Pure photons for continuous-variables

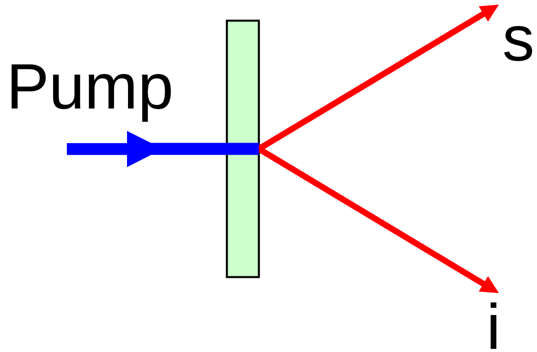
Jeff Lundeen, Peter Mosley, Alfred U'ren, Christine Silberhorn, Ian Walmsley

Outline

1. What are “pure” photons and why should you buy them.
2. Why pure photons are important for continuous variable systems.
3. A look at our all new twin-beam source.

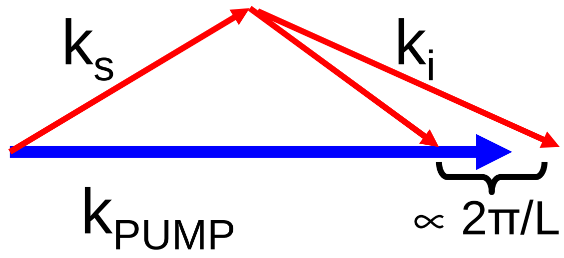
Spontaneous Parametric Downconversion

Downconversion

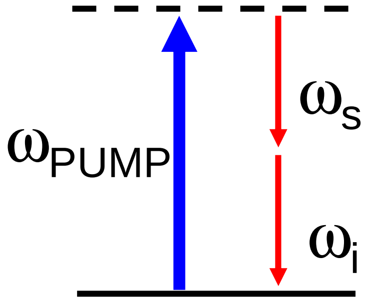


- A pump photon is spontaneously converted into two lower frequency photons in a material with a nonzero $\chi^{(2)}$

Momentum is conserved..

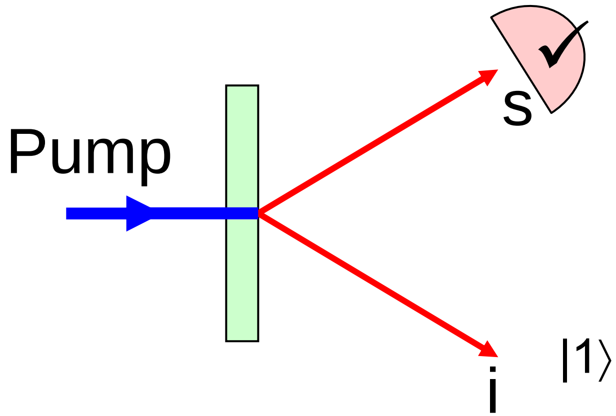


..as well as energy

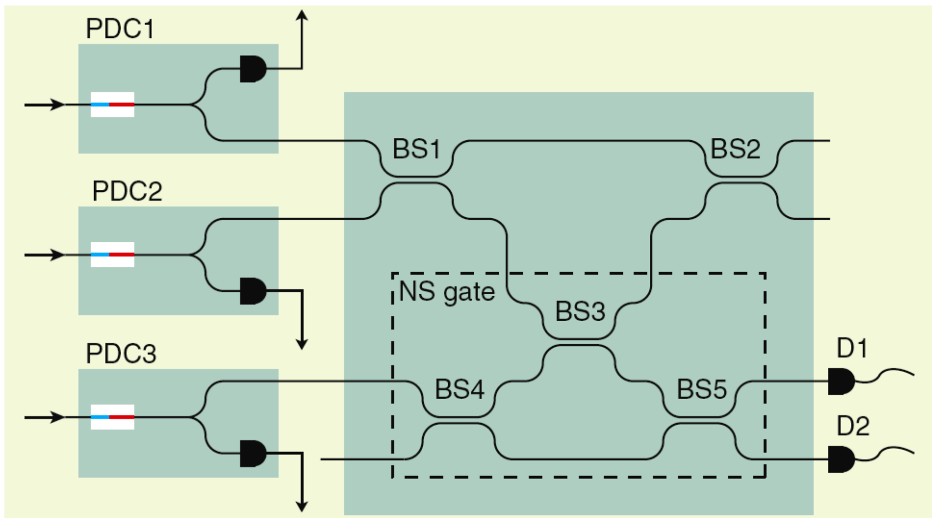


$\varphi_{PUMP} = \varphi_s + \varphi_i$

Heralded Single-Photons



- Discrete Variable measurement-based quantum-computing requires heralded photons and a quantum memory



T. Ralph, A. W. nad W.J. Munro, and G. Milburn, "Simple scheme for efficient linear optics quantum gates," Phys. Rev. A **65**, 012314 (2001).

The Two-photon Spectrum

$$|\psi\rangle \propto \iint d\omega_s d\omega_i f(\omega_s,\omega_i) a^\dagger(\omega_s) a^\dagger(\omega_i)|vac\rangle,$$

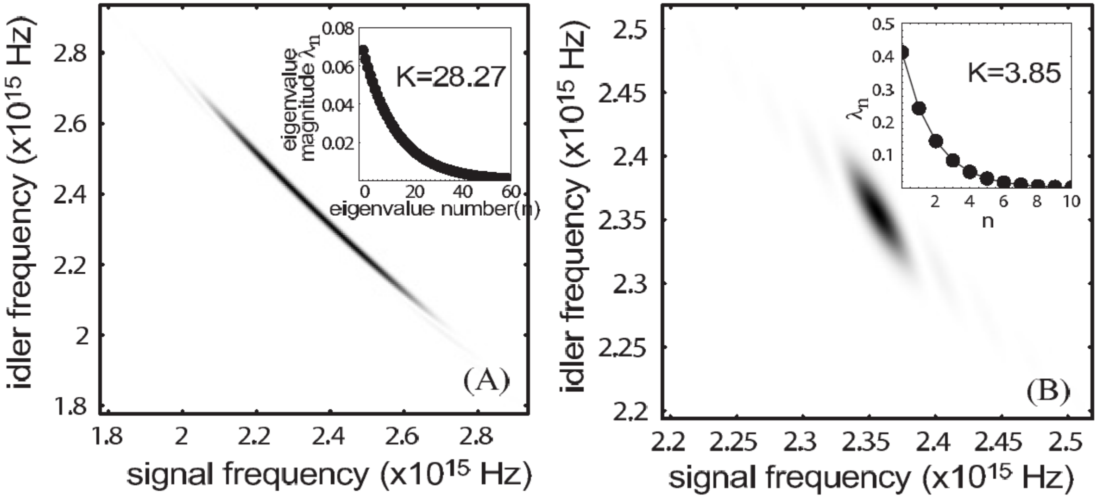
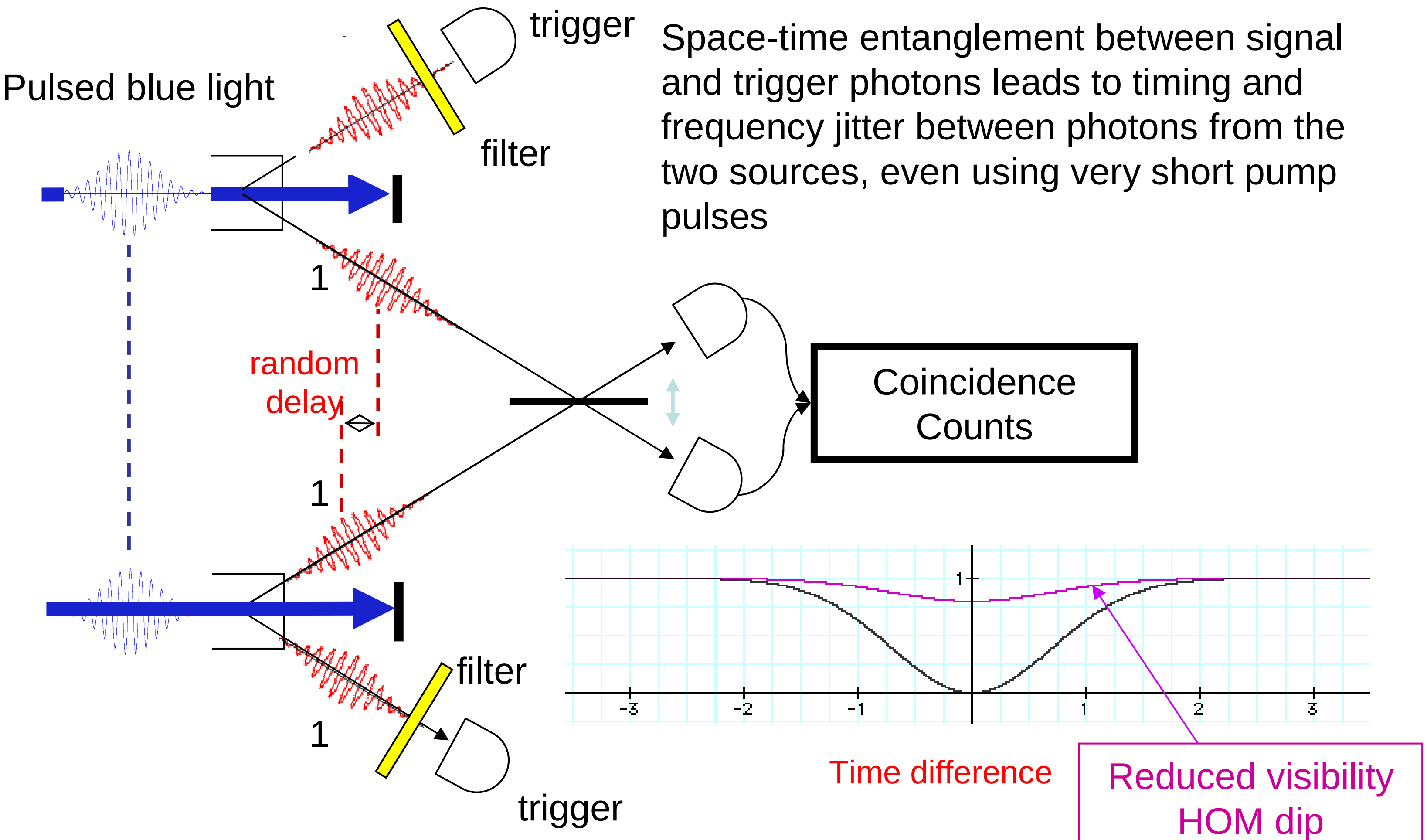


Figure 2.4: Joint spectral intensity of ultrafast-pumped (15 nm bandwidth) PDC centered at 800 nm from a 1 mm long BBO crystal. (A) shows an example of a two photon state involving non-collinear type I phase- matching and (B) shows a two photon state in the case of collinear type II phase matching. Note that type I PDC has a higher degree of spectral entanglement as quantified by the value of the cooperativity parameter K.

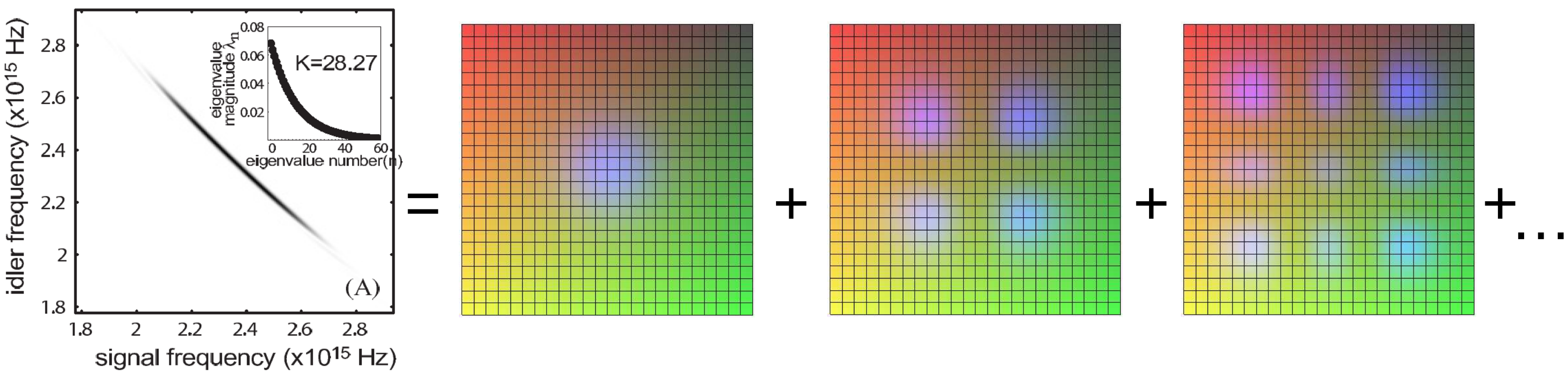
Timing Jitter

Space-time entanglement between signal and trigger photons leads to timing and frequency jitter between photons from the two sources, even using very short pump pulses



The Schmidt-mode Decomposition

$$f(\omega_s, \mathbf{k}_s^\perp, \mu_s; \omega_i, \mathbf{k}_i^\perp, \mu_i) = \sum_n \sqrt{\lambda_n}\psi_n(\omega_s, \mathbf{k}_s^\perp, \mu_s)\phi_n(\omega_i, \mathbf{k}_i^\perp, \mu_i)$$



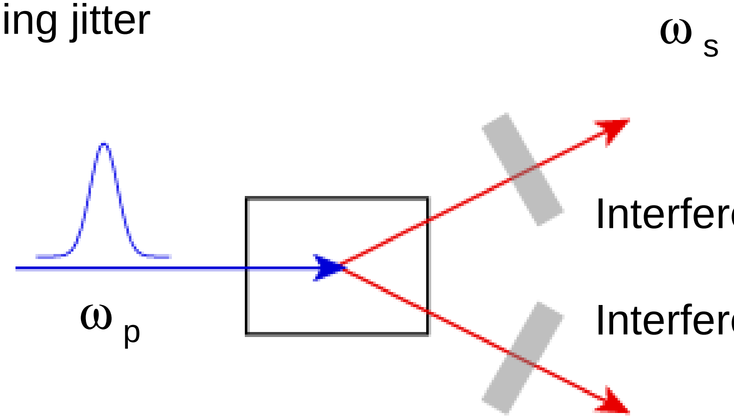
Purity, $\pi = \mathrm{Tr}(\rho_s'^2) = \sum_k \lambda_k^2$

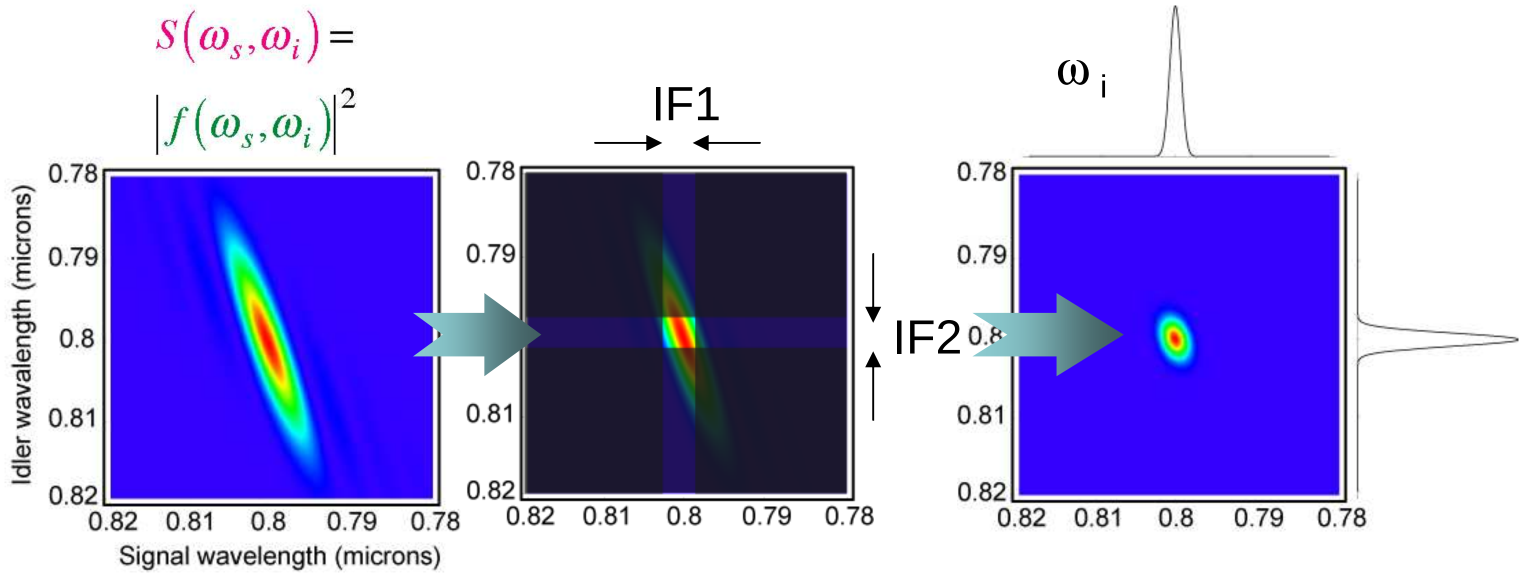
$\pi = \frac{1}{K}$ → Schmidt number

• The joint spectrum can be decomposed into a sum of seperable of seperable states.

Filtering

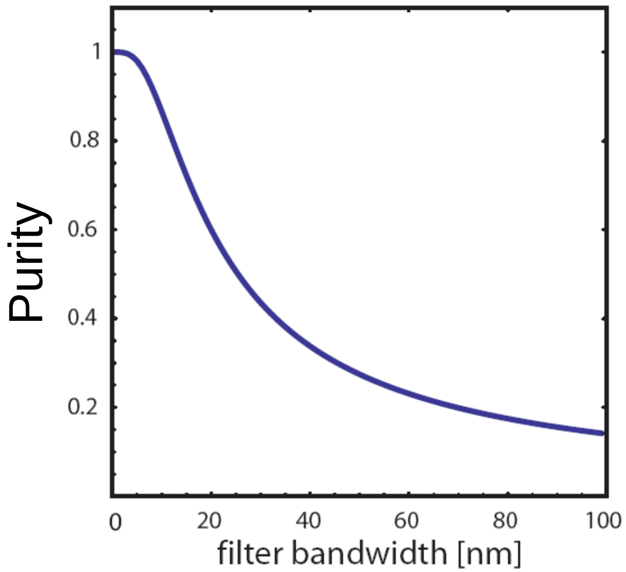
• Spectral filtering can remove correlations by making the photon duration larger than the timing jitter





Asymptotic Purity

- With tight enough filters the two-photon state will be pure



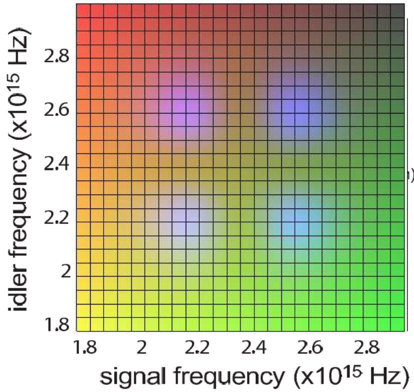
Filtering with a joint spectrum characterized by a correlation width of 10nm

- But filtering comes with reduced count rates .. so you can't win.
- Is it possible to eliminate entanglement at the source?

Types of Filters

- If we could project onto one Schmidt mode, the other photon would be left in the pure state of the conjugate Schmidt mode

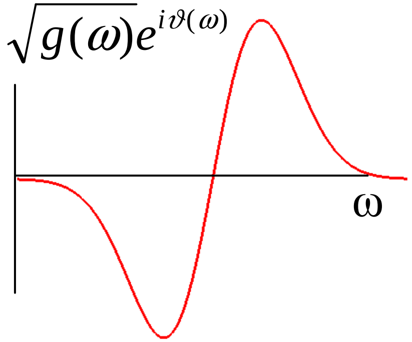
$$f(\omega_s, \mathbf{k}_s^\perp, \mu_s; \omega_i, \mathbf{k}_i^\perp, \mu_i) = \sum_n \sqrt{\lambda_n} \psi_n(\omega_s, \mathbf{k}_s^\perp, \mu_s) \phi_n(\omega_i, \mathbf{k}_i^\perp, \mu_i)$$



POM Filter $$|filter\rangle = \int d\omega \sqrt{g(\omega)} e^{i\vartheta(\omega)} |\omega\rangle_t$$

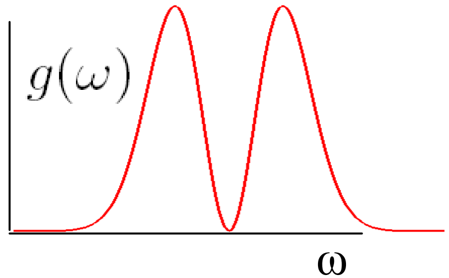
$$\hat{\prod} = |filter\rangle\langle filter|$$

e.g. time and frequency filter, fast detector, Homodyne detection



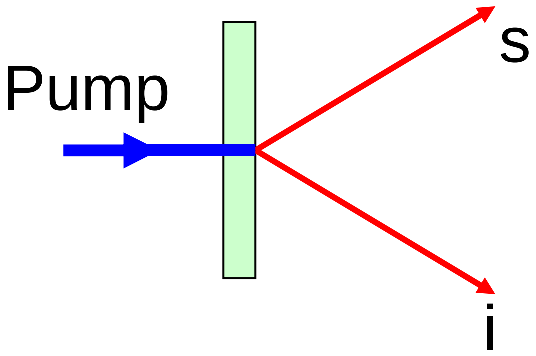
POVM Filter $$\hat{\Pi} = \int d\omega g(\omega) |\omega\rangle_t \langle\omega|_t$$

e.g. bandpass filter and slow detectors



Pulsed squeezing

• Parametric downconversion is known as Optical Parametric Amplification in the squeezing community



$$|\Psi\rangle = \sqrt{1-|\lambda|^2}\sum_{n=0}^{\infty}\lambda^n|n\rangle_s|n\rangle_i$$

• A twin-beam squeezed state is produced
• This is a single-mode model. It ignores the many frequency modes.

Schmidt modes in CVs

- The Schmidt mode decomposition previously discussed was only for the first non-zero term in the output.

$$|\psi\rangle \propto \iint d\omega_s d\omega_i f(\omega_s,\omega_i) a^\dagger(\omega_s) a^\dagger(\omega_i)|vac\rangle,$$

$$f(\omega_s,\mathbf{k}_s^\perp,\mu_s;\omega_i,\mathbf{k}_i^\perp,\mu_i) = \sum_n \sqrt{\lambda_n}\psi_n(\omega_s,\mathbf{k}_s^\perp,\mu_s)\phi_n(\omega_i,\mathbf{k}_i^\perp,\mu_i)$$

- The Schmidt decomposition is still applicable outside the perturbative regime

$$|\Psi_j\rangle = \sqrt{1-|\lambda_j|^2}\sum_{n=0}^{\infty}\lambda_j^n|n\rangle_s|n\rangle_i \qquad \frac{1}{L_{\mathrm{NL}}} = \frac{\omega_p^2 d_{\mathrm{eff}} E_0}{8c^2 k(\omega_p/2)},$$

$$|\Psi_{Total}\rangle = \bigotimes_{j=0}^{\infty}|\Psi_j\rangle \qquad \zeta = L/L_{\mathrm{NL}} = 15$$

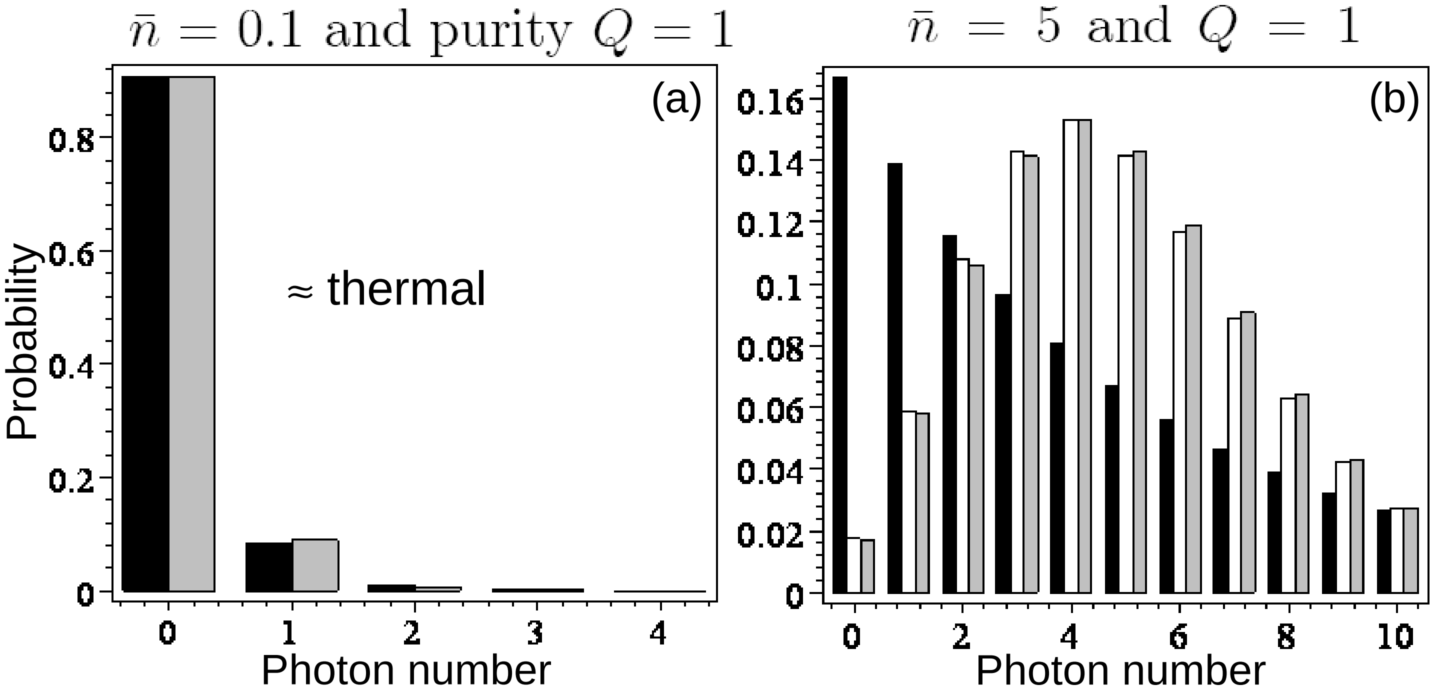
- The OPA output is a collection of two-mode squeezers, each with a different squeezing parameter λ_j

Phys. Rev. A 73, 063819 (2006): Wasilewski et al.

Multimode Photon Statistics

- Without a Schmidt mode filter one measures the sum of the photons created in all the modes

Photon number statistics in one output beam



Black: Single-frequency mode, Grey: OPA multimode, White: Multithermal

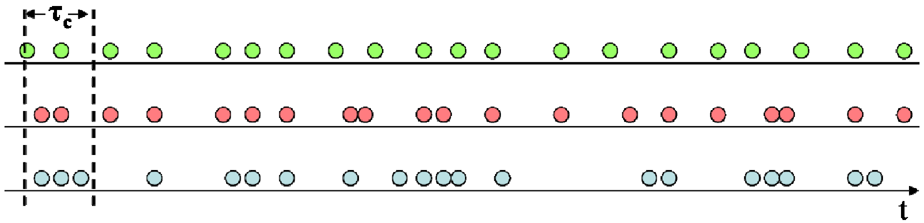
- Multimode Squeezing changes the photon distribution in each of the twin-beams.

Source Purity from Photon Statistics

• If we assume the source always produces photons in pairs, in the weak squeezing limit an OPA output has purity

$$\text{Purity, } Q = (V - \bar{n})/\bar{n}^2$$
$$= g^{(2)}(0) - 1$$

• The purity is independent of the distribution Schmidt modes, λ_j



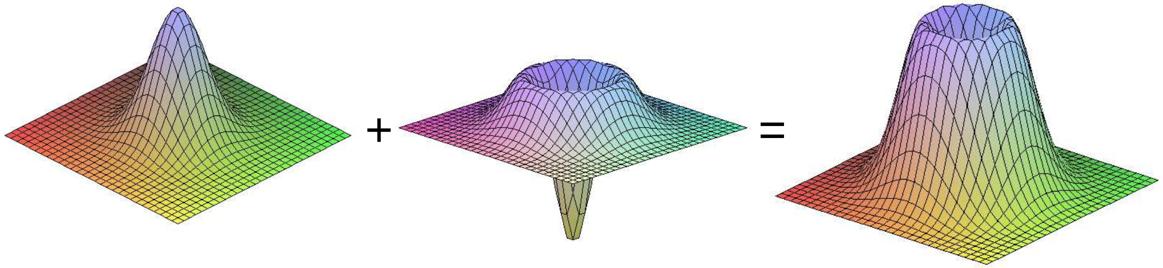
Photon detections as a function of time for a) antibunched, b) random, and c) bunched light

• The amount of photon bunching depends on the number of modes that are available to create a photon in.
• With only one frequency mode, we are guaranteed to get stimulated emission (bosonic enhancement)

Filtering and CV entanglement

- Can we use filtering to eliminate the multimode nature of emission?

Filtering introduces loss and mixes in the vacuum state:



|0>

|1>

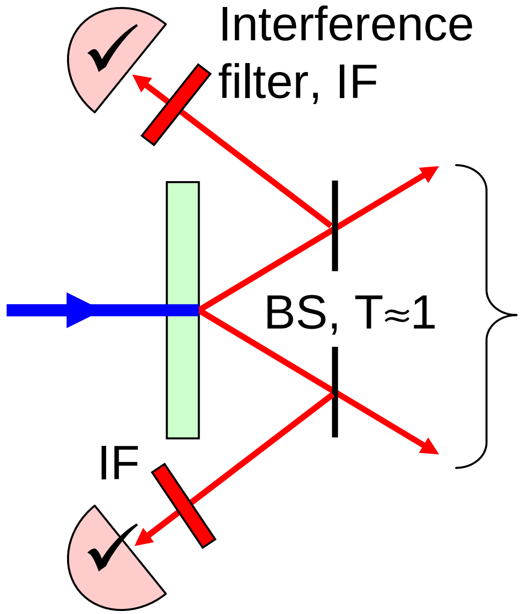
a|0><0|+b|1><1|
Wigner Function does not go negative

- What if we had ideal lossless filters?

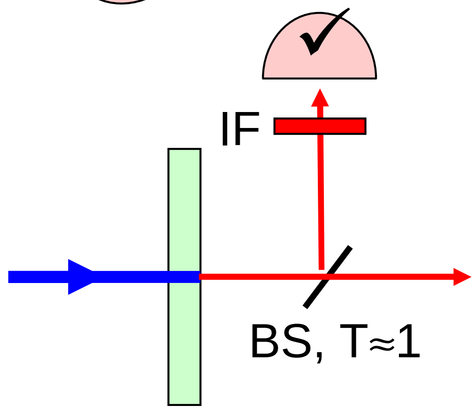
Filtering and CV entanglement

Degaussification

D.E. Browne, et al. Phys. Rev. A 67, 062320 (2003)



Photon Subtraction



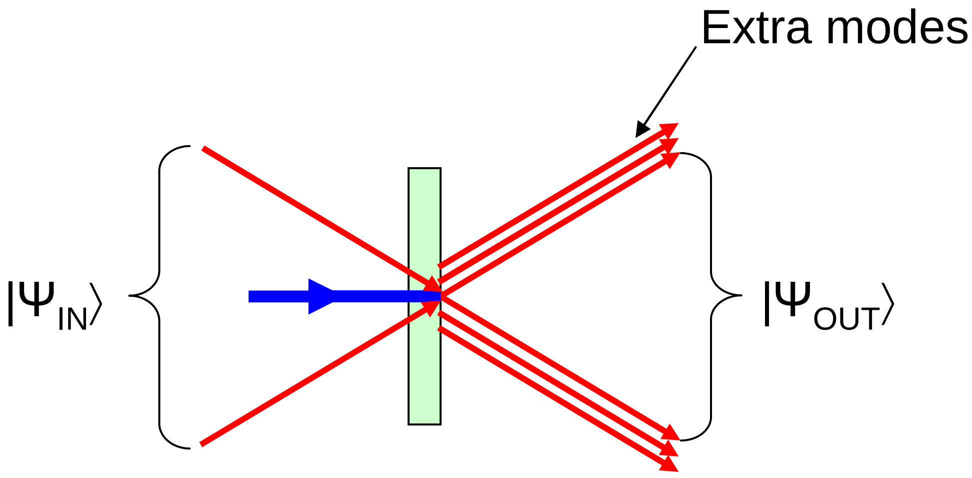
P. P. Rohde, quant-ph/0609004

A. Ourjoumtsev, et al. Science 312, 83 (2006)

- Even Ideal lossless frequency filters do not work in these protocols, since not all the photons in either beam are filtered.

Squeezing as a Gaussian Operation

• CV quantum computing requires the full range of Gaussian operations including squeezing



• A multimode squeezer will add vacuum squeezed states to the input pulse.

• If the input is not in a Schmidt mode, it will also squeeze different components of the input pulse by different amounts

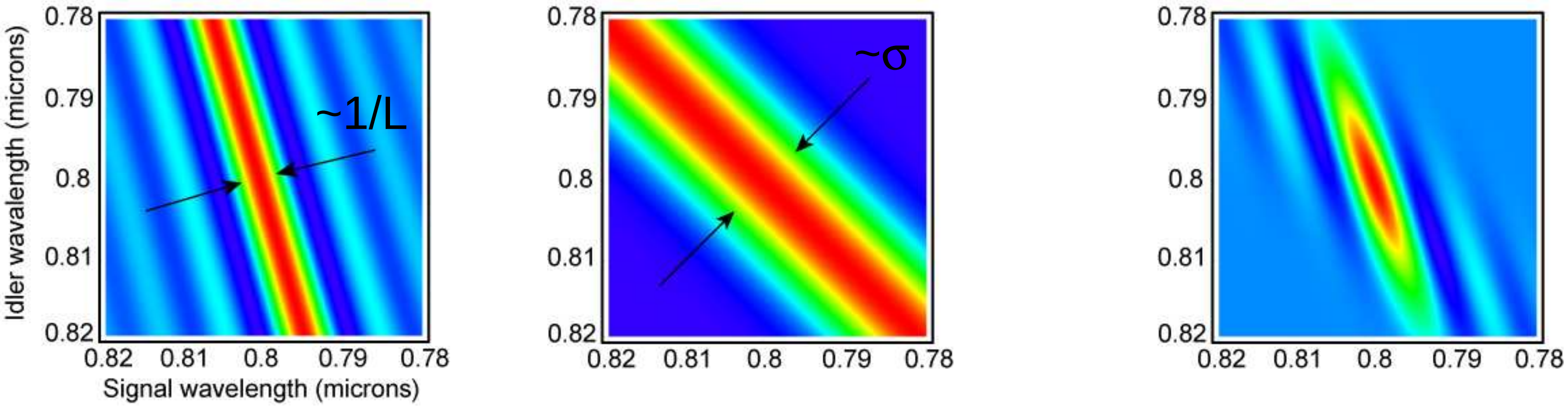
The Solution

- Choose the dispersion in the crystal to give us a factorable state
- One Schmidt mode: $f(\omega_s,\omega_i)=h(\omega_s) \times g(\omega_i)$

$$|\psi\rangle = \frac{1}{(2\pi)^2}\iint d\omega_s d\omega_i f(\omega_s,\omega_i)\hat{a}_s^\dagger(\omega_s)\hat{a}_i^\dagger(\omega_i)|vac\rangle$$

Phasematching function x Pump envelope function = Joint spectral amplitude

$\phi(\omega_s,\omega_i)$ $\alpha(\omega_s,\omega_i)$ $f(\omega_s,\omega_i)$



- Two photon probability distribution: (Joint spectral intensity)

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

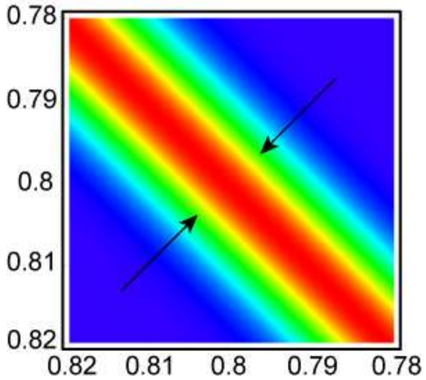
Grice *et al*, PRA **64**, 063815 (2001)

Tilting the Crystal Function

- Pump function is fixed at 45 degrees but we can control the phasematching function through the pump wavelength, crystal angle and crystal type.

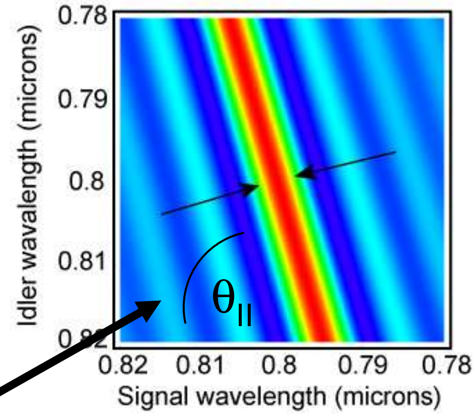
Pump envelope function

$\alpha(\omega_s, \omega_i)$



Phasematching function

$\phi(\omega_s, \omega_i)$

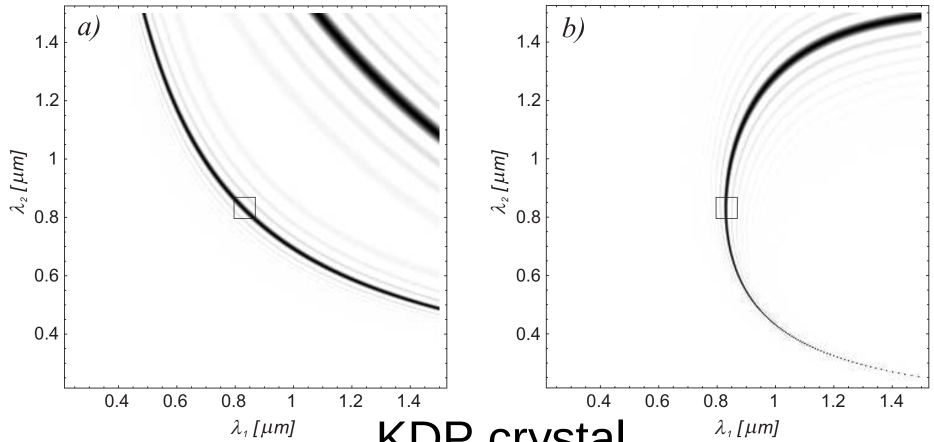


$$\theta_{II} = -\arctan\left(\frac{\tau_s}{\tau_i}\right) = -\arctan\left(\frac{k_s' - k_p'}{k_i' - k_p'}\right)$$

- θ_{II} is set by the delay between the pump and signal and idler, τ_s and τ_i
- $90 < \theta_{II} < 180$ degrees for a factorable state

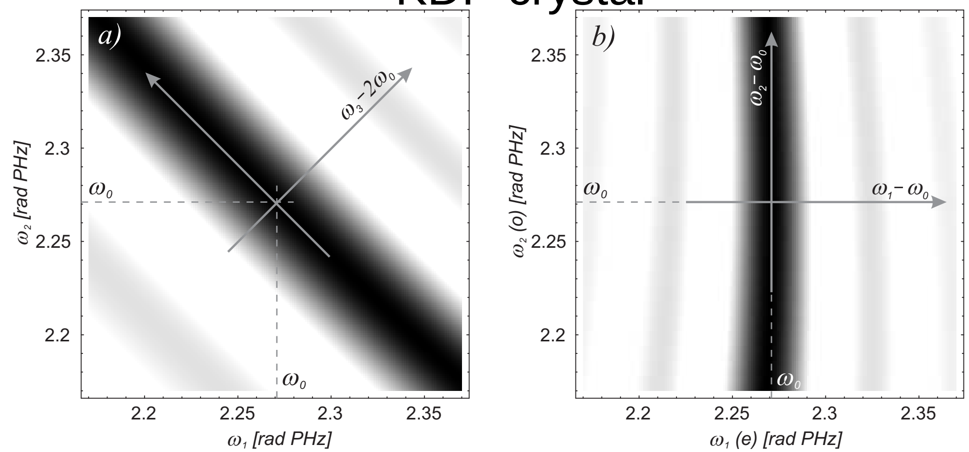
Type I vs Type II

- Type I downconversion: photons in pair have the same polarization
- Type II downconversion: photons in pair have opposite polarizations



KDP crystal

Closeup:



Type I

Type II

Eliminating Spacetime Correlations

Spectral entanglement removed via group-delay engineering:

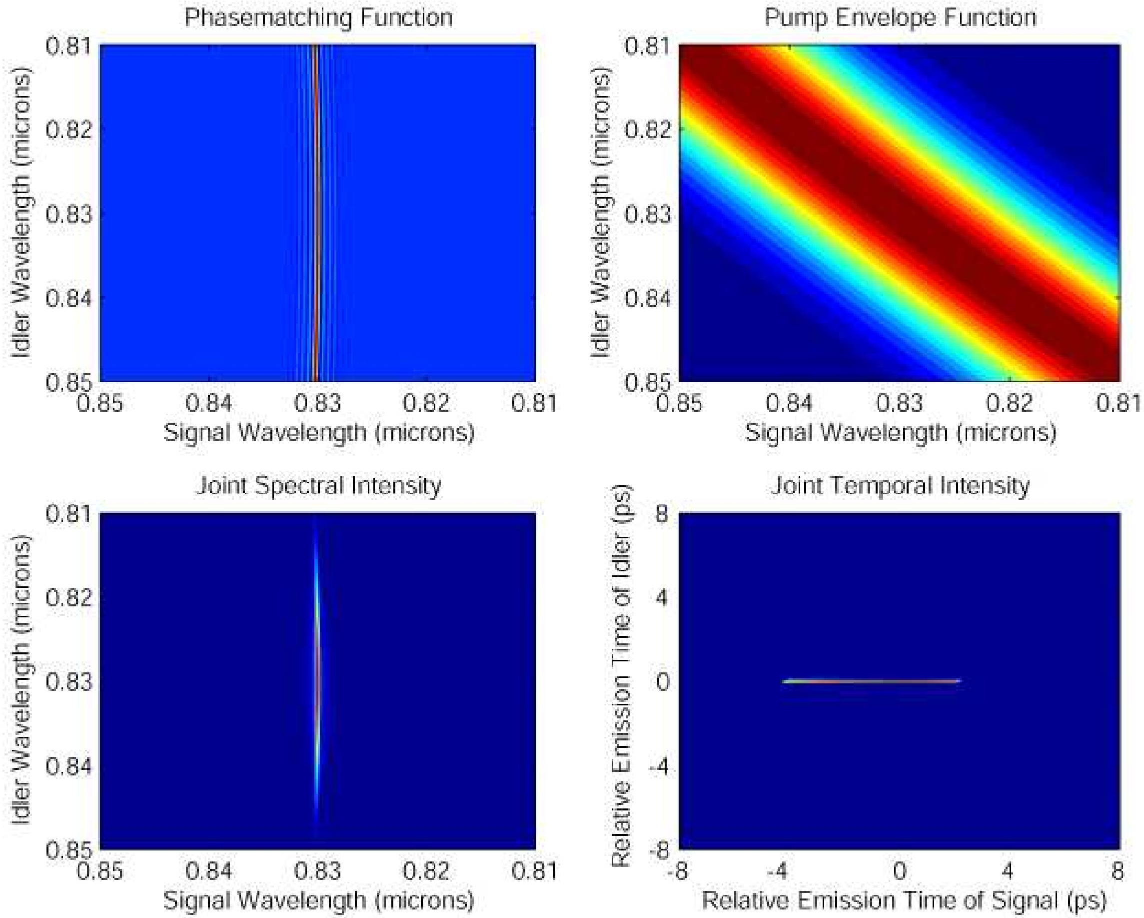
asymmetric GVM

$$v_g(pump) = v_g(idler)$$
$$v_g(pump) \neq v_g(signal)$$

+

Broadband pump

s: ~ monochromatic
i: broadband



This condition occurs in KDP at 800nm

Individual photon spectra

$$v_g(pump) = v_g(idler)$$

$$v_g(pump) \neq v_g(signal)$$

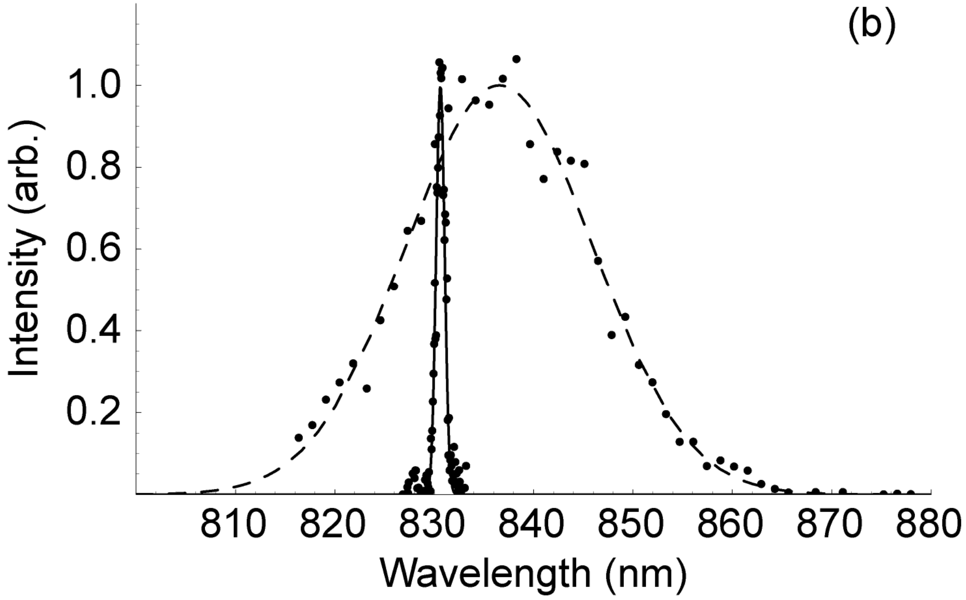
+

Broadband pump

s: $\Delta\lambda$ = 1 nm; τ = 2 ps
i: $\Delta\lambda$ = 22 nm; τ = 20 fs

Essentially no timing jitter

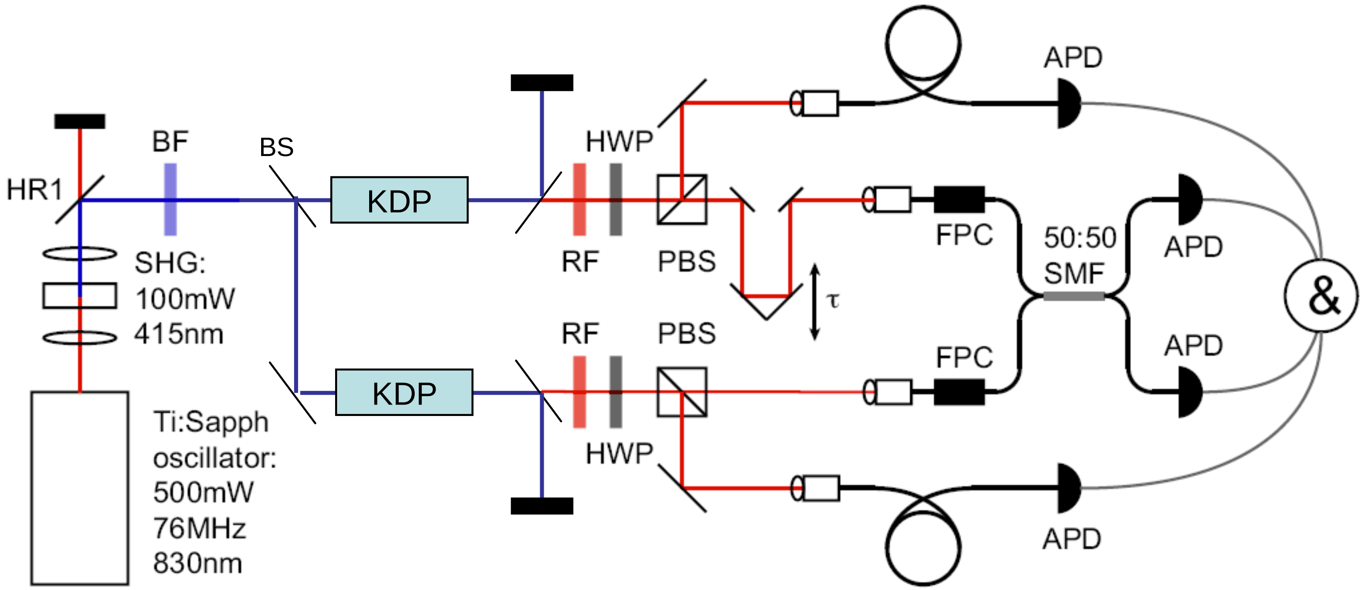
s : $\Delta\tau$ < 0.1 fs
i; $\Delta\tau$ < 10 as

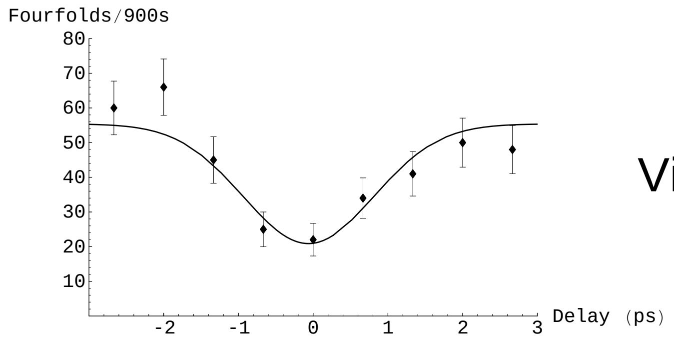


Spectra measured with an amplified CCD and a grating spectrometer

Testing Single-Photon Purity

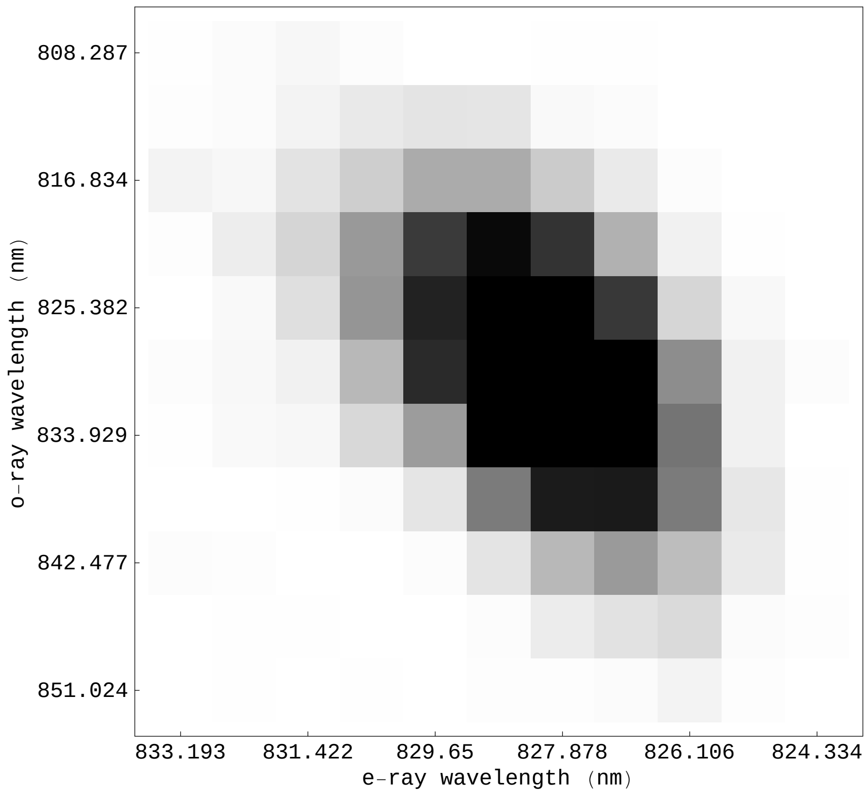
- Measure purity with the Hong-Ou-Mandel Interference effect





Visibility/Purity = 65%

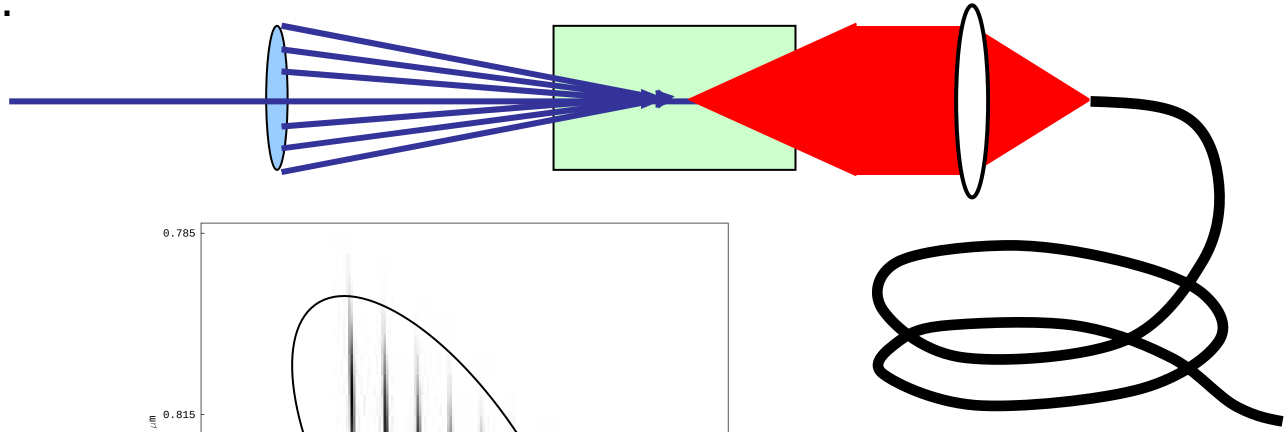
Experimental Joint Spectra

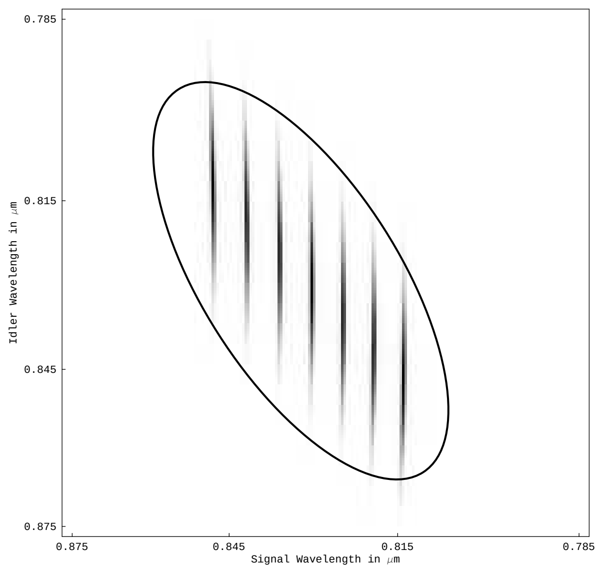


- Experimental Joint Spectra from 20mm crystal with light focusing.
- Measured with two grating spectrometers and translatable single photon detectors.

Reasons for Tilted Spectra

- The theory is for a single k-vector. To couple the downconversion into fibers we need to focus into the KDP crystal.

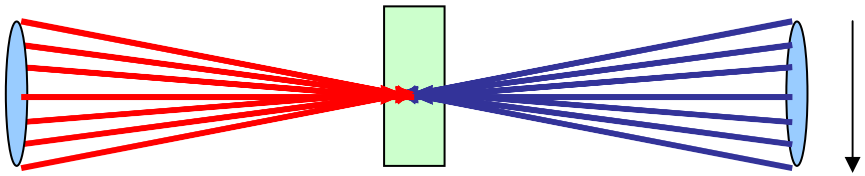


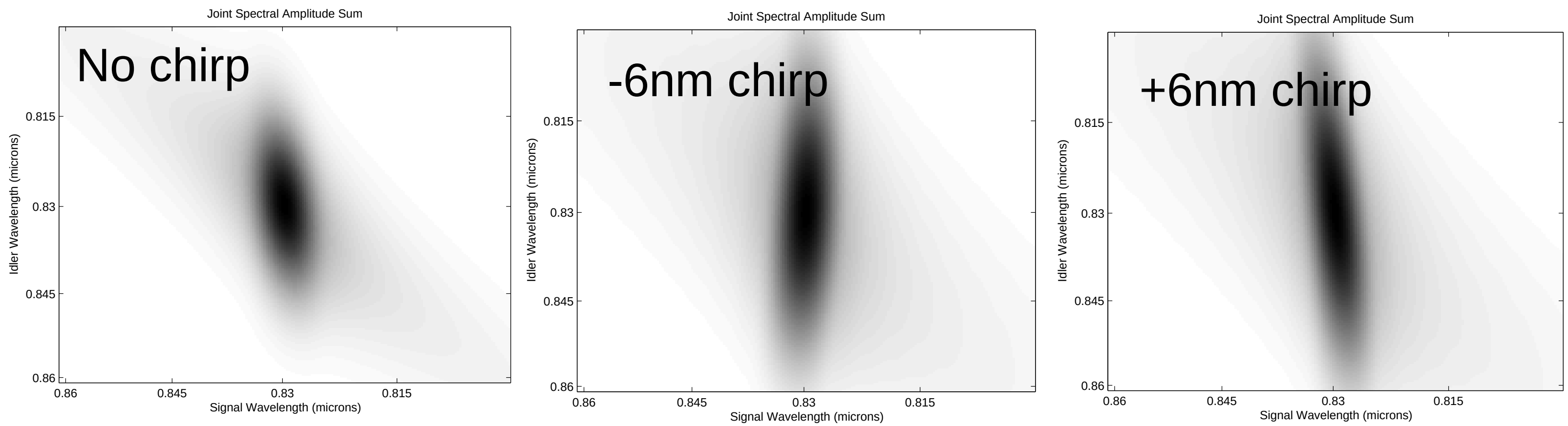


Joint Spectral Intesity for 20mm xtal, pumped at 415nm, changing angle in steps of 0.5 deg.

More Reasons for Tilted Spectra

- Focusing in the Second Harmonic Setup means the opposite effect from the last slide occurs. Different angles emerge with different central frequencies.

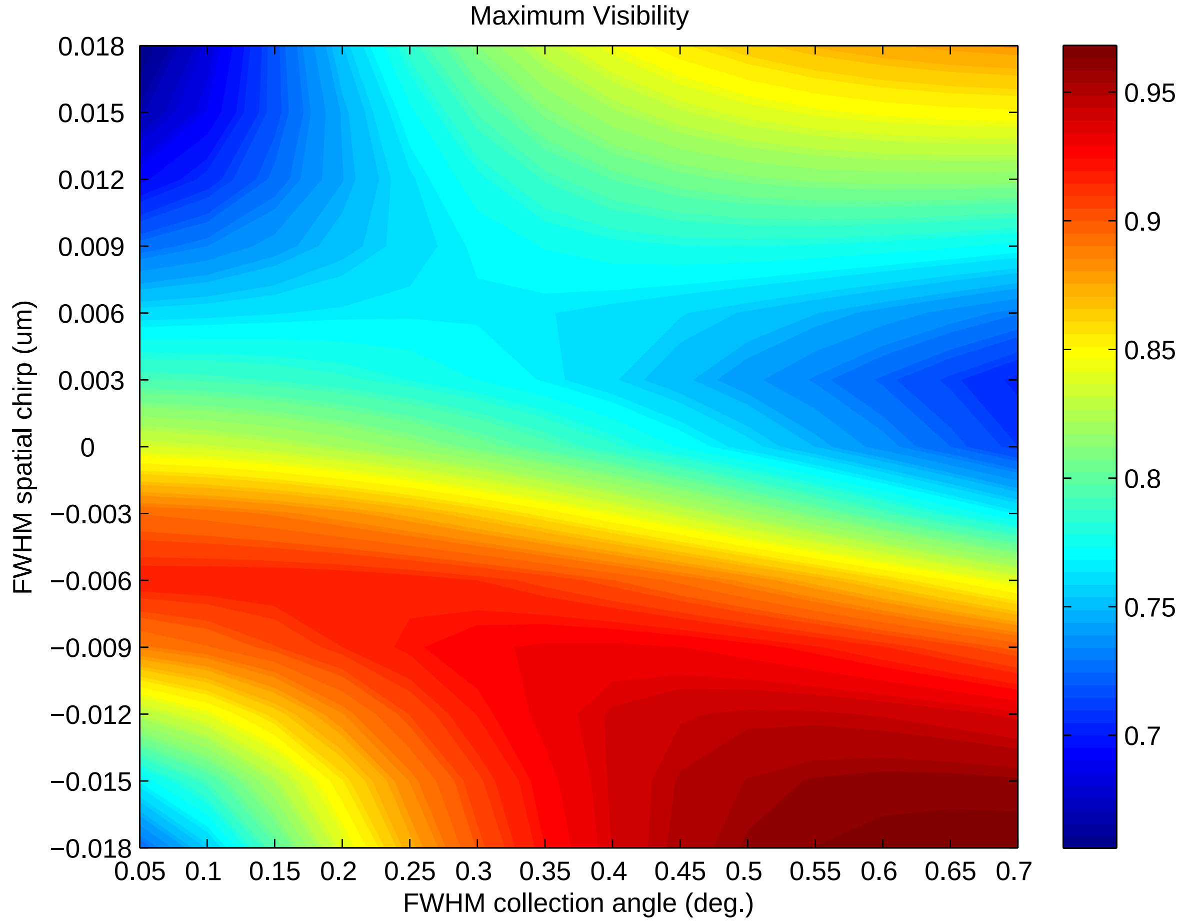




Numerical model: Joint Spectrum for 5mm xtal, 250mm lens, 150mm lens after, pump at 415nm, phasematched for degeneracy

Numerical Optimization

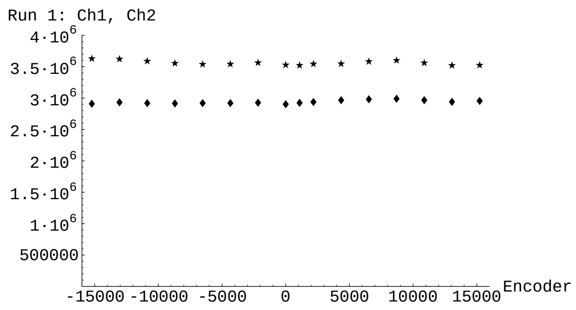
- Collection angle into fibers matters as well.



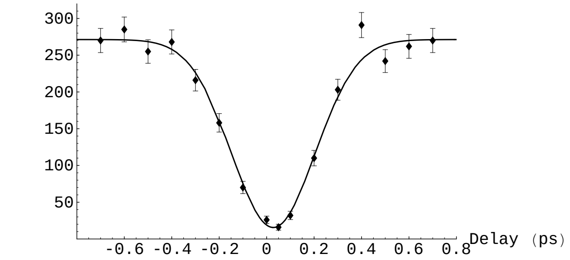
Fight fire with fire

- Counterbalance tilt resulting from focusing with the tilt from the spatial chirp

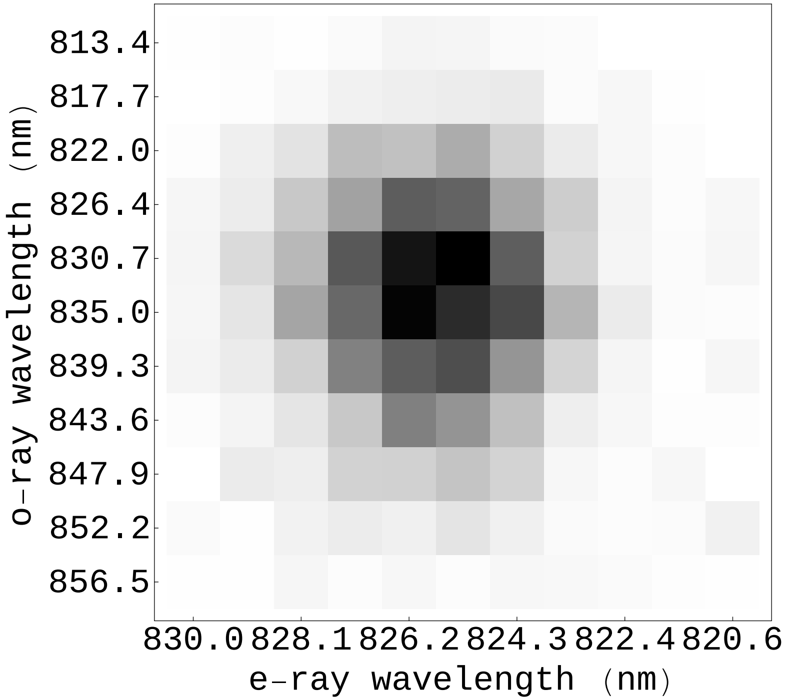
Coincidence Rates



Fourfolds



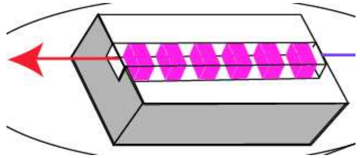
Visibility/Purity = 95%
L = 5mm, f = 250mm



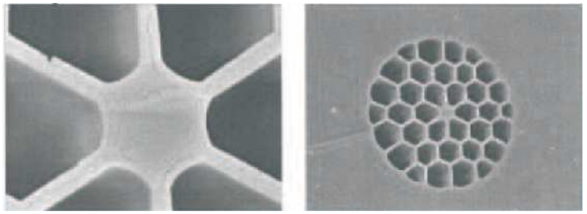
Experimental joint spectrum

What's next?

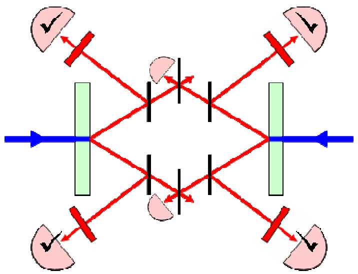
• Waveguides: Index contrast is too low to modify dispersion with waveguiding



• Four-wave mixing in Photonic Crystal fibers: Many controls for dispersion (e.g. core size, filling fraction, birefringence, two pumps). Attempting this now.



• Continuous Variable Quantum Information Experiments in collaboration with Martin Plenio and Jens Eisert (e.g. CV entanglement distillation)



Conclusions

- Producing pure photonic states is important for both discrete and continuous variable quantum optics.
- The answer is group-velocity matching in the source to create a factorable spectral state.
- Bulk systems will also require consideration of the angular emission from the source.