

Formation of the Stationary Dark-State Polaritons Dressed by Dipole-Dipole interaction toward the realization of dark-state polariton Bose-Einstein condensation

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Motivation

A Bose-Einstein condensation (BEC) of dark-state polaritons (DSPs) was proposed in 2008 [1]. The DSP describes a propagating probe field in an electromagnetically induced transparency (EIT) media as the superpositions of probe photons and atomic ground-state coherences. According to the proposal, a DSP-BEC is expected to have higher critical temperature than atomic BEC and a longer lifetime than the exciton-polariton BEC. Furthermore, a three-dimensional DSP-BEC system is achievable without the cavity. To achieve the BEC, not only the reduction of transverse momentum distribution of the DSP [2], but the longitudinal momentum distribution of DSP also must be cooled down. Therefore, the DSPs need to be stationary [3]. In this study, we propose a platform of stationary dark-state polaritons (DSPs) dressed by the dipole-dipole interaction (DDI) to achieve Bose-Einstein condensation (BEC) of DSP and experimentally demonstrate the formation of the scheme [4].

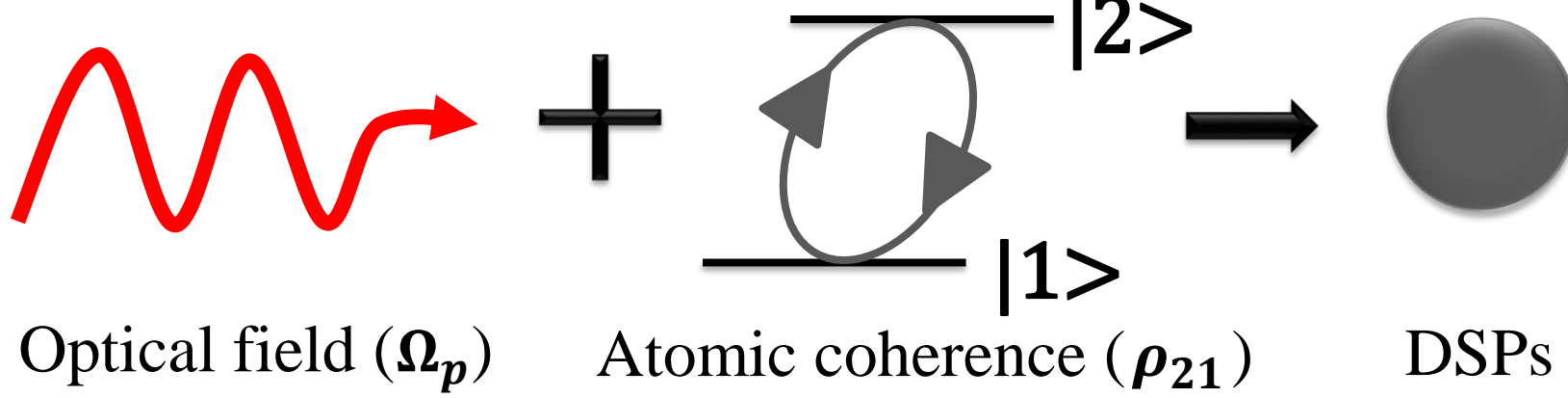
Introduction

Dark state polaritons (DSPs):

- Superposition of the probe photon (optical component) and the atomic coherence.
- Bosonic quasi-particles

$$\Psi = \cos \theta \Omega_p - \sin \theta \sqrt{2\eta c} \rho_{21}$$

$$\tan \theta = \sqrt{2\eta c} / \Omega_c$$

$$\eta = OD/2L$$


Optical field (Ω_p) + Atomic coherence (ρ_{21}) → DSPs

Dark-State Polariton Bose-Einstein Condensation (DSP-BEC) [1]

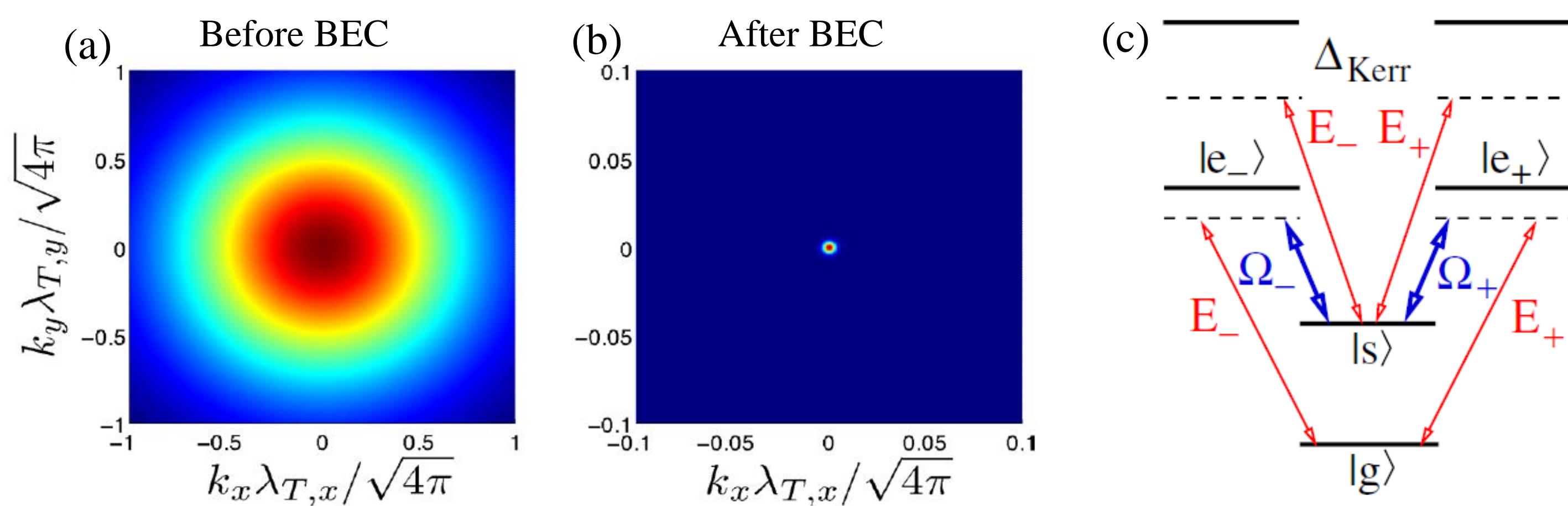


Fig.1 Transverse emission profile (a) before DSP-BEC and (b) after DSP-BEC. (c) Proposed transition scheme to achieve DSP-BEC with Kerr-type nonlinearity DSP-DSP interactions.

Demonstration of the Thermalization process in the Transverse Plane [2]

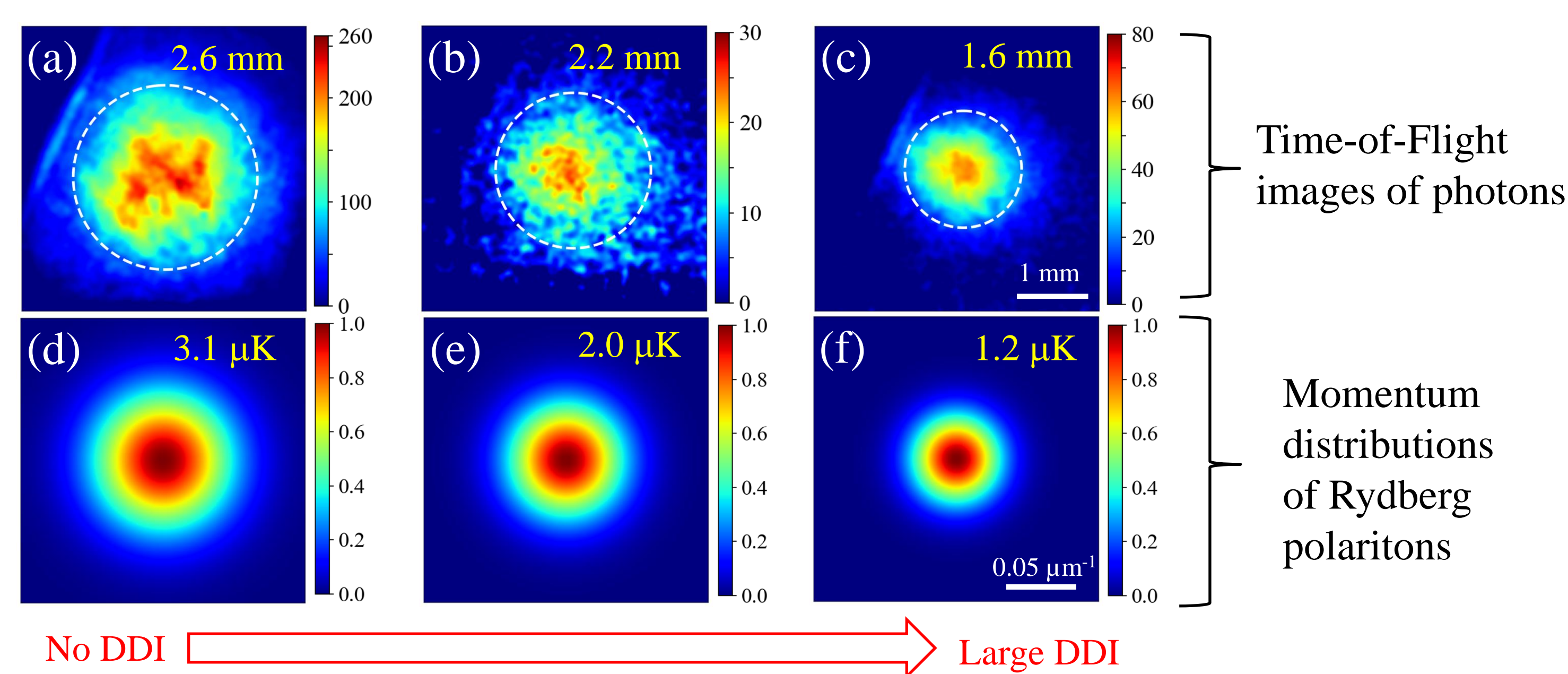
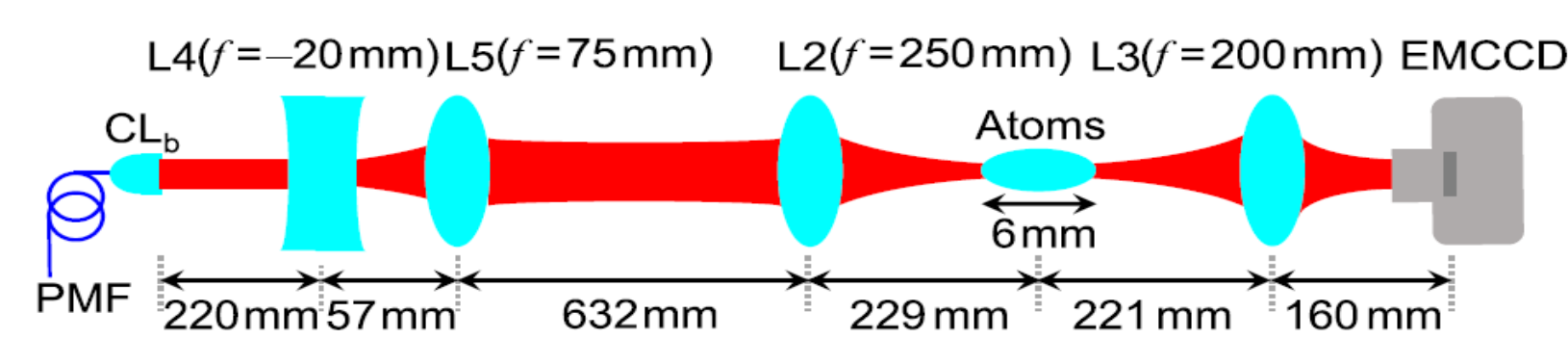


Fig. 2 (a)-(c) Time-of-flight images at the far field to measure probe beam profiles. When leaving the atom cloud, photons carry Rydberg polaritons' momentums. (e)-(f) The transverse momentum distribution of Rydberg polaritons.

➤ A larger DDI results in a narrower momentum distribution and a lower transverse temperature.

• Key elements for taking the images of the probe beam.



Generation of the Stationary DSPs [3]

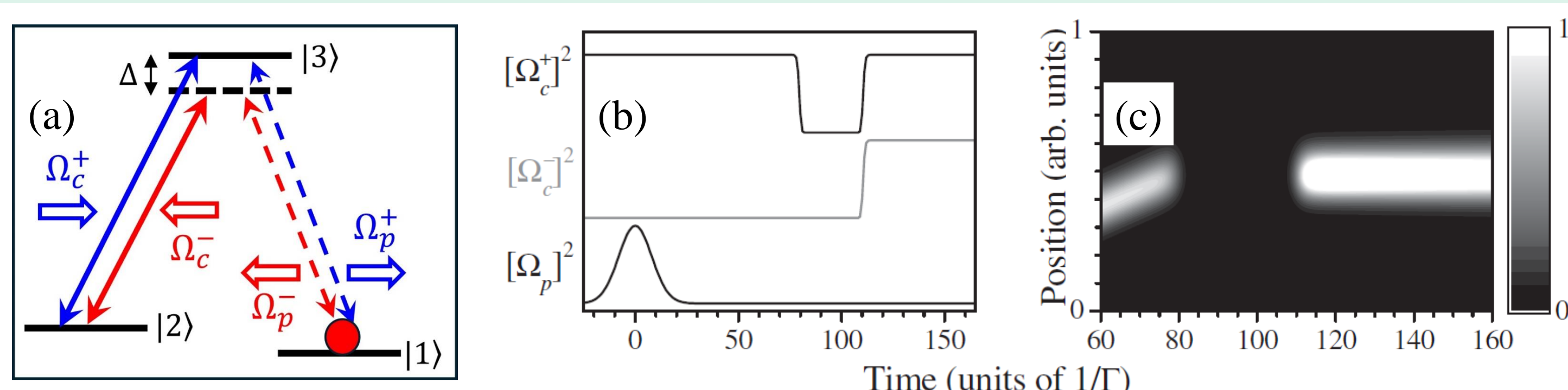


Fig. 3 (a) Relevant energy levels and laser excitations for the generation of the stationary DSP. (b) Time sequence for the DSP generation. (c) Numerical simulations of the probe intensity as a function of time.

Acknowledgement

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Stationary DSP dressed by DDI [4]

Experimental demonstration of the formation of stationary DSP dressed by DDI

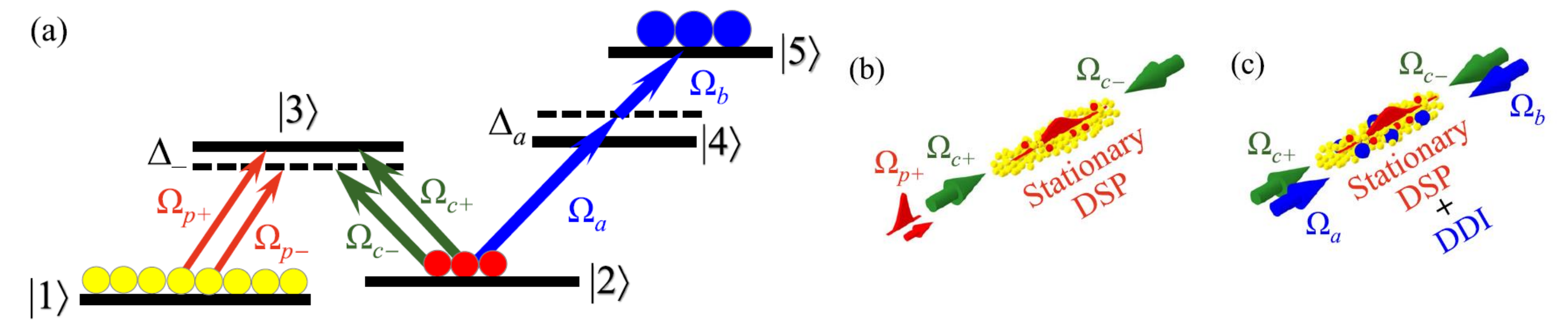


Fig.4 (a) Relevant energy levels and laser excitations. (b), (c) Propagation directions of the laser fields in the measurements of stationary DSPs without and with the DDI.

Formation of the stationary DSP dressed by DDI: DDI induced attenuation

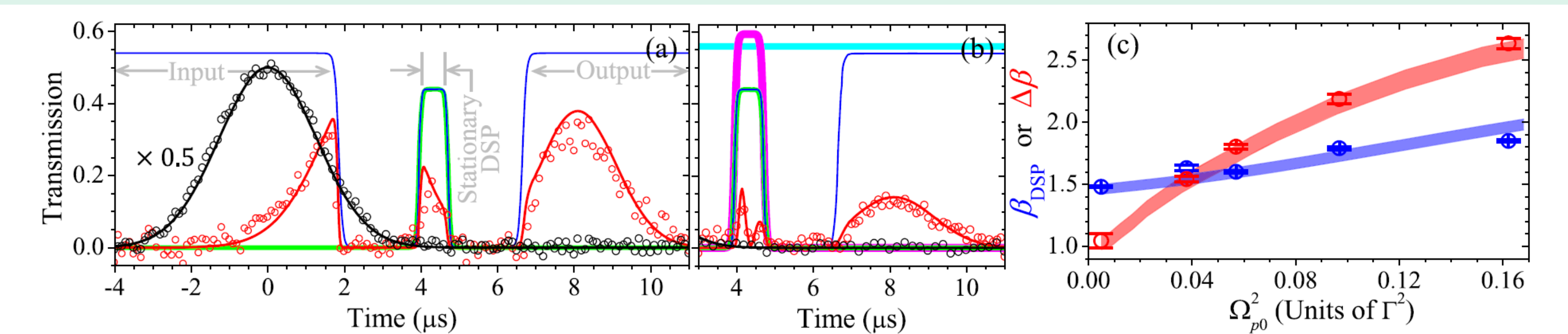


Fig.5 Representative data of the formation of the stationary DSP (a) without DDI and (b) with DDI demonstrate the consistency with predictions. (c) DDI-induced attenuation ($\Delta\beta$) with increasing the Rydberg state population or equivalently the input probe intensity. Increasing $\Delta\beta$ with increasing input probe intensity represents DDI dressing.

Formation of the stationary DSP dressed by DDI: DDI induced phase shift

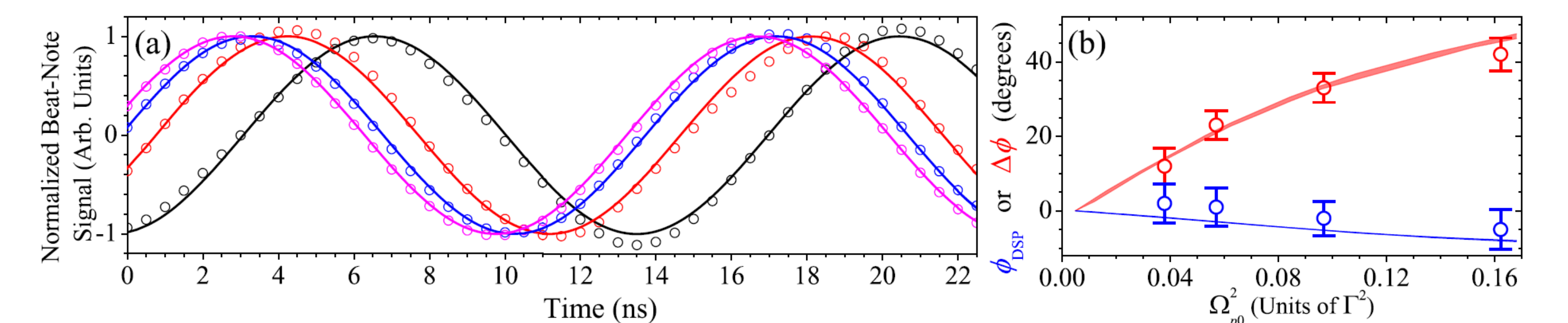


Fig.6 (a) Representative data of normalized beat-note signals showing phase evolutions at the peaks of the retrieved probe pulses with increasing the Rydberg state population. (b) DDI-induced phase shift ($\Delta\phi$) with increasing the Rydberg state population or equivalently the input probe intensity. Increasing $\Delta\phi$ with increasing input probe intensity represents DDI dressing.

Formation of the stationary DSP dressed by DDI: various principal quantum numbers

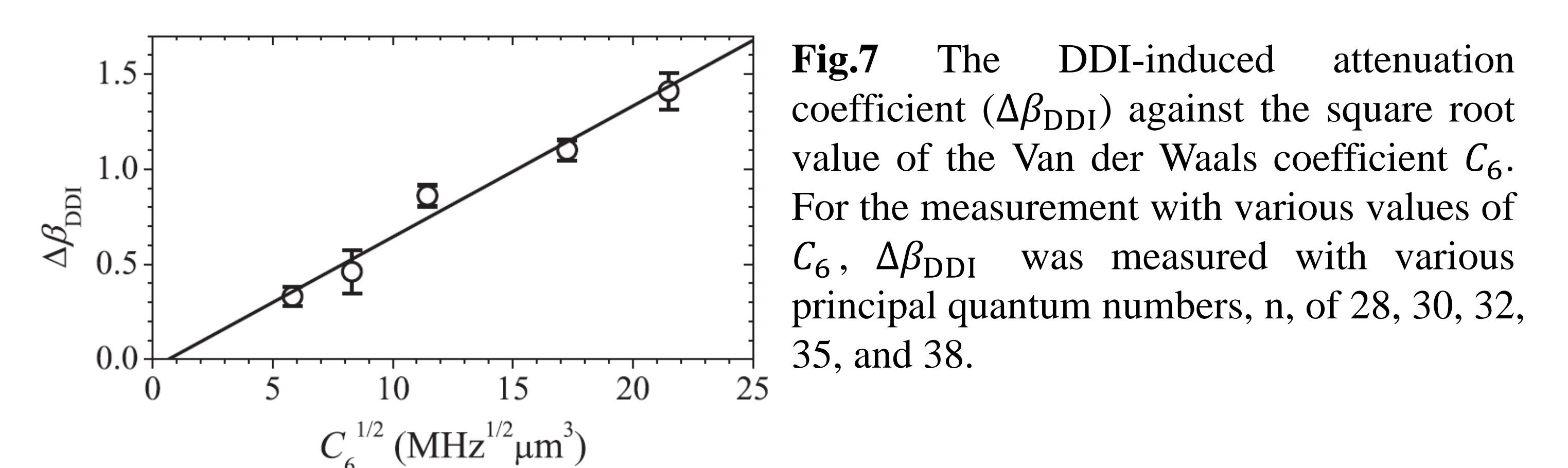


Fig.7 The DDI-induced attenuation coefficient ($\Delta\beta_{DDI}$) against the square root value of the Van der Waals coefficient C_6 . For the measurement with various values of C_6 , $\Delta\beta_{DDI}$ was measured with various principal quantum numbers, n , of 28, 30, 32, 35, and 38.

Features of DDI-dressed stationary DSPs and its prospect

	Atomic BEC	DDI-dressed Stationary DSPs	2D Exciton-Polariton BEC
m^*	$10^4 m_e$	$\sim 10^{-2} m_e$	$10^{-5} m_e$
n	$10^{13} \sim 10^{15} \text{ cm}^{-3}$	$\sim 10^{10} \text{ cm}^{-3}$	$10^{10} \sim 10^{12} \text{ cm}^{-3}$
T_c	$< 1 \mu\text{K}$	$\sim 1 \text{ mK}$	$> 1 \text{ K}$
τ	$> 1 \text{ ms}$	$\sim 1 \mu\text{s}$	$< 100 \text{ ps}$

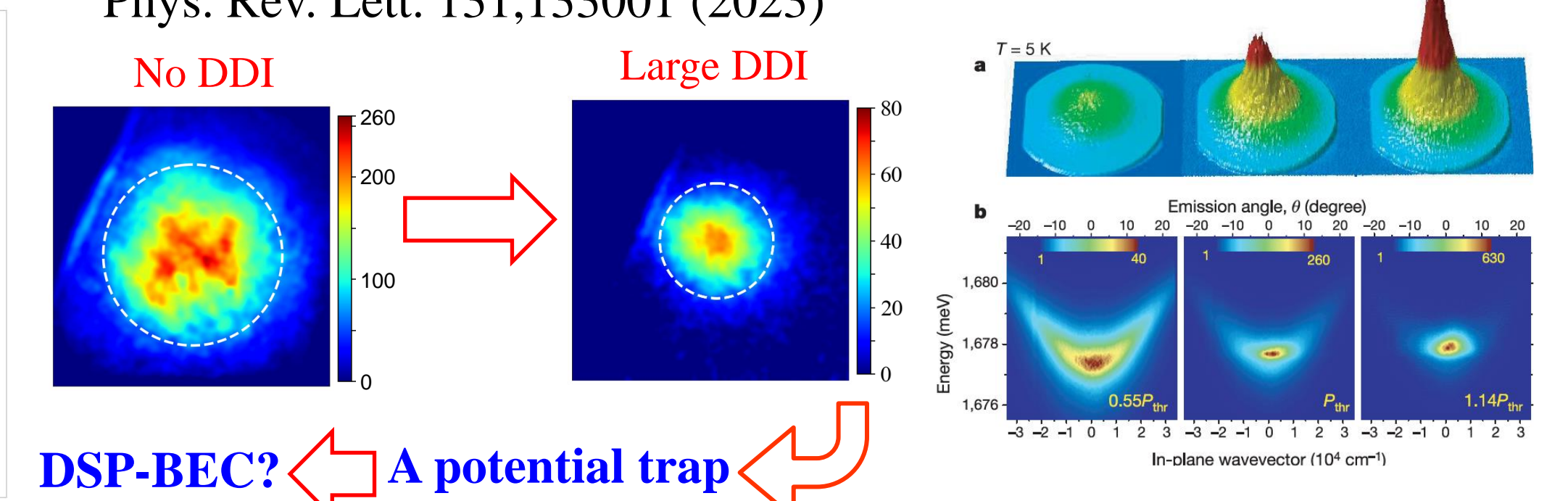
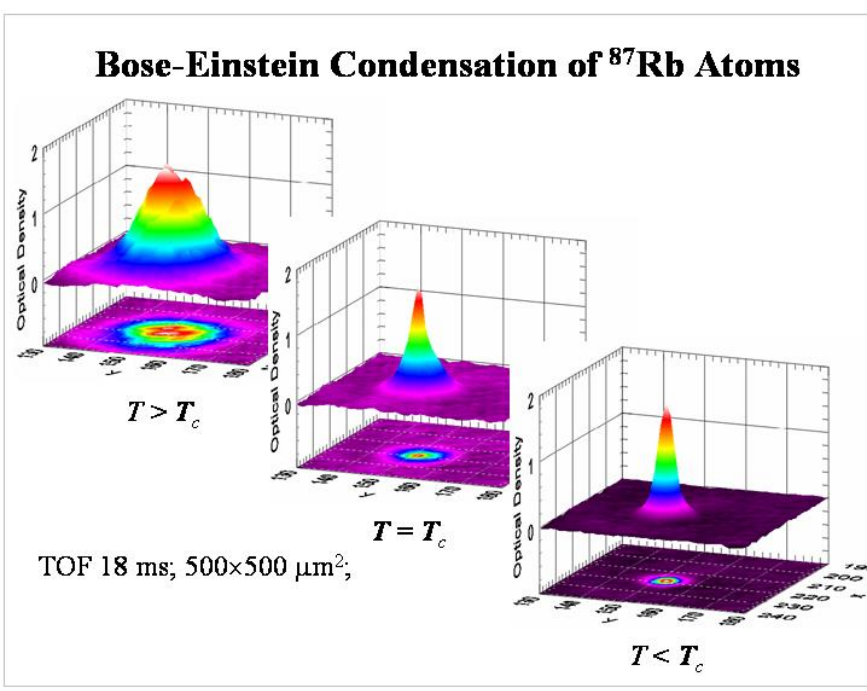
Ultracold Atom Lab (NTHU)

Estimated current condition:

$T_c = 4.0 \text{ mK} / T_p = 3.8 \mu\text{K} / R_c = 33 \text{ MHz}$

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Nature 443, 409 (2006).



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