Efficient Quantum Memory for Photonic Polarization Qubits

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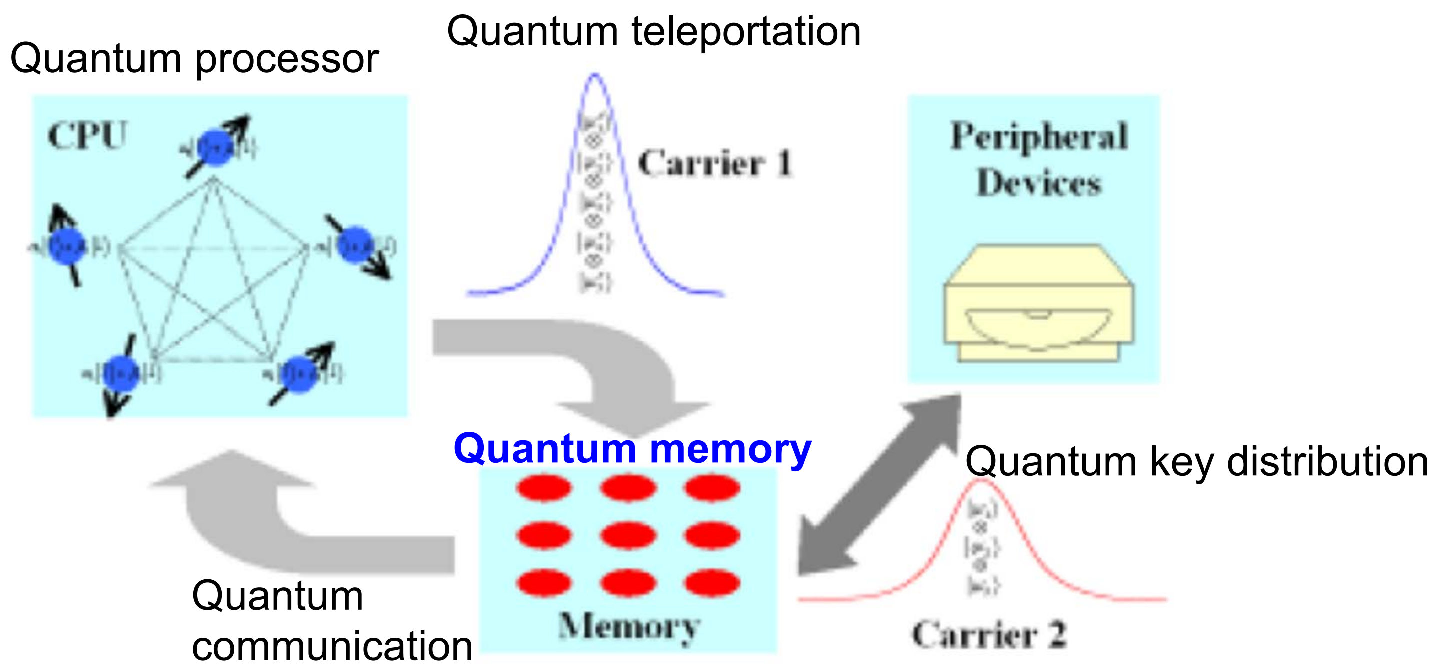
Quantum 2.0: Turning quantum weirdness into use

- Use of the fascinating properties of quantum mechanics, such as uncertainty principle, coherent superposition, quantum entanglement… as resources for the information technology.
- Spirit of quantum 2.0: Pursuit for perfection.



Outline

- Introduction to optical quantum memory ?
- Highly-efficient coherent optical memory based on electromagnetically induced transparency (EIT) [1]
- Towards broadband EIT-based memory[2]
- Development of a quantum light source based on cavity-enhanced spontaneous parametric down-conversion (SPDC)[3]
- Efficient quantum memory for heralded single photons & polarization qubitd[4,5]
- Conclusions

1, Y.-F. Hsiao,..., YCC*, Phys. Rev. Lett. 120, 183602(2018)
2, Y.-C. Wei,..., YCC*, Phys. Rev. A. 102, 063720(2020)
3, P.-J. Tsai, YCC*, Quantum Sci & Techno, 3, 034005(2018)
4, P.-J. Tsai,.., YCC*, Phys. Rev. Reseach, 2, 033155(2020)
5, Y.-C. Tseng, ..., YCC*, arXiv:2011.14948

What is optical quantum memory ?

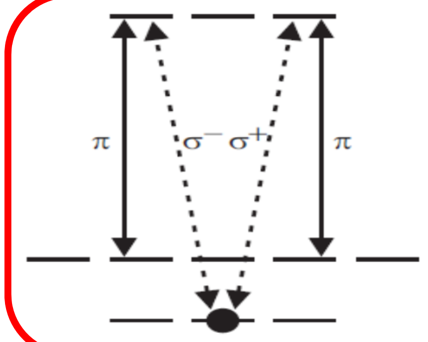
$|\Psi_{in}\rangle$ → **Quantum memory** → $|\Psi_{out}\rangle$

Photonic quantum state (flying qubit)

e.g. $|\Psi\rangle = c_1|\sigma^+\rangle + |c_2|\sigma^-\rangle$

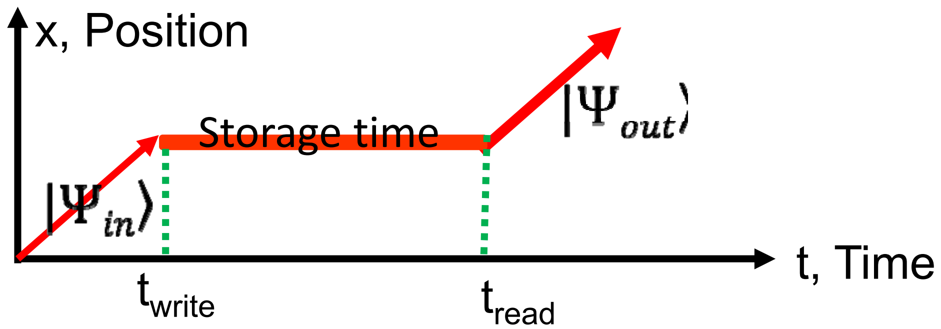
Atomic quantum state (stationary qubit), e.g.

Retrieve on demand



Coherent absorption & emission

$$c_+|\sigma^+\rangle + c_-|\sigma^-\rangle \Rightarrow$$
$$c_+|F=2, m=1\rangle + c_-|F=2, m=-1\rangle$$

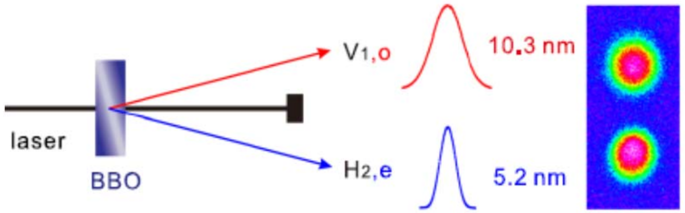


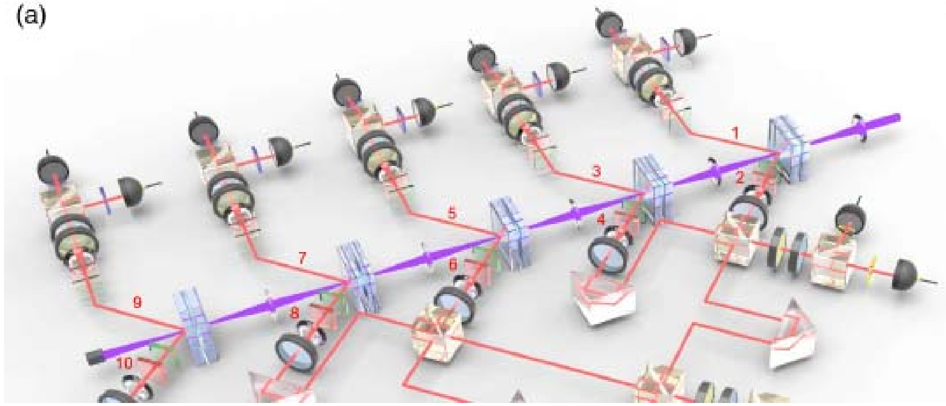
QM postpone the collapse of a wavefunction.

Why optical quantum memory (QM) 1/2 ?

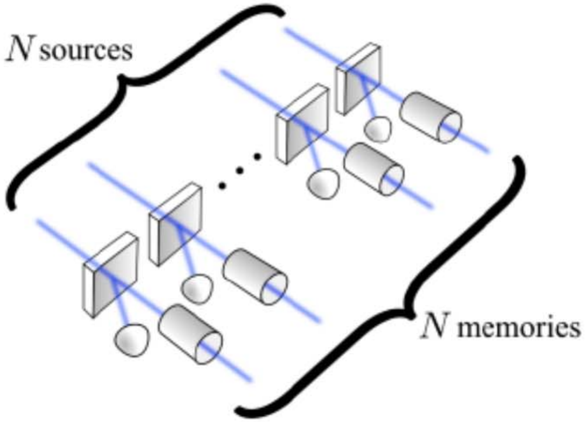
- Synchronization of probabilistic events: QM-assisted multi-photon generation

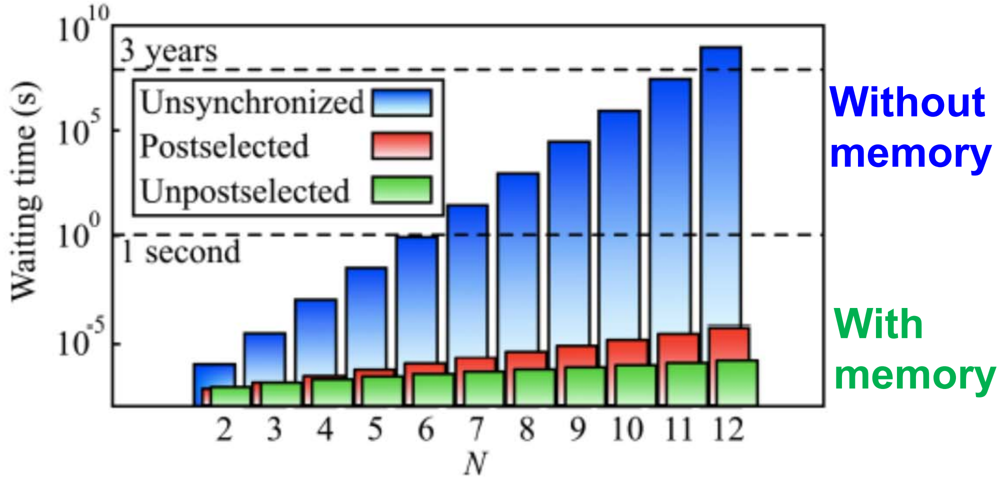
Spontaneous parametric downconversion (SPDC)
Entangled 10-photon, ~**1 event/hour**
X.L. Wang et al PRL 117, 210502(2016)





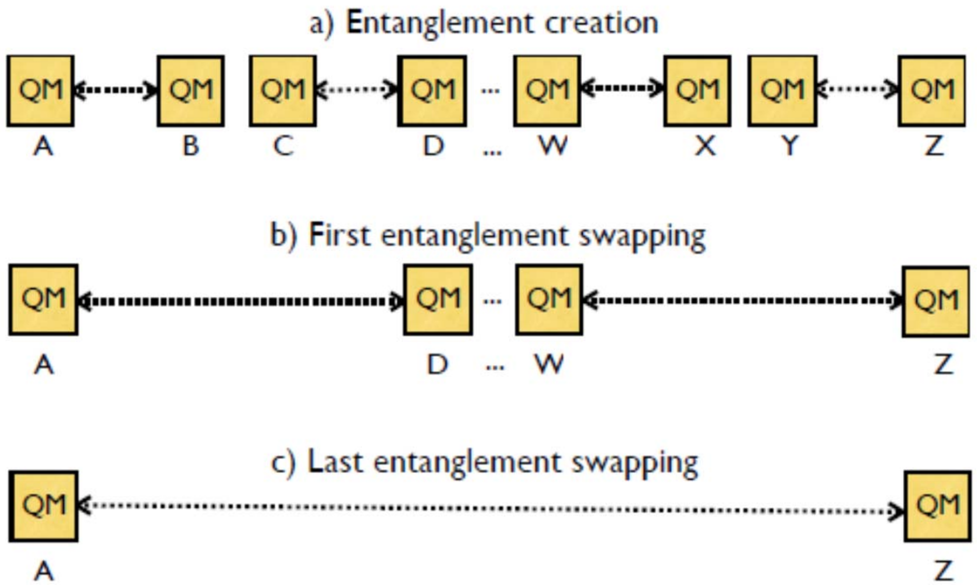
Enhancing multiphoton rate by QM
J. Nunn et. al. PRL 110, 133601(2013)





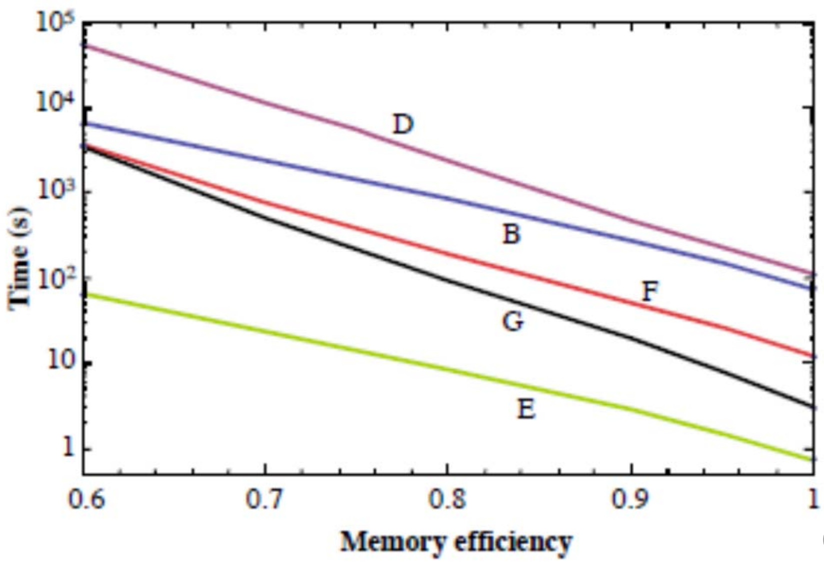
Why optical quantum memory (2/2) ?

- Photon loss is a problem in quantum key distribution (no-cloning theorem): 0.2 dB/km fiber loss and 10GHz photon rate→1 Hz detection rate for 500 km and 10^{-10} Hz for 1000 km (1 photon/300 years)!
- High-performance quantum memory a key component for quantum repeater protocol which allows the wait-until-success strategy !



N. Sangouard et al, Rev. Mod. Phys. 83, 33(2011)

- An increase of 1% in SE decrease the entanglement distribution time by 7-18%, depending on the protocol.



Performance Parameters for a Quantum Memory

Fidelity: How well the quantum state remains?

$$F_{|\Psi_{\mathrm{in}}\rangle} = \inf_{|\Psi_{\mathrm{in}}\rangle} \sqrt{\langle \Psi_{\mathrm{in}} | \, \rho_{\mathrm{out}} \, | \Psi_{\mathrm{in}} \rangle}.$$

Noise level : noise reduces the non-classical feature

Storage time : How long the quantum state can be stored ?

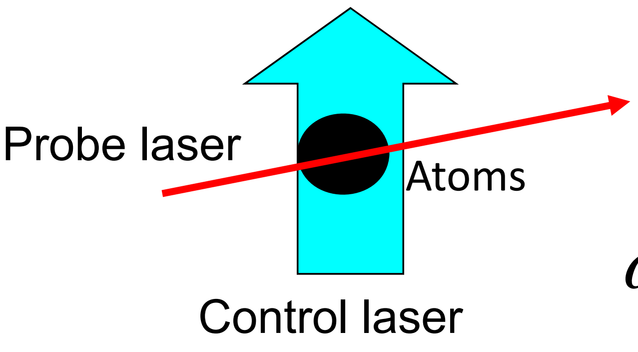
Bandwidth (capacity) : How many states can one store?

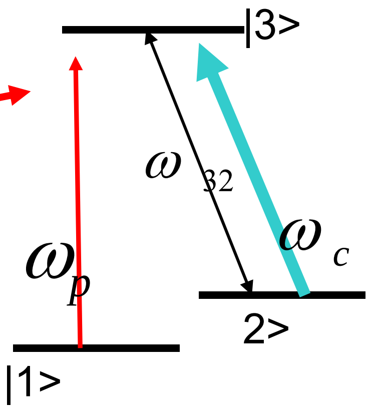
Our focus

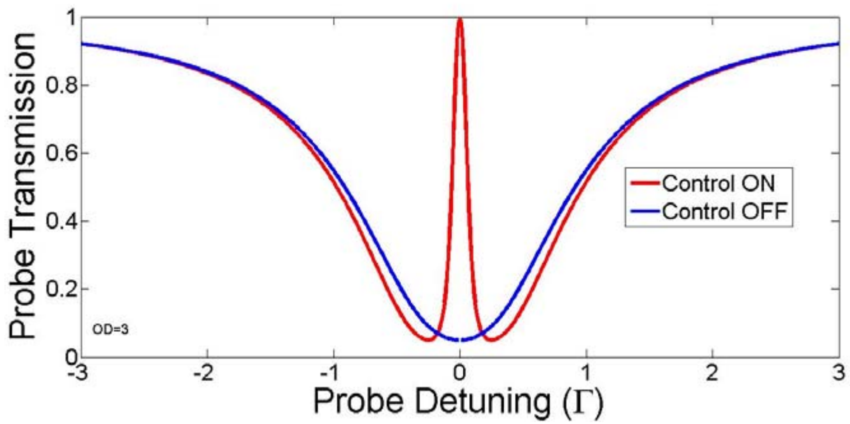
Efficiency : What percentage of photon left after the storage?

$$\mathrm{SE} = \frac{N_{out}}{N_{in}}$$

Electromagnetically induced transparency (EIT)





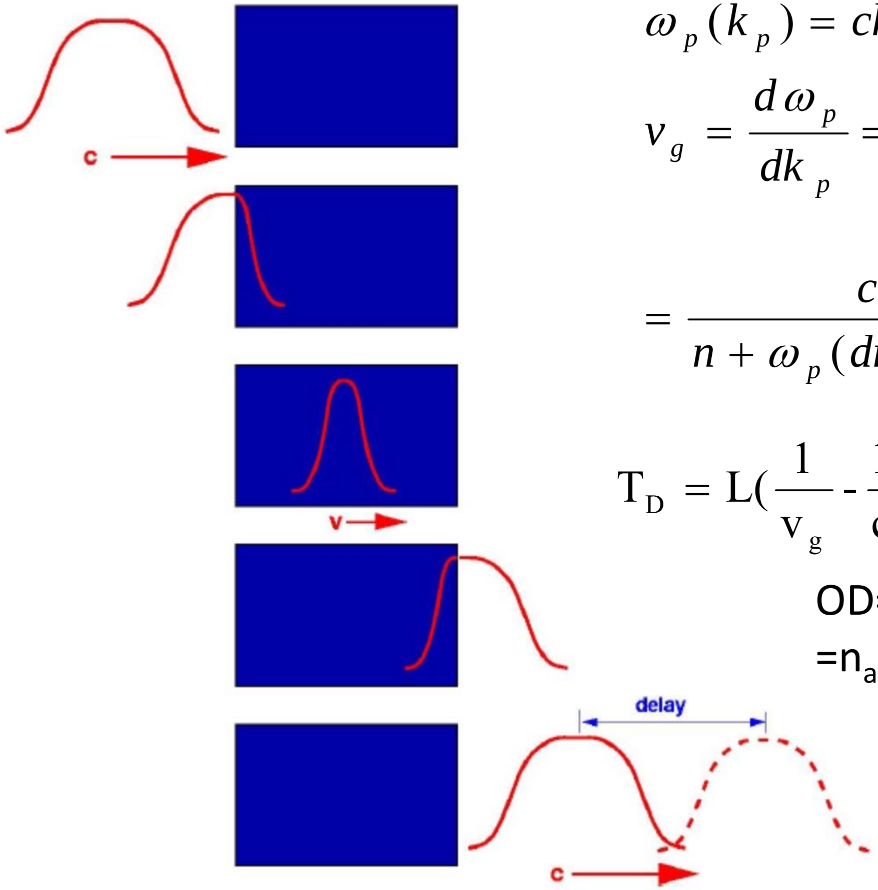


- A **dark state** of the Hamiltonian containing atom-photon interactions and decouples from the excited state.

$$H = \begin{pmatrix} 0 & 0 & -\frac{\hbar\Omega_p^*}{2} \\ 0 & -\hbar\delta_2 & -\frac{\hbar\Omega_c^*}{2} \\ -\frac{\hbar\Omega_p}{2} & -\frac{\hbar\Omega_c}{2} & -\hbar\delta_p \end{pmatrix}; \quad |D\rangle = \frac{\Omega_c}{\sqrt{\Omega_c^2+\Omega_p^2}}|1\rangle - \frac{\Omega_p}{\sqrt{\Omega_c^2+\Omega_p^2}}|2\rangle$$

M. Fleischhauer et al. Rev. Mod. Phys. 77, 633,2005

EIT and Slow Light



$$\omega_p(k_p) = ck_p / n(\omega_p)$$

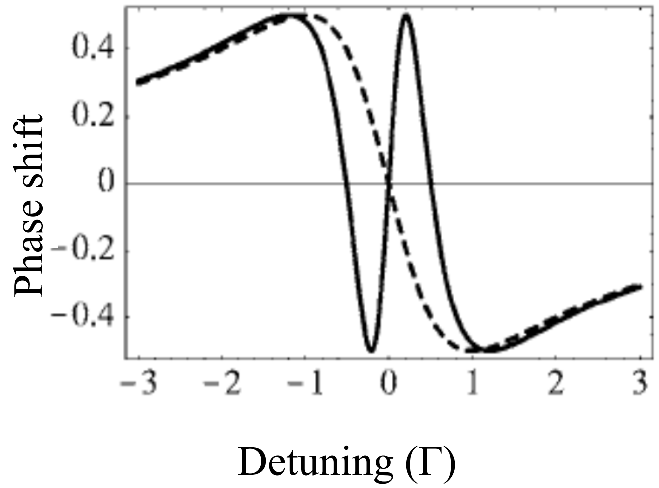
$$v_g = \frac{d\omega_p}{dk_p} = \frac{1}{dk_p / d\omega_p}$$

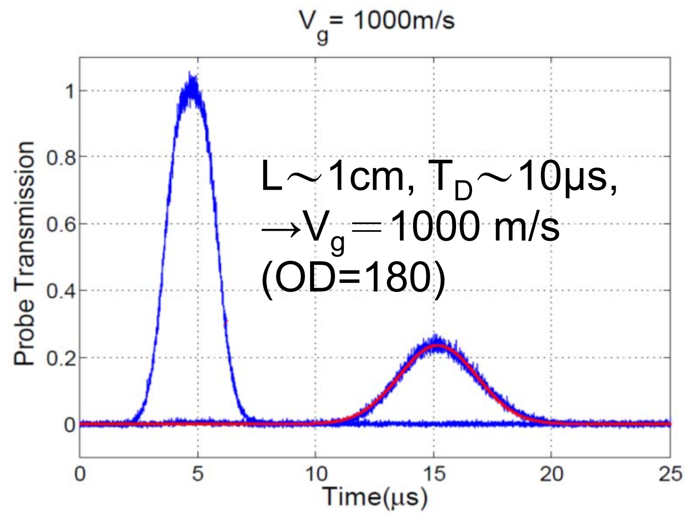
$$= \frac{c}{n + \omega_p (dn / d\omega_p)}$$

$$T_D = L\left(\frac{1}{v_g} - \frac{1}{c}\right) \cong \frac{(OD)\,\Gamma}{\Omega_c^2}$$

OD= optical depth

$=n_a\sigma_{abs}L$



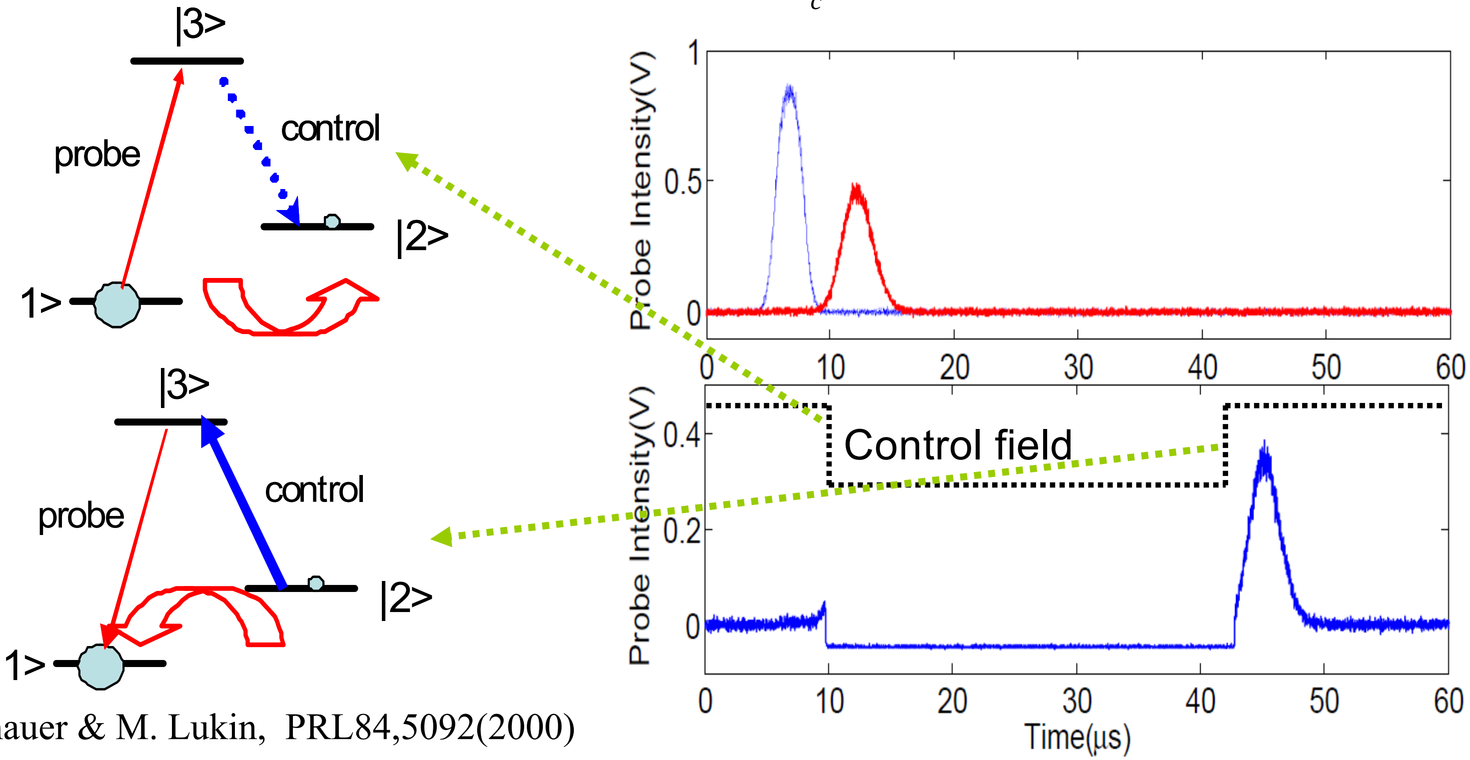


Dark-state polariton and Optical quantum memory

- Slow light can be viewed as a dark-state polariton, which is a coherent superposition of light field and collective atomic coherence and tuned by the control field.

$$\Psi(z,t) = \cos\theta E_p(z,t) - \sin\theta\sqrt{N}\rho_{21}(z,t)e^{i\Delta kz}$$

$$\tan\theta = N\frac{3\lambda^2}{2\pi}c\frac{\Gamma_{31}}{\Omega_c^2};[\frac{\partial}{\partial t} + c\cos^2\theta\frac{\partial}{\partial z}]\Psi(z,t) = 0; v_g = c\cos^2\theta$$



M Fleischhauer & M. Lukin, PRL84,5092(2000)

EIT quantum memory for high efficiency (1/2)

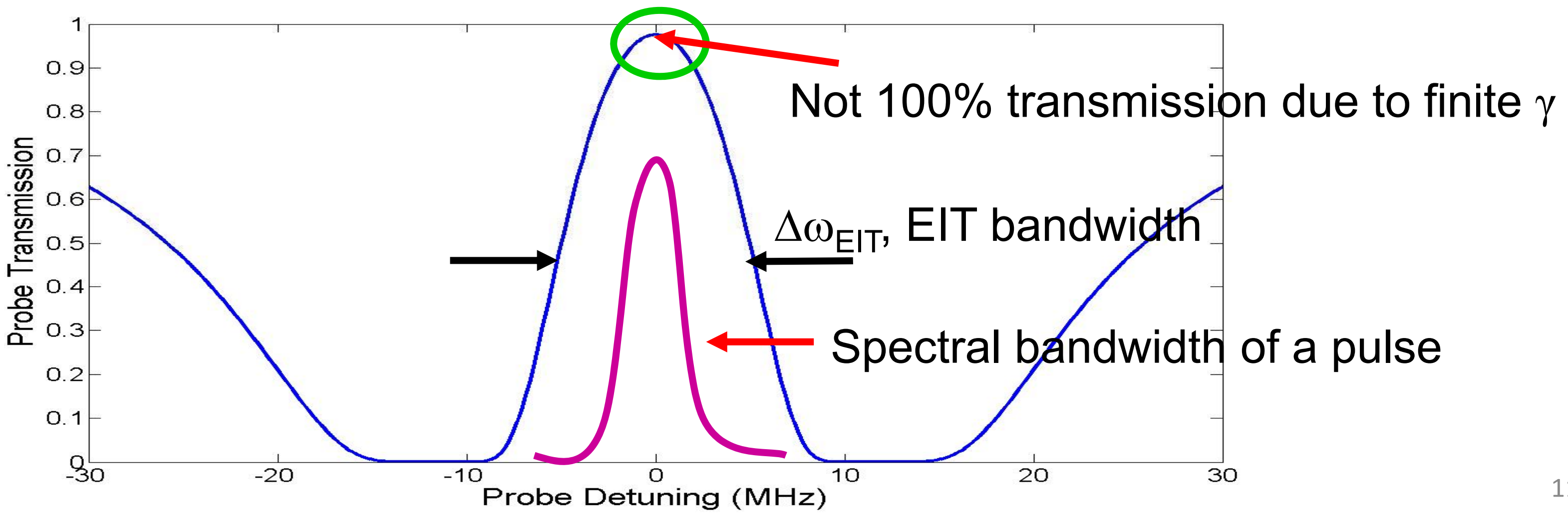
- By solving the Maxwell-Bloch equation, one gets

$$\eta_{\text{trans}} = \frac{\exp(-2\gamma T_D)}{\sqrt{1+\left(\frac{4\ln 2}{T_p \Delta\omega_{EIT}}\right)^2}} = \frac{\exp(-2\gamma T_D)}{\sqrt{1+\frac{16\ln 2}{OD}\left(\frac{T_D}{T_P}\right)^2}} \qquad T_D = \frac{(OD)\Gamma}{\Omega_c^2}$$

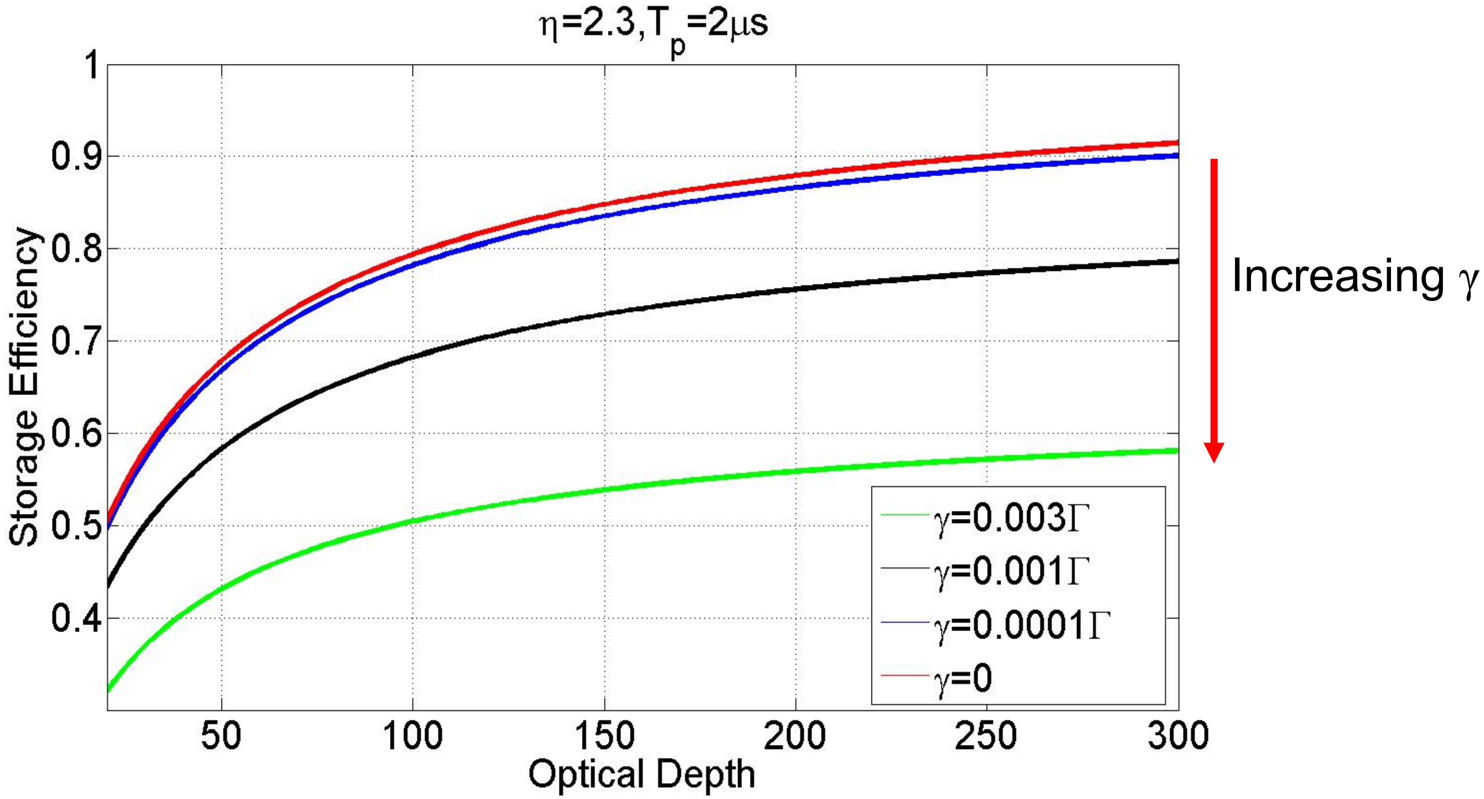
Loss due to finite ground-state decoherence rate γ

Loss due to finite EIT bandwidth

Keep T_D/T_p ~2.5 in order to compress > 99% of pulse into media (minimize leakage loss)

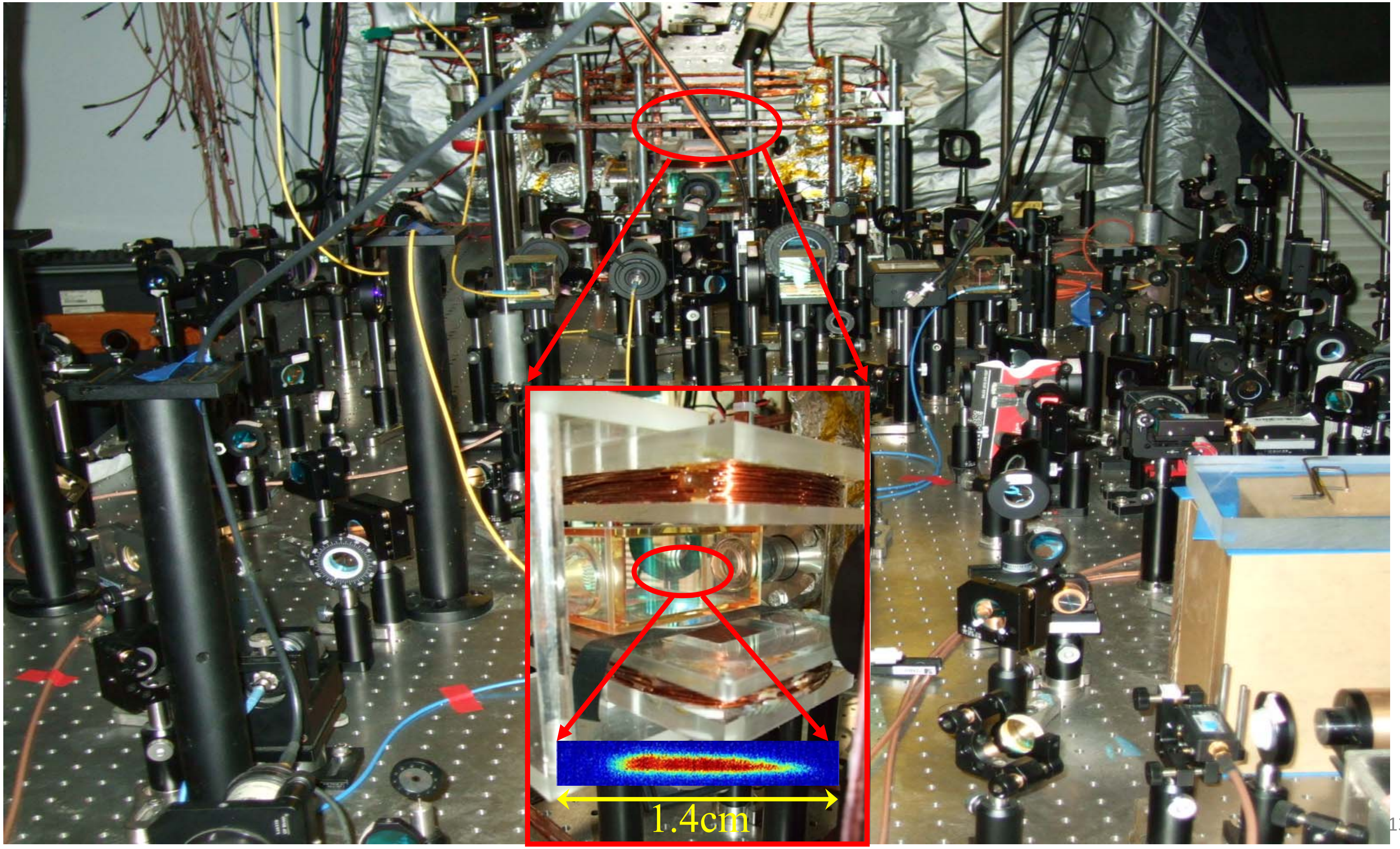


EIT quantum memory for high efficiency (2/2)



- High optical depth and low ground-state decoherence rate are two keys to achieve a high storage efficiency !
- Technically, one also needs high control intensity when increasing the optical depth.

Setup: Cesium elongated magneto-optical trap

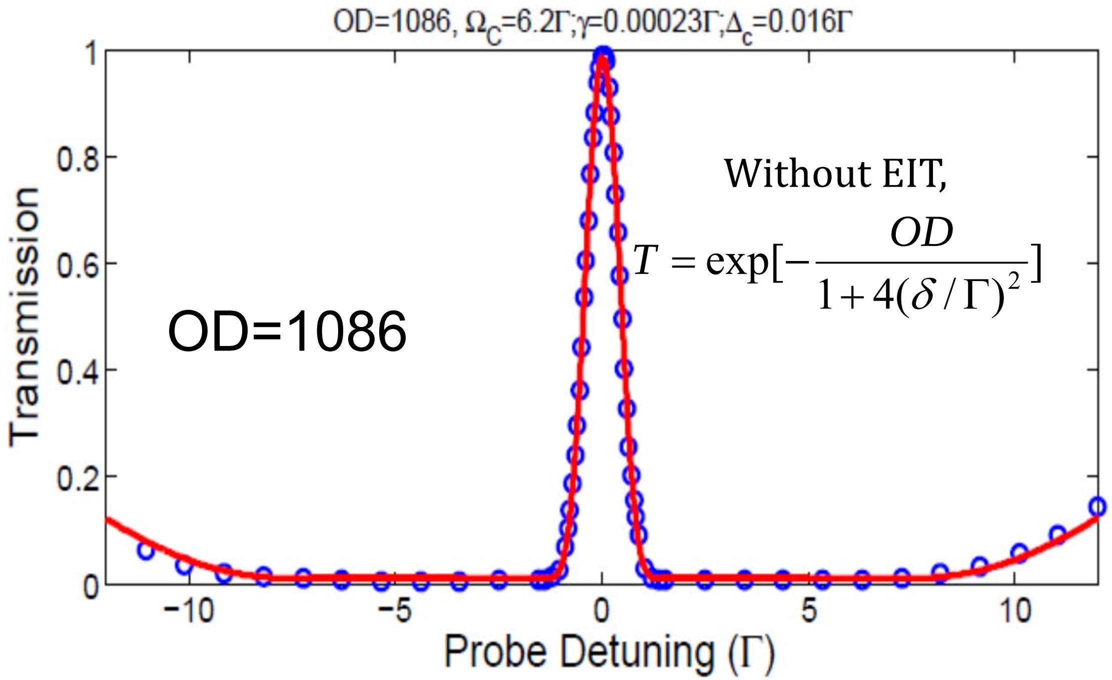


Achieve high-quality EIT atomic media

- Optical depth > 1000 and decoherence rate ~ $10^{-4}\,\Gamma$ in a magneto-optical trap.

$$T = \exp(-1086) \approx 1.66 \times 10^{-477} \Rightarrow T \approx 1, \text{ due to EIT}$$

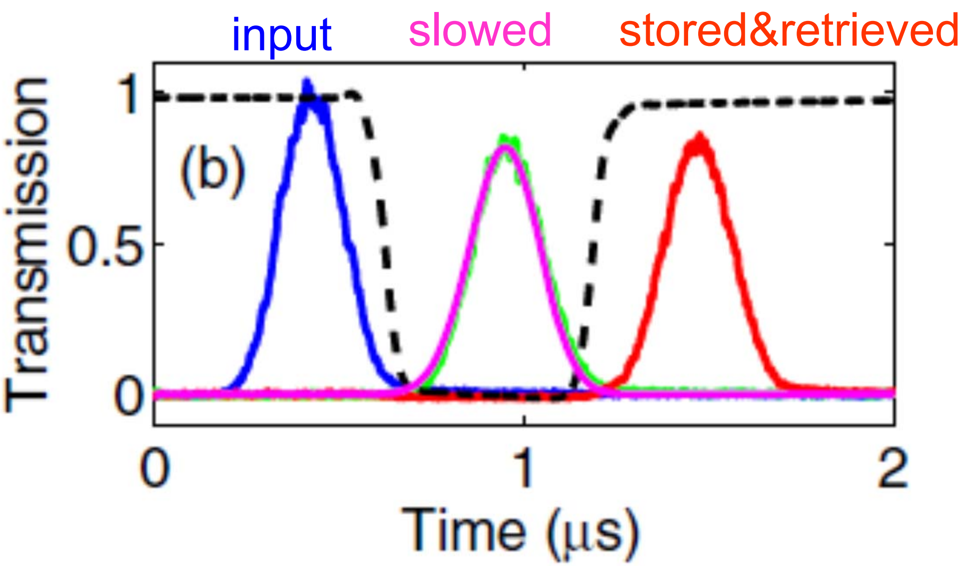
$$\gamma \approx 1 \times 10^{-4}\,\Gamma$$

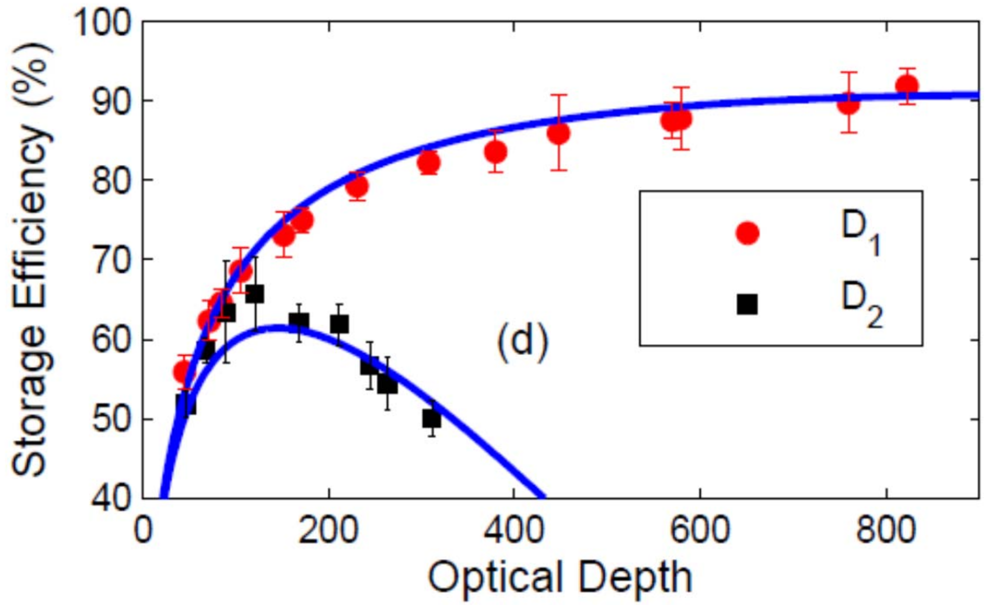


Y.-F. Hsiao…, YCC*, Phys. Rev. A, 90, 055401(2014)

Record-high storage efficiency for EIT memory

- The highest record for storage efficiency (92%) for all kinds of optical memory.





Y.-F. Hsiao…YCC*, Phys Rev. Lett. 120, 183602(2018), cited 106 times @Feb. 17, 2021

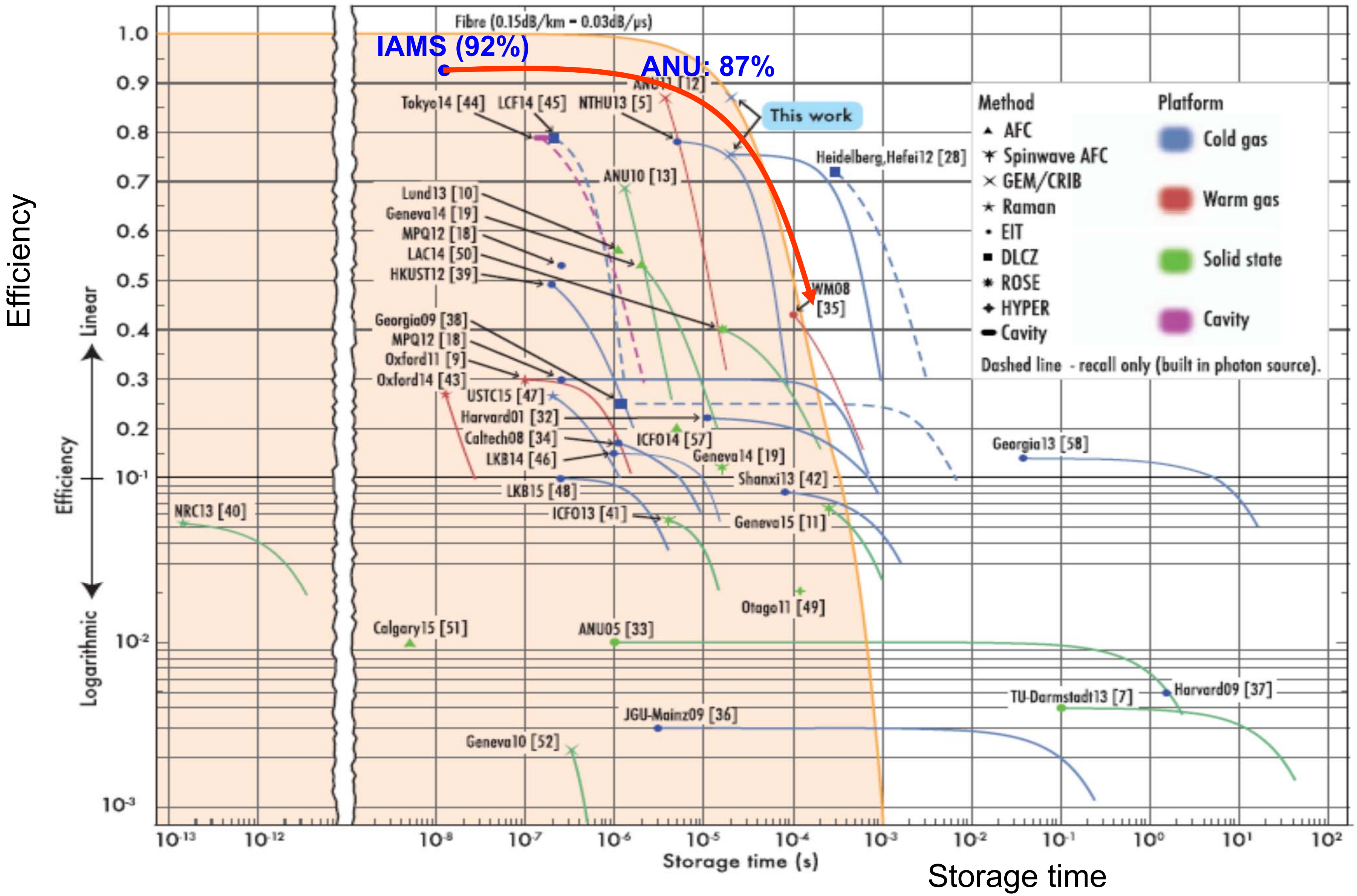
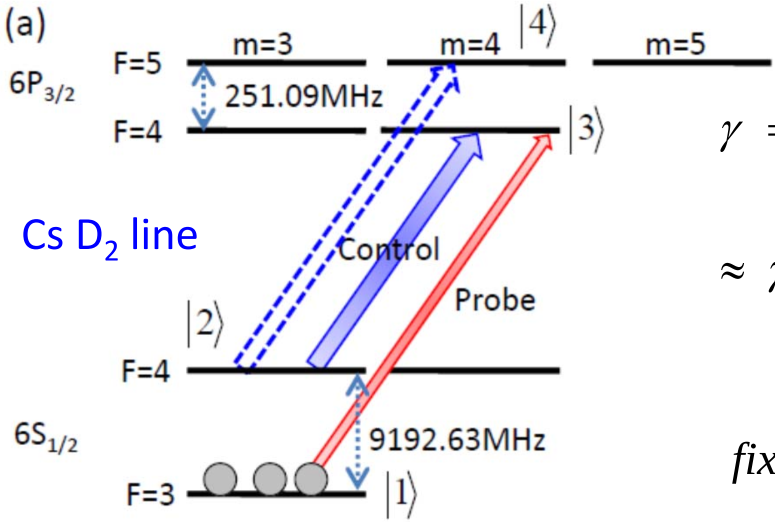


Figure from PK Lam et al. Optica, 3, 1(2016)

Complications 1/2; photon switching effect

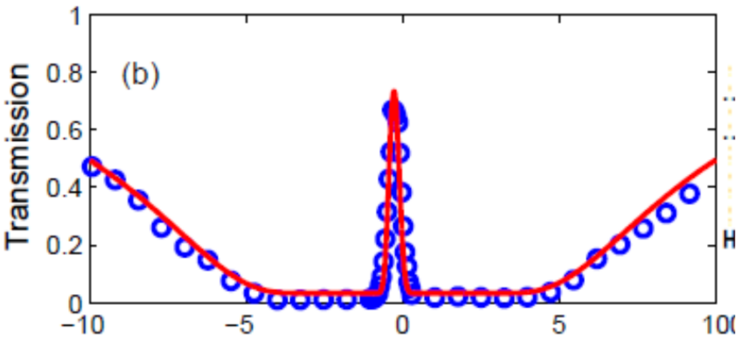
- Off-resonant excitation of the control field to nearby transitions induces a control-intensity-dependent decoherence rate.
- Resolve this problem by implementing EIT in cesium D_1 line and conducting Zeeman-state optical pumping.

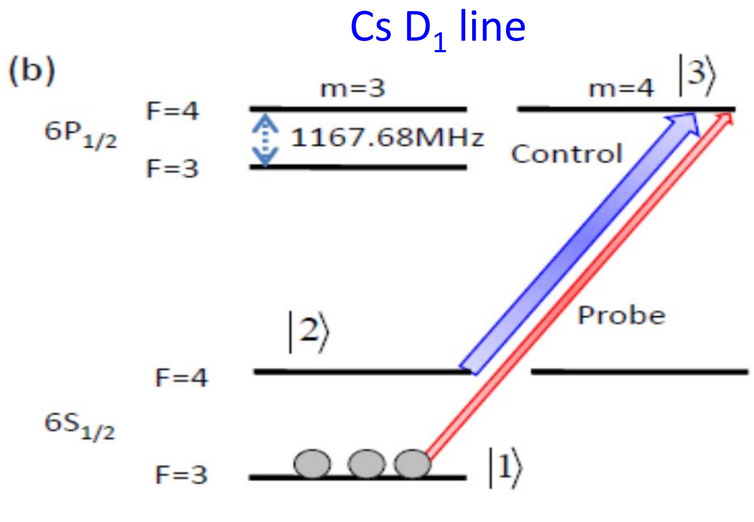


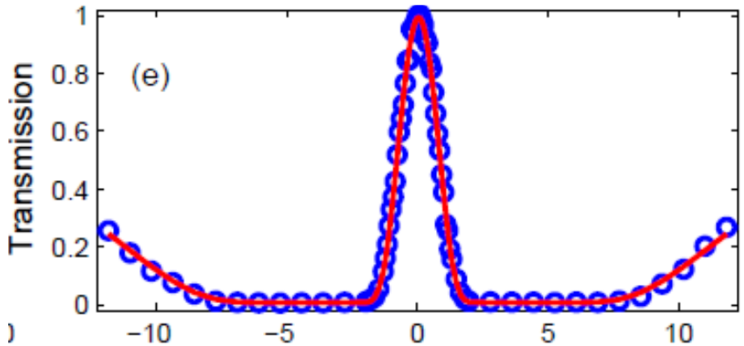
$$\gamma = \gamma_0 + \frac{\Omega_c^2 \Gamma}{2\Omega_c^2 + \Gamma^2 + 4\Delta^2}$$

$$\approx \gamma_0 + \frac{\Omega_c^2}{4\Delta^2}\Gamma$$

$$fixed \quad , T_d = \frac{(OD)\Gamma}{\Omega_c^2}$$

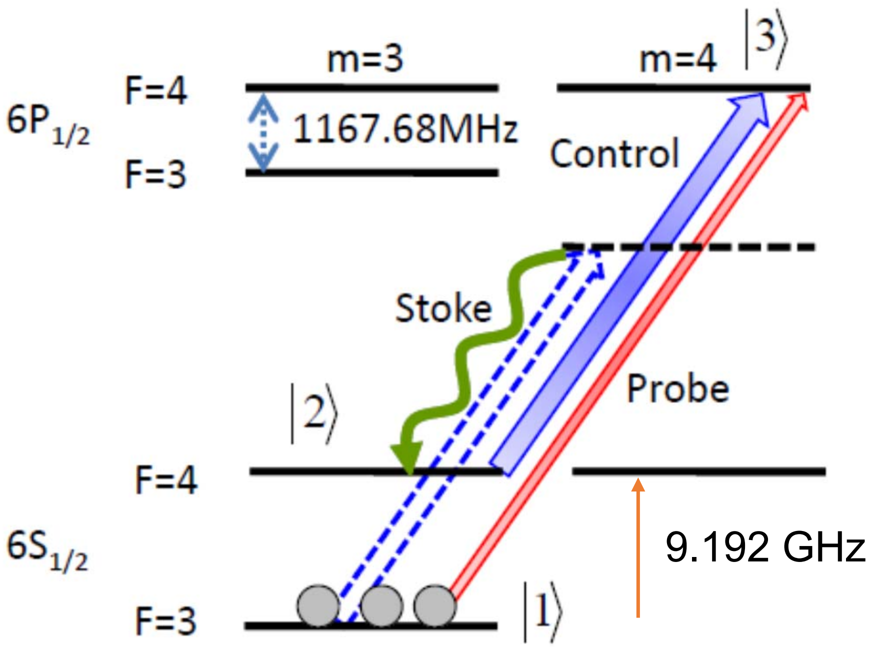




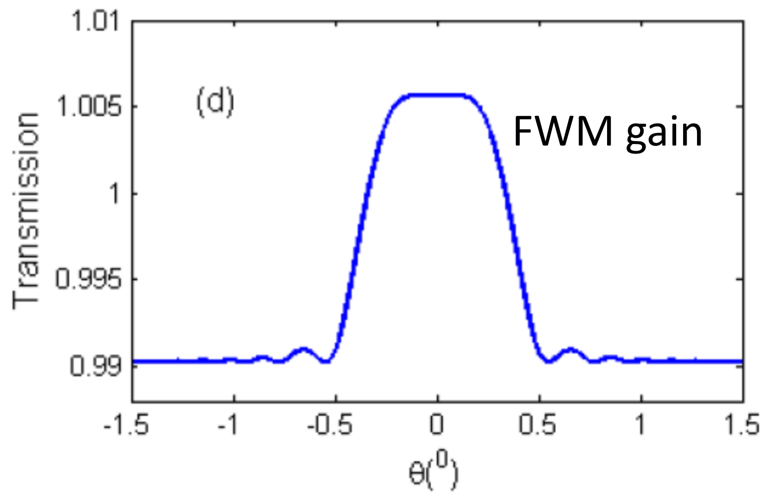


Complications 2/2 : Four-wave mixing

- Off-resonant excitation of the control field on the probe transition induces the FWM, which introduce quantum noise to reduce the memory fidelity.
- Reduce the FWM by breaking the phase matching condition through the geometry arrangement between the control and probe beams.



$$\Delta k_z = (\vec{k}_{probe} - 2\vec{k}_{control} + \vec{k}_{Stoke}) \bullet \hat{z}$$

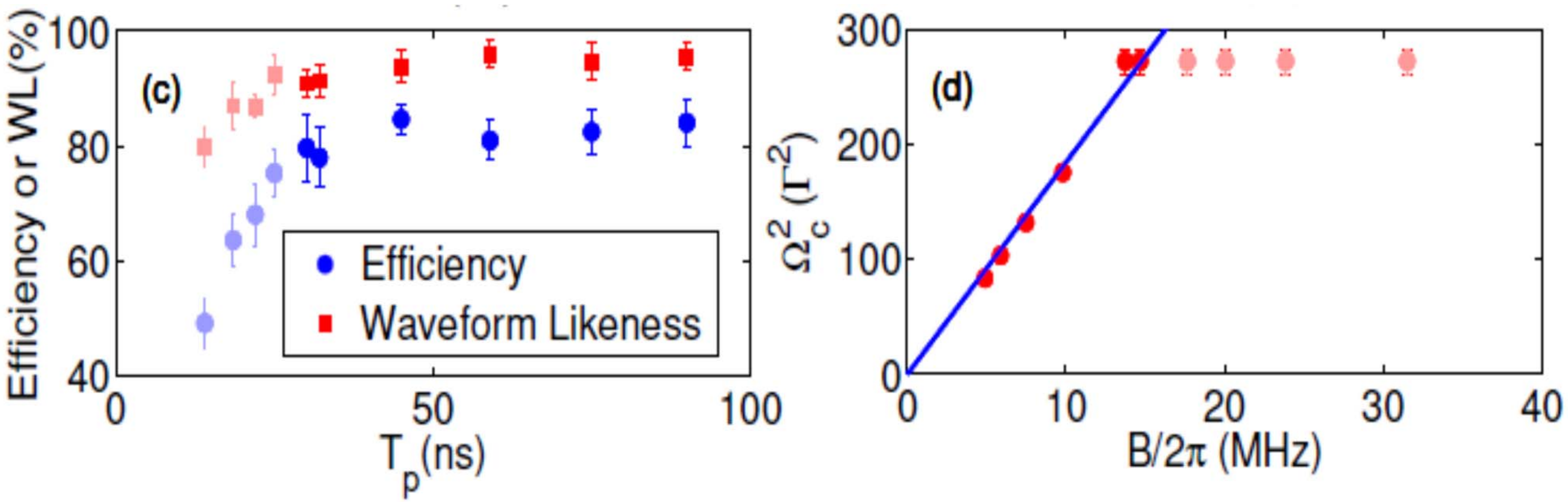


Y-F. Hsiao…, YCC* Opt. Lett. 39, 3394(2014)
Y.-F. Hsiao…YCC*, PRL. 120, 183602(2018)

Fleischhauer et al., PRA 88, 013823(2013);

Towards broadband EIT-based optical memory

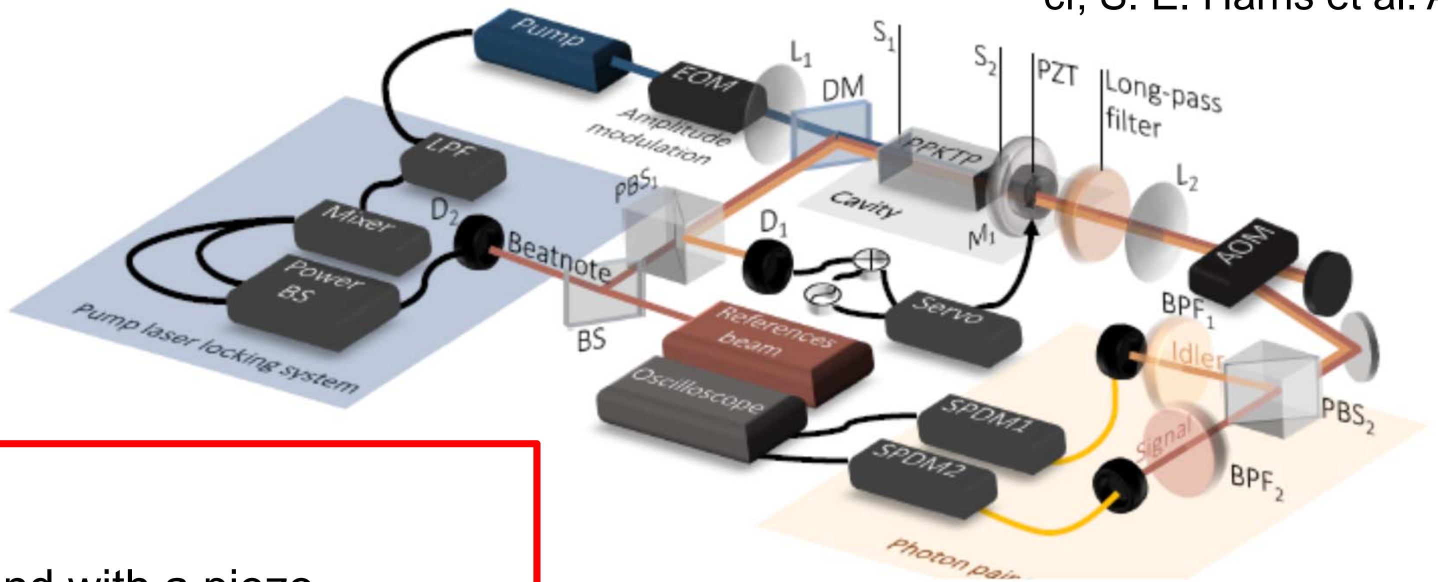
- High optical depth & strong control field are requirements to achieve a high bandwidth.
- Achieved > 80% efficiency for 30-ns pulses (~15MHz) and > 50% efficiency for 14 ns pulses (31MHz).
- Currently limited by available control power towards even higher bandwidth.



Y.-C. Wei,…, YCC*, Phys. Rev. A. 102, 063720(2020)

Photon-pair source by cavity-enhanced spontaneous parametric down-conversion (SPDC)

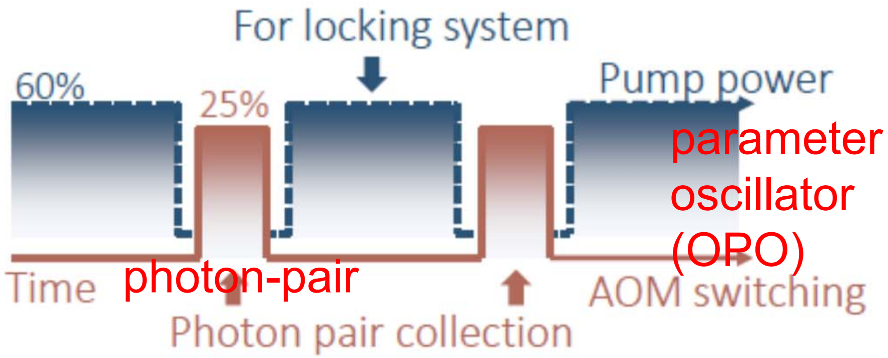
cf, S. E. Harris et al. APL 101,051108



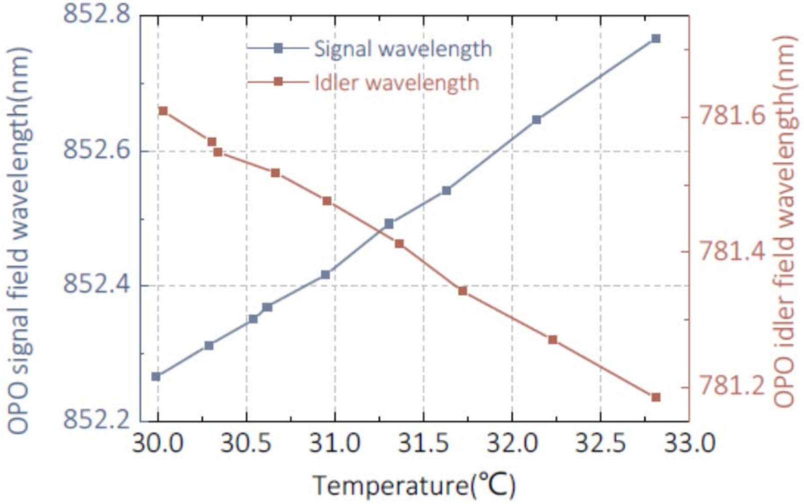
Features

1, One cavity end with a piezo,
easy tuning & frequency locking

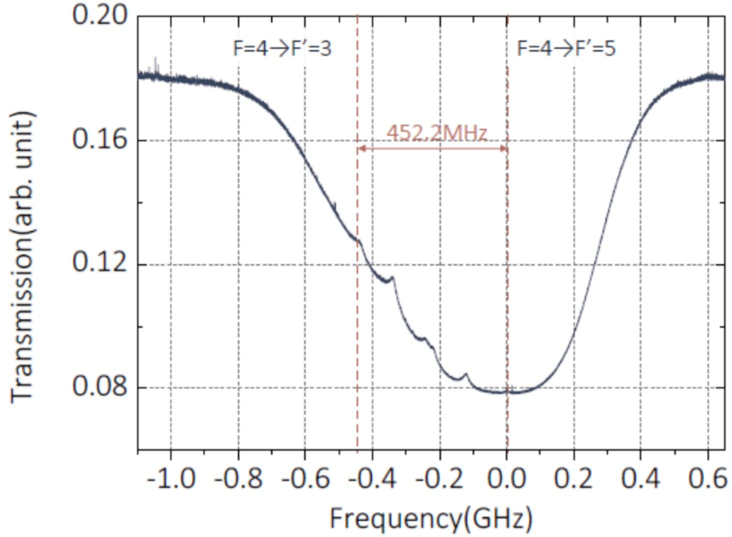
2, Switching OPO/photon-pair modes,
OPO allow easy wavelength monitoring & alignment



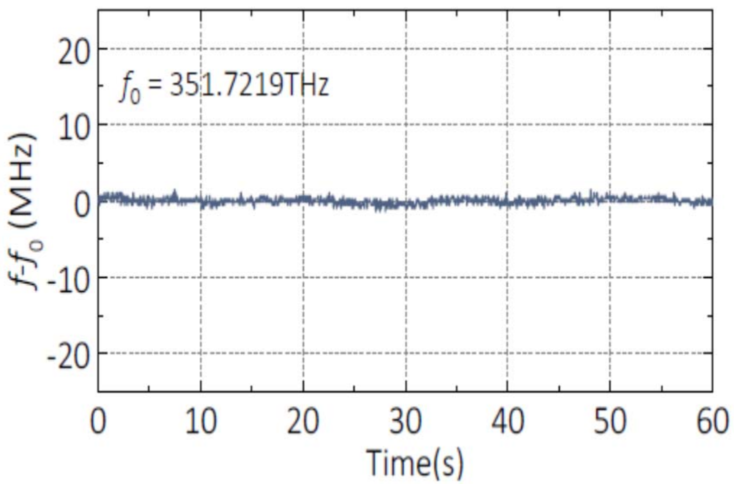
Wavelength tuning



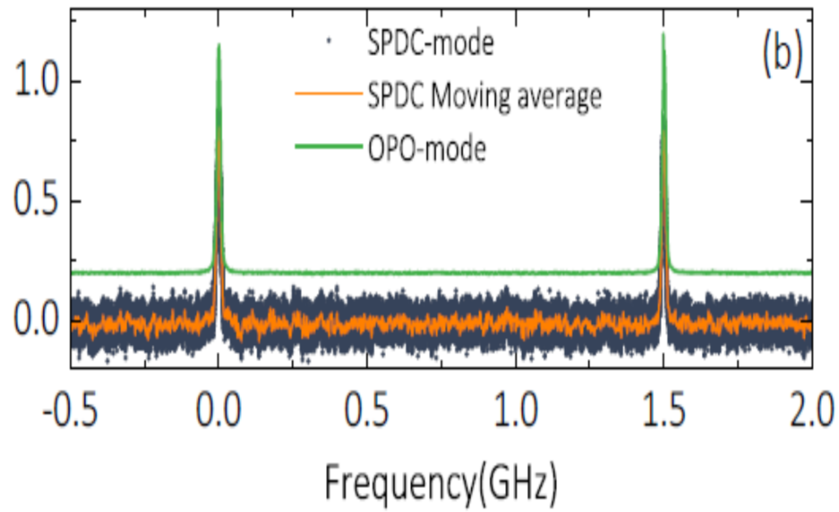
Cesium D_2 line



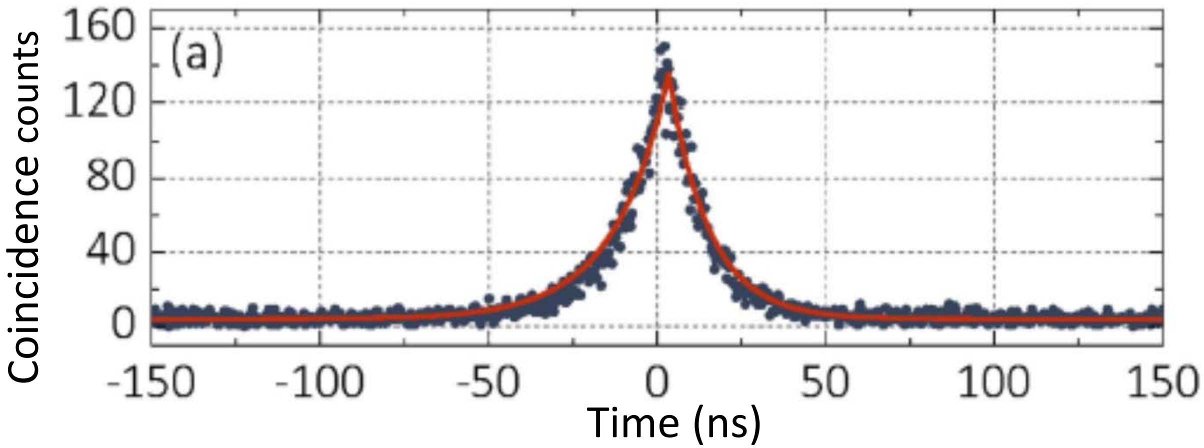
Frequency stabilization



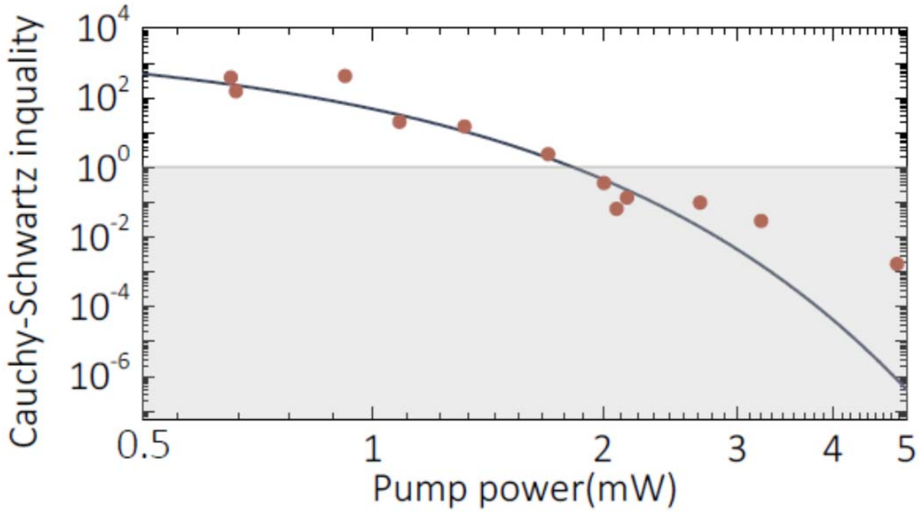
Single longitudinal mode



Glauber correlation function $G^{(2)}_{s,i}(\tau) = \langle \hat{a}^{\dagger}_i(t+\tau)\hat{a}^{\dagger}_s(t)\hat{a}_s(t)\hat{a}_i(t+\tau)\rangle$



- Bandwidth~ 6.6 MHz, compared to Cs D_2 natural linewidth of 5.2 MHz.
- Nonclassicality: violation of Cauchy-Schwarz inequality by a factor of up to 425.

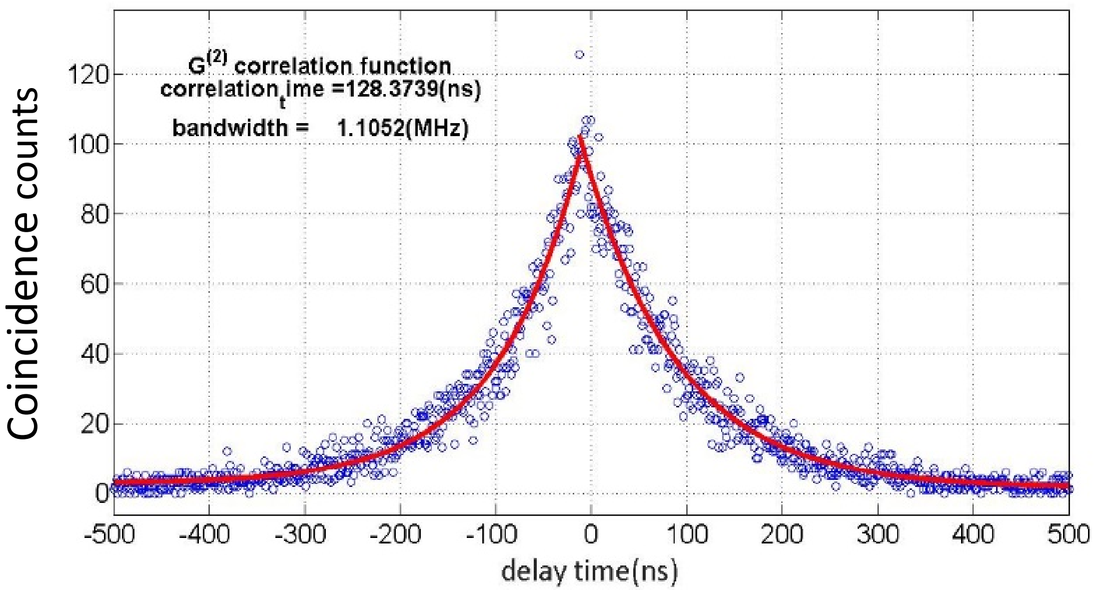


$$[g^{(2)}_{s,i}(0)]^2/[g^{(2)}_{s,s}(0)g^{(2)}_{i,i}(0)] \leq 1$$

P.-J. Tsai, YCC*, Quantum Sci & Techno, 3, 034005(2018)

An improved photon-pair source at Cs D_1 line

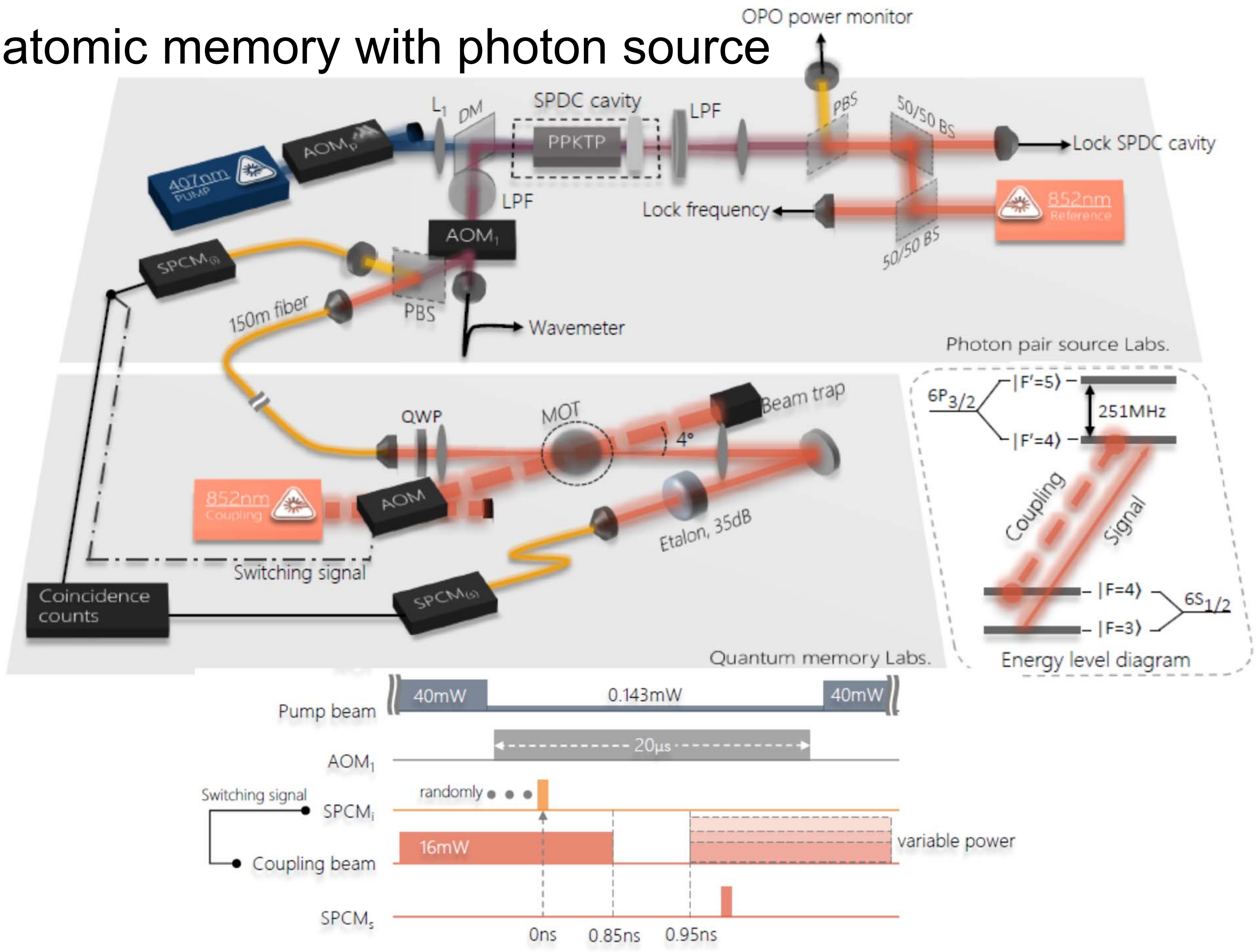
- Quantum memory operating at Cs D_1 line (~894.6 nm) is better due to a smaller photon-switching effect.
- We recently built a new photon-pair source at 894.6 nm with a bandwidth of ~2 MHz.



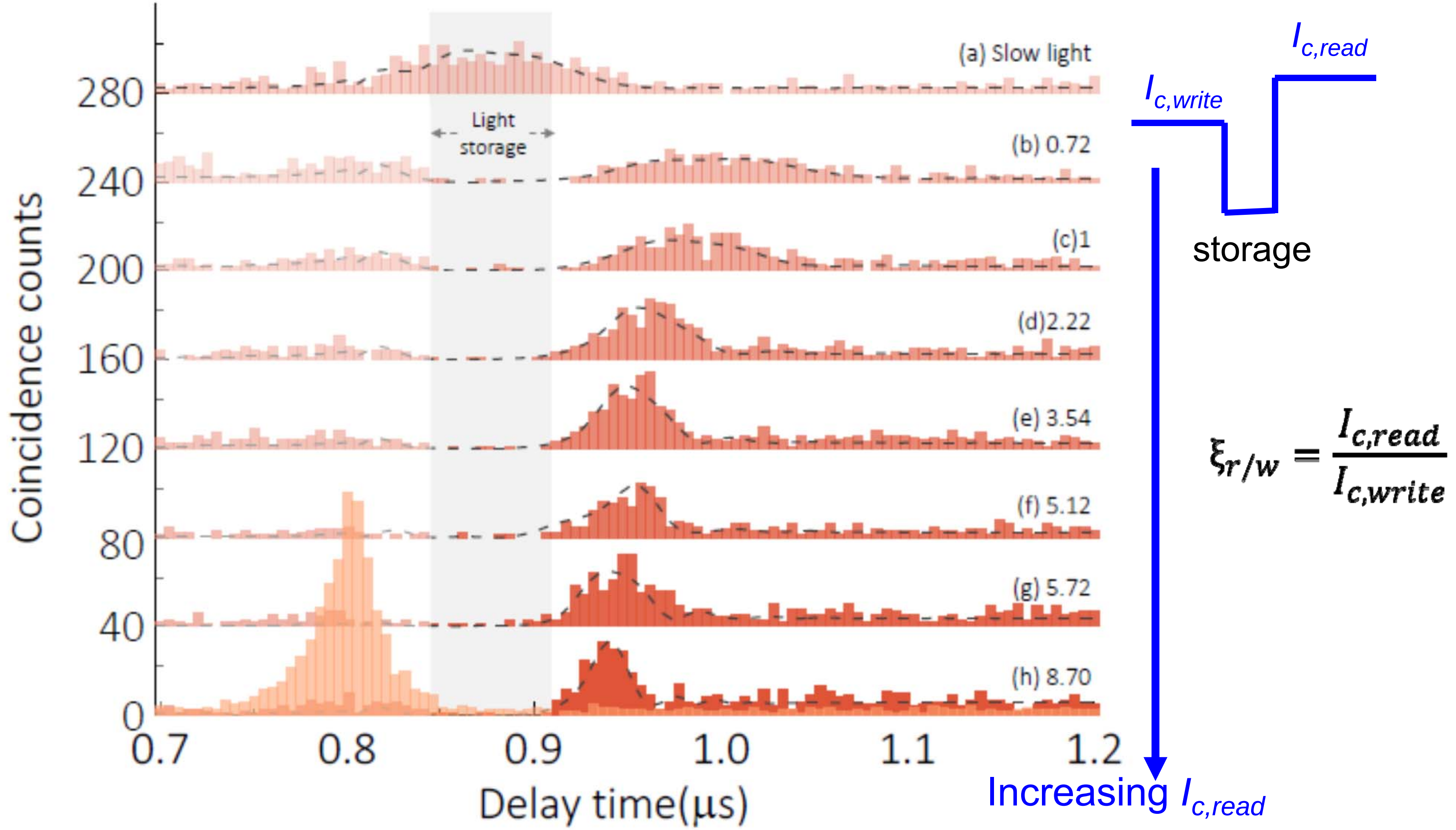
Bandwidth : 2.2 MHz

Efficient quantum memory for heralded single photons

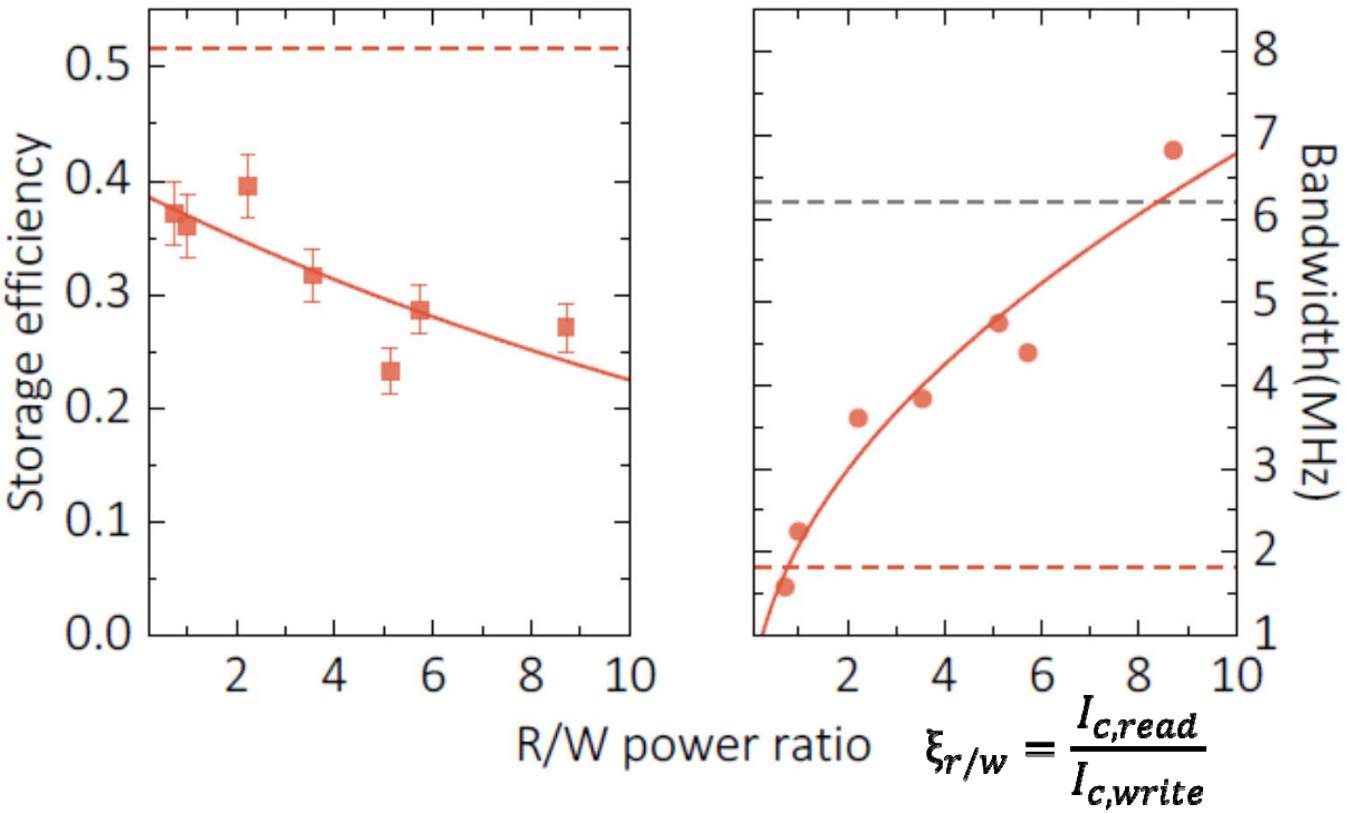
Combing atomic memory with photon source



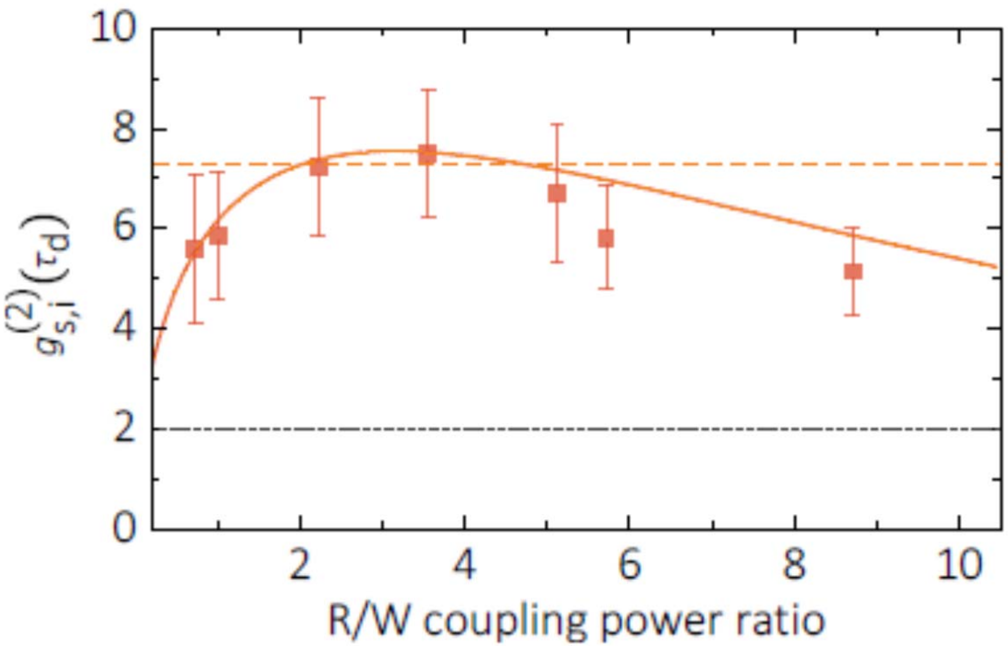
Storage and manipulation of heralded single photons



- Relatively low efficiency (~36 %) @ Cs D_2 line:
  1) bandwidth of single photons is too large
  2) D_2 line photon switching effect
  3) Optical depth not enough in the new MOT system (up to 80).
- Waveform (bandwidth) manipulation of single photons by memory



Manipulate the non-classical cross correlation



$$\xi_{r/w} = \frac{I_{c,read}}{I_{c,write}}$$

enhancement

Photon switching effect

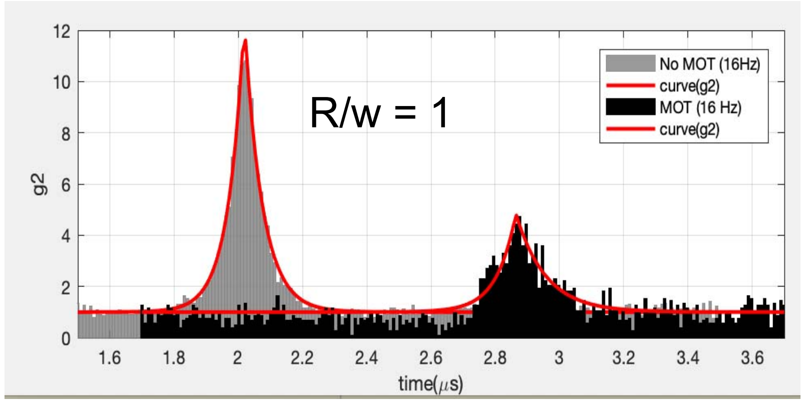
$$g^{(2)}_{s,i}(\tau_d) = \frac{N_{s,i}\sqrt{\xi_{r/w}}\,e^{-\gamma_s \xi_{r/w}}}{\alpha \xi_{r/w} + N_b},$$

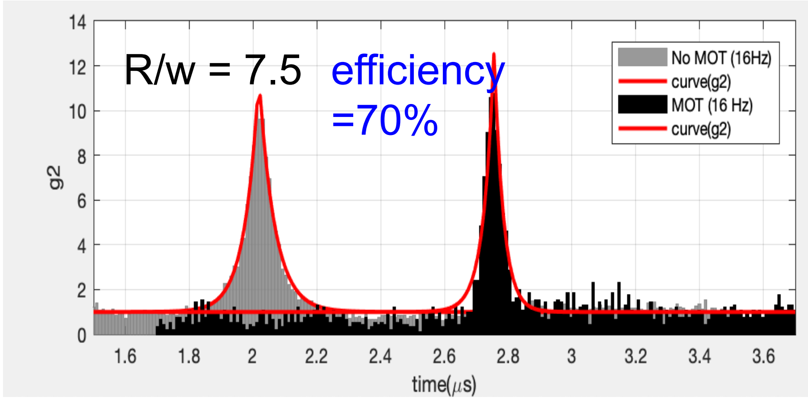
Control leakage

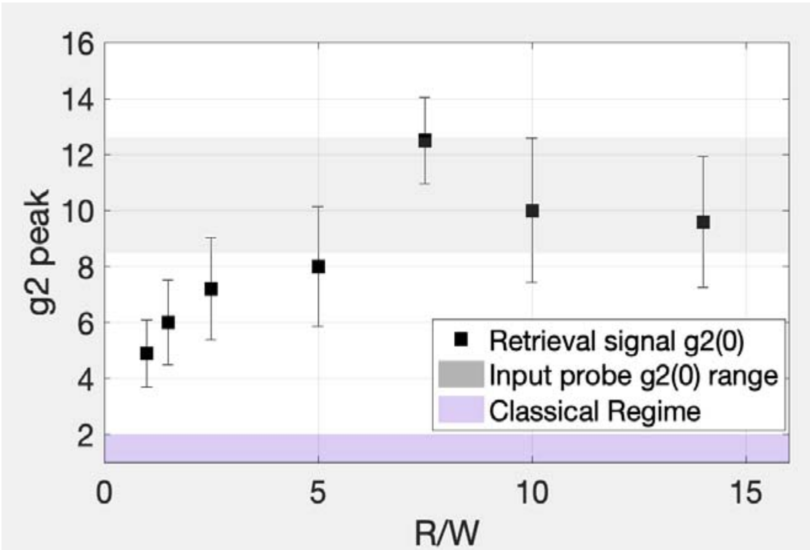
Stray light/detector dark counts

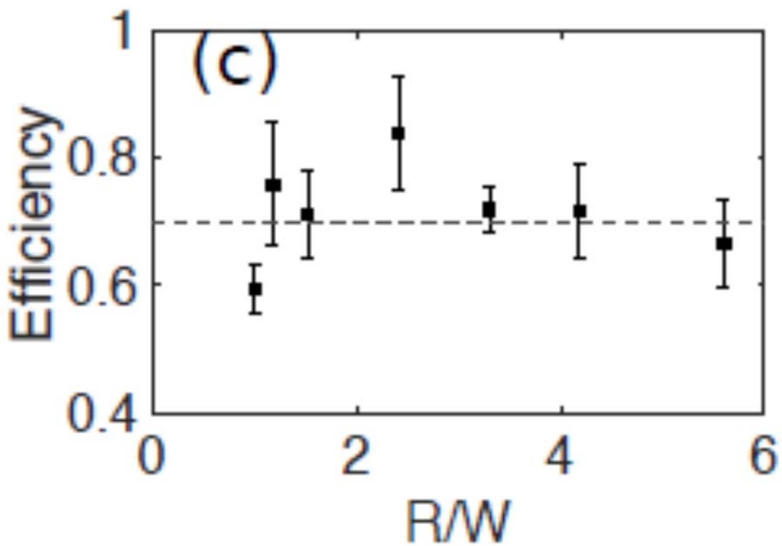
P.-J. Tsai,.., YCC*, **Phys. Rev. Reseach**, 2, 033155(2020)

Recent results for quantum storage @ D_1 EIT System

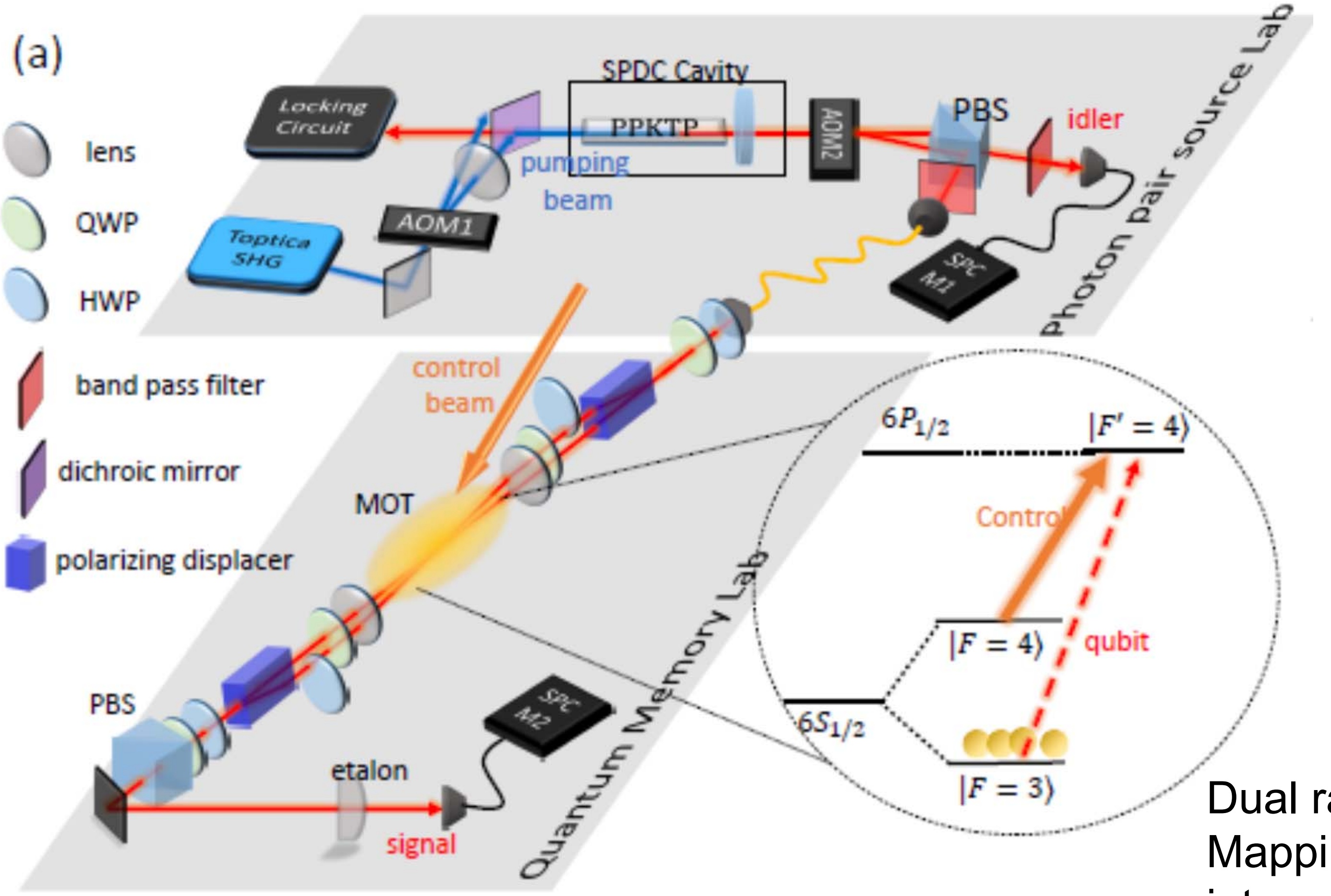








Quantum memory for polarization qubit

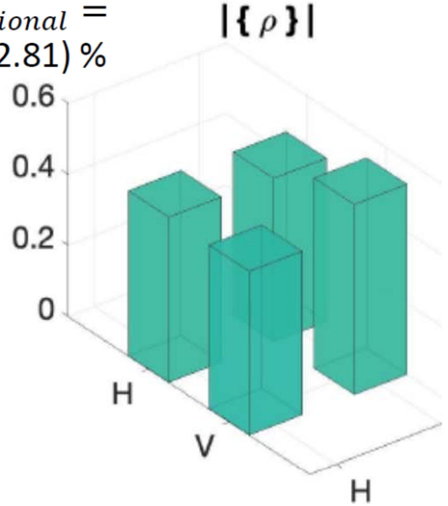


Dual rail scheme:
Mapping the polarization modes into spatial modes

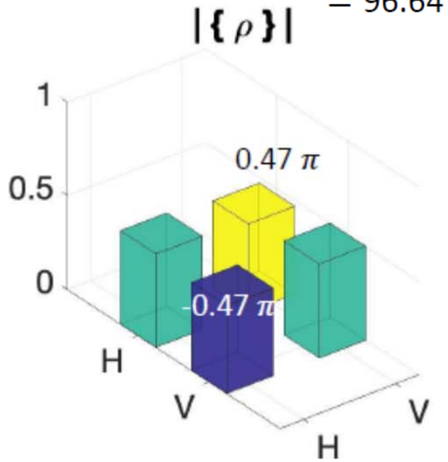
Fidelity for polarization qubits after storage

Consider $|\mathrm{D}\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$

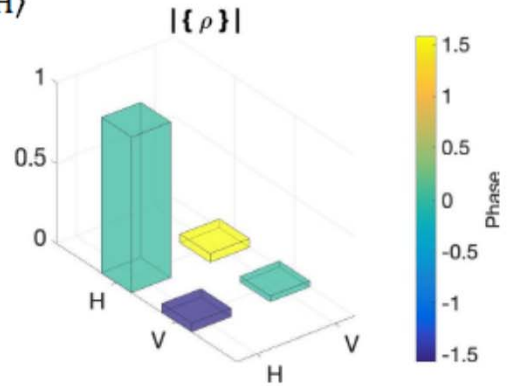
$\mathcal{F}_{conditional} =$ 95.96 (2.81) %



Consider $|\mathrm{R}\rangle = \frac{1}{\sqrt{2}}|(H\rangle + i|V\rangle)$ $\mathcal{F}_{conditional}$ = 96.64 (3.12)%

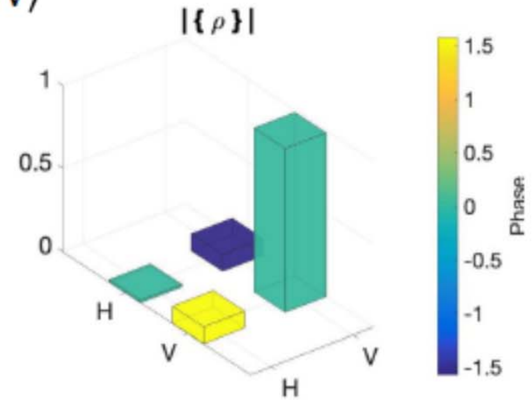


$|\mathrm{H}\rangle$



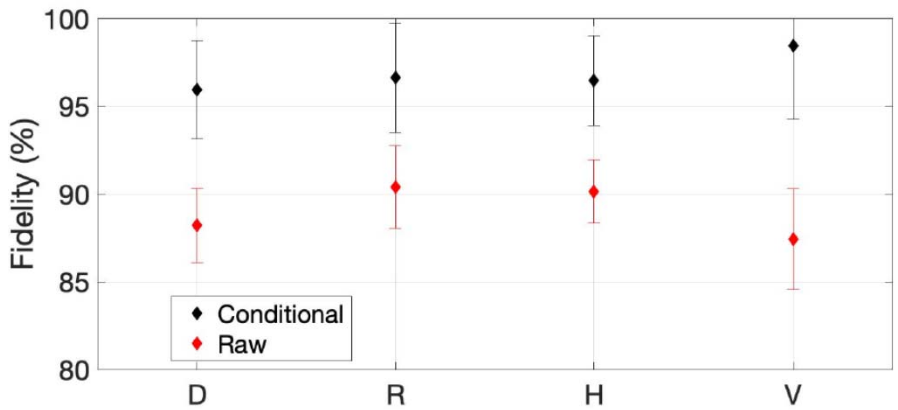
$\mathcal{F}_{conditional}$ = 96.47 (2.55) %

$|\mathrm{V}\rangle$



$\mathcal{F}_{conditional}$ = 98.45 (4.17) %

Fidelity > ~96% for four polarization states



Y.-C. Tseng, …, YCC*, **arXiv**:2011.14948

Conclusions

- Obtain a high optical depth (>1000) and a low decoherence rate ($10^{-4}\,\Gamma$) with a MOT setup.
- Obtain a record-high storage efficiency of 92% for EIT-based coherent optical memory!
- Push the EIT-memory bandwidth to ~30 MHz .
- Developed a bright, narrowband, single-mode, and convenient photon-pair source lockable to atomic transition.
- Demonstrated quantum storage and manipulation of single photons with EIT atomic memories (36% efficiency @ Cs D_2 line and >70% @ D_1 line)
- Demonstrated quantum memory for polarization qubits with a fidelity > 96%.

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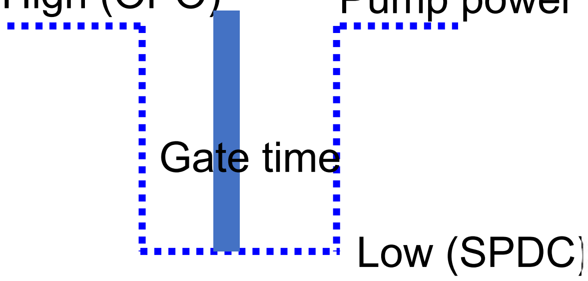
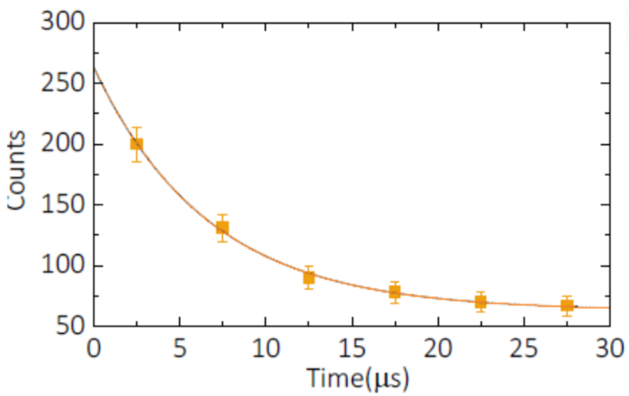
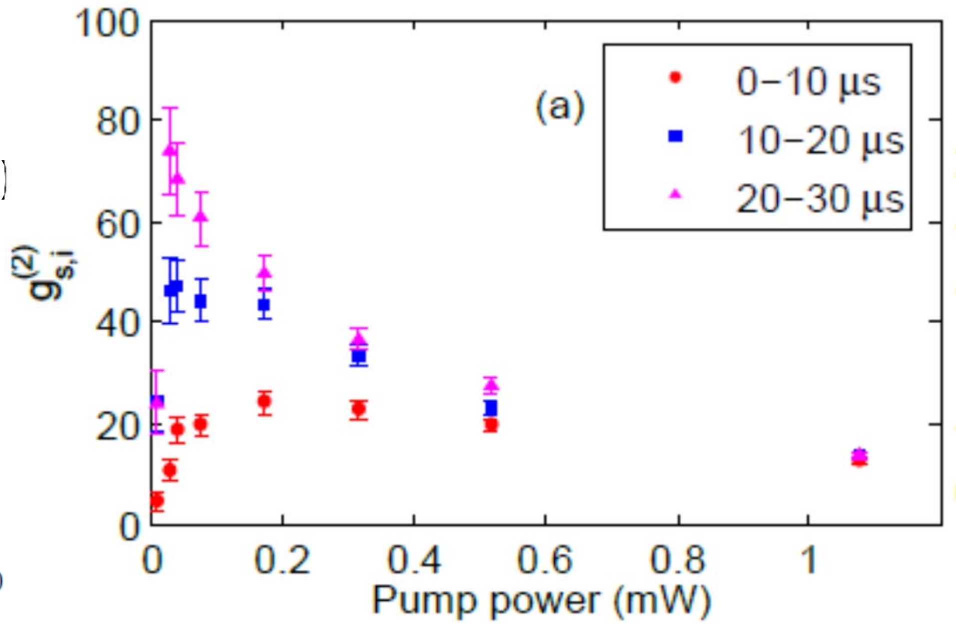
Noise Sources

- Noise is a serious issue in quantum storage which degrades the quantum feature.
- Noises from SPDC photon source, stray light, control leakage, Raman-generated photons due to cold atom and hot vapor…





The OPO leakage !



Noise from Raman-generated Photons

- These highlight the absolute requirement of quantum technology!