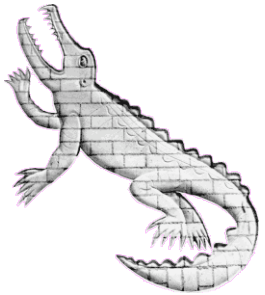
Polaritons in Disordered Microcavities: blue-shift, phase diagram & Rayleigh scattering

Francesca Maria Marchetti

Cavendish Laboratory -- University of Cambridge



J Keeling, MH Szymanska, PB Littlewood

5th PMP meeting, Lund -- 25 March 2006

Outline

I. Thermodynamics

✓ Disordered quantum wells (CdTe)

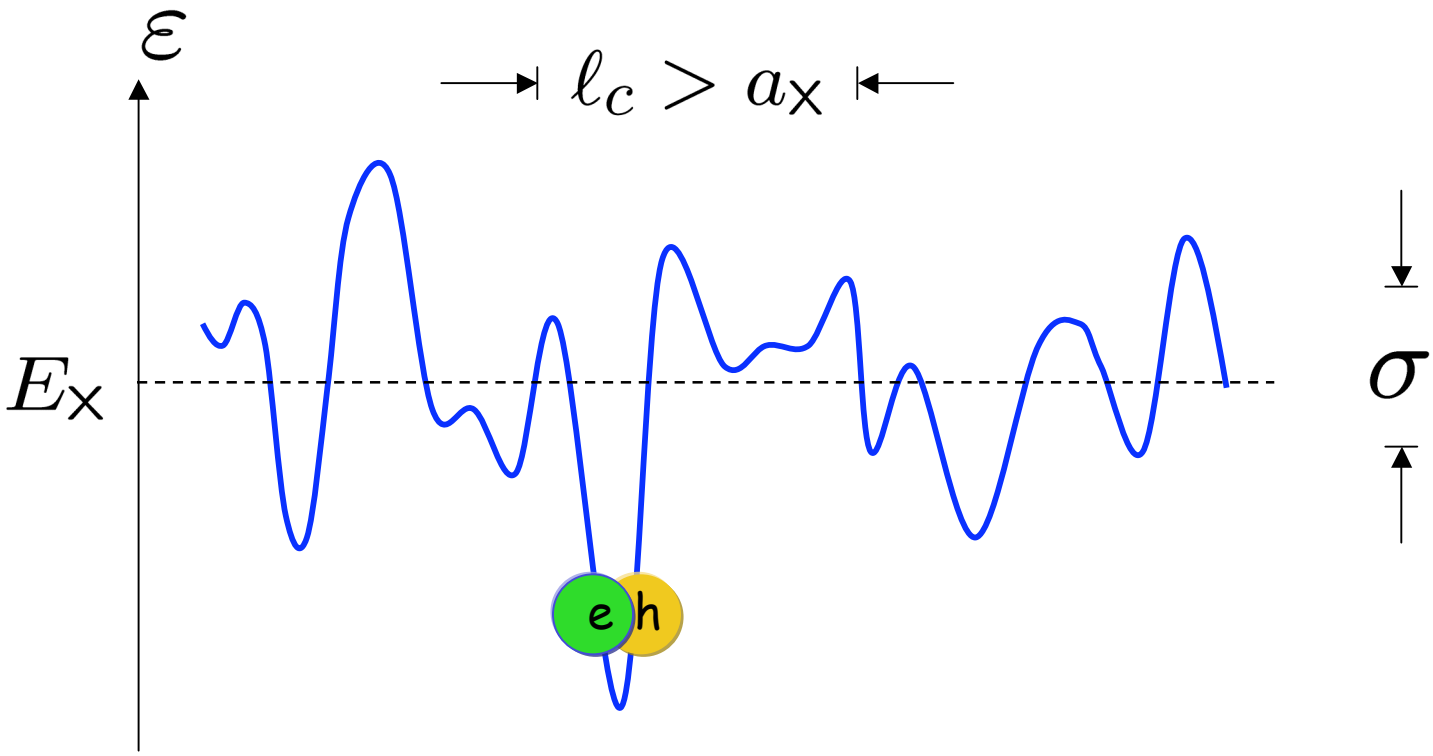
✓ Lower polariton blue-shift: disordered vs. clean

✓ Polaritons phase diagram:
from BEC (BKT) to 'long-range' interactions

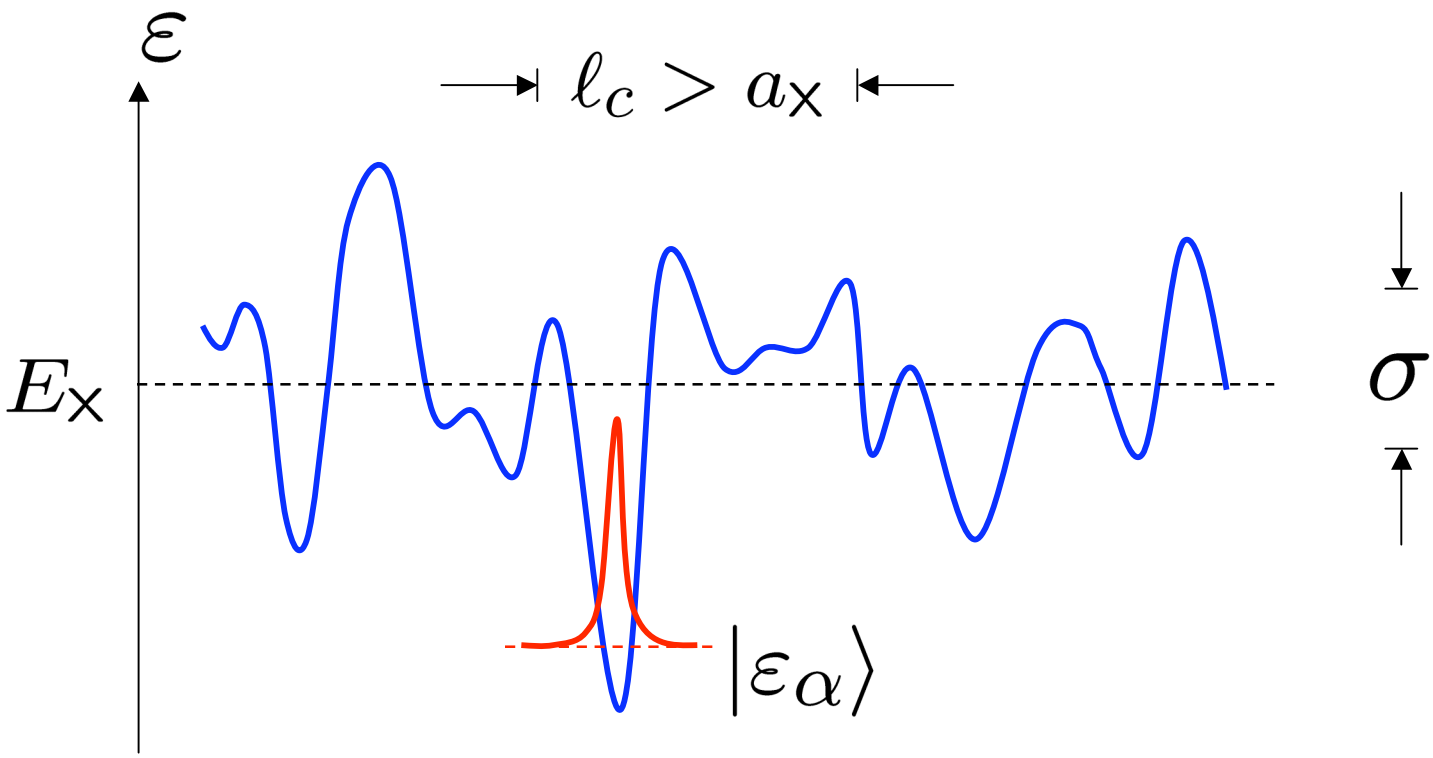
✓ Probing the condensed state: resonant Rayleigh scattering

II. Non-equilibrium: pump & decay (Marzena)

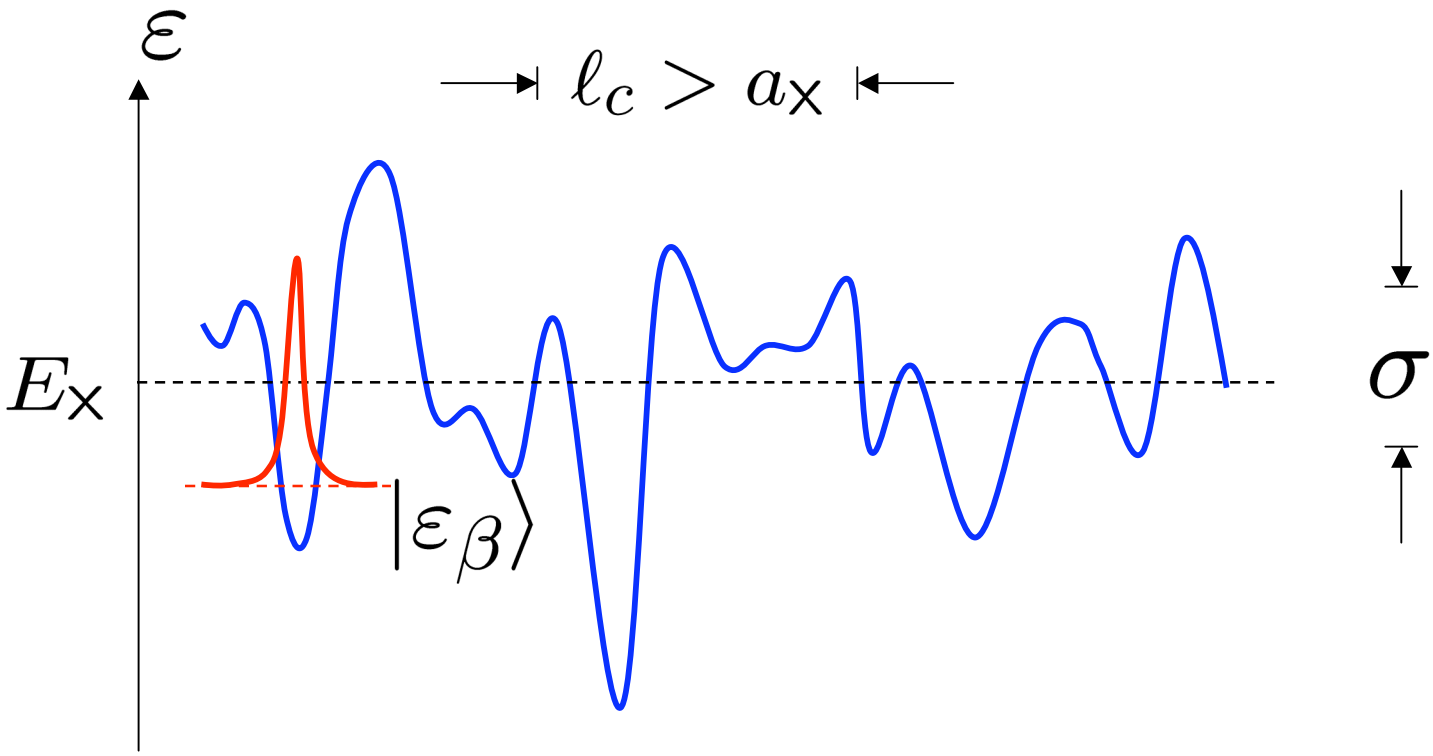
Excitons in Disordered QWs



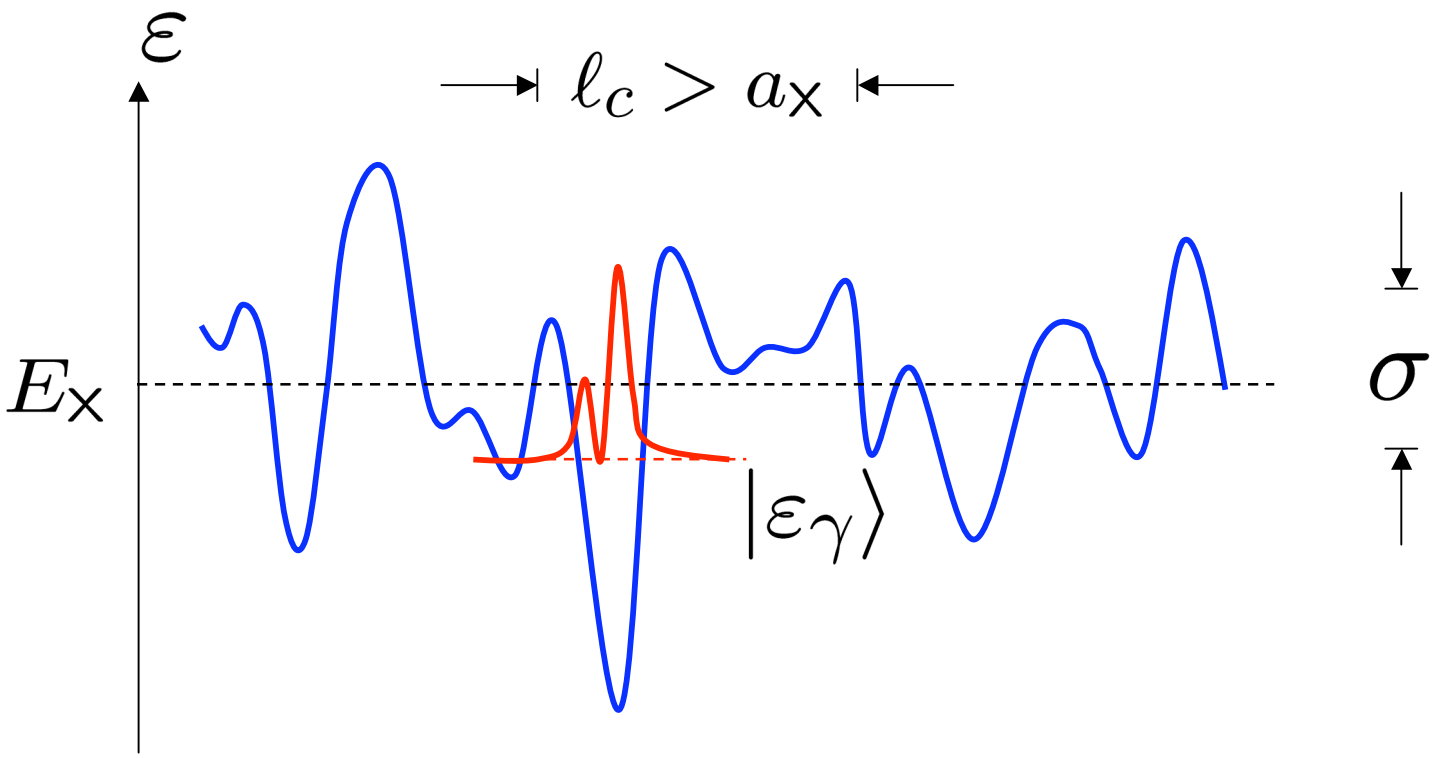
Excitons in Disordered QWs



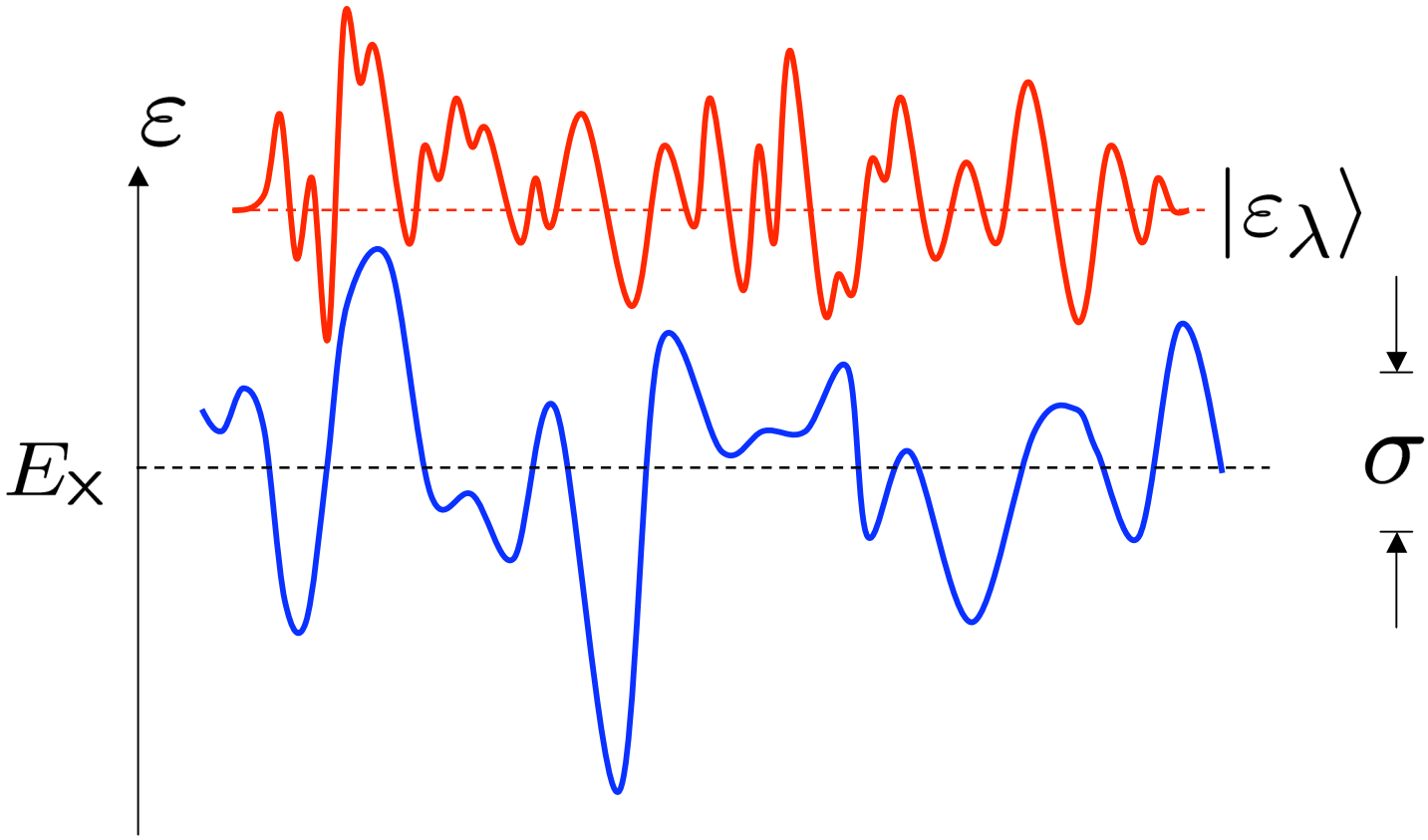
Excitons in Disordered QWs



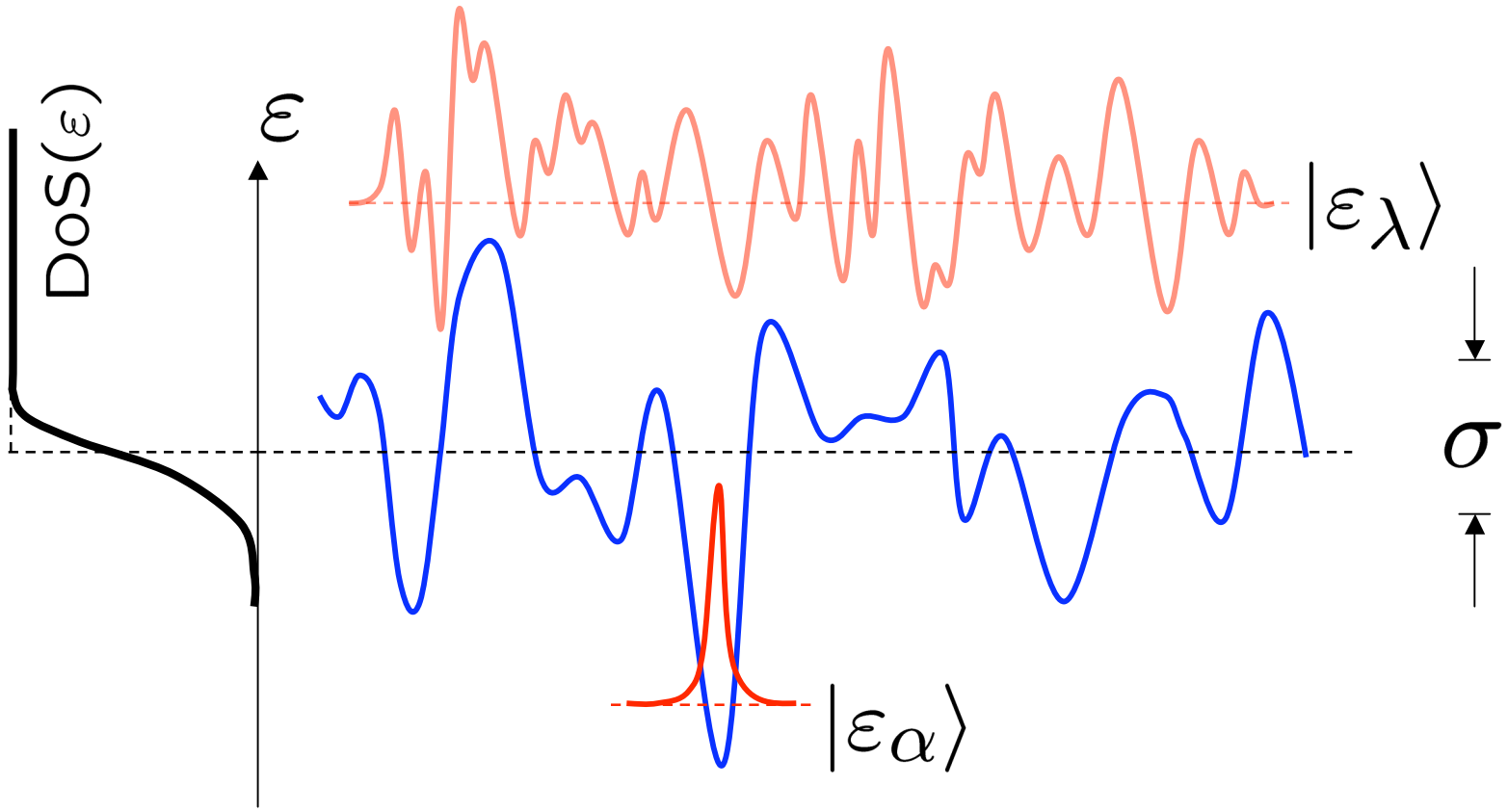
Excitons in Disordered QWs



Excitons in Disordered QWs



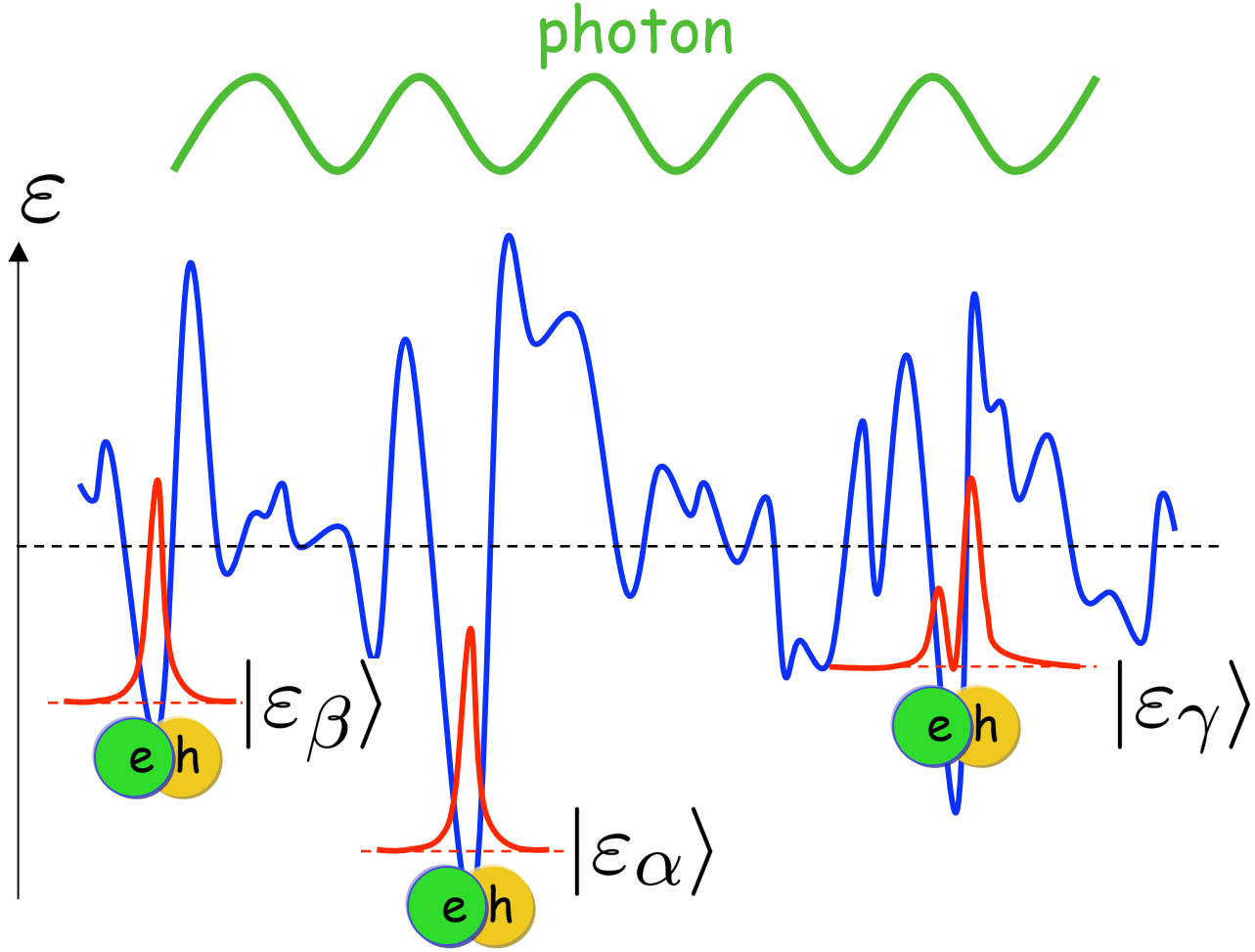
Excitons in Disordered QWs



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

Coupling to Light

$$g_{\alpha,\mathbf{p}} \propto \langle \varepsilon_\alpha | \mathbf{p} \rangle$$

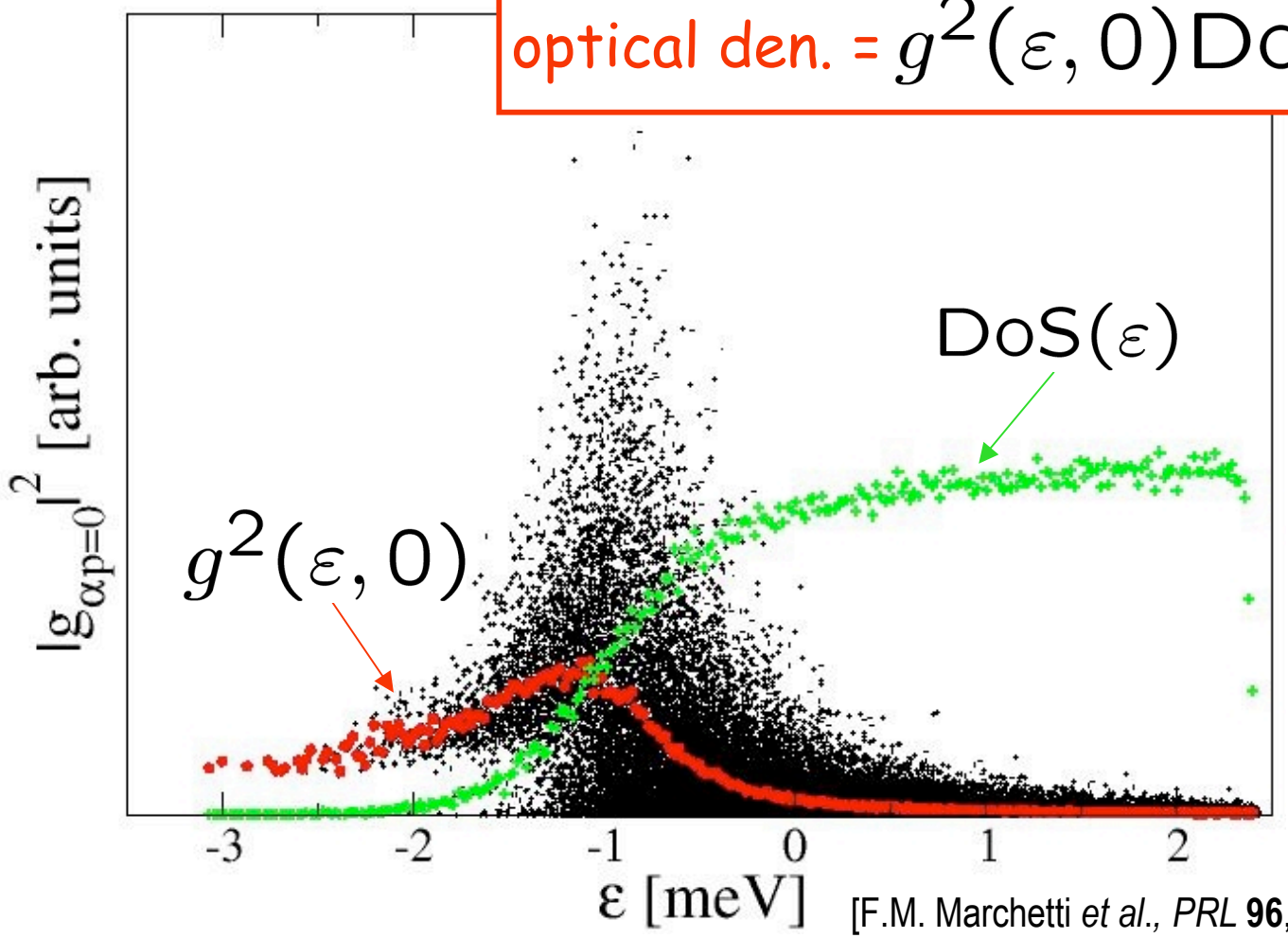


Coupling to Light

[R. Zimmermann *et al.*, *Pure & Appl. Chem.* **69**, 1179 (1997)]

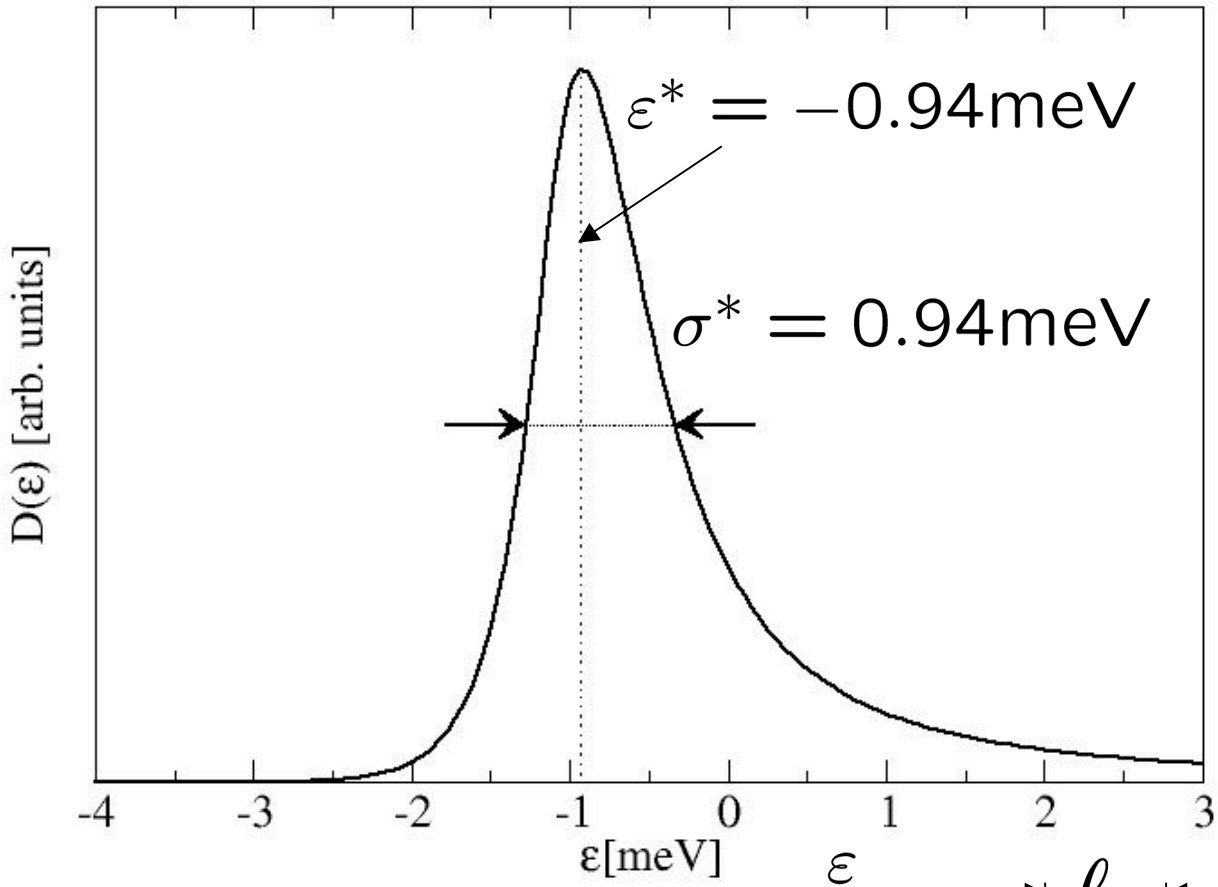
$$g_{\alpha,\mathbf{p}} \propto \langle \varepsilon_\alpha | \mathbf{p} \rangle$$

optical den. = $g^2(\varepsilon, 0)\mathrm{DoS}(\varepsilon)$



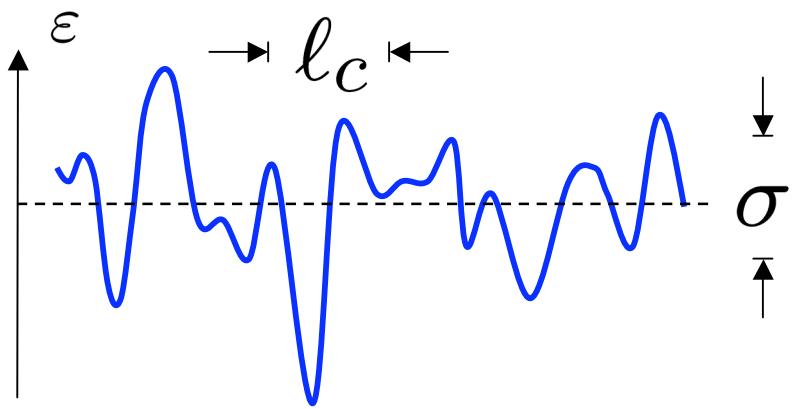
[F.M. Marchetti *et al.*, *PRL* **96**, 066405 (2006)]

Excitonic Optical Density

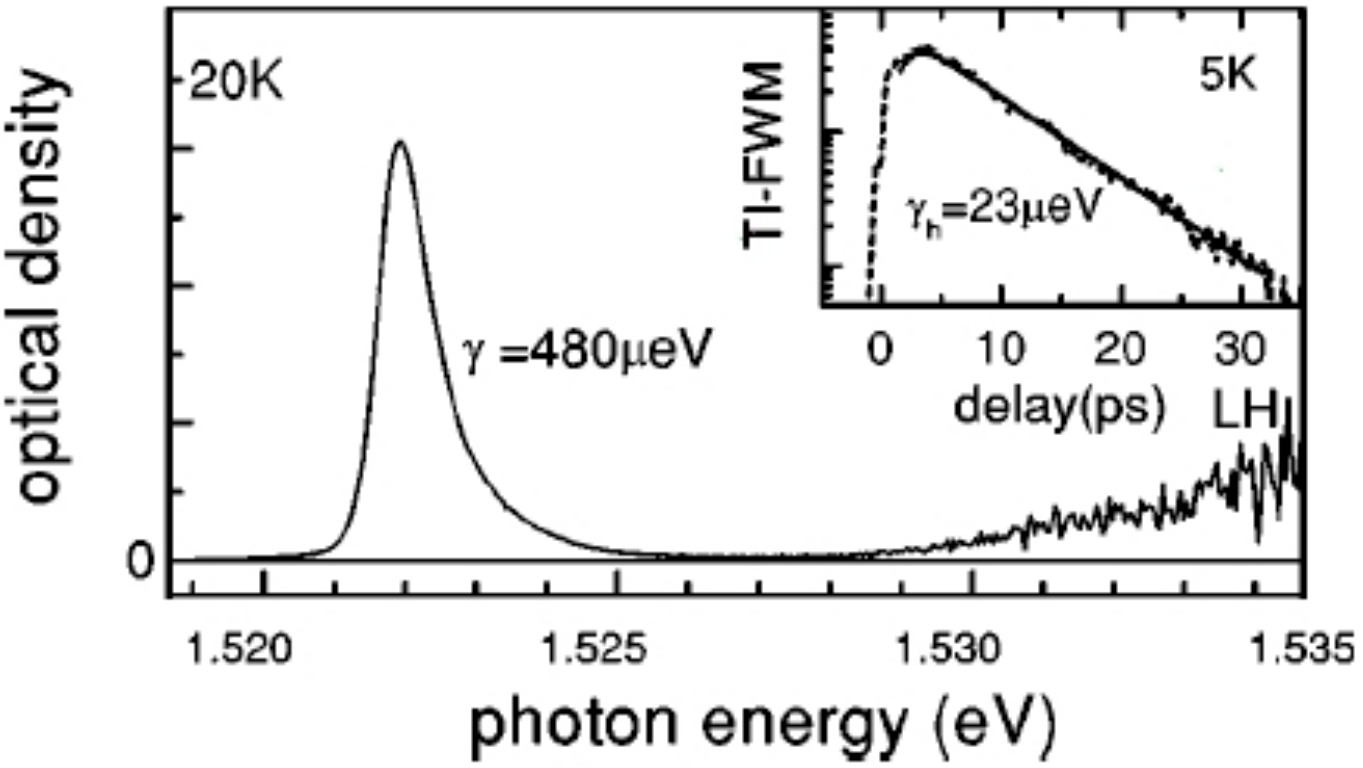


✓ Asymmetry

$$\frac{\sigma}{E_c = \hbar^2/(2m_x \ell_c^2)} \sim 1$$



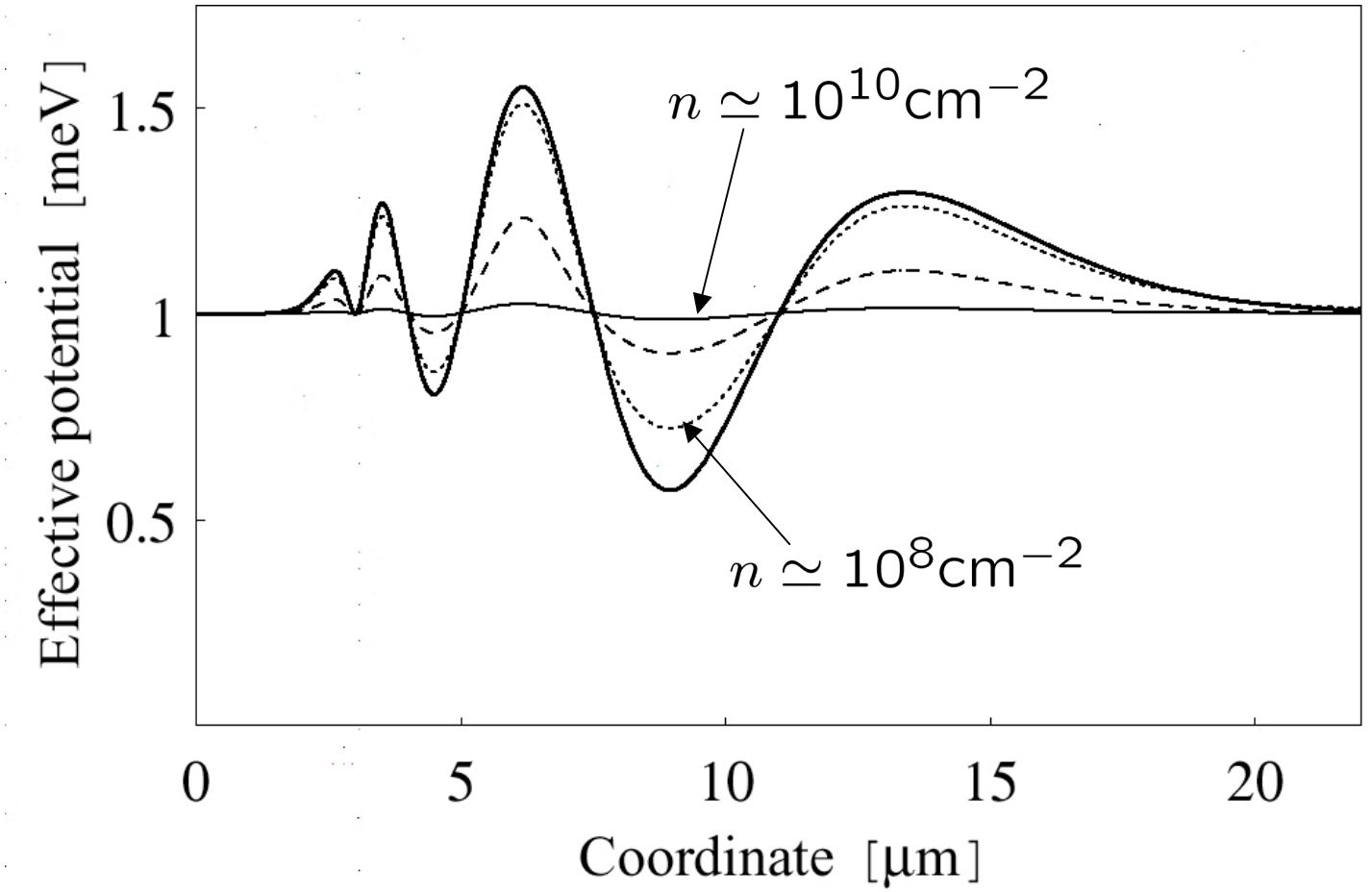
Excitonic Optical Density



[P. Borri *et al., Phys. Rev. B* **63**, 035307 (2000)]

Coupled Quantum Wells

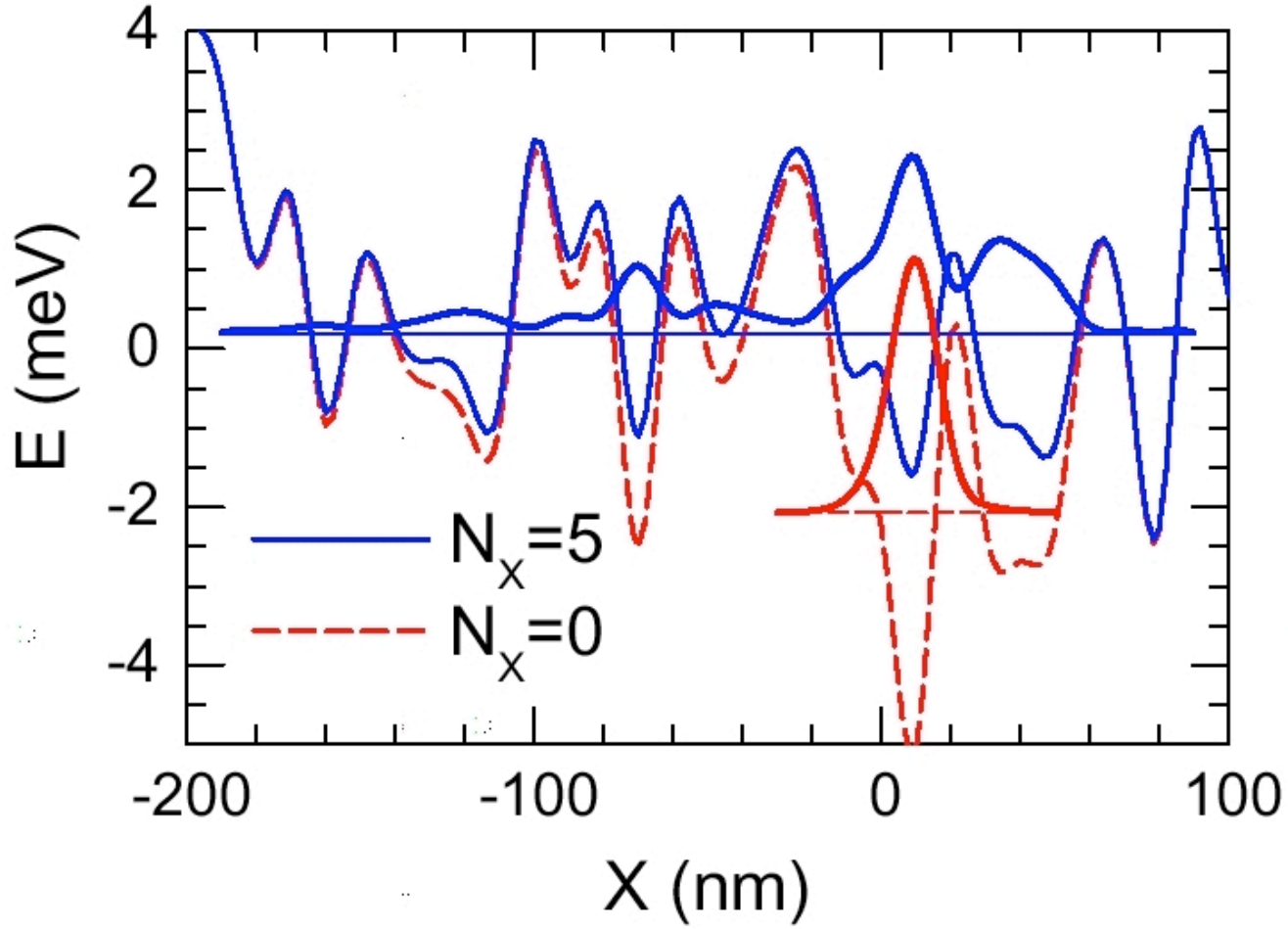
- ✓ Screening of the disorder potential (dipole-dipole interaction)



[A.L. Ivanov, *Europhys. Lett.* **59**, 586 (2002)]

Coupled Quantum Wells

- ✓ Screening of the disorder potential (dipole-dipole interaction)

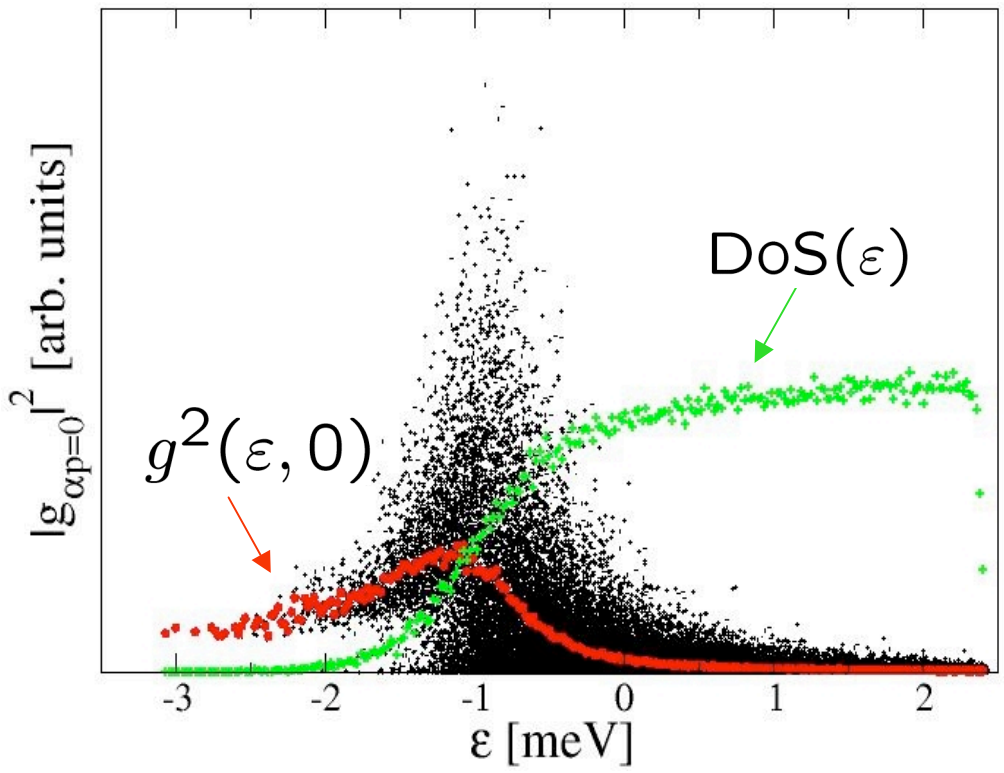


[A.L. Ivanov, *Europhys. Lett.* **59**, 586 (2002)]

[R. Zimmermann, *Solid State Comm.* **134**, 43 (2005)]

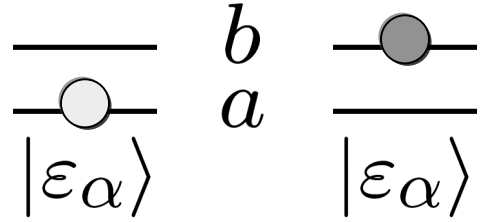
Model for Cavity Polaritons

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

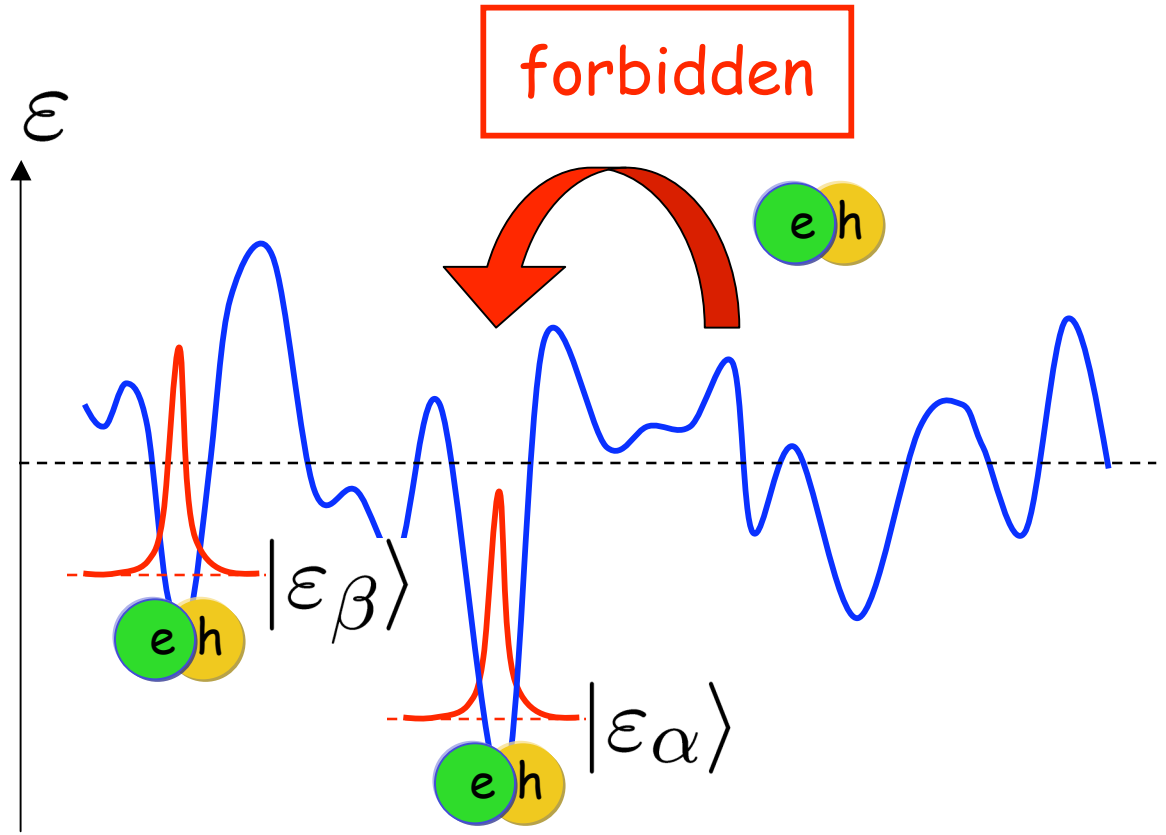


Model for Cavity Polaritons

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



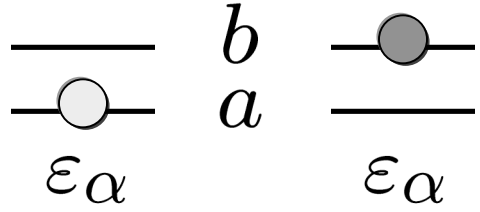
two-level system



Model for Cavity Polaritons

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

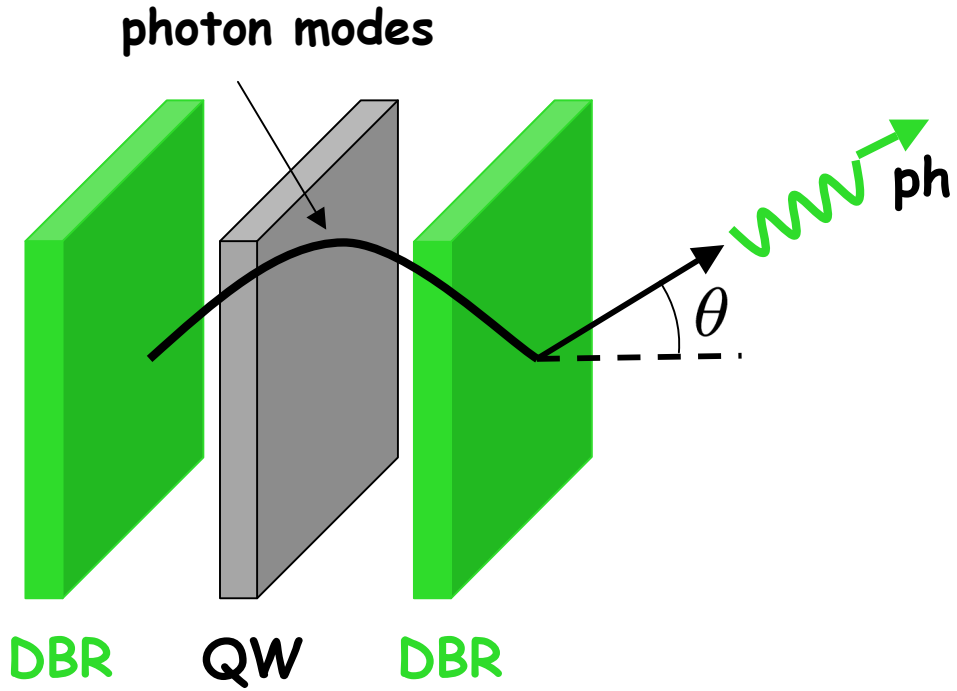
$$+ \sum_{\mathbf{p}} \omega_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \psi_{\mathbf{p}}$$



two-level system

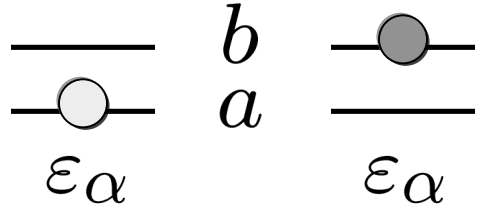
$$\omega_{\mathbf{p}} \simeq \omega_0 + \frac{\mathbf{p}^2}{2m_{\mathrm{ph}}}$$

photon modes



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

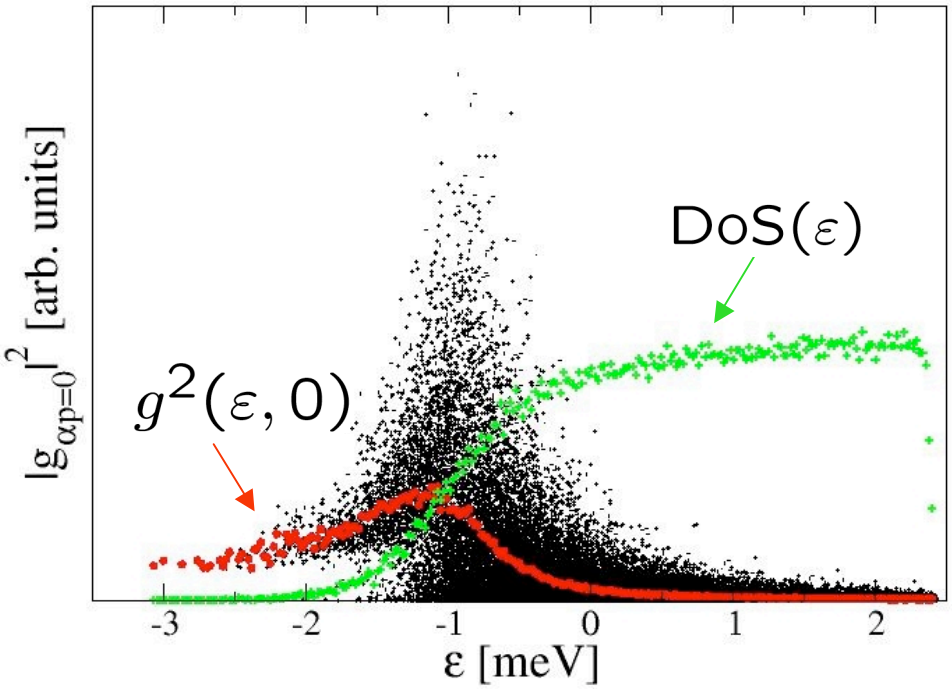
$$+ \sum_{\mathbf{p}} \omega_{\mathbf{p}} \psi_{\mathbf{p}}^\dagger \psi_{\mathbf{p}}$$

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

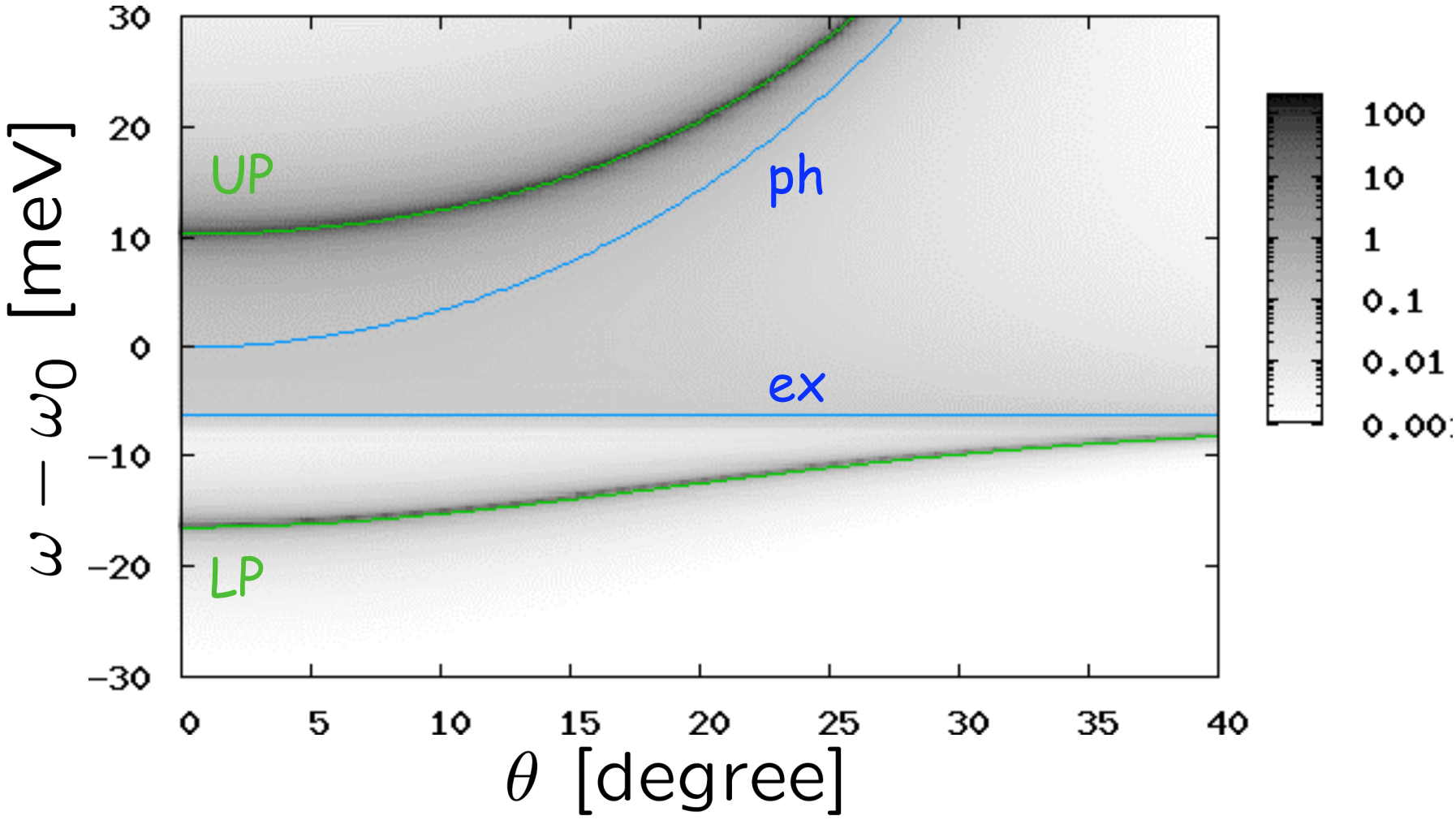
photon modes

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

dipole coupling

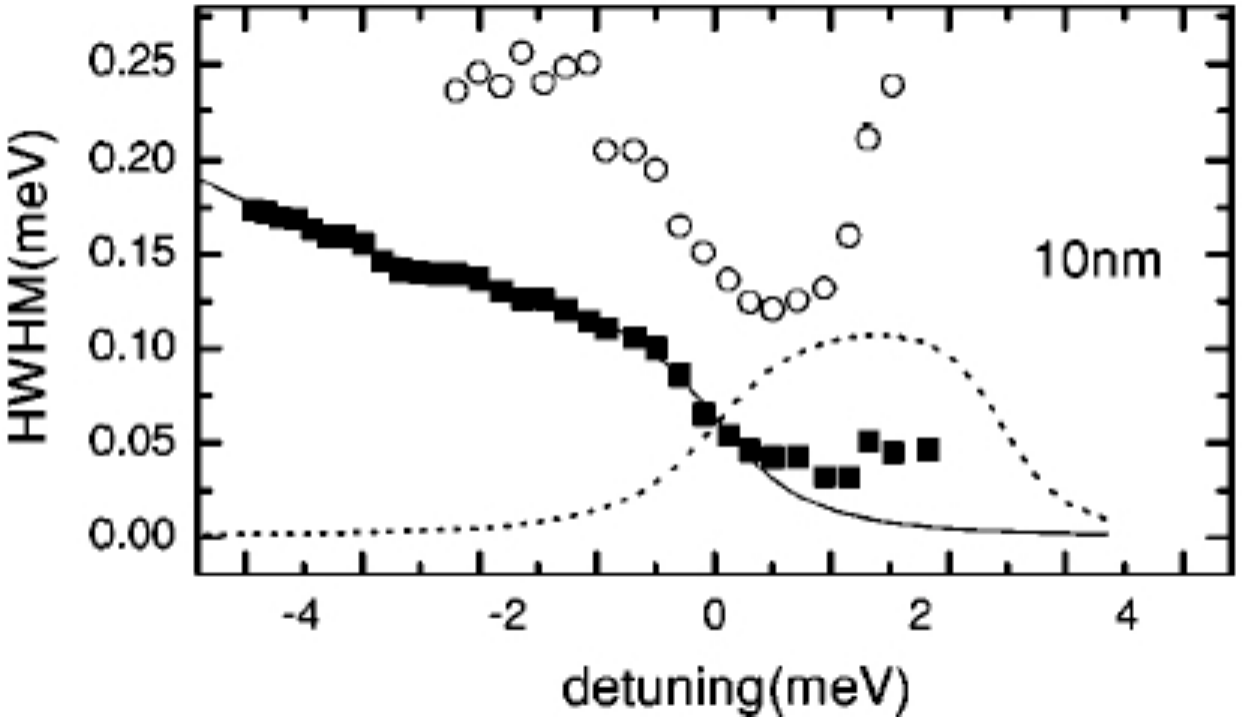


Dilute (Bosonic) Limit



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

Inhomogeneous Line-width

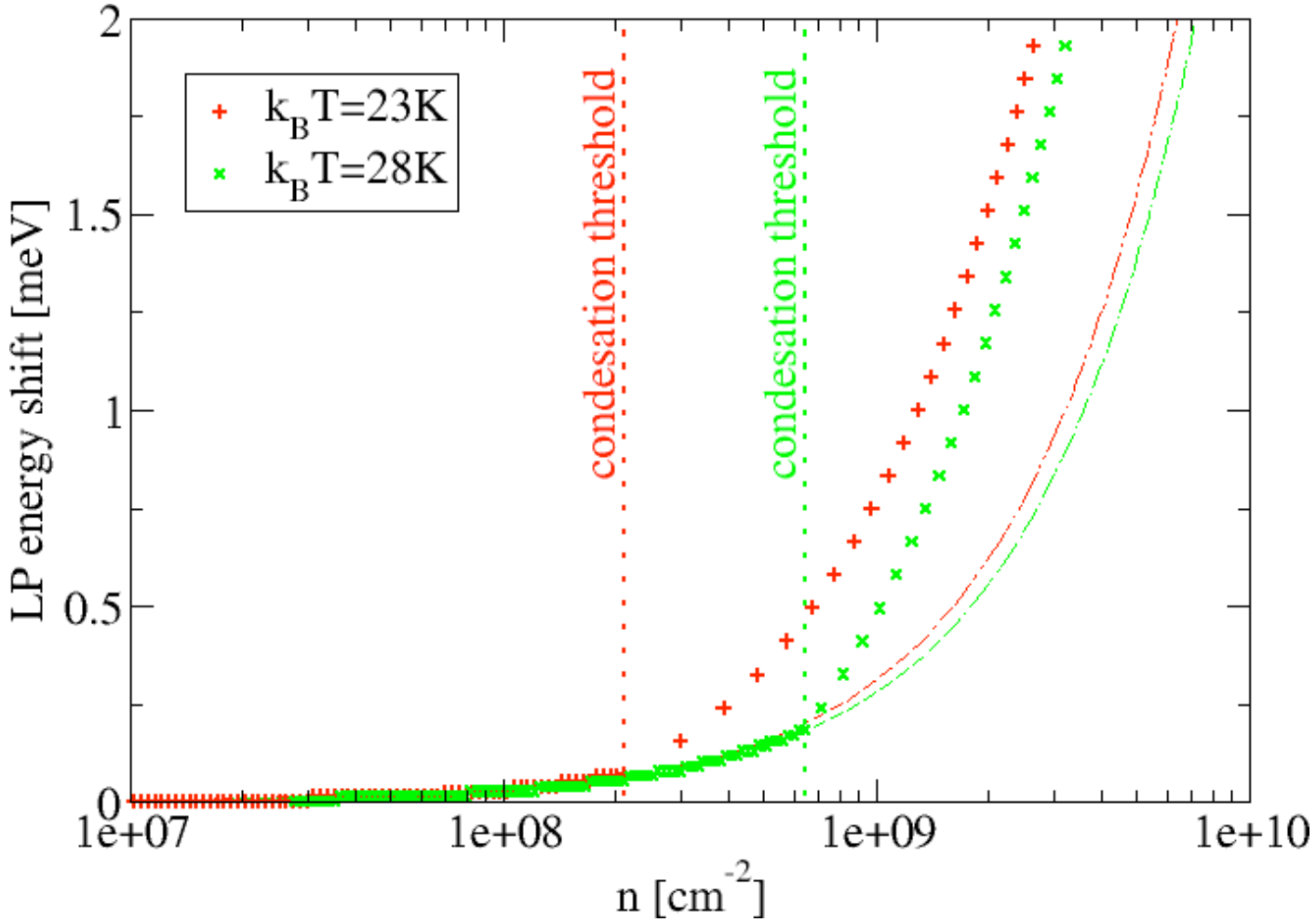


[P. Borri *et al., Phys. Rev. B* **63**, 035307 (2000)]

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

Dilute (Bosonic) Limit: blue-shift

✓ Linear shift below threshold for condensation (low temp)

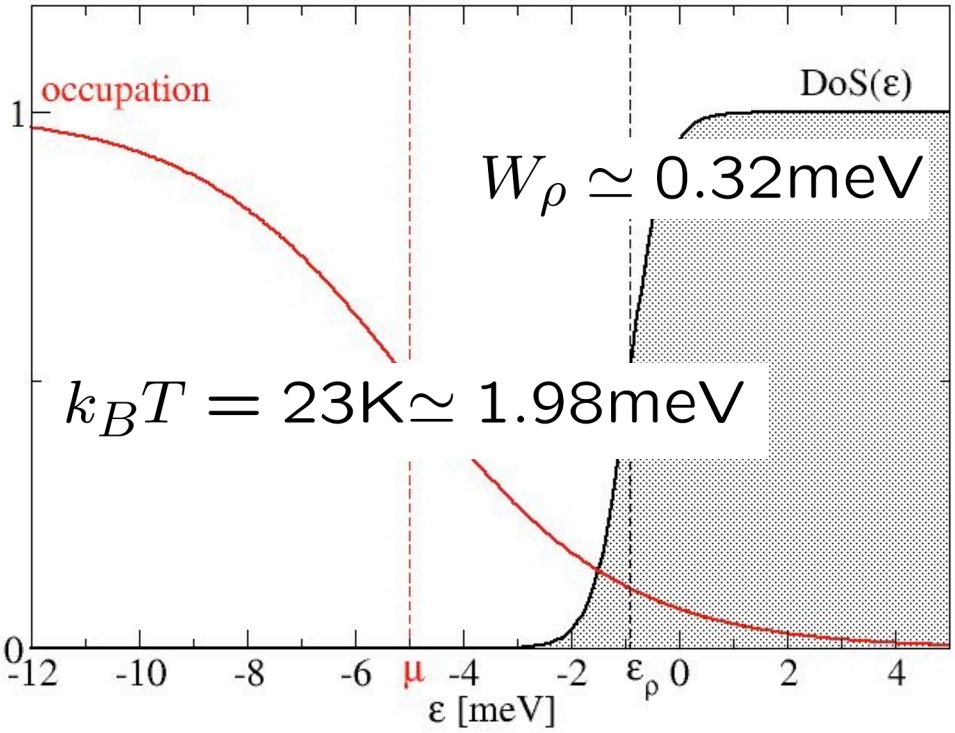


Dilute (Bosonic) Limit: blue-shift

$$\delta E_{\mathrm{LP}} \sim \Omega_R n \frac{1}{m_{\mathrm{X}} W_\rho}$$

or

$$\sim \Omega_R n \frac{1}{m_{\mathrm{X}} k_B T}$$

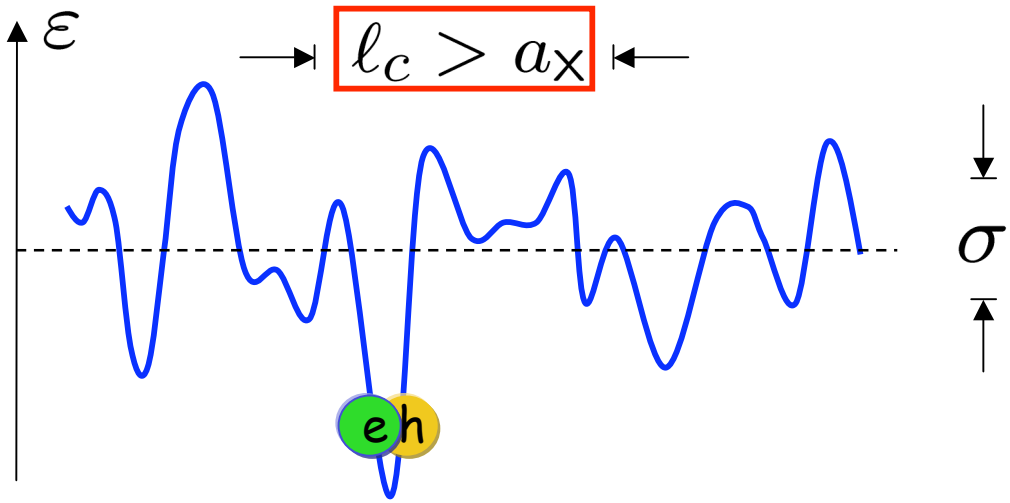


...vs clean limit:

$$\delta E_{\mathrm{Coul}} \sim \mathcal{R}\mathrm{y}_{\mathrm{X}} n a_{\mathrm{X}}^2$$

or

$$\delta E_{\mathrm{sat}} \sim \Omega_R n a_{\mathrm{X}}^2$$

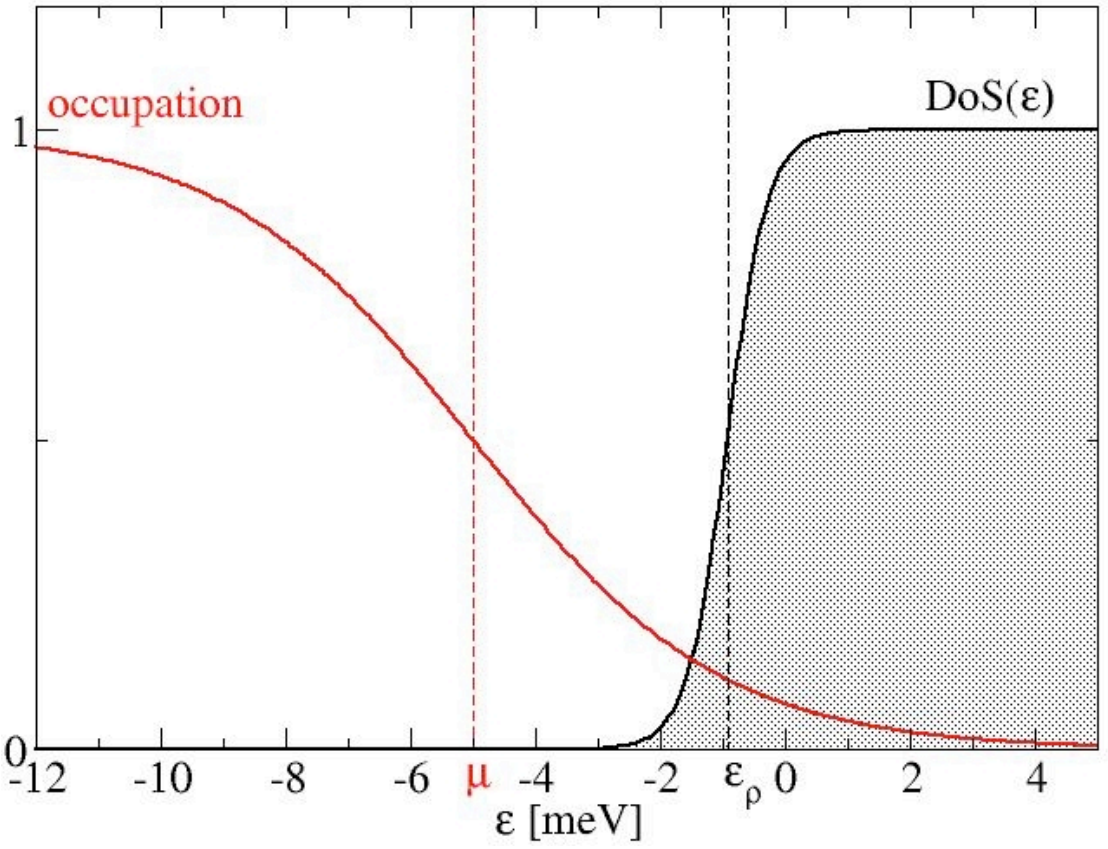


[C. Ciuti *et al.*, *PRB* **62**, R4825 (2000)]

Validity at Higher Densities

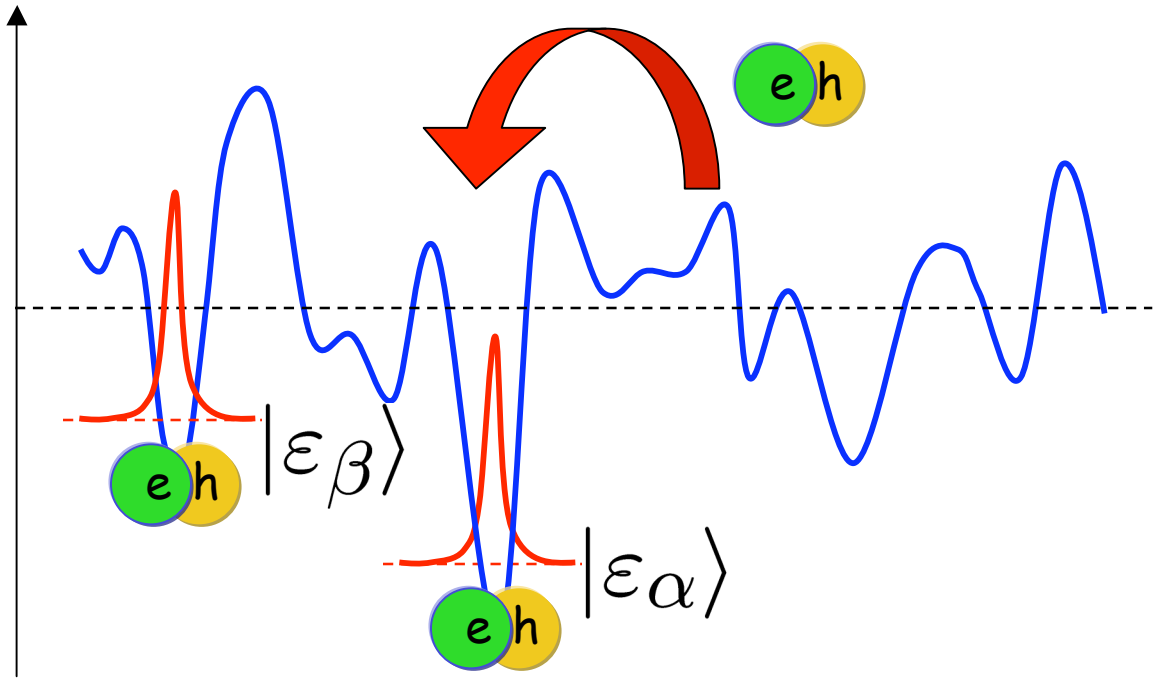
- ✓ Neglected Coulomb interaction between $|\varepsilon_\alpha\rangle$ and $|\varepsilon_\beta\rangle$ (restrict the occupation to the states in the tail)

- ✓ Double-occupancy



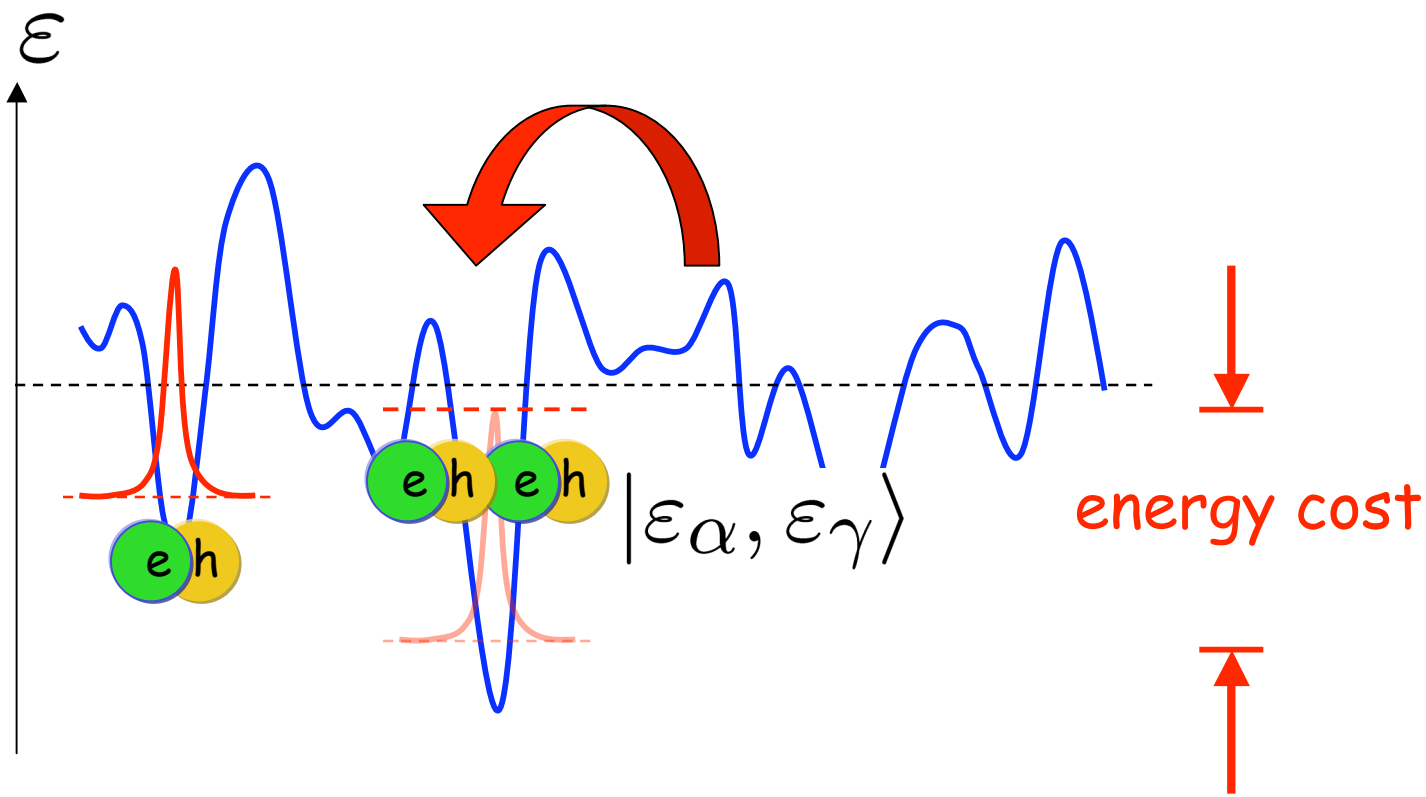
Validity at Higher Densities

- ✓ Neglected Coulomb interaction between $|\varepsilon_\alpha\rangle$ and $|\varepsilon_\beta\rangle$ (restrict the occupation to the states in the tail)
- ✓ Double-occupancy

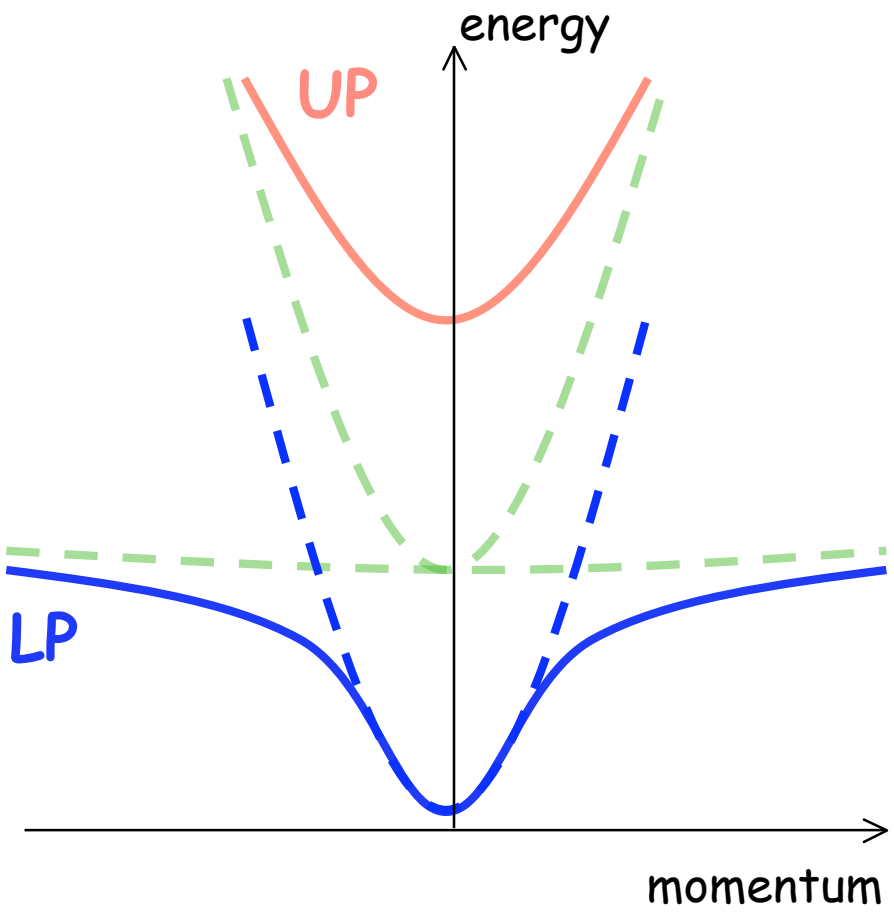


Validity at Higher Densities

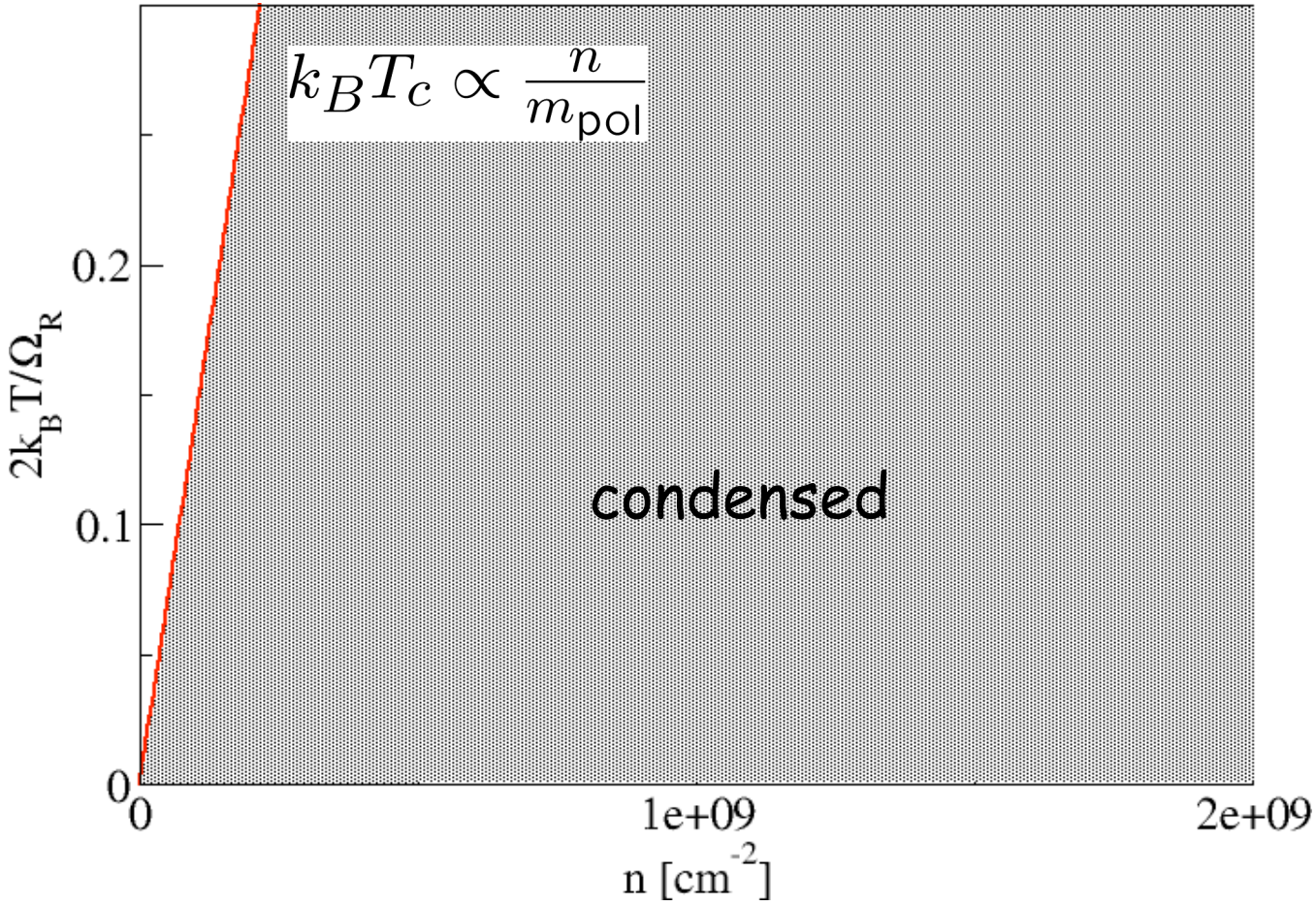
- ✓ Neglected Coulomb interaction between $|\varepsilon_\alpha\rangle$ and $|\varepsilon_\beta\rangle$ (restrict the occupation to the states in the tail)
- ✓ Double-occupancy



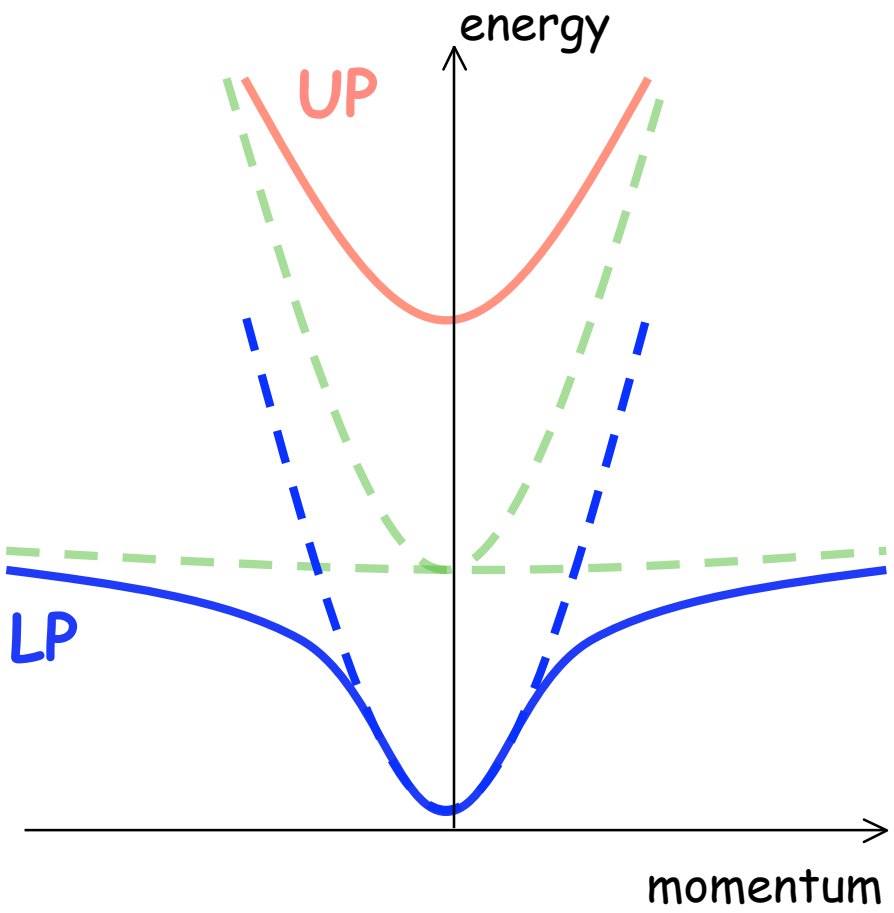
Phase Diagram



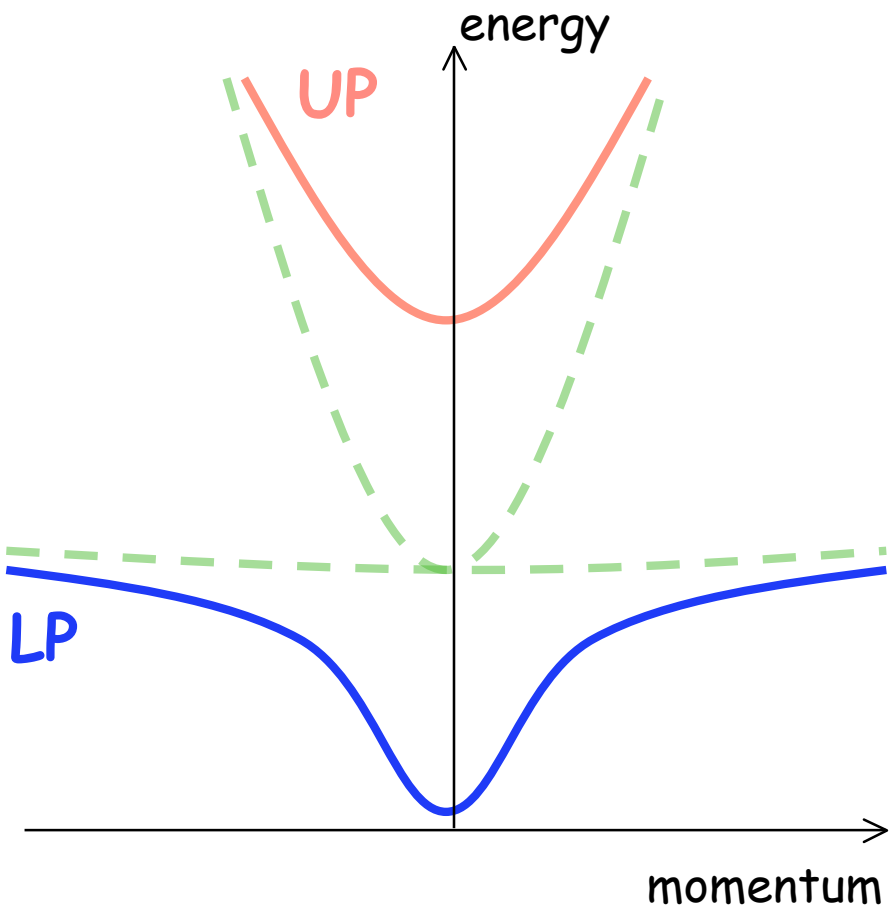
Phase Diagram



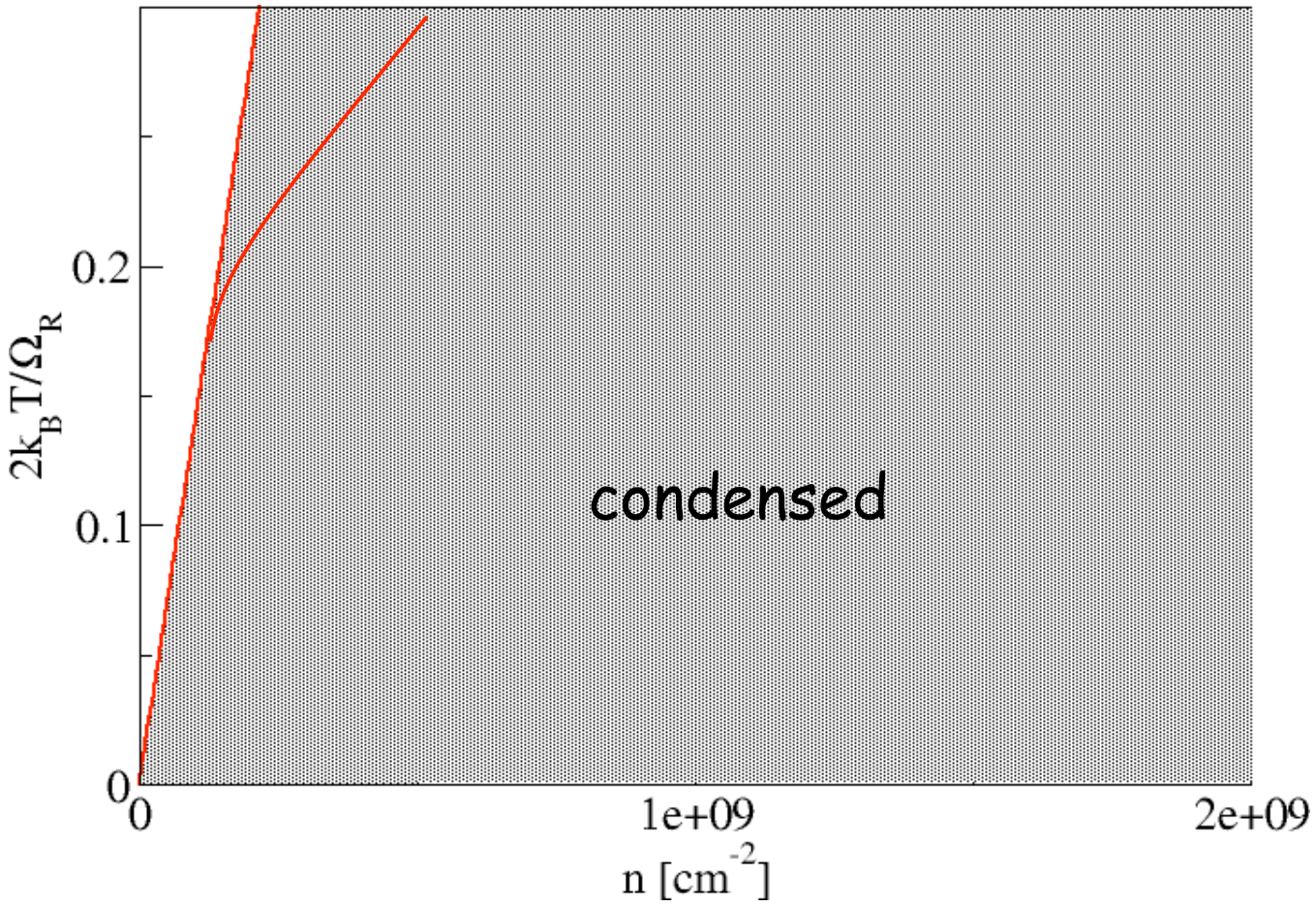
Phase Diagram



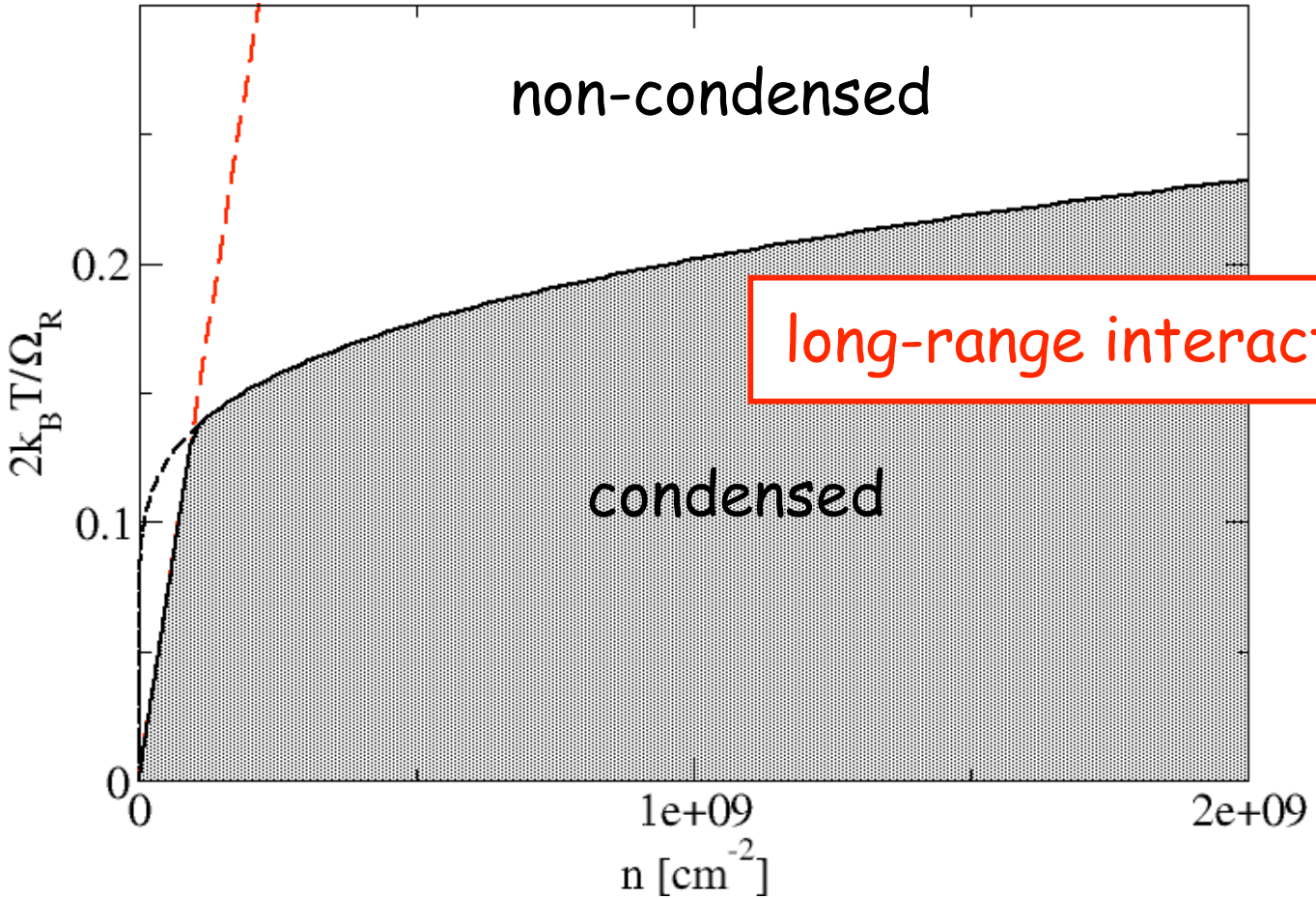
Phase Diagram



Phase Diagram



Phase Diagram



✓ When $k_B T_c \sim \Omega_R$, deviations from BEC of structureless polaritons

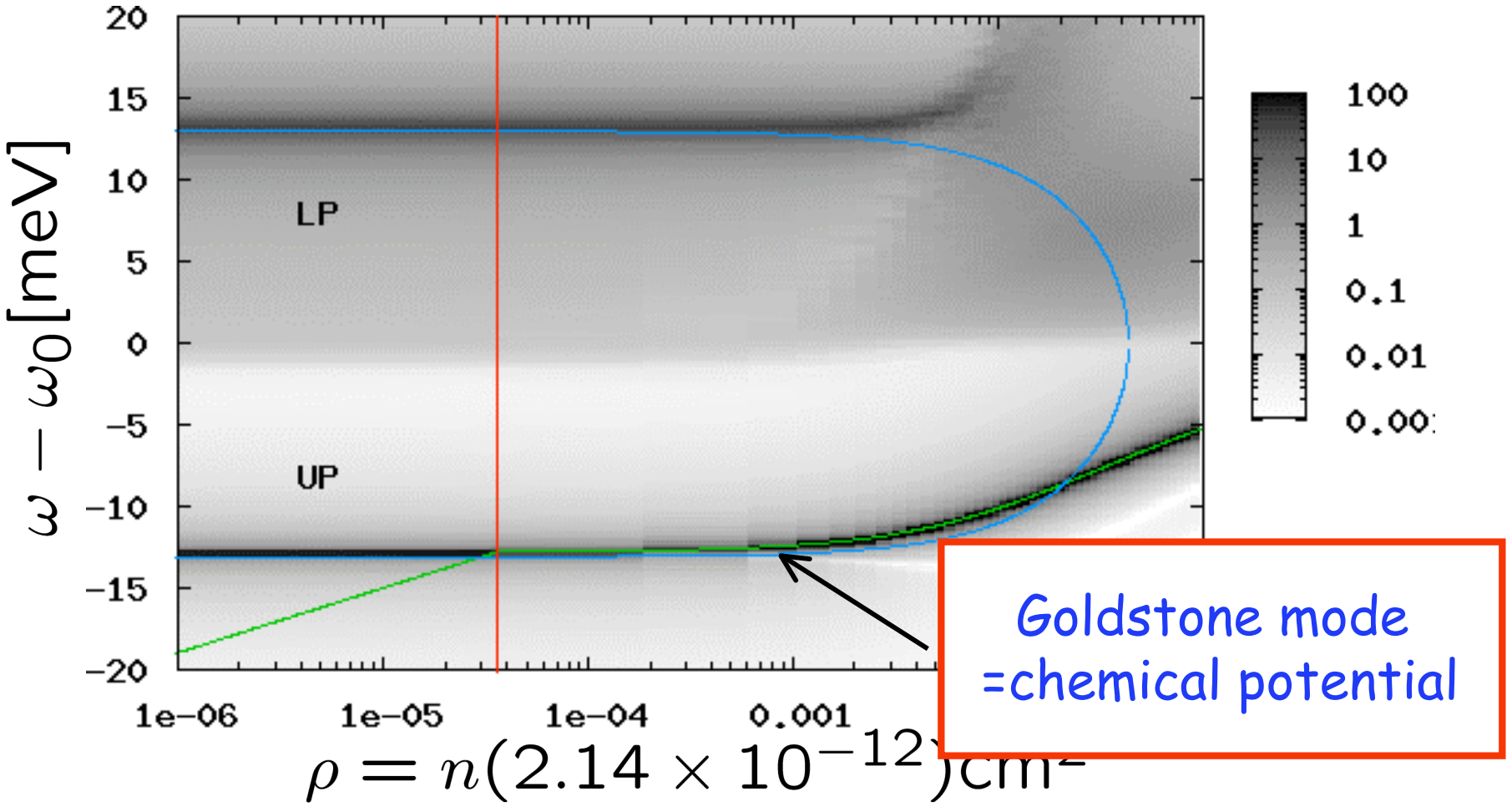
[J. Keeling *et al.*, *PRL* **93**, 226403 (2004)]

[F.M. Marchetti *et al.*, *PRL* **96**, 066405 (2006)]

From Polaritonic to Condensed Spectra

✓ Fixing temperature $k_B T = 23\text{K}$ $(\delta = +6\text{meV})$

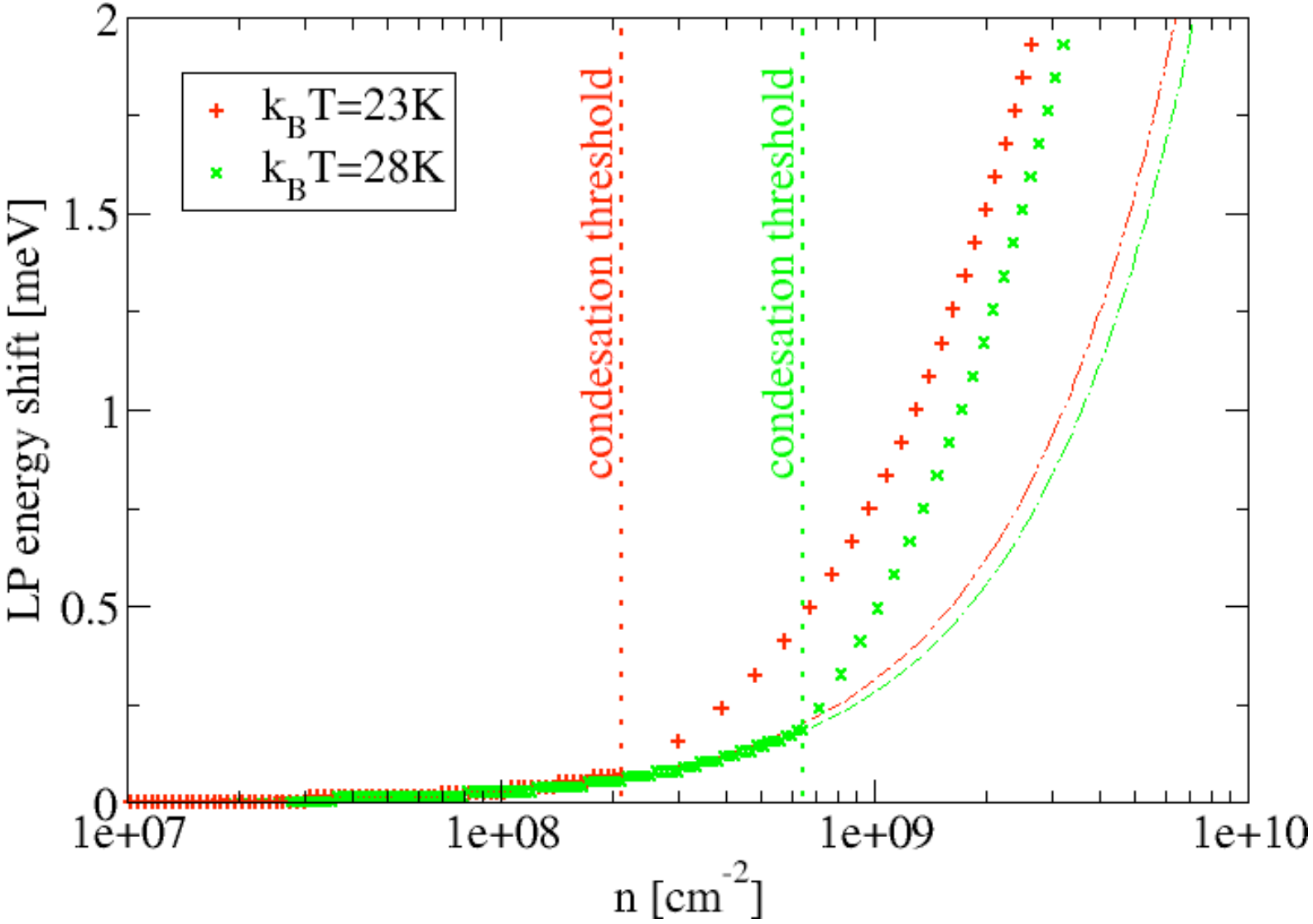
ρ_C (critical density)



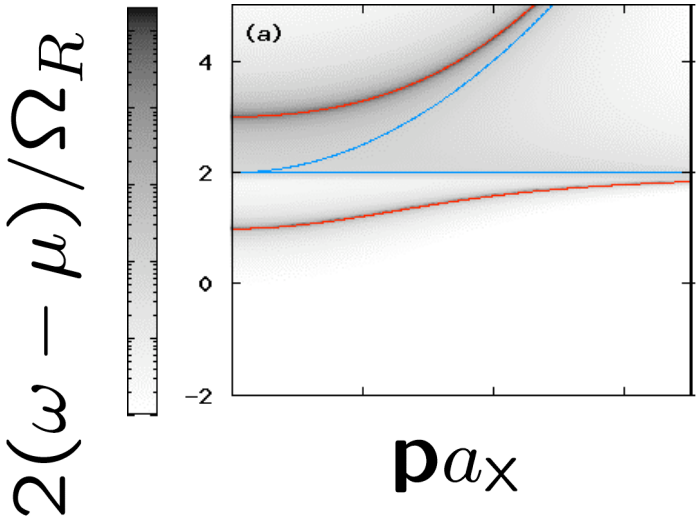
Goldstone mode
=chemical potential

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

Blue-Shift

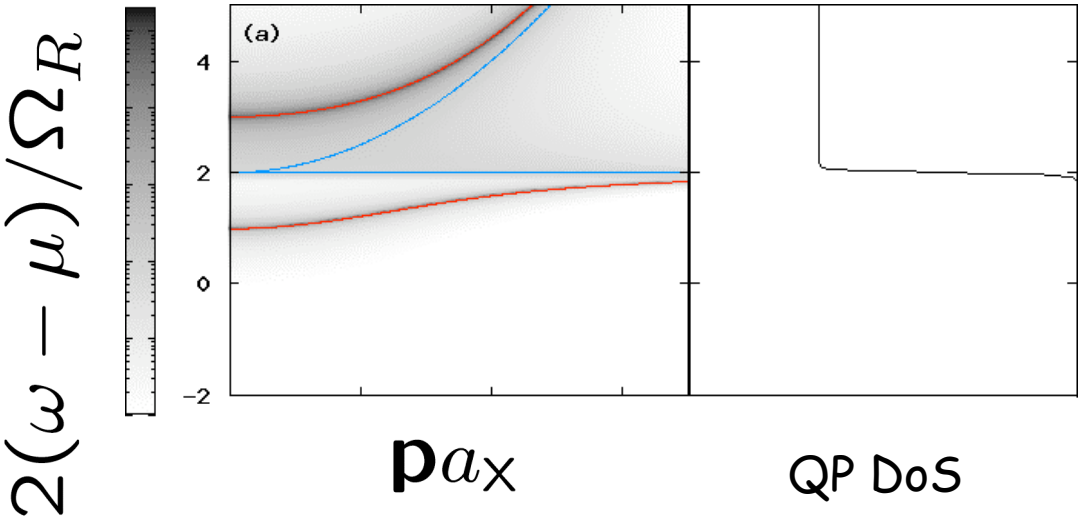

2
1.5
1
0.5
0
LP energy shift [meV]
1e+07
1e+08
1e+09
1e+10
n [cm^-2]
k_B T=23K
k_B T=28K
condesation threshold
condesation threshold

Spectral Weight



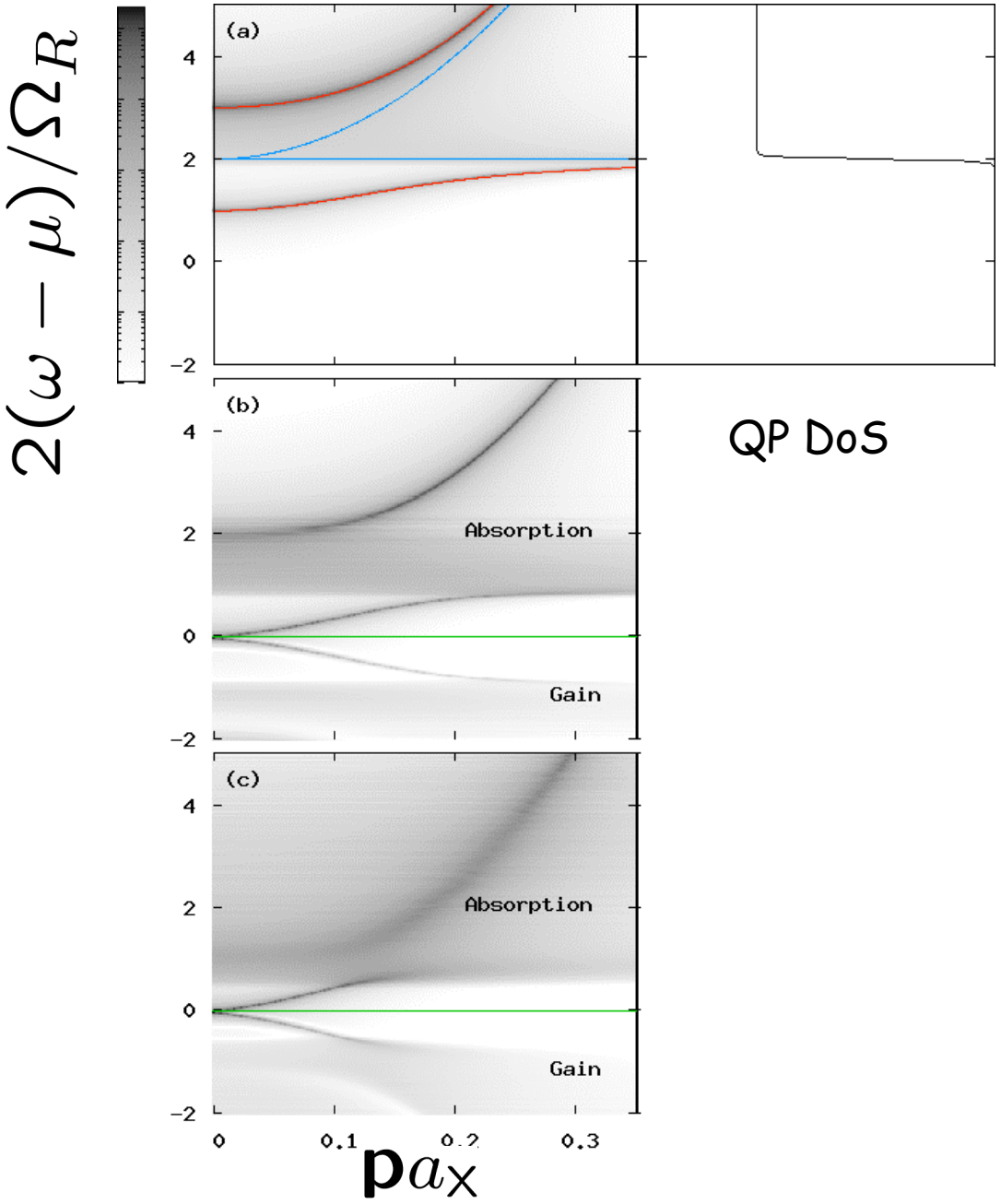
non-condensed

Spectral Weight



non-condensed

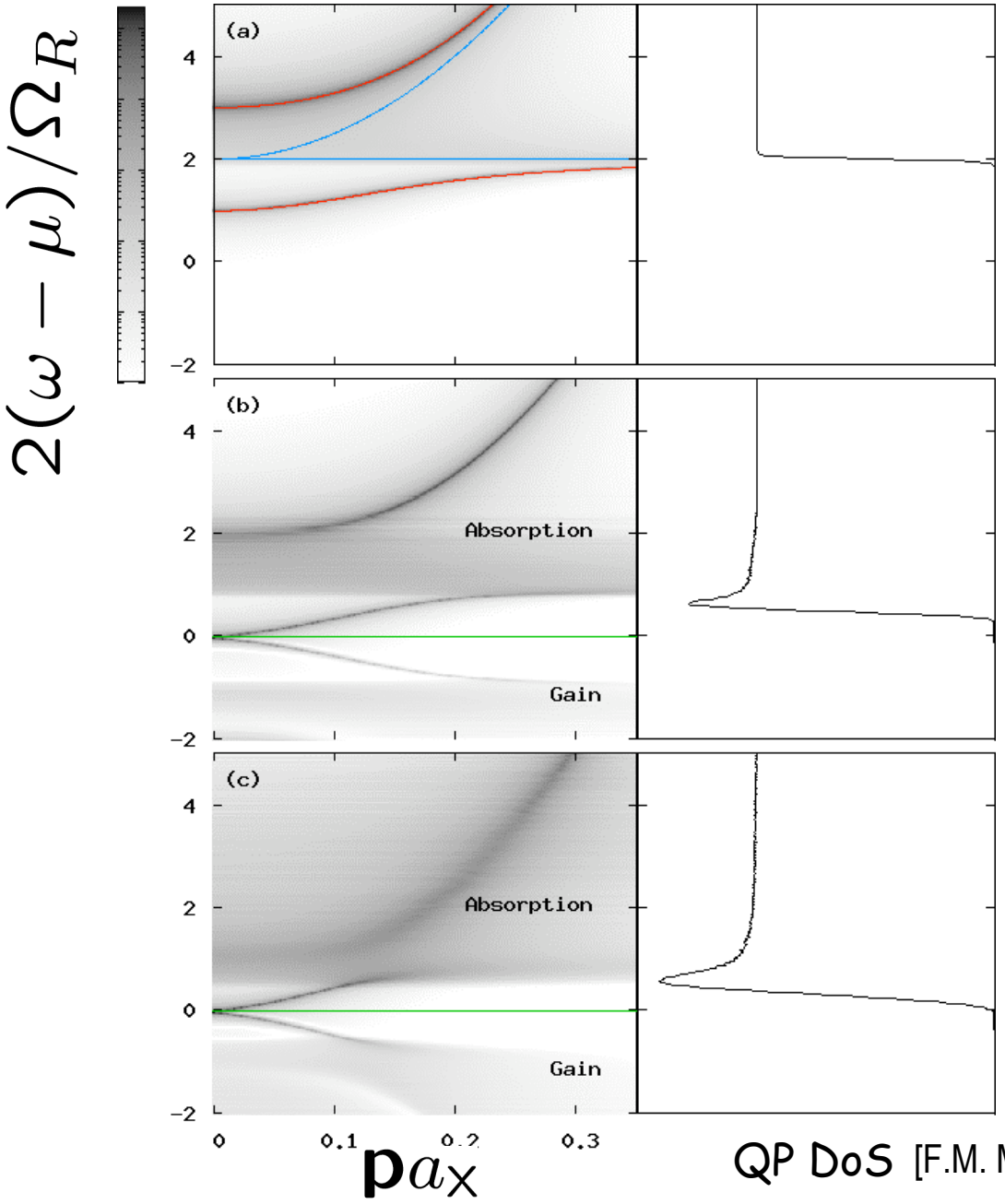
Spectral Weight



non-condensed

condensed

Spectral Weight

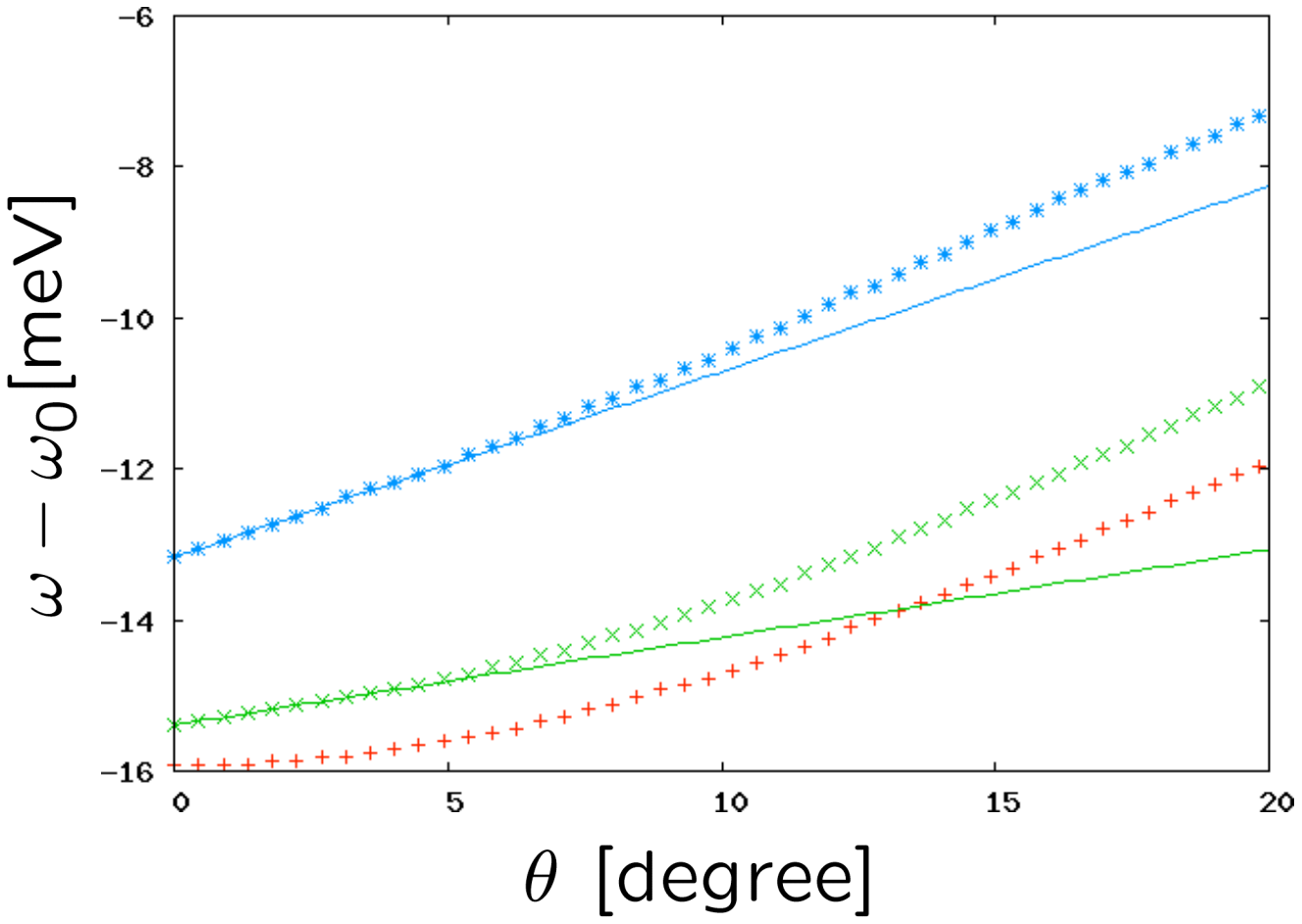


non-condensed

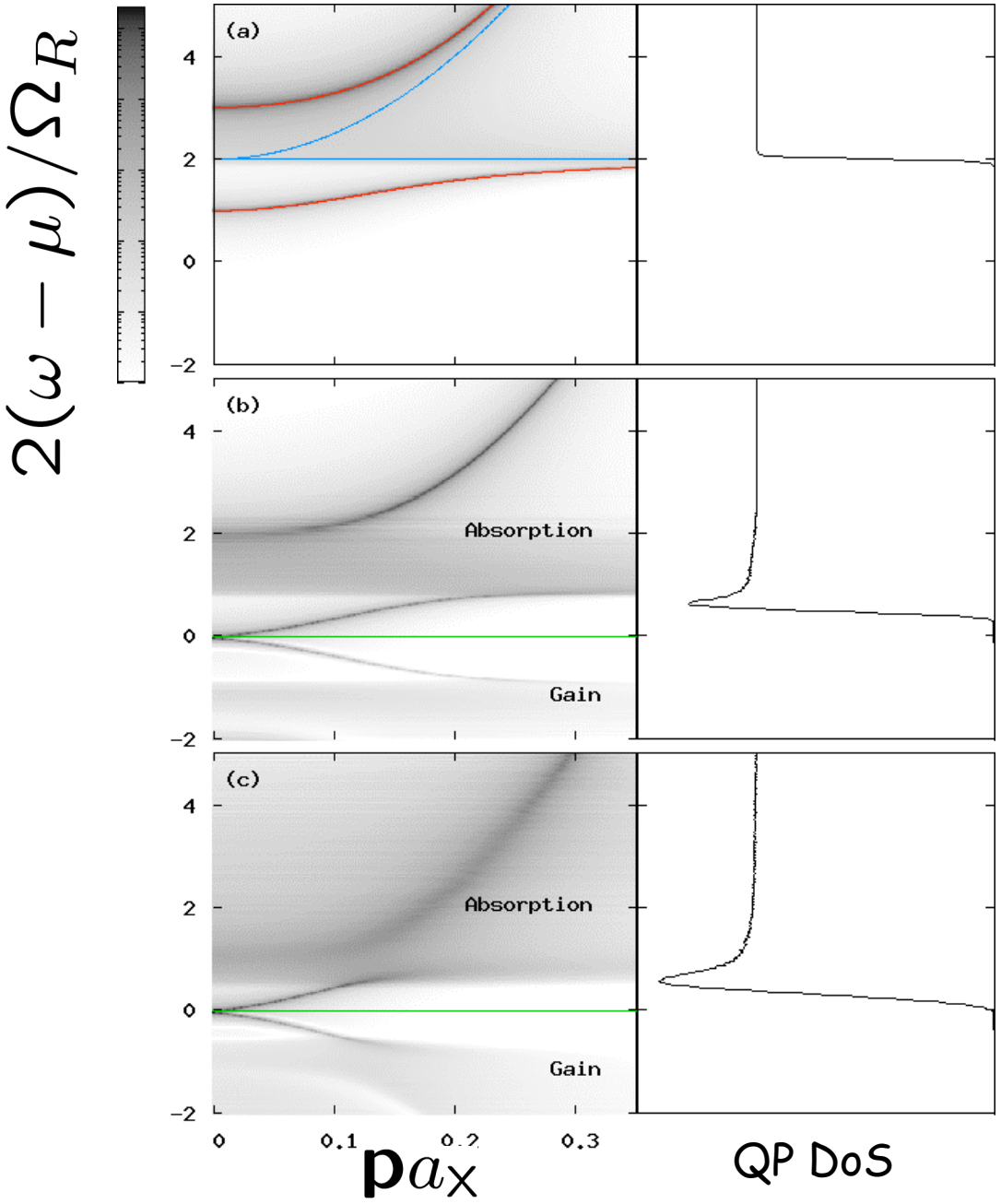
condensed

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

Goldstone Mode



Spectral Weight x Occupation

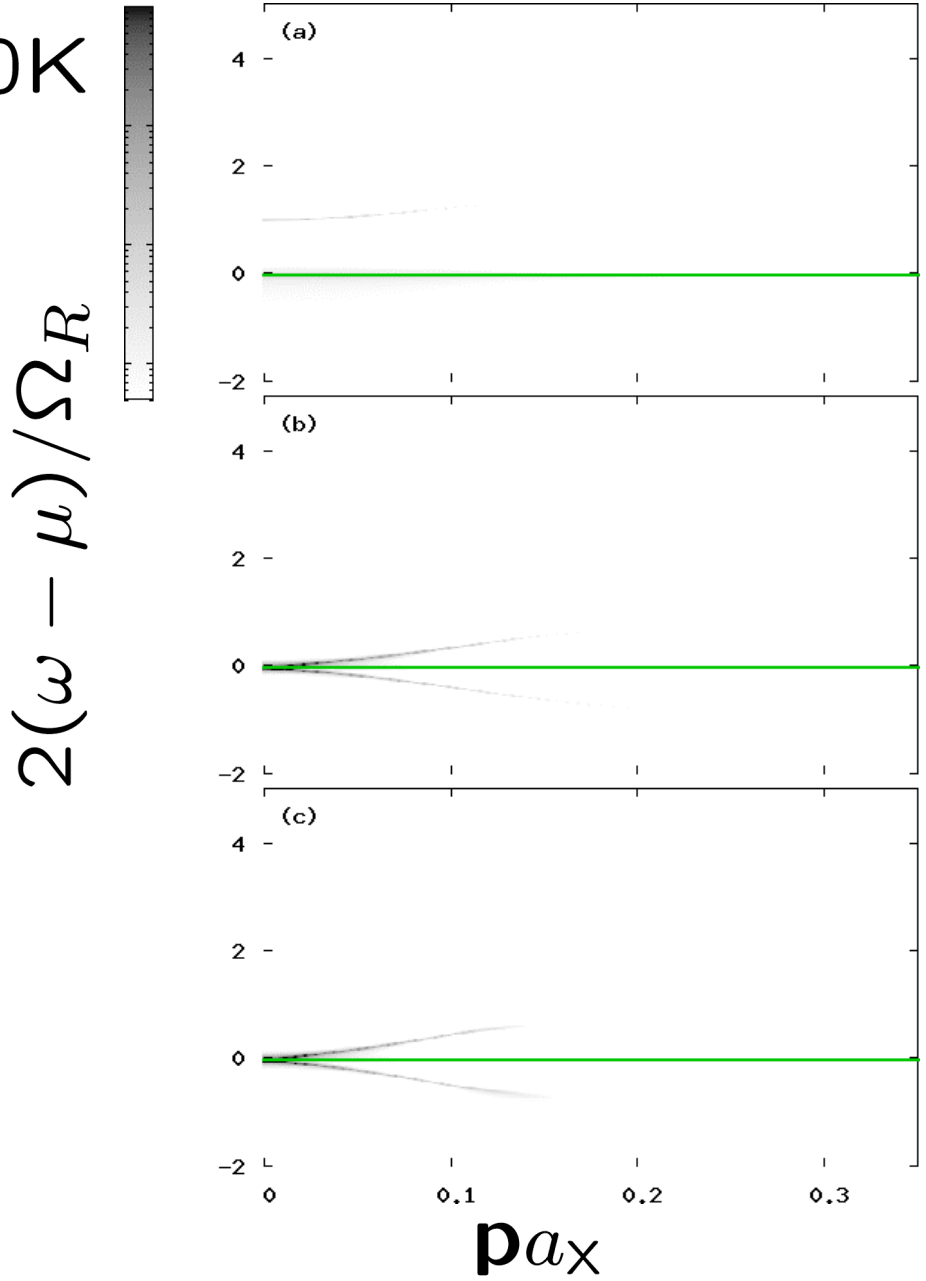


non-condensed

condensed

Incoherent Photoluminescence

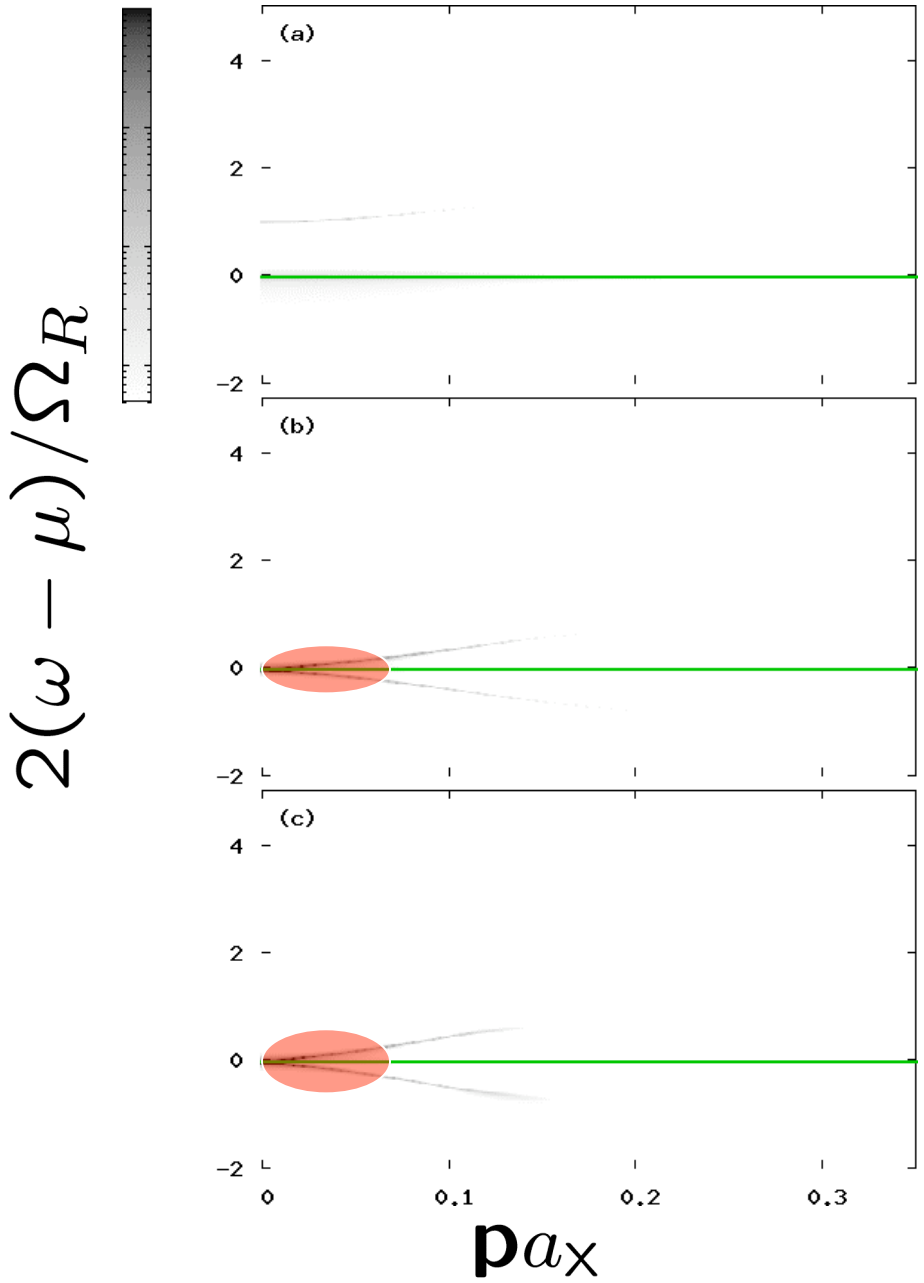
$k_B T = 20\mathrm{K}$



non-condensed

condensed

Incoherent Photoluminescence

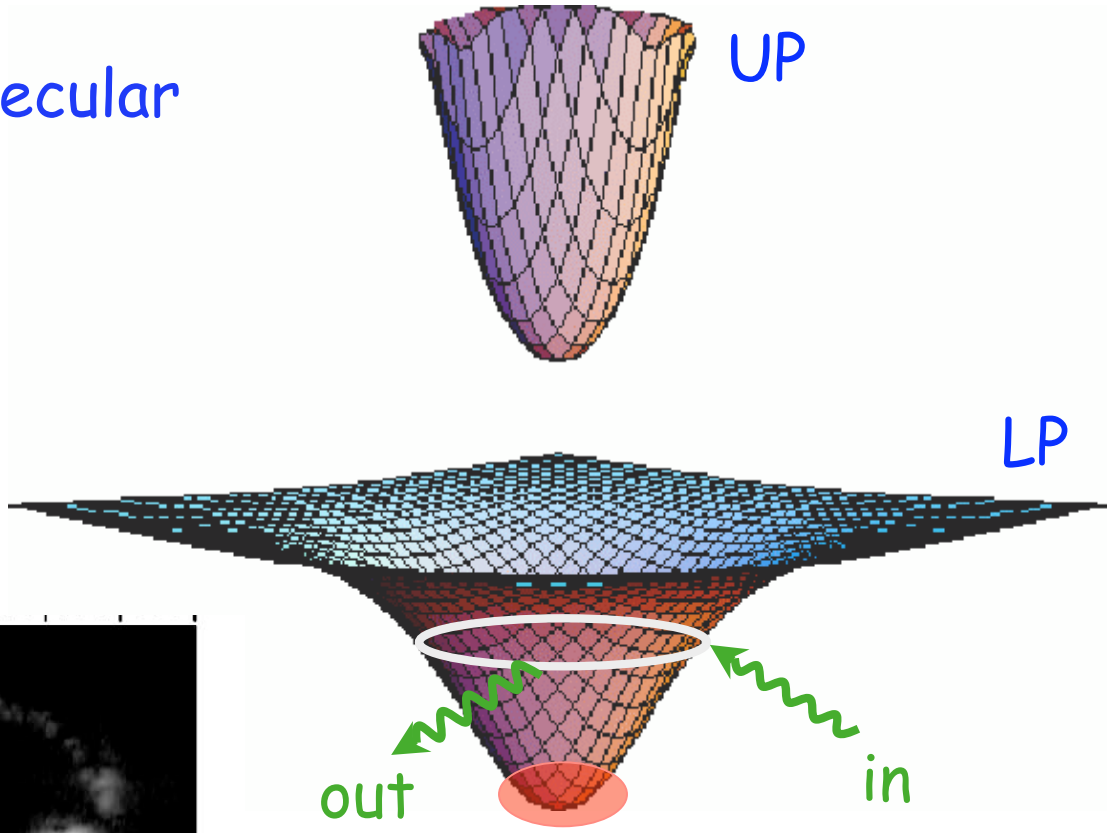


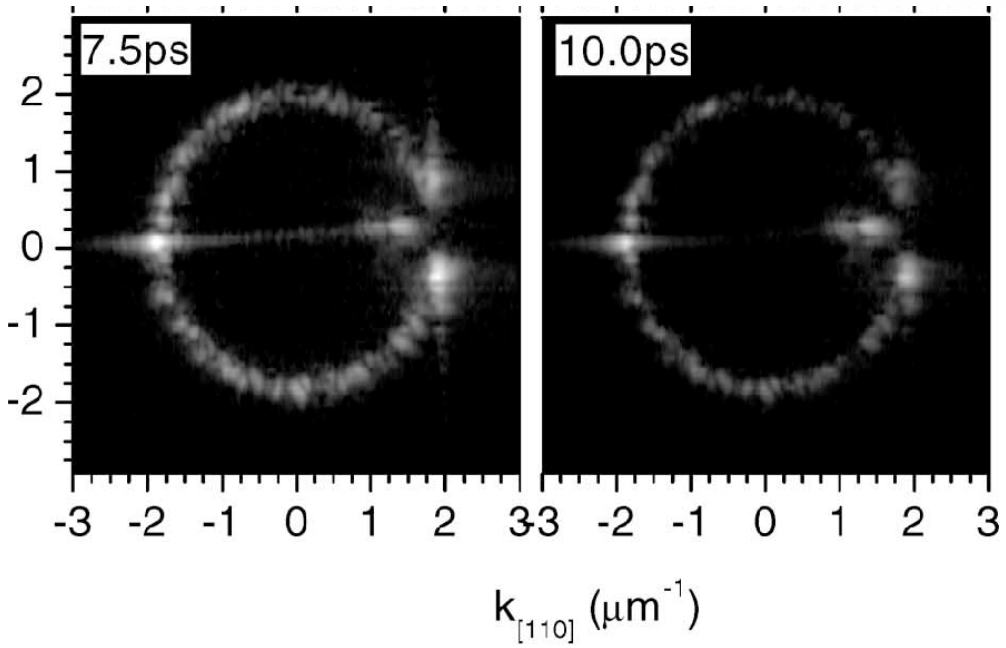
non-condensed

condensed

Resonant Rayleigh Scattering

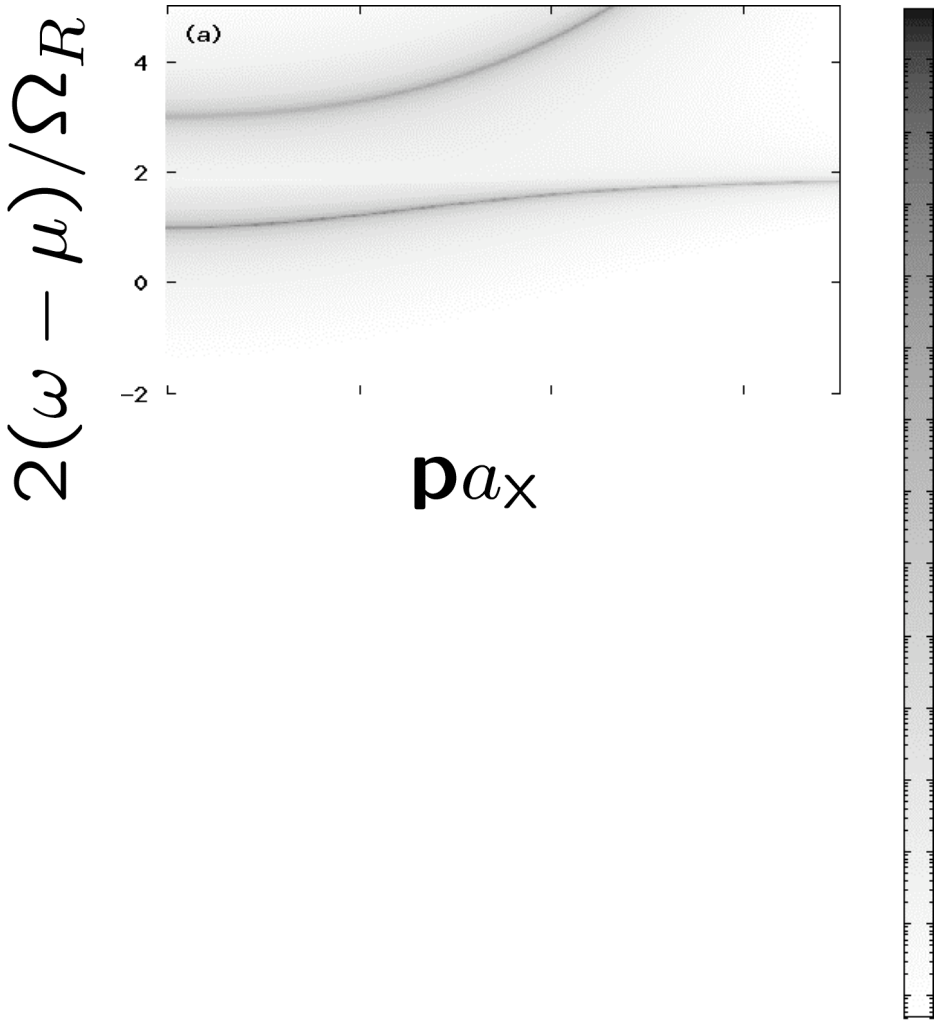
- ✓ Light emission in non-specular scattering directions





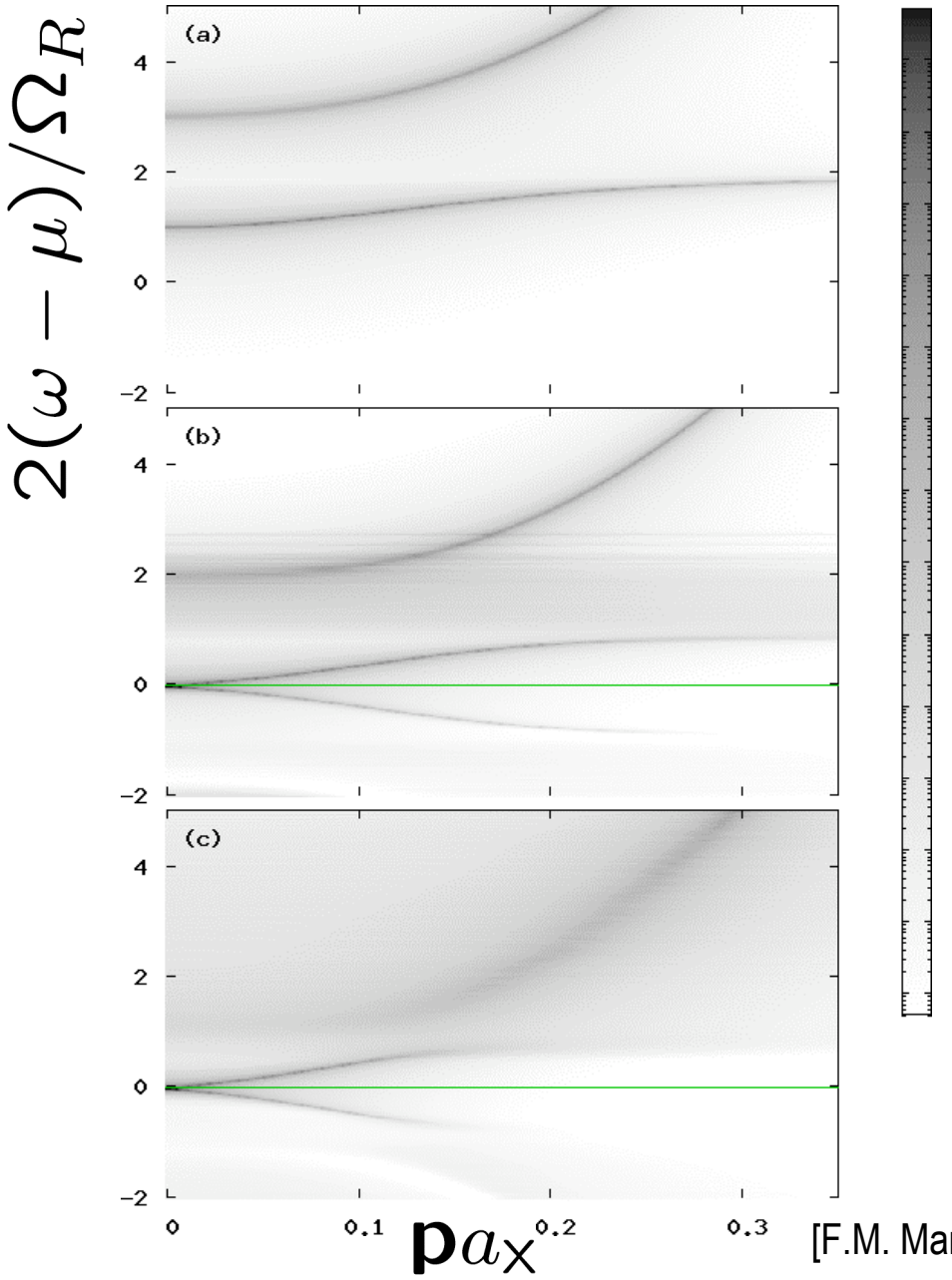
[W. Langbein&J. M. Hvam, *PRL* **88**, 047401 (2002)]

Resonant Rayleigh Scattering



non-condensed

Resonant Rayleigh Scattering



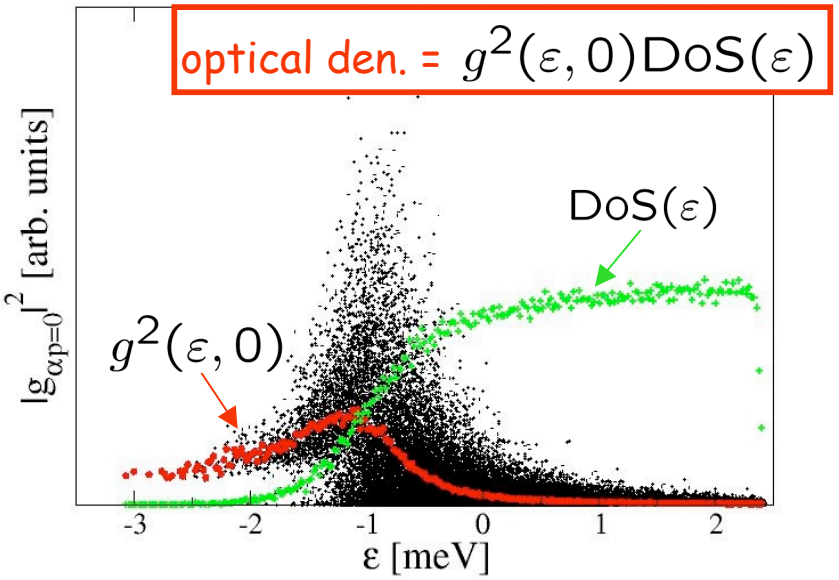
non-condensed

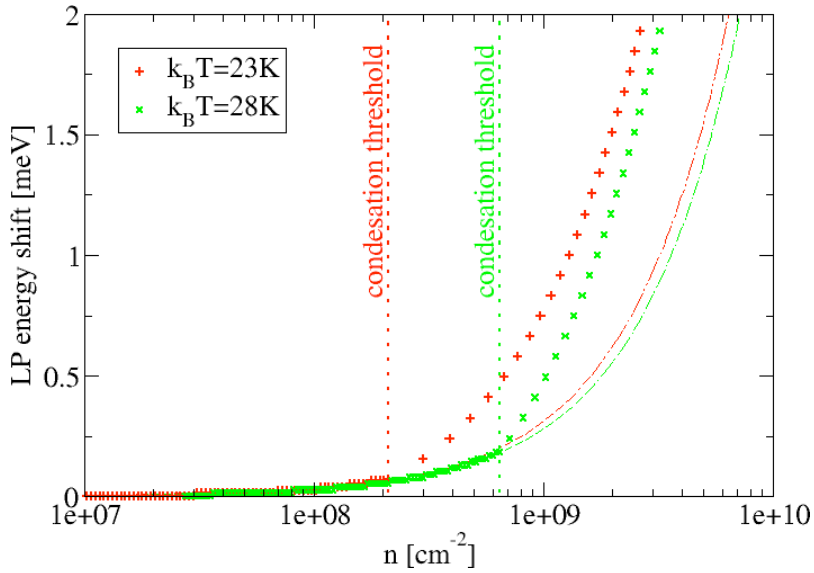
condensed

[F.M. Marchetti *et al.*, *PRL* **96**, 066405 (2006)]

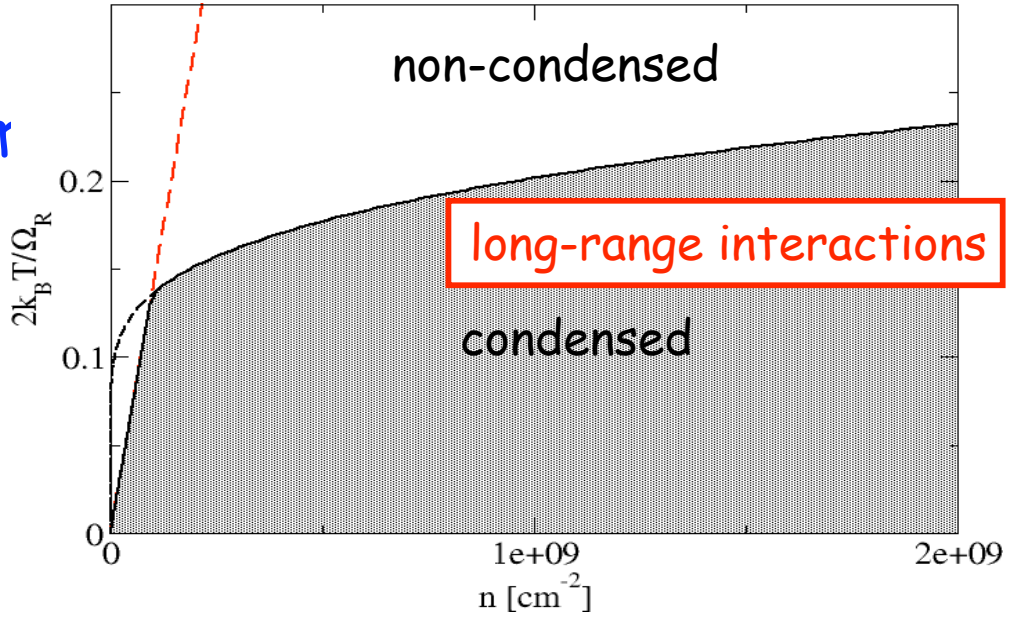
Conclusions

✓ Polaritons in disordered microcavities



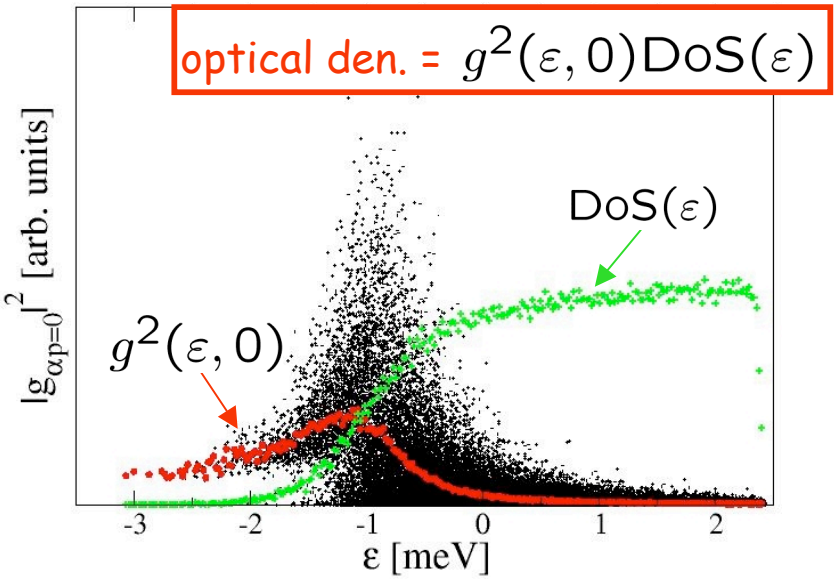


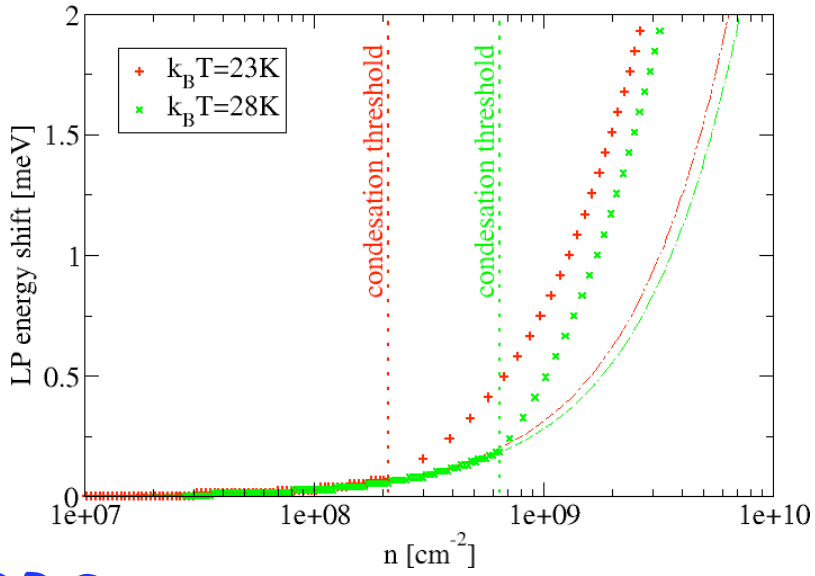
✓ Phase diagram



Conclusions

✓ Polaritons in disordered microcavities





✓ Probing the condensed state: RRS