Rabi Oscillations when not alone...

L. Dominici, D. Colas, A. Rahmani, S. Donati, D. Ballarini, M. De Giorgi, G. Gigli, E. del Valle, **F. P. Laussy**, D. Sanvitto

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erc

RQC Russian Quantum Center

National Research Council of Italy

دانشگاه یزد

ibs International Workshop Physics of Exciton-Polaritons in Artificial Lattices, Center for Theoretical Physics of Complex Systems — Daejeon, South Korea, May 2017.

$$H = \omega_a a^\dagger a + \omega_b b^\dagger b + g(a^\dagger b + ab^\dagger), \qquad (1)$$

...

Equation (1) can be straightforwardly diagonalized for bosonic modes, giving $H=\omega_U p^\dagger p+\omega_L q^\dagger q$, where

$$\omega_{\substack{U\\L}} = \frac{\omega_a + \omega_b}{2} \pm \sqrt{g^2 + \left(\frac{\Delta}{2}\right)^2}, \qquad (2)$$

with new Bose operators $p=\cos\theta a+\sin\theta b$ and $q=-\sin\theta a +\cos\theta b$, determined by the *mixing angle*, $\theta=\arctan[g/(\frac{\Delta}{2} + \sqrt{g^2+(\frac{\Delta}{2})^2})]$, and the detuning

$$\Delta = \omega_a - \omega_b. \qquad (3)$$

...

cavity, the time evolution of the probability to have an exciton when there was initially one (at $t=0$) reads

$$|\langle 0,1|e^{-iHt}|0,1\rangle|^2 = \sin^4\theta + \cos^4\theta + 2\sin^2\theta\cos^2\theta\cos[(\omega_U-\omega_L)t]. \qquad (5)$$

The probability oscillates between the bare modes at the so-called *Rabi frequency*, given by the difference between the polariton energies $\omega_U-\omega_L$. For convenience of notation, we

F. P. Laussy, E. del Valle, and C. Tejedor. *Luminescence spectra of quantum dots in microcavities. I. Bosons.* Phys. Rev. B, **79**:235325, 2009.

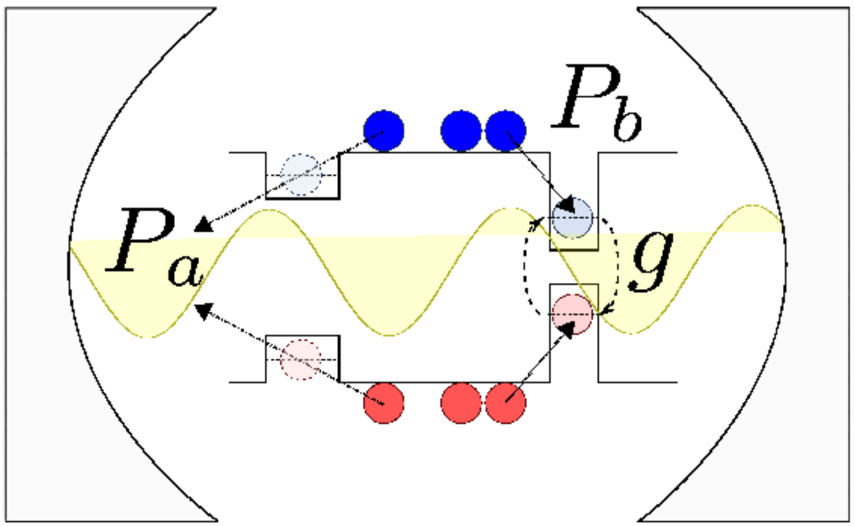
Rabi Oscillations with pump & decay.

LAUSSY, DEL VALLE, AND TEJEDOR PHYSICAL REVIEW B **79**, 235325 (2009)

$$\partial_t\rho = \mathcal{L}\rho = i[\rho, H] \tag{9a}$$

$$+ \sum_{c=a,b} \frac{\gamma_c}{2}(2c\rho c^\dagger - c^\dagger c\rho - \rho c^\dagger c) \tag{9b}$$

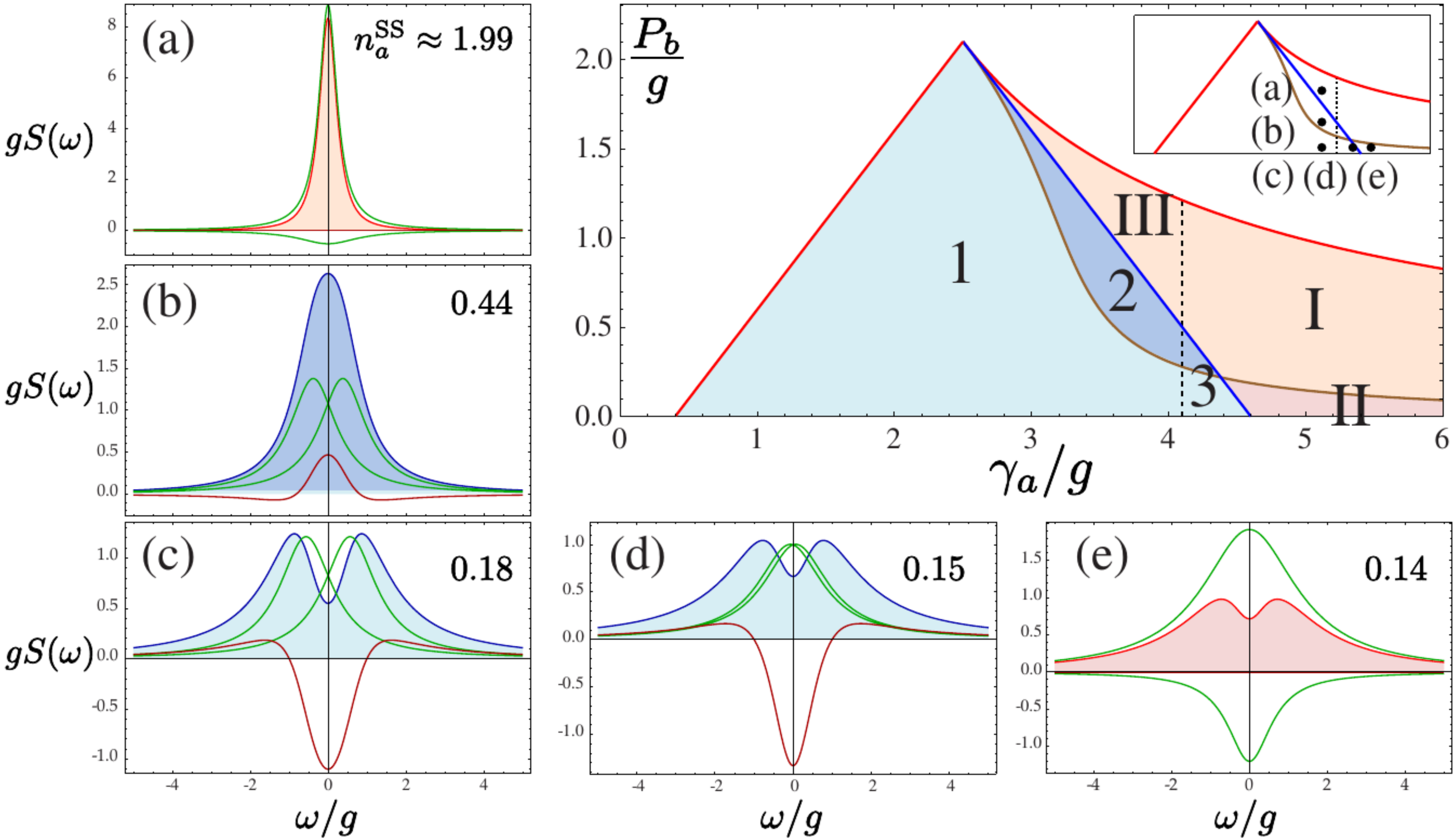
$$+ \sum_{c=a,b} \frac{P_c}{2}(2c^\dagger\rho c - cc^\dagger\rho - \rho cc^\dagger). \tag{9c}$$



F. P. Laussy, E. del Valle, and C. Tejedor. *Strong coupling of quantum dots in microcavities*.
Phys. Rev. Lett., **101**:083601, 2008

Rabi Oscillations with pump & decay.

LUMINESCENCE SPECTRA OF QUANTUM… . I. BOSONS PHYSICAL REVIEW B **79**, 235325 (2009)



Rabi Oscillations with pump & decay.

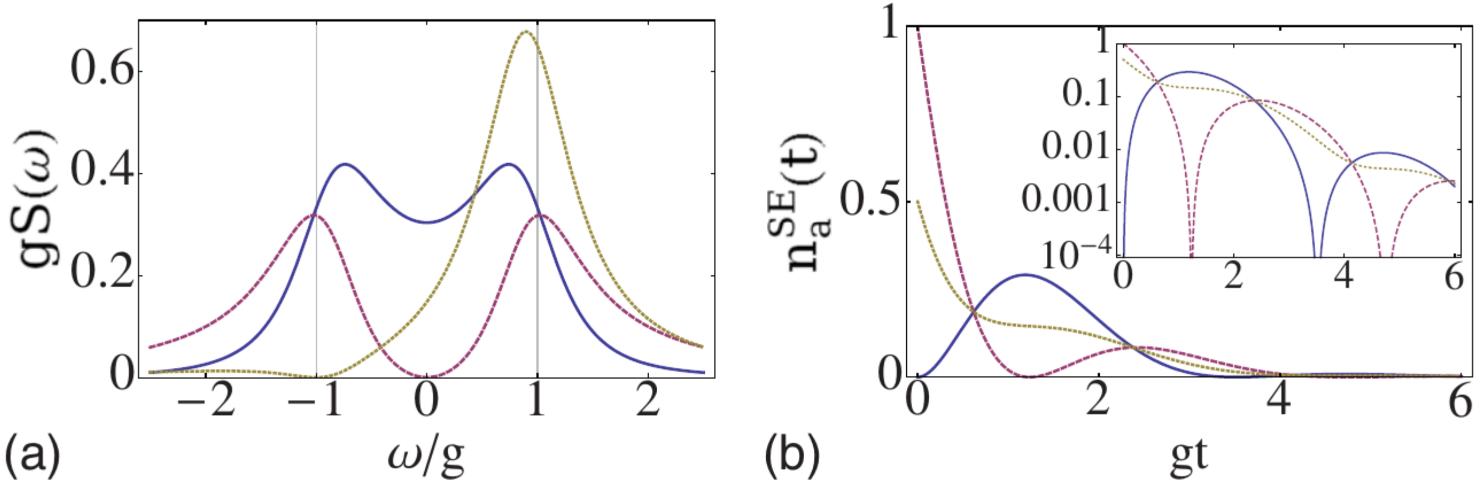


FIG. 6. (Color online) (a) Strong-coupling spectra $S_0^{SE}(\omega)$ and (b) its corresponding mean number dynamics $n_a^{SE}(t)$ for the spontaneous emission of three different initial states. In blue solid, one exciton; in purple dashed, one photon; and in brown dotted, one upper polariton. Parameters are $\gamma_a = 1.9g$ and $\gamma_b = 0.1g$. Inset of (b) is the same in log scale.

Looking backwards: a short history of microcavities in solids

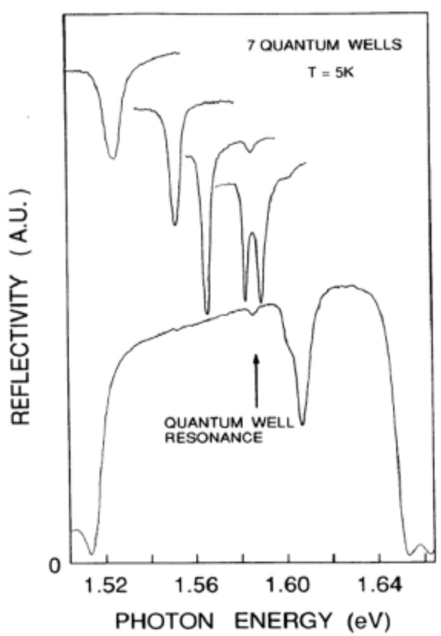
Phys. Stat. Sol. B, **242**:2345, 2005.

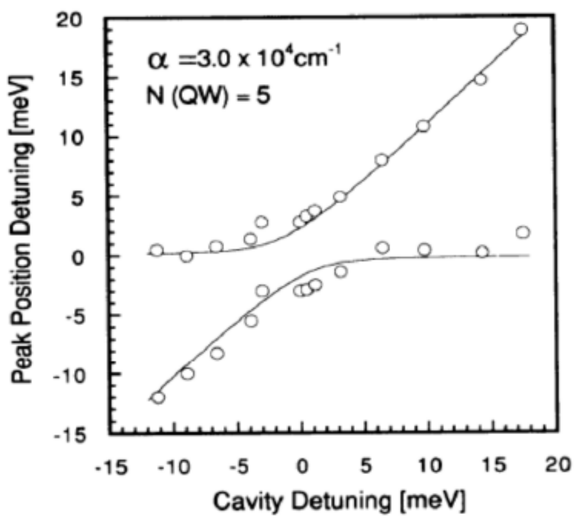
Let me describe the sequence of events that led to the discovery of CPs. I was at the University of Tokyo for four months in the summer of 1991, hosted by Professor Arakawa, and I was looking for some experiments to do. After some wonderings about QWs in high magnetic fields and QD excitation spec-

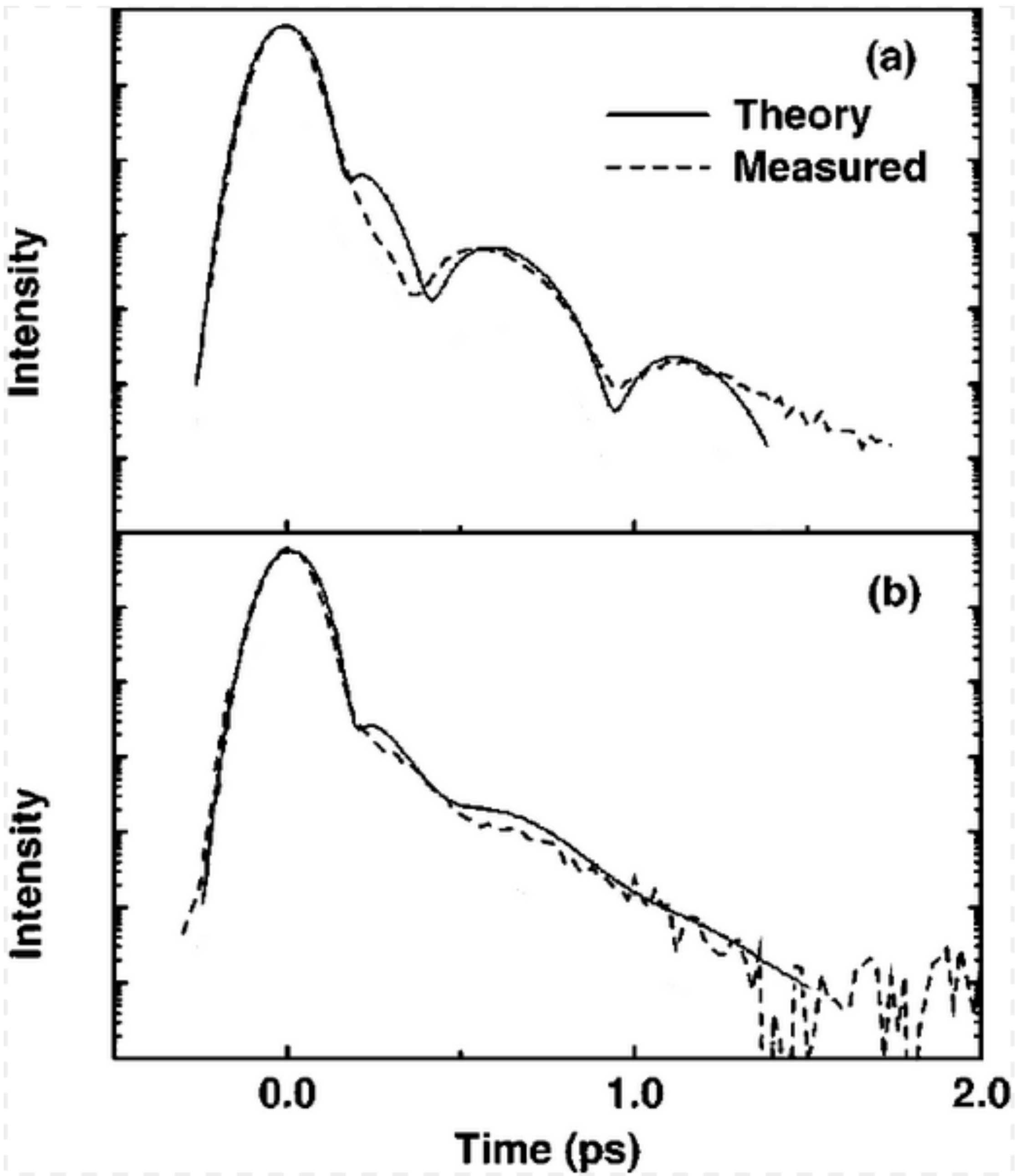
...

As for publication, one referee of *Physical Review Letters* (PRL) observed that everything was fine with the experiment and the model, but as such phenomena had already been observed in atomic physics, it did not warrant publication in PRL. The second referee said exactly the same thing on experiment, model and atomic physics, but reached the opposite conclusion in that it was so surprising that it would occur in the solid state that it certainly was PRL material. After another two months, the third referee that I had requested just came up with the remark: 'That's what we like in physics: always good for surprises' and it was published [28].

C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa. *Observation of the coupled exciton-photon mode splitting in a semiconductor quantum microcavity*. Phys. Rev. Lett., **69**:3314, 1992.

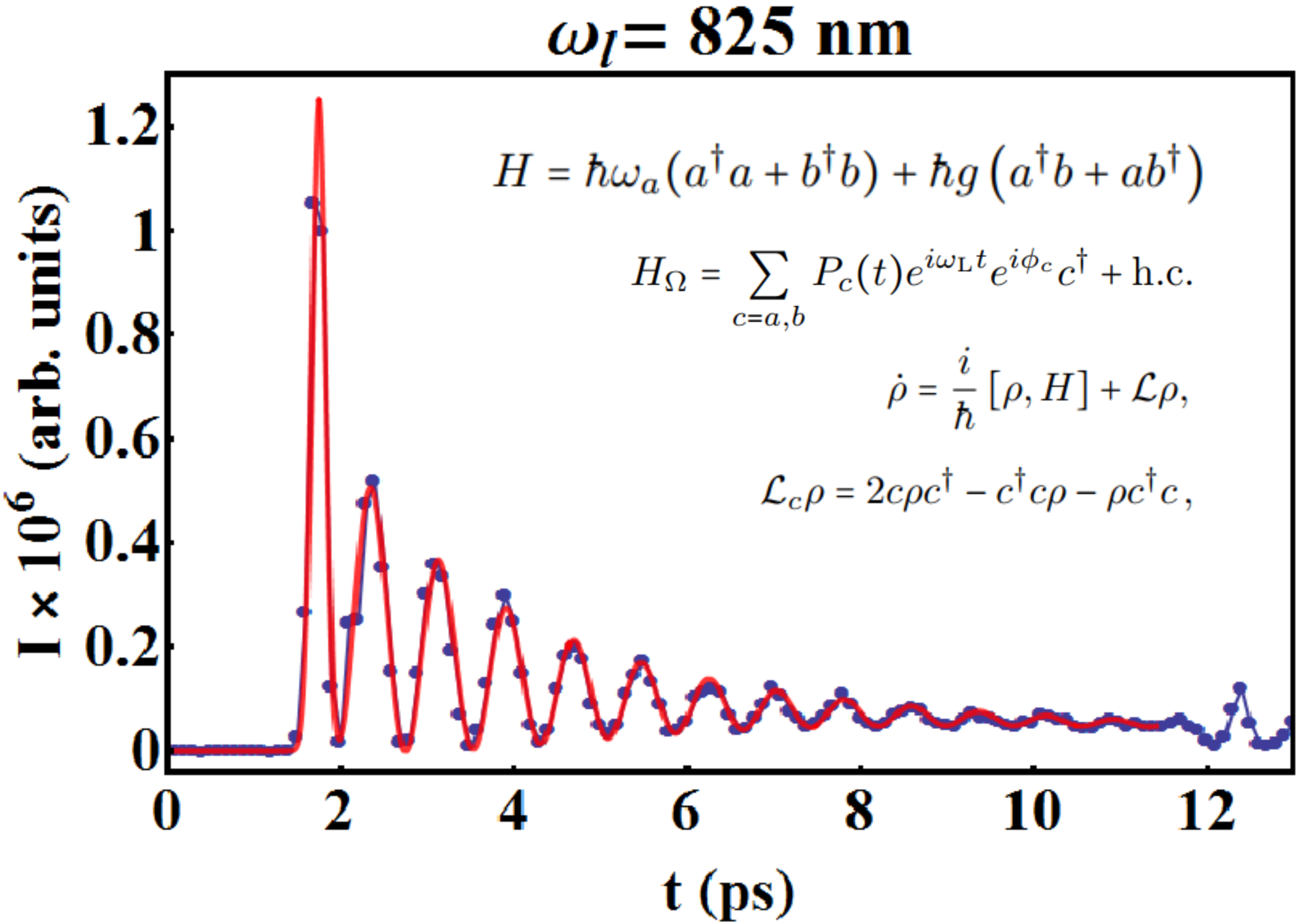




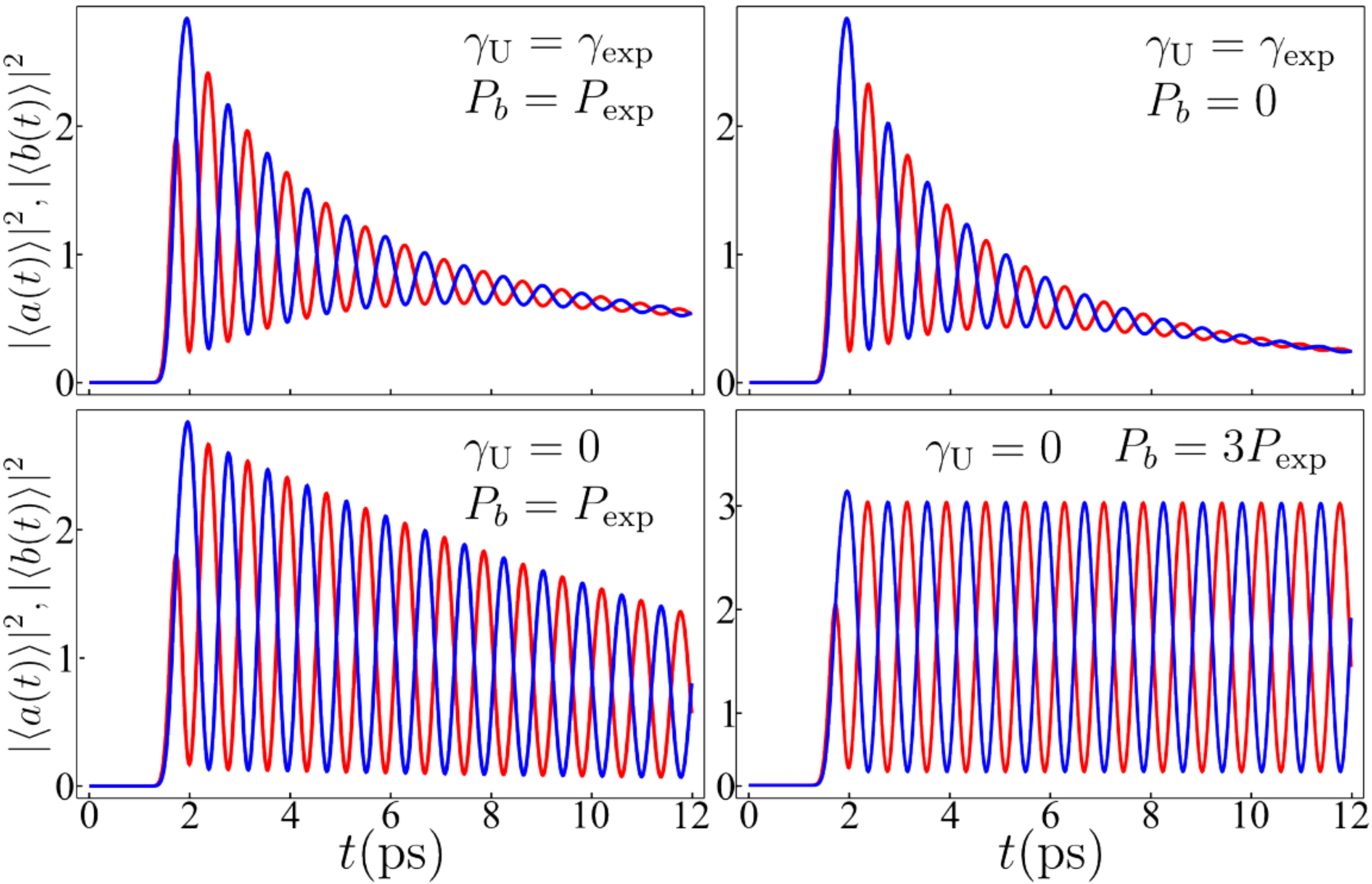


V. Savona and C. Weisbuch. *Theory of time-resolved light emission from polaritons in a semiconductor microcavity under resonant excitation*. Phys. Rev. B, **54**:10835, 1996

L. Dominici, D. Colas, S. Donati, J. P. Restrepo Cuartas, M. De Giorgi, D. Ballarini, G. Guirales, J. C. López Carreño, A. Bramati, G. Gigli, E. del Valle, F. P. Laussy, and D. Sanvitto. *Ultrafast control and Rabi oscillations of polaritons*. Phys. Rev. Lett., **113**:226401, 2014.



$$\mathcal{L}\rho = \frac{\gamma_a}{2}\mathcal{L}_a\rho + \frac{\gamma_b}{2}\mathcal{L}_b\rho + \frac{\gamma_{\mathrm{U}}^{\mathrm{R}}}{2}\mathcal{L}_u\rho + \frac{\gamma_{\mathrm{U}}^{\phi}}{2}\mathcal{L}_{u^\dagger u}\rho + \frac{P_b e^{-\gamma_{P_b} t}}{2}\mathcal{L}_{b^\dagger}\rho\,,$$



The most general quantum state of two coupled oscillators:

$$\rho = \sum_{\substack{k,l=0 \\ n,m=0}} \rho_{\substack{kl \\ nm}} |kl\rangle\langle nm| \quad \text{or} \quad |\psi(t)\rangle = \sum_{n,m=0}^{\infty} \alpha_{nm}(t)\,|nm\rangle\,.$$

The basic state realized in the experiment:

$$|\psi(t)\rangle = |\alpha(t)\rangle\,|\beta(t)\rangle\,.$$

Not to be (too much) confused with:

$$|\Psi(t)\rangle = \alpha(t)|1_a, 0_b\rangle + \beta(t)|0_a, 1_b\rangle$$

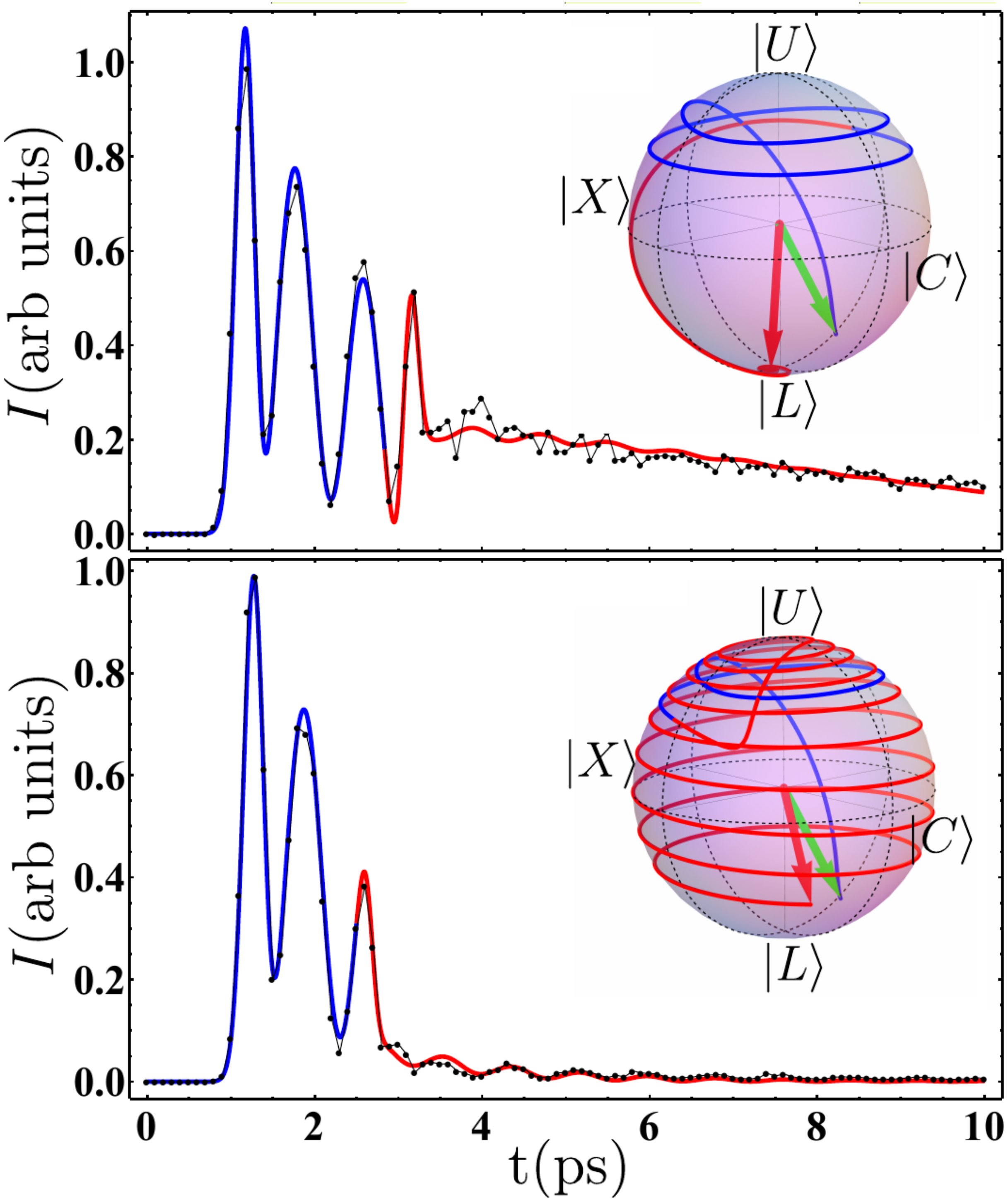
An example of a convenient simplification,
the exact solution for the coherent fractions without pulses:

$$\langle a(t)\rangle = \left[a_0 \cosh(\frac{1}{4}Rt) - \left(\frac{b_0 G + a_0 \Gamma}{R}\right)\sinh(\frac{1}{4}Rt)\right]\exp(-\frac{1}{4}\gamma t)\,,$$

$$\langle b(t)\rangle = \left[b_0 \cosh(\frac{1}{4}Rt) + \left(\frac{-a_0 G + b_0 \Gamma}{R}\right)\sinh(\frac{1}{4}Rt)\right]\exp(-\frac{1}{4}\gamma t)\,,$$

where:

$$\begin{aligned}
\gamma &= \gamma_a + \gamma_b + \gamma_{\mathrm{U}} - P_b\,,\\
\Gamma &= P_b - \gamma_b + \gamma_a\,,\\
G &= i4g + \gamma_{\mathrm{U}}\,,\\
R &= \sqrt{G^2 + \Gamma^2}\,,
\end{aligned}$$



Ultrafast Control and Rabi Oscillations of Polaritons

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[2]*Istituto Italiano di Tecnologia, IIT-Lecce, Via Barsanti, 73010 Lecce, Italy*

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[4]*Universitá del Salento, Via Arnesano, 73100 Lecce, Italy*

[5]*Instituto de Física, Universidad de Antioquia, Medellín AA 1226, Colombia*

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We report the experimental observation and control of space and time-resolved light-matter Rabi oscillations in a microcavity. Our setup precision and the system coherence are so high that coherent control can be implemented with amplification or switching off of the oscillations and even erasing of the polariton density by optical pulses. The data are reproduced by a quantum optical model with excellent accuracy, providing new insights on the key components that rule the polariton dynamics.

DOI: 10.1103/PhysRevLett.113.226401 PACS numbers: 71.36.+c, 78.47.J-

Rabi oscillations [1] are the embodiment of quantum interactions: when a mode a is excited and is coupled to a second mode b, the excitation is transferred from a to b and when the symmetric situation is established, the excitation comes back in a cyclical unitary flow. When this occurs at the single particle level between two-level systems, it provides the ground for qubits [2], which, if they can be further manipulated, opens the possibility to perform quantum information processing [3]. Such an oscillation is of probability amplitudes and therefore is a strongly quantum mechanical phenomenon, that involves maximally entangled states

$$|\Psi(t)\rangle = \alpha(t)|1_a, 0_b\rangle + \beta(t)|0_a, 1_b\rangle. \quad (1)$$

The same physics also holds, not at the quantum level, but with coherent states of the fields, a situation known in the literature as implementing an "optical atom" [4] or a "classical two-level system" [5]. The oscillation is then more properly qualified as "normal mode coupling" [6,7] as it is now between the fields themselves,

$$|\psi(t)\rangle = |\alpha(t)\rangle|\beta(t)\rangle, \quad (2)$$

rather than their probability amplitudes. The denomination of Rabi oscillations remains, however, popular also in this case [8,9]. While of limited value for hardcore implementation of quantum information processing, it is desirable for fundamental purposes and semiclassical applications to have access to such classical qubits, or "cebits" [10]. In particular, they can help to explore the origin and mechanism of nonlocality and parallelization in genuinely quantum systems [11], as well as providing classical counterparts useful for proof-of-principle demonstration, design, and optimization of the actual quantum version [12]. Such classical two-level systems have been pursued for decades [13] and recently enjoyed a boost with the rise of nanomechanical optics [5,14]. There is another system which provides an ideal platform to implement both genuinely quantum [15] and classical versions [16] of the two-level system: polaritons [17]. A polariton is by essence a two-level system, arising from strong light-matter coupling between a cavity photon and a semiconductor exciton. In planar microcavities embedding inorganic quantum wells (QWs), which is the case of interest here, the system has enjoyed considerable attention for its quantum properties at the macroscopic level [18], such as Bose-Einstein condensation [19], superfluidity [20,21] and a wealth of quantum hydrodynamics features [22–25], culminating with the demonstration of possible devices [26,27] and pioneering logical operations [28]. While Rabi oscillations are at the heart of polariton physics, they are so fast in a typical microcavity—in the subpicosecond time range—that they are typically glossed over and the macroscopic physics of polaritons investigated in their coarse graining. Pioneering attempts to observe them showed the inherent difficulty and reported hardly two oscillations with 3 orders of magnitude loss of contrast each time [29], attributed to the inhomogeneous broadening of excitons by the theory [30], which could provide a qualitative agreement only. Later reports through pump-probe techniques [31–33], in particular, in conjunction with an applied magnetic field [34], increased their visibility but remained tightly constrained to their bare observation. Since polaritons are increasingly addressed at the single particle level [35,36], it becomes capital to harness their Rabi dynamics [37].

In this Letter, thanks to significant progress in both the quality of the structures (the sample description is given in the Supplemental Material [38]) and in the laboratory state of the art, we have been able to both neatly observe and control the microcavity polariton Rabi dynamics. This brings microcavities one step further as platforms to engineer various states of light-matter coupling. We can

Rabi Oscillations with polarization.

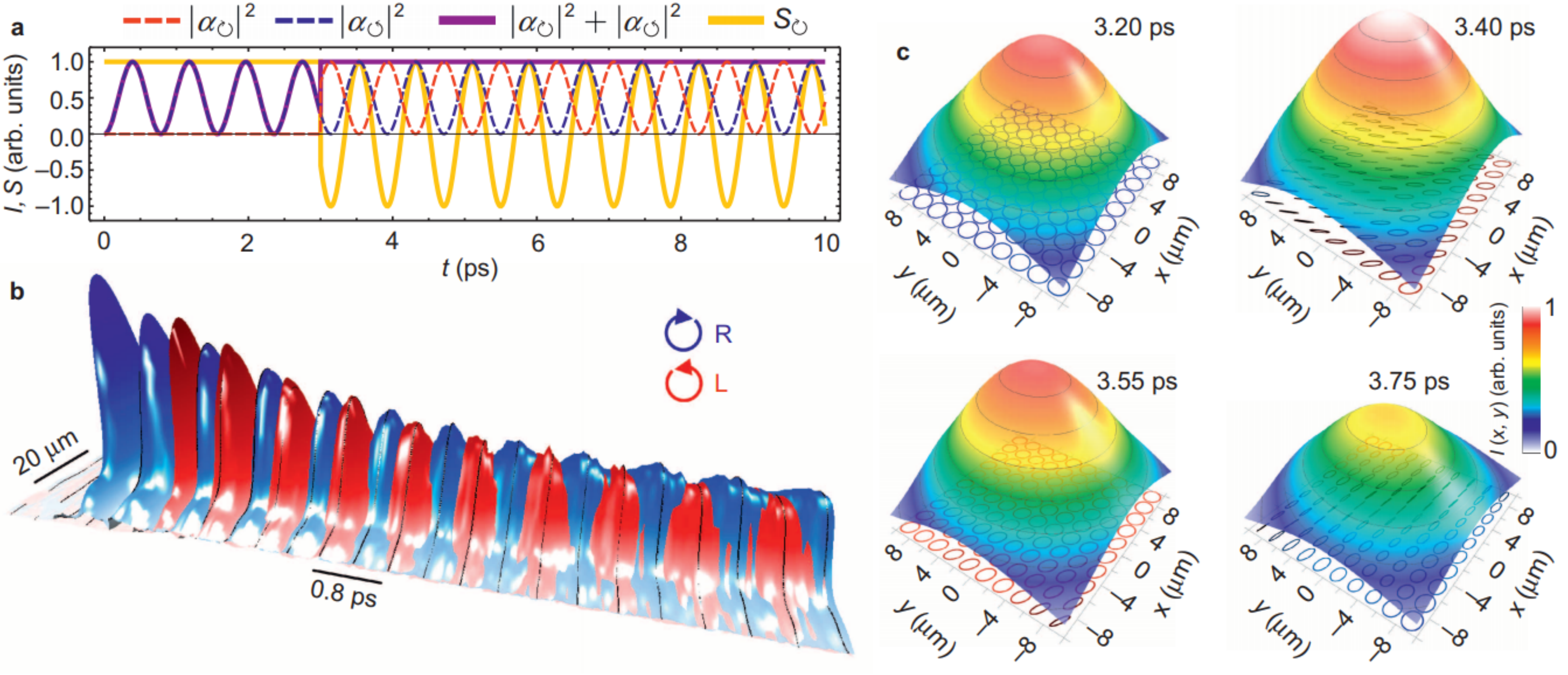
Polarization shaping of Poincaré beams by polariton oscillations

David Colas[1], Lorenzo Dominici[2,3], Stefano Donati[2,3,4], Anastasiia A Pervishko[5], Timothy CH Liew[5], Ivan A Shelykh[5,6,7], Dario Ballarini[2], Milena de Giorgi[2], Alberto Bramati[8], Giuseppe Gigli[2,4], Elena del Valle[1], Fabrice P Laussy[1,9], Alexey V Kavokin[9,10] and Daniele Sanvitto[2]

Light: Science & Applications (2015) 4, e350; doi:10.1038/lsa.2015.123

www.nature.com/lsa

Rabi Oscillations with polarization.

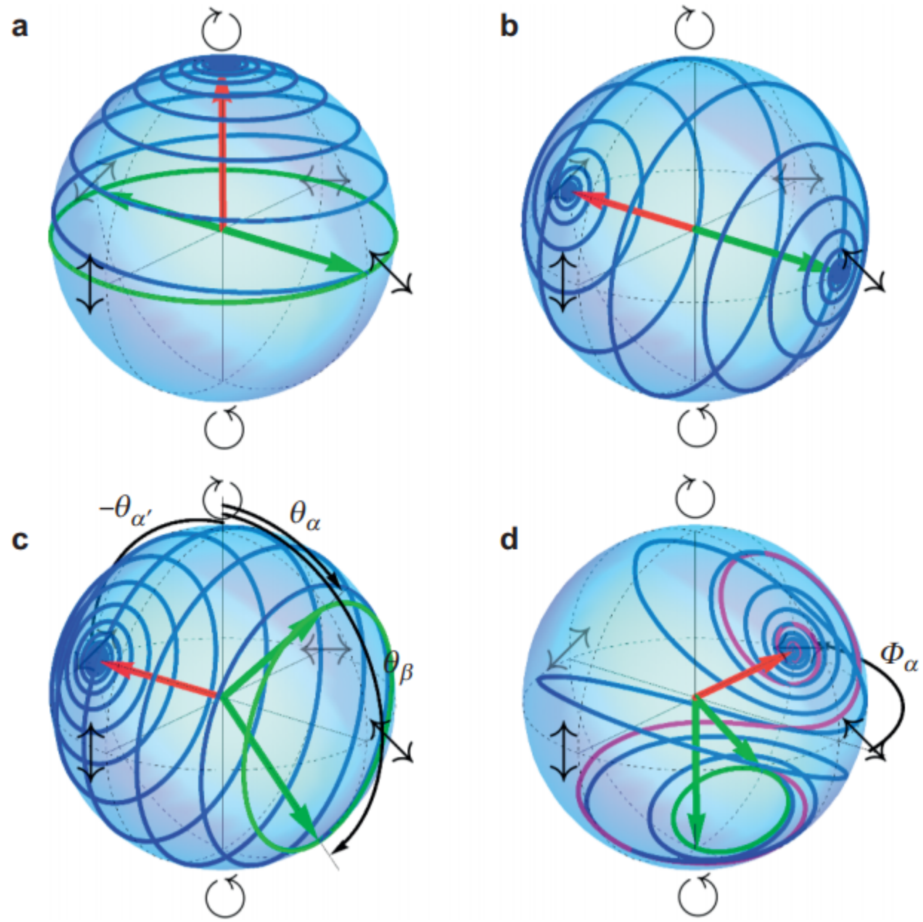


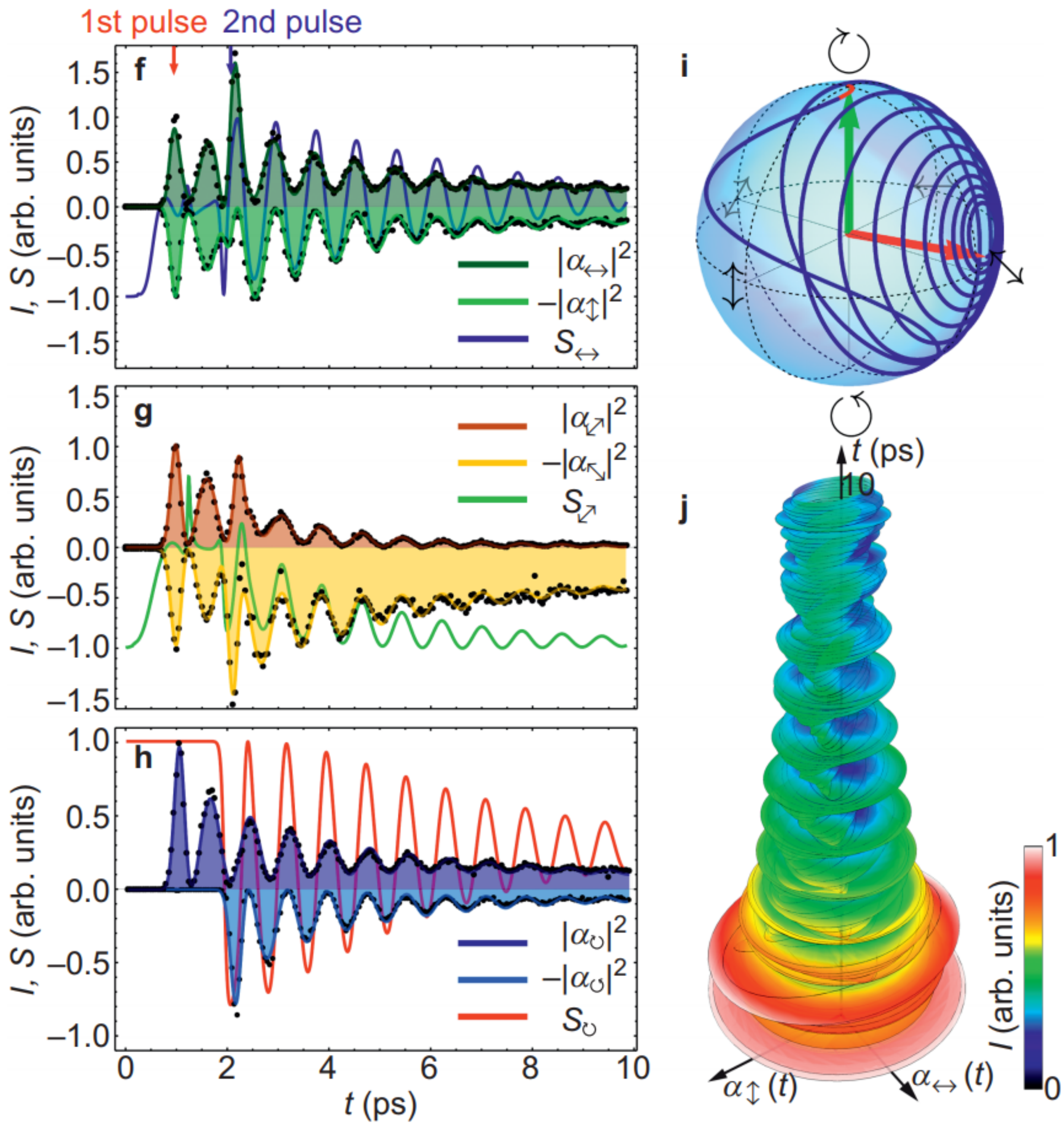
triggered by the first pulse, one then gets to the reversed situation of a constant intensity of oscillating polarization, as also seen on the figure.

The dynamics of polarization is conveniently pictured on the Poincaré sphere. In the case without decay or with the same decay rate for both types of polaritons (upper and lower), the trajectory is a circle, shown as a green trace in Figure 3. Depending on the respective polariton states for the two polarizations, various circles are realized, from an equator for full-amplitude Rabi oscillations (panel a) down to a single point for polaritons in both polarizations (panel b). The circle thus formed can be defined on the sphere, in a given basis (we will work in the circular one) by two couples of angles (θ_ξ, Φ_ξ) for $\xi = \alpha, \beta$, defined by the ratios of polarization $R_\alpha = \alpha_\circlearrowleft / \alpha_\circlearrowright$ and $R_\beta = \beta_\circlearrowleft / \beta_\circlearrowright$ of the photon α and matter β fields at $t = 0$, respectively. The relation follows straightforwardly from Equation (2) by geometric construction as:

$$\theta_\xi = 2\arccos\left(1/\sqrt{1+|R_\xi|^2}\right), \tag{5a}$$

$$\Phi_\xi = \phi_\xi + \arg R_\xi. \tag{5b}$$





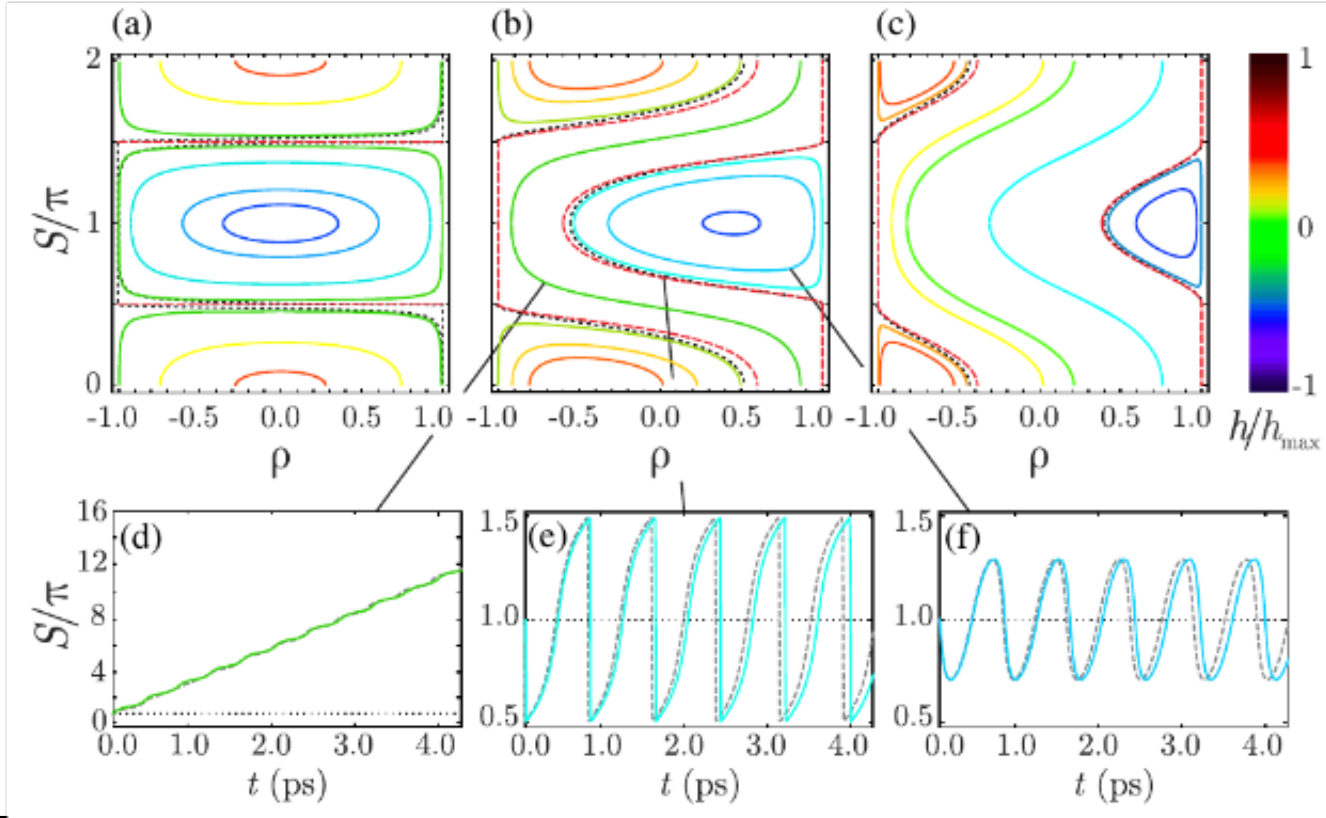
1st pulse
2nd pulse
f
g
h
i
j
I, S (arb. units)
t (ps)
I (arb. units)

Rabi Oscillations with phase difference.

PRL 115, 186402 (2015) PHYSICAL REVIEW LETTERS week ending 30 OCTOBER 2015

Detuning-Controlled Internal Oscillations in an Exciton-Polariton Condensate

N. S. Voronova,[1,*] A. A. Elistratov,[2] and Yu. E. Lozovik[3,4,5]



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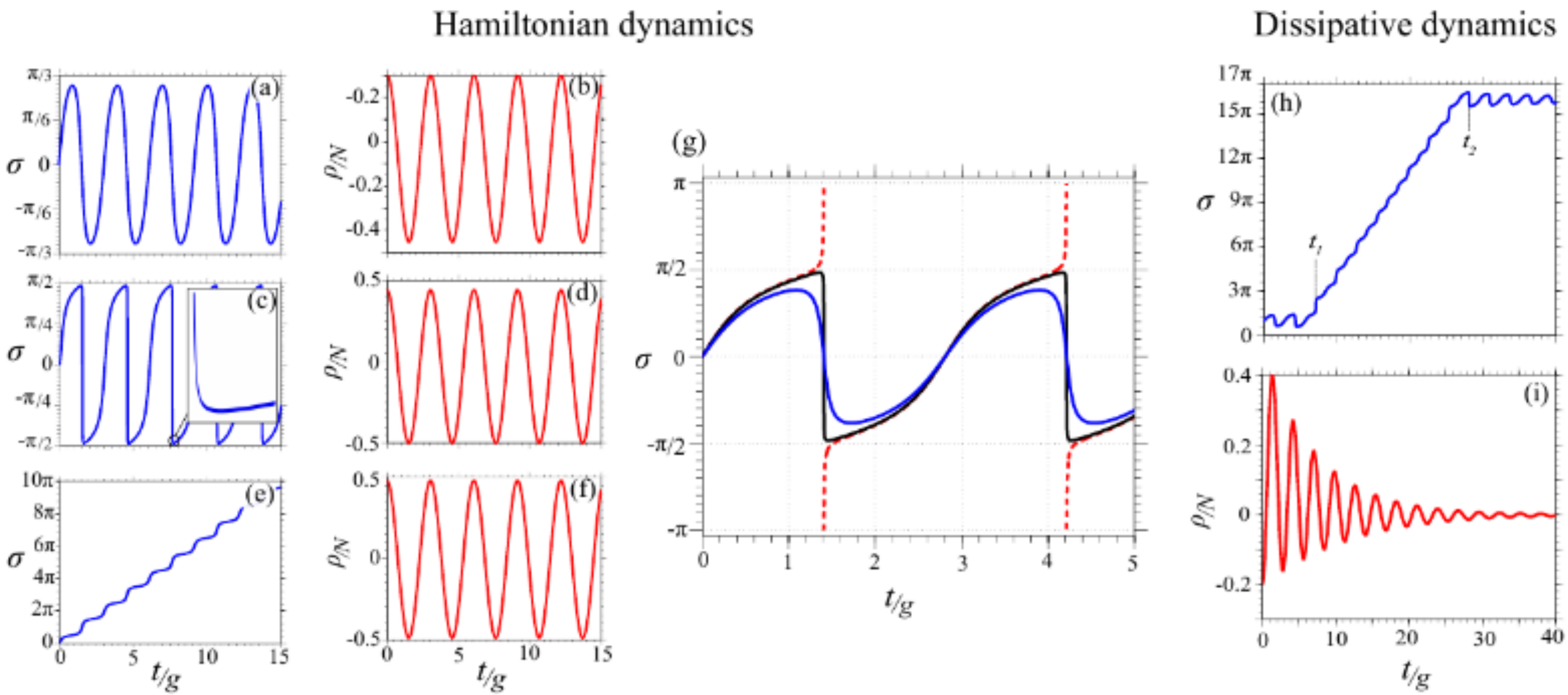
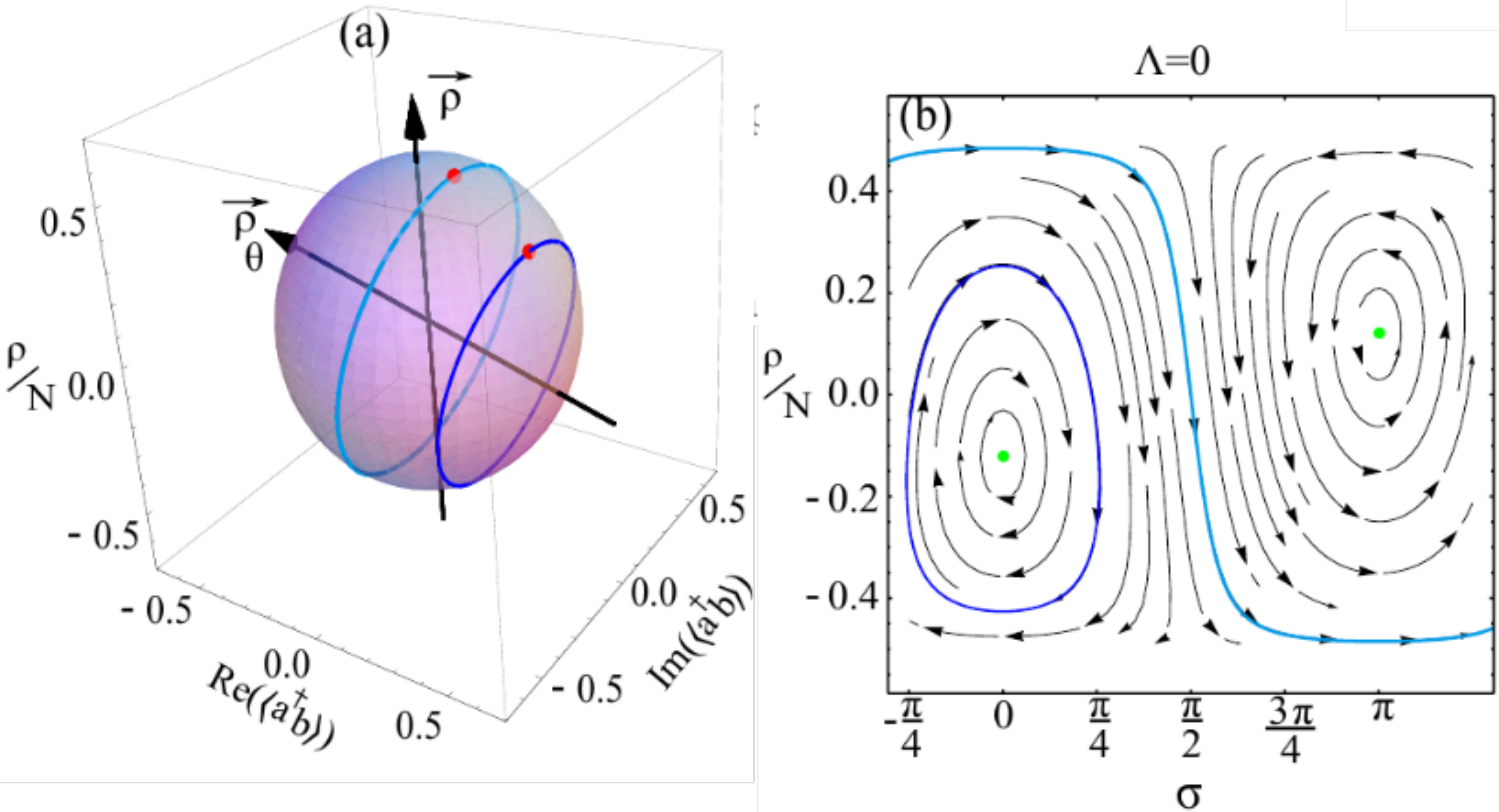
Polaritonic Rabi and Josephson Oscillations

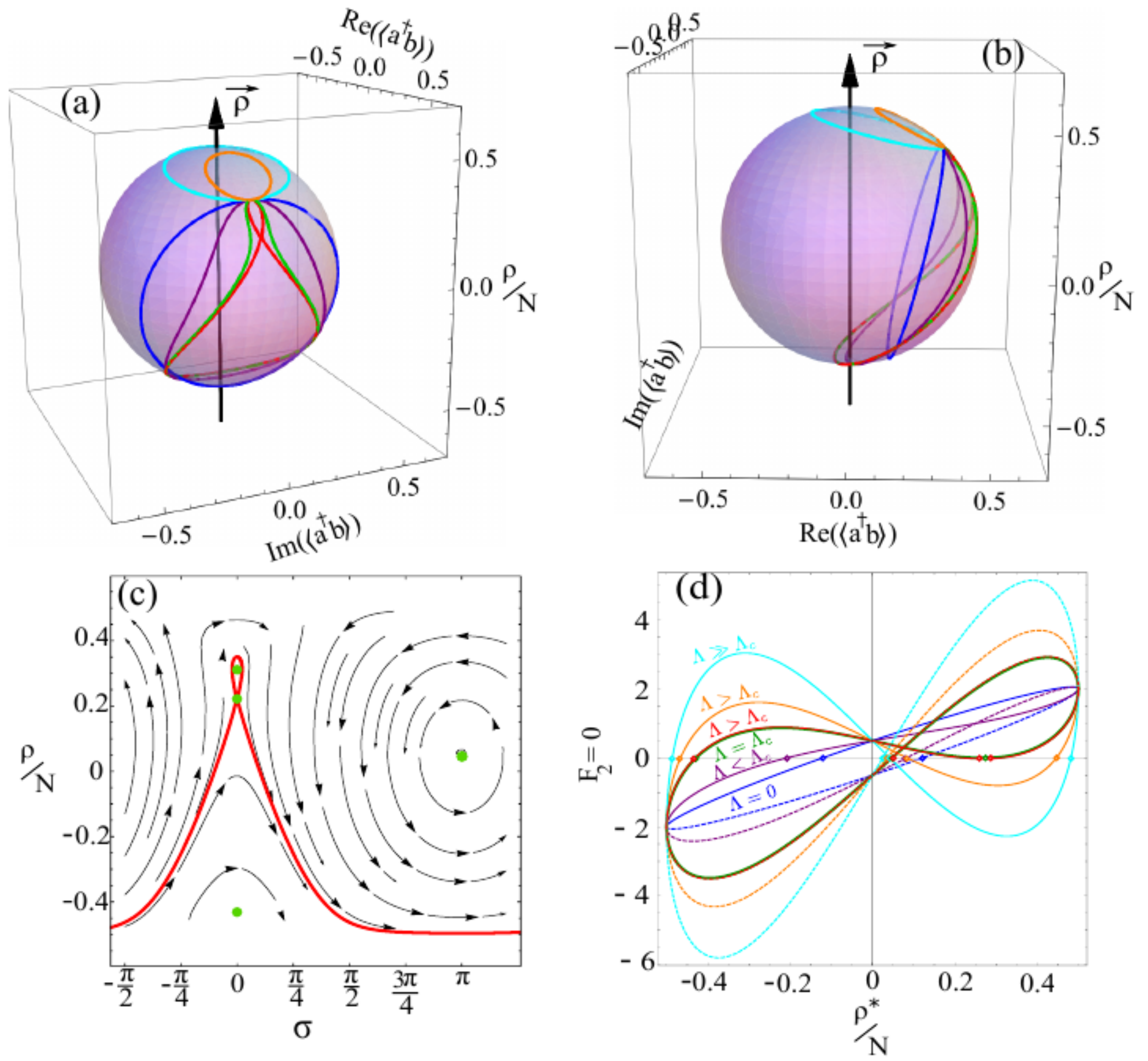
Amir Rahmani[1] & Fabrice P. Laussy[2,3]



Diagonalizing these equations, we get one key result for the dynamics:

$$|\langle a_\theta^\dagger b_\theta \rangle|^2 + \rho_\theta^2 = (N(t)/2)^2 + \mathcal{P}(t)\,, \qquad (8)$$





(a)
Re(⟨a†b⟩)
−0.5 0.0 0.5
ρ/N
0.5
0.0
−0.5
Im(⟨a†b⟩)
−0.5 0.0 0.5
(b)
Im(⟨a†b⟩)
Re(⟨a†b⟩)
−0.5 0.0 0.5
ρ/N
0.5
0.0
−0.5
(c)
ρ/N
0.4
0.2
0
-0.2
-0.4
σ
-π/2 -π/4 0 π/4 π/2 3π/4 π
(d)
F2=0
4
2
0
- 2
- 4
- 6
Λ ≫ Λc
Λ > Λc
Λ > Λc
Λ = Λc
Λ < Λc
Λ = 0
ρ*/N
-0.4 -0.2 0 0.2 0.4

Rabi Oscillations with momentum.

PRL **116,** 026401 (2016) PHYSICAL REVIEW LETTERS week ending 15 JANUARY 2016

Self-Interfering Wave Packets

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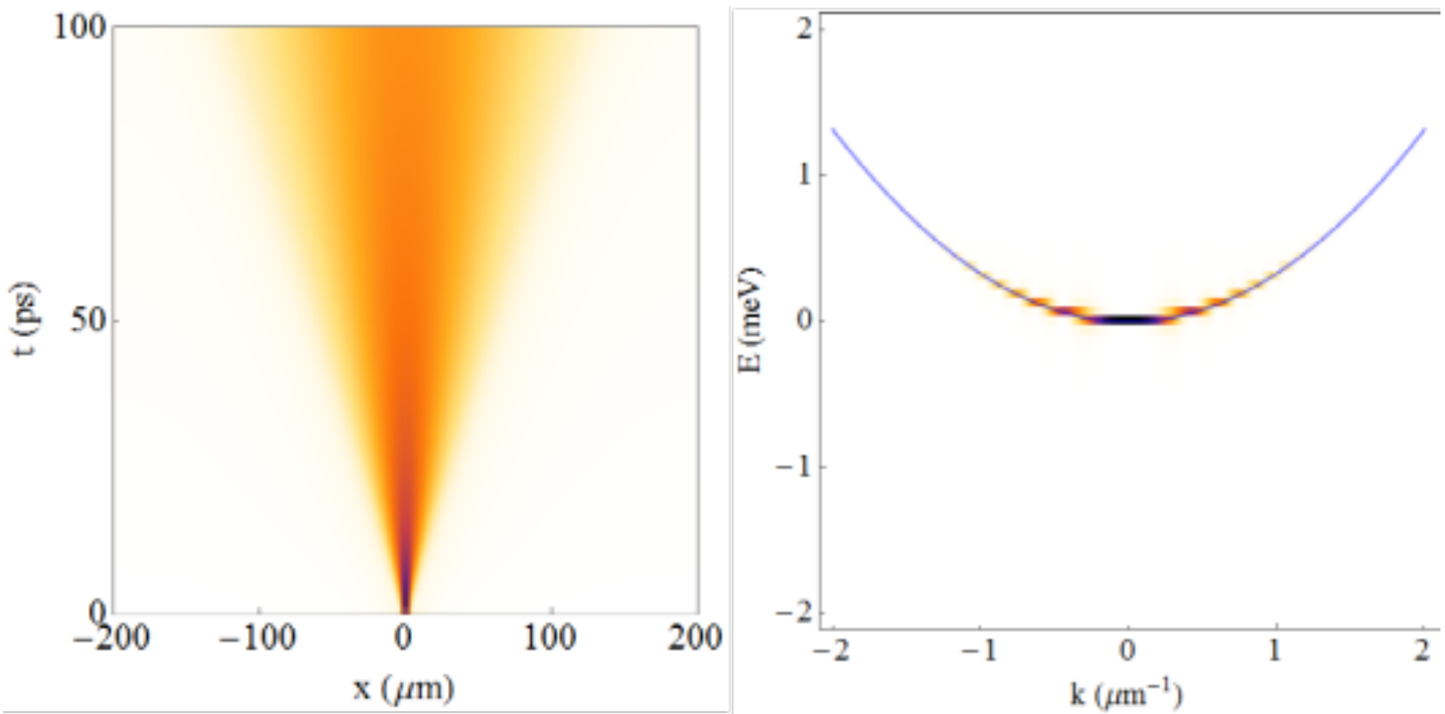
(Received 11 July 2015; revised manuscript received 5 October 2015; published 13 January 2016)

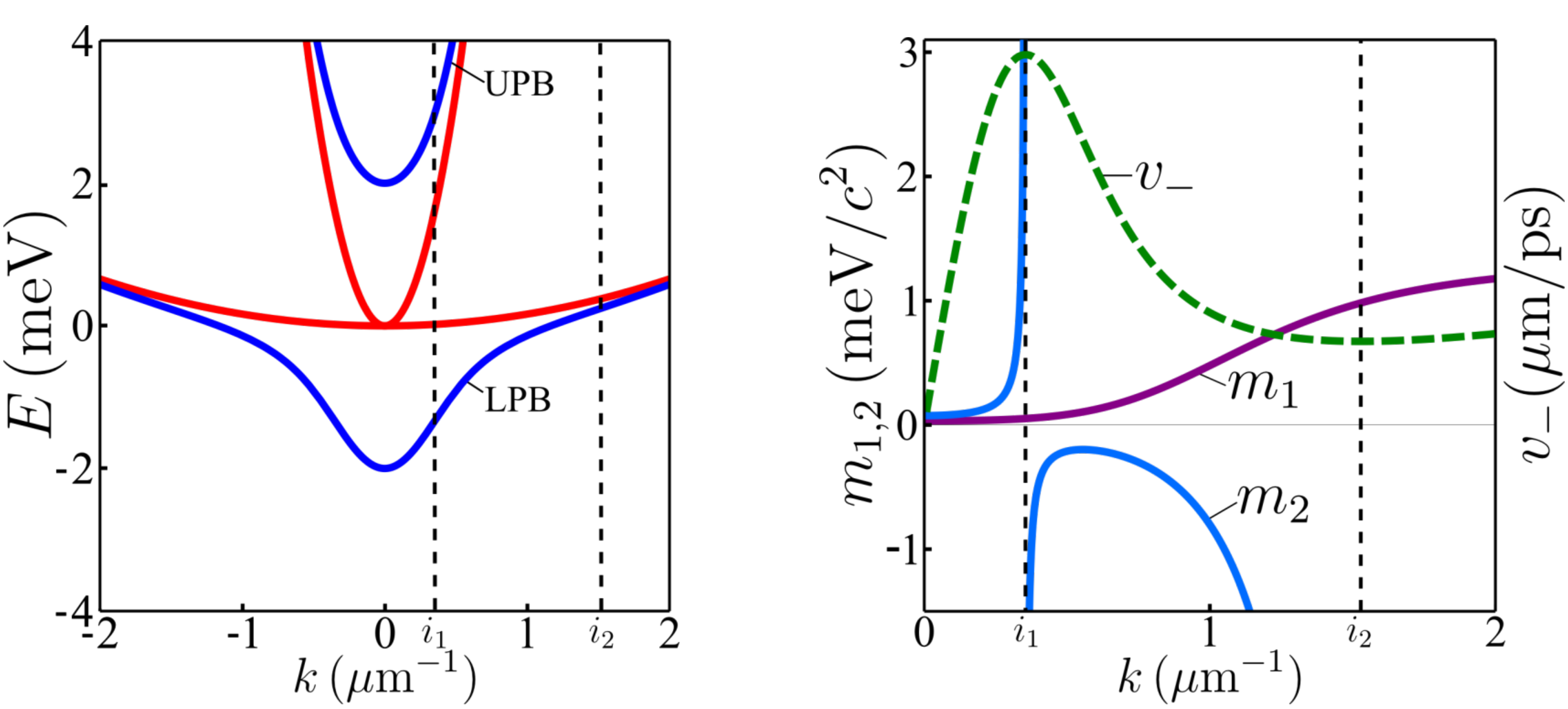
We study the propagation of noninteracting polariton wave packets. We show how two qualitatively different concepts of mass that arise from the peculiar polariton dispersion lead to a new type of particlelike object from noninteracting fields—much like self-accelerating beams—shaped by the Rabi coupling out of Gaussian initial states. A divergence and change of sign of the diffusive mass results in a "mass wall" on which polariton wave packets bounce back. Together with the Rabi dynamics, this yields propagation of ultrafast subpackets and ordering of a spacetime crystal.

$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2m}\nabla^2\psi$$

$$\psi(t_0, x) = \mathrm{e}^{-\frac{x^2}{2\sigma_x^2}}$$

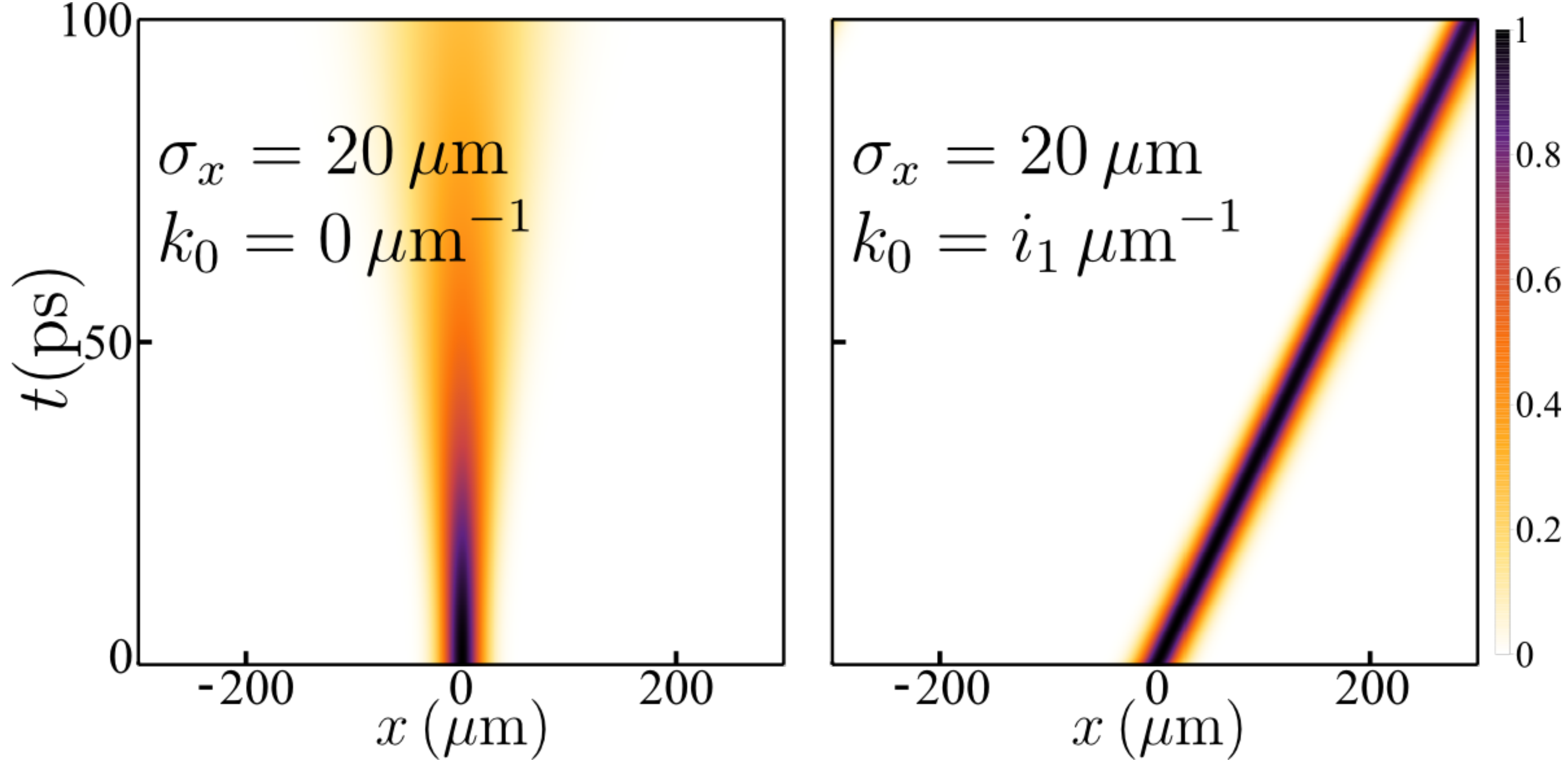
$$\sigma_x(t) = \sqrt{\sigma_x^2(0) + \left(\frac{\hbar t}{2m_2\sigma_x(0)}\right)^2}$$



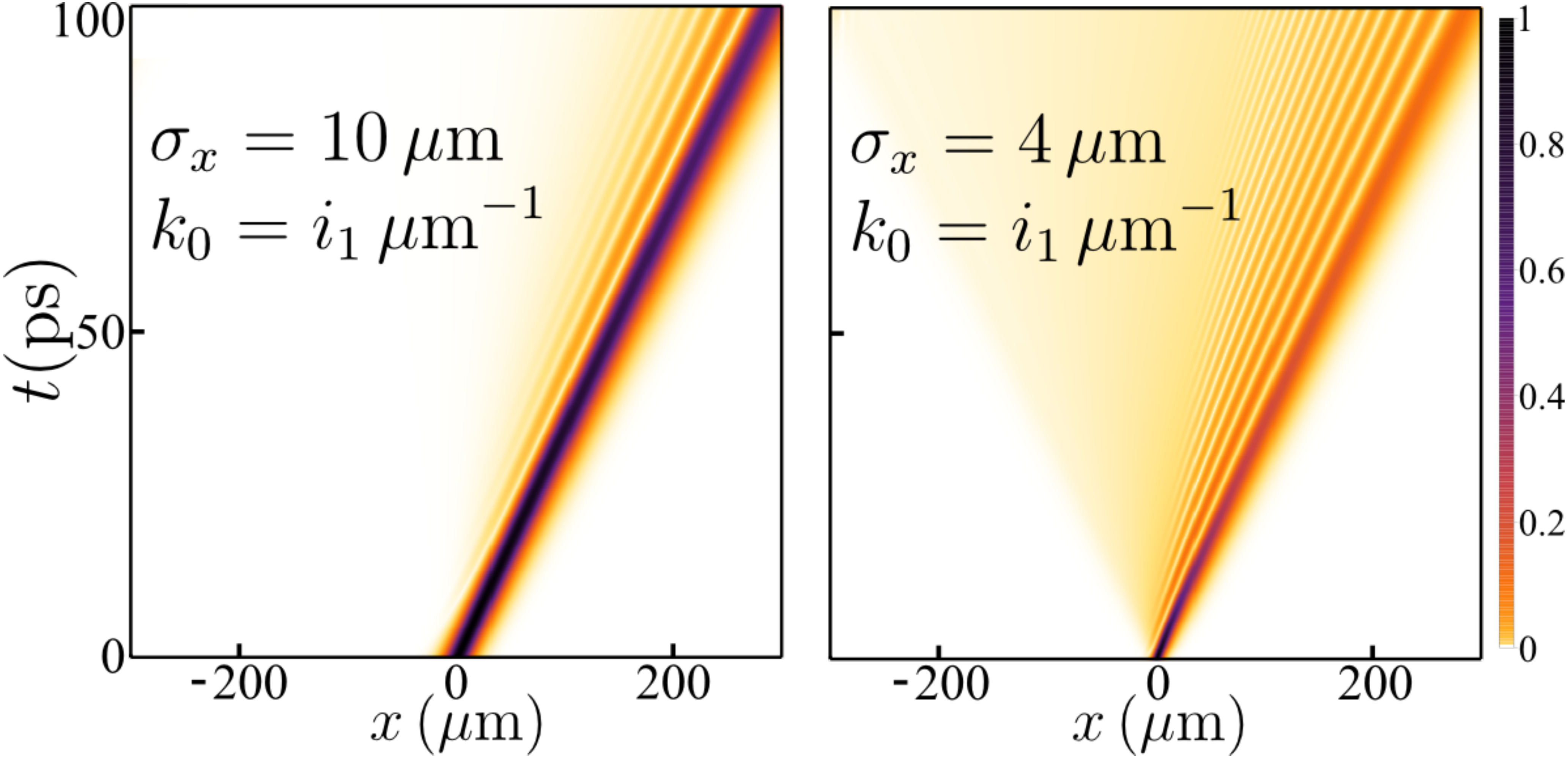


Inertial mass: $m_1(E,k) = \hbar^2 k(\partial_k E)^{-1}$

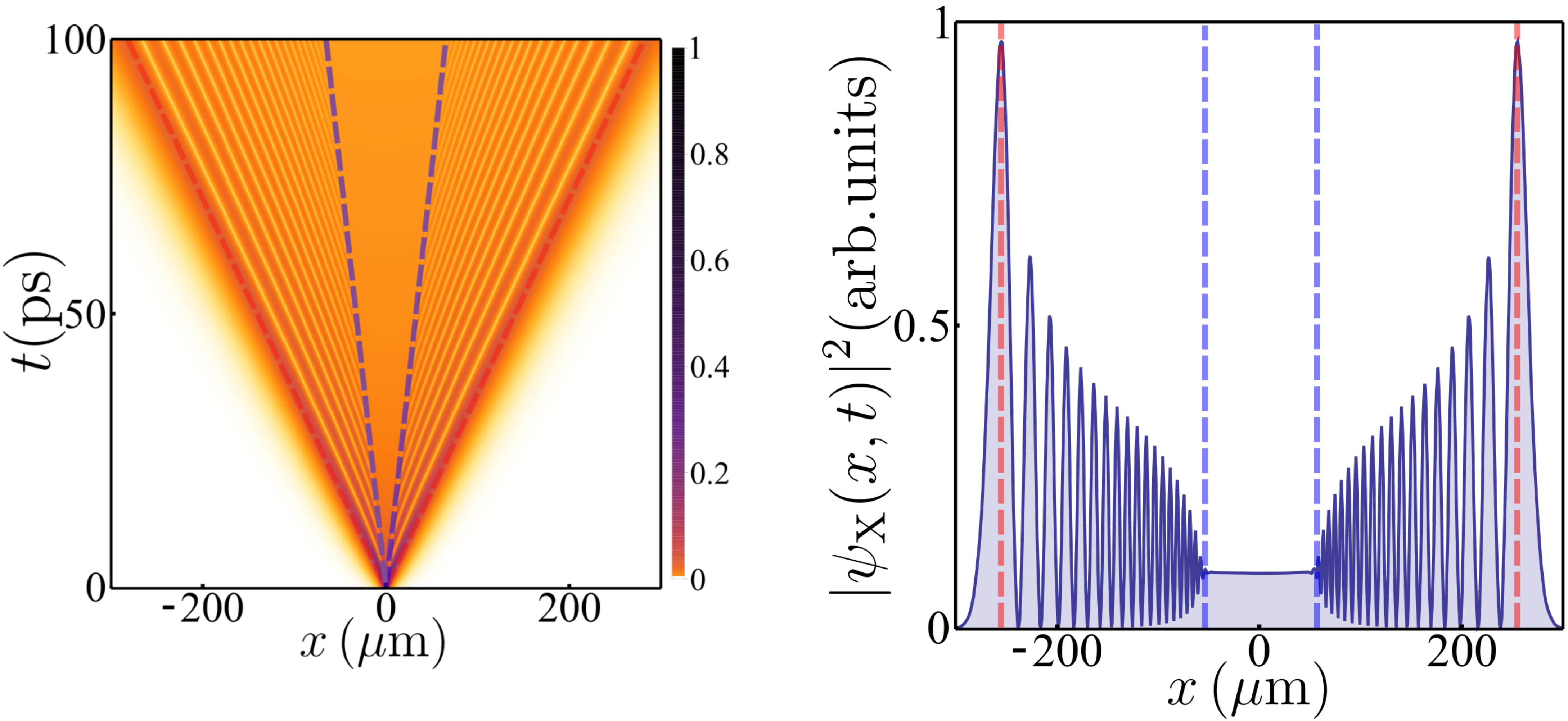
Diffusive mass: $m_2(E,k) = \hbar^2 (\partial_k^2 E)^{-1}$



$\sigma_x = 20\,\mu$m
$k_0 = 0\,\mu\text{m}^{-1}$
$\sigma_x = 20\,\mu$m
$k_0 = i_1\,\mu\text{m}^{-1}$
t(ps)
100
50
0
-200
0
200
x (μm)
-200
0
200
x (μm)
1
0.8
0.6
0.4
0.2
0



100
50
0
$t\,(\mathrm{ps})$
-200
0
200
$x\ (\mu m)$
$\sigma_x = 10\,\mu m$
$k_0 = i_1\,\mu m^{-1}$
-200
0
200
$x\ (\mu m)$
$\sigma_x = 4\,\mu m$
$k_0 = i_1\,\mu m^{-1}$
1
0.8
0.6
0.4
0.2
0

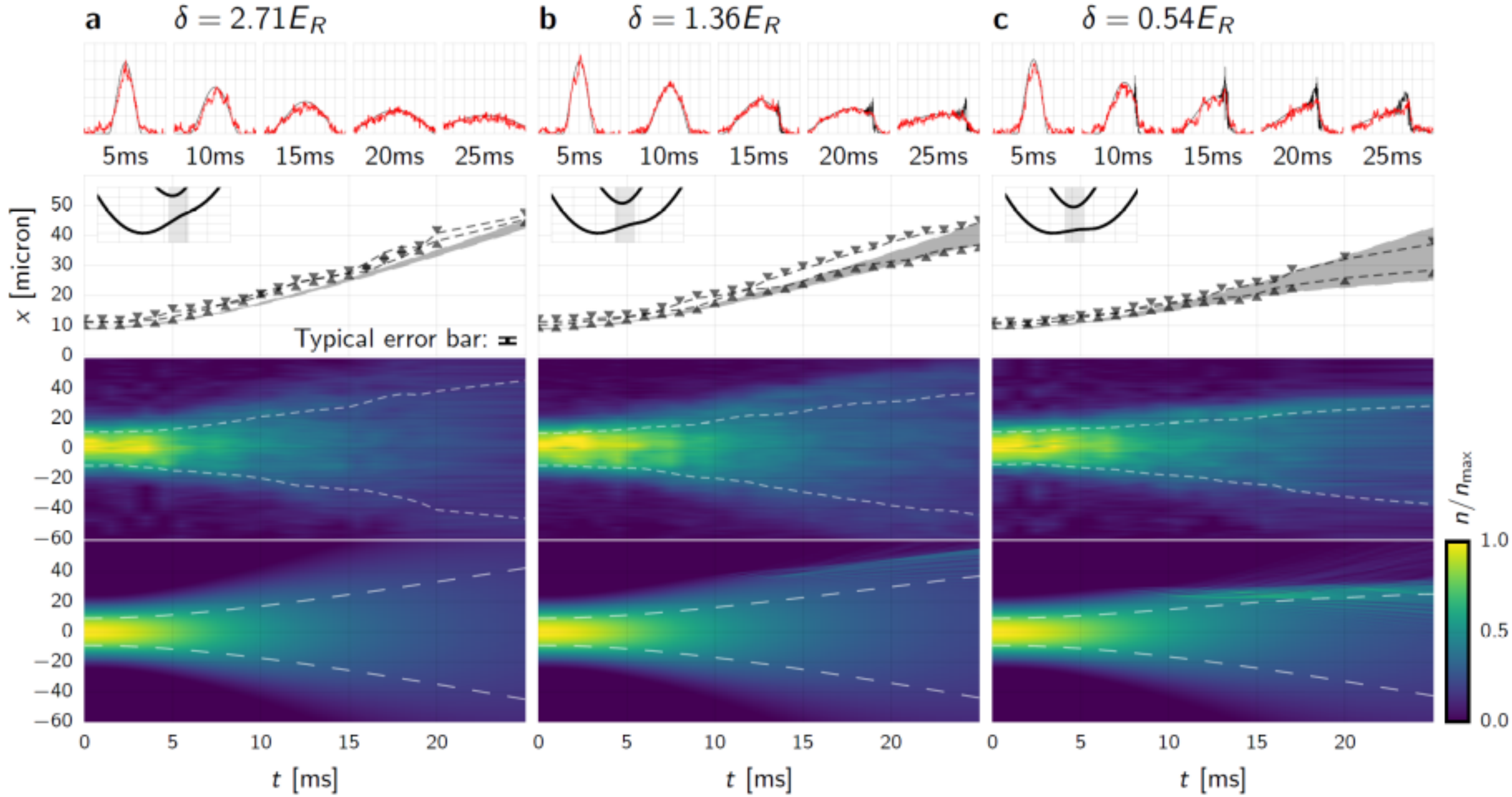


100
50
0
t(ps)
-200
0
200
x (μm)
1
0.8
0.6
0.4
0.2
0
1
0.5
0
|ψX(x, t)|2(arb.units)
-200
0
200
x (μm)

Negative-Mass Hydrodynamics in a Spin-Orbit–Coupled Bose-Einstein Condensate

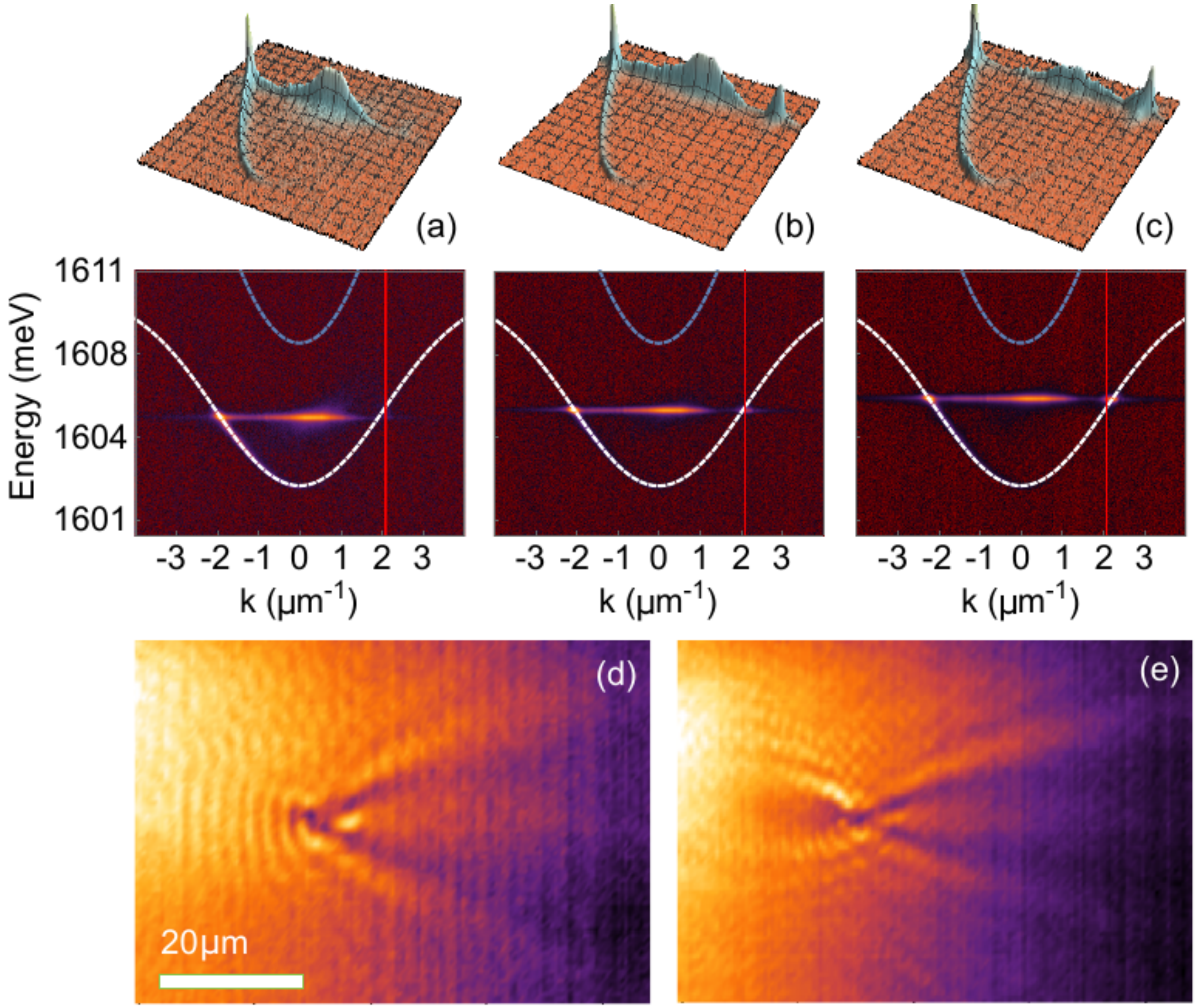
M. A. Khamehchi, Khalid Hossain, M. E. Mossman, Yongping Zhang, Th. Busch, Michael McNeil Forbes, and P. Engels

Phys. Rev. Lett. **118**, 155301 – Published 10 April 2017

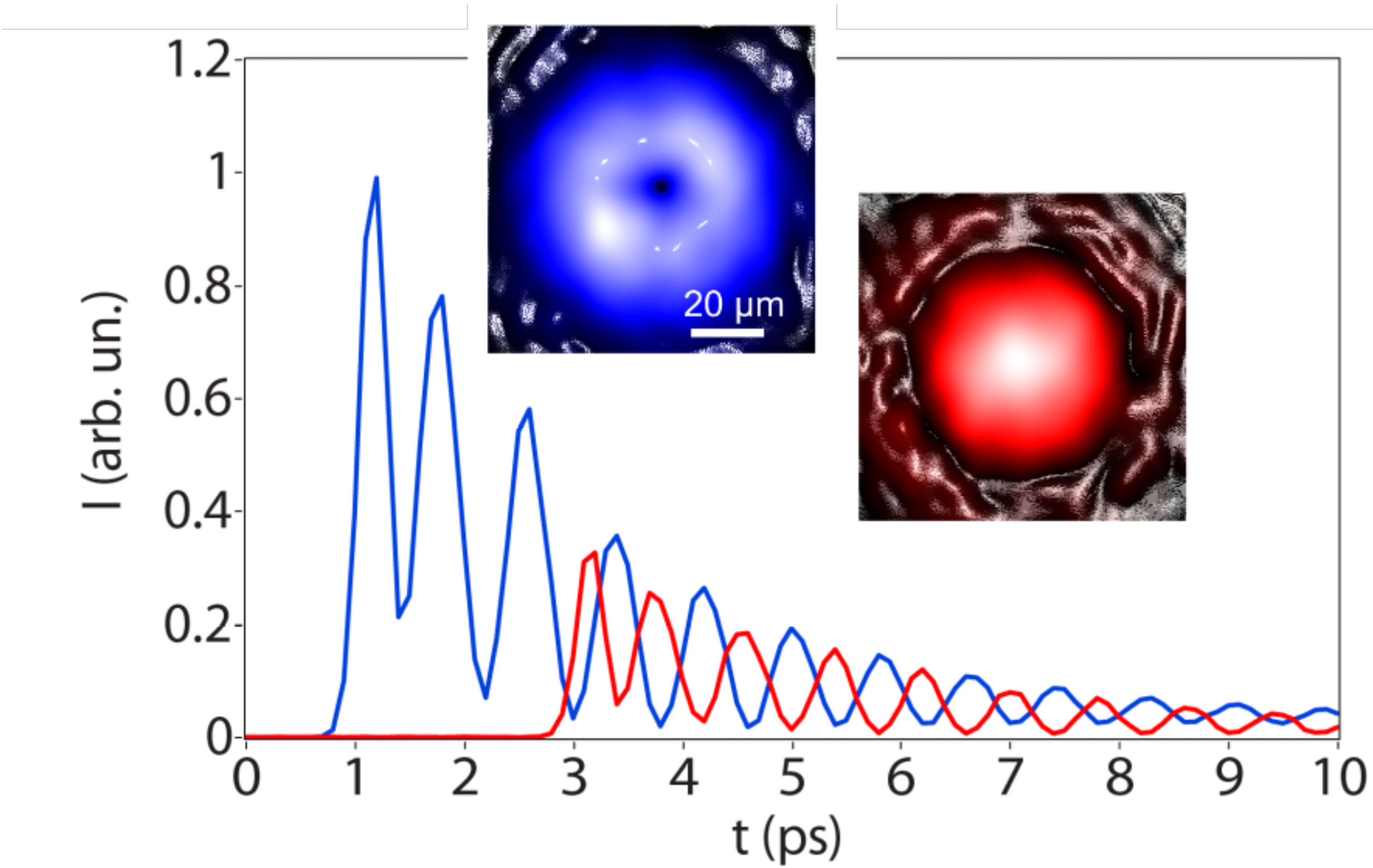


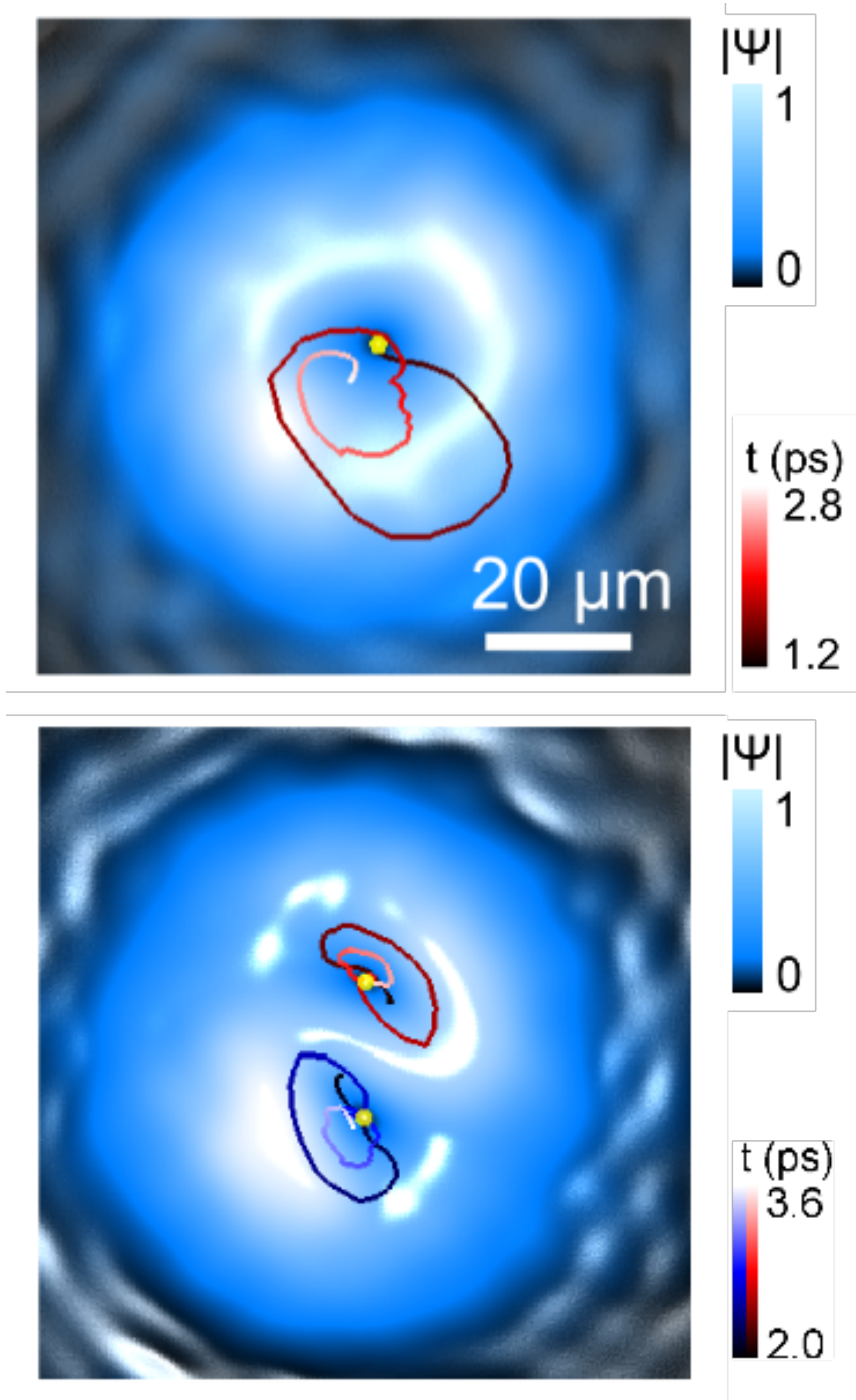
Formation of a macroscopically extended polariton condensate without an exciton reservoir

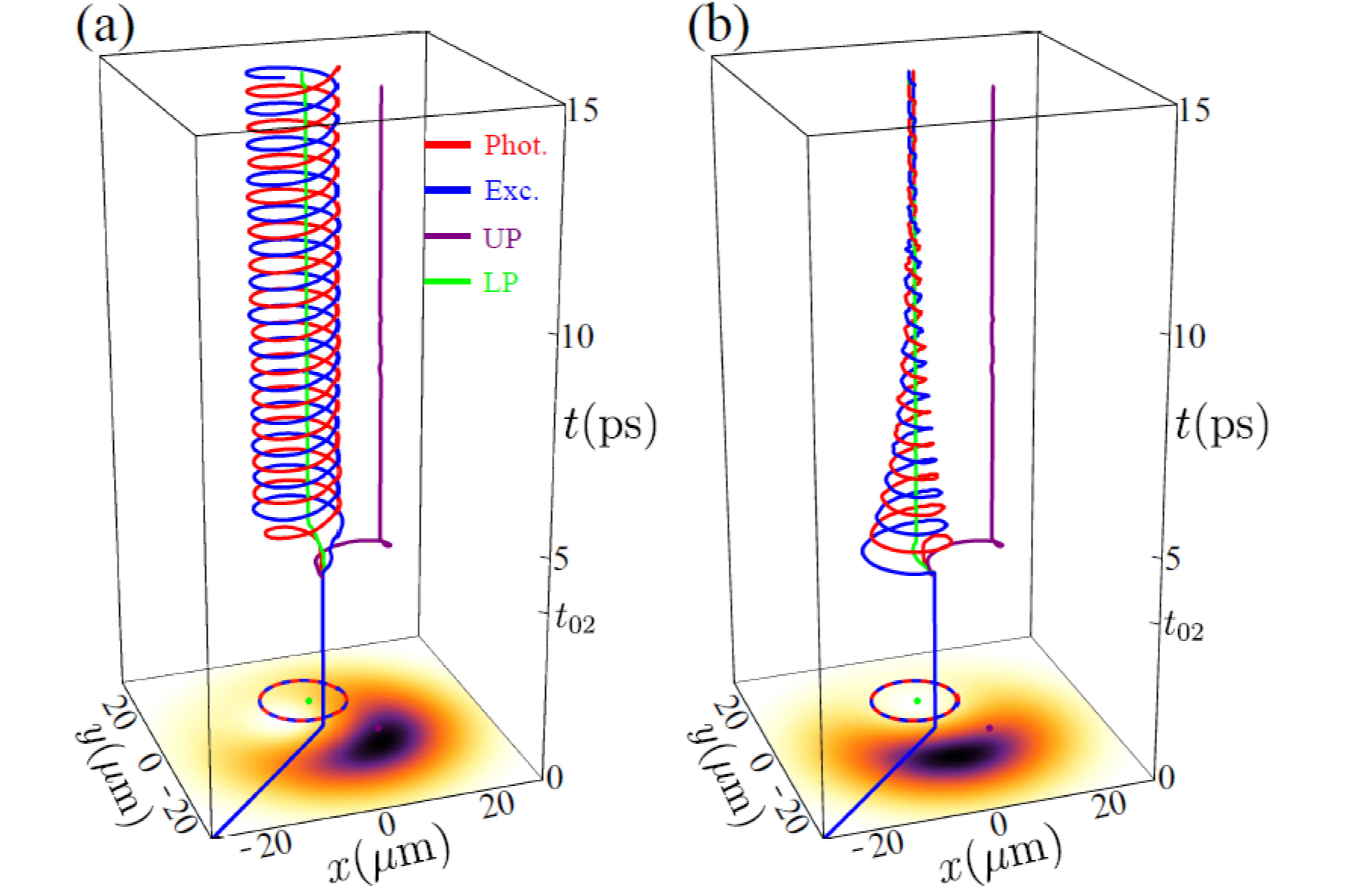
Dario Ballarini,[1] Davide Caputo,[1,2] Carlos Sánchez Muñoz,[3] Milena De Giorgi,[1]
Lorenzo Dominici,[1] Marzena H. Szymańska,[4] Kenneth West,[5] Loren N. Pfeiffer,[5]
Giuseppe Gigli,[1,2] Fabrice P. Laussy,[3,6] and Daniele Sanvitto[1]

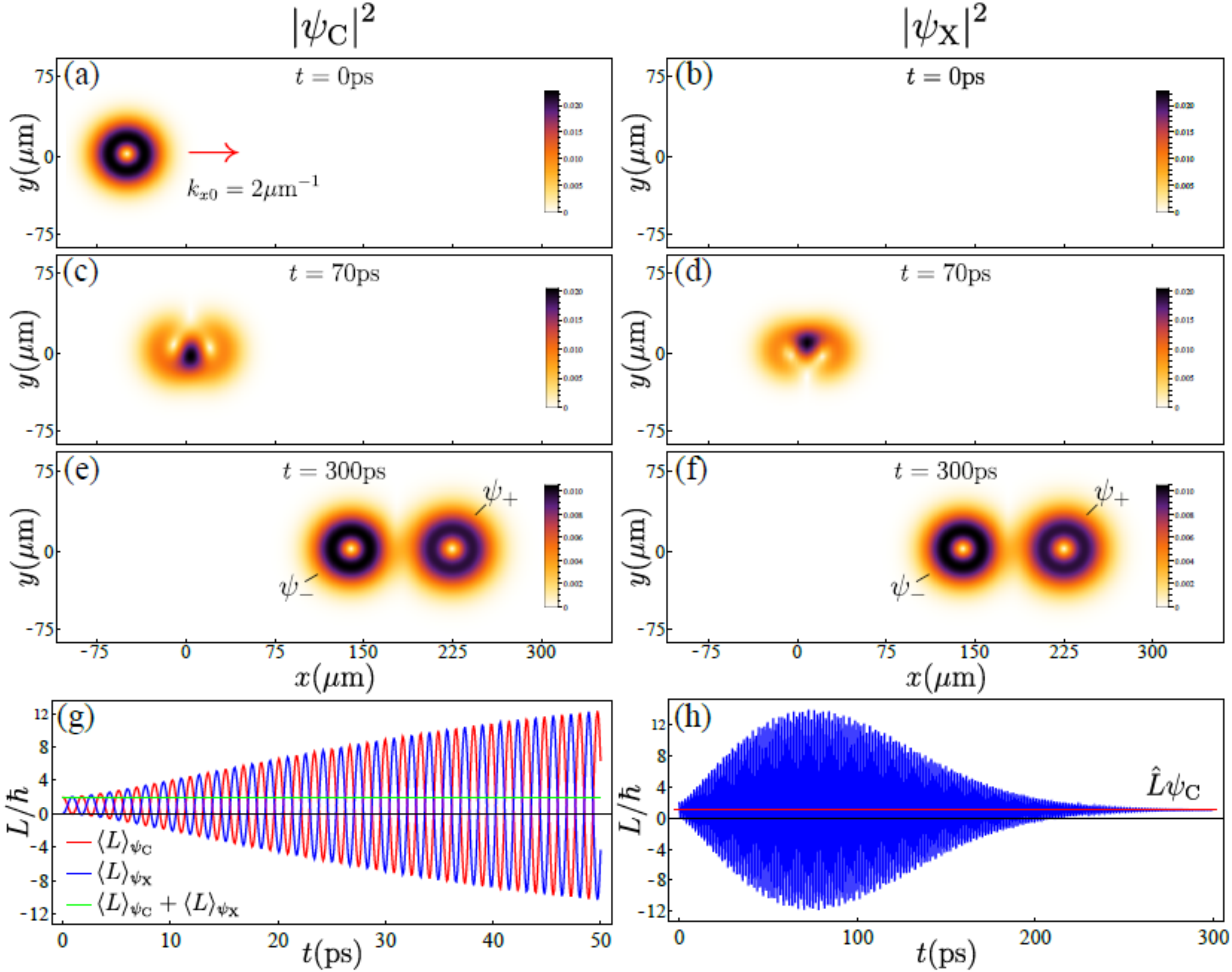


Rabi Oscillations with vortices.

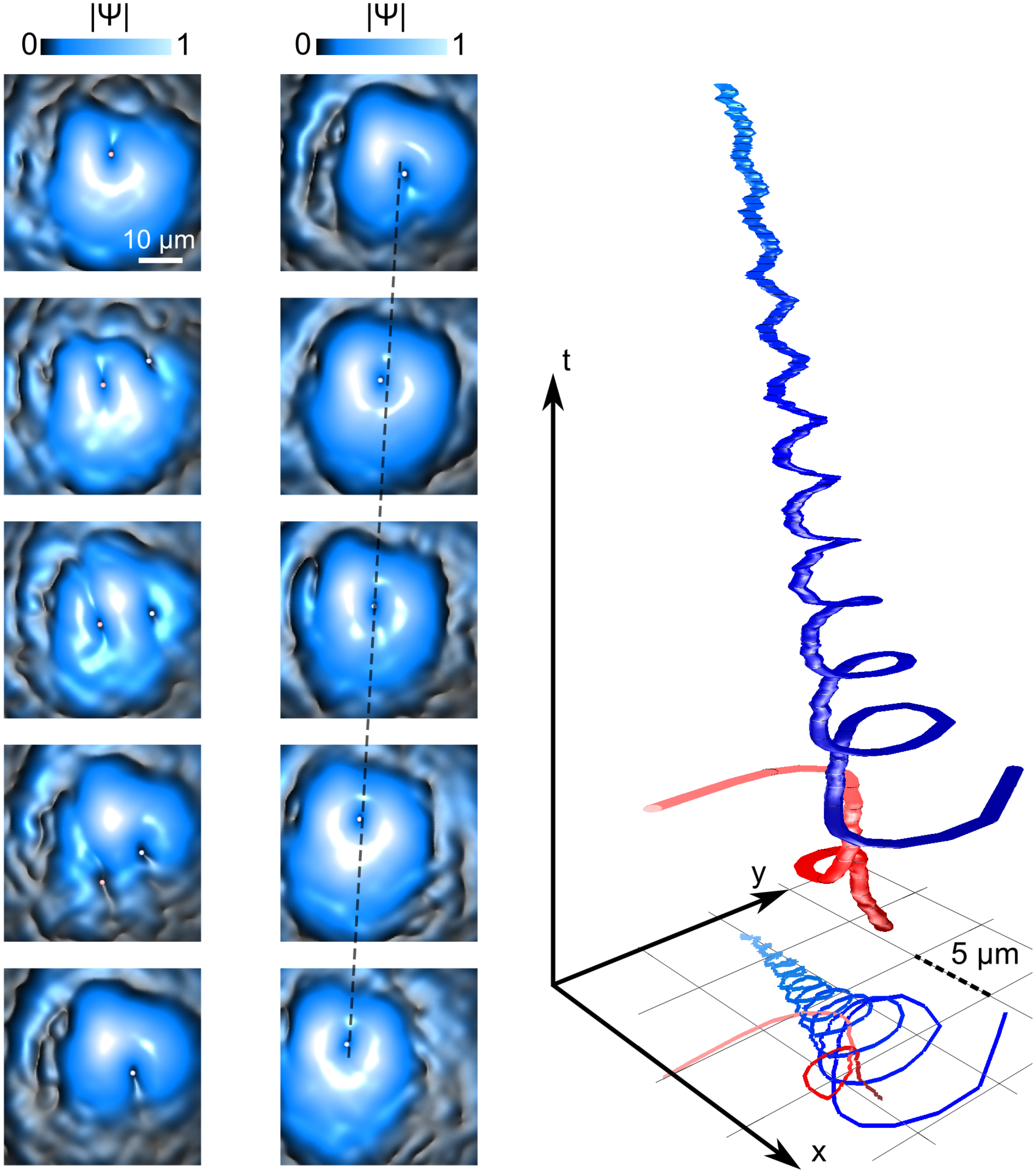



|Ψ|
1
0
t (ps)
2.8
1.2
20 μm
|Ψ|
1
0
t (ps)
3.6
2.0


(a)
(b)
Phot.
Exc.
UP
LP
15
10
5
t_{02}
0
t(ps)
20
0
-20
$y(\mu m)$
-20
0
20
$x(\mu m)$



$|\psi_C|^2$
$|\psi_X|^2$
(a)
$t = 0$ps
$k_{x0} = 2\mu$m$^{-1$}
(b)
$t = 0$ps
(c)
$t = 70$ps
(d)
$t = 70$ps
(e)
$t = 300$ps
ψ_+
ψ_-
(f)
$t = 300$ps
ψ_+
ψ_-
$y(\mu m)$
$x(\mu m)$
(g)
$\langle L\rangle_{\psi_C}$
$\langle L\rangle_{\psi_X}$
$\langle L\rangle_{\psi_C} + \langle L\rangle_{\psi_X}$
$L/\hbar$
t(ps)
(h)
$\hat{L}\psi_C$


|Ψ|
0
1
|Ψ|
0
1
10 μm
t
y
x
5 μm

Rabi Oscillations when not alone...

Conclusions:

We have seen that there is a rich polariton physics due to the light-matter coupling (Rabi oscillations) when in conjonction with other equally simple ingredients (i.e., not requiring strongly-correlated physics of interacting gases).

We have considered i) dissipation, ii) polarization, iii) phase-dynamics, iv) momentum and v) vorticity.

And there still remains much to explore with these only.