The search for the perfect photon

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Oxford Physics
QAIP
EPSRC

Outline

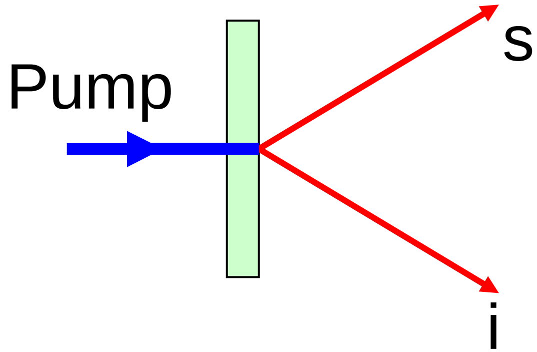
1. What are "pure" photons and why should you buy them.

2. A look at our new pure photon sources.

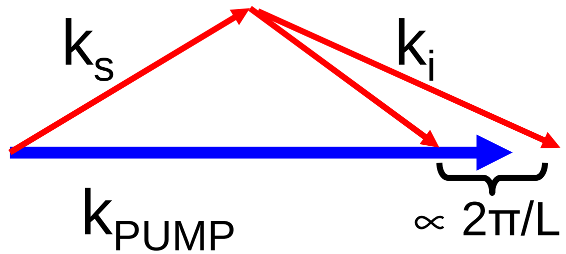
3. Measuring the measurement: Detector tomography

Spontaneous Parametric Downconversion

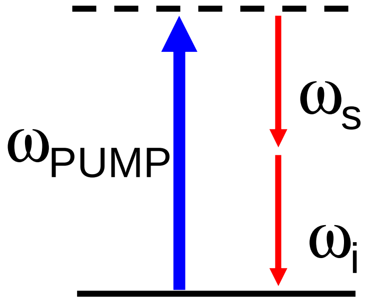
Downconversion



Momentum is conserved..



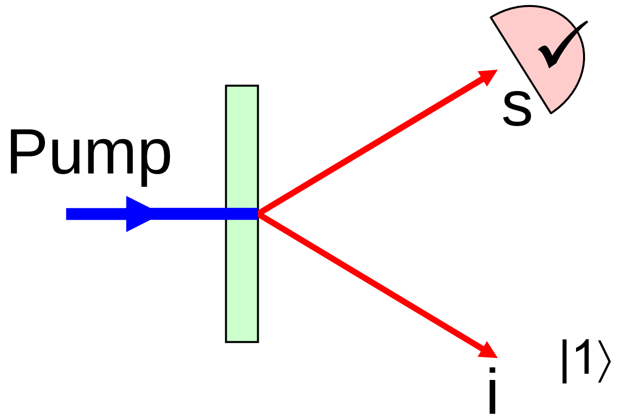
..as well as energy



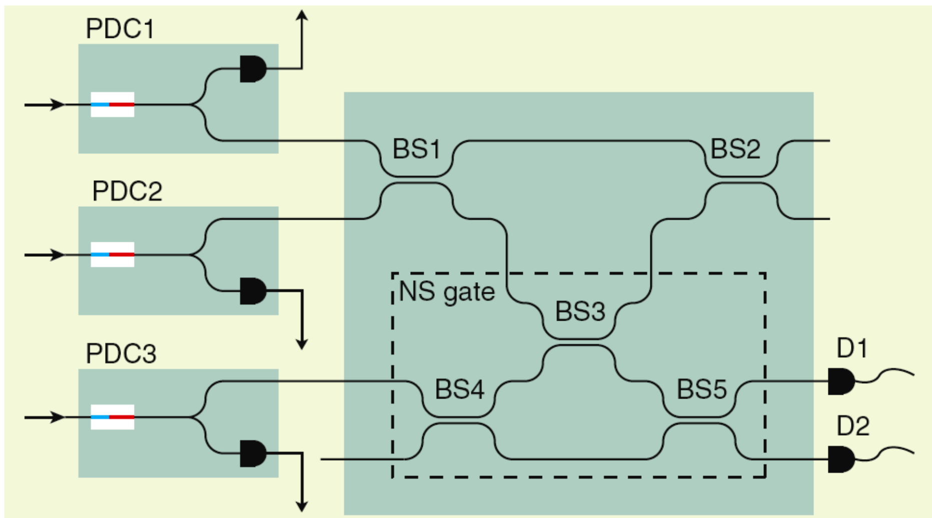
$\varphi_{PUMP} = \varphi_s + \varphi_i$

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

Heralded Single-Photons



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



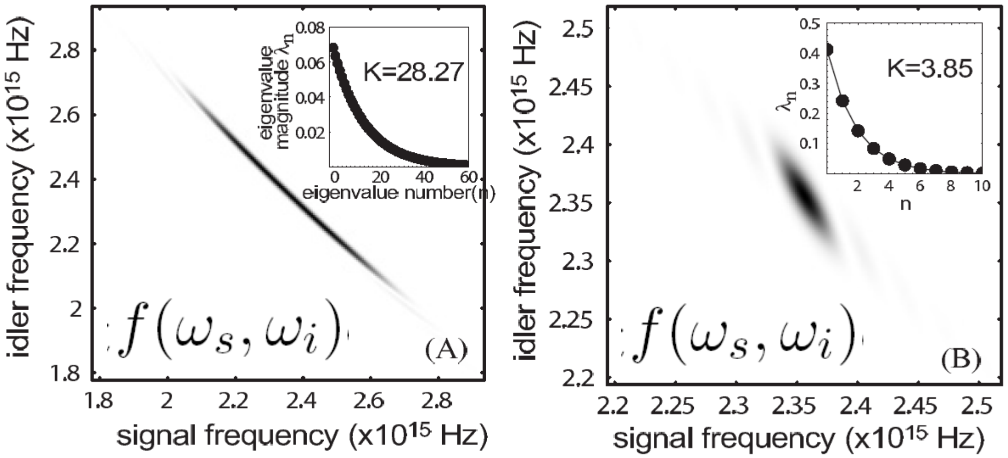
T. Ralph, A. W. nad W.J. Munro, and G. Milburn, "Simple scheme for efficient linear optics quantum gates," Phys. Rev. A **65**, 012314 (2001).

The Two-photon Spectrum

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

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

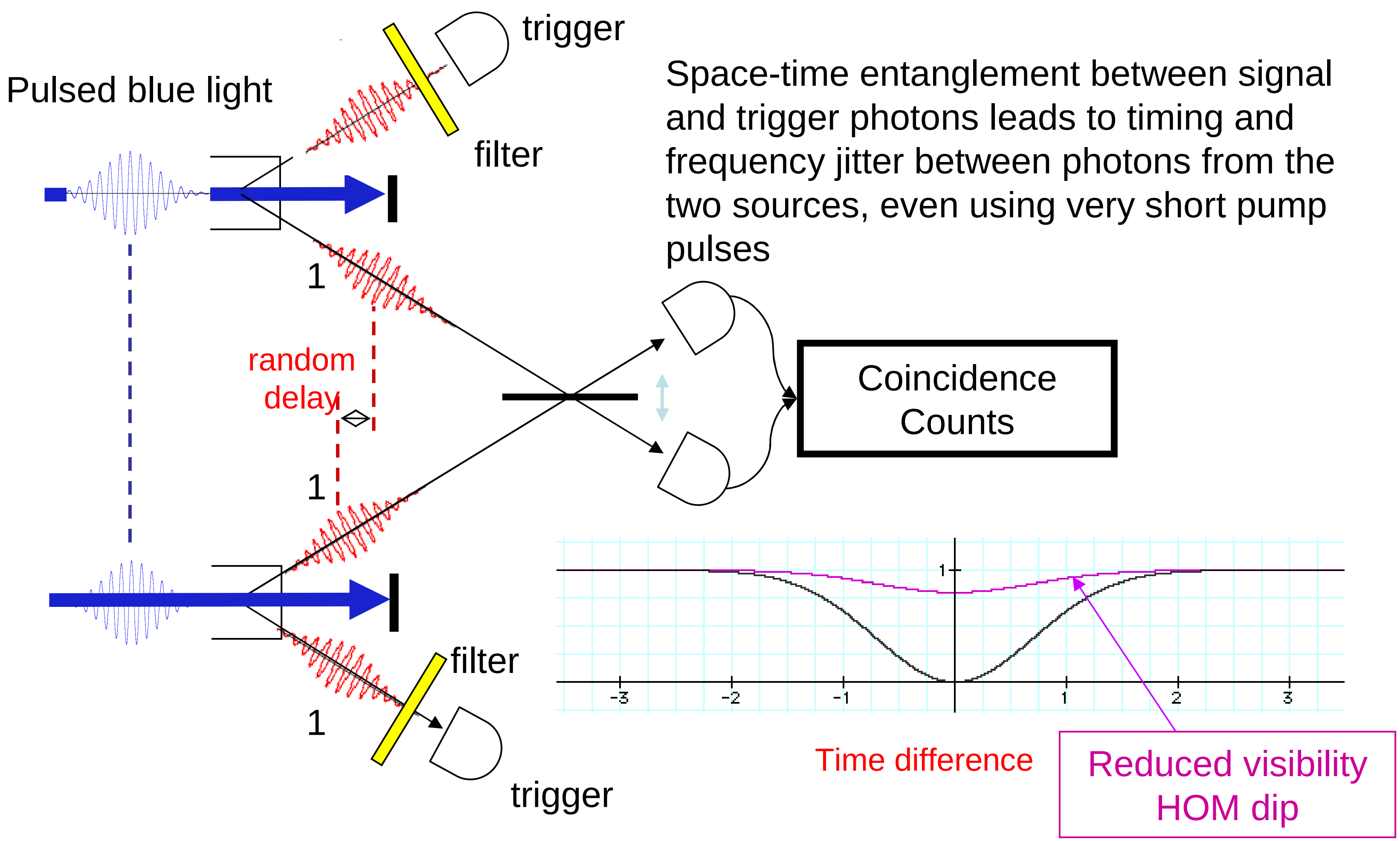
1mm BBO crystal and Δω=15nm pump



Type I Type II

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

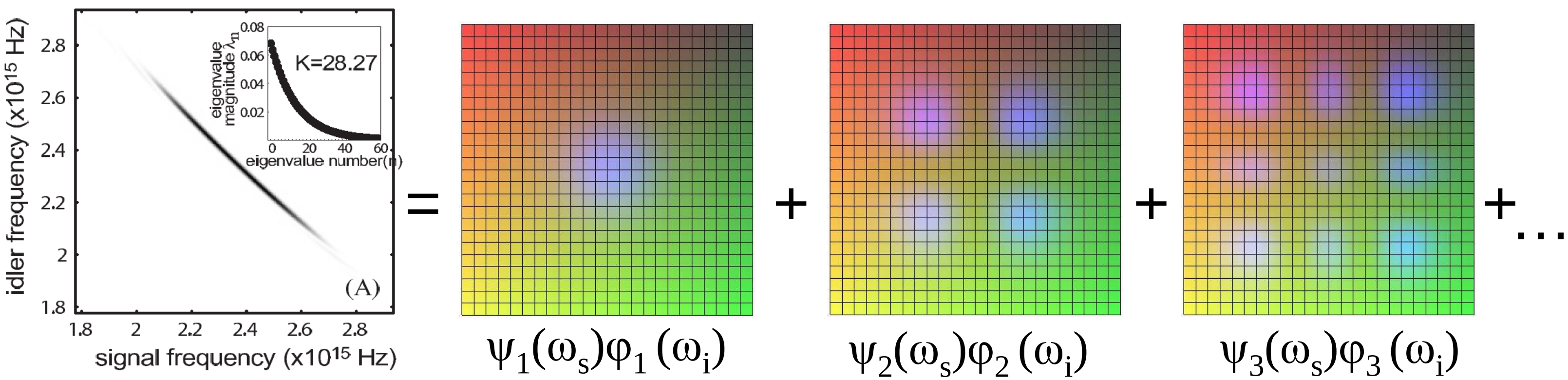
Timing Jitter



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

The Schmidt-mode Decomposition

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



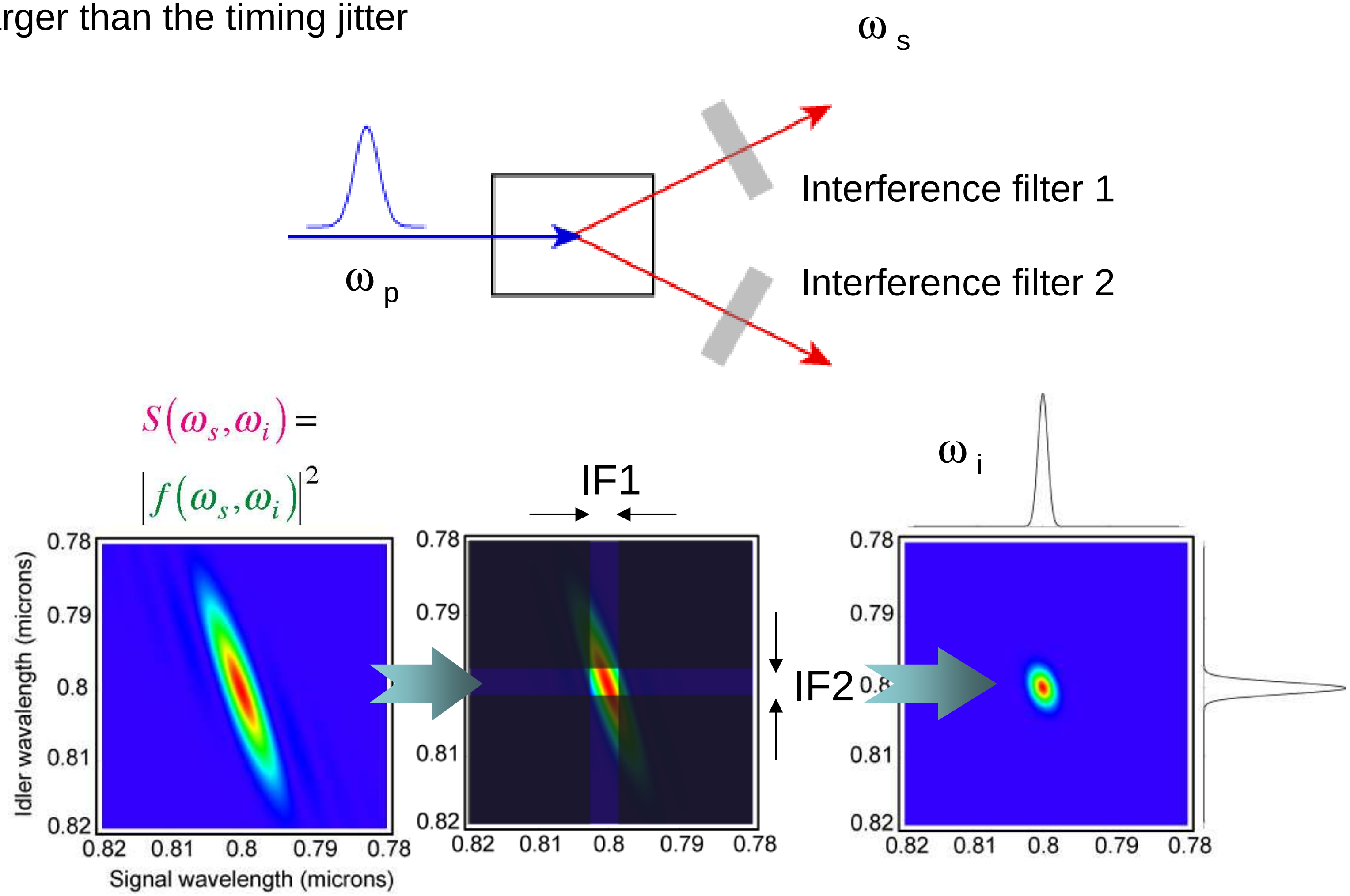
Purity, $\pi = \mathrm{Tr}(\rho_s'^2) = \sum_k \lambda_k^2 = \frac{1}{K}$

Schmidt number

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

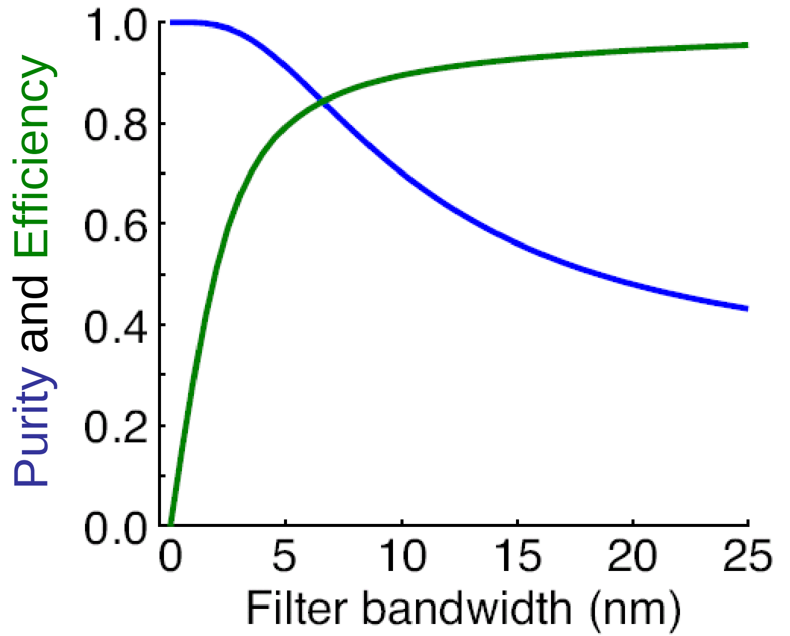
Filtering

- 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



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

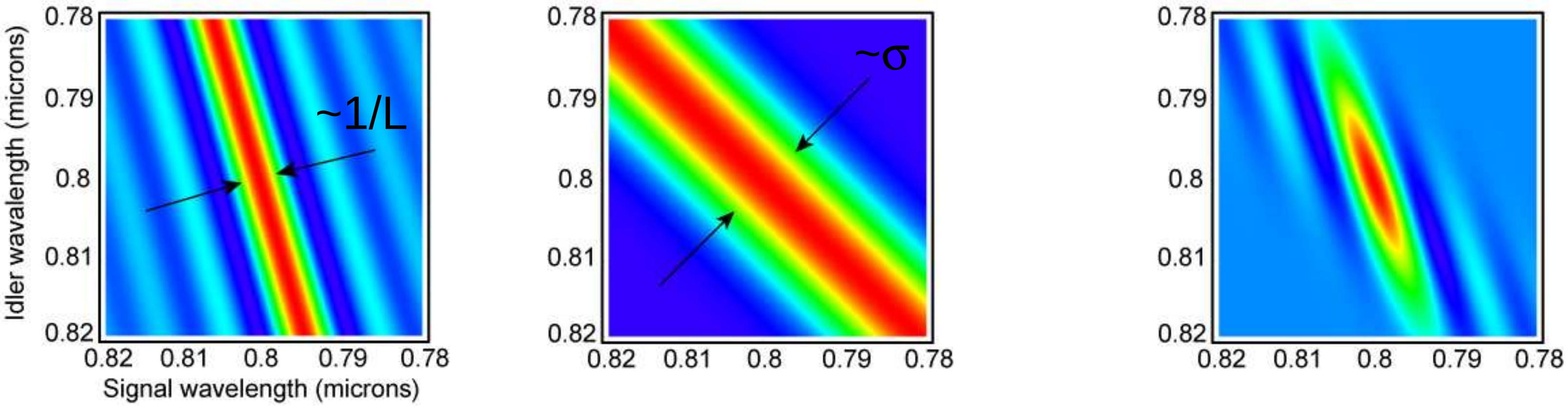
The Solution

- 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

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



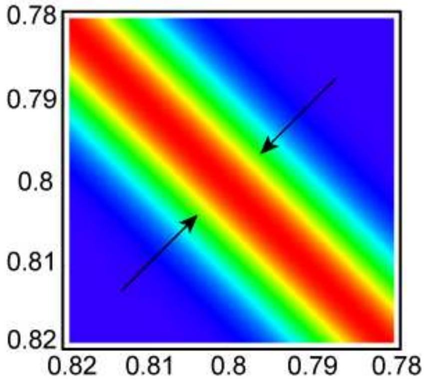
Grice *et al*, PRA **64**, 063815 (2001)

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.

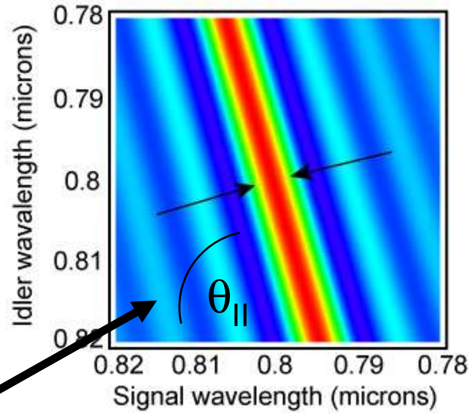
Pump envelope function

$\alpha(\omega_s,\omega_i)$



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

Eliminating Spacetime Correlations

Spectral entanglement removed via group-delay engineering:

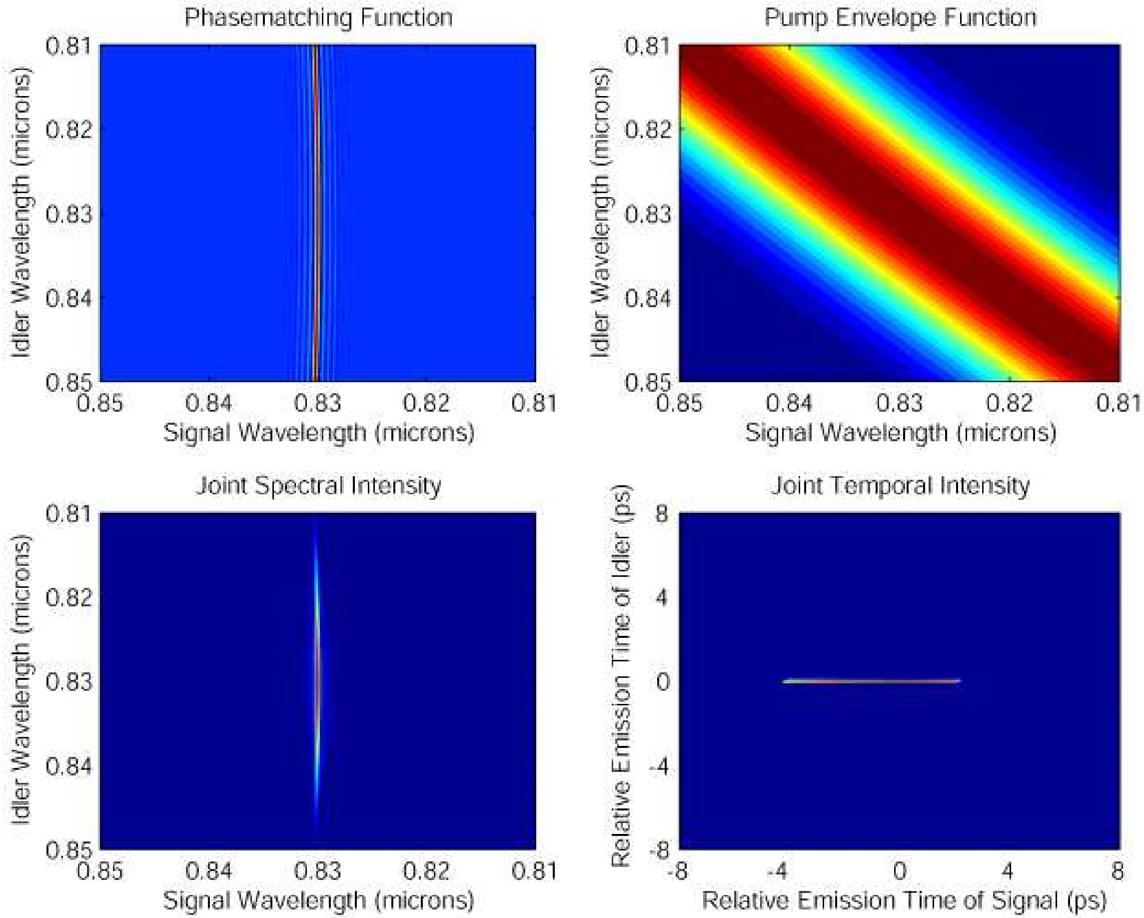
asymmetric GVM

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

+

Broadband pump

s: ~ monochromatic
i: broadband



This condition occurs in KDP at 830nm

Individual photon spectra

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

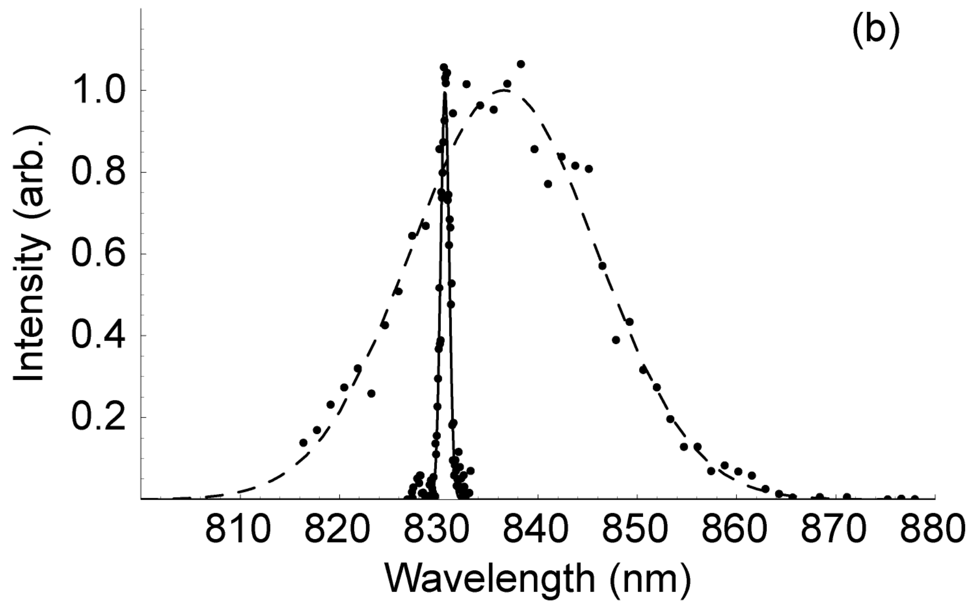
+

Broadband pump

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

Essentially no timing jitter

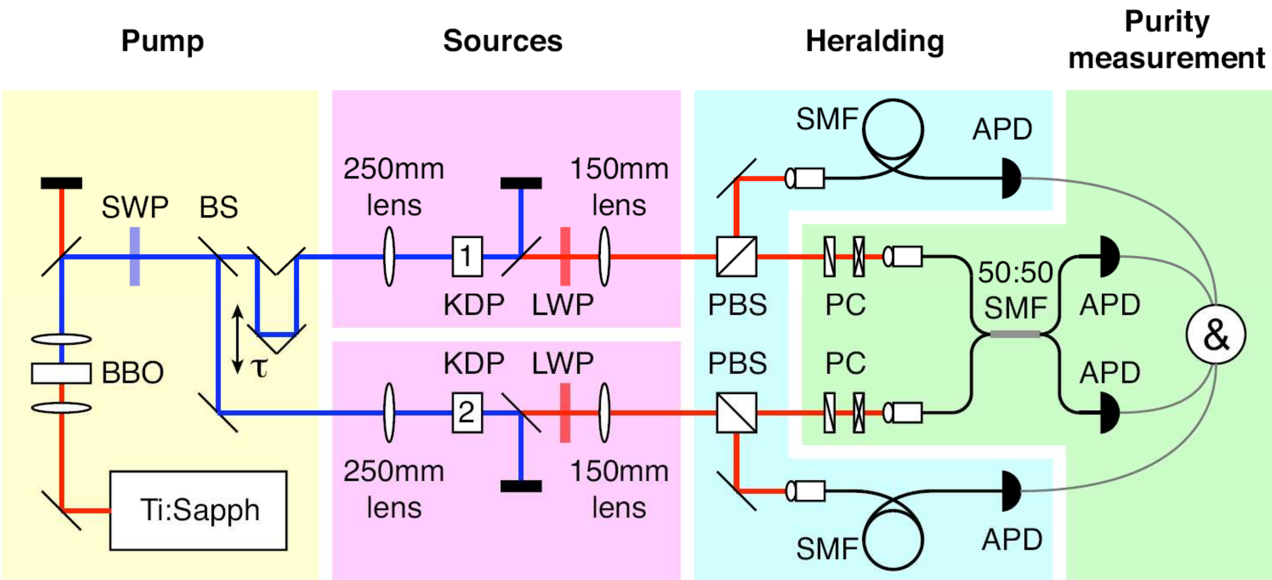
s : $\Delta\tau$ < 0.1 fs
i; $\Delta\tau$ < 10 as



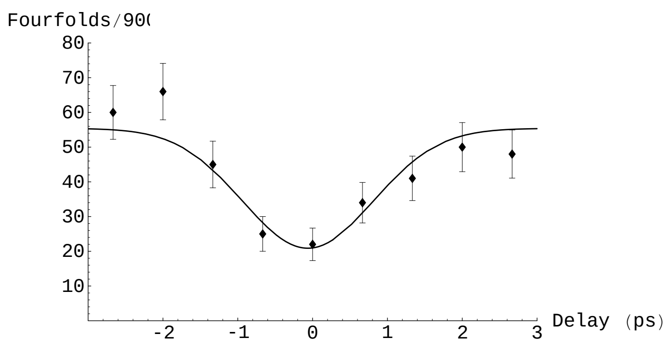
Spectra measured with an amplified CCD and a grating spectrometer

Testing Single-Photon Purity

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

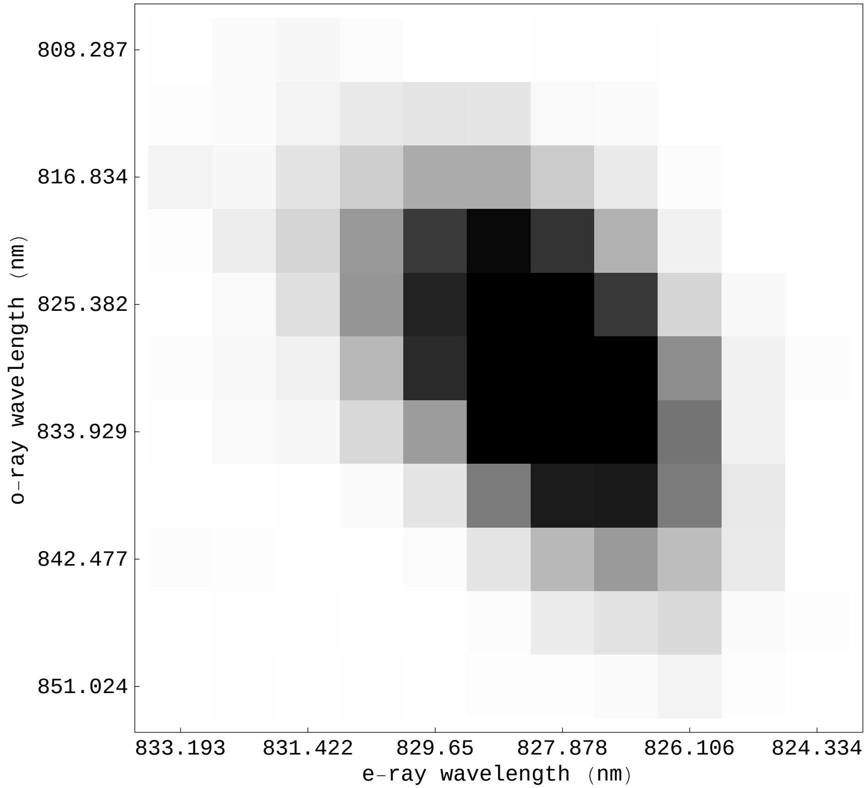


$$V_e = \mathrm{Tr}\left(\hat{\rho}_{e1}\hat{\rho}_{e2}\right) = \frac{\mathrm{Tr}(\hat{\rho}_{e1}^2) + \mathrm{Tr}(\hat{\rho}_{e2}^2) - ||\hat{\rho}_{e1} - \hat{\rho}_{e2}||^2}{2}$$



Visibility/Purity = 65%

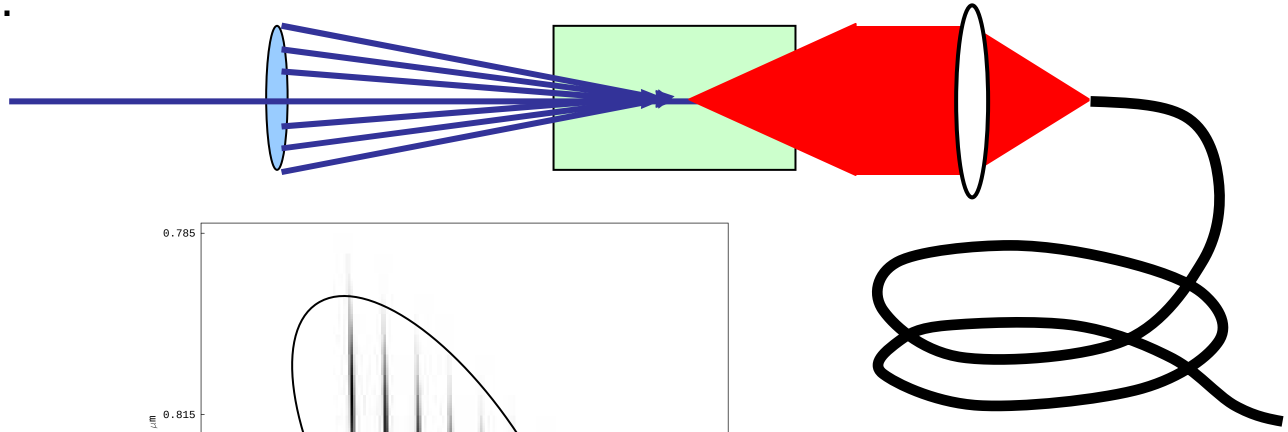
Experimental Joint Spectra

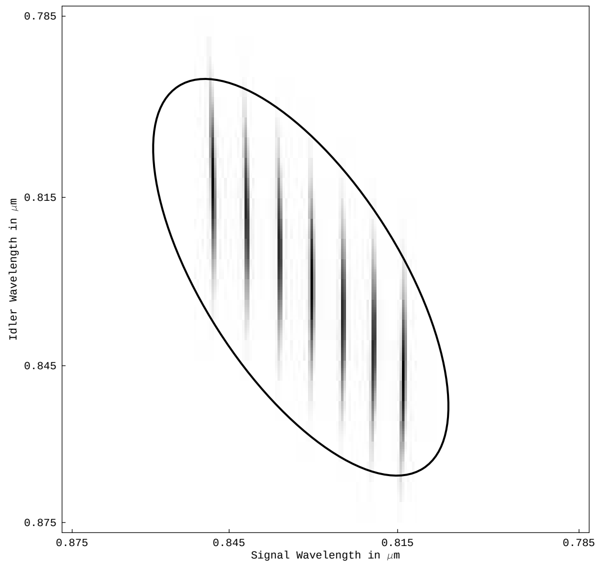


- Experimental Joint Spectra from 20mm crystal with light focusing.
- Measured with two grating spectrometers and translatable single photon detectors.

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.

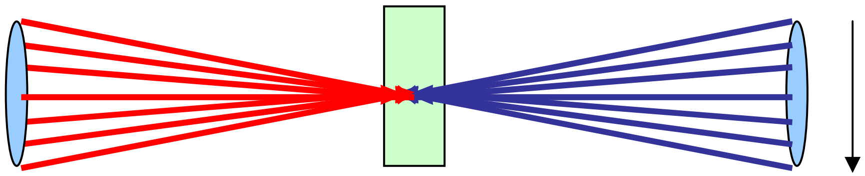




Joint Spectral Intesity for 20mm xtal, pumped at 415nm, changing angle in steps of 0.5 deg.

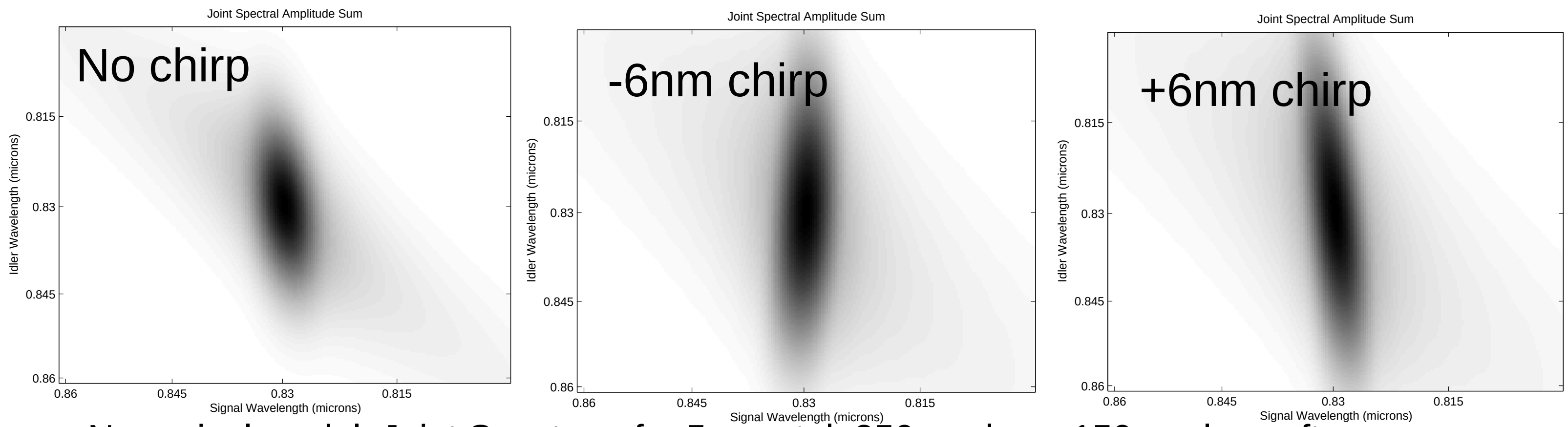
More Reasons for Tilted Spectra

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



Spatial Frequency Chirp

BBO
Second Harmonic Generation

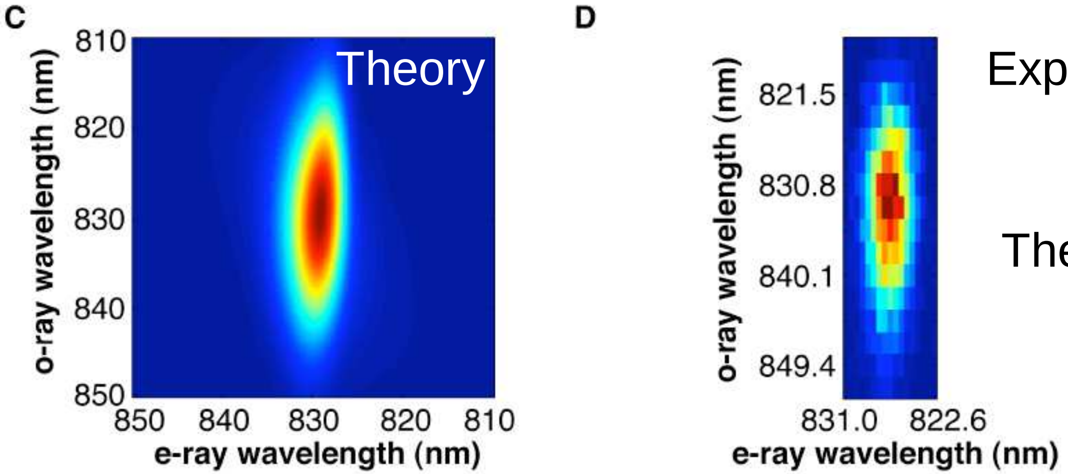


Numerical model: Joint Spectrum for 5mm xtal, 250mm lens, 150mm lens after, pump at 415nm, phasematched for degeneracy

- Solution: Fight fire with fire!

How good are our photons?

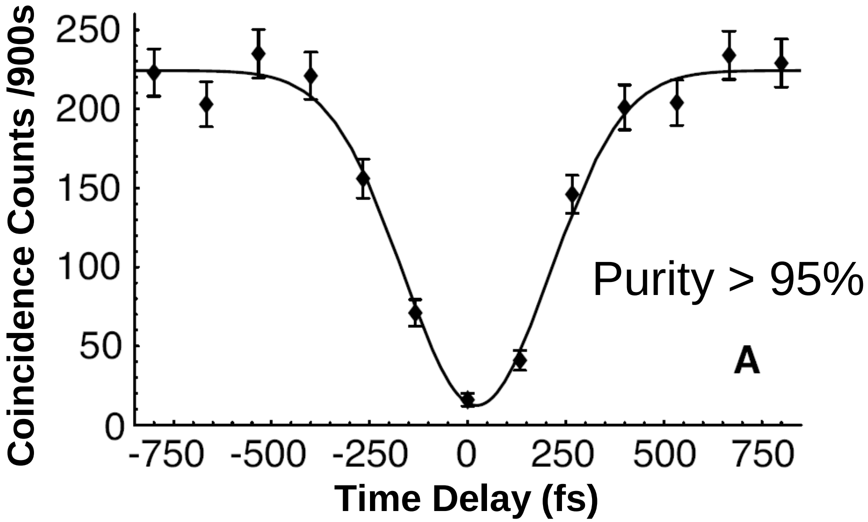
Frequency Correlations



Experiment

Theoretical Purity > 98%

The Purity Test

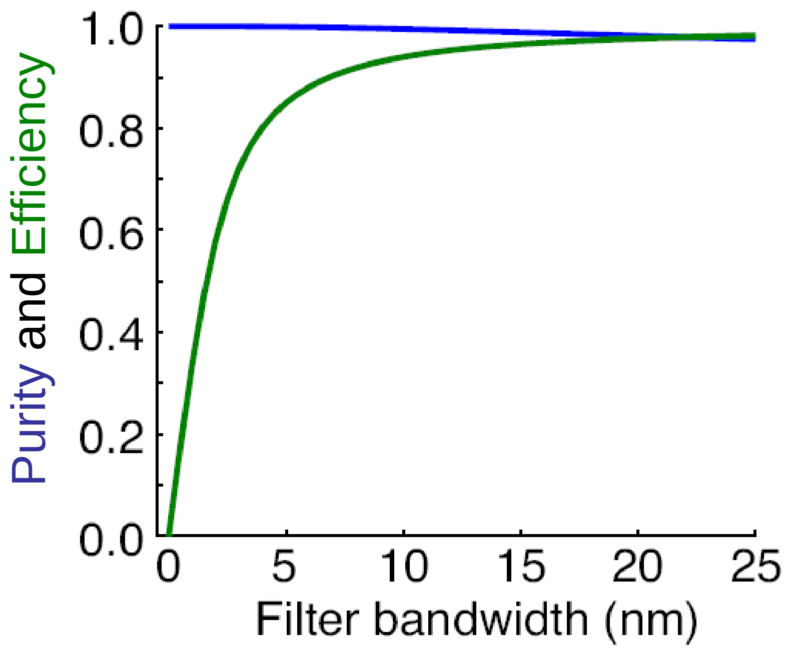


- Heralding efficiency up to 44%
- Four-photon count rates as good as the best sources but with 1/10 the pump power.
- High quality interference with no filters

Peter Mosley, et al.,
Phys. Rev. Lett. **100**, 133601 (2008)

Design a better photon source

Our Source



- No frequency or timing jitter
- No trade-off between efficiency and quality

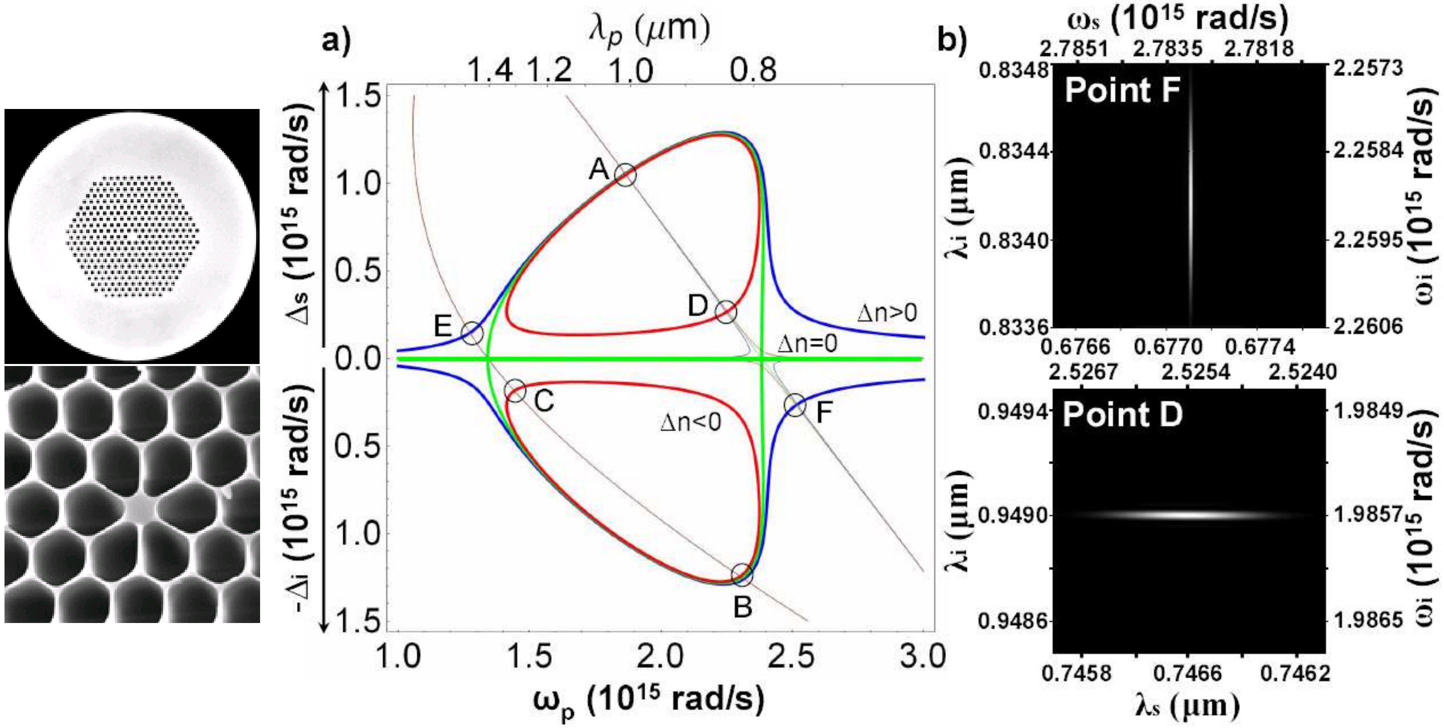
Can we do better?

- Bulk source – heralding efficiency < 60%
- We need to couple in fibres
- Need to design a bulk source without correlations in transverse momentum
- Waveguides can have only one mode.
- Microstructured nonlinear sources allow us to directly engineer the spectral properties of the photons.

Fibre sources of pure photons

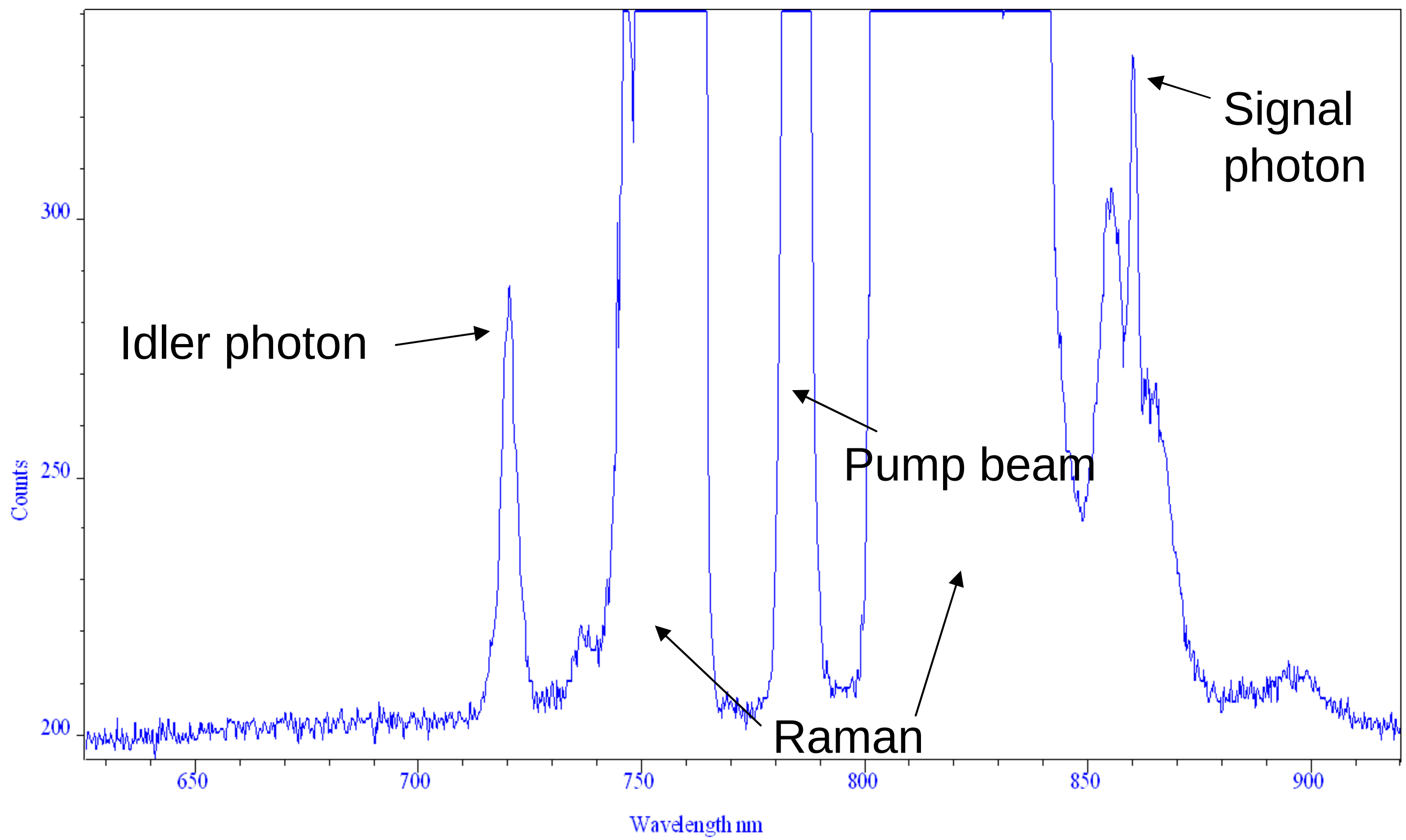
• We have modelled spontaneous four-wave mixing in photonic crystal fibers.

Optics Express, Vol. 15, Issue 22, pp. 14870-14886



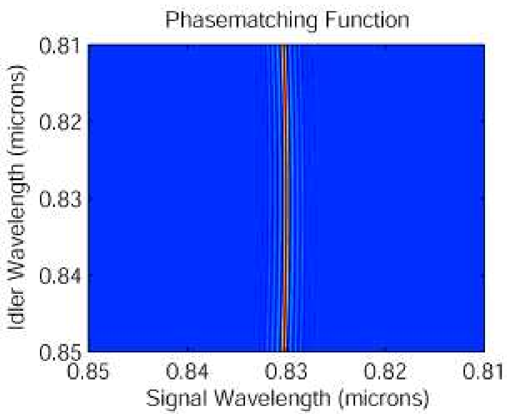
• Any orientation of the crystal function is possible.

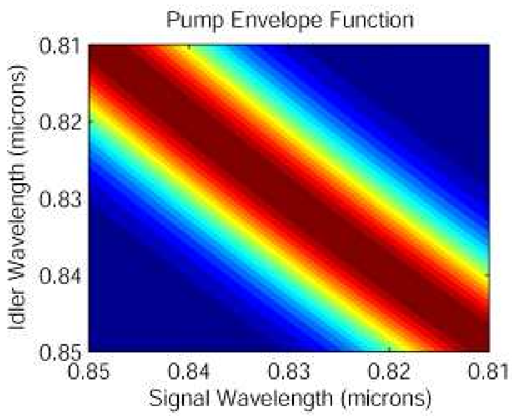
Spontaneous FWM Spectrum

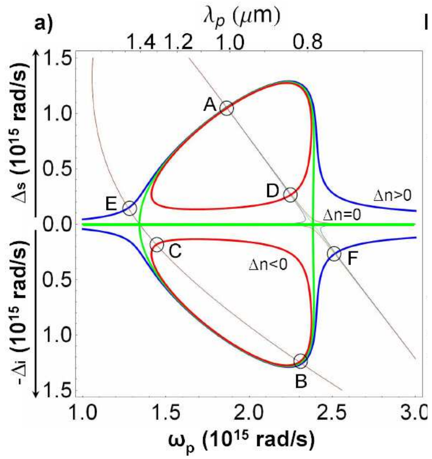


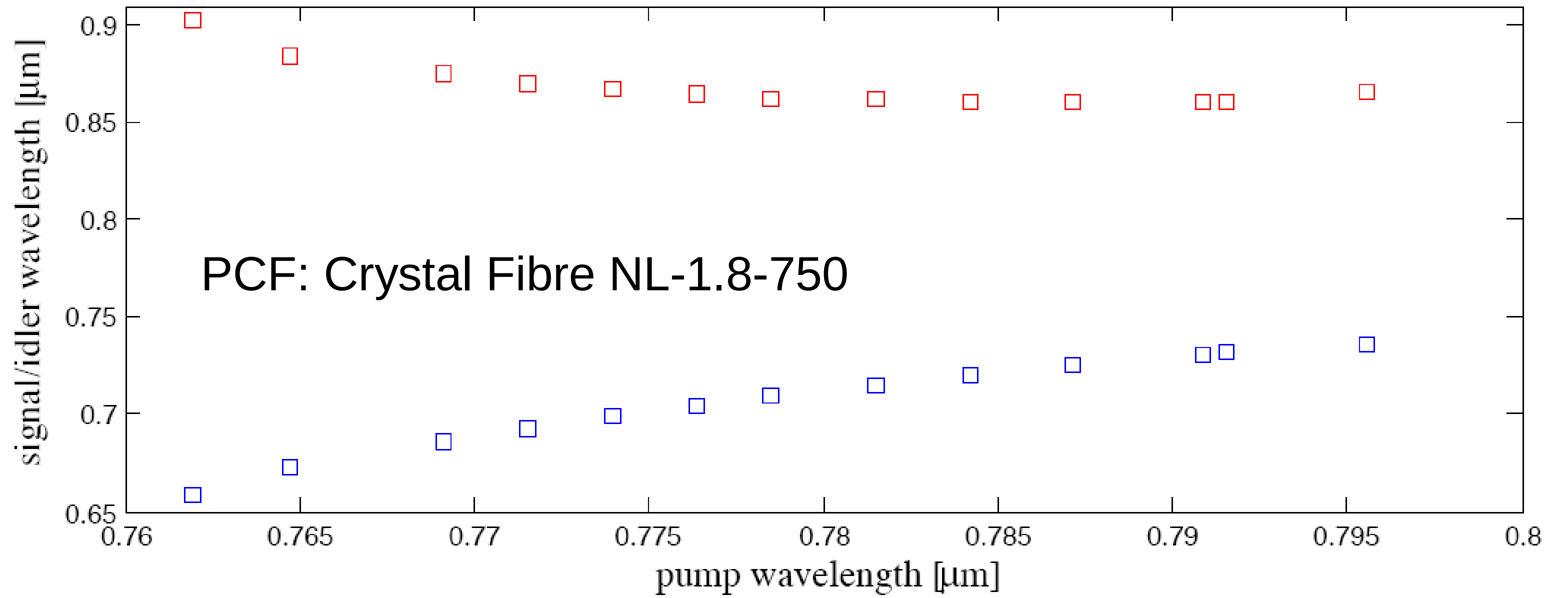
• Past demonstrations by Kumar, Rarity, Migdall, etc.

Finding the right fibre

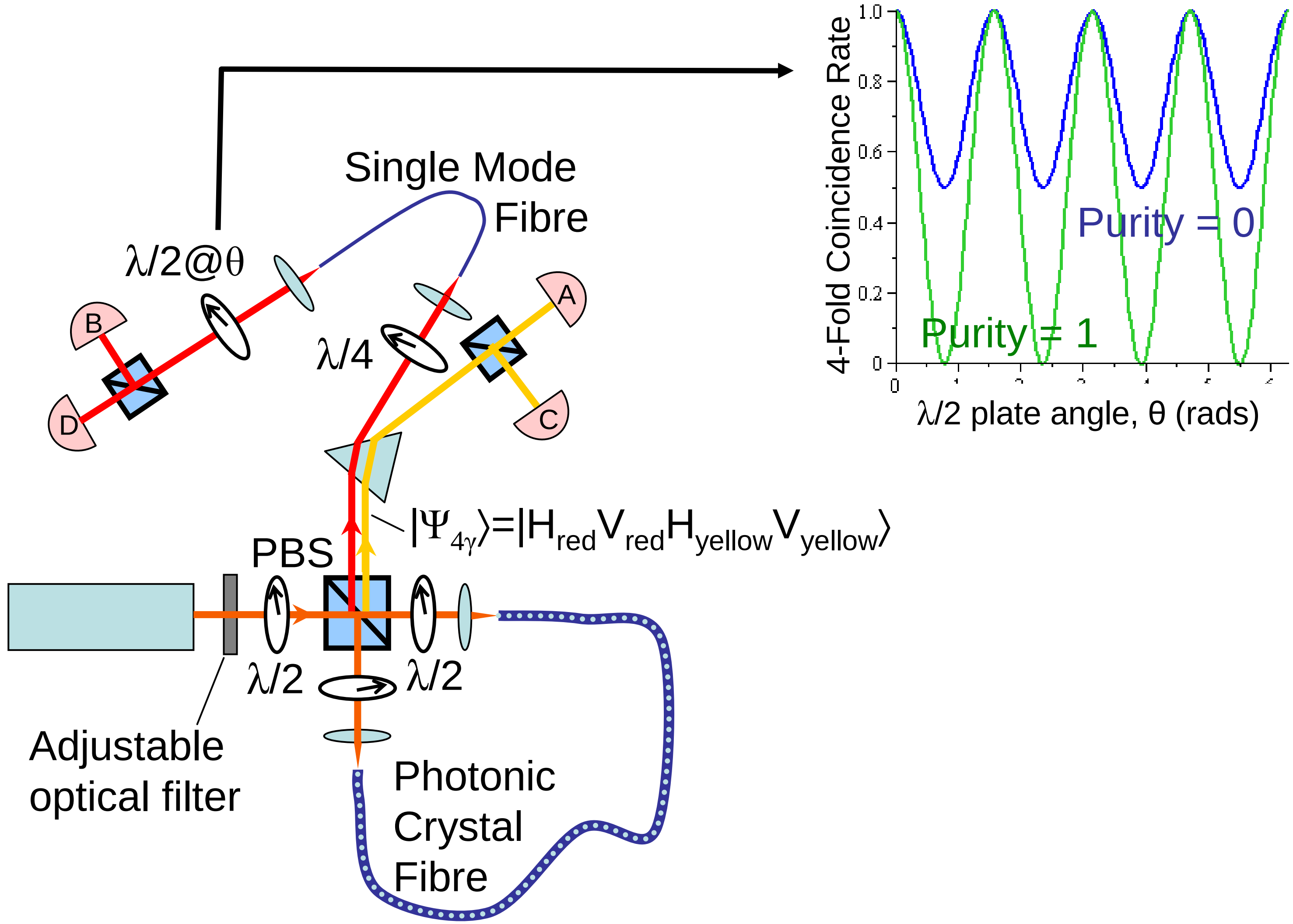








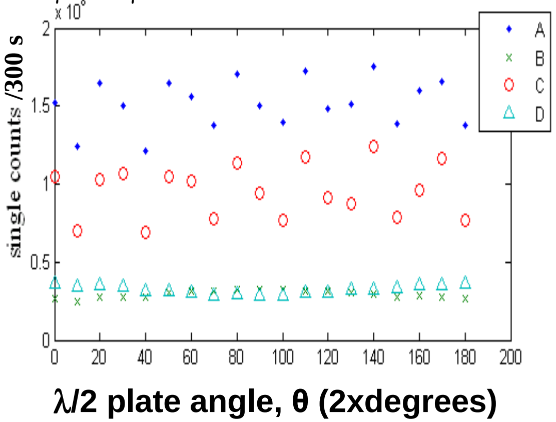
Polarization Test of Purity



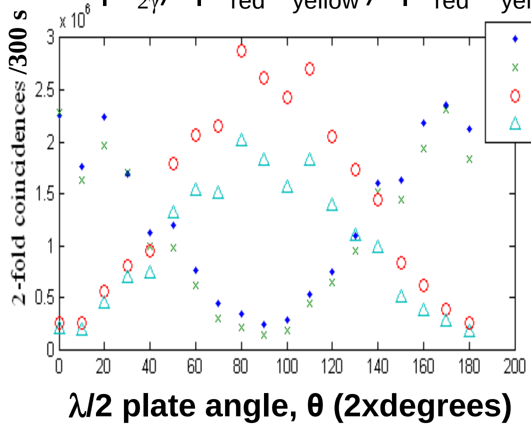
Checking the purity

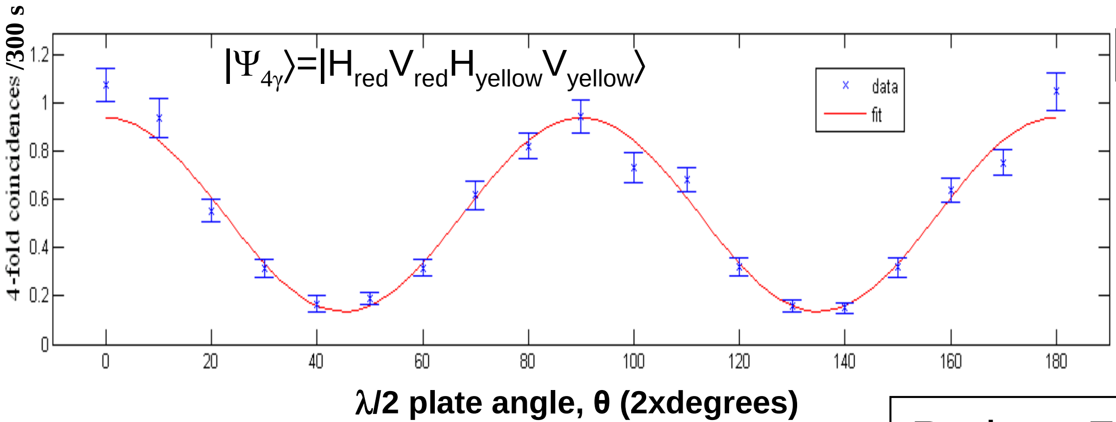
- Singles show that both beams are unpolarized
- The two-folds show regular polarization curves
- The four-folds exhibit non-classical interference

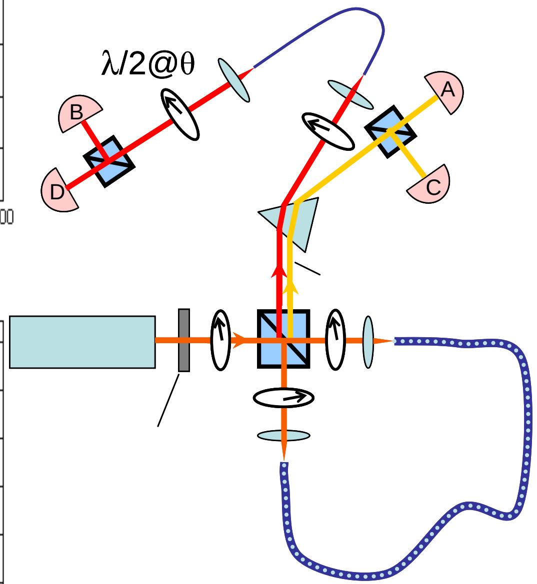
$|\Psi_{1\gamma}\rangle\langle\Psi_{1\gamma}| = |H_{red}\rangle\langle H_{red}| + |V_{red}\rangle\langle V_{red}|$



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

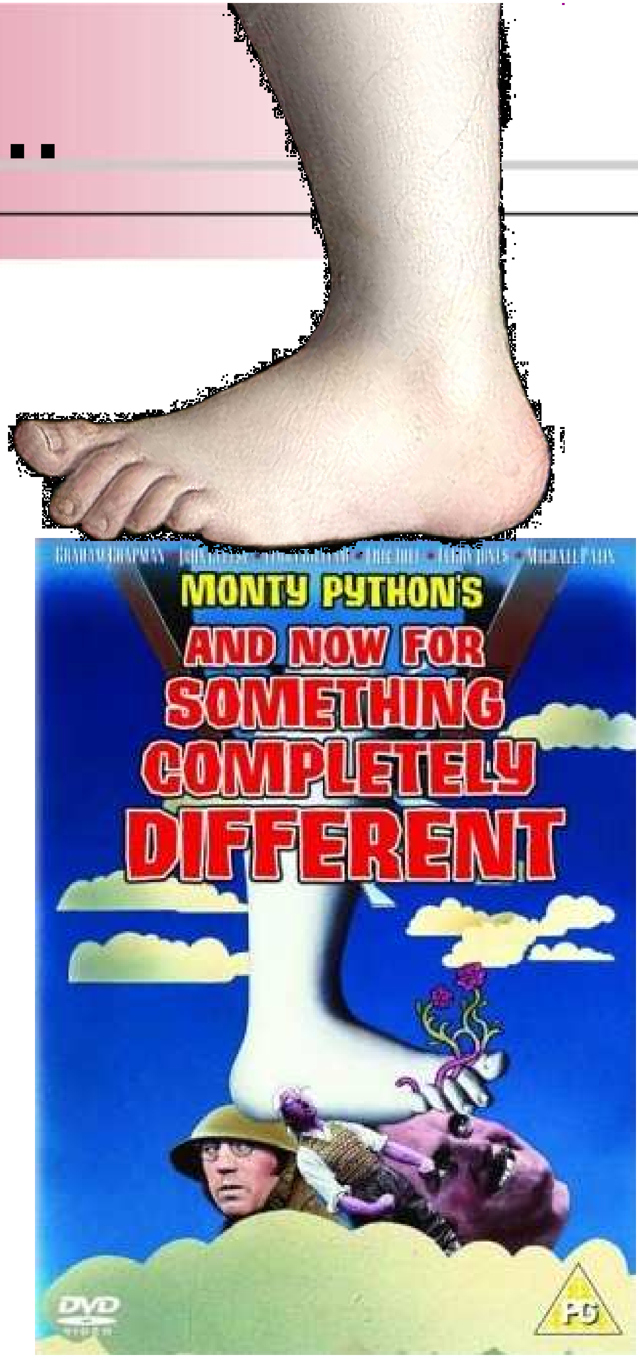






Purity = 71%

And now…


MONTY PYTHON'S
AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT
DVD
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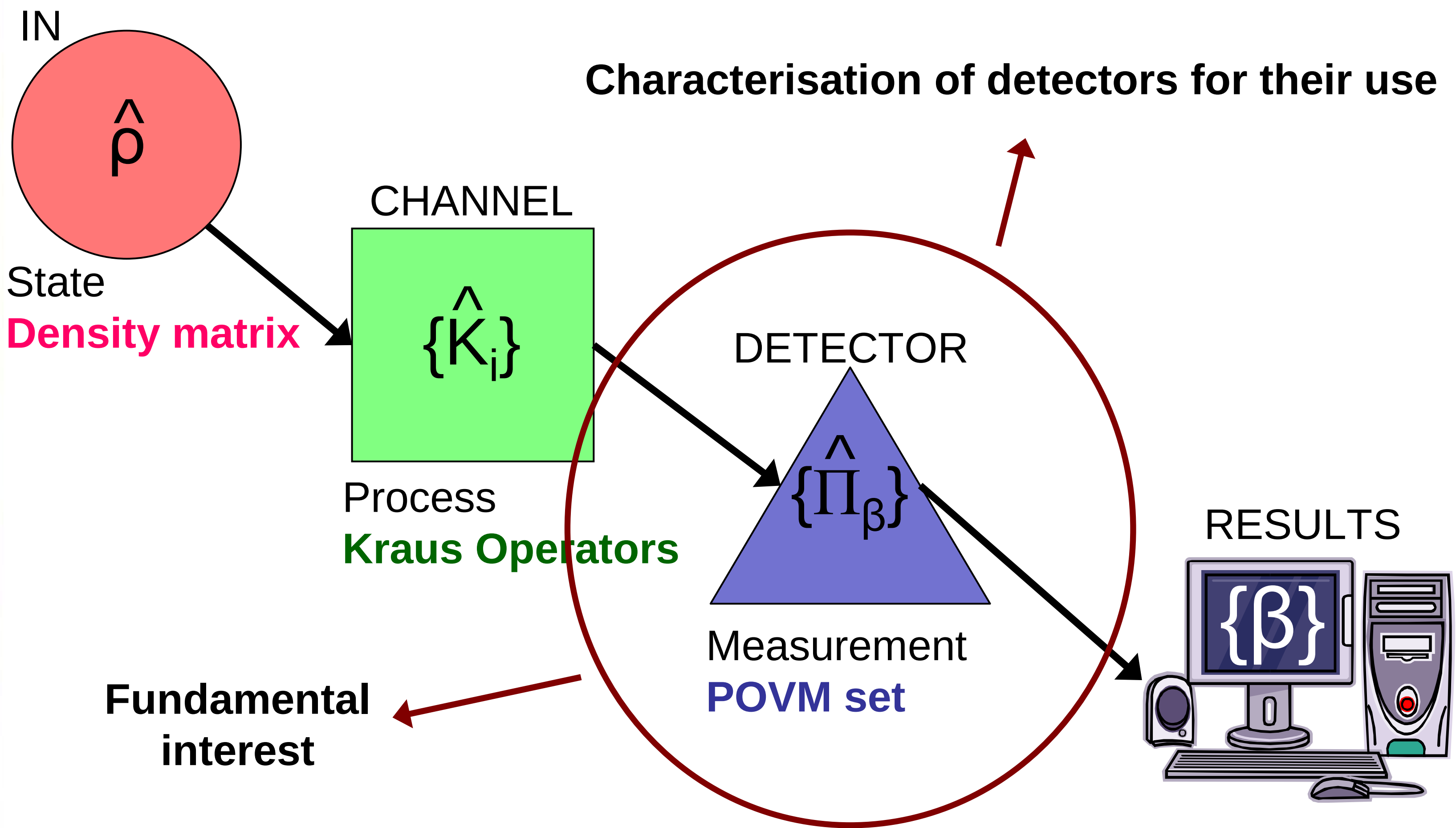
Measuring the Measurement

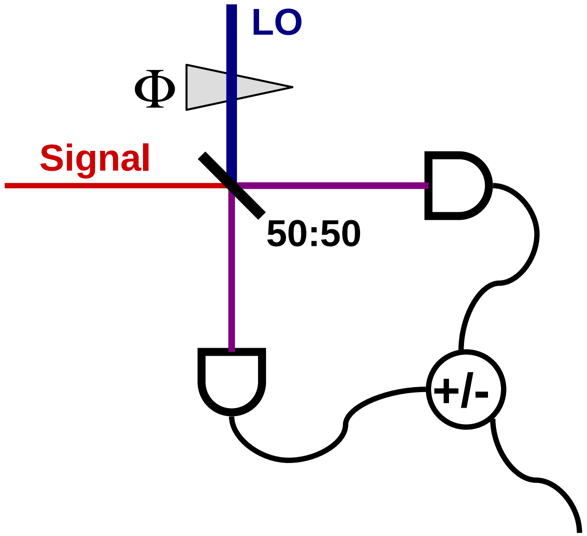
Any quantum experiment can be described in three stages



D.T. Smithey, et al., PRL 70, p.1244
J. Fiurásek, PRA 64, 024102

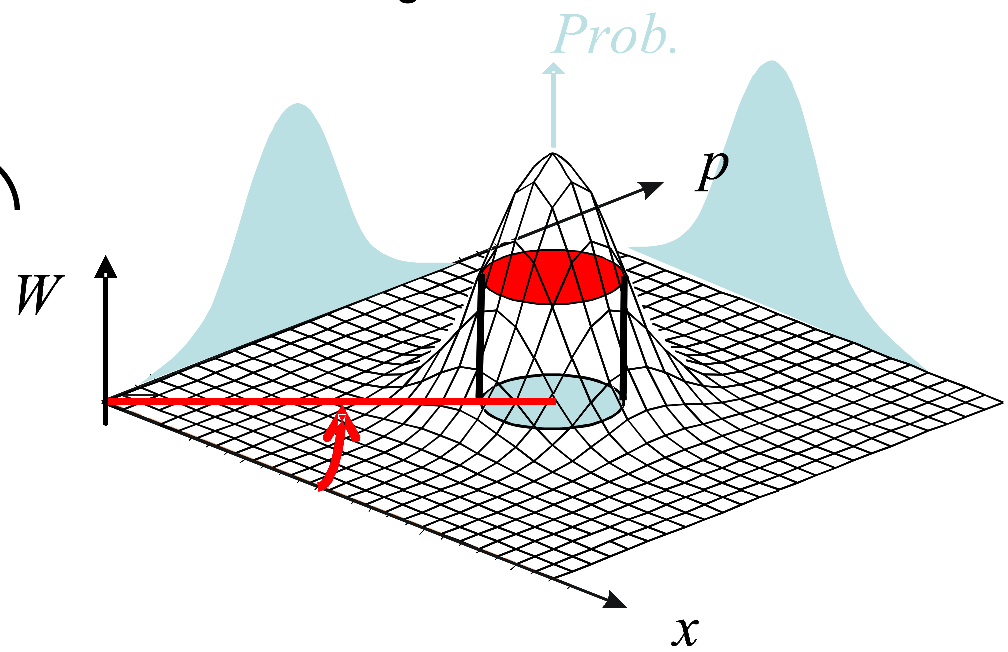
State Tomography

Reconstruction of the state

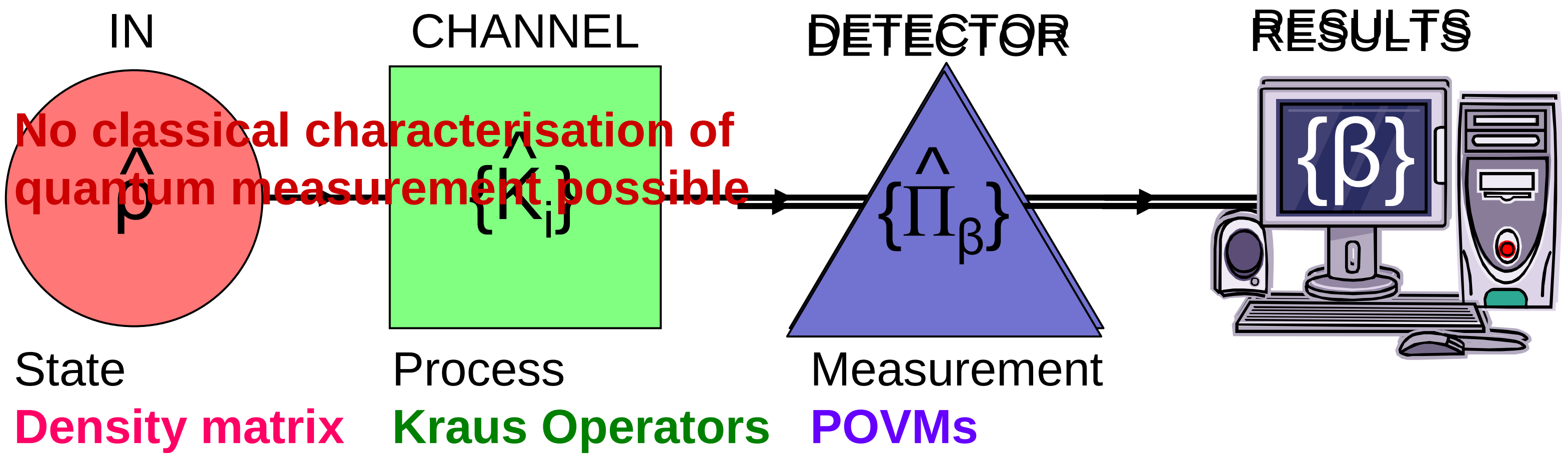


Homodyne tomography

Wigner function



Measurement Tomography



- Complete characterisation of quantum measurement apparatus

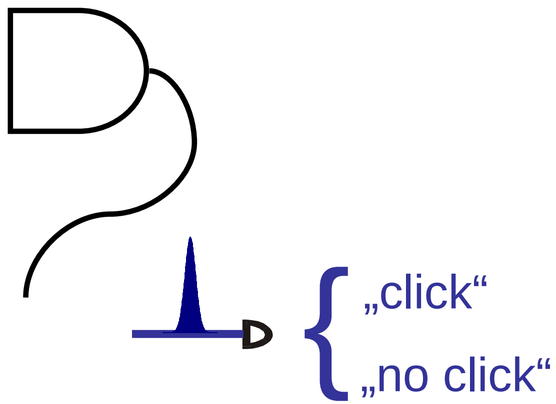
$$P(\beta) = Tr[\hat{\rho}\,\hat{\Pi}_\beta]$$

- Need to know **results** and **probe states** to obtain **POVMs**

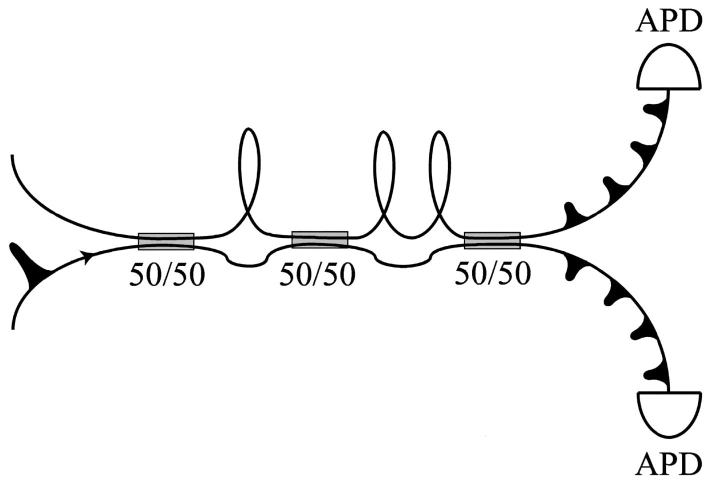
  - Characterise detector before use in state characterisation
    - Need a full set of probe state

Detectors

- Avalanche Photodiode



- Time multiplexed detector



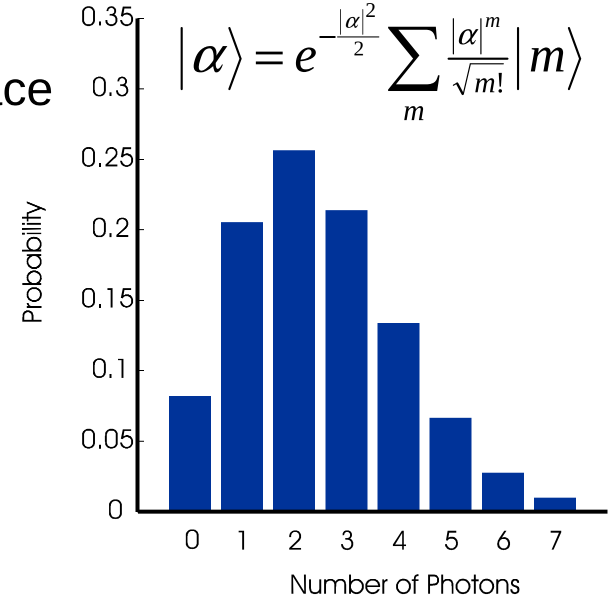
Fiber-assisted detection with photon number resolution, D. Achilles, et al., Optics Letters, 28, 2387-2389 (2003).

- Both detectors are measuring in the photon number space of a mode
- Suitable probe states are coherent states

Coherent Probe State

- Coherent states
  well known properties, span the number-space

$$|\alpha\rangle = e^{-\frac{|\alpha|^2}{2}} \sum_m \frac{|\alpha|^m}{\sqrt{m!}} |m\rangle$$



- Q function of the POVM elements

$$\mathrm{P}_n(\alpha) = Tr[|\alpha\rangle\langle\alpha|\Pi_n] = \langle\alpha|\Pi_n|\alpha\rangle = cQ(\alpha)$$

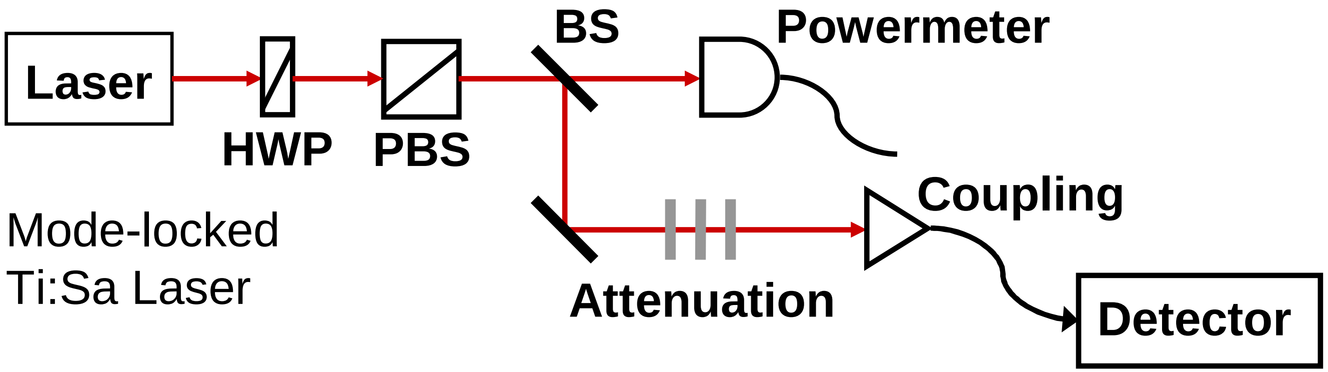
No phase reference in detector

$$\mathrm{P}_n\left(|\alpha_i|^2\right) = \sum_{m=0}^{d-1} e^{-|\alpha_i|^2} \frac{|\alpha_i|^{2m}}{m!} \langle m|\Pi_n|m\rangle$$

P F π

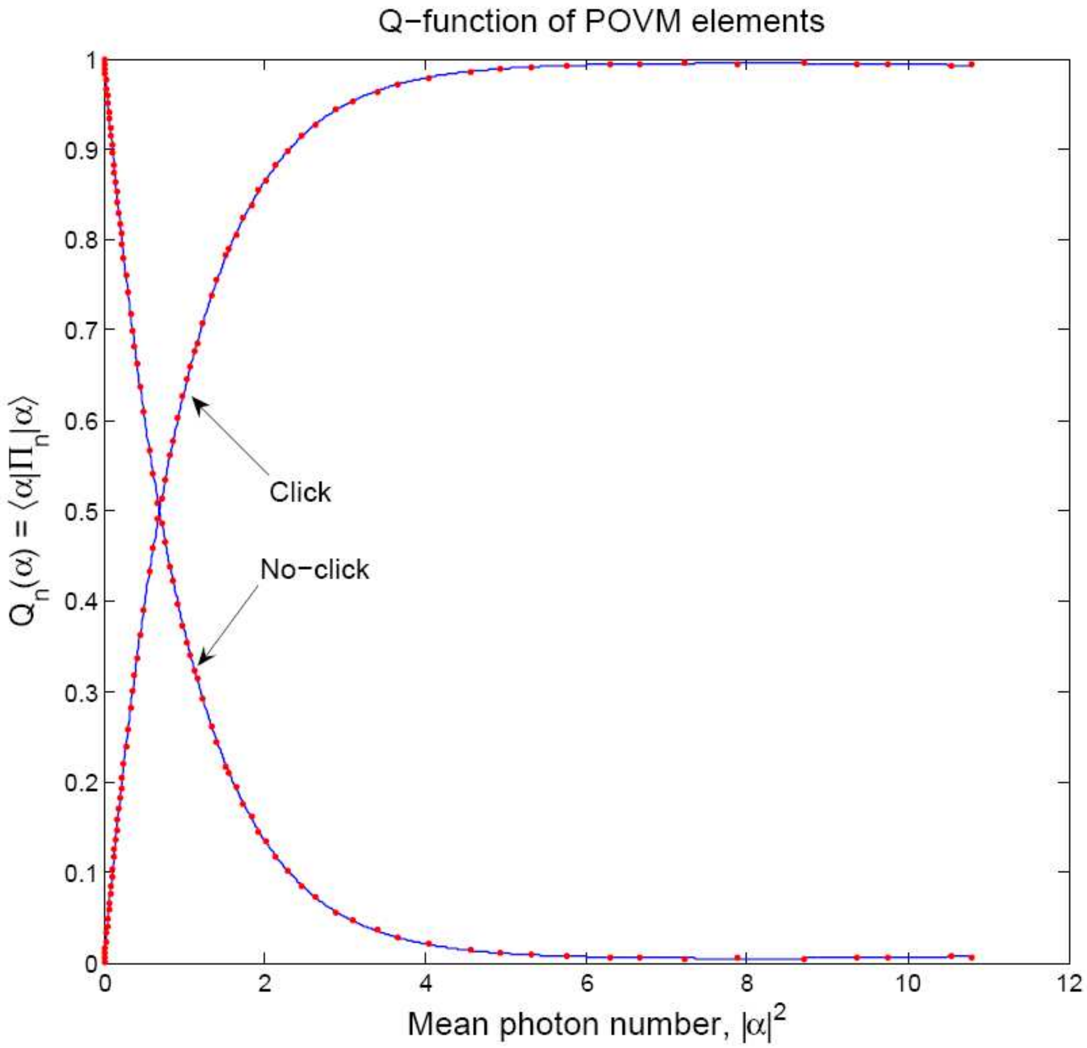
In order to obtain POVMs, minimise $\|\mathrm{P} - F\pi\|$ by convex optimisation

Experimental Setup

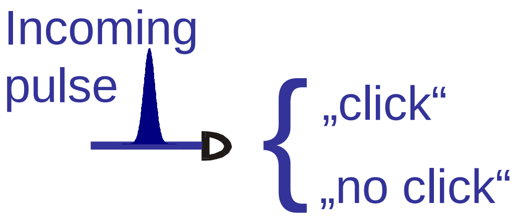


- Use the half-wave plate to create a series of coherent states with different intensities
- For each intensity measure the rates of each detector outcome
- These correspond to different POVM elements
- Measure the intensities of the coherent states with the powermeter in the monitor arm

Results for the APD

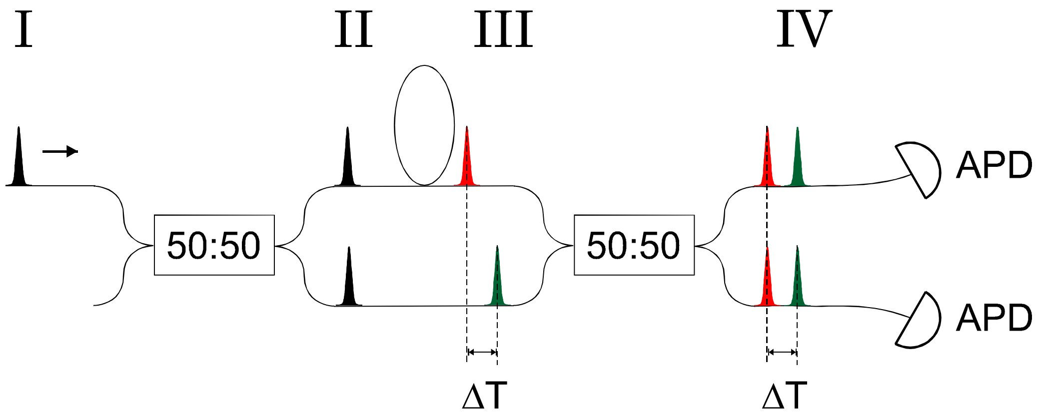


Binary Detector
just two outcomes



Time multiplexed detection (TMD)

Photon number resolved detection using avalanche photodiodes



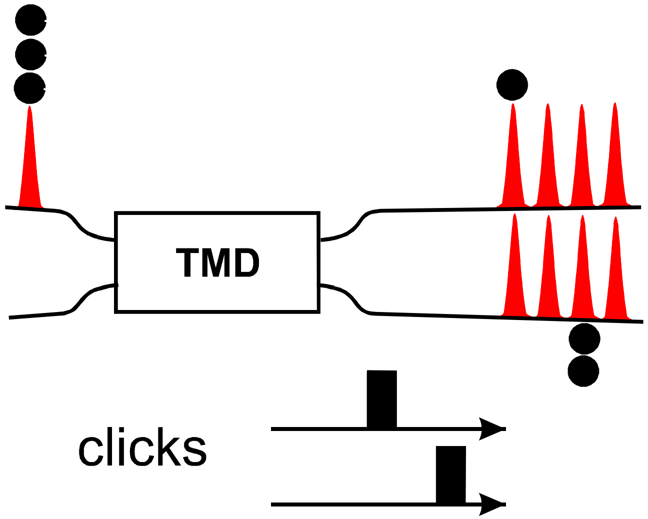
$$\rho = \begin{pmatrix} \rho_{11} & \rho_{21} & \rho_{31} & \cdots \\ \rho_{12} & \rho_{22} & \rho_{32} & \\ \rho_{13} & \rho_{23} & \rho_{33} & \\ \vdots & & & \ddots \end{pmatrix}$$

Mapping between

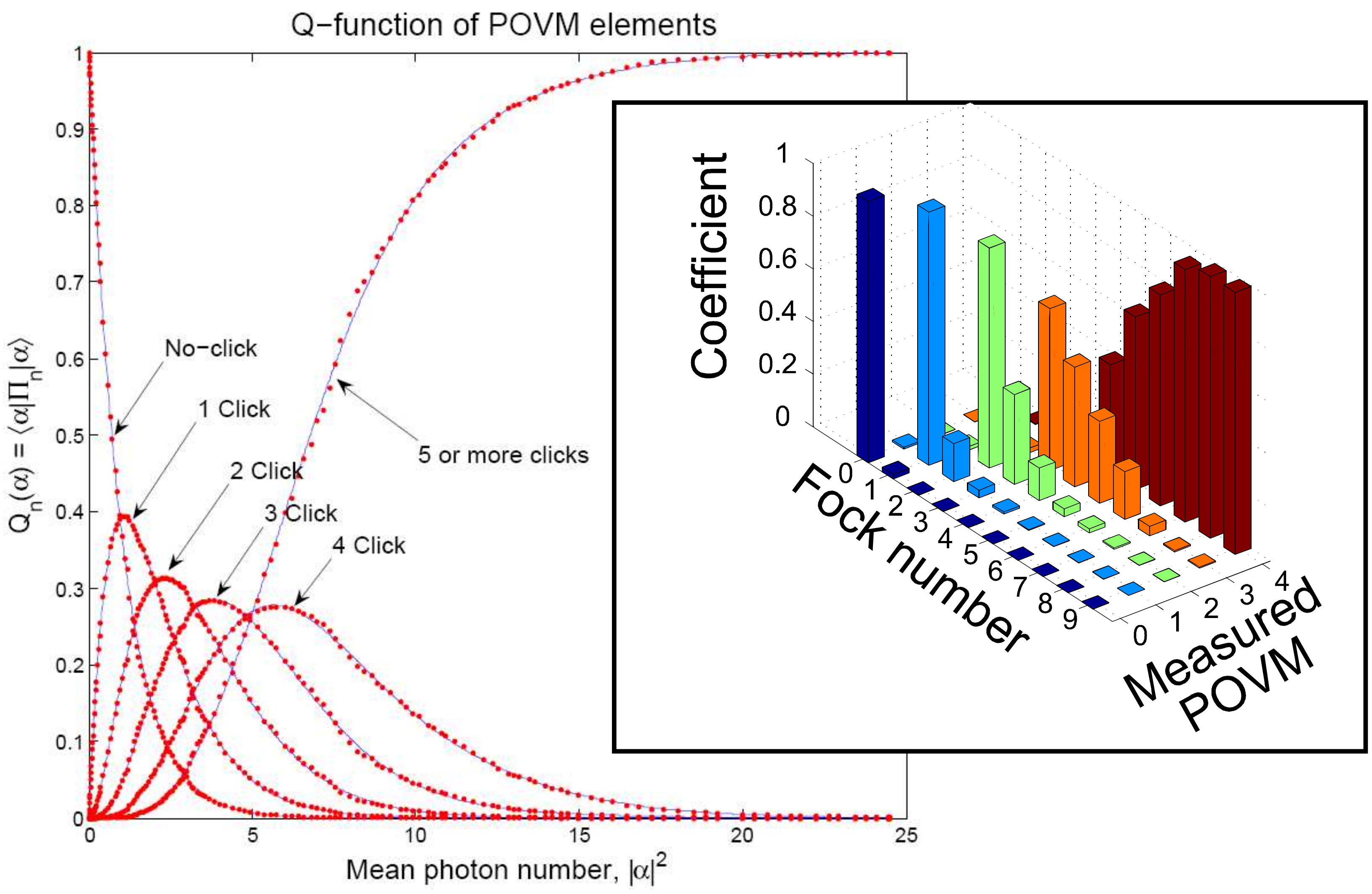
photon number distribution

$$p_k \longrightarrow \rho_n$$

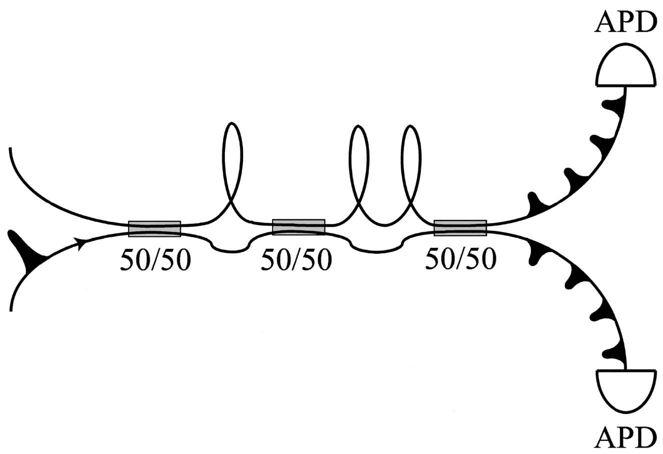
and click statistics



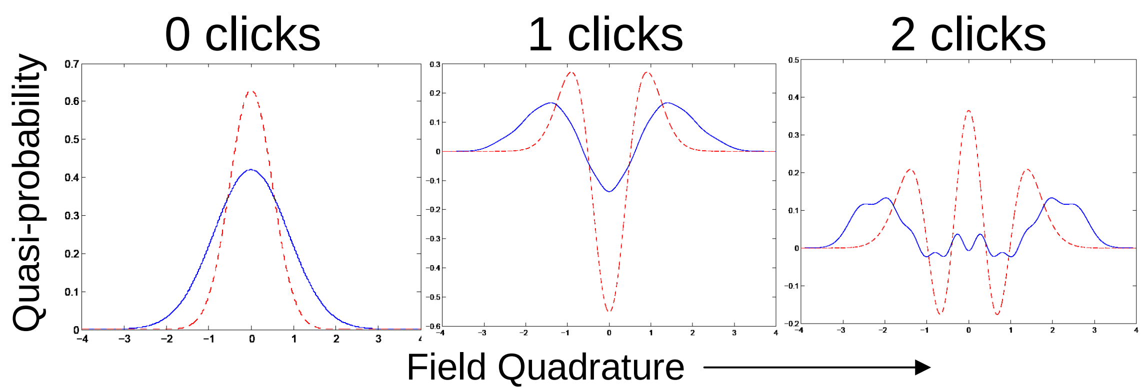
Results for TMD



Tomography Results



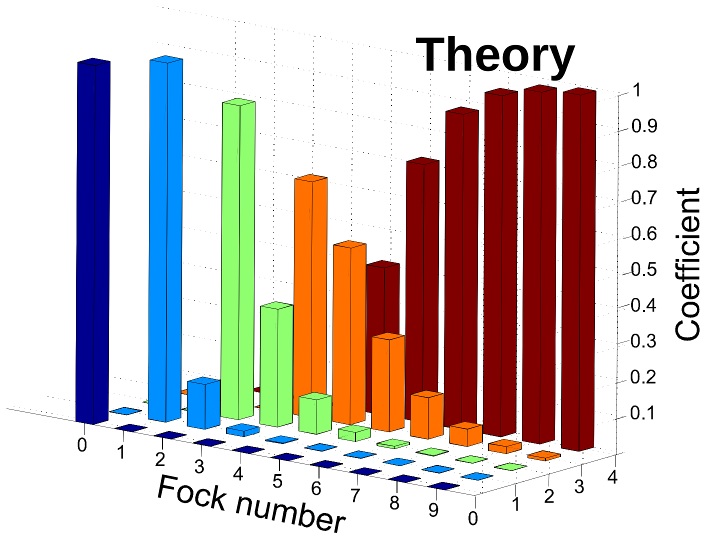
Cross-section of POVM Wigner Function

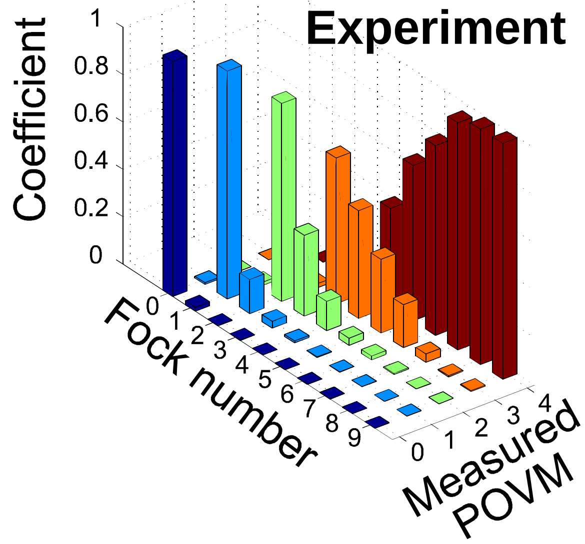


With Loss (47%)

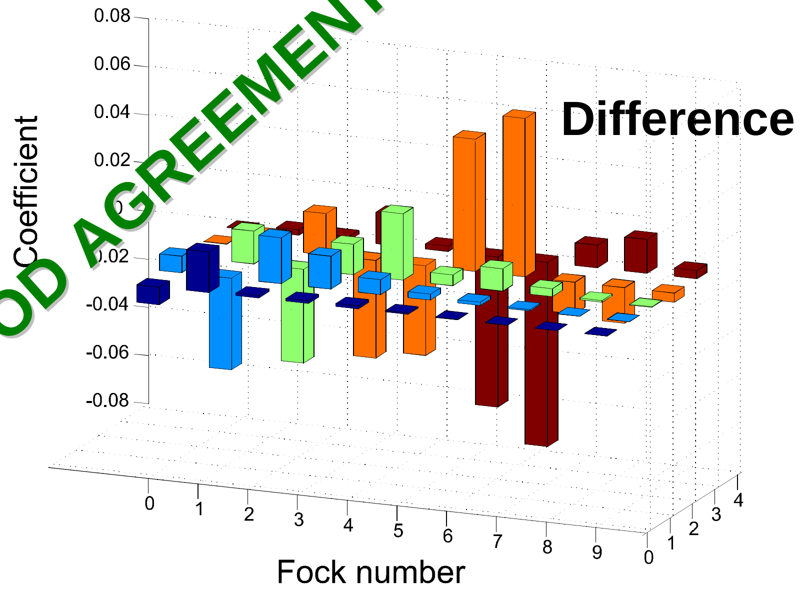
Without Loss

TMD results comparison





GOOD AGREEMENT



Conclusions

- Producing pure photonic states is necessary for quantum logic gates.
- Pure states are possible with careful design of the dispersion in the nonlinear medium
- Fibre sources promise single-mode emission and pure states
- We now have a tool to characterize any quantum detector: detector tomography