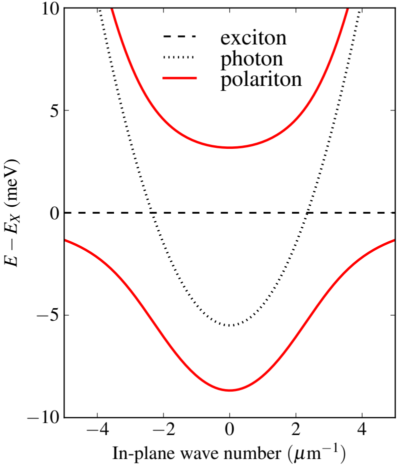
Поляритоны: смешанные состояния света и вещества

Сергей Гаврилов

Лаборатория неравновесных электронных процессов
Институт физики твердого тела
г. Черноголовка

Cavity polaritons are bound exciton-photon states



$$H = \sum_{\mathbf{k}} \Big(E_{C,\mathbf{k}} a^\dagger_{\mathbf{k}} a_{\mathbf{k}} + E_{X,\mathbf{k}} b^\dagger_{\mathbf{k}} b_{\mathbf{k}} + + g(a^\dagger_{\mathbf{k}} b_{\mathbf{k}} + b^\dagger_{\mathbf{k}} a_{\mathbf{k}}) \Big) + + \frac{1}{2} V \sum_{\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3,\mathbf{k}_4} \delta_{\mathbf{k}_1+\mathbf{k}_2,\mathbf{k}_3+\mathbf{k}_4} b^\dagger_{\mathbf{k}_1} b^\dagger_{\mathbf{k}_2} b_{\mathbf{k}_3} b_{\mathbf{k}_4}$$

$$E_{\mathrm{LP,UP}}(\mathbf{k}) = \frac{E_C(\mathbf{k}) + E_X(\mathbf{k})}{2} \mp \mp \frac{1}{2}\sqrt{[E_C(\mathbf{k}) - E_X(\mathbf{k})]^2 + 4g^2}$$

Gross-Pitaevskii equation

Nonequilibrium, i. e., dissipative and coherently driven Bose condensates obey the following equation

$$\boxed{i\hbar\frac{\partial\psi}{\partial t} = [E(-i\hbar\nabla) - i\gamma]\,\psi + V\psi^*\psi\psi + f(t)e^{-iE_p t}}$$

Collective states of cavity polaritons

1. Bose-Einstein condensates
   - phase is free (chosen spontaneously)

   → synchronization, vortices, artificial networks, simulators, . . .

Collective states of cavity polaritons

1. Bose-Einstein condensates
   - phase is free (chosen spontaneously)

   $\rightarrow$ synchronization, vortices, artificial networks, simulators, ...
2. Resonantly driven condensates
   - phase is fixed with respect to the driving field

   $\rightarrow$ optical control: parametric scattering, multistability, switches, ...

Collective states of cavity polaritons

1. Bose-Einstein condensates
   - phase is free (chosen spontaneously)

   $\rightarrow$ synchronization, vortices, artificial networks, simulators, ...
2. Resonantly driven condensates
   - phase is fixed with respect to the driving field

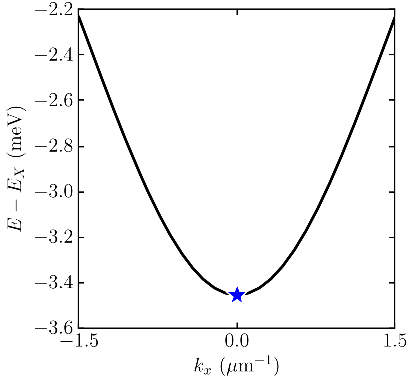
   $\rightarrow$ optical control: parametric scattering, multistability, switches, ...
3. Pulsed resonant excitation and subsequent free evolution
   - ballistic regime

   $\rightarrow$ injected topological excitations

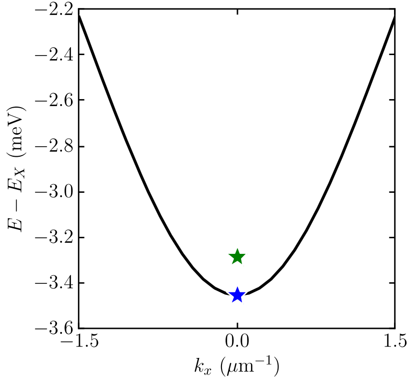
Collective states of cavity polaritons

1. Bose-Einstein condensates
   - phase is free (chosen spontaneously)
   - → synchronization, vortices, artificial networks, simulators, . . .
2. Resonantly driven condensates
   - phase is fixed with respect to the driving field
   - → optical control: parametric scattering, multistability, switches, . . .
3. Pulsed resonant excitation and subsequent free evolution
   - ballistic regime
   - → injected topological excitations
4. Chimera states
   - cavity is homogeneous
   - pump is a resonant plane wave at normal incidence
   - nevertheless, the condensate wave vector is uncertain . . .
   - . . . and the phase is free
   - → new types of topological excitations
   - → spontaneously formed networks

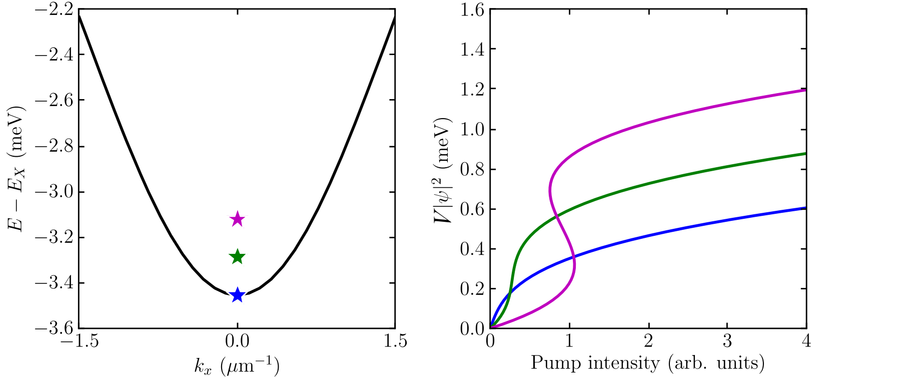
Polariton bistability



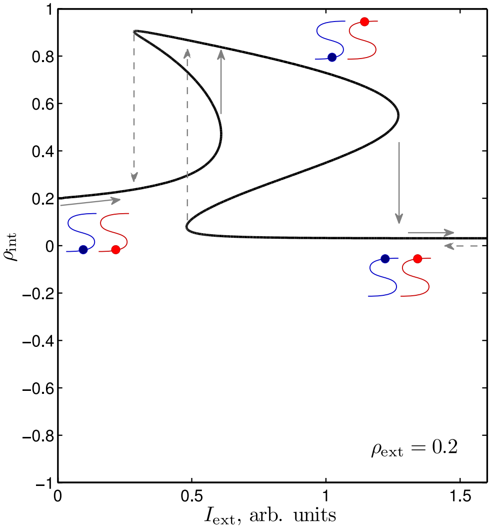
Polariton bistability



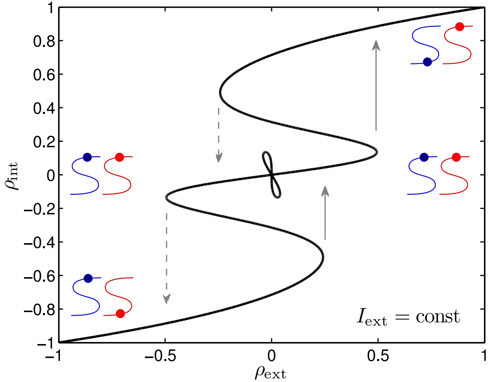
Polariton bistability



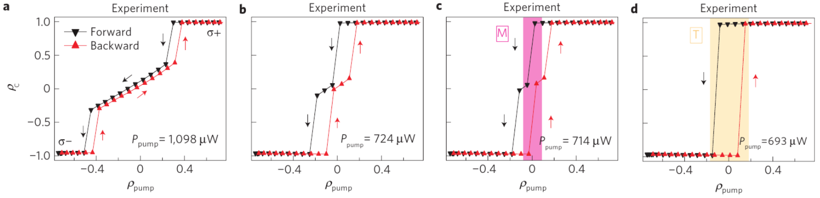
Polarization multistability: predictions (1)



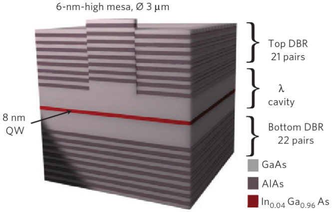
Polarization multistability: predictions (2)



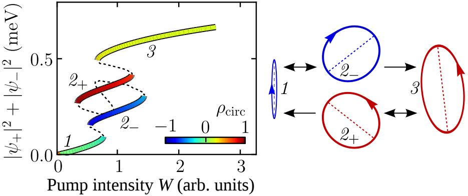
Polariton multistability: continuous-wave experiments



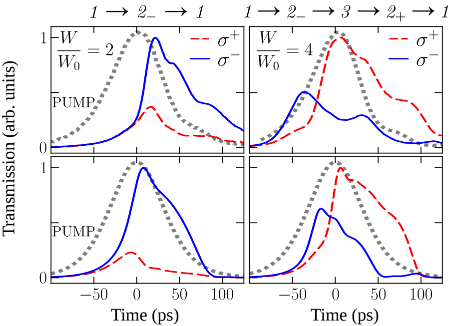
- T. K. Paraiso *et al.*,
  Nat. Mater. **9**, 655 (2010)
- D. Sarkar, S. Gavrilov *et al.*,
  PRL **105**, 216402 (2010)
- C. Adrados *et al.*,
  PRL **105**, 216403 (2010)



Multistability in a magnetic field: experiment



STEADY-STATE SCHEME



EXPERIMENT

MODELING

Polariton solitons

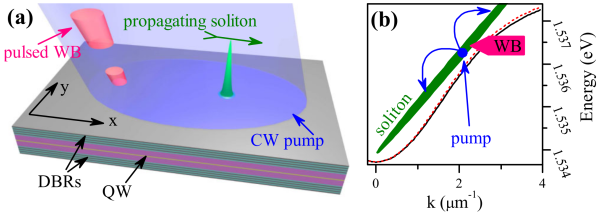
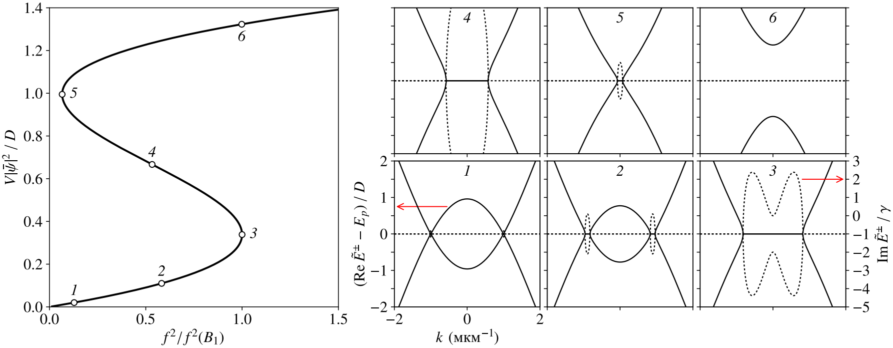


FIG. 1 (color online). (a) Schematic of soliton excitation in a microcavity consisting of distributed Bragg reflectors (DBRs) and a quantum well (QW). The cw pump and pulsed WB are incident along the X direction. (b) Schematic of soliton spectrum and excitation in E-k space with TE (dotted) and TM (solid) polarized polariton dispersions.

Phys. Rev. Lett. **112**, 046403 (2014)

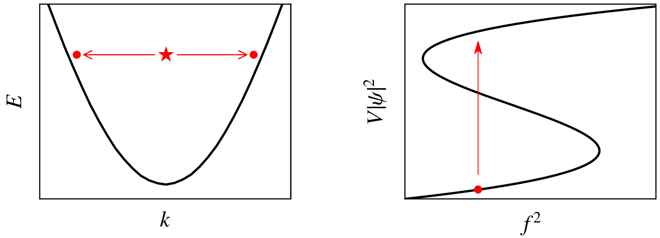
Bistability and Bogolyubov excitations



$$\psi(t) = \bar{\psi} e^{-iE_p t/\hbar} \quad \Rightarrow \quad |\bar{\psi}|^2 = \frac{f^2}{(D - V|\bar{\psi}|^2)^2 + \gamma^2}, \quad \text{where } D = E_p - E_{\mathrm{LP}}(k=0)$$

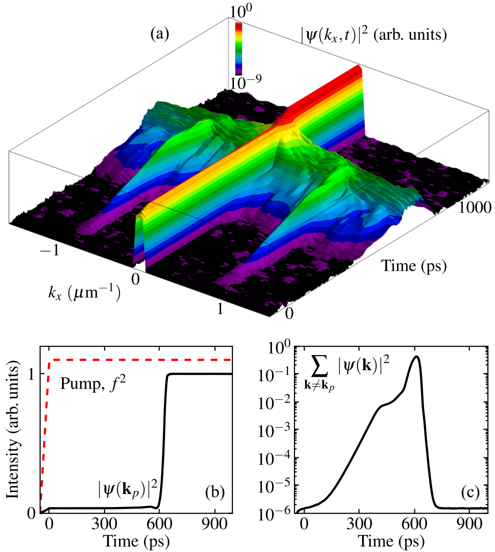
$$\tilde{E}^{\pm}(\mathbf{k}) = E_p - i\gamma \pm \sqrt{\left(E_p - E_{\mathrm{LP}}(\mathbf{k}) - 2V|\bar{\psi}|^2\right)^2 - \left(V|\bar{\psi}|^2\right)^2}.$$

What happens above the scattering threshold?

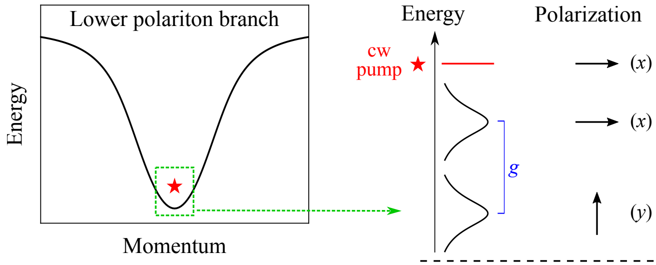


- Pair scattering $(\mathbf{k}, \mathbf{k}) \to (\mathbf{k}', 2\mathbf{k}' - \mathbf{k})$ involves accumulation of energy at constant above-resonance excitation.
- The condensate drifts towards the upper branch of steady-state solutions.
- Near the magic angle, this results in macro-occupation of 0 and $2\mathbf{k}$.
- At $\mathbf{k} = 0$, the effect is only transient. All solutions are one-mode.

Transitions between steady states: dynamics "with blowup"



Spinor system



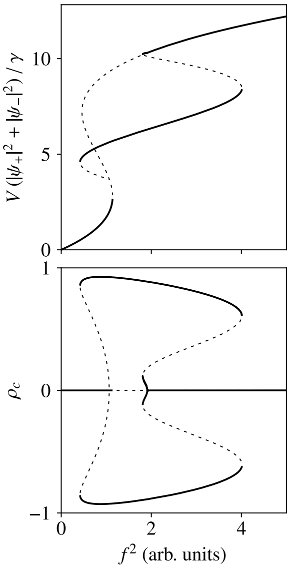
$$\psi_\pm = \frac{1}{\sqrt{2}}(\psi_x \mp i\psi_y)$$

$$i\hbar\frac{\partial\psi_+}{\partial t} = \left(\hat{E}_{\mathrm{LP}} - i\gamma\right)\psi_+ + \frac{g}{2}\psi_- + V\psi_+^*\psi_+\psi_+ + fe^{-iE_pt/\hbar}$$

$$i\hbar\frac{\partial\psi_-}{\partial t} = \left(\hat{E}_{\mathrm{LP}} - i\gamma\right)\psi_- + \frac{g}{2}\psi_+ + V\psi_-^*\psi_-\psi_- + fe^{-iE_pt/\hbar}$$

- The equations for ψ_+ and ψ_- are exactly the same.
- The model is perfectly homogeneous and spin-symmetric.

Spontaneous spin symmetry breakdown ($g \gtrsim \gamma$)



Full intensity vs. pumping power

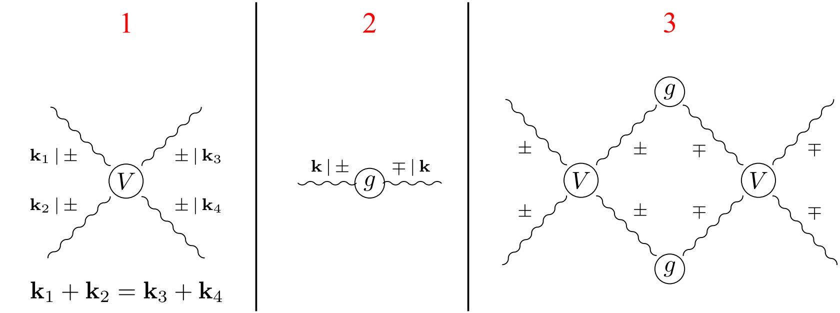
Corresponding circular-polarization degree

S. S. Gavrilov *et al.*, APL **102**, 011104 (2013)

A. V. Sekretenko *et al.*, PRB **88**, 205302 (2013)

S. S. Gavrilov *et al.*, PRB **90**, 235309 (2014)

Interaction processes and loop instability

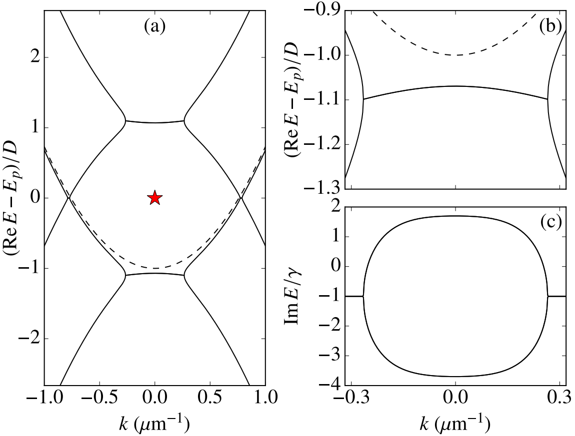


1 is the pair interaction. It preserves momentum and spin.
2 is the spin coupling. It does not imply real transitions in a forced (resonantly driven) system, but ...
1 + 2 lead to spontaneous breakdown of spin symmetry.
After the symmerty has broken,
3 comes into play and leaves no one-mode solutions at all, given that $g > 4\gamma$.

4^{th} order bogolons

They simultaneously:

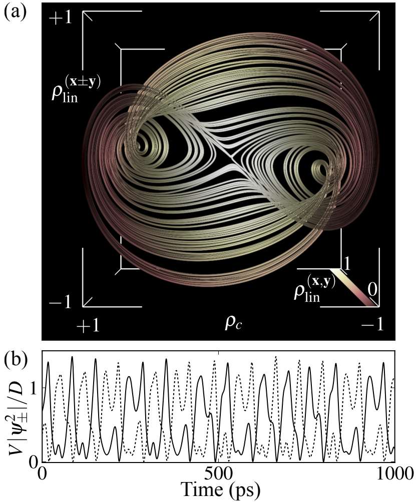
- allow spins to be reversed
- and lift the freqency denegeracy.



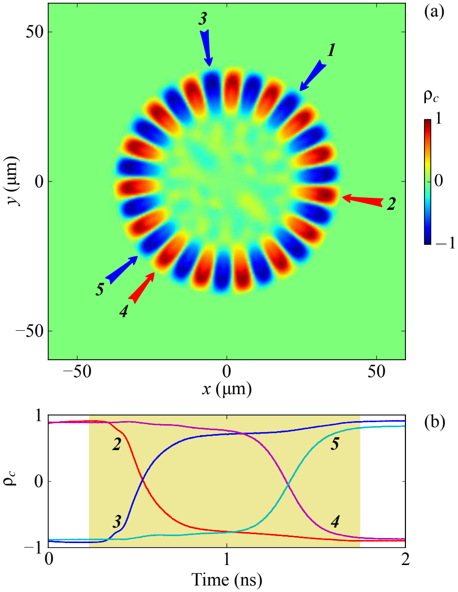
To keep it short and simple

- The interaction is repulsive $\Rightarrow$ local perturbations tend to spread and relax.
- However, all plane-wave solutions turn out to be forbidden.
- The condensate wave vector is uncertain.
- This results in lifted phase locking with respect to the driving field.

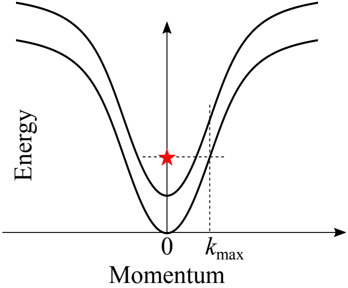
0-D systems (small micropillars) exhibit “rapid” chaos

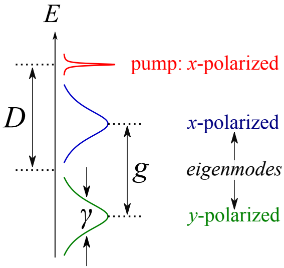


1D systems: strongly ordered spin networks



The condensate wave vector in uncertain





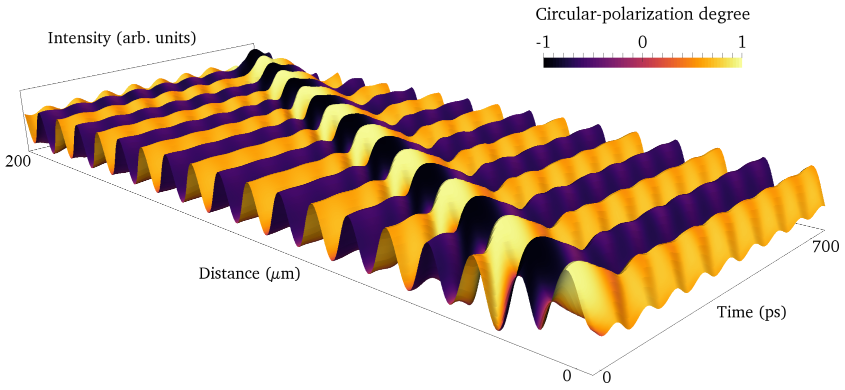
$$\frac{\hbar^2 k_{\max}^2}{2m} \approx D + \frac{g}{2}$$

$$\Delta k \sim k_{\max}$$

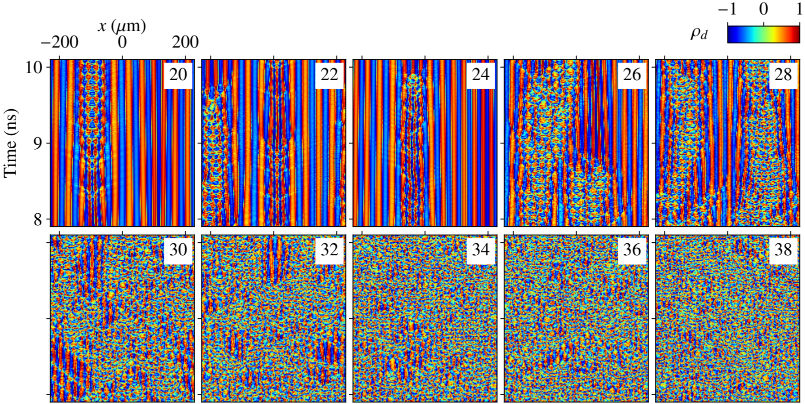
$$a_{\min} \sim \frac{1}{k_{\max}}$$

$a_{\min}$ is close to the acutally seen size of spin granules.

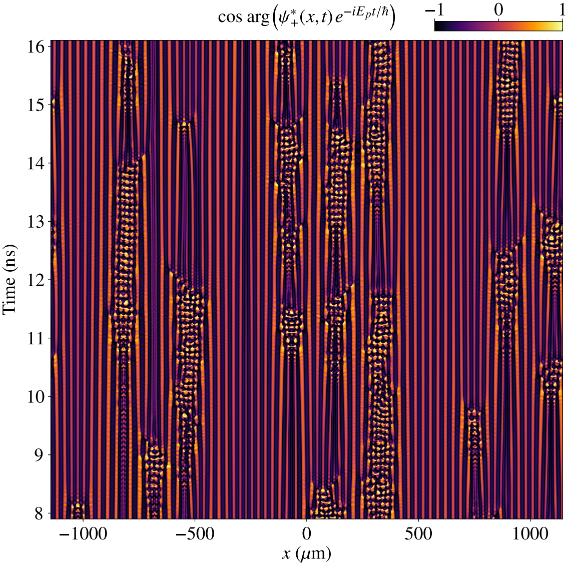
Instability of 1D systems: Spontaneously born solitons



Route to turbulence & chimera states (series overs g/γ)

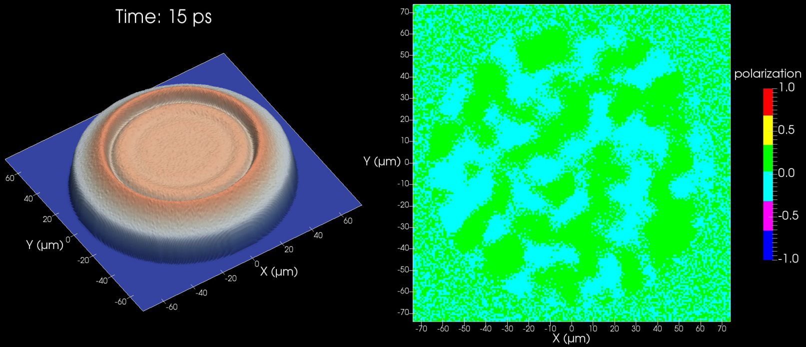


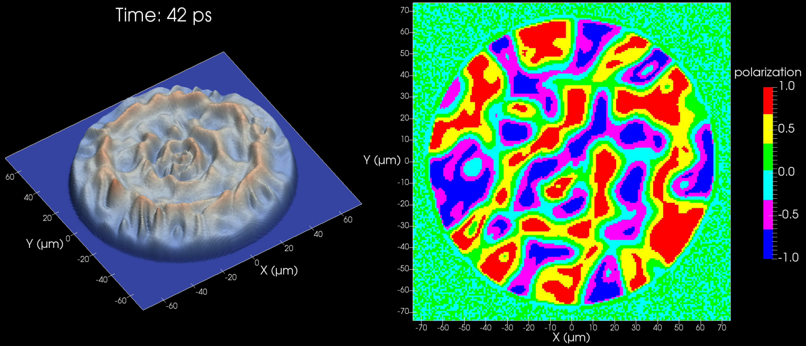
Chimera states combine synchronized and desynchronized domains

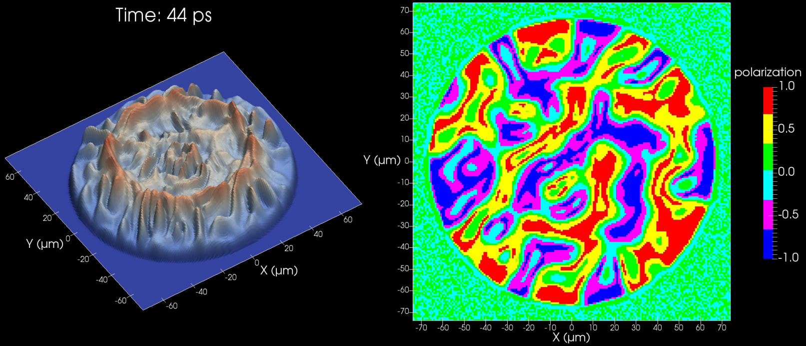


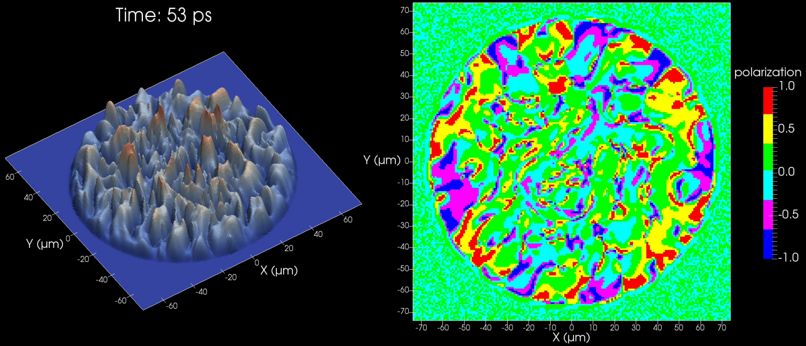
Let us now turn to 2D systems

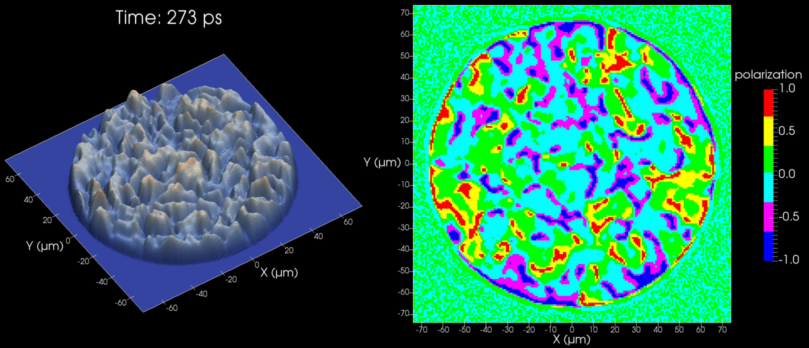
Time: 15 ps




Time: 42 ps
Y (μm)
X (μm)
polarization
1.0
0.5
0.0
-0.5
-1.0

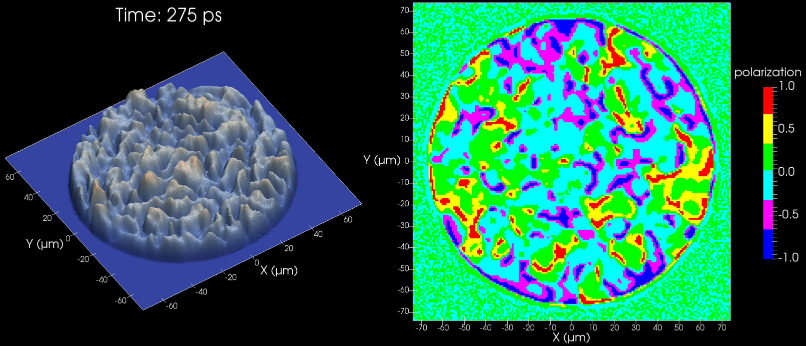

Time: 44 ps
Y (μm)
X (μm)
60
40
20
0
-20
-40
-60
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
polarization
1.0
0.5
0.0
-0.5
-1.0


Time: 53 ps
Y (μm)
X (μm)
polarization
1.0
0.5
0.0
-0.5
-1.0

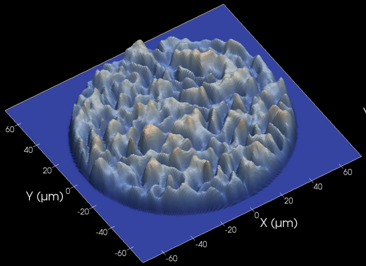


Time: 273 ps
Y (μm)
X (μm)
60
40
20
0
-20
-40
-60
Y (μm)
X (μm)
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
polarization
1.0
0.5
0.0
-0.5
-1.0

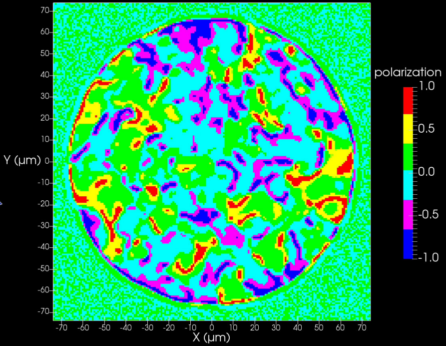
Time: 275 ps



Time: 278 ps

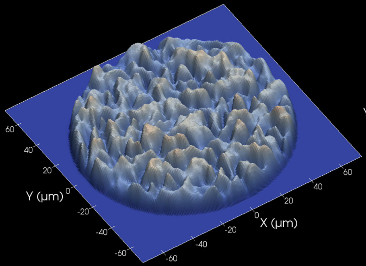


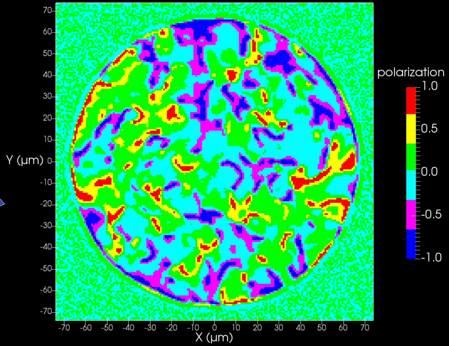
60
40
20
0
-20
-40
-60
Y (µm)
-60
-40
-20
0
20
40
60
X (µm)



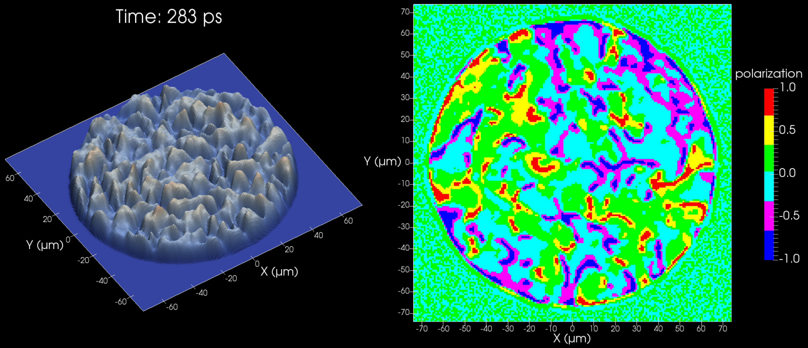
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Y (µm)
-70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70
X (µm)
polarization
1.0
0.5
0.0
-0.5
-1.0

Time: 280 ps

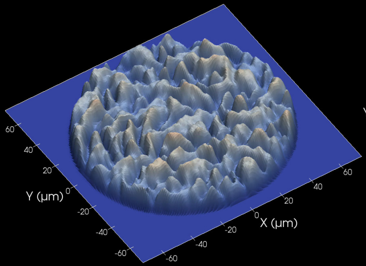

Y (μm)
60
40
20
0
-20
-40
-60
X (μm)
-60
-40
-20
0
20
40
60


Y (μm)
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
X (μm)
-70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70
polarization
1.0
0.5
0.0
-0.5
-1.0

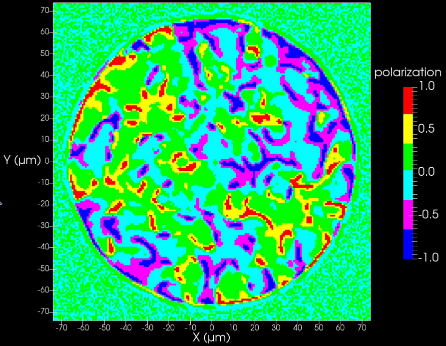
Time: 283 ps


Y (μm)
X (μm)
60 40 20 0 -20 -40 -60
70 60 50 40 30 20 10 0 -10 -20 -30 -40 -50 -60 -70
-70 -60 -50 -40 -30 -20 -10 0 10 20 30 40 50 60 70
polarization
1.0
0.5
0.0
-0.5
-1.0

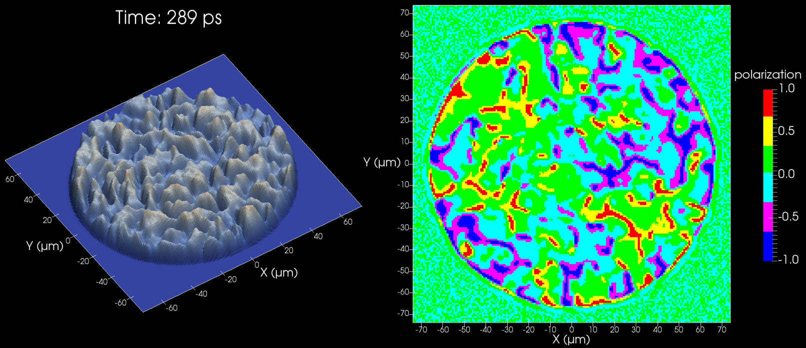
Time: 286 ps



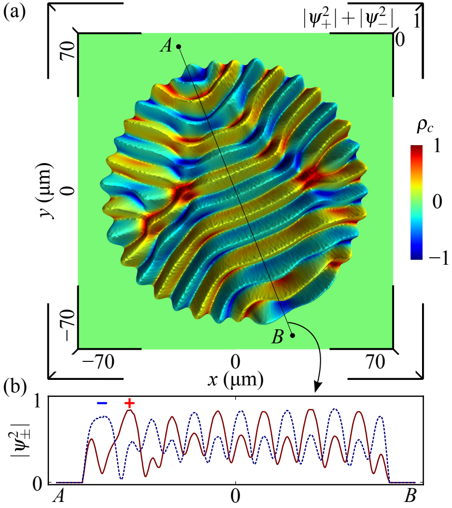
Y (μm)
X (μm)
60
40
20
0
-20
-40
-60



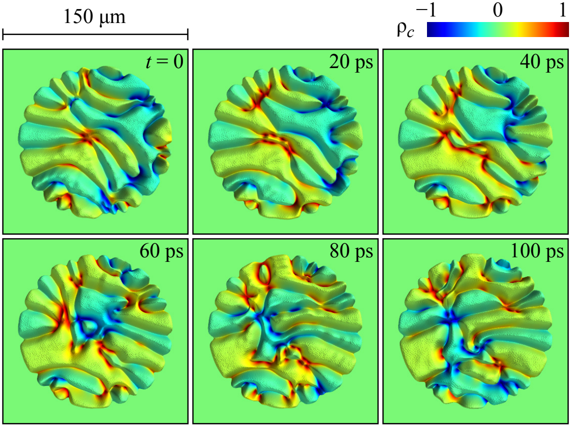
Y (μm)
X (μm)
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
polarization
1.0
0.5
0.0
-0.5
-1.0


Time: 289 ps
Y (μm)
X (μm)
polarization
1.0
0.5
0.0
-0.5
-1.0

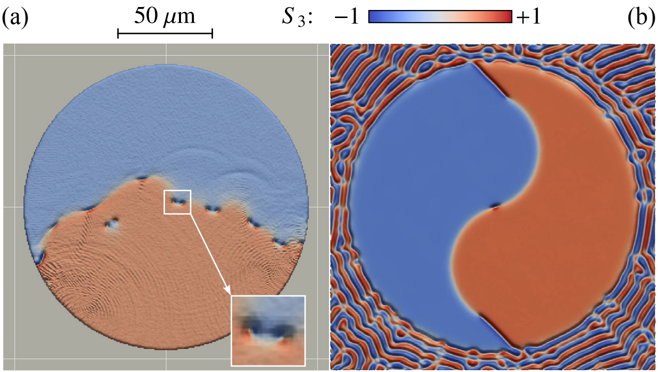
2D systems exhibit filaments



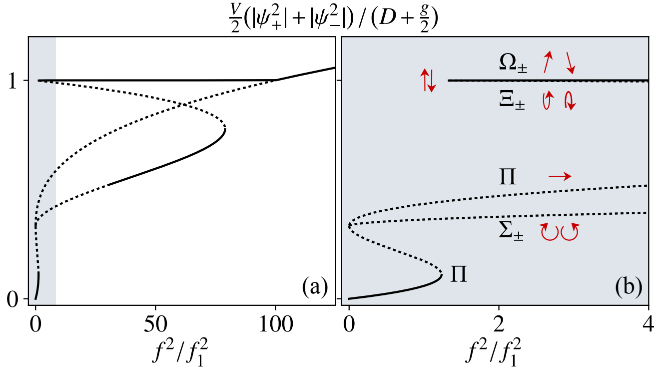
Filaments can evolve chaotically



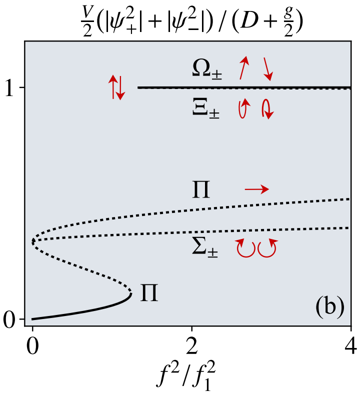
Vortices under resonant cw driving



Steady states at a greater g/γ

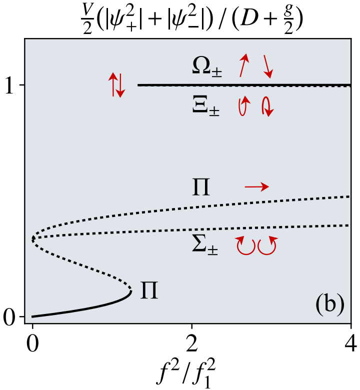


Steady states at a greater g/γ



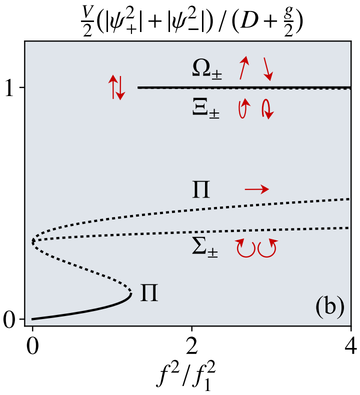
- Only two stable solutions: Ω_+ and Ω_-.

Steady states at a greater g/γ



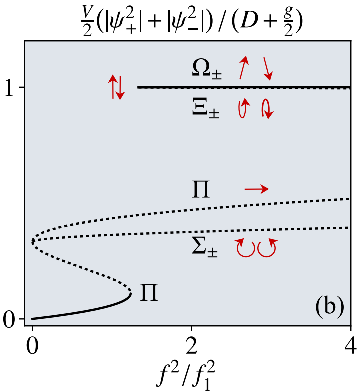
- Only two stable solutions: Ω_+ and Ω_-.
- Under spin-symmetric excitation, each of them is chosen spontaneously.

Steady states at a greater g/γ



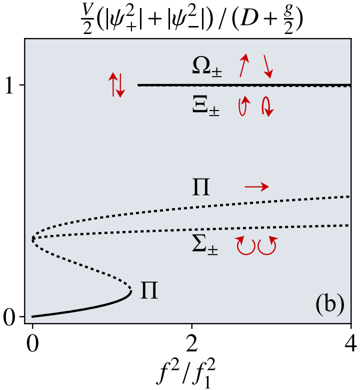
- Only two stable solutions: Ω_+ and Ω_-.
- Under spin-symmetric excitation, each of them is chosen spontaneously.
- They have the same intensity,
- but opposite phases.

Steady states at a greater g/γ



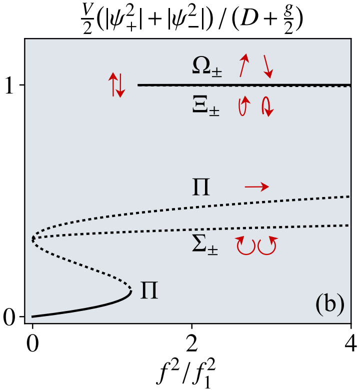
- Only two stable solutions: Ω_+ and Ω_-.
- Under spin-symmetric excitation, each of them is chosen spontaneously.
- They have the same intensity,
- but opposite phases.
- They annihilate each other on the boundary, which is thus dilute and highly unstable.

Steady states at a greater g/γ



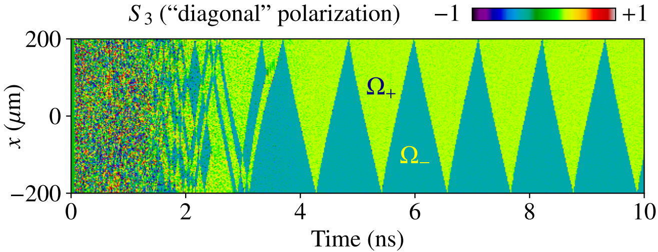
- Only two stable solutions: Ω_+ and Ω_-.
- Under spin-symmetric excitation, each of them is chosen spontaneously.
- They have the same intensity,
- but opposite phases.
- They annihilate each other on the boundary, which is thus dilute and highly unstable.
- The boundary gives birth to dark solitons and quantized vortices.

Steady states at a greater g/γ

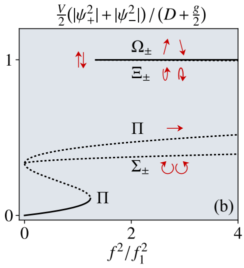


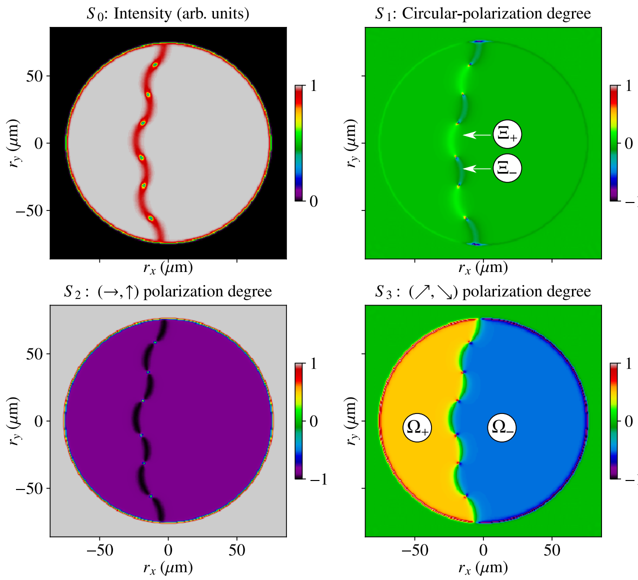
- Only two stable solutions: Ω_+ and Ω_-.
- Under spin-symmetric excitation, each of them is chosen spontaneously.
- They have the same intensity,
- but opposite phases.
- They annihilate each other on the boundary, which is thus dilute and highly unstable.
- The boundary gives birth to dark solitons and quantized vortices.
- $f_1^2 = \frac{2\gamma g}{V}\left(D + \frac{g}{2}\right).$

Interface between Ω_+ and Ω_- behaves as a gark soliton in a 1D system

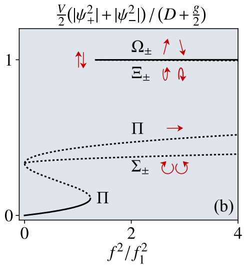


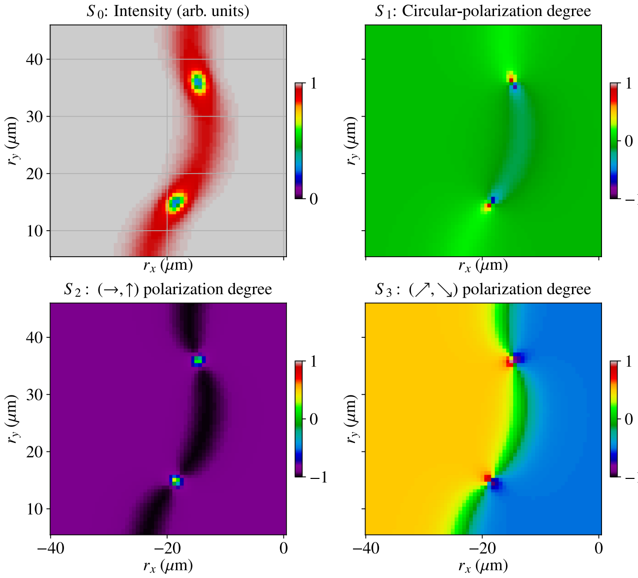
Polarization vortices



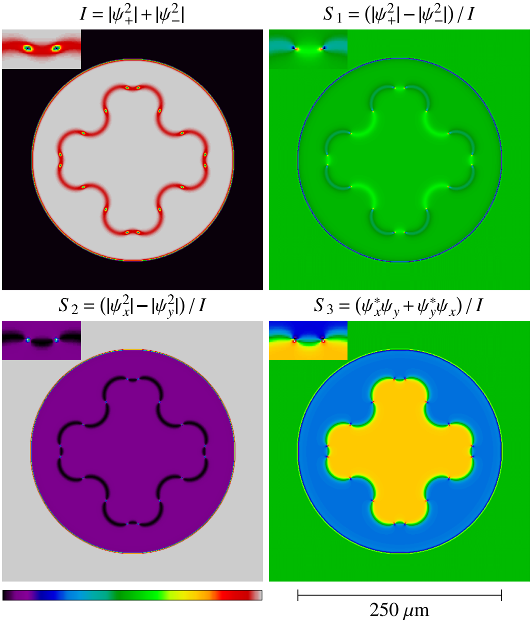


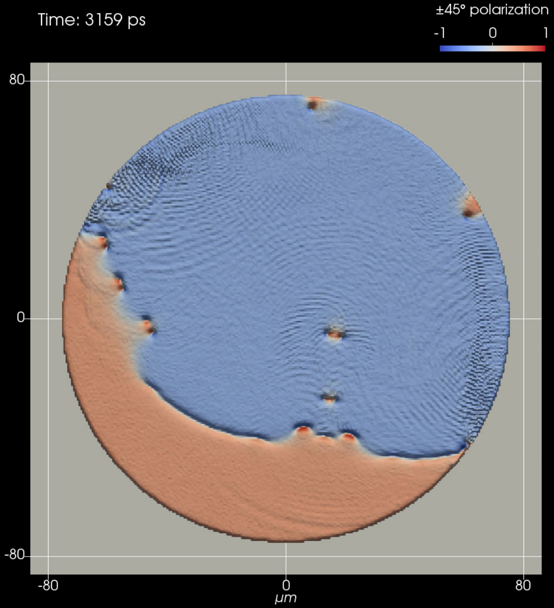
Polarization vortices (magnified)



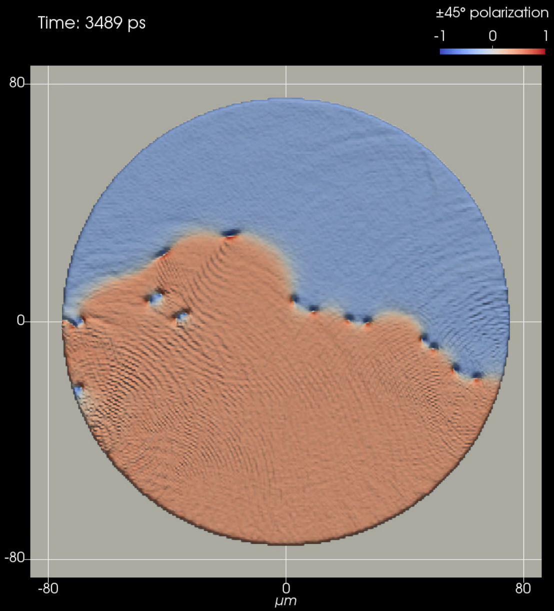


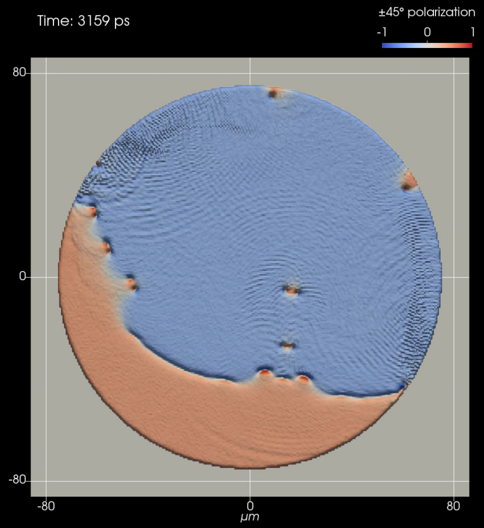
Another example

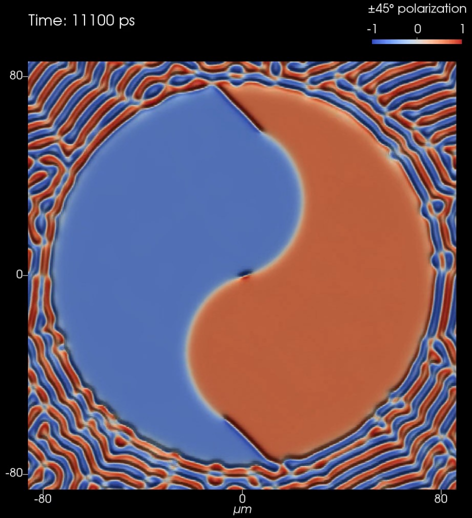



Time: 3159 ps
±45° polarization
-1
0
1
80
0
-80
-80
0
80
μm

Time: 3489 ps




Time: 3159 ps
±45° polarization
-1
0
1
80
0
-80
-80
0
80
μm



Time: 11100 ps
±45° polarization
-1
0
1
80
0
-80
-80
0
80
μm

Февраль 2020 г. *Том 190, № 2*

УСПЕХИ ФИЗИЧЕСКИХ НАУК

ОБЗОРЫ АКТУАЛЬНЫХ ПРОБЛЕМ

Неравновесные переходы, хаос и химерные состояния в системах экситонных поляритонов

С.С. Гаврилов

Рассматриваются экситонные поляритоны, короткоживущие бозе-частицы, которые возникают в полупроводнике под действием света и образуют макроскопически когерентные состояния в когерентном и резонансном внешнем поле. Взаимодействие поляритонов приводит к мультистабильности, спонтанному нарушению спиновой и пространственной симметрии, автоколебаниям и формированию дискретных структур. В результате нарушения симметрии могут возникать парадоксальные "химерные" состояния, в которых упорядоченная и хаотическая подсистемы сосуществуют и определённым образом дополняют друг друга.

Ключевые слова: поляритон, бозе-эйнштейновский конденсат, спинорный конденсат, мультистабильность, спонтанное нарушение симметрии, автоколебания, динамический хаос, химерные состояния, самоорганизация

PACS numbers: 03.75.Kk, 05.45.Xt, **05.65.+b**, 42.65.Sf, 47.20.Ky, **71.36.+c** DOI: https://doi.org/10.3367/UFNr.2019.04.038549