Lecture Note 5

Quantum Memory with Atomic Ensembles

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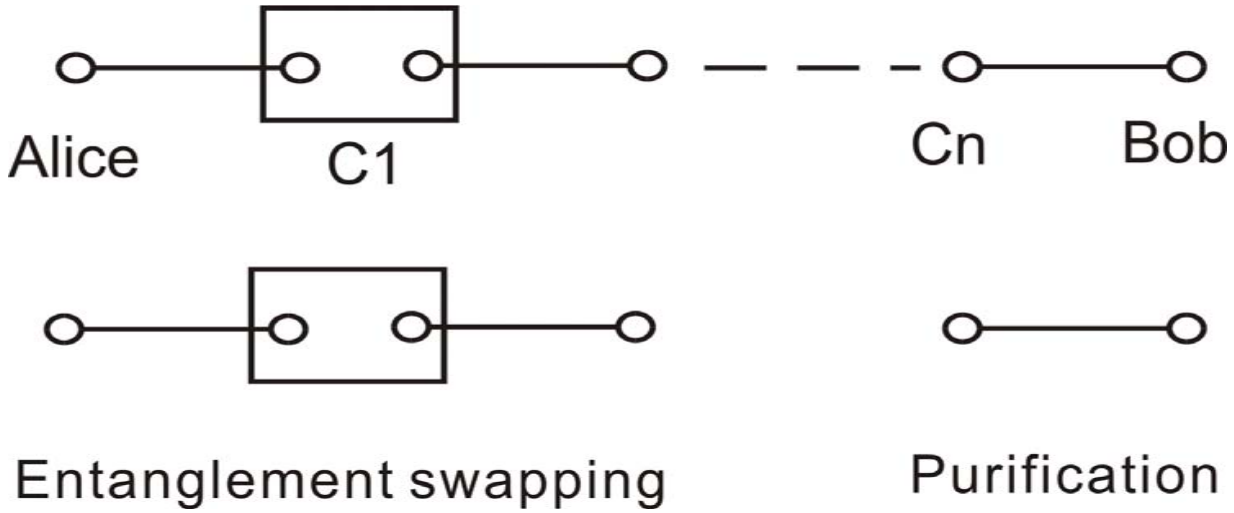
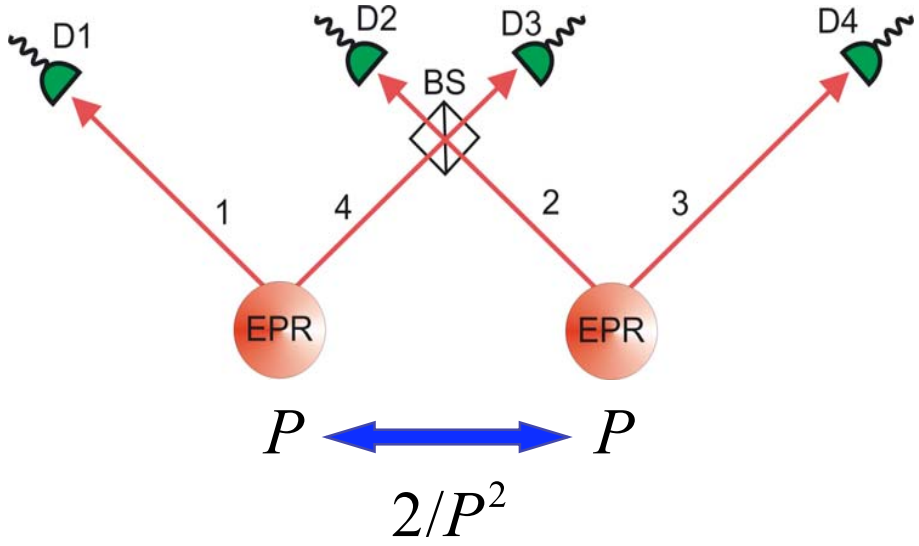
04.06.2008

Difficulties in Long-distance Quantum Communication

Problems	leads	Solutions
Absorption (exponentially)	Photon loss	Entanglement Swapping
Decoherence	Degrading entanglement quality	Entanglement Purification
Synchronization of independent lasers		



Drawbacks of The former QC Experiments



Drawback	**Probabilistic entangled photon source**	**cost of resource** N/P^N
Feasible solution	**Quantum memory (Quantum Repeater)**	**cost of resource** N/P

Novel Solution with Atomic Ensembles!

Storage of light in atomic ensembles

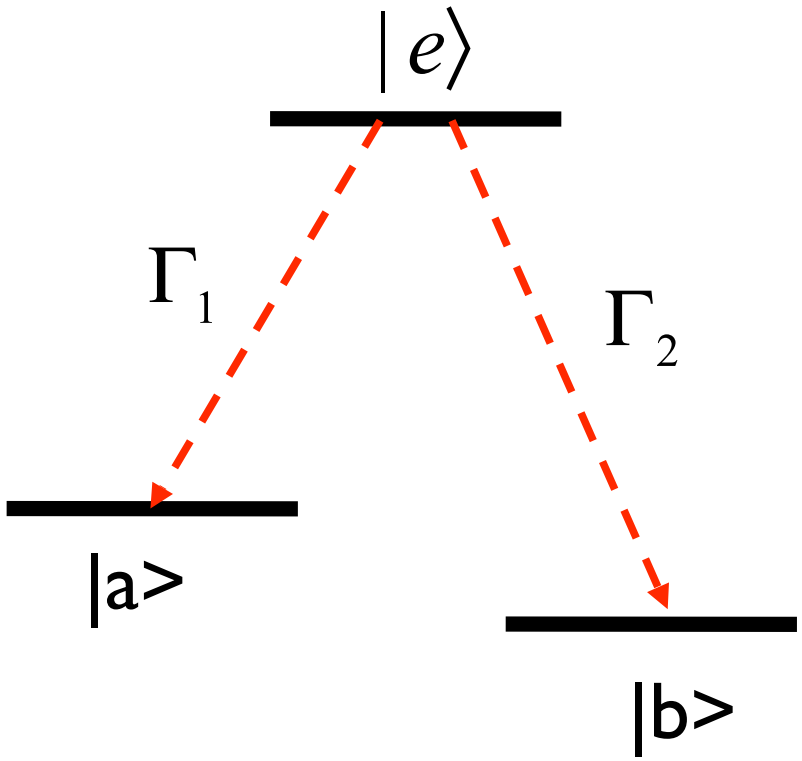
[C. Liu *et al.*, *Nature* **409**, 490 (2001);]
[D. F. Phillips *et al.*, *Phys. Rev. Lett.* **86**, 783 (2001)]

motivate

Long-distance quantum communication with atomic ensembles and linear optics

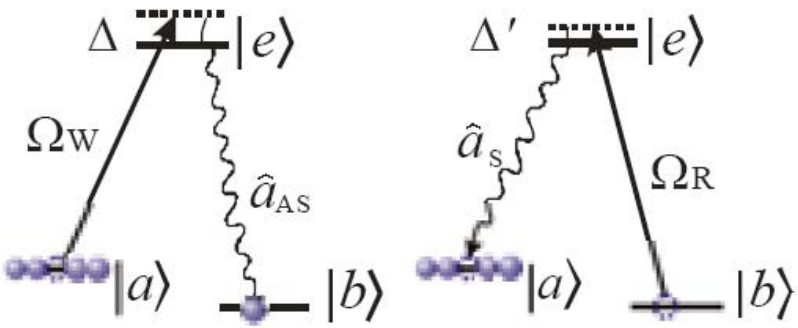
[L.-M. Duan *et al.*, *Nature* **414**, 413 (2001)]

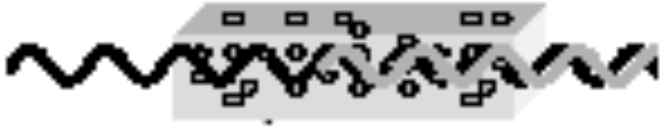
Three level atoms: medium of quantum memory



"DLCZ" protocol

Optically dense Atomic Ensemble
N atoms with Lambda System

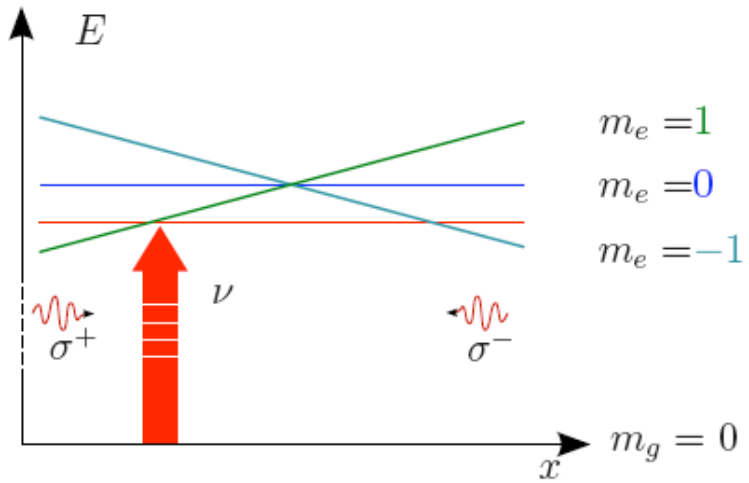


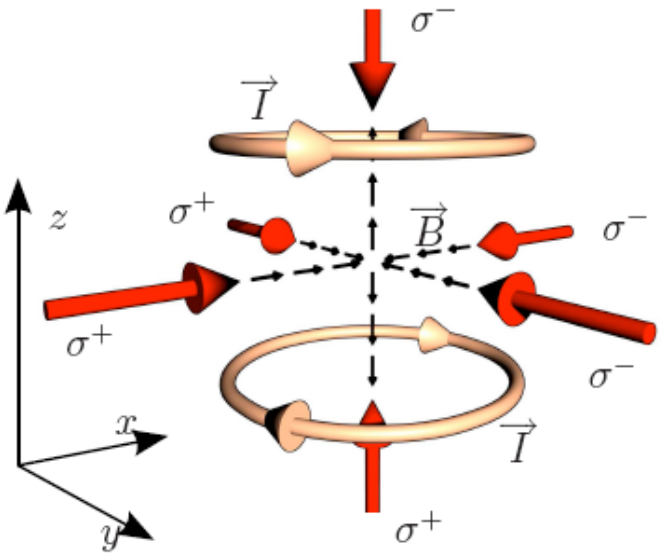


- **Intial state** $|\psi\rangle_0 = \otimes_i |a\rangle_i$
- **After write** $|\psi\rangle = |0_{AS} 0_b\rangle + p^{1/2} |1_{AS} 1_b\rangle + \mathcal{O}(p)$

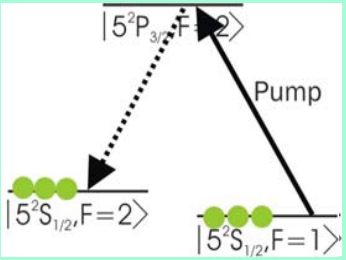
$$|1_b\rangle = \frac{1}{\sqrt{N}} \sum_i |b\rangle_i \langle a| |\Psi\rangle_0$$

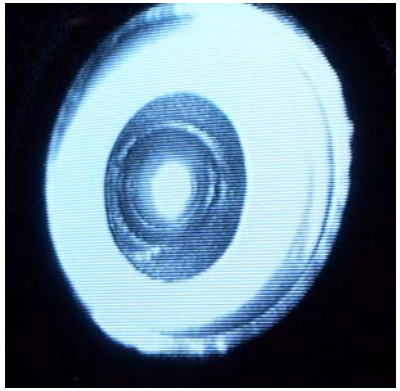
Atomic Ensemble: Magneto-Optical Trap





Step 1:
State preparation

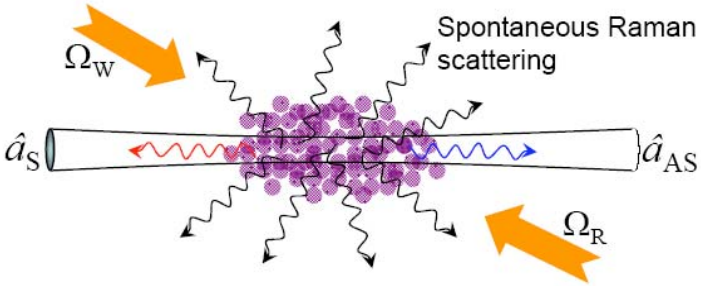


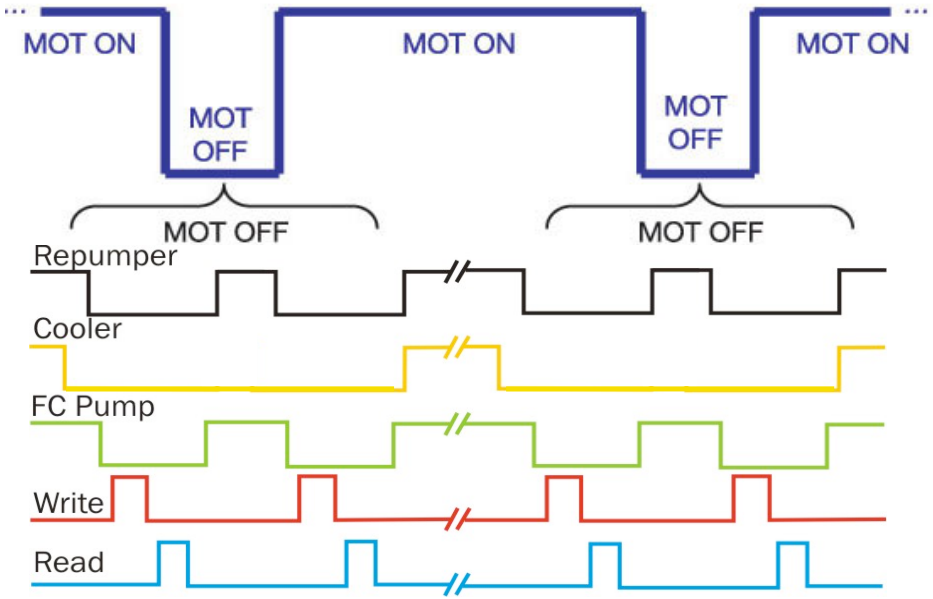


Cold ^{87}Rb- Atoms in MOT:

- Number: $>10^8$
- Density: $\sim 10^{10}$ /cm^3
- Temperature :$\sim$ 100 μK
- Optical Density: $\sim$3
- Size: $\sim$ 3 mm

Basic Experimental Sequence

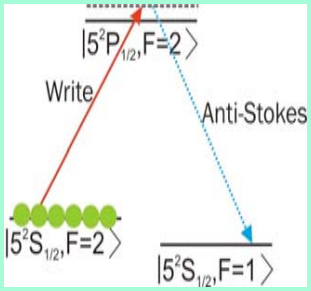




Momentum conservation

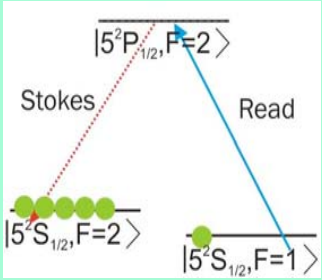
$$\vec{k}_S = \vec{k}_R + \vec{k}_W - \vec{k}_{AS}.$$

Step 2:
Anti-Stokes Photon

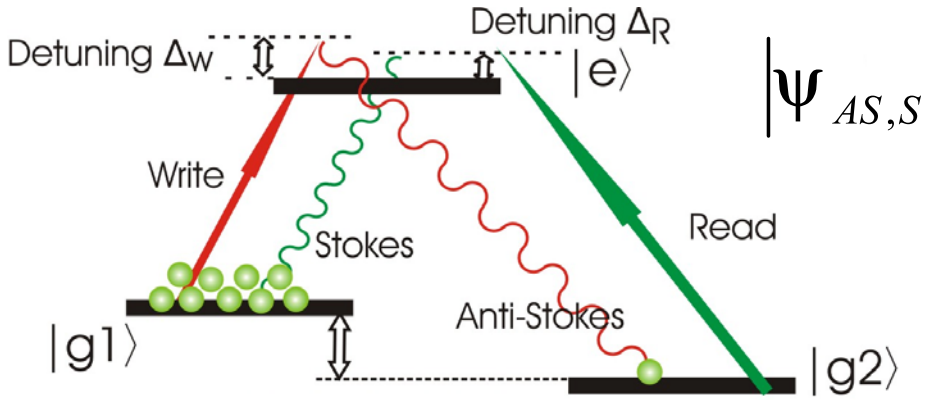


Storage time T

Step 3:
Stokes Photon



Non-classical photon pair Generation



$$\left|\psi_{AS,S}\right\rangle = \left|00\right\rangle + \sqrt{\chi}\left|11\right\rangle + \chi\left|22\right\rangle$$

Quantum mechanics :

$$p_{as} = \chi$$

$$p_s = \chi$$

$$p_{as,s} = \chi$$

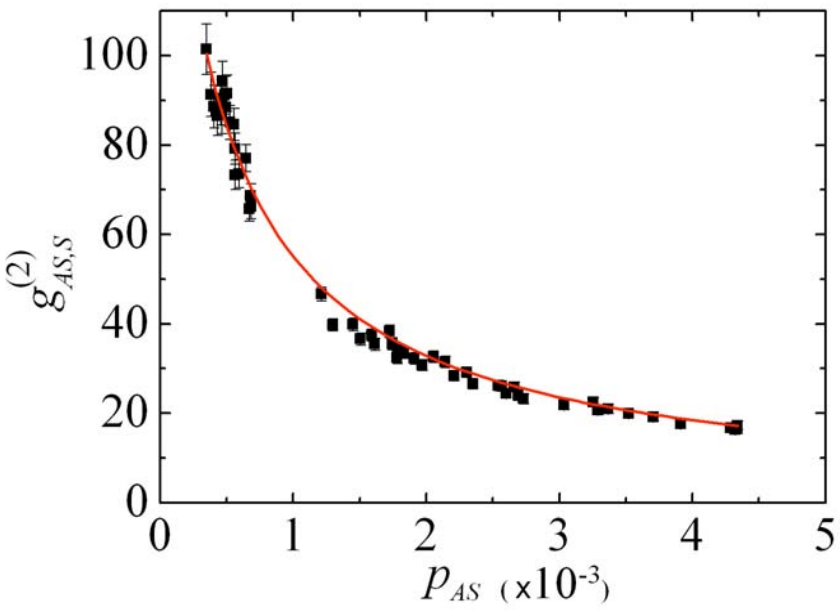
Classical statistics :

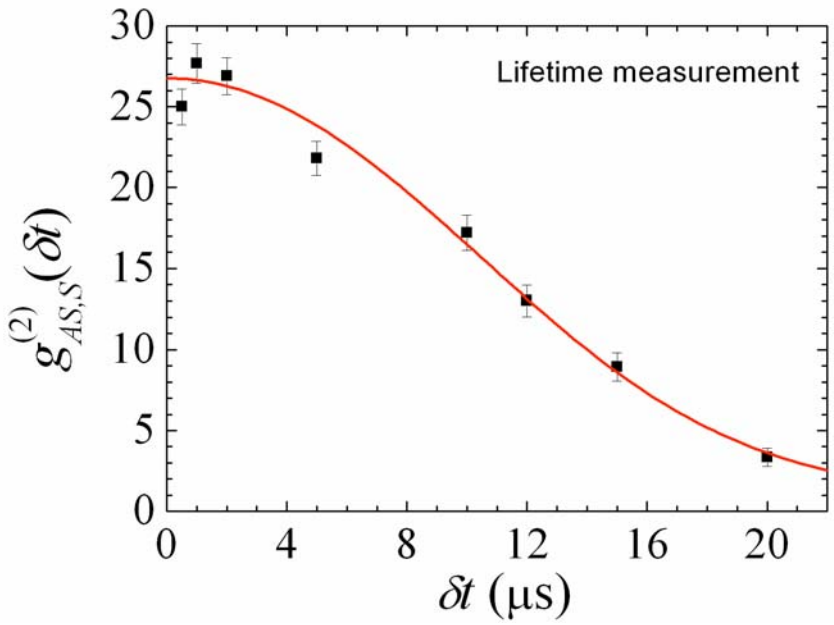
$$p_{as,s} = p_{as} \cdot p_s$$

Cross-correlation is used to show quantum correlation between the single-photon pair

$$g^{(2)}_{as,s} = \frac{p_{as,s}}{p_{as} \cdot p_s} = \frac{1}{\chi} \gg 1, (\chi \ll 1)$$

Quantum Memory: Experimental results



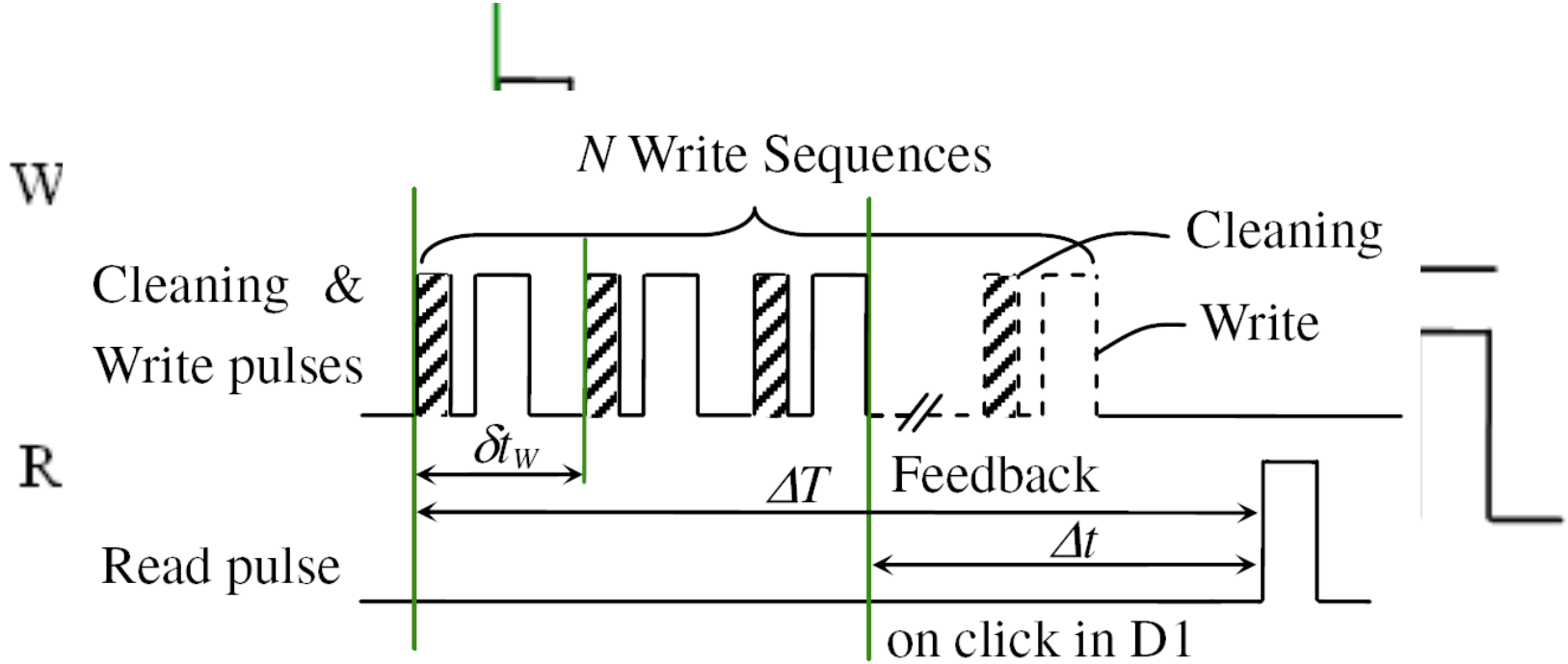


Cross correlation $g^{(2)}_{AS,S}$ of anti-Stokes and Stokes photon VS the detected probability of anti-Stokes photon p_{AS}

$g^{(2)}_{AS,S} > 2$ => *nonclassical light*

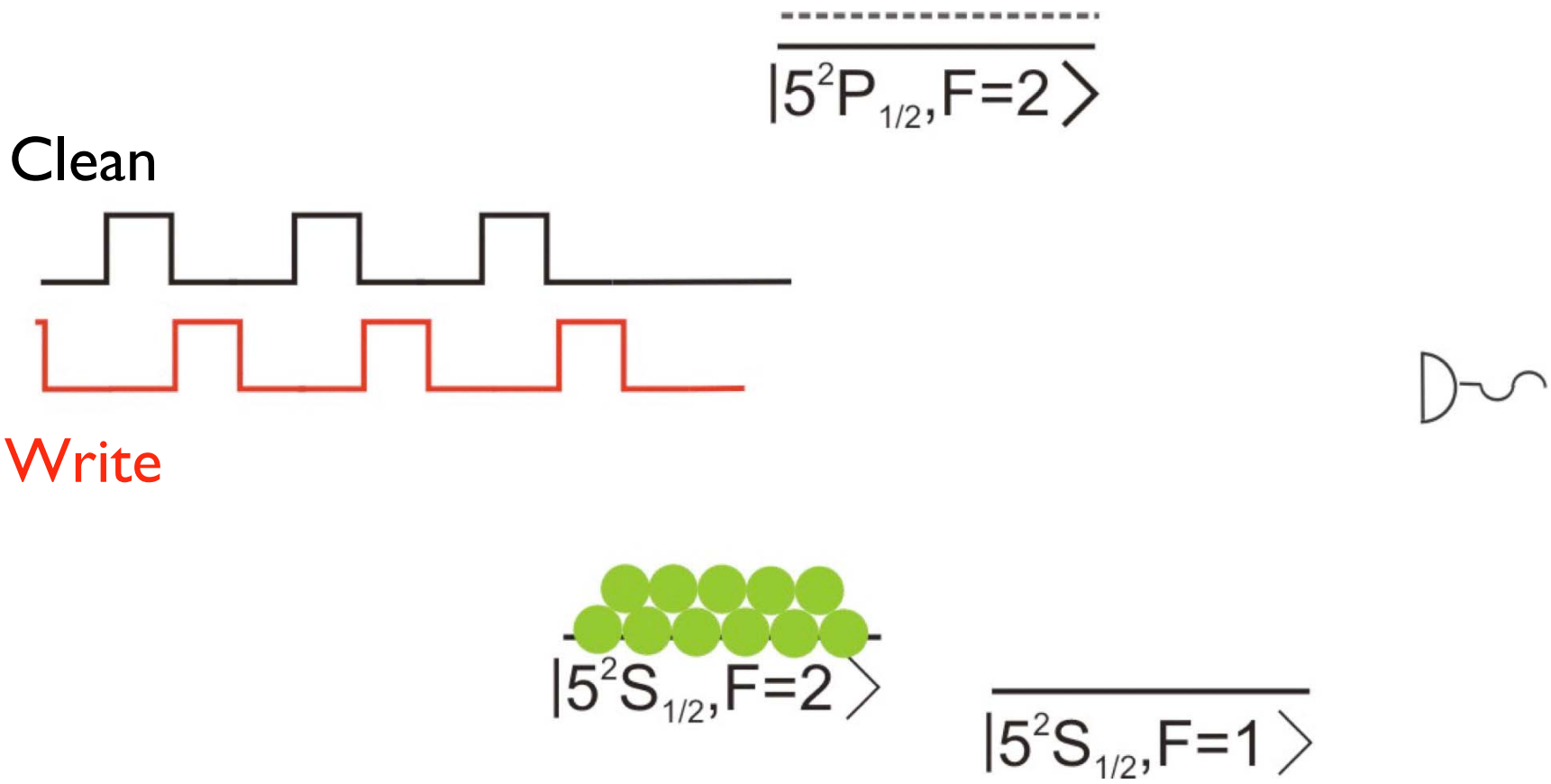
Lifetime measurement of the quantum memory. Due to the dephasing of the collective spin state, the life time is determined to be 13 μs

A Conditional Single Photon Source

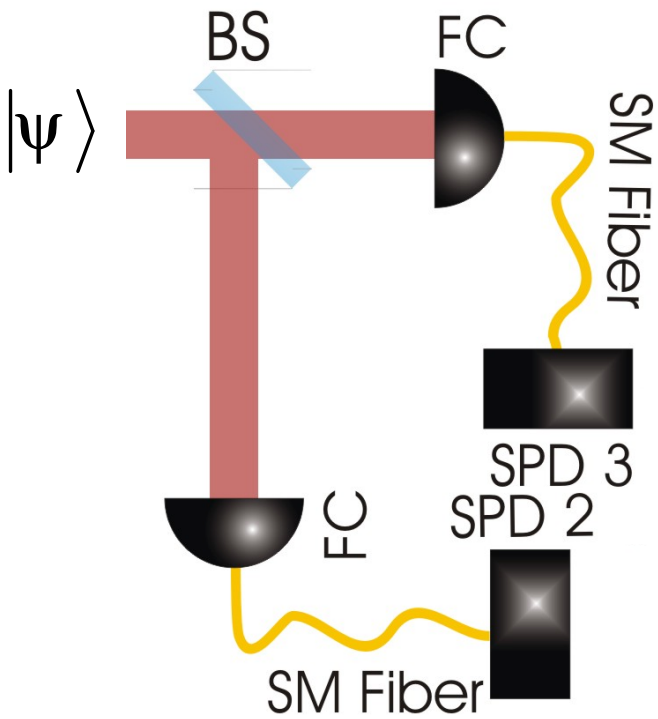


Enhance probabilistic process by application of multiple Write pulses
=> Read-out becomes deterministic

Deterministic and Storable Single-photon Source



Single photon quality



$$\rho_\psi \approx |1\rangle\langle 1| + 2\chi\,|2\rangle\langle 2|$$

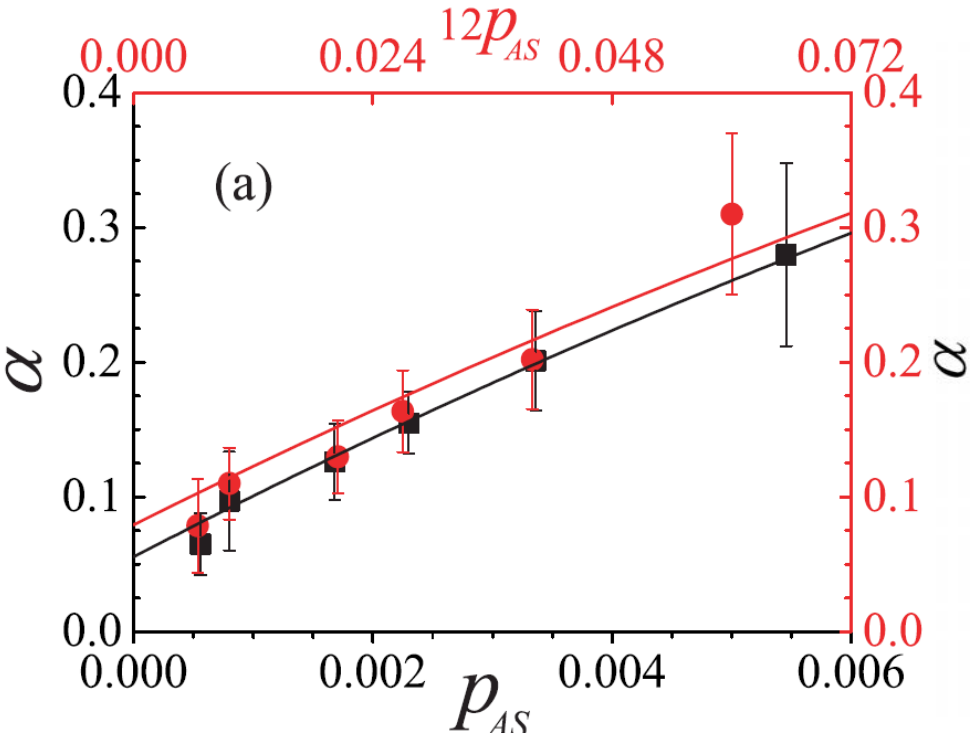
$$p_2 = p_3 = \frac{1}{2}\eta_a$$

$$p_{23} = \chi \cdot \eta_a^{\,2}$$

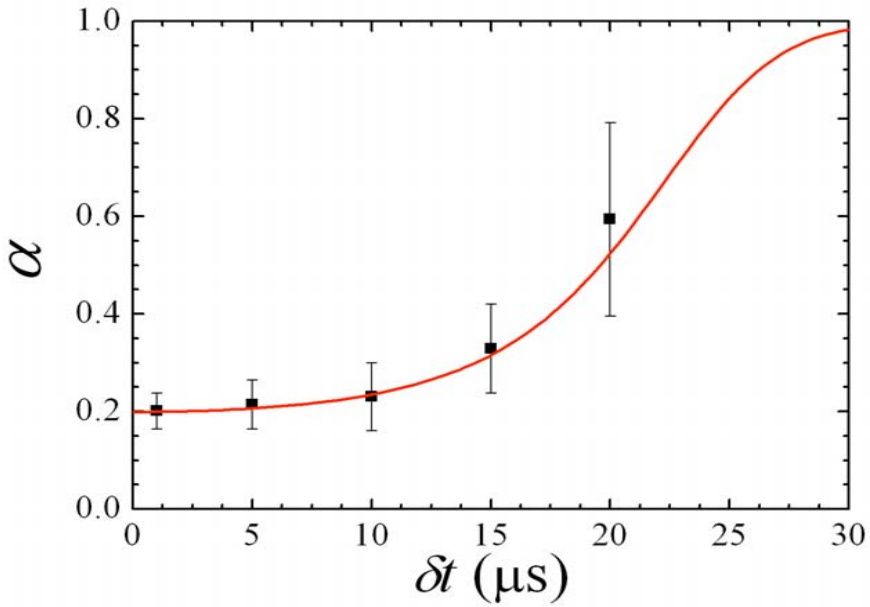
single photon quality is determined by anti-correlation

$$\alpha = {p_{23}}/{p_2 p_3} = 4\chi$$

Deterministic and Storable Single-photon Source



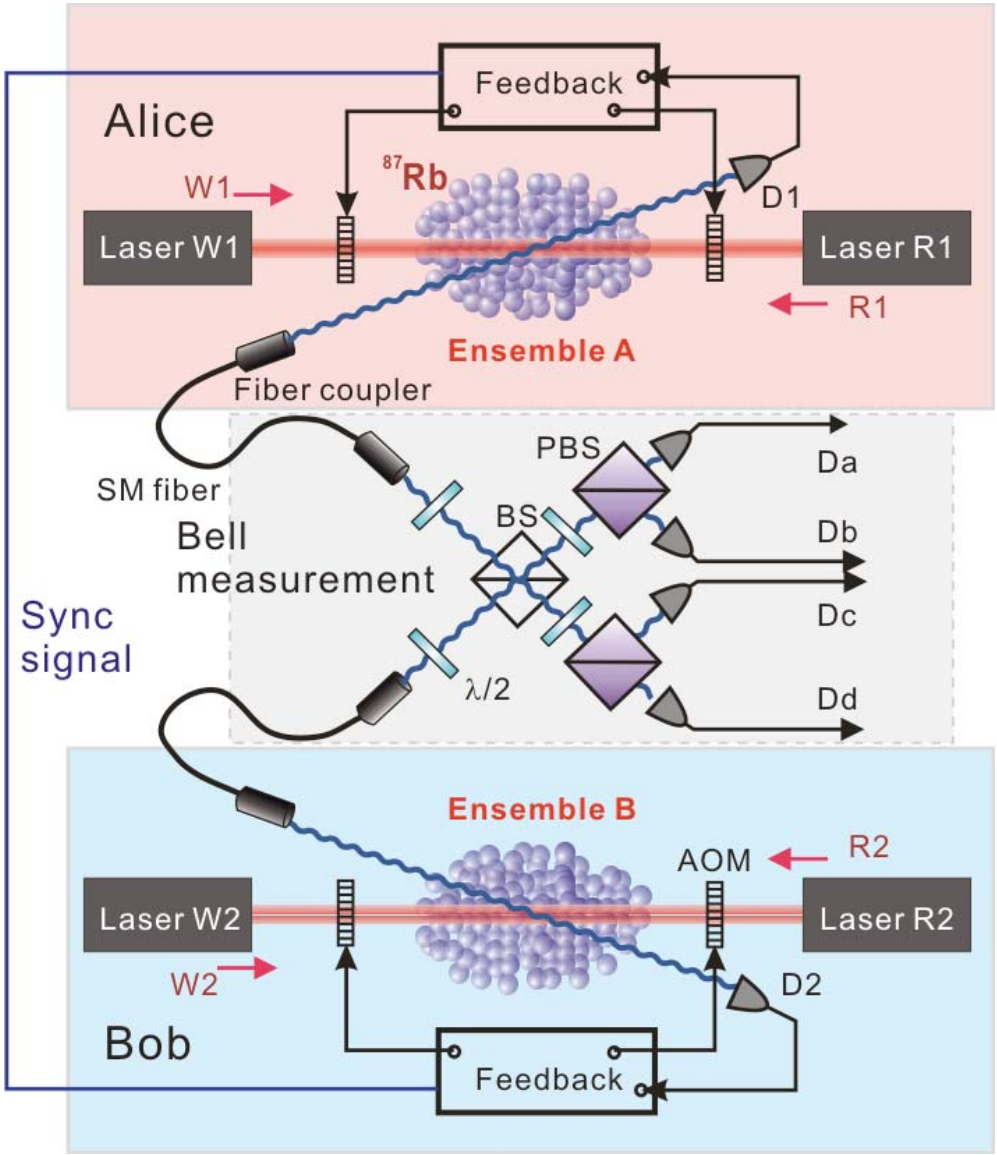
Anti-correlation a of the single photon VS anti-Stokes photon production rate p_1.



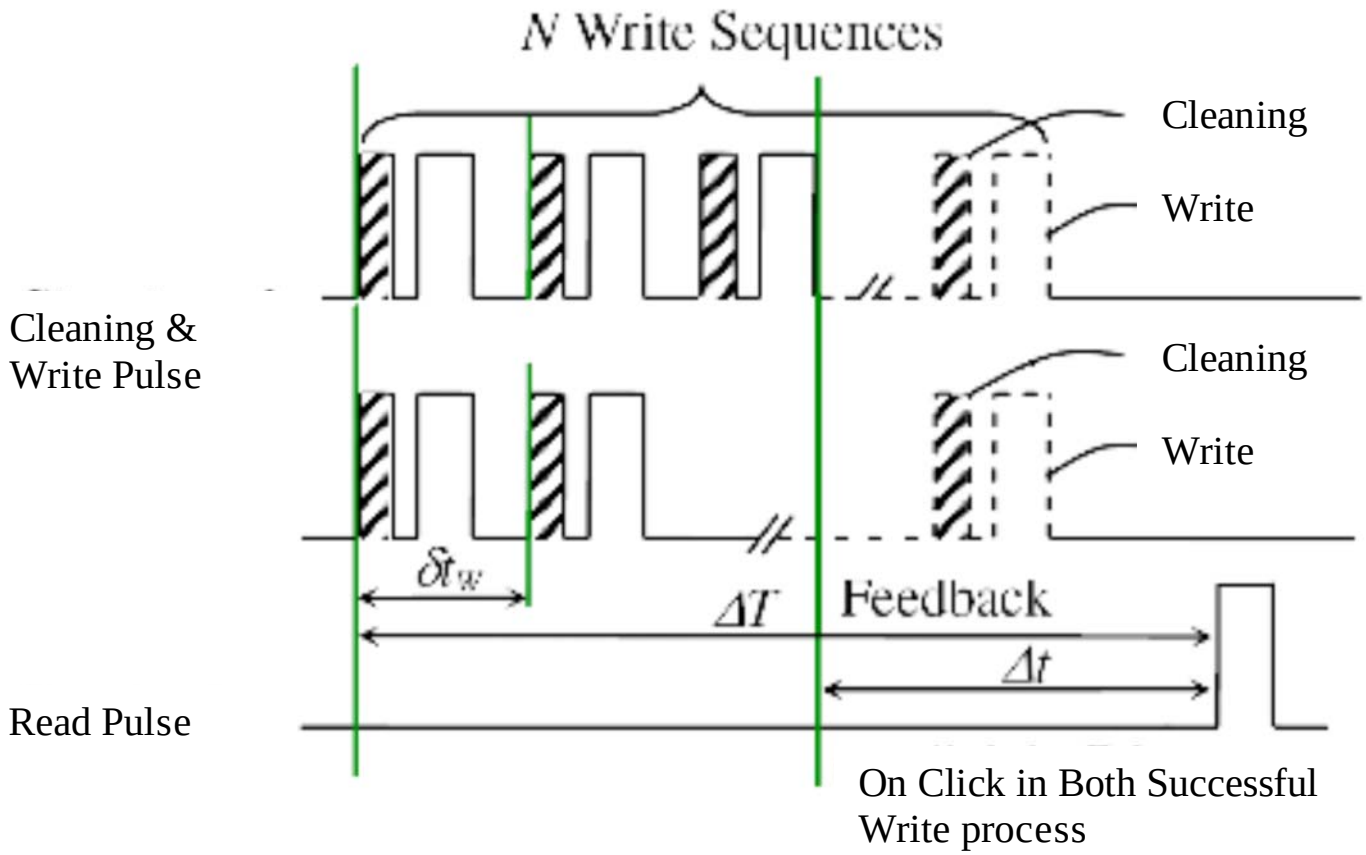
Anti-correlation a of the single photon VS storage time d*t*.

[S. Chen *et al.*, Phys. Rev. Lett. **97** 173004]

$2/p^2 \Rightarrow 2/p$



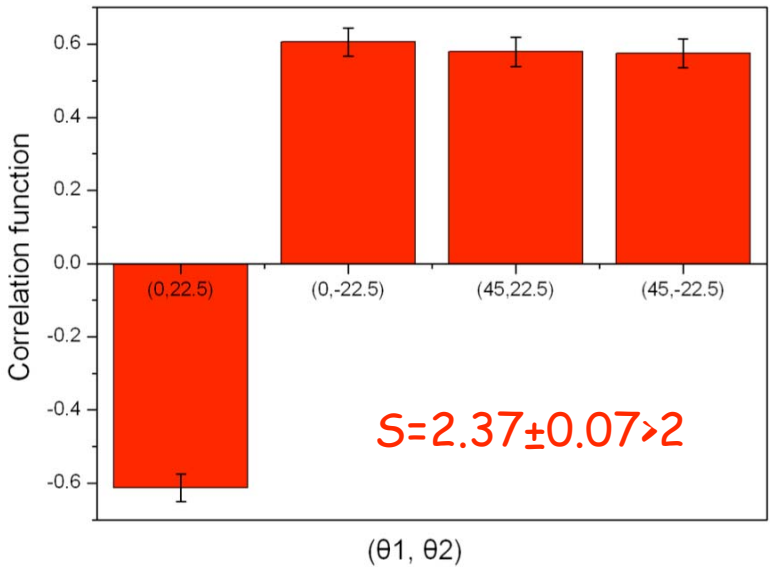
Time Sequence

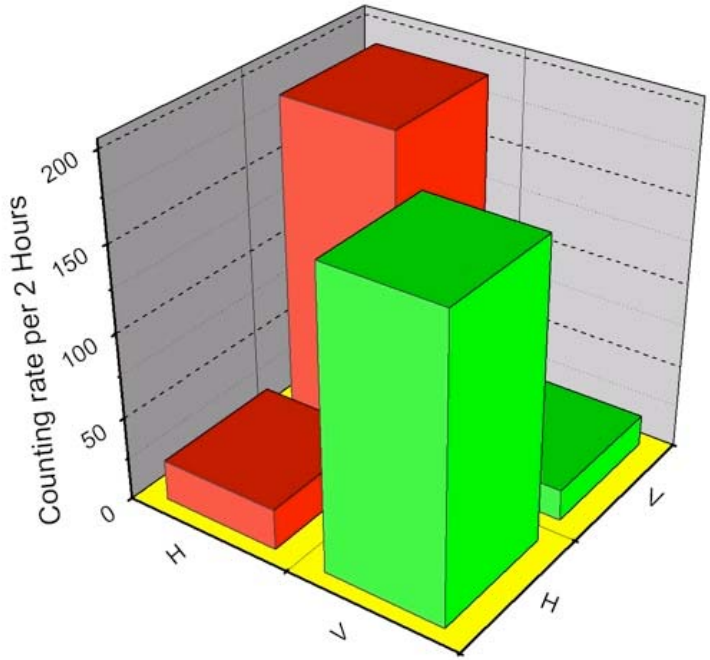


Efficient Generation of Entanglement

$$|\Psi_{\text{eff}}\rangle_{12} = \begin{cases} P_{\text{I}}^2/2, & 1/\sqrt{2}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2); \\ P_{\text{II}}/2, & |H\rangle_1|H\rangle_2; \\ P_{\text{II}}/2, & |V\rangle_1|V\rangle_2. \end{cases}$$

Predicts S=2.3





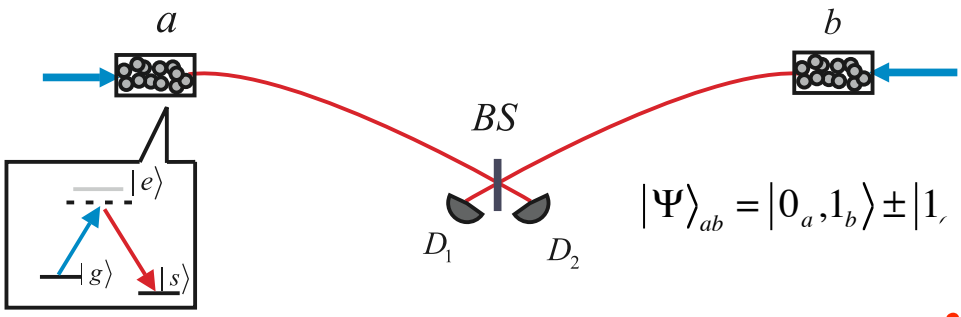
The probability of generation of entanglement is enhanced by 2 order with the help of feedback circuit.

[Z.-S. Yuan et al PRL 98 180503, (2007)]

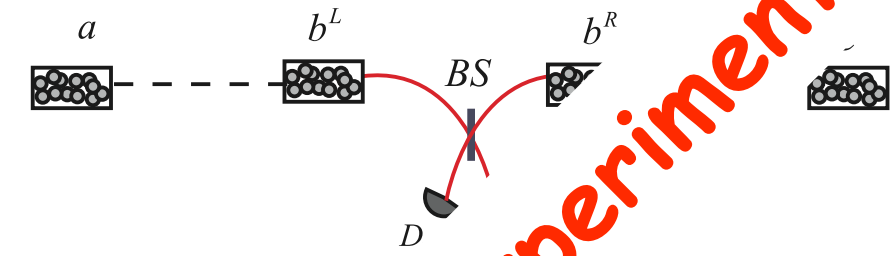
Problem in DLCZ

-- Mach-Zehnder-type interference needed

Entanglement in DLCZ: $|0\rangle|1\rangle$



a. entanglement generation



b. entang wapping

Experimentally Forbidden!!

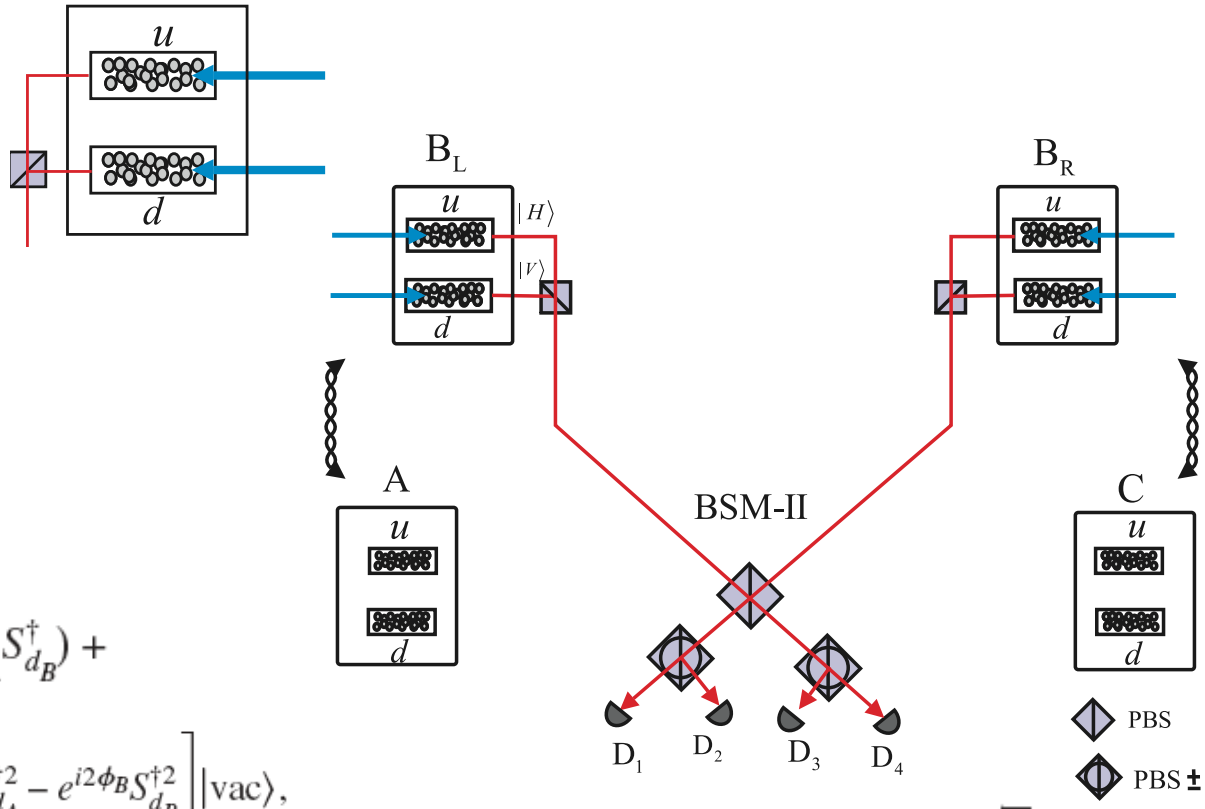
ime jitter at a
itosecond level
a time scale of up to
our.

Realistic:
0.085 fs for transferring a timing signal over 32 km for averaging times of 1 second
[PRL 99, 153601 (2007)]

[Z.-B. Chen *et al.*, Phys. Rev. A **76** 022329 (2007)]

Robust Quantum Repeater

--Hong-Ou-Mandel-type interference is used

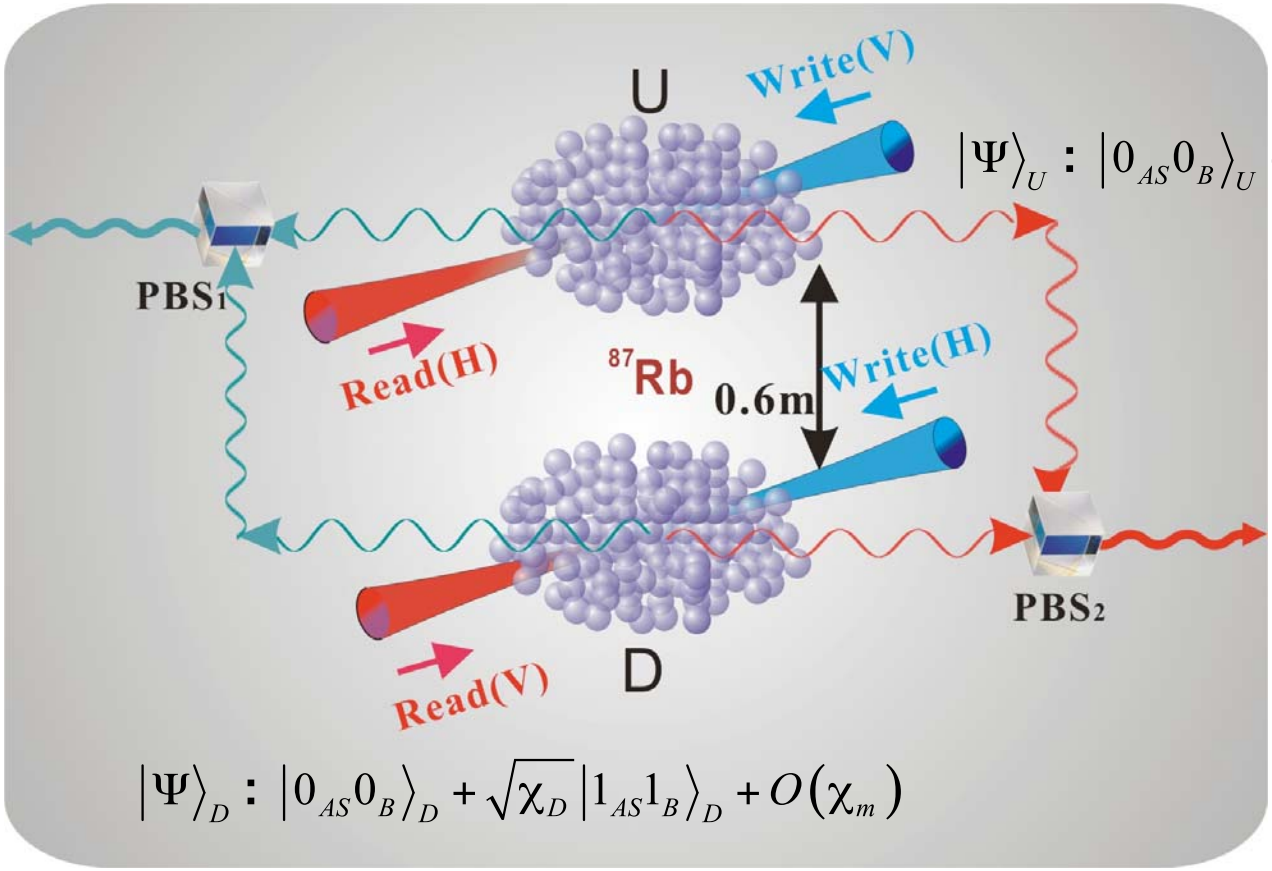


$$|\psi\rangle_{AB} = \left[\frac{e^{i(\phi_A+\phi_B)}}{2}(S^\dagger_{u_A}S^\dagger_{u_B} + S^\dagger_{d_A}S^\dagger_{d_B}) + \frac{1}{4}(e^{i2\phi_A}S^{\dagger 2}_{u_A} + e^{i2\phi_B}S^{\dagger 2}_{u_B} - e^{i2\phi_A}S^{\dagger 2}_{d_A} - e^{i2\phi_B}S^{\dagger 2}_{d_B}\right] |\mathrm{vac}\rangle,$$

$$|\phi^+\rangle_{AC} = (S^\dagger_{u_A}S^\dagger_{u_C} + S^\dagger_{d_A}S^\dagger_{d_C})/\sqrt{2}|\mathrm{vac}\rangle.$$

[B. Zhao *et al.*, Phys. Rev. Lett. **98** 240502 (2007)]

Atom-Photon Entanglement



$$|\Psi\rangle_U : |0_{AS}0_B\rangle_U + \sqrt{\chi_U}\,|1_{AS}1_B\rangle_U + O(\chi_m)$$

$$|\Psi\rangle_D : |0_{AS}0_B\rangle_D + \sqrt{\chi_D}\,|1_{AS}1_B\rangle_D + O(\chi_m)$$

$$|\tilde{H}\rangle = |0_B\rangle_U |1_B\rangle_D$$

$$|\tilde{V}\rangle = |1_B\rangle_U |0_B\rangle_D$$

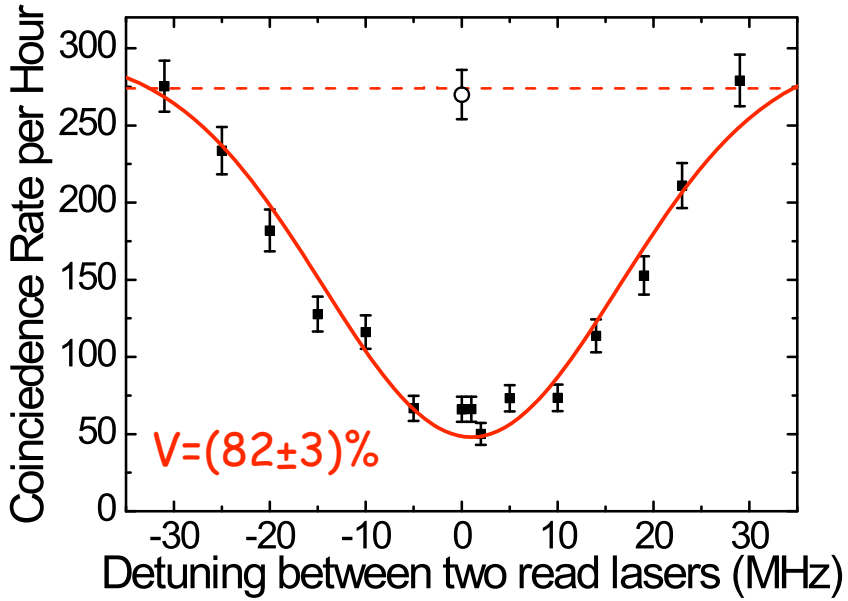
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|\tilde{V}\rangle + e^{i\phi_1}|V\rangle|\tilde{H}\rangle\right) \rightarrow \frac{1}{\sqrt{2}}\left(|H\rangle_{AS}|V\rangle_S + e^{i(\phi_1+\phi_2)}|V\rangle_{AS}|H\rangle_S\right)$$

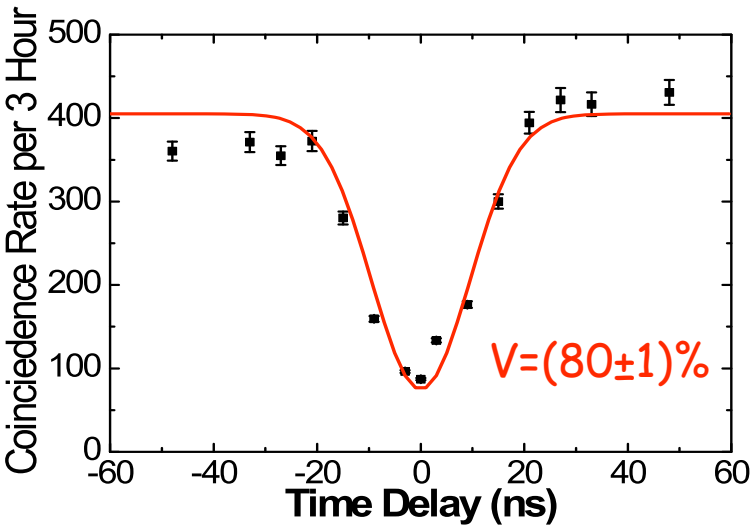
Indistinguishability

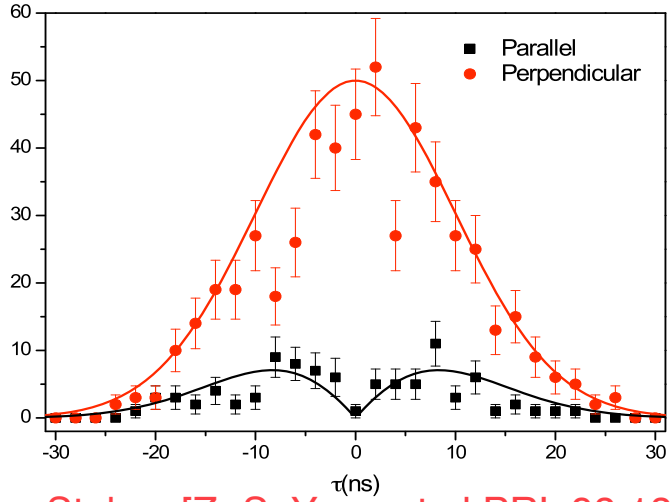
In distinguishable Photons
2-photon interference

$$V = \frac{1}{1+\alpha}, \alpha = 0.15$$

Predicts V=87%





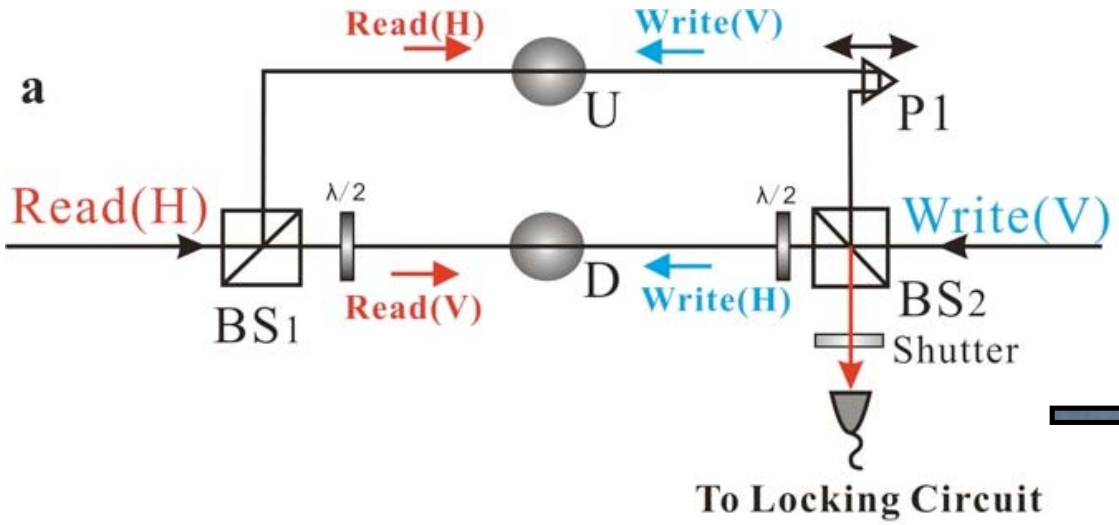


Stokes:[Z.-S. Yuan et al PRL 98 180503, (2007)]
anti-Stokes:[T. Chaneliere et al PRL 98 113602]]

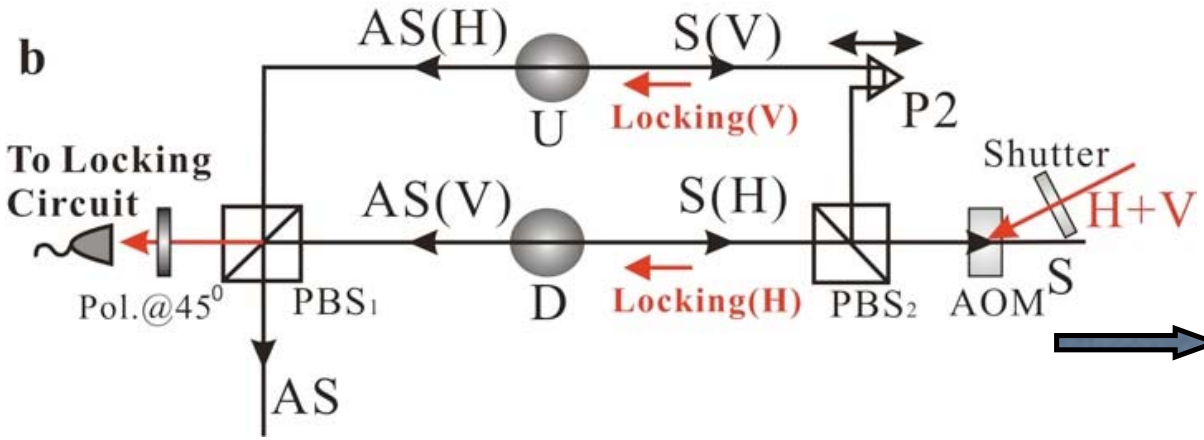
Phase Locking

$$\phi_1 = \Delta\theta_W + \Delta\theta_{AS}$$

$$\phi_2 = \Delta\theta_R + \Delta\theta_S$$

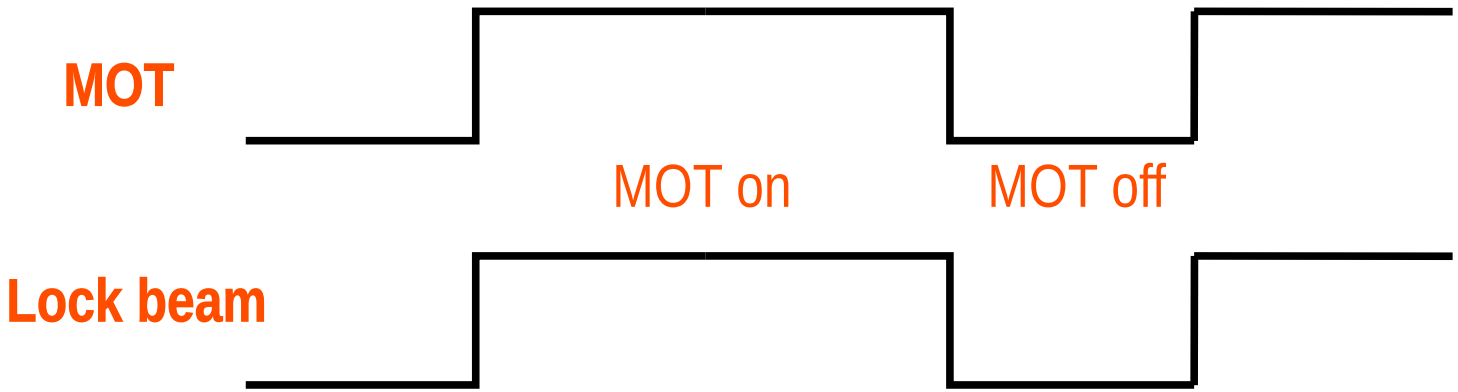


$$\Delta\theta_W + \Delta\theta_R$$



$$\Delta\theta_{AS} + \Delta\theta_S$$

Quality of the Entanglement



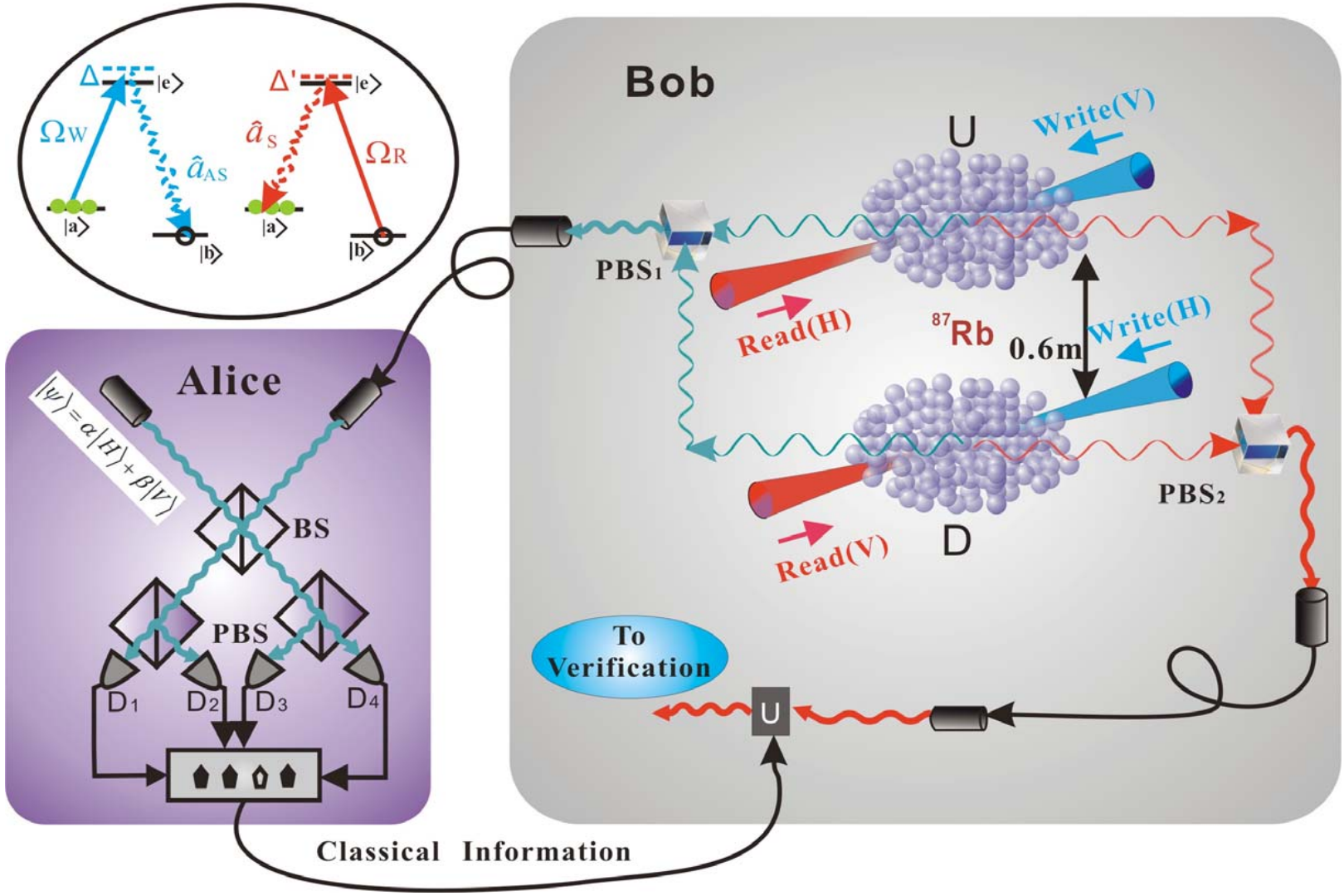
Phase stability after lock

Short term fluctuation: $\pi / 30$

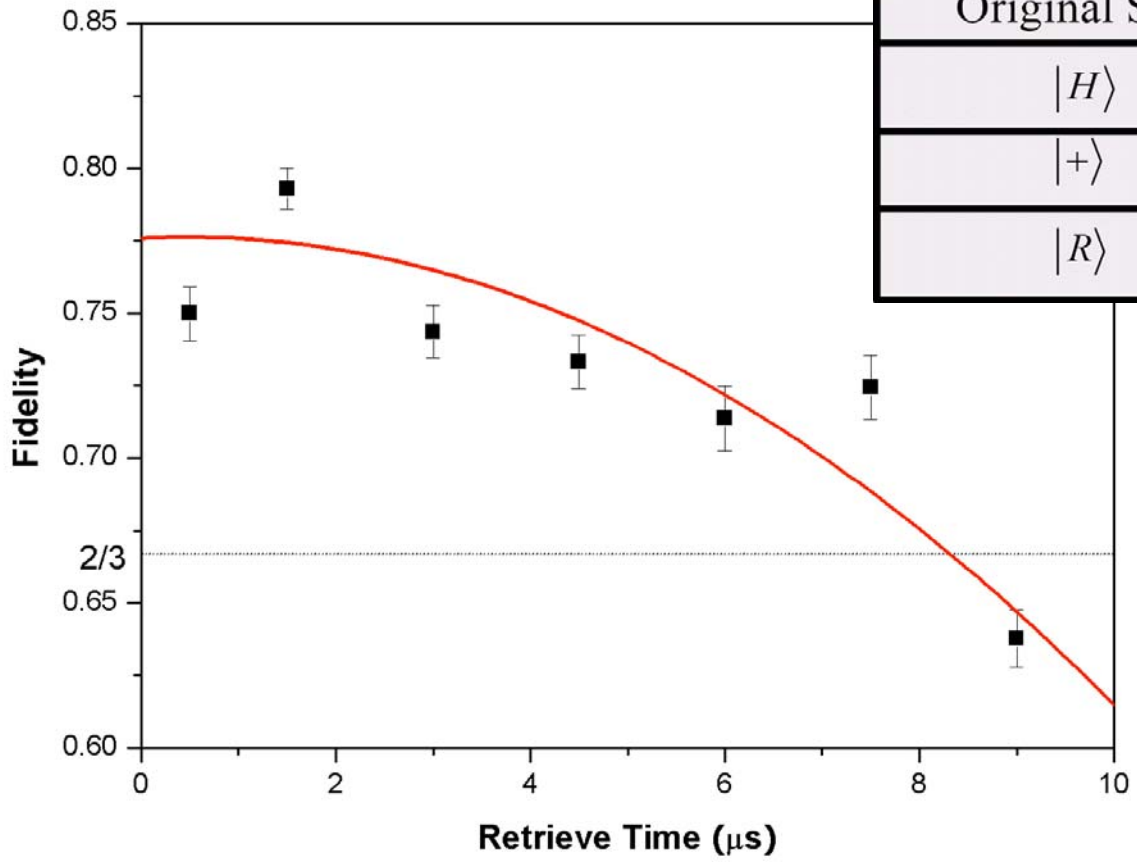
Long term drift: cancelled

Entanglemant signal to noise ratio, 15:1 @ excitation rate of 3‰

Teleport a photonic qubit to atomic qubit



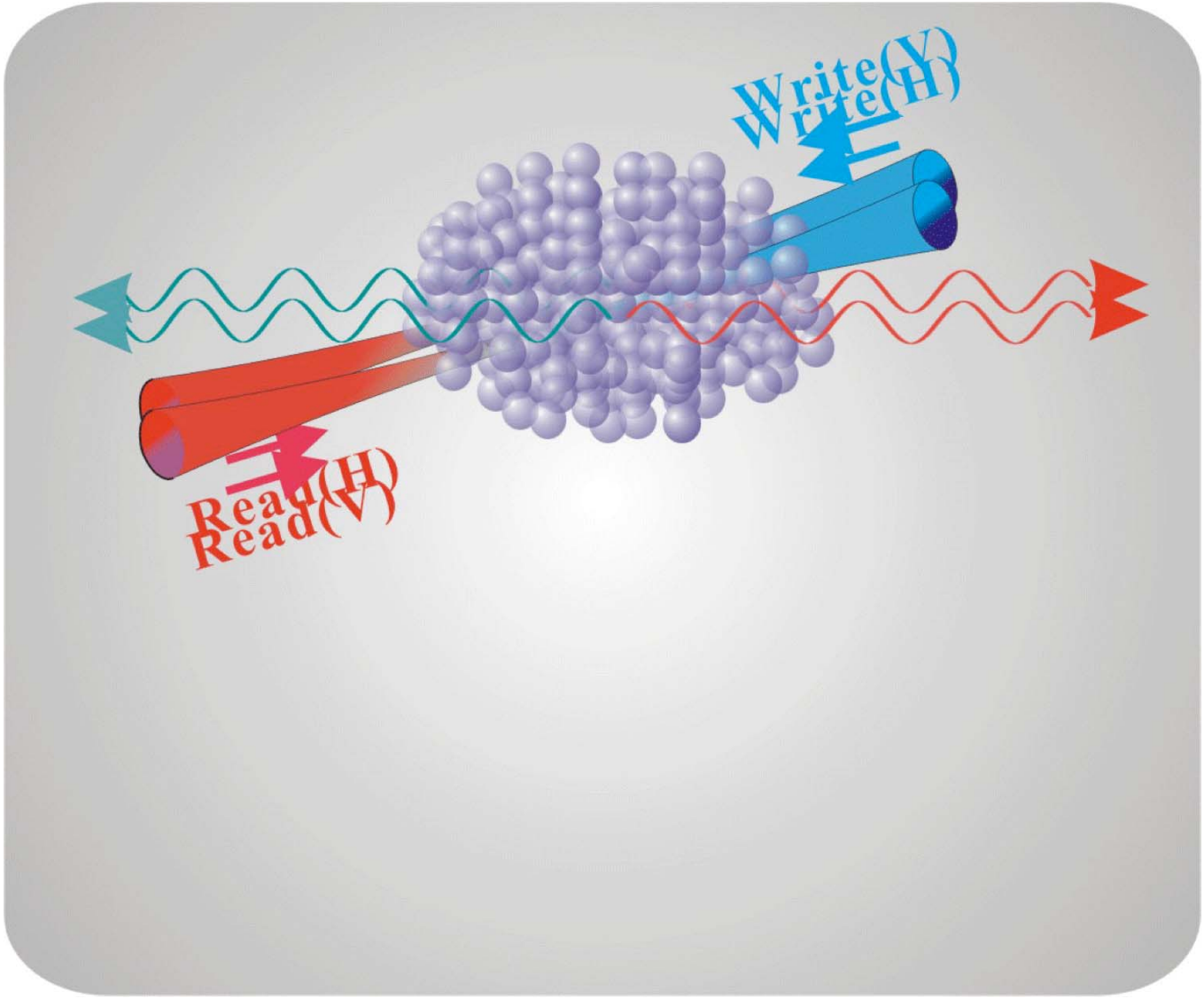
Memory-built-in Teleportation
Fidelities and Storage



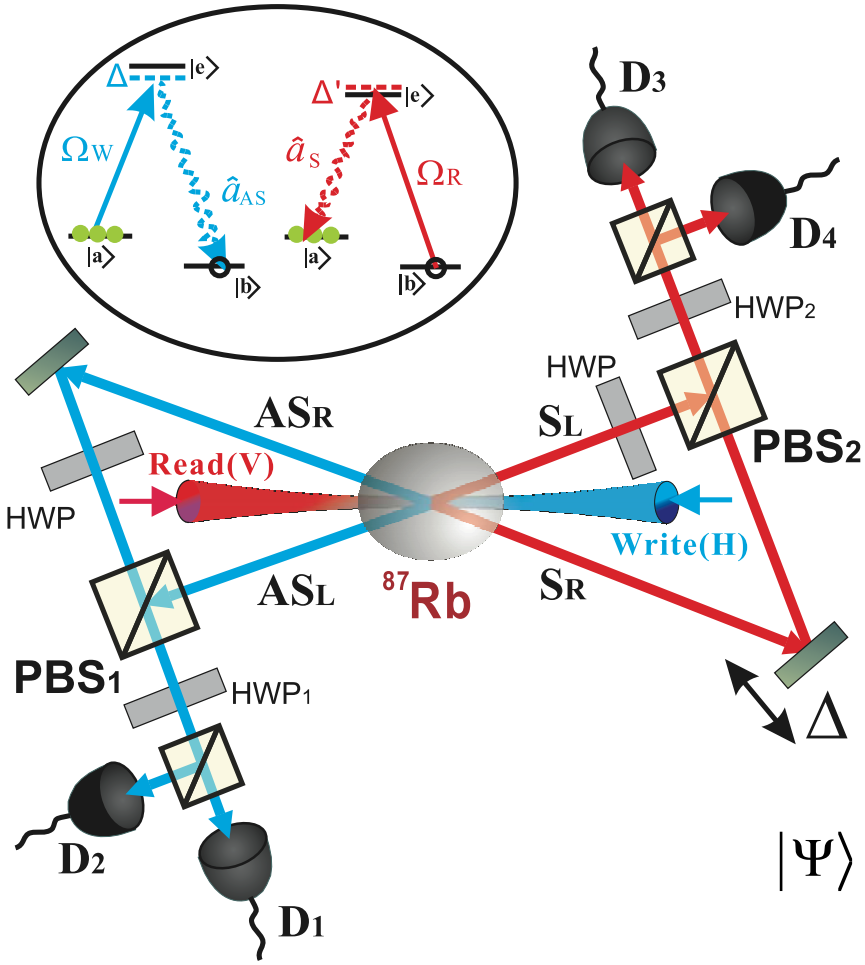
Original State	Fidelities
$\lvert H\rangle$	0.86 (2)
$\lvert +\rangle$	0.74 (1)
$\lvert R\rangle$	0.75 (1)

[Y.-A. Chen *et. al*, Nature Physics **4**, 103 (2008)]

A Novel Entanglement



A novel entanglement



Momentum conservation

$$\vec{k}_S = \vec{k}_R + \vec{k}_W - \vec{k}_{AS}.$$

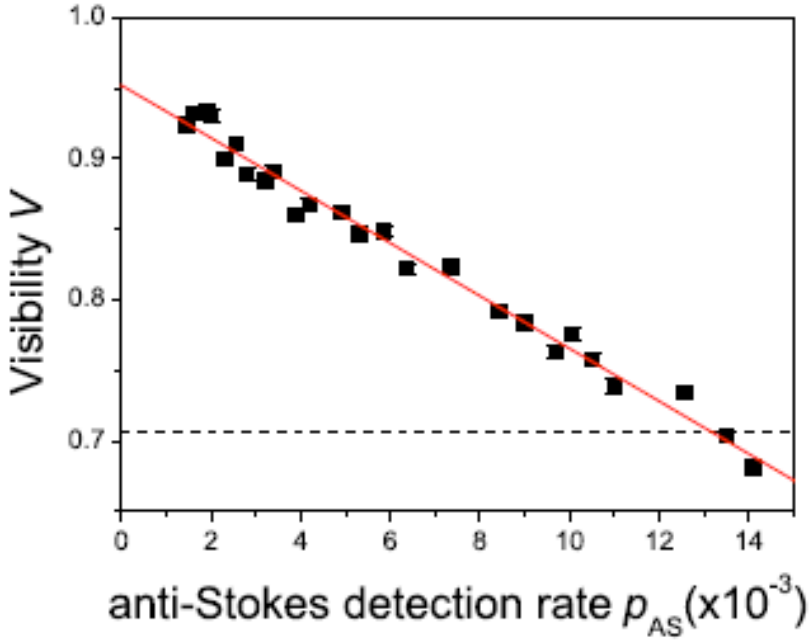
Entangled state

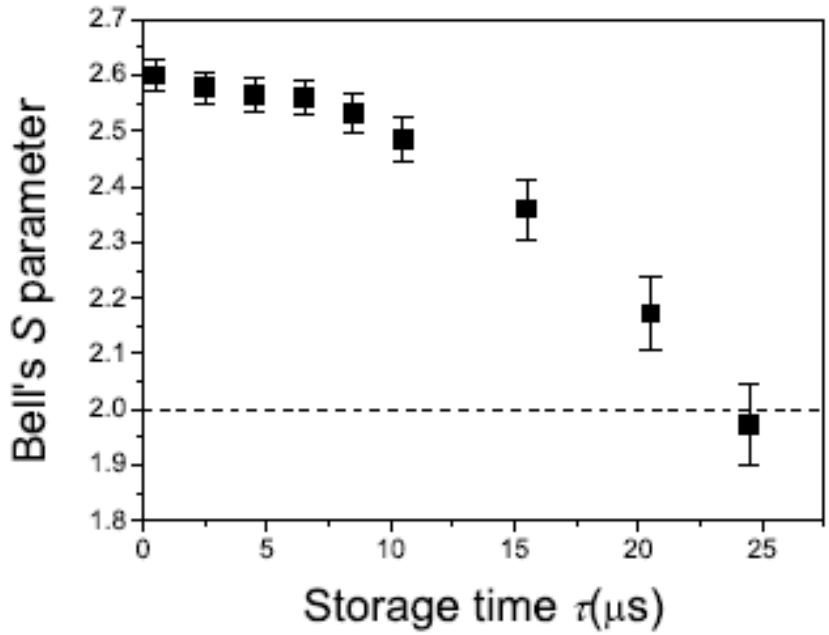
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|R\rangle + e^{i\phi_1}|V\rangle|L\rangle\right)$$

Entanglement verify

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_{AS}|H\rangle_S + e^{i(\phi_1+\phi_2)}|V\rangle_{AS}|V\rangle_S\right)$$

Characterization of the novel Atom-Photon entanglement source



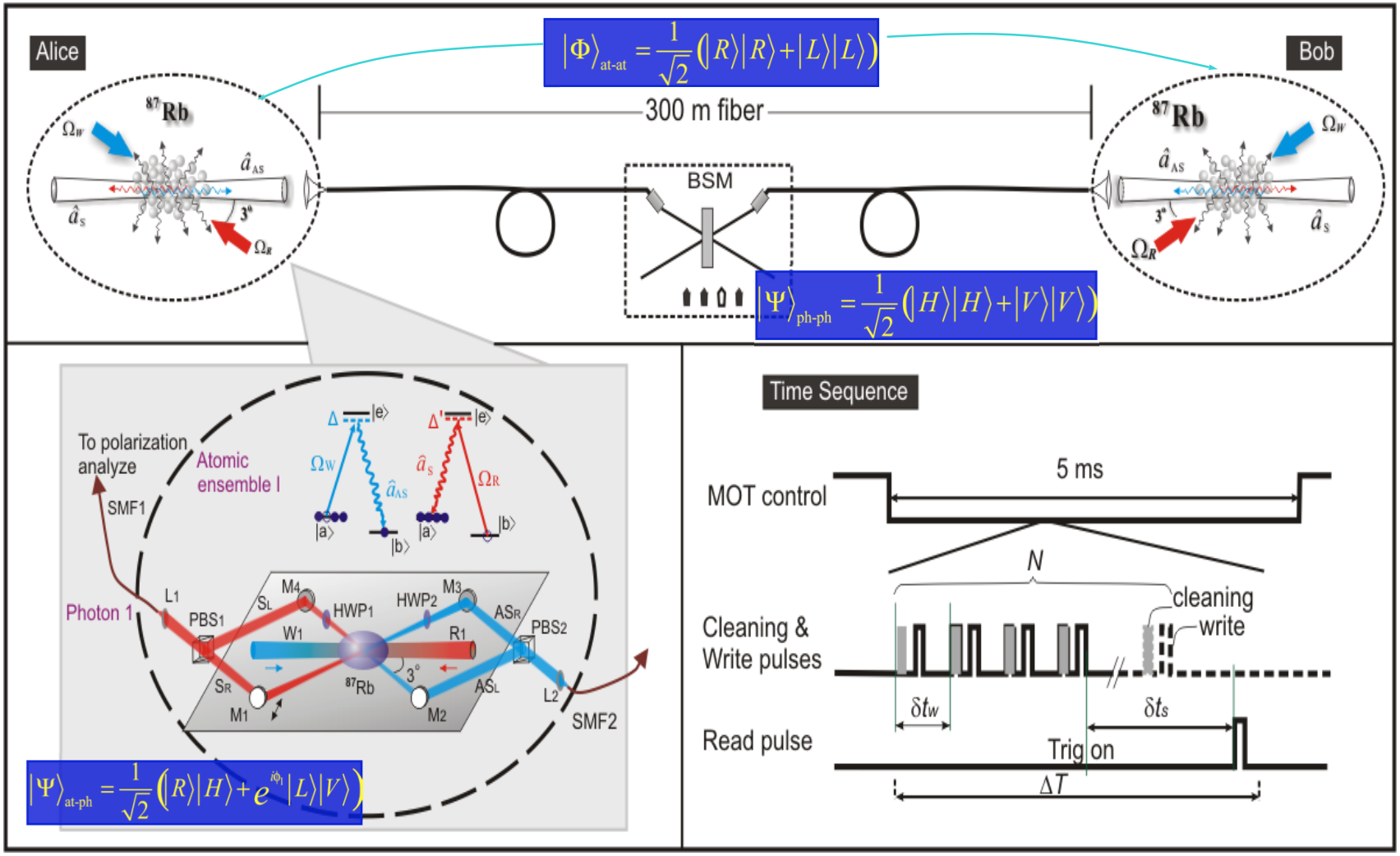


Visibility of the entanglement

entanglement storage

[S. Chen *et. al*, Phys. Rev. Lett **99**, 180505 (2007)]

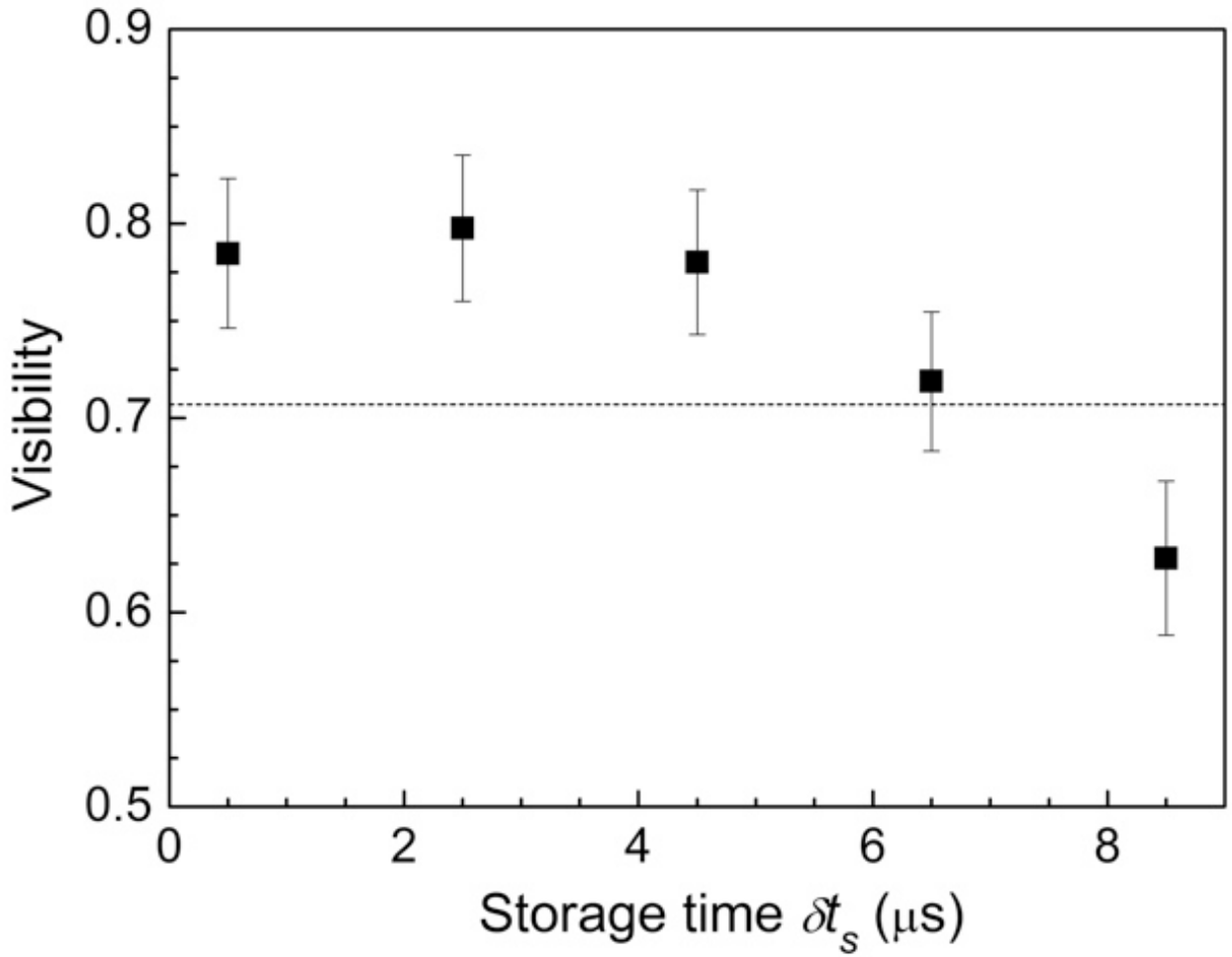
Entangling two Remote Atomic Qubits



Swapping result

Bell inequality in 500 ns

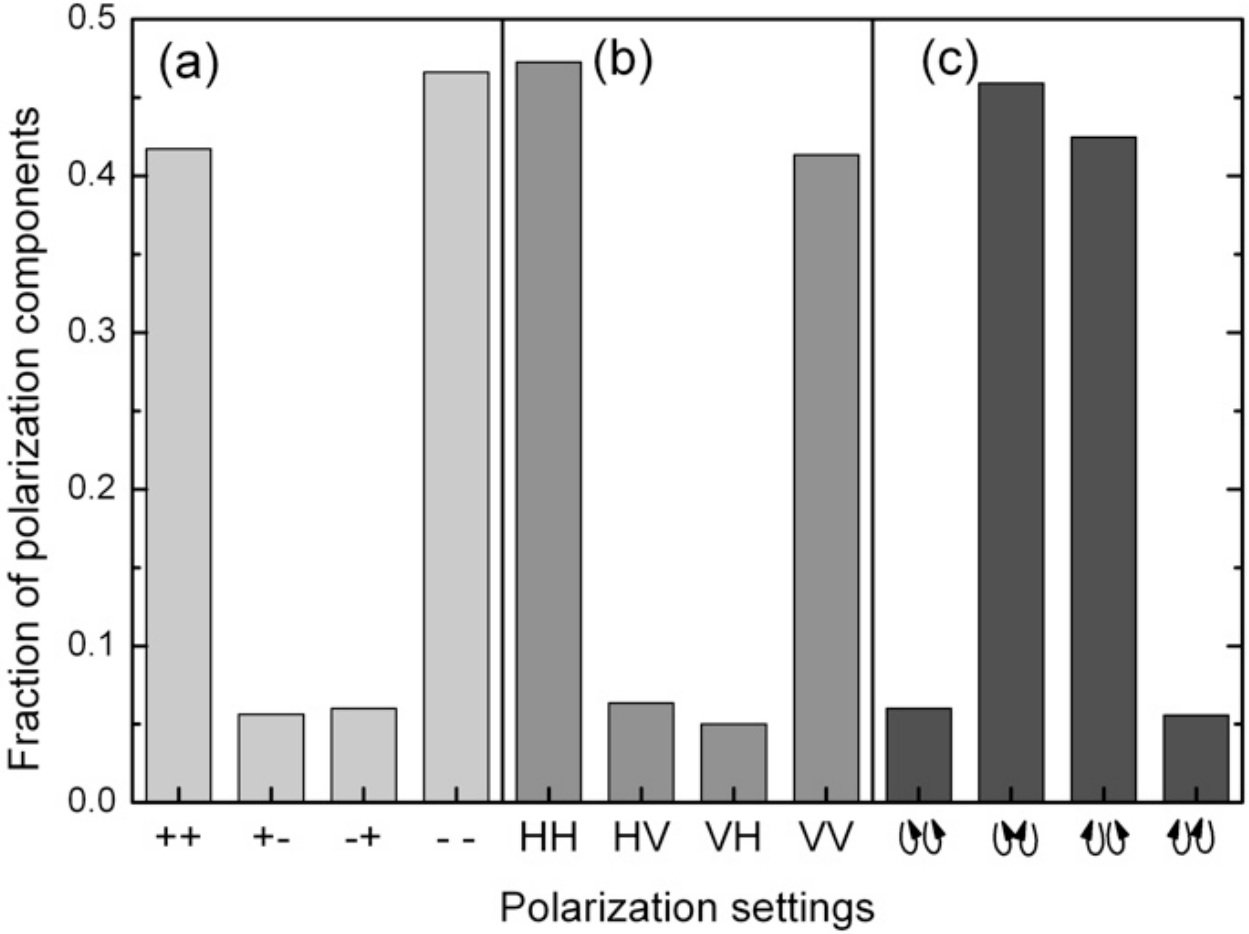
S=2.26±0.07



Entanglement generation via 300 m optical channel

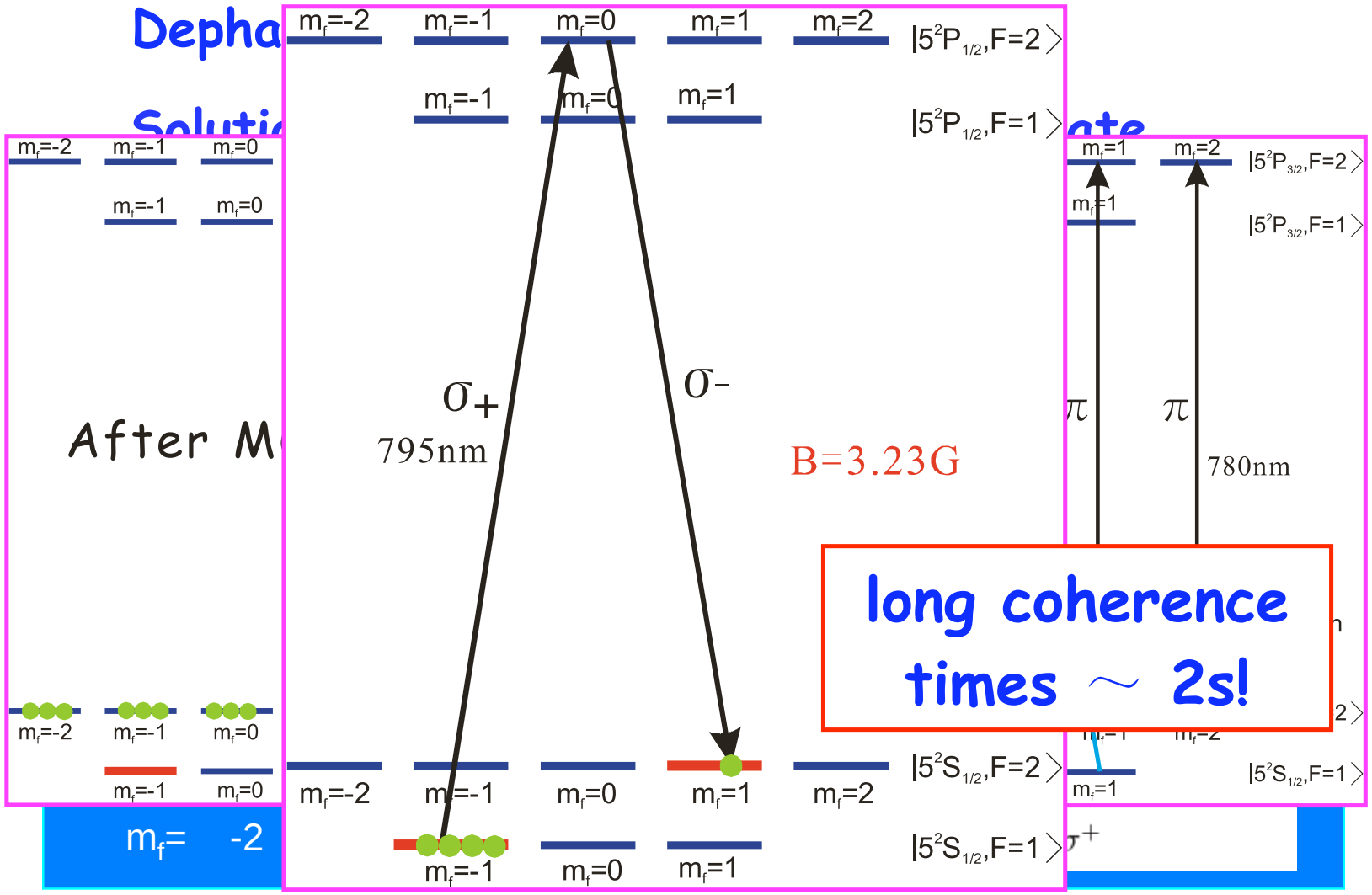
$$\langle W \rangle = -(0.33 \pm 0.02) < 0$$

$$F = Tr\left(\rho \left|\Phi^+\right\rangle_{I,II} \left\langle\Phi^+\right|\right) = 0.83 \pm 0.02$$



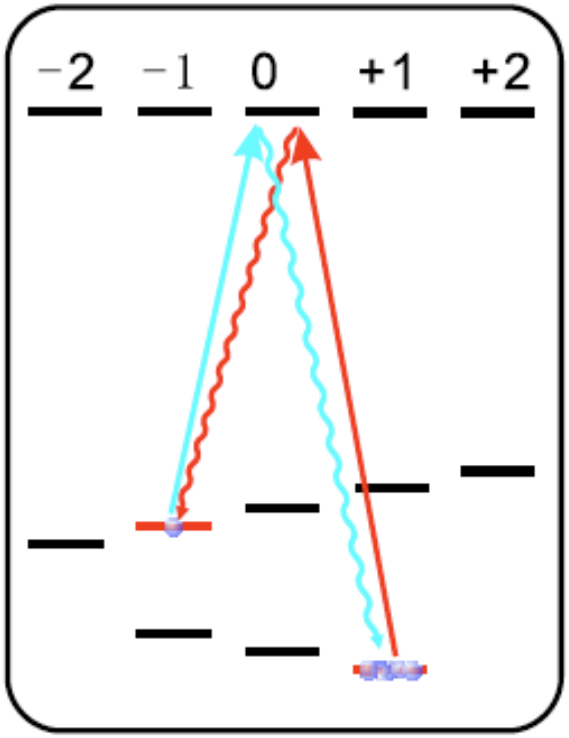
[Z.-S. Yuan *et al.*, Nature, under review (2008); preprint available at http://arxiv.org/abs/0803.1810]

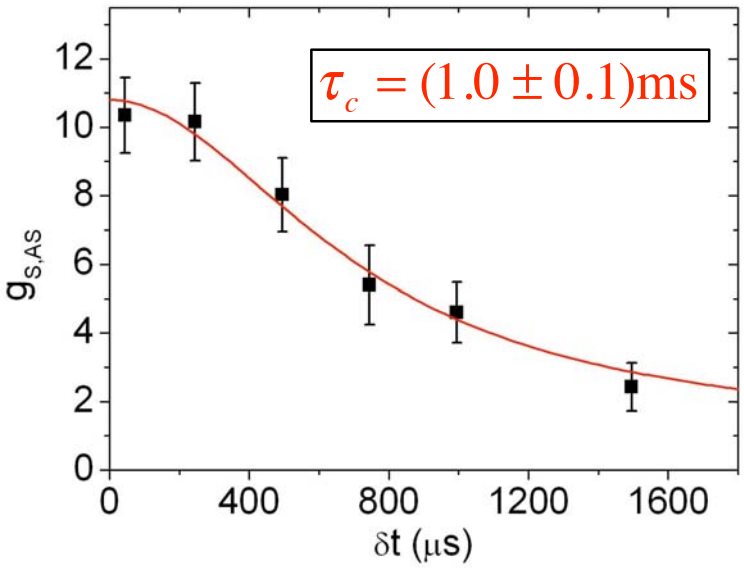
Extending the Lifetime by "Clock State"



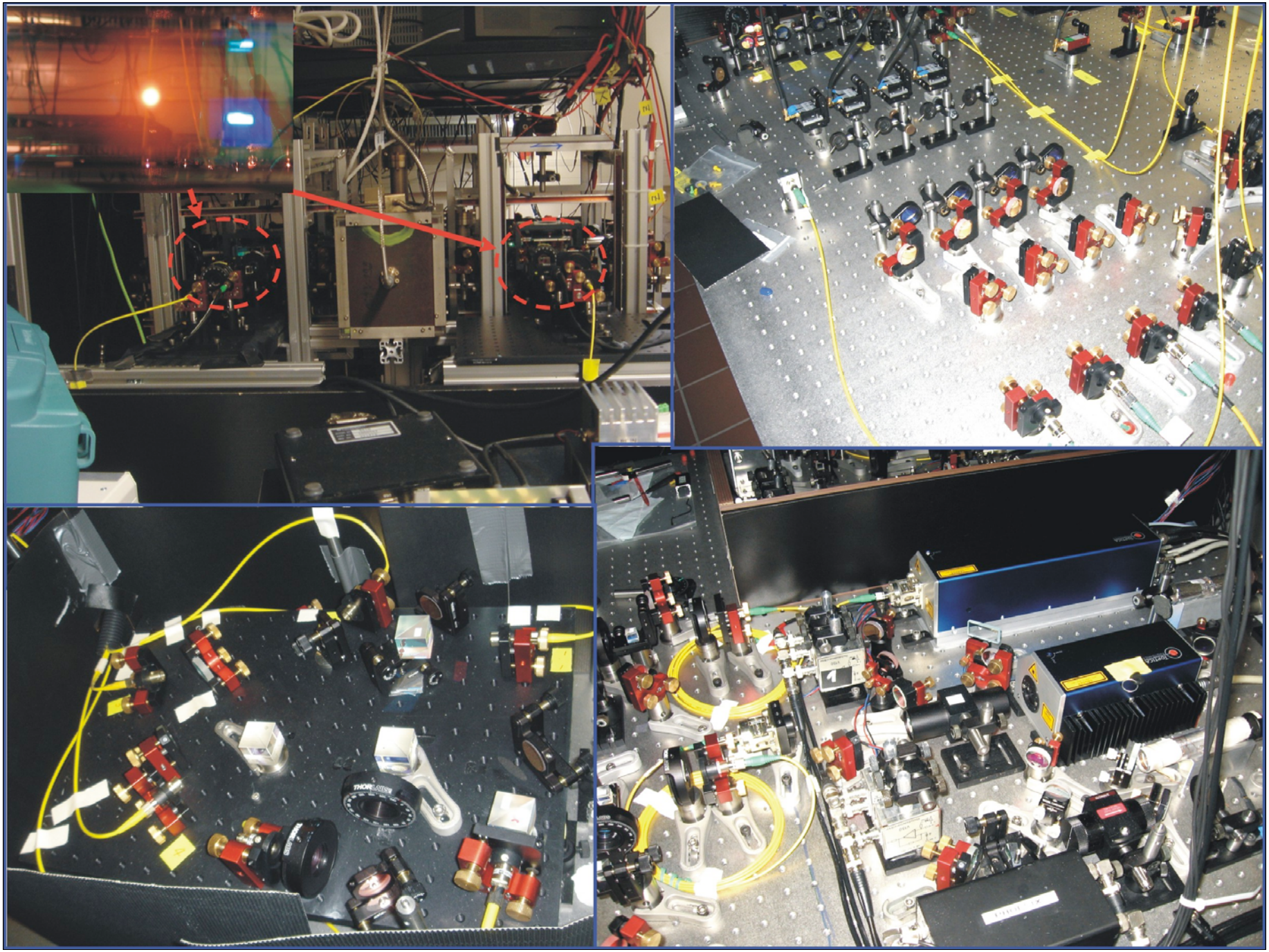
Extending the Lifetime by "Clock State"

- Lifetime limited by loss of atoms
- Even longer lifetime requires colder atoms





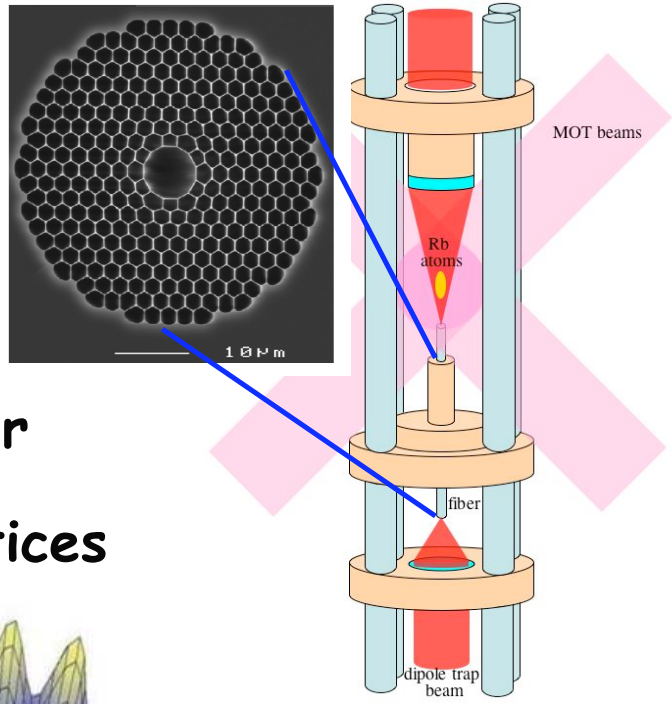
[B. Zhao *et al.*, Nature Physics, under review (2008)

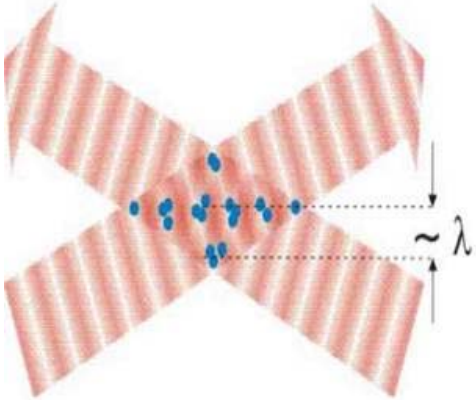

THORLABS

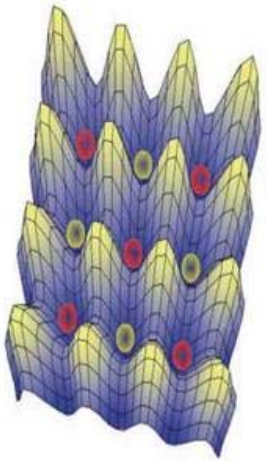
Outlook

1. Long lifetime high retrieve efficiency quantum memory

- $|m_f=-1,F=1\rangle$ & $|m_f=1,F=2\rangle$ 2s @ 3.23G
- Prevent atom motion
  - ➢ Trap atoms in photonic band gap hollow core fiber
  - ➢ Trap atoms in optical lattices

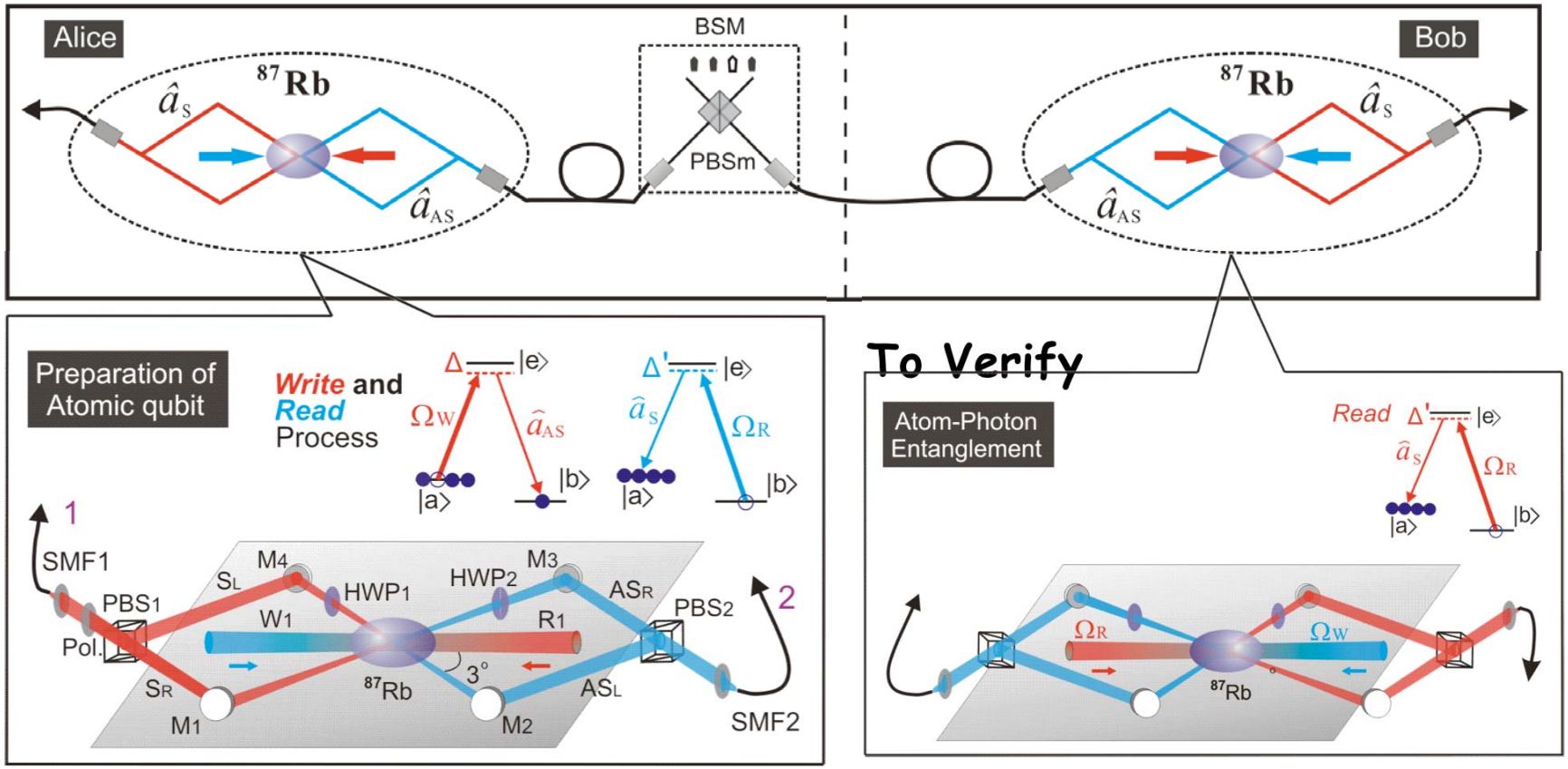






Outlook

2. long-distance quantum teleportation of atomic qubits

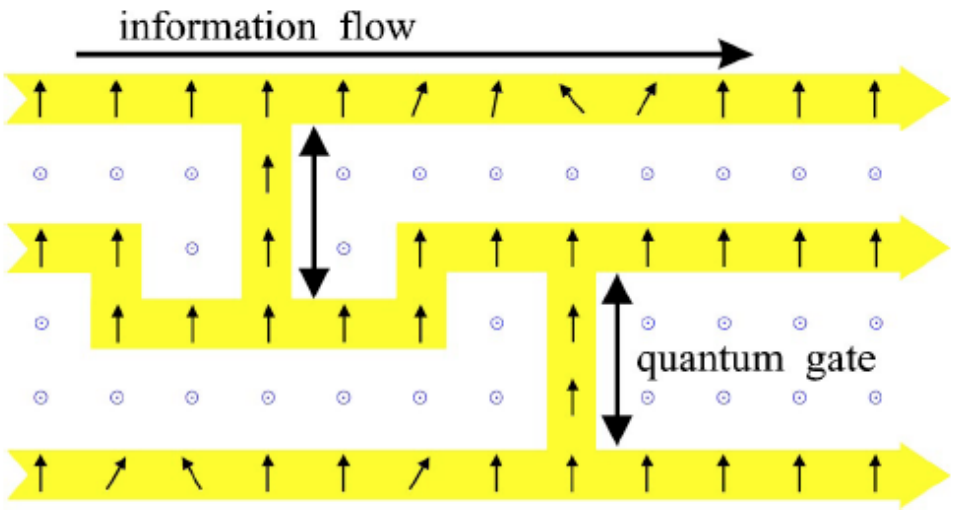


Deterministicly preparation of $\alpha|R\rangle+\beta|L\rangle$

Outlook

3. Quantum computation & quantum simulation

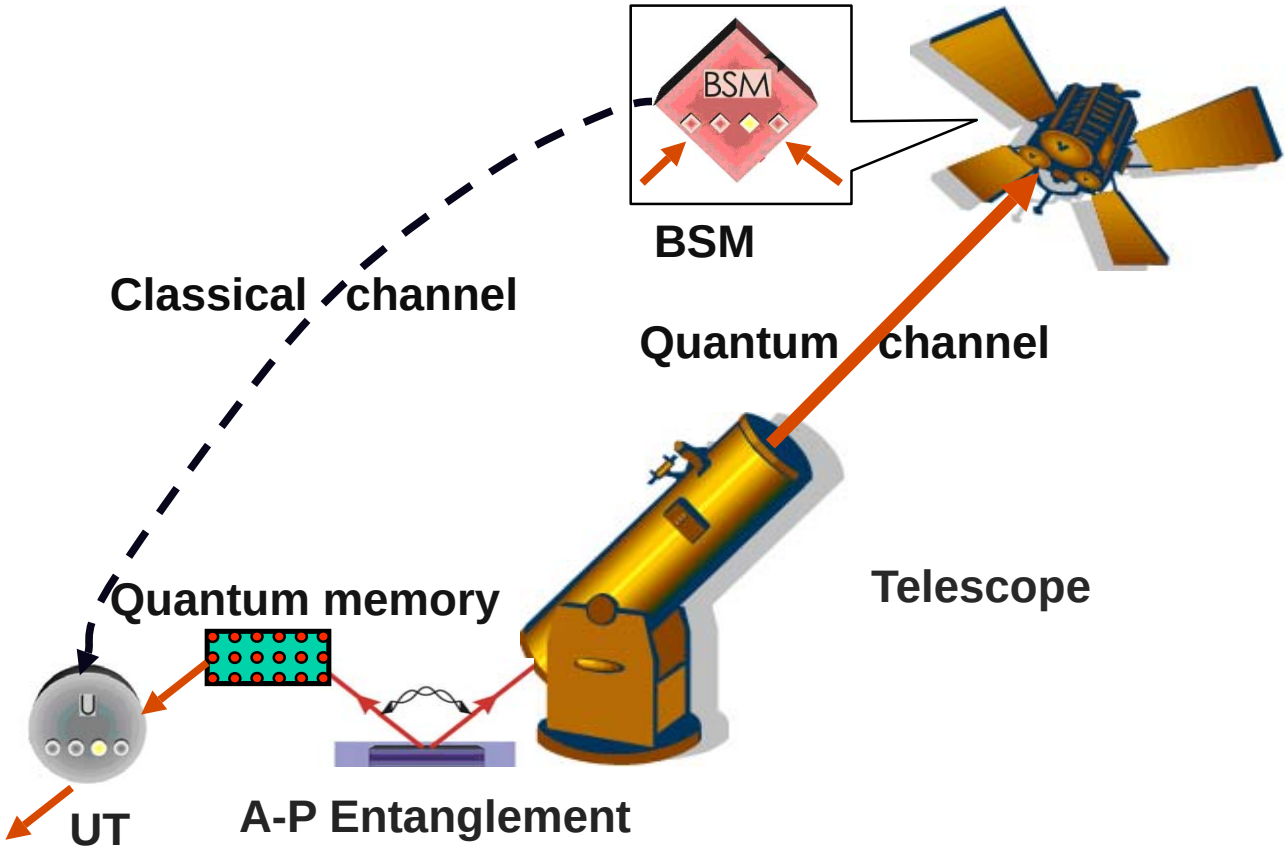
- Efficient and deterministic generation of single photons & entanglement via feedback circuit
- Generation of "cluster state"
- One-way quantum computing
- Quantum simulation



Outlook

4. satellite-based quantum communication

- Quantum teleportation



|Photons> + |Atoms>

Powerful Quantum Superposition

Brilliant Future in Quantum Communication!