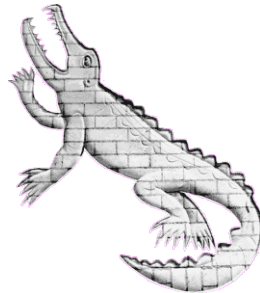# Signatures of Condensation in Disordered Microcavities

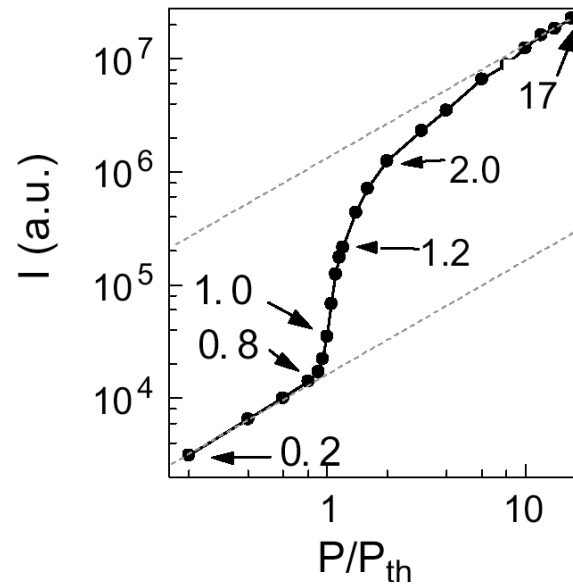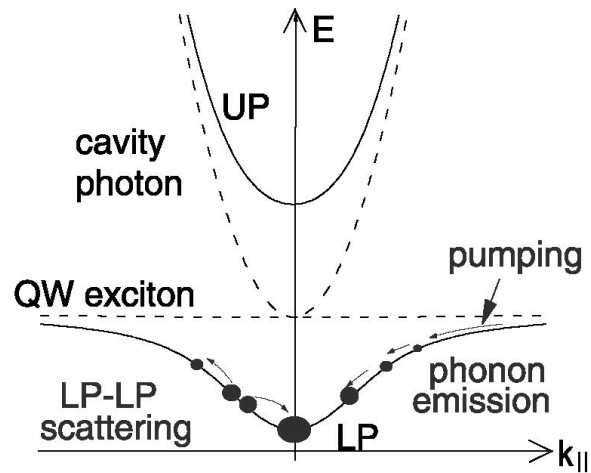## Francesca Maria Marchetti

Cavendish Laboratory -- University of Cambridge

J Keeling, MH Szymanska, PB Littlewood
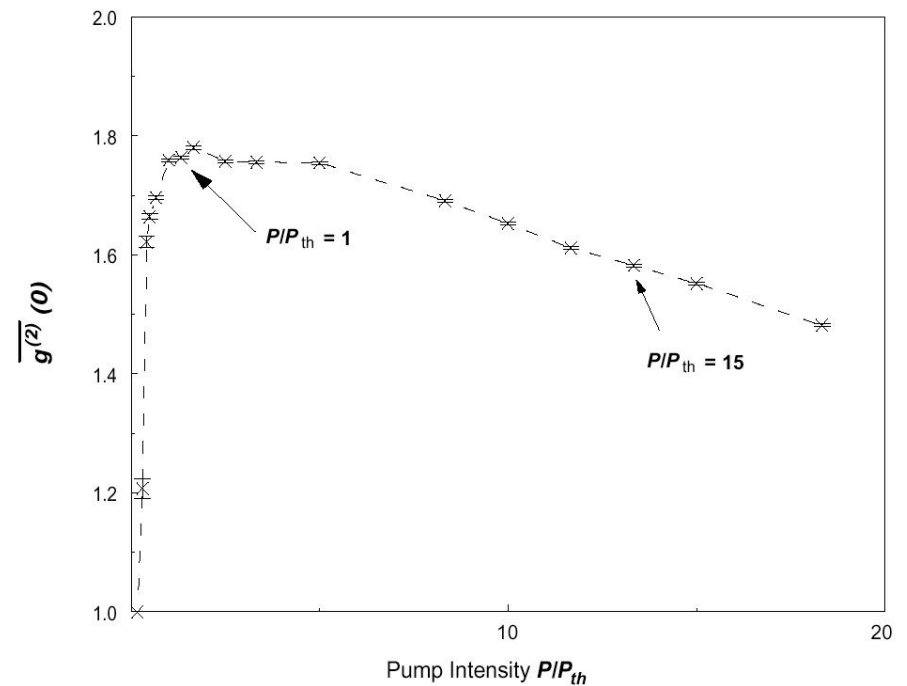
ICSCE2, Southampton, 9 September 2005
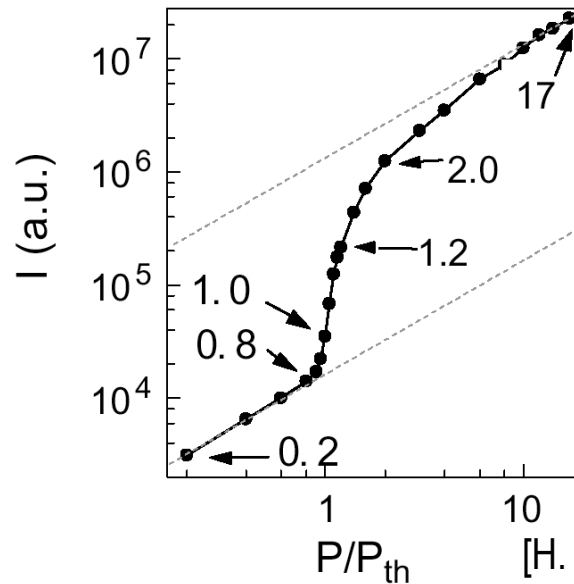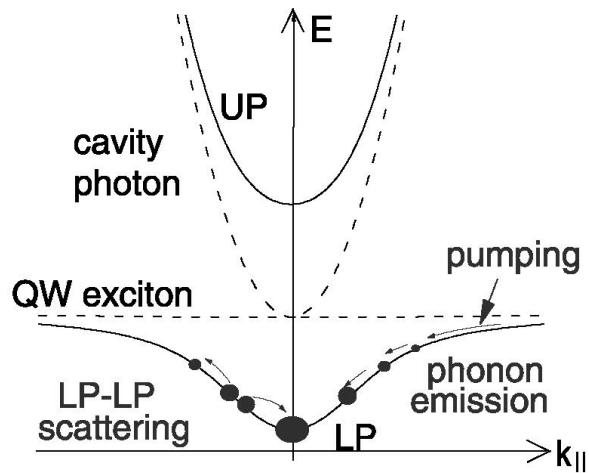
Towards Condensation

UP

cavity photon

QW exciton

pumping

LP-LP scattering

LP

phonon emission

$k_{||}$

E

I (a.u.)

10^7

10^6

10^5

10^4

17

2.0

1.2

1.0

0.8

0.2

1   10

P/P_{th}

[Le Si Dang et al., PRL **81**, 3920 (1998)]

[H. Deng et al., Science **298**, 199 (2002)]

✓ Second-order coherence of photons

$\overline{g^{(2)}(0)}$

2.0

1.8

1.6

1.4

1.2

1.0

$P/P_{th} = 1$

$P/P_{th} = 15$
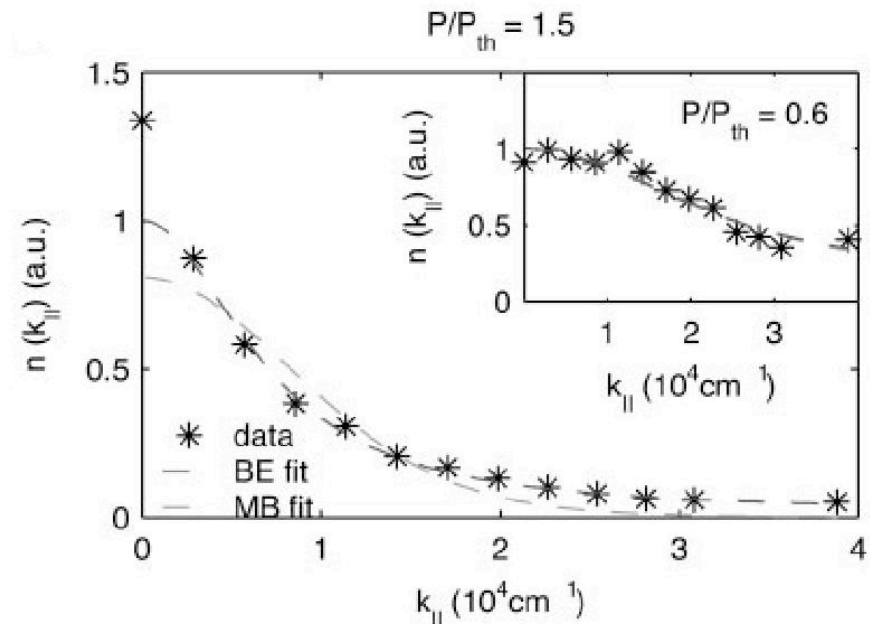
10   20

Pump Intensity P/P_{th}

Towards Condensation

[H. Deng et al.,
Science **298**, 199 (2002)]

[H. Deng et al., PNAS **100,** 15318 (2003)]

✓ Second-order coherence of photons

✓ Narrowing in the angular (momentum) distribution

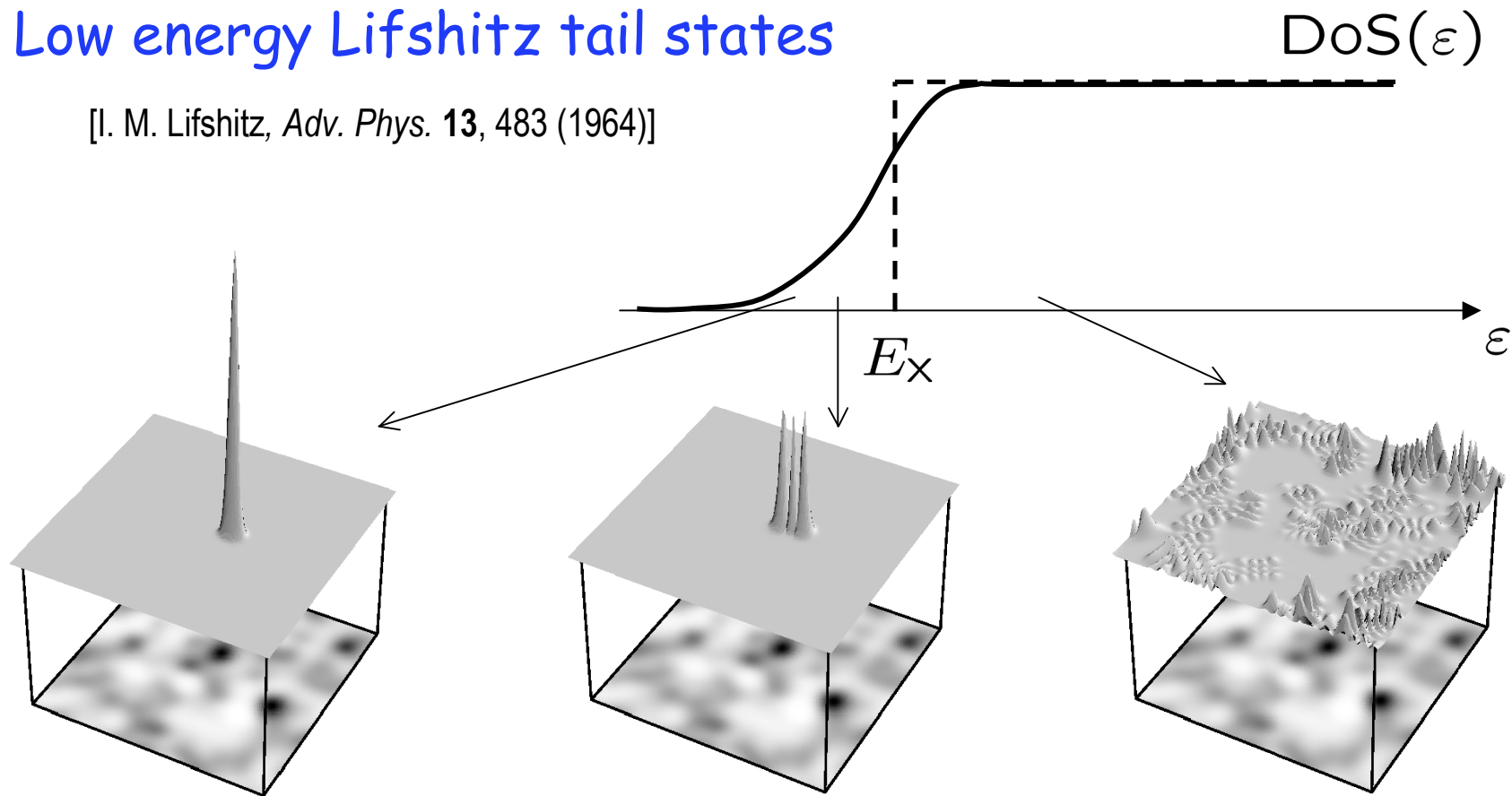✓ Interference fringes

[M. Richard et al. PRL **94**, 187401 (2005)]

Excitons in Disordered QWs

✓ Interface and alloy fluctuations

$$\Psi_{ex} = \varphi_{1s}(\mathbf{r})\Phi_\alpha(\mathbf{R}) \qquad \left[-\frac{\nabla^2}{2m_X} + V(\mathbf{R})\right]\Phi_\alpha(\mathbf{R}) = \varepsilon_\alpha\Phi_\alpha(\mathbf{R})$$

✓ Low energy Lifshitz tail states

[I. M. Lifshitz, *Adv. Phys.* **13**, 483 (1964)]

$\text{DoS}(\varepsilon)$

E_X

ε

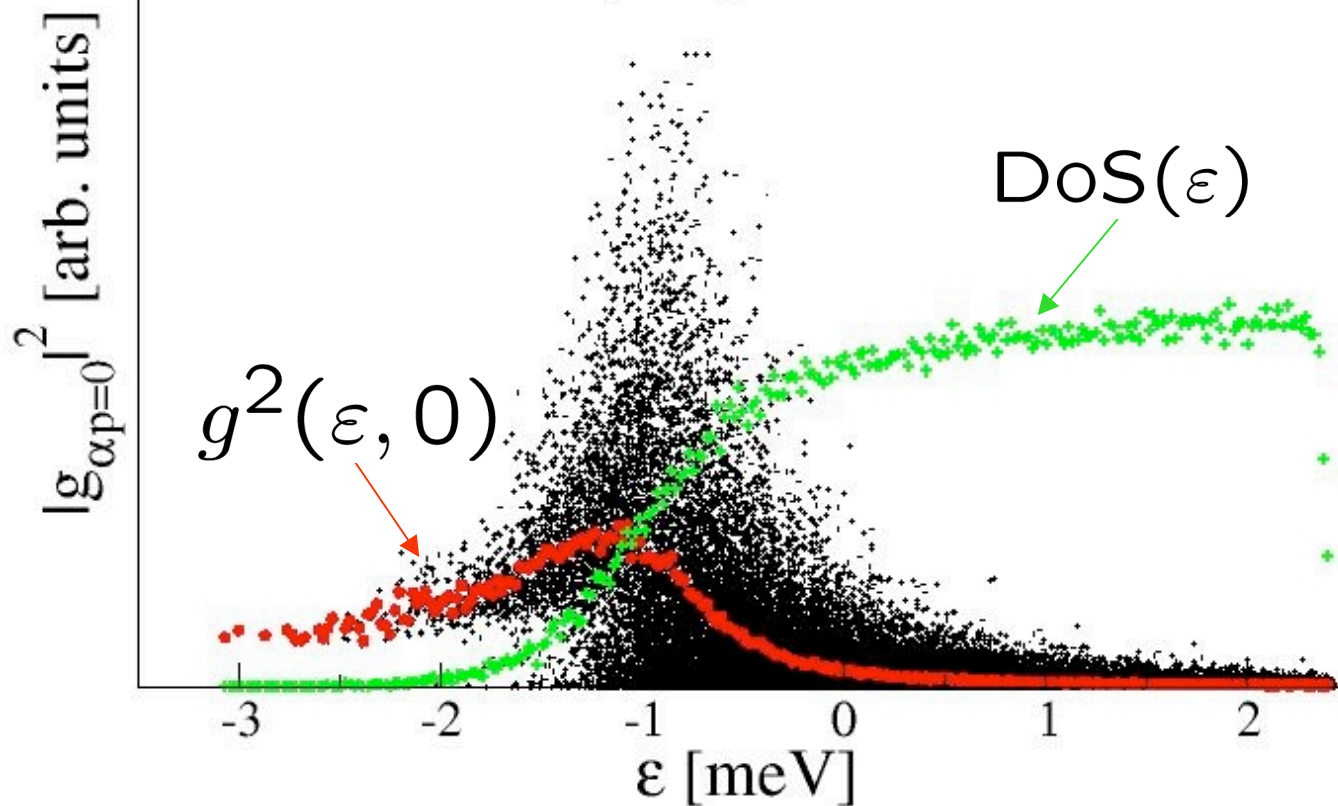[E. Runge and R. Zimmermann, *Adv. in Solid State Phys.* **38**, 251 (1997)]

Coupling to Light

[R. Zimmermann *et al., Pure & Appl. Chem.* **69**, 1179 (1997)]
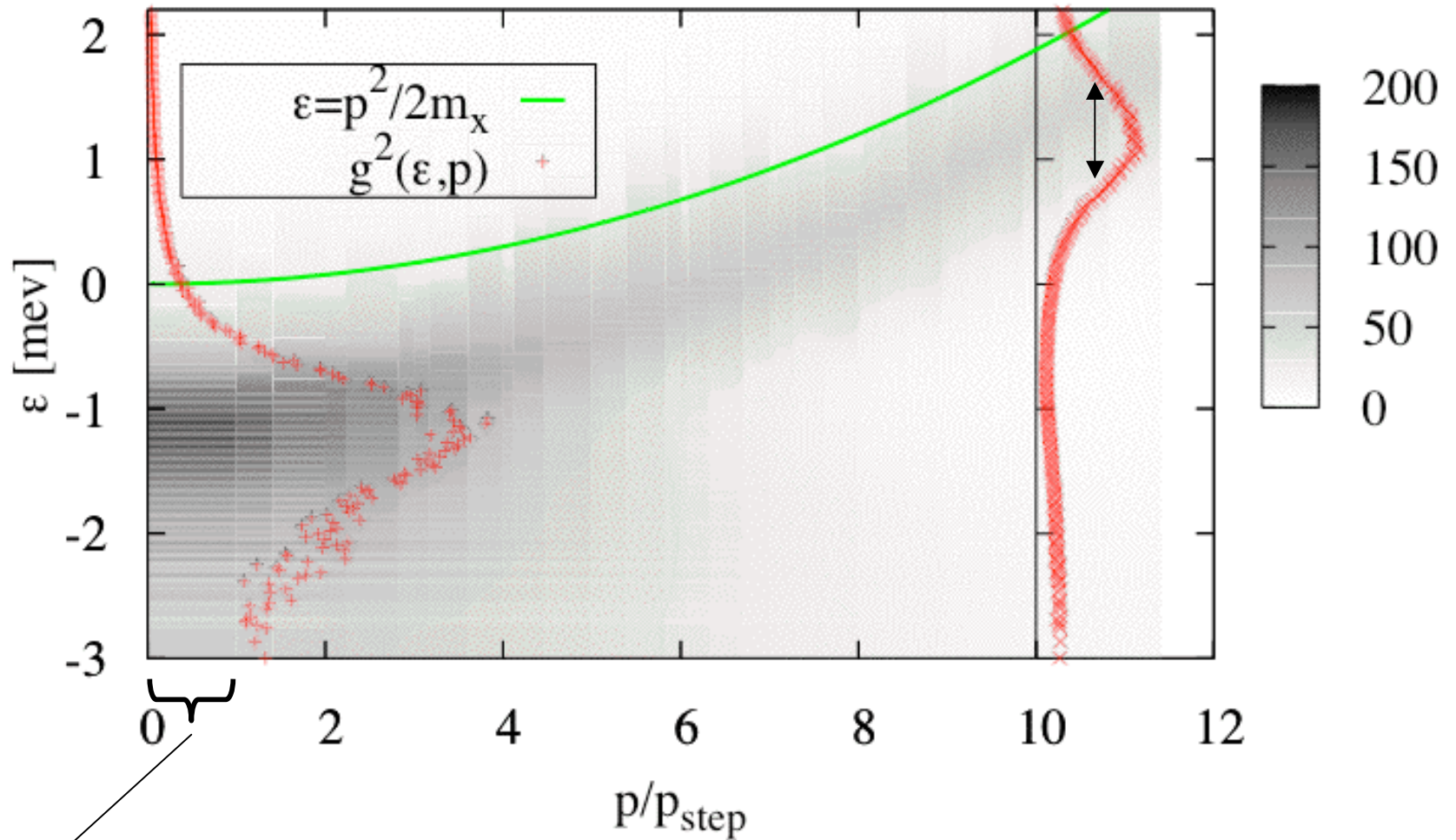[E. Runge, in *Solid State Physics* vol.**57**, 149 (2002)]

$$g_{\alpha,\mathbf{p}} \propto \varphi_{1s}(0) \int d\mathbf{R} e^{-i\mathbf{p}\cdot\mathbf{R}} \Phi_\alpha(\mathbf{R})$$

absorption = $g^2(\varepsilon, 0) \mathrm{DoS}(\varepsilon)$

Crossover to Plain-Wave States

$$\frac{1}{\tau} = 1.16\text{meV}$$
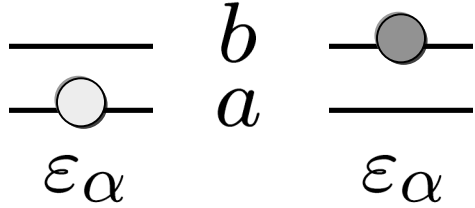

$$p_{\text{step}} = \frac{2\pi}{L} = 6.3 \times 10^{-4}\text{cm}^{-1} \mapsto 36°$$
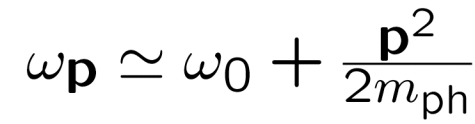
A Simplified Model for Cavity Polaritons

$$\hat{H} = \sum_{\alpha} \frac{\varepsilon_{\alpha}}{2} \left(b_{\alpha}^{\dagger} b_{\alpha} + a_{\alpha} a_{\alpha}^{\dagger} \right)$$

two-level system

$$+ \sum_{\mathbf{p}} \omega_{\mathbf{p}} \psi_{\mathbf{p}}^{\dagger} \psi_{\mathbf{p}}$$

$$\omega_{\mathbf{p}} \simeq \omega_0 + \frac{\mathbf{p}^2}{2m_{\mathrm{ph}}}$$

photon modes

$$+ \frac{1}{\sqrt{\mathcal{A}}} \sum_{\alpha} \sum_{\mathbf{p}} \left(g_{\alpha,\mathbf{p}} \psi_{\mathbf{p}} b_{\alpha}^{\dagger} a_{\alpha} + \mathrm{h.c.} \right)$$
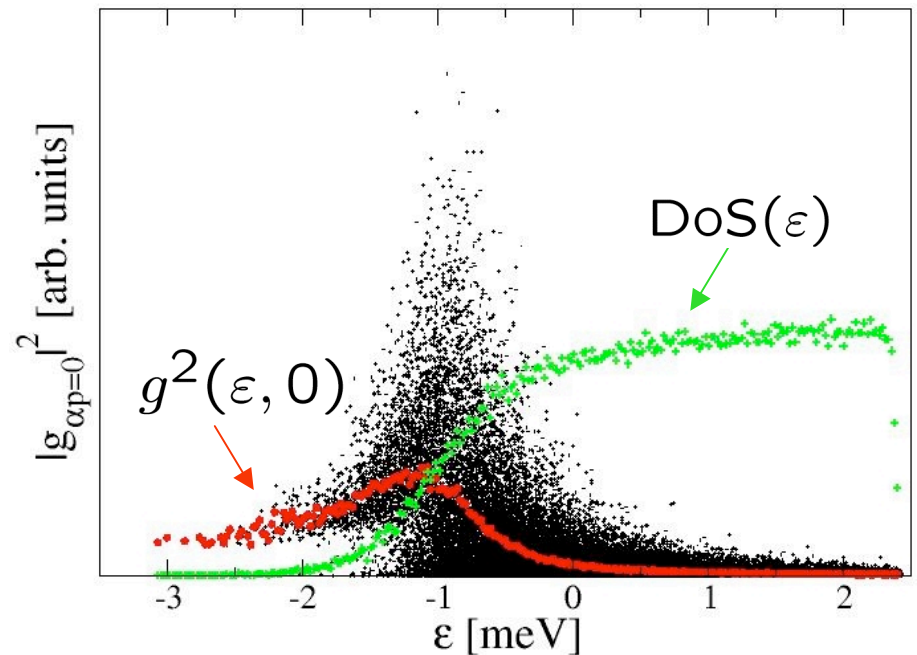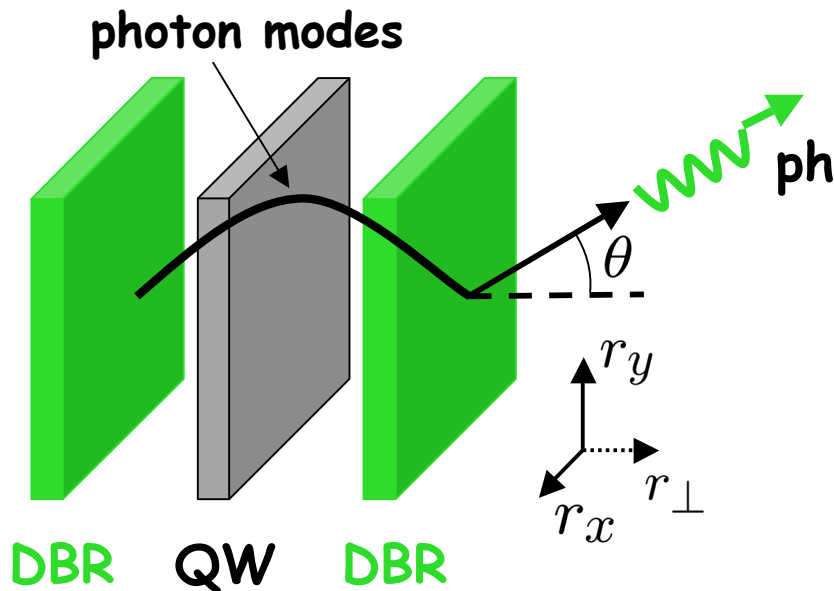
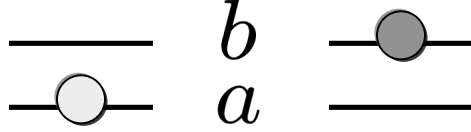dipole coupling

A Simplified Model for Cavity Polaritons

$$\hat{H} = \sum_\alpha \frac{\varepsilon_\alpha}{2}\left(b_\alpha^\dagger b_\alpha + a_\alpha a_\alpha^\dagger\right)$$

two-level system

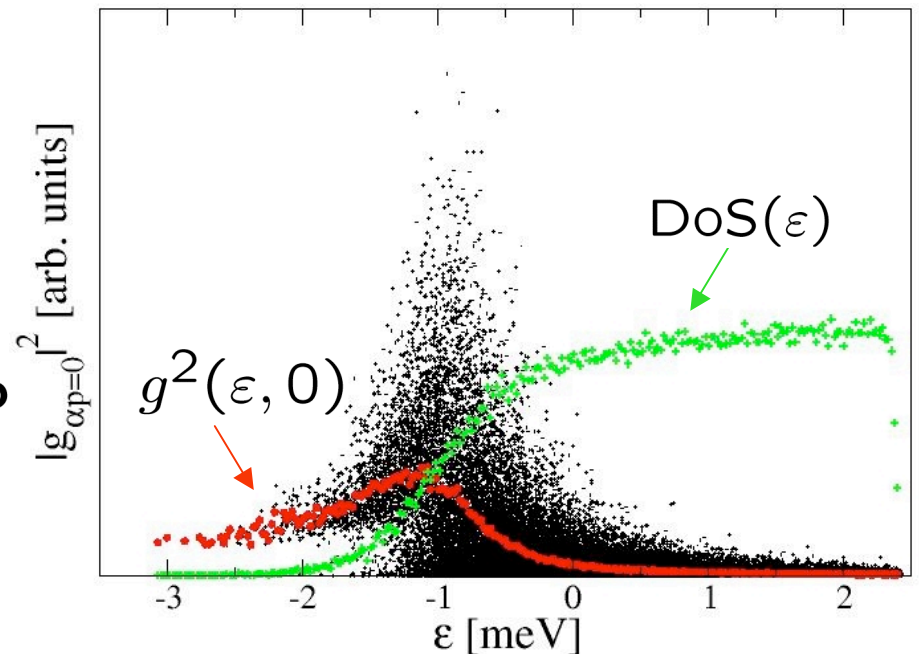$$+ \sum_{\mathbf{p}} \omega_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \psi_{\mathbf{p}}$$

$$\omega_{\mathbf{p}} \simeq \omega_0 + \frac{\mathbf{p}^2}{2m_{\mathrm{ph}}}$$

photon modes

$$+ \frac{1}{\sqrt{\mathcal{A}}} \sum_\alpha \sum_{\mathbf{p}} \left(g_{\alpha,\mathbf{p}} \psi_{\mathbf{p}} b_\alpha^\dagger a_\alpha + \mathrm{h.c.}\right)$$
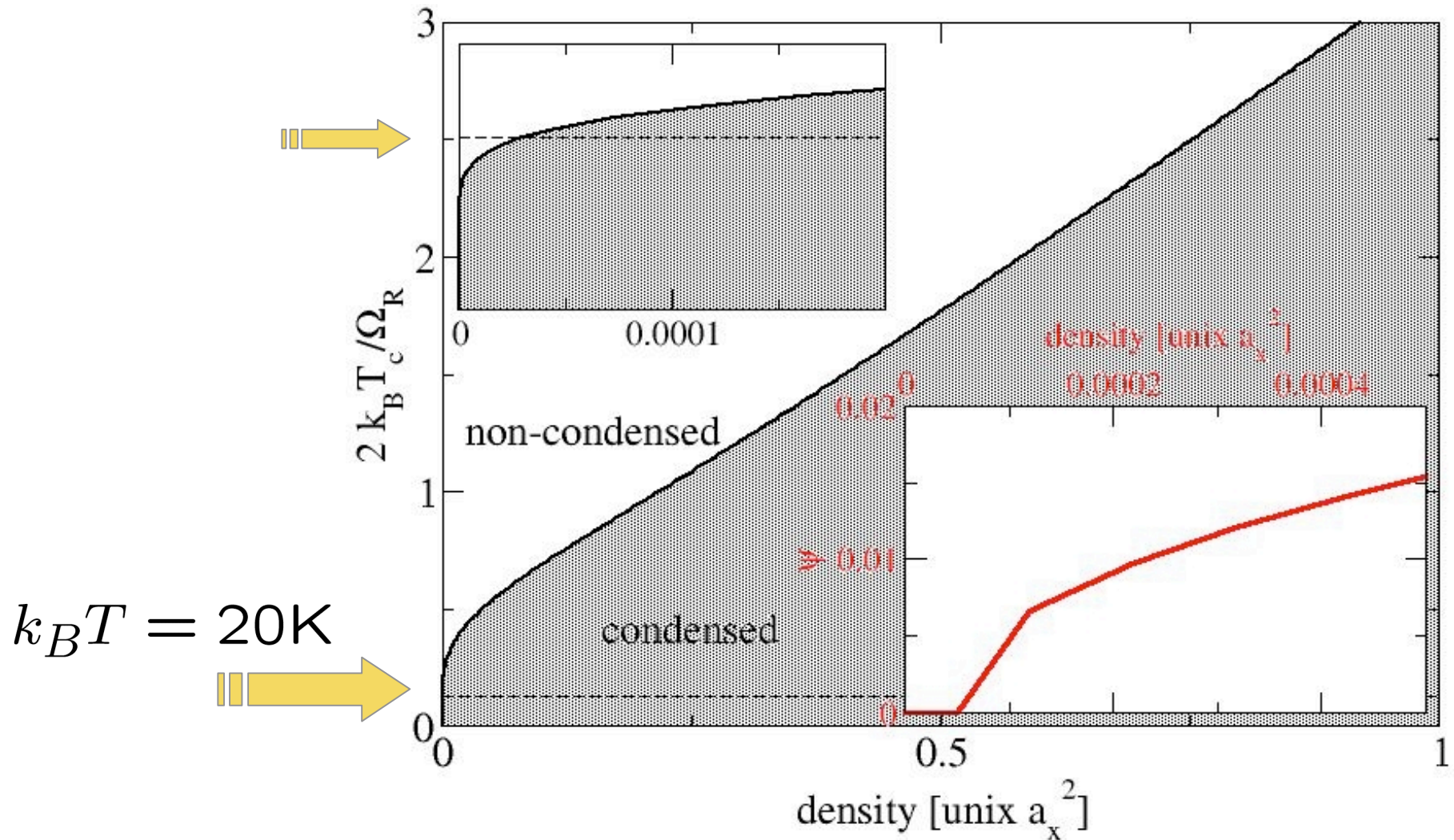
dipole coupling

✓ Conservation of the number of particles

$$\hat{N} = \sum_\alpha \frac{1}{2}\left(b_\alpha^\dagger b_\alpha + a_\alpha a_\alpha^\dagger\right) + \sum_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \psi_{\mathbf{p}}$$

Transition to a Condensed Phase

$k_B T = 20\text{K}$

✓ Beyond mean-field:
BEC-BCS crossover
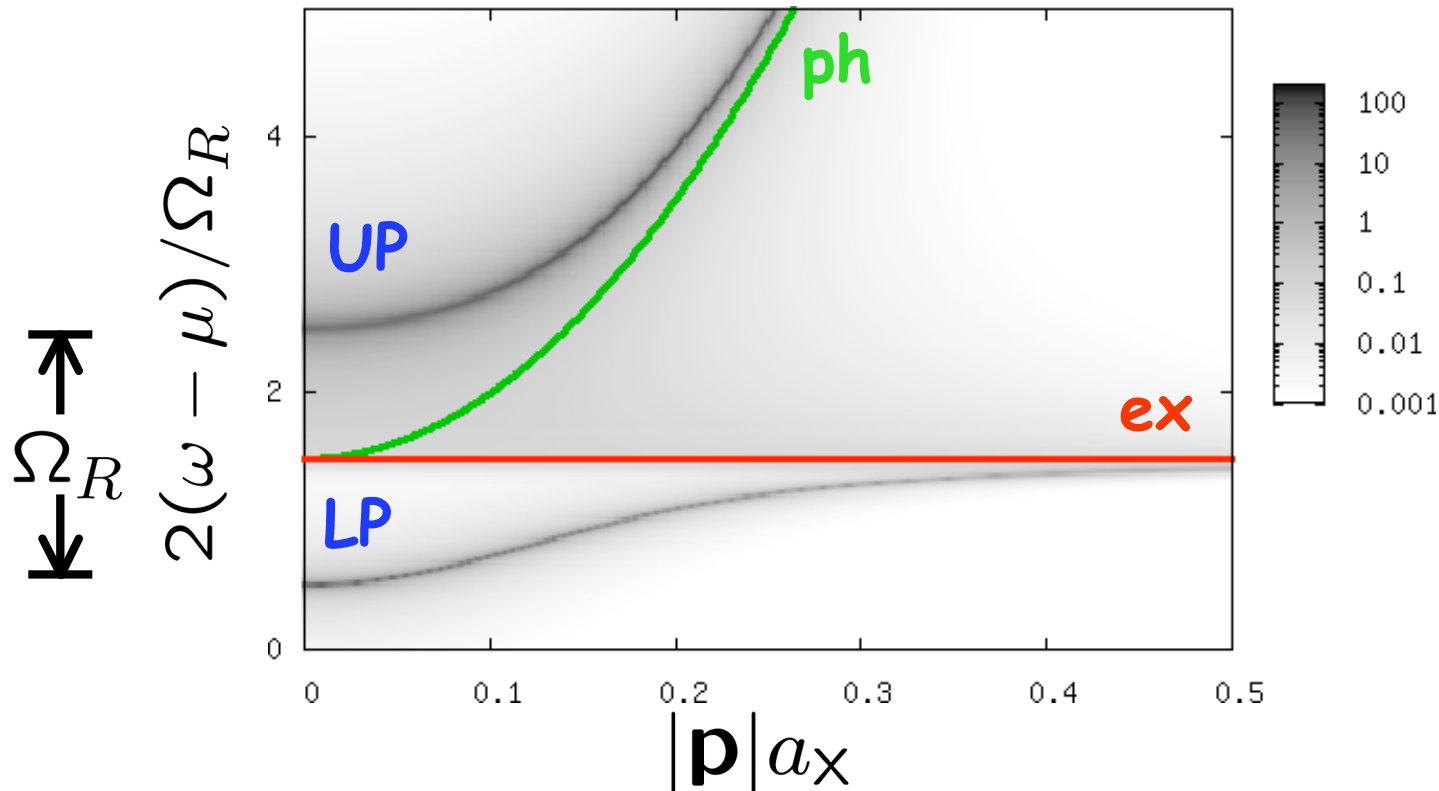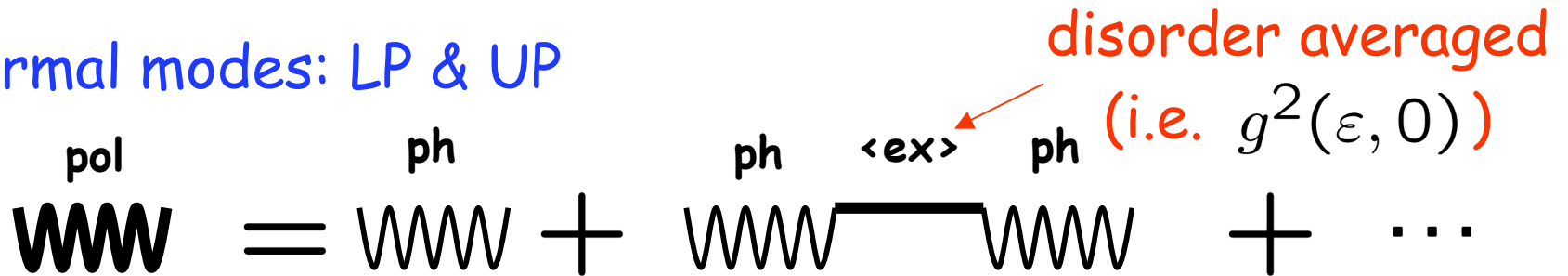
[J. Keeling et al., PRL 93, 226403 (2004)]

[J. Keeling et al., cond-mat/0503184]

[see M. Szymanska talk]
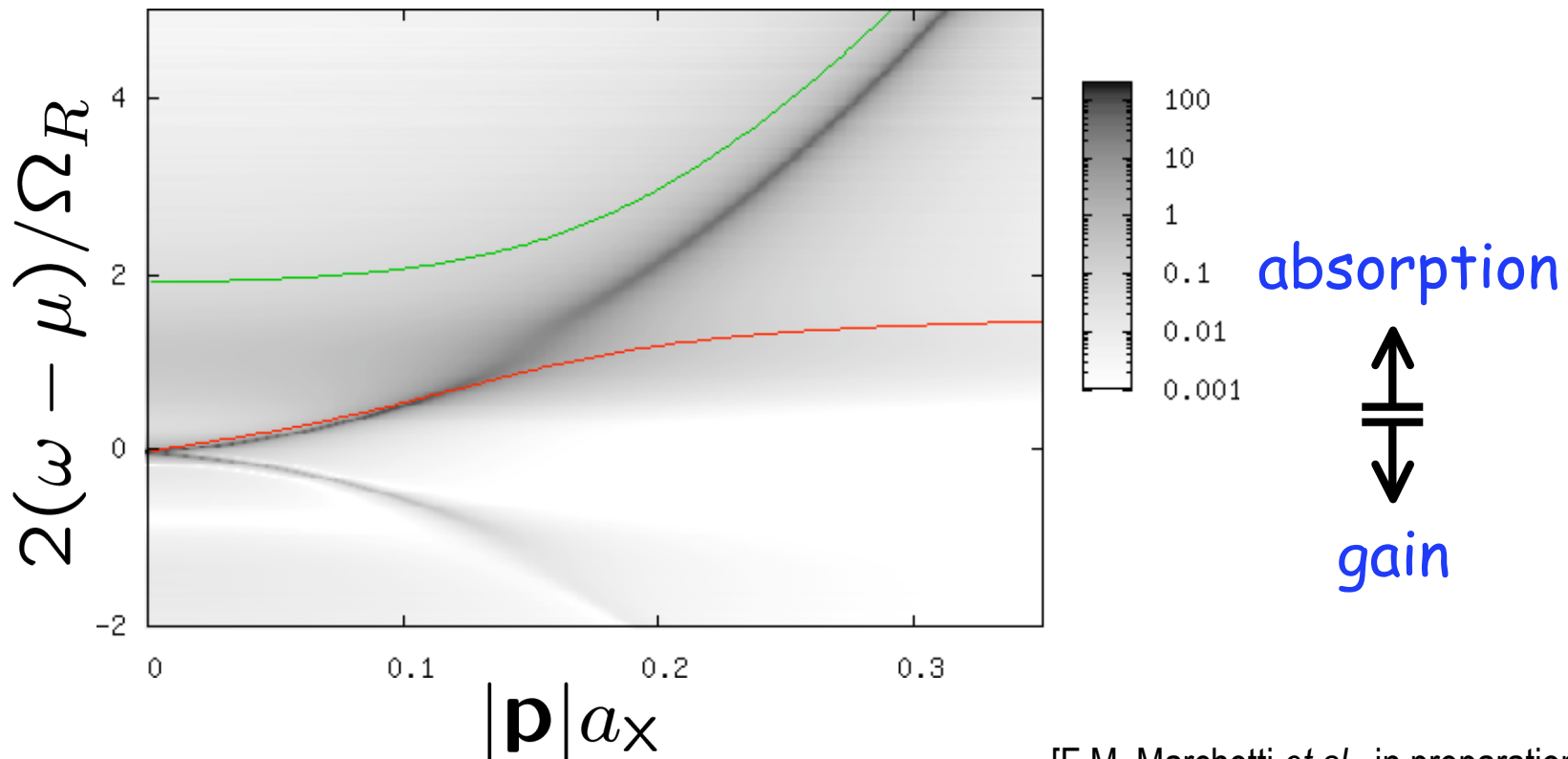
Non-condensed Photoluminescence

✓ Normal modes: LP & UP

disorder averaged (i.e. $g^2(\varepsilon, 0)$)

pol **ph** **ph** **<ex>** **ph**

$$\text{WWW} = \text{WWW} + \text{WWW}\,\overline{}\,\text{WWW} + \cdots$$

✓ Linear dispersion model   [D. M. Whittaker, *PRL* **80**, 4791 (1998)]

Condensed Photoluminescence

✓ Normal modes $\begin{cases} \text{LP} \longrightarrow \text{Goldstone mode} \\ \text{UP} \longrightarrow \text{'massive' mode} \end{cases}$

✓ 'Particle-hole' excitations $E_\alpha = \sqrt{(\varepsilon_\alpha - \mu)^2/4 + |g_{\alpha,0}|^2\langle\psi\rangle^2}$

absorption
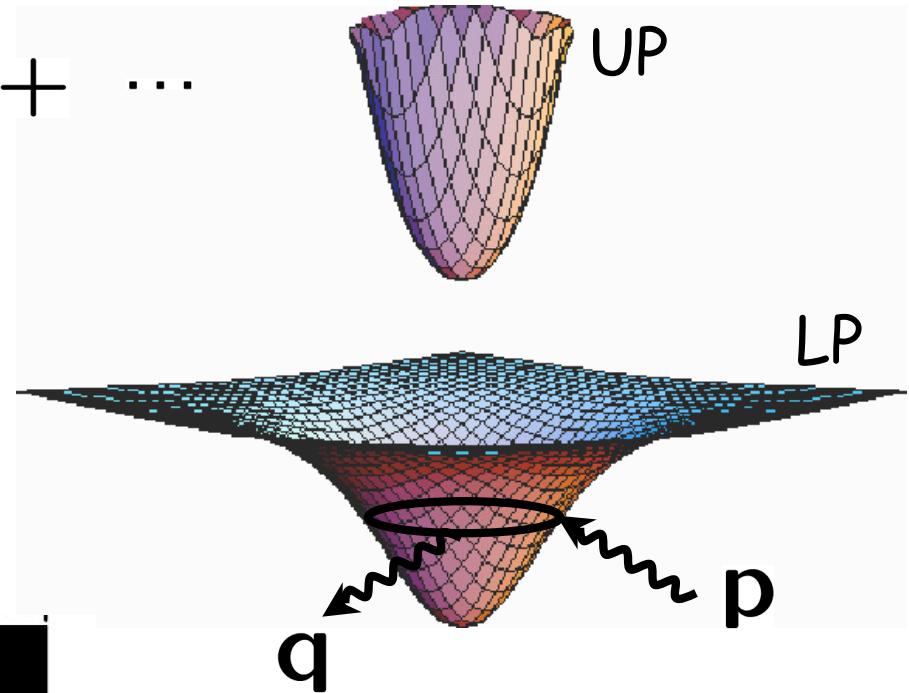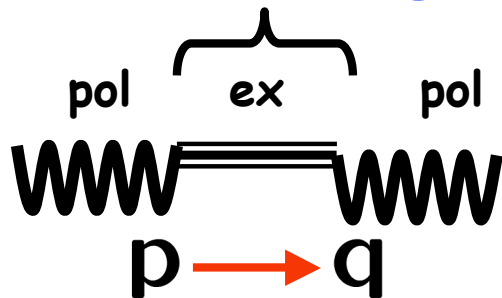
gain

[F.M. Marchetti *et al.*, in preparation]

Resonant Rayleigh Scattering

pol
ph   ph <ex> ph

$$\mathsf{WWW} = \mathsf{WWW} + \mathsf{WWW} \overline{} \mathsf{WWW} + \cdots$$

UP

scattering

pol   ex   pol

$$\mathsf{WWW} = \mathsf{WWW}$$

$$p \longrightarrow q$$

LP

p

q

light emission in non-specular
scattering directions

[W. Langbein & J. M. Hvam, *PRL* **88**, 047401 (2002)]

7.5ps   10.0ps

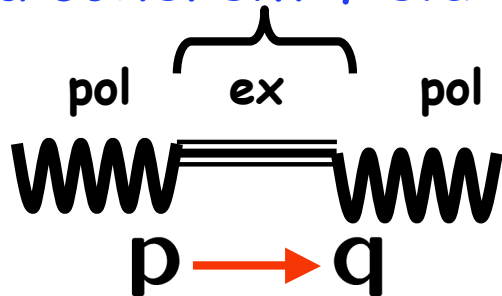$k_{[110]}$ (µm^{-1})

[T. Freixanet *et al.*, *PRB* **60**, 8509 (1999)]]
[M Gurioli *et al.*, *PRB* **64**, 165309 (2001)]]
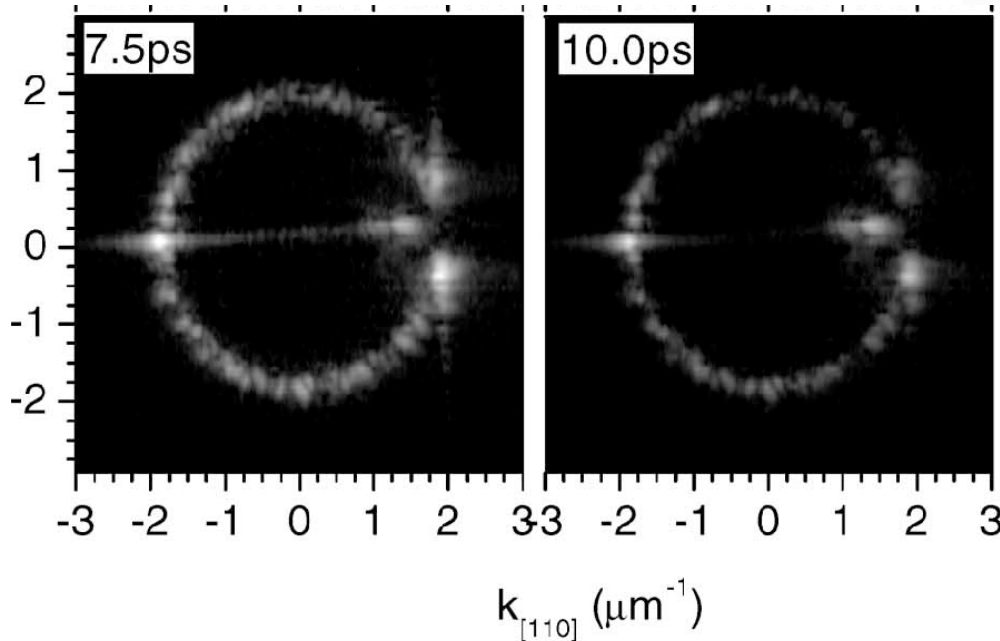
Resonant Rayleigh Scattering

scattering on
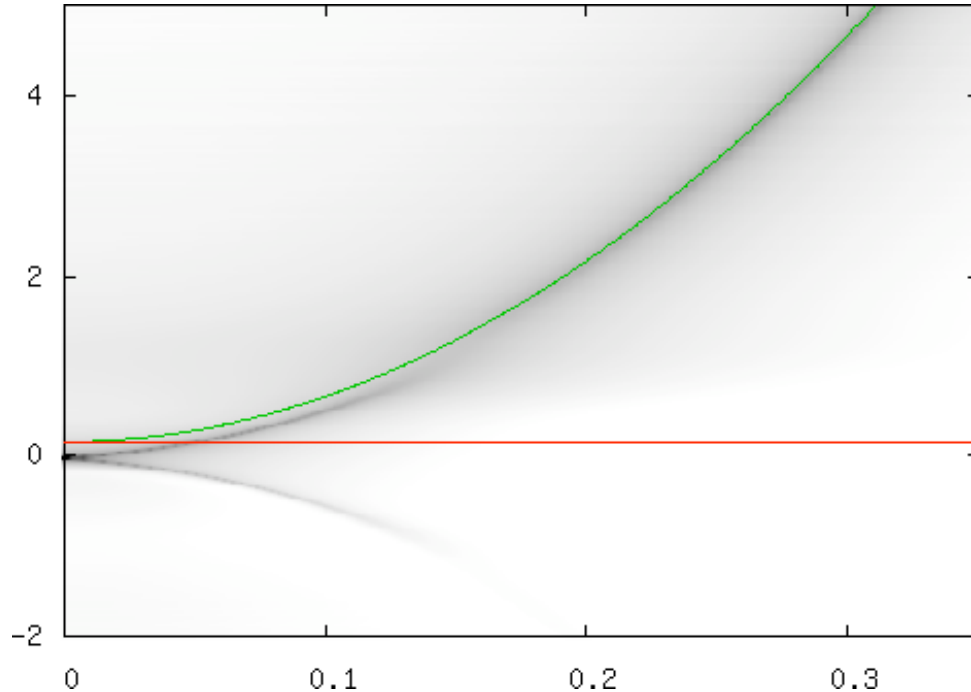excitons in presence
of a coherent field

'new'
quasi-modes

UP

LP

pol   ex   pol

p ⟶ q

q

p
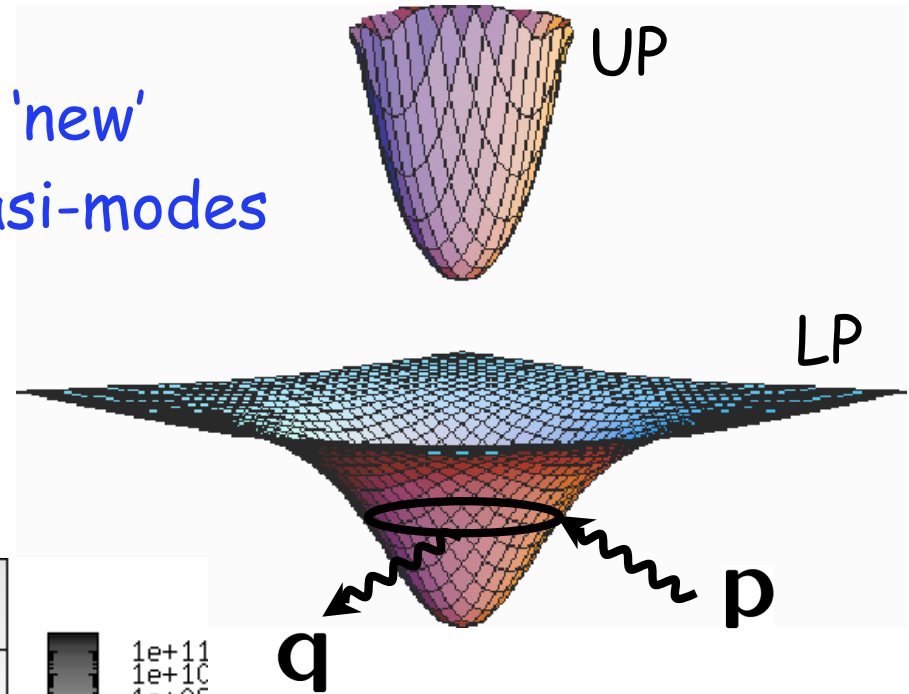
[D. M. Whittaker, *PRB* **61**, R2433 (2000)]

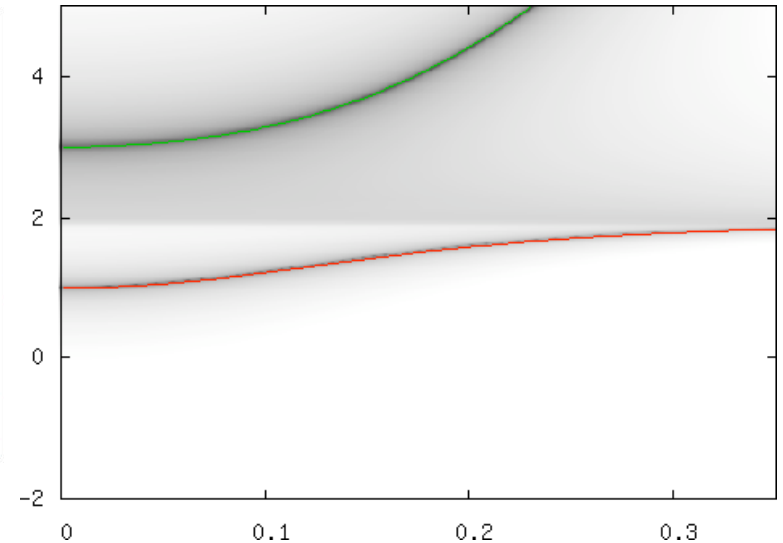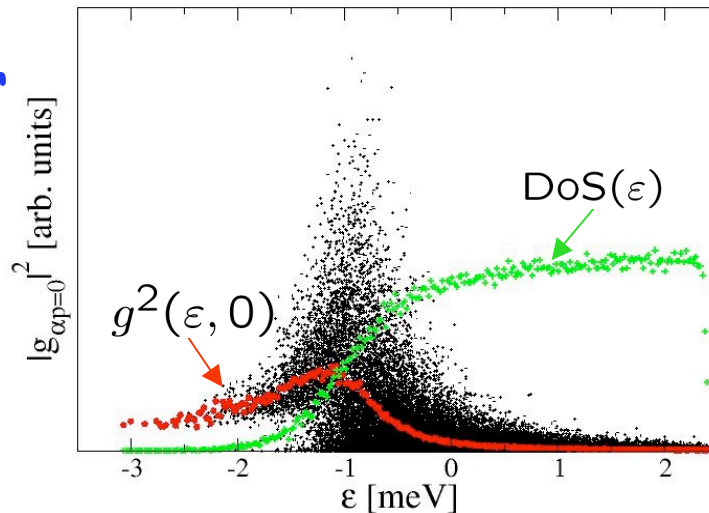[A. V. Shchegrov *et al.*, *PRL* **84**, 3478 (2000)]

[I. Carusotto & C. Ciuti, *PRL* **93**, 166401 (2004)]

[F.M. Marchetti *et al.*, in preparation]

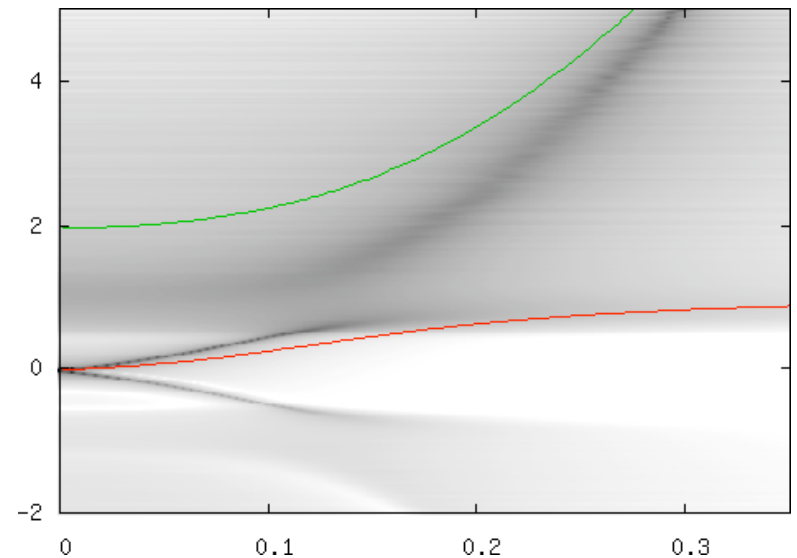# Conclusions

✓ Model for disordered cavity polaritons

✓ Transition to the condensed phase increasing the density

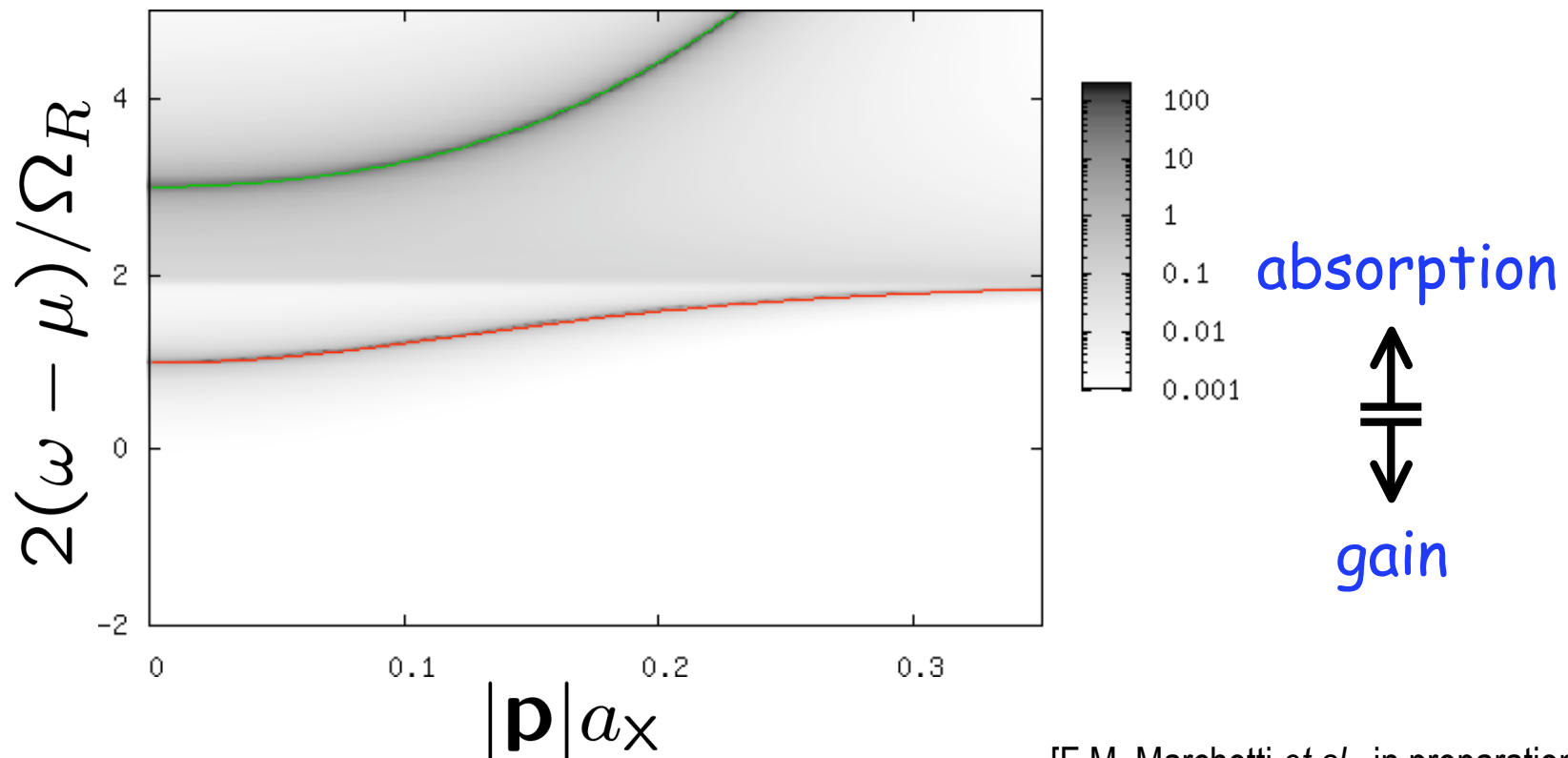✓ Signatures of condensation:

photoluminescence

Resonant Rayleigh scattering

Condensed Photoluminescence

✓ Normal modes
{ LP $\longrightarrow$ Goldstone mode
  UP $\longrightarrow$ 'massive' mode

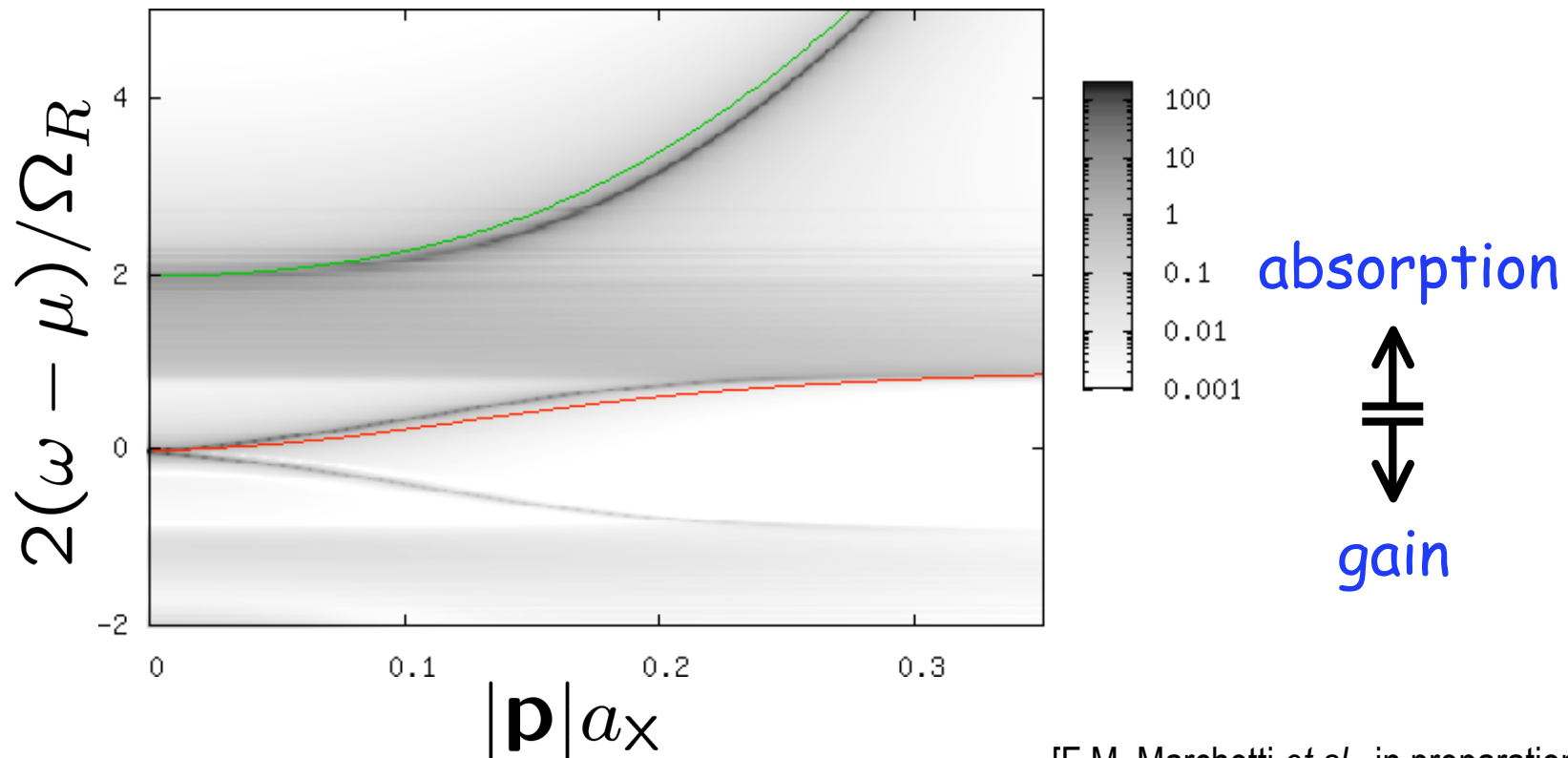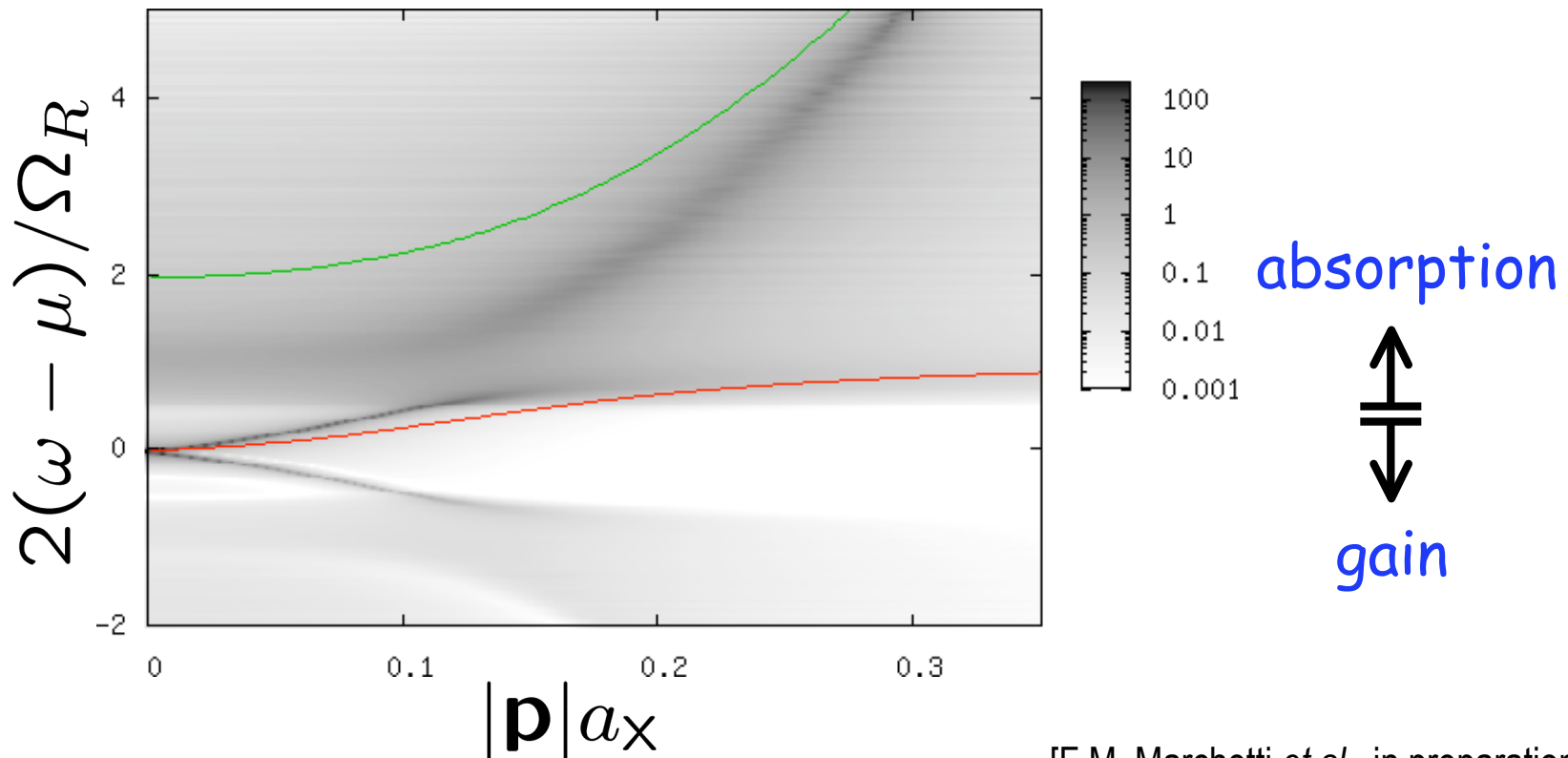✓ 'Particle-hole' excitations $E_\alpha = \sqrt{(\varepsilon_\alpha - \mu)^2/4 + |g_{\alpha,0}|^2 \langle \psi \rangle^2}$

[F.M. Marchetti *et al.*, in preparation]

Condensed Photoluminescence

✓ Normal modes $\begin{cases} \text{LP} \longrightarrow \text{Goldstone mode} \\ \text{UP} \longrightarrow \text{'massive' mode} \end{cases}$

✓ 'Particle-hole' excitations $\quad E_\alpha = \sqrt{(\varepsilon_\alpha - \mu)^2/4 + |g_{\alpha,0}|^2 \langle\psi\rangle^2}$
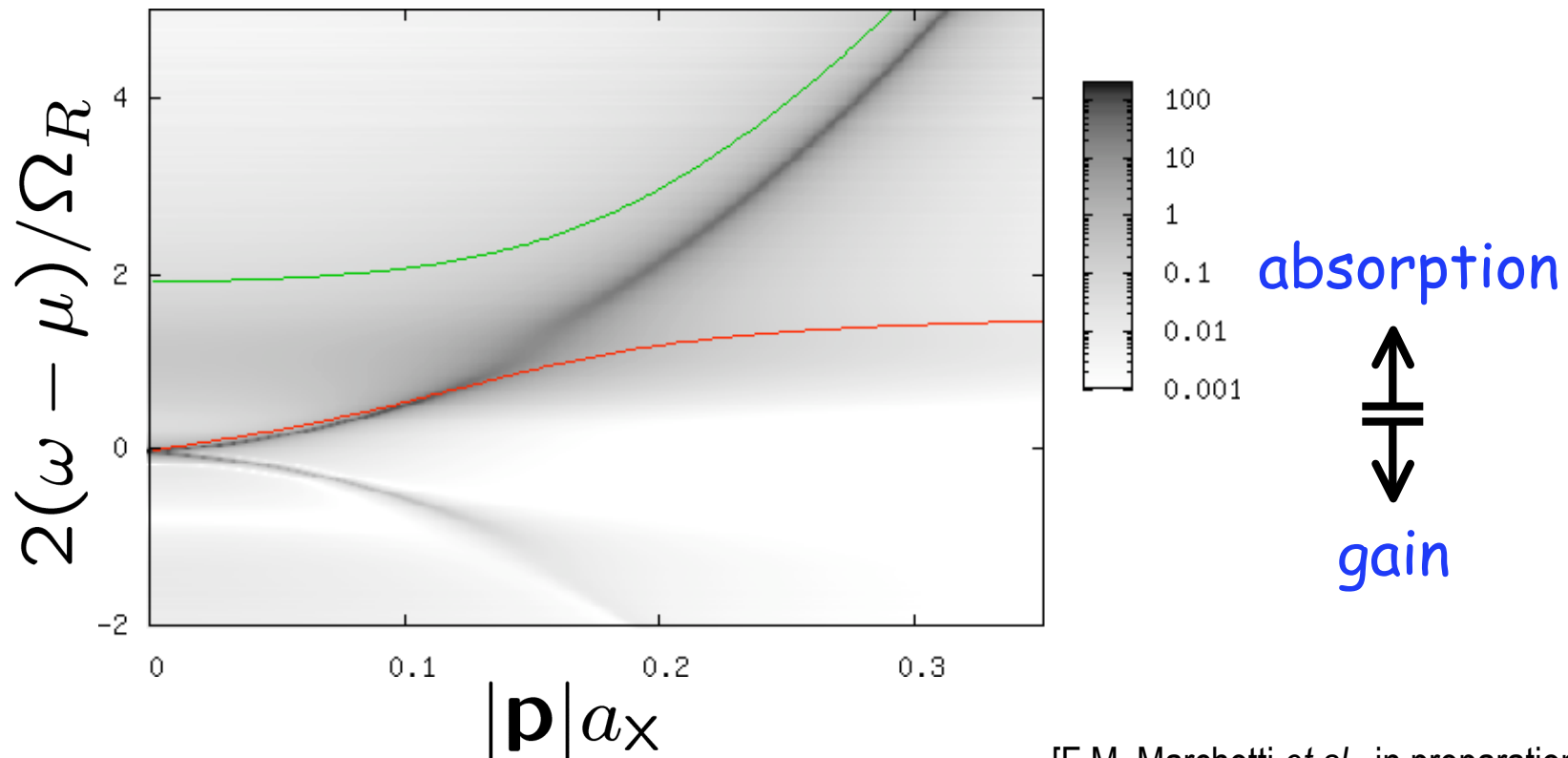

absorption

↕

gain

[F.M. Marchetti *et al.*, in preparation]

Condensed Photoluminescence

✓ Normal modes $\left\{\begin{array}{l} \text{LP} \longrightarrow \text{Goldstone mode} \\ \text{UP} \longrightarrow \text{'massive' mode} \end{array}\right.$
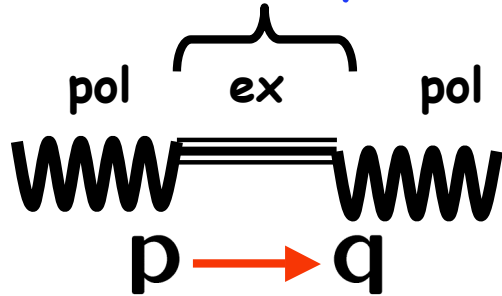
✓ 'Particle-hole' excitations $\quad E_\alpha = \sqrt{(\varepsilon_\alpha - \mu)^2/4 + |g_{\alpha,0}|^2 \langle\psi\rangle^2}$

absorption

gain

[F.M. Marchetti *et al.*, in preparation]

Condensed Photoluminescence

✓ Normal modes $\begin{cases} \text{LP} \longrightarrow \text{Goldstone mode} \\ \text{UP} \longrightarrow \text{`massive' mode} \end{cases}$

✓ 'Particle-hole' excitations $\quad E_\alpha = \sqrt{(\varepsilon_\alpha - \mu)^2/4 + |g_{\alpha,0}|^2\langle\psi\rangle^2}$
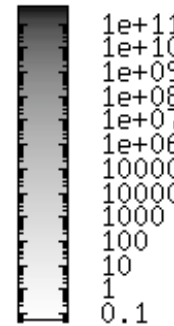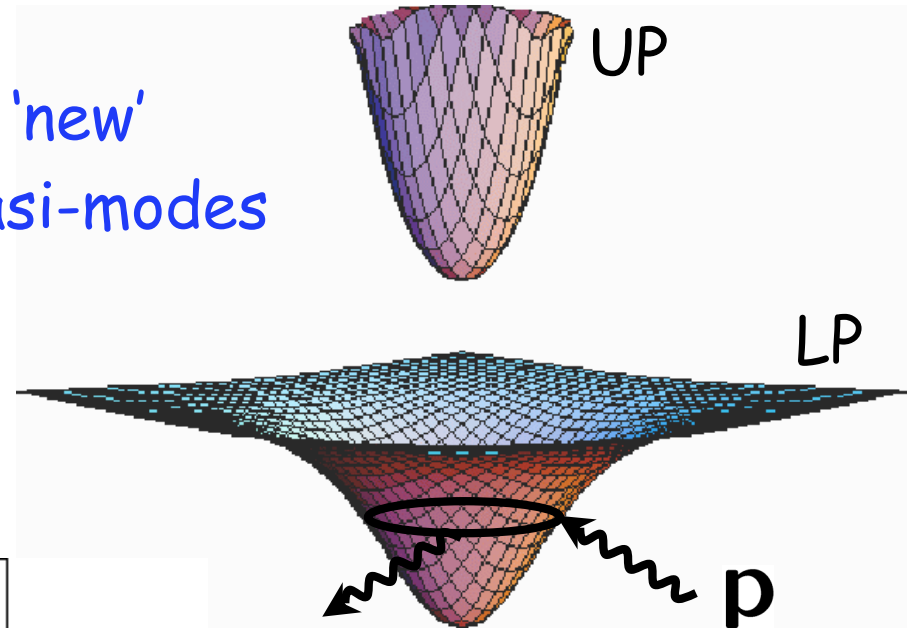

absorption

gain

[F.M. Marchetti *et al.*, in preparation]

Resonant Rayleigh Scattering

scattering on
excitons in presence
of a coherent field

'new'
quasi-modes

UP

LP

pol   ex   pol

p ⟶ q
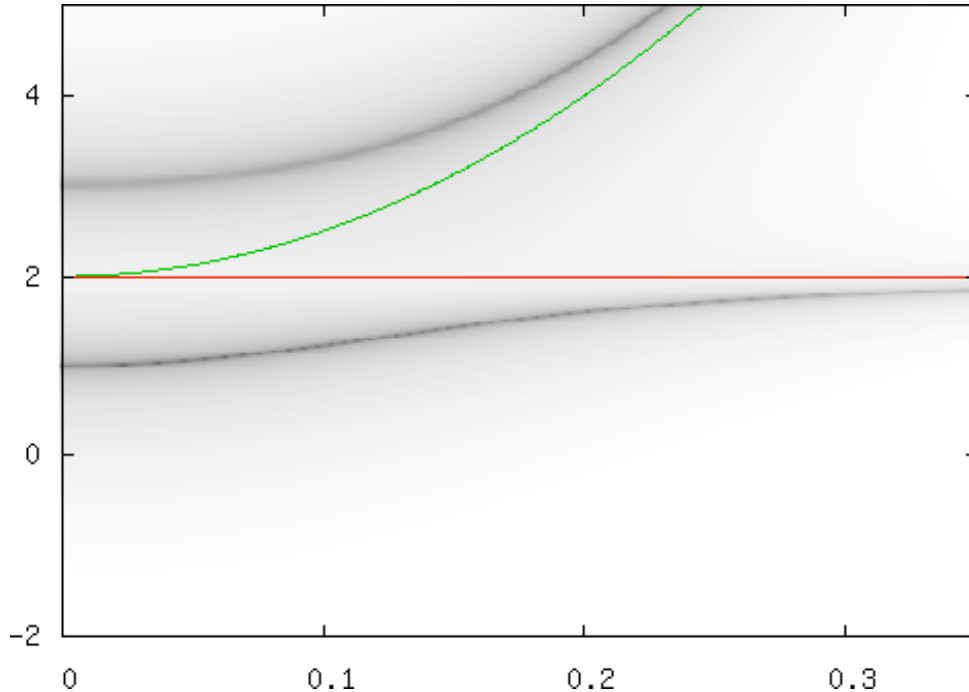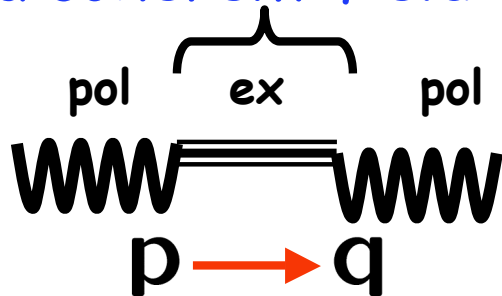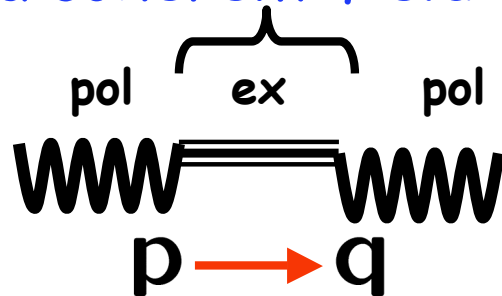
p

q

[I. Carusotto & C. Ciuti, *PRL* **93**, 166401 (2004)]

[F.M. Marchetti *et al.*, in preparation]

Resonant Rayleigh Scattering

scattering on
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UP

LP

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p ⟶ q

q   p

[I. Carusotto & C. Ciuti, *PRL* **93**, 166401 (2004)]

[F.M. Marchetti *et al.*, in preparation]

Resonant Rayleigh Scattering

scattering on
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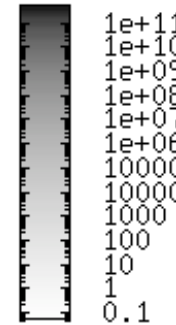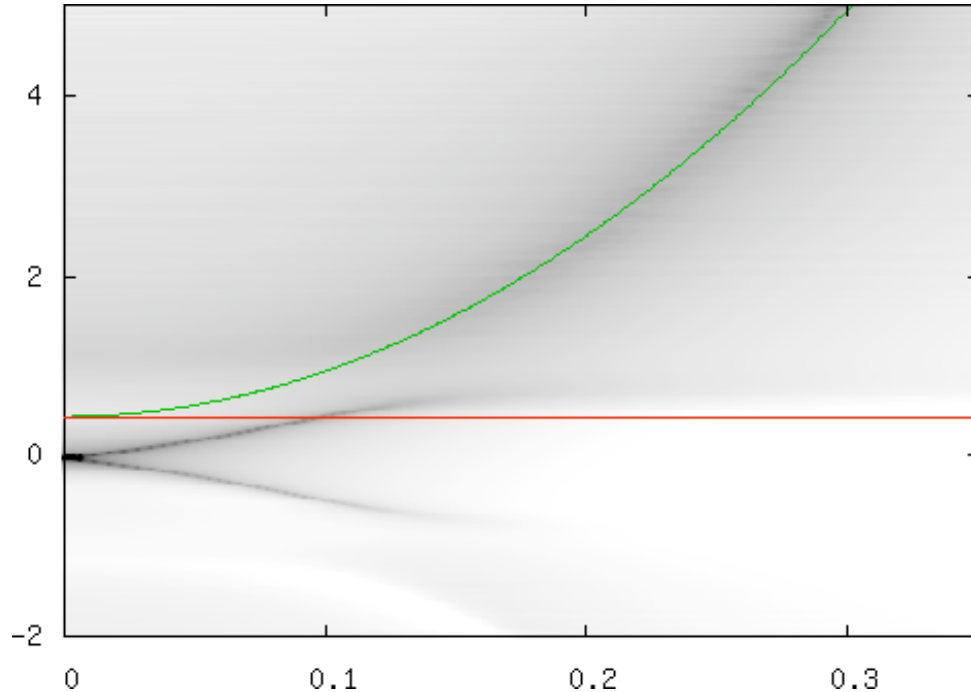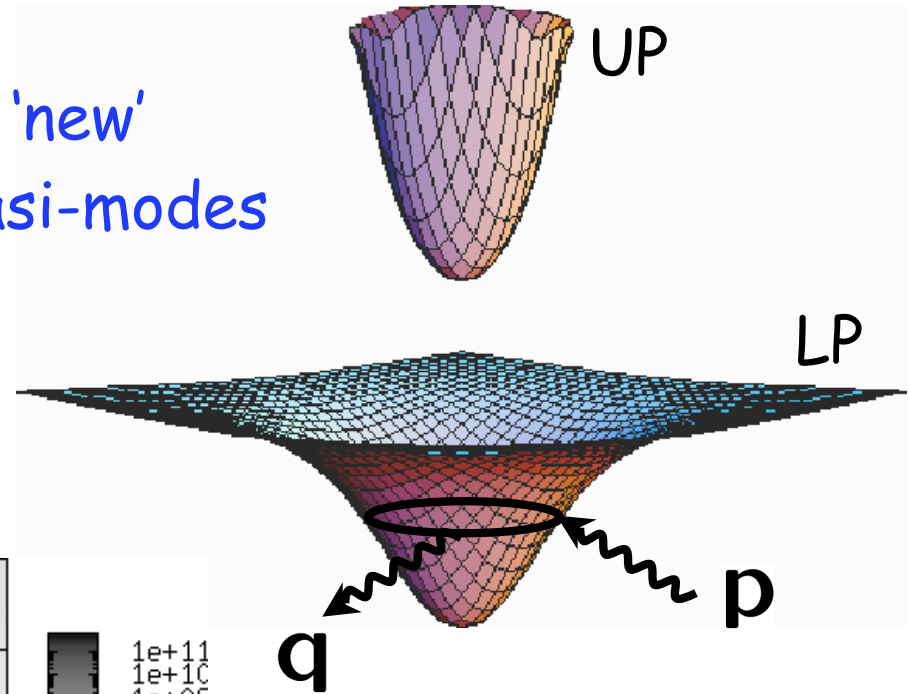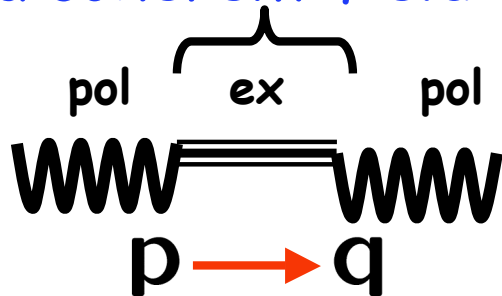[I. Carusotto & C. Ciuti, *PRL* **93**, 166401 (2004)]

[F.M. Marchetti *et al.*, in preparation]

Resonant Rayleigh Scattering

scattering on
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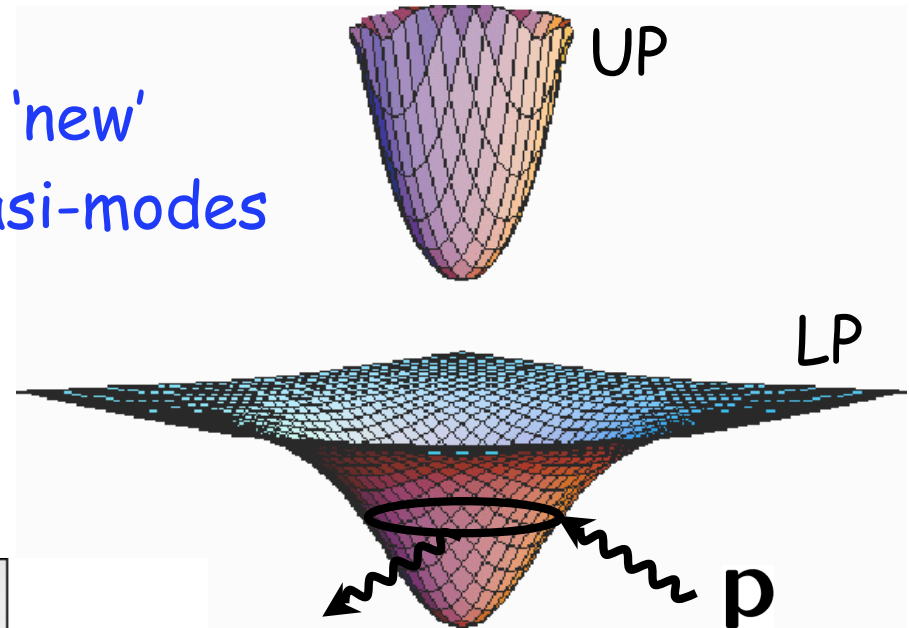[I. Carusotto & C. Ciuti, *PRL* **93**, 166401 (2004)]

[F.M. Marchetti *et al.*, in preparation]