Probing quantum many-body correlations in polariton microcavities

Francesca Maria Marchetti
In collaboration with

Meera Parish
Monash University

Jesper Levinsen
Monash University

Jonathan Keeling
St Andrews

[arxiv (to appear at some point hopefully soon)]

Probing quantum many-body correlations in polariton microcavities
Motivation: Beyond polariton condensation

- Polariton condensation
- Condensation in lattices: Dirac cones, topological bands,
  - St-Jean et al. Nat Phot (2017)
- Superfluidity (Landau criterion)
- Persistency of currents
- Pattern formation
  - Dreismann et al. PNAS (2014)

Probing quantum many-body correlations in polariton microcavities
Motivation: Beyond polariton condensation

PHENOMENOLOGY OF NON-LINEAR CLASSICAL WAVES

- Polariton condensation
  
- Condensation in lattices: Dirac cones, topological bands, ...

- Superfluidity (Landau criterion)
  
- Persistency of currents

- Pattern formation

Probing quantum many-body correlations in polariton microcavities
Motivation: Beyond polariton condensation

**PHENOMENOLOGY OF NON LINEAR CLASSICAL WAVES**

- Mean-field theory
  \[ \hat{a}_0 \simeq \langle \Phi | \hat{a}_0 | \Phi \rangle = \sqrt{n} \]

- Generalised Gross-Pitaevskii (complex Ginzburg-Landau) equation
  \[ \hat{\psi}_0(\mathbf{r}, t) = \phi_0(\mathbf{r}) \hat{a}_0(t) \simeq \psi_0(\mathbf{r}, t) \]

\[ i\hbar \partial_t \psi_0 = \left( -\frac{\hbar^2 \nabla^2}{2m} - i\gamma + V_{\text{ext}} + g|\psi_0|^2 \right) \psi_0 + P \]

[Marchetti et al. PRL(2010)]

Fluctuations (quantum)

Condensate: semiclassical
\[ |\Phi\rangle = e^{\sqrt{n}\hat{a}_0^\dagger}|0\rangle \]
Motivation: Beyond polariton condensation

**PHENOMENOLOGY OF NON-LINEAR CLASSICAL WAVES**

- Mean-field theory
  \[ \hat{a}_0 \approx \langle \Phi | \hat{a}_0 | \Phi \rangle = \sqrt{n} \]

- Generalised Gross-Pitaevskii (complex Ginzburg-Landau) equation
  \[ i\hbar \partial_t \Psi_0 = \left( -\frac{\hbar^2 \nabla^2}{2m} - i\gamma + V_{\text{ext}} + g |\Psi_0|^2 \right) \Psi_0 + P \]

[errors in the text due to quality of the image]

Probing quantum many-body correlations in polariton microcavities
Probing quantum many-body correlations in polariton microcavities

**Motivation** Beyond polariton condensation

**PHENOMENOLOGY OF NON-LINEAR CLASSICAL WAVES**

- Mean-field theory
  \[ \hat{a}_0 \simeq \langle \Phi | \hat{a}_0 | \Phi \rangle = \sqrt{n} \]

- Generalised Gross-Pitaevskii (complex Ginzburg-Landau) equation

\[ \hat{\Psi}_0(r, t) = \phi_0(r)\hat{a}_0(t) \simeq \psi_0(r, t) \]

\[ i\hbar \partial_t \psi_0 = \left( -\frac{\hbar^2 \nabla^2}{2m} - i\gamma + V_{\text{ext}} + g|\psi_0|^2 \right) \psi_0 + P \]

[Berceanu et al. PRB (2015)]

Probing quantum many-body correlations in polariton microcavities
Motivation: Beyond polariton condensation

**PHENOMENOLOGY OF NON-LINEAR CLASSICAL WAVES**

- Mean-field theory
  \[ \hat{a}_0 \approx \langle \Phi | \hat{a}_0 | \Phi \rangle = \sqrt{n} \]

- Generalised Gross-Pitaevskii (complex Ginzburg-Landau) equation
  \[ \hat{\psi}_0(r, t) = \phi_0(r)\hat{a}_0(t) \approx \psi_0(r, t) \text{ classical field} \]
  \[ i\hbar \partial_t \psi_0 = \left( -\frac{\hbar^2 \nabla^2}{2m} - i \gamma + V_{\text{ext}} + g |\psi_0|^2 \right) \psi_0 + P \]

[Diaz-Camacho et al. PRB (2018)]

Probing quantum many-body correlations in polariton microcavities
Motivation
Beyond mean-field effects?

Interaction strength > kinetic energy
> lifetime broadening

- Observing polariton quantum correlated behaviour is challenging
Motivation: Beyond mean-field effects? Few-body

- Observing polariton quantum correlated behaviour is challenging
- Few-particle level
  - Fiber cavities (fully confined photonic dots)
    - non-linearities enhanced by spatial confinement
    - weak polariton blockade

Interaction strength > kinetic energy > lifetime broadening

Probing quantum many-body correlations in polariton microcavities

- [Munoz-Matutano arXiv: 1712.0551]
- [Delteil arXiv: 1805.04020]
Motivation Beyond mean-field effects? Few-body

- Observing polariton quantum correlated behaviour is challenging
- Few-particle level
  - Fiber cavities (fully confined photonic dots)
    - non-linearities enhanced by spatial confinement
    - weak polariton blockade
  - Engineering polariton quantum states
    [Cuevas e al. Sci Adv (2018)]

interaction strength > kinetic energy

lifetime broadening

Probing quantum many-body correlations in polariton microcavities
Motivation

Beyond mean-field effects? Many-body

**OUR PROPOSAL**

**Quantum impurity physics**

- Engineer and probe beyond mean-field quantum correlations in a many-body polariton system

**Bose polaron**

- A mobile impurity is dressed by the excitations of a quantum-mechanical medium (beyond mean-field)

Probing quantum many-body correlations in polariton microcavities
Motivation: Beyond mean-field effects? Many-body

Quantum impurity physics
- Engineer and probe beyond mean-field quantum correlations in a many-body polariton system

Bose polaron
- A mobile impurity is dressed by the excitations of a quantum-mechanical medium (beyond mean-field)

Probing quantum many-body correlations in polariton microcavities
Motivation: Beyond mean-field effects? Many-body effects

Our Proposal

Quantum impurity physics
- Engineer and probe beyond mean-field quantum correlations in a many-body polariton system

Bose polaron
- A mobile impurity is dressed by the excitations of a quantum-mechanical medium (beyond mean-field)

Probing quantum many-body correlations in polariton microcavities
Motivation: Beyond mean-field effects? Many-body

**OUR PROPOSAL**

**Quantum impurity physics**
- Engineer and probe beyond mean-field quantum correlations in a many-body polariton system

**Bose polaron**
- A mobile impurity is dressed by the excitations of a quantum-mechanical medium (beyond mean-field)

Probing quantum many-body correlations in polariton microcavities
Motivation Beyond mean-field effects? Many-body

**OUR PROPOSAL**

**Quantum impurity physics**
- Engineer and probe beyond mean-field quantum correlations in a many-body polariton system

**Bose polaron**
- A mobile impurity is dressed by the excitations of a quantum-mechanical medium (beyond mean-field)
  - attractive polaron branch

Probing quantum many-body correlations in polariton microcavities
Motivation
Beyond mean-field effects? Many-body

**OUR PROPOSAL**

**Quantum impurity physics**
- Engineer and probe beyond mean-field quantum correlations in a many-body polariton system

**Bose polaron**
- A mobile impurity is dressed by the excitations of a quantum-mechanical medium (beyond mean-field)
  - attractive polaron branch
  - repulsive polaron branch

Probing quantum many-body correlations in polariton microcavities
The seminar
Microcavity polaritons

Probing quantum many-body correlations in polariton microcavities
Microcavity polaritons

![Diagram of a microcavity polariton system with a cavity mirror, QW, and another cavity mirror.](Image)

- Small cavity photon mass $m_c \sim 10^{-4} m_x$

Probing quantum many-body correlations in polariton microcavities
Microcavity polaritons

- Small cavity photon mass $m_c \sim 10^{-4} m_x$
- Short lifetime $10 - 100$ ps (non-equilibrium)
Microcavity polaritons

- Small cavity photon mass $m_c \sim 10^{-4} m_X$
- Short lifetime $10 - 100\,\text{ps}$ (non-equilibrium)
- Tunability
  - detuning $\delta$

Probing quantum many-body correlations in polariton microcavities
Microcavity polaritons

- Small cavity photon mass $m_c \sim 10^{-4} m_X$
- Short lifetime 10 – 100 ps (non-equilibrium)
- Tunability
  - detuning $\delta$

Probing quantum many-body correlations in polariton microcavities
Microcavity polaritons

- Small cavity photon mass $m_c \sim 10^{-4} m_X$
- Short lifetime $10 - 100 \text{ ps (non-equilibrium)}$
- Tunability
  - detuning $\delta$

Probing quantum many-body correlations in polariton microcavities
Microcavity polaritons

- Small cavity photon mass $m_c \sim 10^{-4} m_x$
- Short lifetime $10 - 100$ ps (non-equilibrium)
- Tunability
  - detuning $\delta$
  - pumping, probing

Probing quantum many-body correlations in polariton microcavities
Microcavity polaritons

- Small cavity photon mass $m_c \approx 10^{-4} m_X$
- Short lifetime $10 - 100 \text{ ps}$ (non-equilibrium)
- Tunability
  - detuning $\delta$
  - pumping, probing
  - INTERACTIONS

Probing quantum many-body correlations in polariton microcavities
Exciton spin, light polarization & interactions

$E_{\text{(GaAs)}}$

electron $m = \pm \frac{1}{2}$

heavy hole $m = \pm \frac{3}{2}$
Exciton spin, light polarization & interactions

$E_{\text{GaAs}}$ 

electron $m = +\frac{1}{2}$ 

heavy hole $m = -\frac{3}{2}$ 

$X_{\downarrow}$ 

Probing quantum many-body correlations in polariton microcavities
Probing quantum many-body correlations in polariton microcavities
Exciton spin, light polarization & interactions

Probing quantum many-body correlations in polariton microcavities
Exciton spin, light polarization & interactions

Probing quantum many-body correlations in polariton microcavities
Exciton spin, light polarization & interactions

$E (\text{GaAs})$

- electron $m = +\frac{1}{2}$
- heavy hole $m = -\frac{3}{2}$

- bright exciton $m = -1: X_\downarrow$

Exciton-exciton interactions

- $\uparrow\uparrow$ and $\downarrow\downarrow$: repulsive
- $\uparrow\downarrow$: attractive

Strong coupling to light: bipolaritons?

$2\omega_{X_0} - E_B = \omega_{XX_0}$

Probing quantum many-body correlations in polariton microcavities
Biexciton resonance
Biexciton resonance
Biexciton resonance

Probing quantum many-body correlations in polariton microcavities
Biexciton resonance

2-body scattering: polariton T-matrix. [Wouters PRB (2007)]

\[
\frac{1}{t(E)} = \frac{1}{t_{XX}(E)} \frac{m_C}{m_X} d(E)
\]

\[
\ln \left( \frac{E_B}{-E} \right) \quad \text{negligible for } m_C = 10^{-4} m_X
\]
Biexciton resonance: 2-body level

2-body scattering: polariton T-matrix. [Wouters PRB (2007)]

\[
\frac{1}{t(E)} = \frac{1}{t_{XX}(E)} \frac{m_C}{m_X} d(E)
\]

\[
\ln \left( \frac{E_B}{-E} \right) \text{ negligible for } m_C = 10^{-4} m_X
\]

Probing quantum many-body correlations in polariton microcavities
Biexciton resonance: 2-body level

2-body scattering: polariton T-matrix. [Wouters PRB (2007)]

\[
\frac{1}{t(E)} = \frac{1}{t_{XX}(E)} \left[ \frac{m_C}{m_X} d(E) \right]
\]

\[
\ln \left( \frac{E_B}{E} \right) \text{ negligible for } m_C = 10^{-4} m_X
\]

Probing quantum many-body correlations in polariton microcavities
Biexciton resonance: 2-body level

- 2-body scattering: polariton T-matrix. [Wouters PRB (2007)]

\[
\frac{1}{t(E)} = \frac{1}{t_{XX}(E)} \frac{m_C}{m_X} d(E)
\]

\[
\ln\left(\frac{E_B}{-E}\right) \quad \text{negligible for } m_C = 10^{-4} m_X
\]

- bipolariton = biexciton

Probing quantum many-body correlations in polariton microcavities
Probing quantum many-body correlations in polariton microcavities

Biexciton resonance: many-body level

probe: $k, \omega$

pump: $\omega_{LP0}$ at finite density $n > 0$
Model

- Hamiltonian

probe: \((X_\downarrow, C_\downarrow)\) basis

\[
\hat{H} = \sum \left[ \omega_X \hat{X}_\uparrow \hat{X}_\downarrow + \omega_C \hat{C}_\uparrow \hat{C}_\downarrow + \frac{\Omega_R}{2} \left( \hat{X}_\uparrow \hat{C}_\downarrow + \text{h.c.} \right) \right]
\]
Model

- Hamiltonian
  - probe: \((X_\downarrow, C_\downarrow)\) basis
  - pump: \(L_\uparrow \rightarrow \sqrt{n}\delta_{k,0} + L_\uparrow\)

\[
\hat{H} = \sum \left[ \omega_X \hat{X}_\downarrow \hat{X}_\downarrow + \omega_C \hat{C}_\downarrow \hat{C}_\downarrow + \frac{\Omega_R}{2} \left( \hat{X}_\downarrow \hat{C}_\downarrow + \text{h.c.} \right) \\
+ (\omega_{LP} - \omega_{LP0}) \hat{L}_\uparrow \hat{L}_\uparrow \right] \\
+ \sum \left[ g\hat{L}_\uparrow \hat{X}_\downarrow \hat{L}_\downarrow + \sqrt{n}g \hat{X}_\downarrow \hat{X}_\downarrow \left( \hat{L}_\uparrow + \hat{L}_\downarrow \right) \right]
\]

Probing quantum many-body correlations in polariton microcavities
Model

- Hamiltonian
  - probe: \((X_↓, C_↓)\) basis
  - pump: \(\hat{L}_↓ \rightarrow \sqrt{n}\delta_{k,0} + \hat{L}_↑\)

- Variational wavefunction

\[ \hat{H} = \sum \left[ \omega_X \hat{X}_↓ \hat{X}_↓ + \omega_C \hat{C}_↓ \hat{C}_↓ + \frac{\Omega_R}{2} \left( \hat{X}_↓ \hat{C}_↓ + \text{h.c.} \right) \right. \]
\[ \left. + (\omega_{LP} - \omega_{LP0}) \hat{L}_↑ \hat{L}_↑ \right] \]
\[ + \sum \left[ g\hat{L}_↑ \hat{X}_↓ \hat{L}_↑ + \sqrt{n} g \hat{X}_↓ \hat{X}_↓ \left( \hat{L}_↑ \hat{L}_↑ \right) \right] \]

\[ |\psi\rangle = \left( \alpha_X \hat{X}_↑ + \sum \beta_X \hat{X}_↑ \hat{L}_↑ \right) + \frac{1}{2} \sum \beta_X \hat{X}_↑ \hat{L}_↑ \hat{L}_↑ + \alpha_C \hat{C}_↑ + \sum \beta_C \hat{C}_↑ \hat{L}_↑ \right) \]
\[ + \frac{1}{2} \sum \beta_C \hat{C}_↑ \hat{L}_↑ \hat{L}_↑ \right) |\Phi\rangle \]
Model

- Hamiltonian
  - probe: \((X_\downarrow, C_\downarrow)\) basis
  - pump: \(\mathcal{L}_\uparrow \rightarrow \sqrt{n}\delta_{k,0} + \mathcal{L}_\uparrow\)  
  - reservoir 
  - q excitation

- Variational wavefunction
  \[
  \hat{H} |\psi\rangle = E |\psi\rangle
  \]

- Transmission: photon Green's function
  \[
  G_C(\omega) = \sum_n \frac{|\alpha_C^{(n)}|^2}{\omega - E_n + i0}
  \]
  \[
  T(\omega) = |G_C(\omega)|^2
  \]

\[
\hat{H} = \sum \left[ \omega_X \hat{X}_\downarrow \hat{X}_\downarrow + \omega_C \hat{C}_\downarrow \hat{C}_\downarrow + \frac{\Omega_R}{2} \left( \hat{X}_\downarrow \hat{C}_\downarrow + \text{h.c.} \right) \right.
\]
\[
+ (\omega_{\text{LP}} - \omega_{\text{LP0}}) \hat{L}_\uparrow \hat{L}_\uparrow
\]
\[
+ \sum \left[ g \hat{L}_\uparrow \hat{X}_\downarrow \hat{L}_\downarrow + \sqrt{n}g \hat{X}_\downarrow \hat{X}_\downarrow \left( \hat{L}_\uparrow \hat{L}_\downarrow + \hat{L}_\downarrow \hat{L}_\uparrow \right) \right]
\]

\[
|\psi\rangle = \left( \alpha_X \hat{X}_\downarrow + \sum \beta_X \hat{X}_\uparrow \hat{L}_\downarrow + \frac{1}{2} \sum \beta_X \hat{X}_\uparrow \hat{L}_\uparrow \hat{L}_\uparrow + \right.
\]
\[
\alpha_C \hat{C}_\downarrow + \sum \beta_C \hat{C}_\uparrow \hat{L}_\downarrow + \frac{1}{2} \sum \beta_C \hat{C}_\uparrow \hat{L}_\uparrow \hat{L}_\uparrow \left| \Phi \right. \right)
\]

Probing quantum many-body correlations in polariton microcavities
Biexciton resonance: many-body level

Probe: $k, \omega$

Probing quantum many-body correlations in polariton microcavities
Biexciton resonance: many-body level

Probing quantum many-body correlations in polariton microcavities

probe: $\mathbf{k}, \omega$

pump: $\omega_{LP_0}$ at finite density $n > 0$
Biexciton resonance: many-body level

Probing quantum many-body correlations in polariton microcavities

probe: $\mathbf{k}, \omega$

pump: $\omega_{LP0}$ at finite density $n > 0$

$\leftarrow$ repulsive polaron branch

$\leftarrow$ attractive polaron branch

$\frac{\omega - \omega_{X0}}{\Omega_R}$
Biexciton resonance: many-body level

- probe: \( \mathbf{k}, \omega \)
- pump: \( \omega_{LP0} \) at finite density \( n > 0 \)

Attractive polaron branch
Repulsive polaron branch

Probing quantum many-body correlations in polariton microcavities
Biexciton resonance: many-body level

Probing quantum many-body correlations in polariton microcavities
Probing quantum many-body correlations in polariton microcavities

Biexciton resonance: many-body level

**probe:** $k = 0, \omega$

**pump:** $\omega_{LP0}$ at finite density $n > 0$ (low)

splitting of branches close to the biexciton resonance

$X_2$ = 

\[\text{Probing quantum many-body correlations in polariton microcavities}\]
Probing quantum many-body correlations in polariton microcavities

**Biexciton resonance: many-body level**

- **Probe:** \( k = 0, \omega \)
- **Pump:** \( \omega_{LP0} \) at finite density \( n > 0 \) (high)

Splitting of branches close to the biexciton resonance:

\[
X_2 = \begin{array}{c}
\uparrow \quad \downarrow
\end{array}
\]

Additional splitting close to the triexciton resonance:

\[
X_3 = \begin{array}{c}
\uparrow \\
\downarrow \\
\uparrow
\end{array}
\]
Density dependence of the $X_2$ & $X_3$ resonances

- Minimal splitting of anticrossings

- $X_2$ resonance: $\Delta \omega_2 \simeq \sqrt{nE_B/m_X}$

- $X_3$ resonance: $\Delta \omega_3 \propto n$

Probing quantum many-body correlations in polariton microcavities
Polarisation pump-probe experiments

- Pump-probe spectroscopy in transmission

- Qualitative agreement for splitting but:
  - Broad pump (LP and UP populated)
  - Interpretation in terms of a mean-field 3 coupled oscillator model
  - No multi-point quantum correlations ($X_3$)

- Narrow pump (only LP)
  - No branch splitting
  - No study of density dependence

Probing quantum many-body correlations in polariton microcavities
Access beyond mean-field many-body polariton correlations via pump-probe spectroscopy

Quantum impurity physics (Bose polaron)

Two-point and three-point correlations are enhanced by biexciton $X_2$ and triexciton $X_3$ resonances

Characteristic density dependence of branch splitting

Prompt addition experim investigation

Simpler then 2D optical spectroscopy

Probing quantum many-body correlations in polariton microcavities