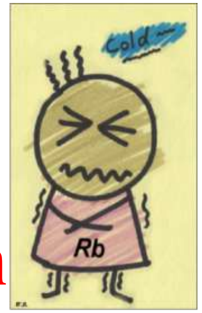


From the Hot-Atom Source of Heralded Single Photons for Quantum Communication to the Cold-Atom Many-Body System of Dark-State Polaritons for Realization of a New-Type BEC

Electromagnetically Induced Transparency (EIT) and Slow Light

Ite A. Yu

Department of Physics & Center for Quantum Science and Technology
National Tsing Hua University

Acknowledgements

Collaborators in the Studies of Heralded Single Photon (HSP)

Dr. Ying-Cheng Chen
AS

Prof. Yong-Fan Chen
NCKU

Prof. Chih-Sung Chuu
NTHU

NSTC 112-2112-M-007-020-MY3, 112-2119-M-007-007, and 111-2639-M-007-001-ASP

Collaborators in the Studies of Dark-State Polariton (DSP)

Gediminas
Juzeliūnas
Vilnius U.

Marcis
Auzinsh
U. Latvia

Wen-Te Liao
Natl. Central
U.

Ying-Cheng
Chen
Academia
Sinica

Julius
Ruseckas
Vilnius U.

Teodora
Kirova
U. Latvia

Yi-Hsin
Chen
Natl. Sun
Yat-sen U.

Yong-Fan
Chen
Natl. Cheng
Kung U.

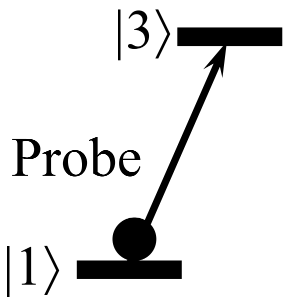
NSTC 111-2639-M-007-001-ASP
Taiwan-Latvia-Lithuania Collaboration Program NSTC 111-2923-M-008-004-MY3

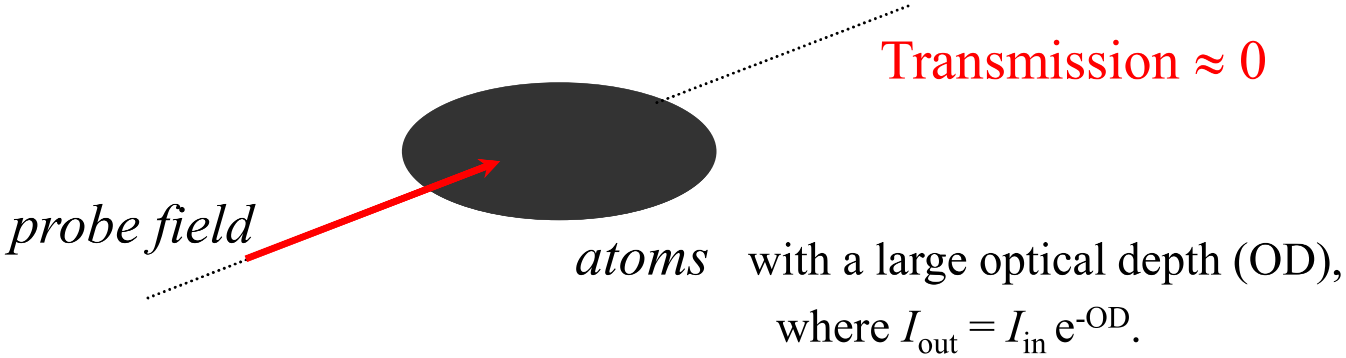

霞喀羅古道石鹿登山口
2024/8/29
2024.08.29 07:27

Group Members 2023/2/13

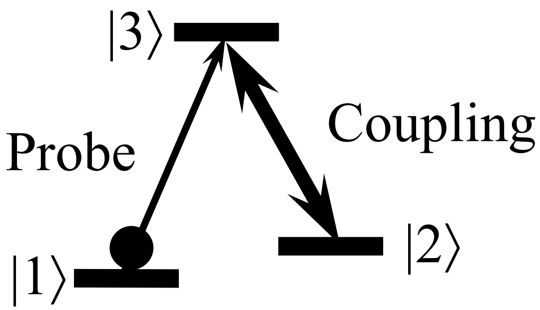
Electromagnetically Induced Transparency,
Slow Light,
Light Storage or Quantum Memory,
and
Stationary Light

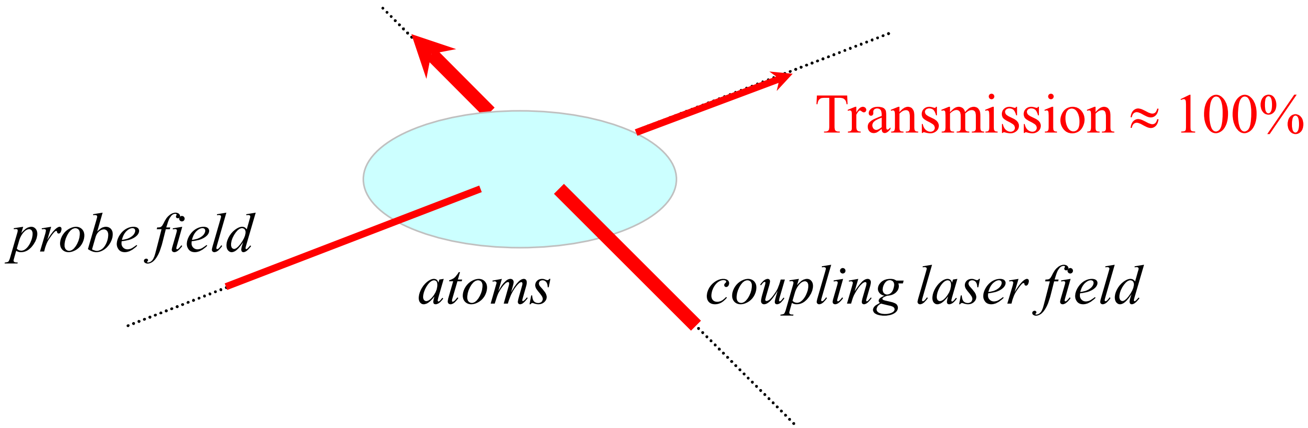
Electromagnetically Induced Transparency (EIT) Effect





- A probe field is tuned to the resonance.
- The probe suffers a large absorption due to a large OD.

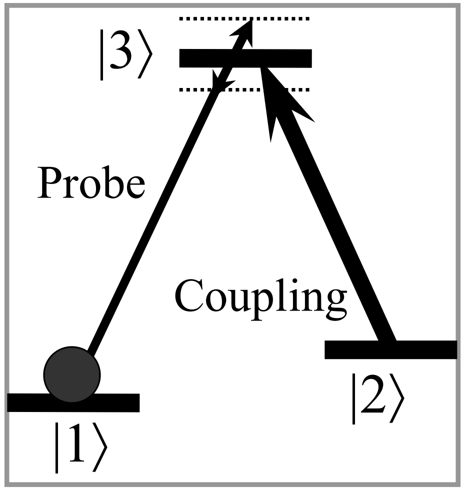




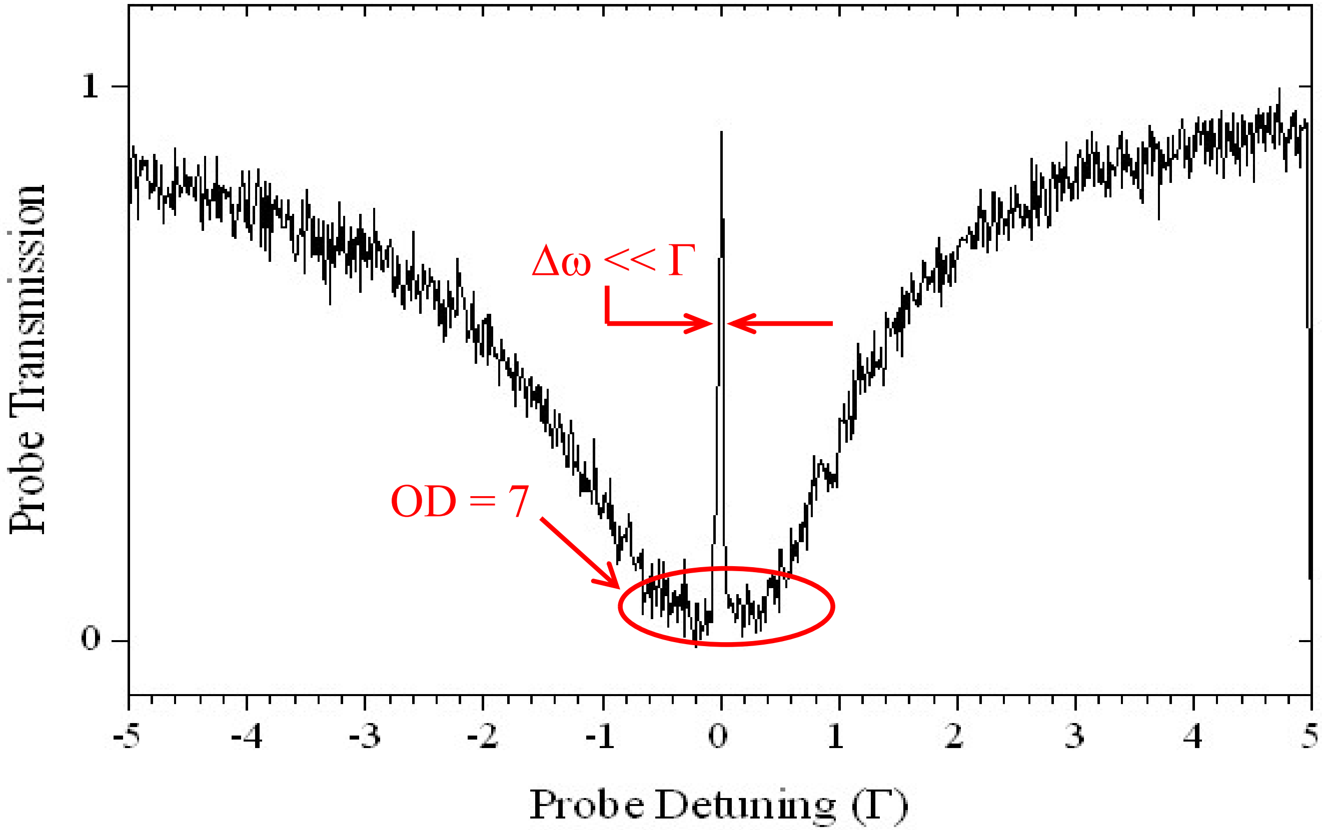
- The presence of a coupling field can suppress the absorption.
- The coupling (**EM** wave) **makes** the medium **transparent** for the probe due to quantum interference.

EIT Spectrum

Y. F. Chen, Y. C. Liu, Z. H. Tsai, S. H. Wang, & IAY, PRA 72, 033812 (2005).



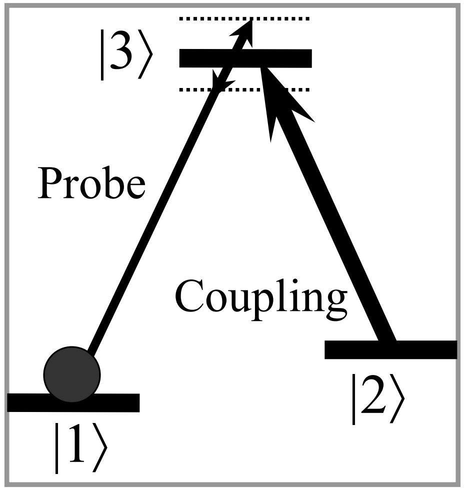
Γ = 6 MHz is the natural linewidth of the excited state |3⟩.



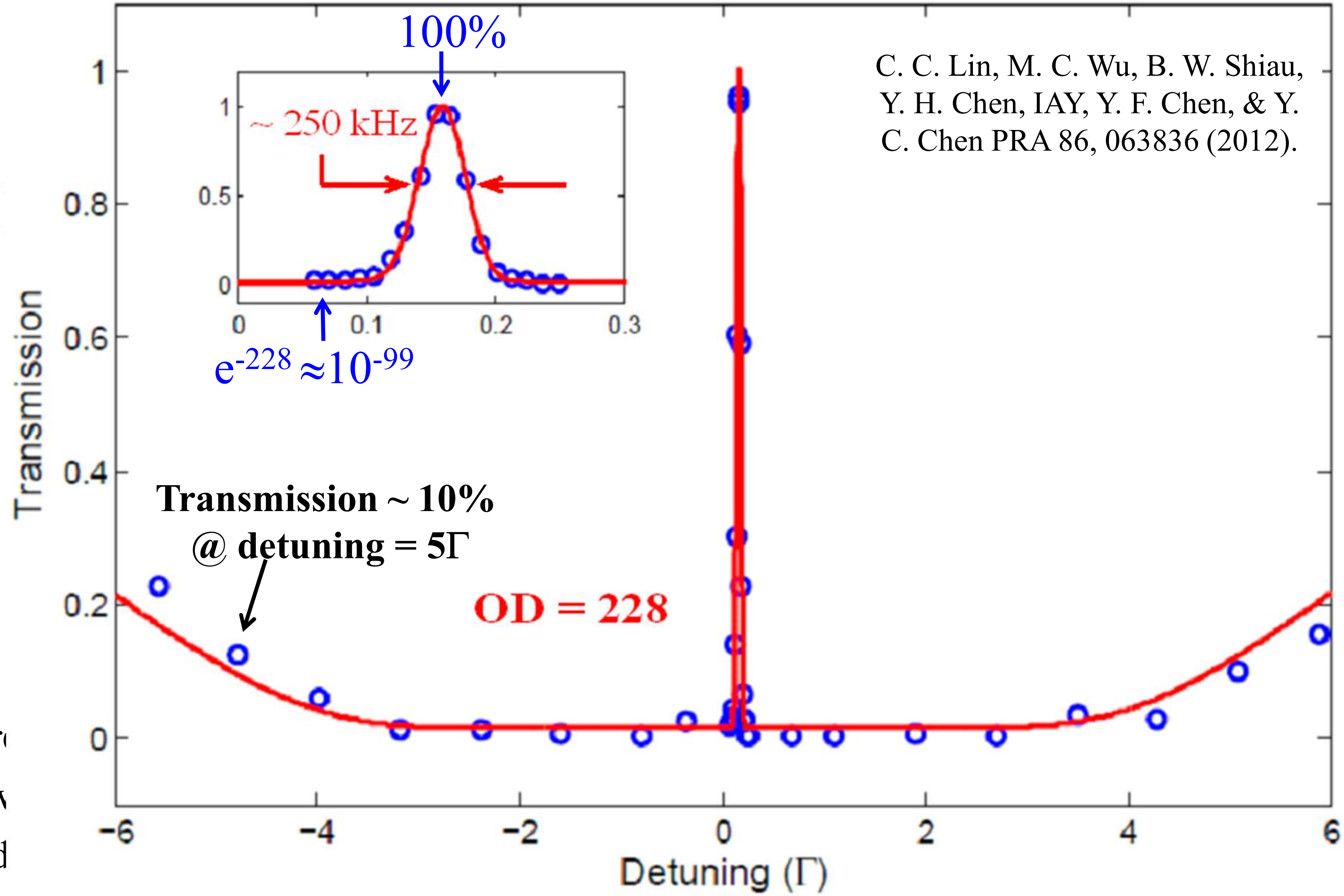
- Near the resonance frequency, T is nearly 0 ($e^{-7} \approx 0.1\%$). Right on the resonance frequency, $T \approx 100\%$.
- Transparency window is much narrower than the natural linewidth, Γ.
- The high-contrast and narrow-width spectrum reveals a large chromatic dispersion.

EIT Spectrum

Y. F. Chen, Y. C. Liu, Z. H. Tsai, S. H. Wang, & IAY, PRA 72, 033812 (2005).



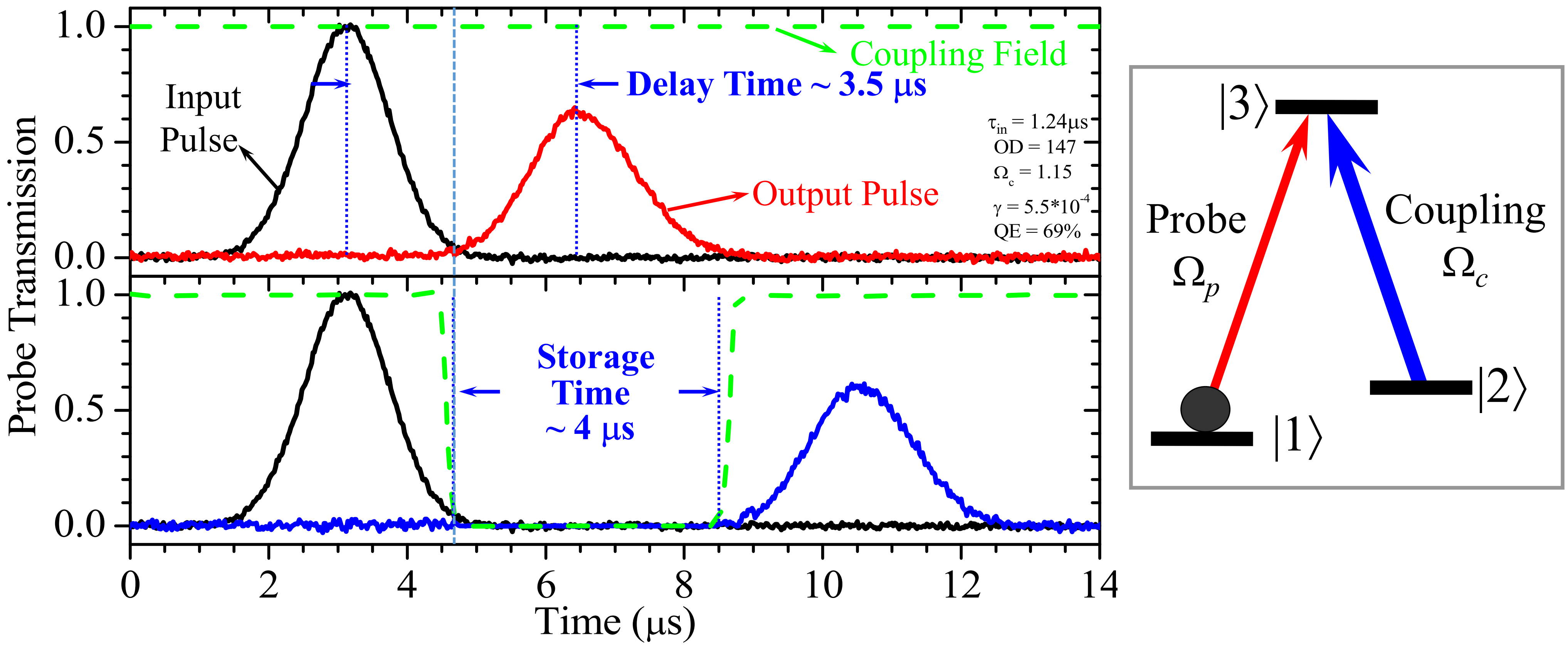
Γ = 6 MHz is the natural linewidth of the excited state |3⟩.



- Near the resonance fr
- Transparency window
- The high-contrast and

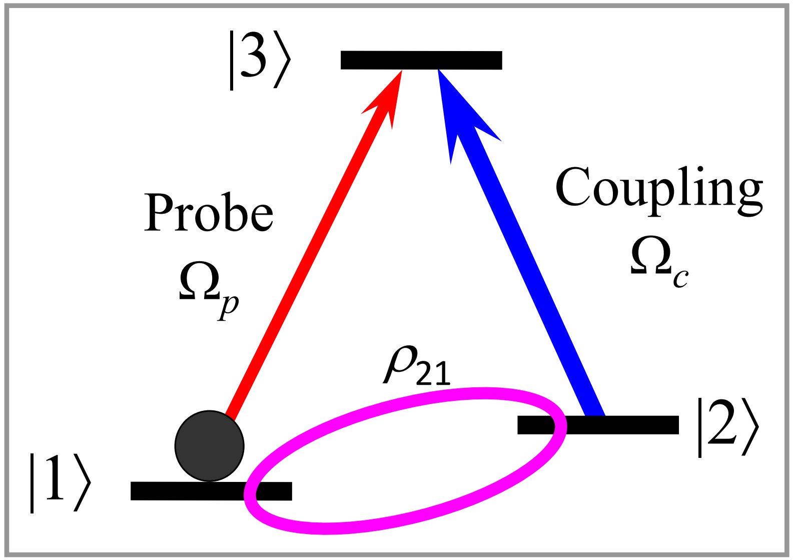
Slow Light and Storage of Light

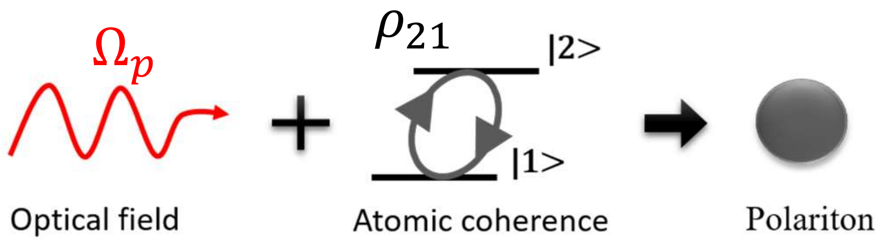
Y. H. Chen, M. J. Lee, I. C. Wang, S. Du, Y. F. Chen, Y. C. Chen, & IAY, PRL 110, 083601 (2013).



- The EIT effect gives rise to slow light and storage of light.
- In the constant presence of the coupling, the light speed $\leq c/10^5$. The 1 km-long pulse is compressed to 1 cm in the atoms. The gap of ~ 4 μs in the probe signal demonstrates the storage of light.

Dark-State Polariton (DSP)





$$\Psi = \cos\theta\,\Omega_p - \sin\theta\,\sqrt{\eta c}\,\rho_{21}; \qquad \tan\theta = \frac{\sqrt{\eta c}}{\Omega_c}$$

η: OD per unit length

$$\frac{\partial \Psi}{\partial t} + \frac{\Omega_c^2}{\eta\Gamma}\frac{\partial \Psi}{\partial z} - \frac{\Omega_c^2}{2\eta^2\Gamma}\frac{\partial^2 \Psi}{\partial z^2} = 0$$

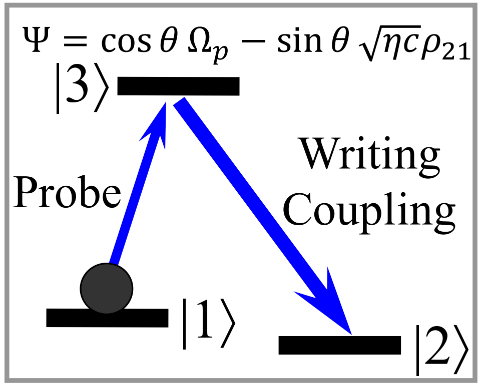
Group velocity　　Loss due to EIT bandwidth

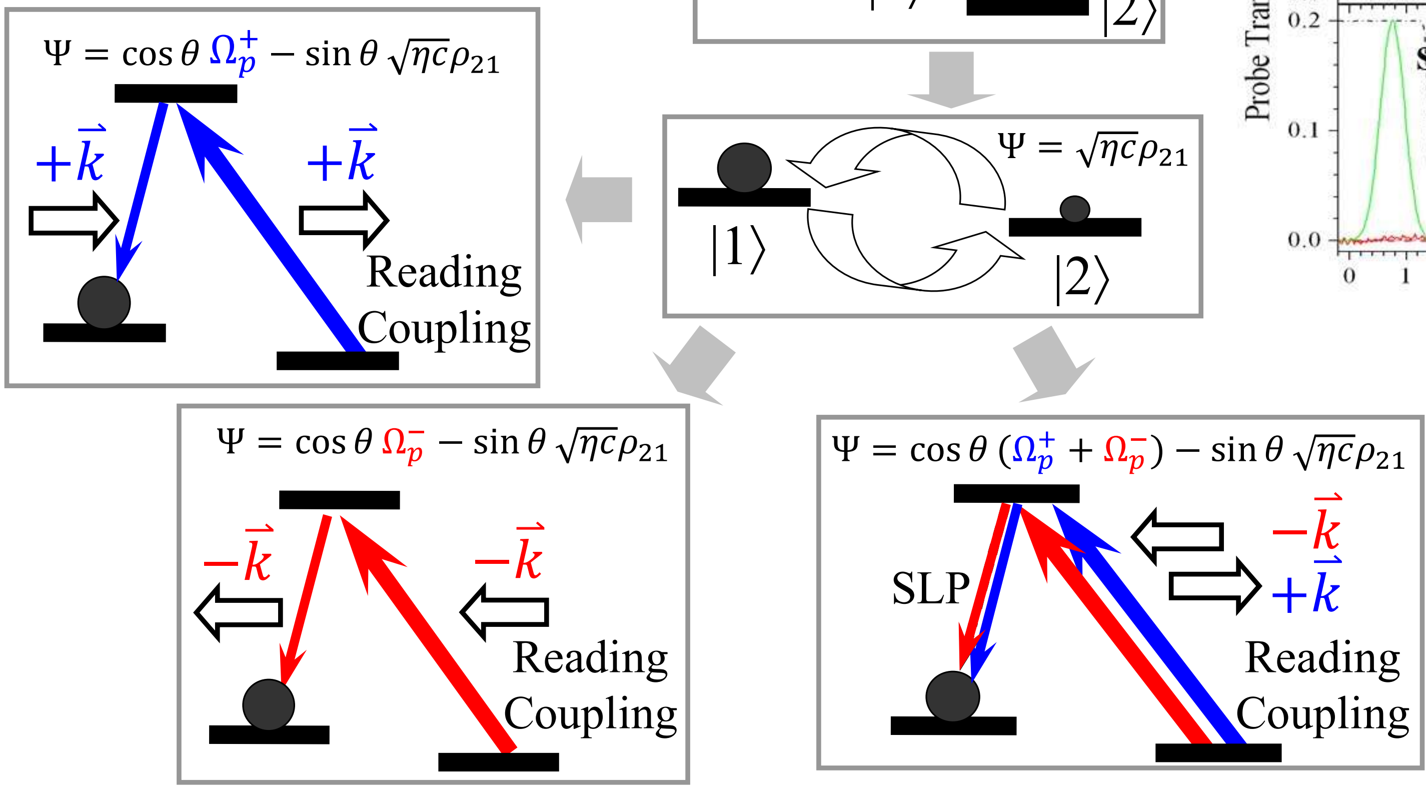
- The coupling and probe generate the ground-state coherence ρ_{21} in the EIT system, which is an indication of a stronge light-matter coupling, i.e., slow light.
- To describe the collective behavior of photons and atoms under the strong coupling, the DSP is the superposition of photon and atomic coherence, a bosonic quasi-particle.

Storage and Retrieval

Light storage is the exchange of wave functions between photons and atoms, i.e., quantum memory.

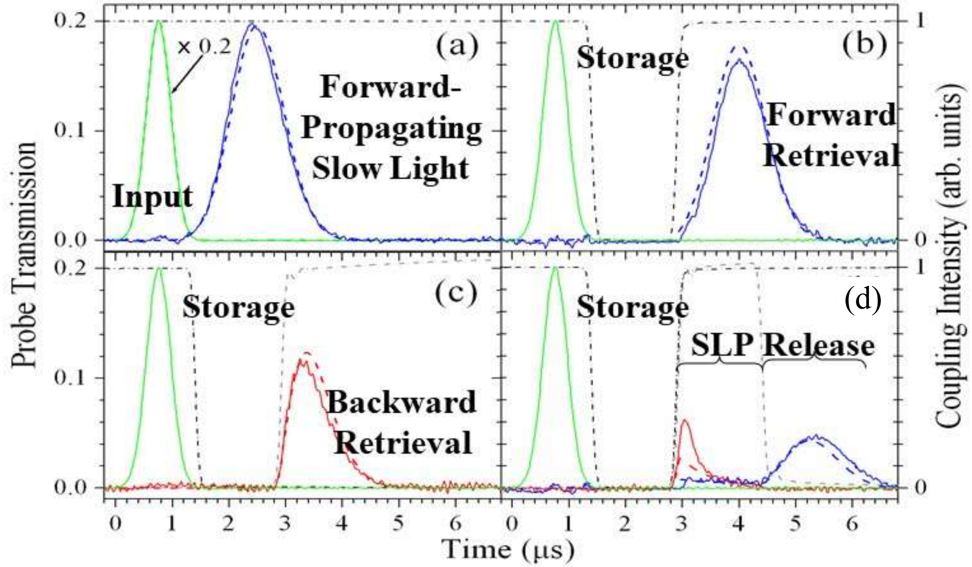
$$\tan\theta = \sqrt{\eta c}/\Omega_c$$





Observation of SLP or SDSP

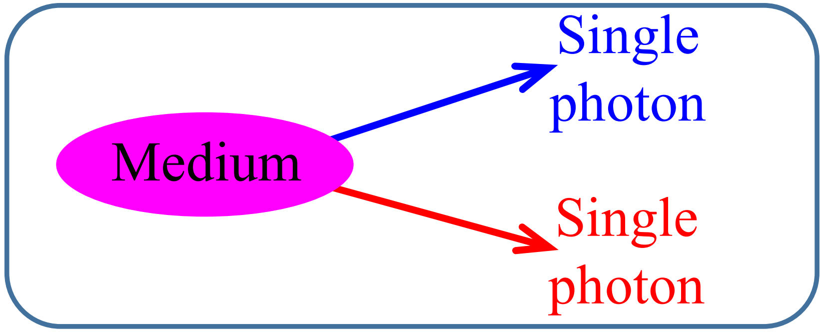
Y. W. Lin, W. T. Liao, T. Peters, H. C. Chou, J. S. Wang, H. W. Cho, P. C. Kuan, & IAY, PRL 102, 213601 (2009).



The stationary light pulse (SLP) is formed by the four-wave mixing (FWM) retrieval, i.e., by simultaneously switching on the forward and backward coupling fields to make the probe photons proceed the random walk.

A Narrow-Linewidth High-Brightness Biphoton Source

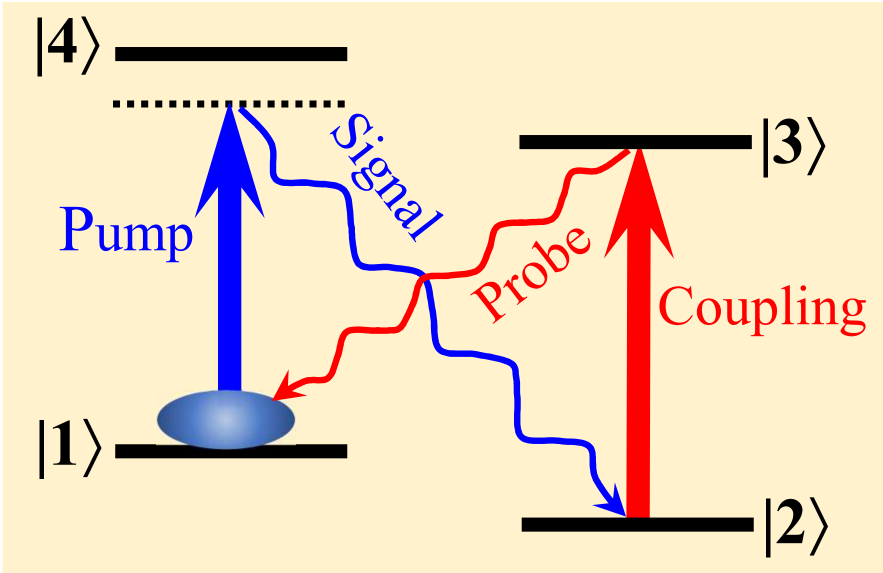
What are heralded single photons or, aka, biphotons? Why are they useful?



- The **biphoton** is a pair of time-correlated single photons.
- Single photons are optical qubits, but they appear randomly in time. It is difficult to use qubits in the random timing.
- Biphotons also appear randomly in time.
- The second photon of a pair is called the **heralded single photon (≡ biphoton)**.
- It is more convenient to use heralded single photons or qubits in quantum communication or quantum information processing.

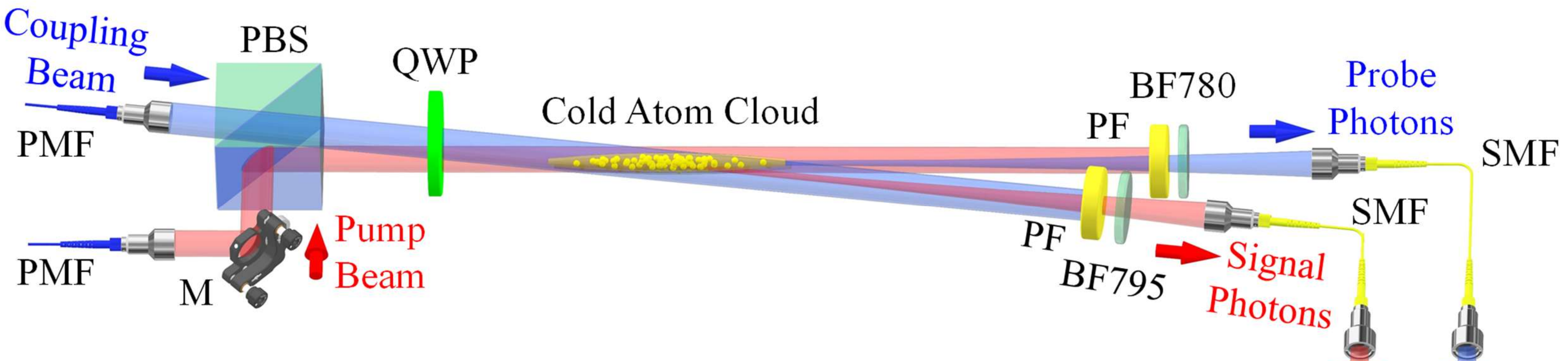
Biphoton Sources Based on Atoms and SFWM

J.-M. Chen, T. Peters, P.-H. Hsieh, & IAY, "Review of Biphoton Sources based on the Double-Λ Spontaneous Four-Wave Mixing Process," Adv. Quantum Technol. 7, 2400138 (2024).

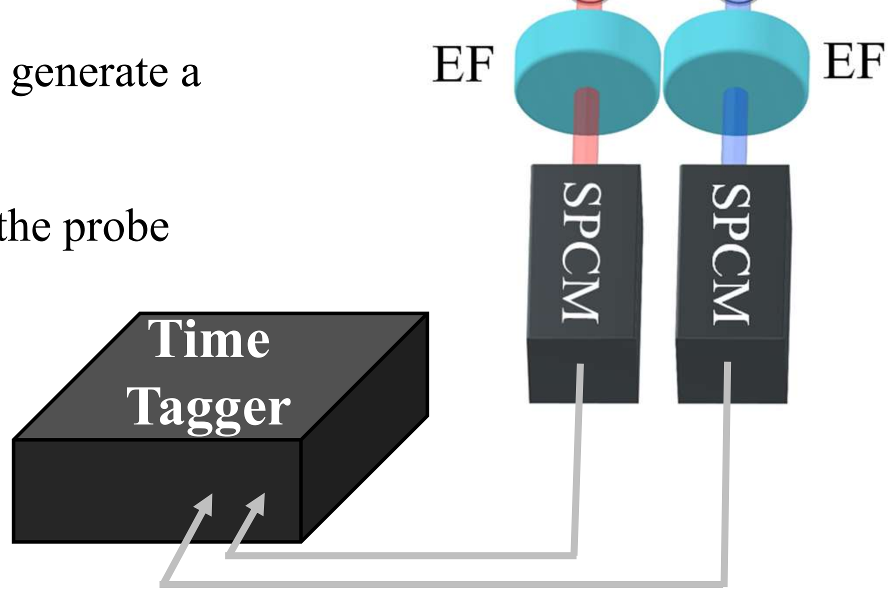


- The vacuum fluctuation induces a Raman transition to generate the signal photon and also the coherence between states 1 and 2.
- The coupling field utilizes the coherence to generate the probe photon based on the EIT effect.
- The EIT effect makes the probe photon become slow light.

Biphoton Generation Experiment

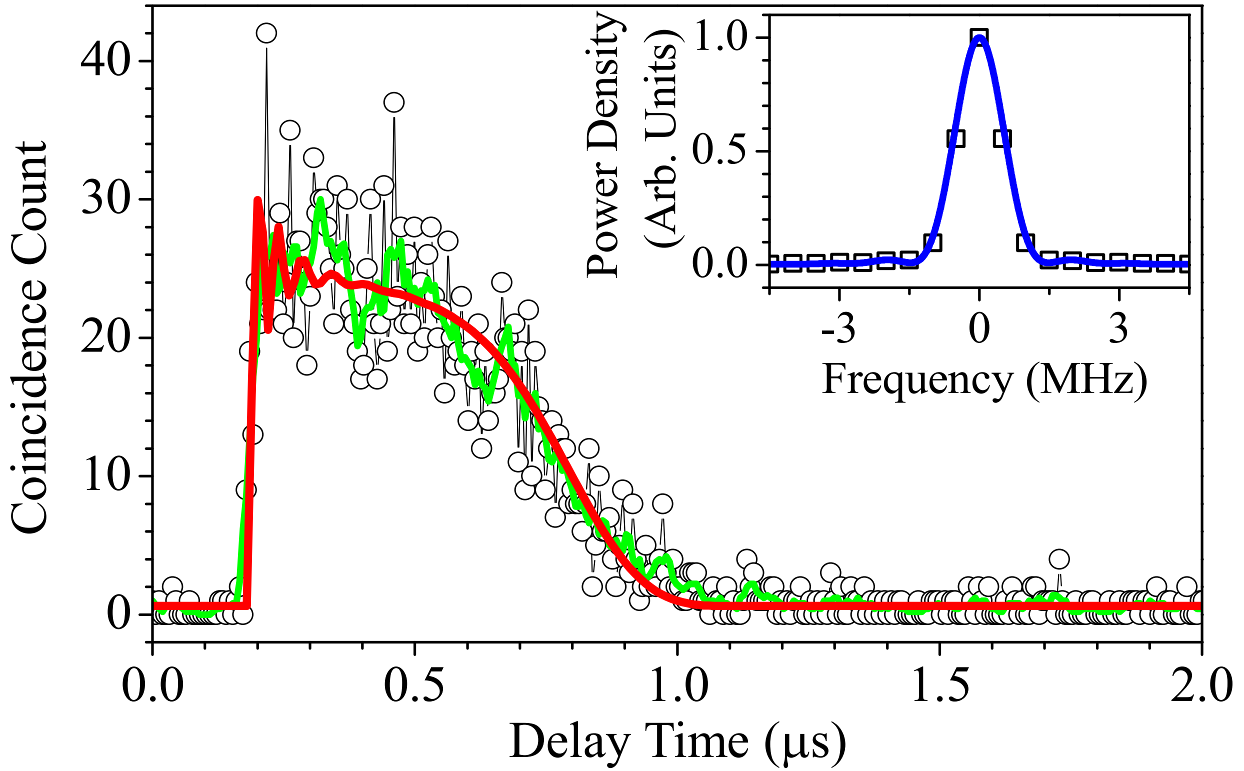


- Two laser fields (coupling and pump) are applied to the atoms to generate a biphoton pair (i.e., a signal and a probe photons).
- Inside the atoms, the signal photon propagates at speed of *c* and the probe photon is slow light.
- **Coincidence count**: The signal photon makes a trigger for the time tagger, which records the delay time of the probe photon's arrival.



Temporal Profile of the Biphoton Wave Packet in Cold Atoms

Data represent biphoton wave packet $|\psi|^2$, where ψ is the wave function of two-photon correlation.



Temporal FWHM 0.57 μs

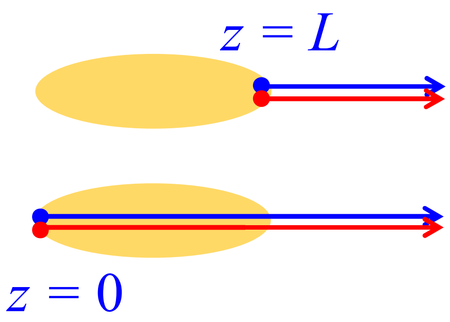
Spectral FWHM 1.2 MHz

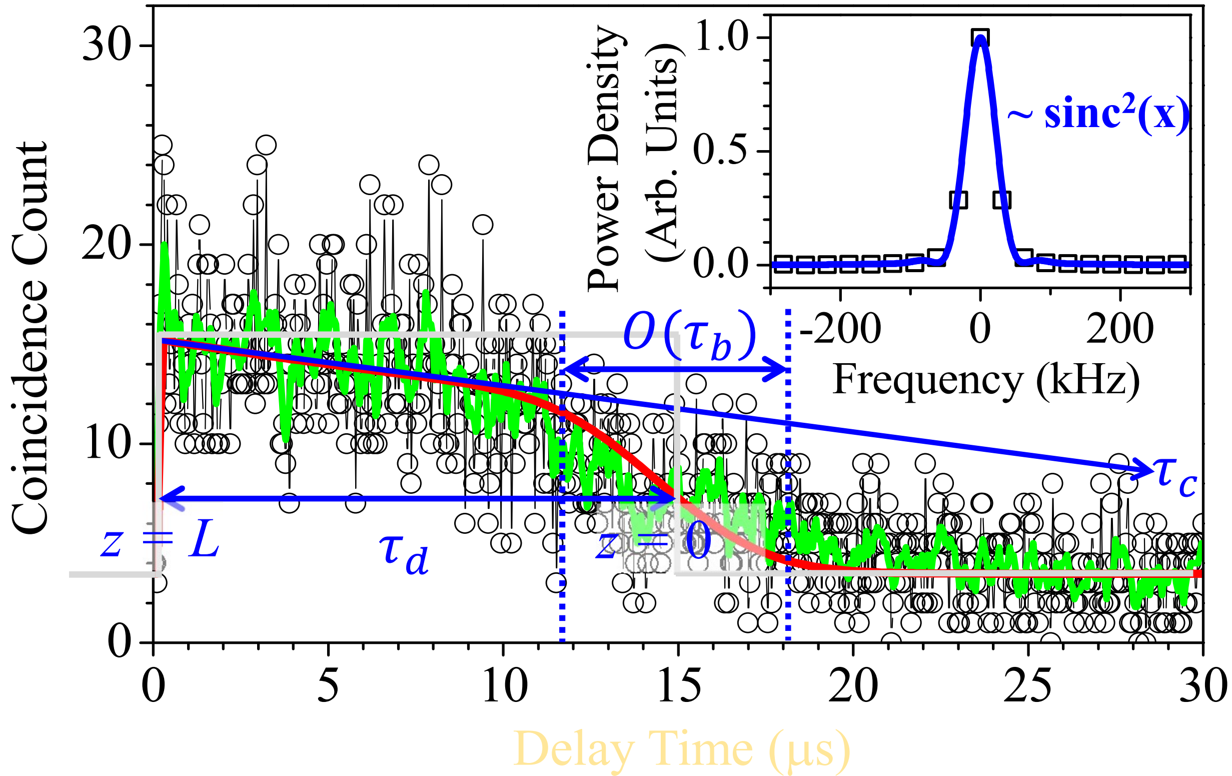
- Circles are the two-photon coincidence counts, green line is the result of 4-point moving average of the circles, and red line is the theoretical prediction.
- In the inset, squares and blue line are the Fourier transforms of the data and the prediction.

The Longest Biphoton with the Narrowest Linewidth to Date

Y.-S. Wang, K.-B. Li, C.-F. Chang, T.-W. Lin, J.-Q. Li, S.-S. Hsiao, J.-M. Chen, Y.-H. Lai, Y.-C. Chen, Y.-F. Chen, C.-S. Chuu, & IAY, APL Photonics 7, 126102 (2022).

A long coherence time plus a high optical depth enables temporally-long biphotons.





Temporal FWHM 13.4 μs

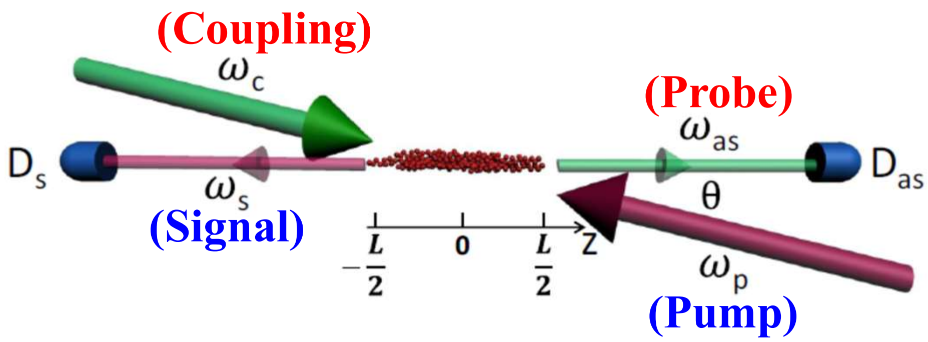
Spectral FWHM 50 kHz

Narrow-linewidth heralded single photons can (1) achieve better efficiencies of quantum operations; (2) be employed in quantum network of superconducting qubits driven by narrow-linewidth microwaves; (3) interact with ion qubits of narrow-linewidth transitions.

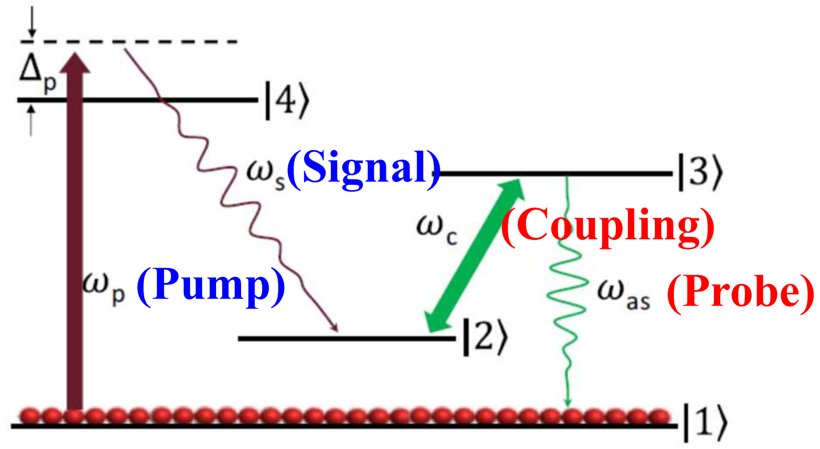
A Room-Temperature Atomic Vapor Cell

- A cylindrical glass cell is commercially available and has a diameter of 1 inch and a length of 7.5 cm.
- The cell is filled with the vapor of isotopically enriched ^{87}Rb atoms.
- The inner wall is coated with paraffin film. So, we only heated it up to about 65 °C.

Phase Mismatch in the Counter-Propagation Scheme



Counter-Propagation



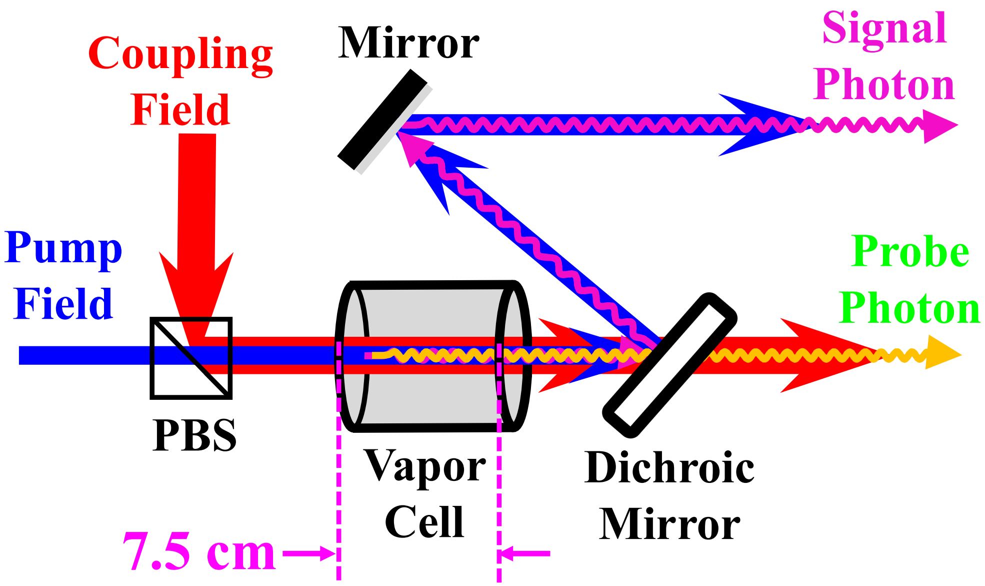
Two absorption-emission processes

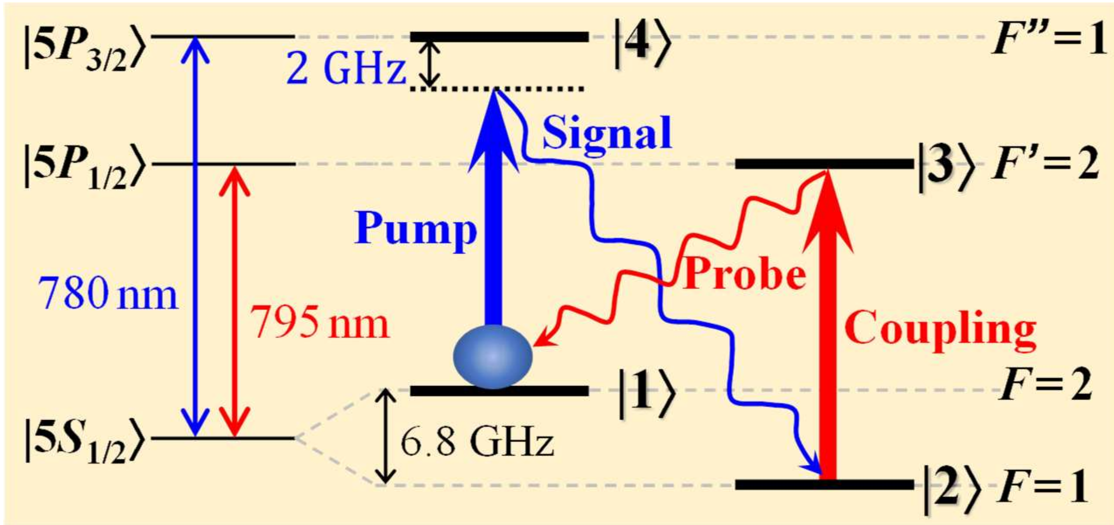
$$\Delta\vec{k} = \left(\vec{k}_{\text{pump}} - \vec{k}_{\text{signal}}\right) + \left(\vec{k}_{\text{coupling}} - \vec{k}_{\text{probe}}\right) = \left(\frac{\omega_{21}}{c}\right)(-\hat{z}) + \left(-\frac{\omega_{21}}{c}\right)\hat{z} = -\frac{2\omega_{21}}{c}\hat{z}$$

Typically, $\omega_{21} = 2\pi \times 6.8$ GHz. $\left|\Delta\vec{k}\right| = \frac{2\pi}{8.8\ cm}$

- Previously, SFWM biphoton sources utilized the counter-propagation scheme.
- The degree of phase mismatch is given by $L\left|\Delta\vec{k}\right|$ (L: the medium length). At L = 7.5 cm, the phase mismatch reduces the generation rate by 1000 folds!

Phase-Mismatch-Free in the All Co-Propagation Scheme

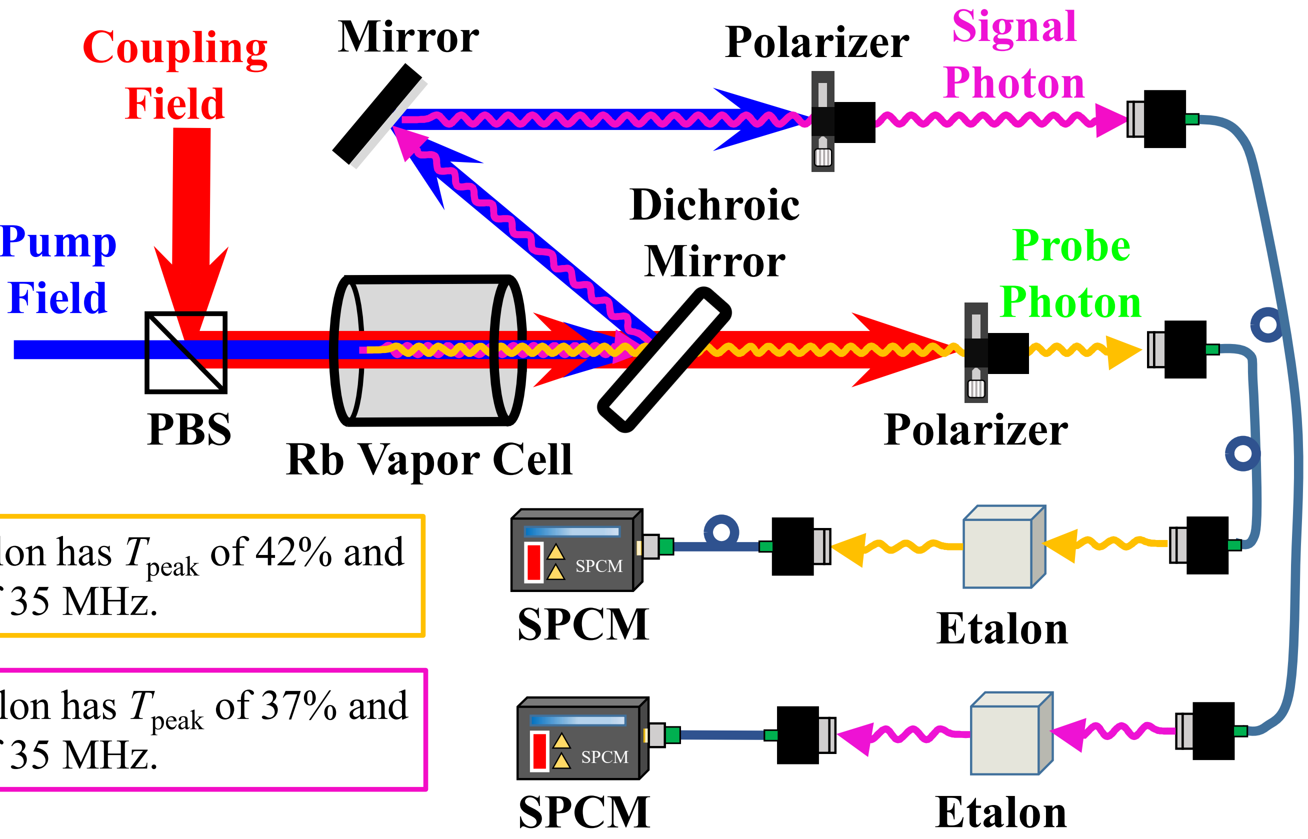




$$\Delta\vec{k} = (\vec{k}_{\text{pump}} - \vec{k}_{\text{signal}}) + (\vec{k}_{\text{coupling}} - \vec{k}_{\text{probe}}) = \left(-\frac{\omega_{12}}{c}\right)\hat{z} + \left(\frac{\omega_{12}}{c}\right)\hat{z} = \mathbf{0}!$$

- Our biphoton source utilized the all co-propagation scheme.
- The all-copropagation scheme ensures the phase match, and also maintains a low decoherence rate, which enables a narrow linewidth.

High Extinction for Laser Light



The polarization filter provides an extinction ratio (ER) of 60 (48) dB to block the pump (coupling) field.

The probe etalon blocks the coupling field with an ER of 88 dB.

The signal etalon blocks the pump field with an ER of 74 dB.

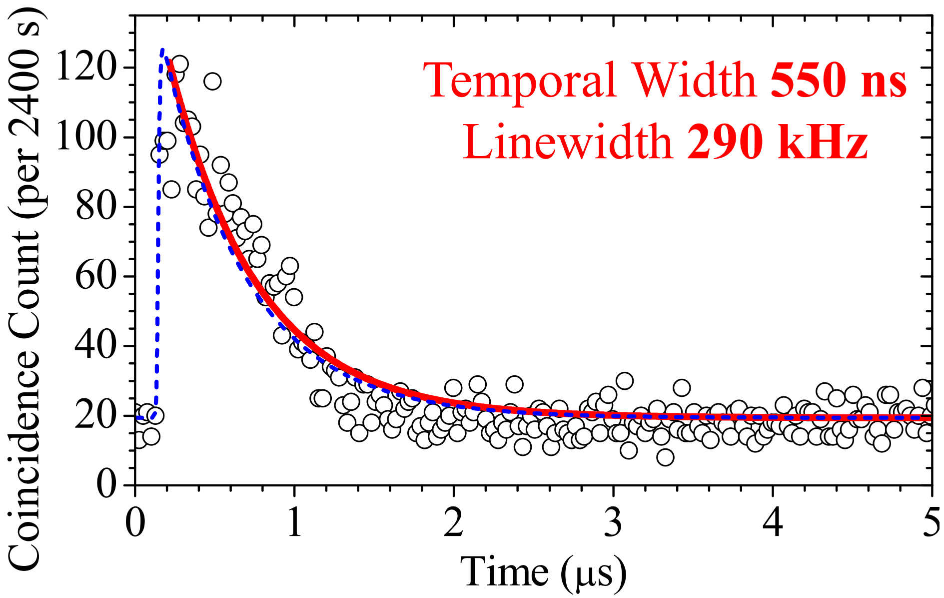
The probe etalon has T_{peak} of 42% and the FWHM of 35 MHz.

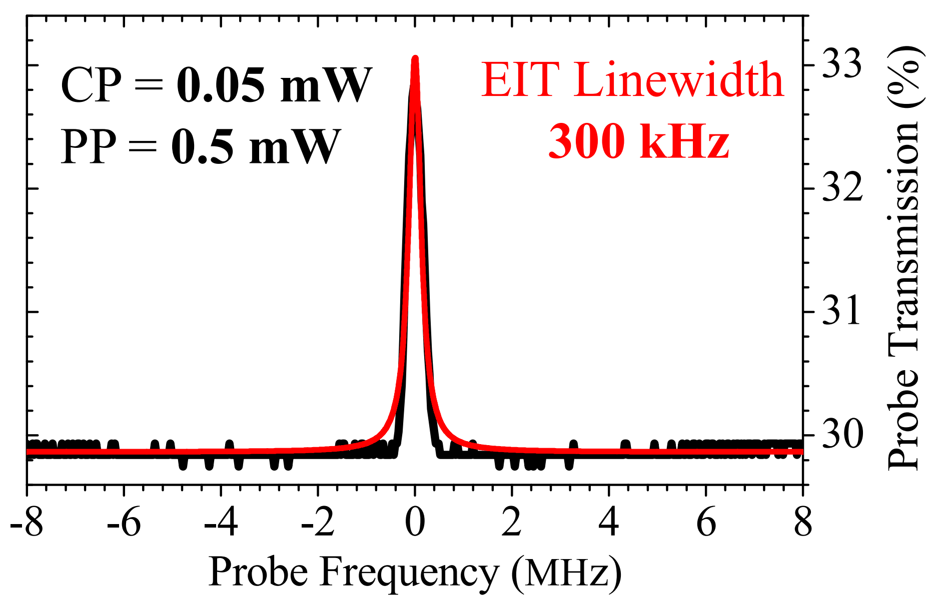
The signal etalon has T_{peak} of 37% and the FWHM of 35 MHz.

- Laser light of 40 mW, and single-photon pulses of 0.4 pW. Their powers differ by **10^{11} folds**!
- Fortunately, an overall ER of ~135 dB to block the pump and coupling fields.

The Narrowest-Linewidth Source of Single-Mode Biphotons among All Kinds of Room-Temperature or Hot Media

C.-Y. Hsu, Y.-S. Wang, J.-M. Chen, F.-C. Huang, Y.-T. Ke, E. K. Huang, W. Hung, K.-L. Chao, S.-S. Hsiao, Y.-H. Chen, C.-S. Chuu, Y.-C. Chen, Y.-F. Chen, & IAY, Opt. Express 29, 4632 (2021). **Editors' Pick.**





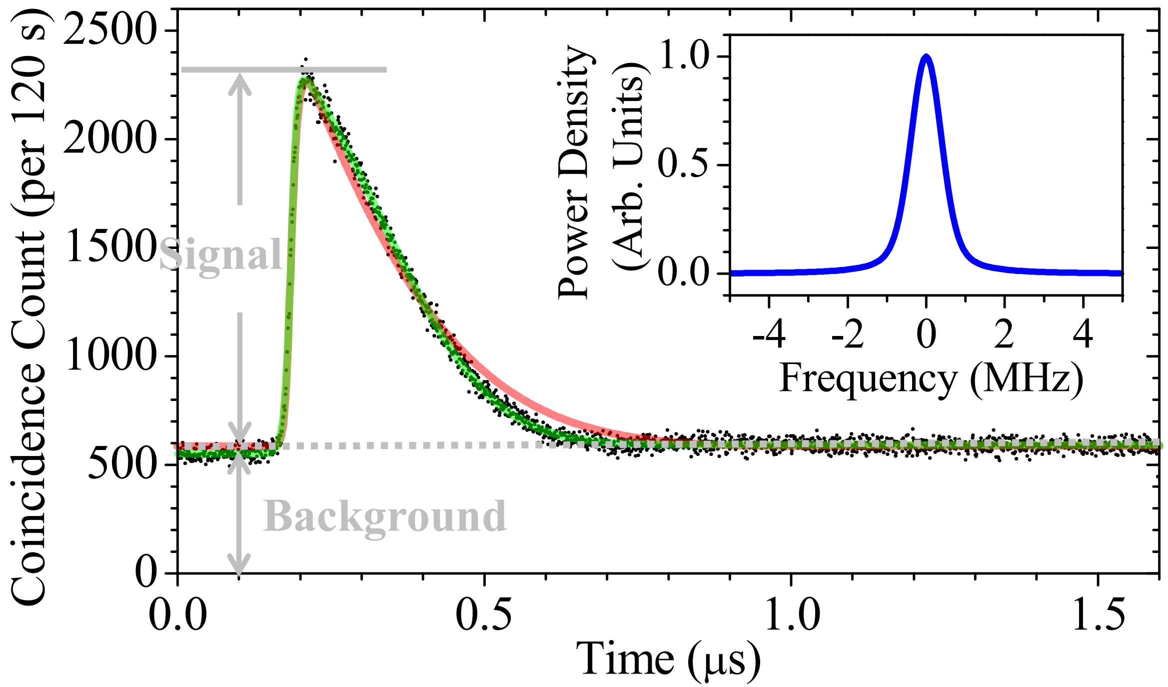
- Biphoton wave packet (left) and EIT spectrum (right) were measured at the same condition.
- The temporal profile is an exponential-decay function due to a short coherence time. The decoherence rate in the experimental system limits the narrowest linewidth.

The Highest Spectral Brightness to Date

J.-M. Chen, C.-Y. Hsu, W.-K. Huang, S.-S. Hsiao, F.-C. Huang, Y.-H. Chen, C.-S. Chuu, Y.-C. Chen, Y.-F. Chen, & IAY, Phys. Rev. Res. 4, 023132 (2022).

Generation Rate
3.7×10^5 pairs/s

Linewidth
960 kHz



SBR
3.1

Violate Cauchy-Schwartz inequality for classical light by **4.2 folds**

- The spectral brightness, i.e., generation rate per linewidth, is the measure of success rate of a quantum information process.
- The high generation rate, together with the narrow linewidth, results in a spectral brightness of 3.8×10^5 pairs/s/MHz, better than all known results with all kinds of media.

Comparison between Different Kinds of Biphoton Sources

		Best Linewidth	Best Spectral Brightness	Linewidth Tunability	Frequency Tunability	Notes
Single-Mode SPDC		3 MHz[1]	3.5×10^5 pairs/s/MHz[4]	N.A.	a few GHz	Frequency is set by the temperature.
Cold-Atom SFWM **Our Works**		**50 kHz**[9]	4,700(×10%) pairs/s/MHz[5]	one order of magnitude	N.A.	Duty cycle ≤ 10%.
Integrated Photonics Devices		92 MHz[2]	1.4×10^5 pairs/s/MHz[2]	N.A.	160 MHz[2]	Micro-ring resonator[2] with Q of ~10^6.
Hot-Atom SFWM	Earlier Works	2 MHz[3]	1.4×10^4 pairs/s/MHz[6]	more than one order of magnitude	N.A.	Frequency set by the laser field and hence can be very stable.
	Our Works	**290 kHz**[7]	**3.8×10^5 pairs/s/MHz**[8]		**a few GHz**[10]	

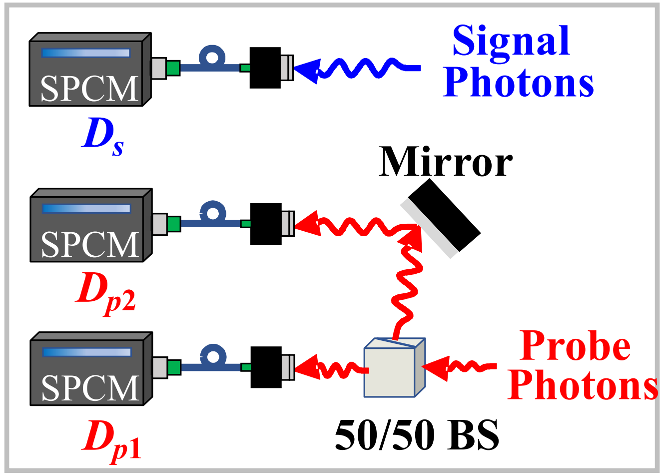
[1] New J. Phys. 18, 123013 (2018).
[2] PRX Quantum 2, 010337 (2021).
[3] Nat. Commun. 7, 12783 (2016).
[4] Phys. Rev. A 92, 063827 (2015).
[5] Optica 1, 84 (2014).
[6] Appl. Phys. Lett. 110, 161101 (2017).
[7] Opt. Express 29, 4632 (2021).
[8] Phys. Rev. Res. 4, 023132 (2022).
[9] APL Photonics 7, 126102 (2022).
[10] arXiv:2502.06344.

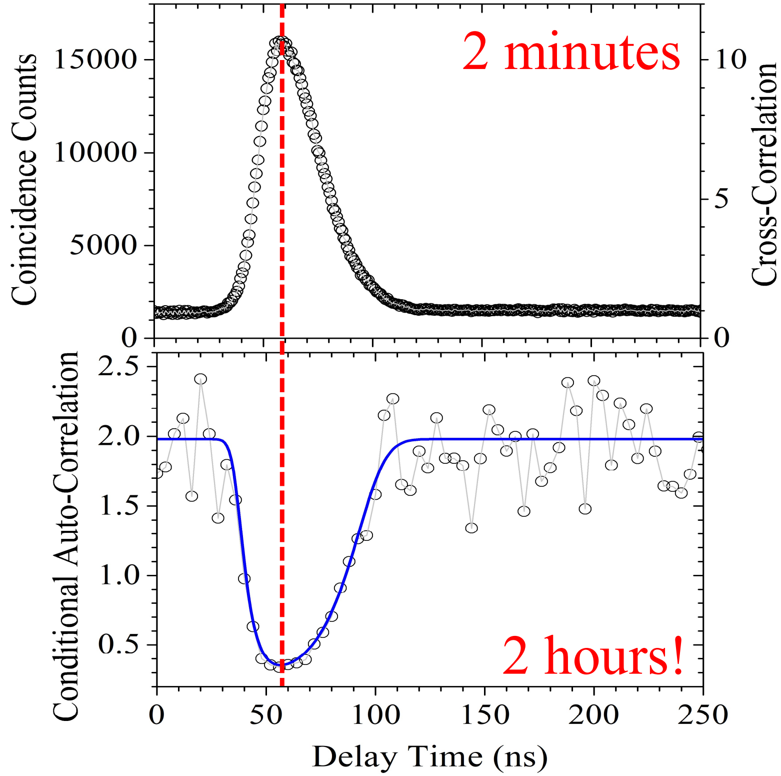
Conditional Auto-Correlation Function of Heralded Single Photons

T.-J. Shih, W.-K. Huang, Y.-M. Lin, K.-B. Li, C.-Y. Hsu, J.-M. Chen, P.-Y. Tu, T. Peters, Y.-F. Chen, & IAY, Opt. Express 32, 13657 (2024).

$$g^{(2)}_{s=1|p,p}(\tau) \equiv \frac{\langle N_s(0)\rangle\langle N_s(0)N_{p1}(\tau)N_{p2}(\tau)\rangle}{\langle N_s(0)N_{p1}(\tau)\rangle\langle N_s(0)N_{p2}(\tau)\rangle}$$

Hanbury-Brown-Twiss (HBT) three-fold coincidence count



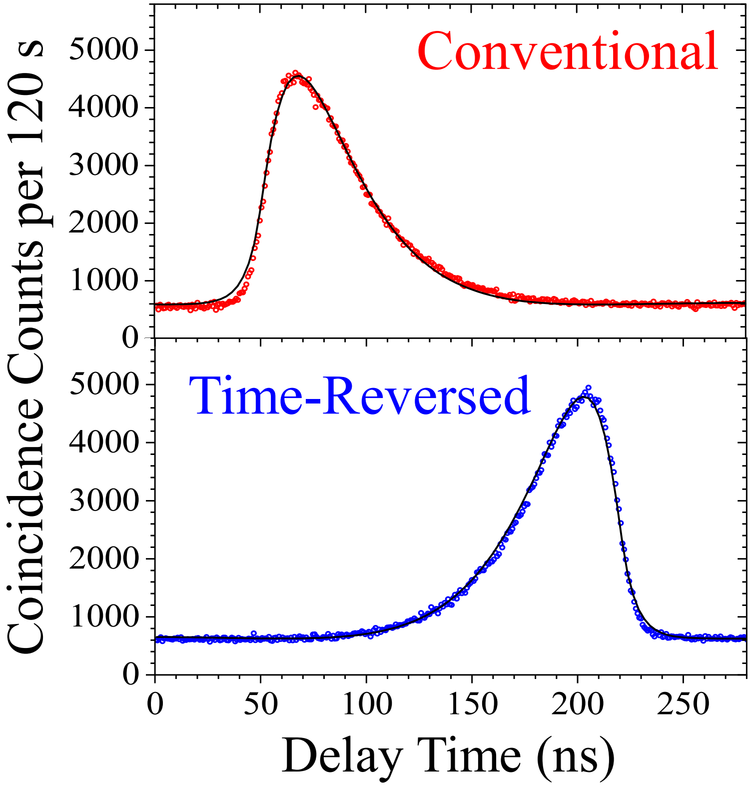


- The CACF is a way to quantify the single-photon purity. However, the CACF measurement of the three-fold HBT-type coincidence count is time-consuming!
- We proposed and experimentally verified a universal formula to predict the CACF from the CCF data, which can work for all kinds of biphoton sources.

Time-Reversed Biphoton Source with the Highest Heralding Probability among All of the Atom-based Sources to Date

W.-K. Huang, B. Kim, T.-J. Shih, C.-Y. Hsu, P.-Y. Tu, T.-Y. Lin, Y.-F. Chen, C.-S. Chuu, & IAY, Quantum Sci. Technol. 10, 015062 (2025).

HP: Probability of detecting a heralded photon upon a trigger from a heralding photon (i.e., not a dummy bullet).

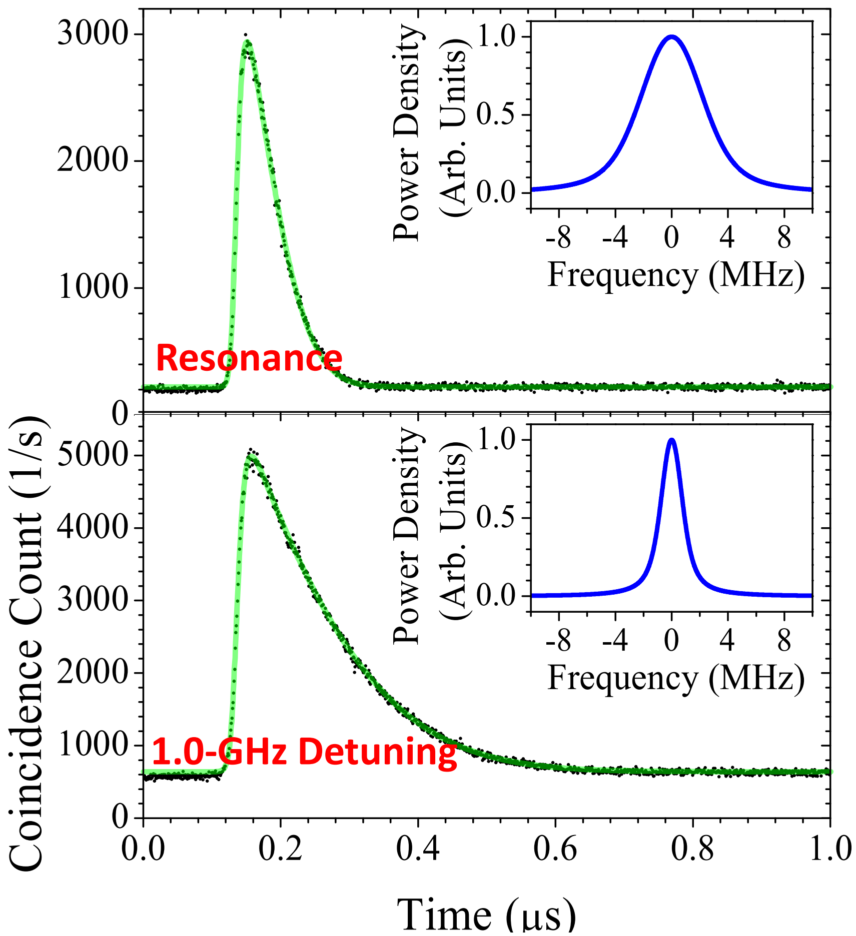


Reference	Medium⋆	Transition Scheme	Heralding Photons§	Temporal FWHM	Detection Efficiency†	Heralding Efficiency	Heralding Probability*
This work	RHA	Double Λ	Probe	47 ns	13±1%	10.7±0.1%	82±6%
Ref. [5]	LCA	Double Λ	Signal	200 ns	27%	17%	64%
Ref. [14]	LCA	Double Λ	Signal	30 ns	1.4%	0.90%	64%
Ref. [13]	LCA	Double Λ	Probe	24 ns	8%	3.4%	43%
Ref. [1]	LCA	Double Λ	Signal	140 ns	7.1%	3.0%	43%
Ref. [23]	RHA	Double Λ	Probe	3.8 ns	23~42%‡	9.0%	21~39%‡
Ref. [10]	LCA	Double Λ	Signal	160 ns	22~40%‡	7.2%	18~32%‡
Ref. [22]	RHA	Double Λ	Signal	180 ns	11%	3.4%	31%
Ref. [52]	RHA	Diamond	Signal	0.45 ns	68%	16%	24%
Ref. [15]	RHA	Double Λ	Signal	64 ns	15%	3.1%	21%
This work	RHA	Double Λ	Signal	46 ns	9.4±0.5%	2.02±0.02%	21±1%
Ref. [53]	RHA	Ladder	Signal	1.9 ns	32%	5.8%	18%
Ref. [9]	LCA	Double Λ	Signal	700 ns	26%	3.2%	12%
Ref. [17]	RHA	Double Λ	Signal	1.3 ns	13~23%‡	1.5%	6.5~12%‡
Ref. [54]	RHA	Ladder	Signal	1.9 ns	32%	3.5%	11%
Ref. [55]	RHA	Diamond	Idler	0.5 ns	10%	0.5~0.9%‡	5~9%‡
Ref. [21]	RHA	Double Λ	Signal	180 ns	11%	0.88%	8.0%
Ref. [56]	RHA	Ladder	Signal	0.56 ns	60%	0.24%	0.4%

RHA: room-temperature or hot atoms. LCA: laser-cooled atoms.

Protecting Heralded Single Photons with a Far-Detuned Frequency

W.-K. Huang, T.-Y. Lin, P.-Y. Tu, Y.-F. Chen, & IAY, arXiv:2502.06344.



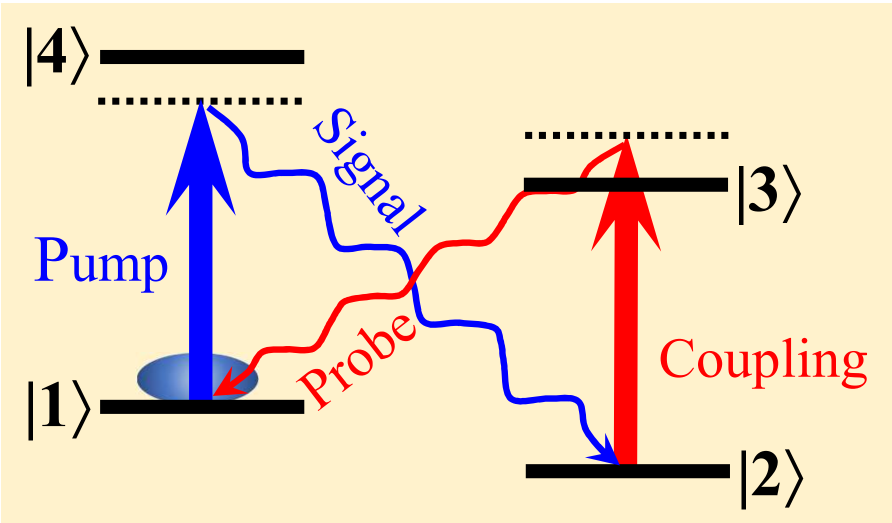
$\Delta_c/2\pi$ (GHz)	R_g (10^5/s)	τ_w (ns)	$\Delta\omega/2\pi$ (MHz)	SB (10^5/s/MHz)	SBR	h_p
0.0	1.79±0.03	63.6±0.7	5.2±0.1	0.34±0.01	12.4±0.3	26.2±0.4%
0.2	2.32±0.01	54.1±0.5	5.1±0.1	0.46±0.01	16.4±0.7	38.0±0.3%
0.7	5.35±0.09	65±1	3.0±0.1	1.78±0.07	11.9±0.3	74±1%
1.0	6.42±0.03	132±1	1.83±0.03	3.51±0.06	6.8±0.1	79.9±0.4%

Δ_c: the coupling detuning; R_g: generation rate; τ_w: temporal FWHM; $\Delta\omega$: spectral FWHM; SB: spectral brightness; SBR: signal-to-background ratio; h_p: heralding probability.

- We introduce the new tuning knob of the coupling detuning which is counterintuitive to the present theory.
- At the optimum detuning of 1.0 GHz, GR ×3.6, SB ×10, HP ×3.1!
- The surprising results led us to develop a new theory, considering that the far-detuned frequency protects the heralded single photons from a previously unexplored physical mechanism.

Summary of the Hot-Atom Biphoton Source

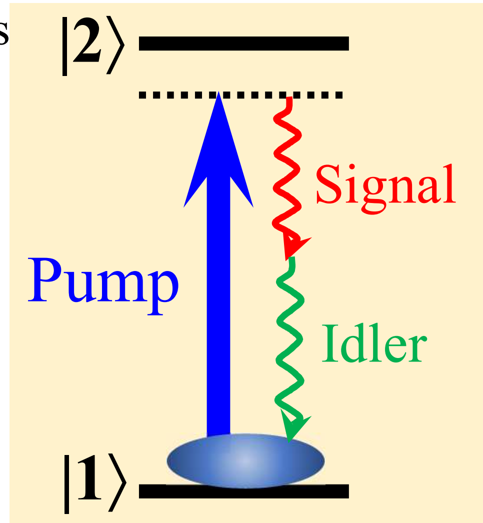
- As the pioneer of cold-atom experiments in Taiwan, I am delightful for our converting the knowledge and experiences learned from the cold atoms into some nice results of the hot atoms, which are more practical in the real-world applications.
- We started to develop the hot-atom biphoton source in 2015, and observed the first biphoton data in 2017 (sFWHM ≈ 5 MHz and GR ≈ 30 pairs/s).
- Now, we have a state-of-art source (sFWHM = 290 kHz, GR = 6.4×10^5 pairs/s, HP = 82%, and SB = 3.5×10^5 pairs/s/MHz close to the ultimate limit, referring to the biphotons inside SMFs).



Spontaneous Four-Wave Mixing (SFWM) Using Atoms

>

Spontaneous Parametric Down-Conversion (SPDC) Using Crystals or IPCs



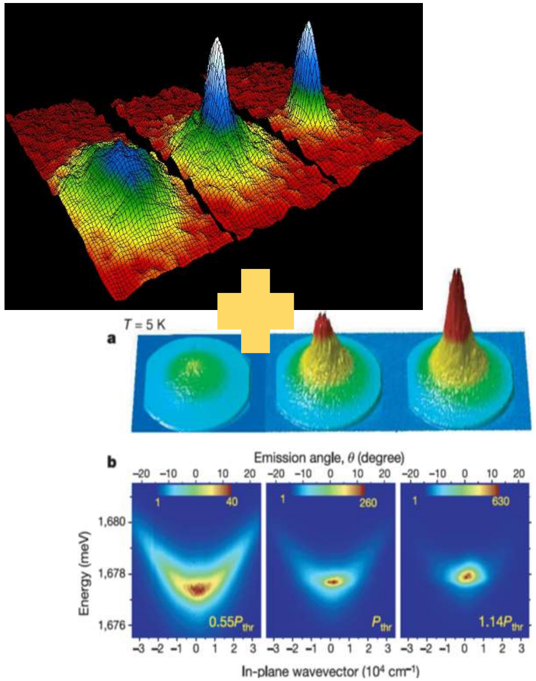
Stationary Dark-State Polaritons Dressed by Rydberg-State Dipole-Dipole Interaction for the Realization of BEC

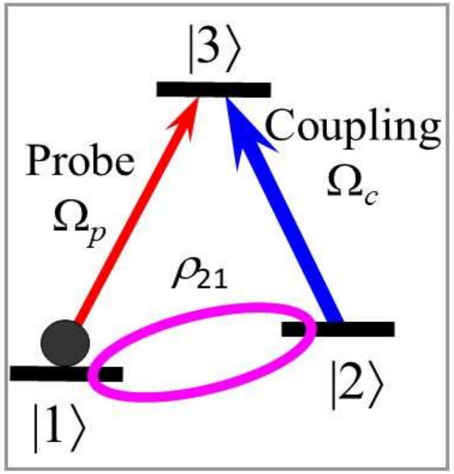
What is the dark-state polariton (DSP)? Slow light.

How to make it stationary? Storage of light and FWM retrieval.

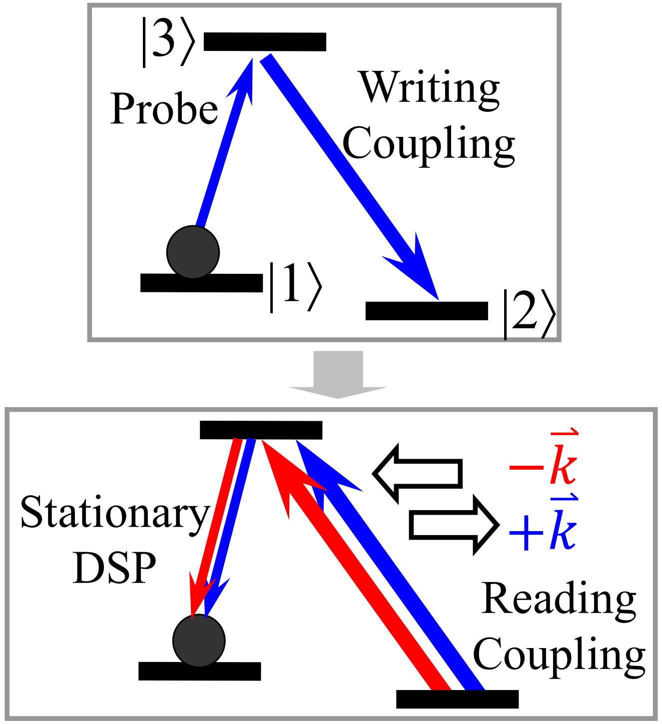
Why do we want to realize the DSP BEC? A new type of BEC.

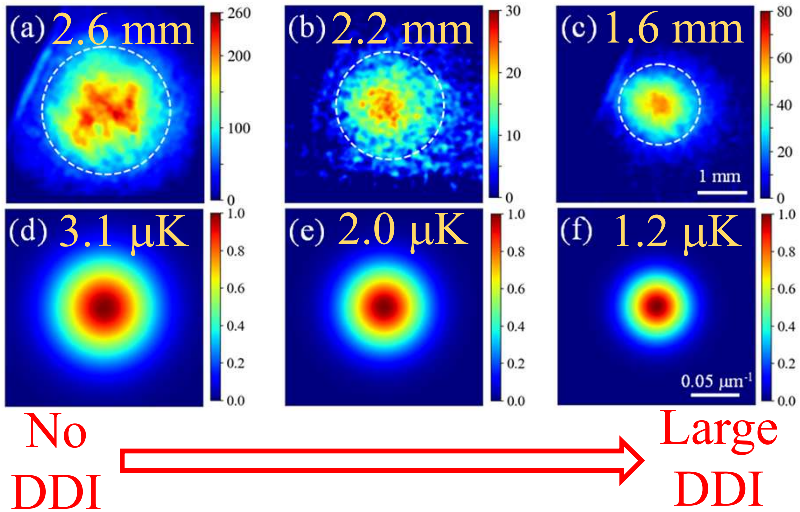
Why is the dipole-dipole interaction (DDI) needed? Thermalization.





$$\Psi = \cos\theta\,\Omega_p - \sin\theta\,\sqrt{\eta c}\rho_{21}$$



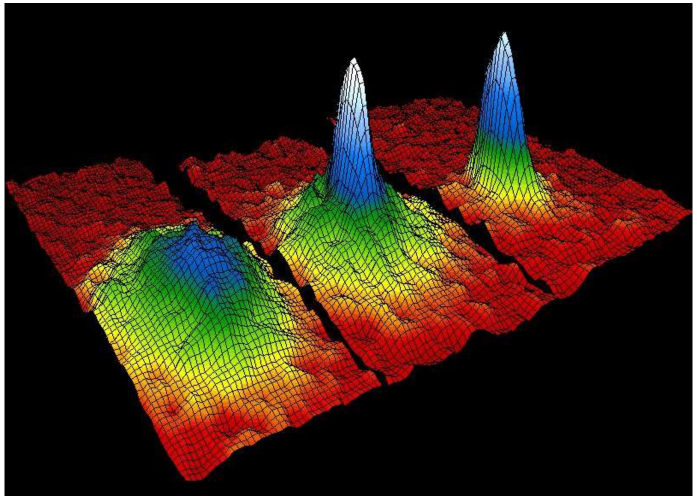


Atomic and Exciton-Polariton Bose-Einstein Condensations

m^*	$10^4\ m_e$	$\sim 10^{-2}\ m_e$	$10^{-5}\ m_e$
n	$10^{13}\sim10^{15}$ cm^{-3}	$\sim 10^{10}$ cm^{-3}	$10^{10}\sim10^{12}$ cm^{-3}
T_c	< 1 μK	~ 1 mK	> 1 K
τ	> 1 ms	~ 1 μs	< 100 ps

Atomic BEC

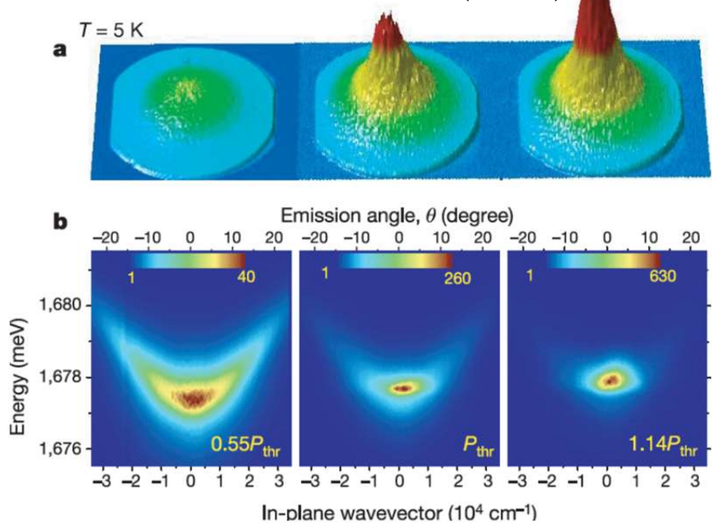
https://jila.colorado.edu/bec/



Dark-State-Polariton BEC?

2D Exciton-Polariton BEC

Nature 443, 409 (2006).



BEC of Stationary DSPs

M. Fleischhauer, J. Otterbach, and R. G. Unanyan, Bose-Einstein Condensation of Stationary-Light Polaritons, PRL 101, 163601 (2008).

- The 1D EOM of DSPs:

$$\frac{\partial\Psi}{\partial t}+\frac{\Omega_c^2}{\eta\Gamma}\frac{\partial\Psi}{\partial z}-\frac{\Omega_c^2}{2\eta^2\Gamma}\frac{\partial^2\Psi}{\partial z^2}=0$$

group velocity of the slow light or DSP

- The 3D EOM of **stationary** DSPs similar to Schrodinger equation with the effective mass *m*:

$$\mathrm{i}\hbar\left(\frac{\partial\Psi}{\partial t}+\frac{(\Omega_{c+}^2-\Omega_{c-}^2)}{\eta\Gamma}\cancel{\frac{\partial\Psi}{\partial z}}-\frac{\Omega_c^2}{2\eta^2\Gamma}\frac{\partial^2\Psi}{\partial z^2}\right)=-\frac{\hbar^2}{2}\left(\frac{1}{m_\parallel}\frac{\partial^2\Psi}{\partial z^2}+\frac{1}{m_\perp}\frac{\partial^2\Psi}{\partial x\partial y}\right)\equiv-\frac{\hbar^2}{2m}\nabla^2\Psi$$

$m_\parallel=\hbar\eta^2\Gamma^2/8\Omega_c^2|\Delta|^2$ $\quad m_\perp=\hbar k_p\eta\Gamma/\Omega_c^2$ $\quad m=(m_\parallel {m_\perp}^2)^{1/3}$

- The 3D nonlinear EOM of stationary DSPs with mean-field energy and decay rate due to an interaction:

$$\mathrm{i}\hbar\frac{\partial\Psi}{\partial t}=-\frac{\hbar^2}{2m}\nabla^2\Psi+\mathrm{i}\hbar\frac{\Omega_c^2}{2\eta^2\Gamma}\frac{\partial^2\Psi}{\partial z^2}+g|\Psi|^2\Psi-\mathrm{i}\hbar\Gamma_{\mathrm{loss}}\Psi$$

interaction-induced mean-field energy

interaction-induced decay rate

Kerr-Type Nonlinearity for the DSP-DSP Interaction

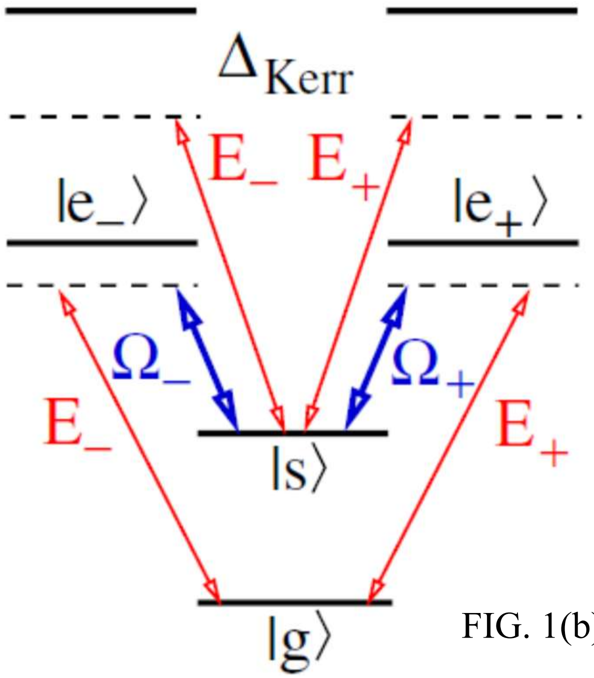


FIG. 1(b)

Copied from PRL 101, 165601 (2008)

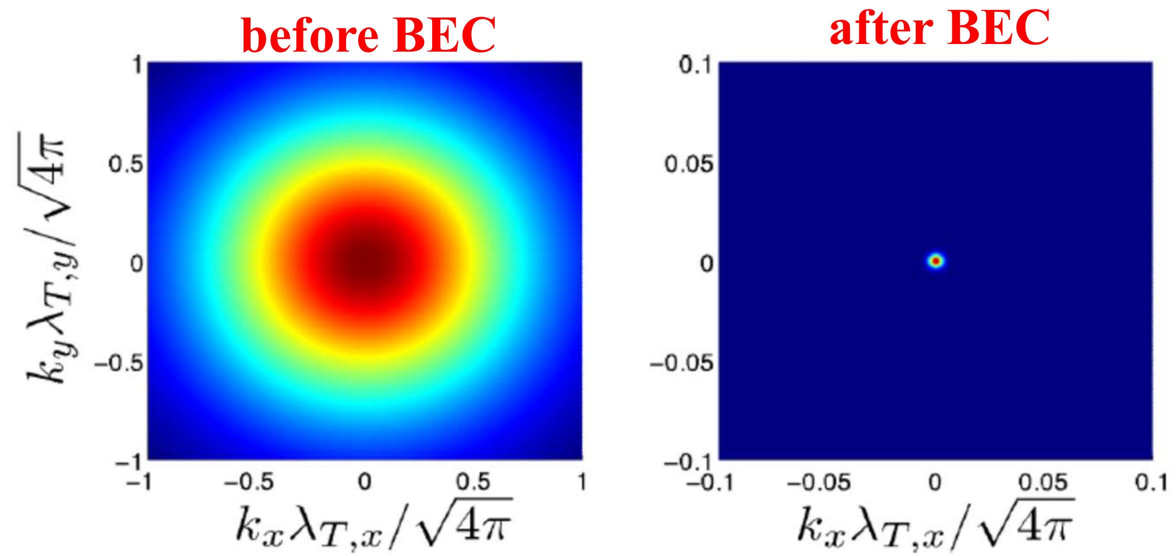


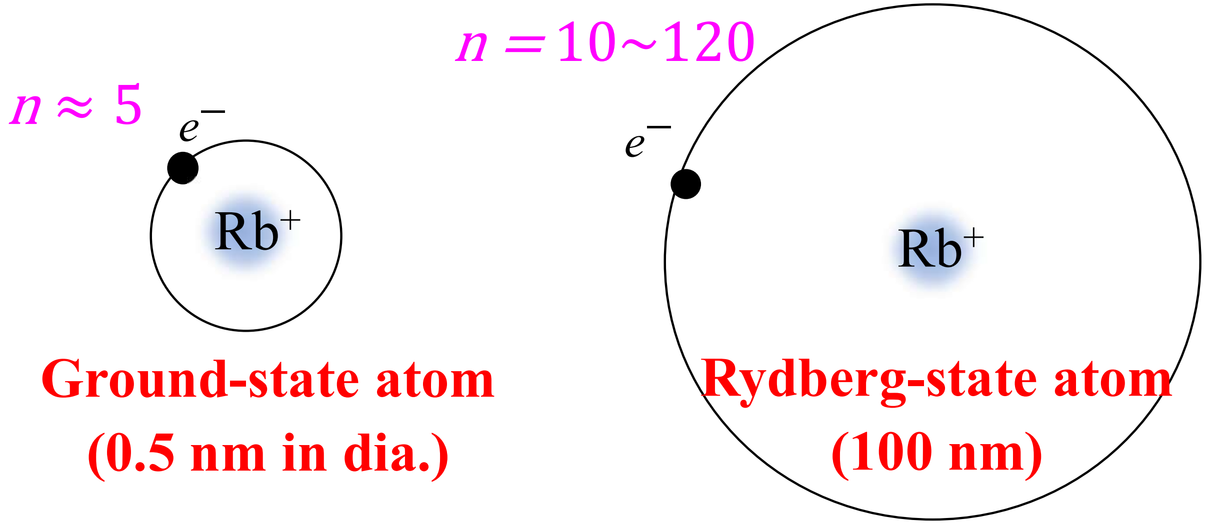
FIG. 3 (color online). (a) Detection of condensation: switching

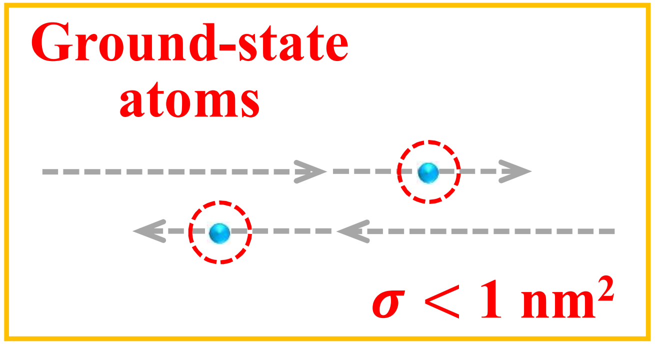
Copied from PRL 101, 165601 (2008)

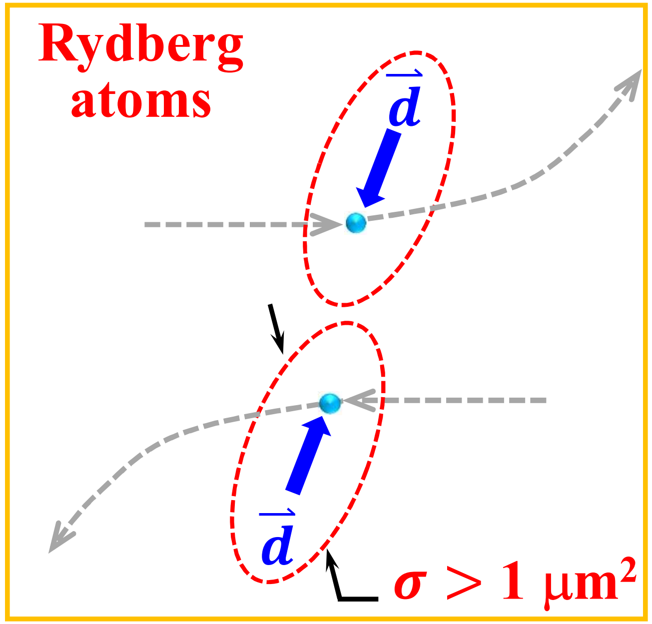
- The Kerr-type nonlinearity is proposed for the DSP-DSP interaction. However, it is typically too weak to have a sufficient elastic collision rate for thermalization.
- Can we utilize the Rydberg-state dipole-dipole interaction instead of the Kerr nonlinearity?

Rydberg Atoms and Dipole-Dipole Interaction (DDI)

For example, rubidium atoms:



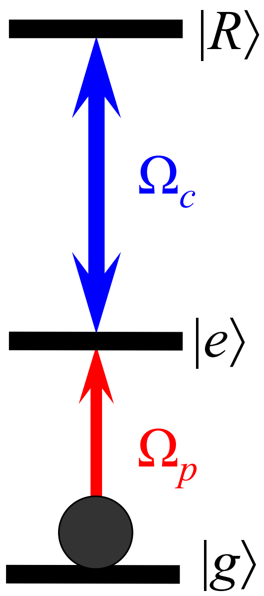


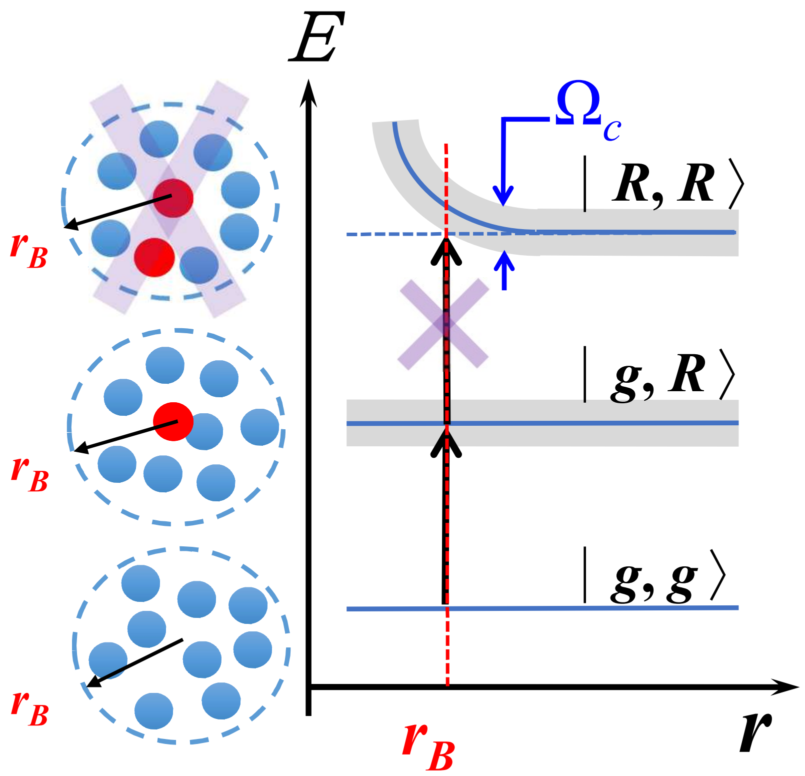


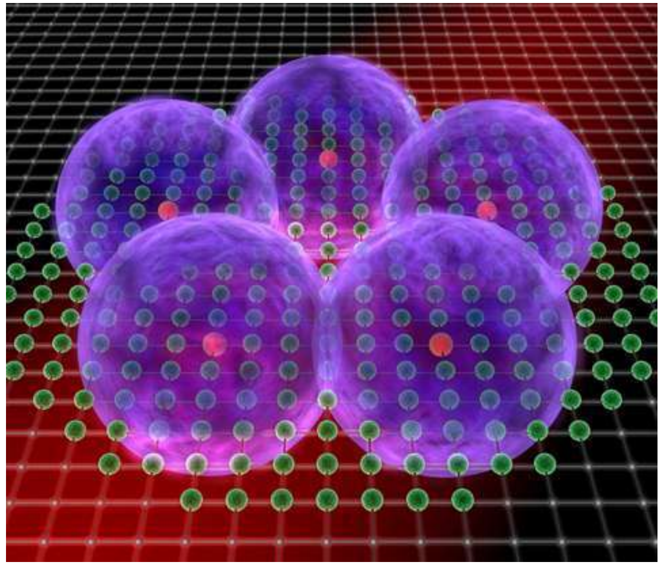
- A Rydberg atom has its electron in an excited state with a large principal quantum number, n.
- Rydberg atoms have a large electric dipole moment ($C_6 \propto n^{11}$ or $C_3 \propto n^4$).
- Rydberg atoms have a long lifetime ($\tau \propto n^3$) together with the strong DDI, making them suitable qubits.

DDI and Dipole Blockade

Rydberg-EIT
Transition Scheme





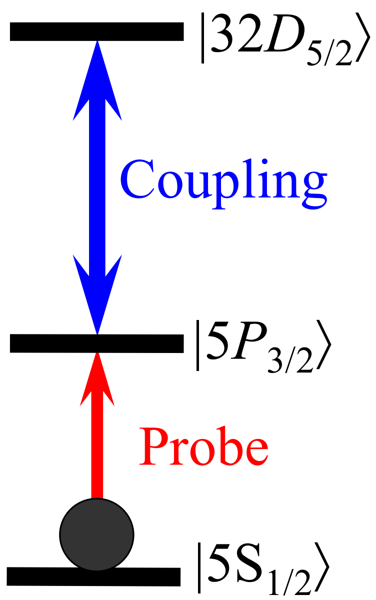


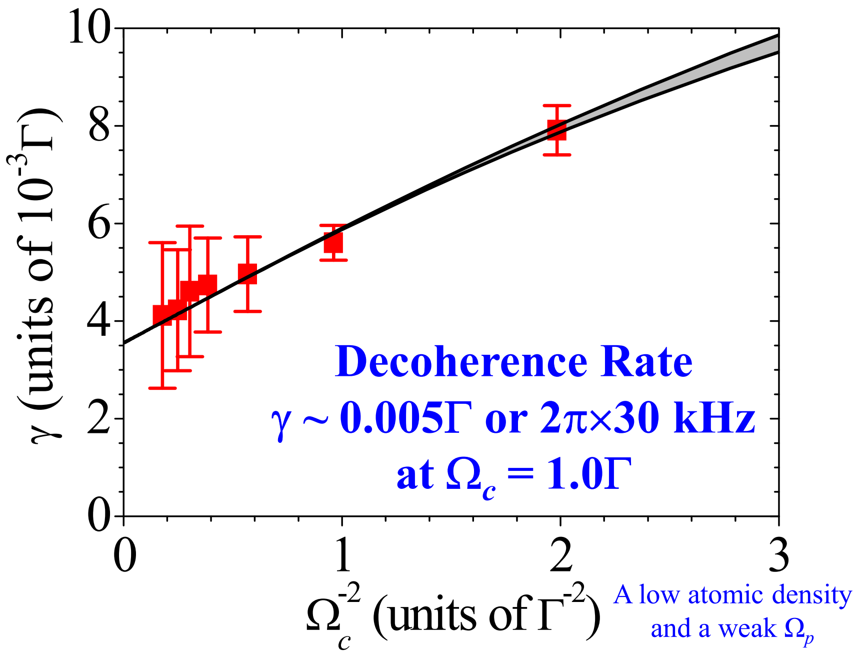
"A New Order in the Quantum World," by Olivia Meyer-Streng (MPQ, Garching, November 1st, 2012. Press Release)

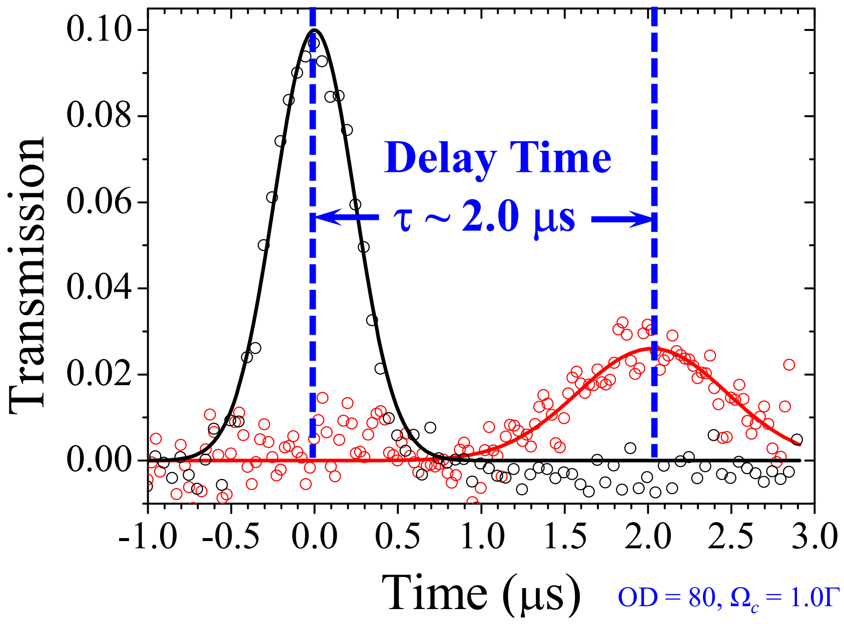
- At $r < r_B$, the energy shift due to the DDI > the transition linewidth, and an excitation of the 2nd Rydberg atom is suppressed. r_B is the blockade radius.
- Only one Rydberg atom is inside the sphere of r_B (blockade sphere).

Slow Light in the Rydberg-Atom System

B. Kim, K.-T. Chen, C.-Y. Hsu, S.-S. Hsiao, Y.-C. Tseng, C.-Y. Lee, S.-L. Liang, Y.-H. Lai, J. Ruseckas, G. Juzeliūnas, & IAY,
PRA 100, 013815 (2019).



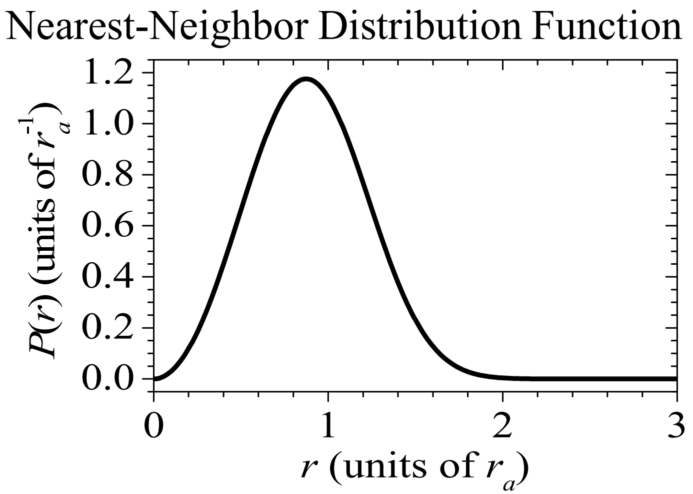




- We utilized the EIT effect, i.e., slow light, to test the decoherence rate in the Rydberg-atom system.
- The intrinsic decoherence rate (accounting for Doppler effect, laser frequency stability, etc.) is small as compared with the DDI-induced decay rate.
- In the presence of DDI, the delay time τ or the interaction time between Rydberg atoms can be 2 μs or longer.

Mean-Field Theory DDI based on the Nearest-Neighbor Distribution

S.-S. Hsiao, K.-T. Chen, & IAY, Opt. Express 28, 28414 (2020).



$P(r) = (3r^2/r_a^2)\mathrm{Exp}(-r^3/r_a^3)$,

where r_a is the half mean distance.

S. Chandrasekhar, Rev. Mod. Phys. 15, 1 (1943).

Dilute Rydberg atoms: $(r_B/r_a)^3 \ll 1$

DDI-induced decoherence rate:

$$\gamma_{\mathrm{DDI}} = \frac{\pi^2\Omega_c\sqrt{|C_6|}}{3\sqrt{\Gamma}}\frac{\sqrt{\sqrt{\Gamma^2+4\Delta_c^2}-2\Delta_c}}{\sqrt{\Gamma^2+4\Delta_c^2}}n_{\mathrm{atom}}\rho_{22}$$

DDI-induced two-photon detuning:

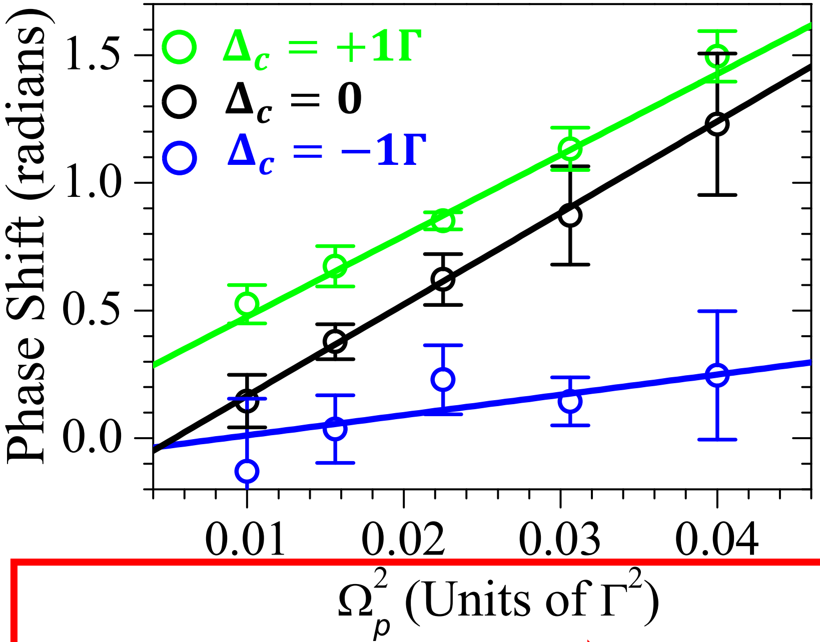
$$\delta_{\mathrm{DDI}} = \pm\frac{\pi^2\Omega_c\sqrt{|C_6|}}{3\sqrt{\Gamma}}\frac{\sqrt{\sqrt{\Gamma^2+4\Delta_c^2}+2\Delta_c}}{\sqrt{\Gamma^2+4\Delta_c^2}}n_{\mathrm{atom}}\rho_{22}$$

C_6: van der Waal coefficient, ρ_{22}: Rydberg-state population, n_{atom}: atomic density, Ω_c: coupling Rabi frequency, Δ_c: coupling detuning, Γ: spontaneous decay rate.

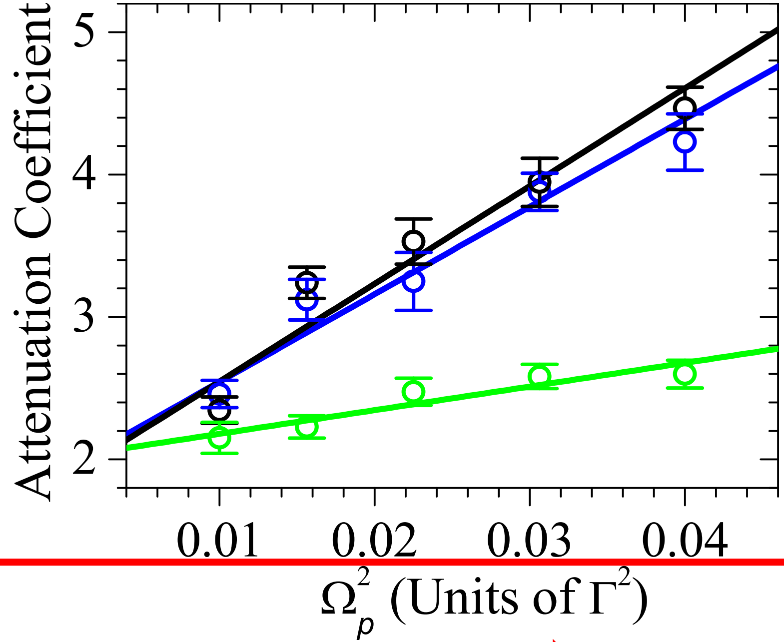
- Under particles being randomly distributed, $P(r)$ is the probability of finding the nearest neighbor at a distance r.
- We derive the analytical formulas for the weak-interaction regime of DDI. $\Delta_c > 0$ and $\Delta_c < 0$ have different DDI effects.

Data of DDI-Induced Phase Shifts and Attenuation Coefficients

$\mathrm{Max}[\Omega_p] = 0.2\Gamma, \Omega_c = 1.0\Gamma, 32D_{5/2} \implies r_a = 4.5\ \mu m; r_B = 2.0\ \mu m.$ $\mathrm{Max}[(r_B/r_a)^3] < 0.09$ is the dilute regime.



Probe intensity or Ω_p^2 ($\propto \rho_{22}$) || Rydberg-atom density || DDI strength



No DDI ⇒ Large DDI

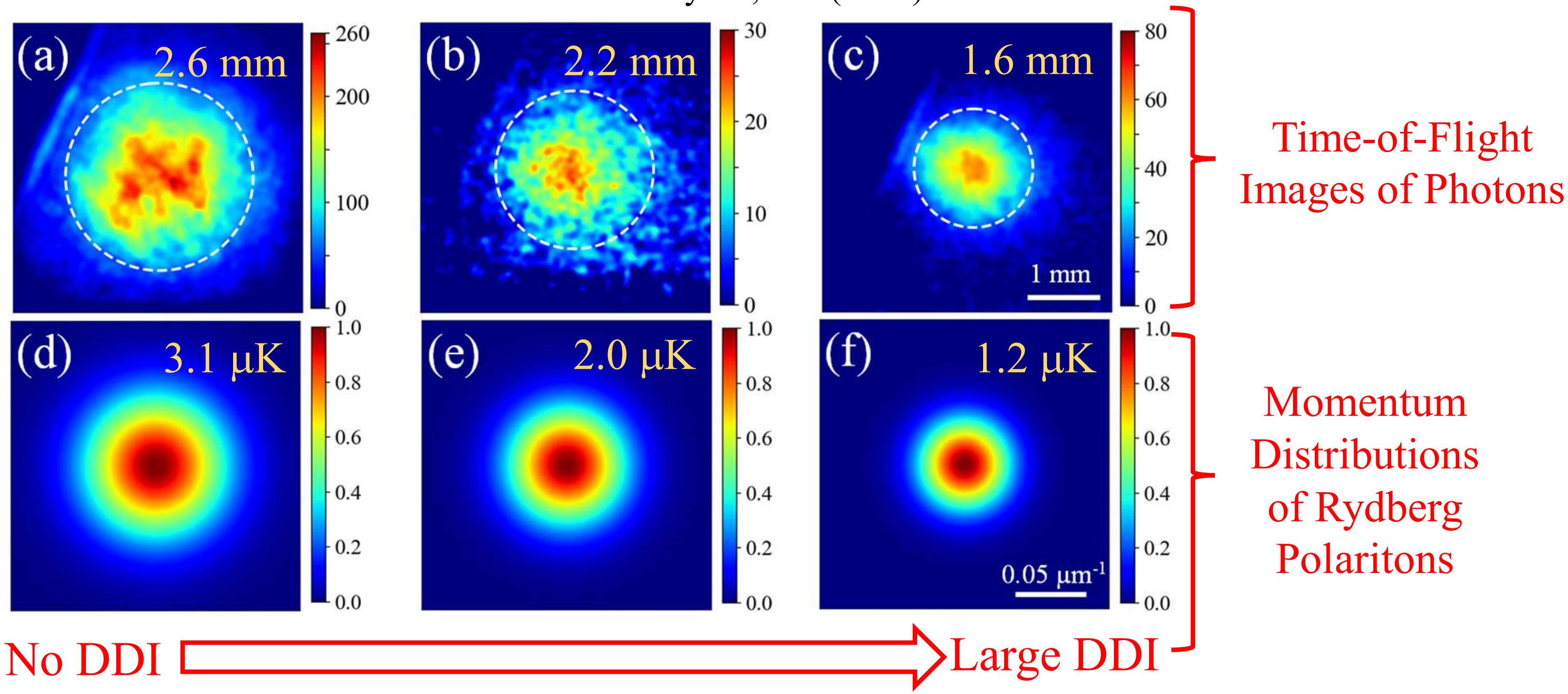
No DDI ⇒ Large DDI

- A larger probe Rabi frequency results in more population in the Rydberg state. The experimental data are consistent with the theoretical predictions.
- Phase shift and attenuation can be viewed as the consequences of elastic collisions (thermalization) and inelastic collisions (decay).

Demonstration of Cooling Effect with Rydberg-State Slow Light

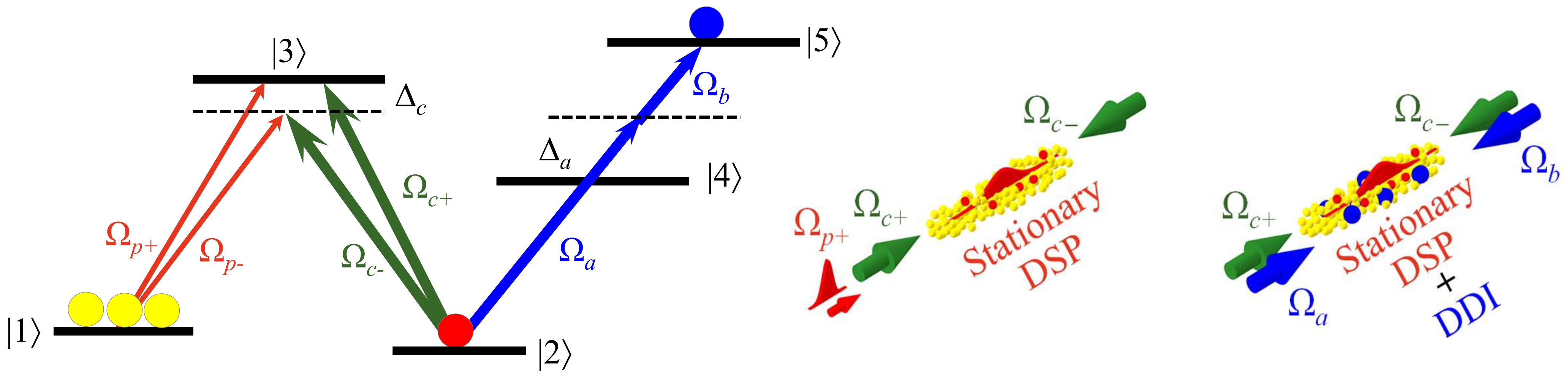
B. Kim, K.-T. Chen, S.-S. Hsiao, S.-Y. Wang, K.-B. Li, J. Ruseckas, G. Juzeliūnas, T. Kirova, M. Auzinsh, YCC, YFC, & IAY

Commun. Phys. 4, 101 (2021)



- Take TOF images at the far field to measure of probe beam profiles. When leaving the atom cloud, photons carry Rydberg polaritons' momentums.
- We can derive the transverse momentum distribution of Rydberg polaritons and thus the transverse temperature.
- A larger DDI results in a narrower momentum distribution and a lower transverse temperature.

The Proposed Transition Scheme



Stationary Dark-State-and-Rydberg-State Polariton:

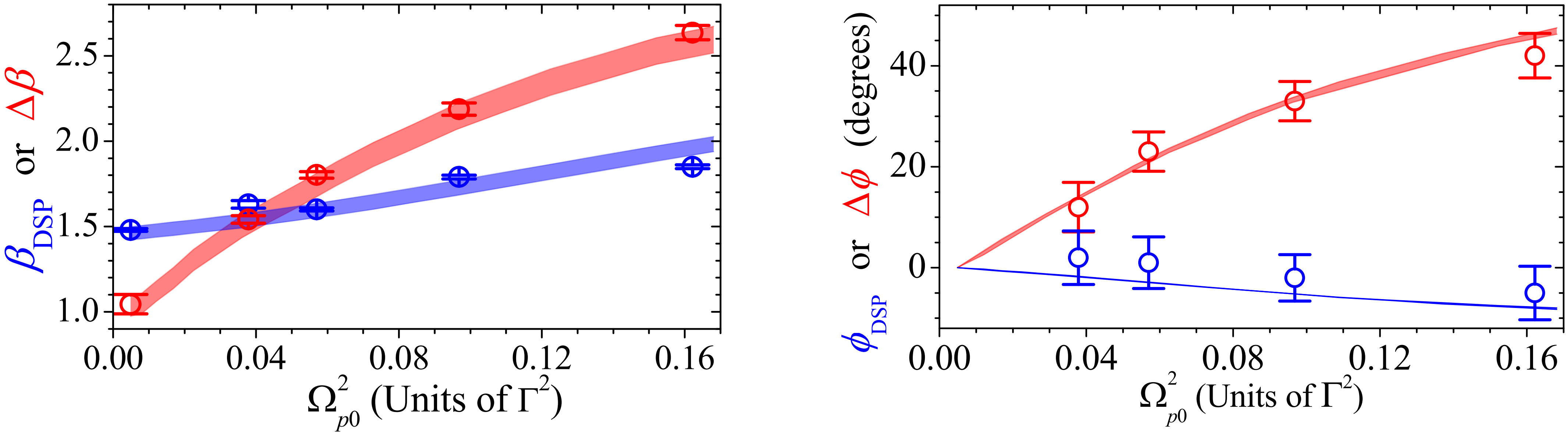
$$\Psi = \cos\theta\,(\Omega_{p+} + \Omega_{p-})/\sqrt{2} - \sin\theta\,\sqrt{\eta c}(\cos\phi\;\rho_{21} + \sin\phi\,\rho_{51}),$$

where $\tan\theta = \sqrt{\eta c}/\Omega_c$, η is the OD per unit length, and $\phi = \Omega t$.

- In the subsystem of |1⟩, |2⟩, and |3⟩, we created the stationary DSPs with the EIT scheme. In the subsystem of |2⟩, |4⟩, and |5⟩, we utilized the two-photon transition to generate the Rabi oscillation between the ground state |2⟩ and Rydberg state |5⟩.
- The population in |5⟩ induced the DDI between the stationary DSPs .

DDI-Induced Attenuation Coefficients and Phase Shifts

B. Kim, K.-T. Chen, K.-Y. Chen, Y.-S. Chiu, C.-Y. Hsu, Y.-H. Chen, & IAY, PRL 131, 133001 (2023).

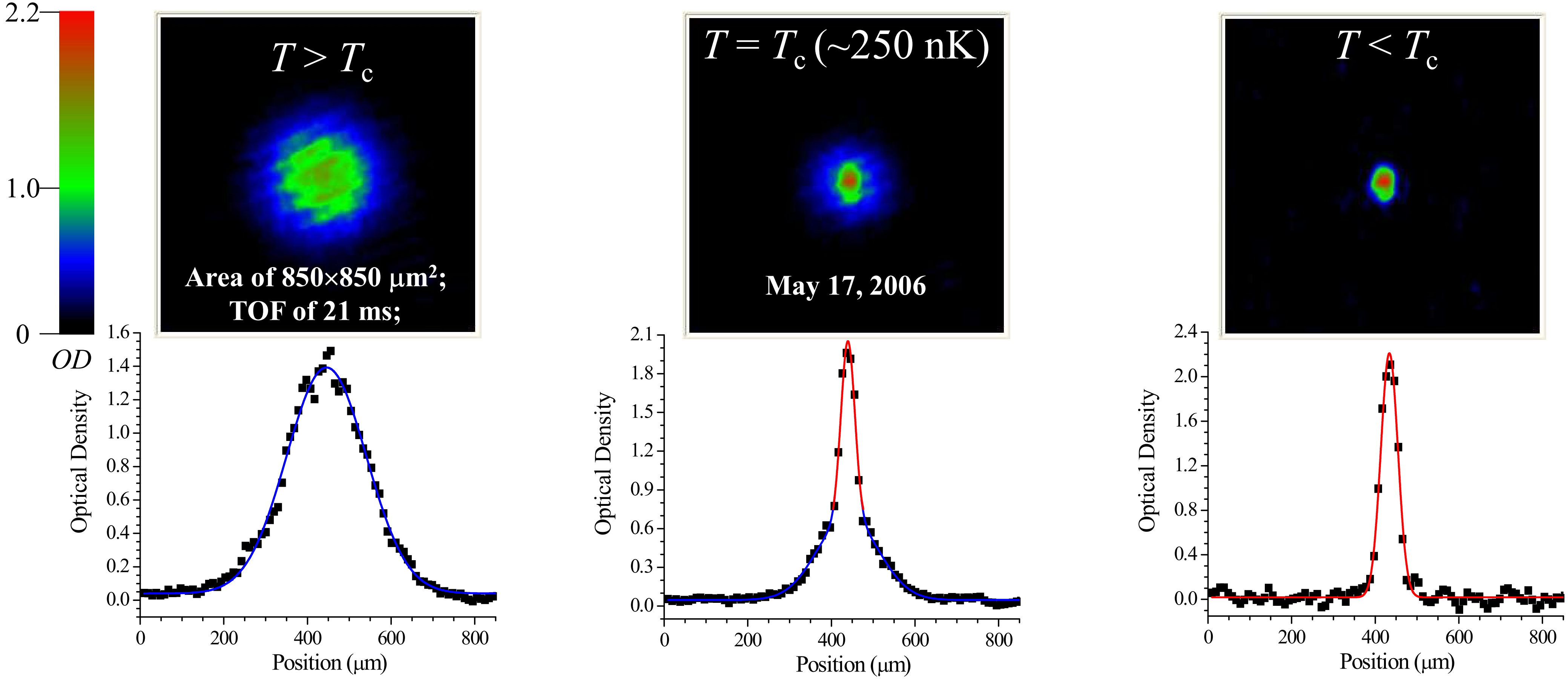


$\mathrm{OD} = 36 \pm 1, \gamma_\Lambda = (9 \pm 1) \times 10^{-4}\Gamma, \Omega_{c0} = 0.54\Gamma, \Omega_{c\pm} = 0.44\Gamma; \gamma_R = 0.02\Gamma, \Delta_a = +5\Gamma, \Omega_a = 2.0\Gamma, \Omega_b = 1.6\Gamma$

- β_{DSP} and ϕ_{DSP}: the attenuation coefficient and phase shift of DSPs. $\Delta\beta$ (or $\Delta\phi$): the difference between attenuation coefficients (or phase shifts) with and without the DDI.
- Red and blue shaded areas are the theoretical predictions with fluctuations in the OD and decoherence rate.
- The consistency between the data and predictions is satisfactory.

Bose-Einstein Condensation (BEC)

H. W. Cho, Y. C. He, T. Peters, Y. H. Chen, H. C. Chen, S. C. Lin, Y. C. Lee, & IAY, Opt. Express 15, 12114 (2007).



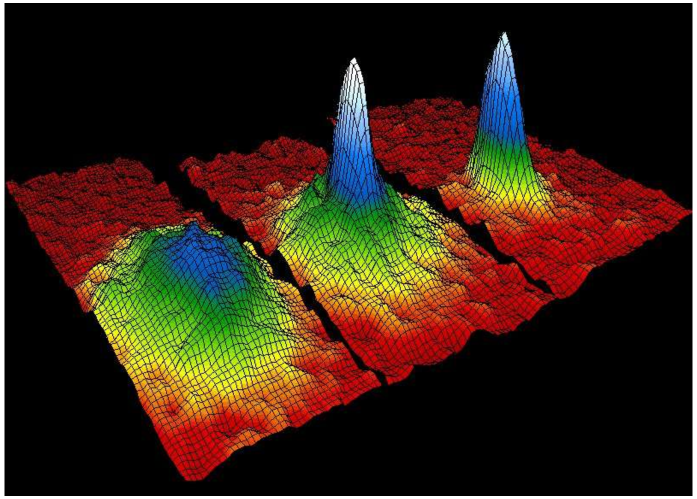
- BEC is formed, when the thermal de Broglie wavelength is about the mean spacing between particles.
- The Bose condensate is a coherent matter wave, superfluid, synthetic quantum matter, ……

Summary of Stationary DSPs Dressed by Rydberg-State DDI

m^*	$10^4\ m_e$	$\sim 10^{-2}\ m_e$	$10^{-5}\ m_e$
n	$10^{13}\sim10^{15}$ cm^{-3}	$\sim 10^{10}$ cm^{-3}	$10^{10}\sim10^{12}$ cm^{-3}
T_c	< 1 μK	~ 1 mK	> 1 K
τ	> 1 ms	~ 1 μs	< 100 ps

Atomic BEC

https://jila.colorado.edu/bec/

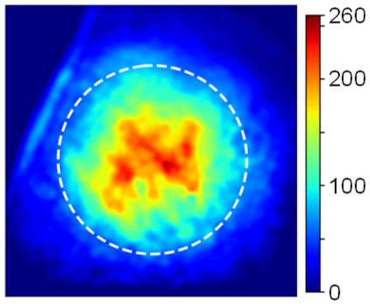


Dark-State-Polariton BEC?

$T_c = 4.0$ mK

$T_p = 3.8$ μK

$R_c = 33$ μs^{-1}



Need a trap for DSPs?

Avoid dark Rydberg states!

2D Exciton-Polariton BEC

Nature 443, 409 (2006)