Generation of pure photons in an optical fibre

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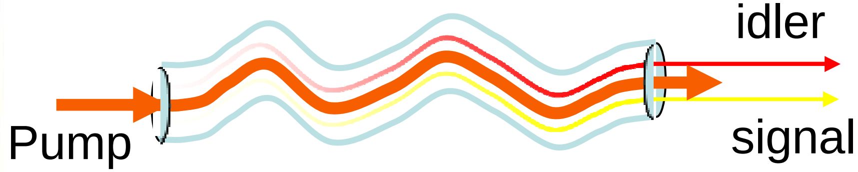
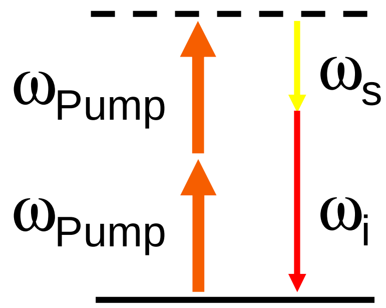
Spontaneous FWM

Optical Fibre



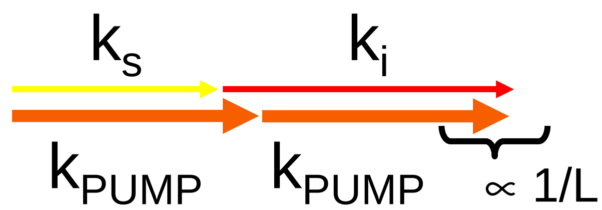
Energy is conserved…



- Two pump photons are spontaneously converted into two sideband photons in a $\chi^{(3)}$ material.

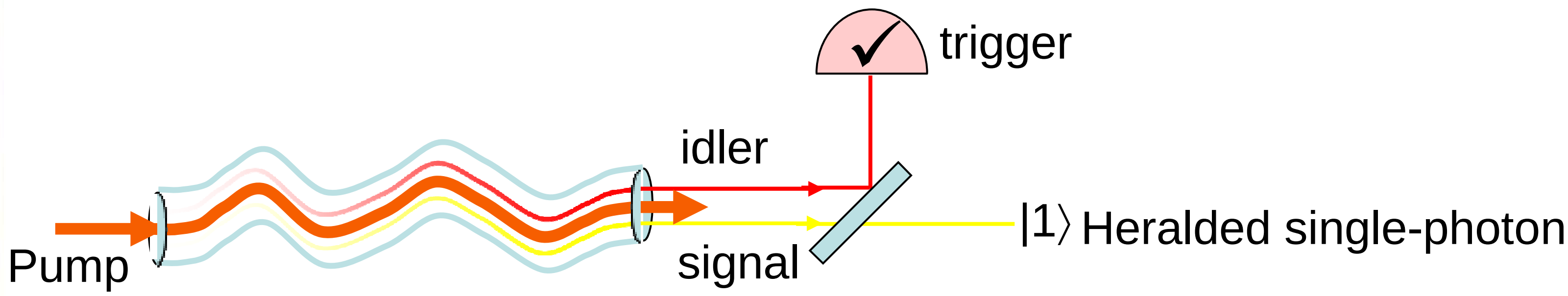
- small core size ($\rightarrow$ high intensity) and long interaction length compensate for small $\chi^{(3)}$ vs. the $\chi^{(2)}$ in crystals

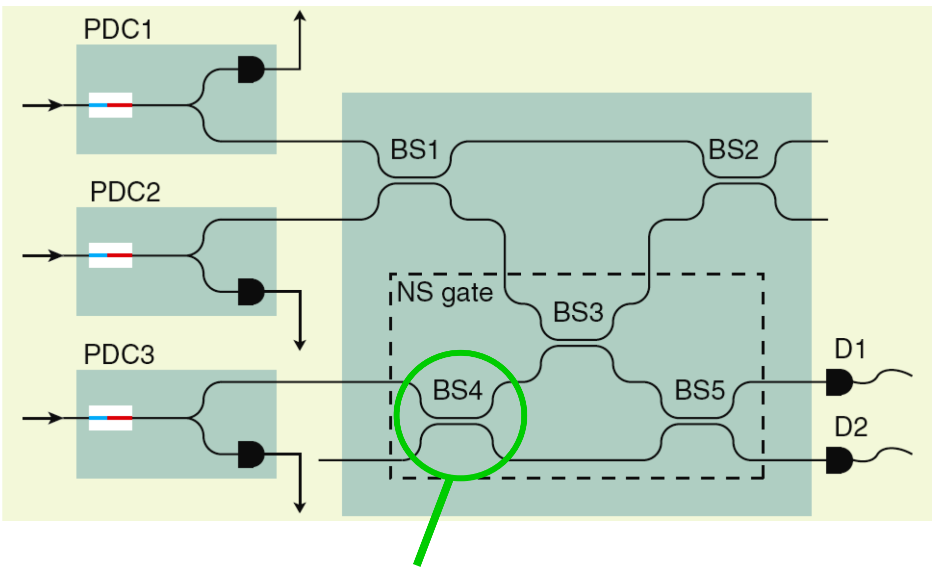
… as well as momentum



1. J. E. Sharping, M. Fiorentino, and P. Kumar, Opt. Lett. **26**, 367–369 (2001)
2. H. Takesue and K. Inoue, Phys. Rev. A **70**, 031802(R) (2004)
3. J. Rarity, J. Fulconis, J. Duligall, W. Wadsworth, and P. Russell, Opt. Exp. **13**. 534 (2005)
4. J. Fan and A. Migdall, Opt. Exp. **13**, 5777 (2005)

Heralded Single-Photons





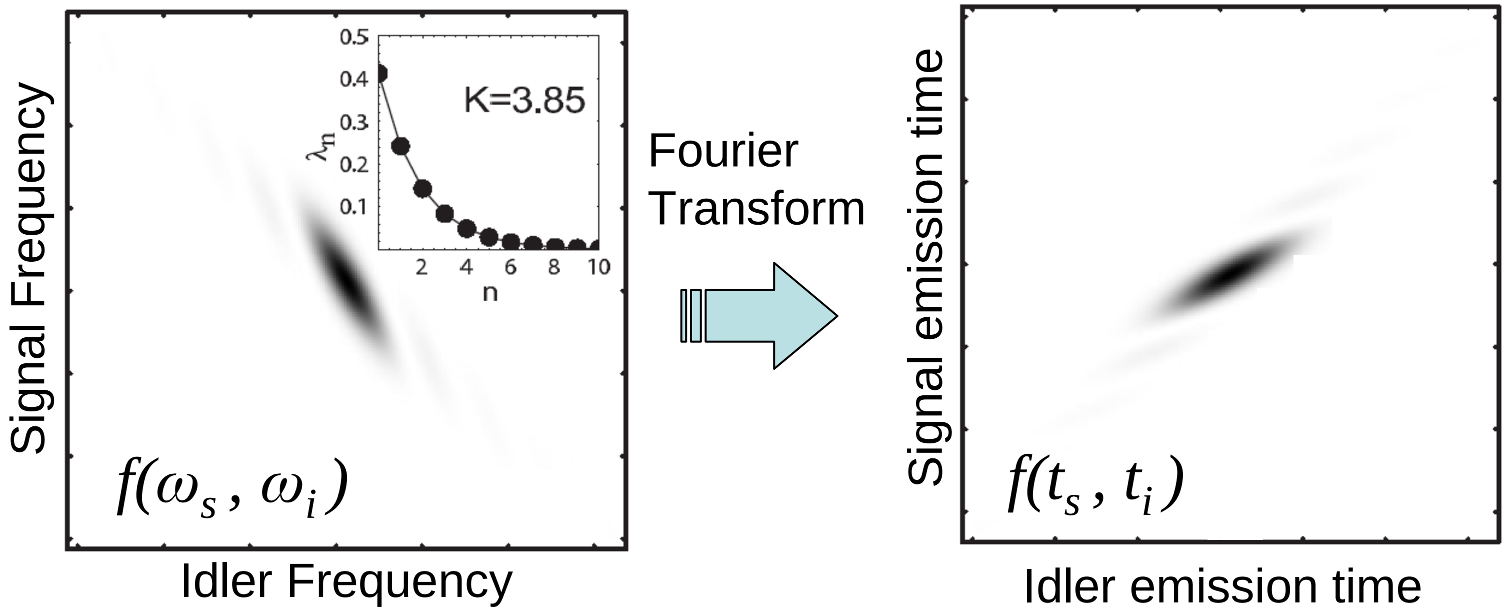
• Discrete Variable measurement-based quantum-computing requires heralded photons and a quantum memory

• High visibility Hong-Ou-Mandel interference is critical for optical quantum logic gates. **For this we need photons in a pure state.**

The Two-photon Spectrum

- Energy and momentum conservation create correlations between the two photons.

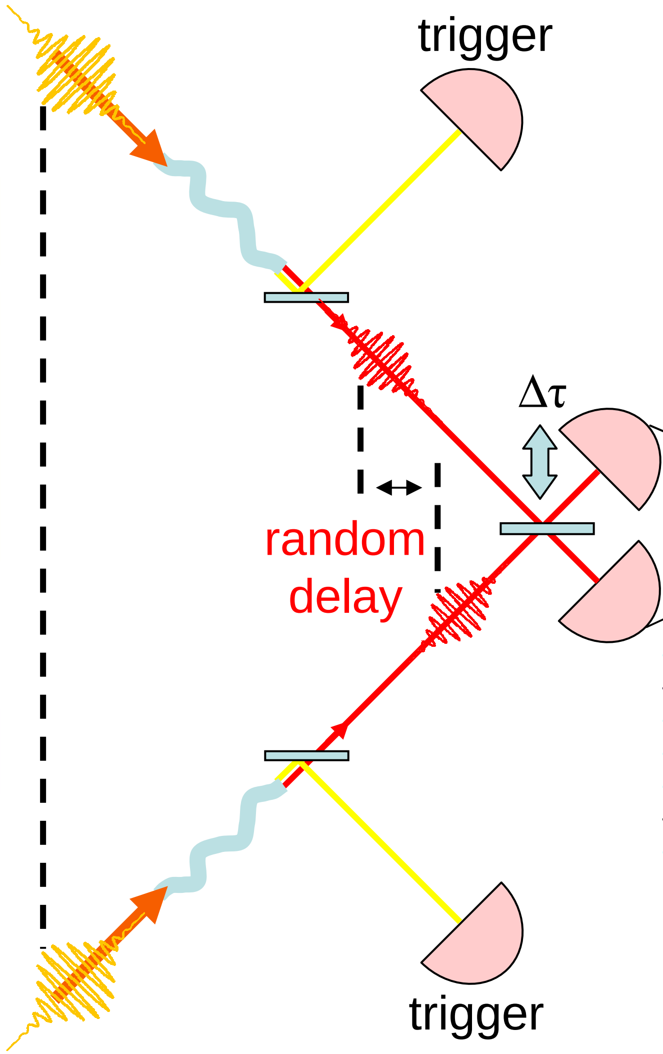
$$|\psi\rangle \propto \iint d\omega_s d\omega_i f(\omega_s, \omega_i) a^\dagger(\omega_s) a^\dagger(\omega_i)|vac\rangle,$$

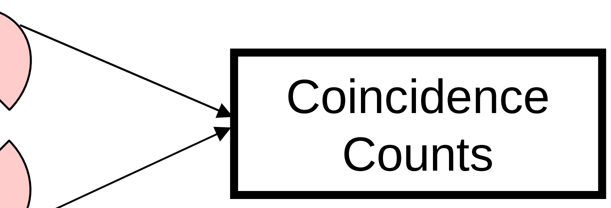


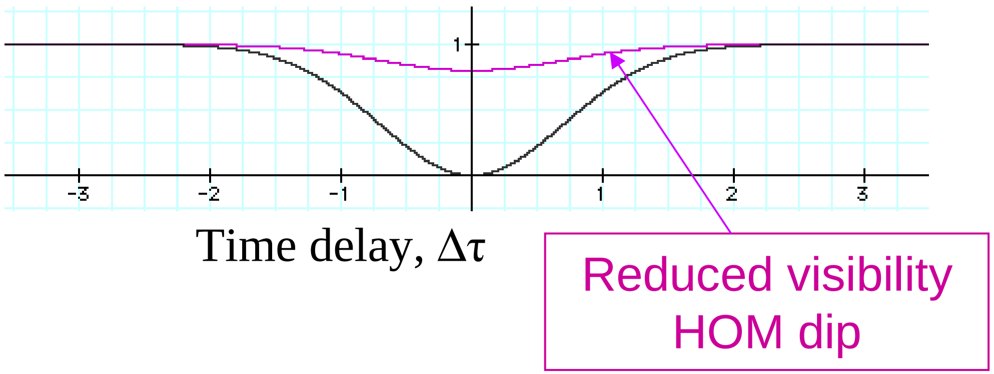
- Single photon detectors do not have fs time- or nm spectral-resolution
- This leads to a fundamental problem

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







Visibility = $\mathrm{Tr}(\hat{\rho}_1 \hat{\rho}_2) \approx \mathrm{Tr}(\hat{\rho}^2)$ = Purity

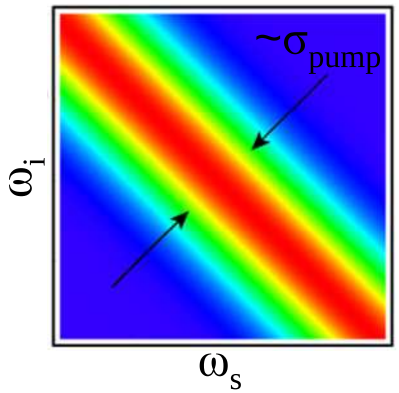
The Solution

- The goal is a factorable joint spectrum: $f(\omega_s,\omega_i)=h(\omega_s)\cdot g(\omega_i)$

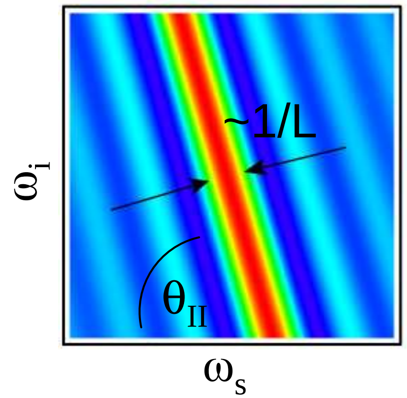
$$|\psi\rangle = \frac{1}{(2\pi)^2}\iint d\omega_s d\omega_i f(\omega_s,\omega_i)\hat{a}_s^\dagger(\omega_s)\hat{a}_i^\dagger(\omega_i)|vac\rangle$$

•With a single pump beam we can make the following approximation:

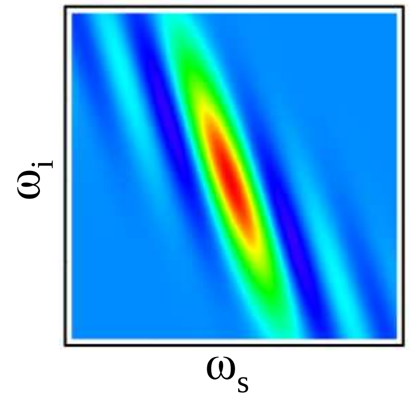
Pump envelope function $\alpha(\omega_s,\omega_i)$ x Fibre function $\phi(\omega_s,\omega_i)$ = Joint spectral amplitude $f(\omega_s,\omega_i)$



fixed at 45°



θ_{II} = -arctan(τ_s/τ_i)



90°< θ_{II} < 180°
for a factorable state

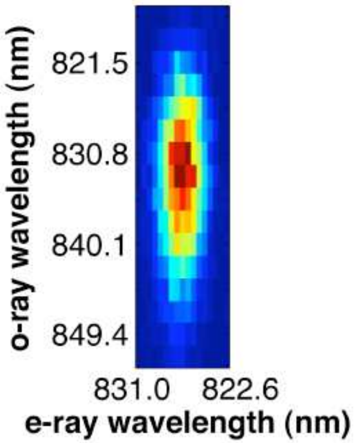
Optics Express, **15**,14870-14886 (2007) with U'Ren and Raymer

- Design the fiber to have the correct dispersion for a factorable state

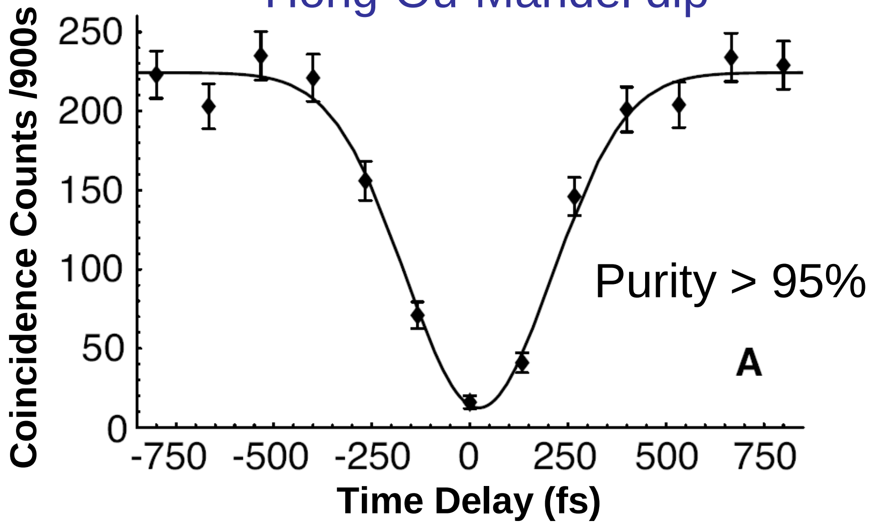
Pure photons in SPDC

• With careful choice of dispersion in a $\chi^{(2)}$ crystal we have engineered the modes the photons are emitted into:

Experimental Joint Spectrum



Hong-Ou-Mandel dip



• Heralding efficiency up to 44%

• Four-photon count rates as good as the best sources but with 1/10 the pump power. (currently get 60 /s with 300 mW/crystal)

• High quality interference with no filters

• Broadest bandwidth heralded photons

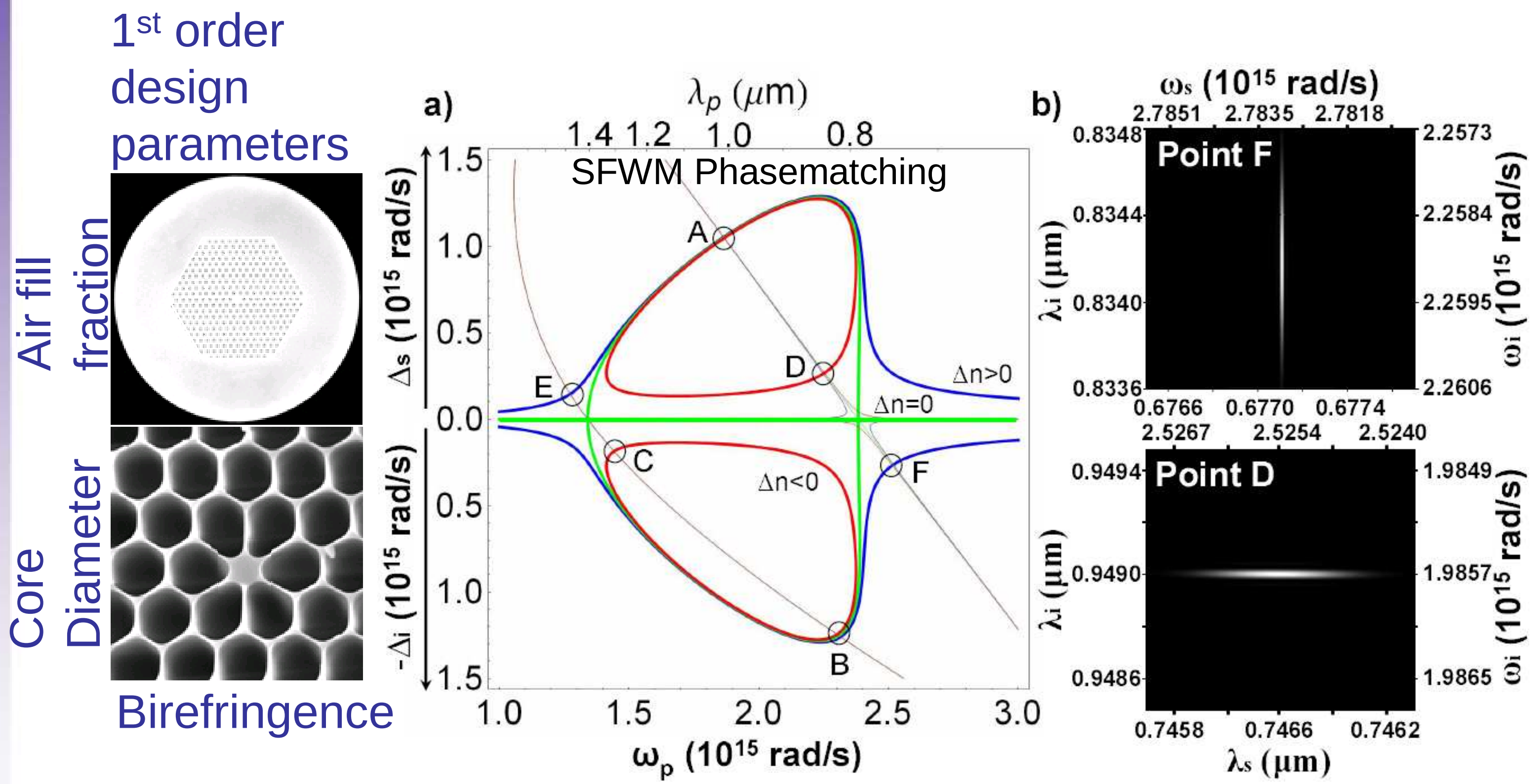
Peter Mosley, Jeff Lundeen,…
Phys. Rev. Lett. **100**, 133601 (2008)

• Drawbacks:
  - ➢ bulk source (hard to couple to fibers)
  - ➢ limited to natural dispersion of nonlinear crystals

Fibre sources of pure photons

• We modelled the dispersion in a solid-core microstructured fiber

Optics Express, **15**,14870-14886 (2007)

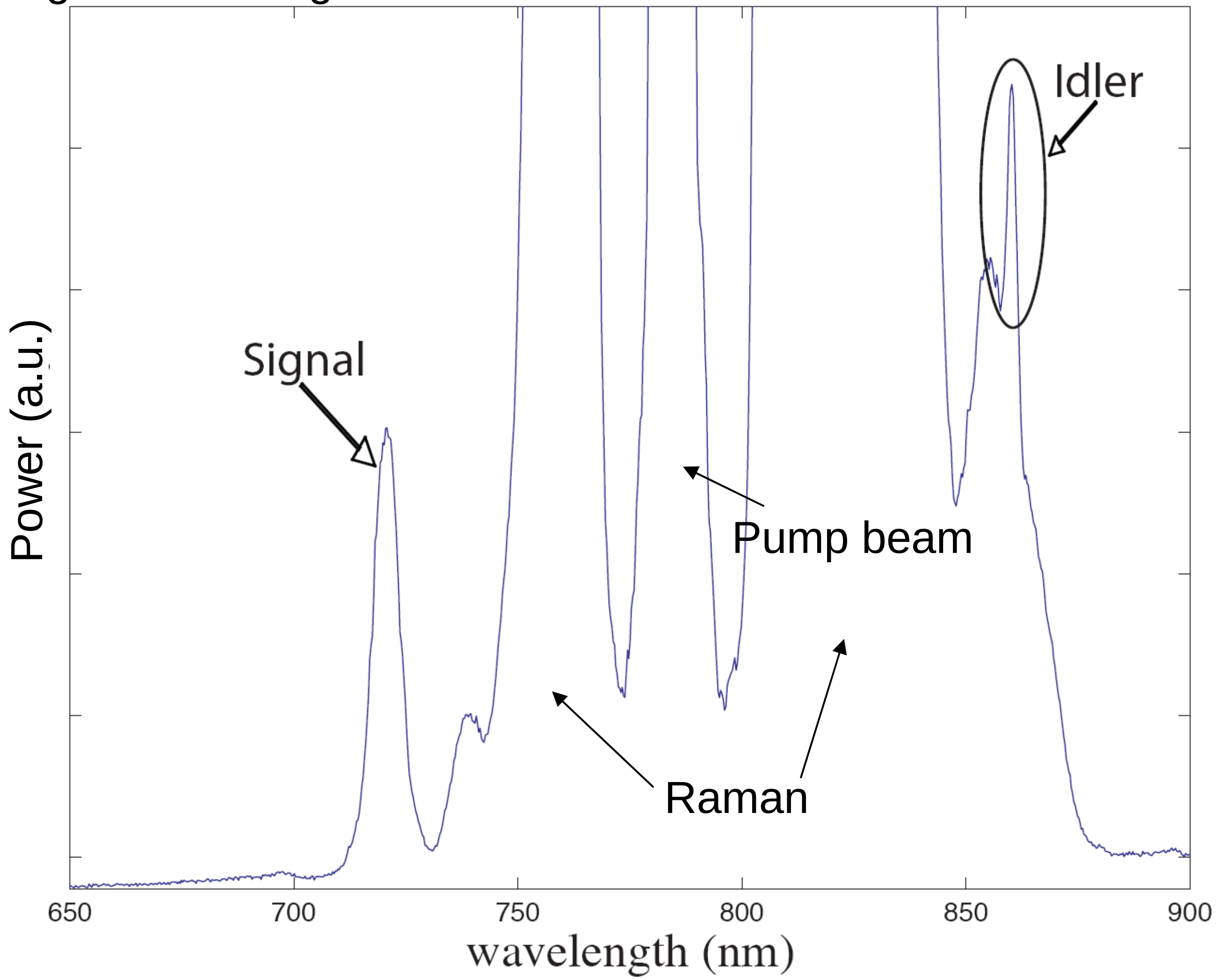


• Any orientation of the phasematching function is possible:

➢ factorable states, frequency correlated or anti correlated states

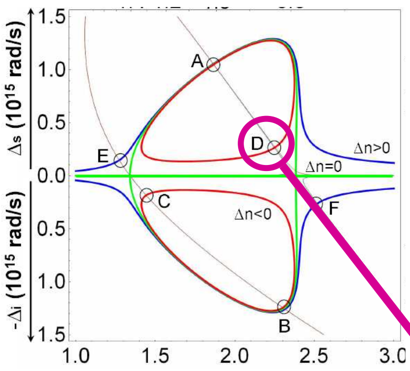
Spontaneous FWM Spectrum

• we record the spectrum of generated light and measure the idler and signal wavelengths.

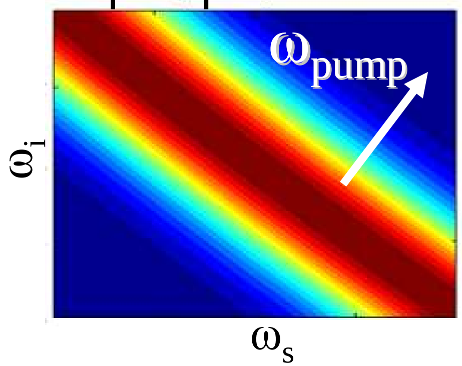


Finding the right fibre

- At the factorable point, ω_i is constant as ω_{pump} is varied

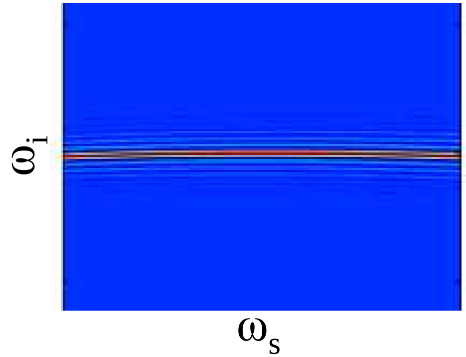


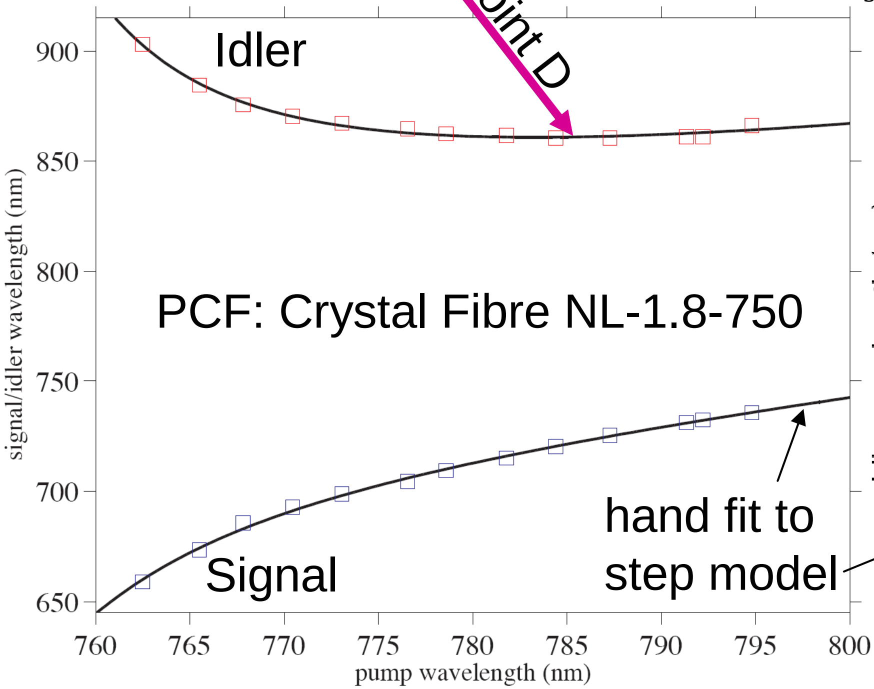
pump function



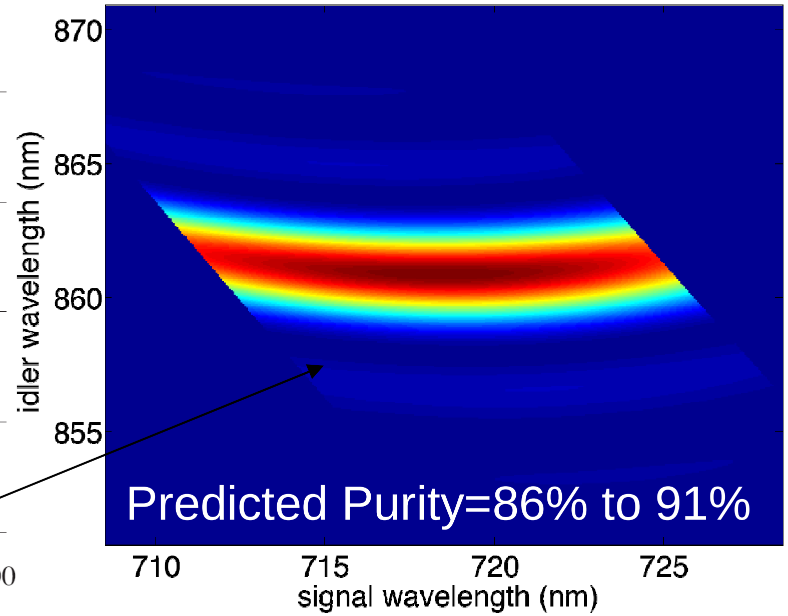
x

fibre function

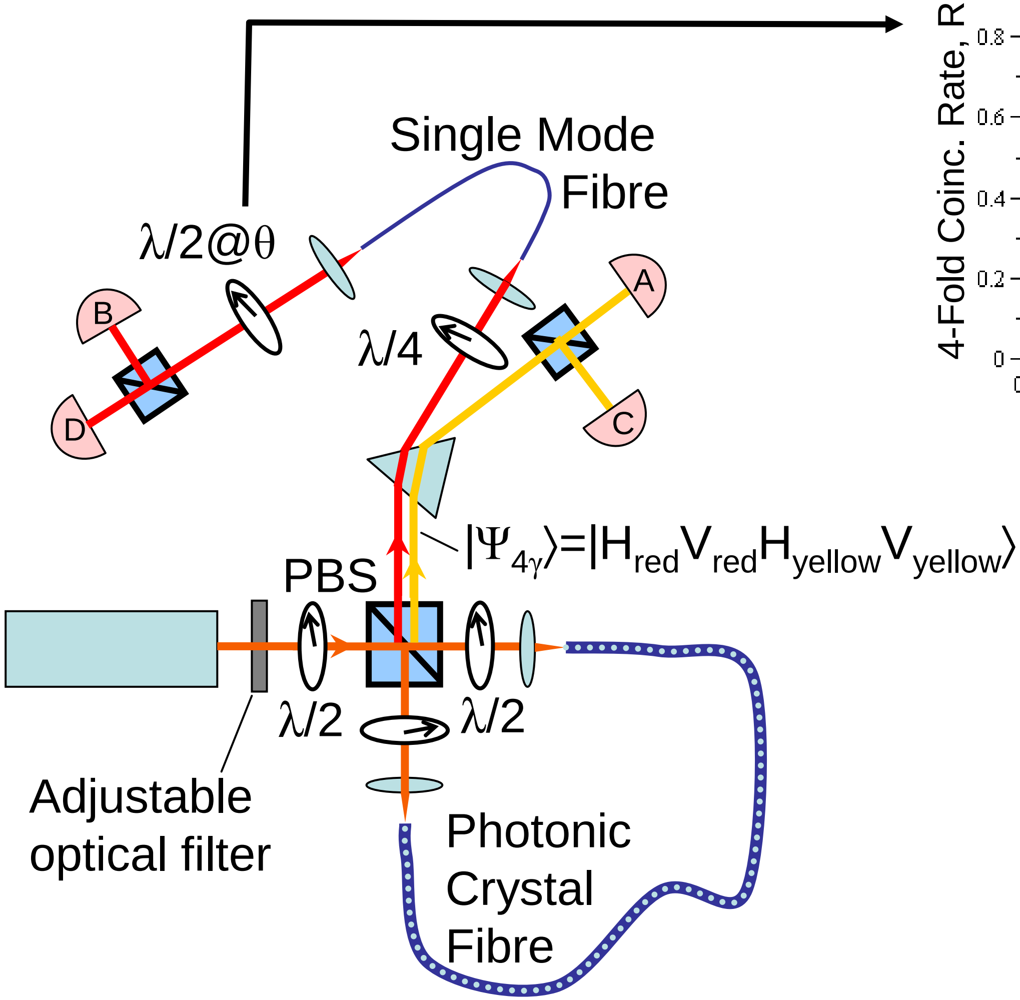


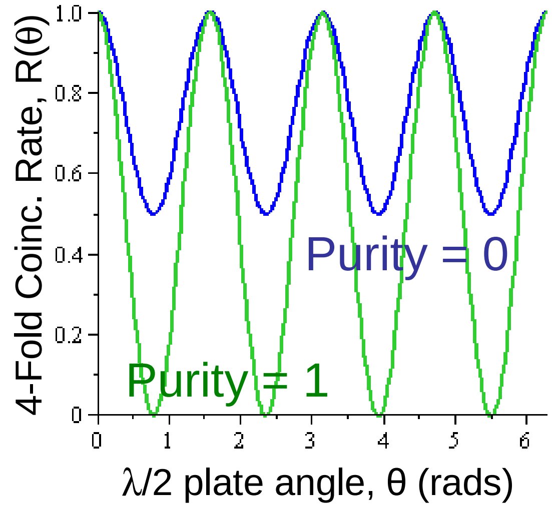


Theoretical Joint Spectrum



Polarization Test of Purity





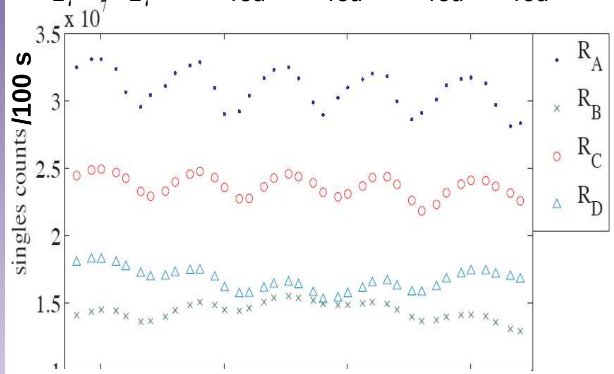
$$R(\theta)=(1-P)+(1+P)\cdot\cos(2\theta)^2$$

$P \equiv$ Purity

Checking the purity

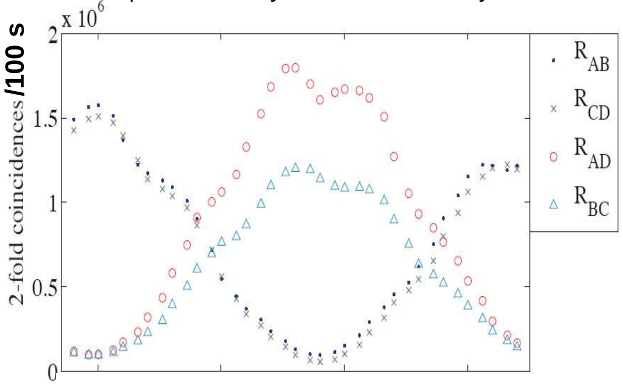
- Singles show that both beams are unpolarized
- The two-folds show regular polarization curves
- The four-folds exhibit non-classical interference

$|\Psi_{1\gamma}\rangle\langle\Psi_{1\gamma}| = |H_{red}\rangle\langle H_{red}| + |V_{red}\rangle\langle V_{red}|$

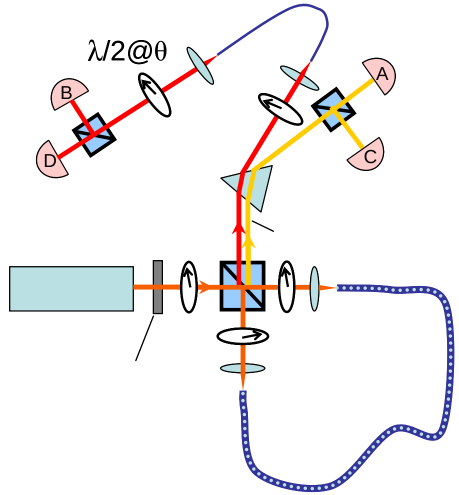


λ/2 plate angle, θ (2xdegrees)

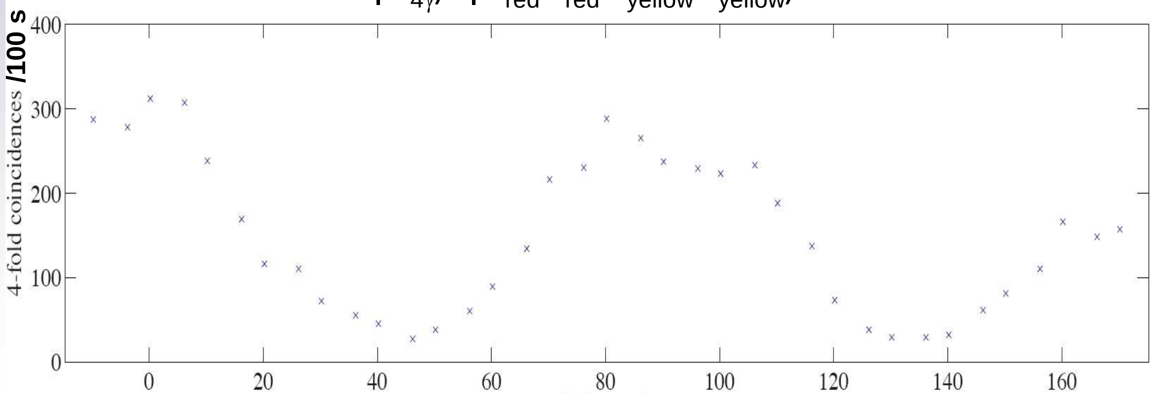
$|\Psi_{2\gamma}\rangle = |H_{red} H_{yellow}\rangle + |V_{red} V_{yellow}\rangle$



λ/2 plate angle, θ (2xdegrees)

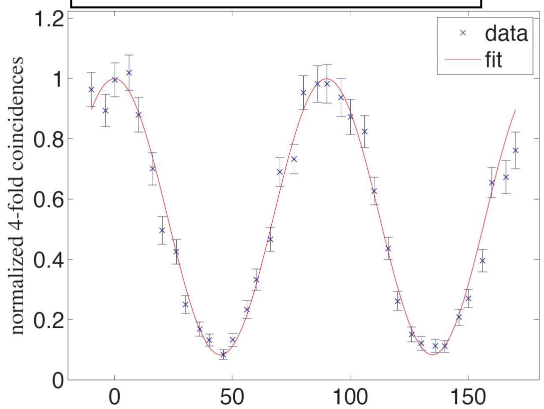


$|\Psi_{4\gamma}\rangle = |H_{red} V_{red} H_{yellow} V_{yellow}\rangle$



λ/2 plate angle, θ (2xdegrees)

Purity = 82%±2%



λ/2 plate angle, θ (2xdegrees)

Summary

- Modal design of photons is possible with four wave mixing.
- Microstructured nonlinear sources (e.g PCF) allow us to directly engineer the spectral properties of the photons.
- Generation of heralded unfiltered pure-state photons has been demonstrated in a waveguide $\rightarrow$ integrated optical circuits $\rightarrow$ scalable quantum information.
- A wide range of states are possible in the same fibre: factorable, ultra-broadband, frequency correlated, frequency anti-correlated.

Just the facts

Fibre:
Crystal Fiber NL-1.8-750
Length=40cm
Core diameter=1.75 µm
Fill fraction=50%

Pump:
0.7 mW per pass
λ_p = 785 nm
$\Delta\lambda_p$ = 8 nm
76 MHz

Photon Pairs:
λ_i = 860 nm
$\Delta\lambda_i$ = 2 nm
λ_s = 720 nm
$\Delta\lambda_s$ = 8 nm
Coinc = 15000 /s
4-folds = 3 /s
Accidentals/coinc < 1/25

Experimental generation of pure state photons in SPDC:
Peter Mosley, et al. Phys. Rev. Lett. **100**, 133601 (2008)

Engineering spectral correlations in SFWM in fibres:
K. Garay-Palmett, et al. Optics Express, **15**,14870-14886 (2007)

Past demonstrations of pair generation in fibres

- J. E. Sharping, M. Fiorentino, and P. Kumar, Opt. Lett. **26**, 367–369 (2001)
- H. Takesue and K. Inoue, Phys. Rev. A **70**, 031802(R) (2004)
- J. Rarity, J. Fulconis, J. Duligall, W. Wadsworth, and P. Russell, Opt. Exp. **13**. 534 (2005)
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Filtering

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