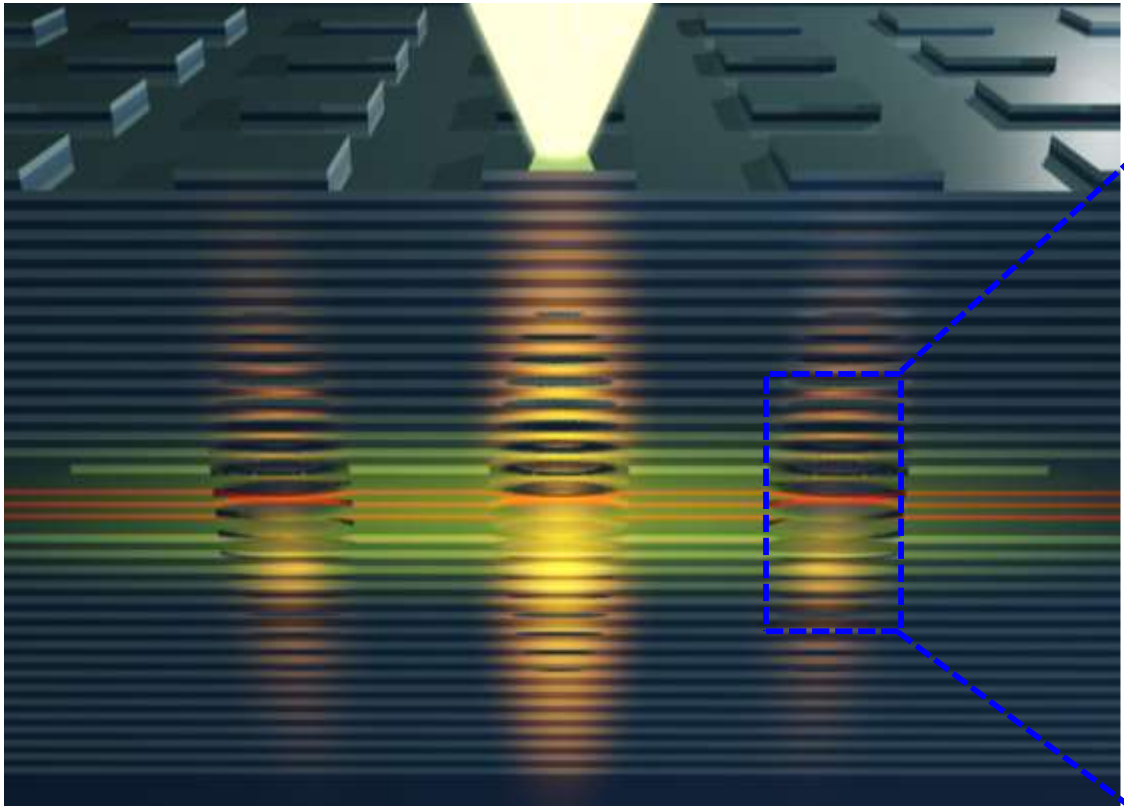
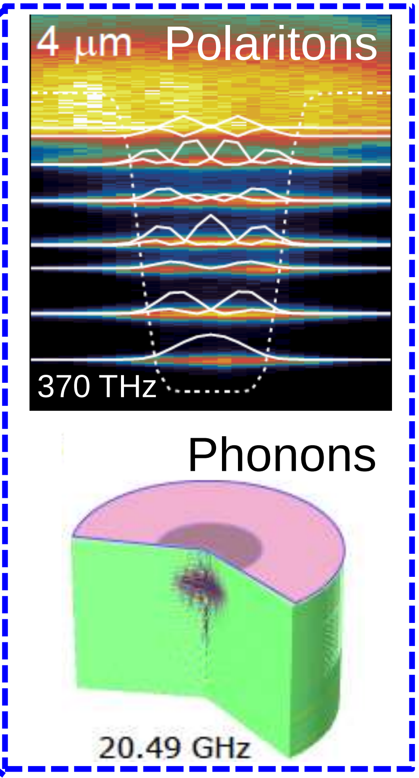
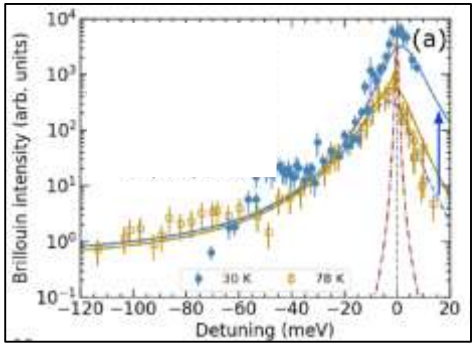
Cavity Optomechanics with Polariton Fluids

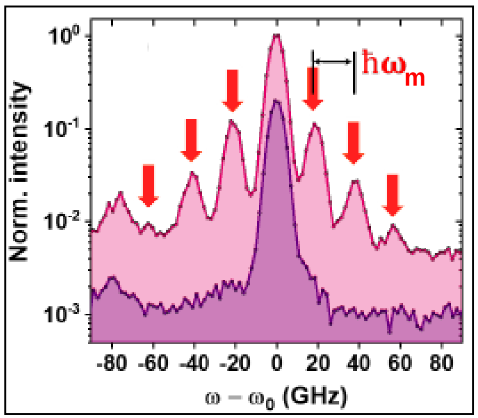
Alex Fainstein

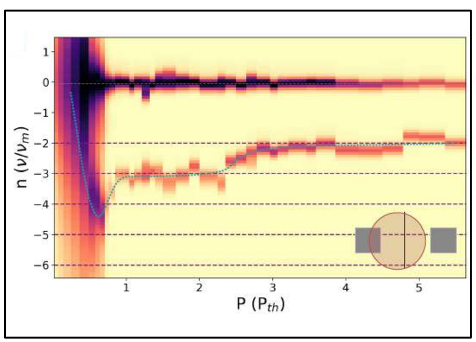




Index







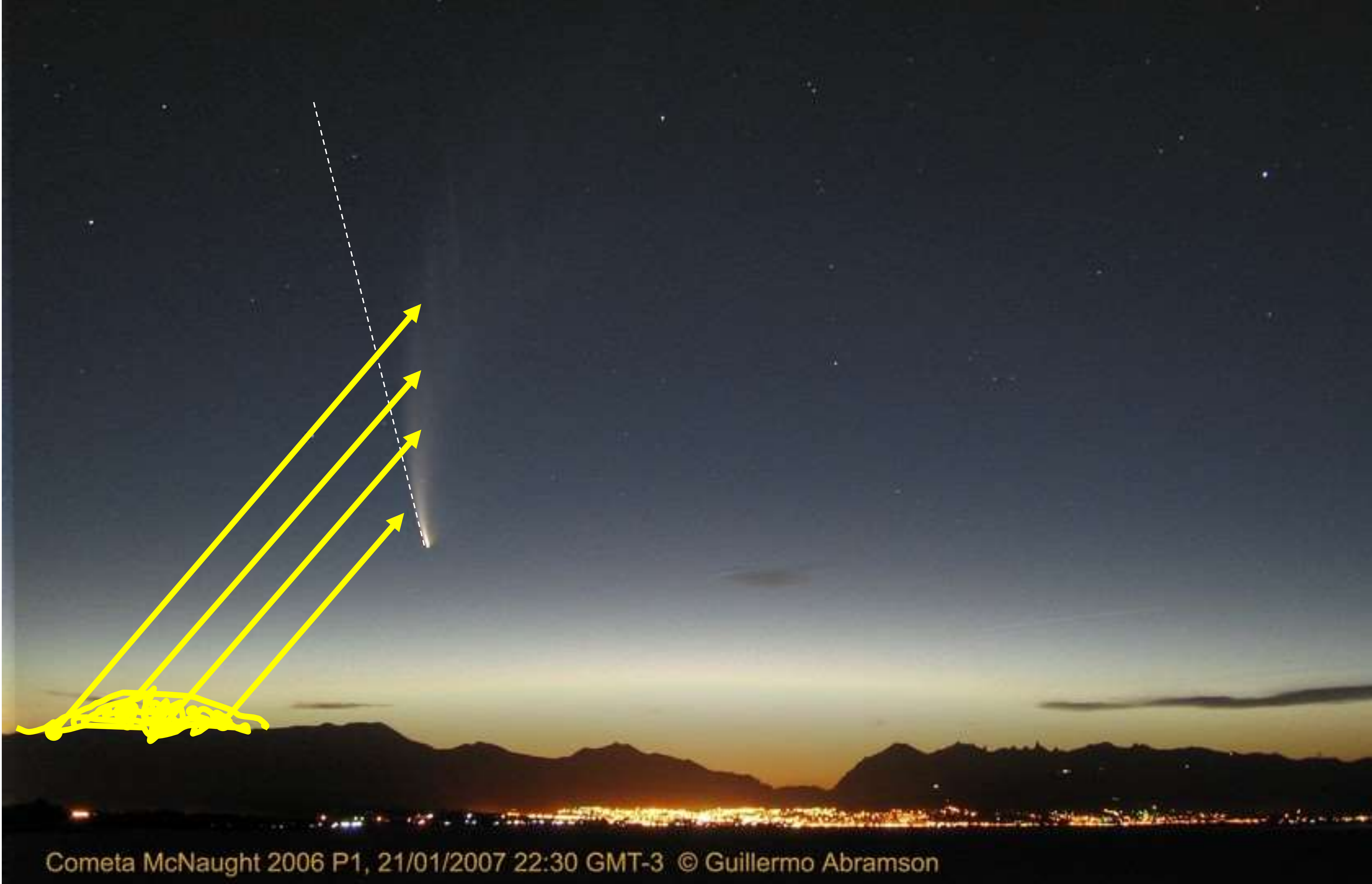
- **Day #1: cavity polaritons**, resonant exciton mediated optomechanical interaction

- **Day #2: self-oscillation**, the optomechanical parametric oscillator

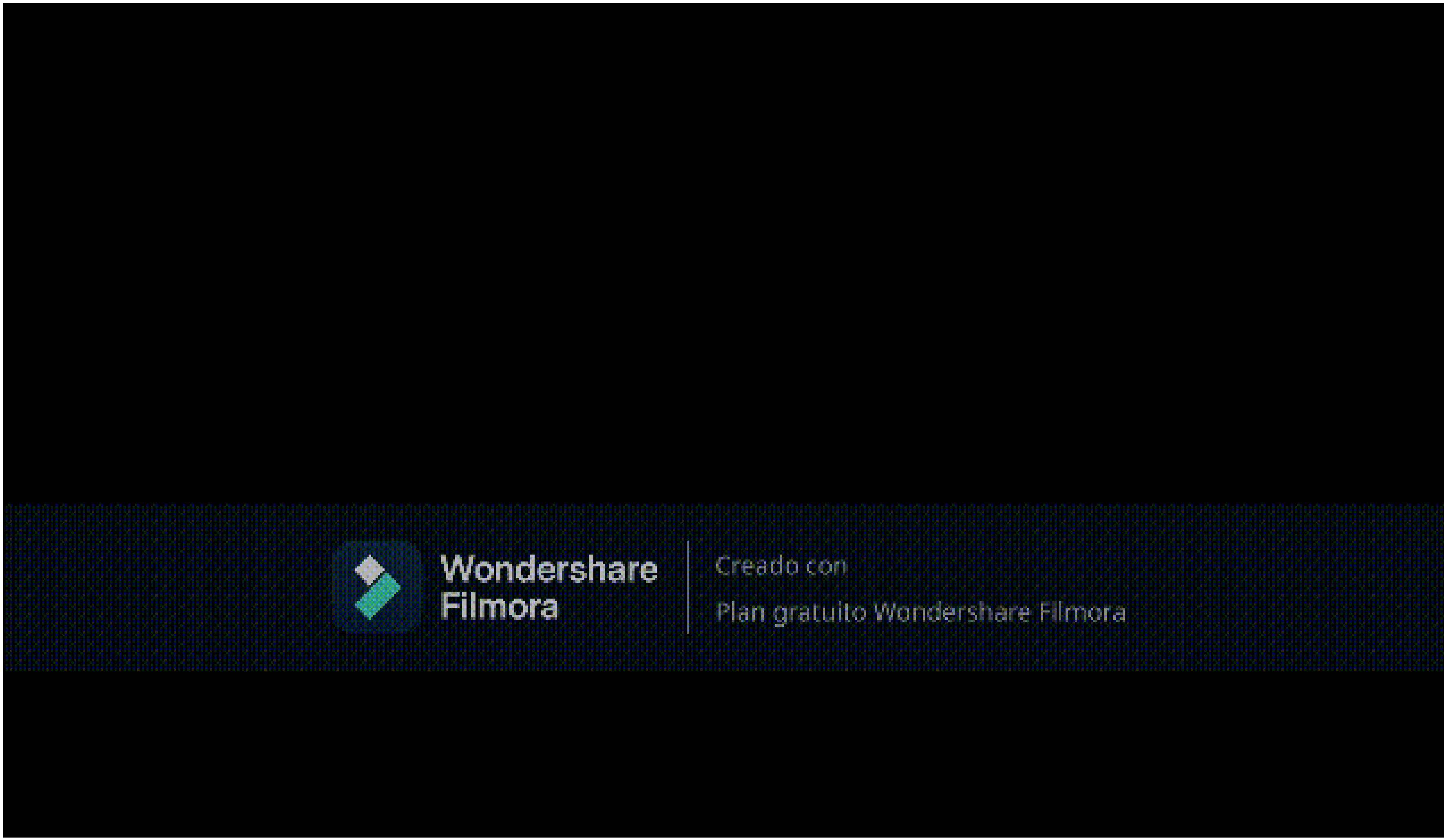
- **Day #3: synchronization,** OM asynchronous locking of polariton states

Bonus: Friday talk, time crystals

How light excerts force on matter
(but does matter act-back on light?)

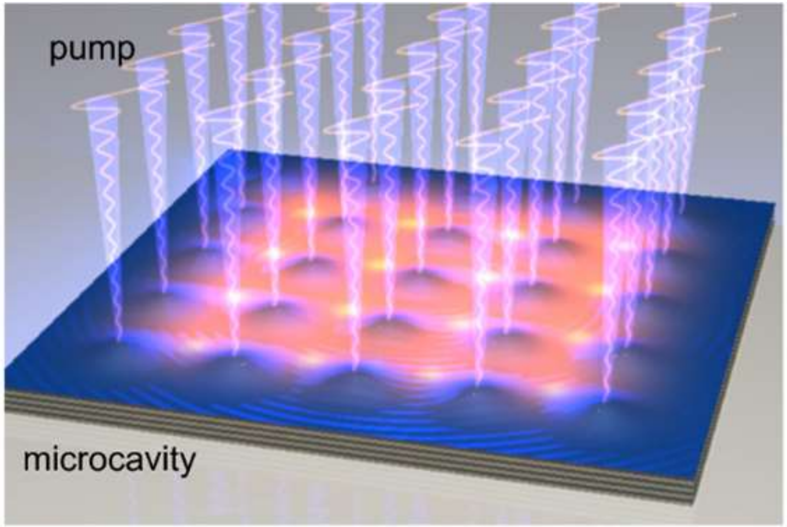


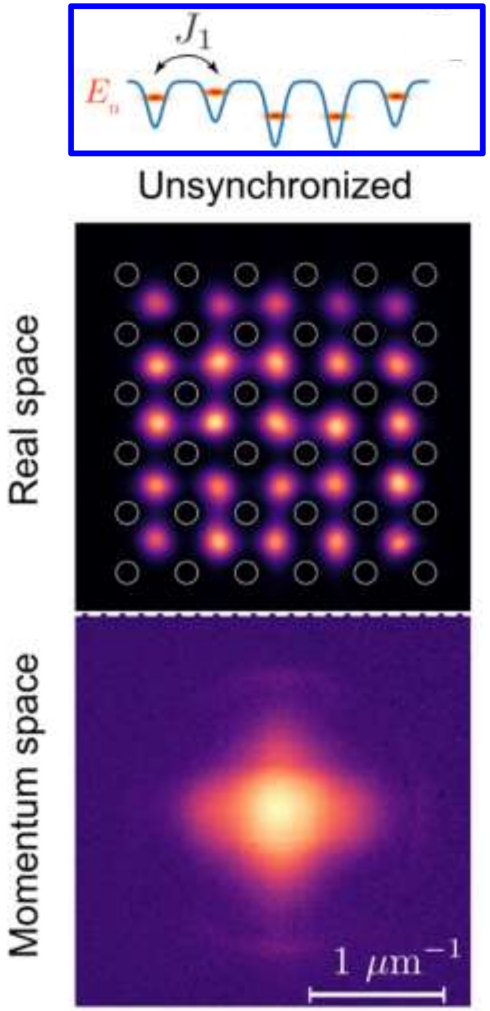
Synchronization



Synchronization of polariton condensates

Arrays of condensates

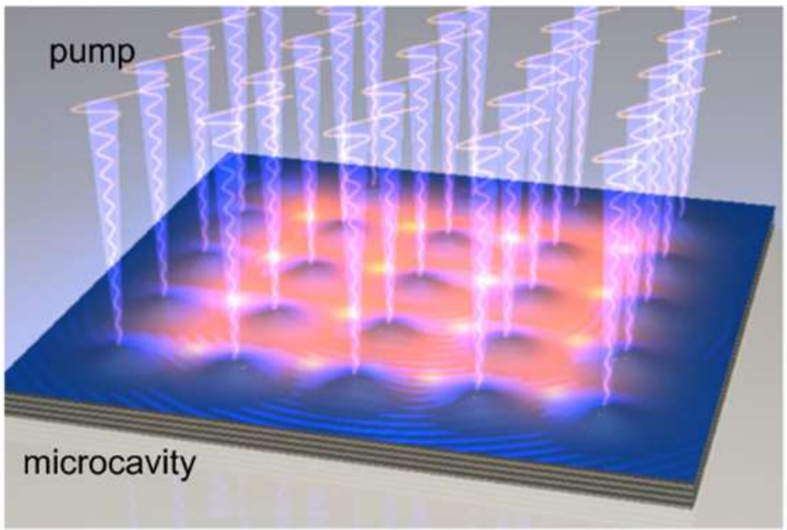


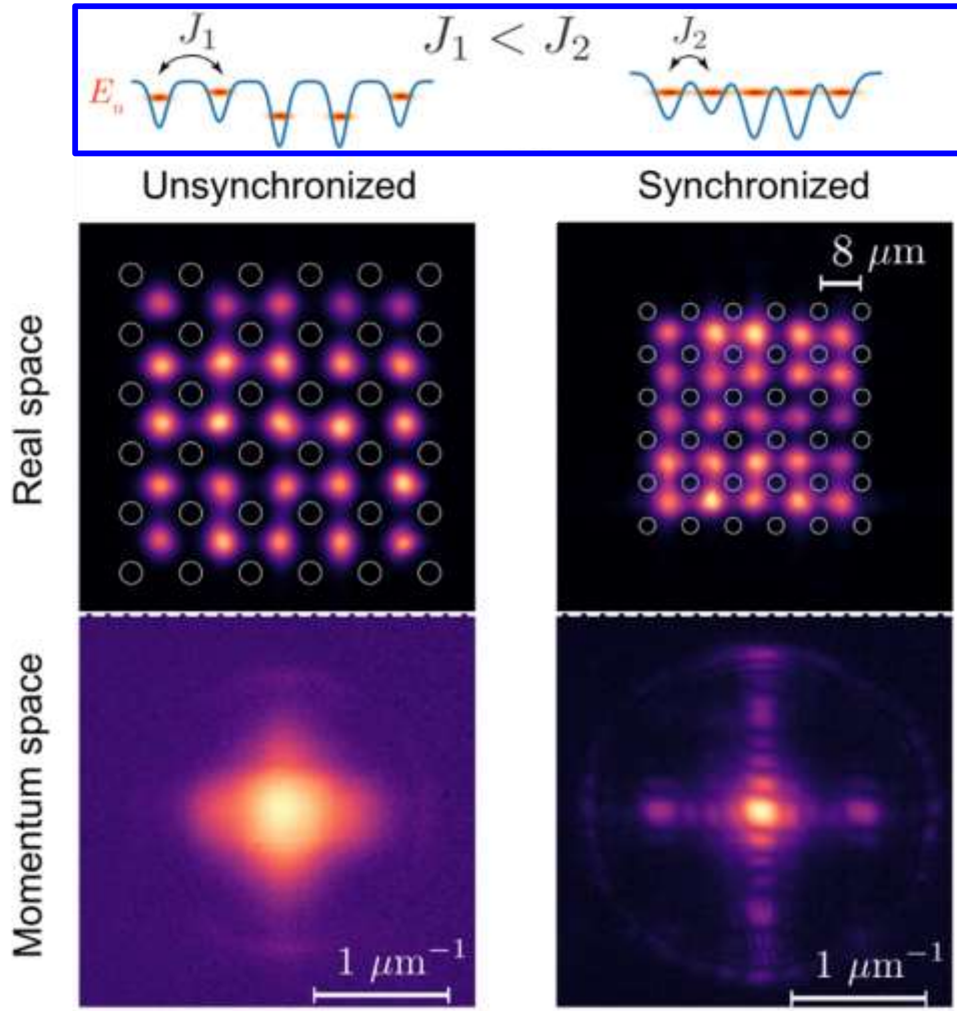


H. Ohadi et al, Phys. Rev. B **97**, 195109 (2018)

Synchronization of polariton condensates

Arrays of condensates





H. Ohadi et al, Phys. Rev. B **97**, 195109 (2018)

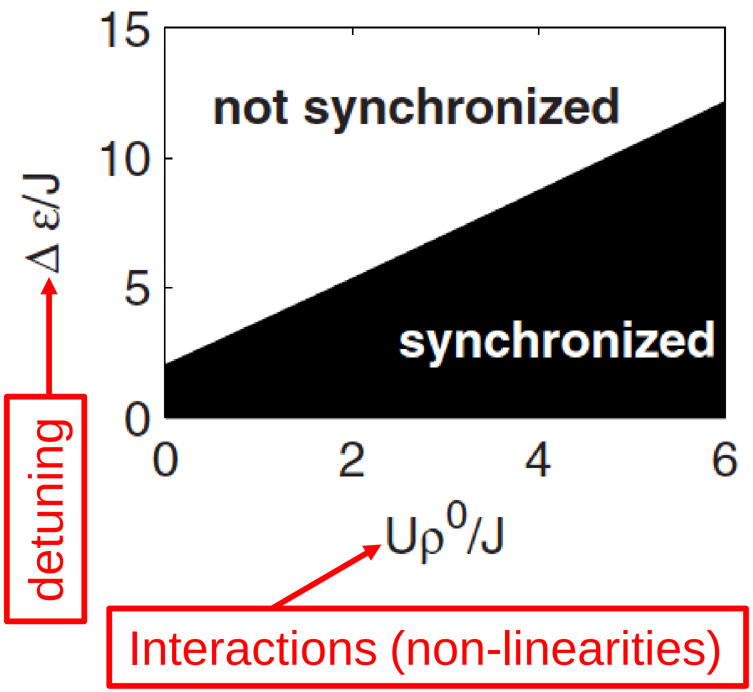
Synchronization of polariton condensates

PHYSICAL REVIEW B 77, 121302(R) (2008)

Synchronized and desynchronized phases of coupled nonequilibrium exciton-polariton condensates

Michiel Wouters

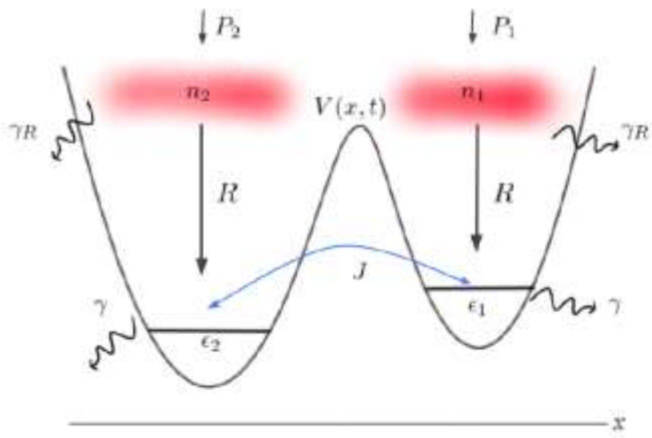
+ Paul R. Eastham, PRB **78**, 035319 (2008)



INGREDIENTS:

- Two coupled condensates
- Detuned by $\Delta\varepsilon$
- Coupled by J
- With interactions U
- And with dissipation!!

Synchronization of polariton condensates



$$i\hbar\dot{\psi}_j = (\varepsilon_j + U_j|\psi_j|^2 + U_j^{\mathrm{R}} n_j)\psi_j - J\psi_{3-j} + \\ + \frac{i\hbar}{2}(R\,n_j - \gamma)\psi_j\,,$$

← TWO CONDENSATES

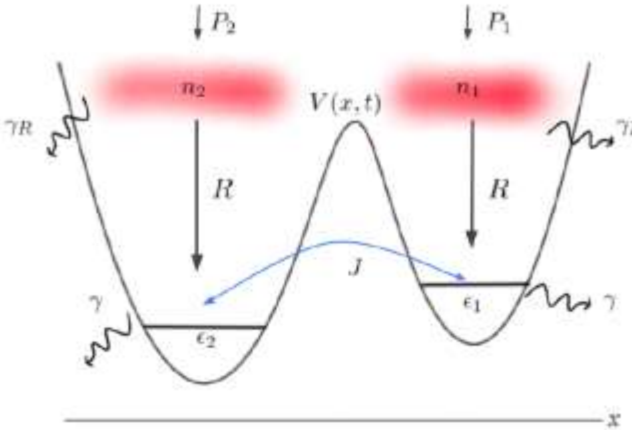
$$\dot{n}_j = P_j - \gamma_{\mathrm{R}}\, n_j - R|\psi_j|^2 n_j\,.$$

← RESERVOIR

J is constant

I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

Synchronization of polariton condensates



$$i\hbar\dot{\psi}_j = (\varepsilon_j + U_j|\psi_j|^2 + U_j^{\mathrm{R}} n_j)\psi_j - J\psi_{3-j} + \\ + \frac{i\hbar}{2}(R n_j - \gamma)\psi_j\,,$$

$$\dot{n}_j = P_j - \gamma_{\mathrm{R}}\, n_j - R|\psi_j|^2 n_j\,.$$

J is constant

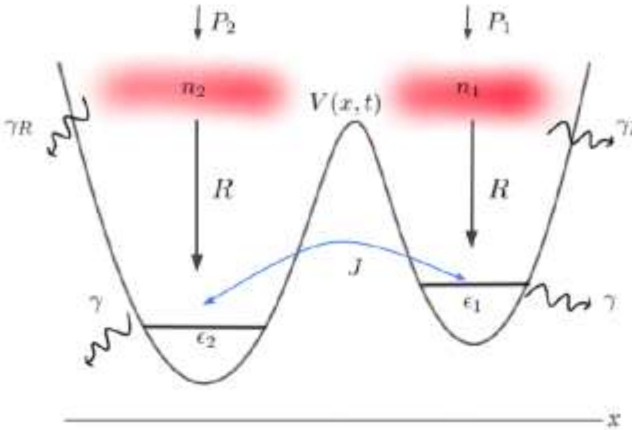
$$\psi_j = \sqrt{N_j}e^{i\theta_j}$$

$$z(t) = \frac{N_1(t) - N_2(t)}{N_0}$$

$$\phi(t) = \theta_1(t) - \theta_2(t)$$

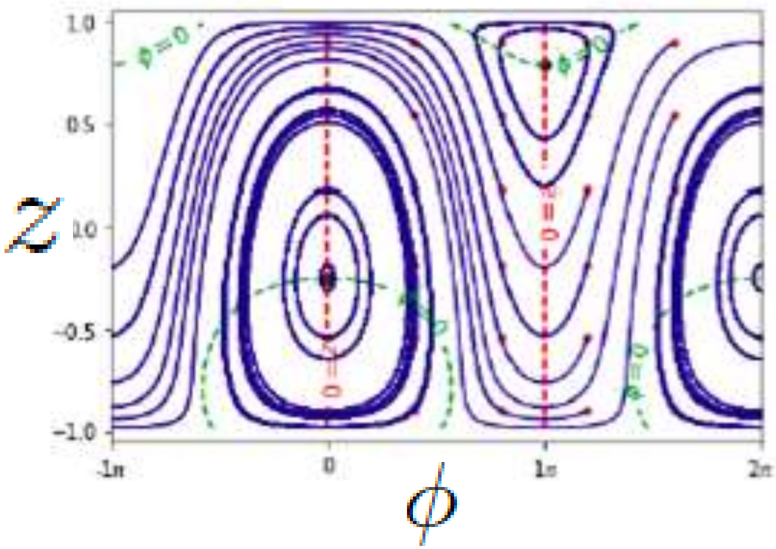
I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

The model: WITHOUT dissipation



$$z(t) = \frac{N_1(t) - N_2(t)}{N_0}$$

$$\phi(t) = \theta_1(t) - \theta_2(t)$$



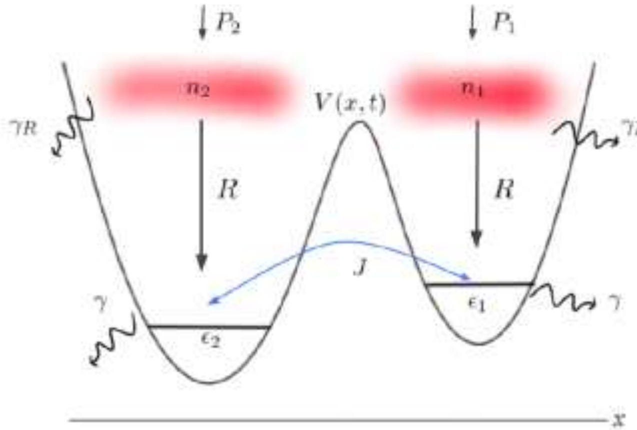
RABI &
JOSEPHSON
OSCILLATIONS

\+

SELF-TRAPPING

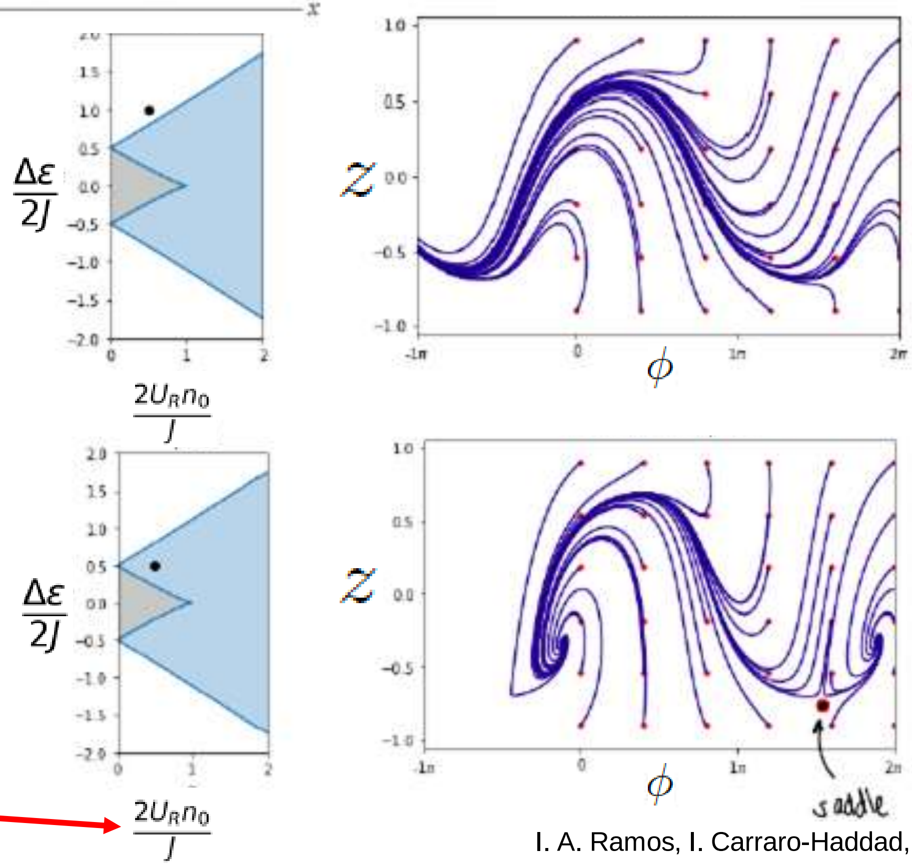
I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

The model: WITH dissipation



$$z(t) = \frac{N_1(t) - N_2(t)}{N_0}$$

$$\phi(t) = \theta_1(t) - \theta_2(t)$$

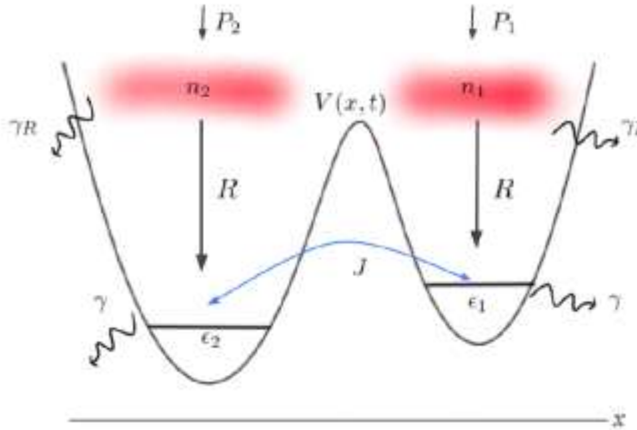


detuning

Interactions

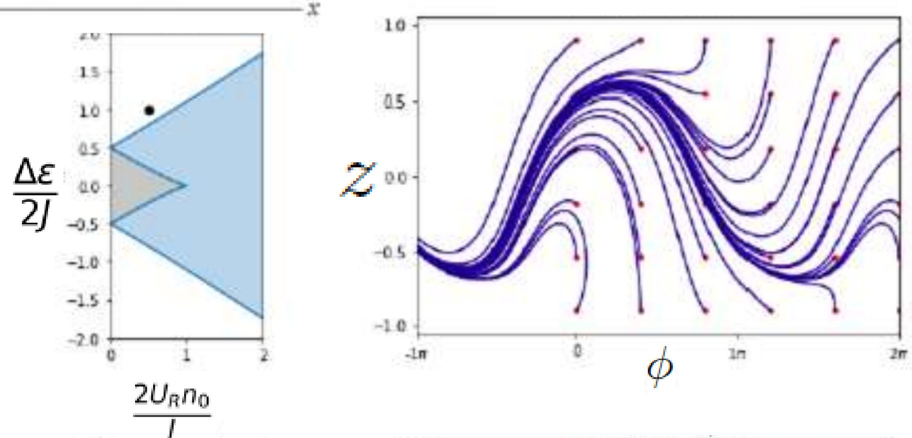
I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

The model: WITH dissipation

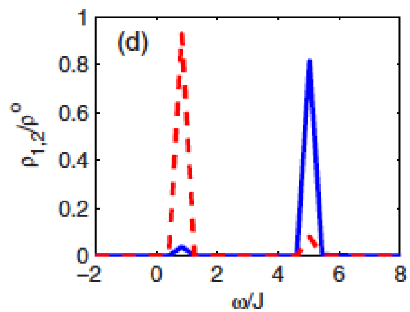


$$z(t) = \frac{N_1(t) - N_2(t)}{N_0}$$

$$\phi(t) = \theta_1(t) - \theta_2(t)$$

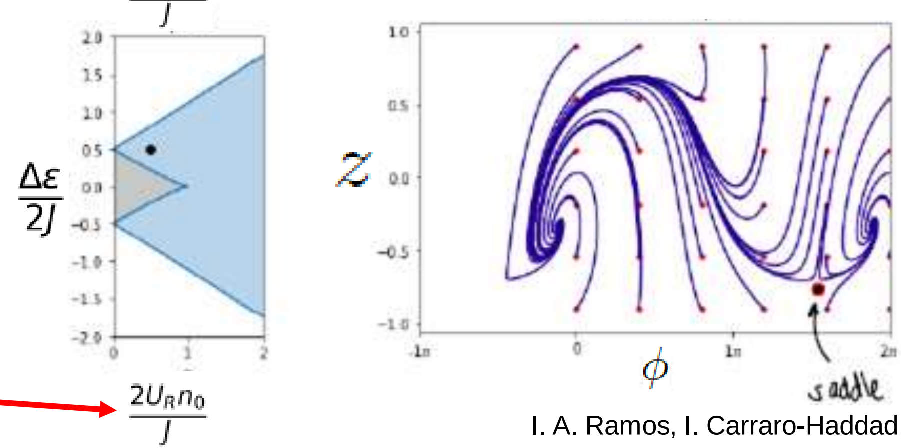


LIMIT CYCLE



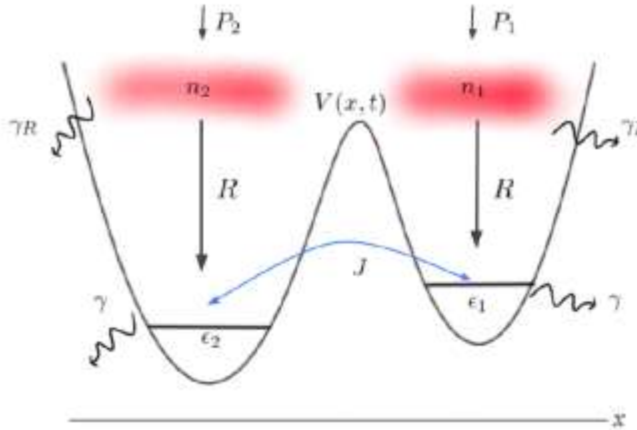
detuning

Interactions



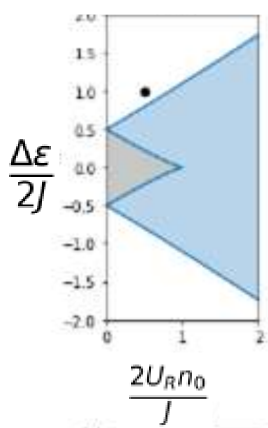
I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

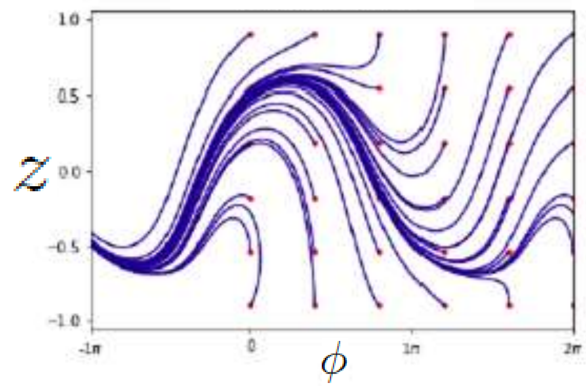
The model: WITH dissipation



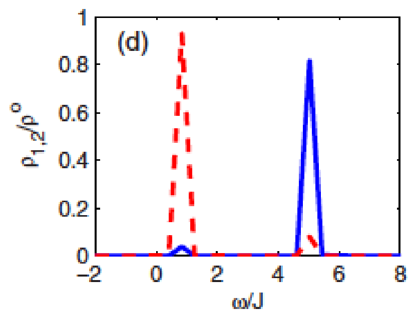
$$z(t) = \frac{N_1(t) - N_2(t)}{N_0}$$

$$\phi(t) = \theta_1(t) - \theta_2(t)$$

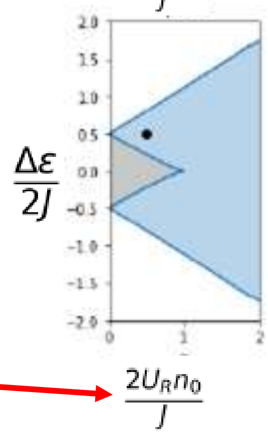




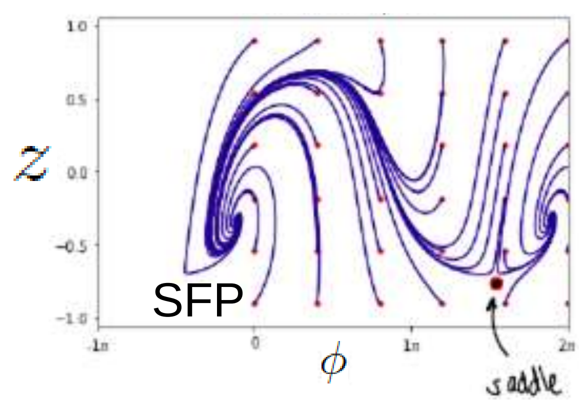
LIMIT CYCLE



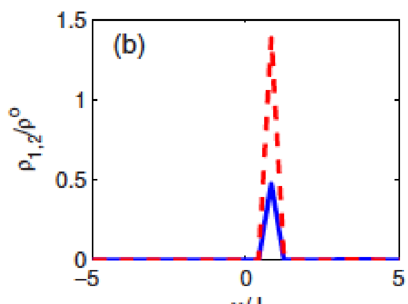
detuning



Interactions

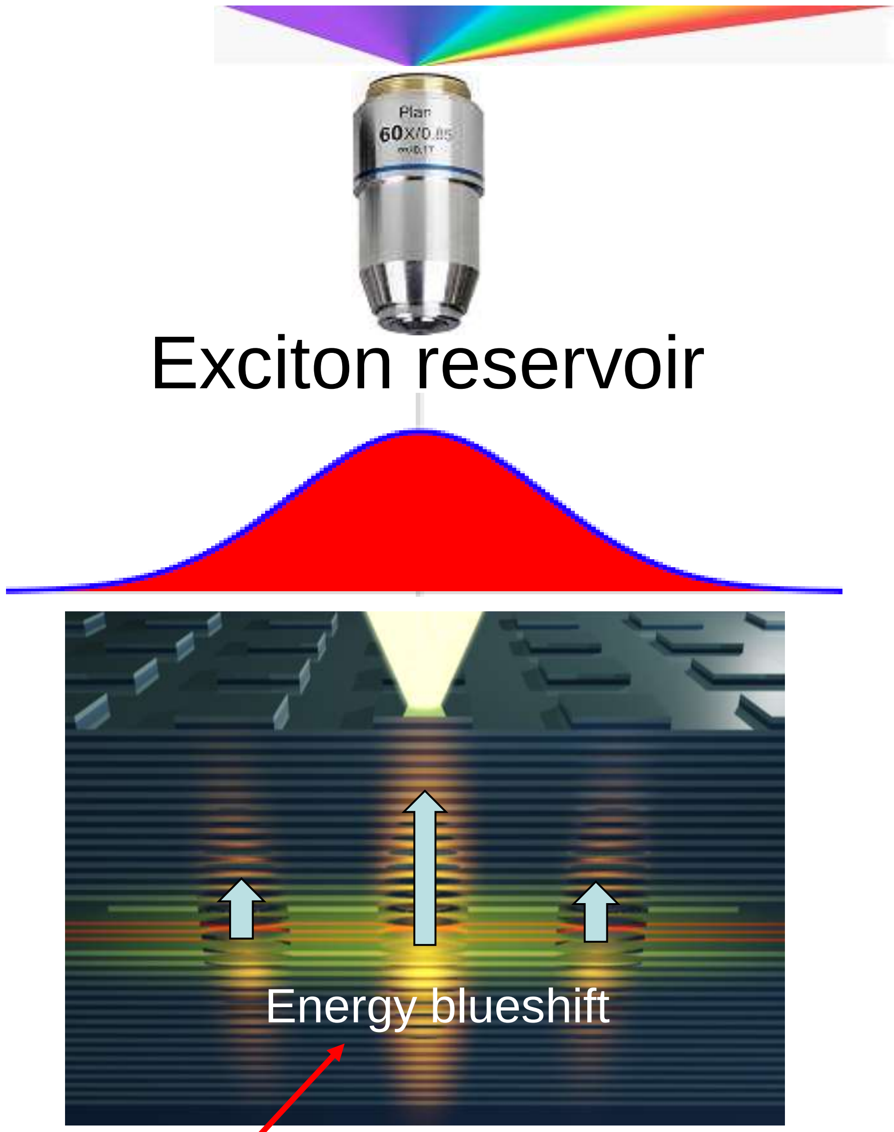


SYNCHRONIZATION



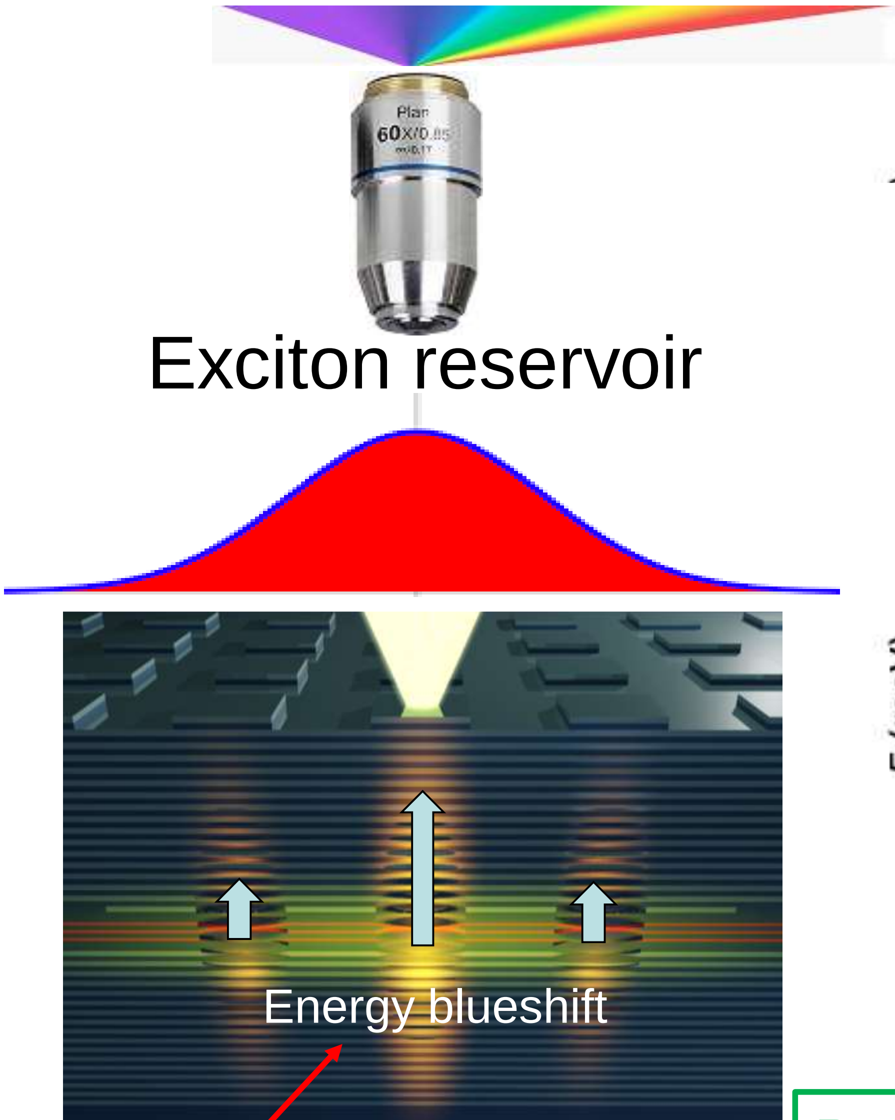
I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

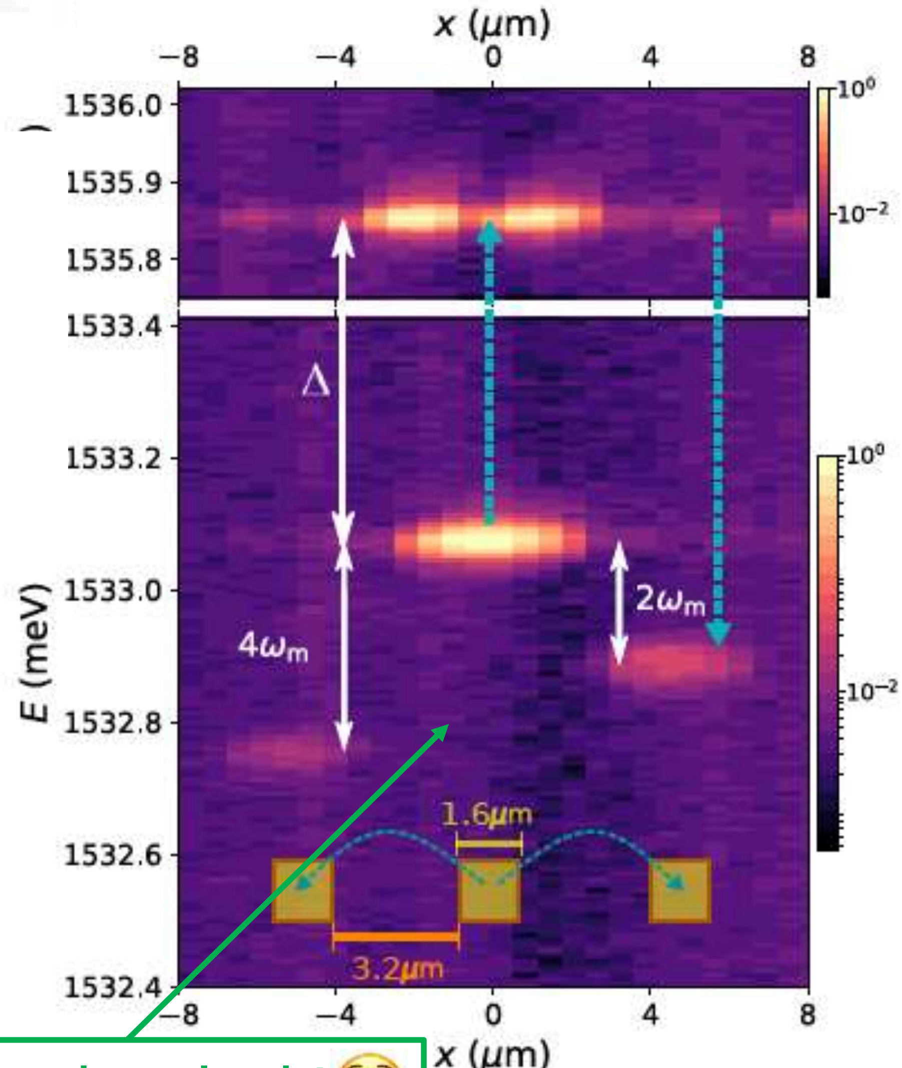
Synchronization: **our** experiments



We strongly detune the traps

Asynchronous locking



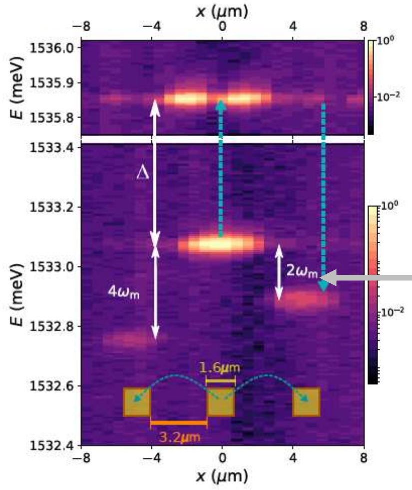


We strongly detune the traps

But they lock! 😲

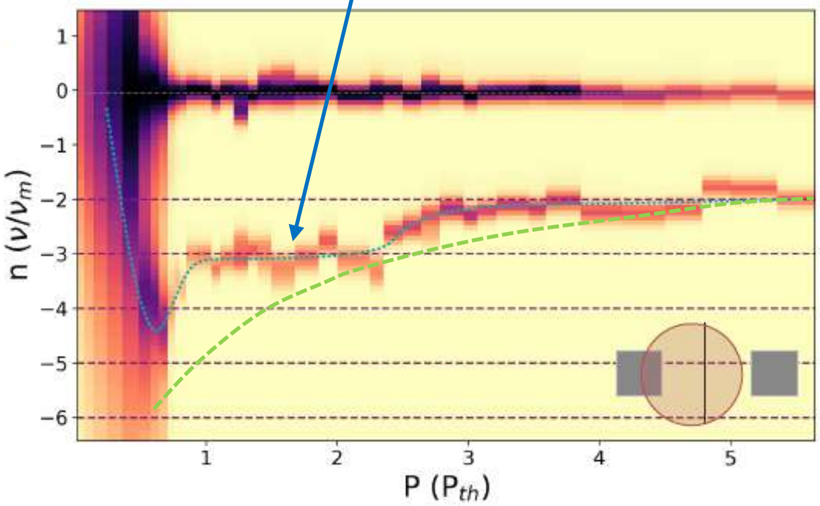
D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

Asynchronous locking: power dependence

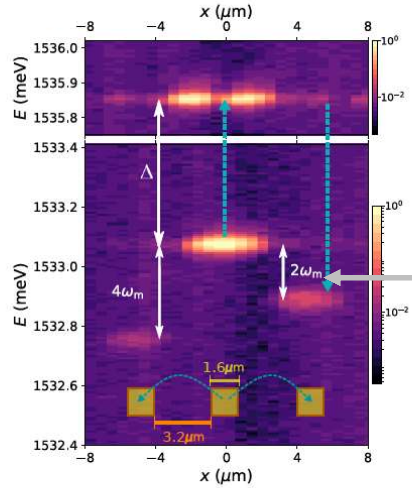


Laser power dependence of detuning

Steps (locking) at integer numbers n of ω_m !!

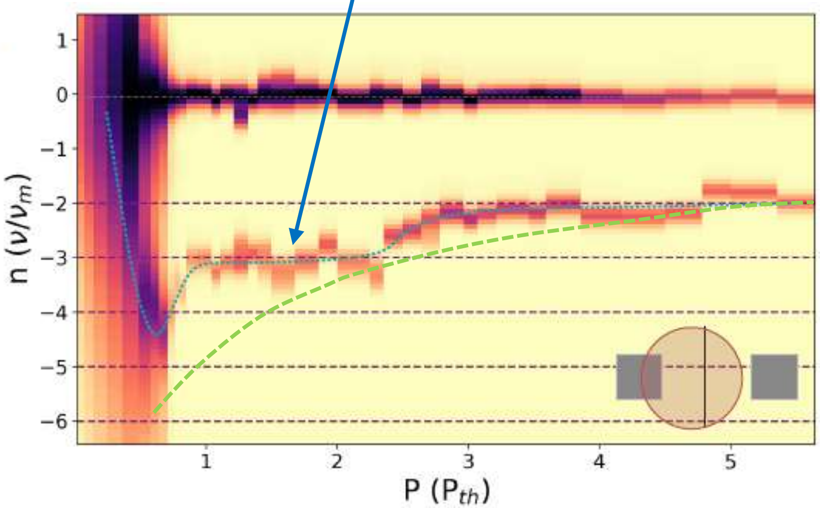


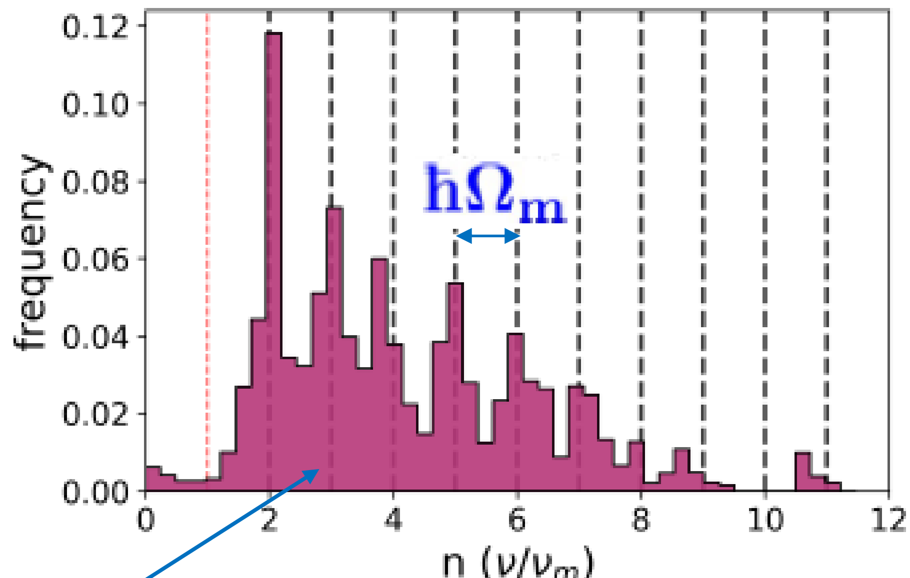
Asynchronous locking: power dependence



Laser power dependence of detuning

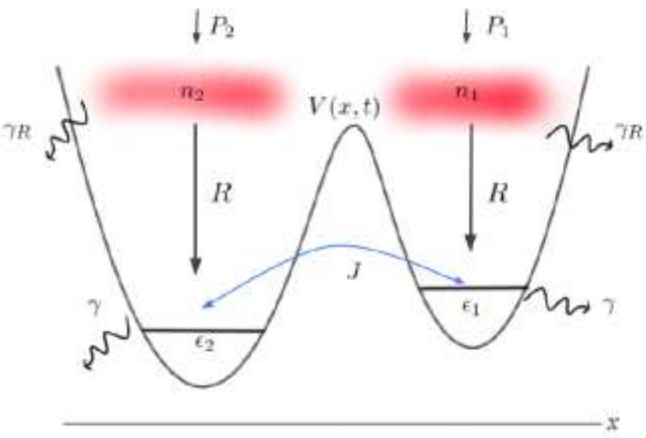
Steps (locking) at integer numbers n of ω_m !!





Sum of 10s of experiments, different arrays, trap sizes and separations

Asynchronous locking: the model



interactions

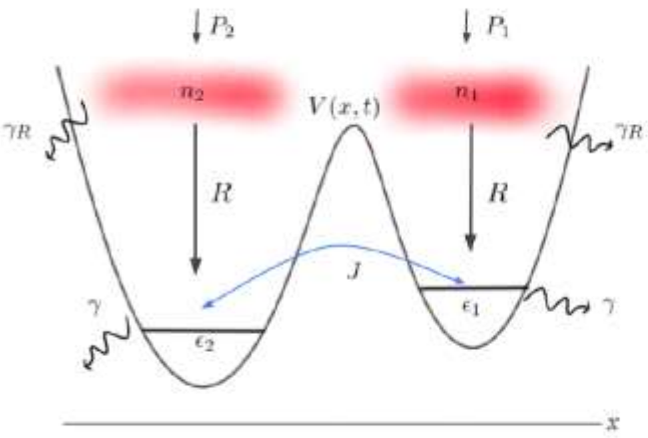
coupling

$$i\hbar\dot{\psi}_j = (\varepsilon_j + U_j|\psi_j|^2 + U_j^{\mathrm{R}} n_j)\psi_j - J\psi_{3-j} + \\ + \frac{i\hbar}{2}(R n_j - \gamma)\psi_j \, ,$$

driving and losses

D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

Asynchronous locking: the model



interactions — coupling

$$i\hbar\dot{\psi}_j = (\varepsilon_j + U_j|\psi_j|^2 + U_j^{\mathrm{R}} n_j)\psi_j - J\psi_{3-j} + \\ + \frac{i\hbar}{2}(R n_j - \gamma)\psi_j \,,$$

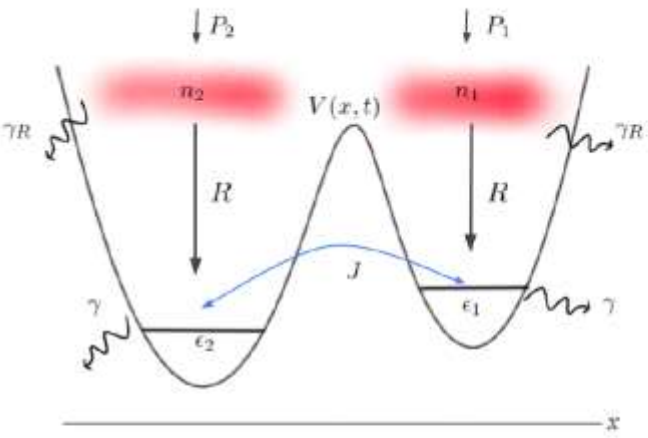
driving and losses

reservoir dynamics: $$\dot{n}_j = P_j - \gamma_{\mathrm{R}}\, n_j - R|\psi_j|^2 n_j \,.$$

cw non-resonant pump

D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

Asynchronous locking: the model



interactions, coupling:

$$i\hbar\dot{\psi}_j = (\varepsilon_j + U_j|\psi_j|^2 + U_j^{\mathrm{R}} n_j)\psi_j - J\psi_{3-j} + \\ + \frac{i\hbar}{2}(R n_j - \gamma)\psi_j \,,$$

driving and losses

reservoir dynamics: $$\dot{n}_j = P_j - \gamma_{\mathrm{R}} n_j - R|\psi_j|^2 n_j \,.$$

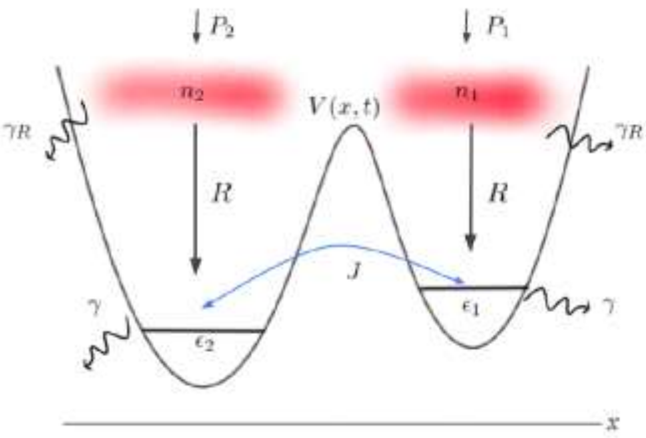
cw non-resonant pump

phonon dynamics: $$\ddot{x} \;=\; -\Gamma\dot{x} - \omega_0^2 x + 4\omega_0 g_0 \rho_0 \mathrm{Re}(\tilde{\psi}_+^* \tilde{\psi}_-)$$

polariton driving

D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

Asynchronous locking: the model



interactions — coupling

$$i\hbar\dot{\psi}_j = (\varepsilon_j + U_j|\psi_j|^2 + U_j^{\mathrm{R}} n_j)\psi_j - J\psi_{3-j} + \\ + \frac{i\hbar}{2}(R n_j - \gamma)\psi_j\,,$$

driving and losses

reservoir dynamics: $$\dot{n}_j = P_j - \gamma_{\mathrm{R}}\, n_j - R|\psi_j|^2 n_j\,.$$

cw non-resonant pump

phonon dynamics: $$\ddot{x} \;=\; -\Gamma\dot{x} - \omega_0^2 x + 4\omega_0 g_0 \rho_0 \mathrm{Re}(\tilde{\psi}_+^* \tilde{\psi}_-)$$

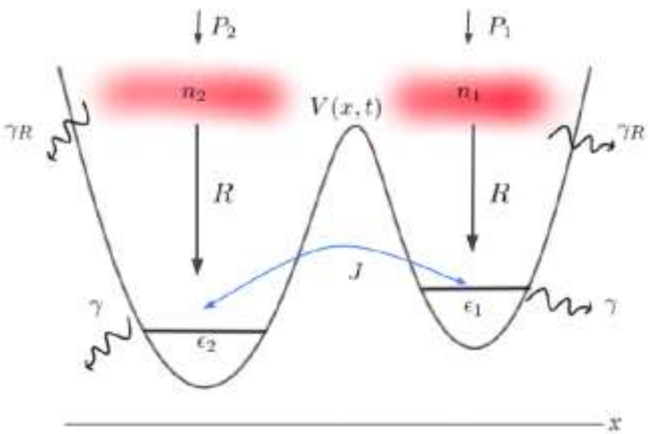
polariton driving

$$\boxed{J \mapsto J_0 + \hbar g_0 \hat{x}}$$

Mechanically modulated inter-site coupling

D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

First: “Frozen” phonon + RWA



$$J(t) = J_m(e^{i2\Omega_m t} + e^{-i2\Omega_m t} + 2)$$

$$\varepsilon_1 \sim \varepsilon_2 + 2\hbar\Omega_m \quad + \text{RWA}$$

$$i\hbar\dot{\psi}_1 = \bar{\varepsilon}_1\psi_1 - J_m e^{-i2\Omega_m t}\psi_2 + \frac{i\hbar}{2}(Rn_1 - \gamma)\psi_1$$

$$i\hbar\dot{\psi}_2 = \bar{\varepsilon}_2\psi_2 - J_m e^{i2\Omega_m t}\psi_1 + \frac{i\hbar}{2}(Rn_2 - \gamma)\psi_2 \, ,$$

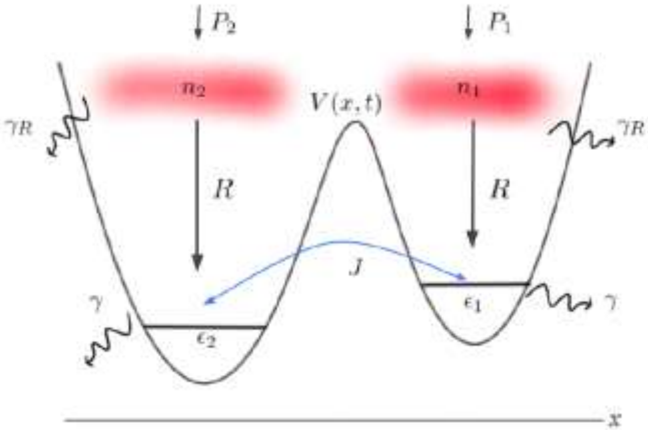
$$\bar{\varepsilon}_j = \varepsilon_j + U_j|\psi_j|^2 + U_j^R n_j$$

$$\dot{n}_j = P_j - \gamma_R n_j - R|\psi_j|^2 n_j$$

D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

First: “Frozen” phonon + RWA



$$J(t) = J_m(e^{i2\Omega_m t} + e^{-i2\Omega_m t} + 2)$$

$$\varepsilon_1 \sim \varepsilon_2 + 2\hbar\Omega_m \quad \text{+ RWA}$$

$$i\hbar\dot{\psi}_1 = \bar{\varepsilon}_1\psi_1 - J_m e^{-i2\Omega_m t}\psi_2 + \frac{i\hbar}{2}(Rn_1 - \gamma)\psi_1$$

$$i\hbar\dot{\psi}_2 = \bar{\varepsilon}_2\psi_2 - J_m e^{i2\Omega_m t}\psi_1 + \frac{i\hbar}{2}(Rn_2 - \gamma)\psi_2 ,$$

$$\bar{\varepsilon}_j = \varepsilon_j + U_j|\psi_j|^2 + U_j^R n_j$$

$$\dot{n}_j = P_j - \gamma_R n_j - R|\psi_j|^2 n_j$$

Same solutions as static case are found proposing:

$$\psi_1 = \sqrt{\rho_1} e^{-i\omega t} e^{i\theta/2} \quad \text{and}$$

$$\psi_2 = \sqrt{\rho_2} e^{-i(\omega - 2\Omega_m)t} e^{-i\theta/2}$$

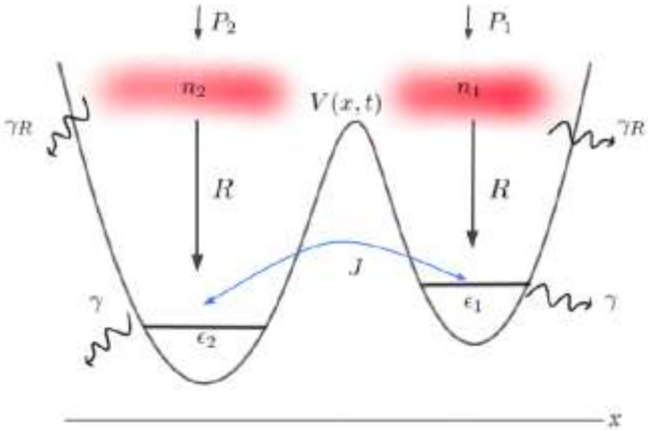
i.e., similar ”sinchronization condition” but displaced to:

$$\varepsilon_2 \rightarrow \varepsilon_2 + 2\hbar\Omega_m$$

D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

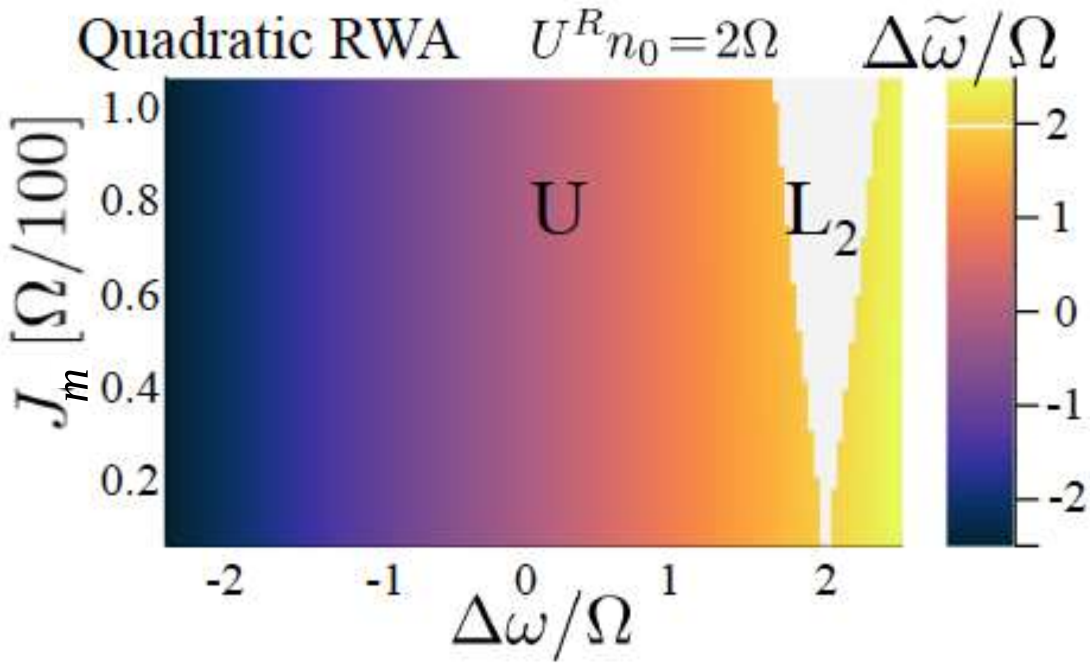
I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

First: "Frozen" phonon + RWA



$$J(t) = J_m(e^{i2\Omega_m t} + e^{-i2\Omega_m t} + 2)$$

$\varepsilon_1 \sim \varepsilon_2 + 2\hbar\Omega_m$ + RWA



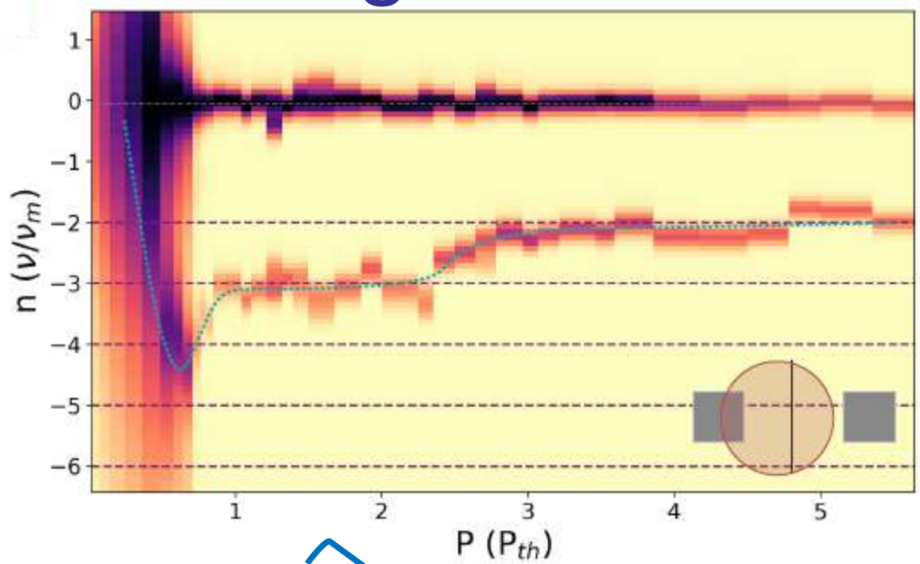
"Locking" regions behave as for synchronization, i.e., are enhanced by J and U

D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

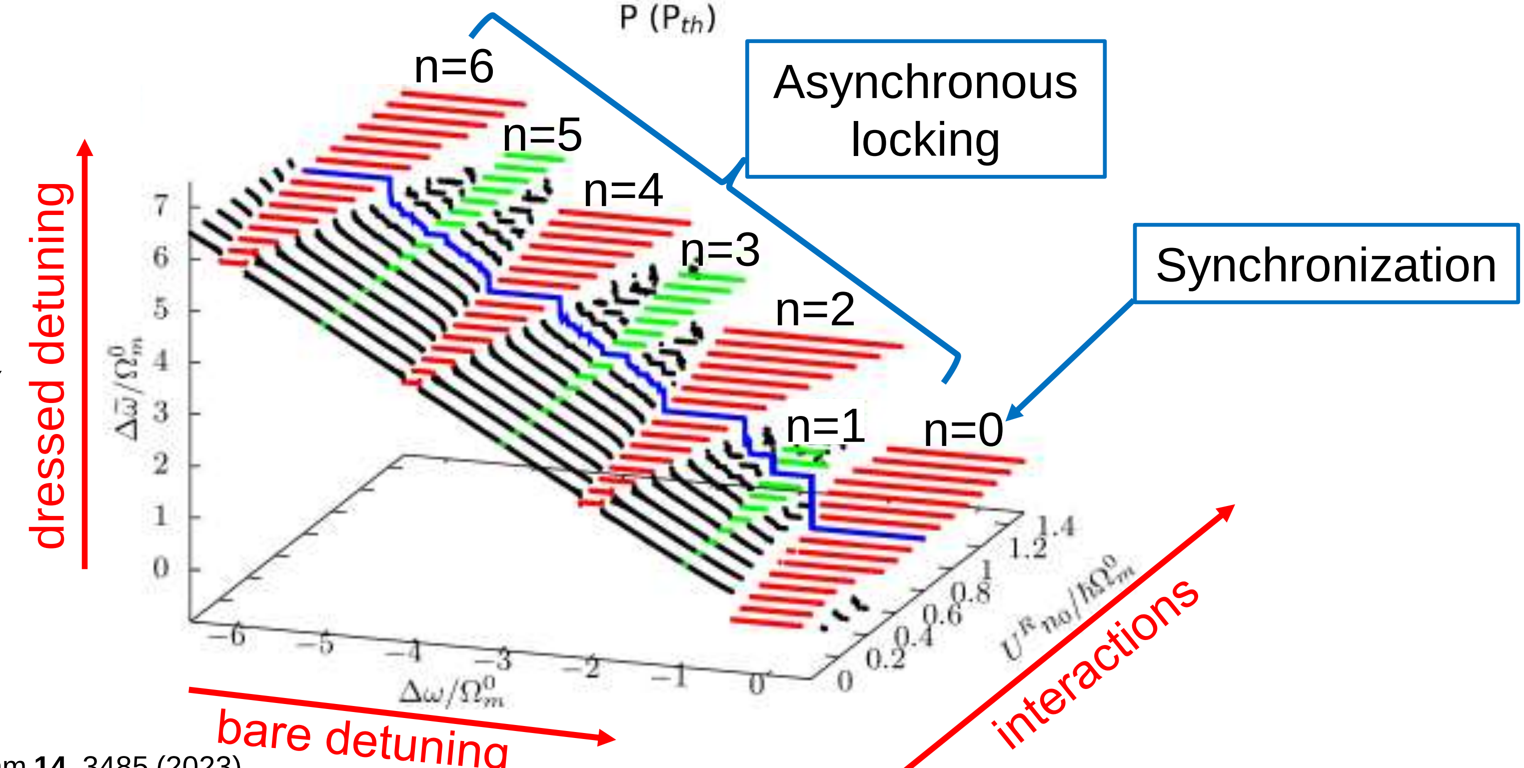
I. A. Ramos, I. Carraro-Haddad, F. Fainstein *et al*, PRB **109**, 165305 (2024)

Asynchronous locking: the full model

EXPERIMENT



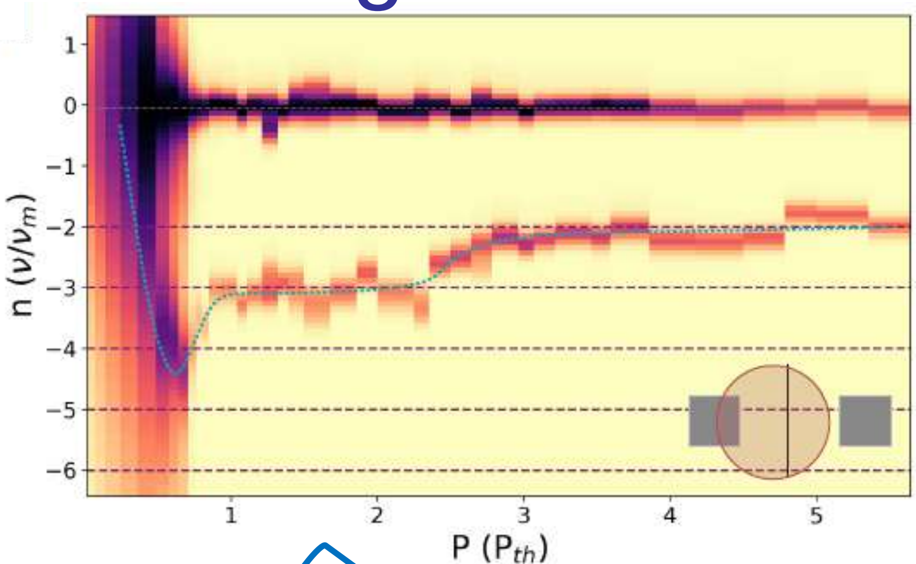
THEORY



D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

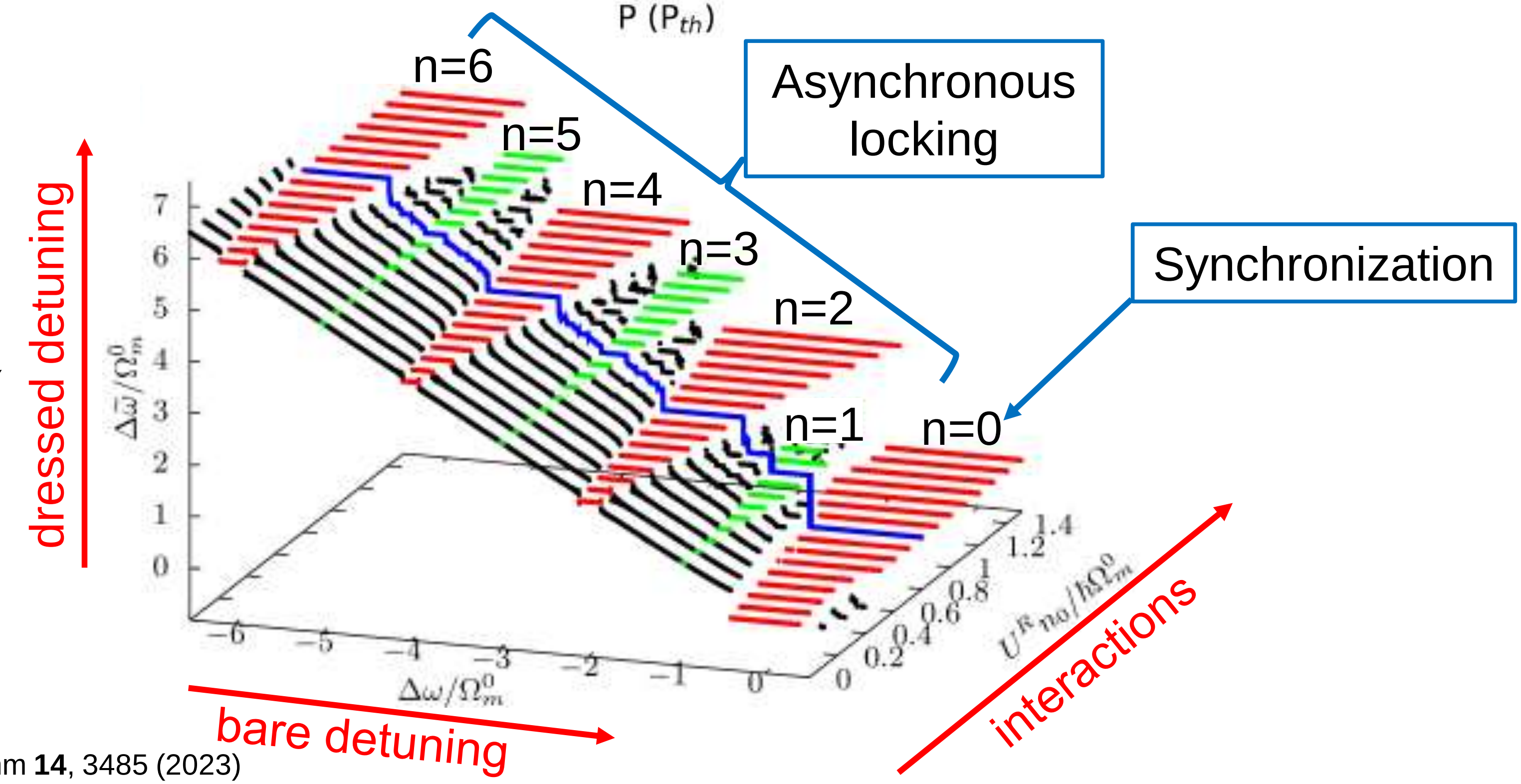
Asynchronous locking: the full model

EXPERIMENT



J. F. Döppler et al., PRE **102**, 062415 (2020)

THEORY

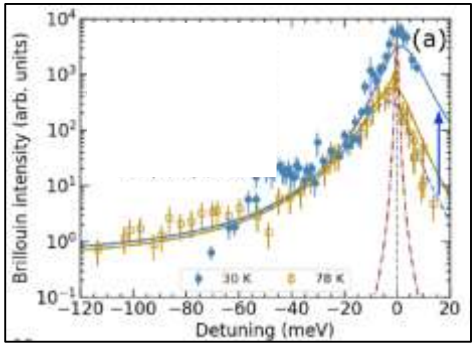


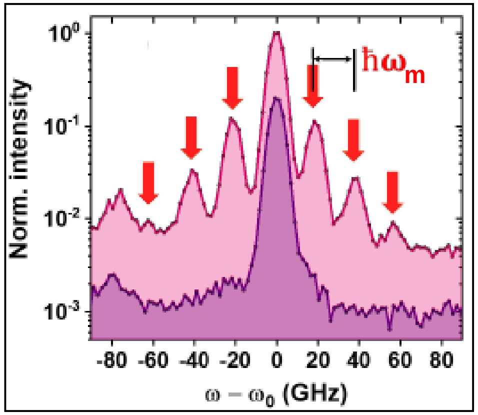
D. Chafatinos *et al*, NatComm **14**, 3485 (2023)

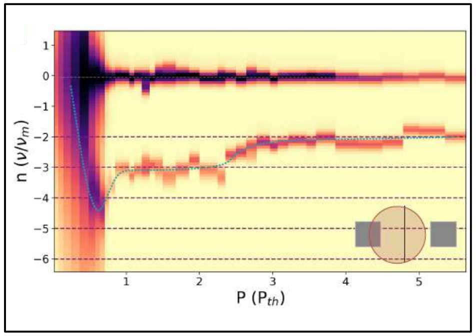
Day #3 wrap-up

- Synchronization. The relevance of coupling, non-linearities and dissipation.
- Synchronization of polariton condensates
- Asynchronous locking of mechanically modulated coupled polariton condensates.

Index







- **Day #1: cavity polaritons**, resonant exciton mediated optomechanical interaction
- **Day #2: self-oscillation**, the optomechanical parametric oscillator
- **Day #3: synchronization,** OM asynchronous locking of polariton states

Bonus: Friday talk, time crystals

Outlook #1: Bidirectional MW-to-optical conversion

PRESS RELEASE

New quasi-particle bridges microwave and optical domains

nature communications

Article

https://doi.org/10.1038/s41467-023-40894-7

Microcavity phonoritons – a coherent optical-to-microwave interface

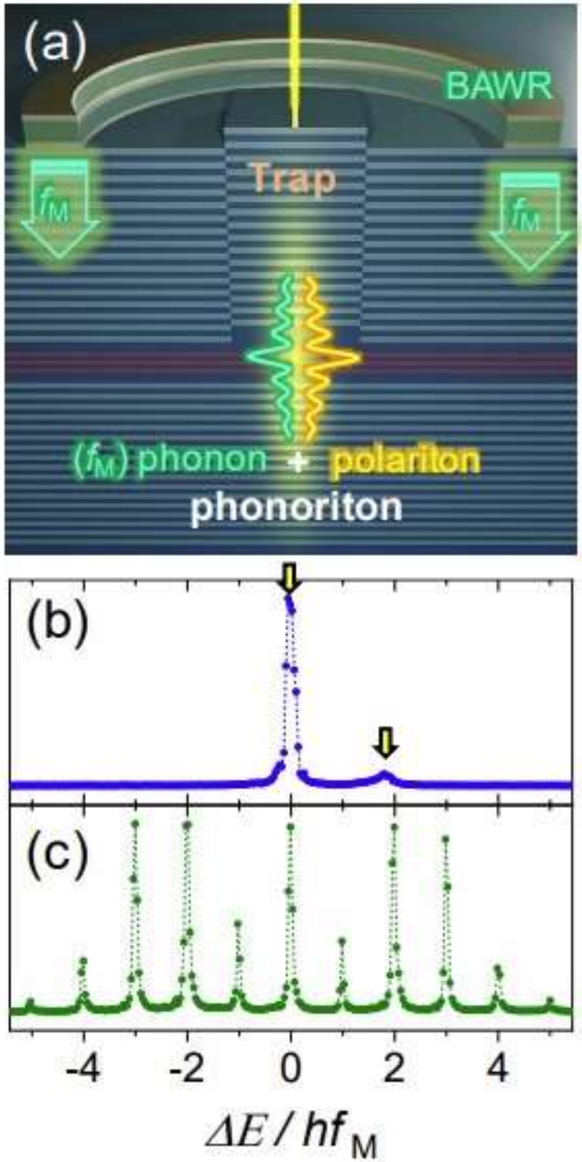
Received: 3 November 2022

Accepted: 14 August 2023

Published online: 18 September 2023

Alexander Sergeevich Kuznetsov[1], Klaus Biermann[1], Andres Alejandro Reynoso[2,3,4], Alejandro Fainstein[2,3] & Paulo Ventura Santos[1]

QUANTUM LIMIT?

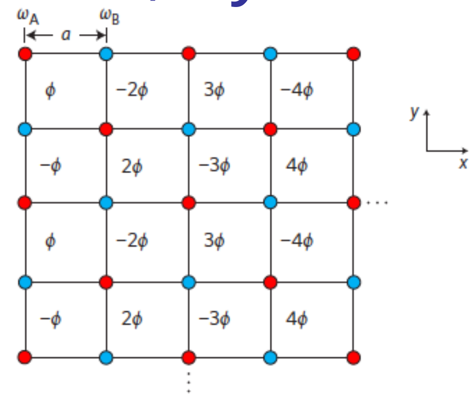


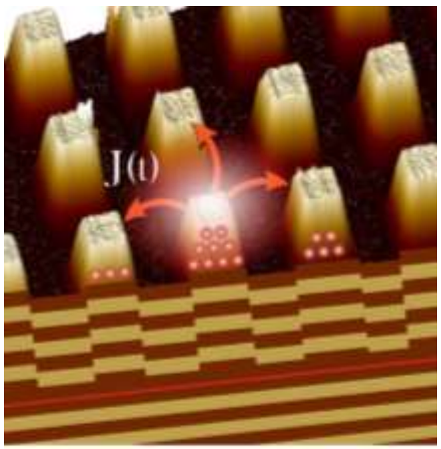
Outlook #2: Spatio-temporal modulation, synthetic B_{eff}

nature photonics | ARTICLES
PUBLISHED ONLINE: 7 OCTOBER 2012 | DOI: 10.1038/NPHOTON.2012.236

Realizing effective magnetic field for photons by controlling the phase of dynamic modulation

Kejie Fang[1], Zongfu Yu[2] and Shanhui Fan[2]*





Two sites 1, 2:

$$i\frac{d}{dt}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} \omega_1 & V\cos(\Omega t+\phi) \\ V\cos(\Omega t+\phi) & \omega_2 \end{pmatrix}\begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

$$\Omega = \omega_1 - \omega_2$$

$$i\frac{d}{dt}\begin{pmatrix} \tilde{a}_1 \\ \tilde{a}_2 \end{pmatrix} = \begin{pmatrix} 0 & \frac{V}{2}e^{-i\phi} \\ \frac{V}{2}e^{i\phi} & 0 \end{pmatrix}\begin{pmatrix} \tilde{a}_1 \\ \tilde{a}_2 \end{pmatrix}$$

Tight binding WITHOUT magnetic field : $H = \sum_{r',r} C^0_{r',r} b^\dagger_{r'} b_r$

+ magnetic field →

$$C_{r',r} = e^{i(e/\hbar)\int_r^{r'} \vec{A}\cdot d\vec{l}}\, C^0_{r',r} \equiv e^{i\phi} C^0_{r',r}$$

"Peierls transformation"

$$\int_1^2 A_{\text{eff}} \cdot d\vec{l} = \phi \qquad B_{\text{eff}} = \frac{1}{a^2}\oint_{\text{plaquette}} A_{\text{eff}}\, dl = \frac{\phi}{a^2}$$

Optical Materials EXPRESS

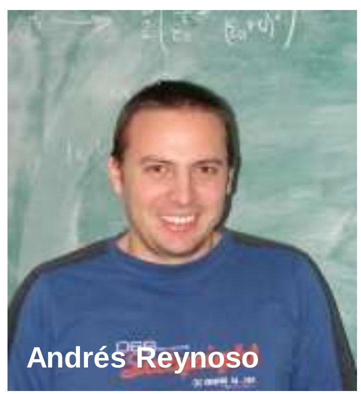
Polaromechanics: polaritonics meets optomechanics

P. V. SANTOS AND A. FAINSTEIN*

*afains@cab.cnea.gov.ar

Paul-Drude-Institut
für Festkörperelektronik

Instituto
Balseiro




Thank you!
ψ
Ω_m
(Copyright © Chafa)