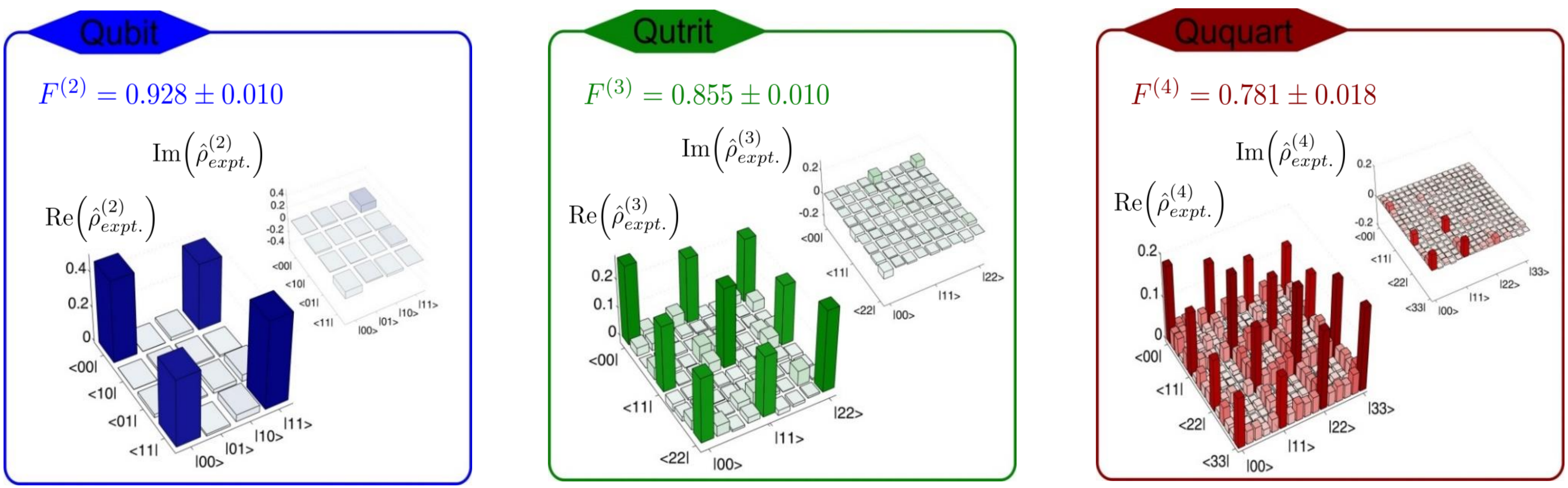
In general $|\psi\rangle^{(d)} = 1/\sqrt{2+\gamma^2}(|0\rangle|0\rangle + \gamma|1\rangle|1\rangle + |2\rangle|2\rangle)$

Quantum State tomography

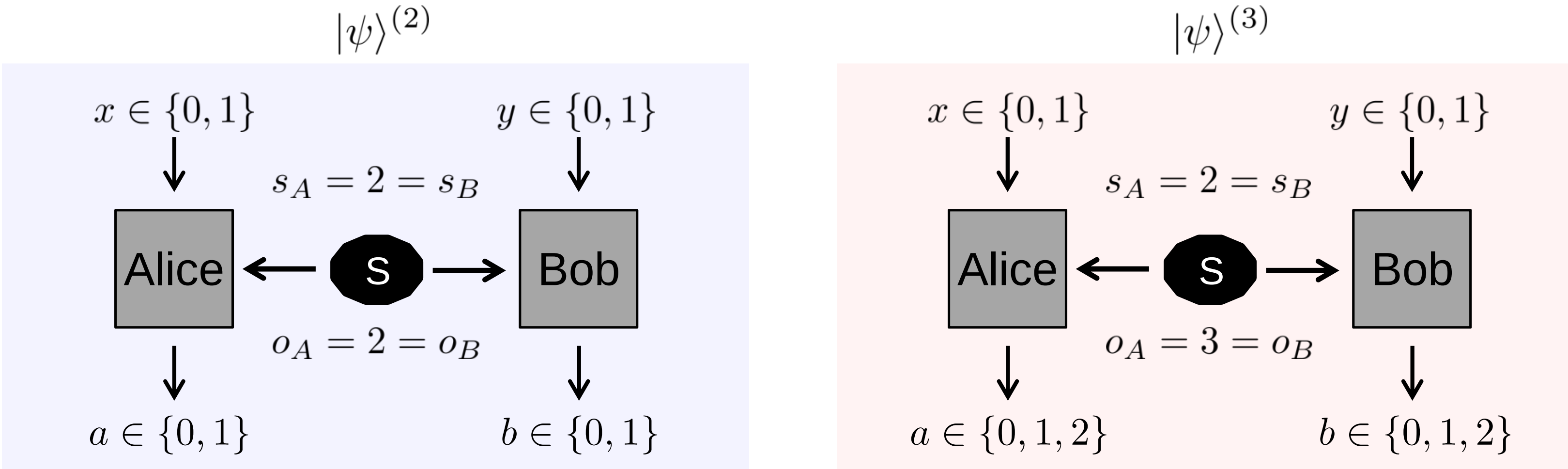
Detected signal is equivalent to the signal of a projective measurement

$$S \propto \left| \langle \chi | \psi \rangle^{(d)} \right|^2 \quad \text{with} \quad |\chi\rangle = \left(\sum_{j=0}^{d-1} u_j^{i*} |j\rangle_i \right) \left(\sum_{j'=0}^{d-1} u_{j'}^{s*} |j'\rangle_s \right)$$

Reconstruction of density matrices for maximally entangled qudits by Maximum Likelihood Estimation



Collins-Gisin-Linden-Massar-Popescu (CGLMP) inequality



B_{2222} B_{2233}

$$I_{2,3}^{\mathrm{CGLMP}} = +\left[P(A_1 = B_1) + P(A_1 = B_1 + 1) + P(A_2 = B_2) + P(A_2 = B_1)\right] - \left[P(A_1 = B_1 - 1) + P(A_1 = B_2) + P(A_2 = B_2 - 1) + P(A_2 = B_1 - 1)\right] \leq 2$$

where the above probabilities are sums of joint probabilities given by

$$P(A_x = B_y + k) = \sum_{j=0}^{d-1} P(A_x = j, B_y = j + k \bmod d) = \sum_{j=0}^{d-1} P(j(j + k \bmod d)|xy)$$

D. Collins, et. al., Phys. Rev. Lett. 88, 040404 (2002)

CGLMP inequalities (with frequency-bins)

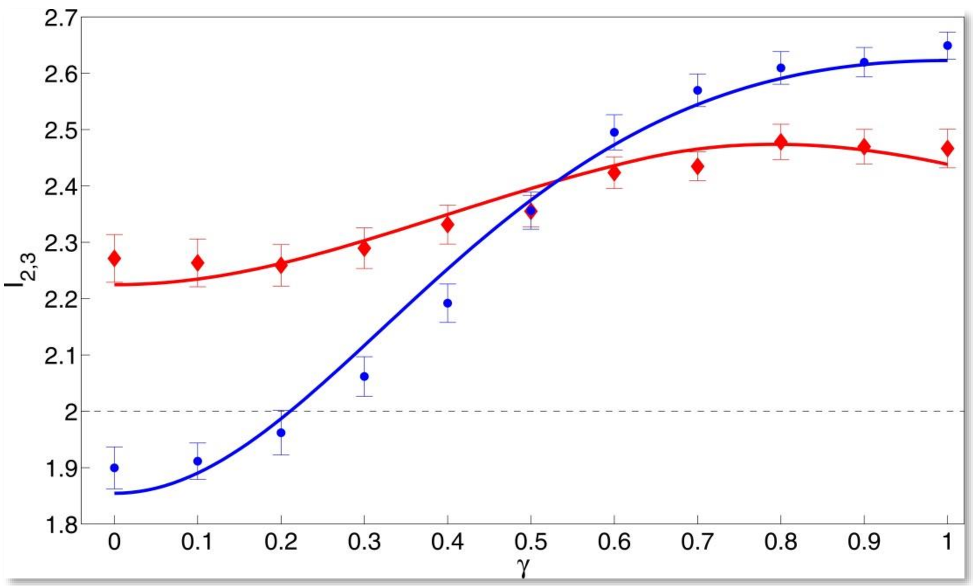
A *non*-maximally entangled qutrit state violates CGLMP stronger than a maximally entangled qutrit

2-qubit state with a γ:

$$|\psi(\gamma)\rangle^{(2)} = \frac{1}{\sqrt{1+\gamma^2}}(|0\rangle_i|0\rangle_s + \gamma|1\rangle_i|1\rangle_s)$$

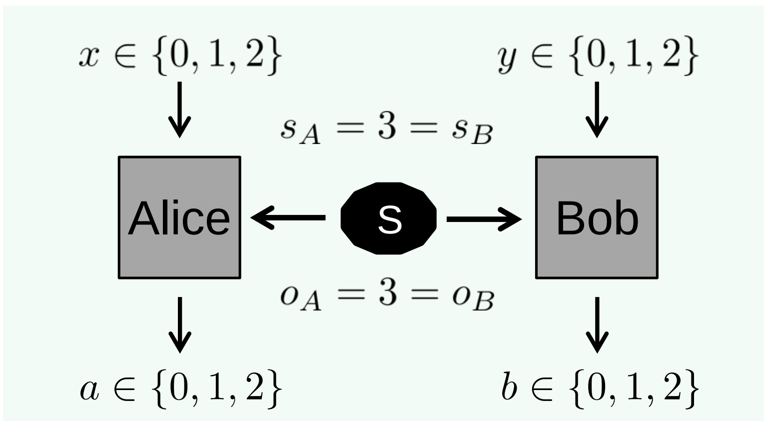
2-qutrit state with a γ:

$$|\psi(\gamma)\rangle^{(3)} = \frac{1}{\sqrt{2+\gamma^2}}(|0\rangle_i|0\rangle_s + \gamma|1\rangle_i|1\rangle_s + |2\rangle_i|2\rangle_s)$$

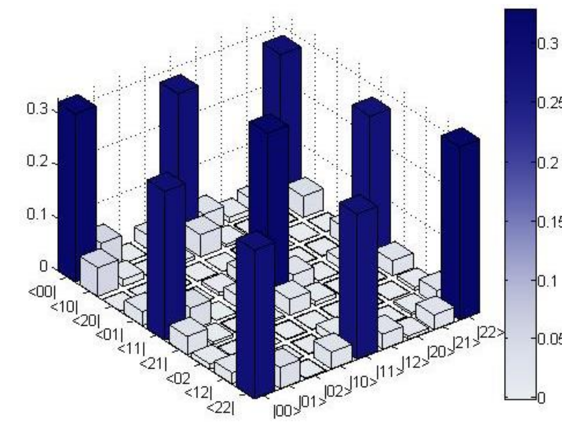


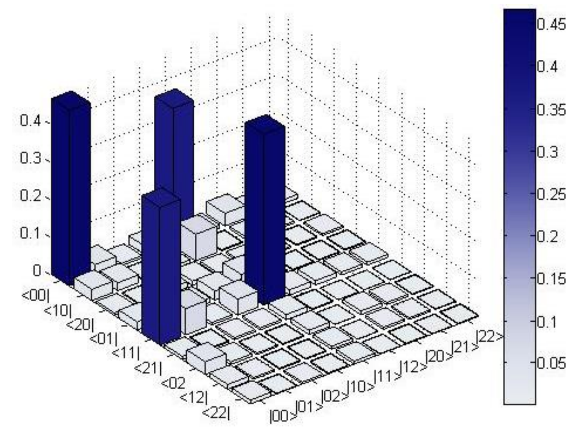
S. Schwarz, et al. (2015). IJQI, 12, 1560026.

Multisettings Bell Scenario



B_{3333}



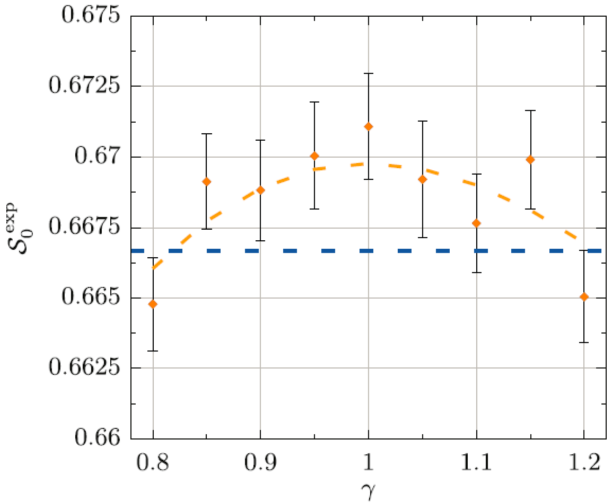


Some multisettings Bell inequalities can be maximally violated already with entangled two-qubit states

2-party, 3-Input, 3-Output Bell scenario

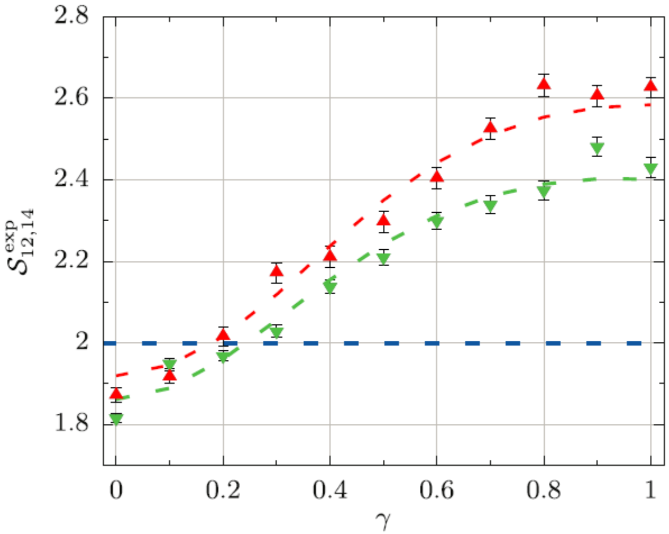
Maximally violated by maximally entangled qutrits

$$|\psi(\gamma,1)\rangle = \frac{|0\rangle_A|0\rangle_B + \gamma|1\rangle_A|1\rangle_B + |2\rangle_A|2\rangle_B}{\sqrt{2+\gamma^2}}$$



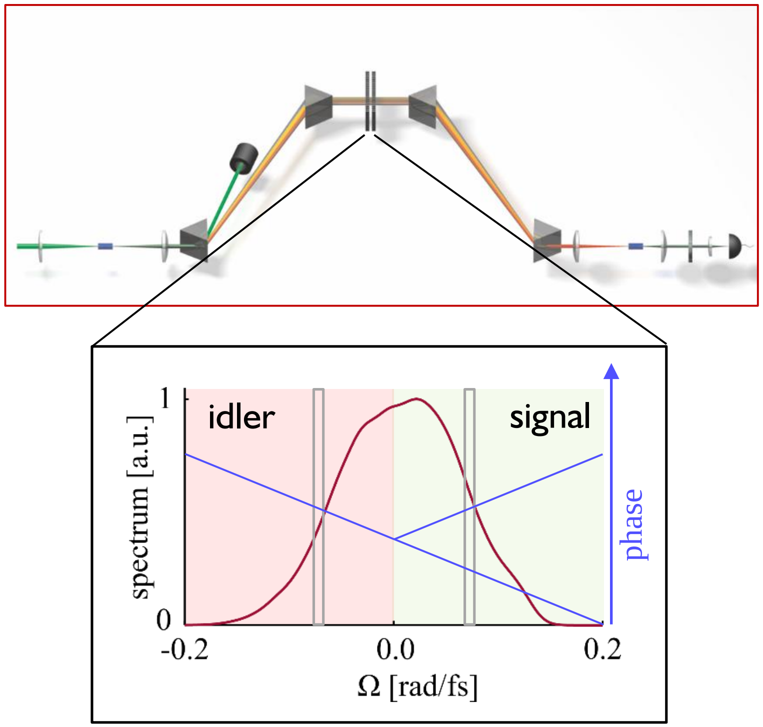
Maximally violated by entangled qubits

$$|\psi(\gamma,0)\rangle = \frac{|0\rangle_A|0\rangle_B + \gamma|1\rangle_A|1\rangle_B}{\sqrt{1+\gamma^2}}$$

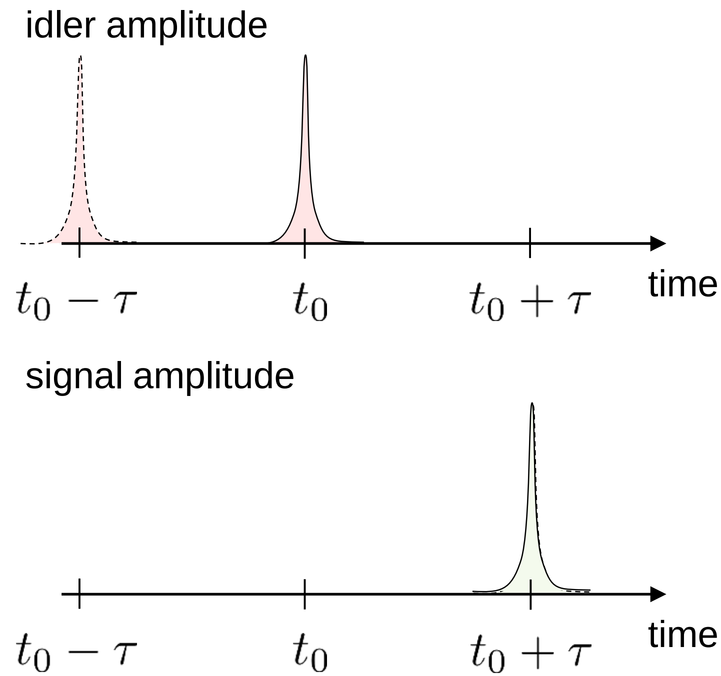


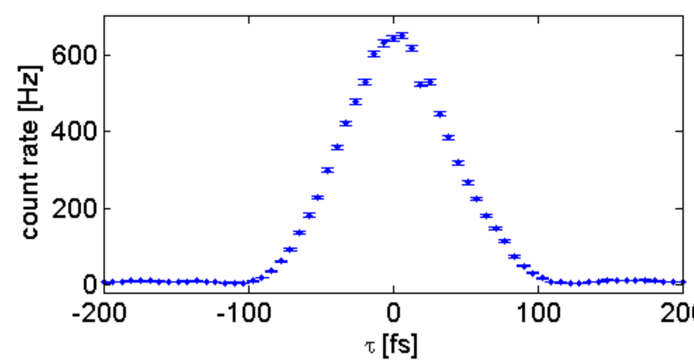
S. Schwarz, et al. NJP, 18(3), 035001 (2016)

Time shift between signal and idler



$$M(\Omega) = \exp\{-i|\Omega|\tau\}$$



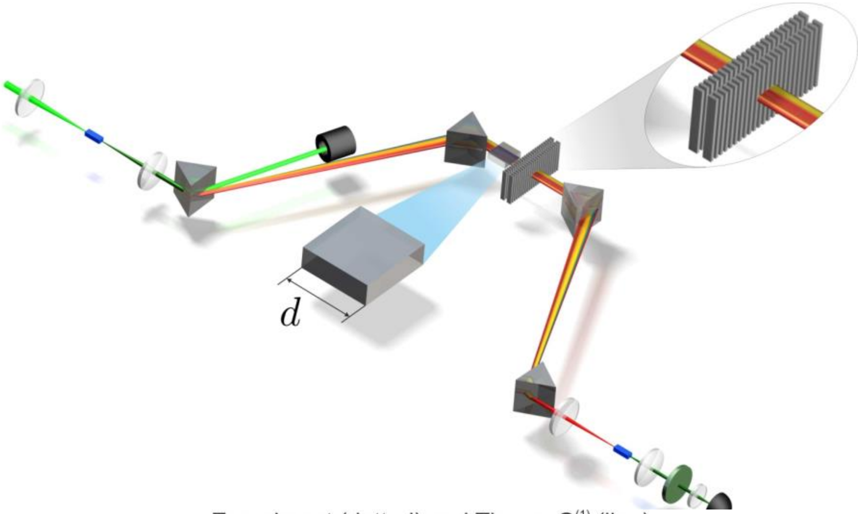


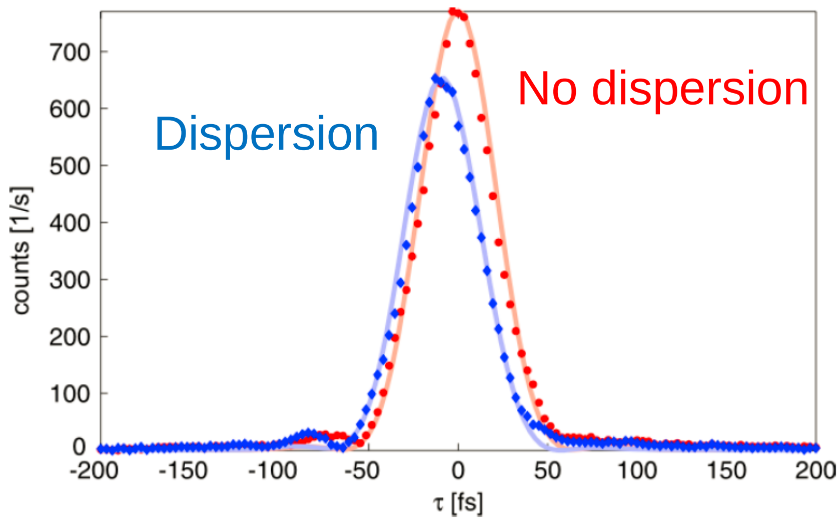
Sensitivity to dispersion

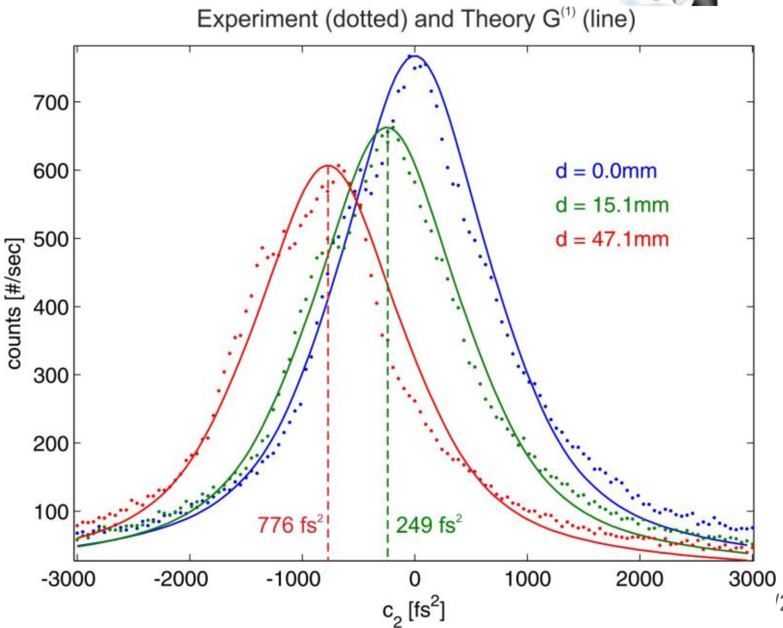
Two photon correlation function $|\Psi(t)|^2$

- Fourier transform of $\Gamma(\omega)$
- Propagates like a fs pulse

… but CW







Dispersion cancellation by entanglement

Minimal broadening of the arrival time difference

minimal broadening

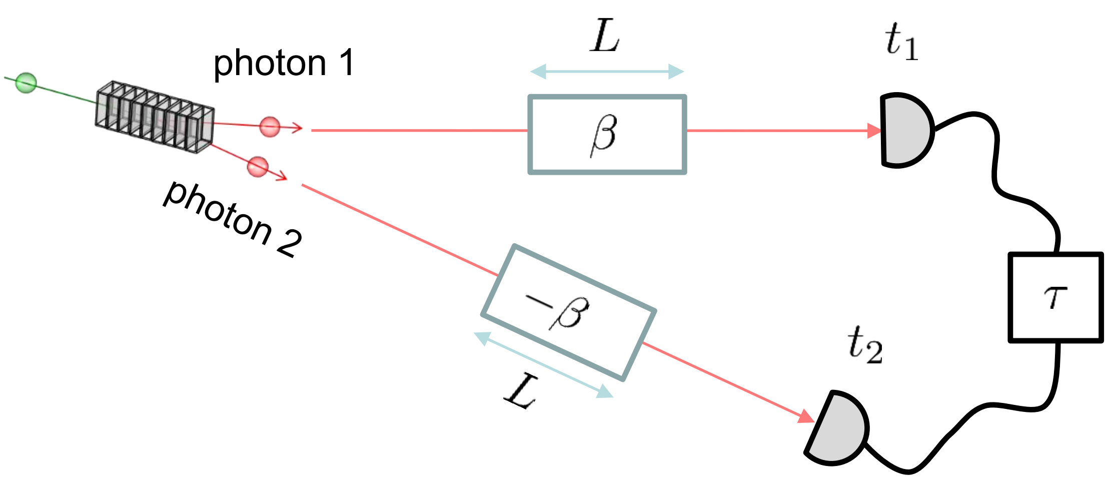
$$(\Delta\tau')^2 \geq (\Delta\tau)^2$$

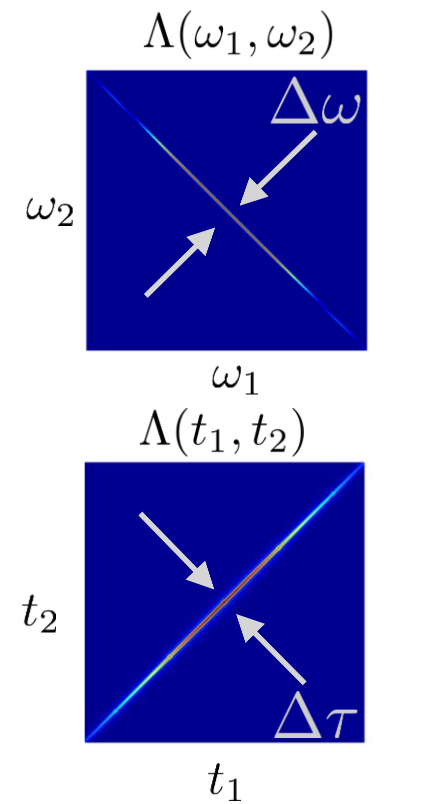
⟷

separable states

$$(\Delta\tau)^2(\Delta\omega)^2 \geq 1$$

$$\tau \doteq t_1 - t_2$$
$$\omega \doteq \omega_1 + \omega_2$$



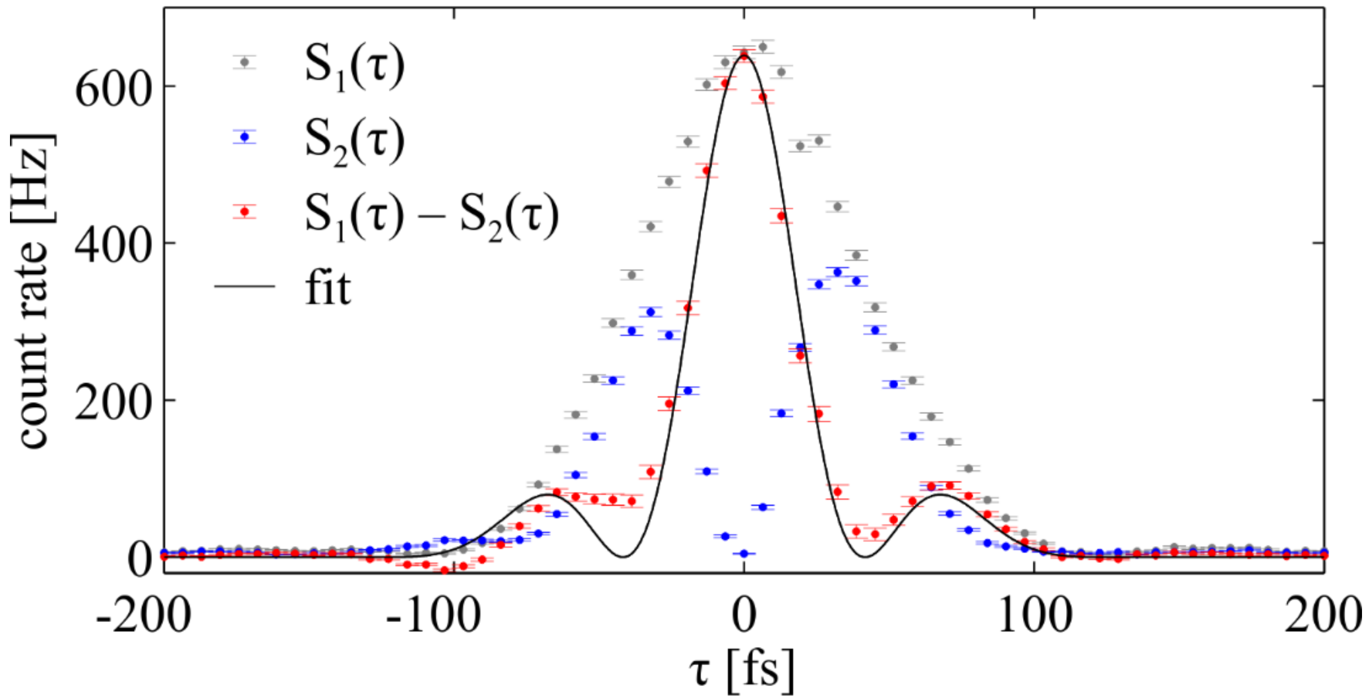


$\Delta\tau$ is the width of $G^{(2)}(t_1 - t_2)$

Measure of G$^{(2)}$

Target function is expressed by two signals

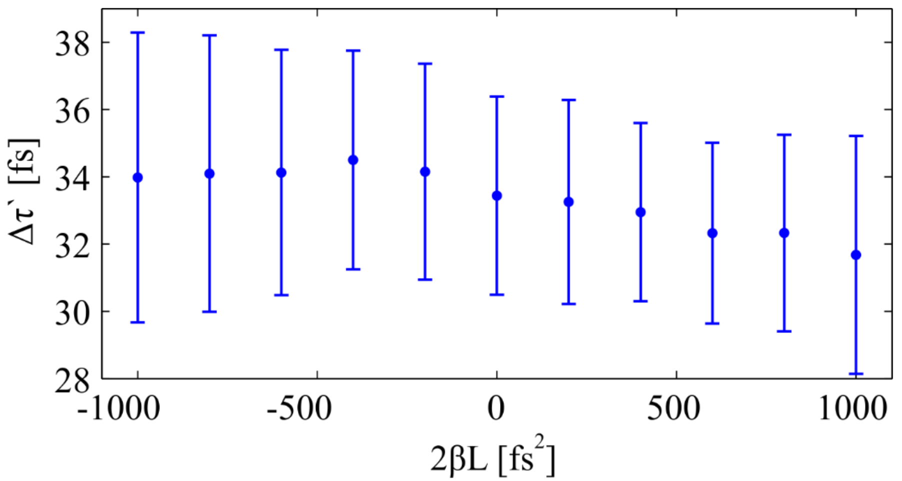
$$G^{(2)}(\tau) \propto S_1[M_1(\Omega)M_\beta(\Omega)] - S_2[M_2(\Omega)M_\beta(\Omega)]$$



Violation of classical inequality

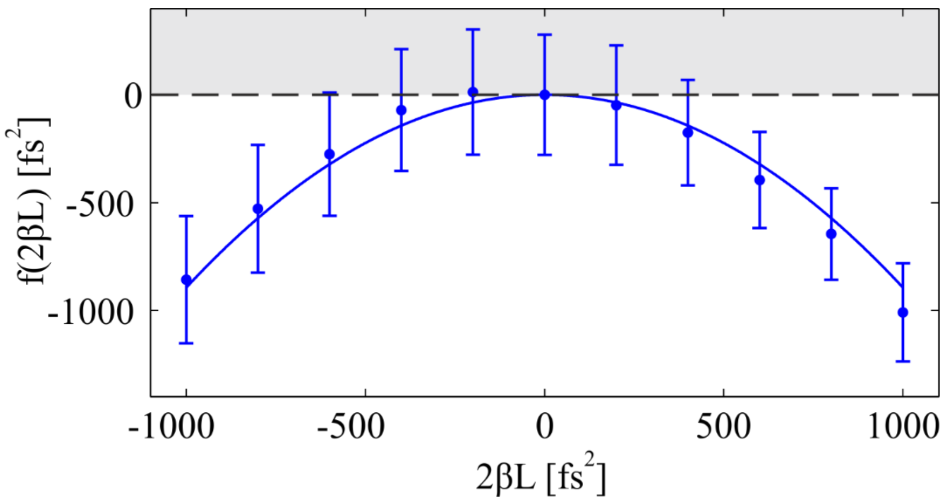
No broadening observed

$$(\Delta\tau')^2 \geq (\Delta\tau)^2 + \frac{(2\beta L)^2}{(\Delta\tau)^2}$$



Violation of minimal broadening

$$\begin{aligned} f(2\beta L) &\doteq (\Delta\tau')^2 - (\Delta\tau)^2 - \frac{(2\beta L)^2}{(\Delta\tau)^2} \\ &\geq 0 \end{aligned}$$



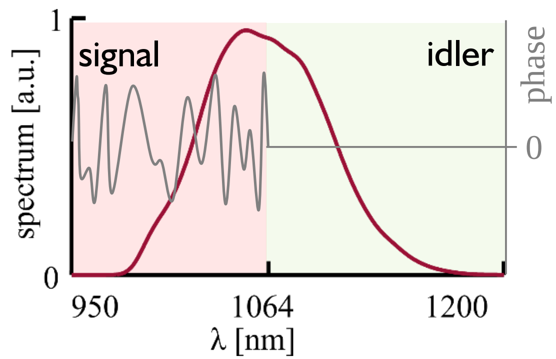
S.Lerch, et al., JOSA B, 50, 055505 (2017)

From entanglement to classical correlation

Entangled two-photon state

$$|\Psi_j\rangle = \int d\Omega \ \Lambda(-\Omega,\Omega) M_j(\Omega) M_j(-\Omega) \left|\Omega\right\rangle_s \left|-\Omega\right\rangle_i , \quad \hat{\rho}_j = |\Psi_j\rangle \langle\Psi_j|$$

Random phase at SLM → destroy fixed phase relation (coherence) between signal and idler



State becomes a weighted mixture

Quantum correlations

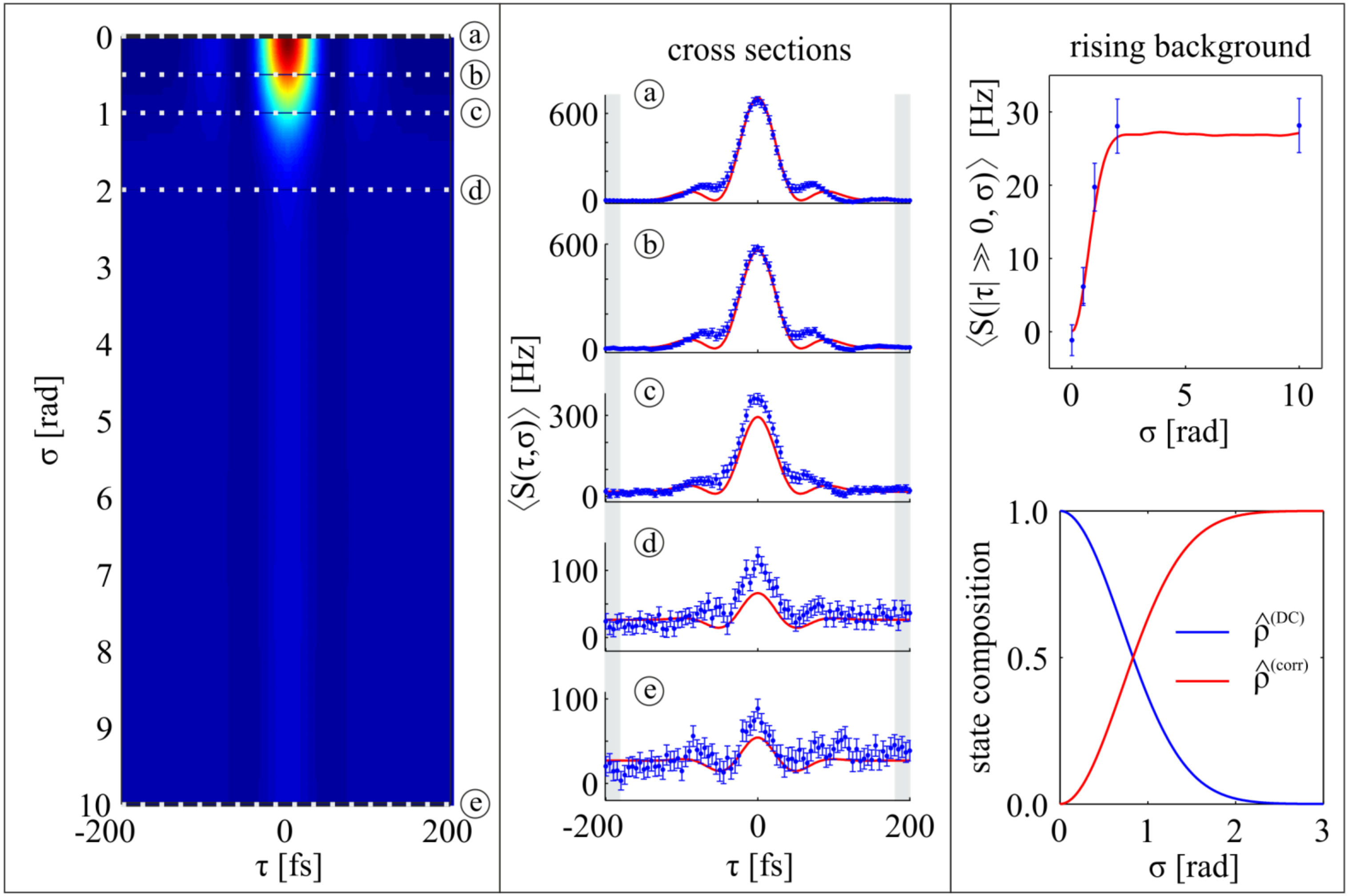
$$\hat{\rho} = e^{-\sigma^2} \left(\int d\Omega \ \Lambda(-\Omega,\Omega) \left|\Omega\right\rangle_s \left|-\Omega\right\rangle_i \right) \left(\int d\Omega' \ \Lambda(-\Omega',\Omega') \left\langle\Omega'\right|_s \left\langle-\Omega'\right|_i \right)$$

$$\left(1 - e^{-\sigma^2}\right) \left\{ \int d\Omega \ |\Lambda(-\Omega,\Omega)|^2 \left[\left|\Omega\right\rangle_s \left|-\Omega\right\rangle_i {}_i\!\left\langle-\Omega\right| {}_s\!\left\langle\Omega\right| \right.\right.$$
$$\left.\left. + (1-\delta(\Omega)) \left|\Omega\right\rangle_s \left|-\Omega\right\rangle_i {}_i\!\left\langle\Omega\right| {}_s\!\left\langle-\Omega\right| \right] \right\}$$

Classical correlations

From entanglement to classical correlation

Arrival time difference between signal and idler



Outlook

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- Conclusion, going to space

Conclusion, going to space

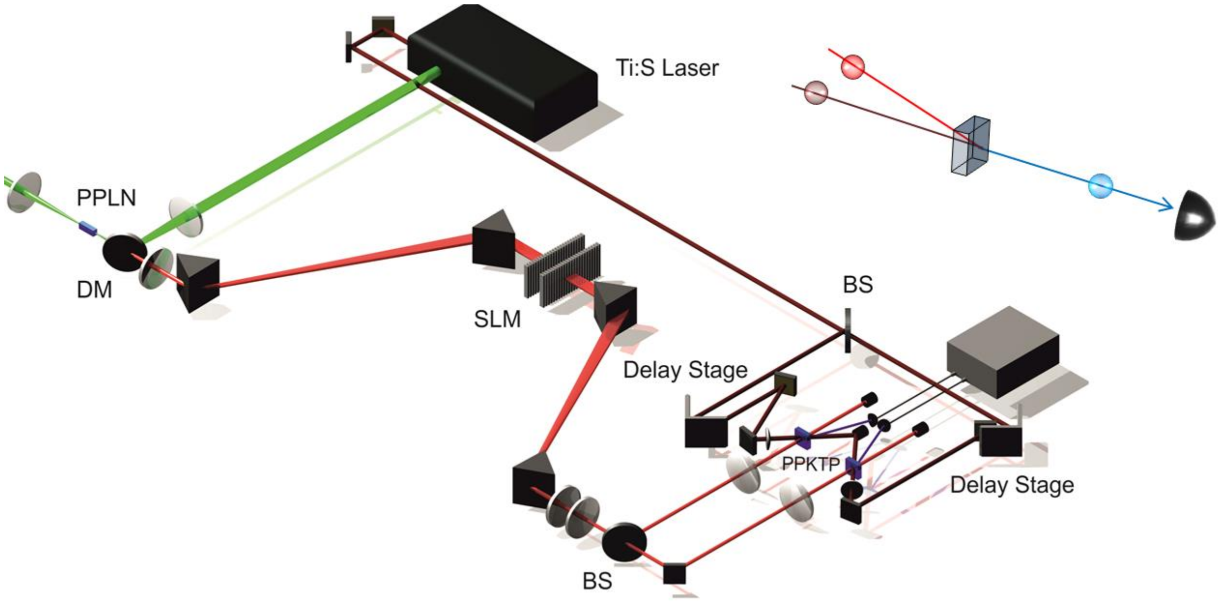
Broadband entangled photons

High temporal resolution

Large dimensional entanglement

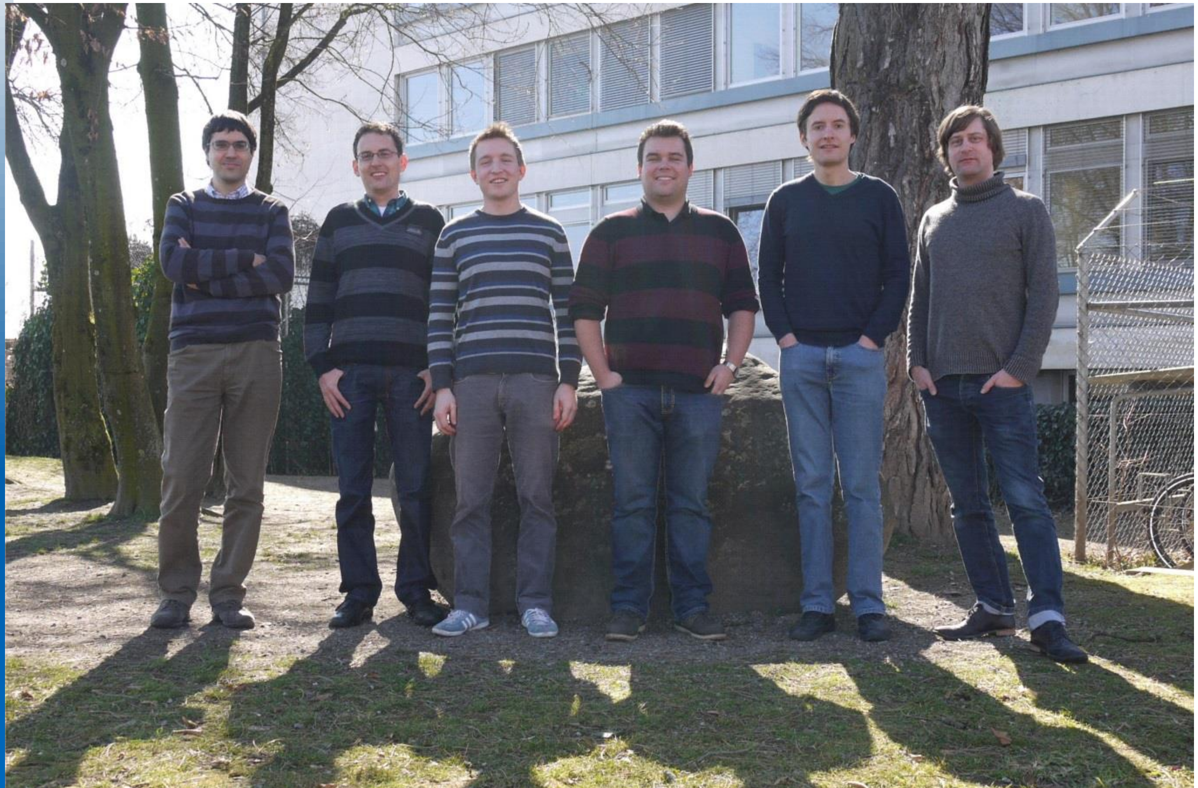
Futur: High rate single photon detection with fs resolution

Non-local detection with fs timing resolution



Increase the duty cycle by space-time coupling

Ackowledgement



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Thank you for your attention!

FNSNF Swiss National Science Foundation

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