

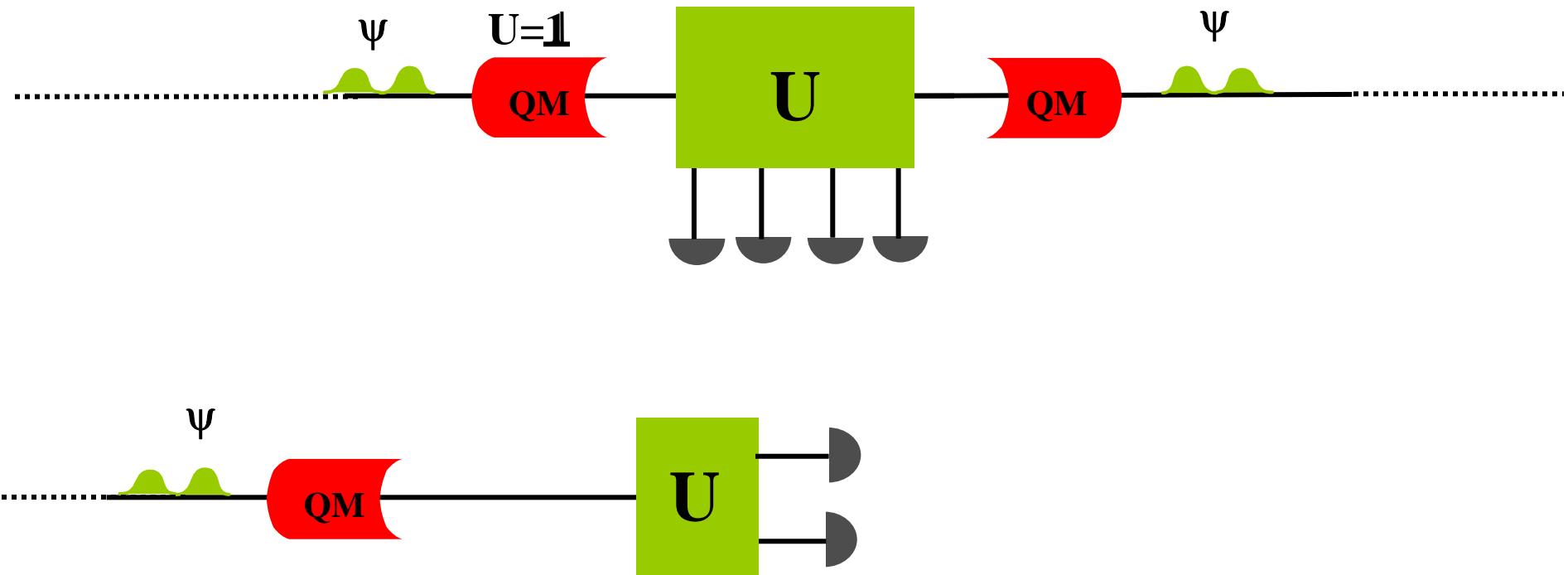
# Photon-Echo Quantum Memory and Controlled State Manipulation

A. Delfan, E. Saglamyurek, C. La Mela, and  
W.Tittel

*Institute for Quantum Information Science  
University of Calgary, Canada*



# Photon-Echo Quantum Memory and Controlled State Manipulation



# **Interferometry using photon-echoes for precision measurements and quantum communication**

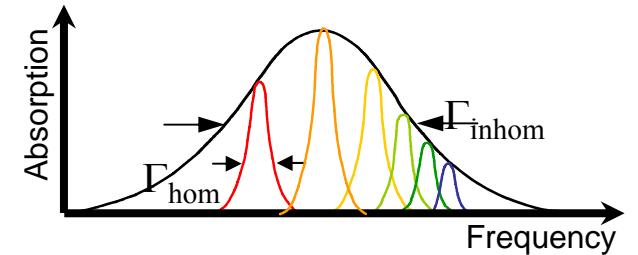
- Photon-echo quantum memory (CRIB)
- Beyond storage
- 3-pulse photon echoes: a test-bed for quantum state storage and manipulation
  - unambiguous state discrimination
- Discussion

# Data storage based on CRIB

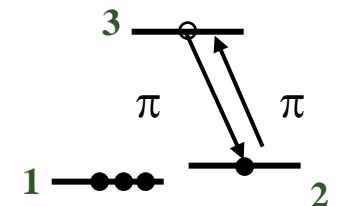
- transfer photonic quantum state to collective excitation of an inhomogeneously broadened atomic ensemble

$$\left( c \frac{\partial}{\partial z} + \frac{\partial}{\partial t} \right) E_f(z, t) = i\beta \int d\Delta G(\Delta) \sigma_f(z, t, \Delta)$$

$$\frac{\partial}{\partial t} \sigma_f(z, t, \Delta) = -i\Delta \sigma_f(z, t, \Delta) + i(\varphi/\hbar) E_f(z, t)$$



- map excited coherence  $\sigma_f$  on  $\sigma_b$  (phase-matching)
- reverse detuning  $\Delta_i \rightarrow -\Delta_i \forall i$
- consider light-field with global phase shift of  $\pi$

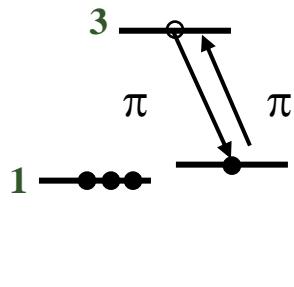


$$(-1) \left( -c \frac{\partial}{\partial z} + \frac{\partial}{\partial t} \right) E_b(z, t) = i\beta \int d\Delta G(\Delta) \sigma_b(z, t, \Delta)$$

$$\frac{\partial}{\partial t} \sigma_f(z, t, \Delta) = (+) i\Delta \sigma_f(z, t, \Delta) (-) i(\varphi/\hbar) E_f(z, t)$$

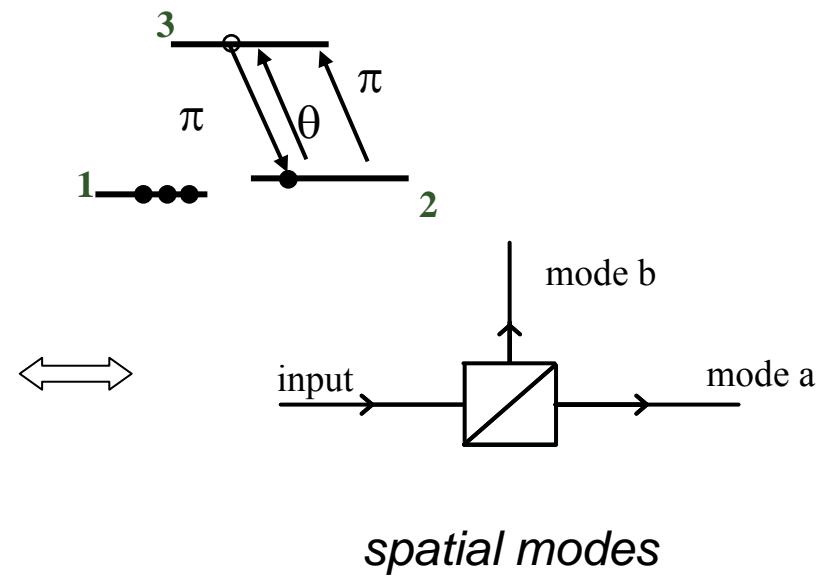
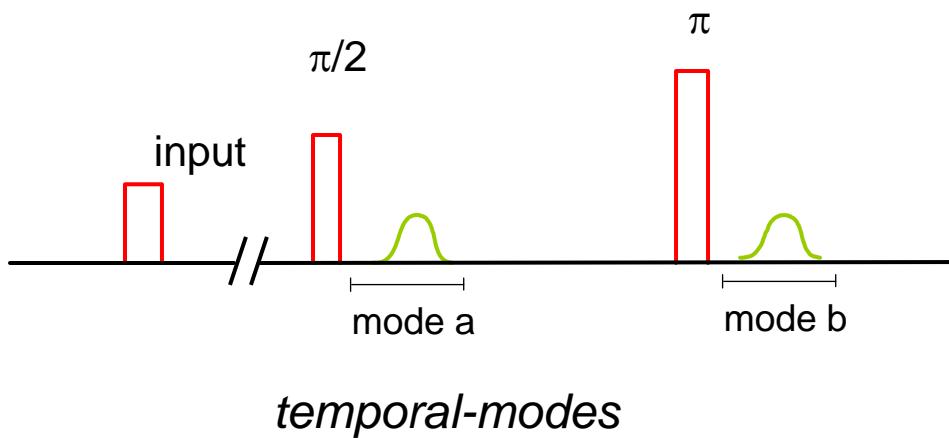
time reversed evolution of atom-light system = perfect recall

Moiseev *et al.*, PRL 2001; Nilsson *et al.*, Opt. Comm. 2005; Kraus, WT *et al.*, PRA 2006;  
Alexander *et al.*, PRL 2006; (Afzelius *et al.*, PRA 2009; Moiseev & WT, quant-ph 2008);  
recent review: Tittel, Afzelius, Chanelière, Cone, Kröll, Moiseev, Sellars, quant-ph 2008



## Data manipulation based on CRIB

transfer coherence from ground states to electronic states using *multiple read pulses*  
 -> possibility to recall an input state in a coherent superposition of several temporal modes (atom mediated *beam splitting*)

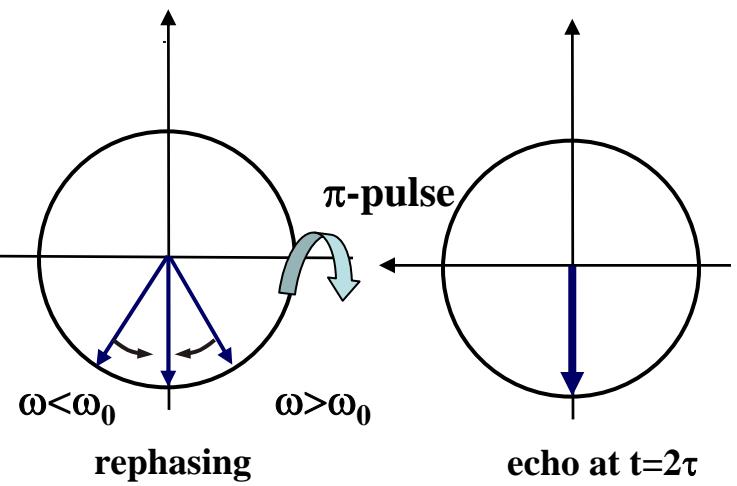
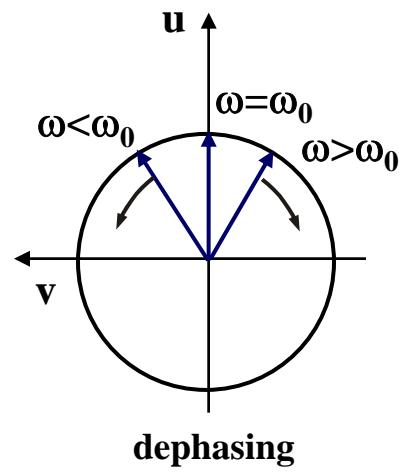
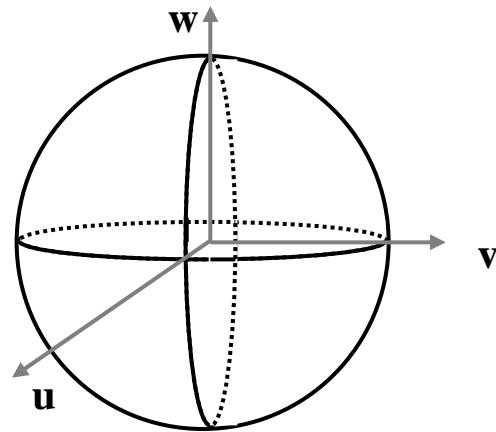
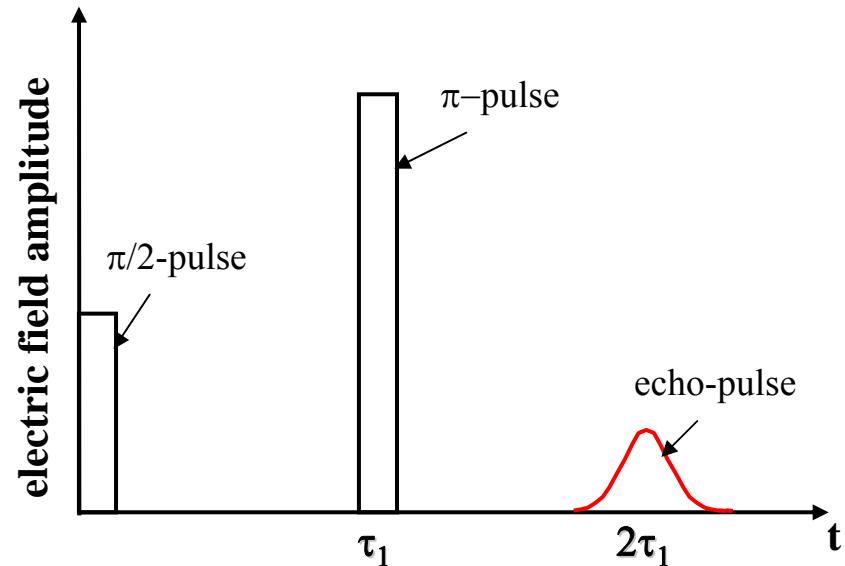
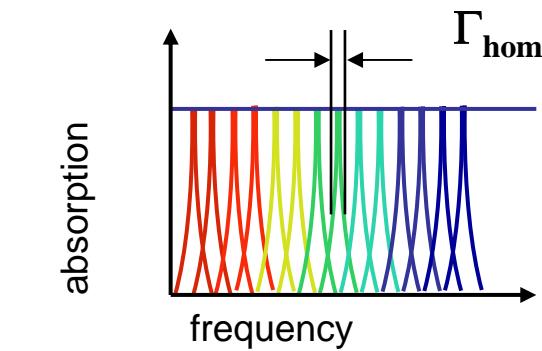


any discrete unitary operator on can be realized with beam splitters & phase shifters

# Data manipulation using traditional photon-echoes

- Photon-echo QM (CRIB) is still challenging (but has been demonstrated: Canberra, Geneva, Orsay, Lund)
- stimulated photon echo approach is similar & simple
- small efficiency
- serves as test-bed for photon-echo based storage (QM) and manipulation

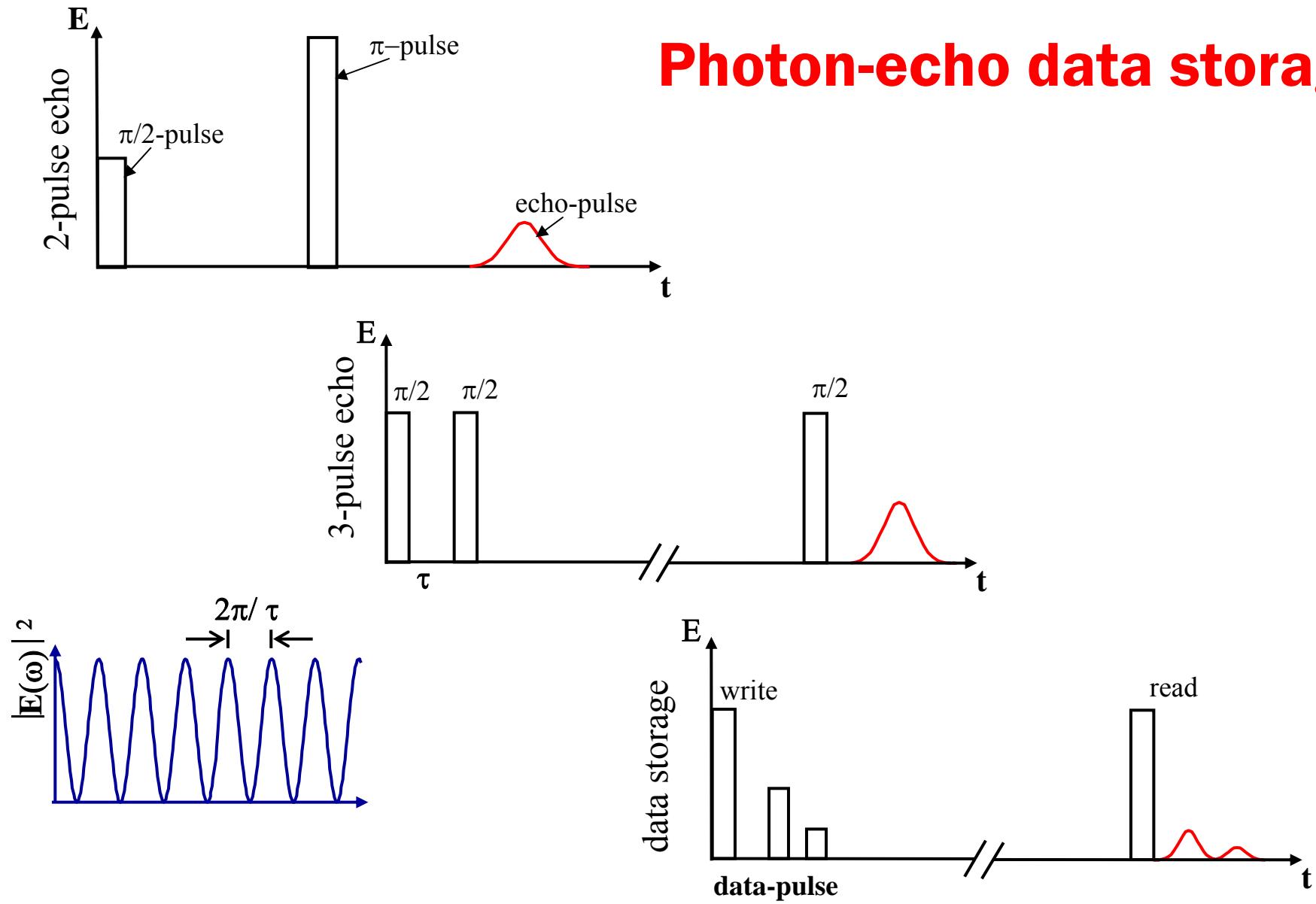
# Photo-echo data storage



Kopvil'em & Nagibarov, Fiz. Metall. Metalloved. 1963  
 Kurnit, Abella & Hartmann, Phys. Rev. Lett. 1964

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# Photon-echo data storage

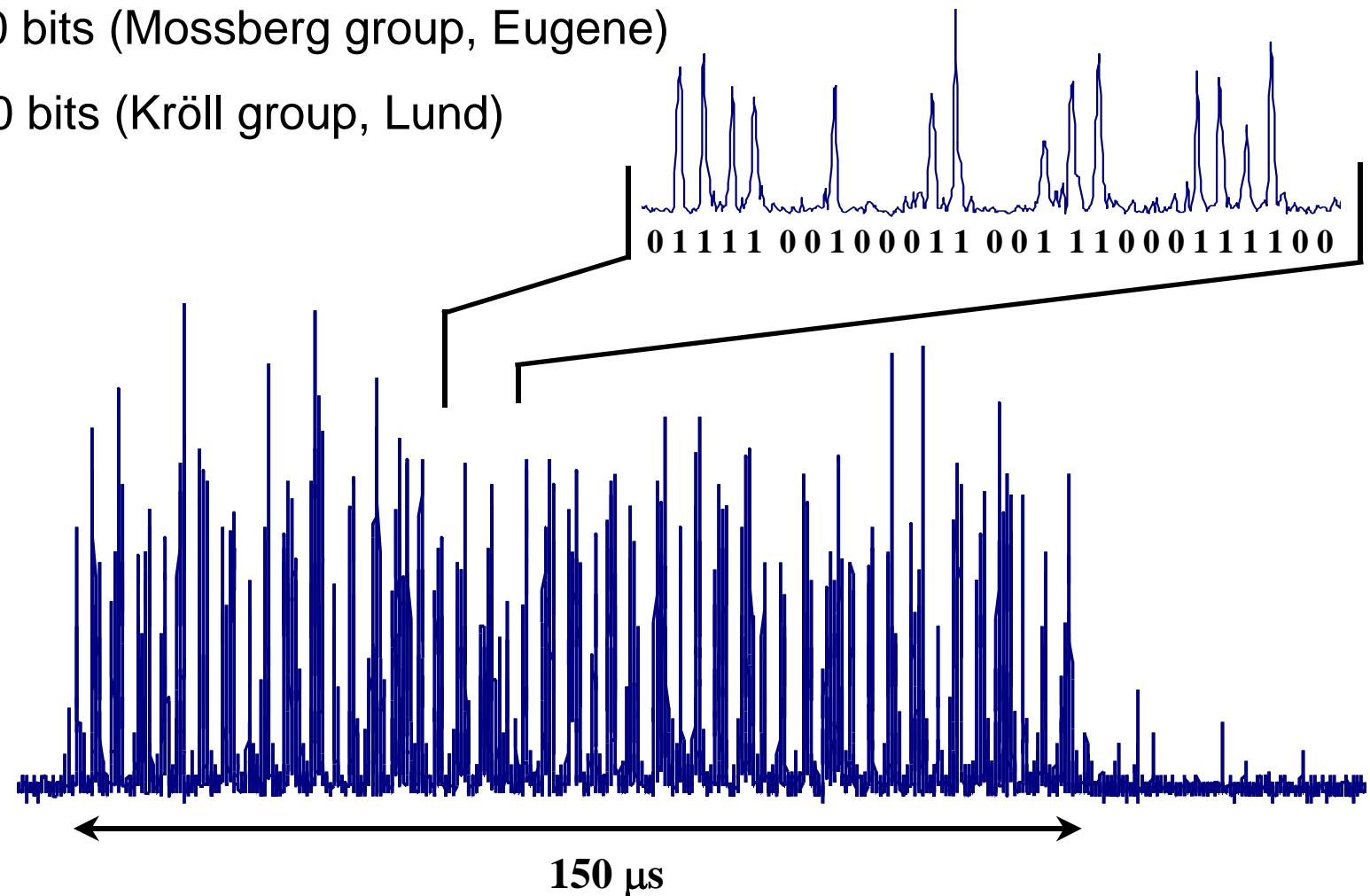


Elyutin, Zakharov, & Manykin, Phys. JETP 1979  
 Mossberg, Opt. Lett. 1982

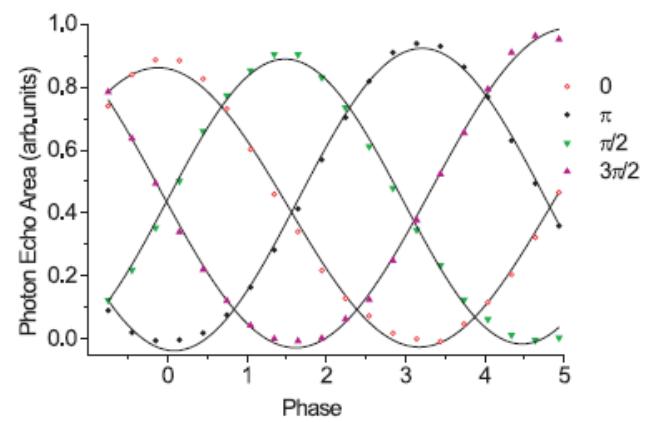
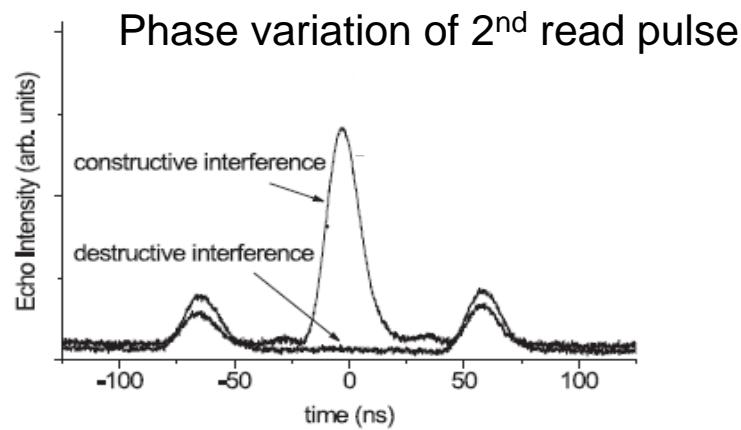
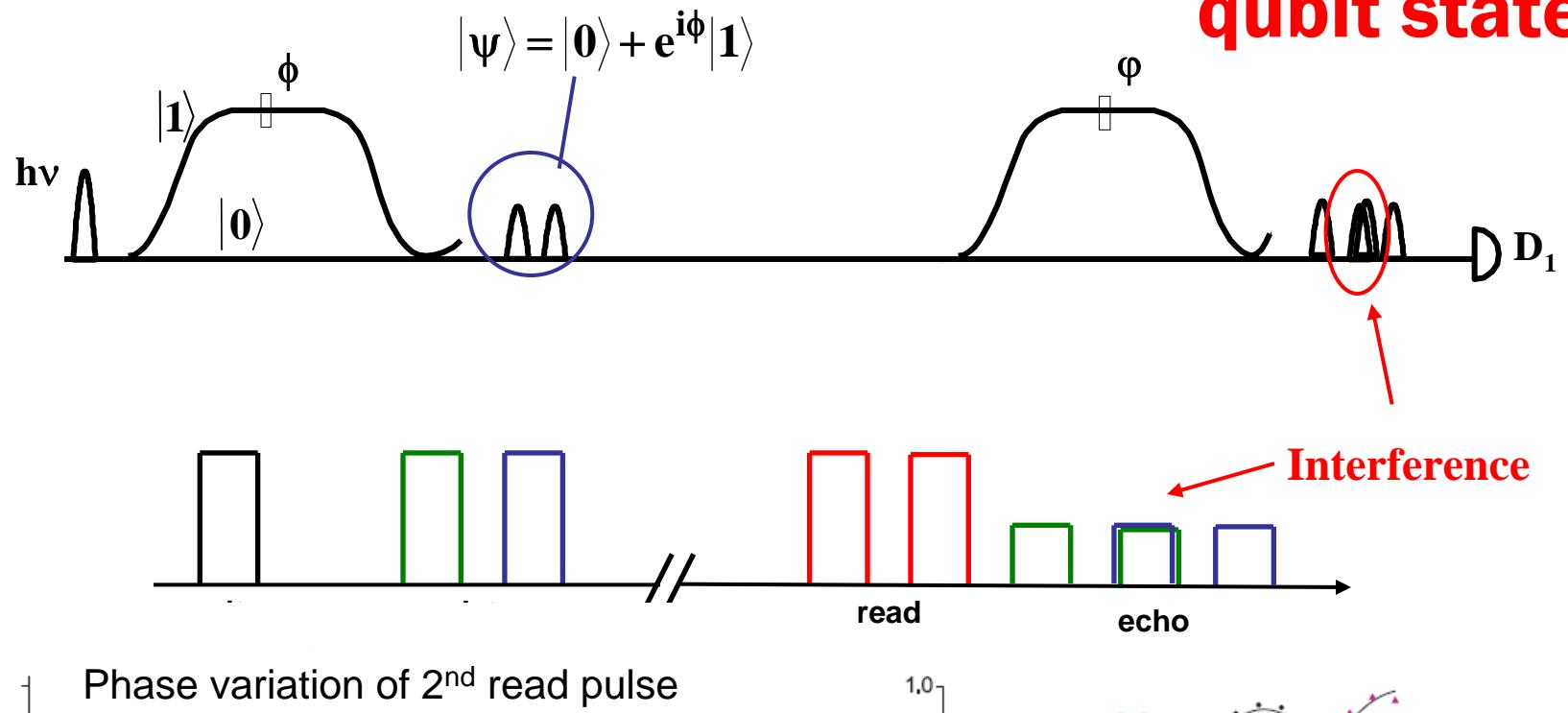
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# Storage of classical data in a single spatial location

- up to 1760 bits (Mossberg group, Eugene)
- below: 330 bits (Kröll group, Lund)



# Two-path interferometer/projection onto qubit states



# Beyond von Neumann measurements

- Measurement operators fulfil completeness relation

$$\sum_i M_i^\dagger M_i = 1$$

- Standard (von Neumann) measurements: projectors onto orthogonal sub-spaces  $\{|\phi_1\rangle, |\phi_2\rangle, \dots |\phi_n\rangle\}$   $\langle\phi_i|\phi_k\rangle = \delta_{ik}$
- Generalized measurements: projection onto non-orthogonal states (Unambiguous State Discrimination)
- Interesting for fundamental understanding and applications of quantum information science

# USD: optics scheme for time-bin qubits (idealized)

$$|\psi_{\pm}\rangle = \sqrt{\frac{1}{3}}|0\rangle \pm \sqrt{\frac{2}{3}}|1\rangle \quad |\langle\psi_+|\psi_-\rangle|=1/3 \neq 0$$

$$p_+ = p_-$$

$$\rightarrow |\psi'_{\pm}\rangle = \sqrt{\frac{1}{3}}|a\rangle \pm \sqrt{\frac{2}{3}}|b\rangle$$

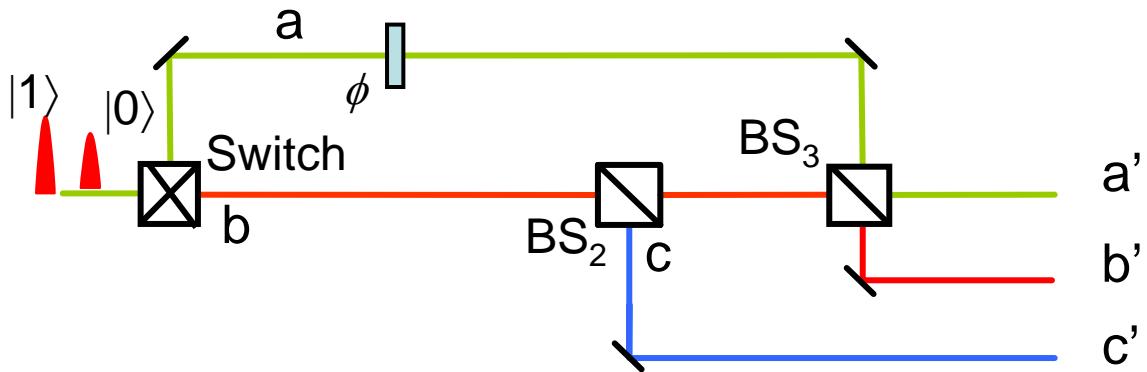
Coupling to mode c (state dependent loss)

$$\rightarrow |\psi''_{\pm}\rangle = \sqrt{\frac{1}{3}}|a\rangle \pm \sqrt{\frac{1}{3}}|b\rangle \pm \sqrt{\frac{1}{3}}|c\rangle$$

Interference on  $BS_3$

$\rightarrow$  Projection onto

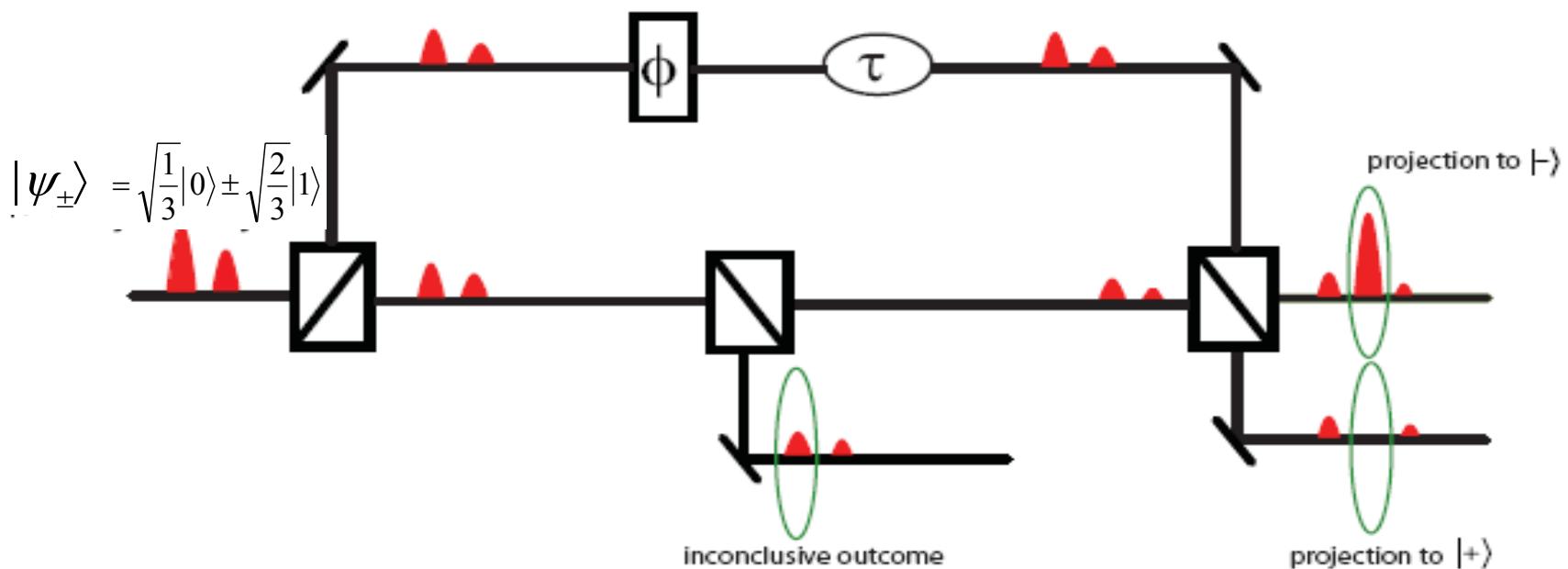
$$|\pm\rangle = \sqrt{\frac{1}{2}}|a\rangle \pm \sqrt{\frac{1}{2}}|b\rangle \quad |\langle+\mid-\rangle|=0$$



- detection in mode a':  $|\psi^+\rangle$
- detection in mode b':  $|\psi^-\rangle$
- detection in mode c': inconclusive

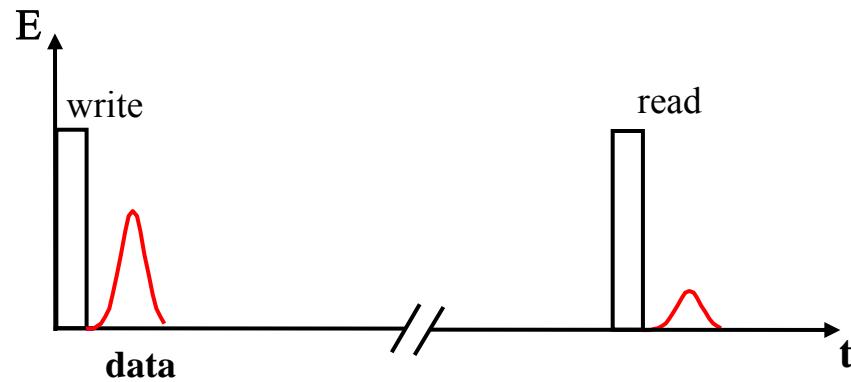
Reliably distinguishable in a fraction of cases  $P=1-|\langle\psi_+|\psi_-\rangle|$

# USD: optics scheme for time-bin qubits (no switch)



# Photon-echoes & unitary transformations

$$\mathcal{E}_{\text{echo}}(t) \propto \mathcal{E}_{\text{write}}^*(t) \mathcal{E}_{\text{data}}(t) \mathcal{E}_{\text{read}}(t) \delta(t_{\text{read}} + t_{\text{data}} - t_{\text{write}} - t) \quad (\Theta \ll \pi/2), \delta \text{ pulses}$$



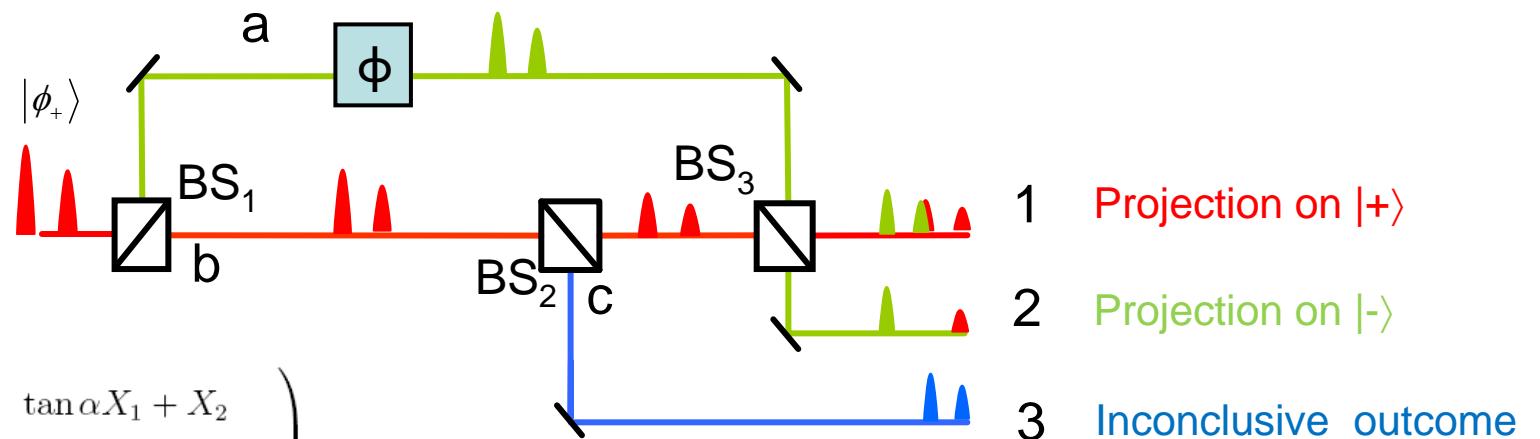
$$|\psi_{out}\rangle = U |\psi_{in}\rangle$$

$$M = \begin{pmatrix} r_{11}e^{i\phi_{11}} & r_{12}e^{i\phi_{12}} \\ r_{21}e^{i\phi_{21}} & r_{22}e^{i\phi_{22}} \end{pmatrix}$$

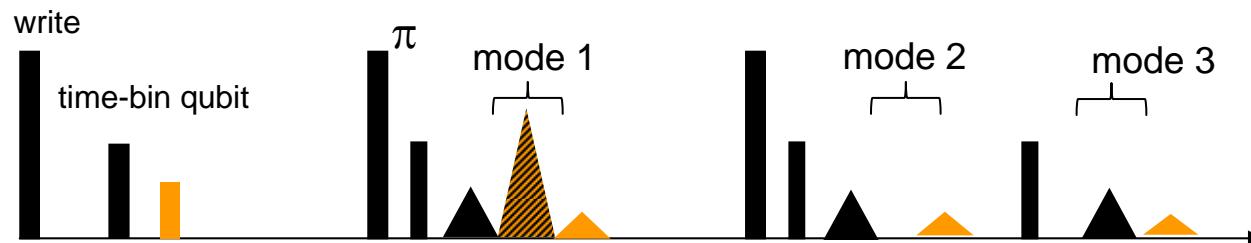
$$M \begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} r_{11}e^{i\phi_{11}} \times \alpha + r_{12}e^{i\phi_{12}} \times \beta \\ r_{21}e^{i\phi_{21}} \times \alpha + r_{22}e^{i\phi_{22}} \times \beta \end{pmatrix}$$

# USD: photon echo scheme (time-bin qubits)

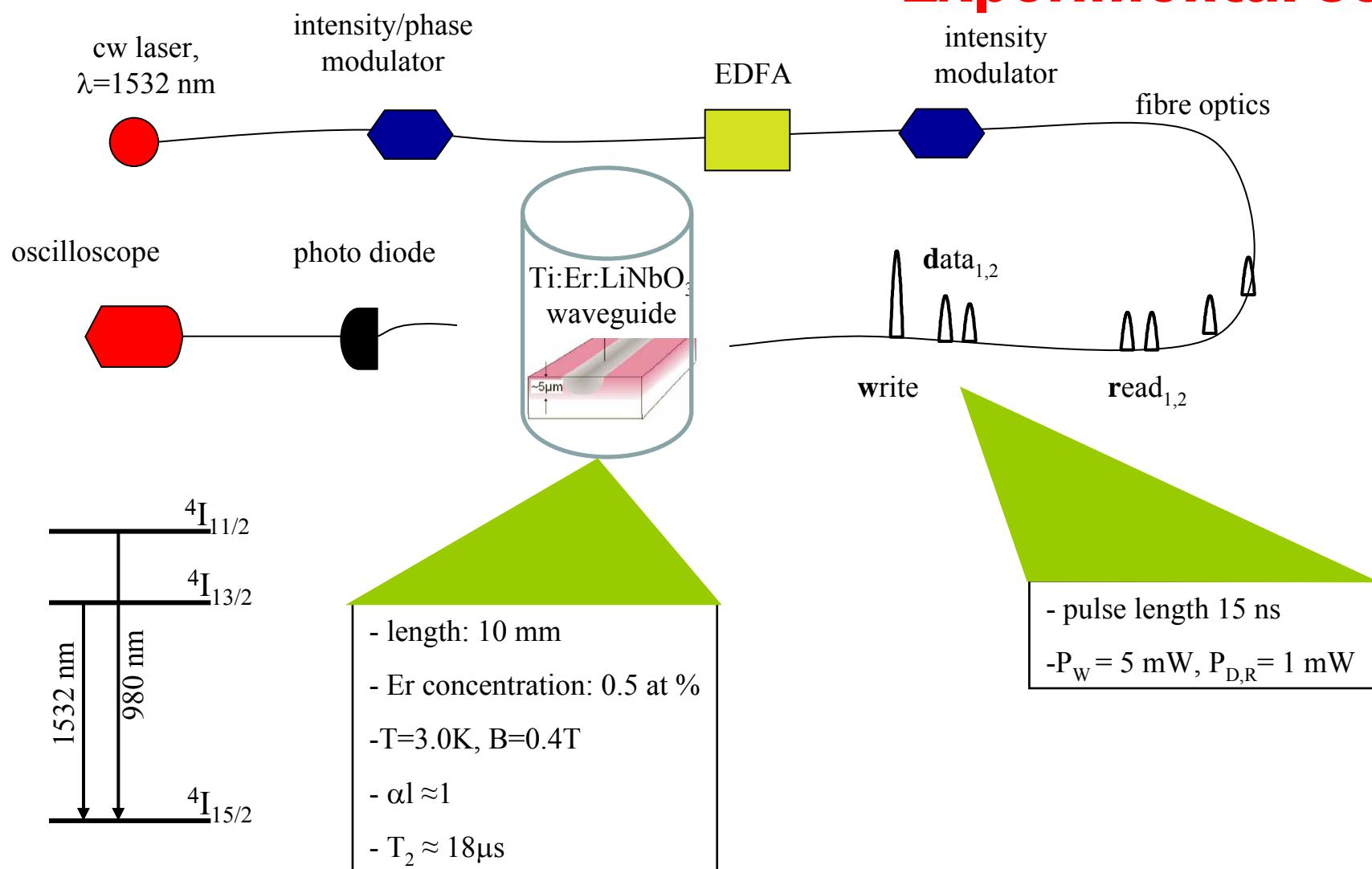
$$|\psi_{\pm}\rangle = \cos\alpha|0\rangle \pm \sin\alpha|1\rangle \quad \cos\alpha > \sin\alpha$$



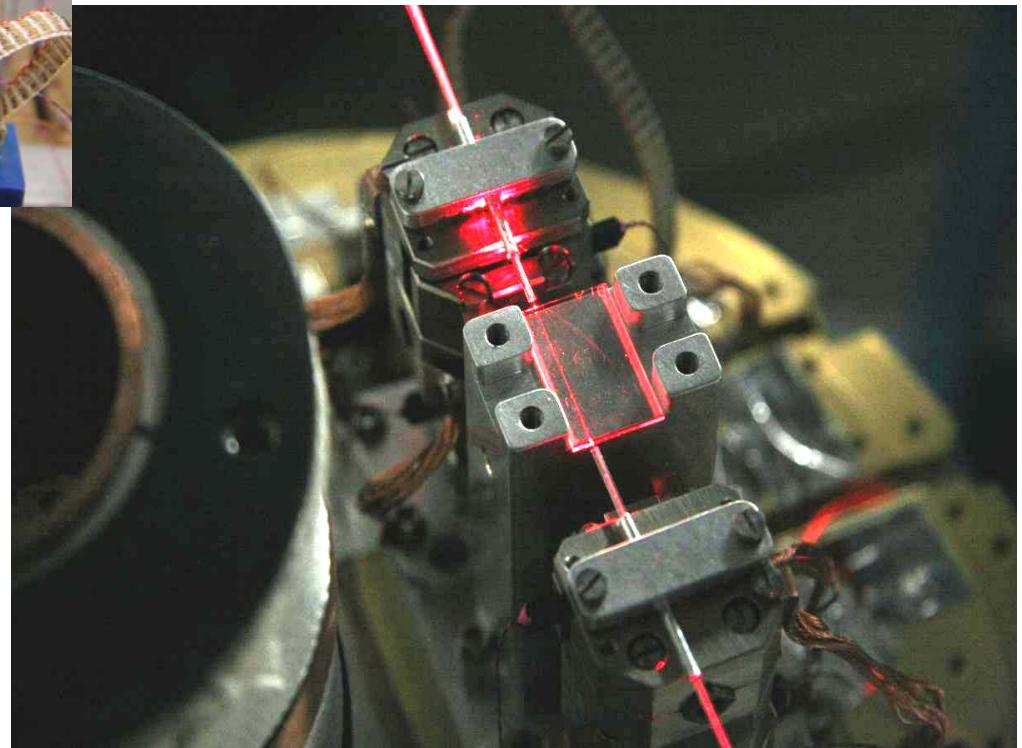
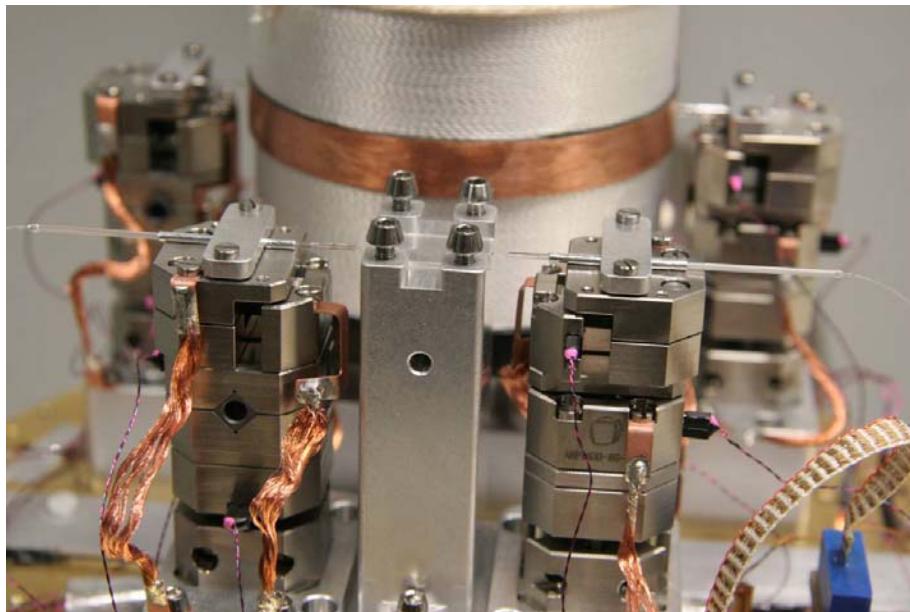
$$U \begin{pmatrix} X_1 \\ X_2 \\ 0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \tan\alpha X_1 + X_2 \\ \tan\alpha X_1 - X_2 \\ \sqrt{2(1 - \tan\alpha^2)} X_1 \end{pmatrix}$$



# Experimental setup

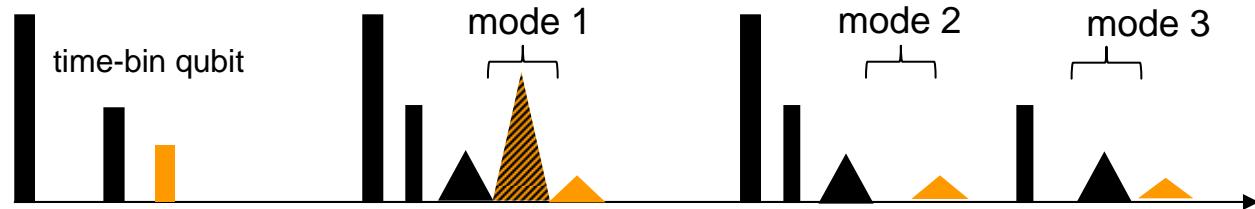


# Experimental setup



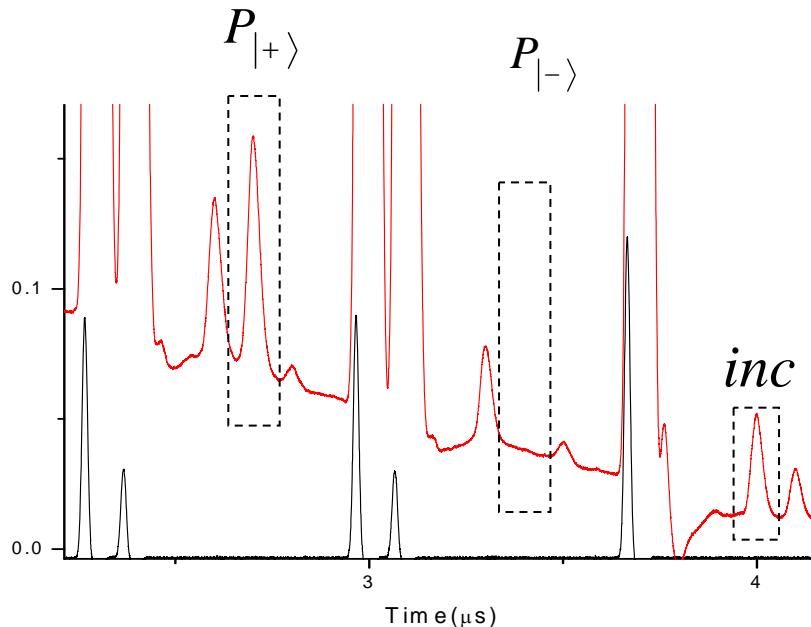
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# Experimental results



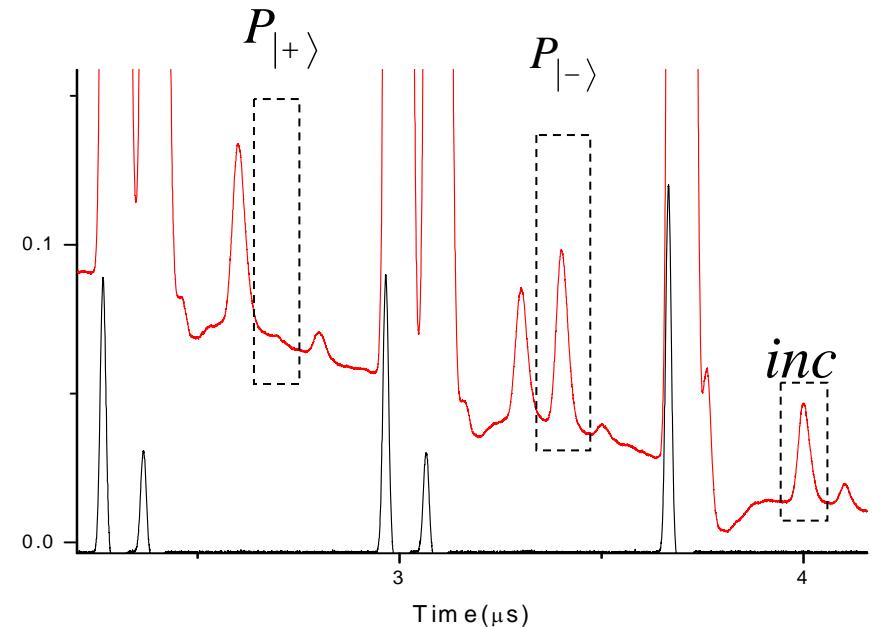
Input:

$$|\phi_+\rangle = \sqrt{\frac{1}{3}}|0\rangle + \sqrt{\frac{2}{3}}|1\rangle$$

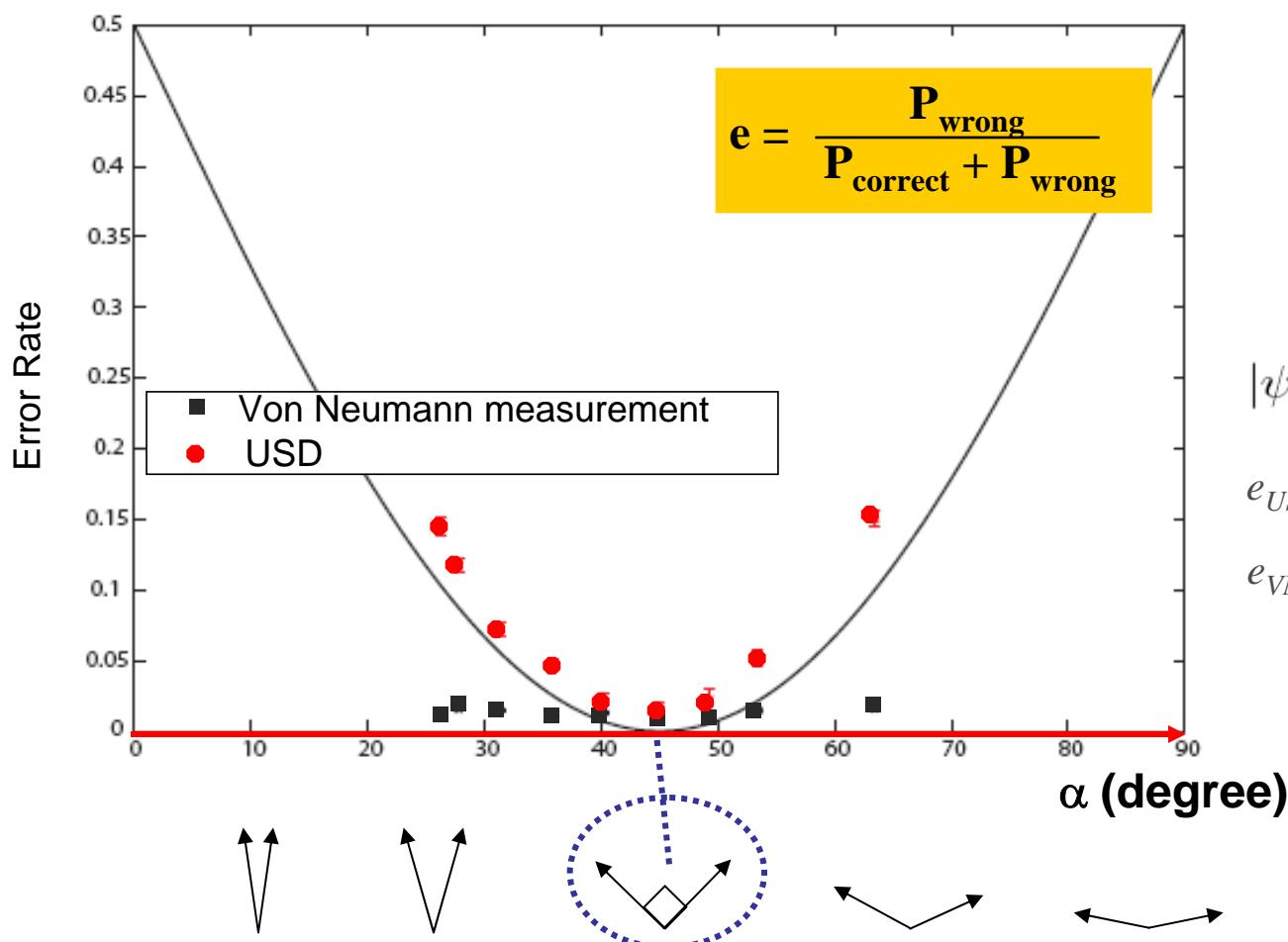


Input:

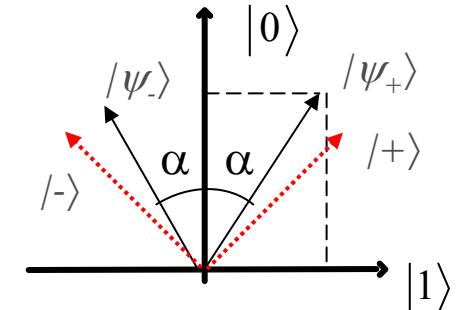
$$|\phi_-\rangle = \sqrt{\frac{1}{3}}|0\rangle - \sqrt{\frac{2}{3}}|1\rangle$$



# Experimental results



$$e = \frac{P_{\text{wrong}}}{P_{\text{correct}} + P_{\text{wrong}}}$$



$$|\psi_{\pm}\rangle = \cos\alpha|0\rangle \pm \sin\alpha|1\rangle$$

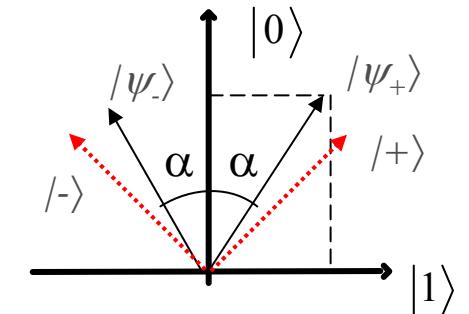
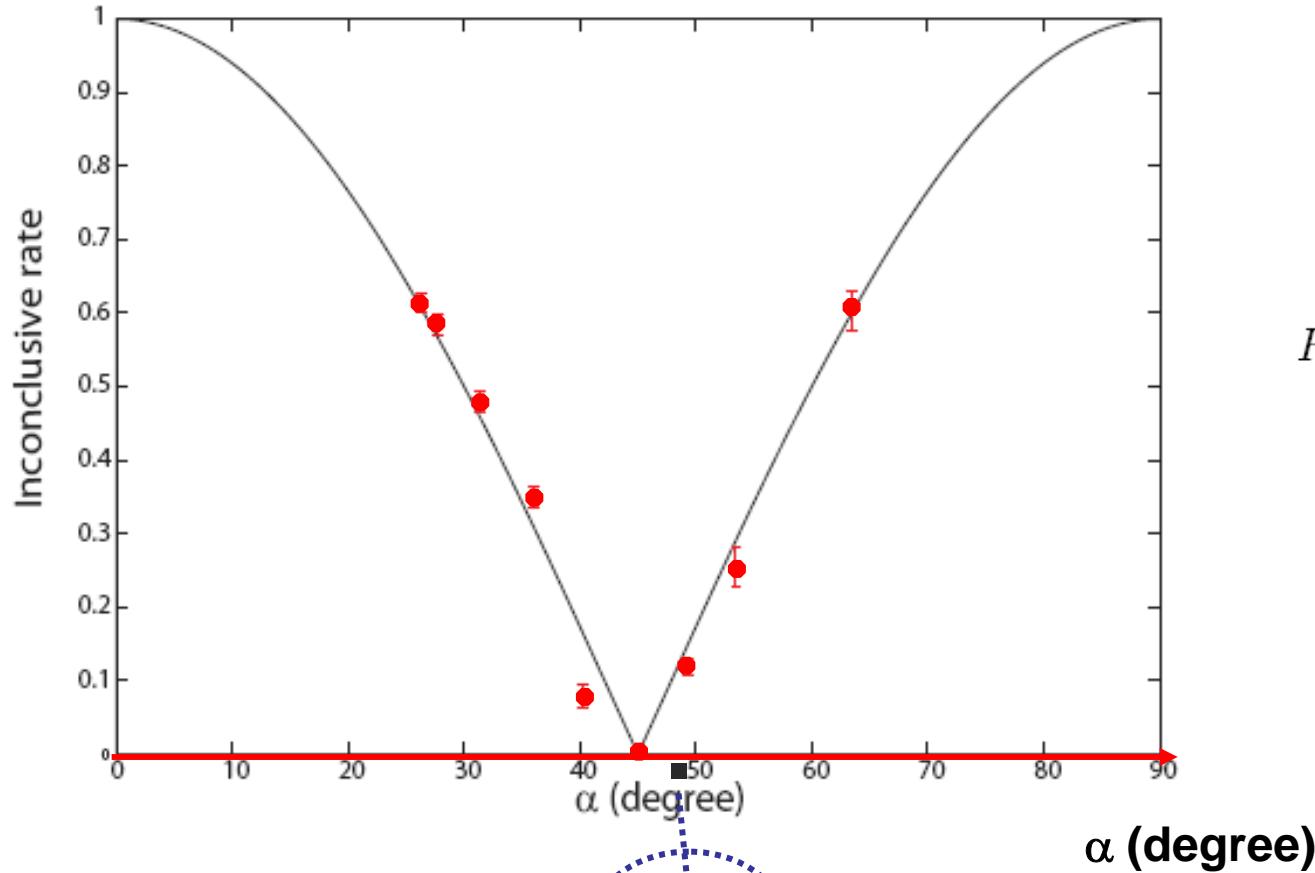
$$e_{\text{USD}} = 0$$

$$e_{\text{VN}} = |\langle \psi_+ | - \rangle|^2 = |\langle + | \psi_- \rangle|^2$$

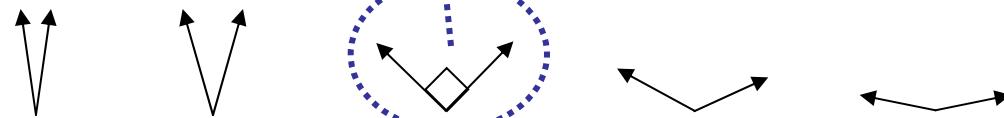
$$= \frac{1}{2} |\cos\alpha - \sin\alpha|^2$$

$$\text{ErrorRate}_{\text{USD}} \leq \text{ErrorRate}_{\text{VonNeumann}}$$

# Experimental results



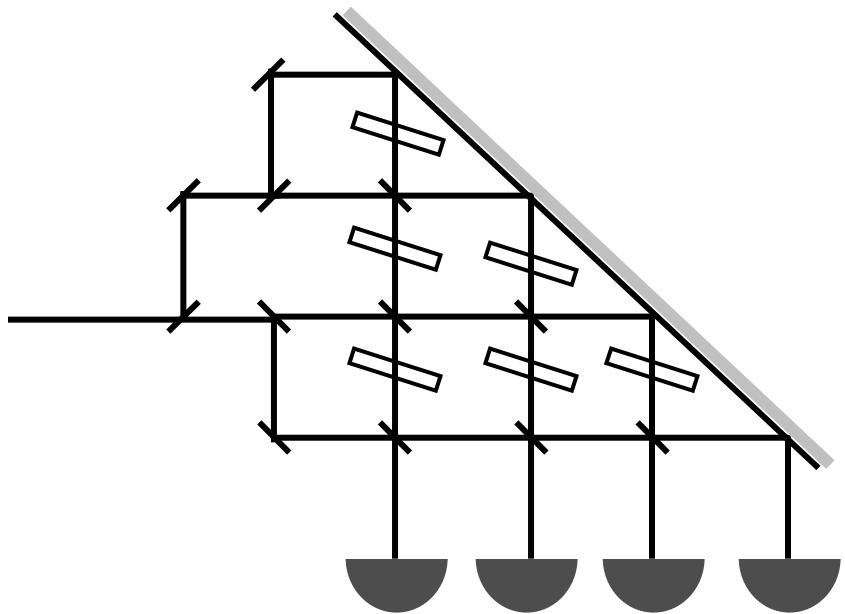
$$P_{inconclusive} = |\langle \psi_+ | \psi_- \rangle|$$
$$= |\cos^2 \alpha - \sin^2 \alpha|$$



## Discussion and summary

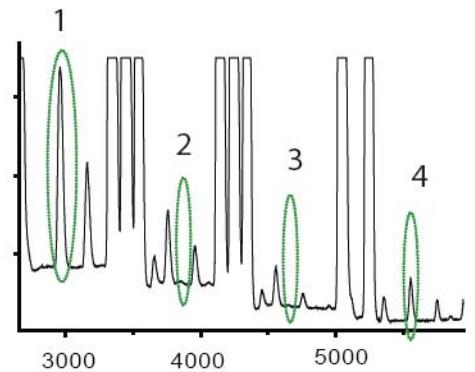
- Storage and data manipulation via photon-echo type atom-light interaction
- Examples: USD for qubits using traditional photon echoes
- Robust and versatile approach (easily generalized to USD for qutrits)
- Open questions:
  - (multi-path) interferometric precision measurements?
  - linear optics Bell state measurements & quantum computing?

# USD with qutrits



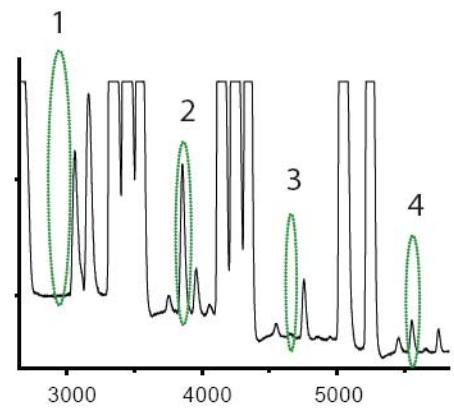
a)

$$|\psi_1\rangle_{out} = \begin{pmatrix} \sqrt{\frac{1}{3}} \\ 0 \\ 0 \\ \sqrt{\frac{2}{3}} \end{pmatrix}$$



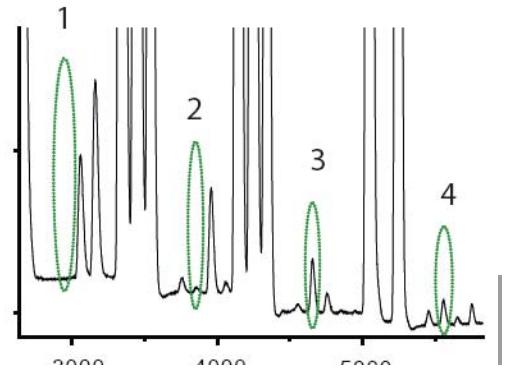
b)

$$|\psi_2\rangle_{out} = \begin{pmatrix} 0 \\ \sqrt{\frac{2}{3}} \\ 0 \\ \sqrt{\frac{1}{3}} \end{pmatrix}$$



c)

$$|\psi_3\rangle_{out} = \begin{pmatrix} 0 \\ 0 \\ \sqrt{\frac{2}{3}} \\ \sqrt{\frac{1}{3}} \end{pmatrix}$$



## Discussion and summary

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- Examples: USD for qubits using traditional photon echoes
- Robust and versatile approach (easily generalized to USD for qutrits)
- Open questions:
  - (multi-path) interferometric precision measurements?
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**Post-doctoral positions  
available**

**Thank you**

**Collaborations:  
Profs N. Gisin and  
W. Sohler**



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