High-Brightness and Narrow-Linewidth Source of Biphotons Generated from a Hot Atomic Vapor

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ASIAA/CCMS/IAMS/LeCosPA/NTNU-Physics/NTU-Physics Joint Colloquium

From Generation of Single Photons to Creation of a Many-Body System of Polaritons

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05/11/2021 (Tue), 14:20-15:20
R104, CCMS-New Physics Building, NTU

Abstract

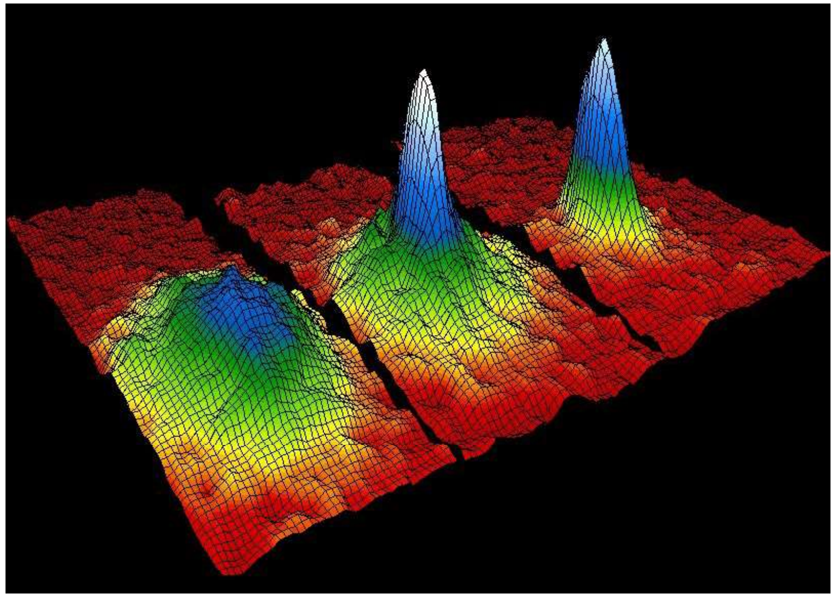
Photons are ideal carriers of information as they possess ultimate speed, hardly interact with the environment, and never collide with each other. We can foresee that photons will be employed to carry quantum information in quantum networks because of the excellent fidelity for carried wave functions. The effect of electromagnetically induced transparency (EIT) has attracted great attention in quantum information science due to its quantum nature of light-matter interface. Slow light arising from the EIT effect greatly enhances the interaction time between light and matters. The EIT-based light storage coherently transfers wave functions between photons and atoms. In this talk, I will report our recent progresses on the source of narrowest-linewidth and high-brightness biphotons, i.e., heralded single photons, and the weakly-interacting many-body system of Rydberg polaritons, both of which are based on the EIT effect. Our works have made the significant advancements in quantum technology, and can lead to the applications of quantum communication and quantum simulators.

Atomic and Exciton-Polariton Bose-Einstein Condensations

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

Atomic BEC

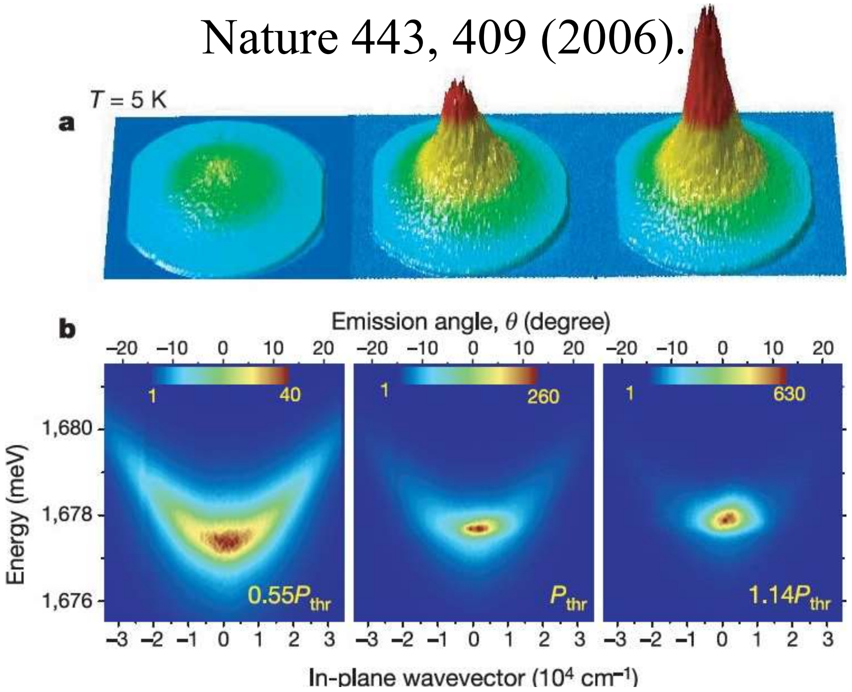
https://jila.colorado.edu/bec/



Can one create a new kind of BEC which is in-between?

2D Exciton-Polariton BEC

Nature 443, 409 (2006).



PHYSICAL REVIEW LETTERS **131,** 133001 (2023)

A New Kind of Quasi-Particles Feasible for the Realization of Bose-Einstein Condensation
可實現波色-愛因斯坦凝體的新型準粒子

Experimental Demonstration of Stationary Dark-State Polaritons Dressed by Dipole-Dipole Interaction

Bongjune Kim[1,*] Ko-Tang Chen,[1] Kuei-You Chen,[1] Yu-Shan Chiu,[1] Chia-Yu Hsu,[1] Yi-Hsin Chen,[2] and Ite A. Yu[1,3,†]
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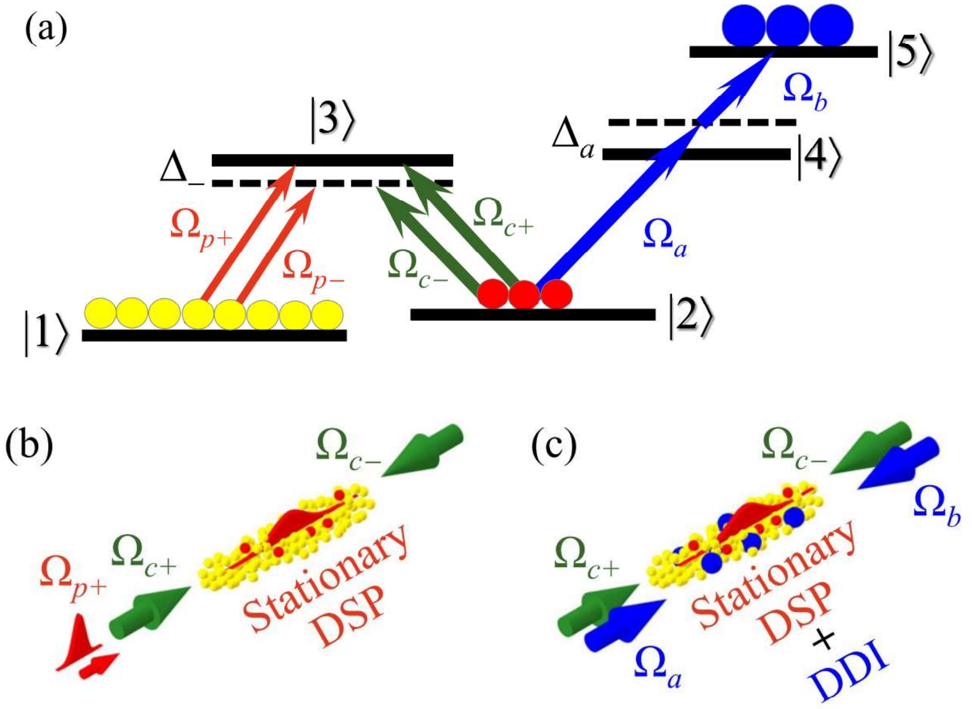
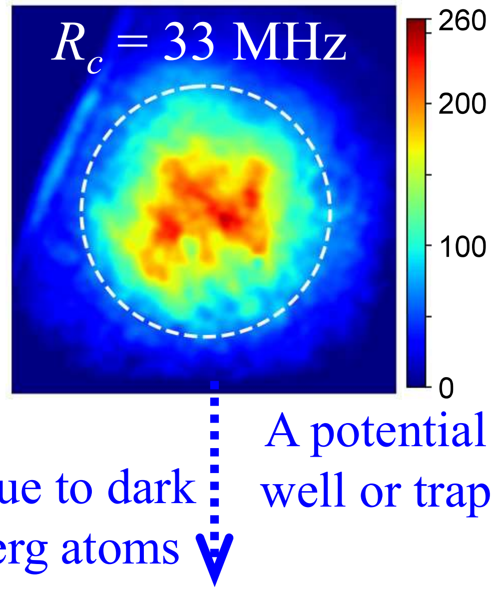


DDI-dressed Stationary DSPs

Employ the formula in PRL 101, 165601 (2008) to estimate the current condition:

$T_c = 4.0$ mK

$T_p = 3.8$ μK



A potential well or trap

Loss due to dark Rydberg atoms

BEC

Acknowledgment

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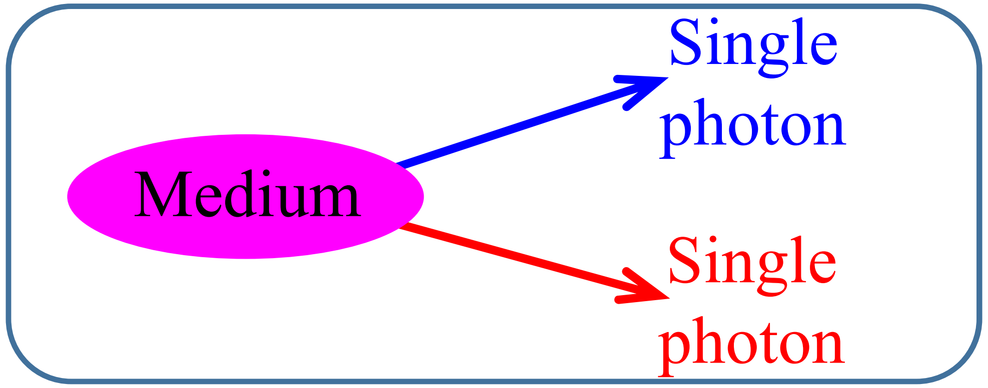
National Science and Technology Council, Taiwan

Group Members 2023/2/13

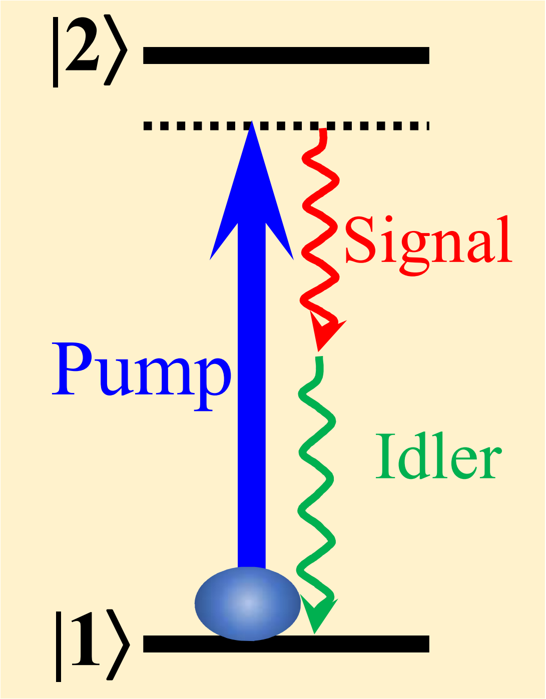
Introduction to Biphotons

What are biphotons?
Why are they useful?



- The **biphoton** is a pair of time-correlated single photons.
- Single photons appear randomly in time. It is difficult to use them in the random timing.
- Biphotons also appear randomly in time. Nevertheless, we can use the first photon of the biphoton to trigger a quantum operation, and employ the second one in the quantum operation.
- So, the second photon of a pair is called the **heralded single photon (≡ biphoton)**.

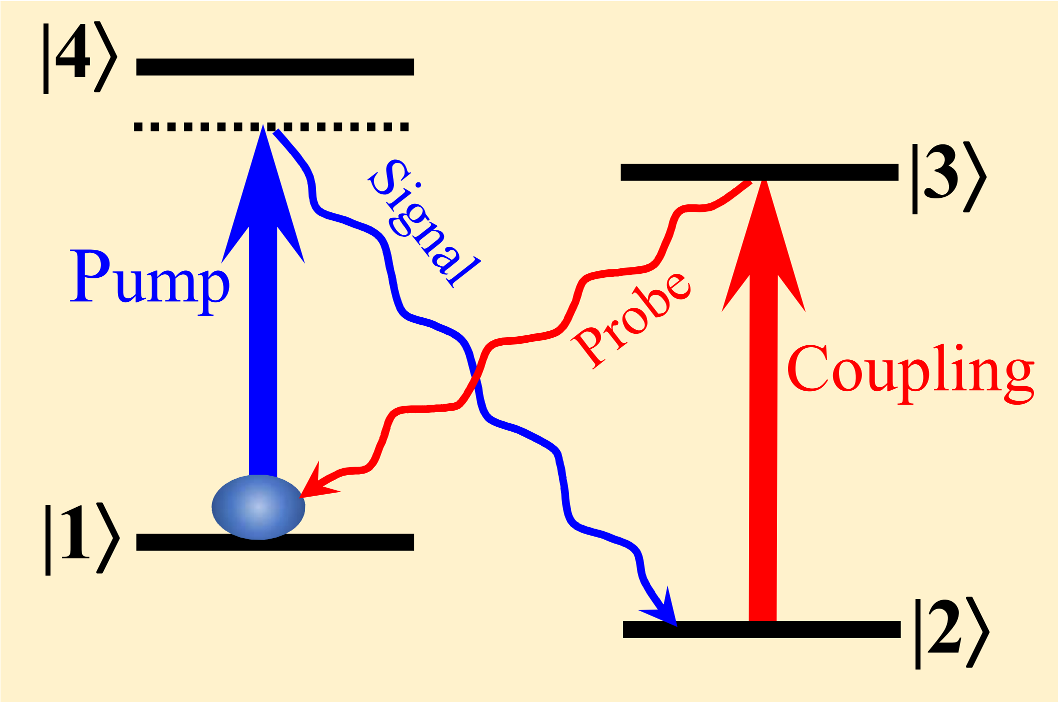
Mechanisms for Generation of Biphotons — SPDC



Spontaneous Parametric Down Conversion

- SPDC: A pump photon is converted to a signal and an idler photons induced by the vacuum fluctuation.
- Typical media are nonlinear crystals.
- Since 1970.

Mechanisms for Generation of Biphotons — SFWM

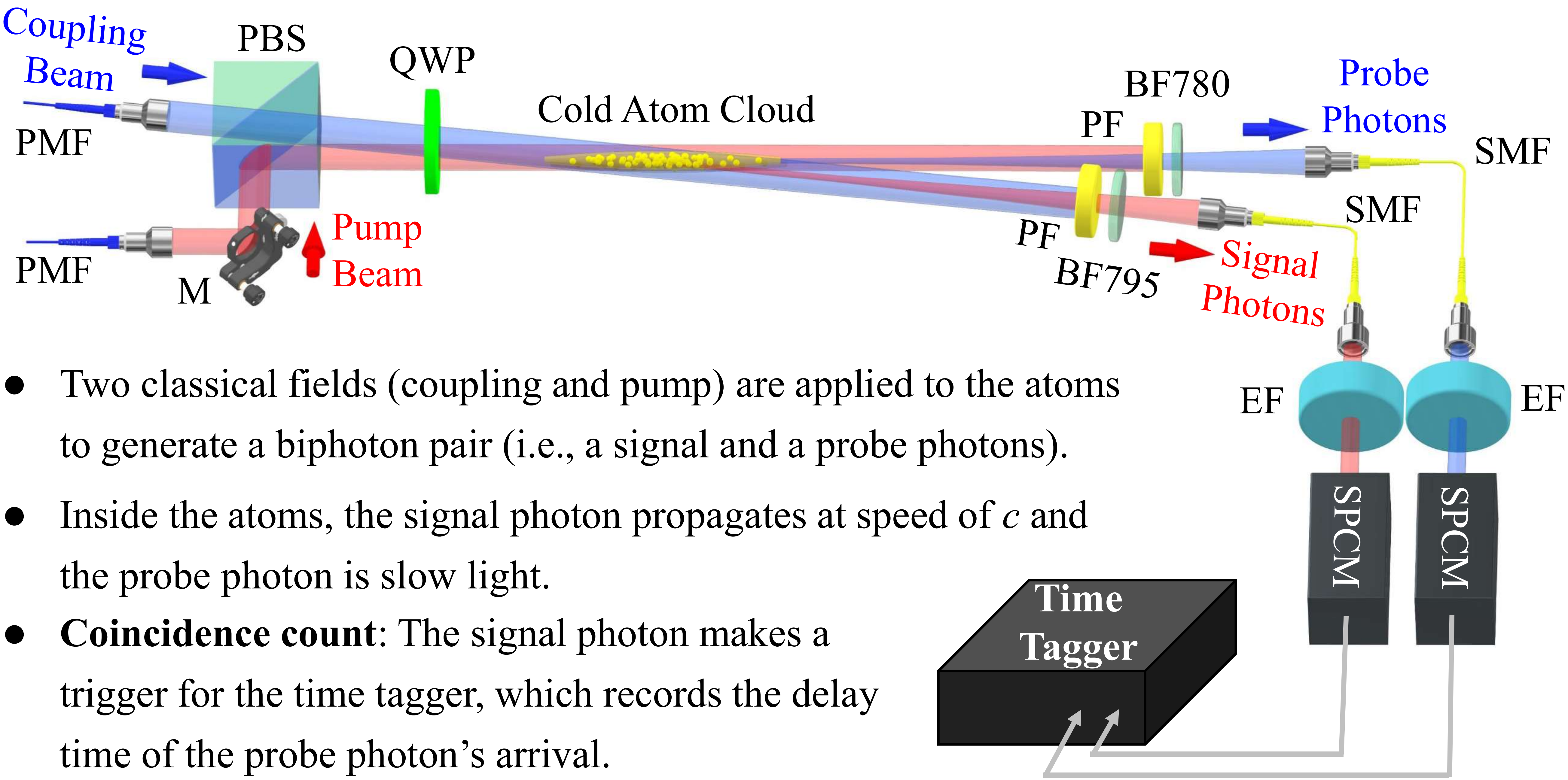


Spontaneous Four-Wave Mixing

- SFWM: 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 similar to the electromagnetically induced transparency (EIT) effect.
- The EIT effect makes the probe photon become slow light.
- Typical media: cold atoms since 2005 and room-temperature or hot atomic vapors since 2016.

Illustration of Biphoton Generation and Wave Packet

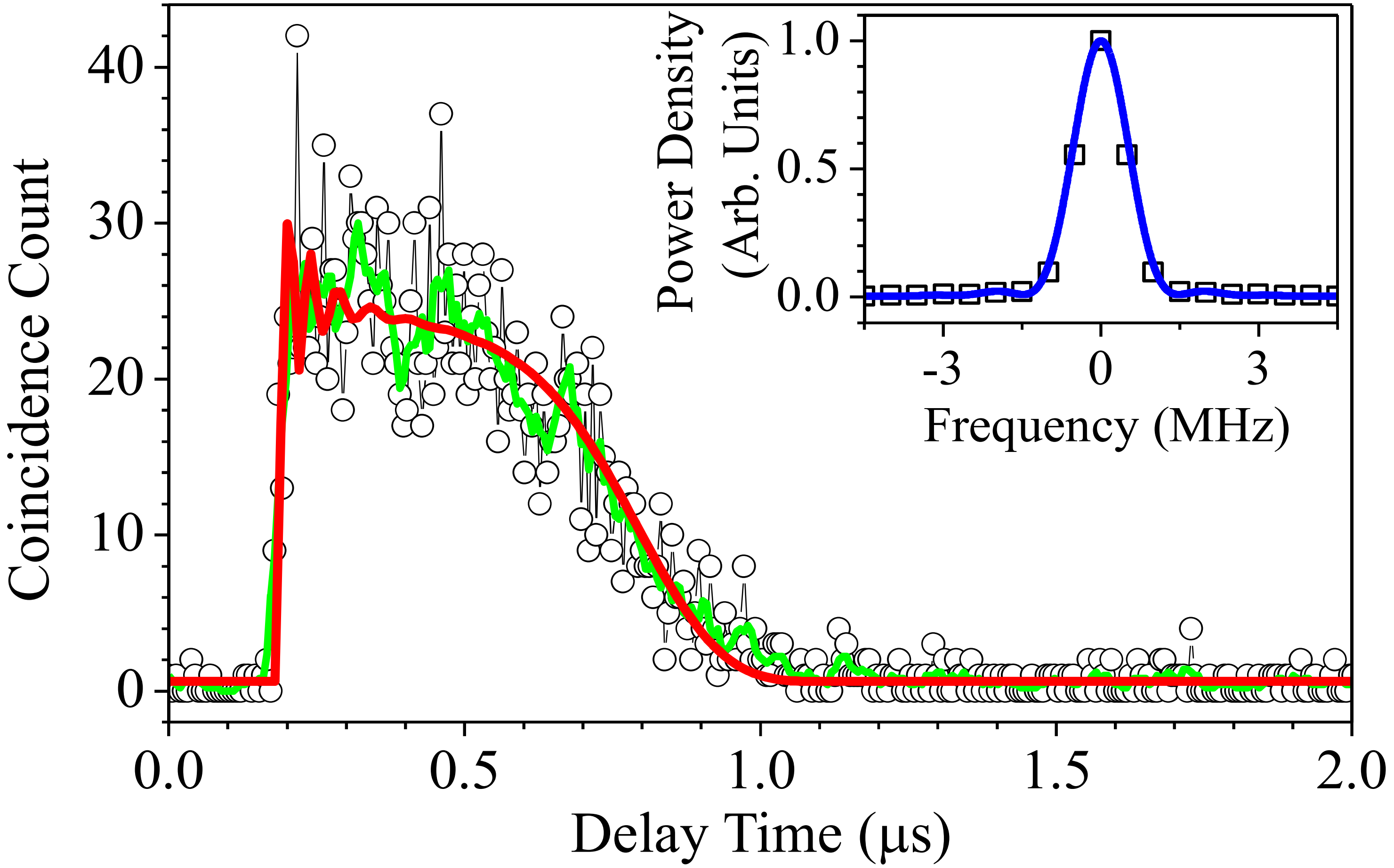
Biphoton Generation from Cold Atoms



- Two classical 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.



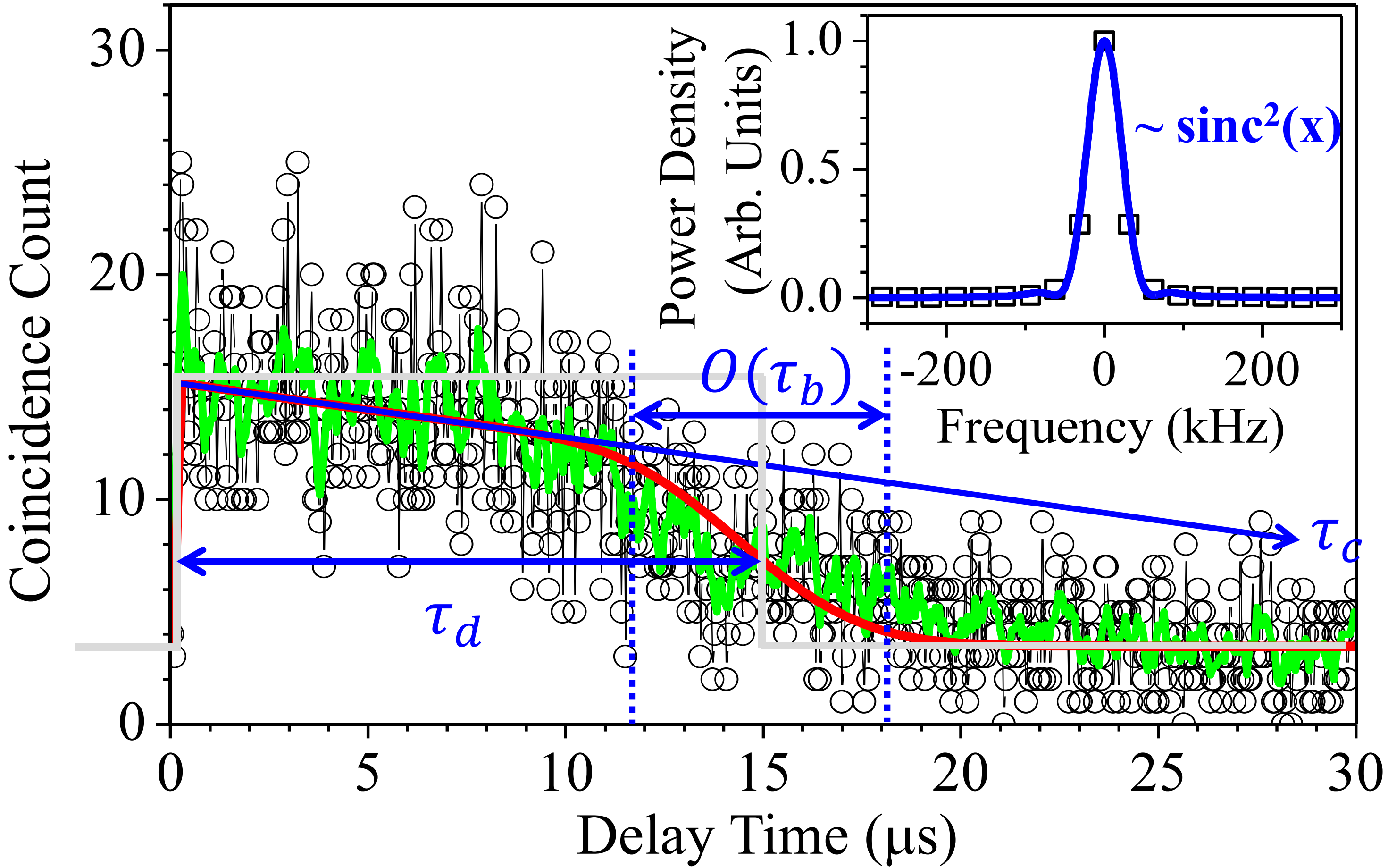
Temporal FWHM 0.57 μs

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 in the World

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, and I. A. Yu,
APL Photonics 7,
126102 (2022).



Temporal FWHM 13.4 μs

Spectral FWHM 50 kHz

- A low decoherence rate plus a high optical depth enables the production of ultralong biphotons.
- 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.

Biphoton Sources with Spectral Profiles of FWHM below 1 MHz

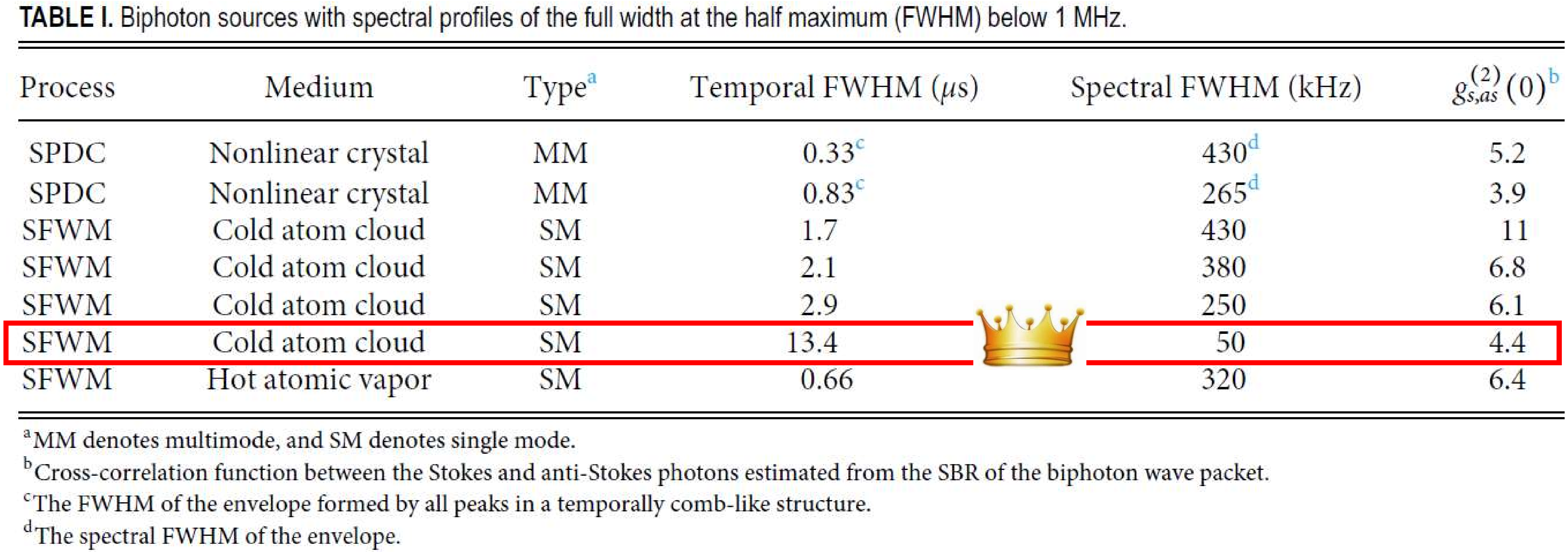


TABLE I. Biphoton sources with spectral profiles of the full width at the half maximum (FWHM) below 1 MHz.

Process	Medium	Type[a]	Temporal FWHM (μs)	Spectral FWHM (kHz)	$g^{(2)}_{s,as}(0)$[b]
SPDC	Nonlinear crystal	MM	0.33[c]	430[d]	5.2
SPDC	Nonlinear crystal	MM	0.83[c]	265[d]	3.9
SFWM	Cold atom cloud	SM	1.7	430	11
SFWM	Cold atom cloud	SM	2.1	380	6.8
SFWM	Cold atom cloud	SM	2.9	250	6.1
SFWM	Cold atom cloud	SM	13.4	50	4.4
SFWM	Hot atomic vapor	SM	0.66	320	6.4

[a] MM denotes multimode, and SM denotes single mode.
[b] Cross-correlation function between the Stokes and anti-Stokes photons estimated from the SBR of the biphoton wave packet.
[c] The FWHM of the envelope formed by all peaks in a temporally comb-like structure.
[d] The spectral FWHM of the envelope.

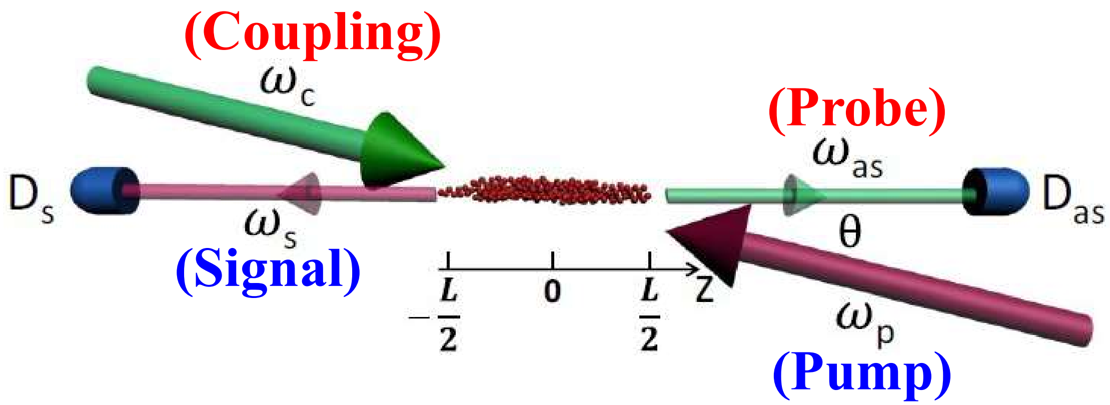
- However, the duty cycle of the biphoton generation with cold atoms is low, e.g., 0.8% in our case and the average generation rate is merely about 30 pairs/s.
- The data in each figure were accumulated by about one hour.

Features of Our Hot-Atom Biphoton Source

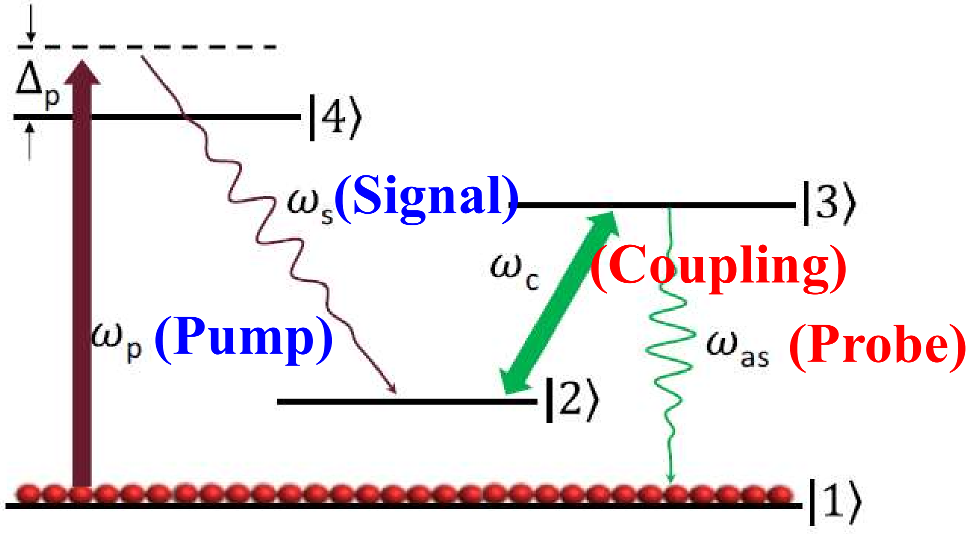
A Room-Temperature Atomic Vapor Cell

- A cylindrical glass cell with 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 and heated to 65 °C.

Phase Mismatch in Others’ Biphoton Experiments



Counter-Propagation



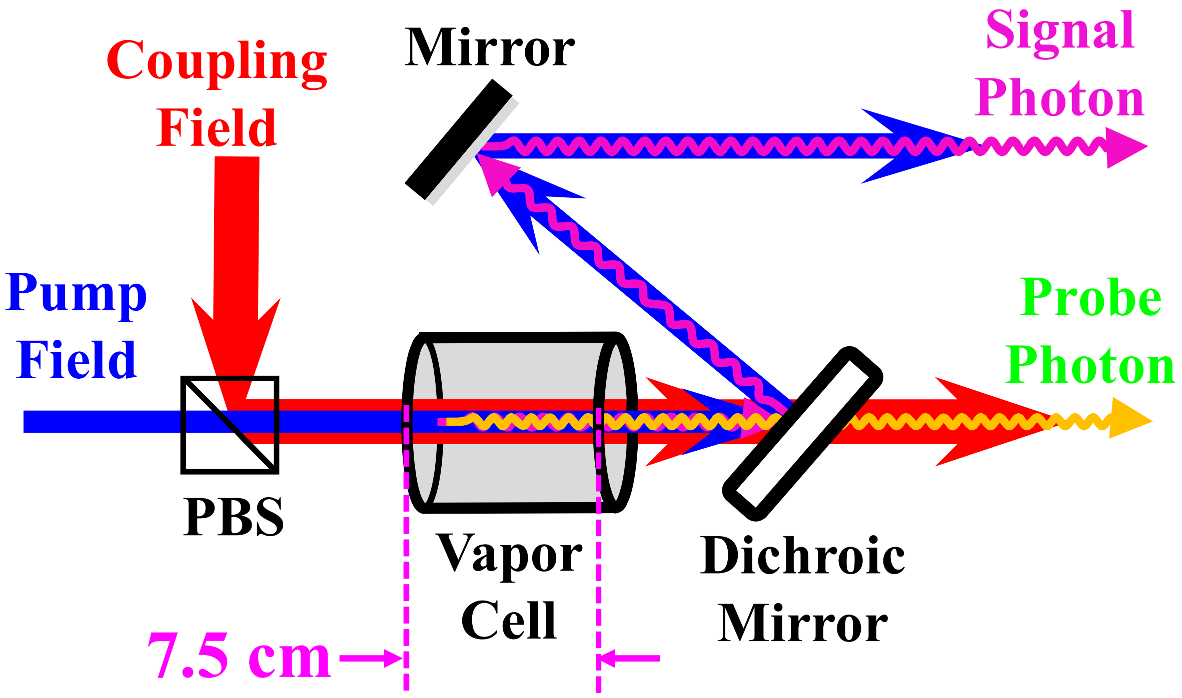
Two absorption-emission processes

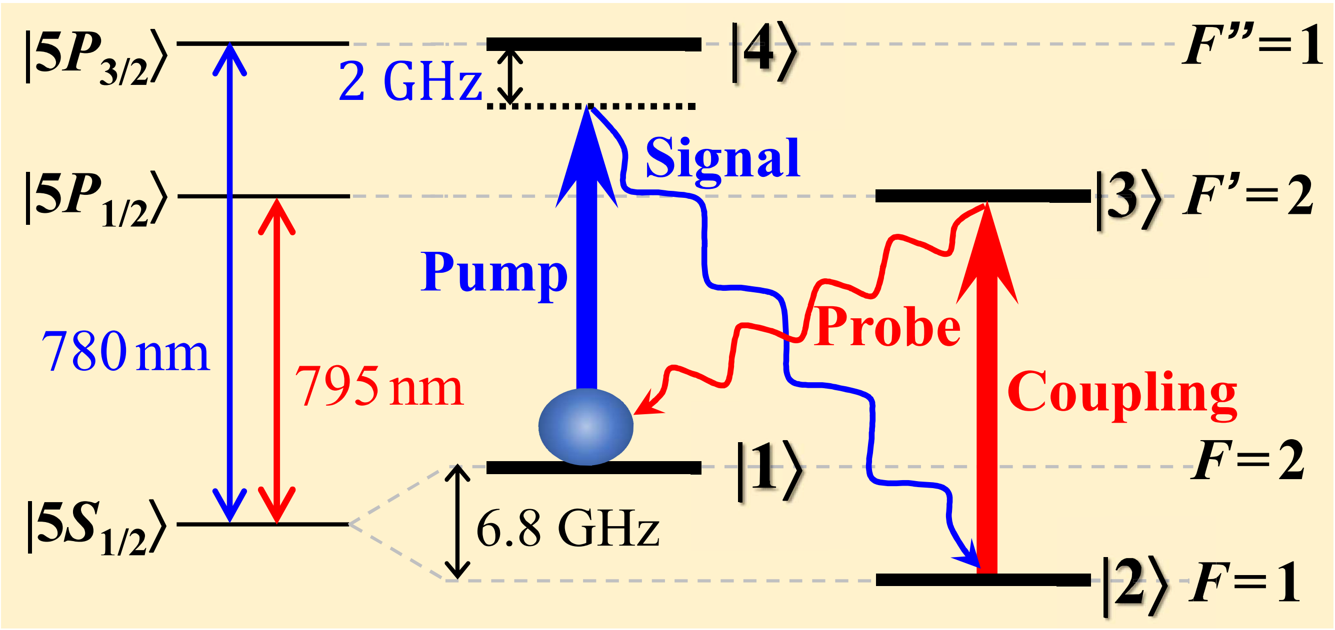
$$\Delta\vec{k} = \left(\vec{k}_{\text{pump}} - \vec{k}_{\text{signal}}\right) + \left(\vec{k}_{\text{coupling}} - \vec{k}_{\text{probe}}\right) = \left(\frac{\omega_{21}}{c}\right)(-\hat{z}) + \left(-\frac{\omega_{21}}{c}\right)\hat{z} = -\frac{2\omega_{21}}{c}\hat{z}$$

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 Our Biphoton Experiment

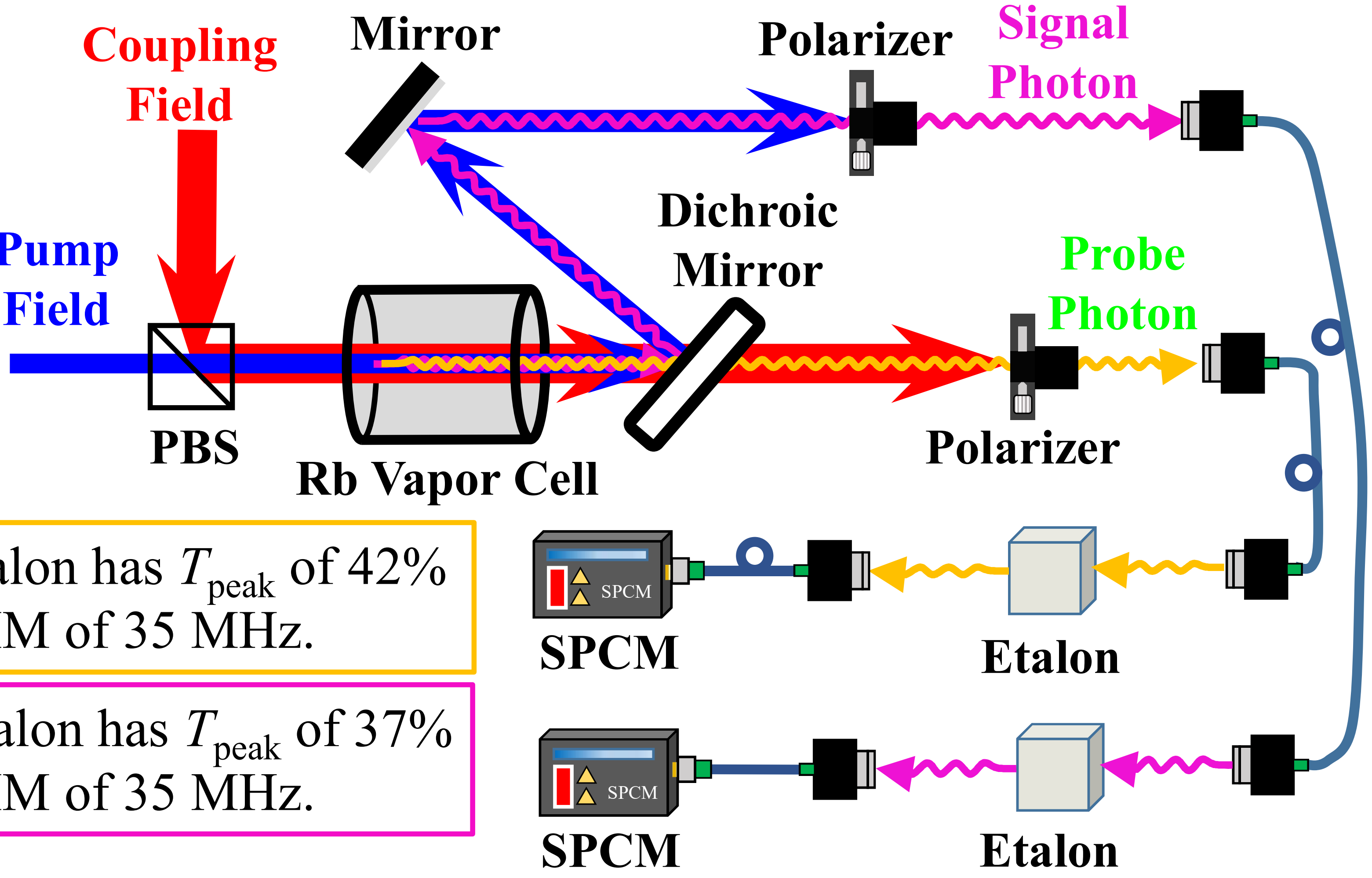




$$\Delta\vec{k} = \left(\vec{k}_{\text{pump}} - \vec{k}_{\text{signal}}\right) + \left(\vec{k}_{\text{coupling}} - \vec{k}_{\text{probe}}\right) = \left(-\frac{\omega_{12}}{c}\right)\hat{z} + \left(\frac{\omega_{12}}{c}\right)\hat{z} = 0!$$

- Our biphoton source utilized the all-copropagation 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.

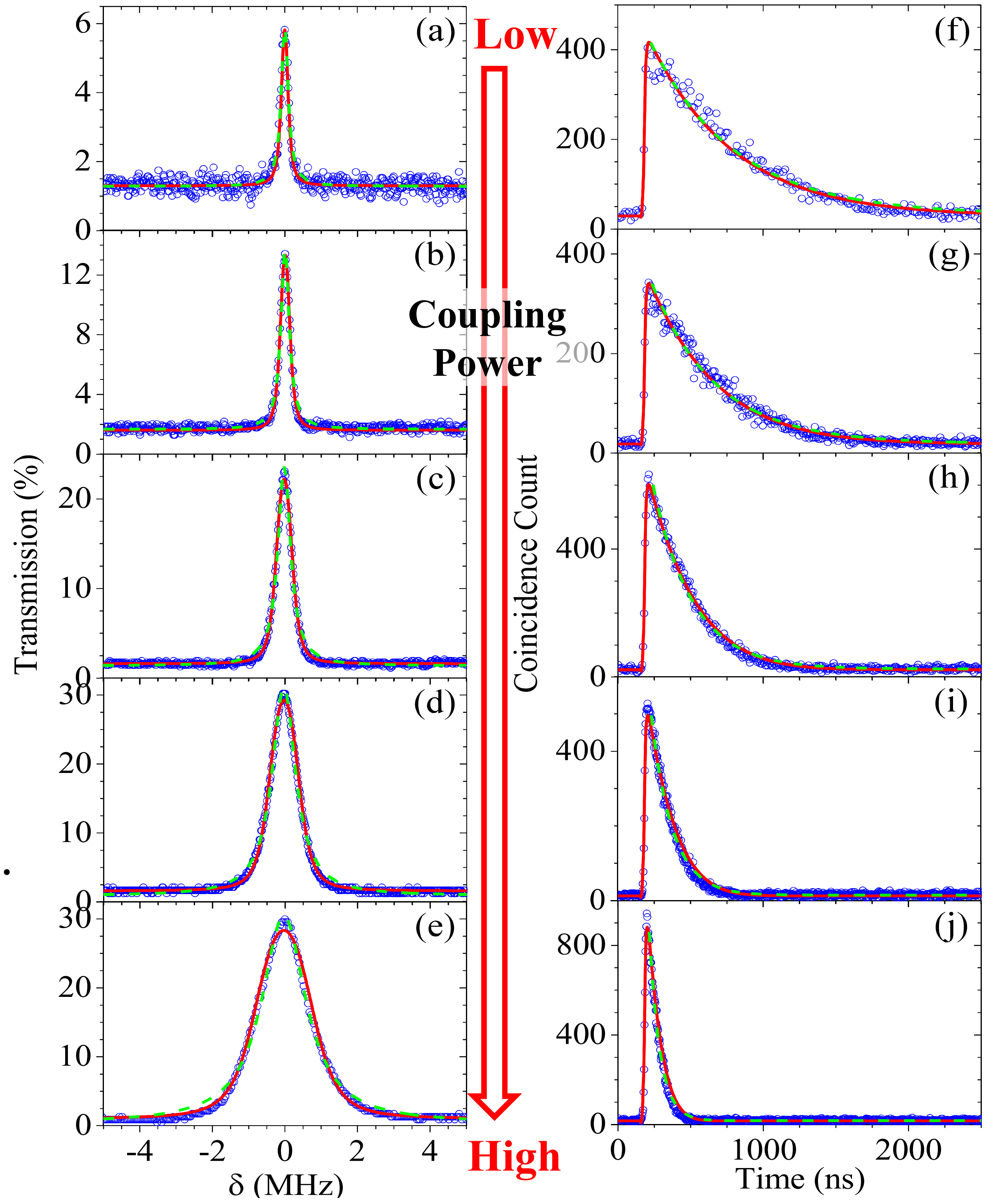
A Narrow-Linewidth, High-Generation Rate Biphoton Source

Biphoton Wave Packet and EIT Spectrum of Hot Atoms

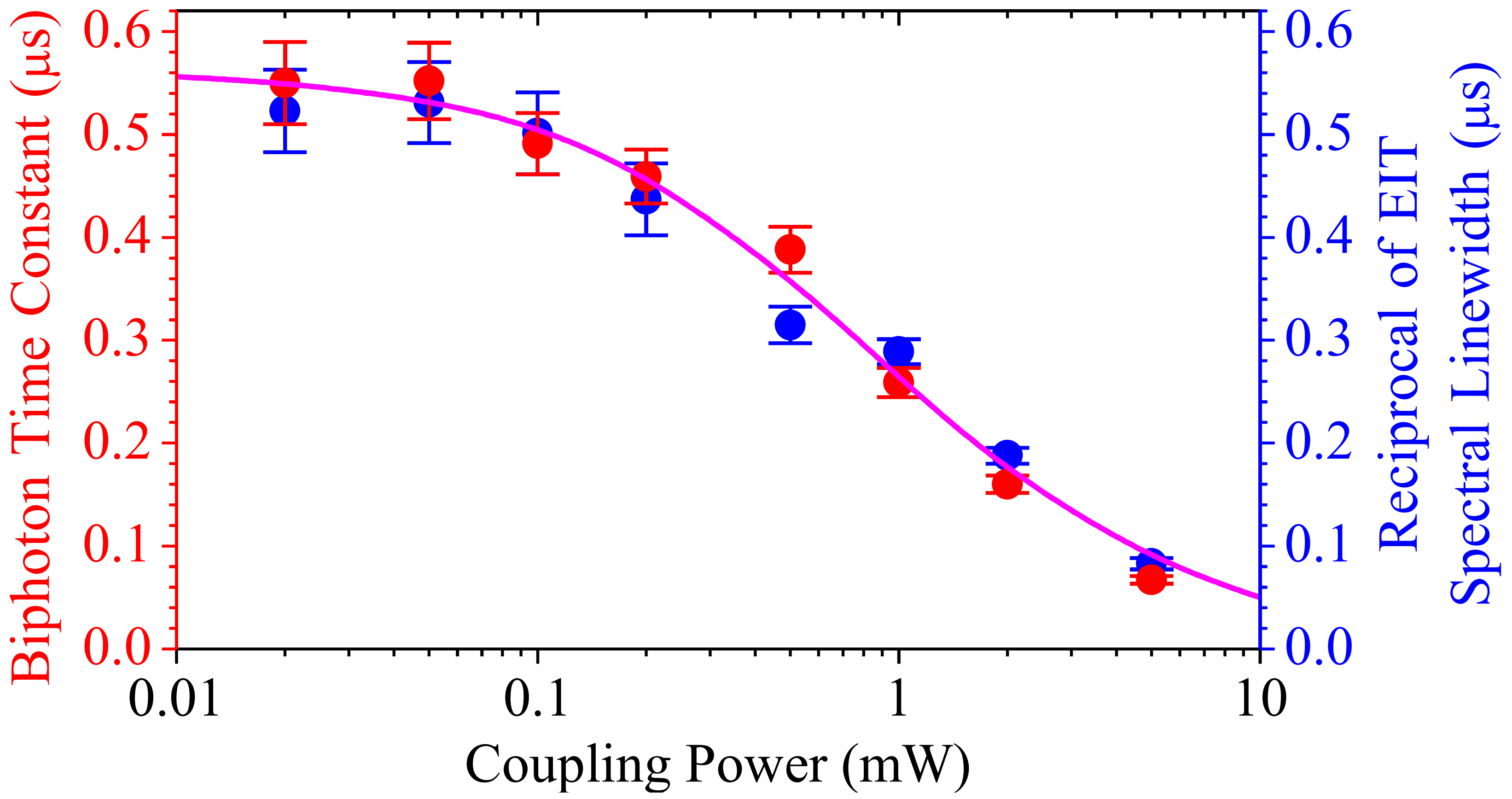
S.-S. Hsiao, W.-K. Huang, Y.-M. Lin, J.-M. Chen, C.-Y. Hsu, and I. A. Yu, Phys. Rev. A 106, 023709 (2022).

In hot atoms, the biphoton wave packet is mainly determined by the EIT spectrum; in cold atoms, it is strongly influenced by the propagation delay time as shown by the earlier slide.

- A higher coupling power makes a broader EIT linewidth & a narrower biphoton temporal width.
- The EIT spectral profile is a Lorentz function.
- The biphoton temporal profile is an exponential-decay function.



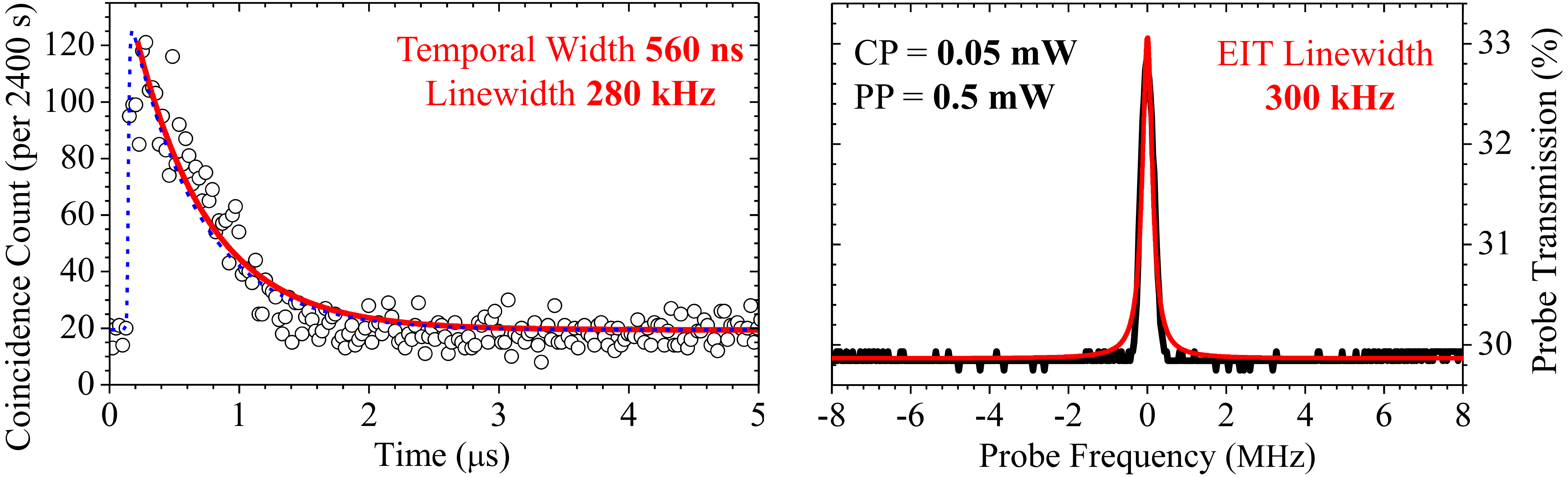
A Biphoton Source with a Highly Tunable Temporal Width



- Data of biphoton temporal widths (red) are consistent with results calculated from those of EIT linewidths (blue), and also in agreement with the theoretical predictions (line).
- The temporal width or spectral linewidth of biphotons can be tuned by about one order of magnitude (from 60 to 560 ns). A higher laser power can make the tuning range larger.

The Narrowest-Linewidth Biphotons Generated from Hot Atoms in the World

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, I. A. Yu, Opt. Express 29, 4632 (2021). **Editors' Pick.**



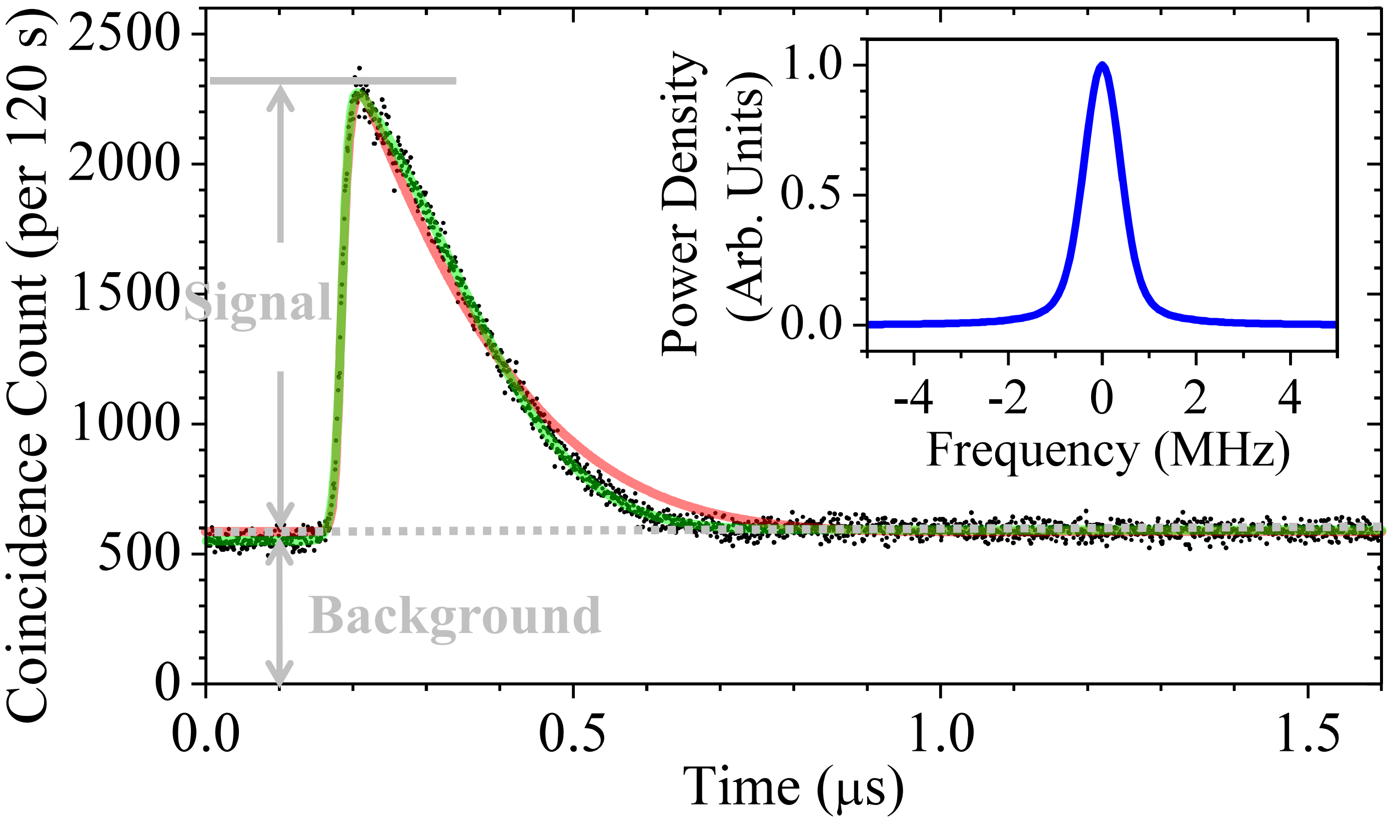
- Biphoton wave packet (left) and EIT spectrum (right) were measured at the same condition.
- The decoherence rate in the experimental system limits the narrowest linewidth.

The Highest Spectral Brightness in the World

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, and I. A. Yu,
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

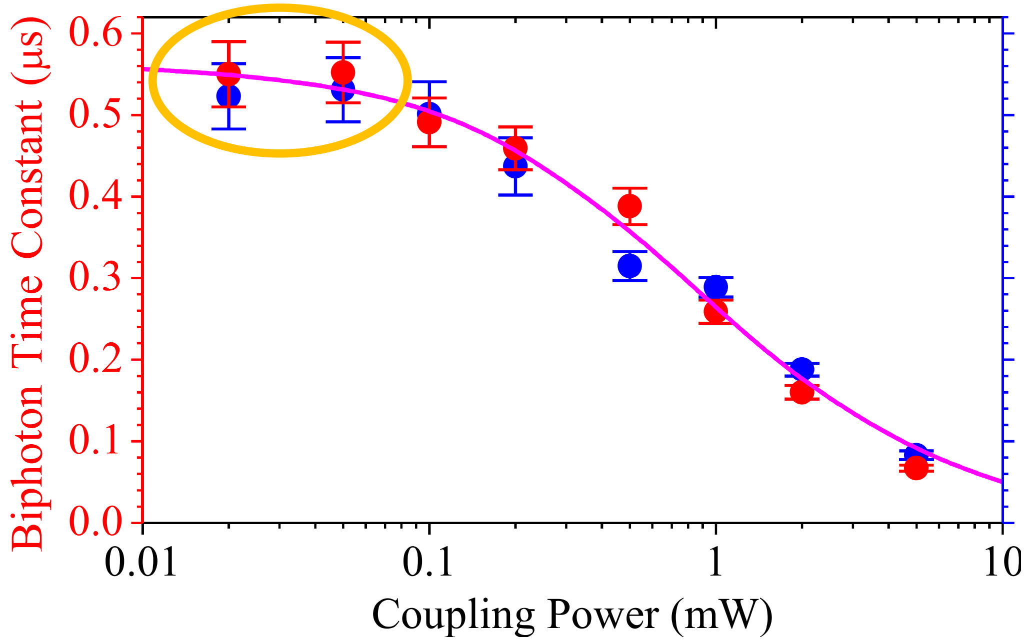
		Best Linewidth	Best Spectral Brightness	Linewidth Tunability	Frequency Tunability	Notes
Single-Mode SPDC		3 MHz[1]	3.5×10^5 pairs/s/MHz[4]	N.A.	👑 a few GHz	
Cold-Atom SFWM **Our Works**		👑 **50 kHz**[9]	4,700(×10%) pairs/s/MHz[5]	one order of magnitude	N.A.	Duty cycle ≤ 10%.
Integrated Photonics Devices		92 MHz[2]	1.4×10^5 pairs/s/MHz[2]	N.A.	160 MHz[2]	Micro-ring resonator[3] with Q of ~10^6.
Hot-Atom SFWM	Earlier Works	2 MHz[3]	1.4×10^4 pairs/s/MHz[6]	👑 one order of magnitude	600 MHz (Rb atoms)	The frequency tunability is determined by width of the Doppler broadening.
	Our Works	**290 kHz**[7]	👑 **3.8×10^5 pairs/s/MHz**[8]			

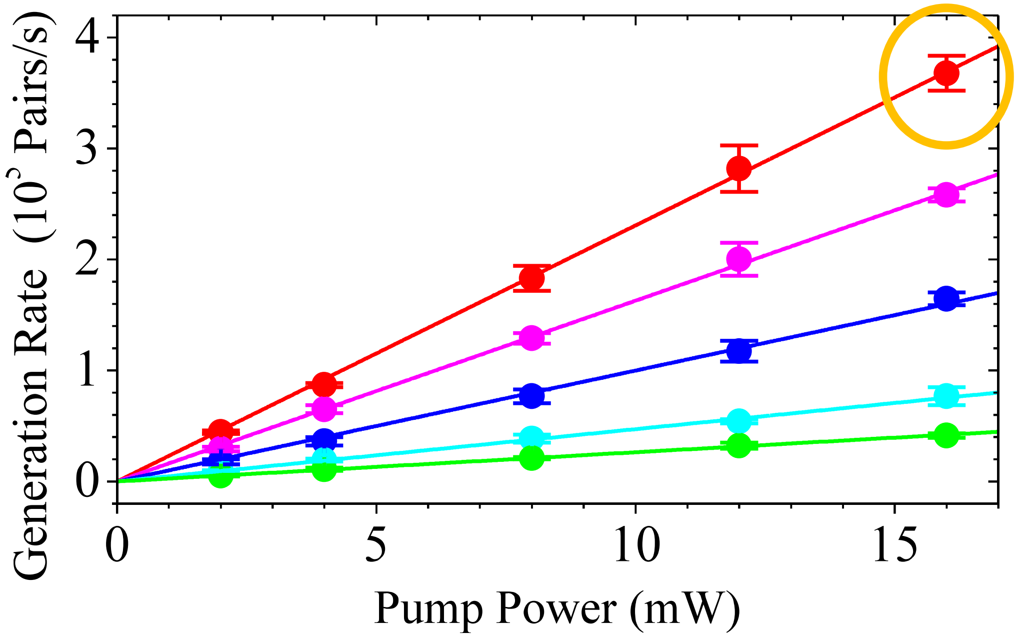
[1] New J. Phys. 18, 123013 (2018).
[2] PRX Quantum 2, 010337 (2021).
[3] Nat. Commun. 7, 12783 (2016).
[4] Phys. Rev. A 92, 063827 (2015).
[5] Optica 1, 84 (2014).
[6] Appl. Phys. Lett. 110, 161101 (2017).
[7] Opt. Express 29, 4632 (2021).
[8] Phys. Rev. Res. 4, 023132 (2022).
[9] APL Photonics 7, 126102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

Conclusion and Outlook

Conclusion

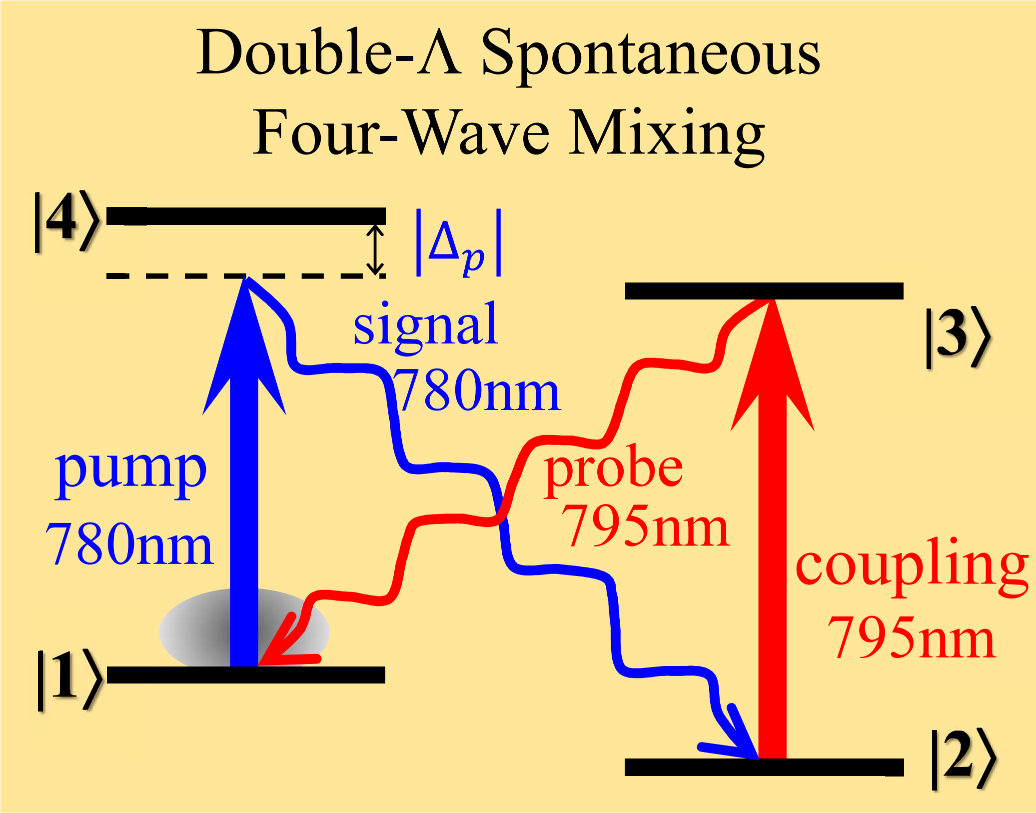
- We started to develop the biphoton source of hot atoms in 2015, and observed the first biphoton data in 2017 (linewidth ≈ 5 MHz, generation rate ≈ 30 pairs/s, and SBR ≈ 0.3).
- Now, we have one of the best and state-of-art biphoton sources in the world.
- The biphoton linewidth can be as narrow as 290 kHz, which is the narrowest among all kinds of single-mode biphotons generated from room-temperature or hot media.
- The generation rate can be as high as 10^6 pairs/s.
- The spectral brightness ≈ 3.7×10^5 pairs/s/MHz, which is the highest spectral brightness of all biphoton sources.





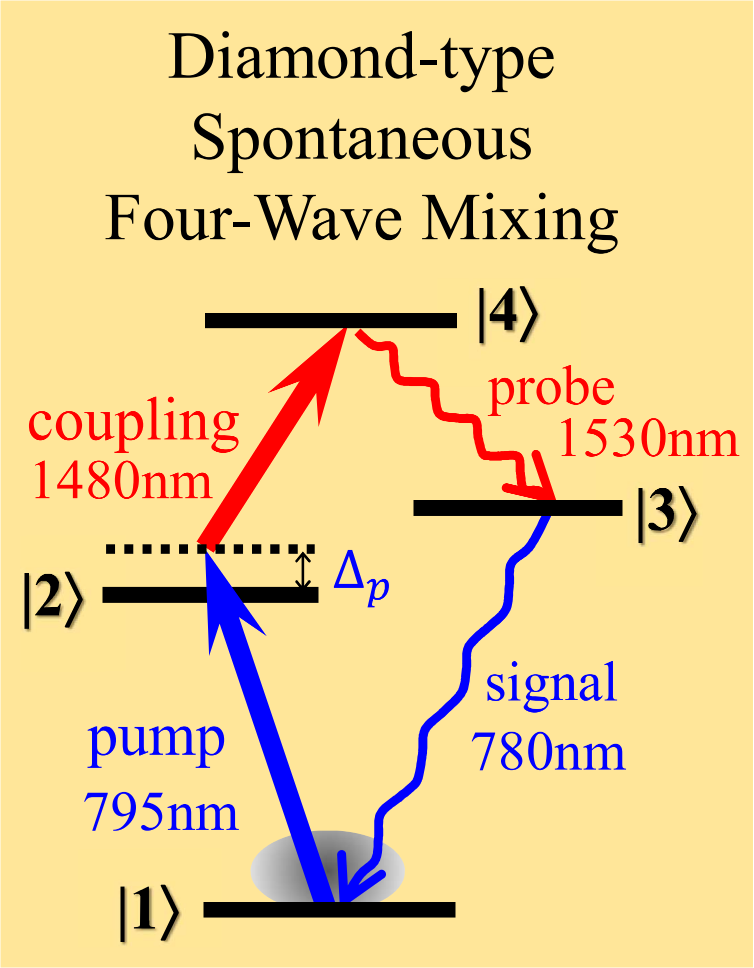
Outlook — A Source of Optical-Communication Biphotons

Now: 795 nm or 780 nm **(-3dB/km in optical fibers)** source


Double-Λ Spontaneous Four-Wave Mixing

Future: 1530nm **(-0.2dB/km in optical fibers)** source

- ➢ High rate
- ➢ Narrow linewidth
- ➢ Large spectral brightness
- ➢ **Movable**
- ➢ **Compact**


Diamond-type Spontaneous Four-Wave Mixing

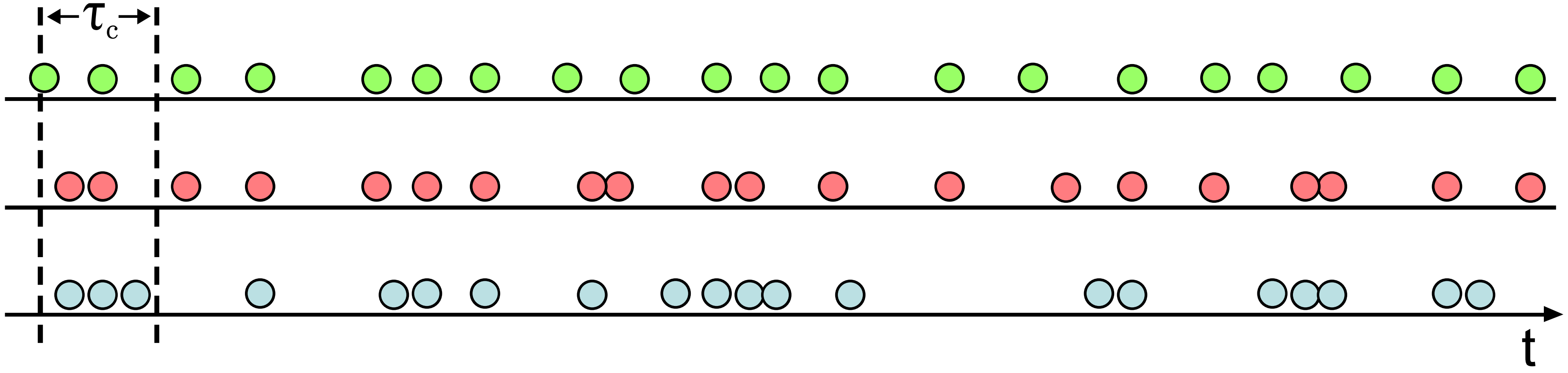
- Our 795 nm or 780 nm heralded-single-photon source is very successful.
- We aim to develop a source of 1530 nm heralded single photons for the optical-fiber communication.
- Can we have a 1530 nm source as good as the current 795 nm source?

Statistics Natures of Photons

Anti-Bunching, Randomly Bunching, and Bunching

https://en.wikipedia.org/wiki/Photon_antibunching

By Ajbura - Vectorised version of File: Photon bunching.png, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=73299604



Photon detections as function of time for a) antibunched, b) random, and c) bunched light

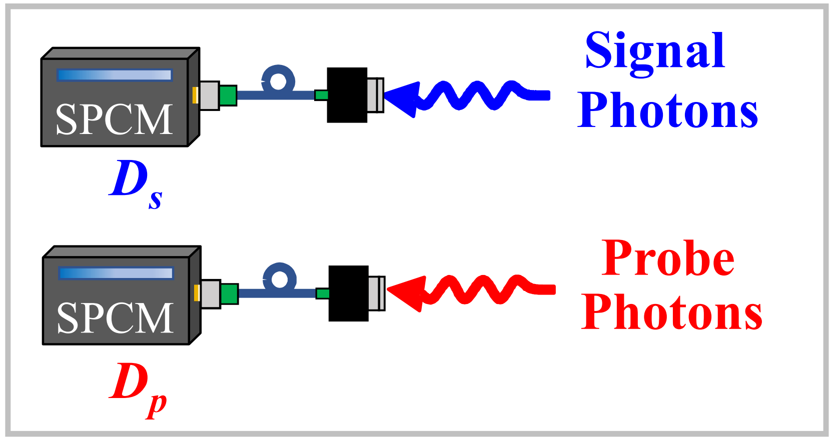
Photon detections as a function of time for a) antibunching (e.g. light emitted from a single atom), b) random (e.g. a coherent state, laser beam), and c) bunching (chaotic light). **τ_c is the coherence time (the time scale of photon or intensity fluctuations).**

One can employ the Hanbury-Brown-Twiss measurement to determine the photon-photon correlation.

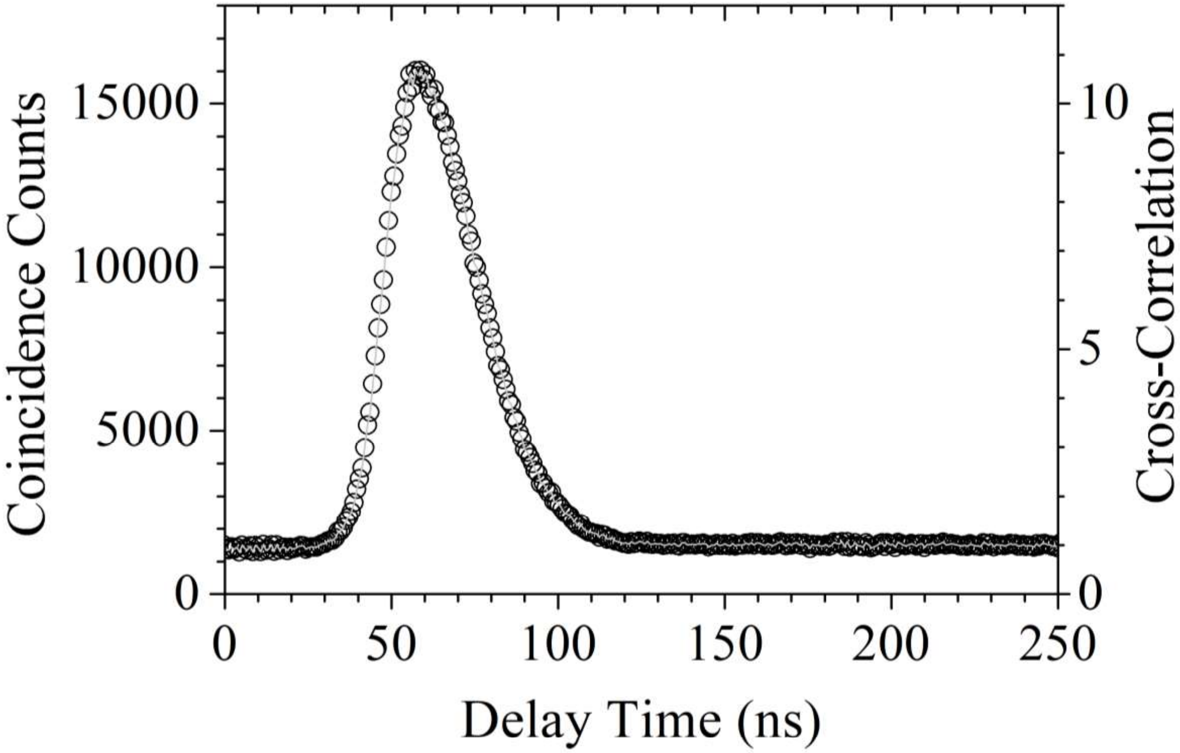
$g^{(2)} < 0.5$: anti-bunching, $g^{(2)} = 1$: randomly bunching, $g^{(2)} > 1.5$: bunching.

Cross-Correlation Function between the Signal and Probe Photons

$$g_{s,p}^{(2)}(\tau) \equiv \frac{\langle N_s(t) N_p(t+\tau) \rangle}{\langle N_s(t) \rangle \langle N_p(t+\tau) \rangle}$$



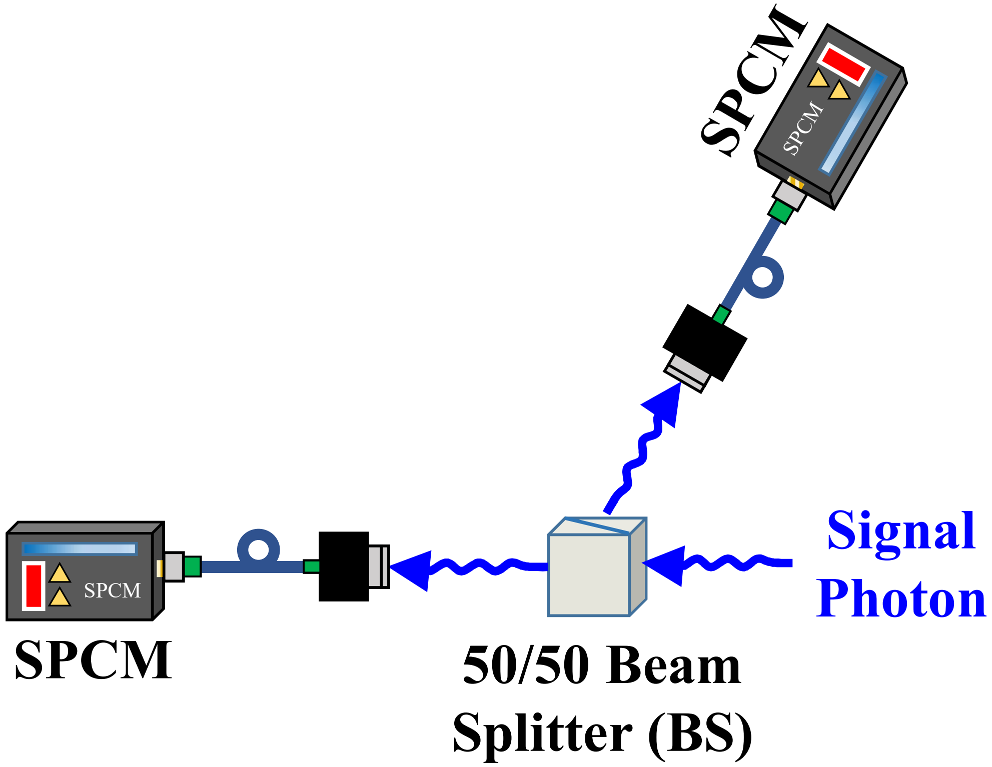
$\text{Max}\left[g_{s,p}^{(2)}\right] \gg 2$ indicates the signal and probe photons are highly correlated.

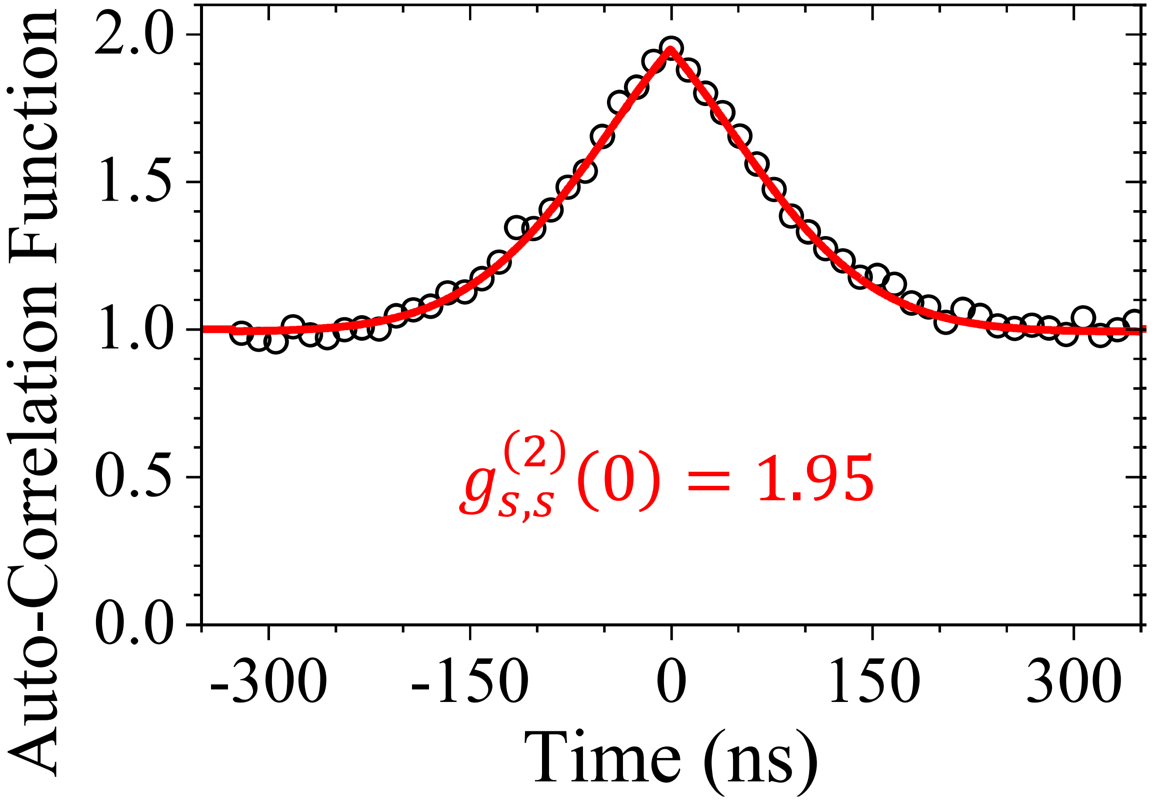


The coincidence count or equivalently the CCF, $g_{s,h}^{(2)}(\tau)$, as a function of the delay time, τ, between the heralding and heralded photons. Data were accumulated for 2 minutes with the bin time of 0.8 ns. Circles connected by gray lines are the experimental data. The biphoton source has a detection rate of 5100±120 counts/s, and the peak of the CCF is 10.6±0.1, where the quoted value and uncertainty are the average and standard deviation of several consecutive measurements under the same condition.

Auto-Correlation Function of the Signal Photons

$$g_{s,s}^{(2)}(\tau) \equiv \frac{\langle N_1(t)N_2(t+\tau)\rangle}{\langle N_1(t)\rangle\langle N_2(t+\tau)\rangle}$$

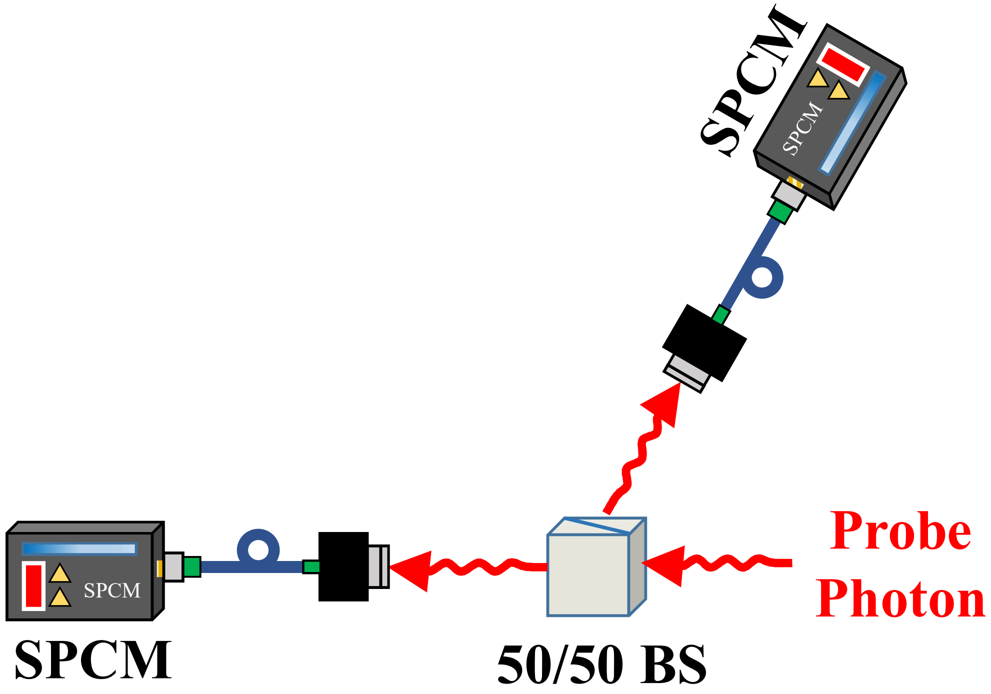


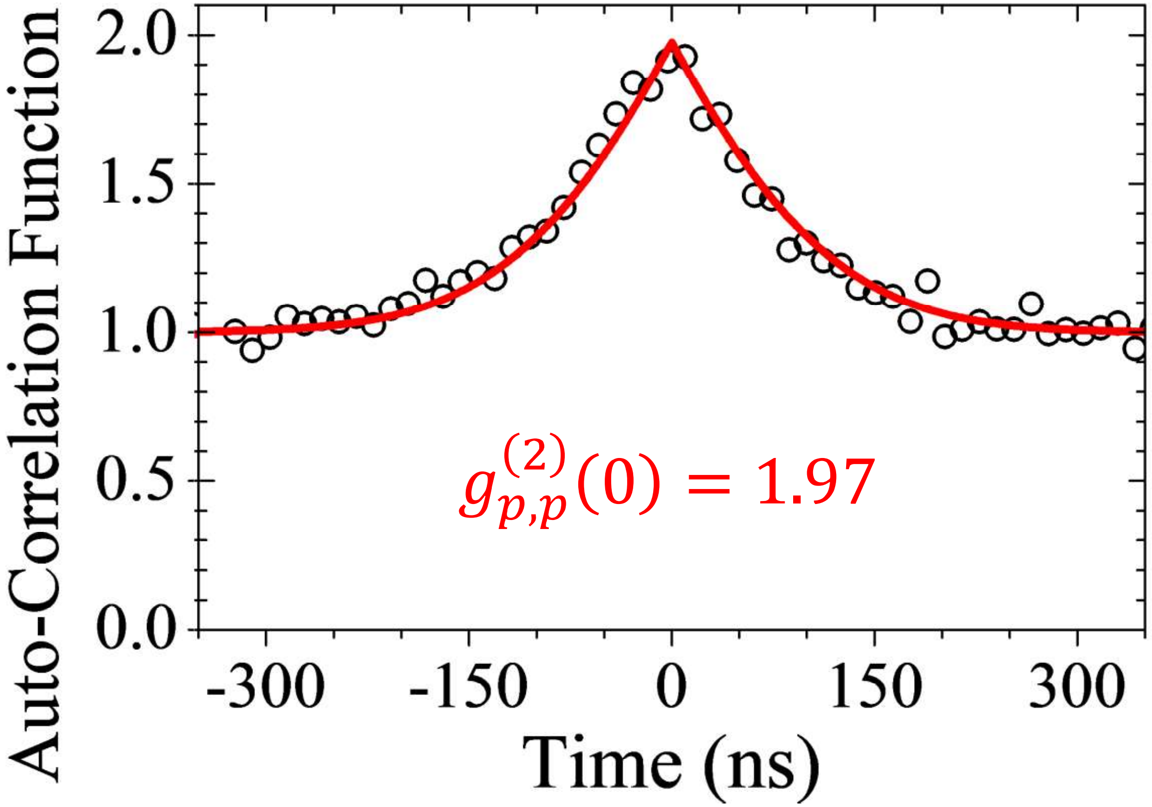


$g_{s,s}^{(2)}(0) \to 2$ indicates the signal photons are thermal light and they are bunching.

Auto-Correlation Function of the Probe Photons

$$g^{(2)}_{p,p}(\tau) \equiv \frac{\langle N_1(t) N_2(t+\tau)\rangle}{\langle N_1(t)\rangle\langle N_2(t+\tau)\rangle}$$

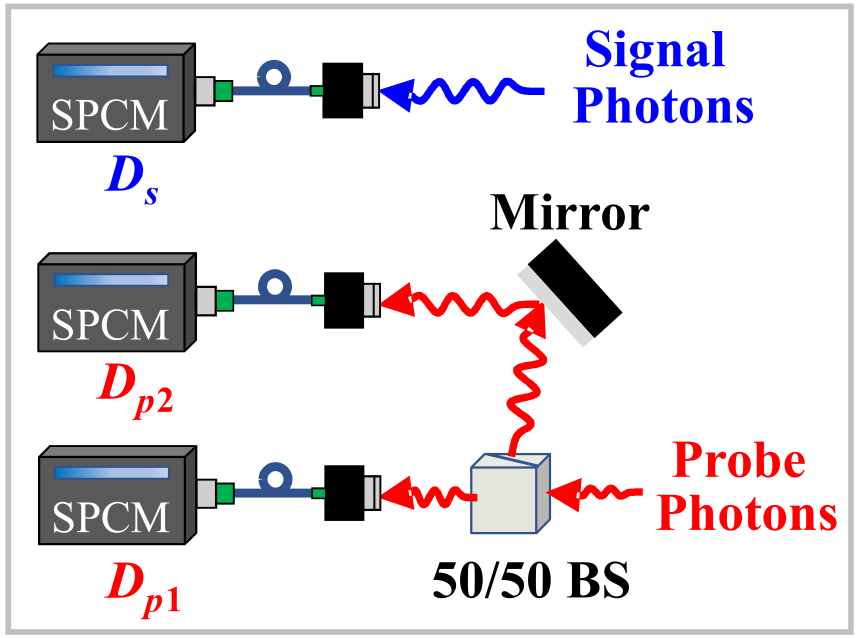


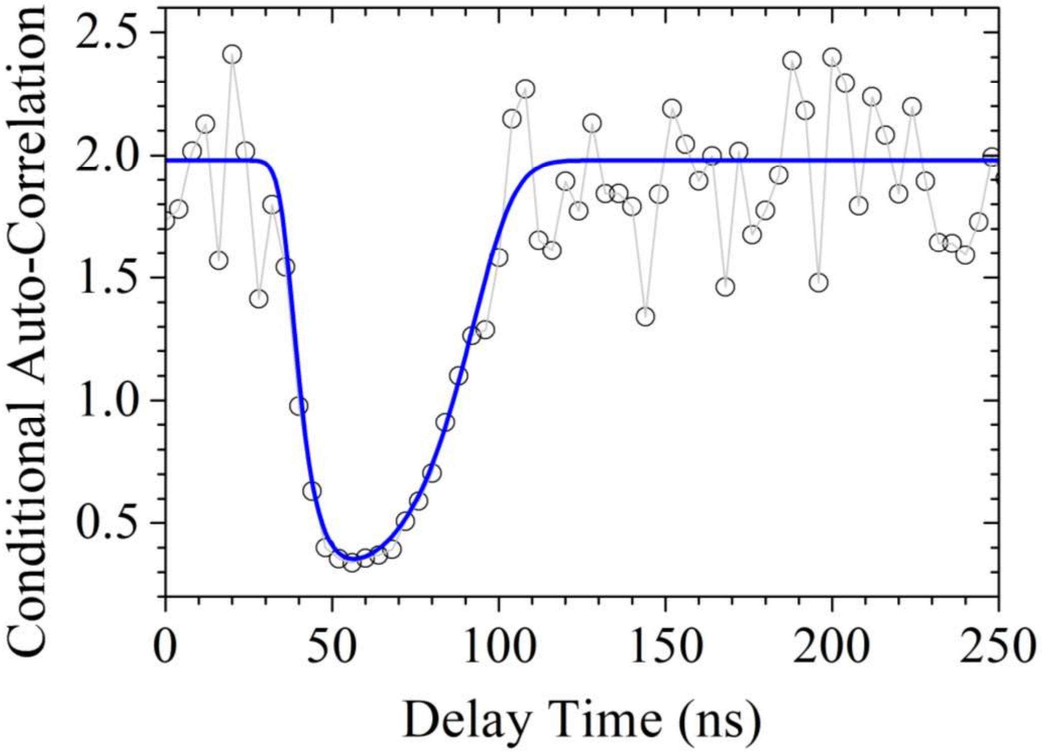


$g^{(2)}_{p,p}(0) \rightarrow 2$ indicates the probe photons are also thermal light and they are bunching.

Measurement of Conditional Auto-Correlation Function

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





The CACF, $g^{(2)}_{s=1|h,h}(\tau)$, as a function of the delay time. Data were accumulated for 120 minutes with the bin time of 4.0 ns. Circles connected by gray lines are the experimental data. The minimum of the CACF is 0.34, and the average value of all the data points after 150 ns is 1.95. Blue line is the theoretical prediction calculated with the formula in Eq. (1), which will be explained in text. In (a) and (b), the time window per trigger was 500 ns, but only the data of the first 250 ns are plotted; P_p = 17 mW and P_c = 42 mW in the measurements.

$g^{(2)}_{s=1|p,p} = 0.34$ indicates the probe photons are anti-bunching!

http://atomcool.phys.nthu.edu.tw/

Thank you for your attention