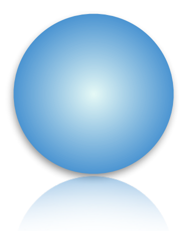
Seminar at Korea University

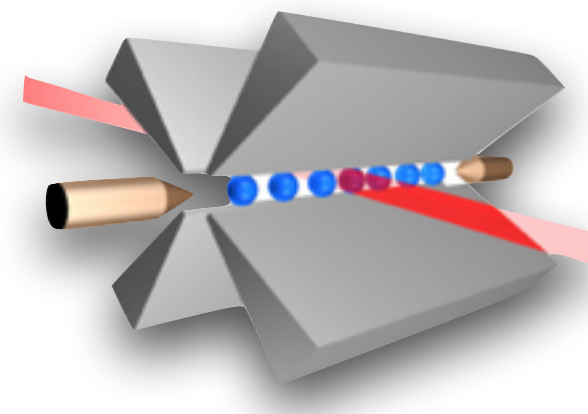
Generation of Entangled Photons and Quantum Memories of Photons in Cold Atoms

Kwang-Kyoon Park

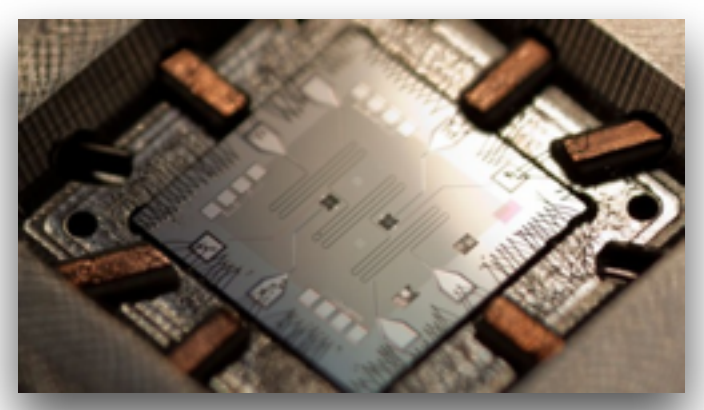
Candidates of physical systems for *quantum information processing* are



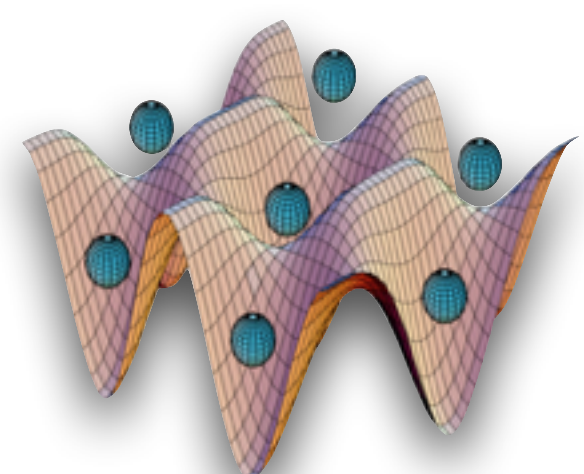
photon



ion trap



superconductor

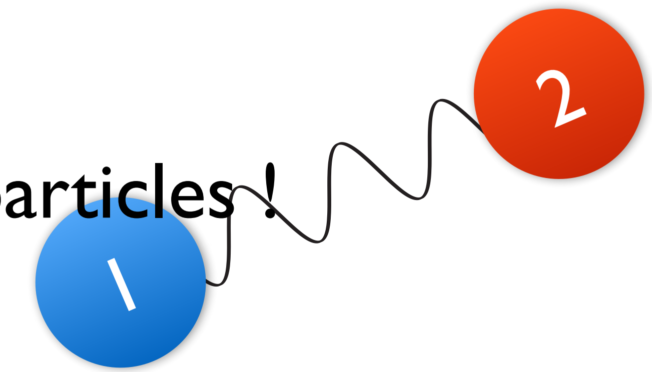


neutral atoms

Entangled Photons

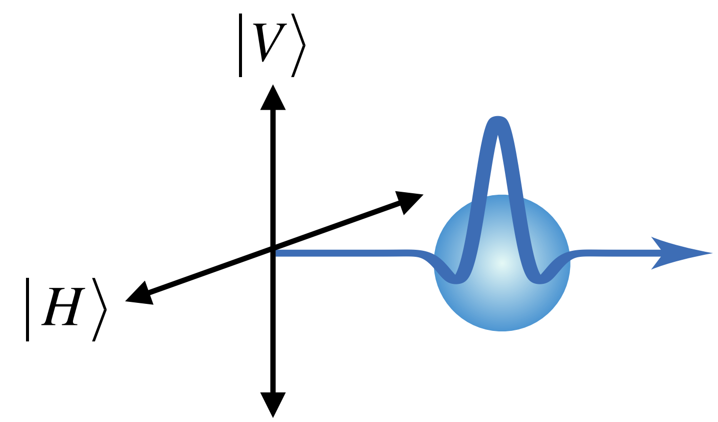
Entangled photons are

Let's consider *only* two particles !



- Discrete variable (e. g. polarization)

$$|\psi\rangle_{total} = \frac{1}{\sqrt{2}}\left(|H\rangle_1 |H\rangle_2 + |V\rangle_1 |V\rangle_2\right)$$



Each particle cannot be fully described without considering the other.
A quantum state is given for the system *as a whole*.

Definition of entanglement is

$$|\psi\rangle_{total} \neq |\psi\rangle_1 \otimes |\psi\rangle_2$$

Entangled photons are

- Continuous variable (e. g. frequency-time)

$$|\psi\rangle_{total} = \int d\omega_1\, d\omega_2 \delta(\omega_0 - \omega_1 - \omega_2)\hat{a}^{\dagger}(\omega_1)\hat{b}^{\dagger}(\omega_2)|0\rangle$$

$$= \int dt_1\, dt_2 \delta(t_2 - t_1)\hat{A}^{\dagger}(t_1)\hat{B}^{\dagger}(t_2)|0\rangle$$

Criterion for entanglement

$$[\Delta(\omega_1 + \omega_2)]^2[\Delta(t_1 - t_2)]^2 \ngeq 1$$

$$\Delta p_i \Delta x_i \geq \hbar / 2$$

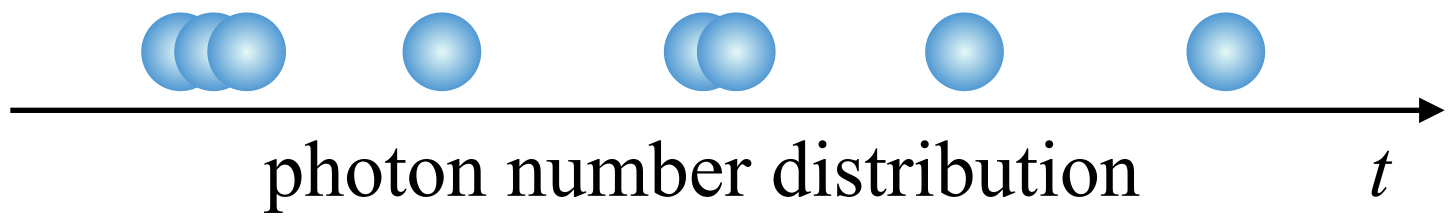
each particle $\Delta\omega_i \Delta t_i \geq 1/2$

for separable states

$$[\Delta(\omega_1 + \omega_2)]^2[\Delta(t_1 - t_2)]^2 \geq 1$$

Classical lights are

Let’s first consider a single mode.



Classical lights

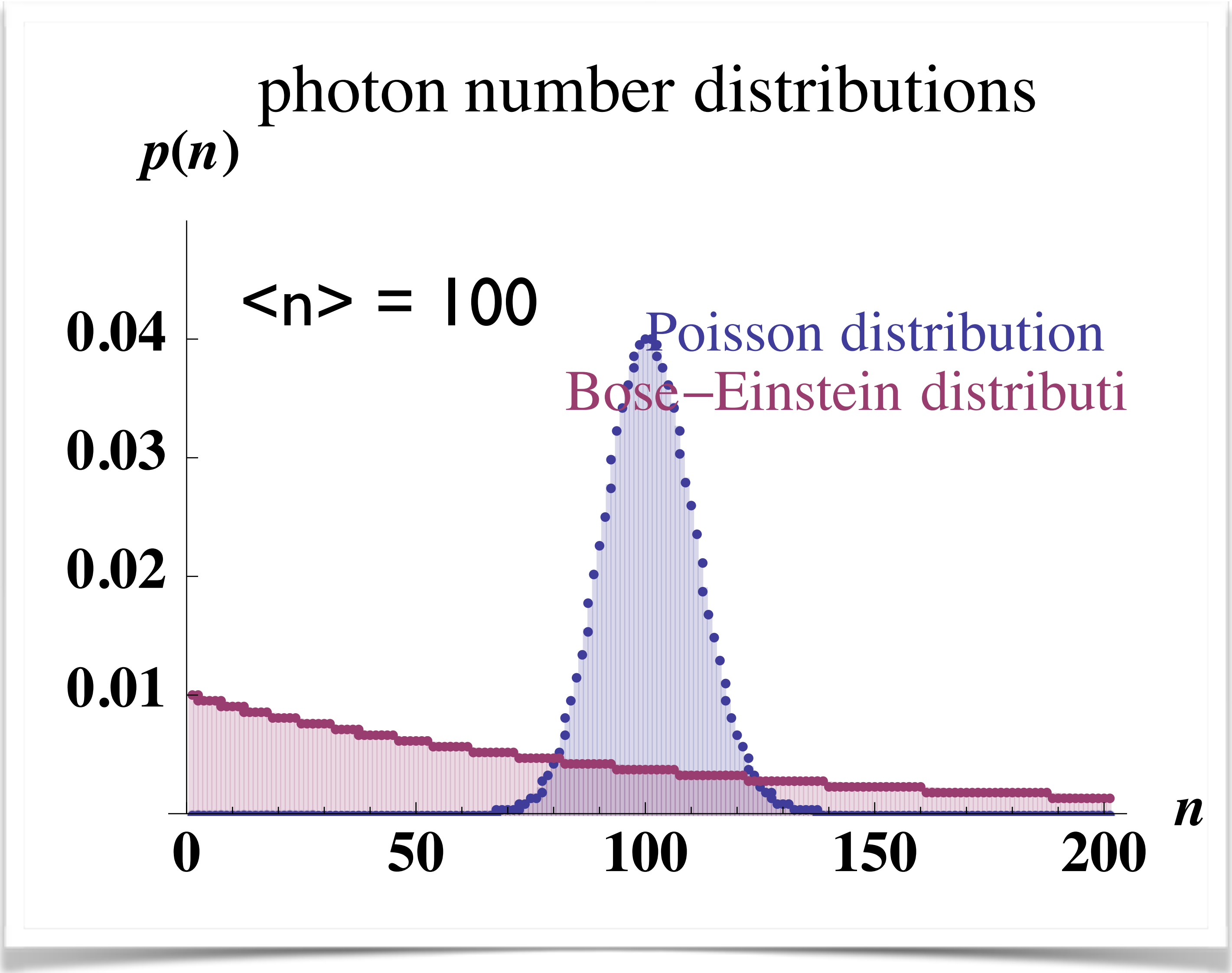
- laser

random

- thermal

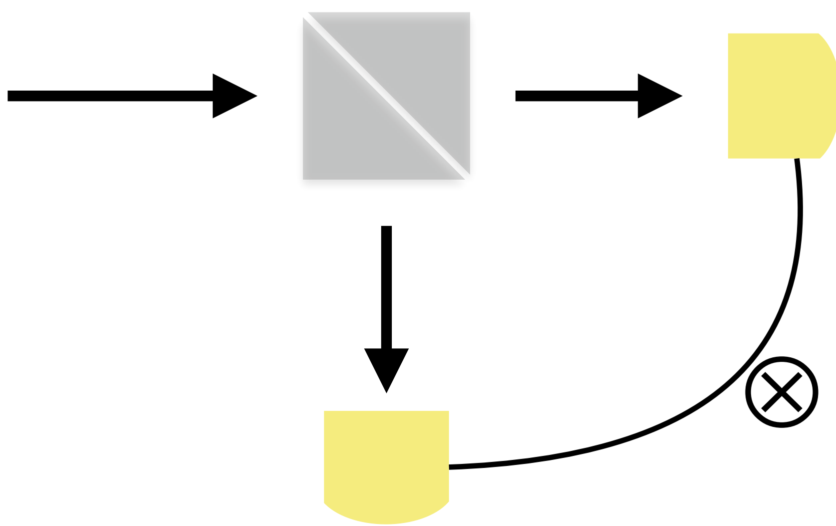
bunched

Classical lights are

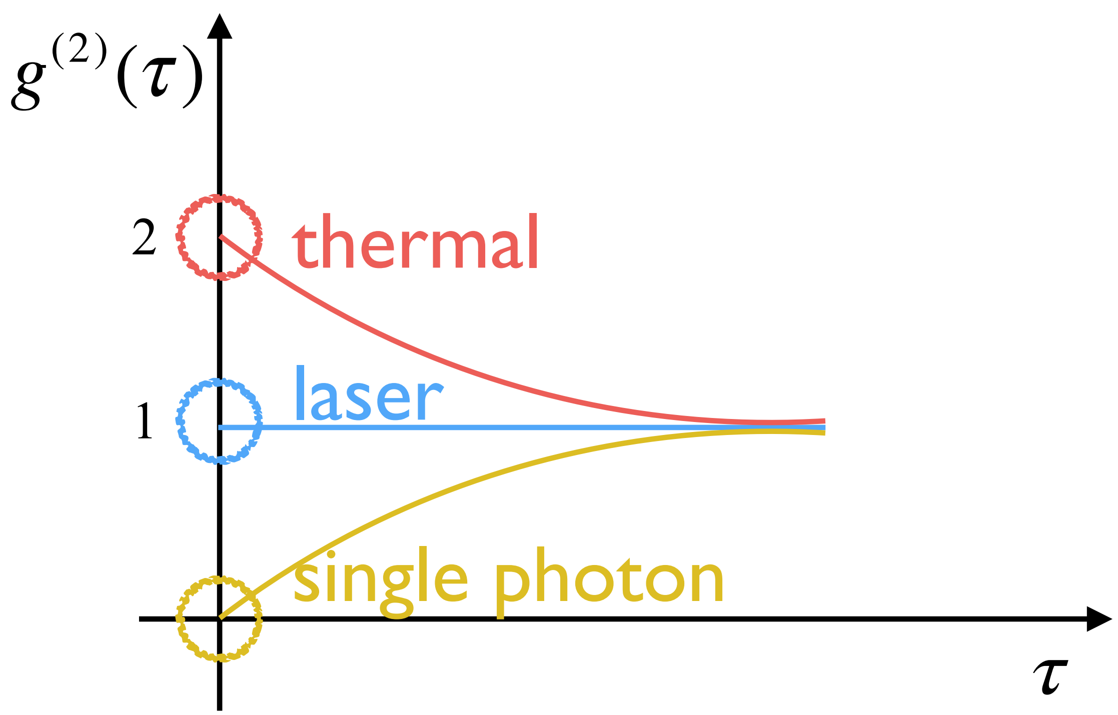


- laser
  - random
  - Poissonian
  - $(\Delta n)^2 = \langle n \rangle$
- thermal
  - bunched
  - super-Poissonian
  - $(\Delta n)^2 > \langle n \rangle$

Hanbury-Brown-Twiss interferometer is used for $g^{(2)}$ measurement.

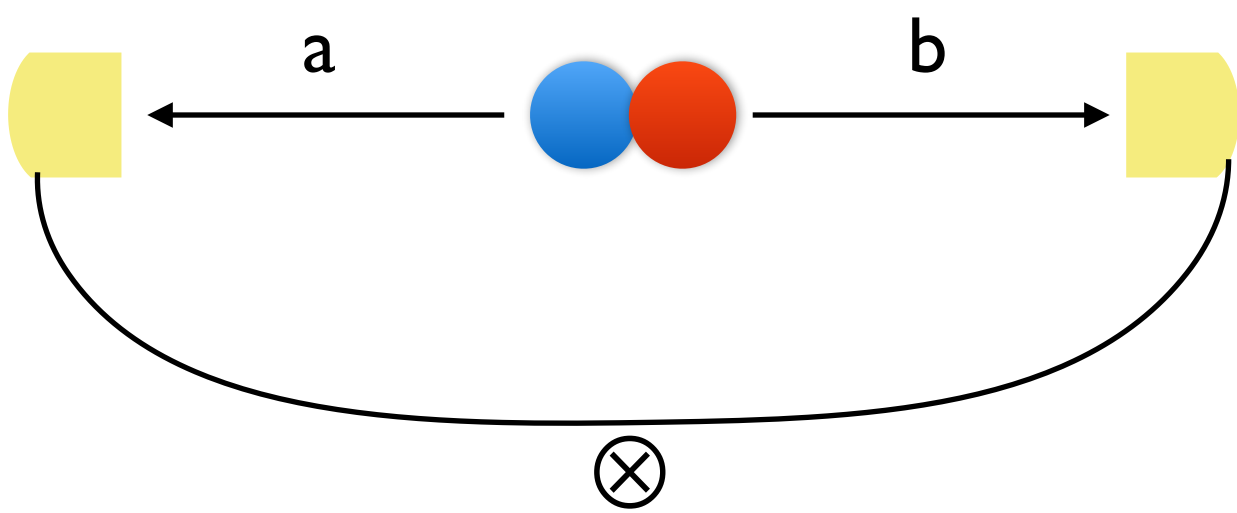


$$g^{(2)}(\tau) = \frac{\left\langle \hat{a}^\dagger(0)\hat{a}^\dagger(\tau)\hat{a}(\tau)\hat{a}(0) \right\rangle}{\left\langle \hat{a}^\dagger \hat{a} \right\rangle^2}$$



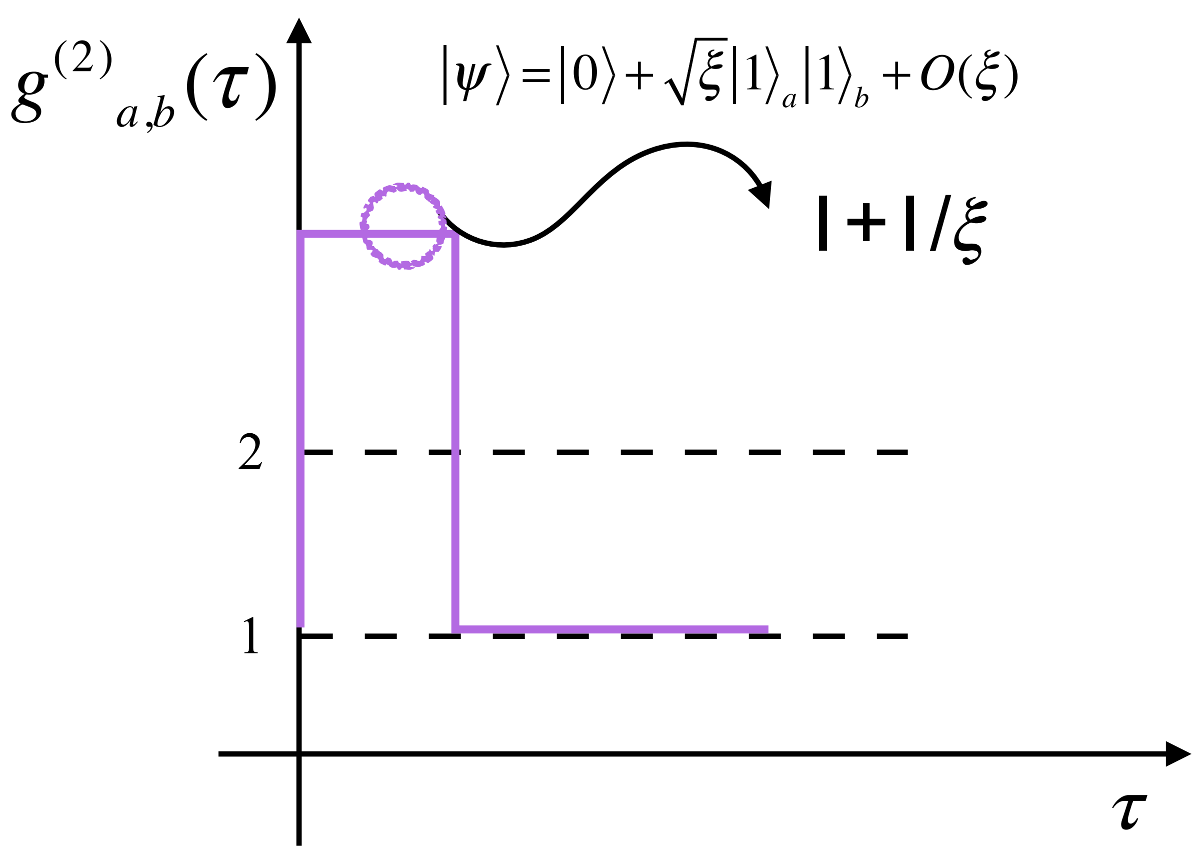
$g^{(2)}(0) \geq 1$ for classical lights

For two modes,



for classical lights

$$R = \frac{[g^{(2)}{}_{a,b}(\tau)]^2}{g^{(2)}{}_{a,a}(0)g^{(2)}{}_{b,b}(0)} \leq 1$$

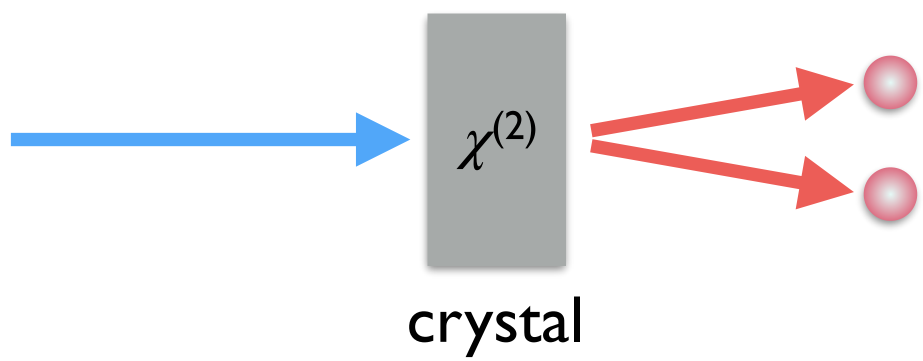


- Two-mode squeezed state is generated via a parametric process where each photon is thermal, but the pair shows strong non-classical correlation.

Kuzmich, A. et al. Generation of nonclassical photon pairs for scalable quantum communication with atomic ensembles. Nature 423, 731–734 (2003).

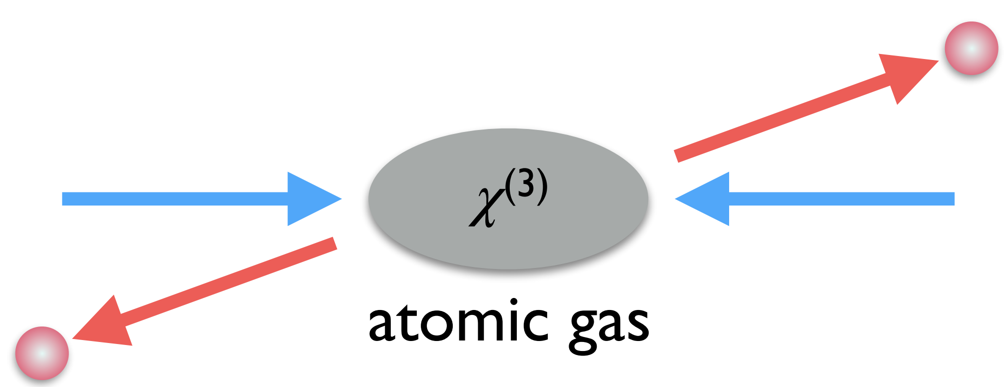
Two well-known *parametric* processes are

- Spontaneous Parametric Down Conversion



three photon process

- Spontaneous Four Wave Mixing (SFWM)



four photon process

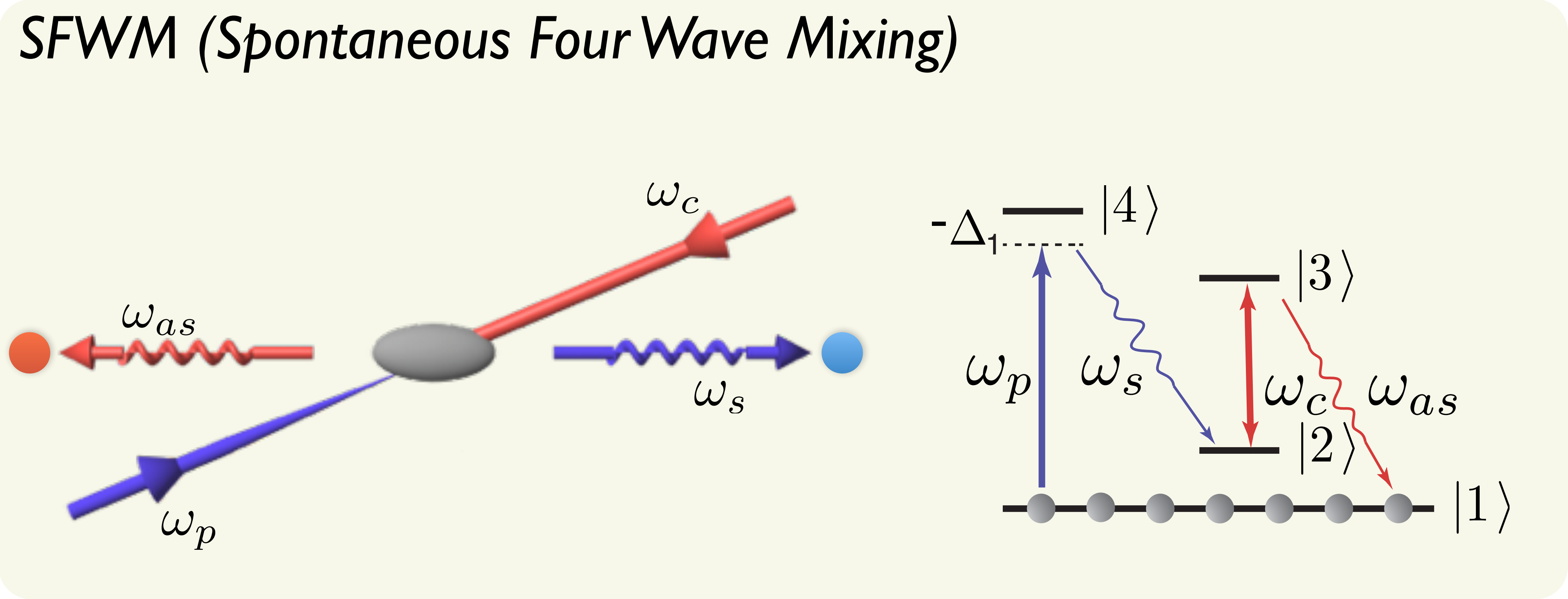
Advantages of SFWM in cold atoms are

- *Narrow* spectral bandwidth (efficient atom-photon interaction)
  - Photons can be stored in a quantum memory based on atoms.
  - Photon-photon interaction can be mediated in atoms.

- *Long* coherence time
  - Time resolvable wave-function.
  - Good for long-distance quantum communication.

Cho, Y.-W., Park, K.-K., Lee, J.-C. & Kim, Y.-H. Generation of nonclassical narrowband photon pairs from a cold rubidium cloud. J. Korean Phys. Soc. 63, 943 (2013).
Du, S., Wen, J. & Rubin, M. H. Narrowband biphoton generation near atomic resonance. J. Opt. Soc. Am. B 25, C98–C108 (2008).

Theory for photon pair generation is



$$\hat{H}_I = \frac{\epsilon_0 A}{4}\int_{-L/2}^{L/2} dz\, \chi^{(3)} E_p^{(+)} E_c^{(+)} \hat{E}_s^{(-)} \hat{E}_{as}^{(-)} + h.c.$$

where

$$E_p^{(+)}(z,t) = E_p\, e^{i(k_p z - \omega_p t)}$$

$$E_c^{(+)}(z,t) = E_c\, e^{i(-k_c z - \omega_c t)}$$

$$\hat{E}_s^{(-)}(z,t) = \int d\omega_s\, \mathcal{E}_s\, \hat{a}_s^{\dagger}(\omega_s) e^{-i(k_s z - \omega_s t)}$$

$$\hat{E}_{as}^{(-)}(z,t) = \int d\omega_{as}\, \mathcal{E}_{as}\, \hat{a}_{as}^{\dagger}(\omega_{as}) e^{-i(-k_{as} z - \omega_{as} t)}$$

$$\mathcal{E}_j = \sqrt{\frac{\hbar\omega_j}{\pi c \epsilon_0 A}}$$

Cho, Y.-W., Park, K.-K., Lee, J.-C. & Kim, Y.-H. Generation of nonclassical narrowband photon pairs from a cold rubidium cloud. J. Korean Phys. Soc. 63, 943 (2013).
Du, S., Wen, J. & Rubin, M. H. Narrowband biphoton generation near atomic resonance. J. Opt. Soc. Am. B 25, C98–C108 (2008).

Theory for photon pair generation is

$$U|0\rangle = \exp\left(-\frac{i}{\hbar}\int dt\,\hat{H}_I\right)|0\rangle$$

$$=|0\rangle - \frac{i}{\hbar}\int dt\,\hat{H}_I|0\rangle + \dots$$

$$|\psi\rangle = -\frac{i}{\hbar}\int dt\,\hat{H}_I|0\rangle$$

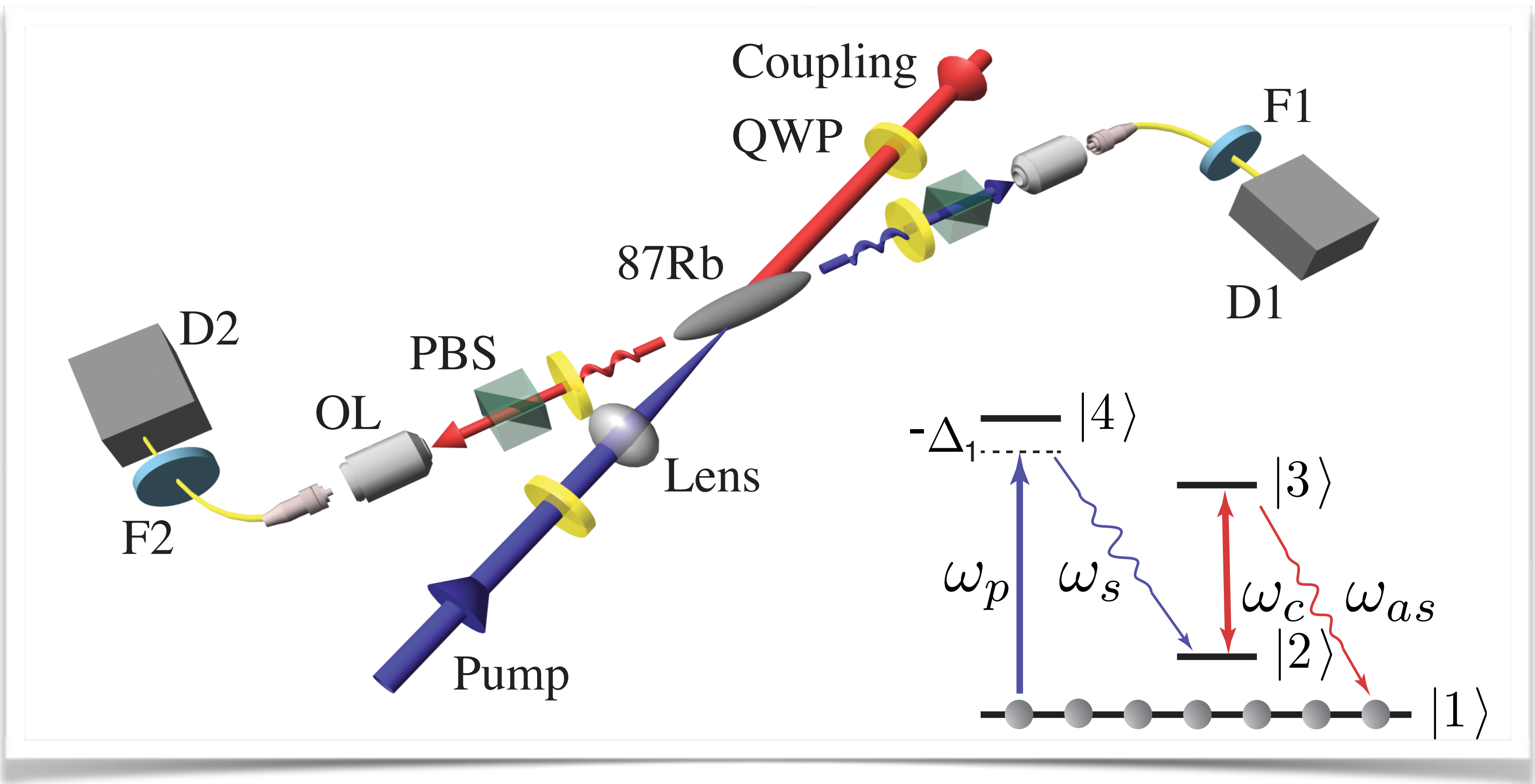
$$\Delta k = k_p - k_c - k_s + k_{as}$$

$$= C\int d\omega_{as}\chi^{(3)}\mathrm{sinc}\left(\frac{\Delta k L}{2}\right)\times \hat{a}_s^\dagger(\omega_p+\omega_c-\omega_{as})\hat{a}_{as}^\dagger(\omega_{as})|0\rangle$$

frequency anti-correlated,
further frequency-time entangled.

Cho, Y.-W., Park, K.-K., Lee, J.-C. & Kim, Y.-H. Generation of nonclassical narrowband photon pairs from a cold rubidium cloud. J. Korean Phys. Soc. 63, 943 (2013).
Du, S., Wen, J. & Rubin, M. H. Narrowband biphoton generation near atomic resonance. J. Opt. Soc. Am. B 25, C98–C108 (2008).

Experimental setup is



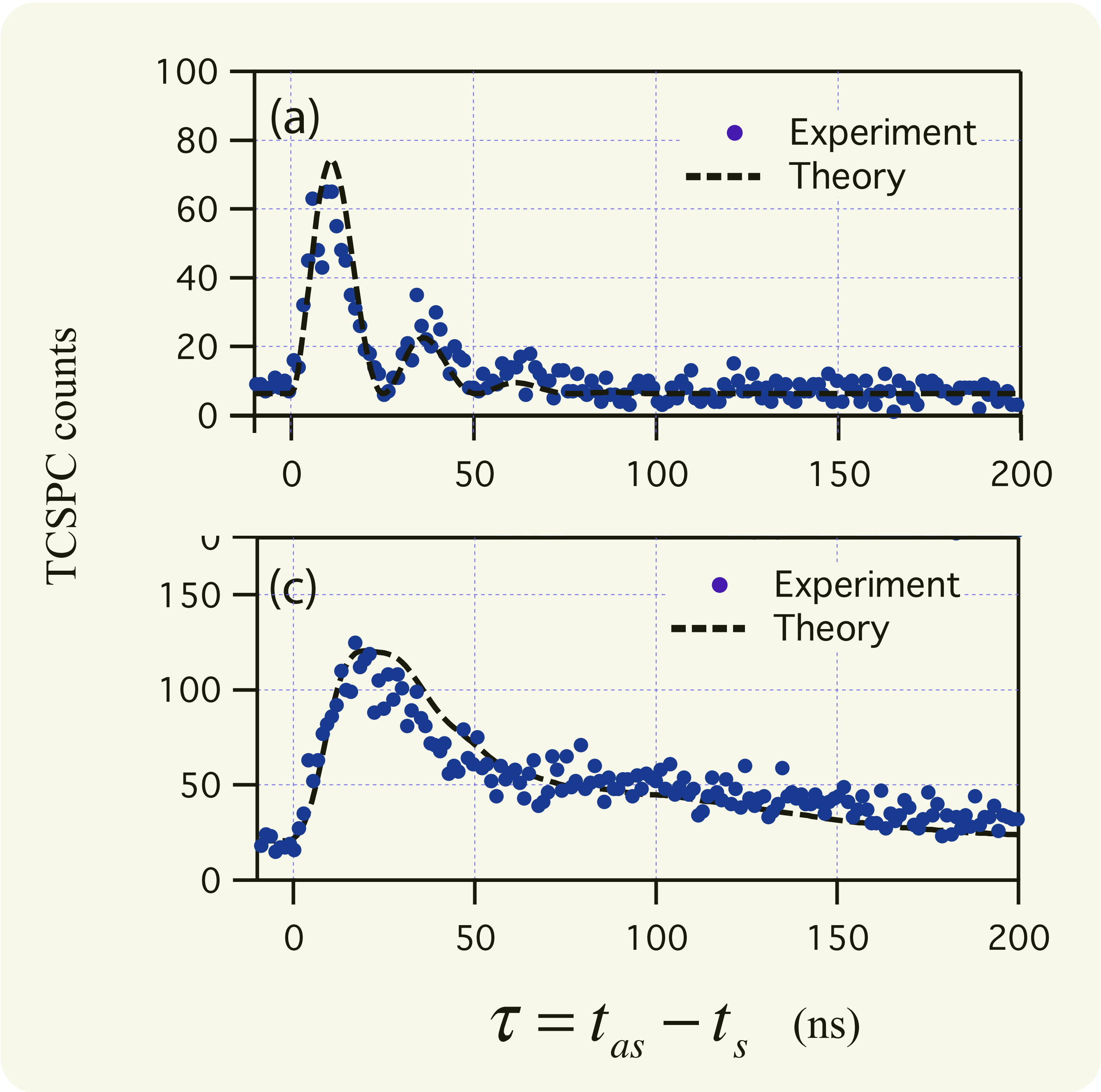
Rb cold atoms

$$|1\rangle \equiv |5S_{1/2}(F=1)\rangle$$
$$|2\rangle \equiv |5S_{1/2}(F=2)\rangle$$
$$|3\rangle \equiv |5P_{1/2}(F'=2)\rangle$$
$$|4\rangle \equiv |5P_{3/2}(F'=2)\rangle$$

Cho, Y.-W., Park, K.-K., Lee, J.-C. & Kim, Y.-H. Generation of nonclassical narrowband photon pairs from a cold rubidium cloud. J. Korean Phys. Soc. 63, 943 (2013).

Measured $g^{(2)}$ violated the inequality, confirming its *non-classical* feature.

$$\mathcal{R} = \frac{\left[g^{(2)}_{s,as}(\tau)\right]^2}{g^{(2)}_{s,s}(0)\, g^{(2)}_{as,as}(0)} \leq 1$$



25±7

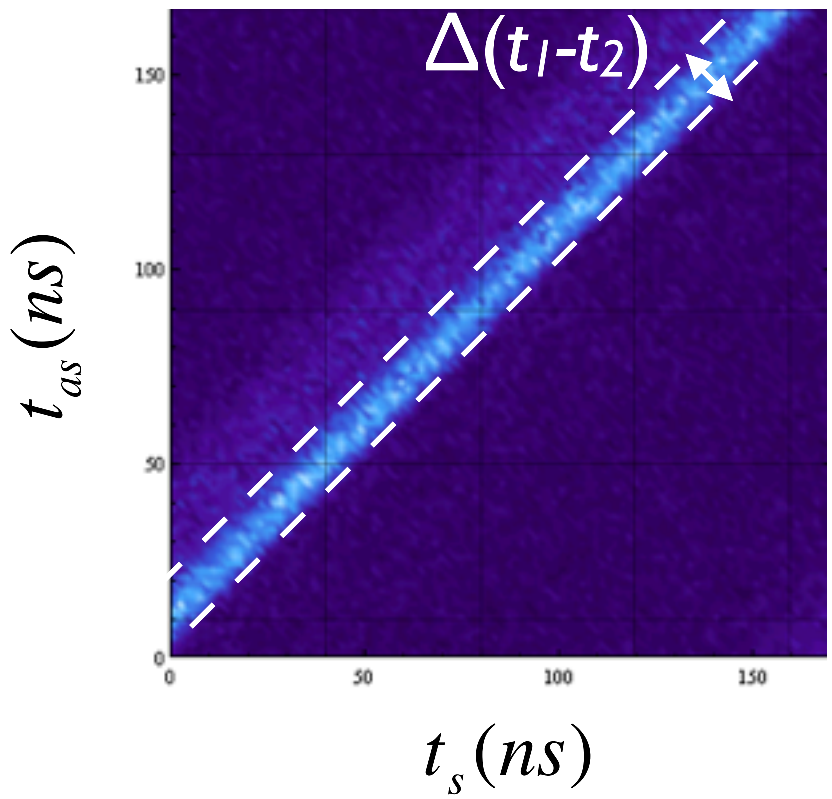
9±2

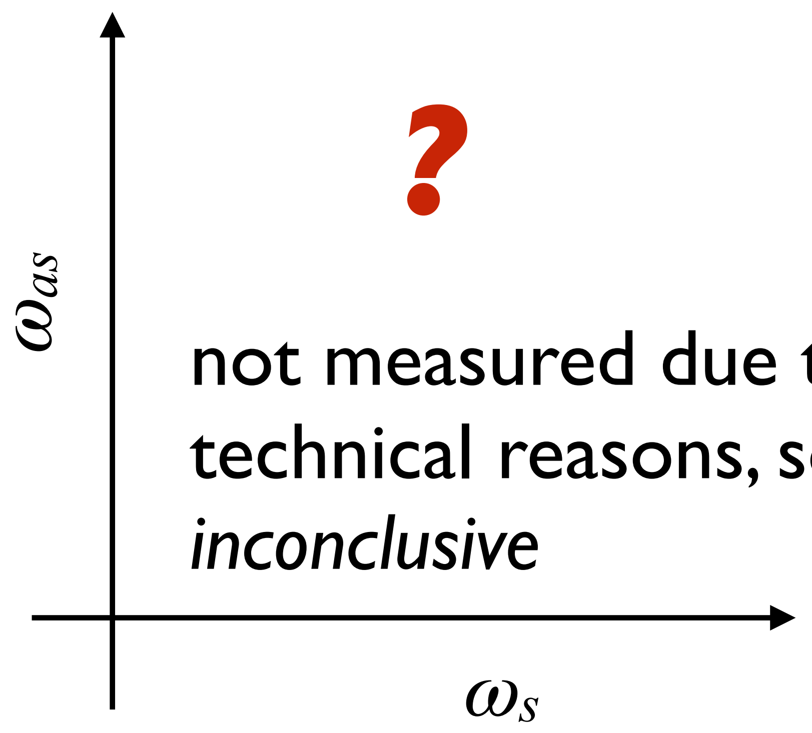
Cho, Y.-W., Park, K.-K., Lee, J.-C. & Kim, Y.-H. Generation of nonclassical narrowband photon pairs from a cold rubidium cloud. J. Korean Phys. Soc. 63, 943 (2013).

Verification of frequency-time entanglement is *inconclusive*.

Criterion for entanglement

$$[\Delta(\omega_1+\omega_2)]^2[\Delta(t_1-t_2)]^2 \ngeq 1$$

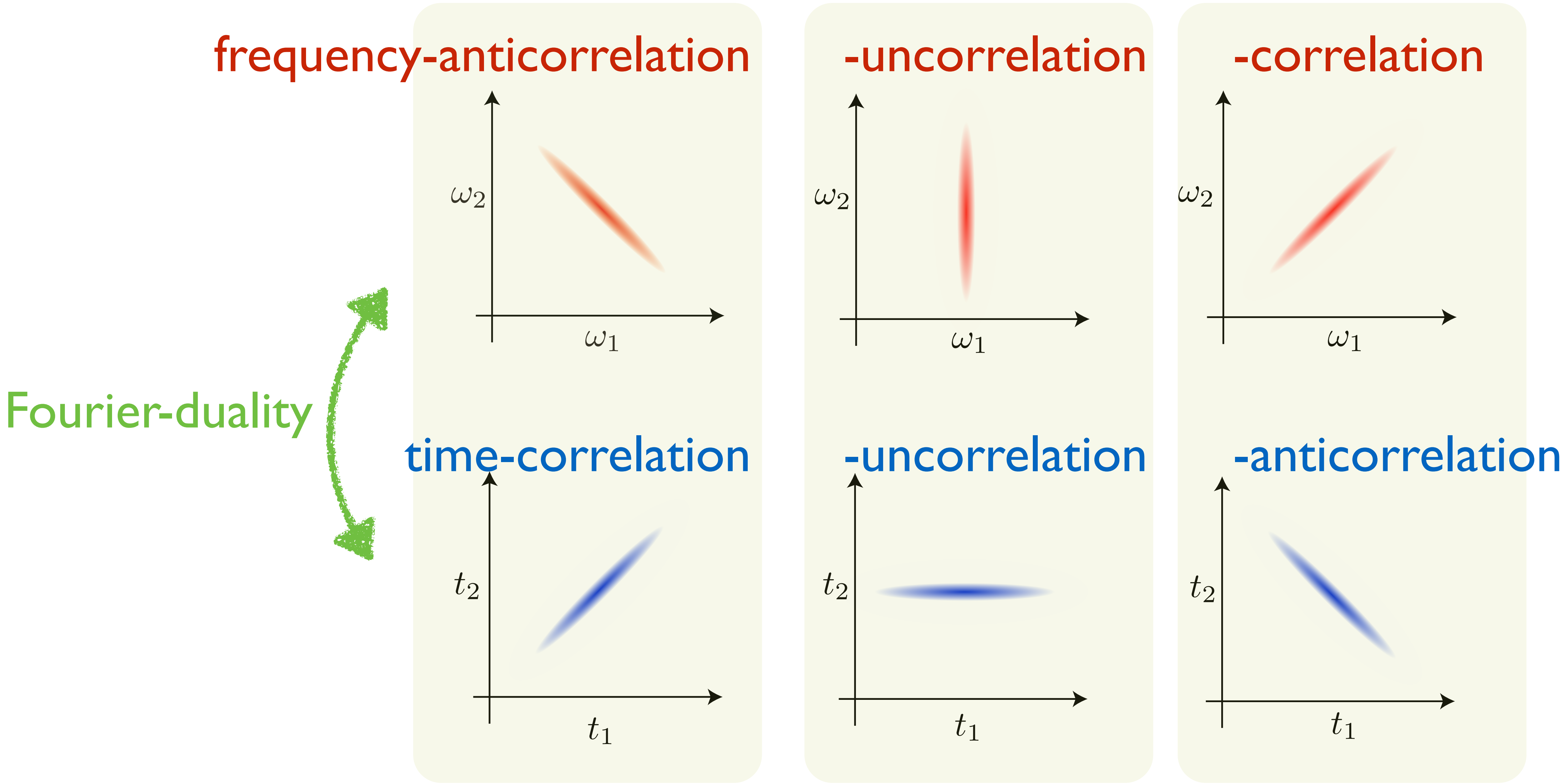




not measured due to technical reasons, so *inconclusive*

Cho, Y.-W., Park, K.-K., Lee, J.-C. & Kim, Y.-H. Engineering Frequency-Time Quantum Correlation of Narrow-Band Biphotons from Cold Atoms. Phys. Rev. Lett. 113, 063602 (2014).

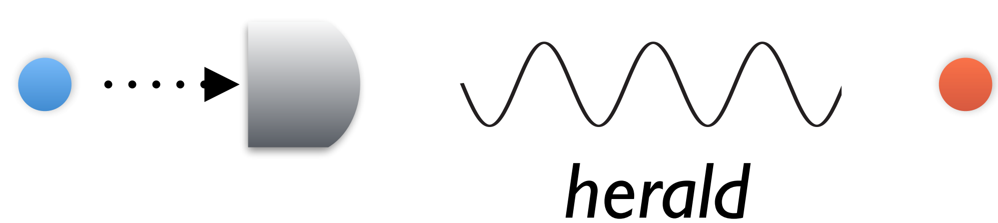
There are several types of frequency-time correlation.



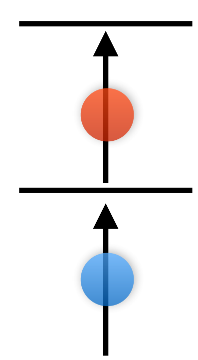
Engineering of frequency-time quantum correlation finds various applications.

- quantum-enhanced clock sync

- high purity single photon generation



- two photon spectroscopy



Theory for a pulsed pump is

$$\hat{H}_I = \frac{\epsilon_0 A}{4}\int_{-L/2}^{L/2} dz\ \chi^{(3)} E_p^{(+)} E_c^{(+)} \hat{E}_s^{(-)} \hat{E}_{as}^{(-)} + h.c.$$

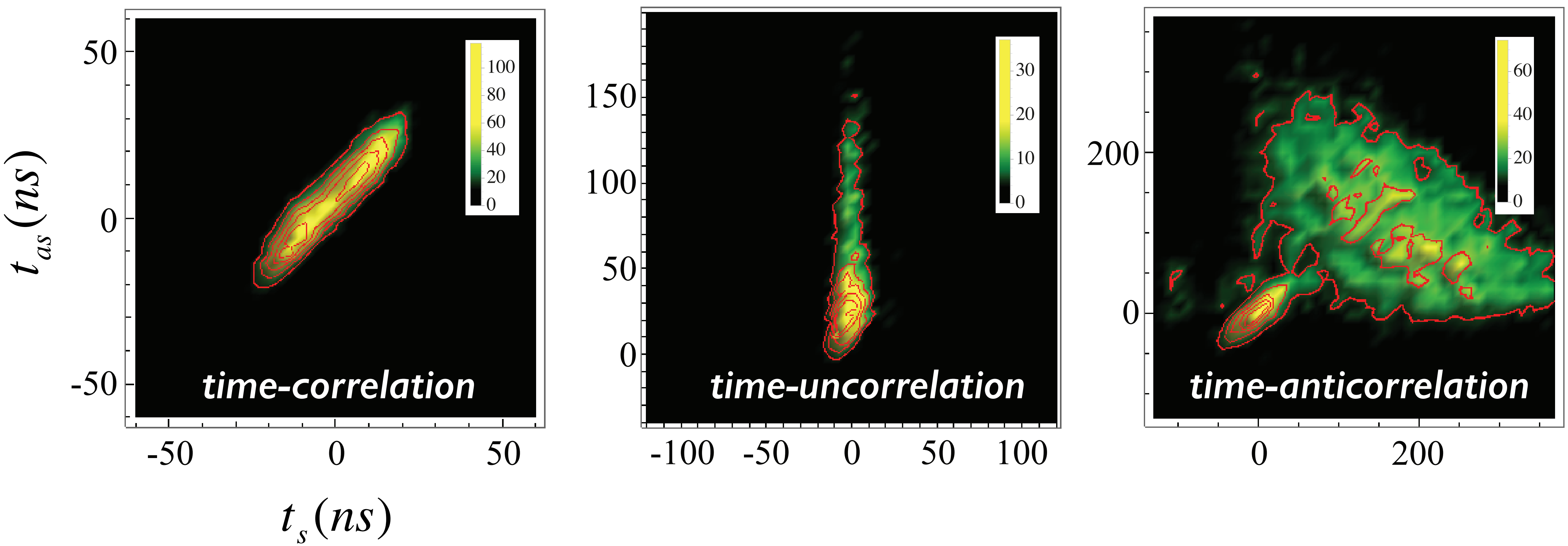
$$E_p^{(+)}(z,t) = \int d\nu_p \tilde{E}_p(\nu_p) e^{i(k_p z - (\bar{\varpi}_p + \nu_p)t)}$$

$$|\Psi\rangle = C\int d\nu_p d\omega_{as} \chi^{(3)}(\omega_{as}) \tilde{E}_p(\nu_p) E_c \mathrm{sinc}\left(\frac{\Delta k L}{2}\right) \times \hat{a}_s^\dagger(\bar{\varpi}_p + \omega_c - \omega_{as} + \nu_p) \hat{a}_{as}^\dagger(\omega_{as}) |0\rangle$$

room for engineering frequency correlation

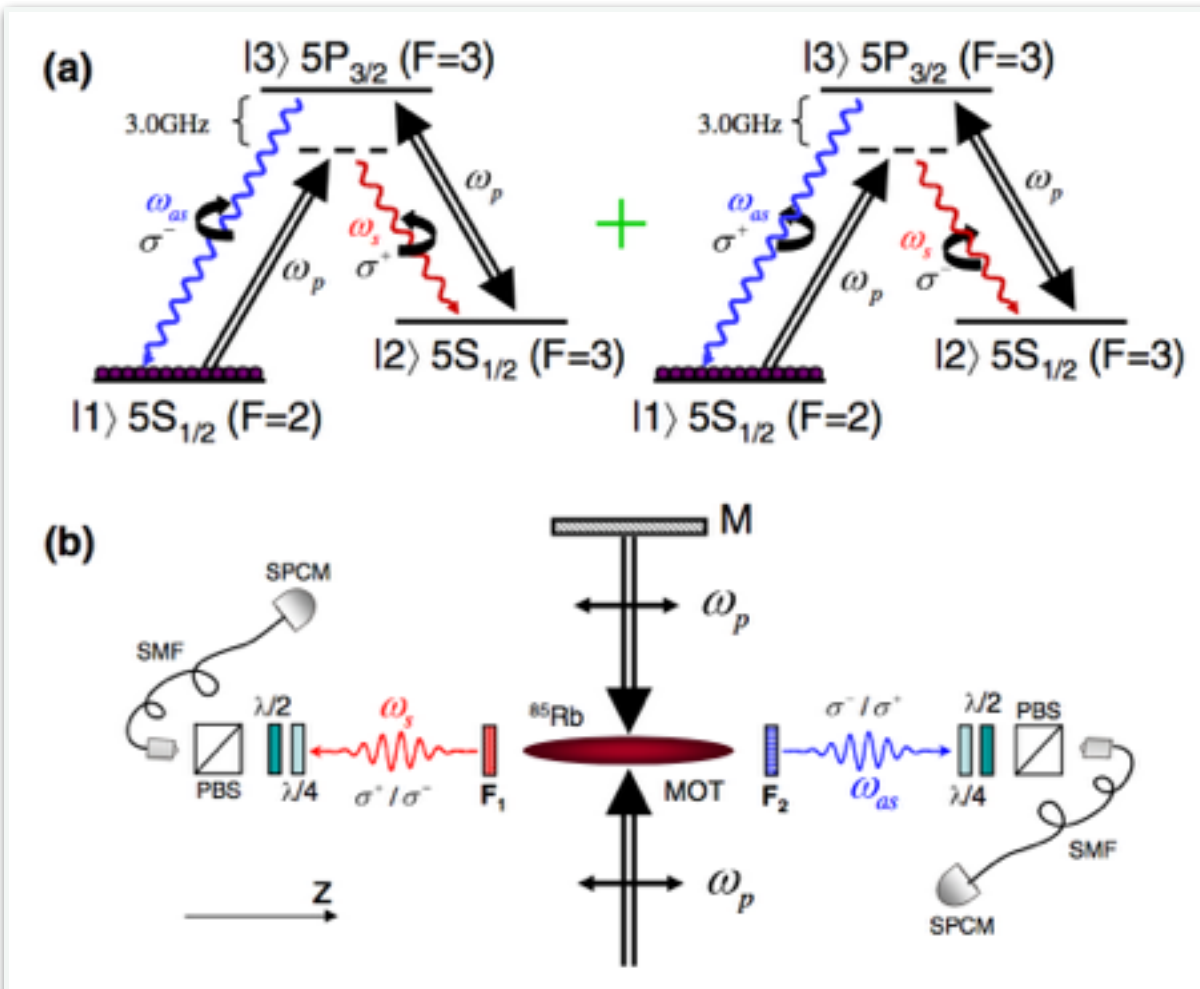
Cho, Y.-W., Park, K.-K., Lee, J.-C. & Kim, Y.-H. Engineering Frequency-Time Quantum Correlation of Narrow-Band Biphotons from Cold Atoms. Phys. Rev. Lett. 113, 063602 (2014).

Frequency-time correlation is engineered.



Cho, Y.-W., Park, K.-K., Lee, J.-C. & Kim, Y.-H. Engineering Frequency-Time Quantum Correlation of Narrow-Band Biphotons from Cold Atoms. Phys. Rev. Lett. 113, 063602 (2014).

Polarization entangled states can be generated.



$$|\psi\rangle_{s,as} = \frac{1}{\sqrt{2}}\left(|\sigma^+\rangle_s|\sigma^-\rangle_{as} + |\sigma^-\rangle_s|\sigma^+\rangle_{as}\right)$$

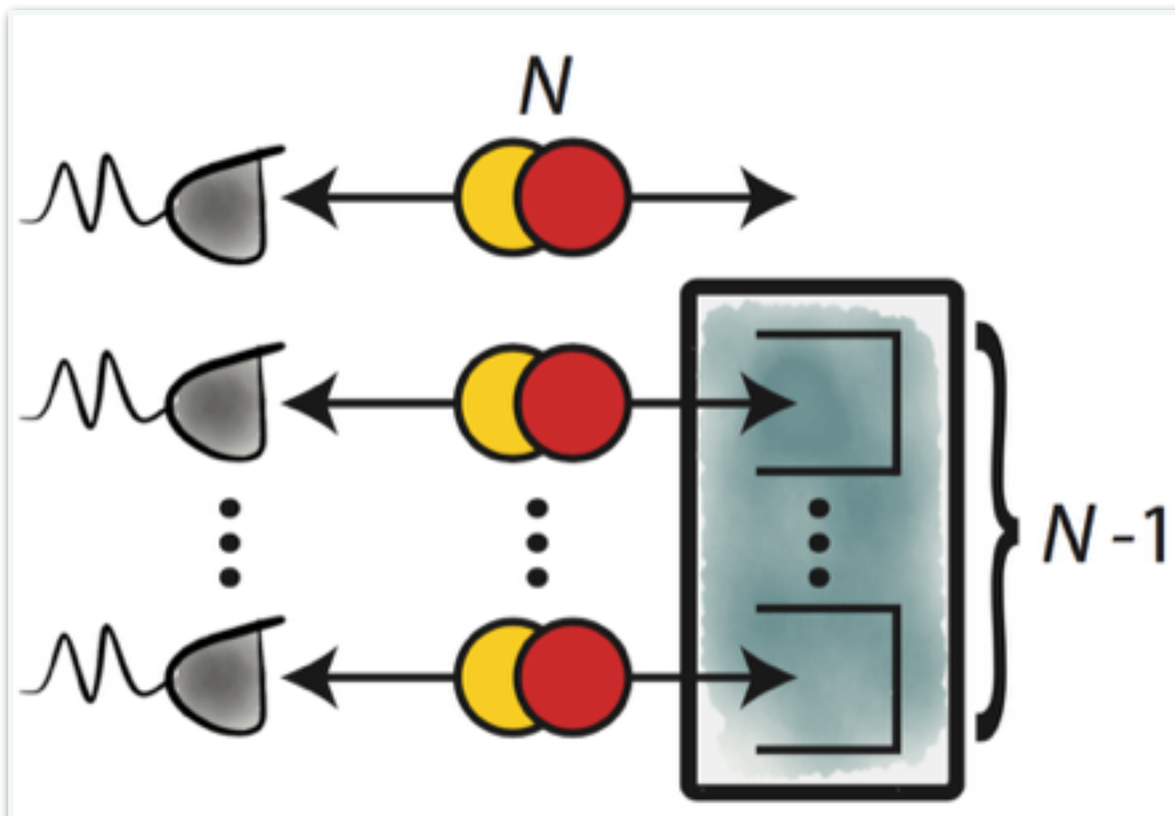
Polarization entanglement is originated from two *indistinguishable* transition paths.

Yan, H. et al. Generation of Narrow-Band Hyperentangled Nondegenerate Paired Photons. Phys. Rev. Lett. 106, 033601 (2011).

Photonic Quantum Memories

Quantum memories are essential in *quantum computation*.

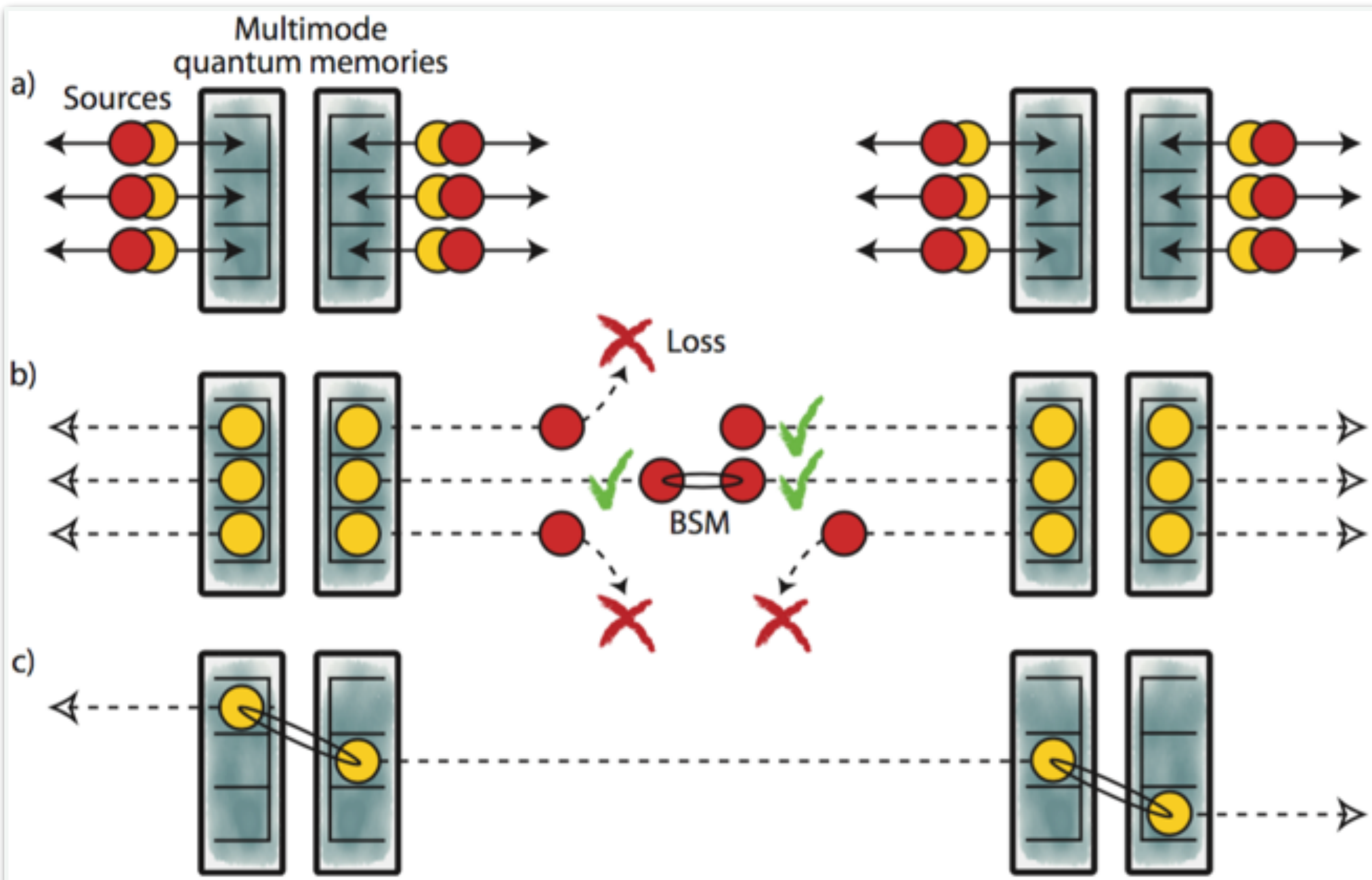
- Quantum memories can *synchronize* multi-photon events to increase the success probability of linear optical quantum gates.



Bussieres, F. et al. Prospective applications of optical quantum memories. J. Mod. Opt. 60, 1519–1537 (2013).

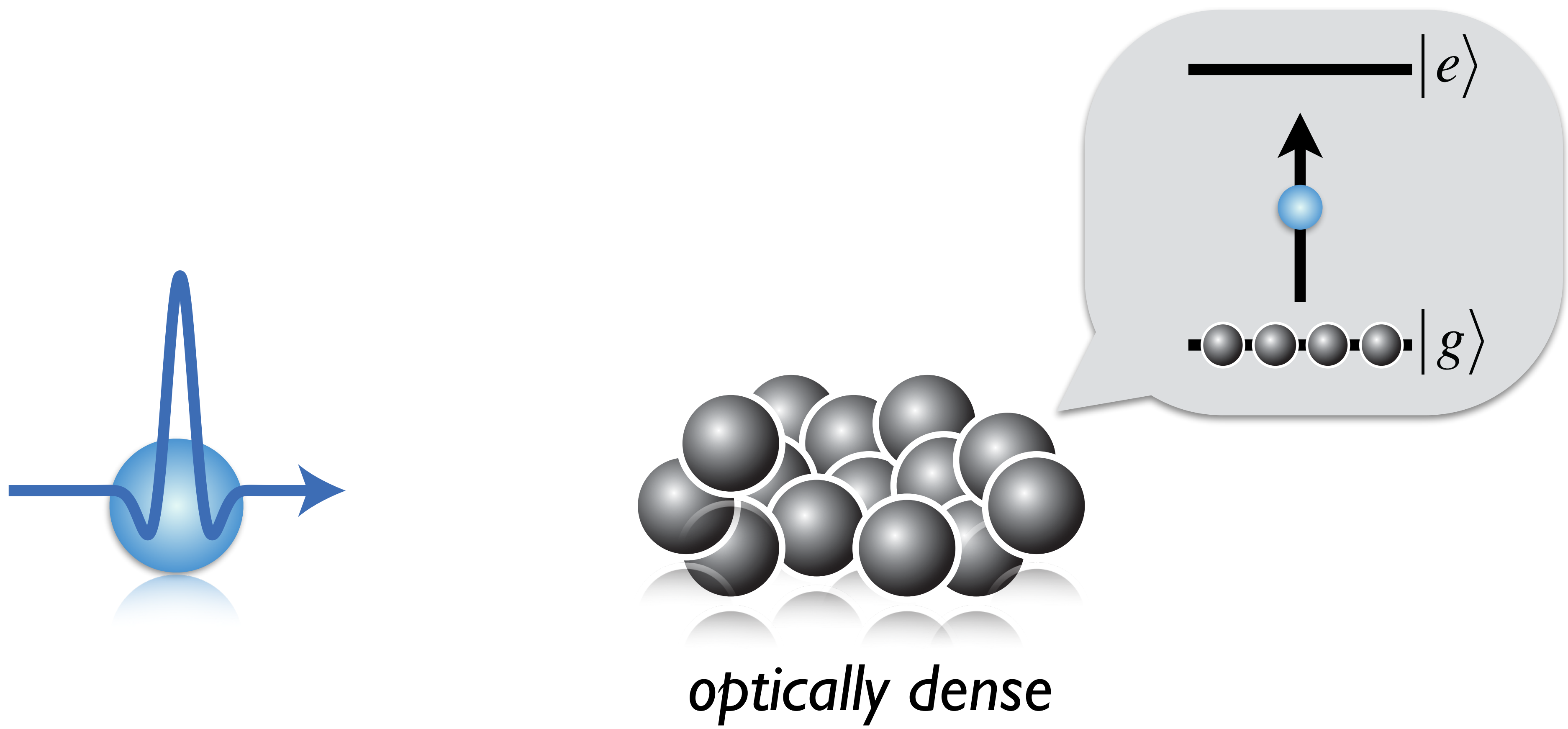
Quantum memories are essential in *quantum communication*.

- Quantum memories help entangled photons to be distributed over long distances.

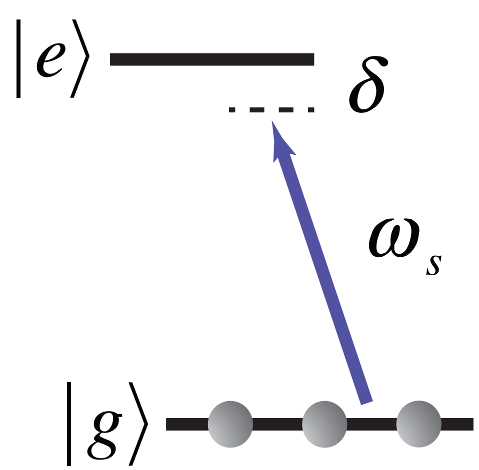


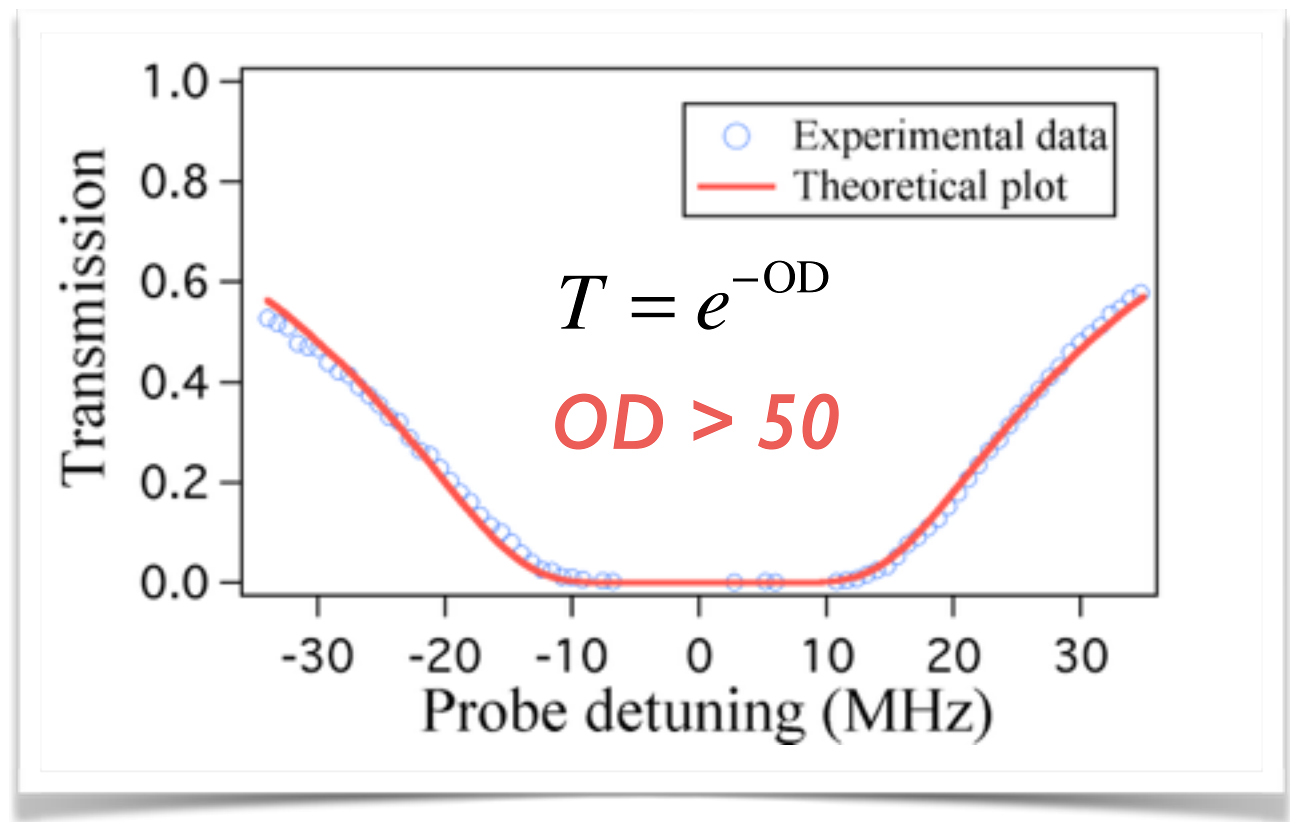
Bussieres, F. et al. Prospective applications of optical quantum memories. J. Mod. Opt. 60, 1519–1537 (2013).

Atomic ensembles can control states of photons efficiently and mediate the interaction.



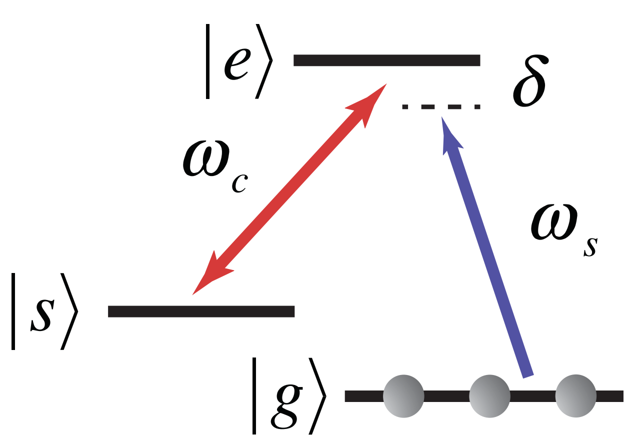
Photons are absorbed in the atomic ensemble with a *high* probability.



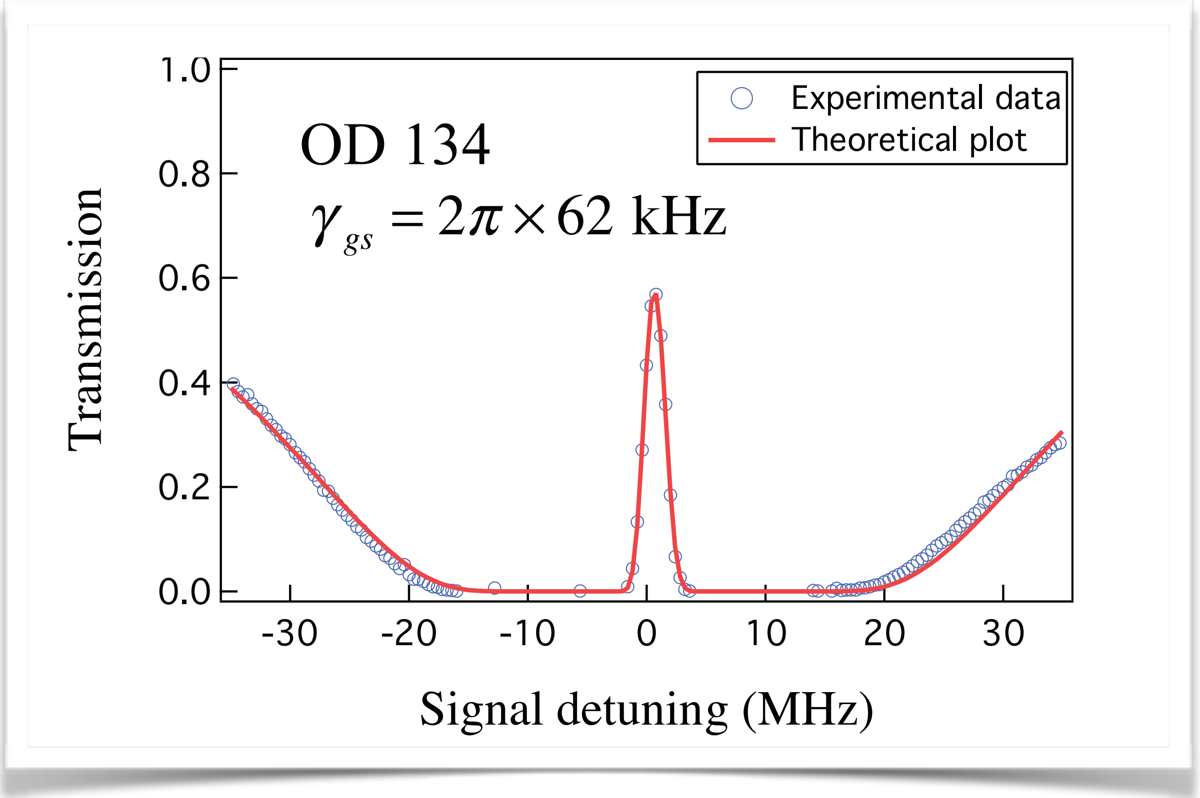


The on-resonant photons can transmit the medium *without absorption.*

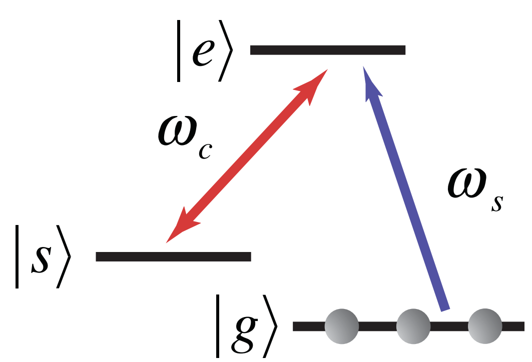
Electromagnetically Induced Transparency (EIT)

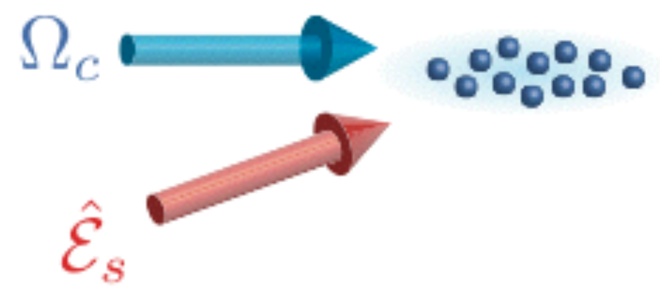


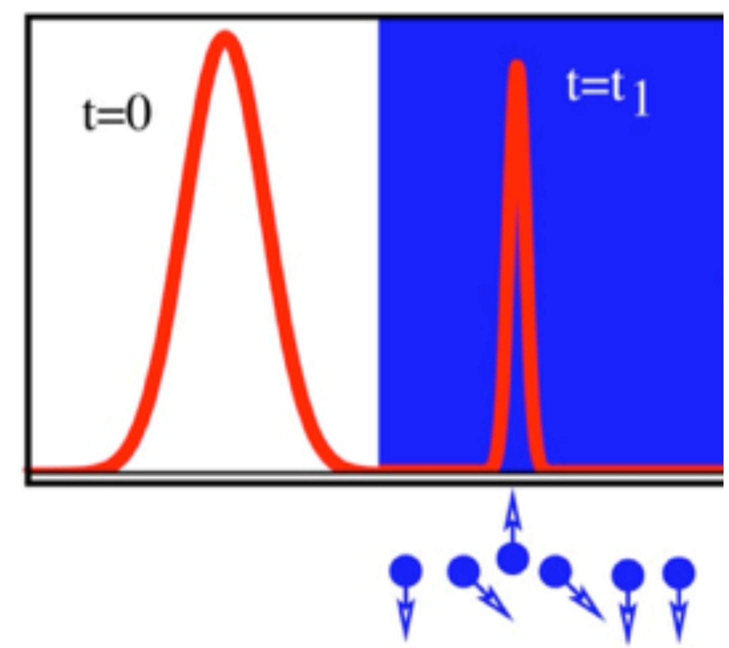
Ground state coherence is induced.



Light pulse propagation in the EIT medium is







- For a single-excitation state, dark state polariton is

$$|D,1\rangle = \cos\theta_d(t)|\bar{g}_{\mathrm{a}}, 1_s\rangle - \sin\theta_d(t)|\bar{s}_{\mathrm{a}}, 0_s\rangle,$$

$$|\bar{s}\rangle_{\mathrm{a}} = \frac{1}{\sqrt{N_A}}\sum_{i=1}^{N_A} e^{-i\Delta k_{sc} z_i}\hat{\sigma}_{gs}^{(i)\dagger}|\bar{g}\rangle_{\mathrm{a}}$$ *collective spin excitation*

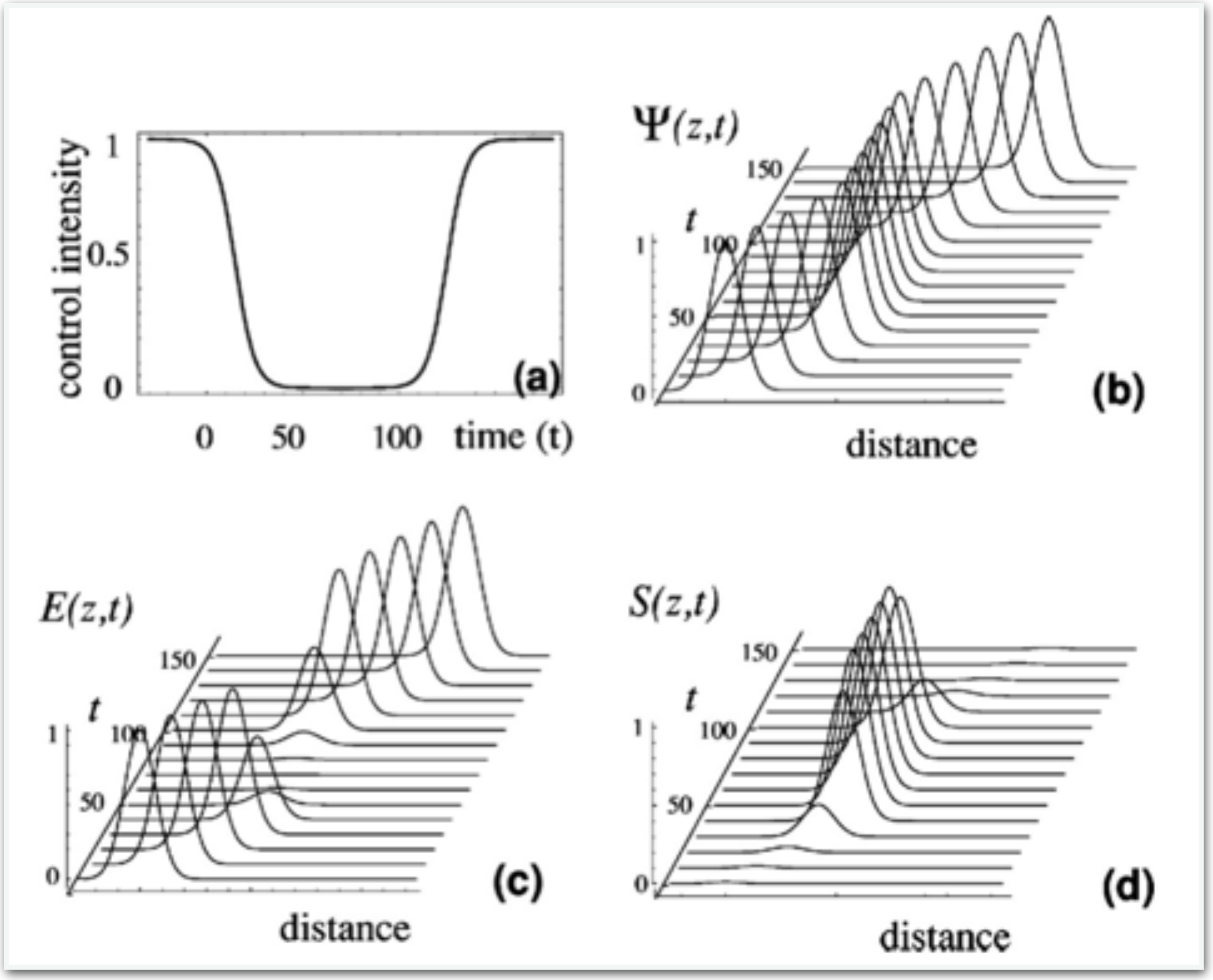
M. D. Lukin, Rev. Mod. Phys. **75**, 457 (2003).

M. Fleischhauer and M. D. Lukin, Phys. Rev. A **65**, 022314 (2002).

The light pulse can be stopped, *optical quantum memory*.

- The photonic excitation is adiabatically mapped into an atomic spin excitation by turning off the control laser.

$$\hat{\Psi}_d(z,t) = \cos\theta_d(t)\hat{\mathcal{E}}_s(z,t) - \sin\theta_d(t)\hat{S}(z,t)$$ *dark state polariton*

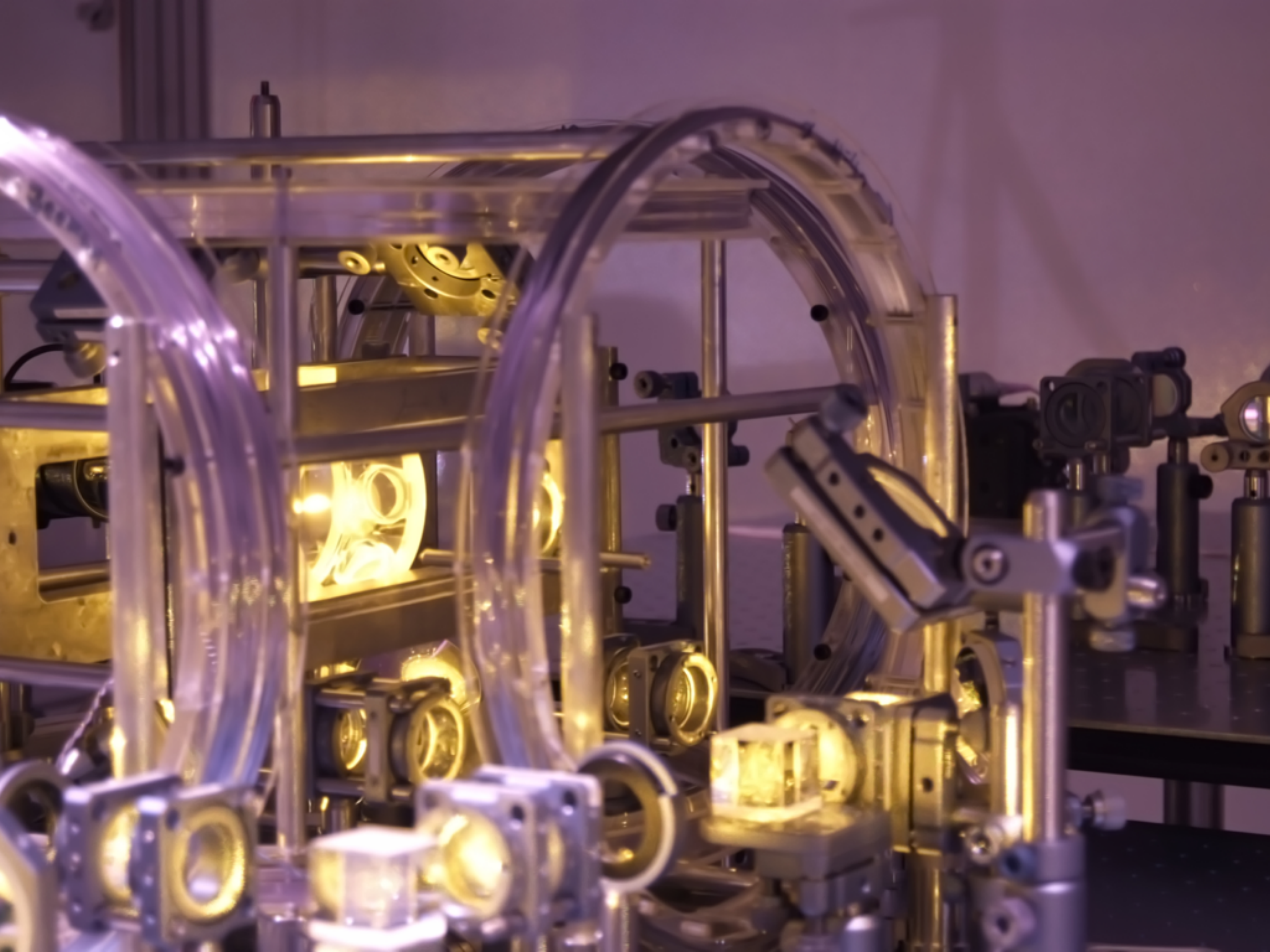


$\tan\theta_d = g_d\sqrt{N_A}/\Omega_c$

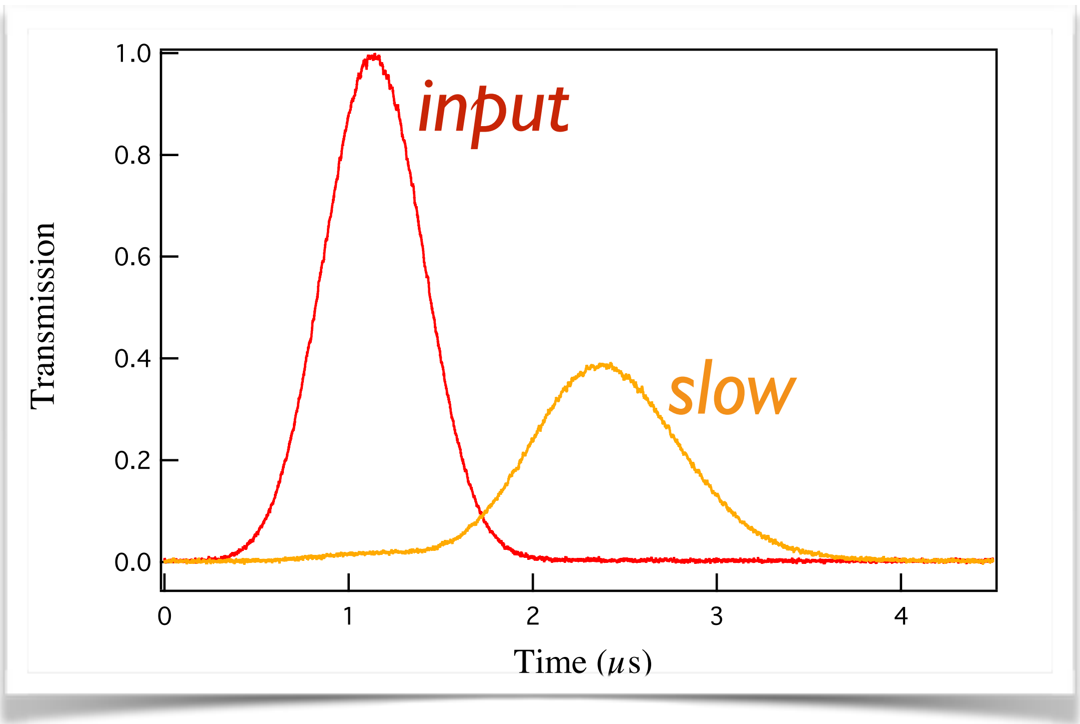
$v_g = c\cos^2\theta$

M. D. Lukin, Rev. Mod. Phys. **75**, 457 (2003).

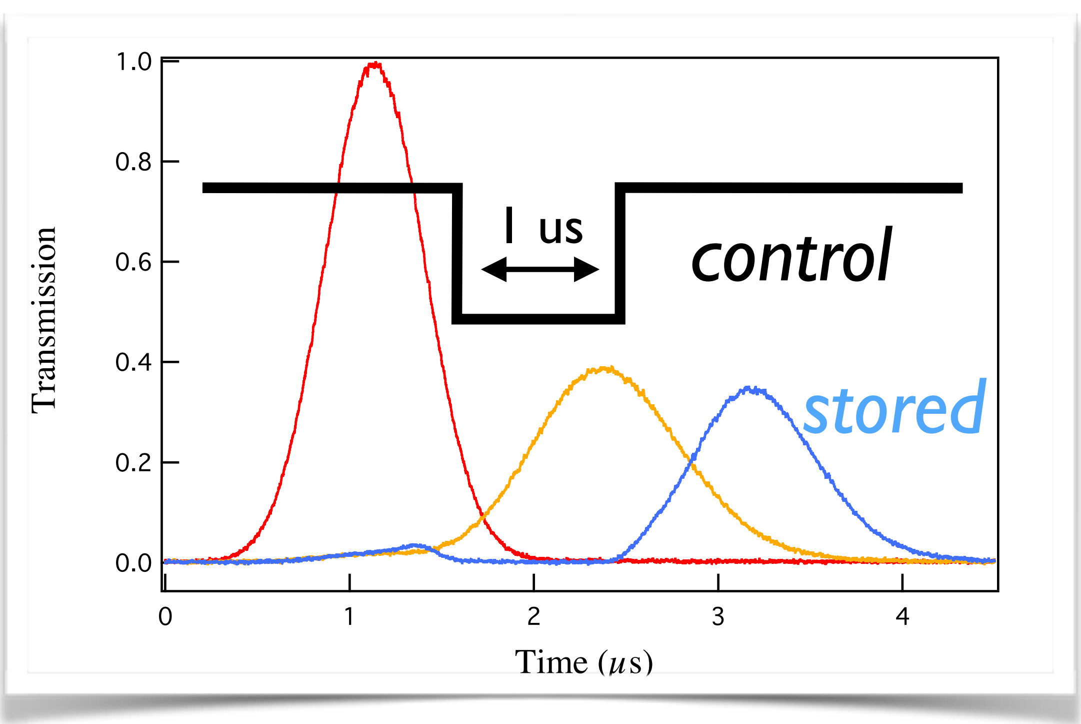
M. Fleischhauer and M. D. Lukin, Phys. Rev. A **65**, 022314 (2002).



Slowing and storing of a light pulse are possible.

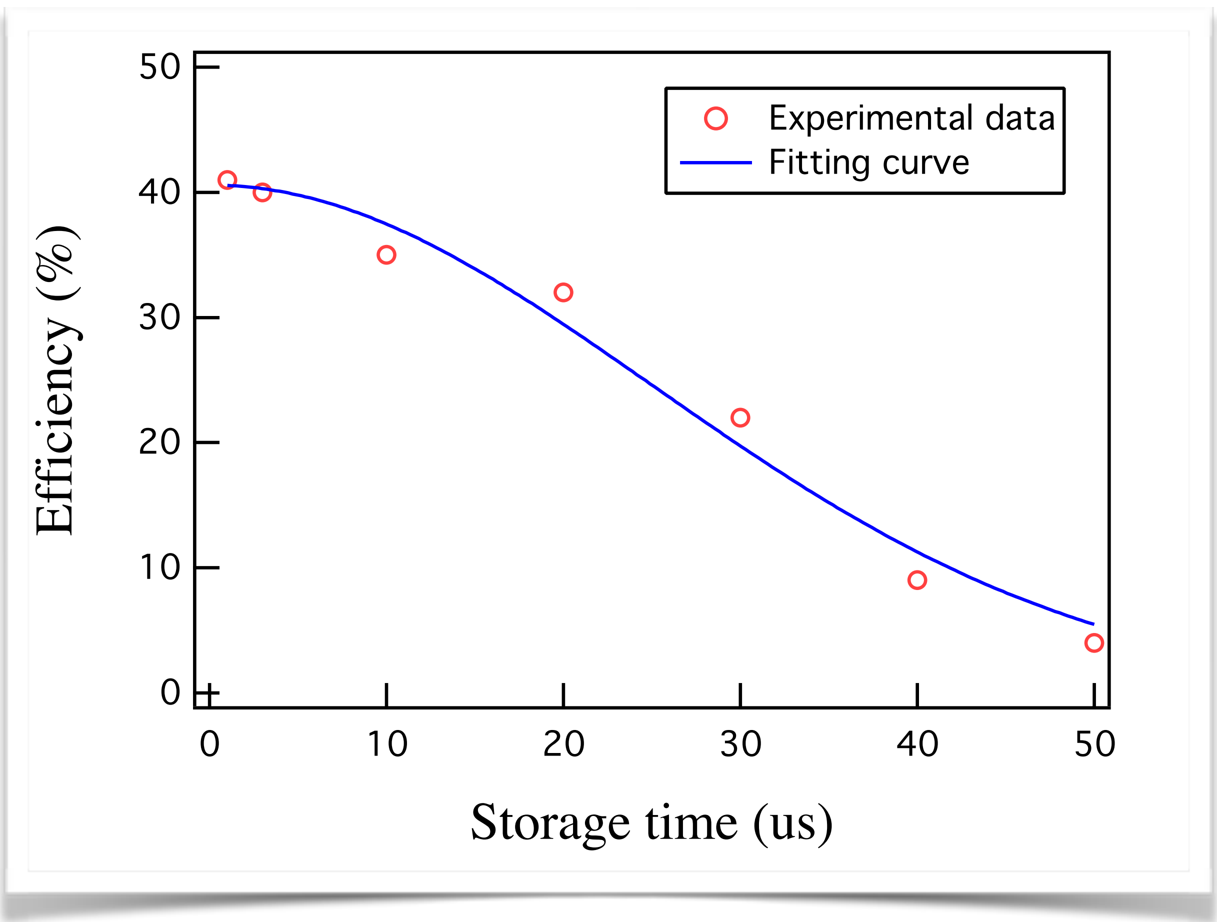


- $V_g \sim 10^{-5}c$.
- 200 m pulse is compressed to 6 mm.



- Full pulse storage is possible.

A light pulse can be stored up to 35 us.



- Storage up to 35 us.
  - (corresponding to 7 km fiber)

Thank you