Photon generation and storage

Generation

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Storage

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Outline

Photon Generation

1. The Goal: CV Entanglement Distillation
2. Generation of pure single photons
3. Measurement of CV Entanglement

Photon Storage

4. A scheme for a broadband quantum memory
5. Three candidate material systems

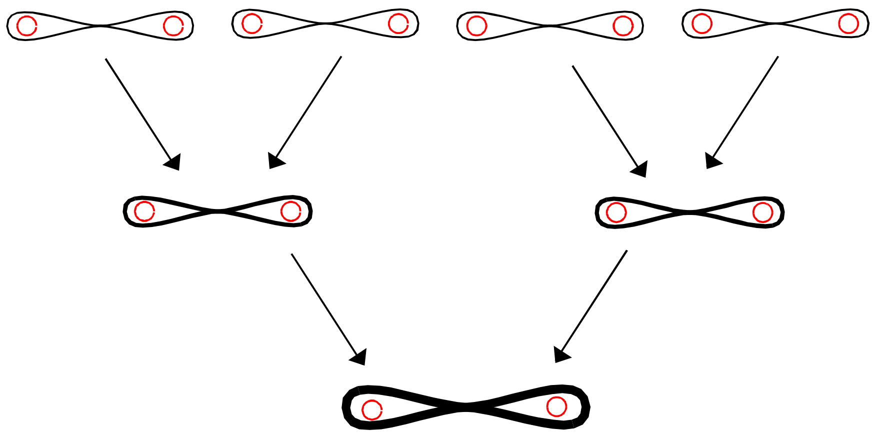
Entanglement Distillation

• Use the electric field quadratures X and P as resources for quantum information.

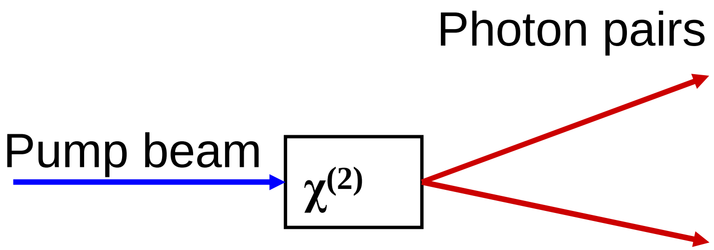
• Two-mode squeezed states are entangled states.

• Entanglement degrades when distributed over channels.

• **Create one pair with a high degree of entanglement by combining many degraded pairs: Entanglement Distillation**.

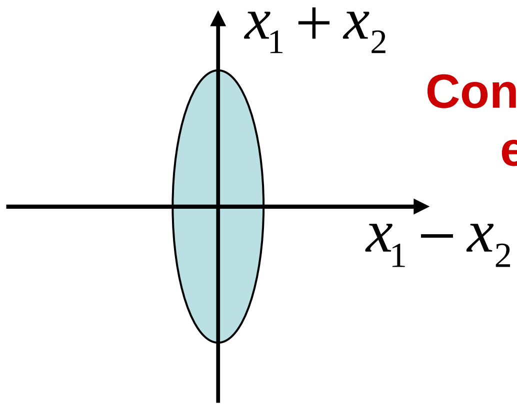


Spontaneous Parametric Downconversion

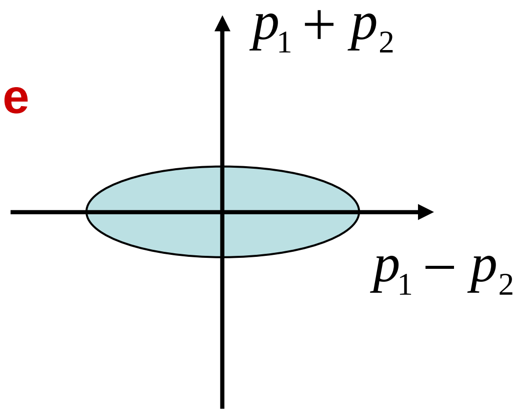


Squeezed two-mode vacuum state

$$W(x_1, p_1, x_2, p_2) = \exp\left(-\frac{(x_1 - x_2)^2 + (p_1 + p_2)^2}{\sigma_A} - \frac{(x_1 + x_2)^2 + (p_1 - p_2)^2}{\sigma_B}\right)$$

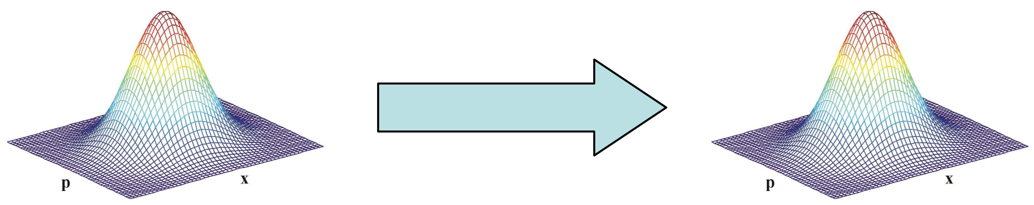


Continuous variable entanglement



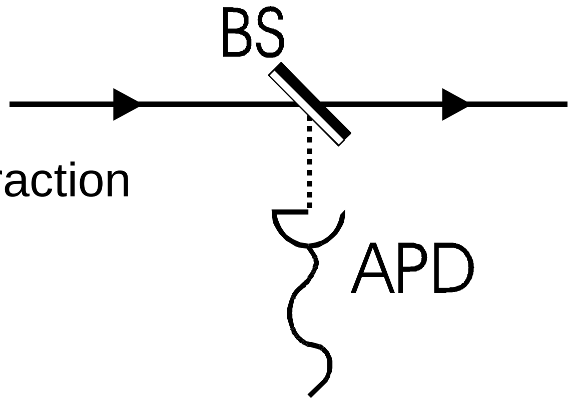
- The produced entangled state has a Gaussian Wigner function

Distillation is impossible with Gaussian states



• **No distillation of Gaussian states is possible by Gaussian operations! (i.e. linear optics + squeezing)**
(Eisert, et al. 2002, PRL89(13), 137903)

• Non-Gaussian operation e.g. Photon subtraction



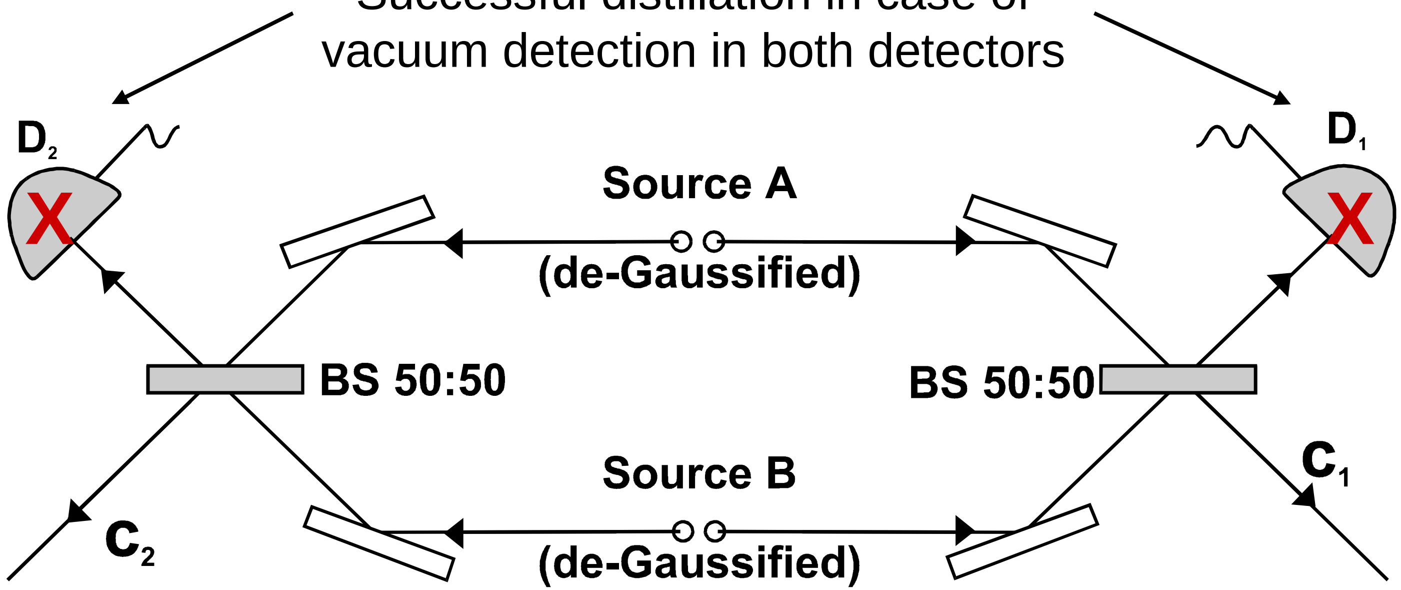
• **After de-Gaussifying once, Gaussian operations are sufficient for distillation**
(Eisert et al. 2004, Ann. of Phys. 311, 431-458)

Distillation Scheme

• Start with ensemble of entangled modes and extract smaller number of modes with higher degree of entanglement

• Iterative scheme – assuming starting with de-Gaussified states
(Browne et al. 2003, PRA 67, 062320)

Successful distillation in case of vacuum detection in both detectors



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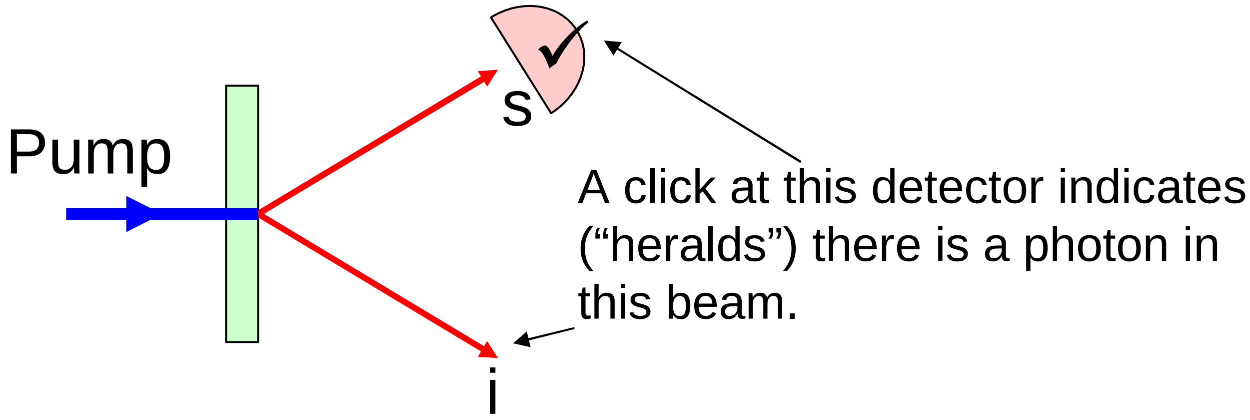
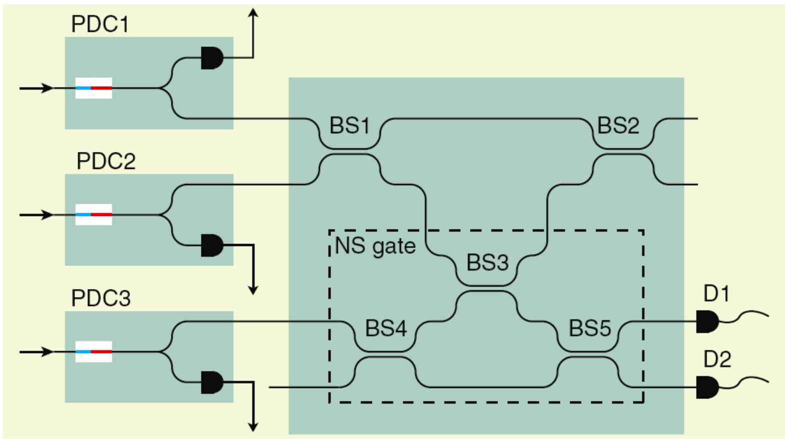
Heralded Single-Photons

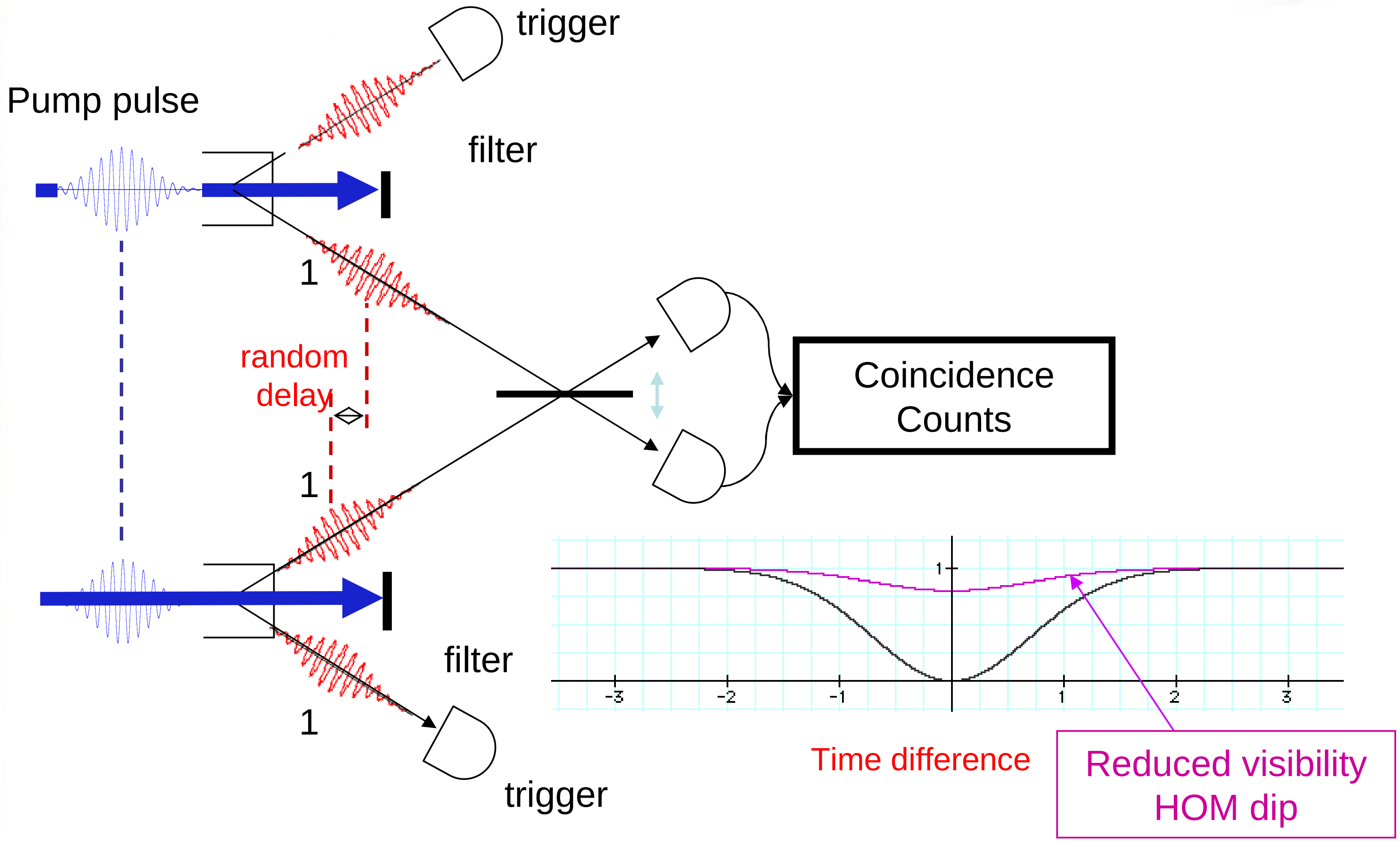


A Quantum Gate



- Photonic quantum-computing requires high-quality heralded photons

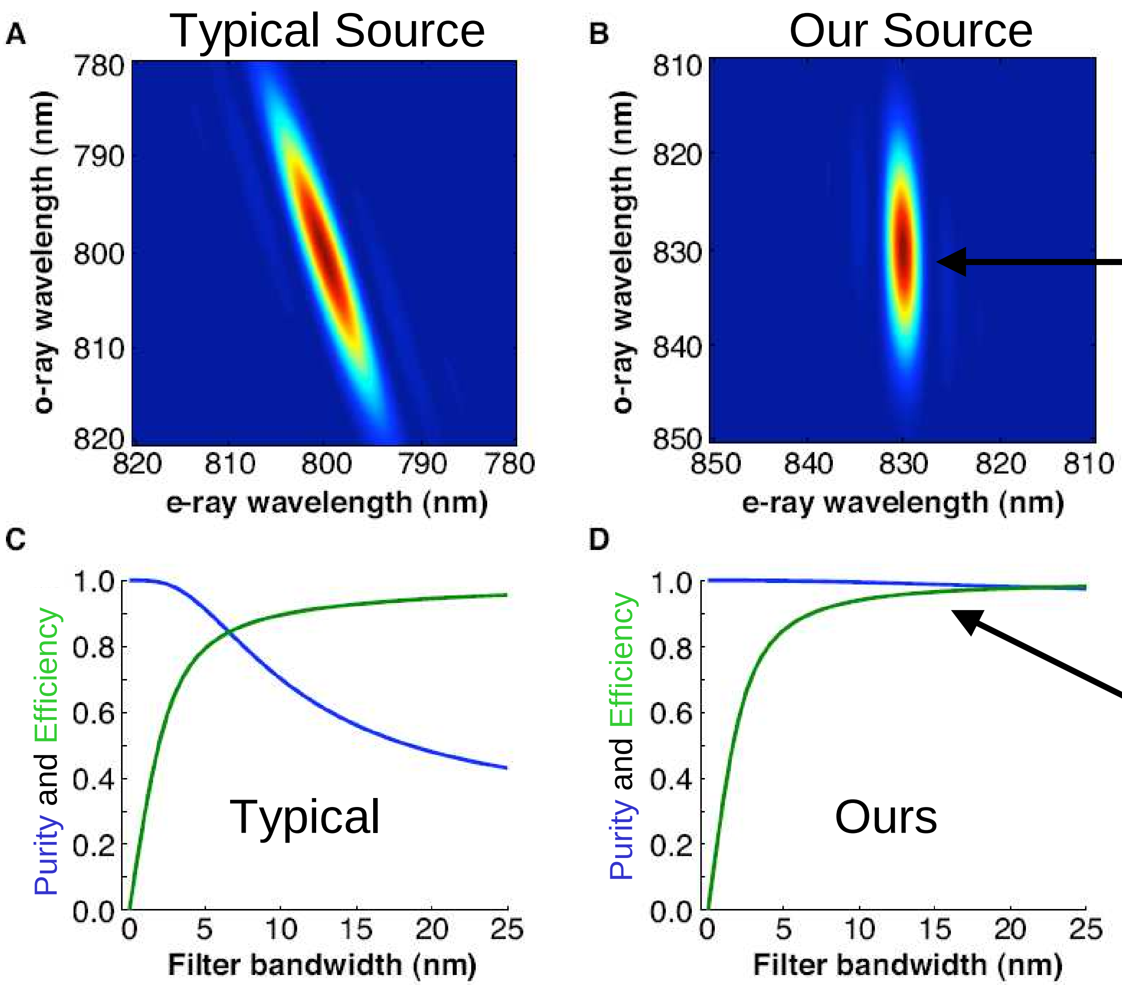
The Problem: Timing Jitter



- Timing and frequency jitter is the main source of error in optical quantum computer gates.

Design a better photon source

Photon Pair Joint Spectrum

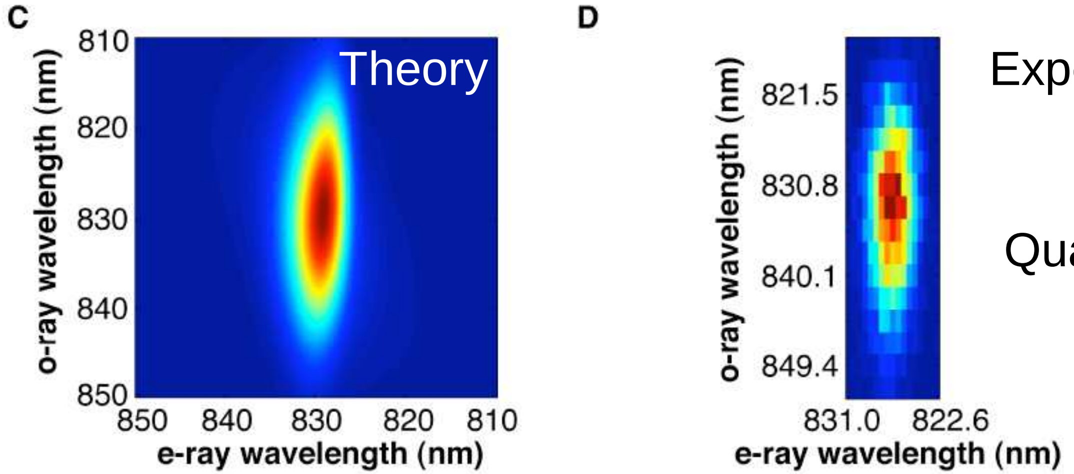


No frequency or timing jitter

No trade-off between efficiency and quality

How good are our photons?

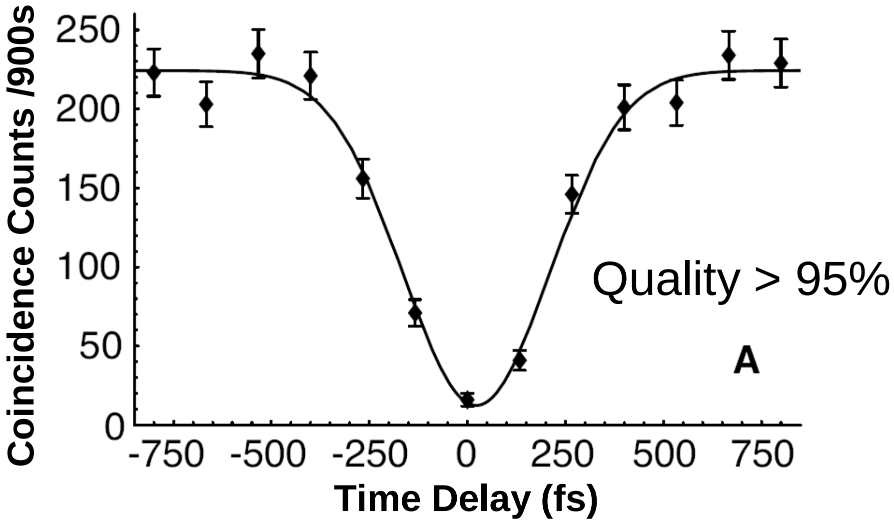
Frequency Jitter



Experiment

Quality > 98%

The Quality Test

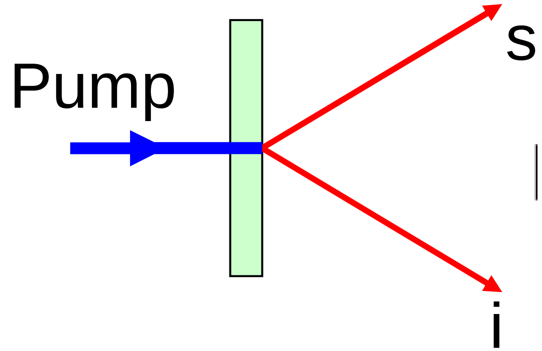


- Heralding efficiency up to 44%
- Four-photon count rates as good as the best sources but with 1/10 the pump power.
- High quality interference with no filters

Peter Mosley, et al.,
arXiv:0711.1054v1 [quant-ph] Nov 2007

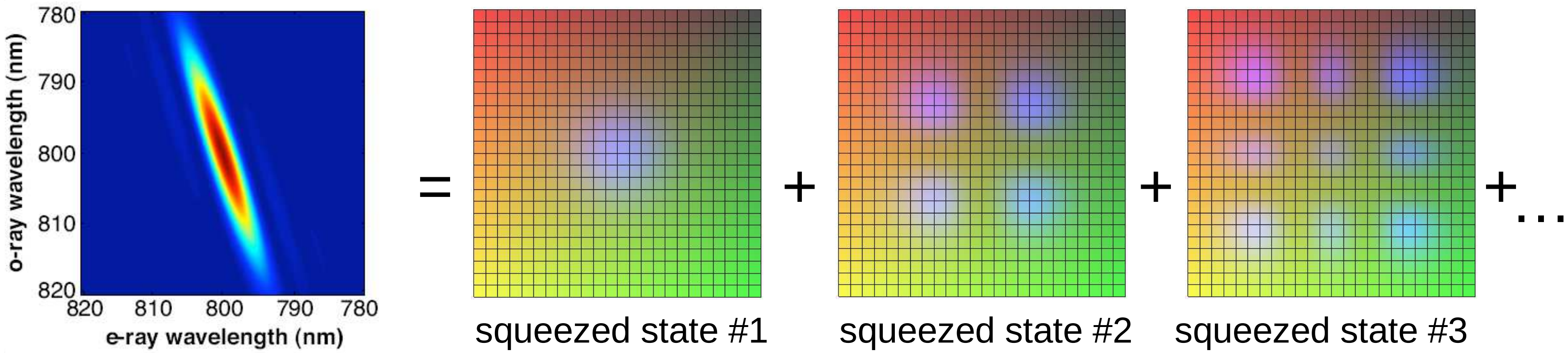
Pulsed squeezing

• Spontaneous parametric downconversion produces a two-mode vacuum squeezed state:



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

• Frequency correlations in the two-photon state indicate there are many squeezed states being produced simultaneously in the crystal.



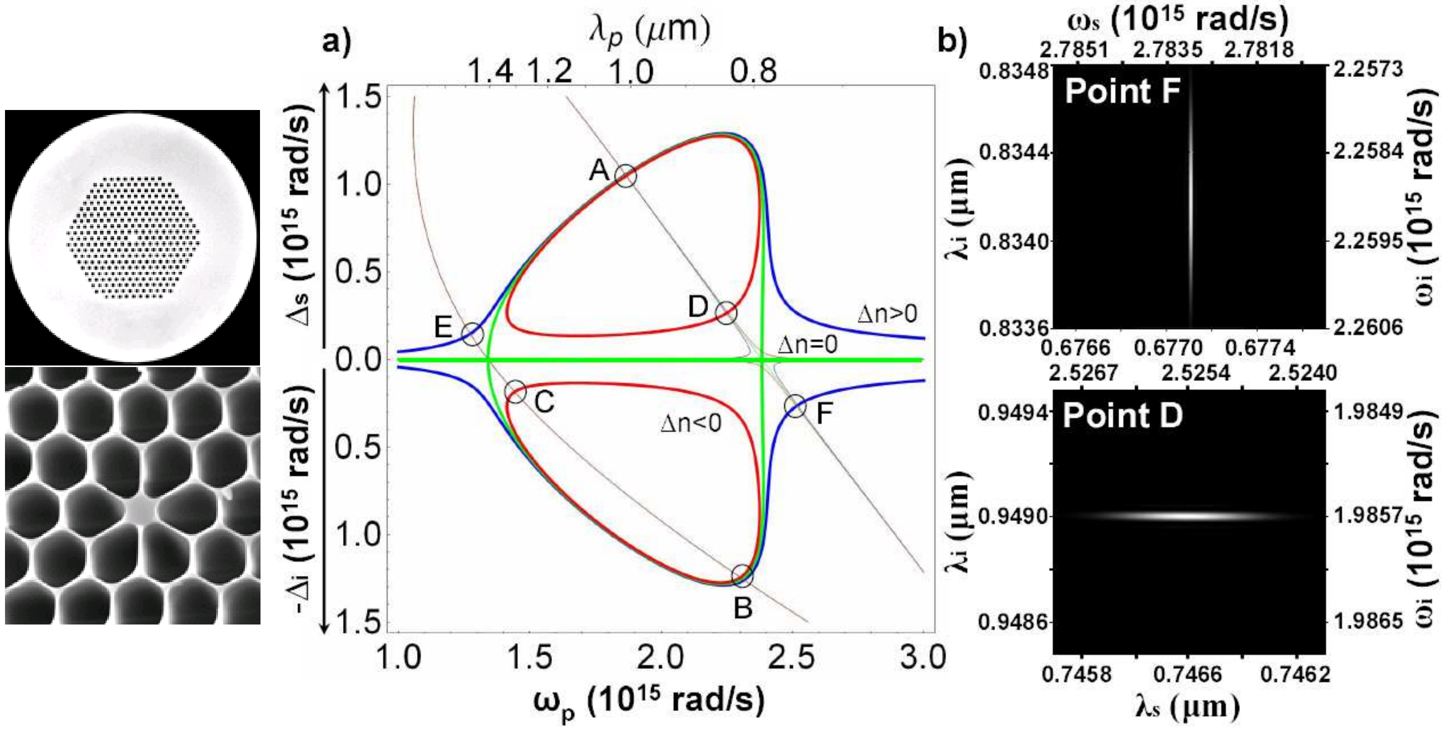
Phys. Rev. A 73, 063819 (2006): Wasilewski et al.

Future sources of pure photons

• Microstructured nonlinear sources allow us to directly engineer the spectral properties of the photons.

• We have modelled spontaneous pair generation in photonic crystal fibers

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



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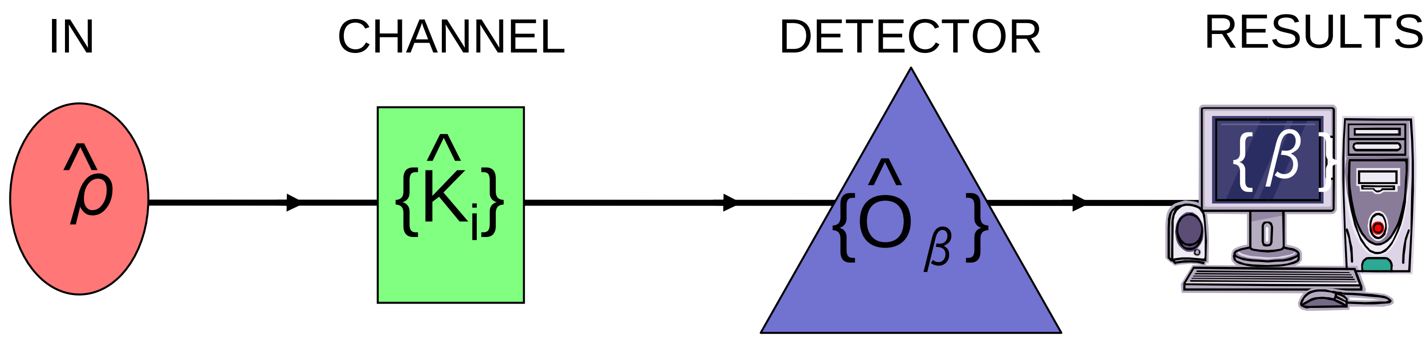
Detector Tomography

- We need to characterize our detectors before we can characterize our states



State
Density matrix

Process
Kraus Operators

Measurement
POVMs

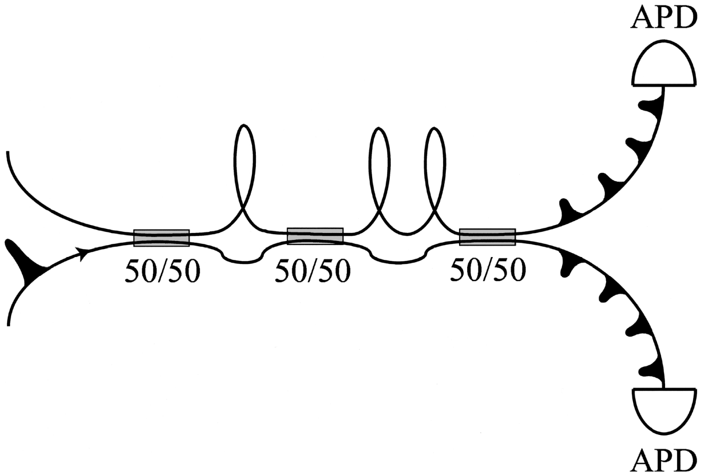
- Complete characterization of quantum measurement apparatus

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

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

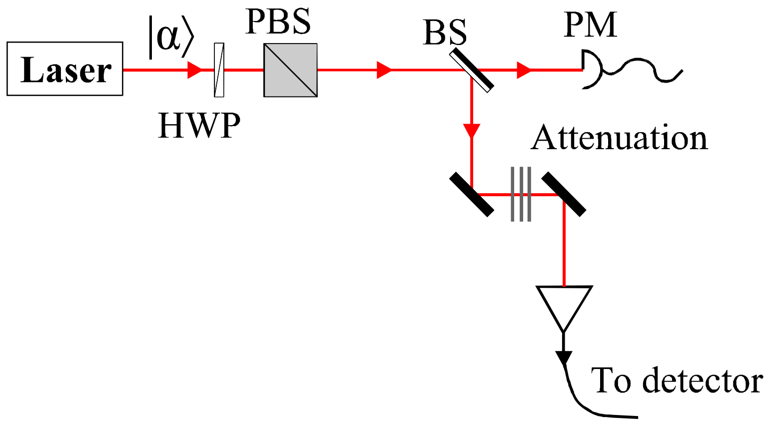
Detectors

- Time multiplexed photon-number detector



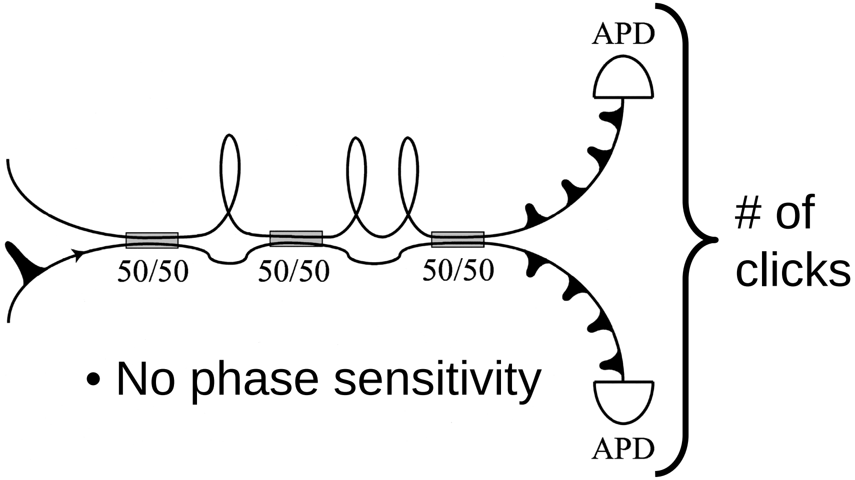
Fiber-assisted detection with photon number resolution,
D. Achilles, et al., Optics Letters, 28, 2387-2389 (2003).

- Detector Tomography Test Bed



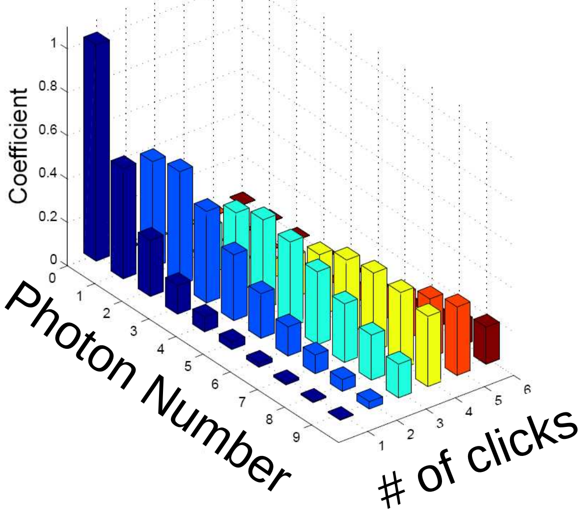
- We are measuring in the photon number space of a mode
- Suitable probe states are coherent states – need a spanning set

Tomography Results

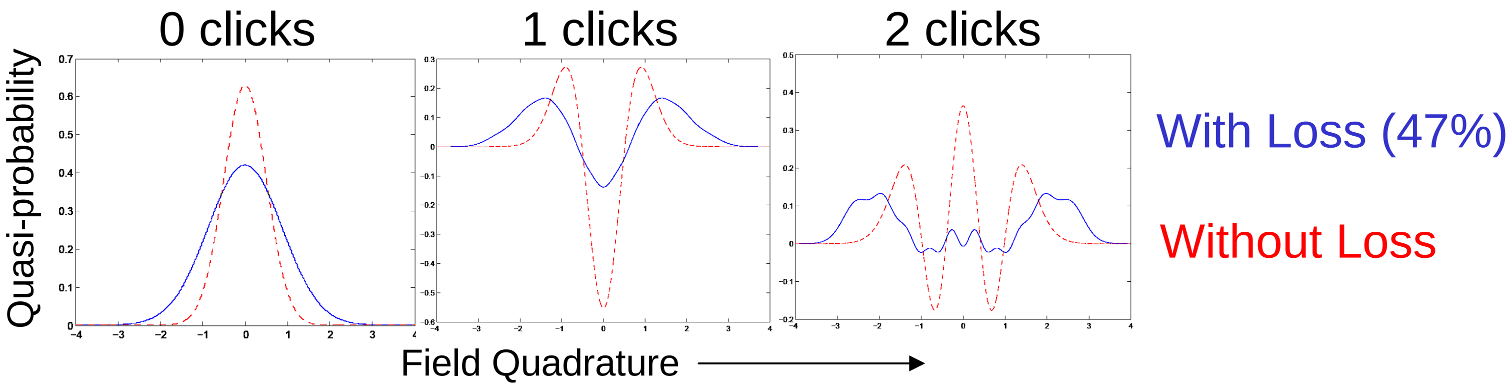


• No phase sensitivity

Diagonals of POVM

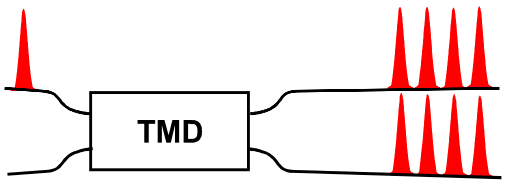


Cross-section of POVM Wigner Function



State Reconstruction

- With the previous photon-number detector only diagonal elements of the state density matrix determined



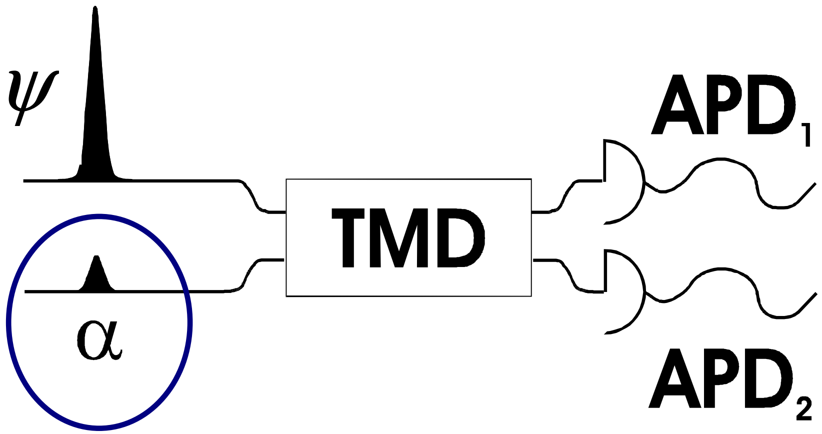
$$\rho = \begin{pmatrix} \rho_{11} & \rho_{21} & \rho_{31} & \cdots \\ \rho_{12} & \rho_{22} & \rho_{32} & \\ \rho_{13} & \rho_{23} & \rho_{33} & \\ \vdots & & & \ddots \end{pmatrix}$$

- Add a **weak coherent phase** reference

- Regular homodyning: $|\alpha\rangle\langle\alpha|$

- Our detector: Variable from $|n\rangle\langle n$ towards $|\alpha\rangle\langle\alpha|$

- More general measurement: Entanglement witnesses, bounds, etc.

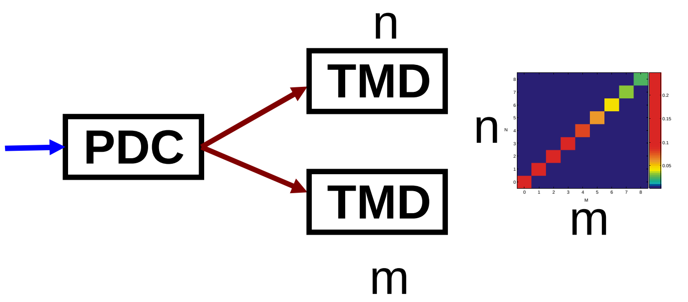


Wallentowitz and W. Vogel, 53, 4528 PRA (1996).

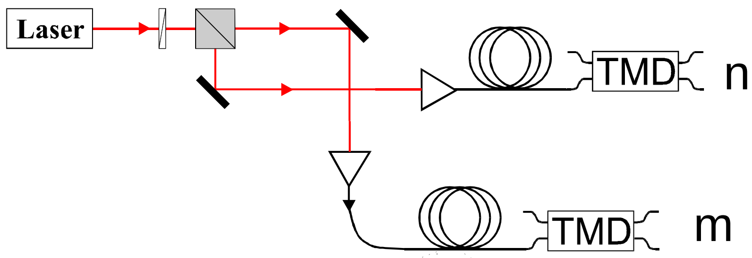
Joint Photon Number Statistics

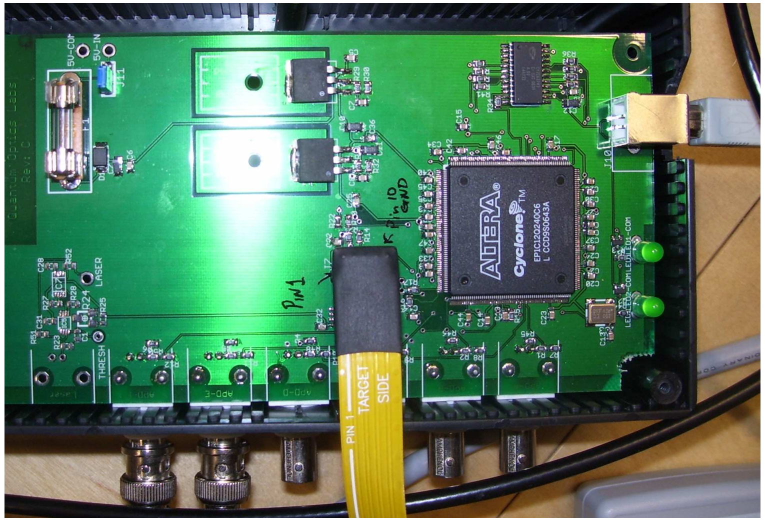
Joint photon statistics for characterisation of two dependent modes

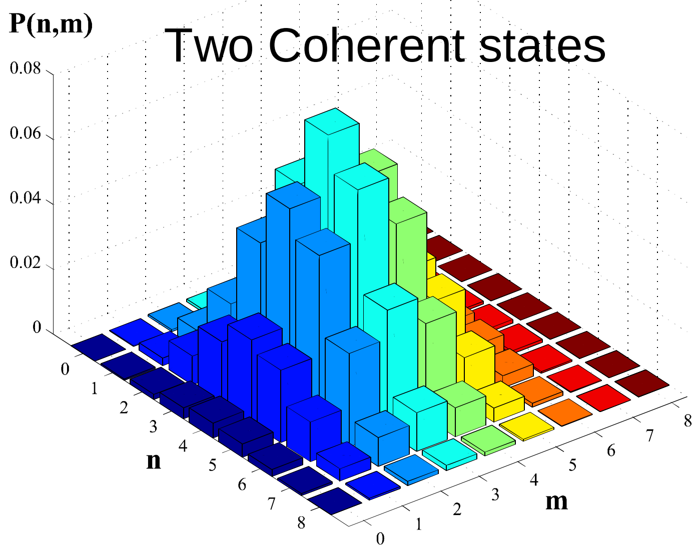
In parametric downconversion



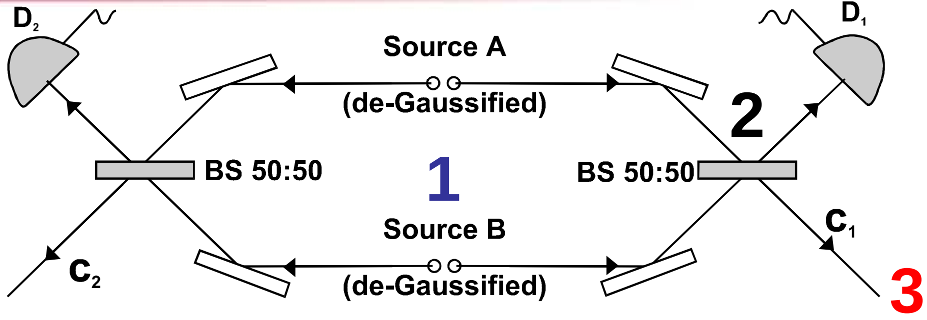
Two coherent states



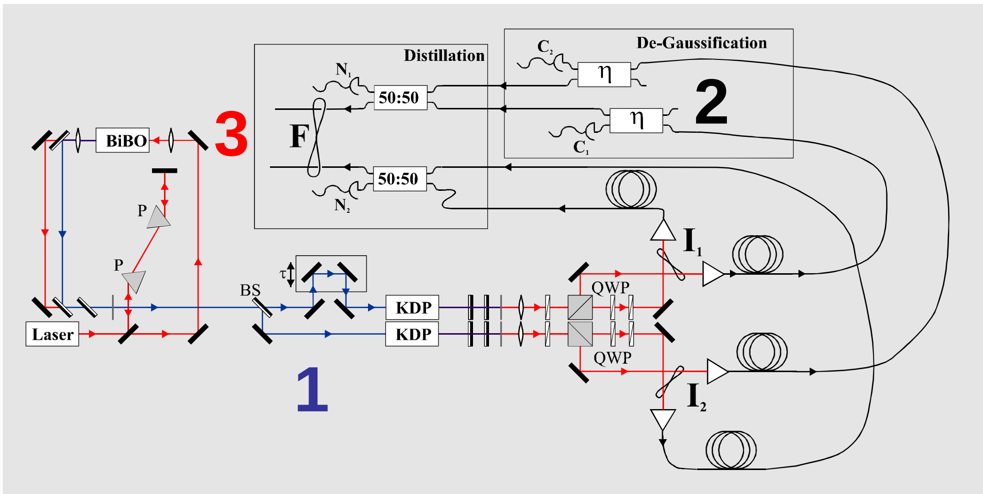




The Experiment



1. Source: Pure photon downconversion extended to the large pump regime.
2. Operations: Implemented in fibers with single photon detectors
3. Entanglement Measurement: Weak Homodyne photon-number resolving detectors – State reconstruction or Entanglement Witness



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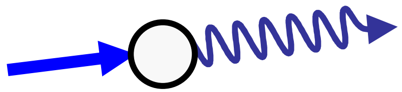
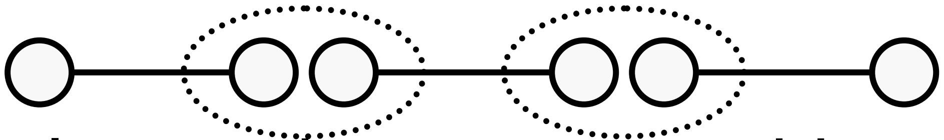
Why a quantum memory?

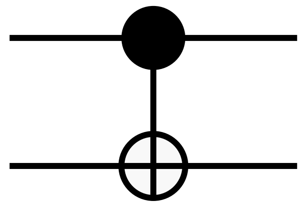
- Deterministic single photon source



- Long-distance transmission of quantum states: quantum repeaters



- Local operations, e.g. 2-qubit gates



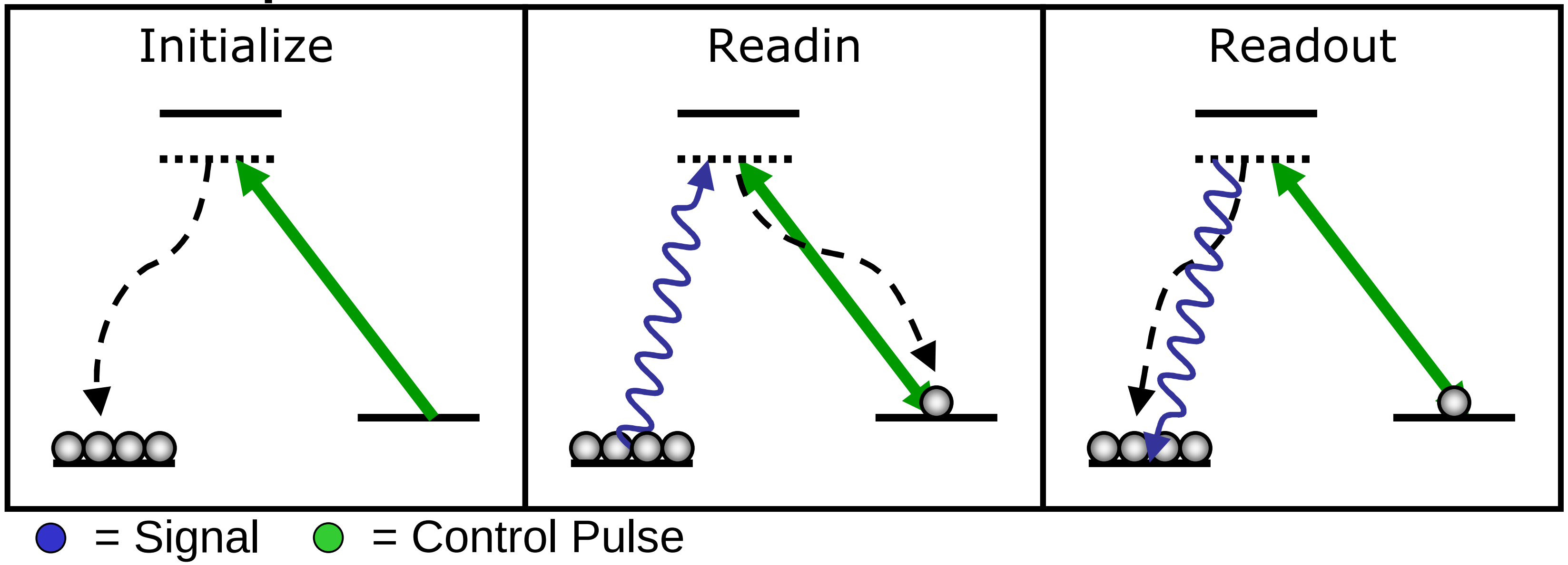
The Perfect Quantum Memory

- Requirements
  - Strong absorption
  - High fidelity
  - Unitary storage
  - High clock rates: ultrashort pulses/Broad-band photons
  - Long storage time
  - Room temperature operation

Raman Scheme

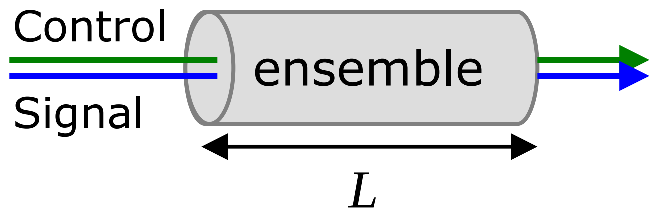
- Off-resonant Raman transition
  - Broadband
  - Tunable
  - Robust
- Steps:

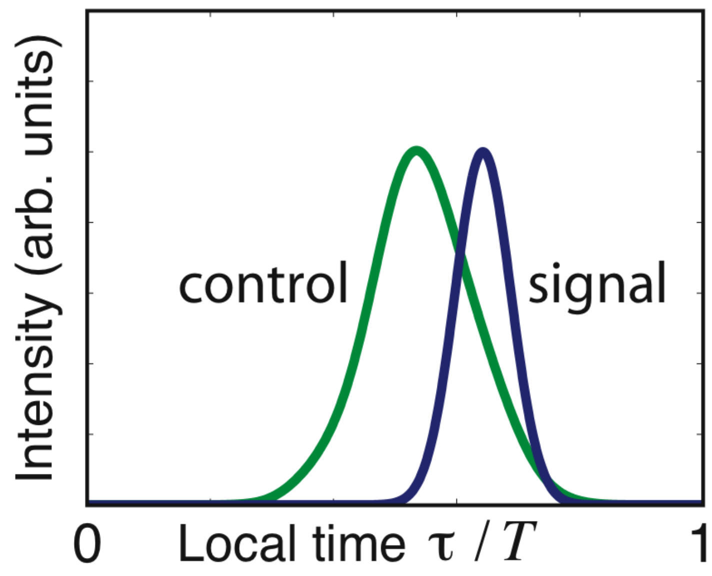
J. Nunn *et al.*, Phys. Rev. A **75**, 011401 (2007).



Theory: Memory Readin

- Optimize absorption
  - Propagation of signal photon through cell
  - Optimize control to maximize absorption

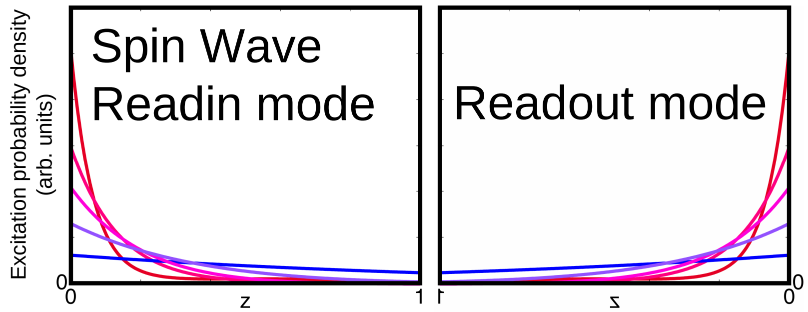




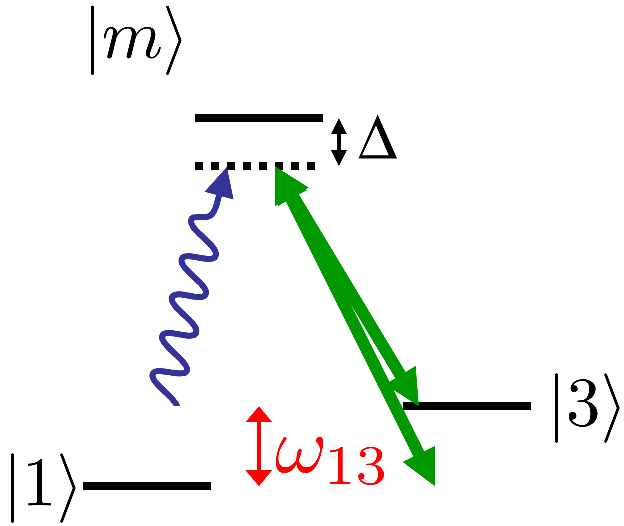
J. Nunn *et al.*, Phys. Rev. A **75**, 011401 (2007).

Theory: Memory Readout

- Forward Readout is not mode-matched



- Use backward readout instead
- Choose different level configuration:
- Angle control field
  - Readin 
  - Readout 



- Phasematched!

K. Surmacz *et al.*, submitted.

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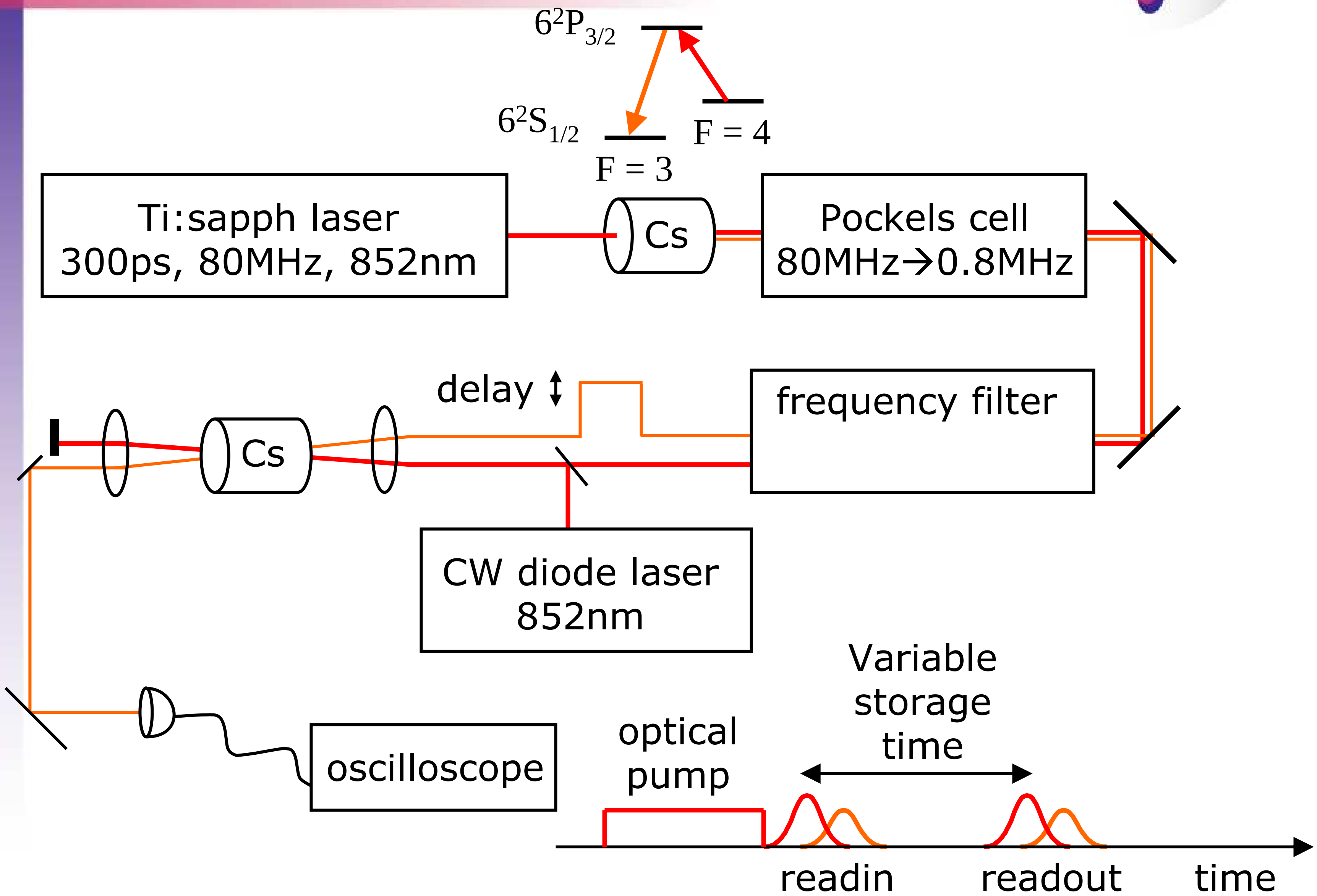
Candidate System #1
Raman in Cesium Vapor

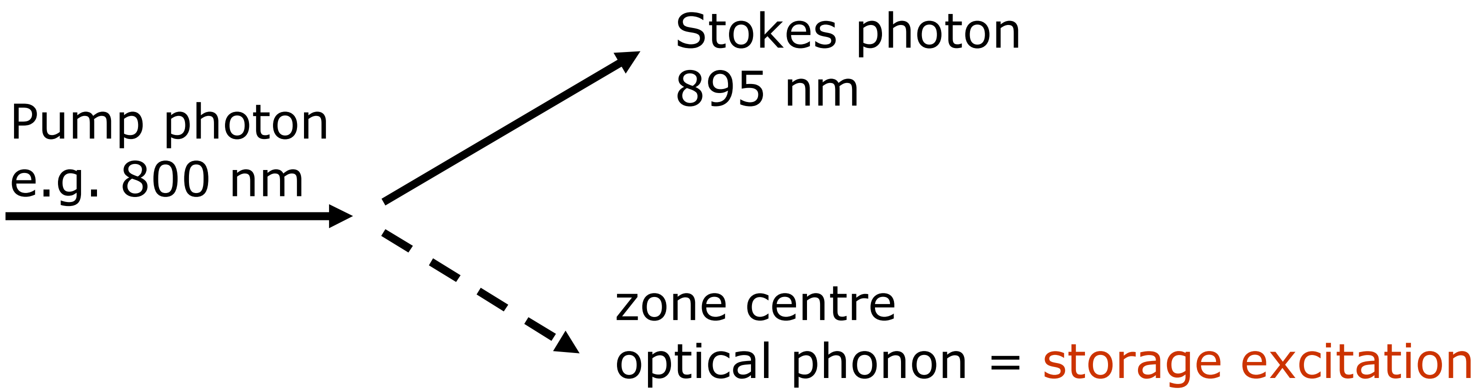
- Room temperature operation
  - T ~ 300 K
- Strong absorption
  - Optical depth d ~ 10^3
- Broadband photons
  - Cesium clock transition ν ~ 9GHz → sub-nanosecond pulses
- Long storage time
  - Dark state lifetime τ ~ few μs

Candidate System #1
Experimental Setup



Candidate System #2
Raman in Diamond

- High temperature, high pressure diamond*
- Raman scatter: two photons, one phonon

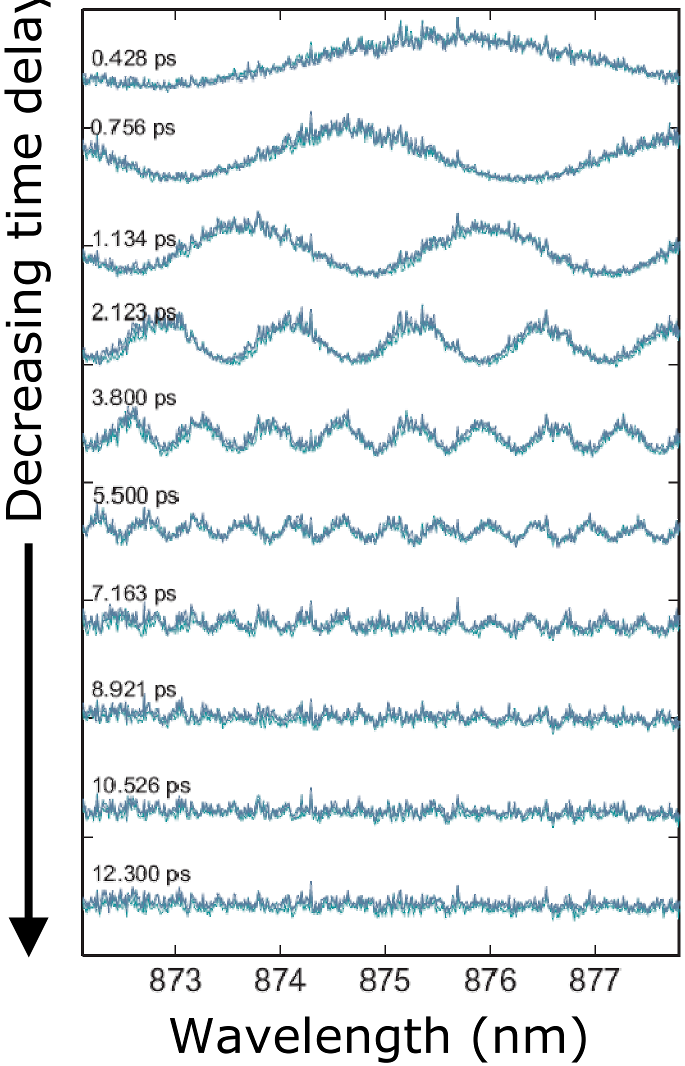


- Stokes photon heralds phonon
- High Stokes shift of 1332 cm^{-1} (165 meV or 40 THz), thus optical phonon modes depopulated at room temperature
- Fast phonon decay, but large bandwidth $\Gamma \tau \sim 300$
Proof of principle solid state quantum memory

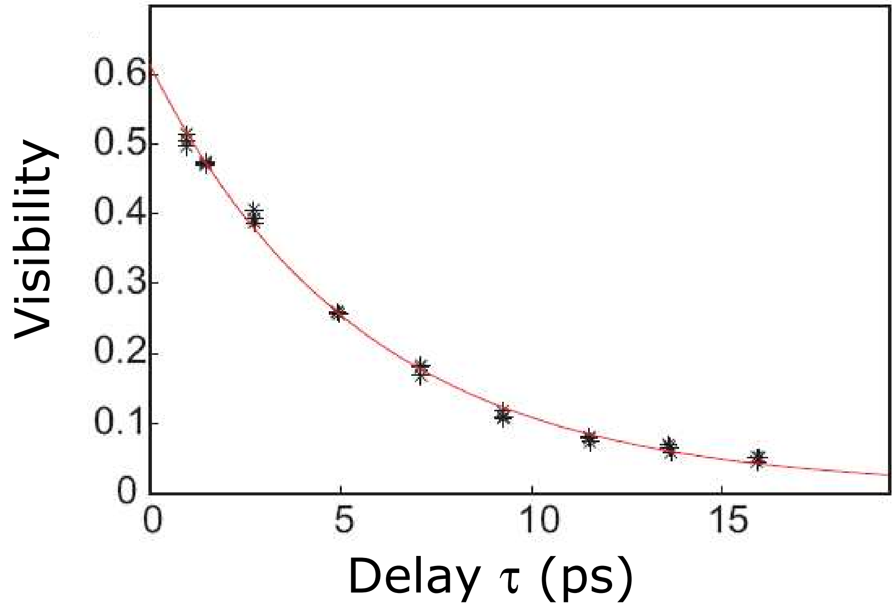
*In collaboration with Paolo Olivero and Steven Prawer, School of Physics, University of Melbourne

Candidate System #2
Phonon Lifetime

Interference between subsequent spontaneous stokes pulses



- Visibility decays with τ as phonon decoheres
- Measured decoherence time: 6.8 ps



F. Waldermann et al., in preparation.

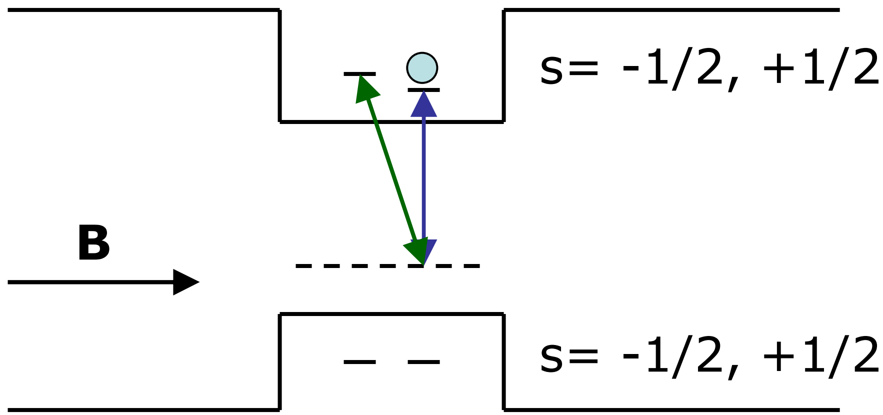
Candidate System #3
Quantum Dots

- Semiconductor quantum dots (QDs)
  - Charged quantum dots in external magnetic field
  - Large dipole moment
  - high density sample growth possible
  - long dephasing time
  - but strong inhomogeneous dispersion of resonances

*F. Waldermann *et al.*, in press, Diam. and Relat. Mater. (2007).
http://dx.doi.org/10.1016/j.diamond.2007.09.009

Candidate System #3
Quantum dots

- Ensemble of negatively charged InAs quantum dots
- Voigt configuration (**B** field perpendicular to sample growth)
- Selection rules allow population transfer from conduction band spin states



- Large Zeeman splitting → broadband possible
- Considering waveguides and cavities to increase interaction strength

Andrew Shields (Toshiba)
David Ritchie (Cambridge)
Christine Nicolle (Cambridge)

Conclusion

- We are developing the tools to do entanglement distillation
  - Two-mode squeezed source
  - State reconstruction
- We are developing a broadband quantum memory
  - Theoretically optimized readin/out
  - Prelimary investigation of three candidate systems