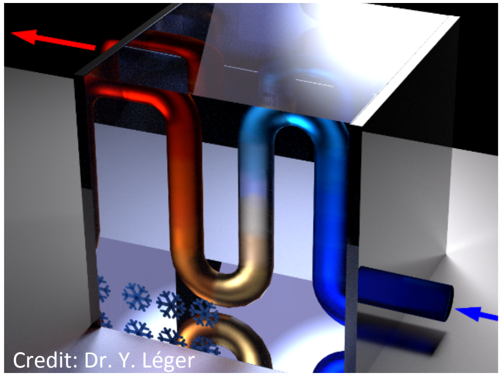
Heat transfers within a nonequilibrium quantum fluid of polaritons

Maxime Richard
CNRS, Université Grenoble Alpes - Institut Néel, Grenoble, France

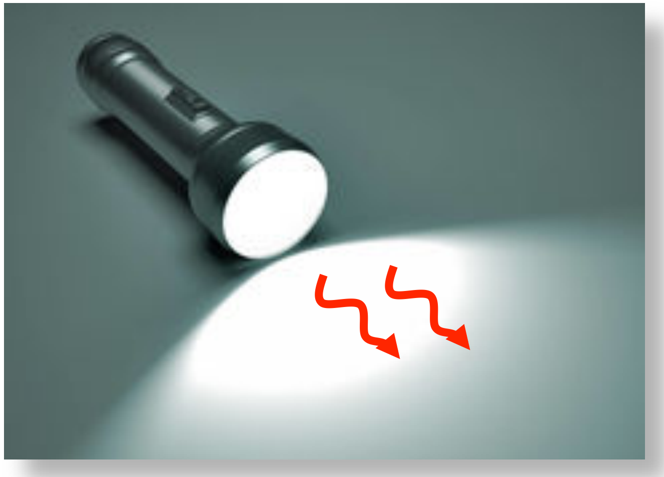

Credit: Dr. Y. Léger

KITP, UCSB June 2018

Quantum fluid of light

Quantum fluid of light

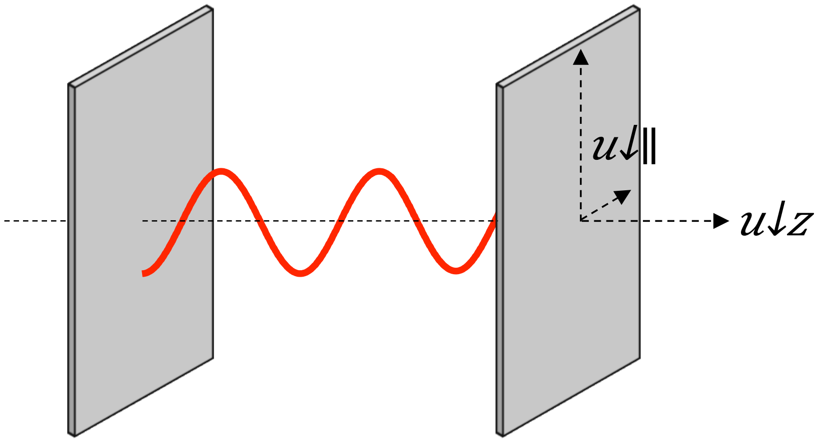
Free space photons



- No mass
- No interactions

Quantum fluid of light

Photons in planar optical cavity



Quantum fluid of light

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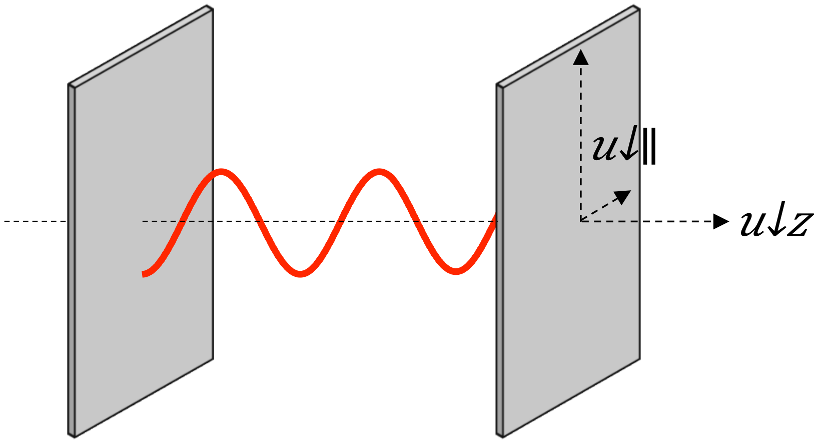
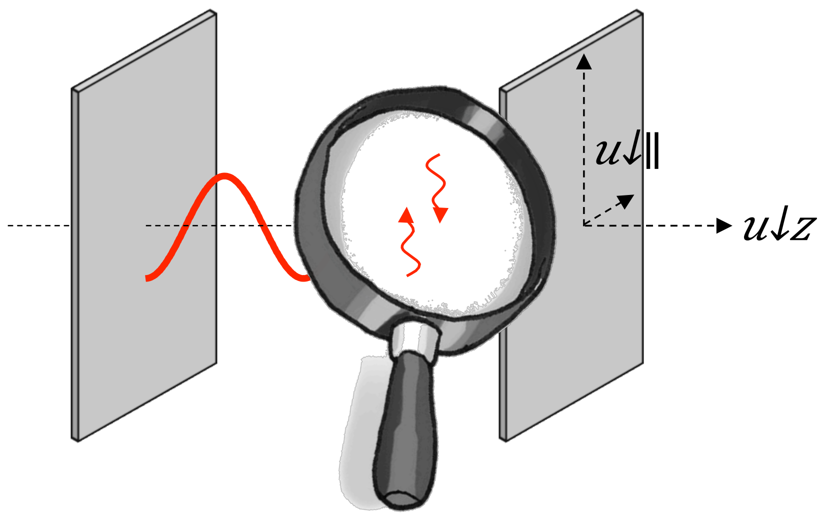


- Well-defined rest mass: $m_\parallel c^2 = \hbar\omega_0$
- Well-defined in-plane momentum: $\hbar k_\parallel$
- Well defined kinetic energy: $\hbar\omega(k_\parallel) \simeq \hbar\omega_0 + \hbar^2 k_\parallel^2 / 2m_\parallel$

≈ 

Quantum fluid of light

Photons in planar optical cavity



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$\approx$

Quantum fluid of light

1. Engineering Interactions

Quantum fluid of light

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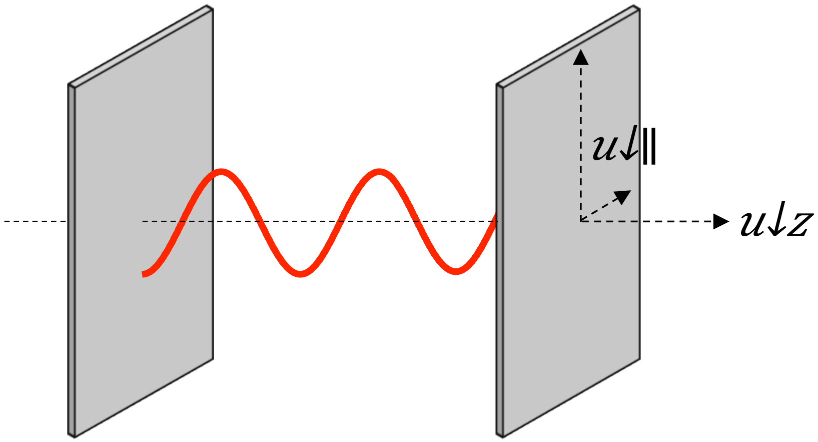
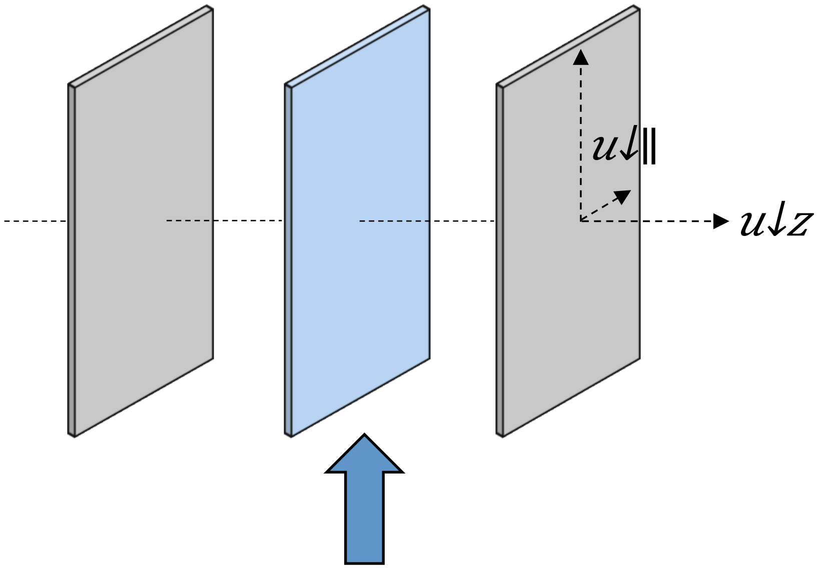
Photons in planar optical cavity



Quantum fluid of light

1. Engineering Interactions

Photons in planar optical cavity



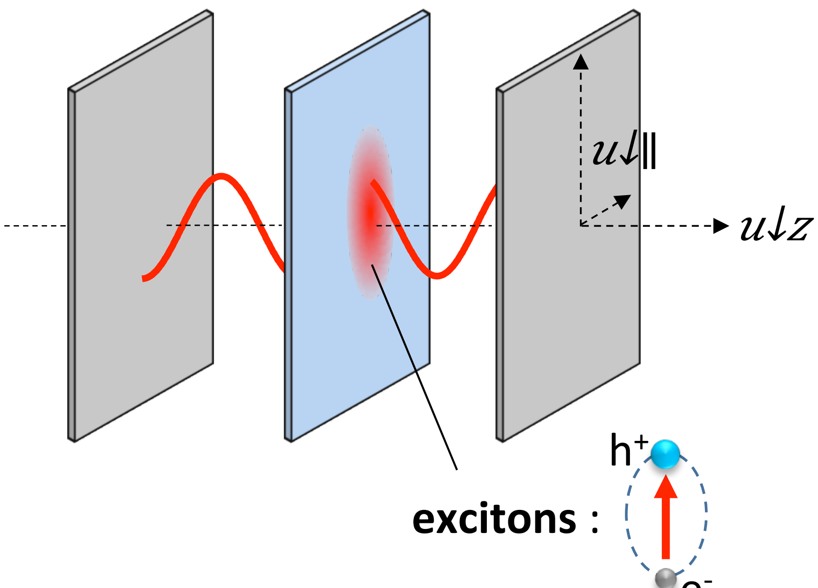
Semiconductor quantum well
e.g. GaAs, CdTe, ZnSe, ZnO etc…

Quantum fluid of light

1. Engineering Interactions

Photons in planar optical cavity

In the strong coupling regime



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Quantum fluid of light

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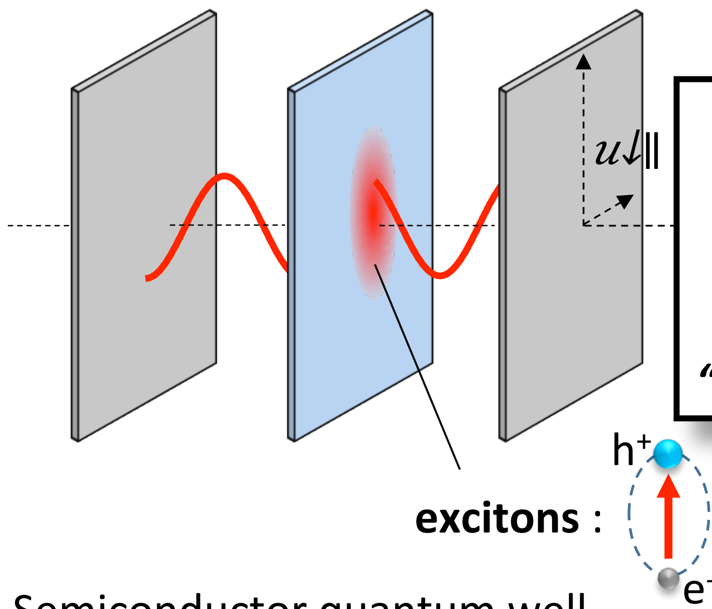
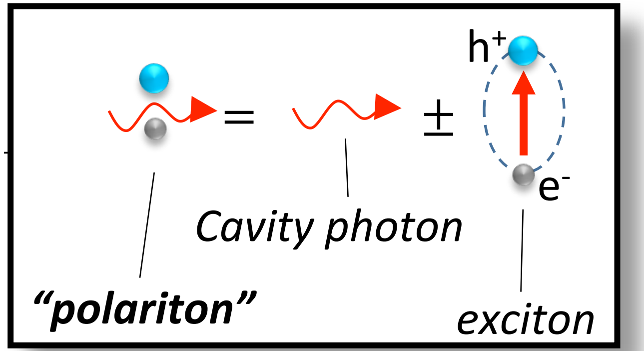


→cavity photons get "**dressed**" by excitons :



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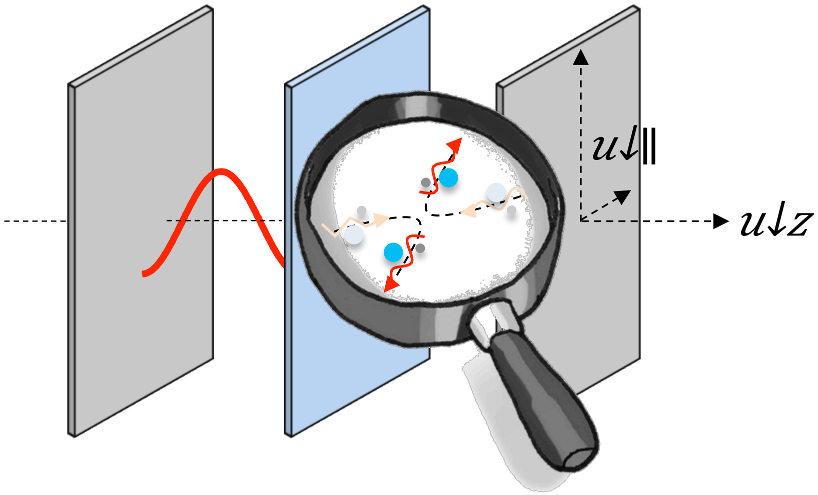

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Quantum fluid of light

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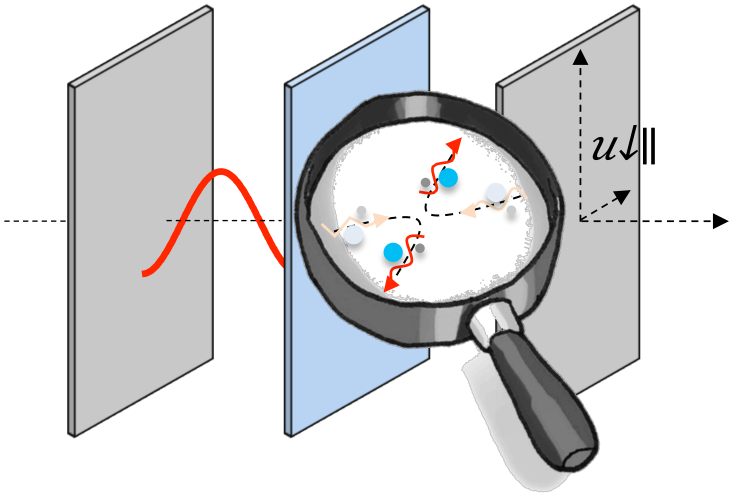

→cavity photons get "**dressed**" by excitons :

⇩

Polaritons do interact With each others

(via Coulomb)

Semiconductor quantum well

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Quantum fluid of light

1. Engineering Interactions

Photons in planar optical cavity

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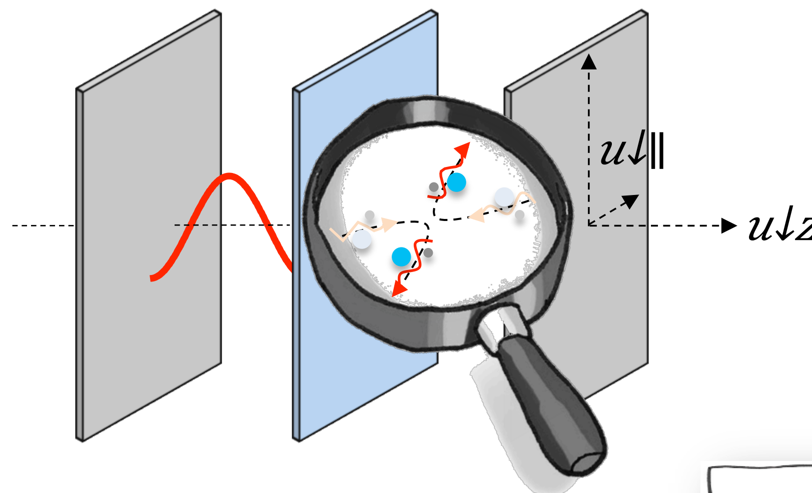

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⇩

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⇩

Polaritons ≈ Fluids of
2D interacting photons

Quantum fluid of light

2. Driven-dissipative nature

Quantum fluid of light

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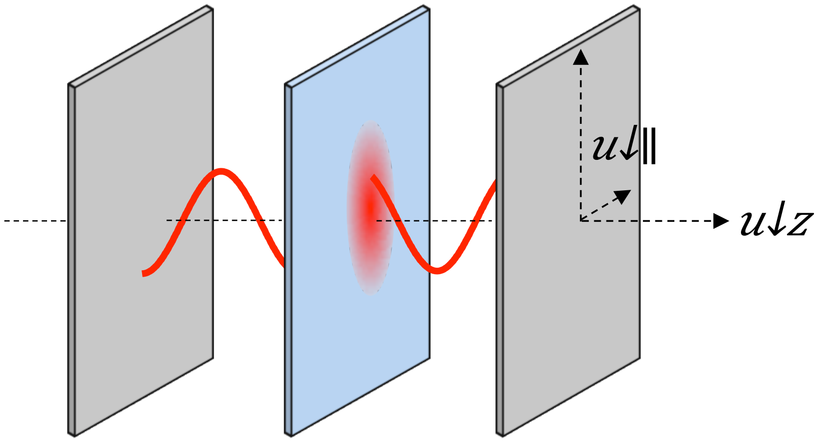
Photons in planar optical cavity

In the strong coupling regime

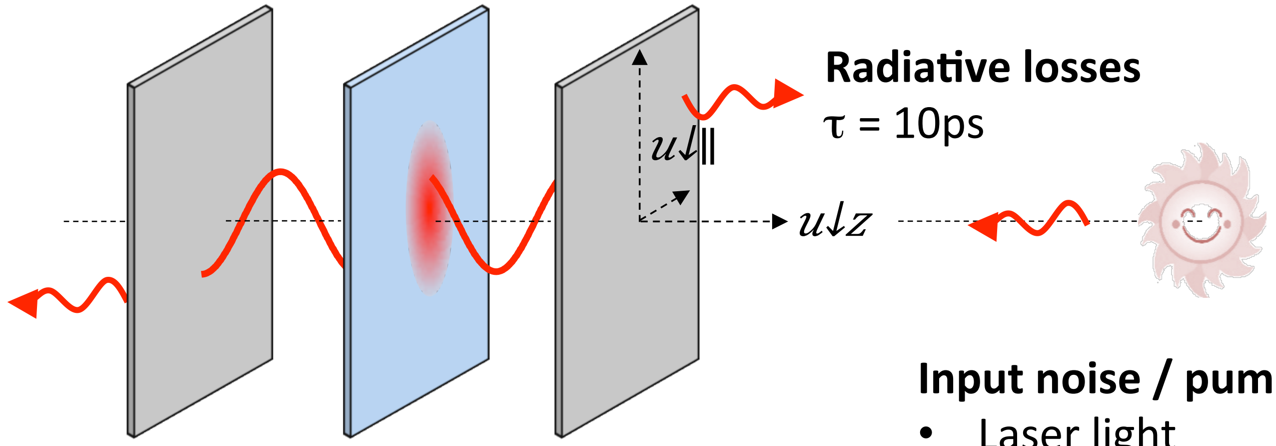


Quantum fluid of light

2. Driven-dissipative nature

Photons in planar optical cavity

In the strong coupling regime



Radiative losses
τ = 10ps

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Input noise / pump

- Laser light
- Thermal light
- EM vacuum
- (…) light

Quantum fluid of light

2. Driven-dissipative nature

Photons in planar optical cavity
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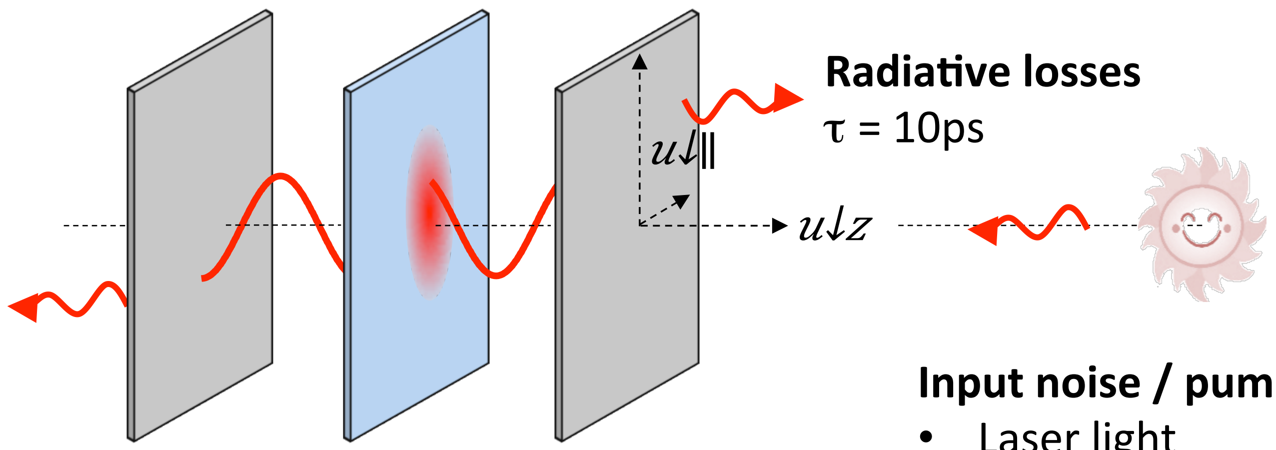

Radiative losses
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Input noise / pump
- Laser light
- Thermal light
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Polaritons **do not live long enough to reach thermal equilibrium**

Quantum fluid of light

2. Driven-dissipative nature

Photons in planar optical cavity

In the strong coupling regime

Radiative losses

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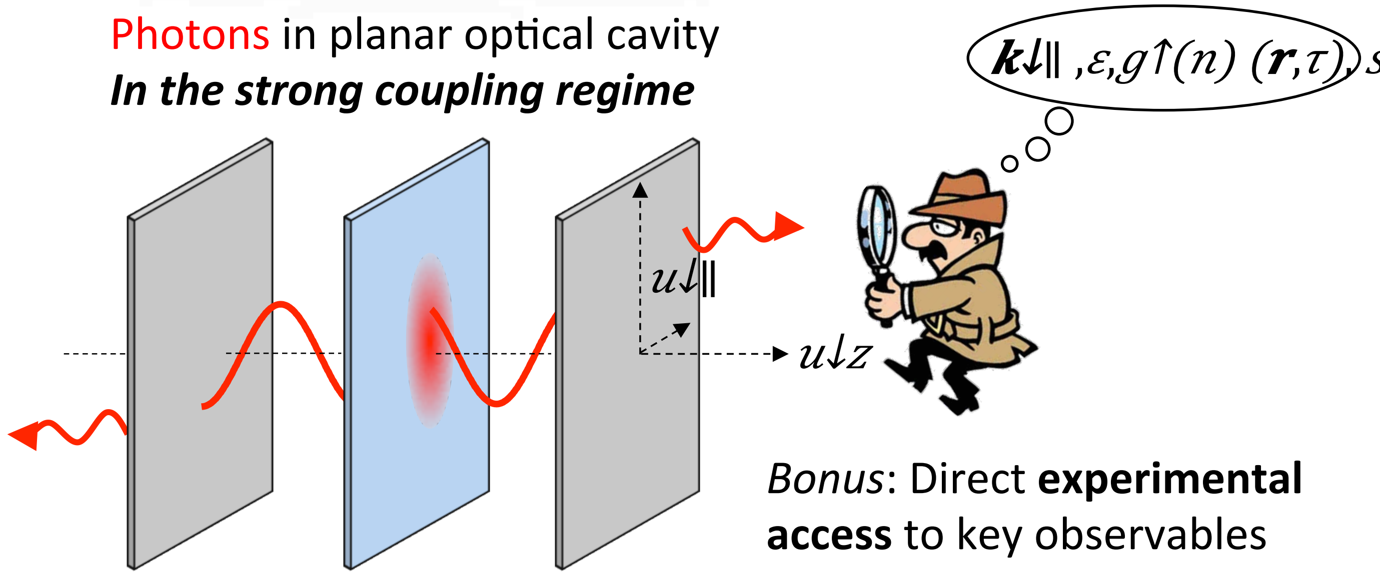

Bonus: Direct **experimental access** to key observables

Quantum fluid of light

3. Polaritons easily turn quantum degenerate

Quantum fluid of light

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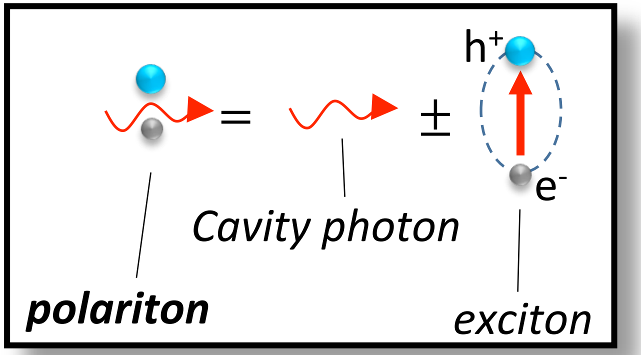
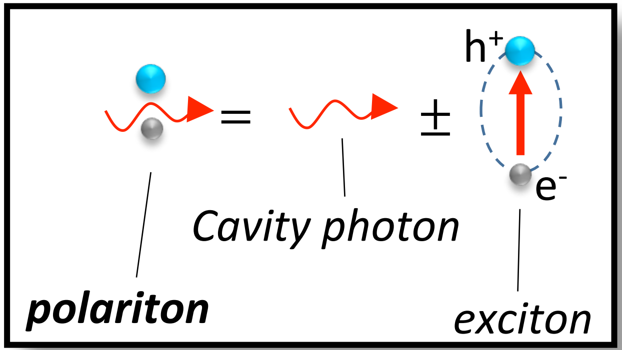


Quantum fluid of light

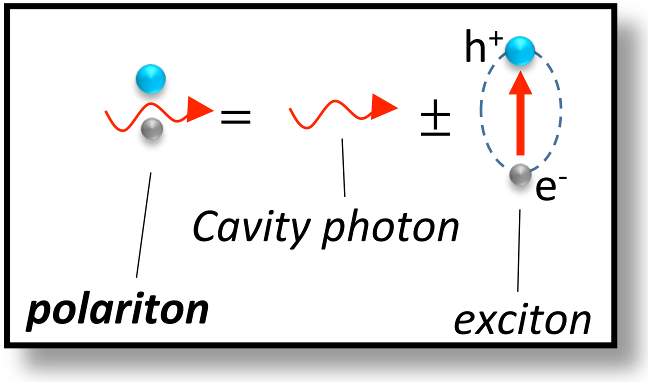
3. Polaritons easily turn quantum degenerate



- Integer spin

Quantum fluid of light

3. Polaritons easily turn quantum degenerate

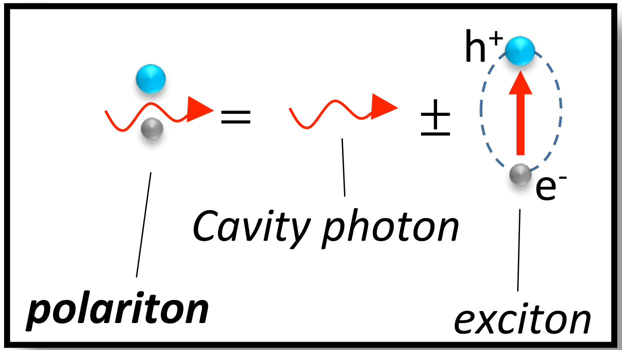


- Integer spin
- $\rho(E) \propto m_{\parallel}$ (2D)

$$\frac{m_{\parallel}}{\text{Mass } \textbf{Rb} \text{ atom}} = 4\times10^{-10}$$

Quantum fluid of light

3. Polaritons easily turn quantum degenerate



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"temperature" / Energy scale for quantum degeneracy is large and "easy" to reach experimentally

Quantum fluid of light

3. Polaritons easily turn quantum degenerate

Ex1: (2006) Driven-dissipative analog of BE condensation [1]

[1] J. Kasprzak, MR *et al.* Nature (2006)

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Quantum fluid of light

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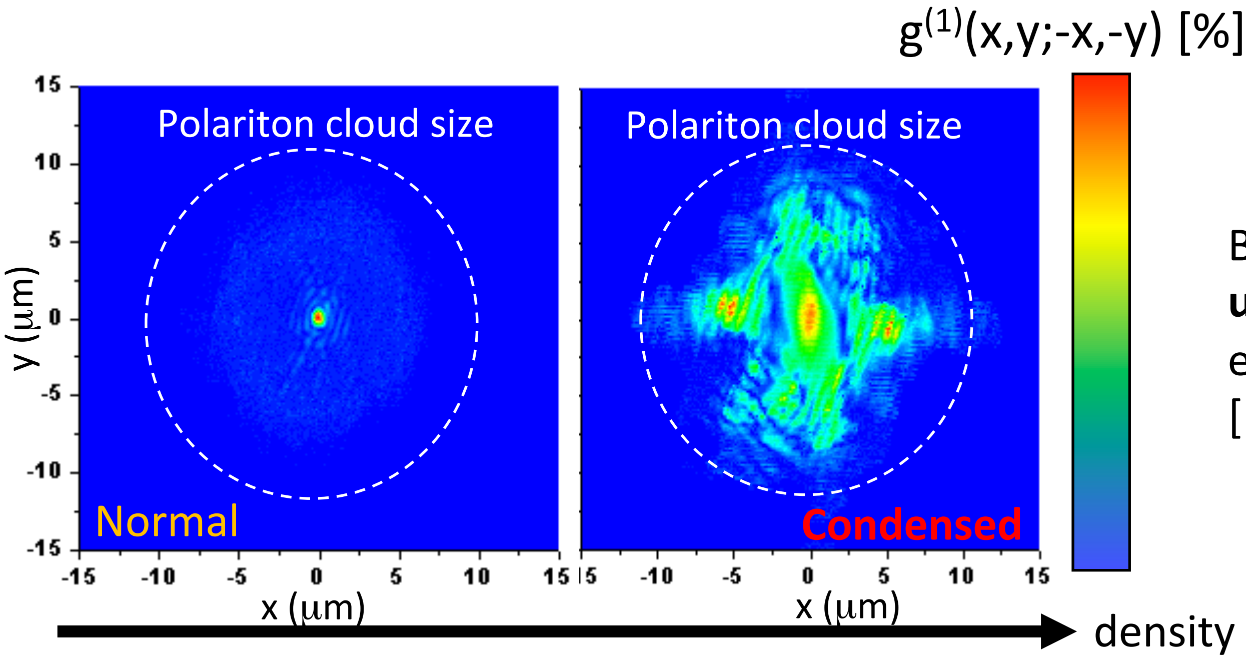


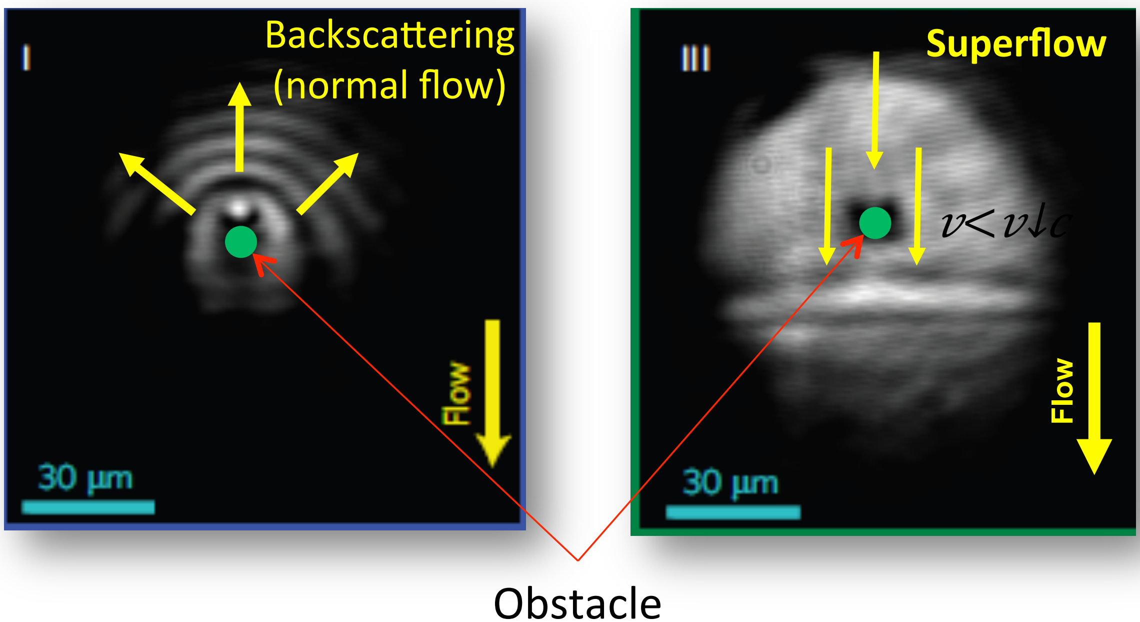
Belongs to a **different universality class** than equilibrium condensation [1b,1c]

[1] J. Kasprzak, MR *et al.* Nature (2006)
[1b] L. M. Sieberer et al. , *Phys. Rev. Lett*. **110** 195301 (2013)
[1c] S. Diehl *Nat. Physics, News&Views,* **11** 446 (2015)

Quantum fluid of light

3. Polaritons easily turn quantum degenerate

Ex2: (2009) Superfluidity according to Landau’s criterion [2]



Superfluid features captured by a driven-dissipative version of gross-Piteavskii equation [3]

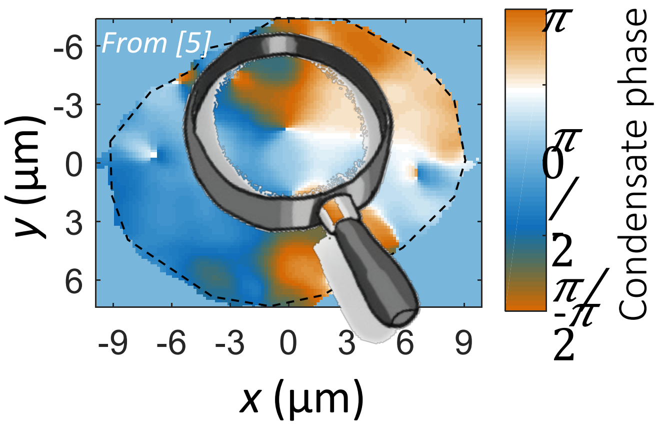
[2] A. Amo et al. Nature Physics **5**, 805 (2009)
[3] I. Carusotto and C. Ciuti Phys. Rev. Lett. **93**, 166401 (2004)

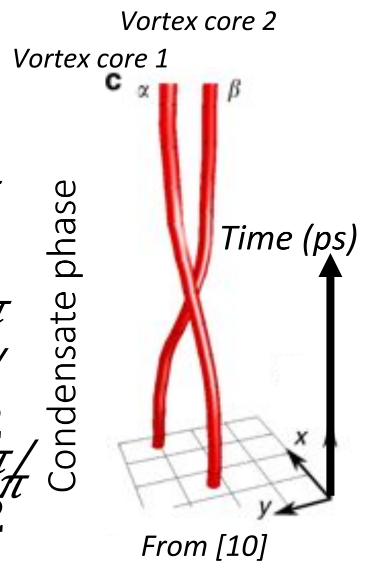
Quantum fluid of light

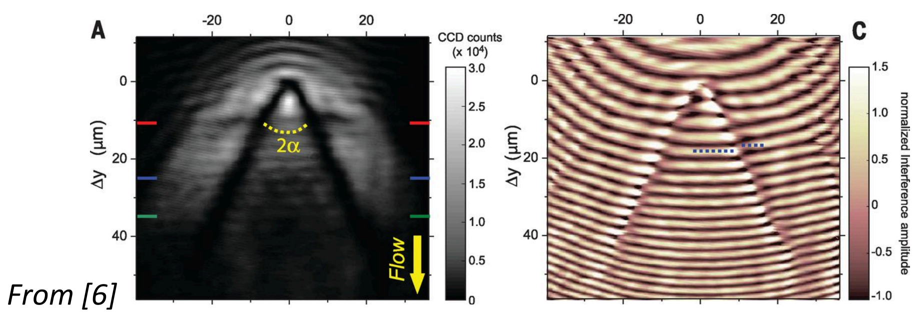
3. Polaritons easily turn quantum degenerate

Ex3: Driven-dissipative quantum hydrodynamics (2008-ongoing) [4]

- Steady-state (SS) **quantized vortices** [5]
- SS Dark and bright **solitons** [6,7]
- Quantum **turbulence** and dynamics [8-10]
- **Spinor** degree of freedom [11,12]
- …



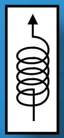




[4] I. Carusotto and C. Ciuti, Rev. Mod. Phys. **85**, 299 (2013)
[5] K. Lagoudakis, MR *et al.* Nat. Phys. **4** 706 (2008)
[6] A. Amo et al. , Science **332**, 167 (2011)
[7] M. Sich et al. Nature Photonics **6**, 50 (2012)
[8] G. Nardin et al. Nature Physics **7**, 635 (2011)
[9] G. Grosso et al. Phys. Rev. Lett. **107**, 245301 (2011)
[10] L. Dominici et al. Nat. Comm. **9**, 1467 (2018)
[11] R. Hivet et al. Nat. Phys. **8**, 724 (2012)
[12] K. Lagoudakis *et al.* Science **326** 974 (2009)à

Quantum fluid of light

4. Polaritons also interact with solid-state vibrations



Quantum fluid of light

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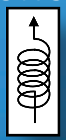
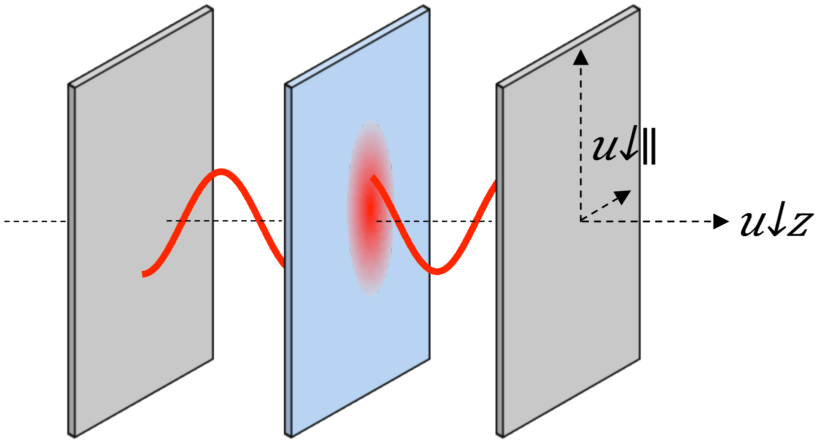
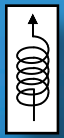


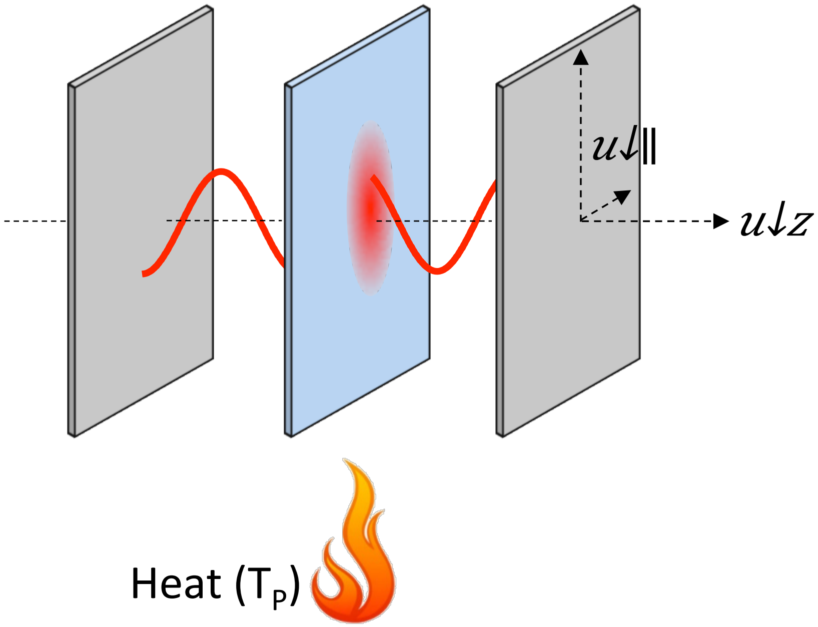


Quantum fluid of light

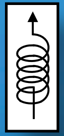
4. Polaritons also interact with solid-state vibrations

phonons





Quantum fluid of light



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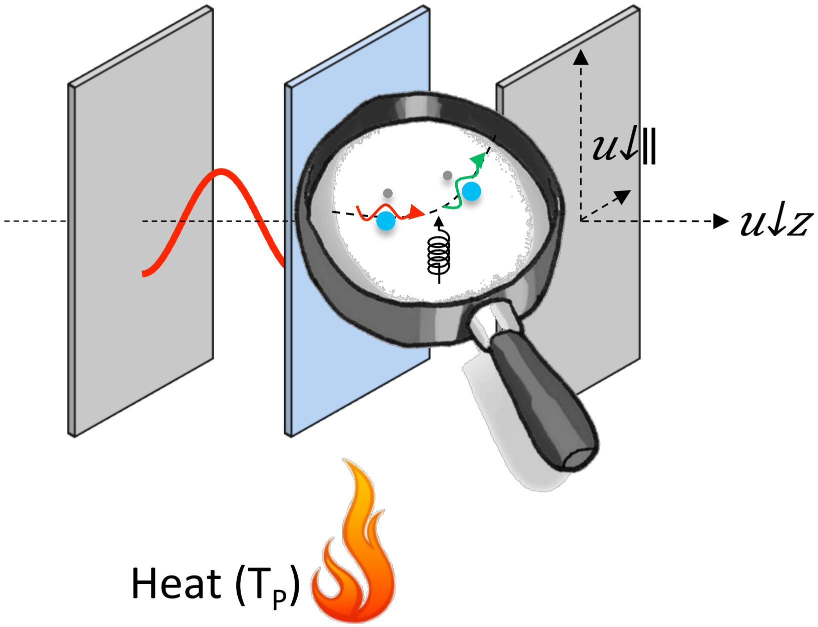

Quantum fluid of light

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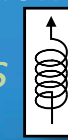

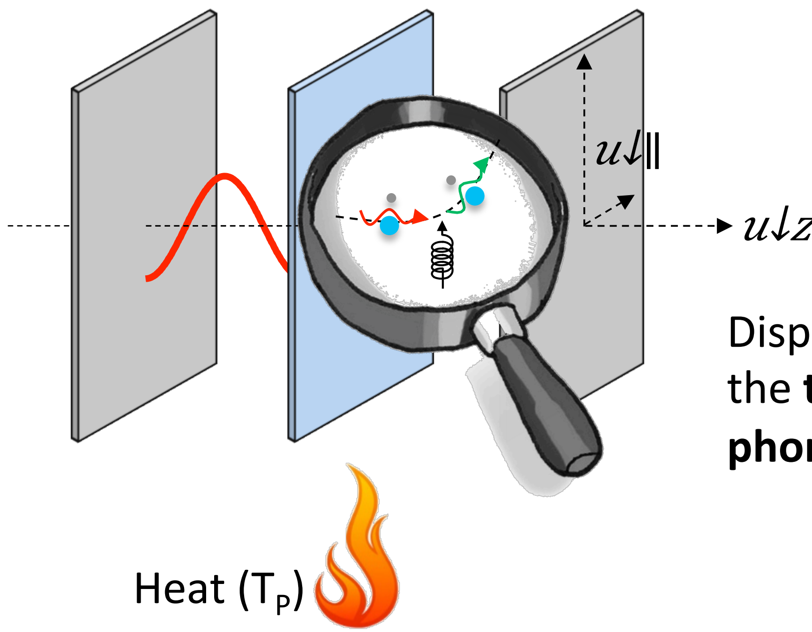

Dispersive **coupling** with the **thermal bath of phonons**

Quantum fluid of light

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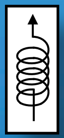
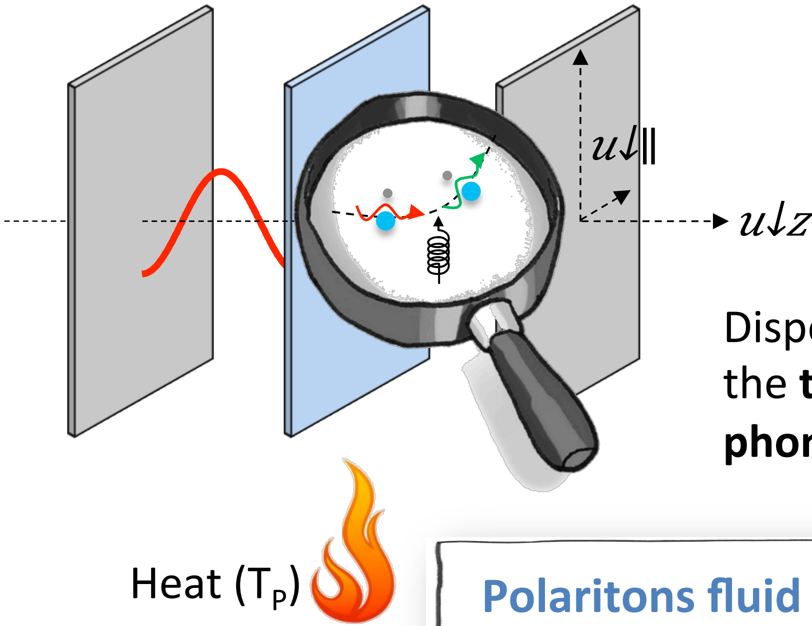


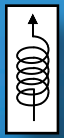


Dispersive **coupling** with the **thermal bath of phonons**

Polaritons fluid can exchange *heat* with a thermal bath at Tp

Quantum fluid of light

phonons

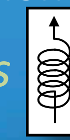
4. Polaritons also interact with solid-state vibrations 

Ex4: Use a "cold" gas of polaritons as a refrigerant [13]

[13] S. Klembt,…MR, Phys. Rev. Lett. **114**, 186403 (2015)

Quantum fluid of light

phonons



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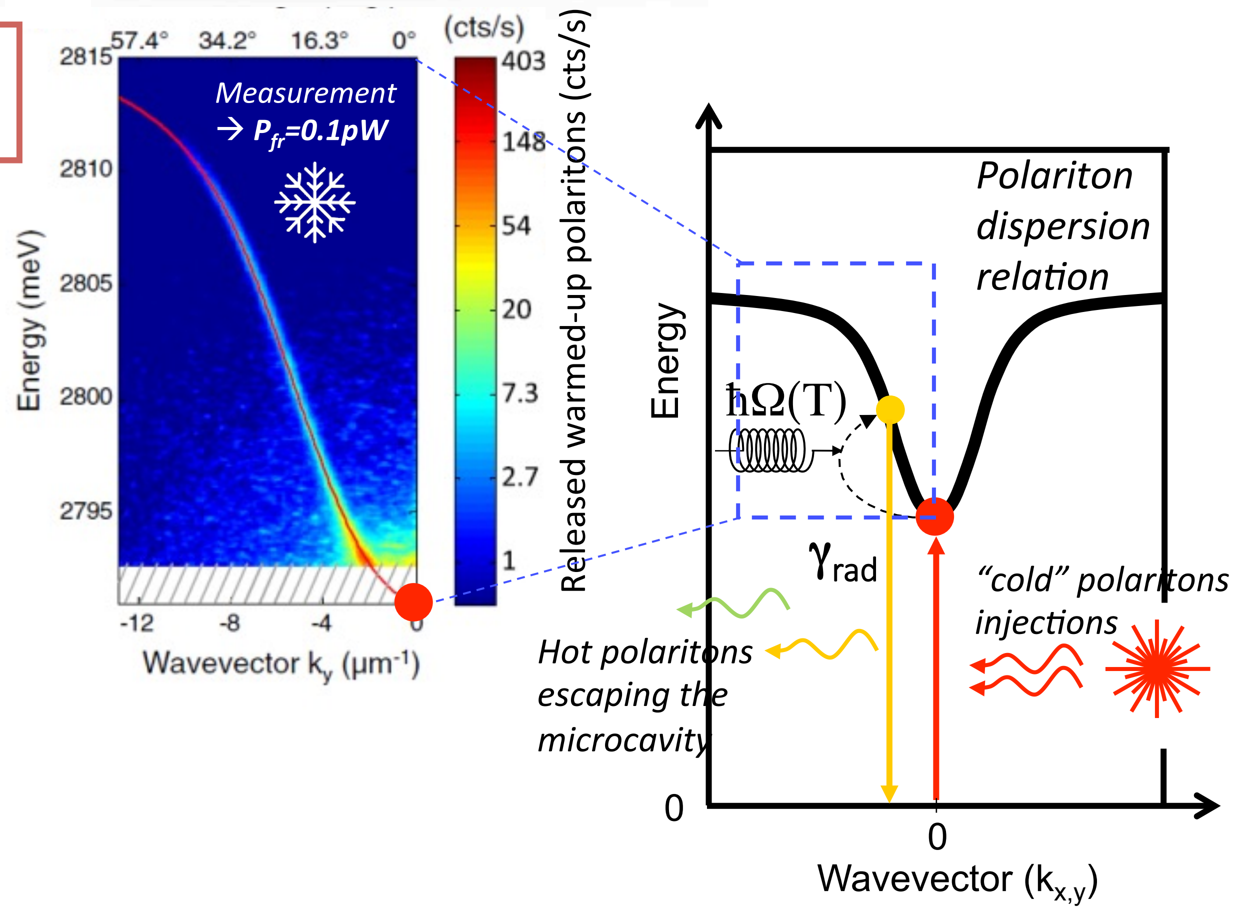

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Intermediate summary

Polaritons…

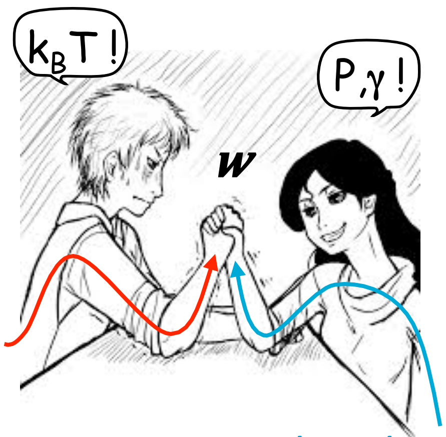
- Have the **kinetic** properties of **2D massive particles**
- **Interact** with **each others** → **Microcanonical**-like thermalization channel
- Get easily into **quantum degeneracy**
- are in a **driven-dissipative situation**
- **Interact** with the **thermal phonons bath** → **Canonical**-like thermalization channel

Intermediate summary

Polaritons…

- Have the **kinetic** properties of **2D massive particles**
- **Interact** with **each others**
- Get easily into **quantum degeneracy**
- are in a **driven-dissipative situation**
- **Interact** with the **thermal phonons bath**

} **Two intrinsically competing features :**



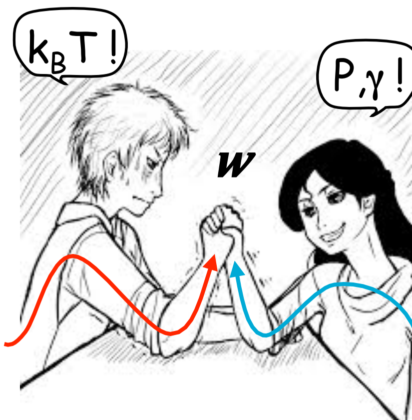
Towards thermal equilibrium

Towards a dynamically stable steady-state

Outline

1. **Define, measure, and control $\boldsymbol{w}$**, the ratio of thermal-to-dynamical regime in a polariton fluid

2. « Hybrid » properties of a polariton condensate at the thermal-to-dynamical **crossover ($\boldsymbol{w}$=1)**



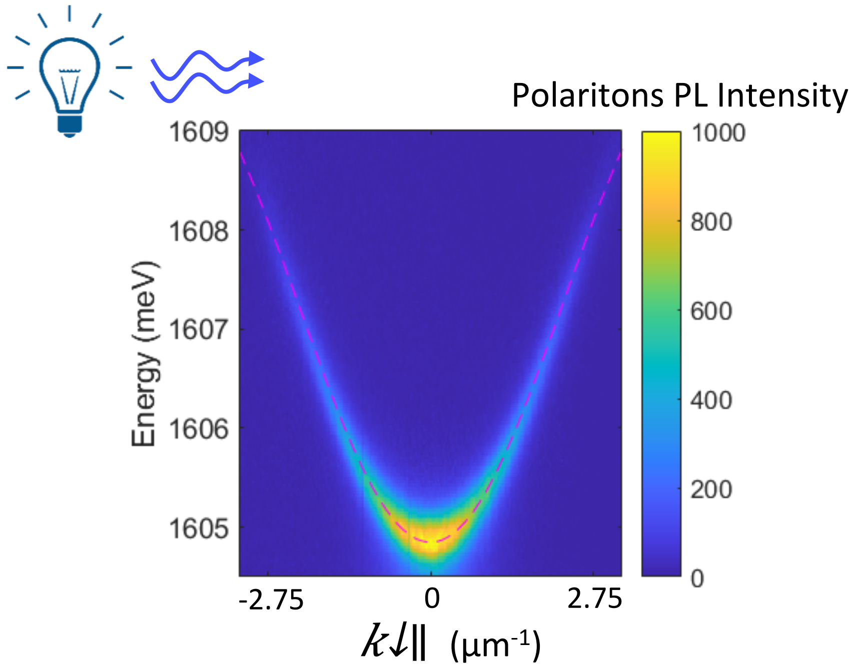
Towards thermal equilibrium

Towards a dynamically stable steady-state

1. Define and measure w

i.e. the ratio of thermal-to-dynamical regime in a polariton fluid

Incoherent nonresonant optical excitation



Typical measurement under incoherent excitation (phonons Tp=10K)

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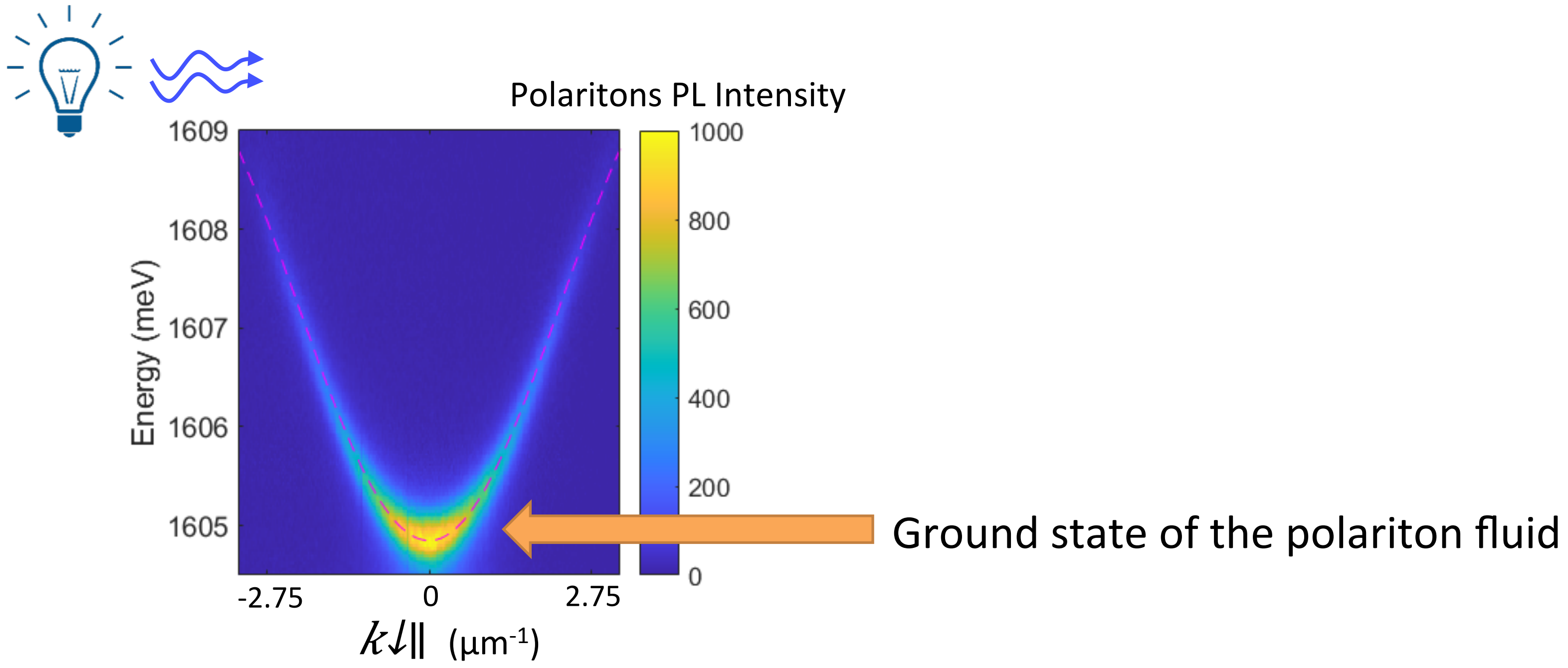
Incoherent nonresonant optical excitation



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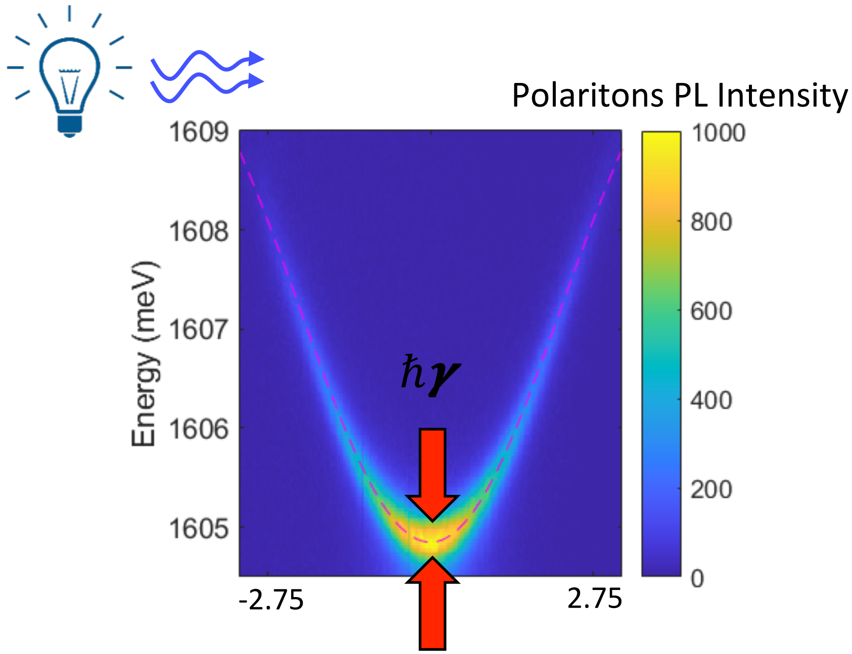

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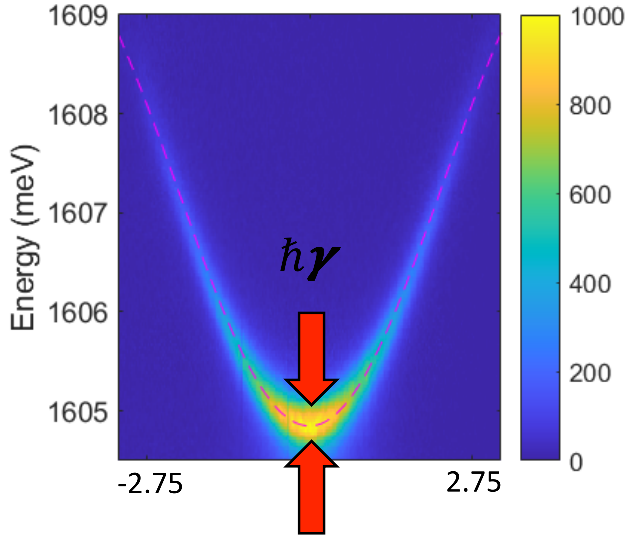
Incoherent nonresonant optical excitation

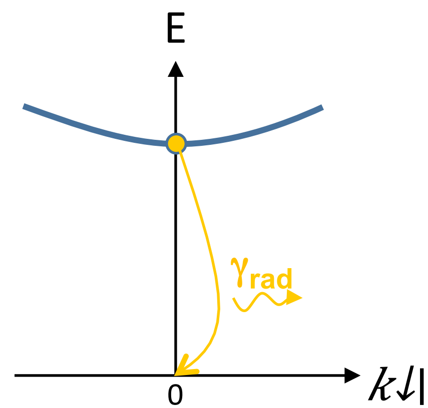
Polaritons PL Intensity



Typical measurement under incoherent excitation (phonons Tp=10K)

$$\gamma(C^2, T_P) = \gamma_{rad}(C^2) + \quad ^{*}$$

* C^2 is the photonic fraction of the polariton state



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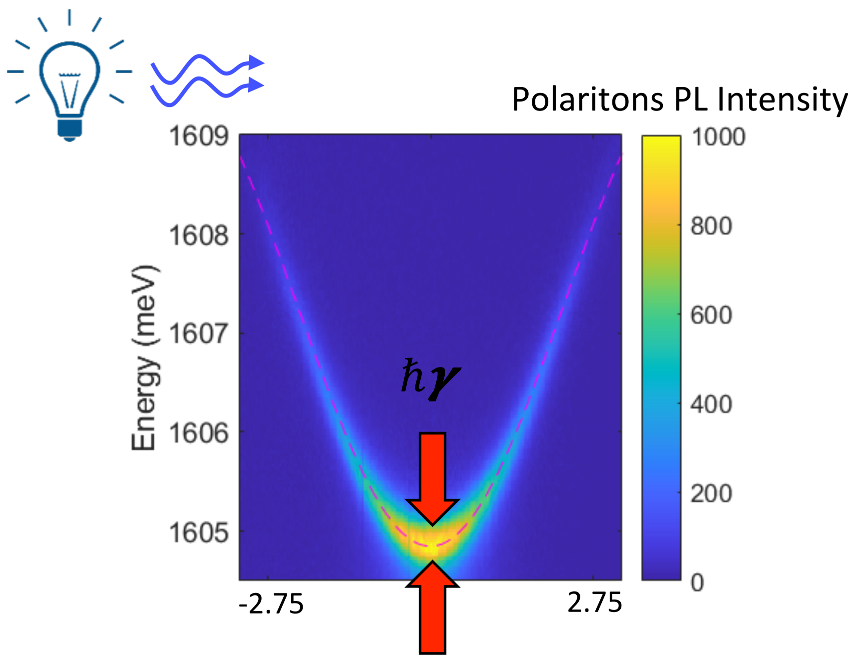

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$$\gamma(C^2, T_P) = \gamma_{rad}(C^2) + \gamma_{nr}(C^2)$$ *

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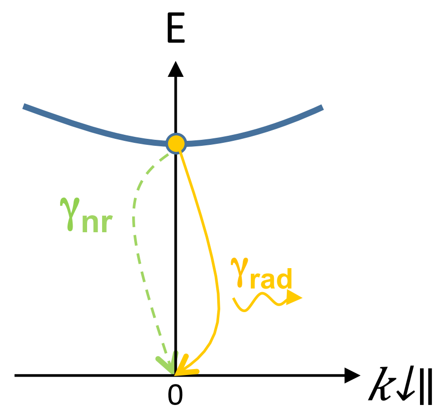

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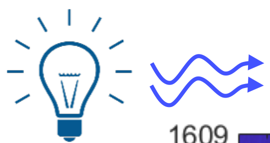
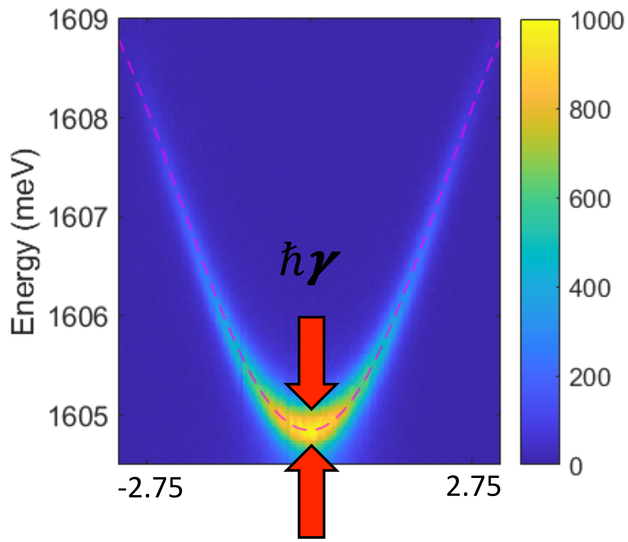
i.e. the ratio of thermal-to-dynamical regime in a polariton fluid

Incoherent nonresonant optical excitation

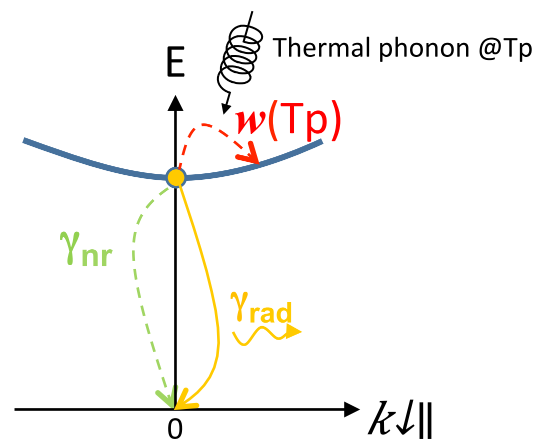


$$\gamma(C^2, T_P) = \gamma_{rad}(C^2) + \gamma_{nr}(C^2) + w(C^2, T$$ *

* **C^2** is the photonic fraction of the polariton state
Tp is the phonon bath temperature



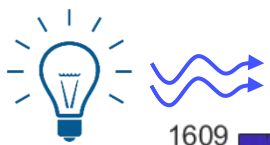
Typical measurement under incoherent excitation (phonons Tp=10K)



1. Define and measure w

i.e. the ratio of thermal-to-dynamical regime in a polariton fluid

Incoherent nonresonant optical excitation



$$\gamma(C^{2},T_{P})=\gamma_{rad}(C^{2})+\gamma_{nr}(C^{2})+w(C^{2},T \quad *$$

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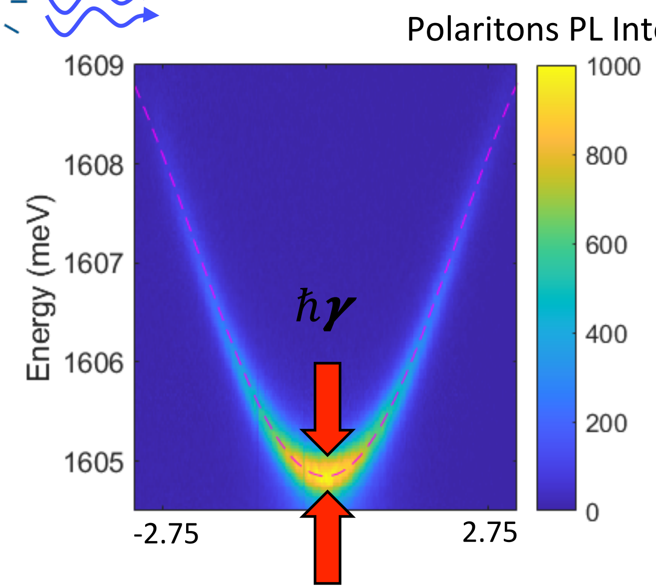
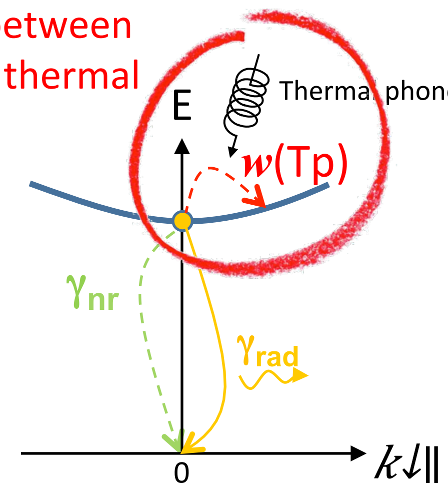


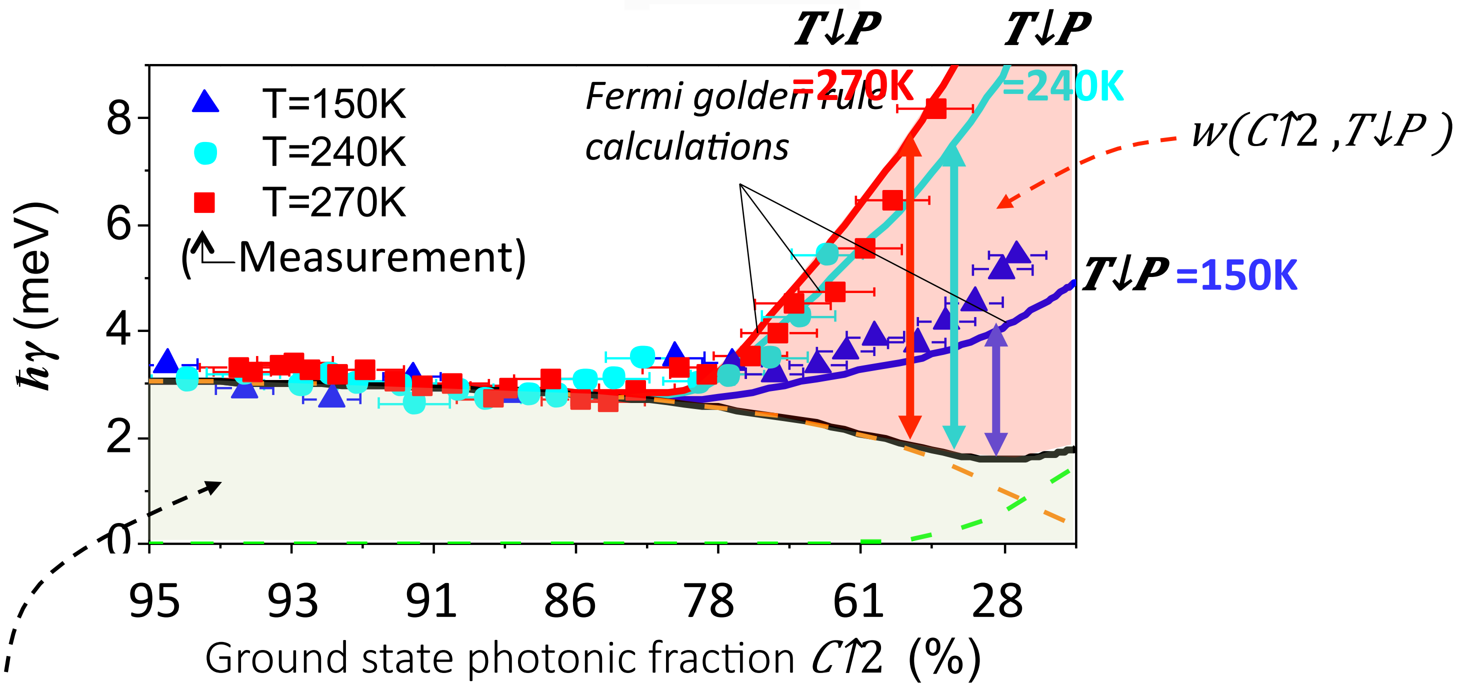
interaction rate (s^{-1}) between the polariton and the thermal reservoir of phonons



Typical measurement under incoherent excitation (phonons Tp=10K)

1. Define and measure w

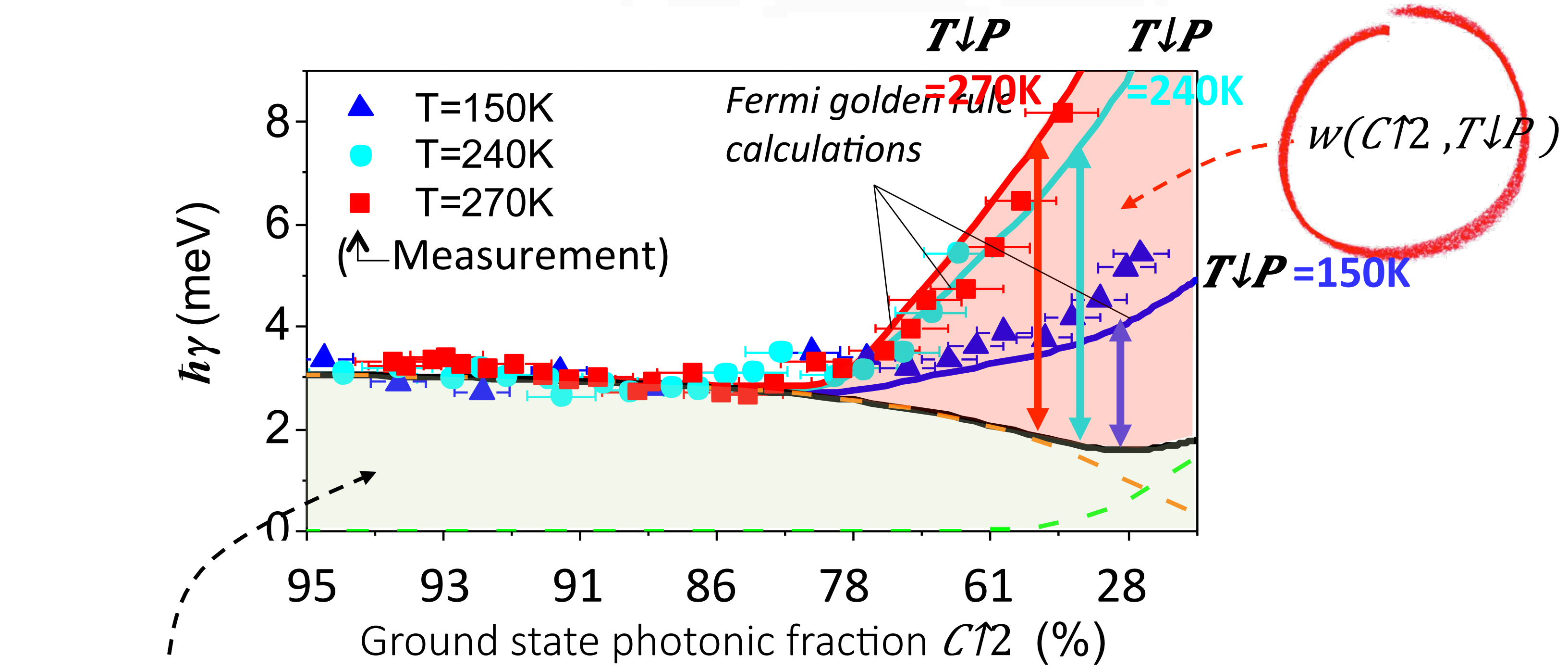
i.e. the ratio of thermal-to-dynamical regime in a polariton fluid



$\gamma_{rad}(C^2) + \gamma_{nr}(C^2)$

1. Define and measure w

i.e. the ratio of thermal-to-dynamical regime in a polariton fluid



w(Tp) is experimentally extracted and quantitatively understood

1. Define and measure ***w***

i.e. the ratio of thermal-to-dynamical regime in a polariton fluid

Definition of the ***thermal-to-dynamical interaction rate ratio***

$$w\,(C^2, T_P) \equiv w(C^2, T_P)/\gamma_{\mathrm{rad}}(C^2)+\gamma_{\mathrm{nr}}(C^2)$$

1. Define and measure w

i.e. the ratio of thermal-to-dynamical regime in a polariton fluid

Definition of the ***thermal-to-dynamical interaction rate ratio***

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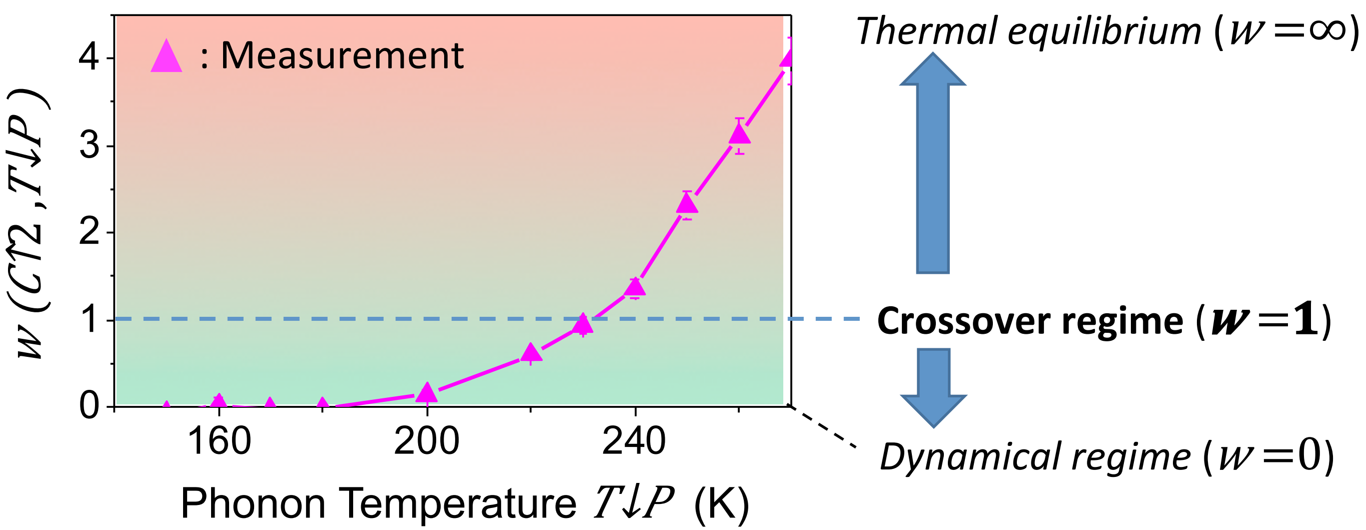

2. Condensation properties at the **thermal-to-dynamical** crossover

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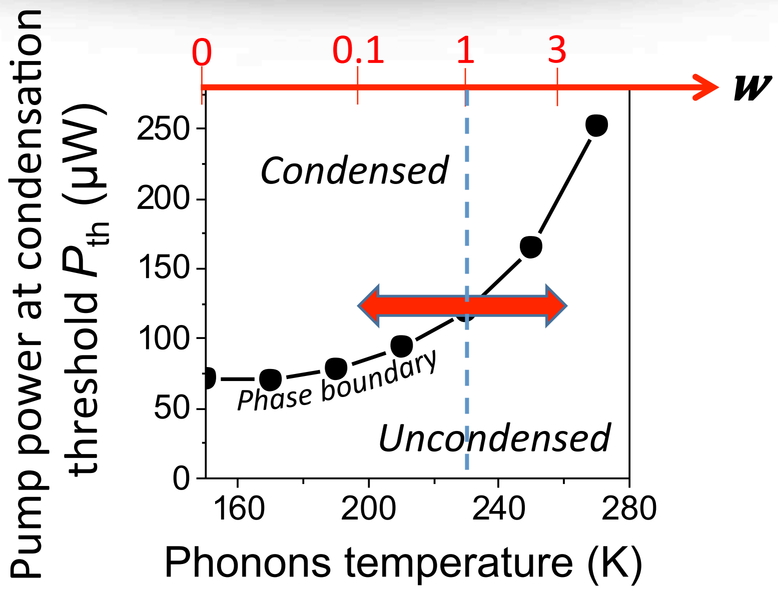

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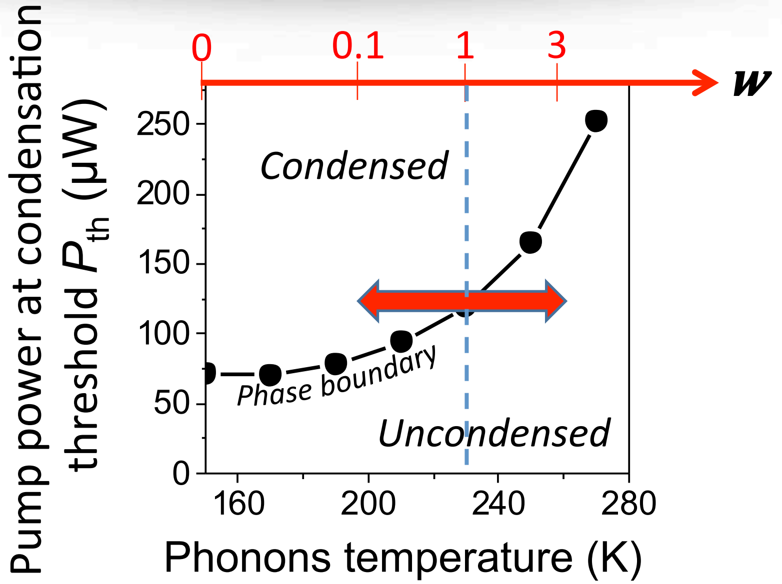
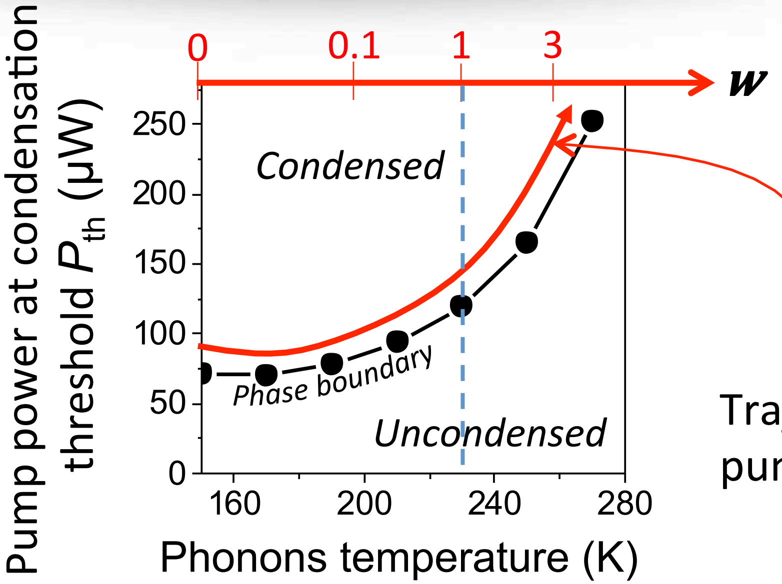


w , ≈degree of thermalization, is a **control parameter of the phase transition → Hybrid nature of the phenomenon**

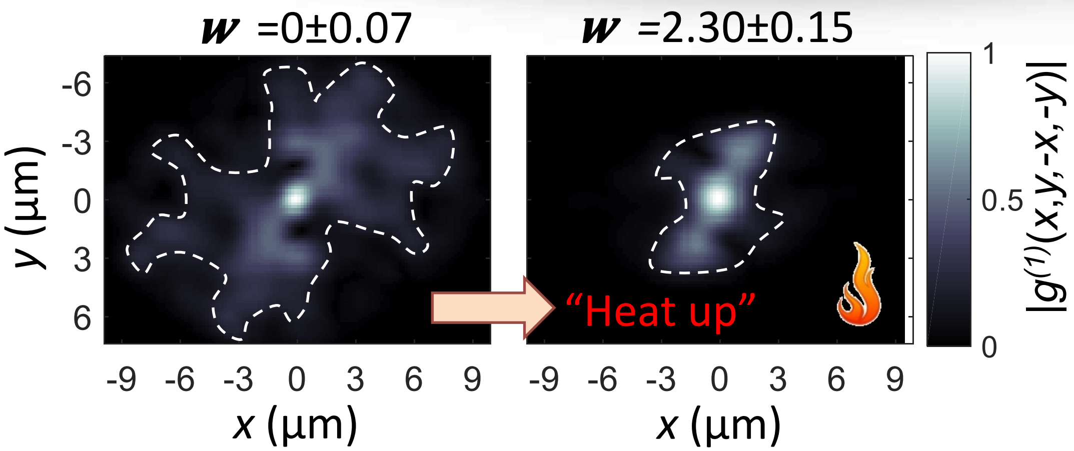
2. Condensation properties at the **thermal-to-dynamical** crossover



Trajectory of fixed pump-to-losses ratio

Goal: characterize the properties of the condensate versus w only

2. Condensation properties at the **thermal-to-dynamical** crossover



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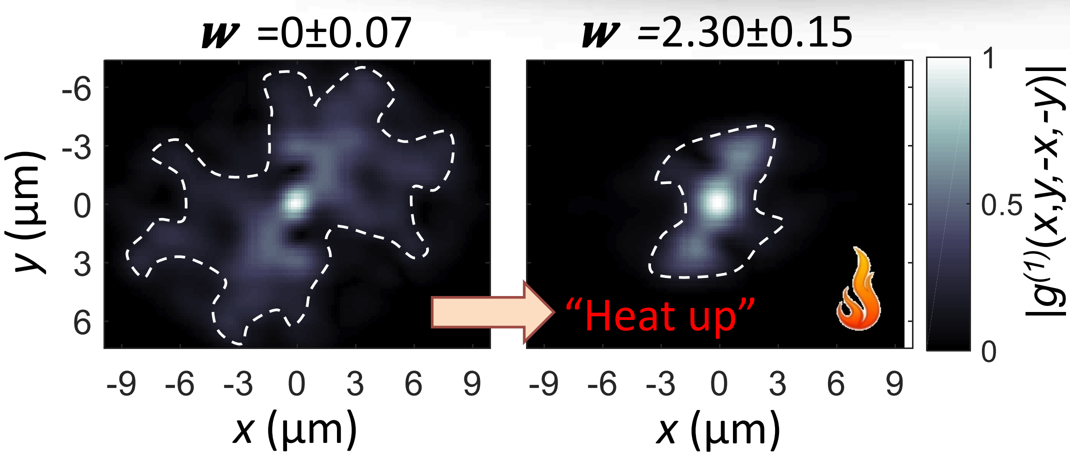
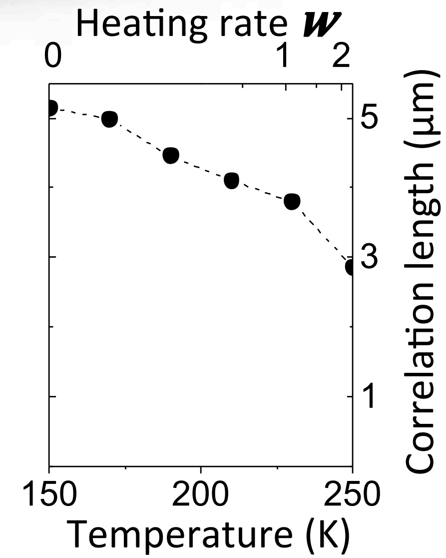
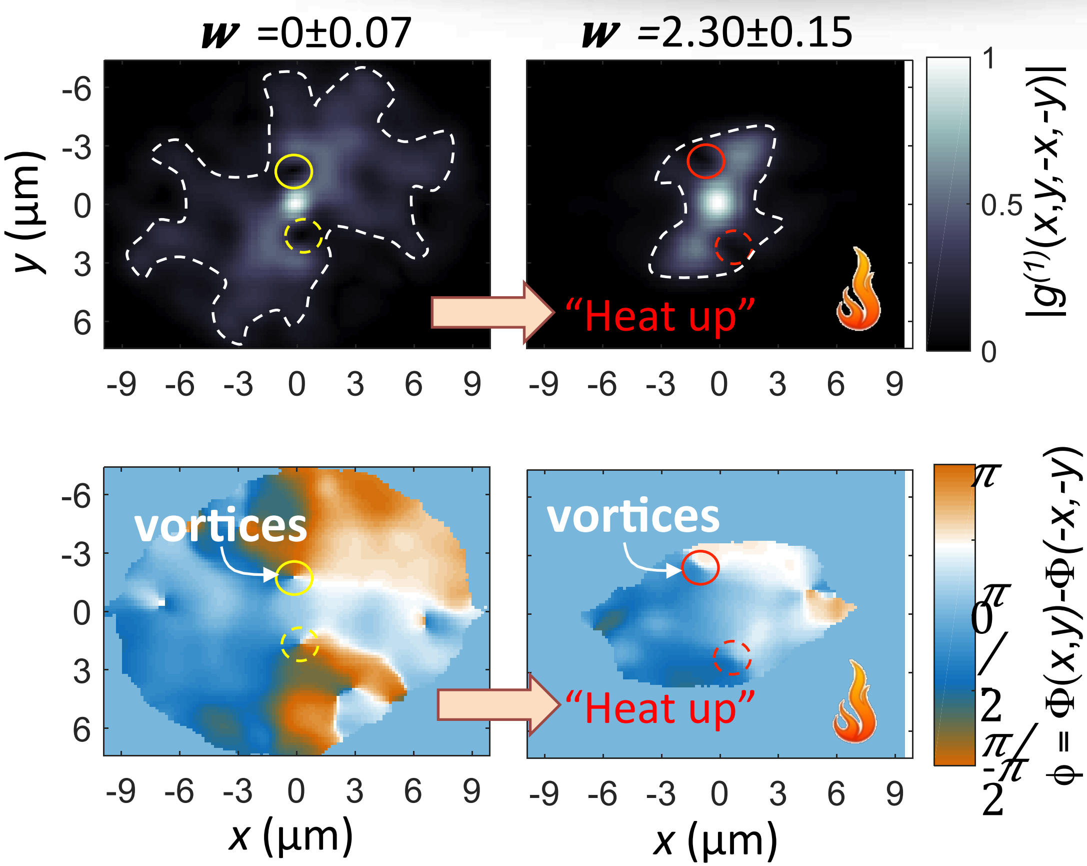




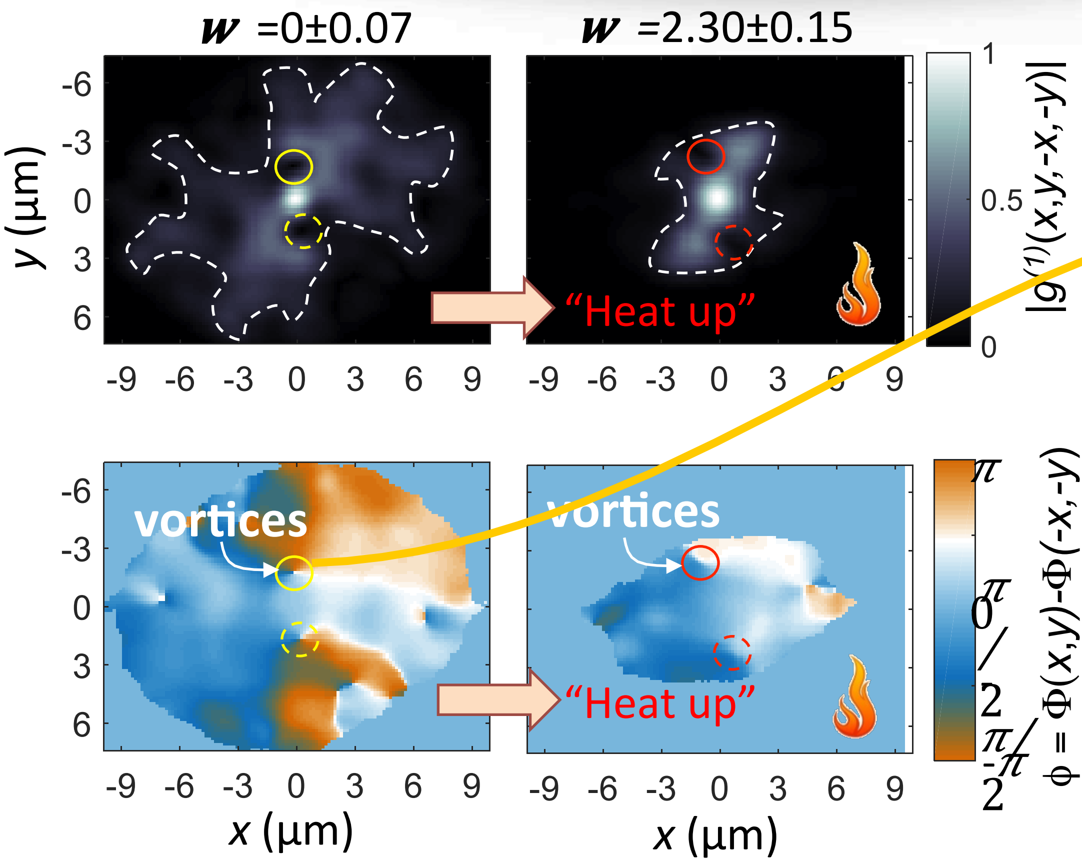
Coherence length **decreases** for increasing w
→ nonequilibrium analog of thermal depletion of the condensate

2. Condensation properties at the **thermal-to-dynamical** crossover

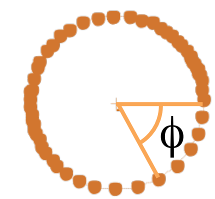


Phase of the condensate

2. Condensation properties at the **thermal-to-dynamical** crossover

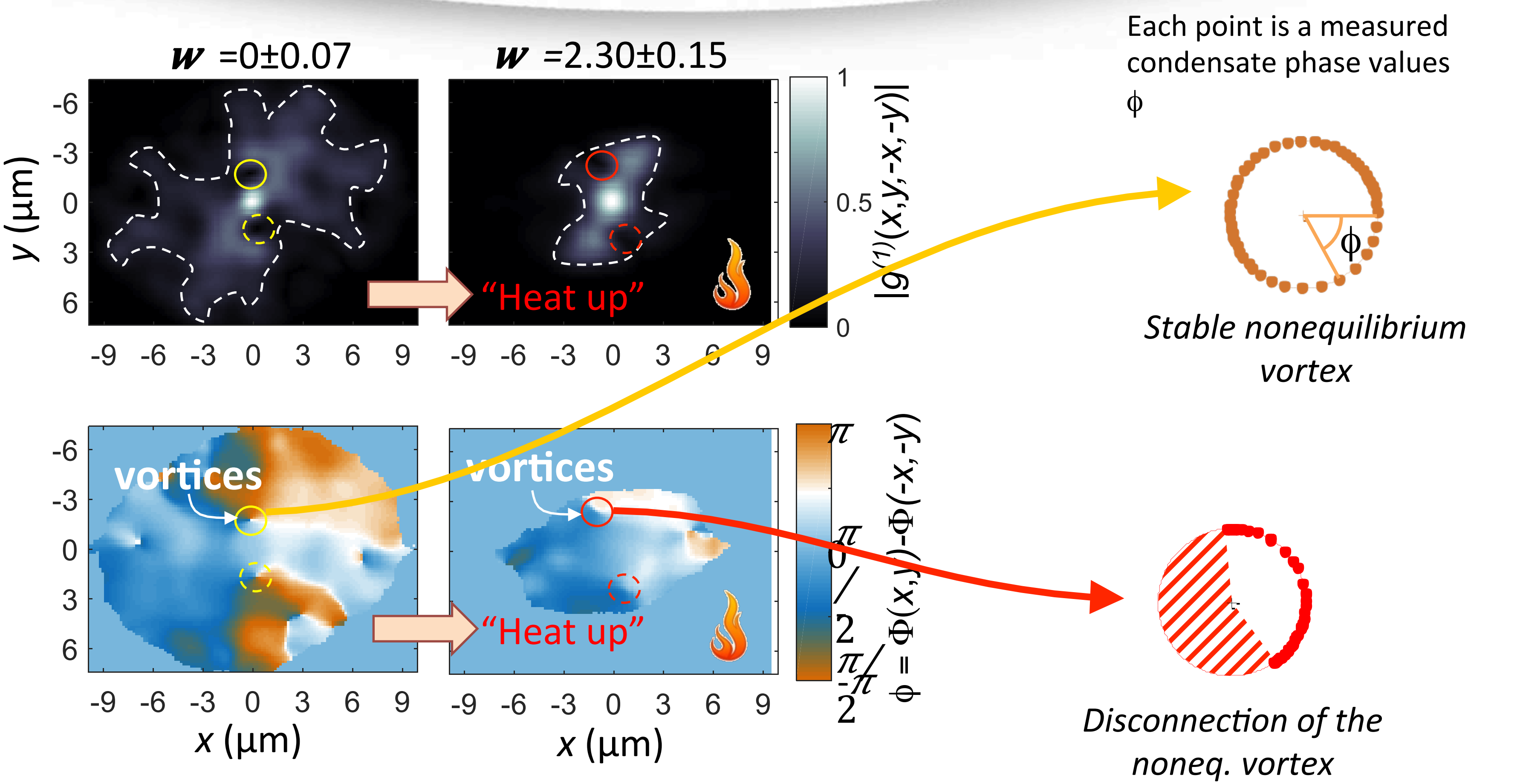


Each point is a measured condensate phase values ϕ



Stable nonequilibrium vortex

2. Condensation properties at the **thermal-to-dynamical** crossover



Thermal destabilization of nonequilibrium vortices

General Summary

Demonstrate and characterize a **hybrid** quantum phase transition :

- Half controlled by drive and losses and
- Half controlled by thermalization
- **Properties are hybrid** as well, with features typical from both realms [13]

[13] S. Klembt,..., MR, Phys. Rev. Lett. **120**, 035301 (2018)

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➢ What determines the stability of topological excitations at $\boldsymbol{w} \sim 1$

➢ New resources to manipulate heat and work: many-body quantum degrees of freedom + not constrained by thermal equilibrium [14]
→ e.g. performances and resources of a polaritonic engine at finite $\boldsymbol{w} \sim 1$? [15]

[13] S. Klembt,…, MR, Phys. Rev. Lett. **120**, 035301 (2018)
[14] S. Klembt,…, MR, Phys. Rev. Lett. **114**, 186403 (2015)
[15] K. Rojan,…, MR & A. Minguzzi, Phys. Rev. Lett **119**, 127401 (2017)

Acknowledgments

"Quantum fluids of light" people

NÉEL institut

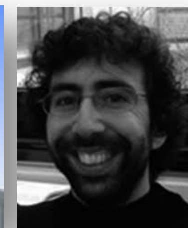
Experiments

Petr Stepanov

Thorsten Klein

Sebastian Klembt

Augustin Baas



Yoan Léger

MACQUARIE University

Thomas Volz

Theory

LPMMC laboratoire de physique et de modélisation des milieux condensés

Anna Minguzzi

UNIVERSITÀ DEGLI STUDI DI TRENTO

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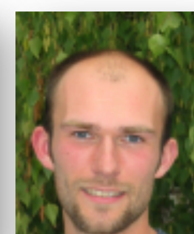

Michiel Wouters

Universiteit Antwerpen

ANR

nano SCIENCES FONDATION

eQus

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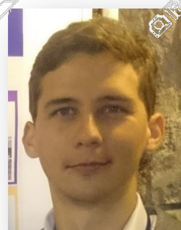
Acknowledgments

“Quantum fluids of light” people

Positions available !

INEEL institut

Experiments



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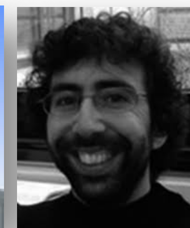

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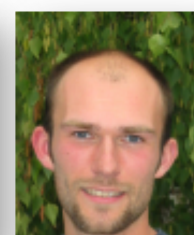

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Universiteit Antwerpen

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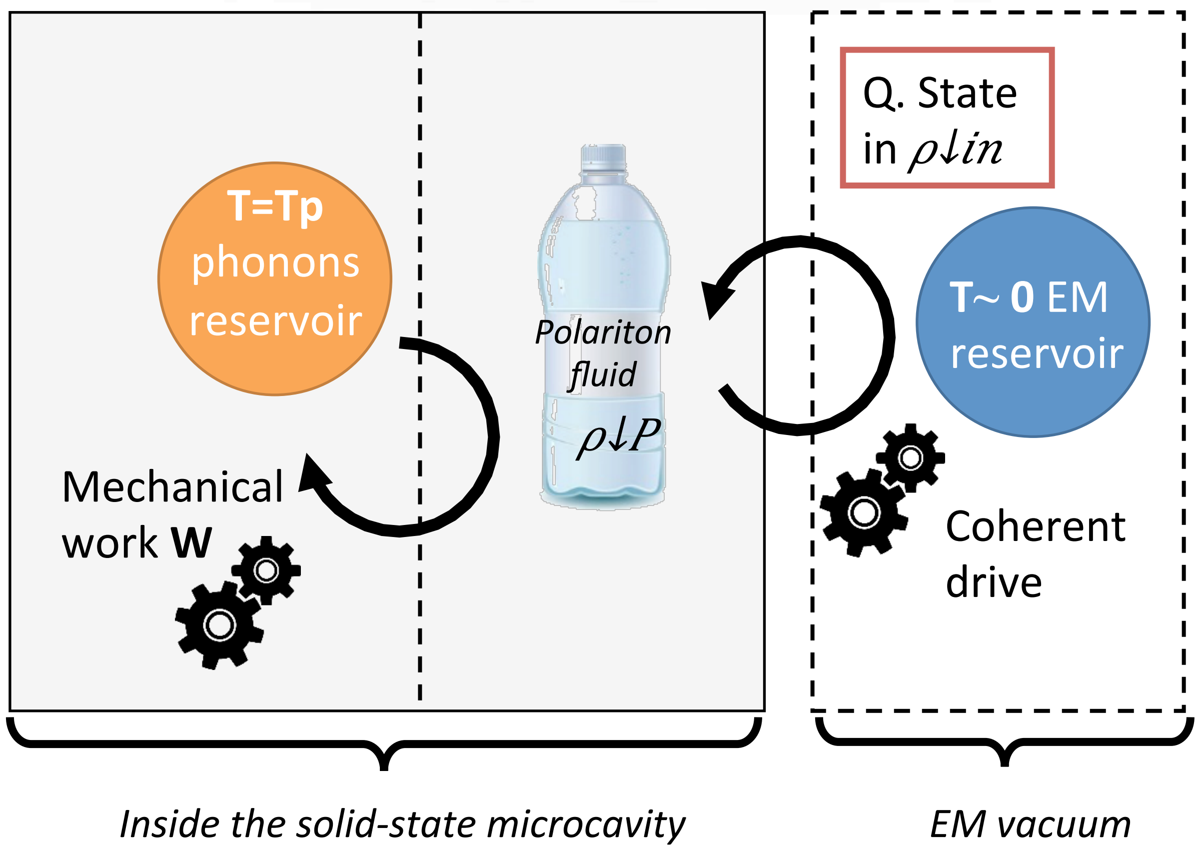
Available Resources in a polaritonic engines



Theory : mean field & thermal noise from phonons

Kinetic term

Static disorder

DD-GPE : condensate dynamics

$$i\hbar\partial_t\Phi = \mathcal{F}^{-1}[E_{lp}(\mathbf{k})]\Phi + U_r\Phi + V_{phon}\Phi + g|\Phi|^2\Phi - i\hbar\frac{\gamma}{2}\Phi + i\frac{\alpha}{2}n_R^2\Phi$$

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DD-GPE : condensate dynamics

losses

$$i\hbar\partial_t\Phi = \mathcal{F}^{-1}[E_{lp}(\mathbf{k})]\Phi + U_r\Phi + V_{phon}\Phi + g|\Phi|^2\Phi$$
$$- i\hbar\frac{\gamma}{2}\Phi + i\frac{\alpha}{2}n_R^2\Phi$$

gain

Theory : mean field & thermal noise from phonons

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Incoherent reservoir dynamics

$$\partial_t n_R = P - \gamma_R n_R - \alpha n_R^2|\Phi|^2$$

Laser excitation

gain

Theory : mean field & thermal noise from phonons

Kinetic term

Static disorder

PP interactions

DD-GPE : condensate dynamics

losses

$$i\hbar\partial_t\Phi = \mathcal{F}^{-1}[E_{lp}(\mathbf{k})]\Phi + U_r\Phi + V_{phon}\Phi + g|\Phi|^2\Phi - i\hbar\frac{\gamma}{2}\Phi + i\frac{\alpha}{2}n_R^2\Phi$$

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Laser excitation

gain

Theory : mean field & thermal noise from phonons

Kinetic term

Stochastic dispersive part of the phonon potential $V_{phon}(x,t)$

Static disorder

PP interactions

DD-GPE : condensate dynamics

losses

$$i\hbar\partial_t\Phi = \mathcal{F}^{-1}[E_{lp}(\mathbf{k})]\Phi + U_r\Phi + V_{phon}\Phi + g|\Phi|^2\Phi - i\hbar\frac{\gamma}{2}\Phi + i\frac{\alpha}{2}n_R^2\Phi$$

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Laser excitation

gain

Theory : mean field & thermal noise from phonons

Thermal phonons potential correlator [16] :

Phonon potential noise power

$$\langle V_{phon}(\mathbf{q}_{\|}, t) V_{phon}(\mathbf{q}'_{\|}, t') \rangle = \delta_{q_{\|}, q'_{\|}} \delta(t - t') f_{\mathbf{q}_{\|}}$$

$$f_{\mathbf{q}_{\|}} = \sum_{q_z} X_0^2 X_{\mathbf{q}_{\|}}^2 |\mathcal{V}_{lo}(\mathbf{q}_{\|}, q_z)|^2 N_{BE}(\mathbf{q}_{\|}, q_z)$$

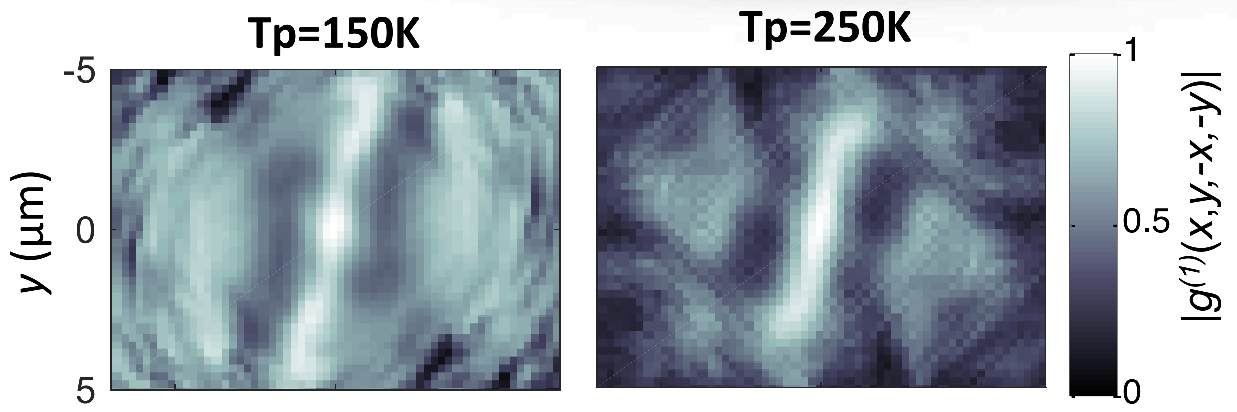
Fröhlich interaction strength

Phonons BE distribution (T)

[16] I. Savenko *et al*. Phys. Rev. Lett. **110** 127402

Theory : mean field & thermal noise from phonons

Results: Spatial correlations



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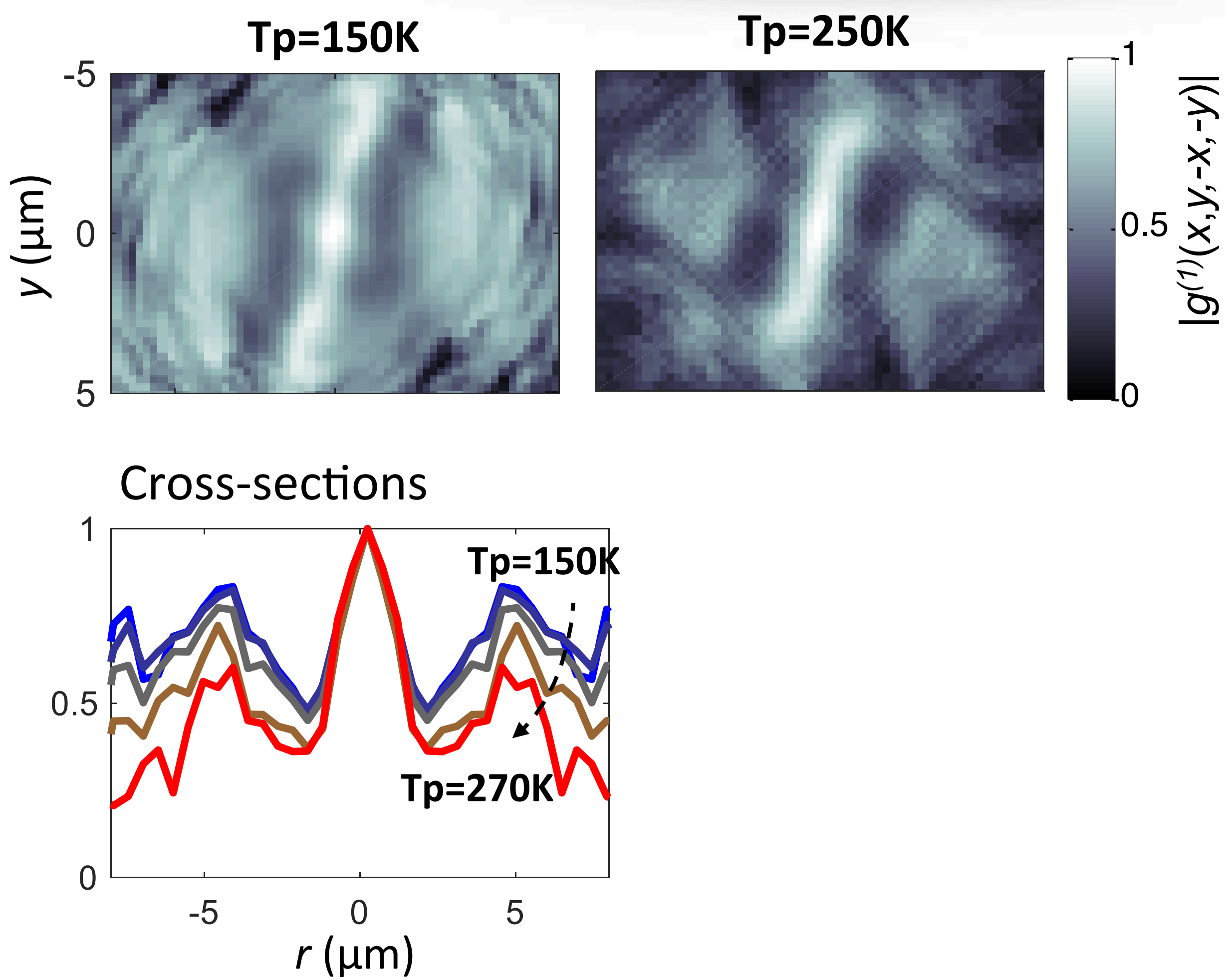

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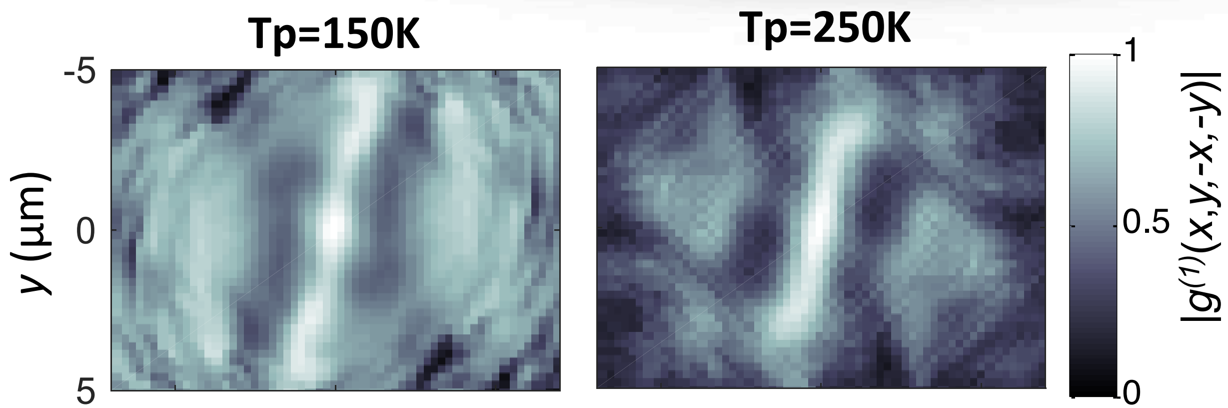
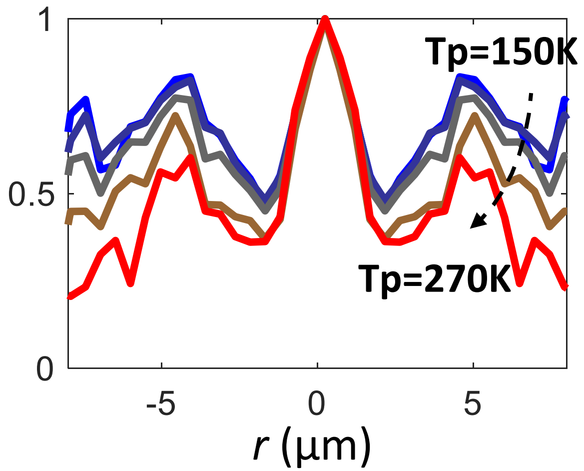
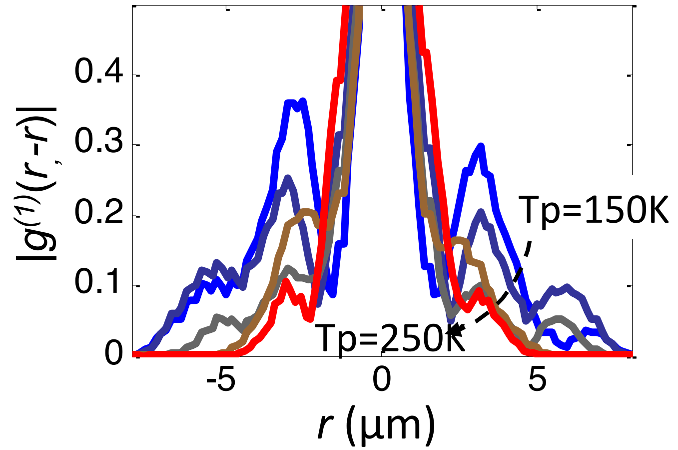


Cross-sections

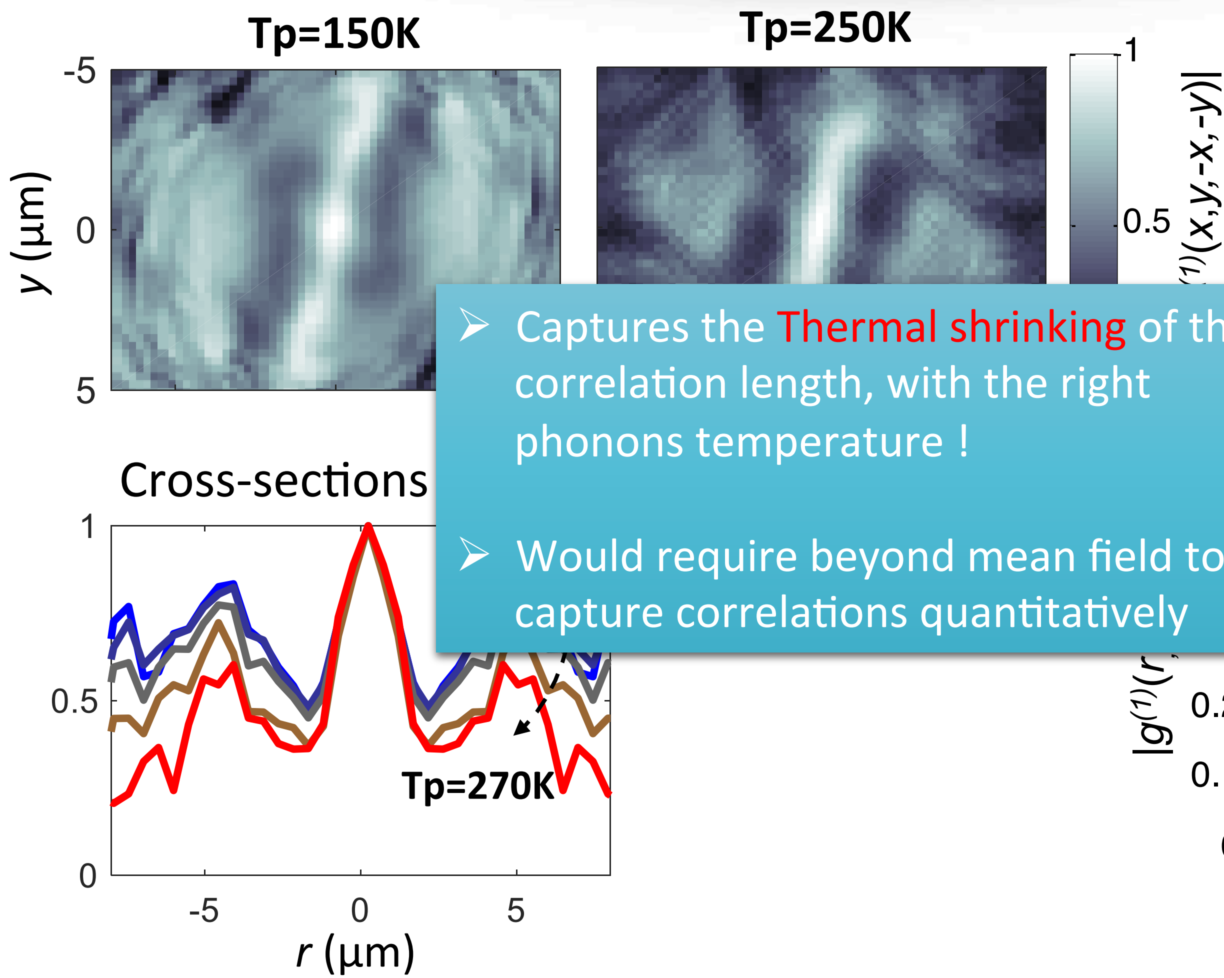


Experiment

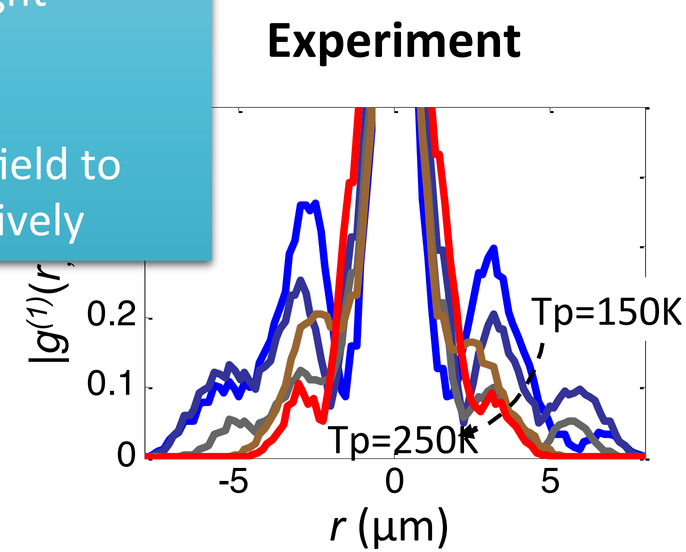


Theory : mean field & thermal noise from phonons

Results: Spatial correlations

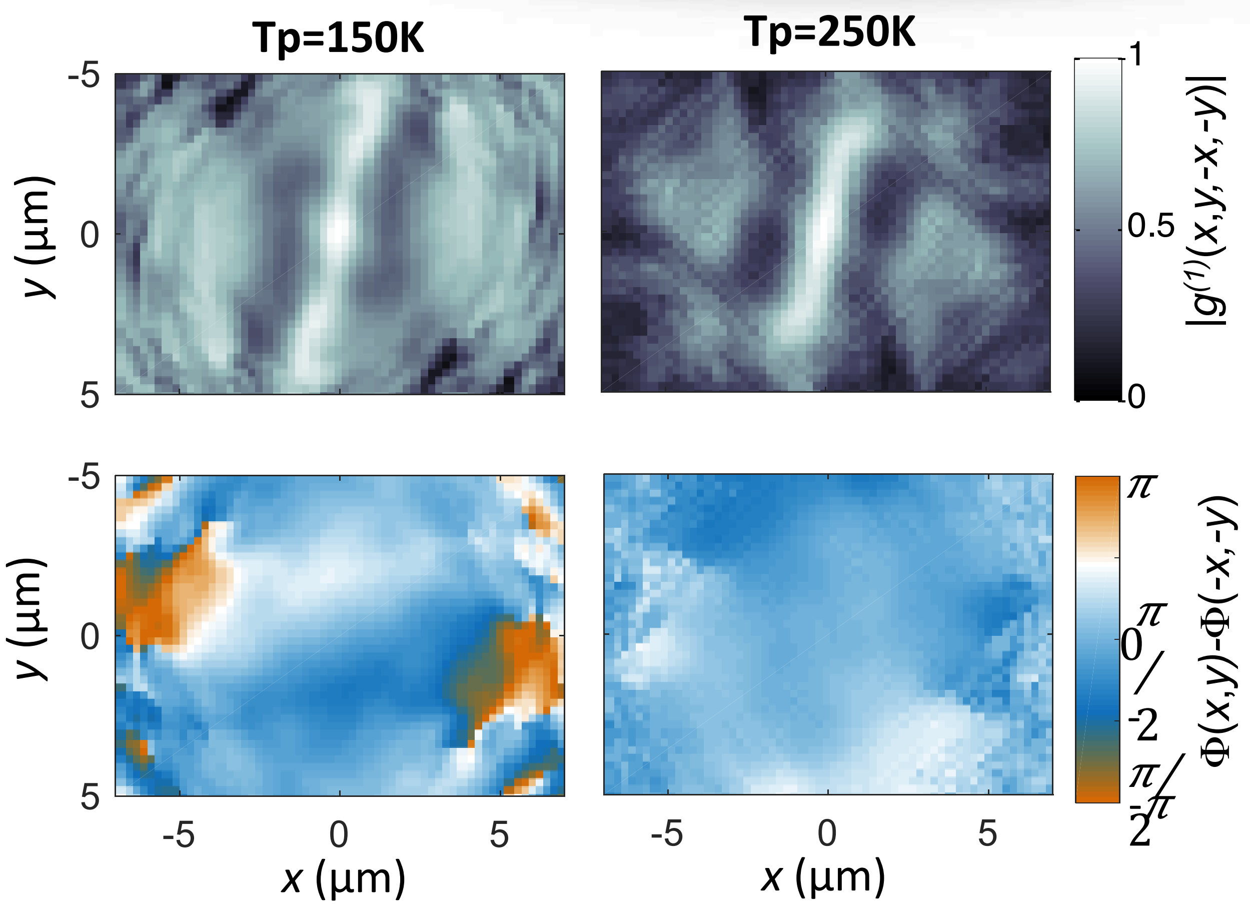


- Captures the Thermal shrinking of the correlation length, with the right phonons temperature !
- Would require beyond mean field to capture correlations quantitatively



Theory : mean field & thermal noise from phonons

Results: Vortices thermal disconnection



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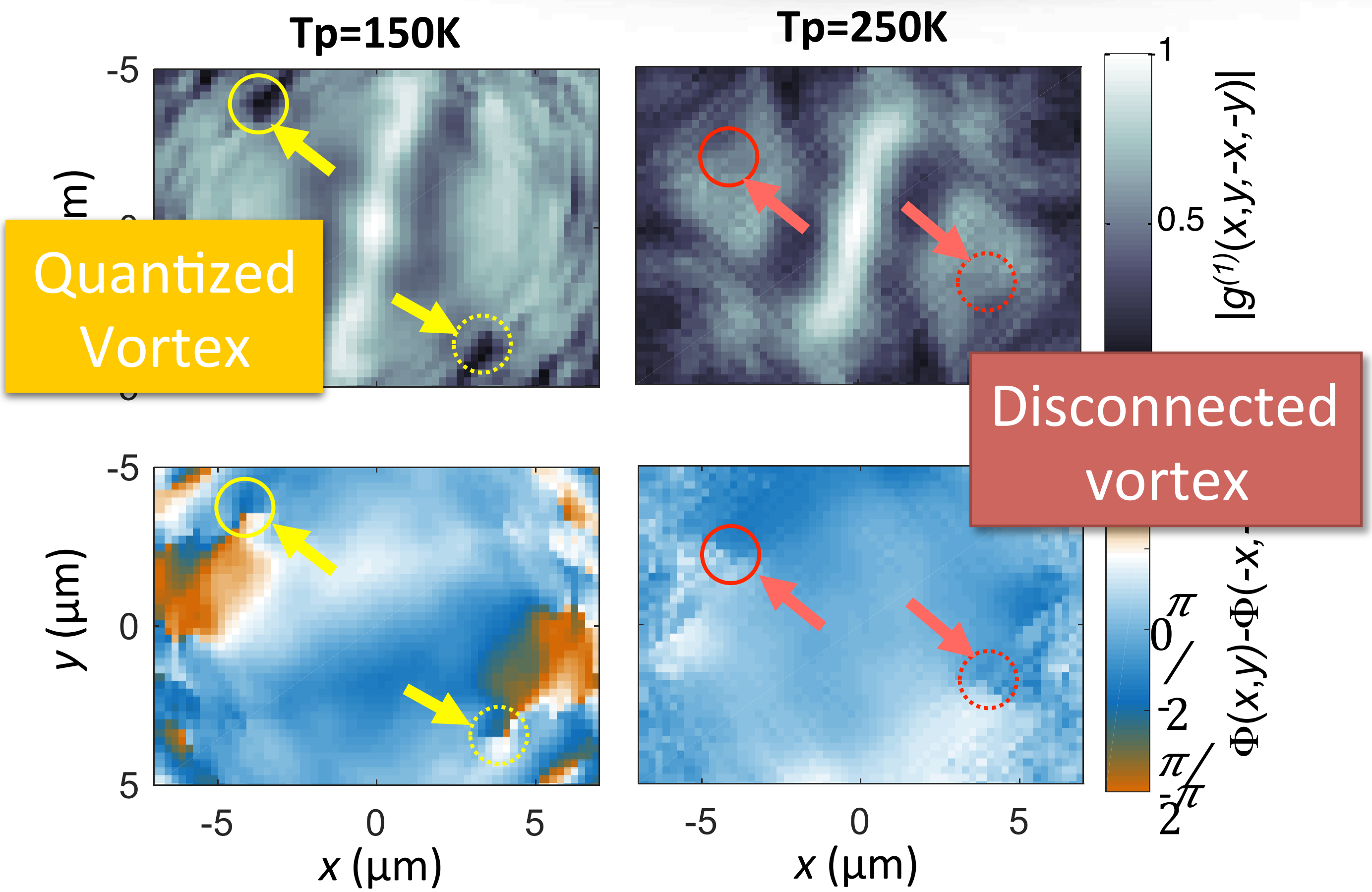

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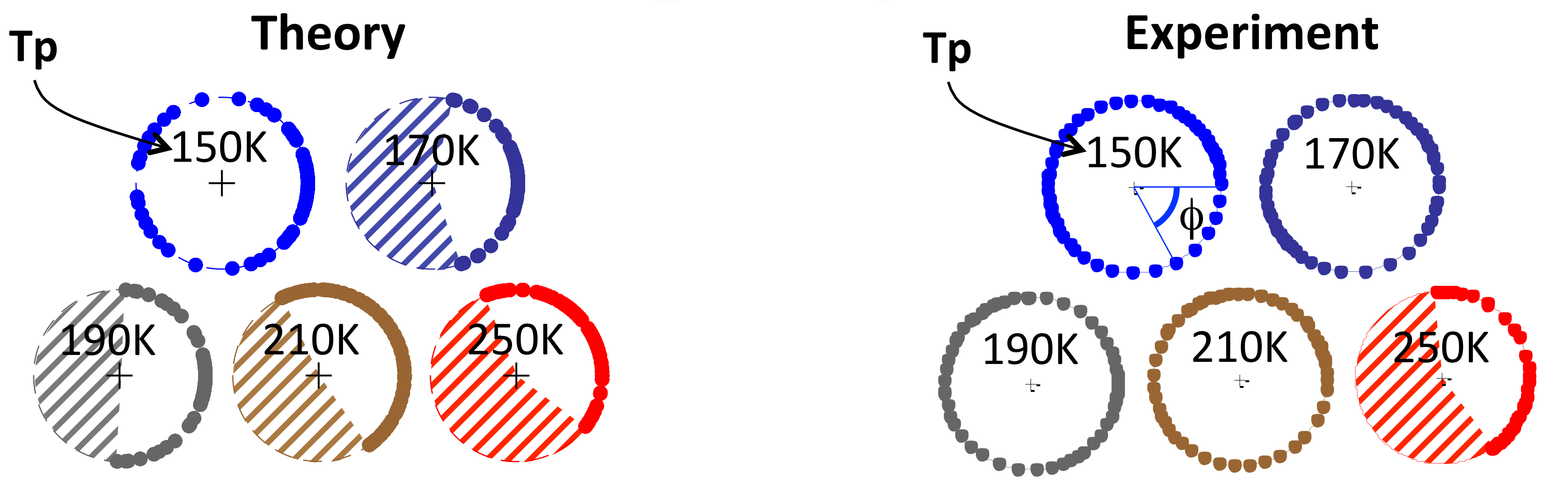
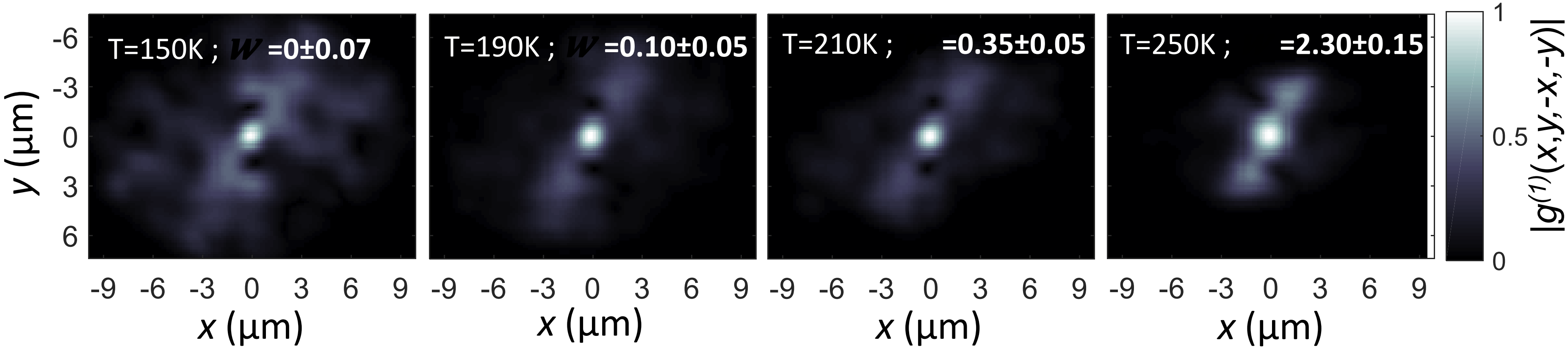


- Captures the vortices thermal disconnection
- Would require beyond mean-field to capture the disconnection temperature

Expt : mean field & thermal noise from phonons

Spatial correlations



Expt : mean field & thermal noise from phonons

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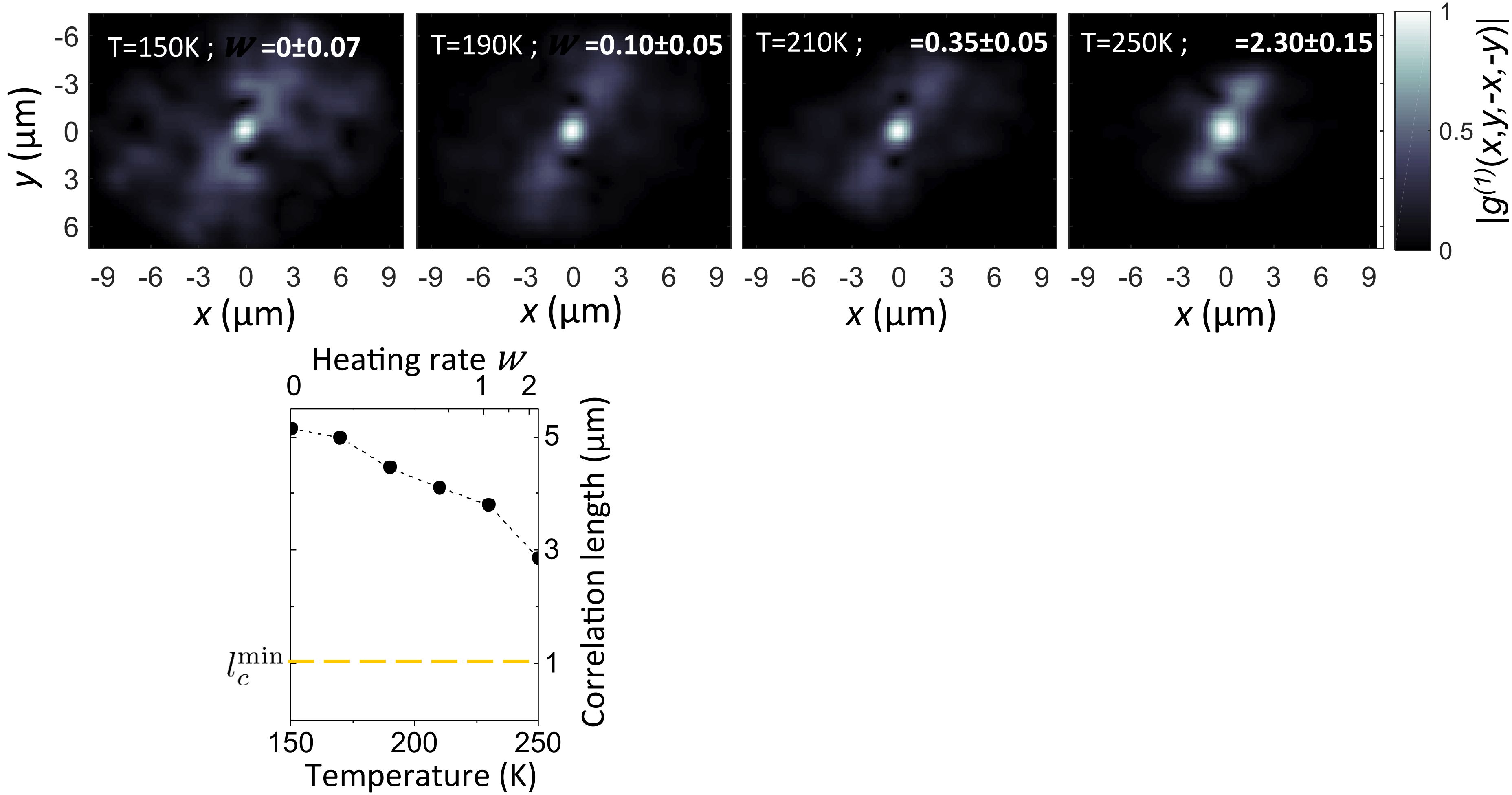

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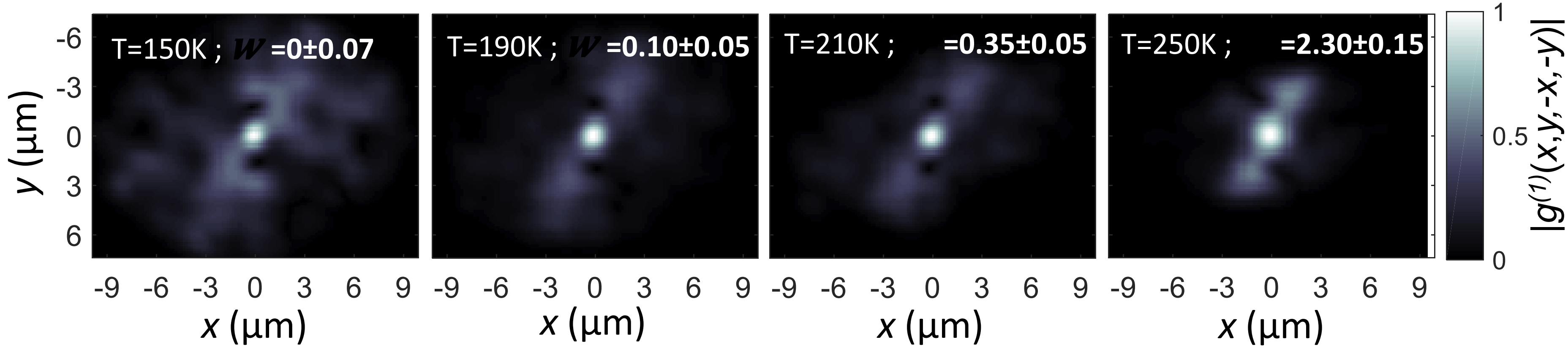
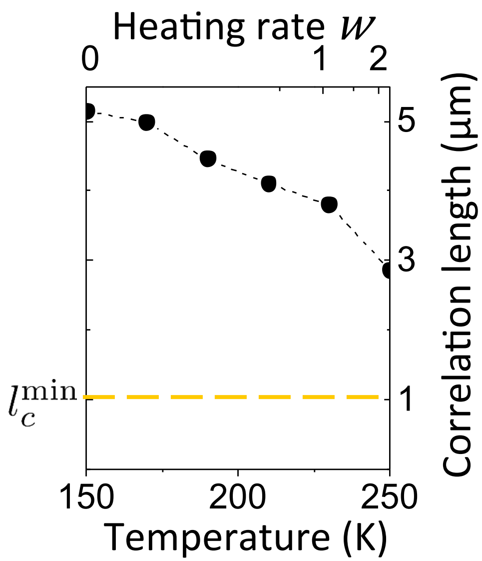
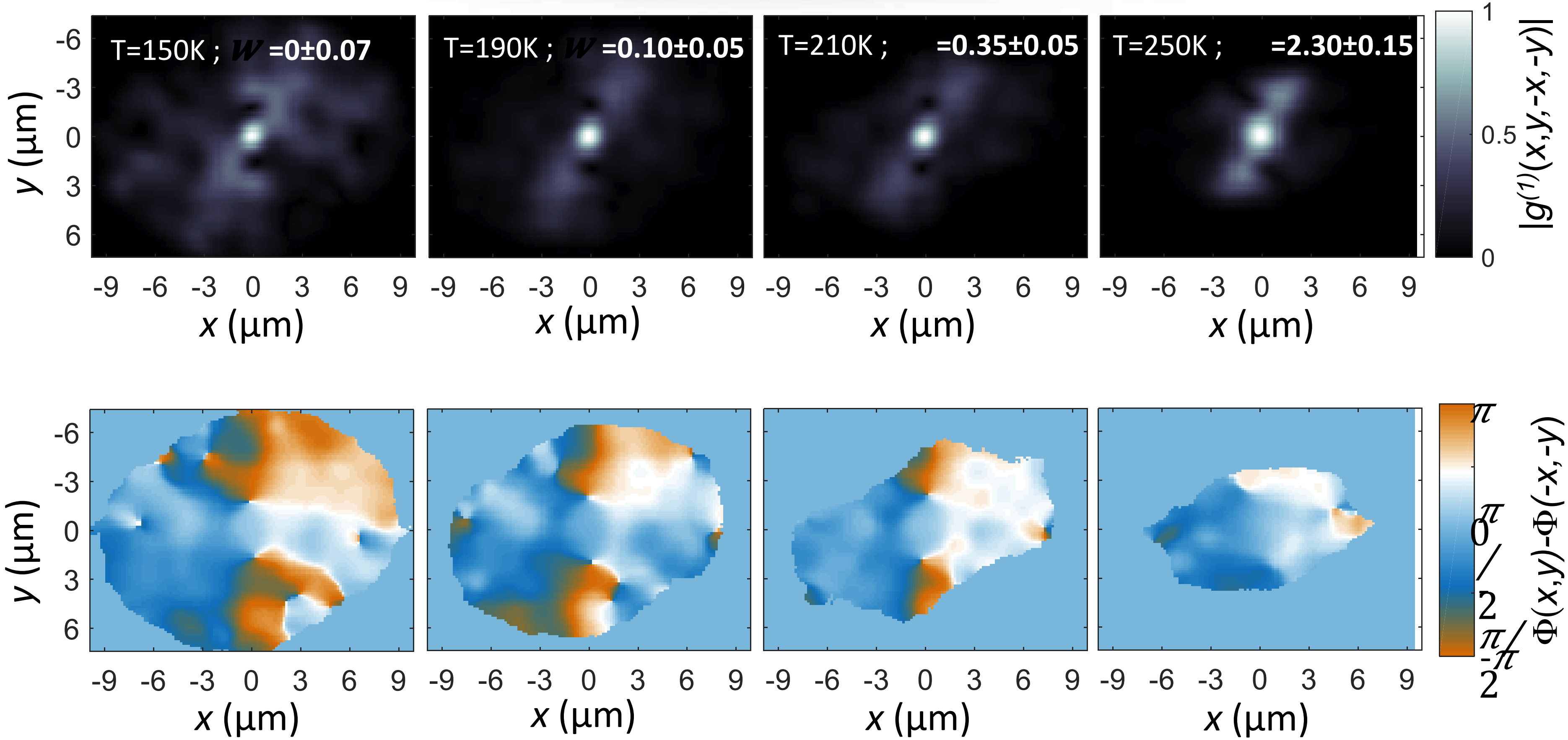




→ correlation length decrease
for increasing absorbed heat $\boldsymbol{w}$
>0.1

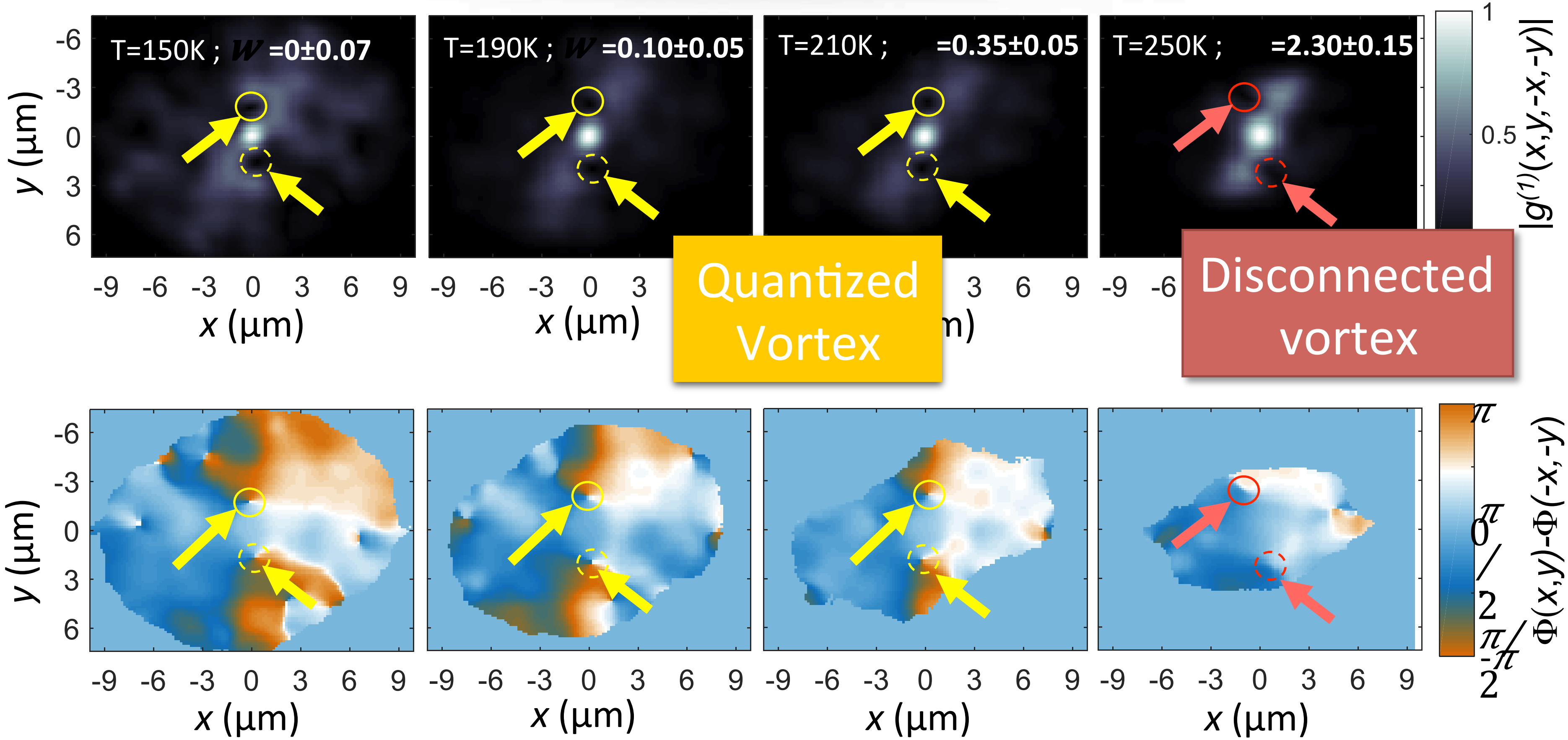
Expt : mean field & thermal noise from phonons

Phase pattern



Expt : mean field & thermal noise from phonons

Vortex thermal stability analysis



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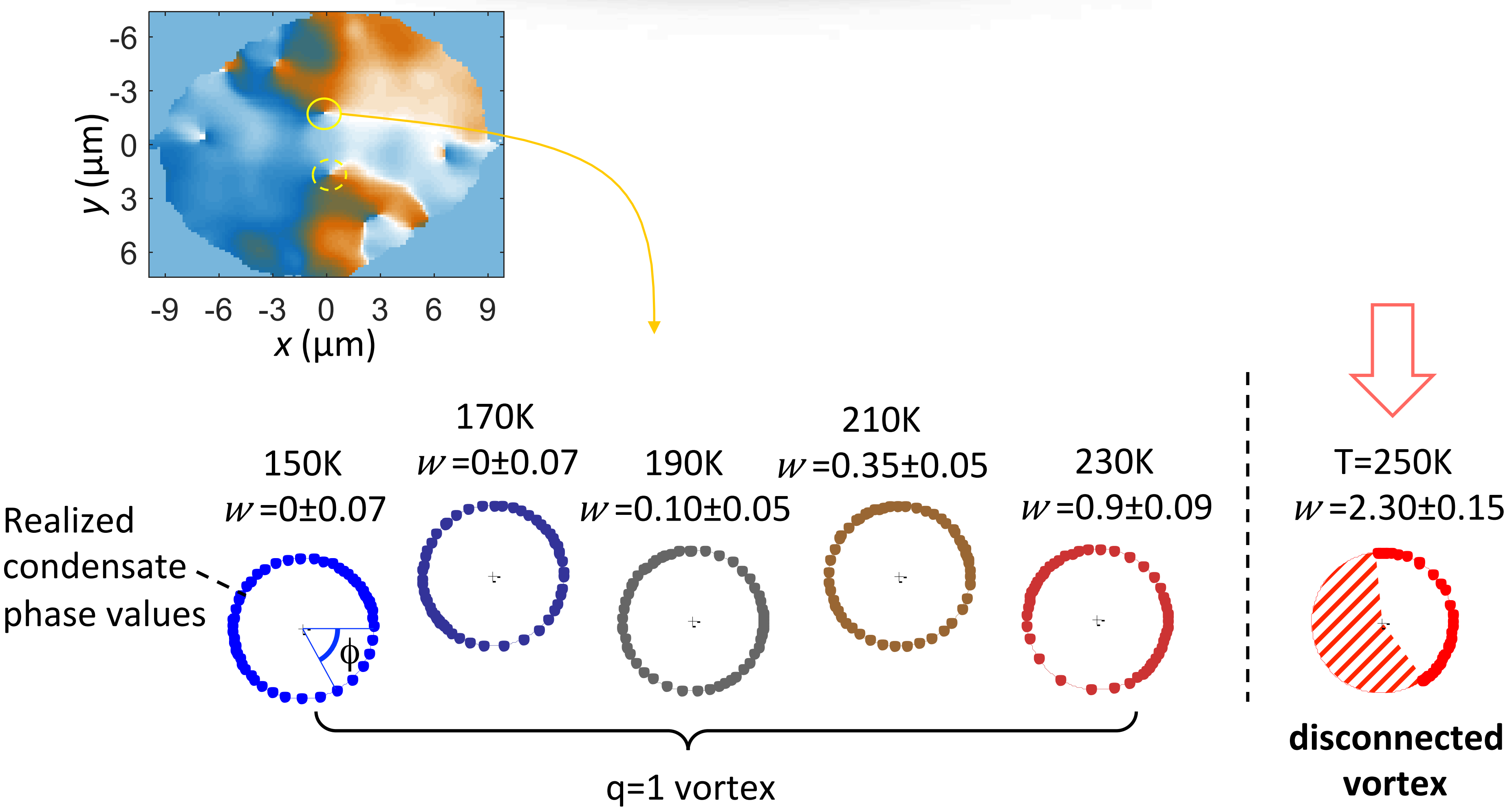
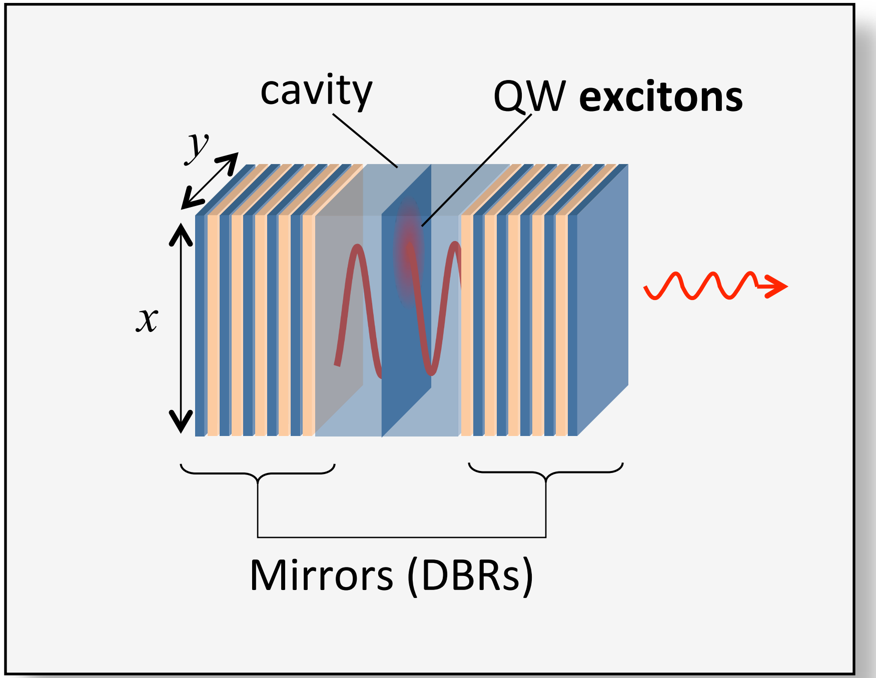


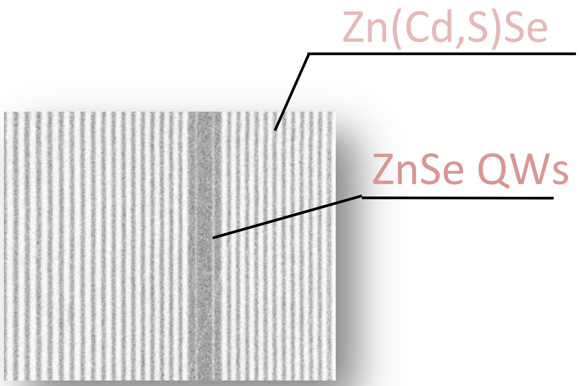
Semiconductor microcavity

Planar semiconductor microcavity



Semiconductor microcavity

Microcavities in
ZnSe compounds



6K<T<270K