Exciton-polaritons: resonant drive and interactions (II)

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Driven-dissipative Gross-Pitaevskii equation

Full Hamiltonian for the lower polaritons (***k***-space):

$$\hat{H}_{\mathrm{LP}} \simeq \sum_{\mathbf{k}} \hbar\omega_X(\mathbf{k})\hat{p}^\dagger_{\mathbf{k}}\hat{p}_{\mathbf{k}} + \frac{V_{\mathbf{0}}^{XX}}{2}|X_0|^4 \sum_{\mathbf{k},\mathbf{k}'\mathbf{q}} \hat{p}^\dagger_{k+q}\hat{p}^\dagger_{k-q}\hat{p}_k\hat{p}_k$$

Full Hamiltonian for the lower polaritons (real-space):

$$\hat{H}_{\mathrm{LP}} = -\frac{\hbar^2}{2m_{\mathrm{LP}}}\int d^2\mathbf{r}\,\hat{\Psi}^\dagger_{\mathrm{LP}}(\mathbf{r})\nabla^2_{\mathbf{r}}\hat{\Psi}_{\mathrm{LP}}(\mathbf{r}) + |X_0|^4\frac{V_0^{XX}}{2}\int d^2\mathbf{r}\,\hat{\Psi}^\dagger_{\mathrm{LP}}(\mathbf{r})\hat{\Psi}^\dagger_{\mathrm{LP}}(\mathbf{r})\hat{\Psi}_{\mathrm{LP}}(\mathbf{r})\hat{\Psi}_{\mathrm{LP}}(\mathbf{r})$$

Heisenberg equation for the field operator:

$$i\hbar\frac{d}{dt}\hat{\Psi}_{\mathrm{LP}}(\mathbf{r},t) = -\frac{\hbar^2}{2m_{\mathrm{LP}}}\nabla^2_{\mathbf{r}}\hat{\Psi}_{\mathrm{LP}}(\mathbf{r},t) + U\hat{\Psi}^\dagger_{\mathrm{LP}}(\mathbf{r},t)\hat{\Psi}_{\mathrm{LP}}(\mathbf{r},t)\hat{\Psi}_{\mathrm{LP}}(\mathbf{r},t)$$

Mean field approximation (classical field):

$$\boxed{i\hbar\frac{d}{dt}\Psi_{\mathrm{LP}}(\mathbf{r},t) = -\frac{\hbar^2}{2m_{\mathrm{LP}}}\nabla^2_{\mathbf{r}}\Psi_{\mathrm{LP}}(\mathbf{r},t) + U\Psi^*_{\mathrm{LP}}(\mathbf{r},t)\Psi_{\mathrm{LP}}(\mathbf{r},t)\Psi_{\mathrm{LP}}(\mathbf{r},t)}$$

Driven-dissipative Gross-Pitaevskii equation

Add terms for dissipation and laser drive:

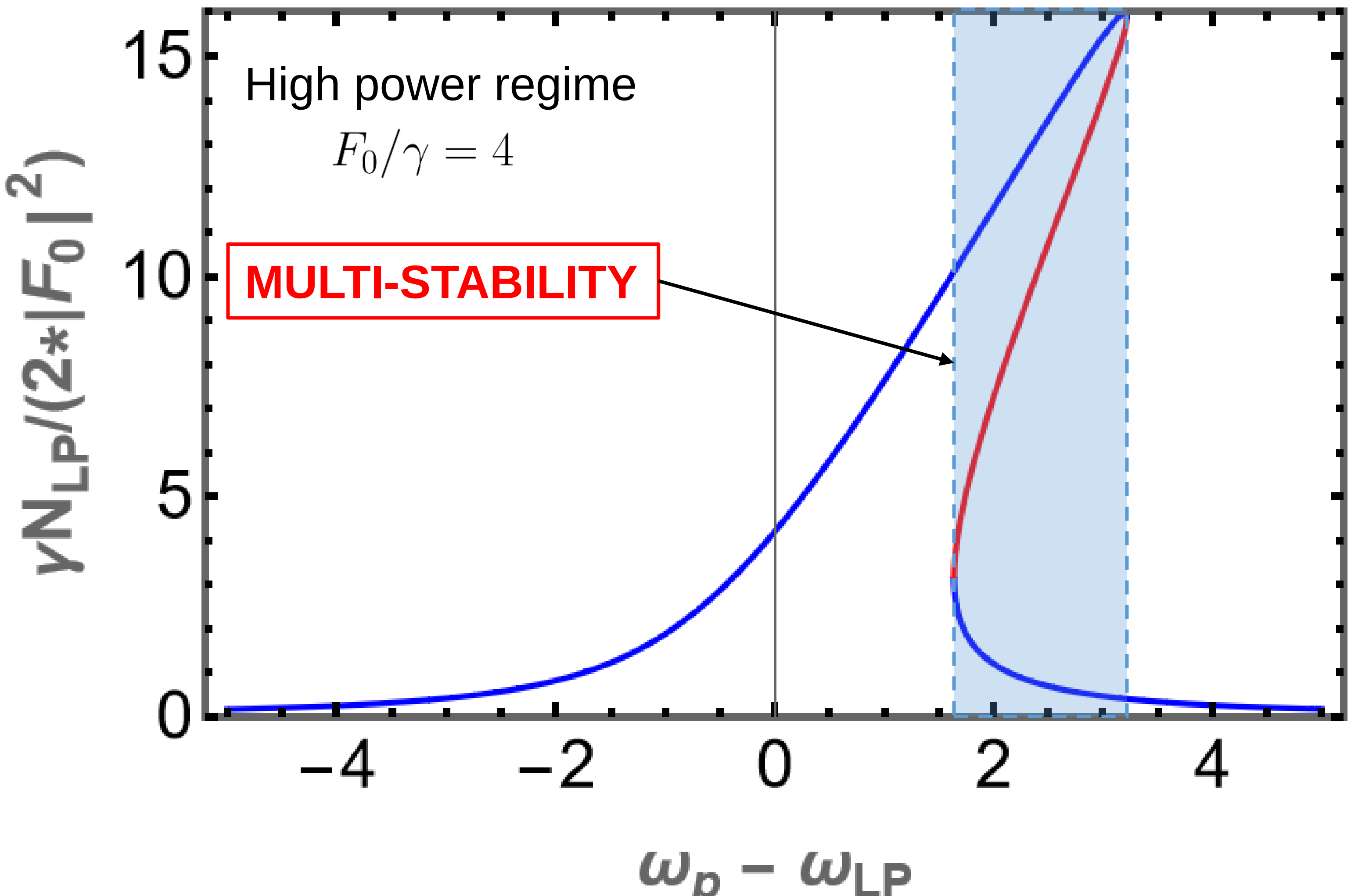
$$i\frac{d}{dt}\psi(\mathbf{r},t) = \left[\omega_0 - \frac{\hbar}{2m}\nabla^2 + \underbrace{\frac{U}{\hbar}n_{\mathrm{LP}}(\mathbf{r},t)}_{\text{Nonlinearity (interactions)}} - \underbrace{i\frac{\gamma}{2}}_{\text{Cavity losses}}\right]\psi(\mathbf{r},t) + \underbrace{iF_{\mathrm{exc}}(\mathbf{r},t)}_{\text{Excitation field}}$$

"Driven-dissipative Gross Pitaevskii equation":

$$\boxed{i\frac{d}{dt}\psi = \left[\omega_0 - \frac{\hbar}{2m}\nabla^2 + gn - i\frac{\gamma}{2}\right]\psi + iF}$$

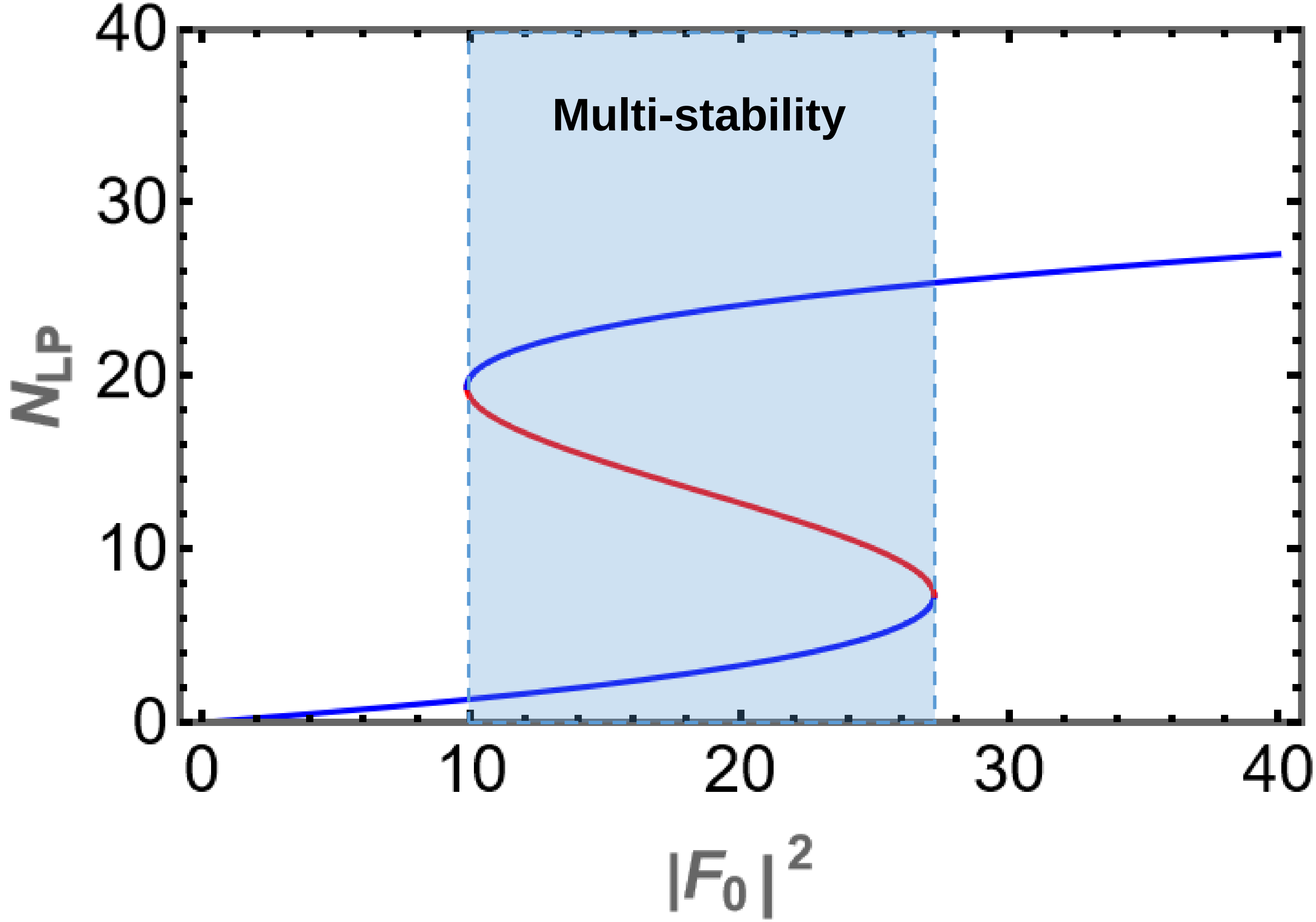
Multi-stability

Scanning the laser energy at fixed laser power.



Multi-stability

Scanning the laser power at fixed laser energy ($\hbar\omega_p$=$\hbar\omega_{LP}$+2γ).



Stability of the solutions

Driven-dissipative GPE: $$\boxed{i\frac{d}{dt}\psi = \left[\omega_0 - \frac{\hbar}{2m}\nabla^2 + gn - i\frac{\gamma}{2}\right]\psi + iF}$$

Assume ***k*=*0***, $F = \sqrt{\frac{\gamma}{2}}F_0 e^{-i\omega_\mathrm{p}t}$ and search solutions of the form $\psi(\mathbf{r},t) = \psi_\mathrm{ss}e^{-i\omega_\mathrm{p}t}$

Steady-state solution: $$\left[\omega_\mathrm{p} - (\omega_0 + g\left|\psi_\mathrm{ss}\right|^2) + i\frac{\gamma}{2}\right]\psi_\mathrm{ss} = i\sqrt{\frac{\gamma}{2}}F_0$$

$$\left[(\omega_p - (\omega_0 + gN_\mathrm{LP}))^2 + \left(\frac{\gamma}{2}\right)^2\right]N_\mathrm{LP} = \frac{\gamma}{2}\left|F_0\right|^2$$

Consider small perturbation on top of steady-state solution:

$$\boxed{\psi(\mathbf{r},t) = \underbrace{\sqrt{N_\mathrm{LP}}e^{-i\omega_\mathrm{p}t}}_{\text{Steady-state solution of GPE}} + \delta\psi_\mathrm{LP}e^{-i(\mathbf{k}\cdot\mathbf{r}-\omega_\mathrm{p}t)}}$$

Linearized GPE

$$i\partial_t \delta\psi = \left(\omega_0 + \frac{\hbar k^2}{2m_{\mathrm{LP}}} - \omega_{\mathrm{p}} - i\frac{\gamma}{2}\right)\delta\psi + \underbrace{2gN_{\mathrm{LP}}\delta\psi + gN_{\mathrm{LP}}\delta\psi^*}$$

Only keep first order terms in δψ and δψ*

Linearized GPE

$$i\partial_t \delta\psi = \left(\omega_0 + \frac{\hbar k^2}{2m_{\mathrm{LP}}} - \omega_{\mathrm{p}} - i\frac{\gamma}{2}\right)\delta\psi + 2gN_{\mathrm{LP}}\delta\psi + gN_{\mathrm{LP}}\delta\psi^*$$

$$-i\partial_t \delta\psi^* = \left(\omega_0 + \frac{\hbar k^2}{2m_{\mathrm{LP}}} - \omega_{\mathrm{p}} + i\frac{\gamma}{2}\right)\delta\psi^* + 2gN_{\mathrm{LP}}\delta\psi^* + gN_{\mathrm{LP}}\delta\psi$$

$$\boxed{i\partial_t \begin{pmatrix}\delta\psi \\ \delta\psi^*\end{pmatrix} = \begin{pmatrix} \left[\omega_{\mathrm{LP}} + \frac{\hbar k^2}{2m_{\mathrm{LP}}} + 2gN_{\mathrm{LP}}\right] - \omega_{\mathrm{p}} - i\frac{\gamma}{2} & gN_{\mathrm{LP}} \\ -gN_{\mathrm{LP}} & \omega_{\mathrm{p}} - \left[\omega_{\mathrm{LP}} + \frac{\hbar k^2}{2m_{\mathrm{LP}}} + 2gN_{\mathrm{LP}}\right] - i\frac{\gamma}{2} \end{pmatrix}\begin{pmatrix}\delta\psi \\ \delta\psi^*\end{pmatrix}}$$

$$i\partial_t \begin{pmatrix}\delta\psi \\ \delta\psi^*\end{pmatrix} = \mathcal{L}_{\mathrm{Bog}}\begin{pmatrix}\delta\psi \\ \delta\psi^*\end{pmatrix}$$

Linearized equation.

Unstable solution when at least one of the eigenvalues has a positive imaginary part.

Linearized GPE

$$i\partial_t \delta\psi = \left(\omega_0 + \frac{\hbar k^2}{2m_{\mathrm{LP}}} - \omega_{\mathrm{p}} - i\frac{\gamma}{2}\right)\delta\psi + 2gN_{\mathrm{LP}}\delta\psi + gN_{\mathrm{LP}}\delta\psi^*$$

$$-i\partial_t \delta\psi^* = \left(\omega_0 + \frac{\hbar k^2}{2m_{\mathrm{LP}}} - \omega_{\mathrm{p}} + i\frac{\gamma}{2}\right)\delta\psi^* + 2gN_{\mathrm{LP}}\delta\psi^* + gN_{\mathrm{LP}}\delta\psi$$

$$\boxed{i\partial_t \begin{pmatrix}\delta\psi \\ \delta\psi^*\end{pmatrix} = \begin{pmatrix} \left[\omega_{\mathrm{LP}} + \frac{\hbar k^2}{2m_{\mathrm{LP}}} + 2gN_{\mathrm{LP}}\right] - \omega_{\mathrm{p}} - i\frac{\gamma}{2} & gN_{\mathrm{LP}} \\ -gN_{\mathrm{LP}} & \omega_{\mathrm{p}} - \left[\omega_{\mathrm{LP}} + \frac{\hbar k^2}{2m_{\mathrm{LP}}} + 2gN_{\mathrm{LP}}\right] - i\frac{\gamma}{2} \end{pmatrix} \begin{pmatrix}\delta\psi \\ \delta\psi^*\end{pmatrix}}$$

$$i\partial_t \begin{pmatrix}\delta\psi \\ \delta\psi^*\end{pmatrix} = \mathcal{L}_{\mathrm{Bog}} \begin{pmatrix}\delta\psi \\ \delta\psi^*\end{pmatrix}$$

```
M = ( ωLP + 2*g*n - ωp - I*γ/2      g*n
      -g*n                          -ωLP - 2*g*n + ωp - I*γ/2 );
(*MatrixForm[M]*)
FullSimplify[Eigenvalues[M]]
```

$$\left\{-\frac{i\gamma}{2} - \sqrt{(g\,n + \omega_{\mathrm{LP}} - \omega_{\mathrm{p}})\,(3\,g\,n + \omega_{\mathrm{LP}} - \omega_{\mathrm{p}})},\ -\frac{i\gamma}{2} + \sqrt{(g\,n + \omega_{\mathrm{LP}} - \omega_{\mathrm{p}})\,(3\,g\,n + \omega_{\mathrm{LP}} - \omega_{\mathrm{p}})}\right\}$$

Unstable solutions

$$\omega_{\rm Bog} = -i\frac{\gamma}{2} \pm \sqrt{(\omega_{\rm LP}(k) + gN_{LP} - \omega{\rm p})(\omega_{\rm LP}(k) + 3gN_{LP} - \omega{\rm p})}$$

Stability condition at *k*=0:

$$(gN_{\rm LP} - \Delta)(3gN_{\rm LP} - \Delta) \leq -\frac{\gamma^2}{4} \qquad \text{(with } \Delta = \omega_{\rm p} - \omega_{\rm LP}\text{)}$$

$$3(gN_{\rm LP})^2 - 4\Delta(gN_{\rm LP}) + \Delta^2 + \frac{\gamma^2}{4} \leq 0$$

Second order polynomial in $gN_{\rm LP}$ with real roots for positive discriminant:

$$16\Delta^2 - 12(\Delta^2 + \frac{\gamma^2}{4}) \geq 0 \qquad \Rightarrow \qquad \boxed{\Delta \geq \frac{\sqrt{3}}{2}} \quad \text{or} \quad \Delta \leq -\frac{\sqrt{3}}{2}$$

Two real roots: $$gN_{\rm LP}^{\pm} = \underbrace{\frac{2}{3}\Delta \pm \frac{1}{3}\sqrt{\Delta^2 - 3\left(\frac{\gamma}{2}\right)^2}}_{\text{Positive only when } \boxed{\Delta \geq 0}}$$

Unstable solutions

Existence of unstable solutions when:

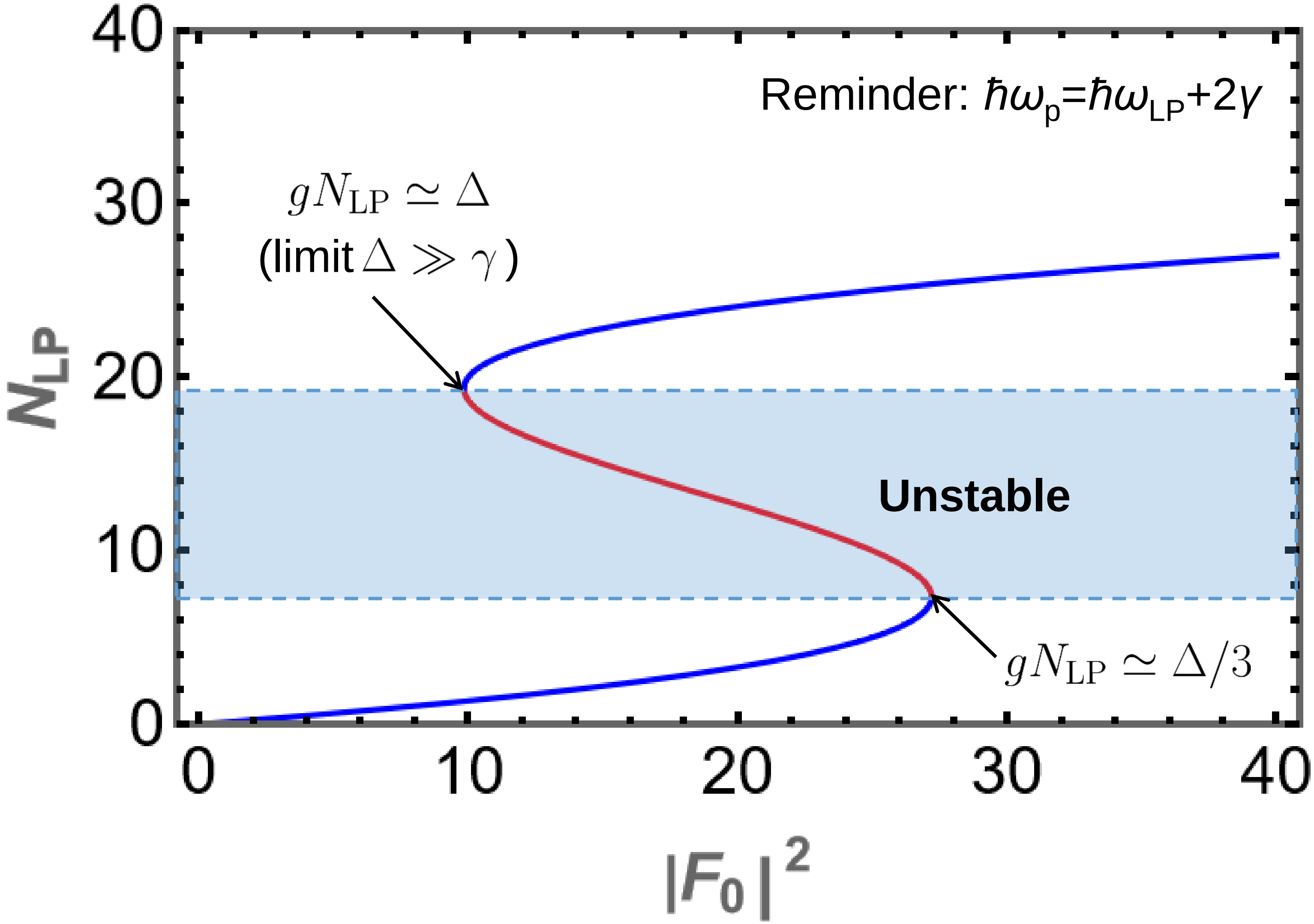
$$\omega_{\mathrm{p}} \geq \omega_{\mathrm{LP}} + \frac{\sqrt{3}}{2}\gamma$$

Obtained in the range:

$$\frac{2}{3}\Delta - \frac{1}{3}\sqrt{\Delta^2 - 3\left(\frac{\gamma}{2}\right)^2} \leq gN_{\mathrm{LP}} \leq \frac{2}{3}\Delta + \frac{1}{3}\sqrt{\Delta^2 - 3\left(\frac{\gamma}{2}\right)^2}$$

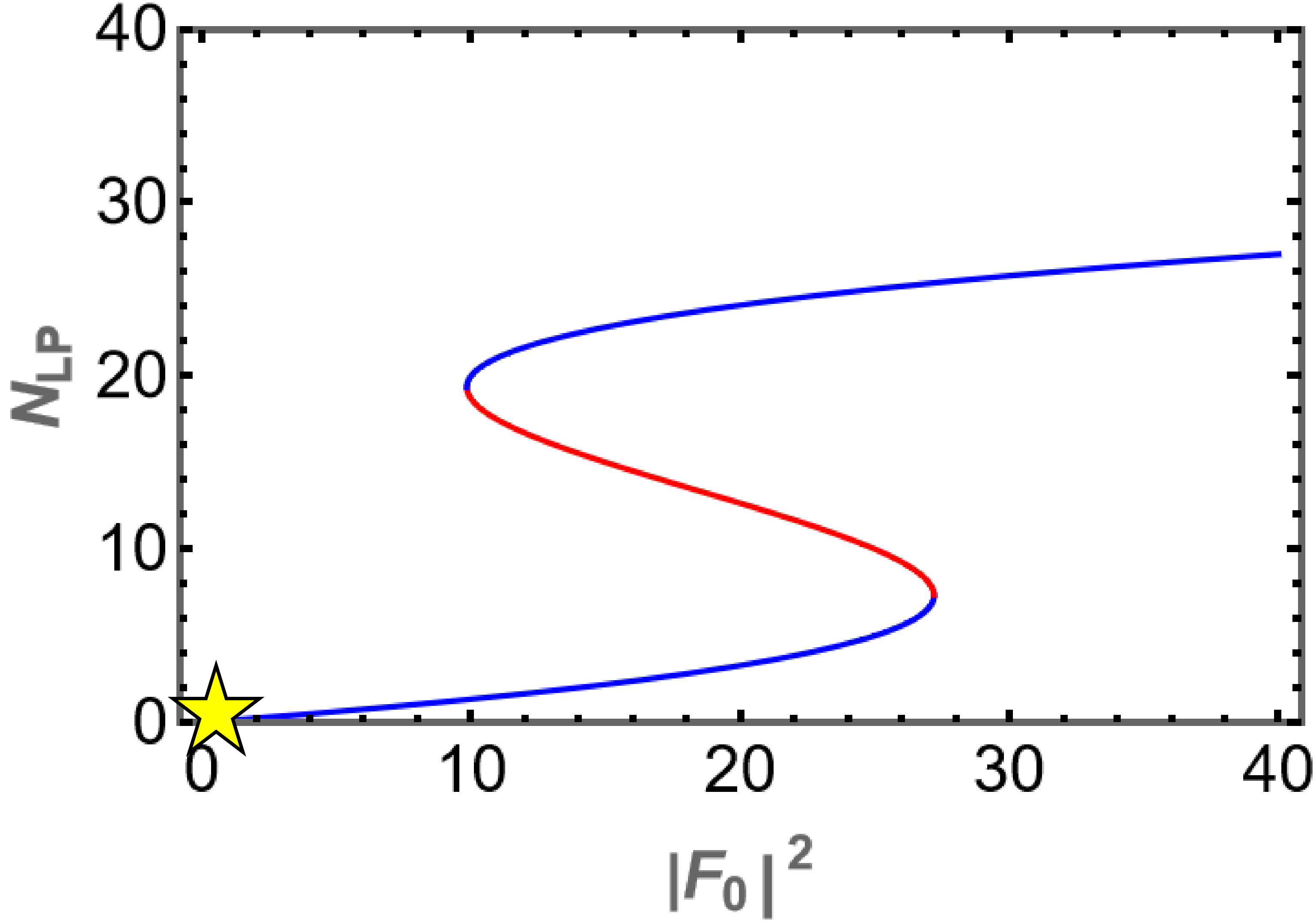
Unstable solutions

One unstable solution ⇒ **BISTABILITY**



Bogoliubov spectrum of excitations

LOW EXCITATION POWER (N_{LP} = 0.1)



Bogoliubov spectrum of excitations

LOW EXCITATION POWER (N_{LP} = 0.1)

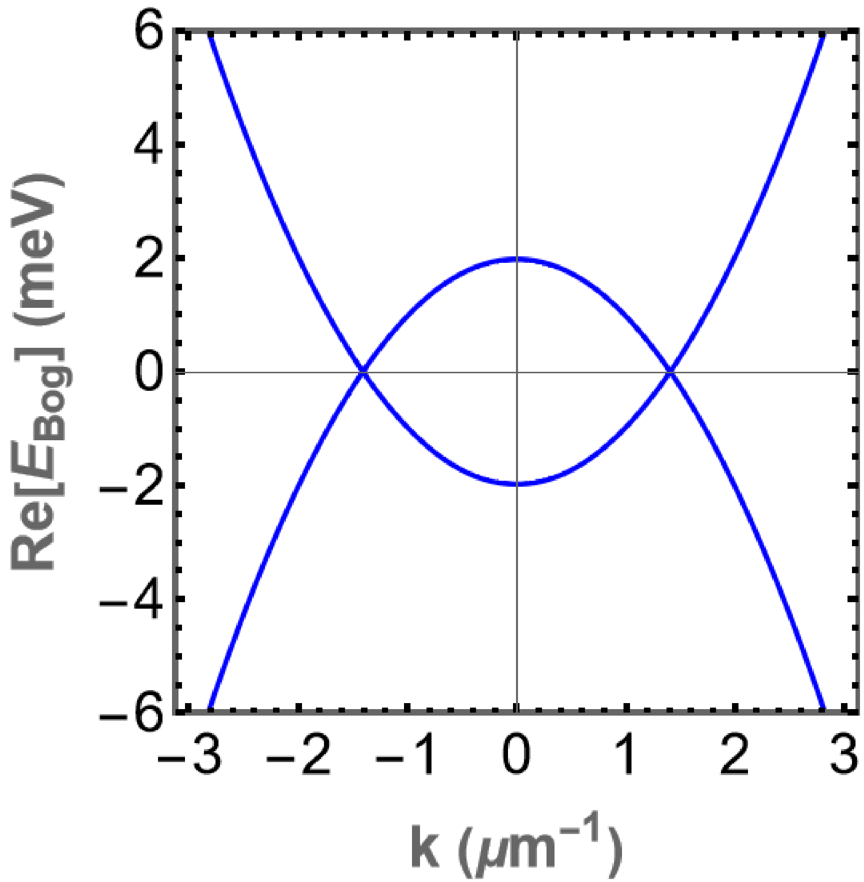
$$gN_{\mathrm{LP}} \ll \Delta \;\Rightarrow\; \omega_{\mathrm{Bog}} \simeq -i\frac{\gamma}{2} \pm [\omega_{\mathrm{LP}}(k) - \omega\mathrm{p}] \;\Rightarrow\; \Re[\omega_{\mathrm{Bog}}] \simeq \omega_{\mathrm{LP}}(k) - \omega_{\mathrm{p}}$$

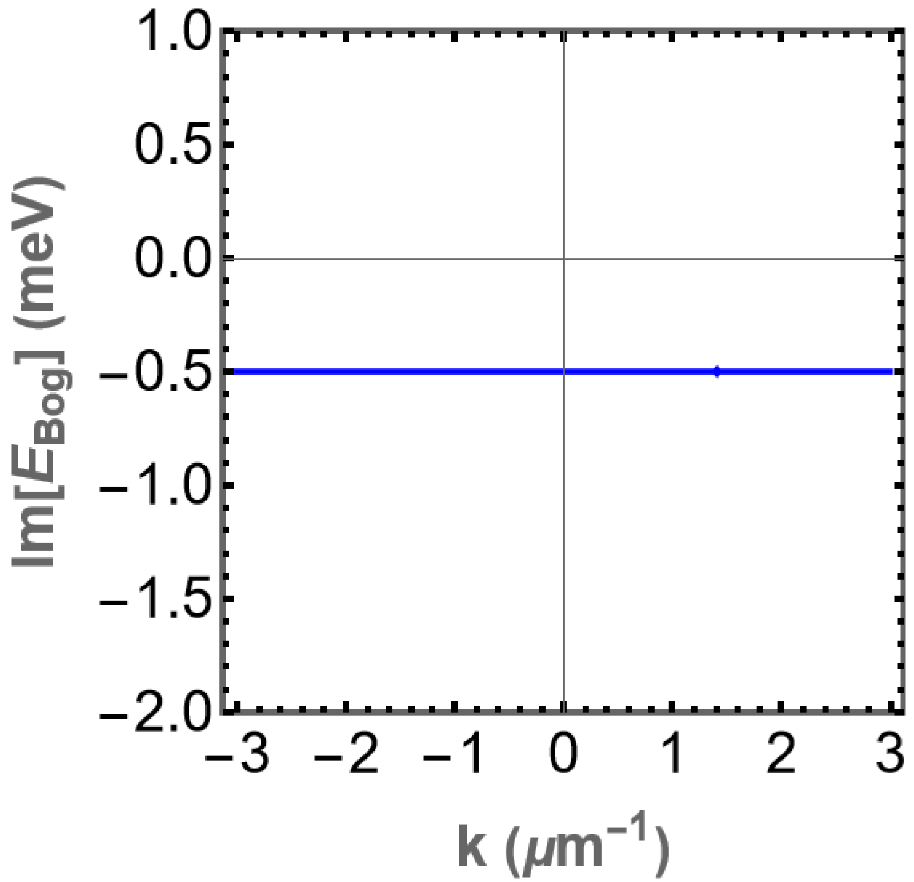
⇒ One recovers the polariton dispersion (linear regime).

Bogoliubov spectrum of excitations

LOW EXCITATION POWER (N_{LP} = 0.1)

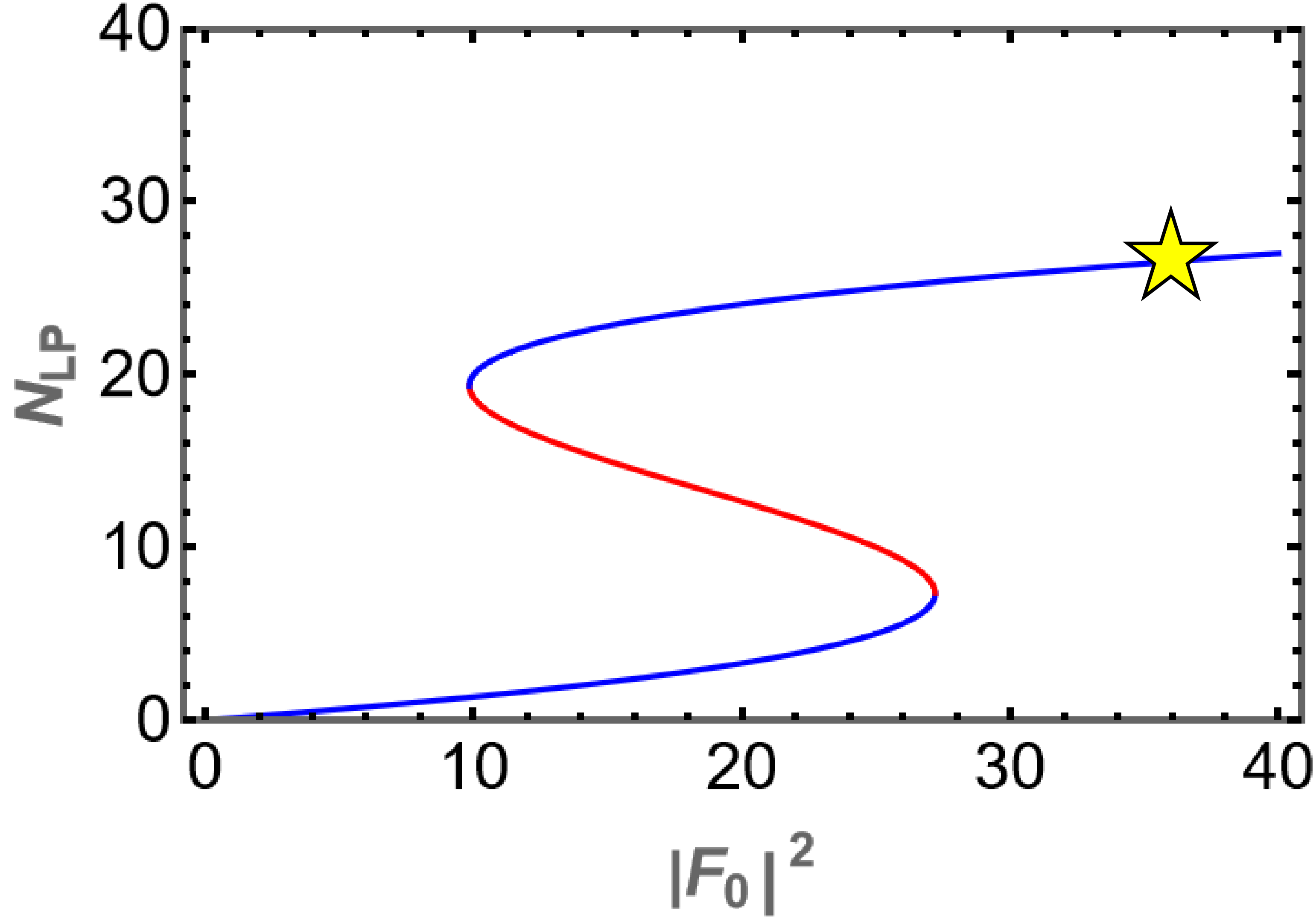
$$gN_{\mathrm{LP}} \ll \Delta \;\Rightarrow\; \omega_{\mathrm{Bog}} \simeq -i\frac{\gamma}{2} \pm [\omega_{\mathrm{LP}}(k) - \omega \mathrm{p}] \;\Rightarrow\; \Re[\omega_{\mathrm{Bog}}] \simeq \omega_{\mathrm{LP}}(k) - \omega_{\mathrm{p}}$$





Bogoliubov spectrum of excitations

HIGH EXCITATION POWER ($N_{LP} = 27$)



Bogoliubov spectrum of excitations

HIGH EXCITATION POWER (N_{LP} = 27)

$gN_{\mathrm{LP}} \gg \Delta$ ⇒ Taylor expansion for small *k* $\frac{\hbar k^2}{2m_{\mathrm{LP}}} - \Delta \ll gN_{\mathrm{LP}}$

$$\omega_{\mathrm{Bog}} = -i\frac{\gamma}{2} \pm \left(\frac{\hbar}{2m_{\mathrm{LP}}}k^2 + gN_{LP} - \Delta\right)^{1/2}\left(\frac{\hbar}{2m_{\mathrm{LP}}}k^2 + 3gN_{LP} - \Delta\right)^{1/2}$$

$$\simeq -i\frac{\gamma}{2} \pm \sqrt{3}gN_{\mathrm{LP}}\left[\left(1 + \frac{1}{2gN_{\mathrm{LP}}}\left(\frac{\hbar k^2}{2m_{\mathrm{LP}}} - \Delta\right)\right)\left(1 + \frac{1}{6gN_{\mathrm{LP}}}\left(\frac{\hbar k^2}{2m_{\mathrm{LP}}} - \Delta\right)\right)\right]$$

$$\simeq -i\frac{\gamma}{2} \pm \left[\frac{2}{\sqrt{3}}(\omega_{\mathrm{LP}}(k) - \omega_{\mathrm{p}}) + \sqrt{3}gN_{\mathrm{LP}}\right]$$

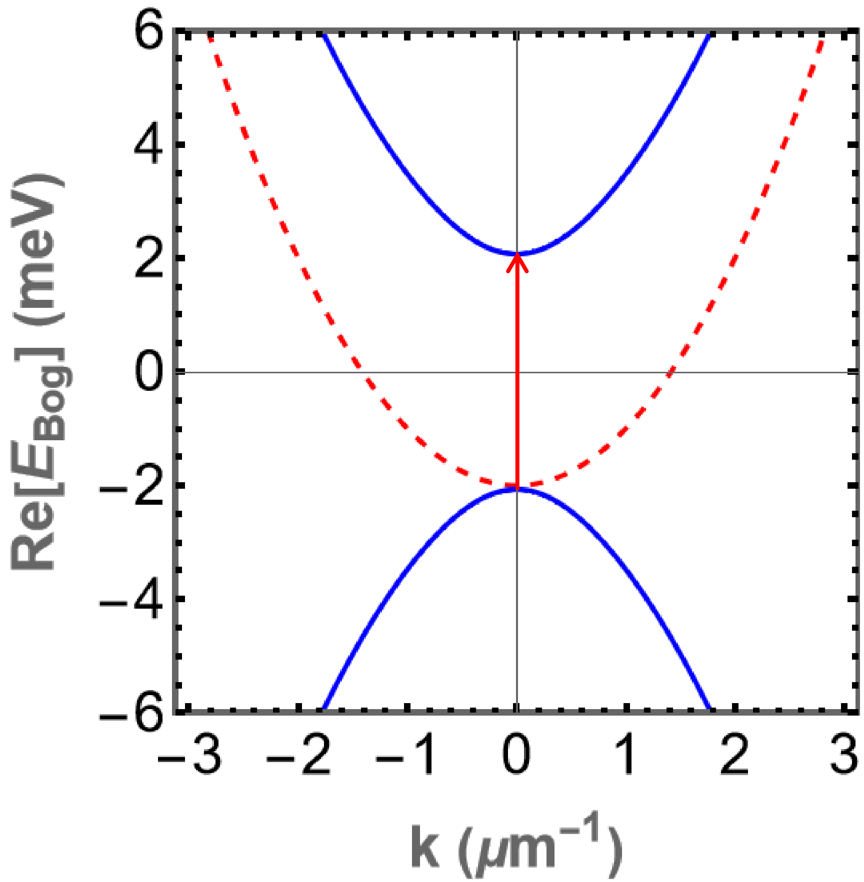
$$\Re[\omega_{\mathrm{Bog}}] \simeq \pm\left[\frac{2}{\sqrt{3}}(\omega_{\mathrm{LP}}(k) - \omega_{\mathrm{p}}) + \sqrt{3}gN_{\mathrm{LP}}\right]$$

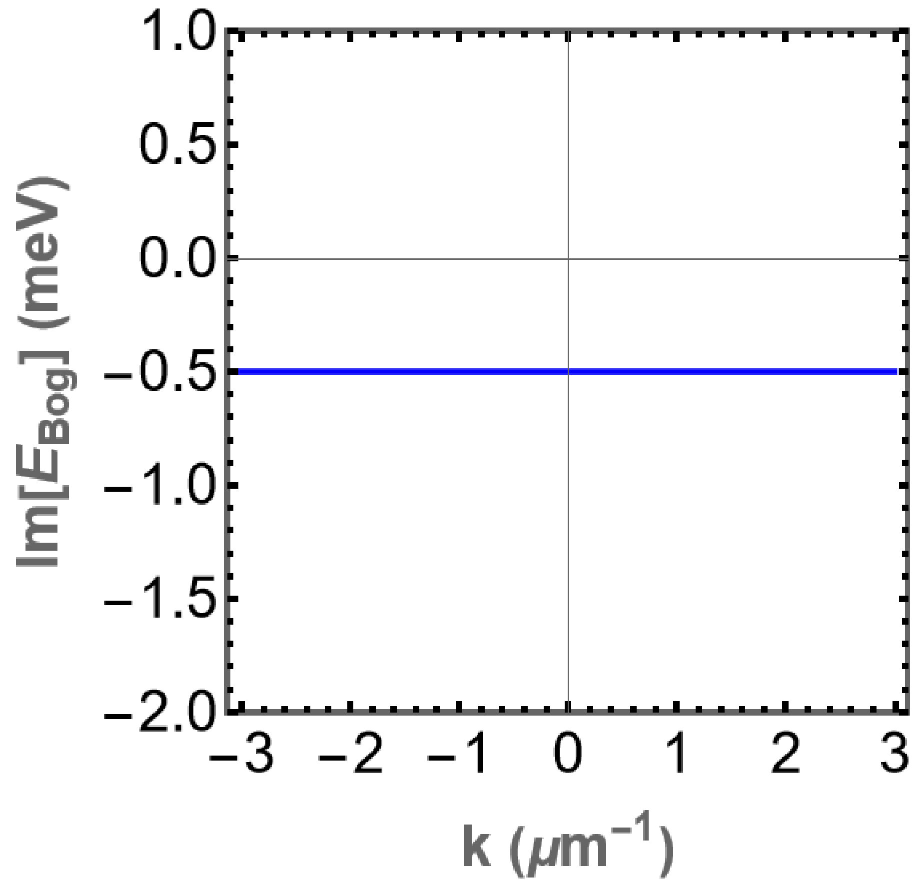
⇒ Two parabolic dispersion shifted by the interaction.

Bogoliubov spectrum of excitations

HIGH EXCITATION POWER (N_{LP} = 27)

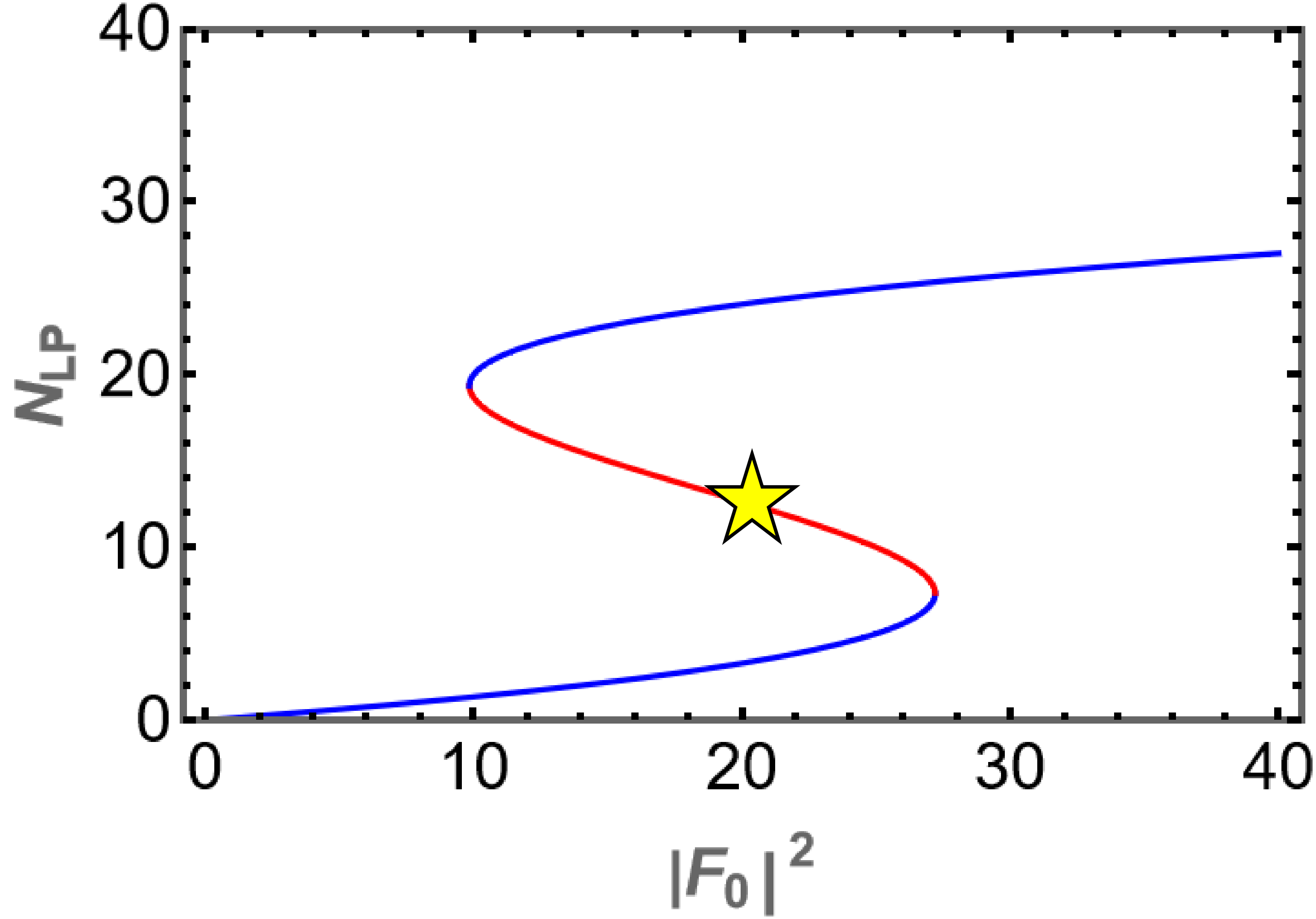
$$gN_{\rm LP} \gg \Delta \quad \Rightarrow \quad \Re[\omega_{\rm Bog}] \simeq \pm\left[\frac{2}{\sqrt{3}}(\omega_{\rm LP}(k) - \omega_{\rm p}) + \sqrt{3}gN_{\rm LP}\right]$$





Bogoliubov spectrum of excitations

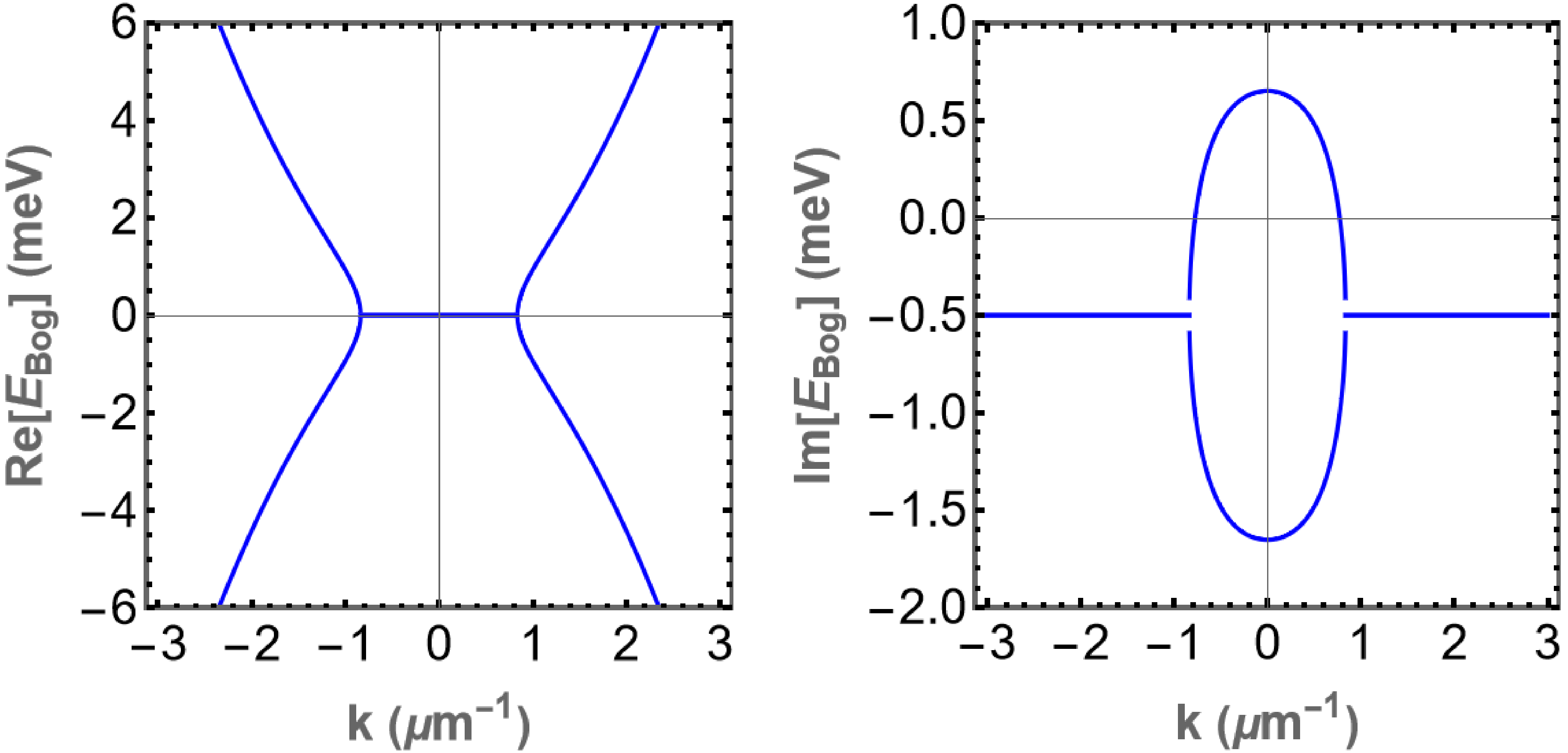
POLARITON POPULATION WITHIN UNSTABLE RANGE (N_{LP} = 13)



Bogoliubov spectrum of excitations

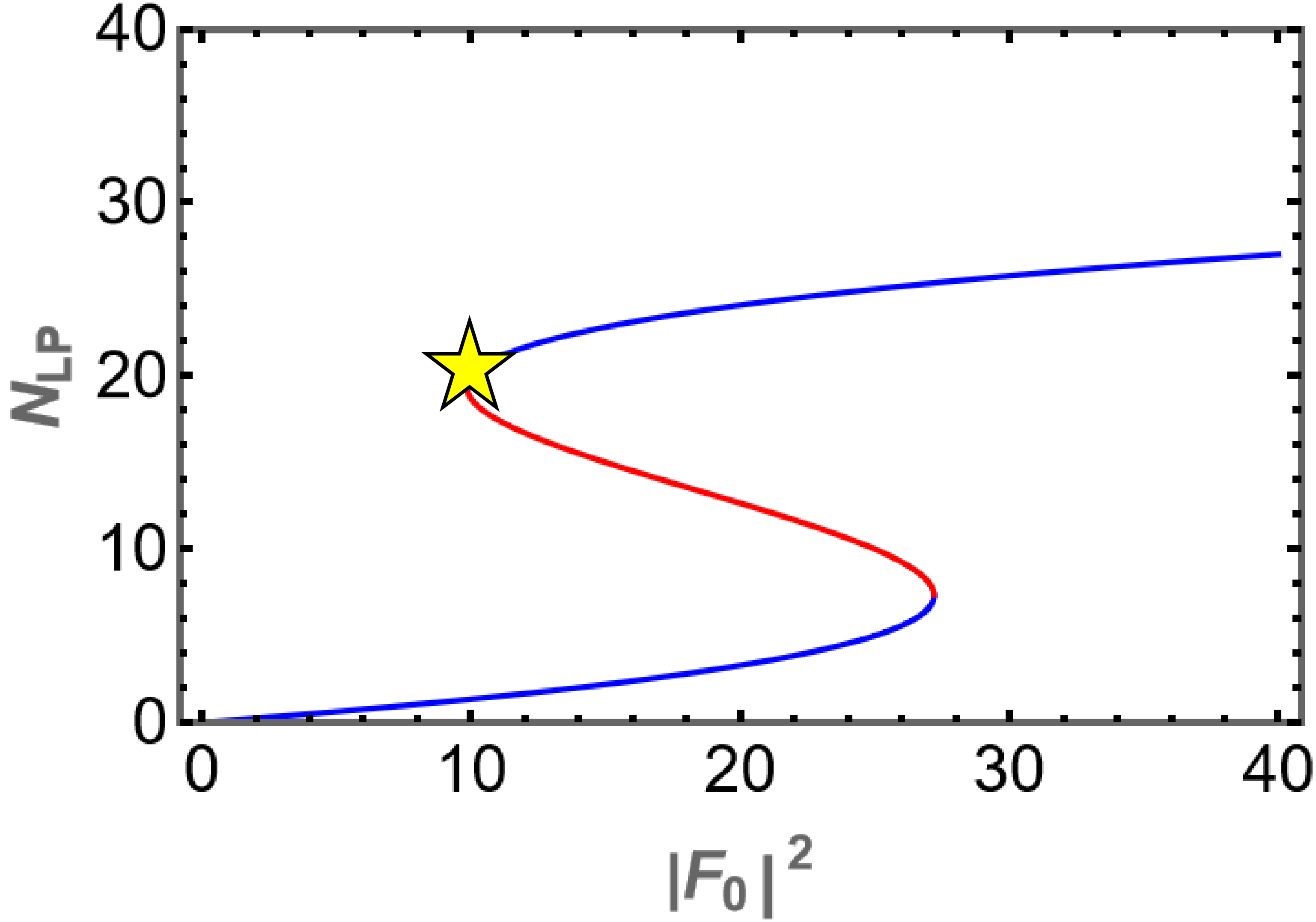
POLARITON POPULATION WITHIN UNSTABLE RANGE (N_{LP} = 13)

⇒ Expect positive imaginary part next to k = 0.



Bogoliubov spectrum of excitations

MEDIUM EXCITATION POWER ($gN_{LP} \approx \Delta$)



Bogoliubov spectrum of excitations

MEDIUM EXCITATION POWER ($gN_{LP} \approx \Delta$)

$$\omega_{\text{Bog}} = -i\frac{\gamma}{2} \pm \sqrt{(\omega_{\text{LP}}(k) + gN_{LP} - \omega\text{p})(\omega_{\text{LP}}(k) + 3gN_{LP} - \omega\text{p})}$$

$$gN_{\text{LP}} \simeq \Delta \quad \Rightarrow \quad \omega_{\text{Bog}} \simeq -i\frac{\gamma}{2} \pm \sqrt{\omega_{\text{LP}}(k)(\omega_{\text{LP}}(k) + 2gN_{\text{LP}})}$$

Taylor expansion (large *k*)

$$\omega_{\text{LP}}(k) \gg 2gN_{\text{LP}}$$

$$\Rightarrow \quad \Re[\omega_{\text{Bog}}] \simeq \pm[\omega_{\text{LP}}(k) + gN_{\text{LP}}]$$

$\boxed{\text{Parabolic dispersion}}$

Taylor expansion (small *k*)

$$2gN_{\text{LP}} \gg \omega_{\text{LP}}(k)$$

$$\Rightarrow \quad \Re[\omega_{\text{Bog}}] \simeq \pm\sqrt{\frac{\hbar}{m}gN_{\text{LP}}} \times k$$

$\boxed{\text{Linear dispersion}}$

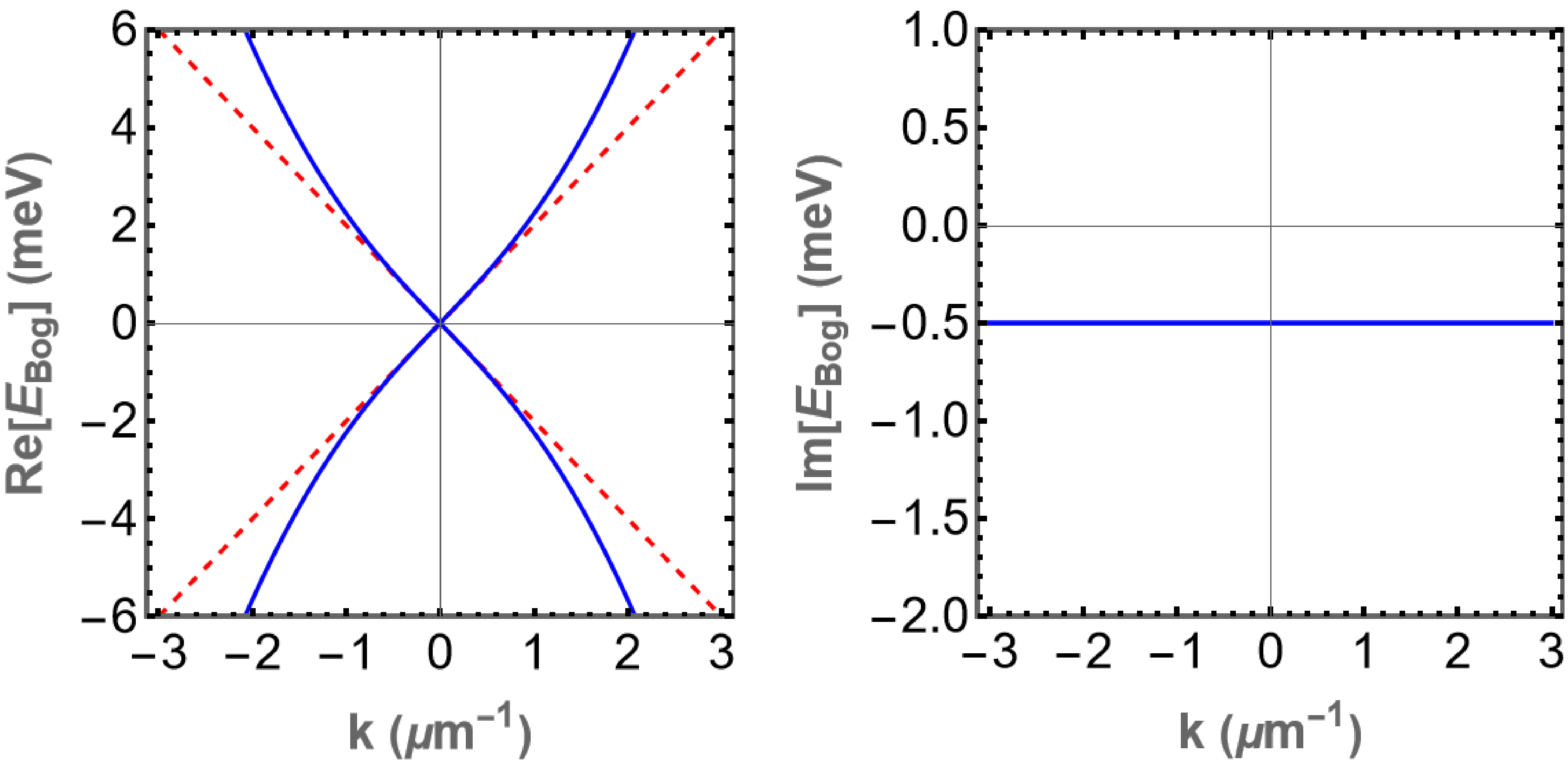
⇒ Phonon-like dispersion

“Speed of sound”: $c_{\text{s}} = \sqrt{\hbar g N_{\text{LP}}/m_{\text{LP}}}$

Bogoliubov spectrum of excitations

MEDIUM EXCITATION POWER ($gN_{LP} \approx \Delta$)

$$gN_{\mathrm{LP}} \simeq \Delta \quad \Rightarrow \quad \omega_{\mathrm{Bog}} \simeq -i\frac{\gamma}{2} \pm \sqrt{\omega_{\mathrm{LP}}(k)(\omega_{\mathrm{LP}}(k) + 2gN_{\mathrm{LP}})}$$



ARTICLE

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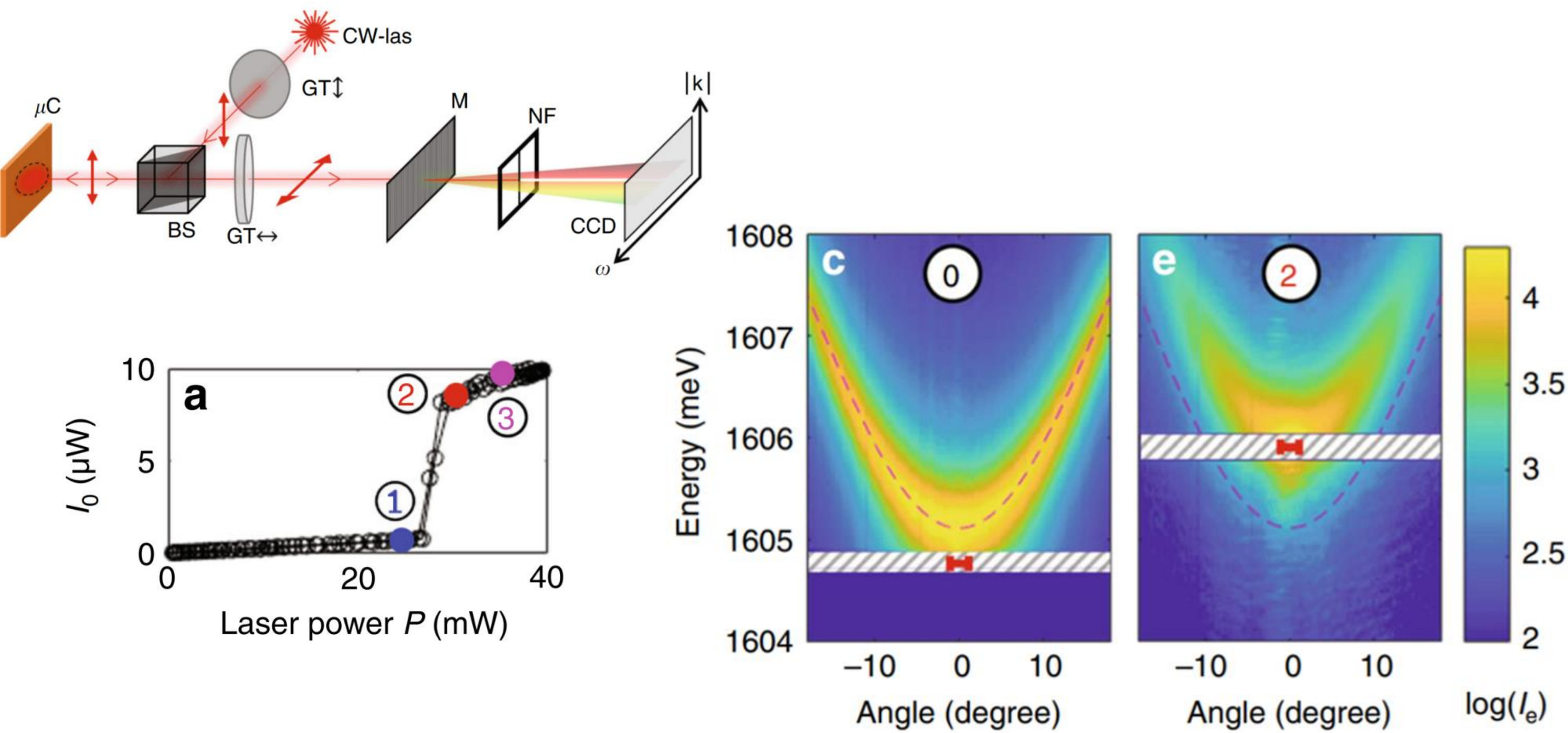
OPEN

Dispersion relation of the collective excitations in a resonantly driven polariton fluid

Petr Stepanov[1], Ivan Amelio[2], Jean-Guy Rousset[1,3], Jacqueline Bloch[4], Aristide Lemaître[4], Alberto Amo[5], Anna Minguzzi[6], Iacopo Carusotto[2] & Maxime Richard[1]



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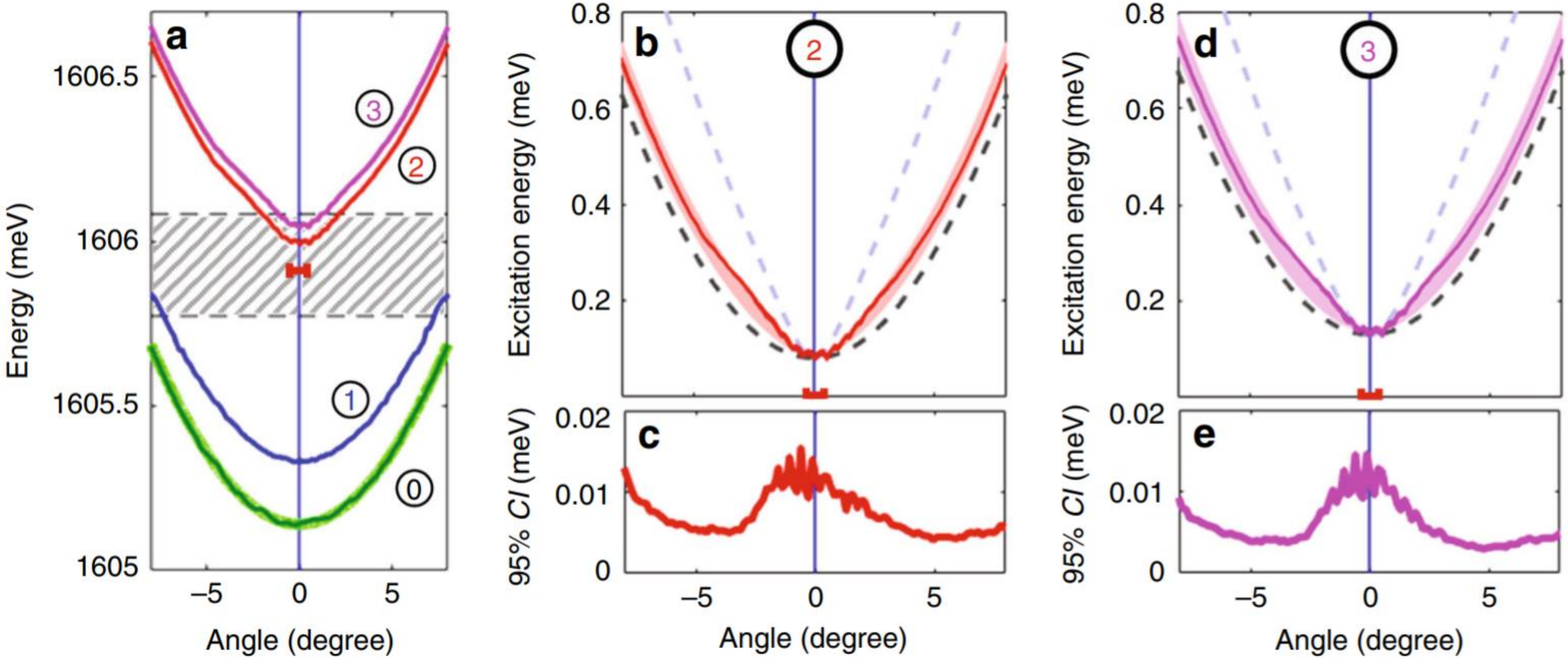
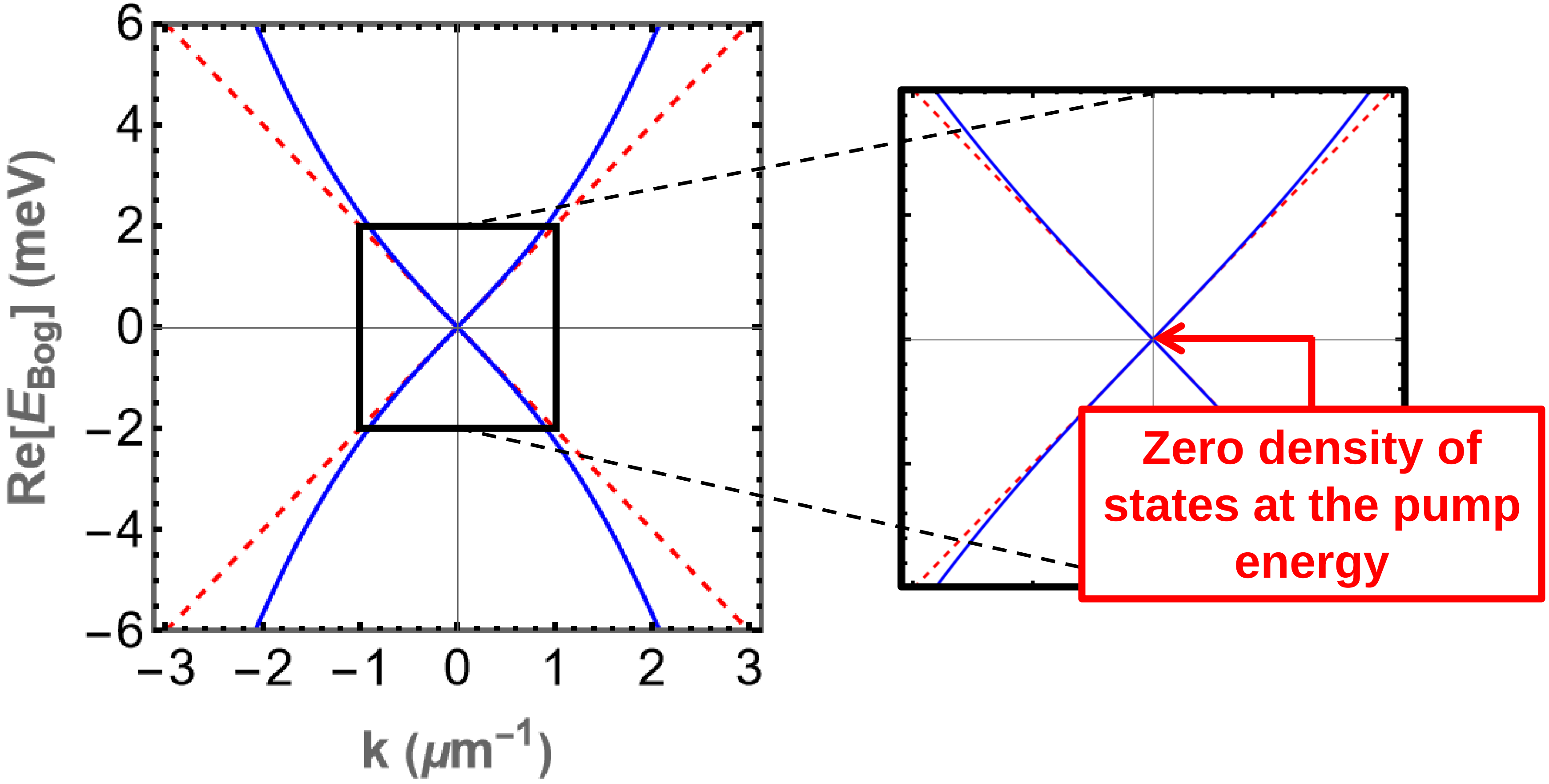


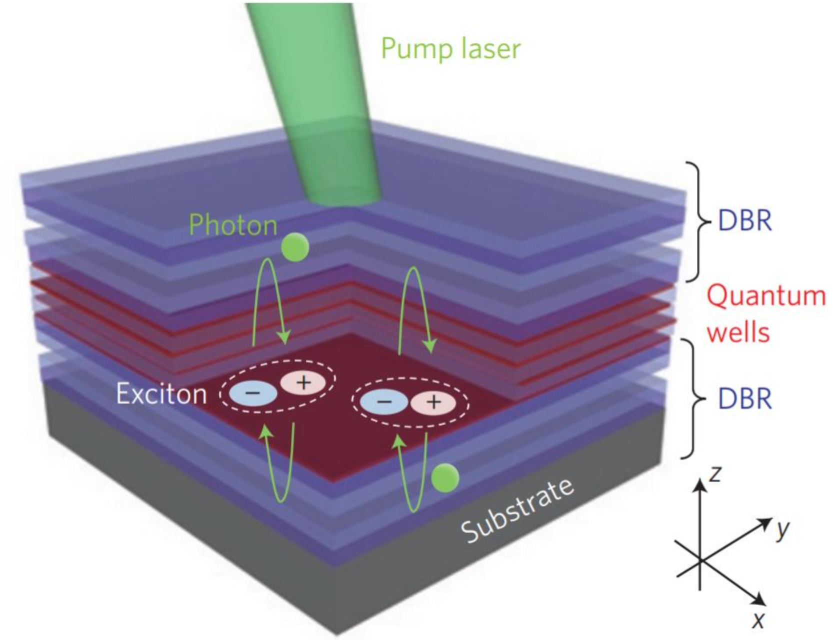
The special case of sonic dispersion relation



No available Bogoliubov mode at the pump energy
⇒ Consequences for polariton superfluidity

Polariton superfluidity

Superfluidity is “the characteristic property of a fluid with **zero viscosity** which therefore flows **without any loss of kinetic energy**”



Induce polariton flow
⇒ pump at $\boldsymbol{k_p \neq 0}$

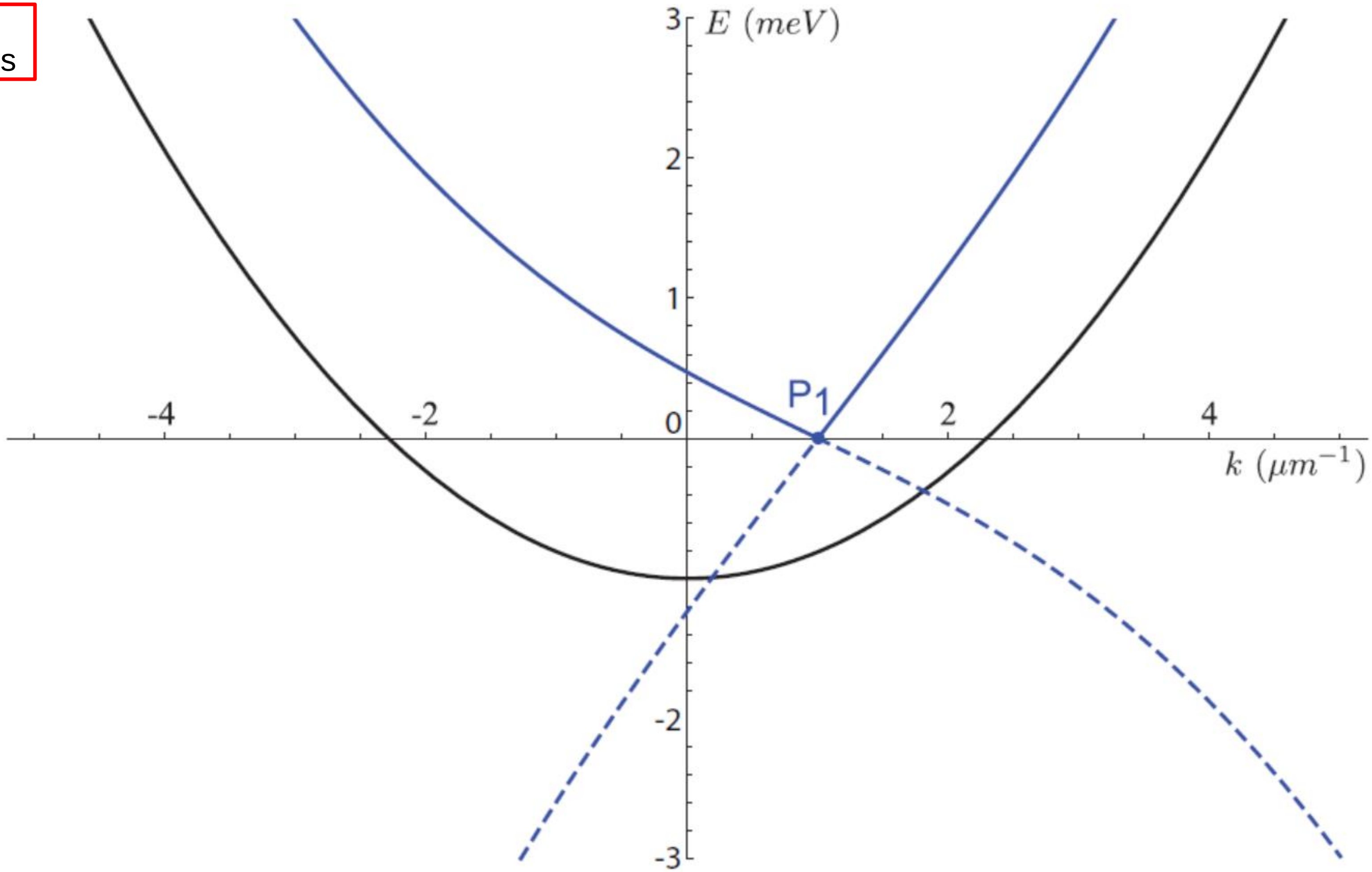
Modified Bogoliubov dispersion:

$$\omega_{\mathrm{Bog}} = (\mathbf{k}-\mathbf{k}_{\mathrm{p}})\cdot\frac{\hbar\mathbf{k}_{\mathrm{p}}}{m_{\mathrm{LP}}} - i\frac{\gamma}{2} \pm \sqrt{\left(\omega_{\mathrm{LP}}(\mathbf{k}_{\mathrm{p}}) + \frac{\hbar(\mathbf{k}-\mathbf{k}_{\mathrm{p}})^2}{2m_{\mathrm{LP}}} + gN_{\mathrm{LP}} - \omega_{\mathrm{p}}\right)\left(\omega_{\mathrm{LP}}(\mathbf{k}_{\mathrm{p}}) + \frac{\hbar(\mathbf{k}-\mathbf{k}_{\mathrm{p}})^2}{2m_{\mathrm{LP}}} + 3gN_{\mathrm{LP}} - \omega_{\mathrm{p}}\right)}$$

Subsonic flow $v_p < c_s$

$$gN_{\rm LP} \simeq \Delta \quad \Rightarrow \quad \omega_{\rm Bog}(\mathbf{k}) \simeq (\mathbf{k}-\mathbf{k}_{\rm p}) \cdot \frac{\hbar \mathbf{k}_{\rm p}}{m_{\rm LP}} \pm c_{\rm s}\,|\mathbf{k}-\mathbf{k}_{\rm p}|$$

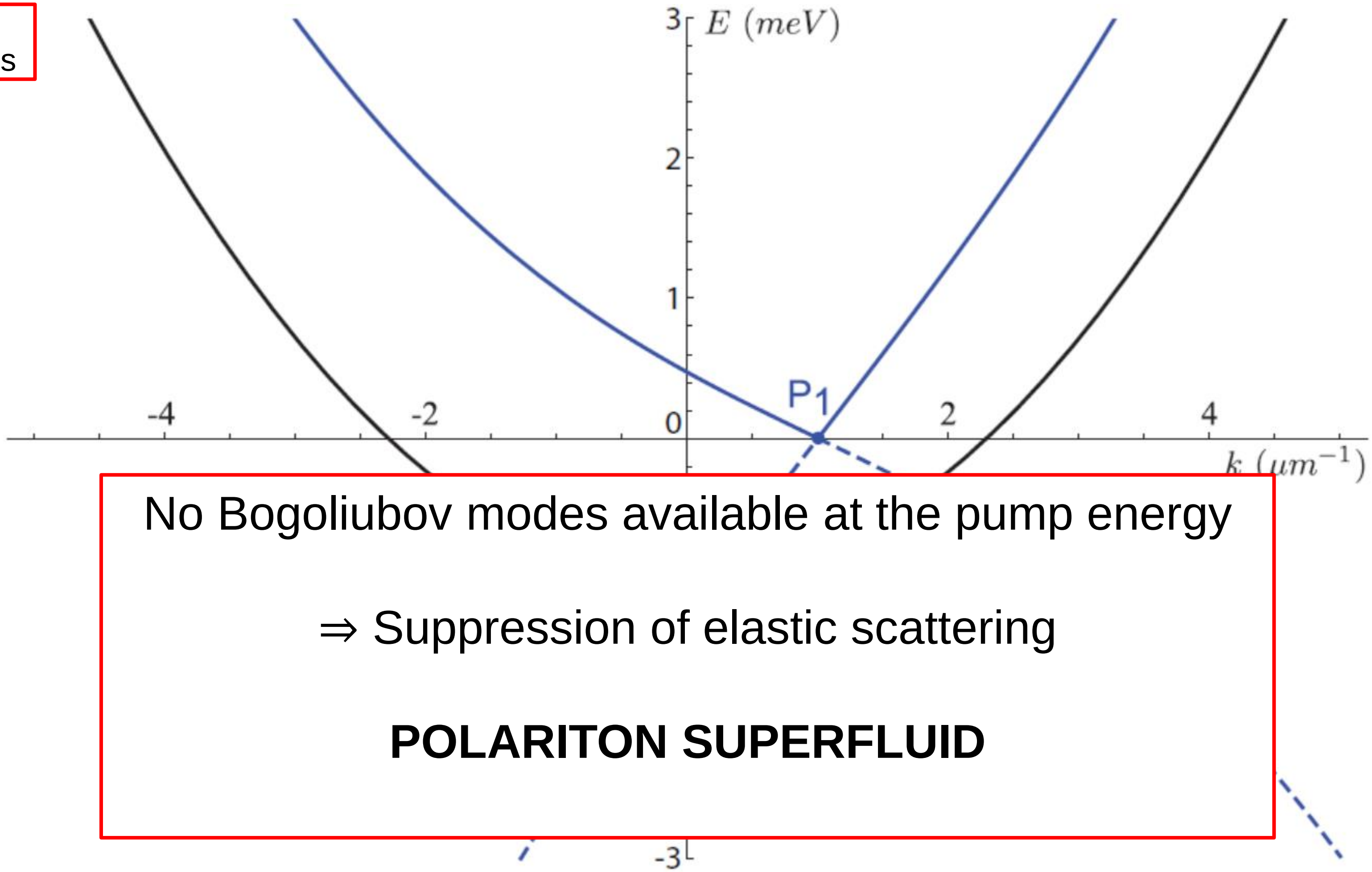
$\boxed{v_p < c_s}$



Subsonic flow $v_p < c_s$

$$gN_{\mathrm{LP}} \simeq \Delta \quad \Rightarrow \quad \omega_{\mathrm{Bog}}(\mathbf{k}) \simeq (\mathbf{k}-\mathbf{k}_{\mathrm{p}}) \cdot \frac{\hbar \mathbf{k}_{\mathrm{p}}}{m_{\mathrm{LP}}} \pm c_{\mathrm{s}} \left|\mathbf{k}-\mathbf{k}_{\mathrm{p}}\right|$$

$\boxed{v_p < c_s}$



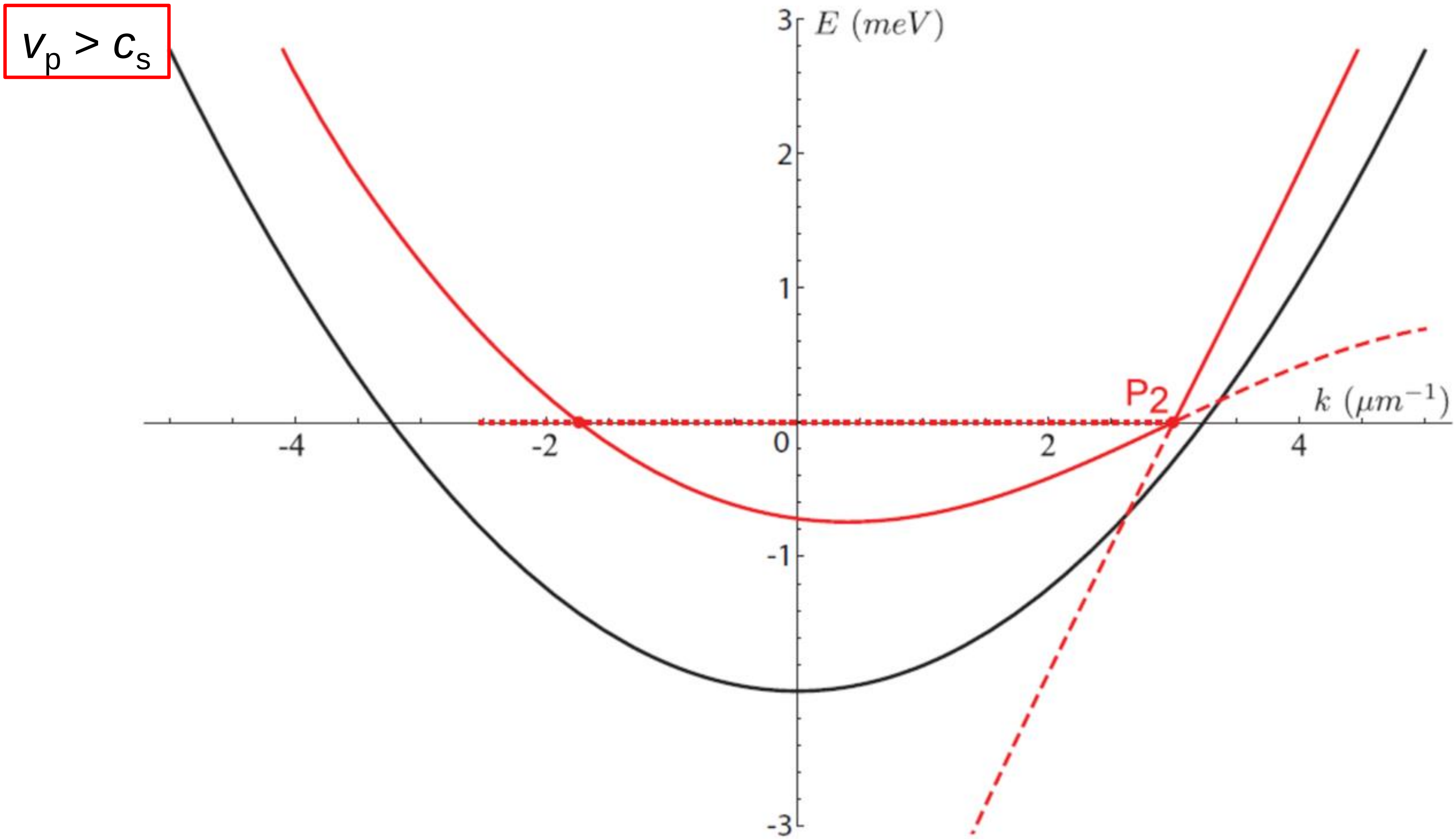
No Bogoliubov modes available at the pump energy

⇒ Suppression of elastic scattering

POLARITON SUPERFLUID

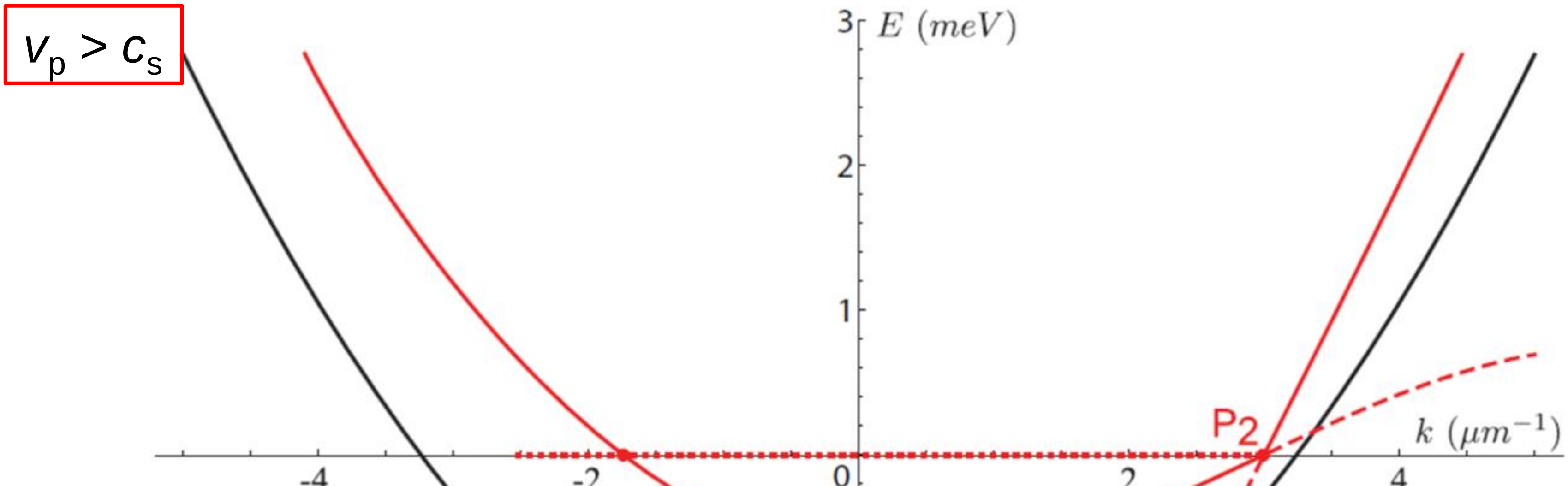
Supersonic flow $v_\mathrm{p} > c_\mathrm{s}$

$$gN_\mathrm{LP} \simeq \Delta \quad \Rightarrow \quad \omega_\mathrm{Bog}(\mathbf{k}) \simeq (\mathbf{k} - \mathbf{k}_\mathrm{p}) \cdot \frac{\hbar \mathbf{k}_\mathrm{p}}{m_\mathrm{LP}} \pm c_\mathrm{s} \, |\mathbf{k} - \mathbf{k}_\mathrm{p}|$$



Supersonic flow $v_p > c_s$

$$g N_{\mathrm{LP}} \simeq \Delta \quad \Rightarrow \quad \omega_{\mathrm{Bog}}(\mathbf{k}) \simeq (\mathbf{k}-\mathbf{k}_{\mathrm{p}}) \cdot \frac{\hbar \mathbf{k}_{\mathrm{p}}}{m_{\mathrm{LP}}} \pm c_{\mathrm{s}} \, |\mathbf{k}-\mathbf{k}_{\mathrm{p}}|$$



Continuum of Bogoliubov modes available at the pump energy

⇒ Elastic scattering allowed

NOT A SUPERFLUID PROPAGATION

-3

VOLUME 93, NUMBER 16 PHYSICAL REVIEW LETTERS week ending 15 OCTOBER 2004

Probing Microcavity Polariton Superfluidity through Resonant Rayleigh Scattering

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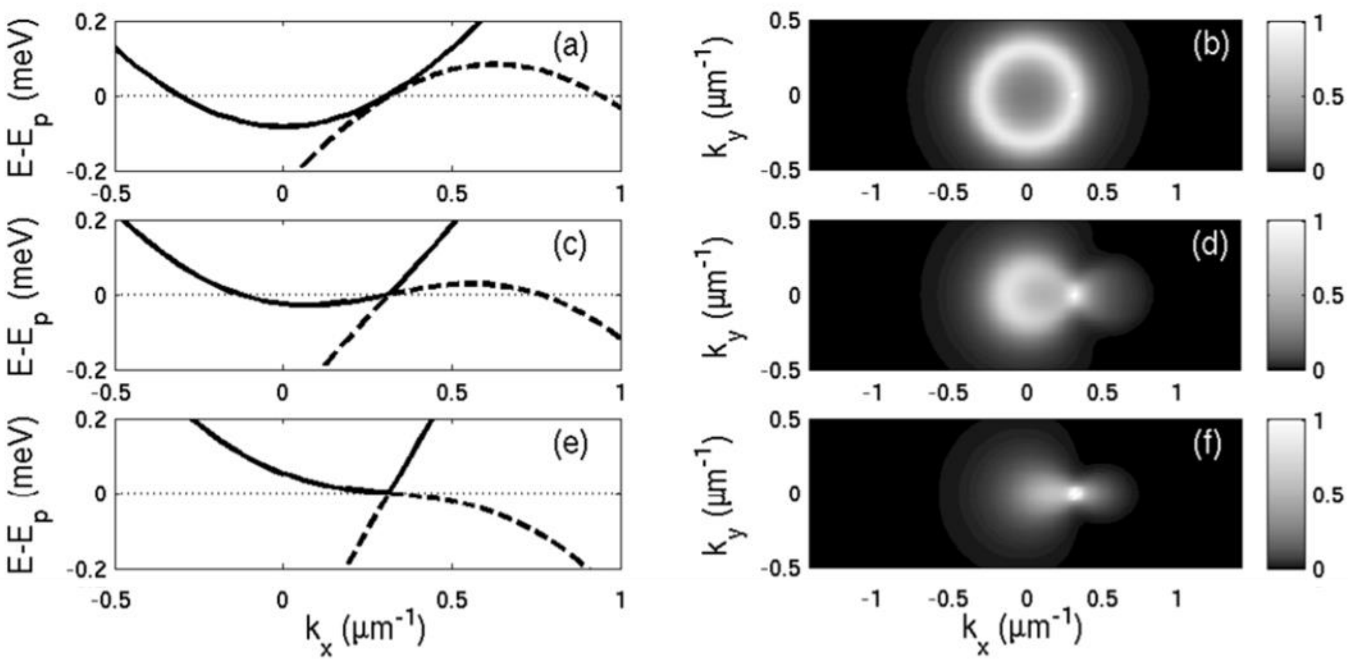
(Received 23 April 2004; published 13 October 2004)

Subsonic case

We study the motion of a polariton fluid injected into a planar microcavity by a continuous wave laser. In the presence of static defects, the spectrum of the Bogoliubov-like excitations reflects onto the shape and intensity of the resonant Rayleigh scattering emission pattern in both momentum and real space.



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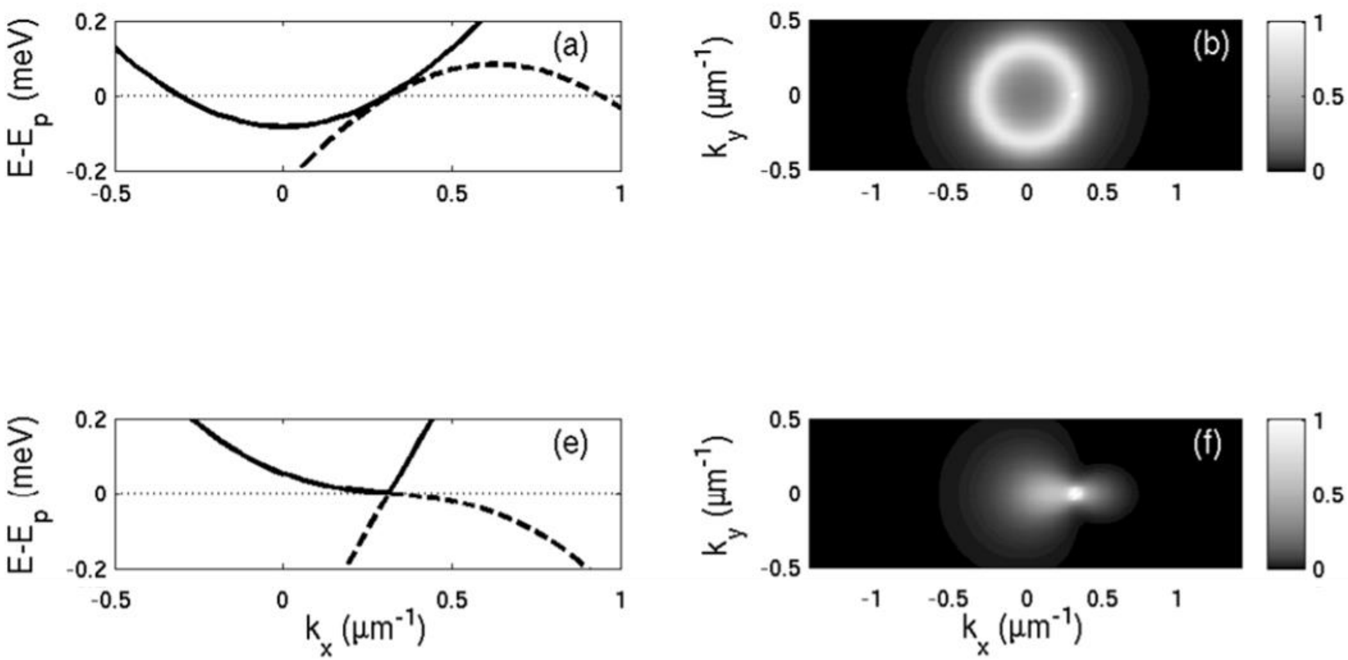
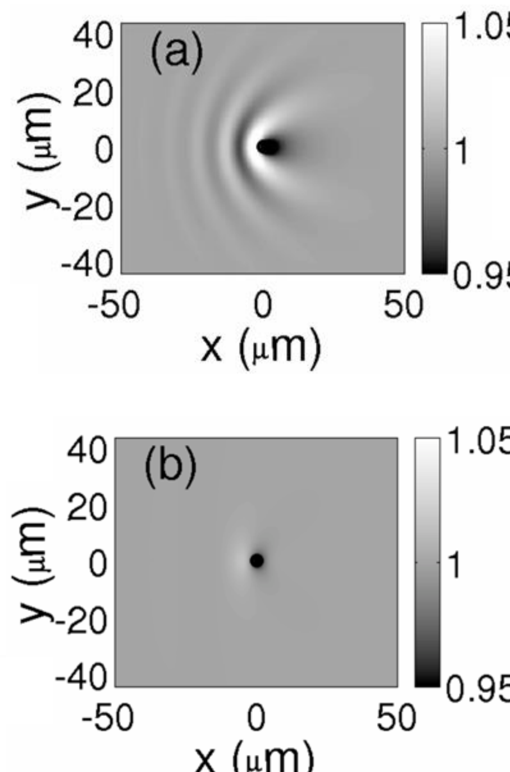
We study the motion of a polariton fluid injected into a planar microcavity by a continuous wave laser. In the presence of static defects, the spectrum of the Bogoliubov-like excitations reflects onto the shape and intensity of the resonant Rayleigh scattering emission pattern in both momentum and real space.



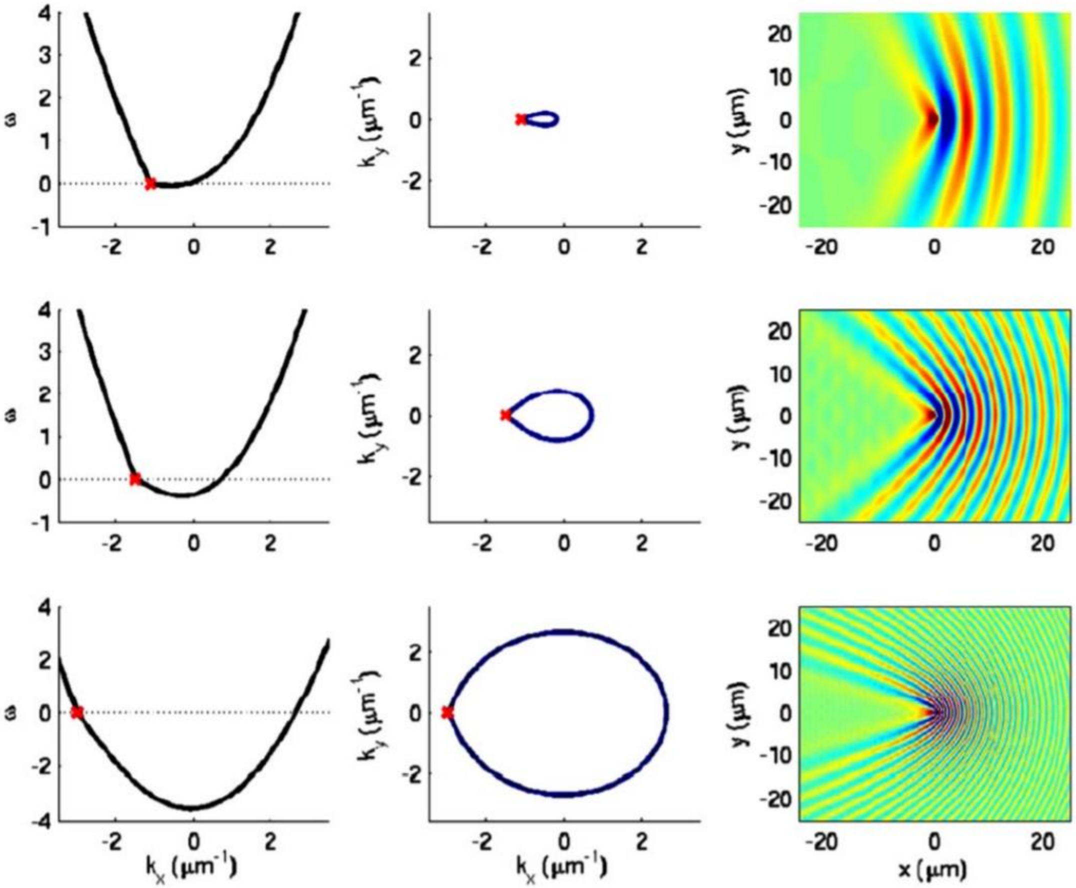


Bogoliubov-Čerenkov Radiation in a Bose-Einstein Condensate Flowing against an Obstacle

I. Carusotto,[1] S. X. Hu,[2,*] L. A. Collins,[2] and A. Smerzi[2,1]
[1]CNR-BEC-INFM, Trento, I-38050 Povo, Italy
[2]Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA
(Received 25 July 2006; published 27 December 2006)

Supersonic case

We study the density modulation that appears in a Bose-Einstein condensate flowing with supersonic velocity against an obstacle.



Conical density modulation downstream of the defect: Cerenkov regime.

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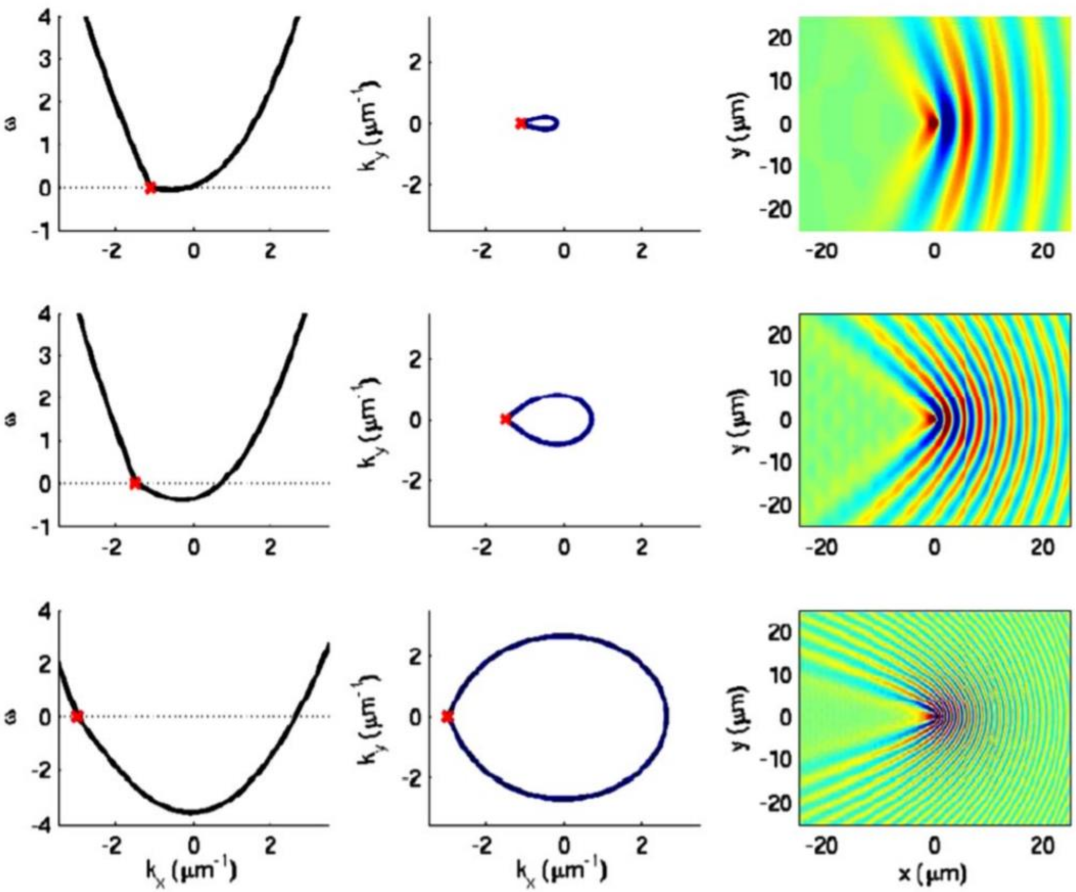
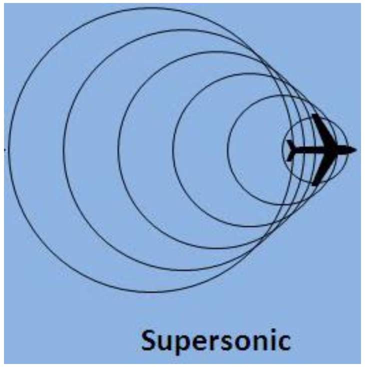


Polariton “Sonic boom”



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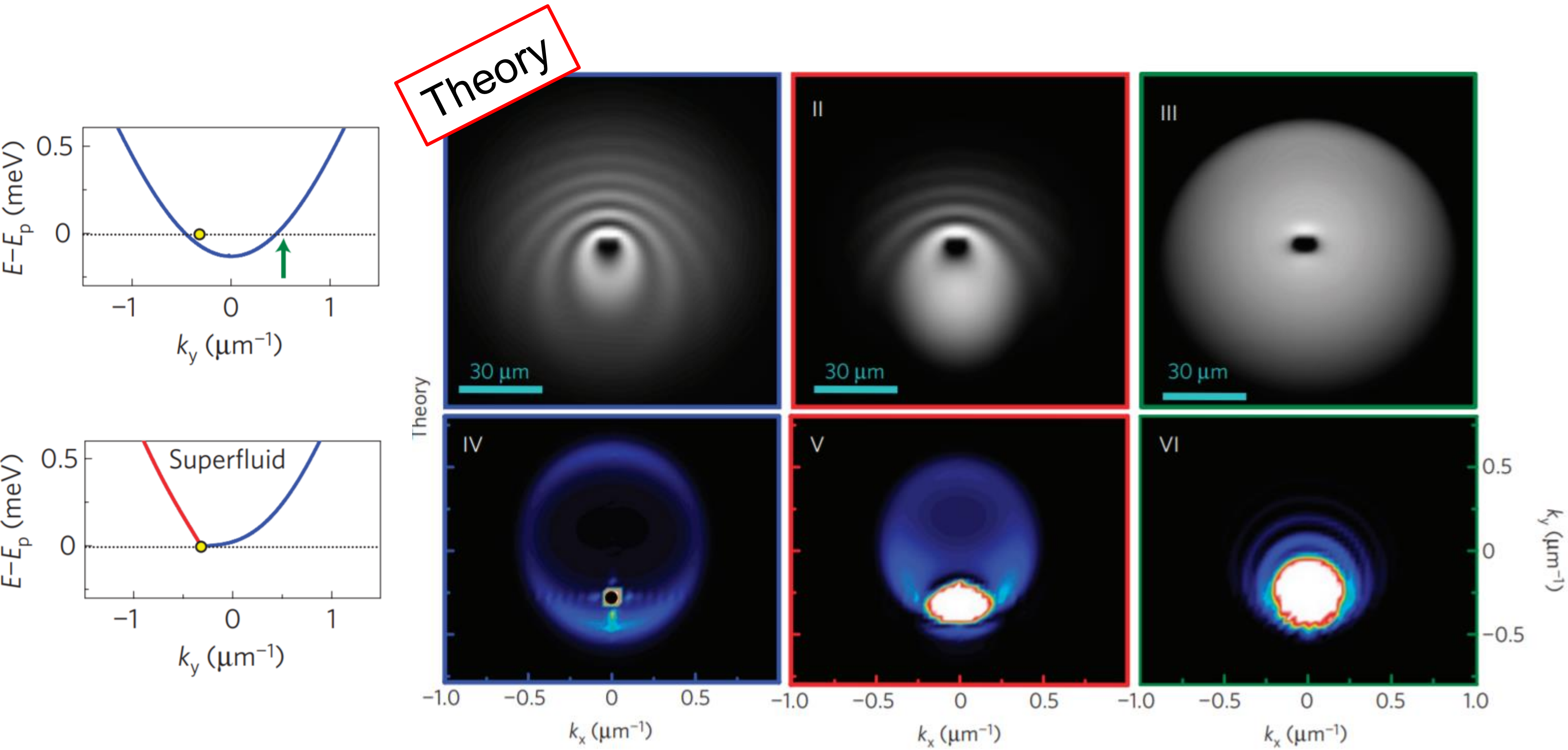
Superfluidity of polaritons in semiconductor microcavities



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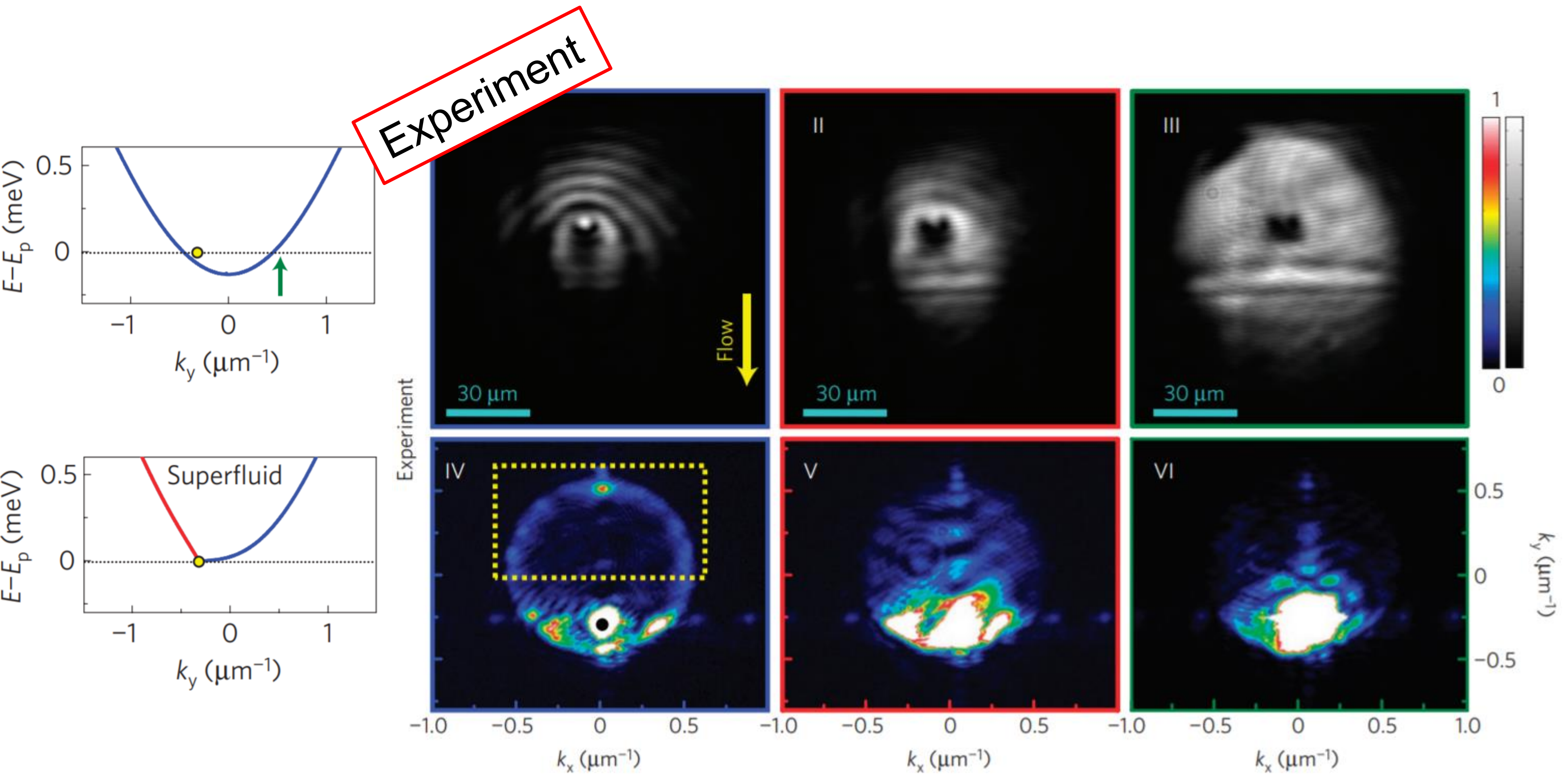

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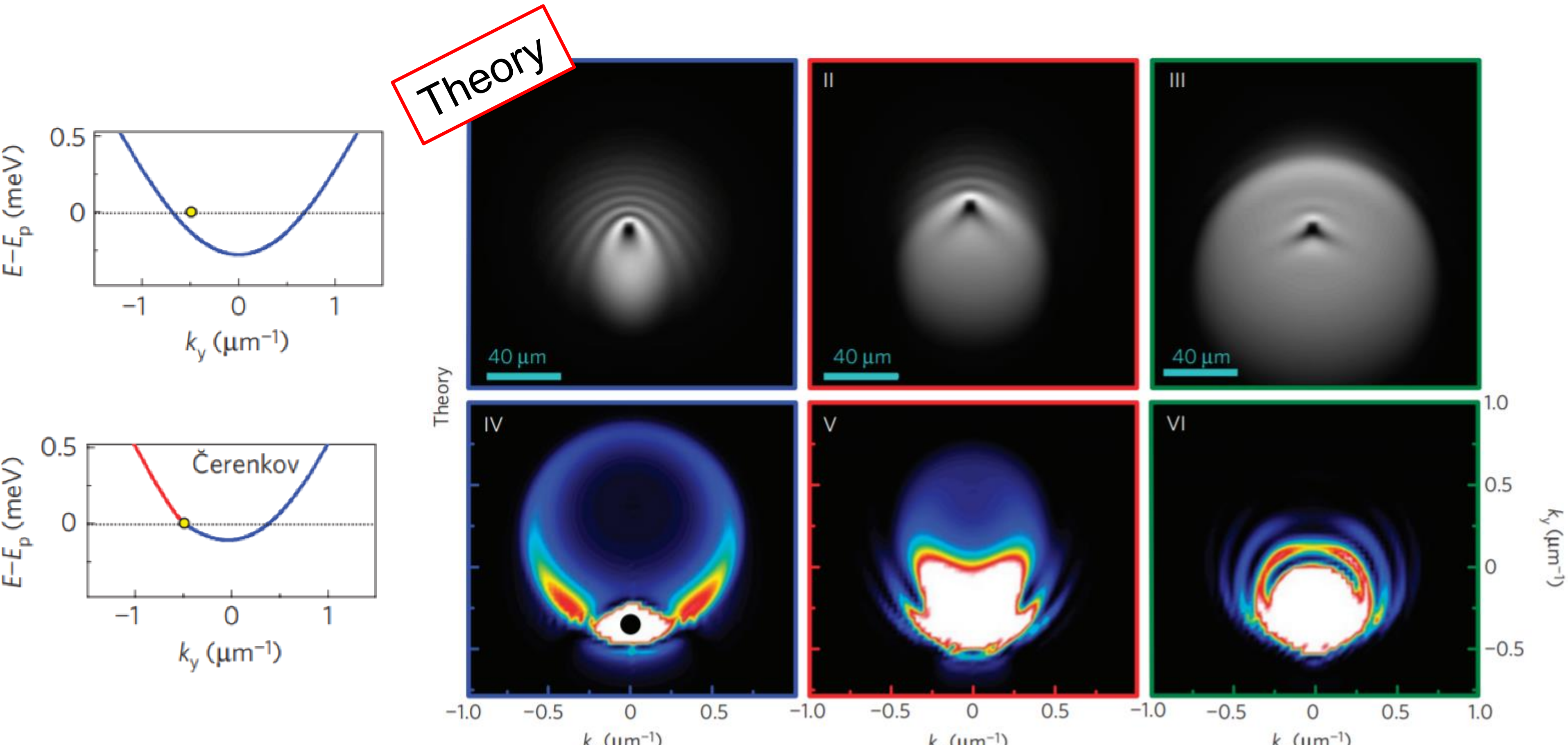

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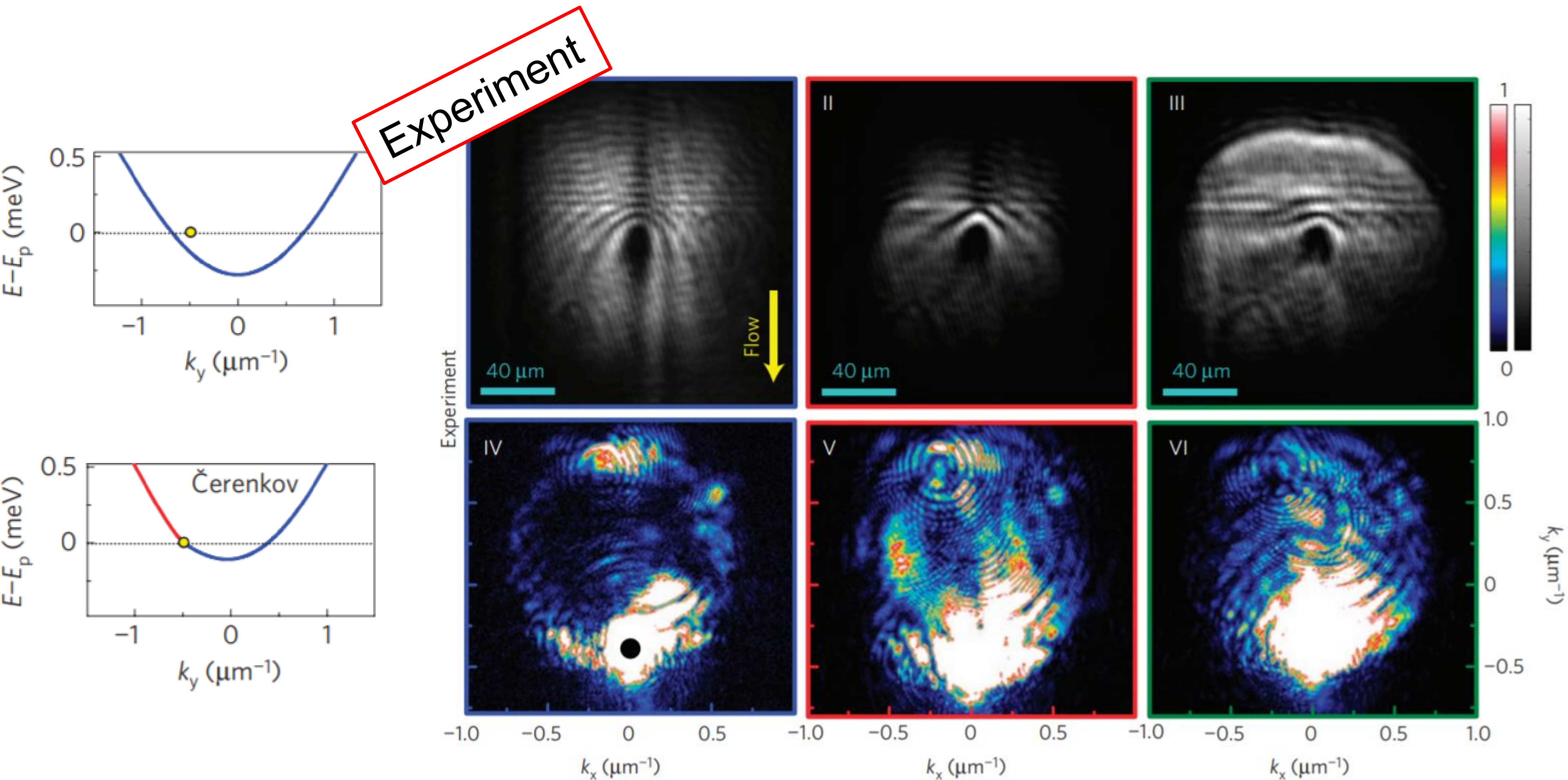

Conclusion

- Cavity exciton-polaritons $\Rightarrow$ “Fluids of light”
- Optical platform for driven-dissipative non-linear hydrodynamics
- Superfluidity is just one example. Plenty of other interesting effects:
  - Solitons, vortices, parametric oscillations, acoustic black holes
- Study synthetic polaritonic matter in lattices (see next class)
- Prospects for quantum polaritonic (current research topic)