A weakly-interacting many-body system of Rydberg polaritons — a new platform for BEC and quantum simulators

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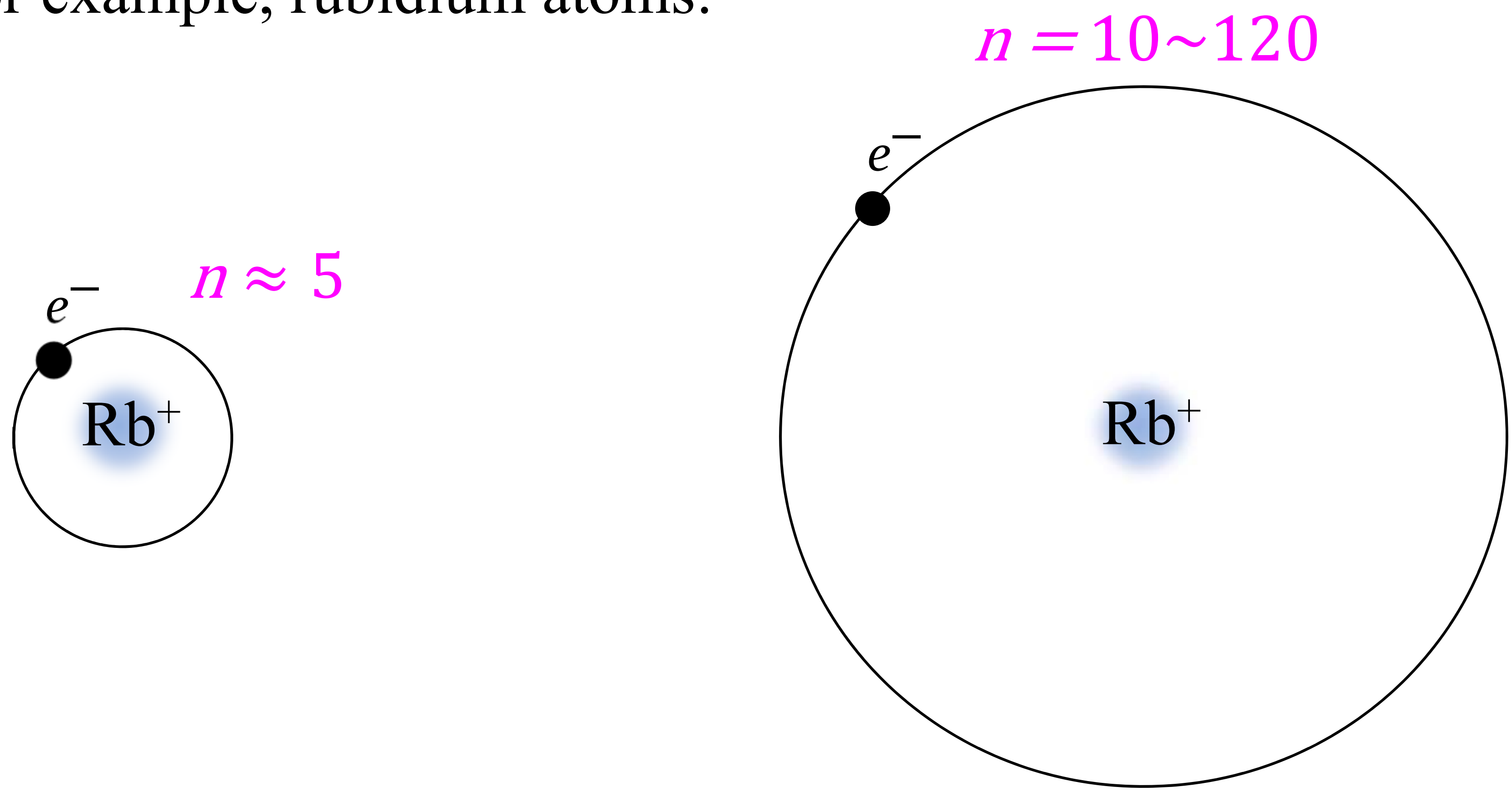
Photo of My Group

2020/8/8 司馬庫斯

Introduction

Rydberg Atoms

- A Rydberg atom has its electron in an excited state with a large principle quantum number, *n*.
- For example, rubidium atoms:

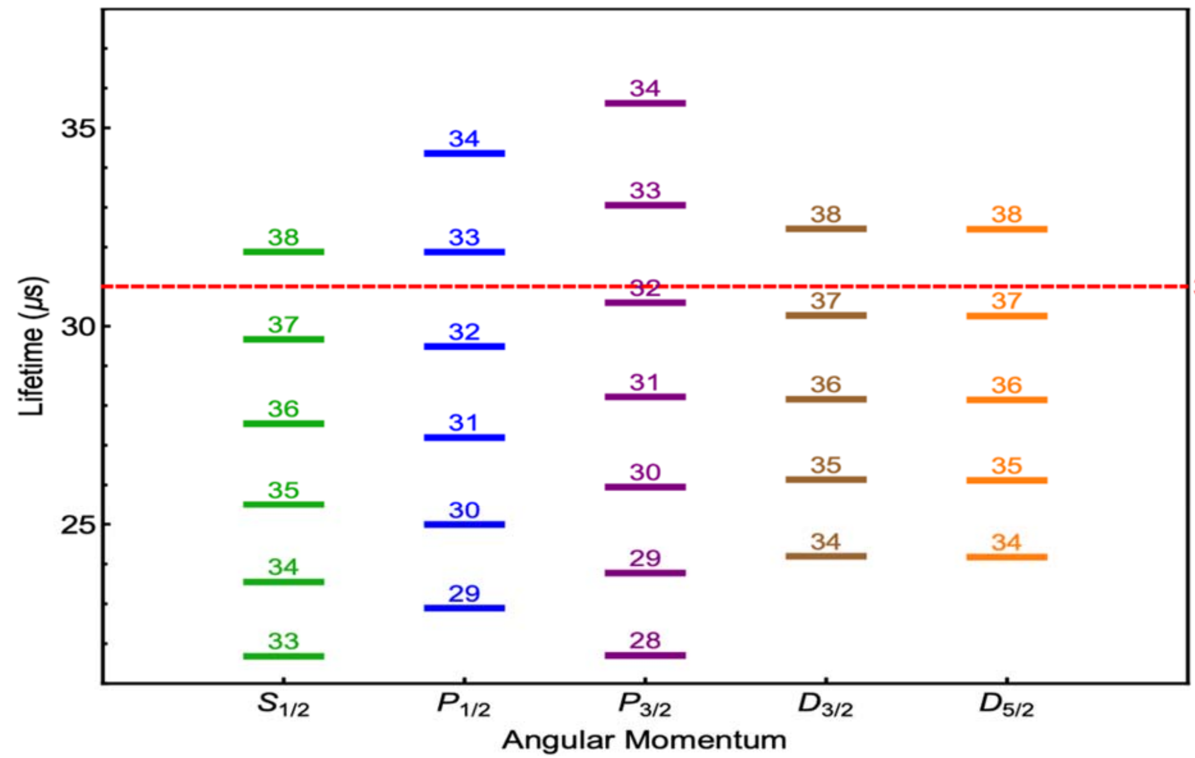


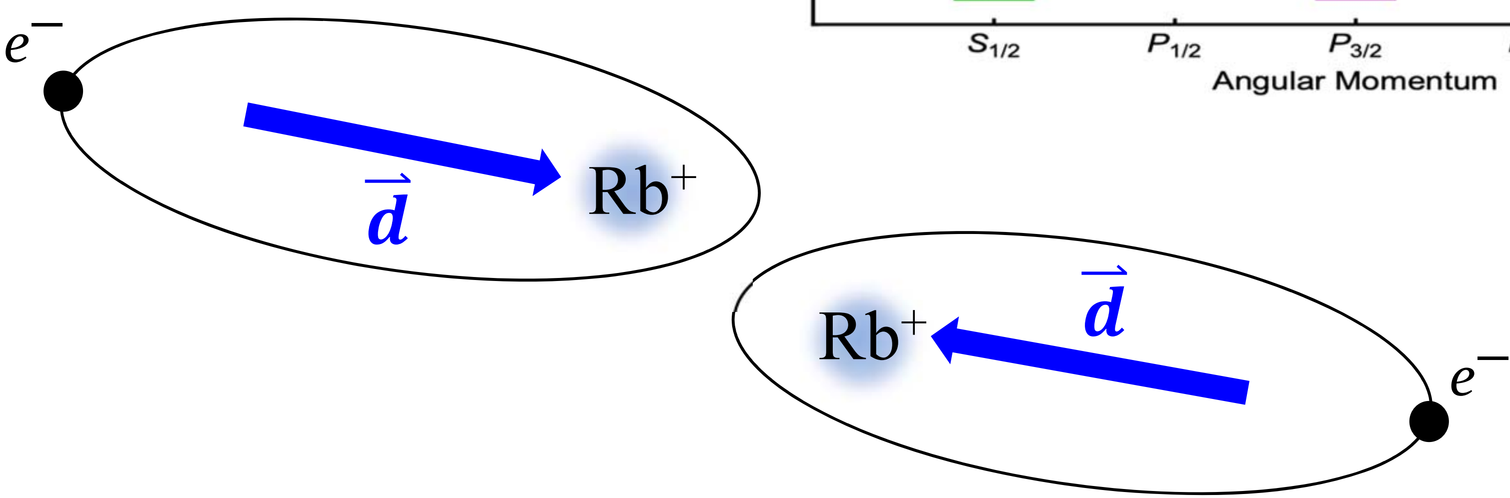
Ground-state Rb atom **Rydberg-state Rb atom**

Characteristics of Rydberg Atoms

- Long radiative lifetime ($\tau \propto n^3$).

- Large electric dipole moment.

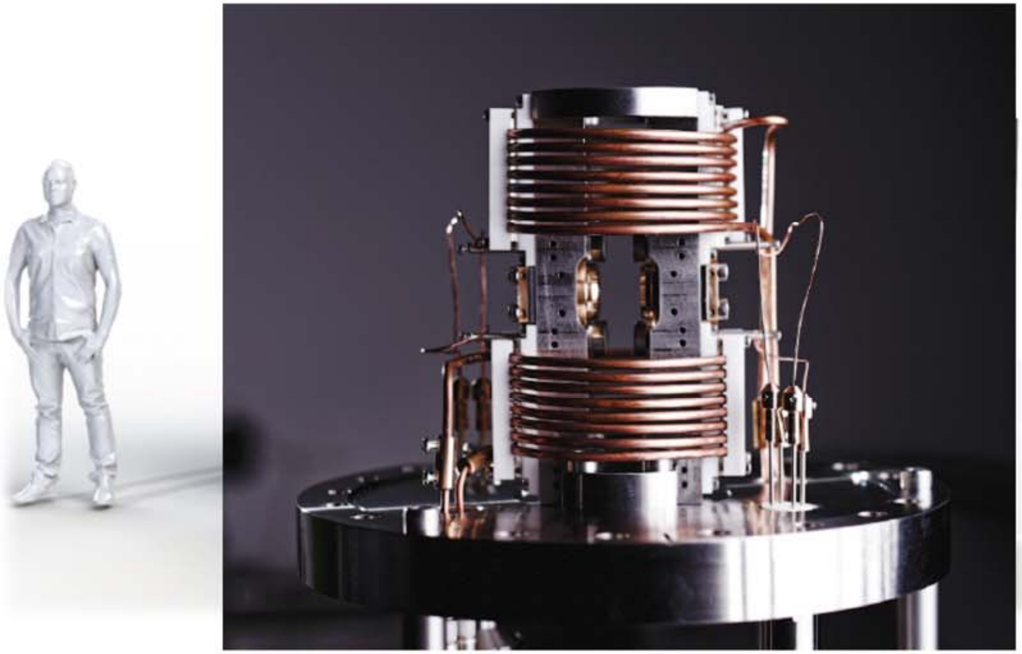




A long lifetime and a large electric dipole moment make them ideal for quantum information processing.

Example: PASQAL

Our mission: Accelerating Quantum Advantage



The core of the QPU

- **Our Heritage:**
  A leading hub of Quantum science & Technology
- **Our Solution:**
  Multi-purpose, flexible, 100 – 1000 qubit Quantum Processing Units (QPUs), built with neutral atoms
- **Our Strength:**
  Powerful Quantum Processing Units ready to be deployed on-premise and exploited on the Cloud

PASQAL is a leading European Quantum company, offering large qubit count, high performance and a maturity level allowing for practical use by both academics & corporates as of today

QUANTUM COMPUTING WITH NEUTRAL ATOMS

Loïc Henriet[1], Lucas Beguin[1], Adrien Signoles[1], Thierry Lahaye[2,1], Antoine Browaeys[2,1], Georges-Olivier Reymond[1], and Christophe Jurczak[1,3]

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[3]Quantonation, 58 rue d'Hauteville, 75010 Paris, France

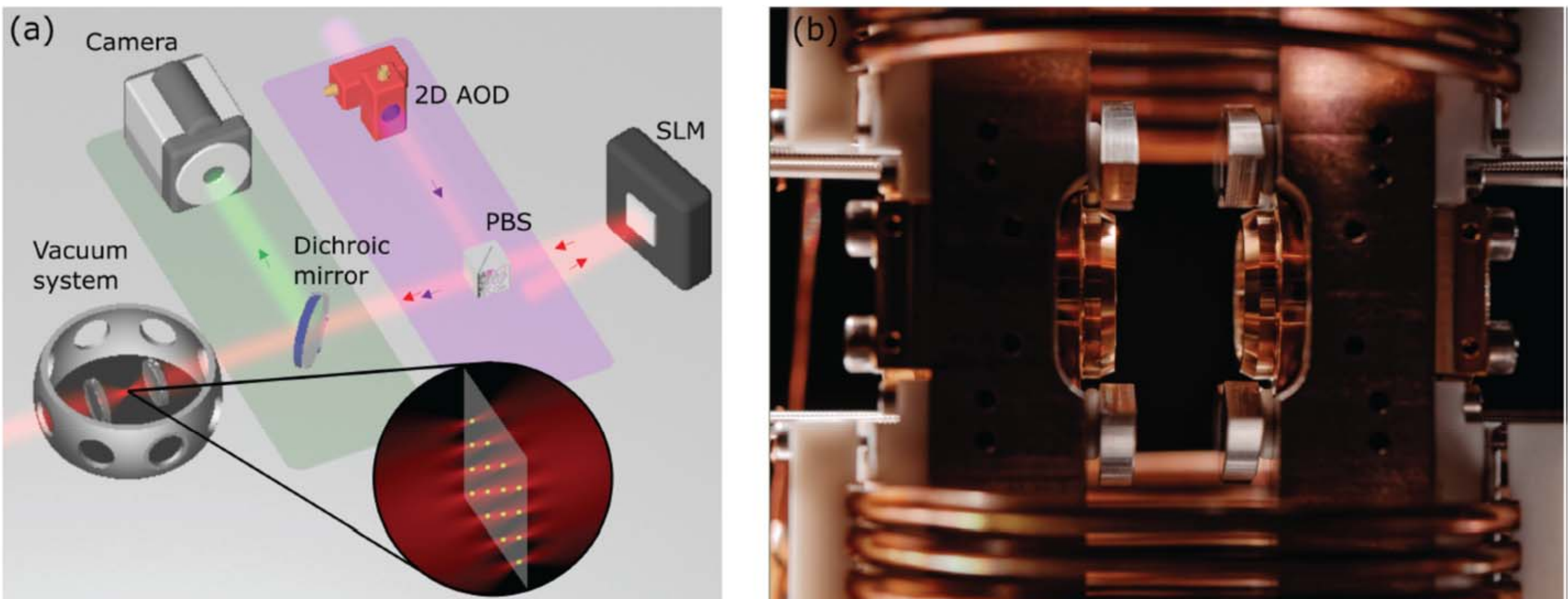


Figure 3: (a) Overview of the main hardware components constituting a quantum processor. The trapping laser light (in red) is shaped by the spatial light modulator (SLM) to produce multiple microtraps at the focal plane of the lens (see inset). The moving tweezers (in purple), dedicated to rearranging the atoms in the register, are controlled by a 2D acousto-optic laser beam deflector (AOD) and super-

Perform the CZ Gate via the Interaction between Two Qubits of Rydberg Atoms

arXiv:2006.12326v2 [quant-ph] 18 Sep 2020

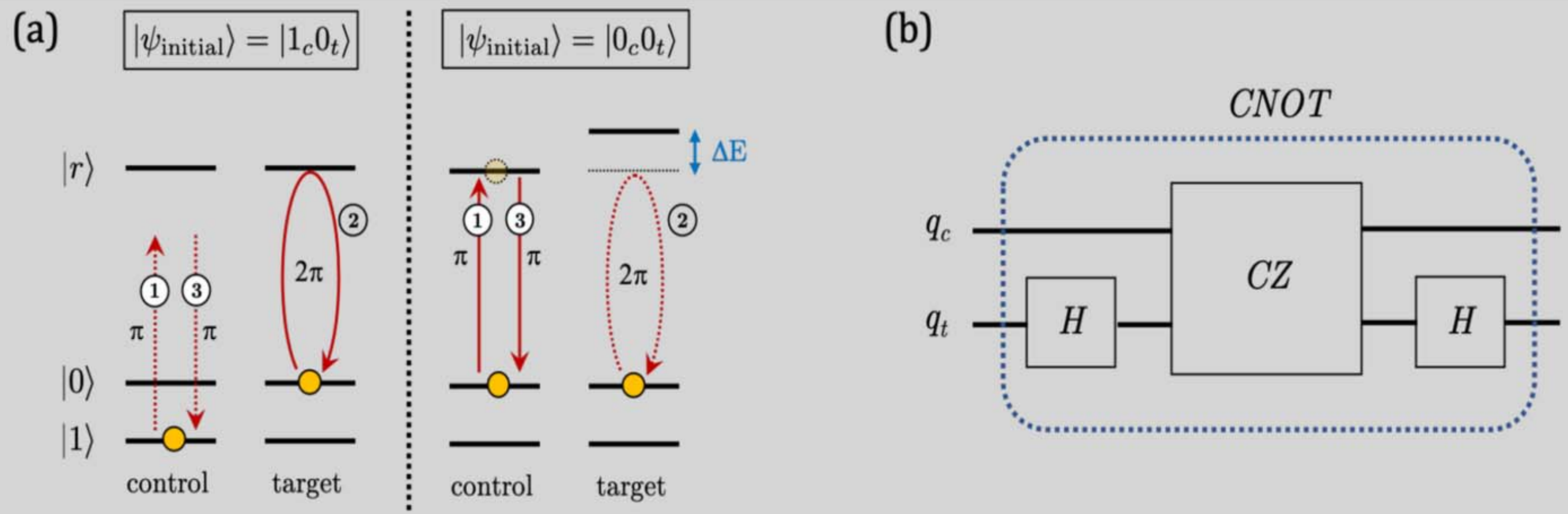
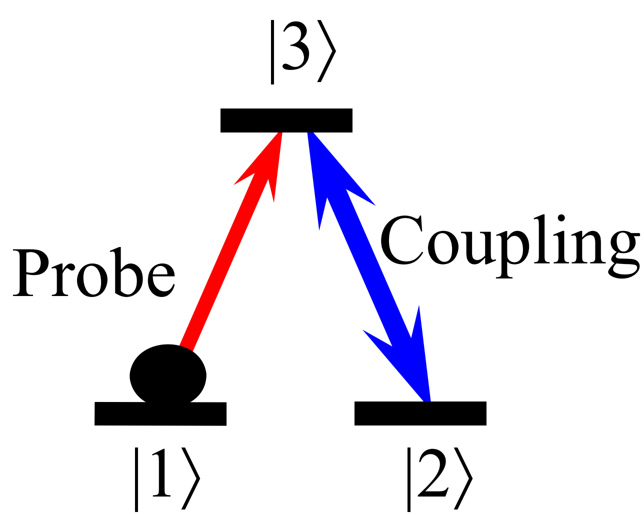
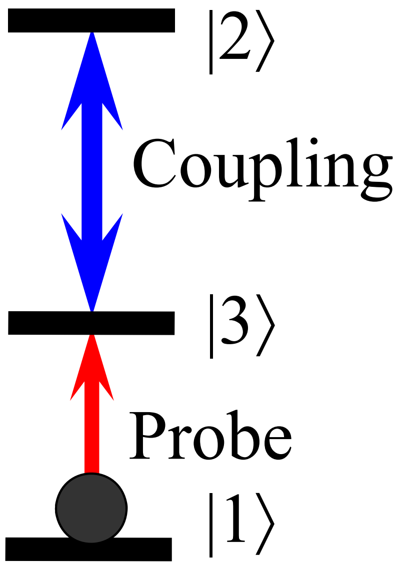


Figure B1.1 | Implementation of the CNOT gate using Rydberg interactions. (a) Principle of the controlled-Z gate based on dipolar Rydberg interaction. First a π pulse is applied on the control atom, then a 2π pulse on the target atom, and finally another π pulse on the control one. (b) Realization of a CNOT gate using a CZ gate and two Hadamard gates.

Excitation to a Rydberg State

- We utilized the transition scheme of electromagnetically induced transparency (EIT) to excite atoms to Rydberg states.
- In the EIT system, a weak probe field (pulses or single photons) and a strong coupling field (classical light) form the Λ-type or ladder-type configurations.
- Slow light and storage of light arise from the EIT effect.

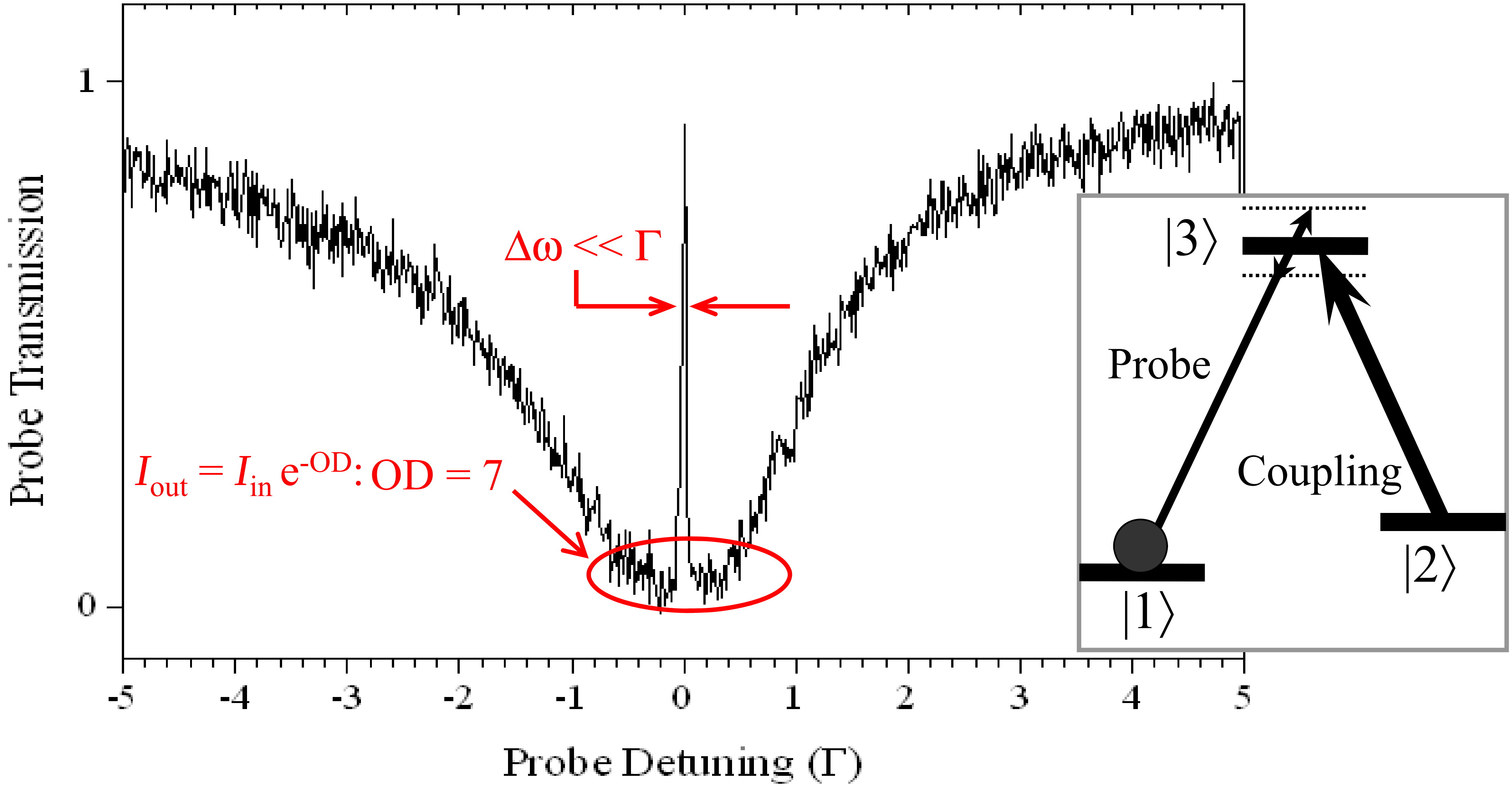




Electromagnetically Induced Transparency (EIT), Slow Light, and Storage of Light

EIT Spectrum

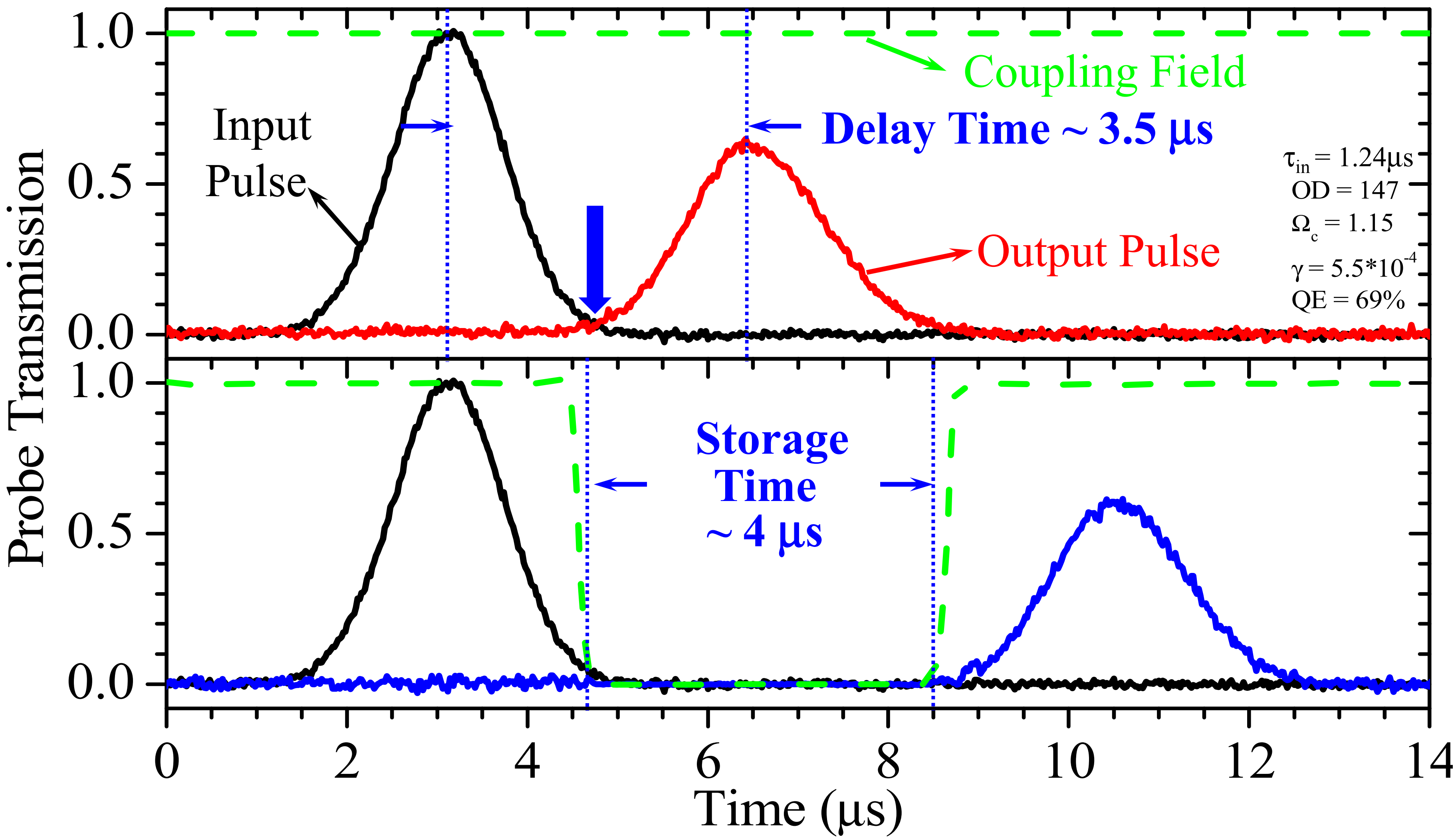
Y. F. Chen, Y. C. Liu, Z. H. Tsai, S. H. Wang, & IAY,* **PRA** 72, 033812 (2005).



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

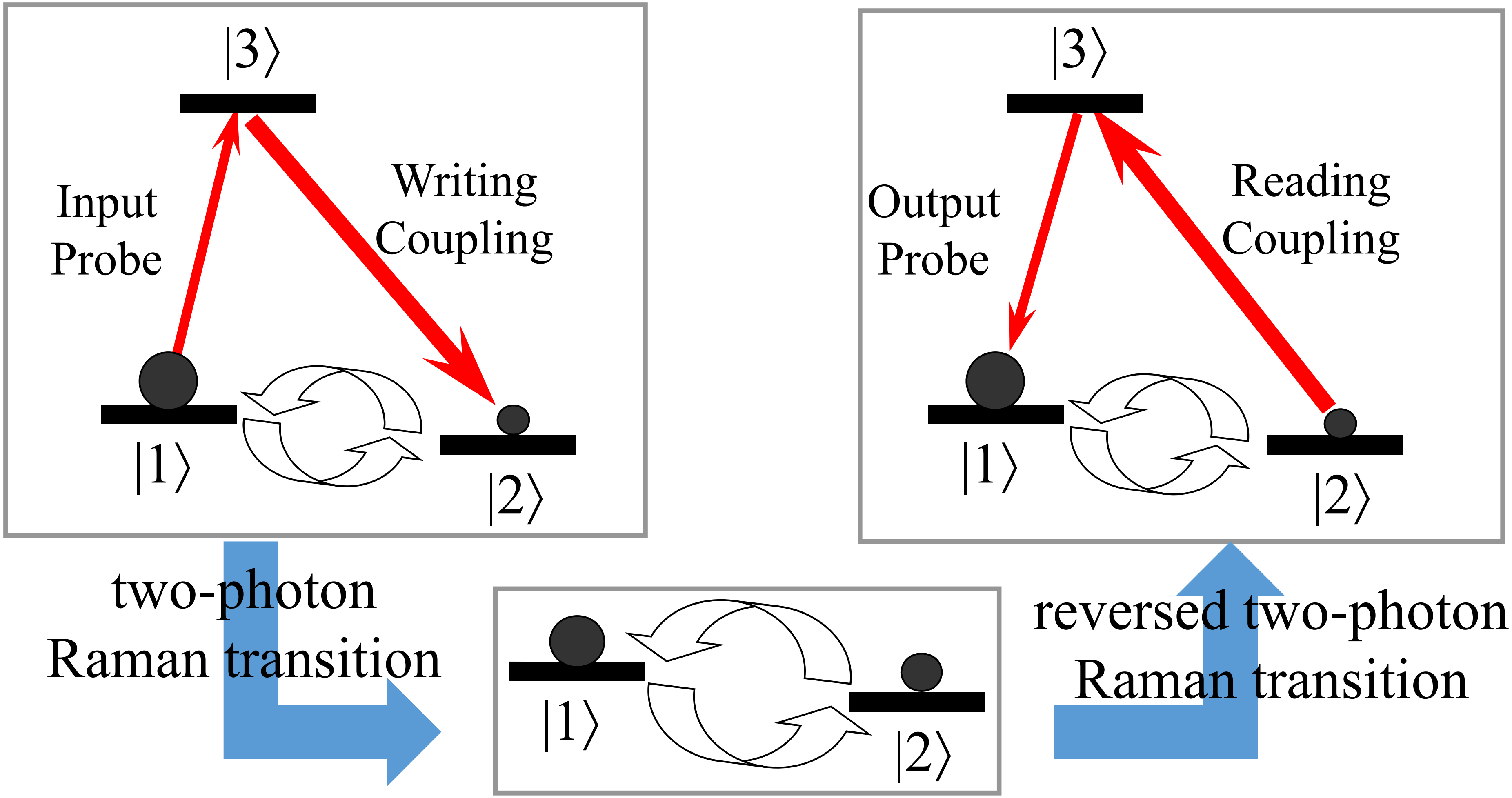
Slow Light and Stopped Light

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



- In the constant presence of the coupling, speed of the light pulse ≤ $c/10^5$.
- The 1 km-long probe pulse is compressed to 1 cm inside the atoms.
- The gap of ~ 4 μs in the probe signal demonstrates the stopped light.

Storage of Light



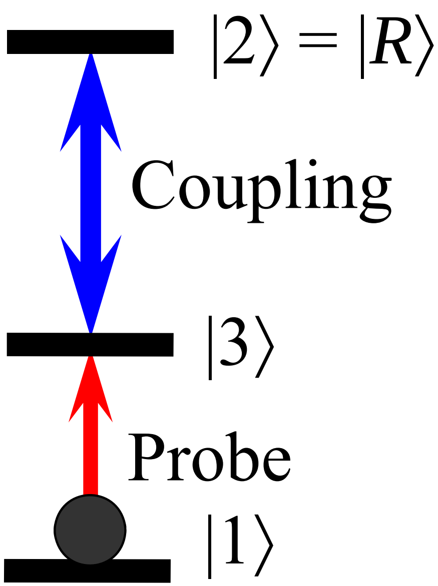
atomic wave function: **ground-state (Raman) coherence**

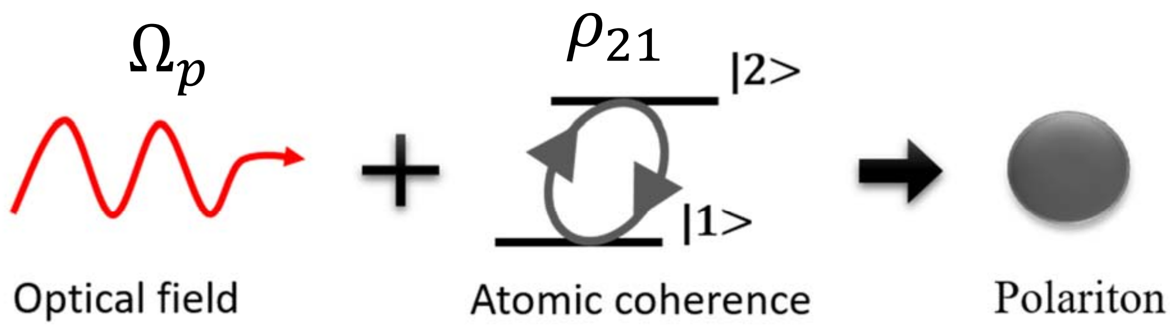
Storage of light due to the EIT effect provides a method for exchange of wave functions between photons and atoms.

A Weakly-Interacting Many-Body System of Rydberg Polaritons

Rydberg Polaritons

- The EIT transition generates the coherence between the Rydberg state and ground state, i.e., Rydberg coherence.





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

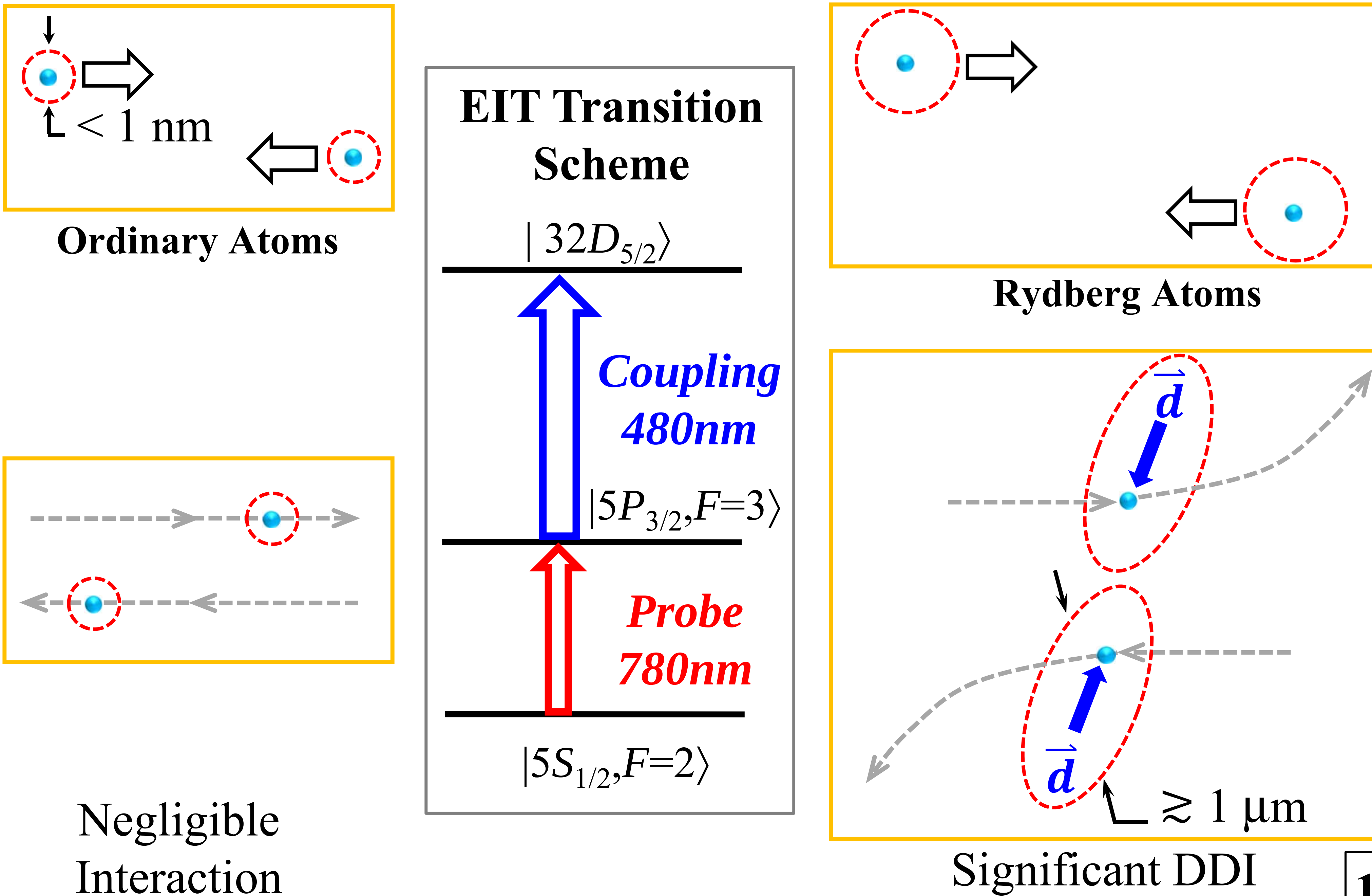
η: OD per unit length

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

Group velocity   Loss due to EIT bandwidth

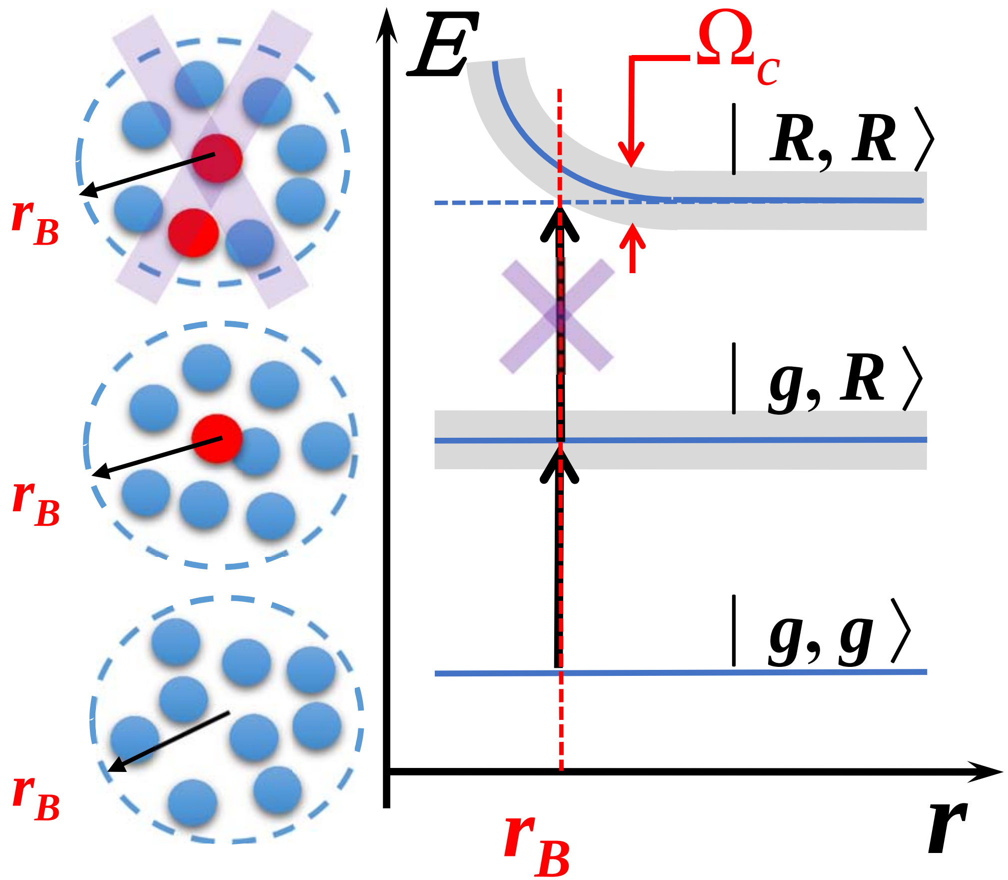
- The Rydberg polariton is the superposition of photon and Rydberg coherence, and it is a bosonic quasi-particle.

Dipole-Dipole Interaction (DDI) of Rydberg Polaritons

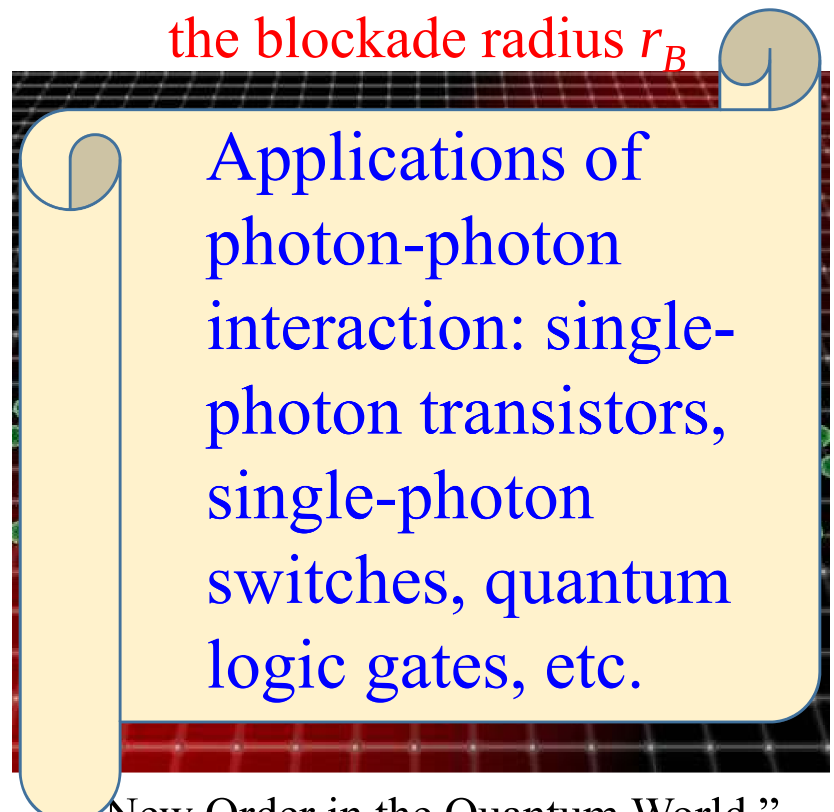


Dipole Blockade

- The DDI causes the energy shift.
- At some distance r_B, the energy shift is equal to the EIT bandwidth. Inside the sphere of the radius r_B, excitation of another atom to $|2\rangle$ is strongly suppressed.



Five blockade spheres of the blockade radius r_B

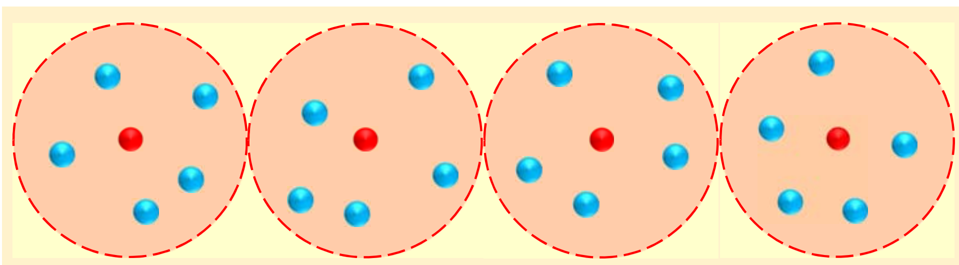


"A New Order in the Quantum World," by Olivia Meyer-Streng (MPQ, Garching, November 1st, 2012. Press Release)

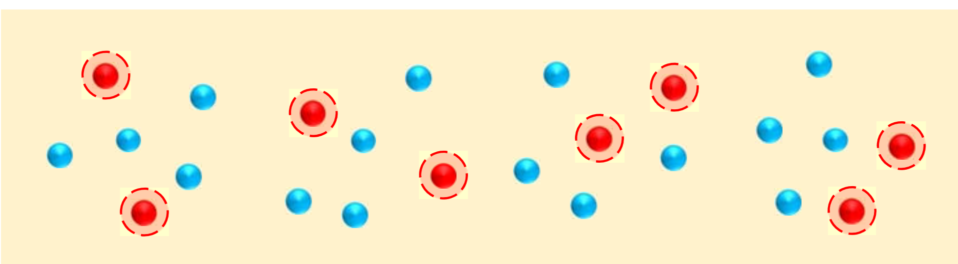
Strong and Weak Interaction Regimes

r_a: the half mean distance between Rydberg atoms.

r_B: the blockade radius.

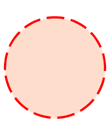


Strong interaction: $(r_B/r_a)^3 \geq 1$



Weak interaction: $(r_B/r_a)^3 \ll 1$

 : Rydberg-state atom

 : blockade sphere

Experimental condition:

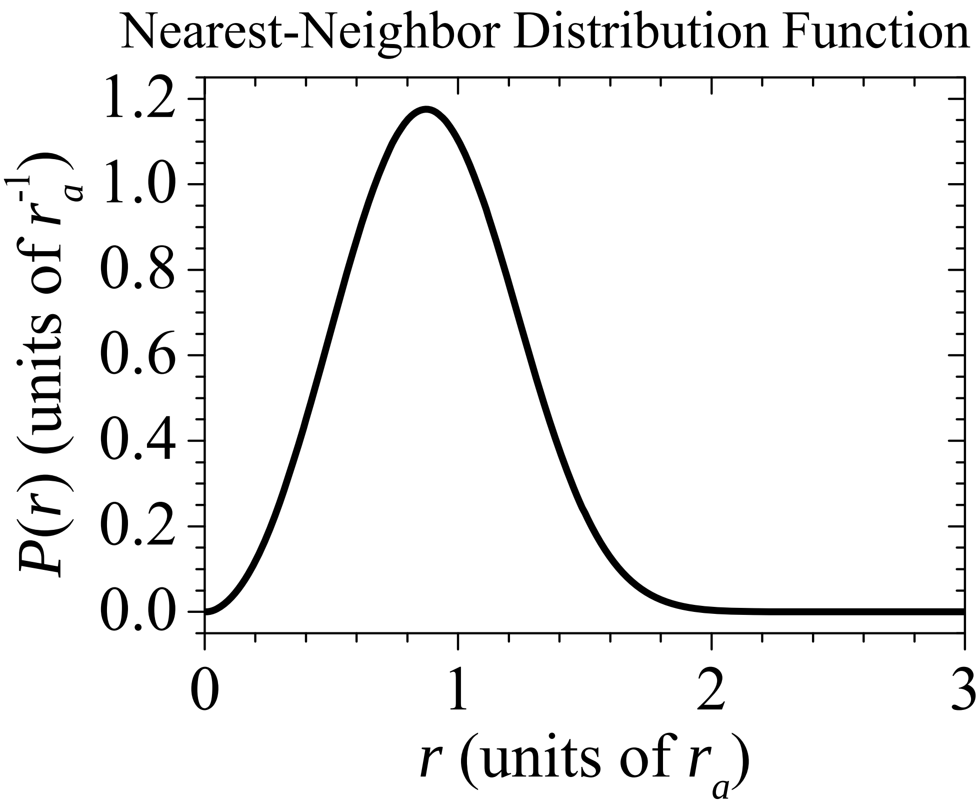
max $\Omega_p = 0.2\Gamma$; $\Omega_c = 1.0\Gamma$; $32D_{5/2}$

$\Longrightarrow\ r_a = 4.5\ \mu m$; $r_B = 2.0\ \mu m$

$(r_B/r_a)^3 < 0.1$

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

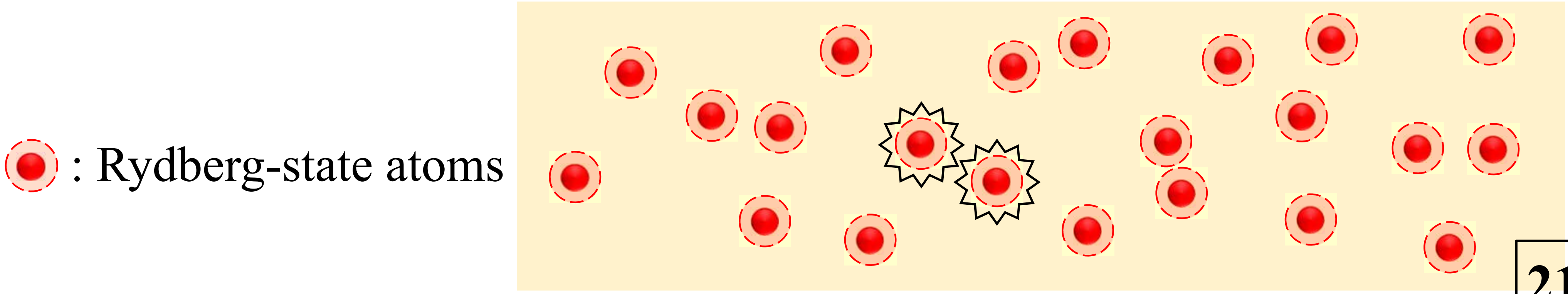
S.-S. Hsiao, K.-T. Chen, & IAY,* Opt. Express 28, 28414 (2020).



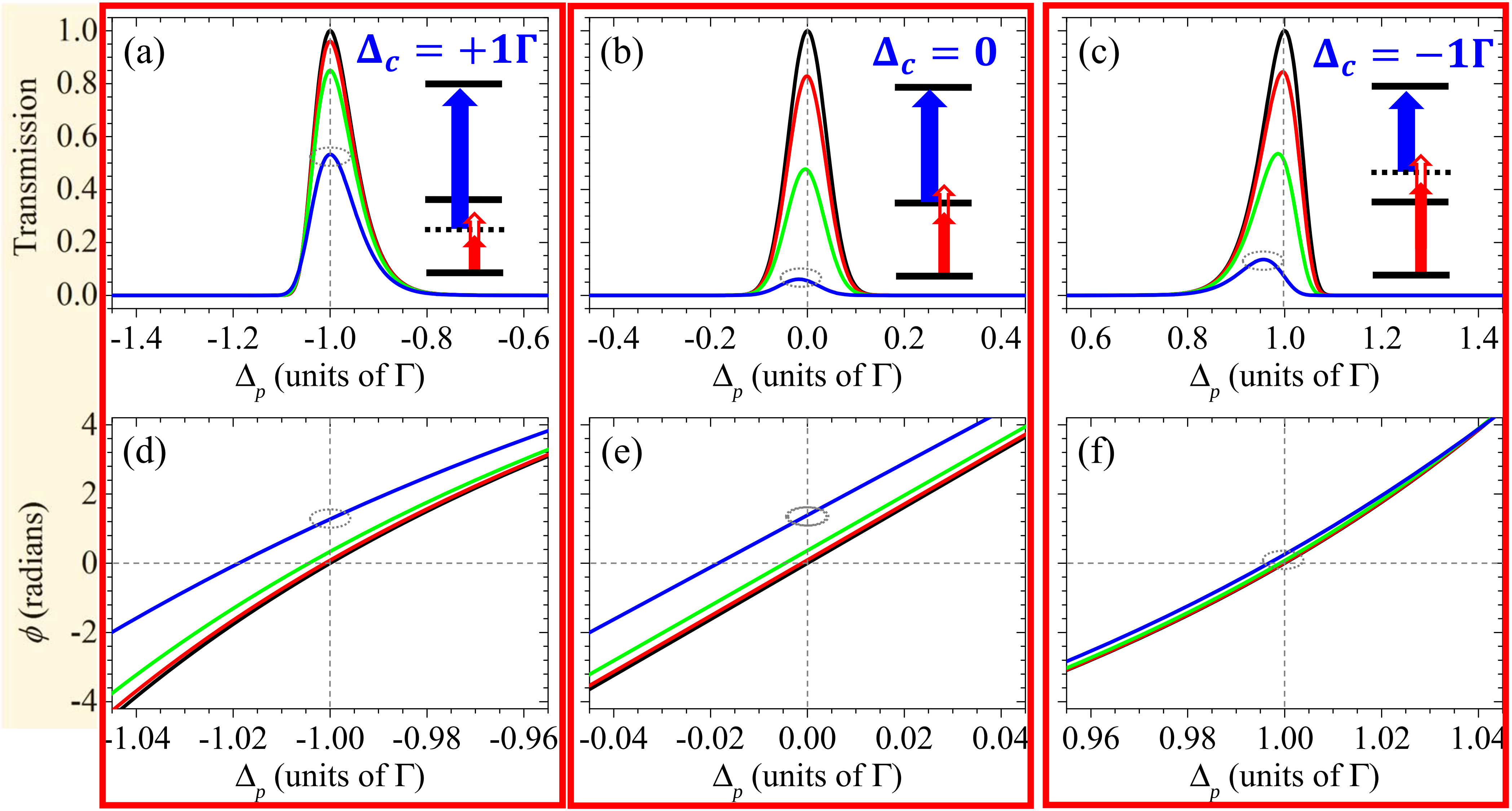
$$P(r) = \frac{3r^2}{r_a^2} \mathrm{Exp}\left(-\frac{r^3}{r_a^3}\right),$$

where $P(r)$ is the probability of finding the nearest neighbor at a distance r, and r_a is the half mean distance between the particles.

S. Chandrasekhar, "Stochastic problems in physics and astronomy," Rev. Mod. Phys. **15**, 1–89 (1943).

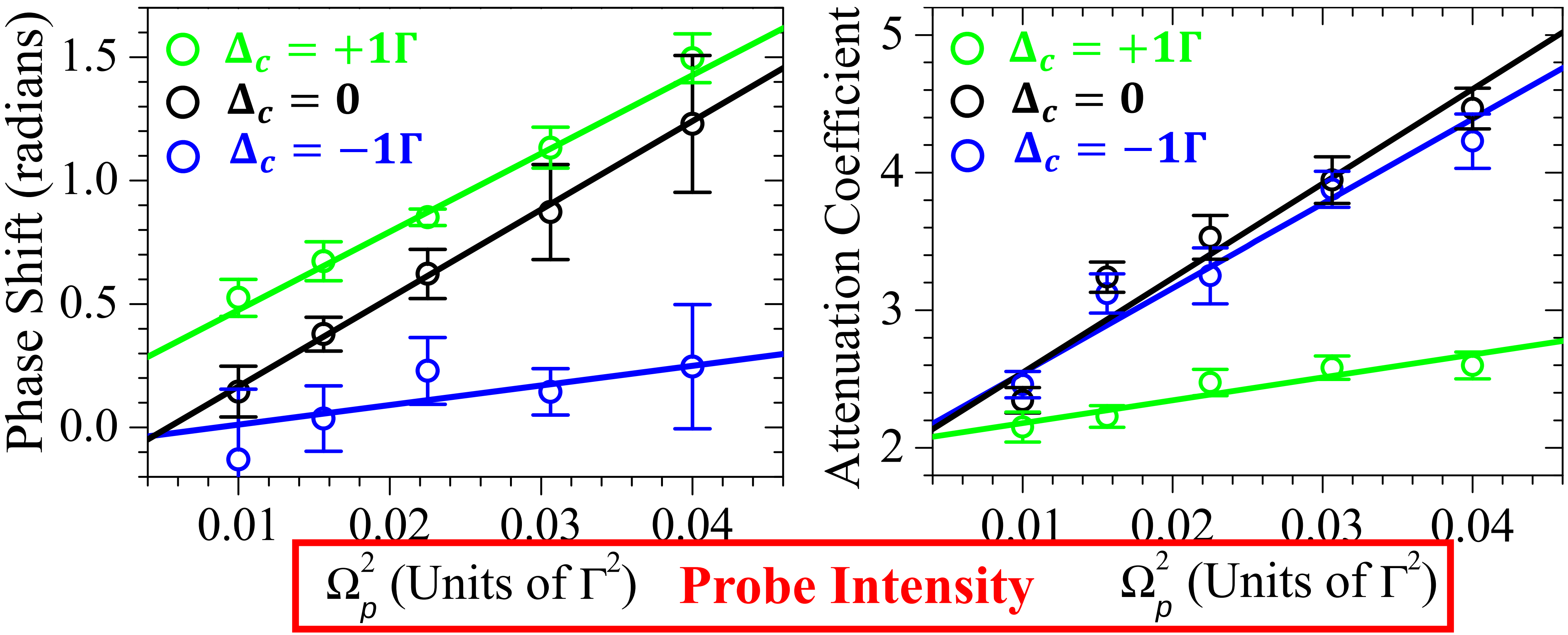


Predictions of DDI-Induced Attenuation and Phase Shift



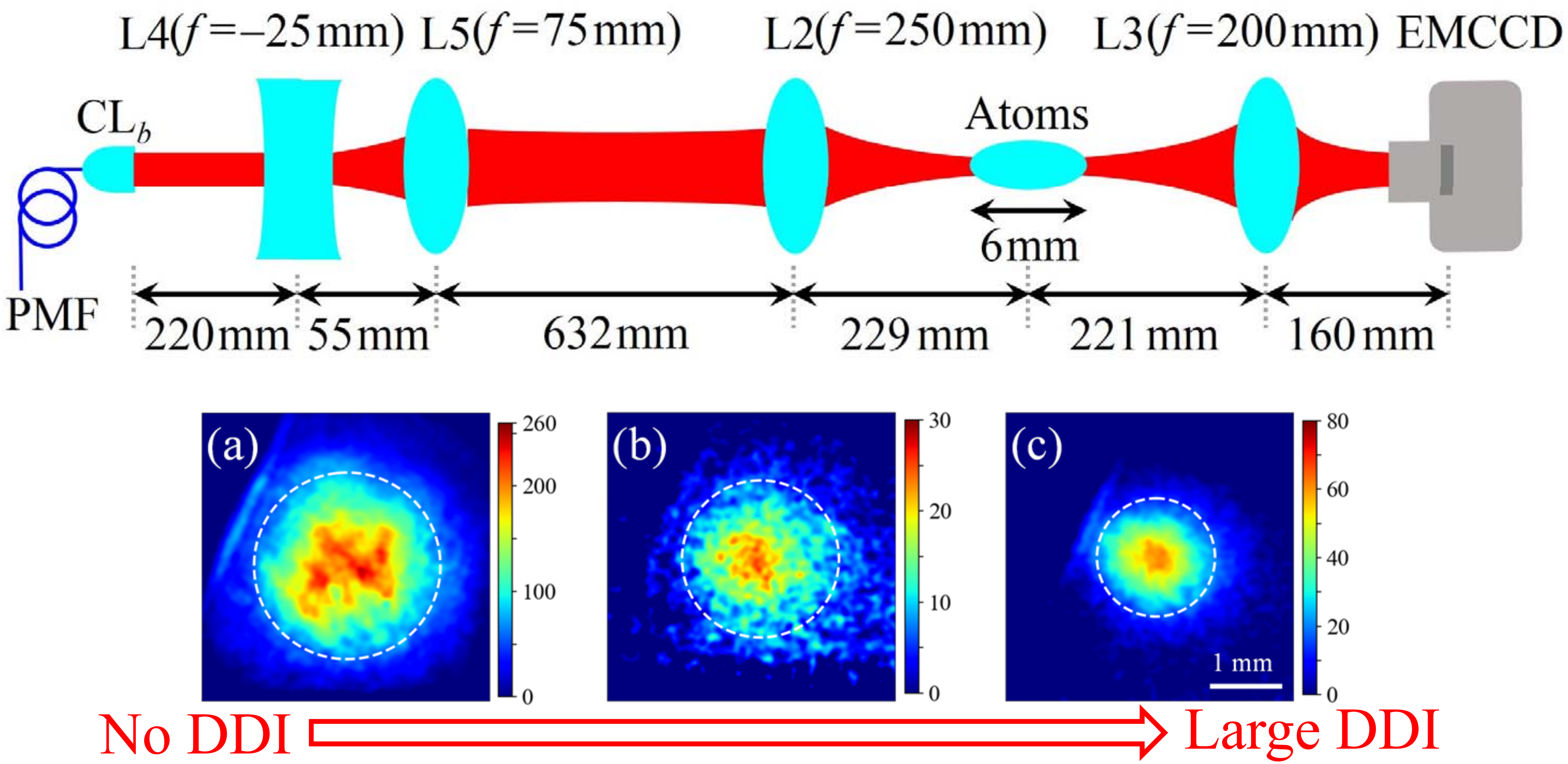
- Spectra of probe transmission (a-c) and phase shift (d-f) versus probe frequency. Black, red, green, and blue lines represent no DDI, $\Omega_p = 0.05\Gamma$, 0.1Γ, and 0.2Γ.
- A larger probe field (more photons) $\Rightarrow$ more DDI (attenuation and phase shift).

Experimental Data of DDI-Induced Phase Shifts and Attenuations



- The experimental data are consistent with the theoretical predictions.
- One views the phase shift and attenuation as the consequences of elastic collisions (thermalization) and inelastic collisions (decay).
- At a positive one-photon detuning, Δ_c, the inelastic collision rate is a little, while the elastic collision rate is still significant.

Transverse Momentum Distributions Measured by Time-of-Flight Images

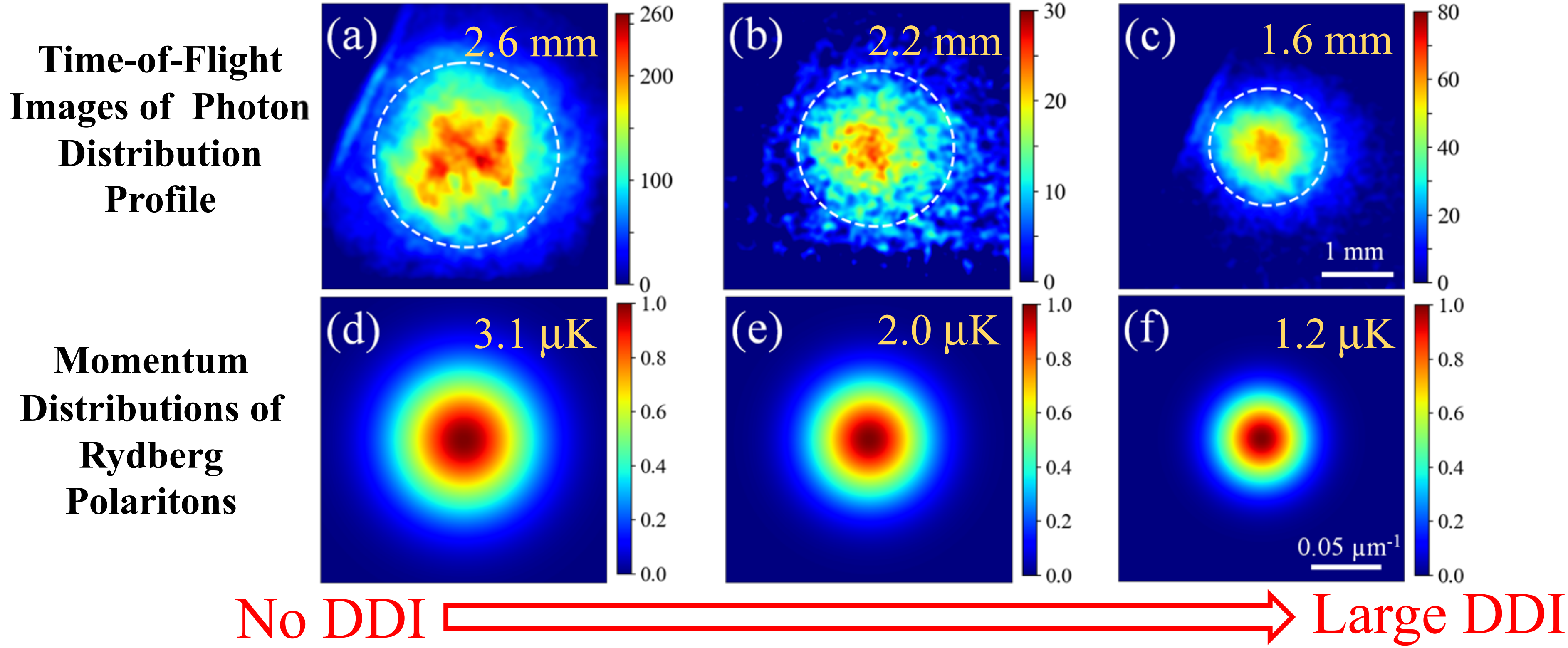


- The transverse momentums of Rydberg polaritons were carried by the probe photons leaving the medium.
- At $\Delta_c = +1\Gamma$, images of the probe beam profile taken by EMCCD (a) in the absence of atoms, and (b,c) in the presence of atoms at $\Omega_p = 0.1\Gamma$ and 0.2Γ.

Cooling Effect in Rydberg Polaritons

B. Kim, K.-T. Chen, S.-S. Hsiao, S.-Y. Wang, K.-B. Li, J. Ruseckas, G. Juzeliūnas, T. Kirova, M. Auzinsh, Y.-C. Chen, Y.-F.Chen, & IAY,* Commun. Phys. 4, 101 (2021)

- We proposed utilizing a high-OD medium and the EIT effect to form a many-body system of Rydberg polaritons.
- For the first time, we observed the cooling effect in this system, suggesting a new platform of Bose-Einstein condensation and quantum simulators.



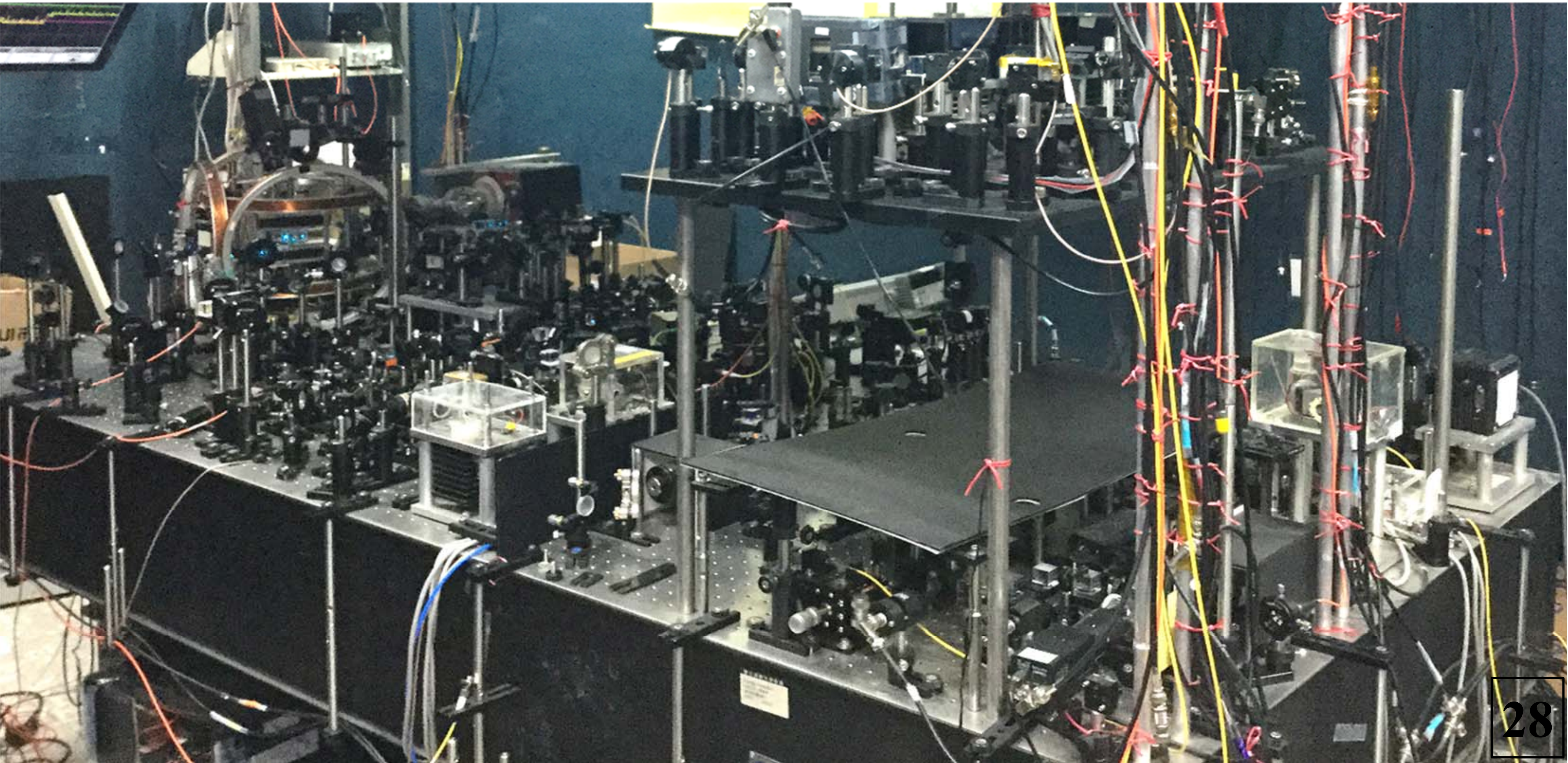
We have created a weakly-interacting many-body system of Rydberg polaritons, and demonstrated the cooling effect in the system.

Bose-Einstein condensation of Rydberg polaritons?

Outlook and Prospects

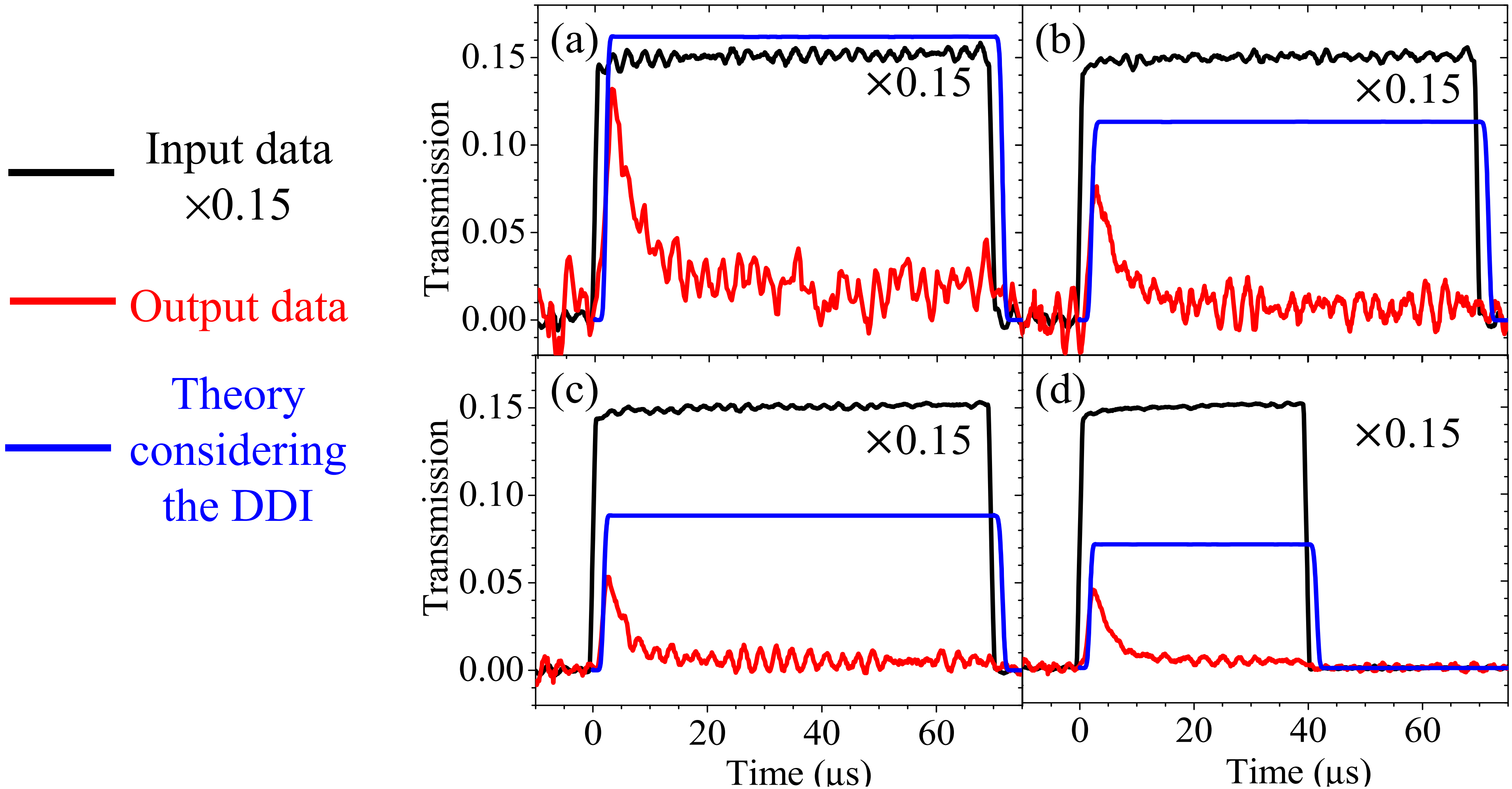
Cold-Atom Experiment of Rydberg EIT

- We have demonstrated the cooling effect in the weakly-interacting many-body system of Rydberg polaritons.
- **Outlook:** stationary light, dark Rydberg atoms, an artificial trap, an efficient evaporative cooling, BEC; photon-photon interaction, ……



Accumulation of DDI-Induced Attenuation

- The probe transmission decreased with time. A larger input probe field resulted in a faster decay and a lower steady-state value.
- The observations suggest that the DDI-induced attenuation increased with time, and population accumulated in some dark Rydberg states.



Stationary Rydberg Polaritons

- In the present experiment, Rydberg polaritons propagated along the medium and were confined in the transverse direction.
- In the future experiment, we will confine Rydberg polaritons in three dimensions by making them stationary.

PRL **102,** 213601 (2009) PHYSICAL REVIEW LETTERS week ending 29 MAY 2009

Stationary Light Pulses in Cold Atomic Media and without Bragg Gratings

Yen-Wei Lin, Wen-Te Liao, Thorsten Peters, Hung-Chih Chou, Jian-Siung Wang, Hung-Wen Cho, Pei-Chen Kuan, and Ite A. Yu*

Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan, Republic of China

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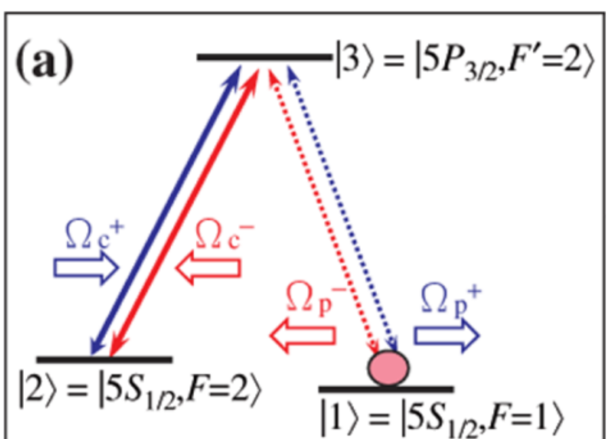

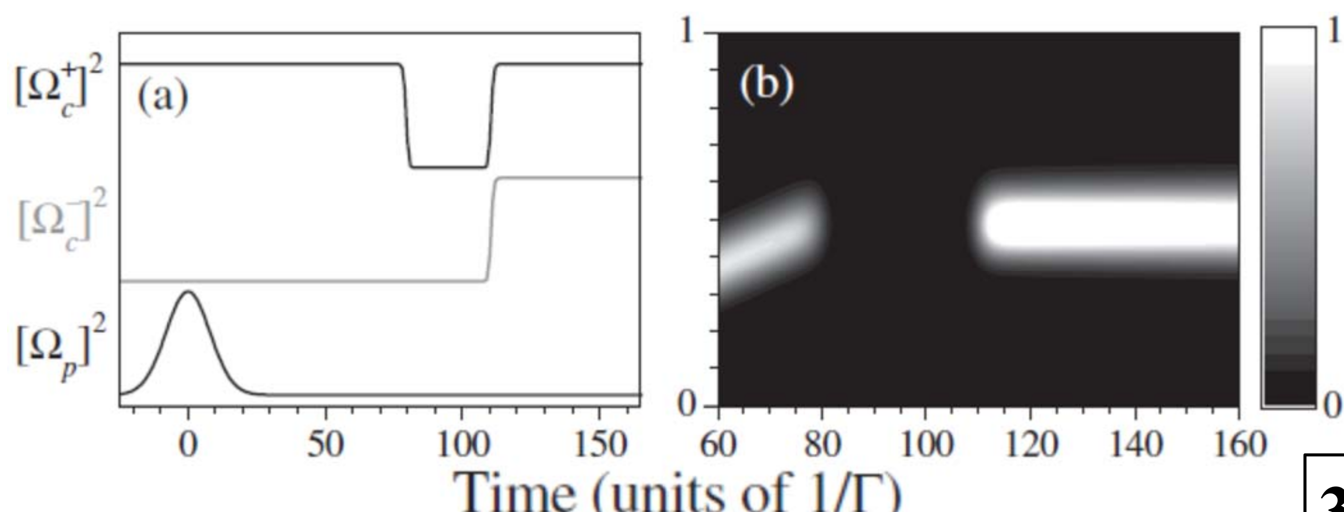

Bose-Einstein Condensation of Rydberg Polaritons

- It has been proposed to employ the stationary light in the Λ–EIT scheme to realize the BEC. However, the interaction is too weak.
- In the Rydberg-EIT scheme, the strong DDI makes the BEC feasible.

PRL **101,** 163601 (2008) PHYSICAL REVIEW LETTERS week ending 17 OCTOBER 2008

Bose-Einstein Condensation of Stationary-Light Polaritons

Michael Fleischhauer,[1] Johannes Otterbach,[1] and Razmik G. Unanyan[1,2]
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(Received 21 July 2008; published 16 October 2008)

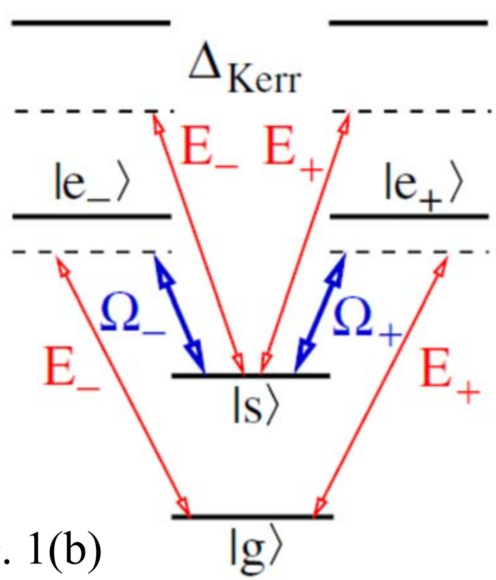

FIG. 1(b)

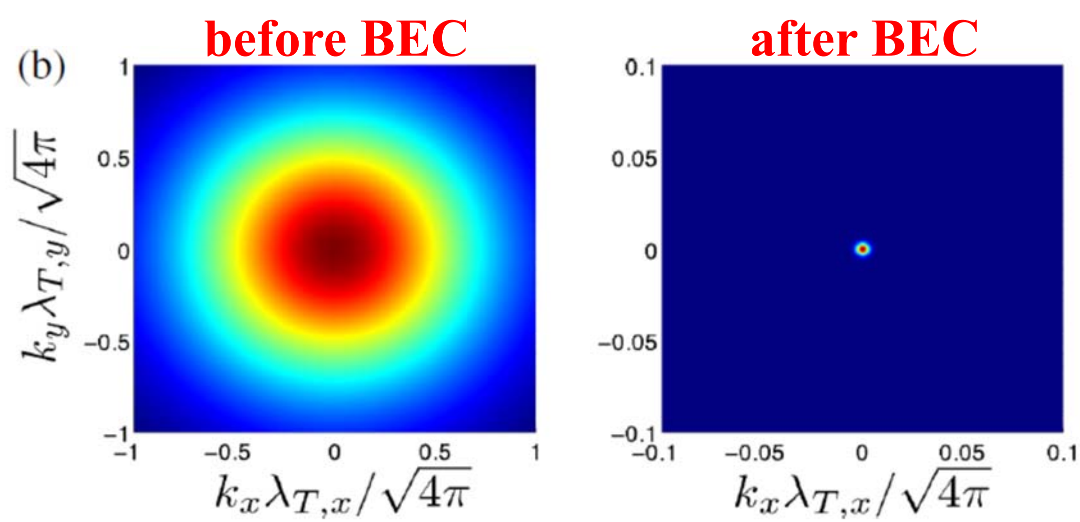

FIG. 3 (color online). (a) Detection of condensation: switching http://atomcool.phys.nthu.edu.tw/

Thank you for your attention