The Abdus Salam International Centre for Theoretical Physics
50th Anniversary 1964–2014

2583-3

Workshop on Coherent Phenomena in Disordered Optical Systems

26 - 30 May 2014

Disorder Effects on Microcavity Polaritons: an Overview

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Disorder Effects on Microcavity Polaritons: an Overview

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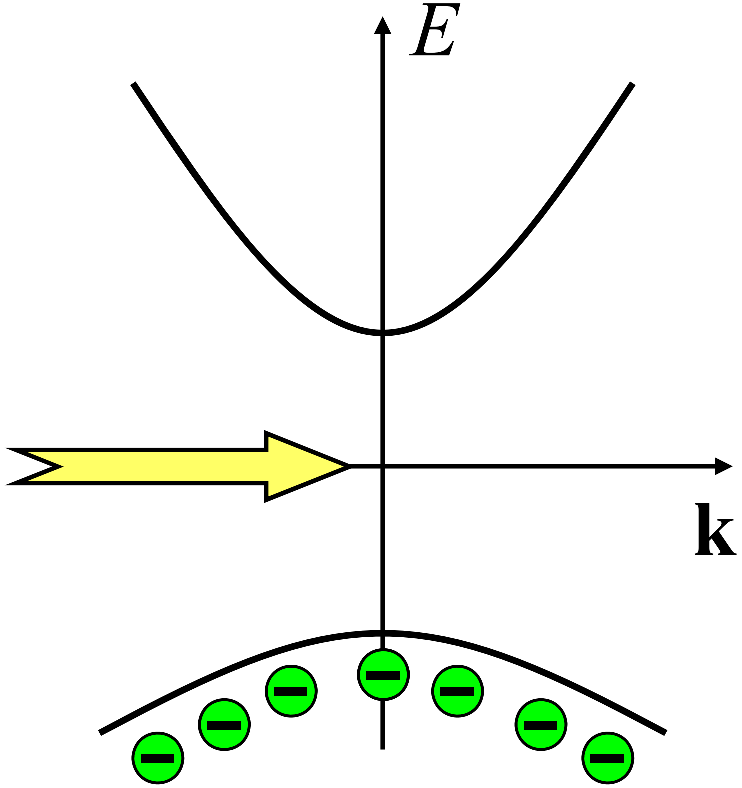
Outlook

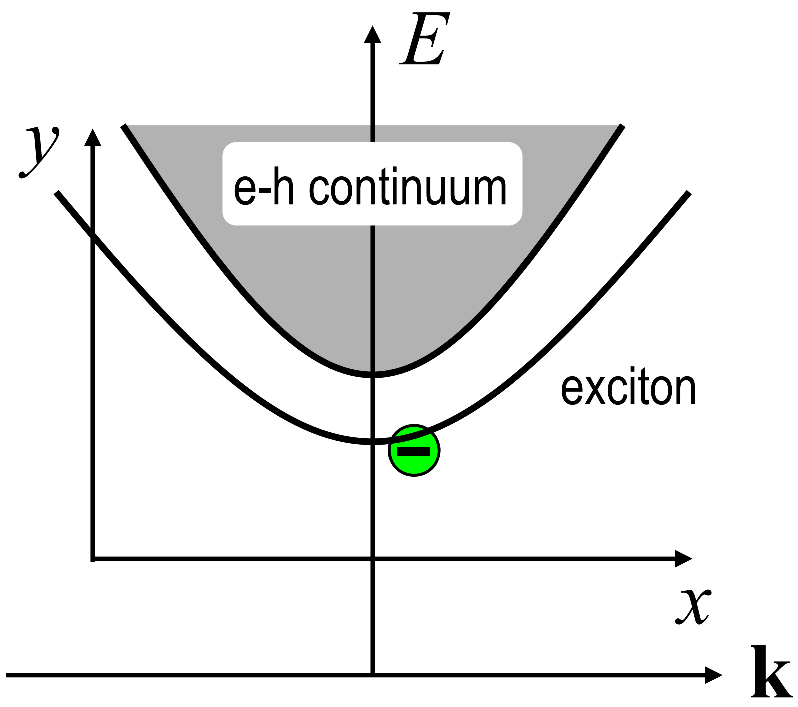
- **Excitons and polaritons: A quick introduction**
- **Disorder and excitons in quantum wells**
- **Disorder and polaritons in microcavities**
- **Disorder and polariton BEC: Some considerations**

V. Savona, J. Phys.: Cond. Mat. **19**, 295208 (2007)

The bibliography of this talk can be found at: **https://www.zotero.org/groups/savonatrieste**

Excitons in semiconductors



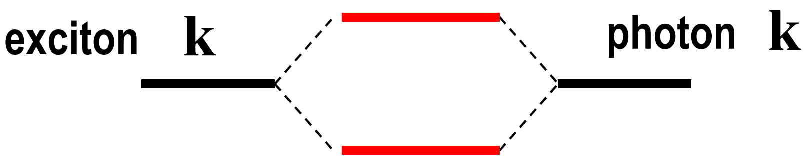


One-particle picture

Two-particle picture

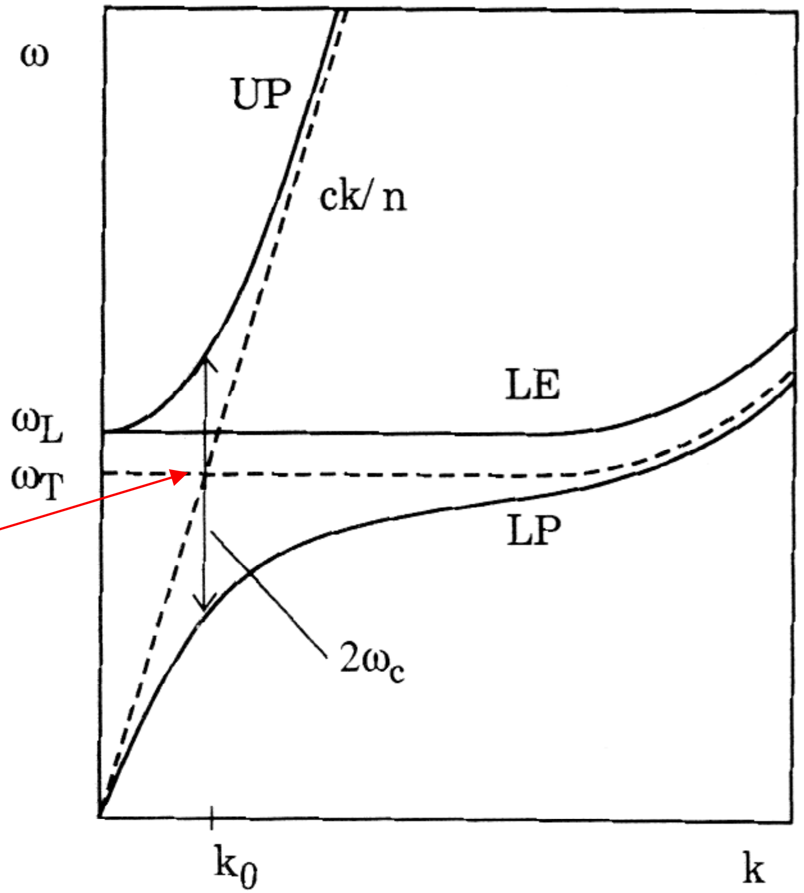
Polaritons in 3-D semiconductors

Linear exciton-photon coupling, momentum conserving



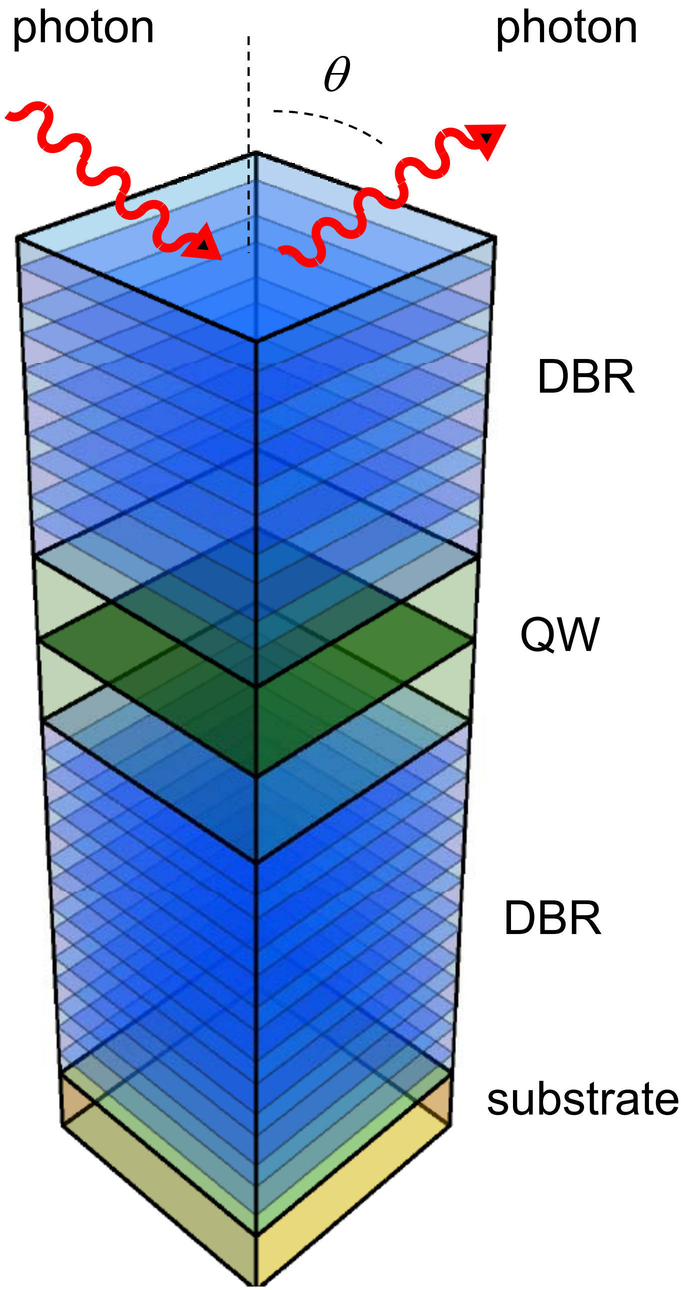
Polaritons as normal modes of the coupled system

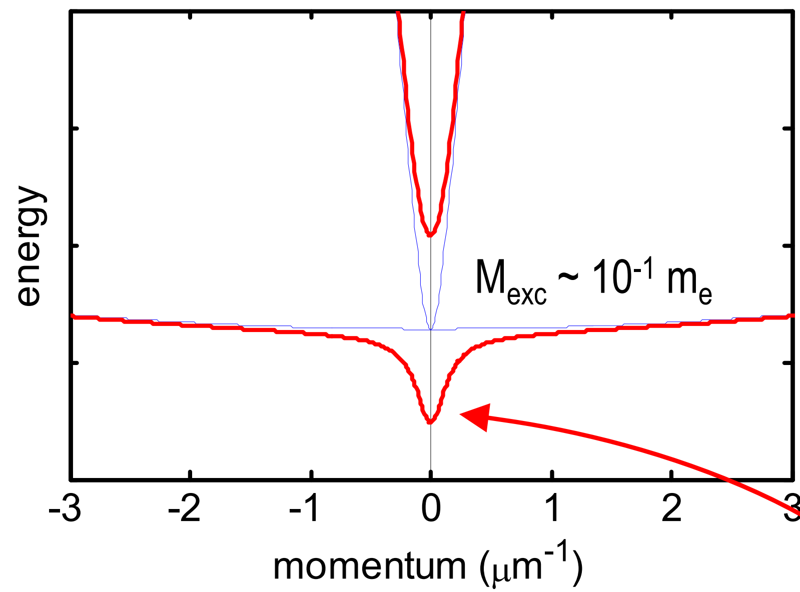
$$|\text{polariton}\rangle = \frac{1}{\sqrt{2}}\left(|\text{photon}\rangle \pm |\text{exciton}\rangle\right)$$



J. J. Hopfield, Phys. Rev. **112**, 1555 (1958)

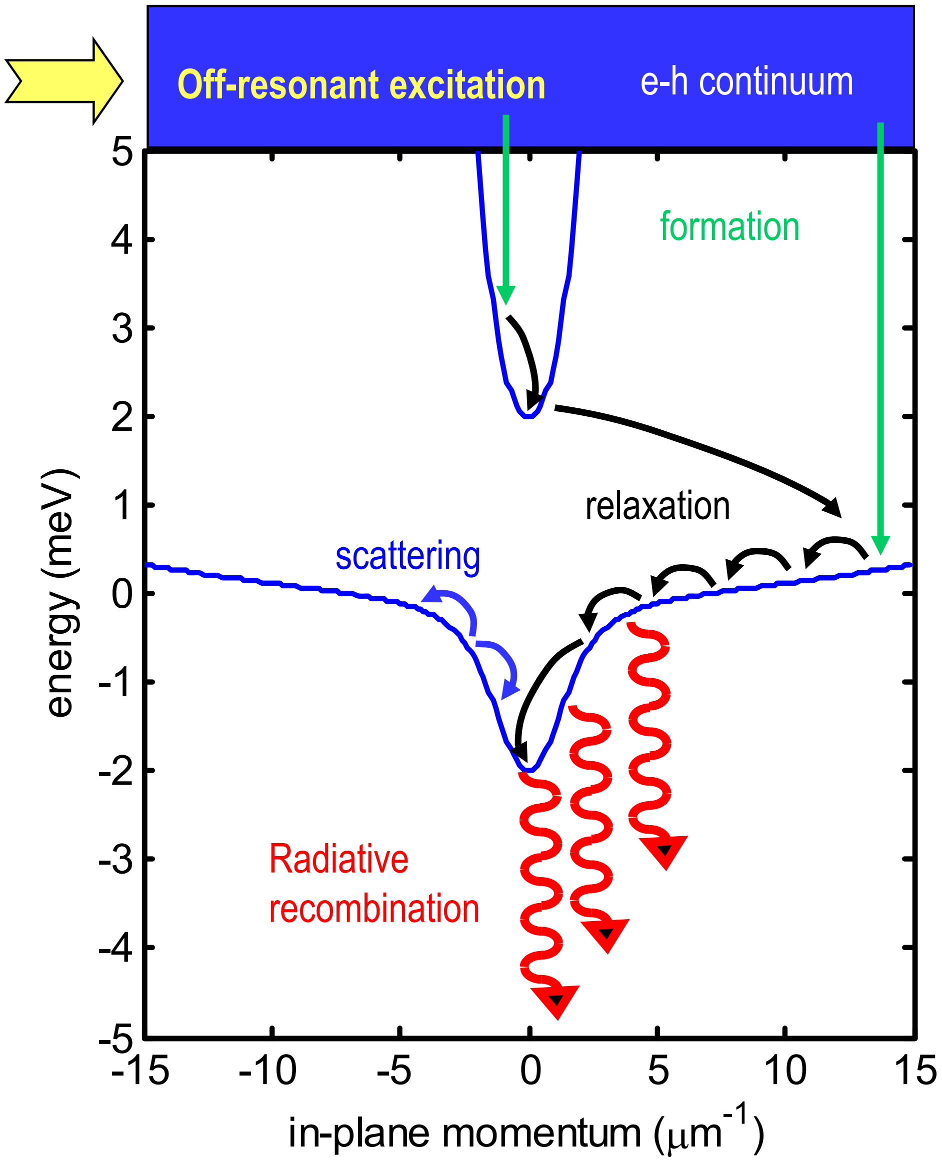
Polaritons in 2-D semiconductor microcavities



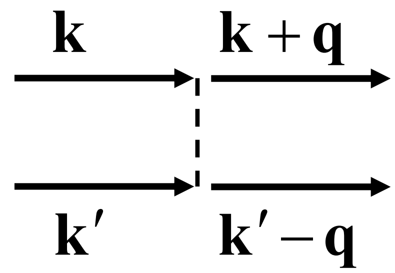


- Optical generation and detection: $k = \dfrac{\omega}{c} \sin\theta$
- Radiative lifetime: ~ 10 ps
- Very light effective mass $M_{pol} \sim 10^{-5}\ m_e$
- Polaritons are Bose particles (low density)
- Polaritons have spin (S=1) and a polarization vector

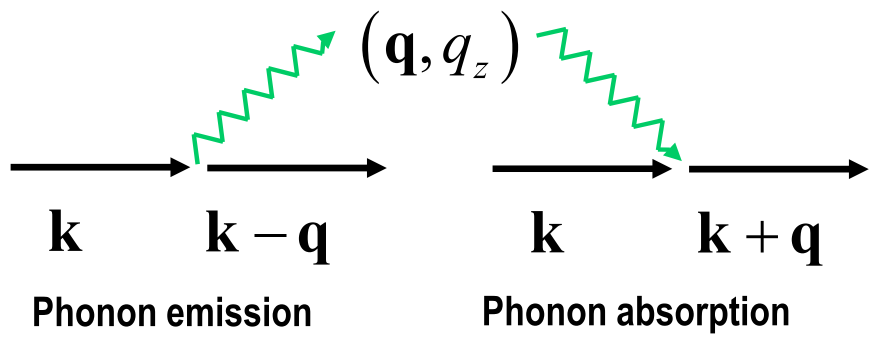
Polariton off-resonant excitation and kinetics



- Polariton-polariton scattering



- Scattering with thermal bath of phonons



Driven-dissipative regime: always (a bit) out of thermal equilibrium

No transport measurements: Mostly optical spectroscopy

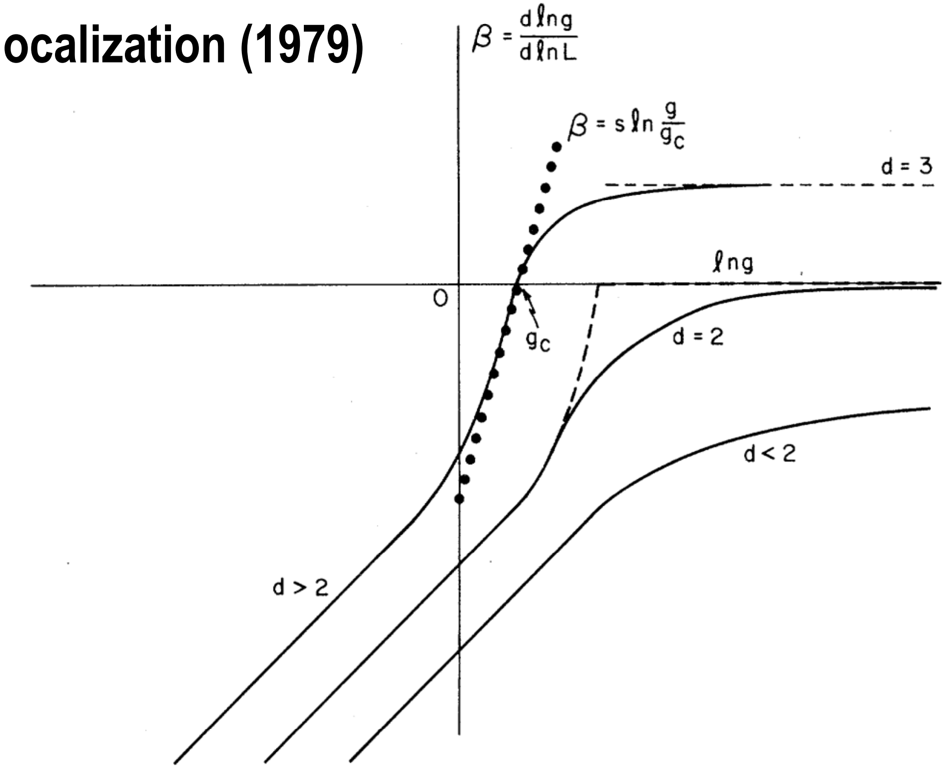
Disorder and dimensionality

Anderson one-parameter scaling theory of localization (1979)

E. Abrahams et al., PRL **42**, 673 (1979).

$g(L)$: **dimensionless conductance**

$$\beta = \frac{d\ln(g(L))}{d\ln(L)}$$: **scaling function**



Losses and dephasing: finite phase coherence length. Diffusive behaviour?

P. W. Anderson et al., PRL **43**, 718 (1979)
B. Altshuler et al., PRB **22**, 5142 (1980)

Many-body interactions: Effective metal-insulator transition?

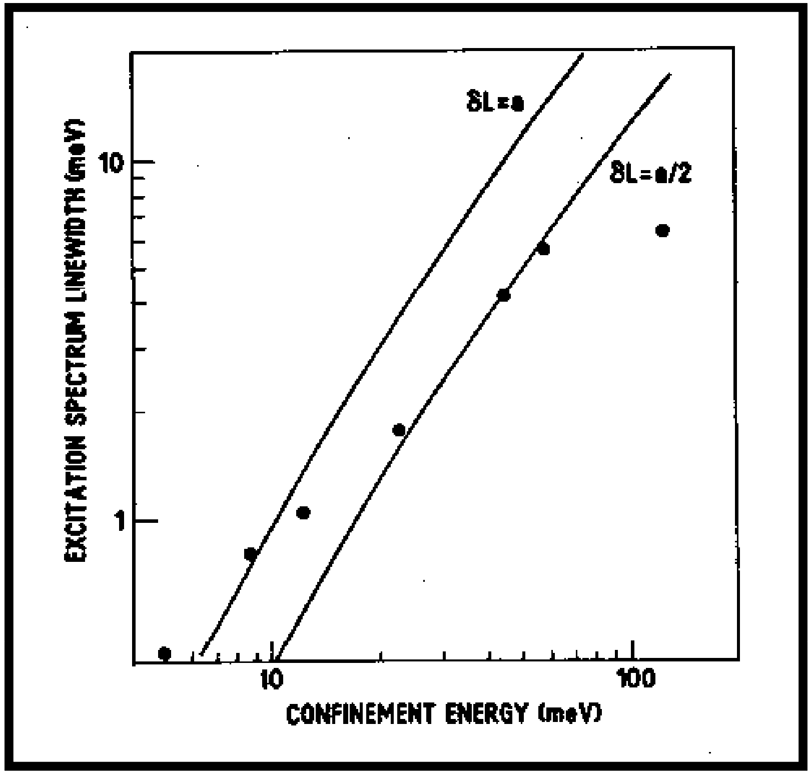
A. Punnoose et al., Science **310**, 289 (2005)
D. Basko et al., Annals of Physics **321**, 1126 (2006)

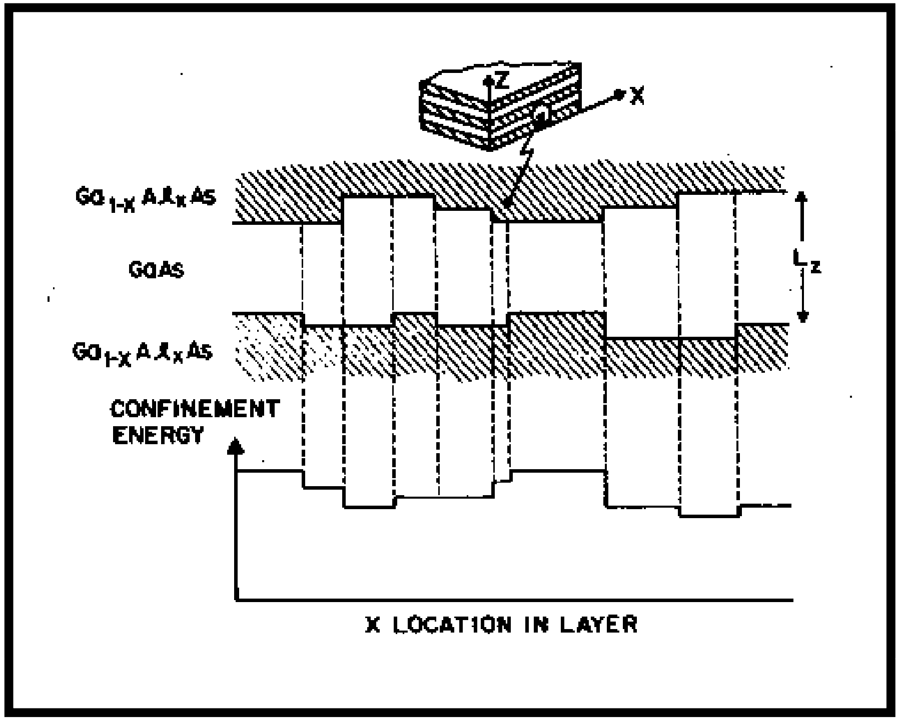
Disorder effects on excitons in quantum wells

For a review:
R. Zimmermann, E. Runge, and V. Savona,
in *Quantum Coherence, Correlation, and Decoherence in Semiconductor Nanostructures*
Ed. T. Takagahara (Academin Press, New York, 2003) p 89

Inhomogeneous broadening of the exciton spectrum

C. Weisbuch et al.,
Solid State Commun. **38**, 709 (1981)



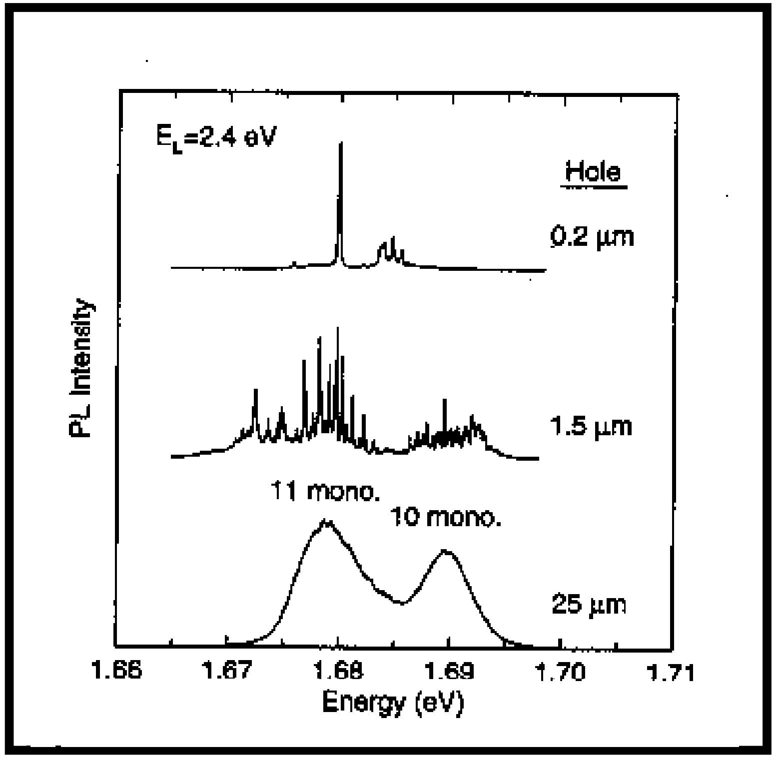


Well-width fluctuations are responsible for inhomogeneous line broadening, which dominates the optical spectra of narrow QWs

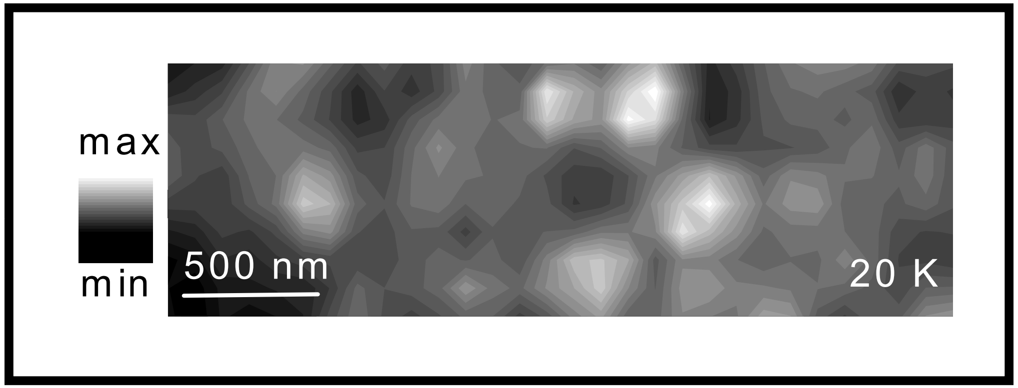
$$\delta E_{conf} \sim \frac{\pi^2\hbar^2}{2M}\frac{\delta L}{L^3}$$

Microscopic exciton spectra

Nano apertures on metal film:
PL spectrum
D. Gammon et al., PRL **76**, 3005 (1996)



NSOM-spectroscopy:
Spectrally-integrated PL
F. Intonti et al., PRL **87**, 076801 (2001)

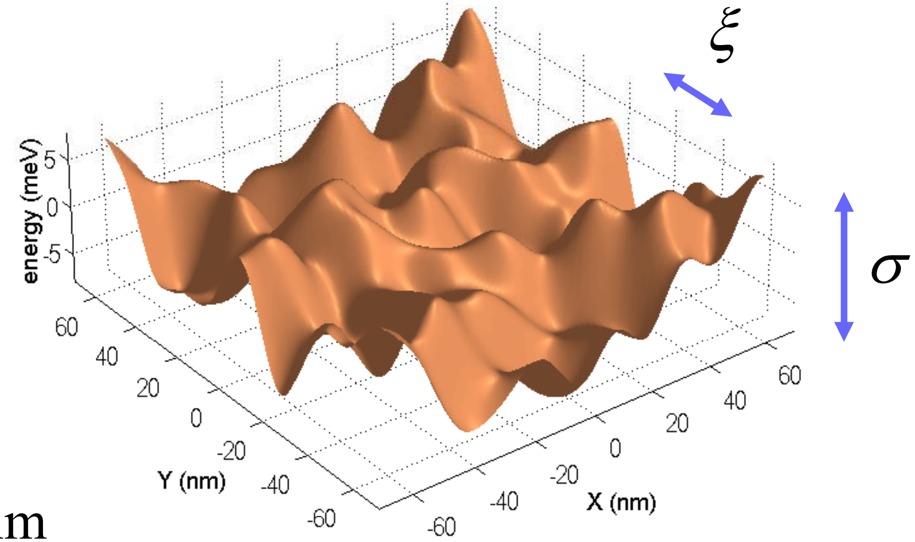


Effective COM potential

Effective COM Schrödinger equation

$$\left(-\frac{\hbar^2}{2M}\nabla^2_{\mathbf{R}} + V(\mathbf{R})\right)\psi_\alpha(\mathbf{R}) = \varepsilon_\alpha \psi_\alpha(\mathbf{R})$$

$$\langle V(\mathbf{R})V(\mathbf{R}')\rangle = \sigma^2 \exp\left[-\frac{(\mathbf{R}-\mathbf{R}')^2}{2\xi^2}\right]$$

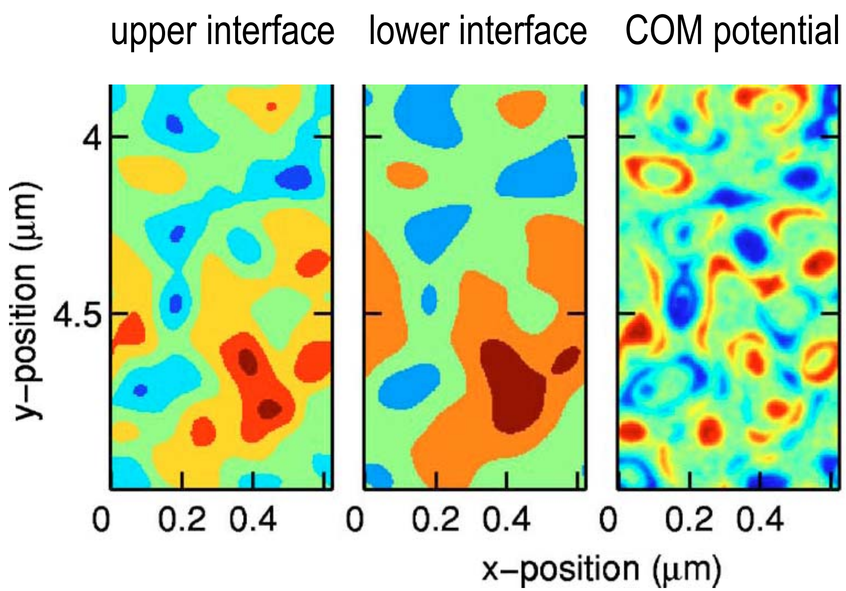


Typically $\sigma \simeq 0.1 \div 1\,\text{meV},\ \xi \simeq 10 \div 50\,\text{nm}$

Some sample-specific features may require a more detailed model

Example: monolayer island formation on growth-interrupted GaAs/AlAs interfaces.

V. Savona and W. Langbein, PRB **74**, 075311 (2006)



Optical density (absorption spectrum)

Density of states:

$$\rho(\varepsilon) = \frac{1}{A}\sum_{\alpha}\delta(\varepsilon - \varepsilon_{\alpha})$$

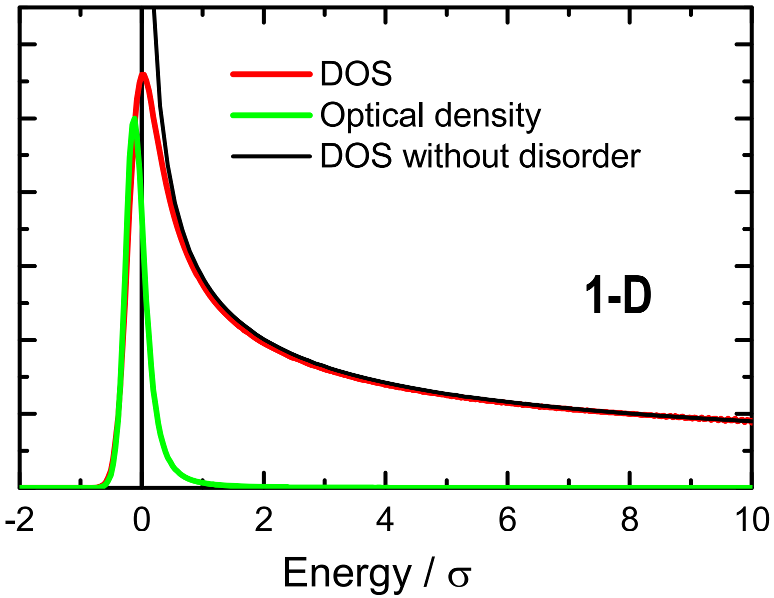
Optical density:

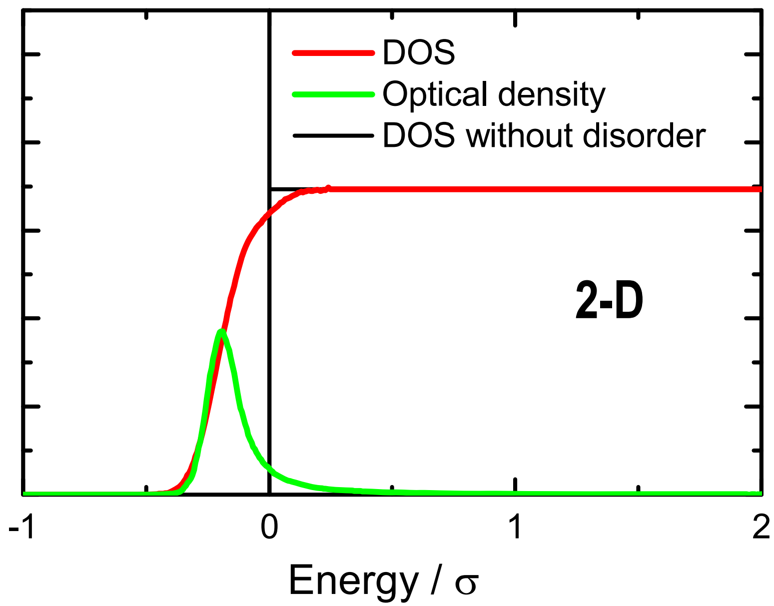
$$D(\varepsilon) \propto \sum_{\alpha}\left|\langle \Psi_{\alpha} | H_{dip} | 0 \rangle\right|^{2}\delta(\varepsilon - \varepsilon_{\alpha})$$

$$= \frac{1}{A}\sum_{\alpha} M_{\alpha}^{2}(k_z, \mathbf{k}_{\parallel} = 0)\,\delta(\varepsilon - \varepsilon_{\alpha})$$

Transition matrix element:

$$M_{\alpha}(\mathbf{k}) \equiv \mu_{cv}\varphi_{1s}(0)\,O_{eh}(k_z)\int d^2R\, e^{i\mathbf{k}_{\parallel}\cdot\mathbf{R}}\,\psi_{\alpha}(\mathbf{R})$$





Scaling properties of the Schrödinger equation

$$\mathbf{R} \to \mathbf{R}/\xi$$
$$\varepsilon \to \varepsilon / E_c$$
$$V \to V / E_c$$

$$\left[-\nabla^2 + V(\mathbf{R})\right]\psi(\mathbf{R}) = \varepsilon\psi(\mathbf{R})$$

$$E_c = \frac{\hbar^2}{2M\xi^2}$$

Scaling parameter: σ / E_c

$$\to 0 \quad \textbf{White-noise limit}$$
$$\to \infty \quad \textbf{Classical limit}$$

White-noise limit: only one relevant energy scale:

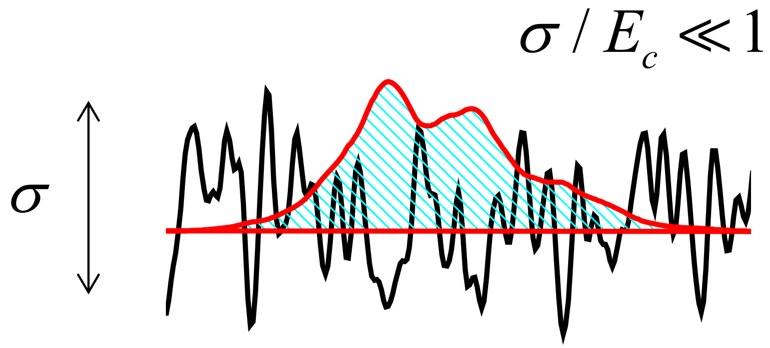
$$\left\langle V(\mathbf{R})V(\mathbf{R}')\right\rangle = w\delta(\mathbf{R}-\mathbf{R}')$$

$$E_0 = \frac{2Mw}{\hbar^2}$$

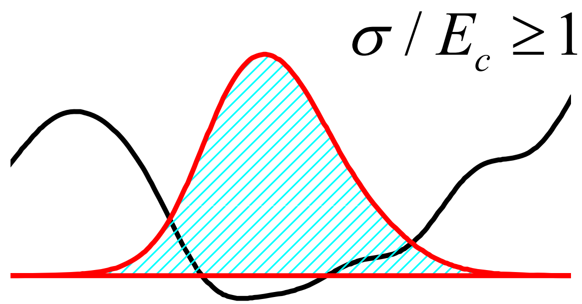
For a realistic potential close to the white-noise limit:

$$E_0 = 2\pi\sigma\left(\frac{\sigma}{E_c}\right)$$

Motional narrowing



Short-range potential: WFs average the energy fluctuations

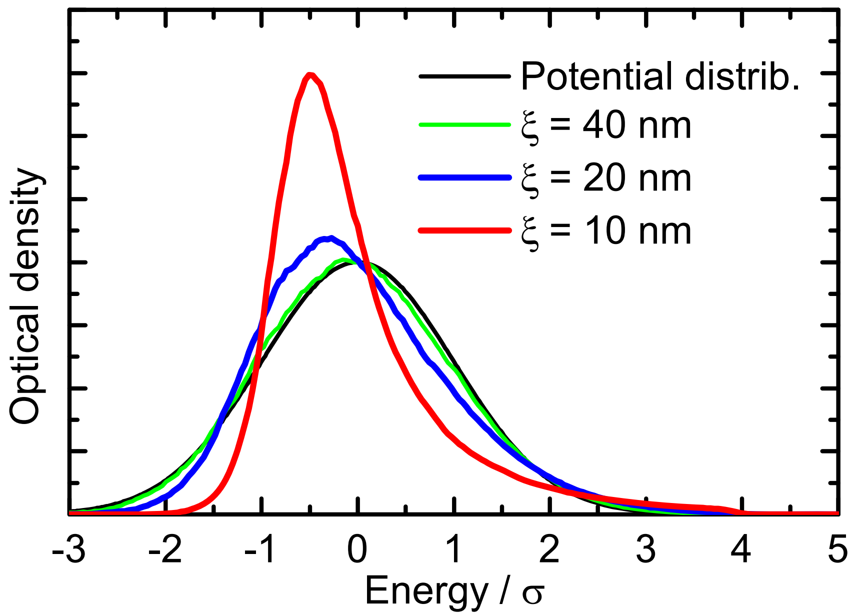


Long-range disorder is well sampled by WFs

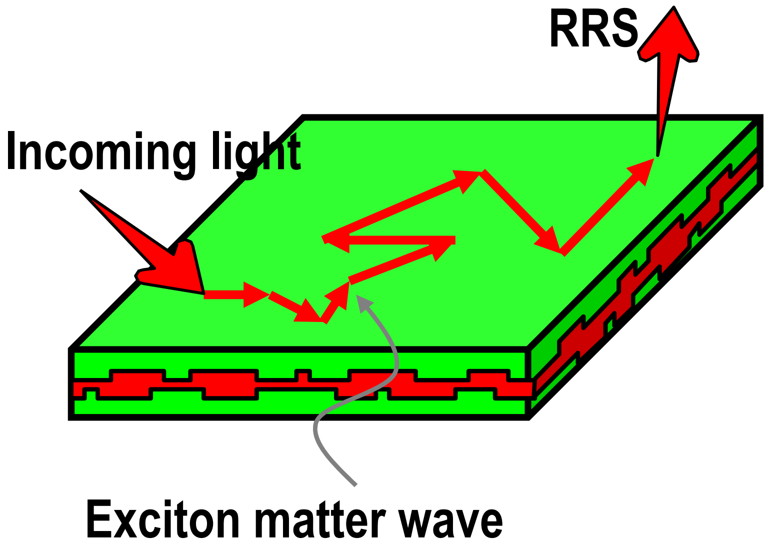
Potential distribution:

$$P(E) = \frac{1}{A} \int d\mathbf{R}\, \delta\left(E - V(\mathbf{R})\right)$$

In the classical limit (long correlation length, large σ, or large mass) it is proportional to the optical density

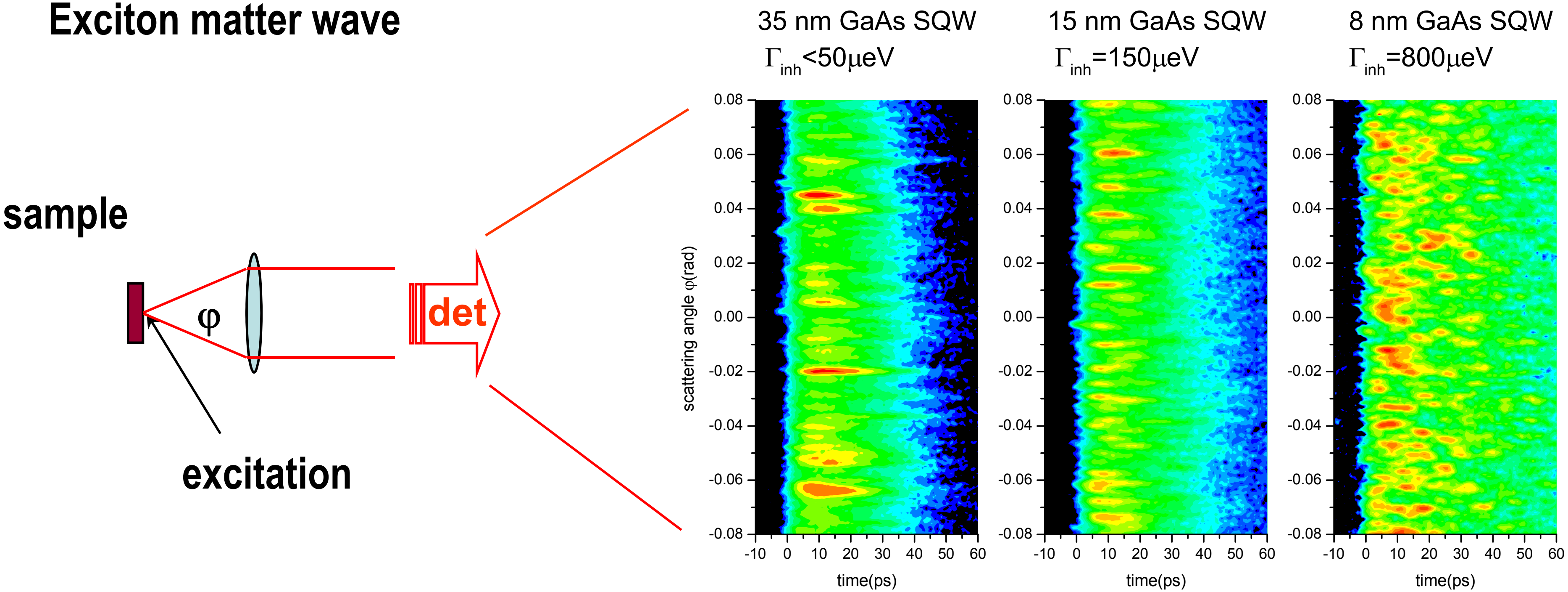


Resonant Rayleigh scattering



Momentum not conserved in linear optical response:
Linear resonant response at all angles.
RRS carries information about disorder and localization

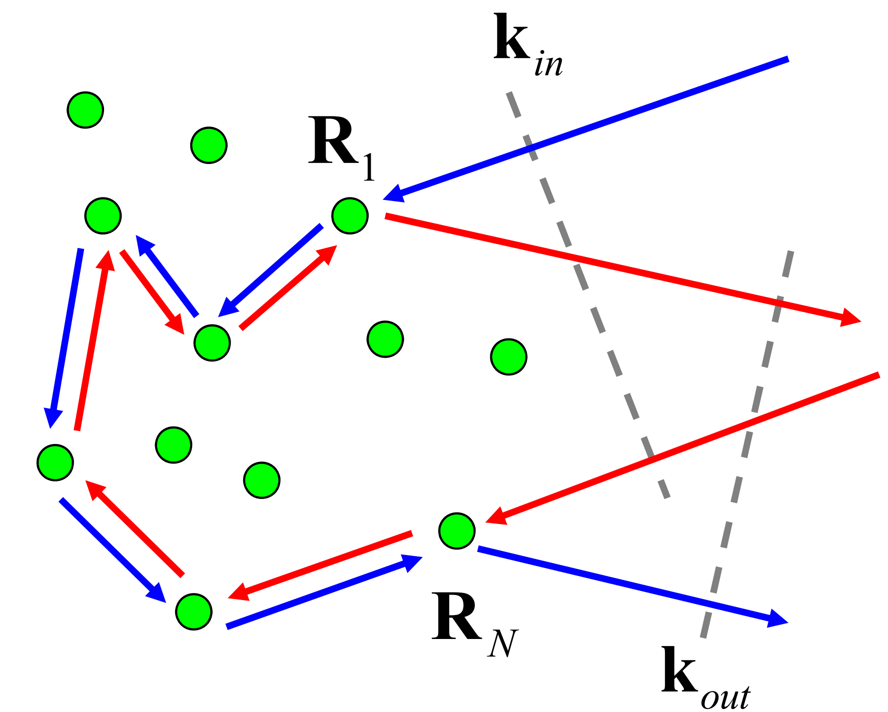
See: V. Savona, J. Phys.: Cond. Mat. **19**, 295208 (2007)
V. Savona and W. Langbein, PRB **74**, 075311 (2006)



From: W. Langbein et al., PRL **82**, 1040 (1999)

θ=0.07rad, T=5K, timeresolution 3ps, 2 orders of magnitude color scale

Enhanced backscattering



$$\left|E_1 + E_2\right|^2 = I\left[1 + \cos\left(\mathbf{q}\cdot\left(\mathbf{R}_1 - \mathbf{R}_N\right)\right)\right]$$

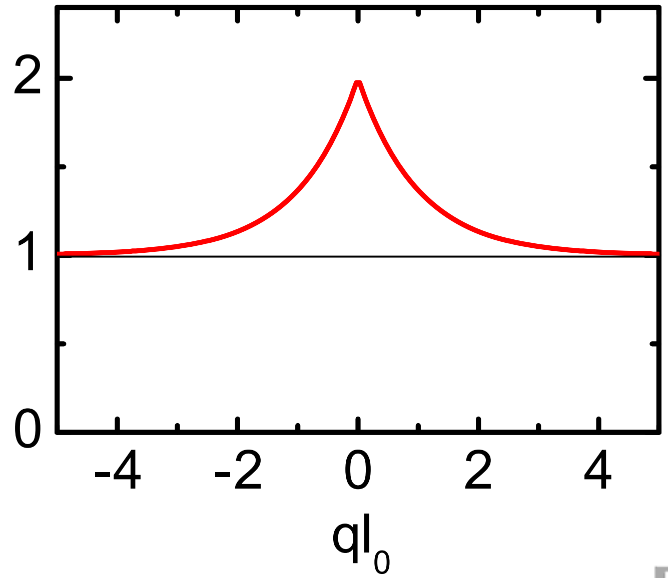
$$\mathbf{q} = \mathbf{k}_{in} + \mathbf{k}_{out}$$

$$q\,l_0 \gg 1 \;\rightarrow\; I$$

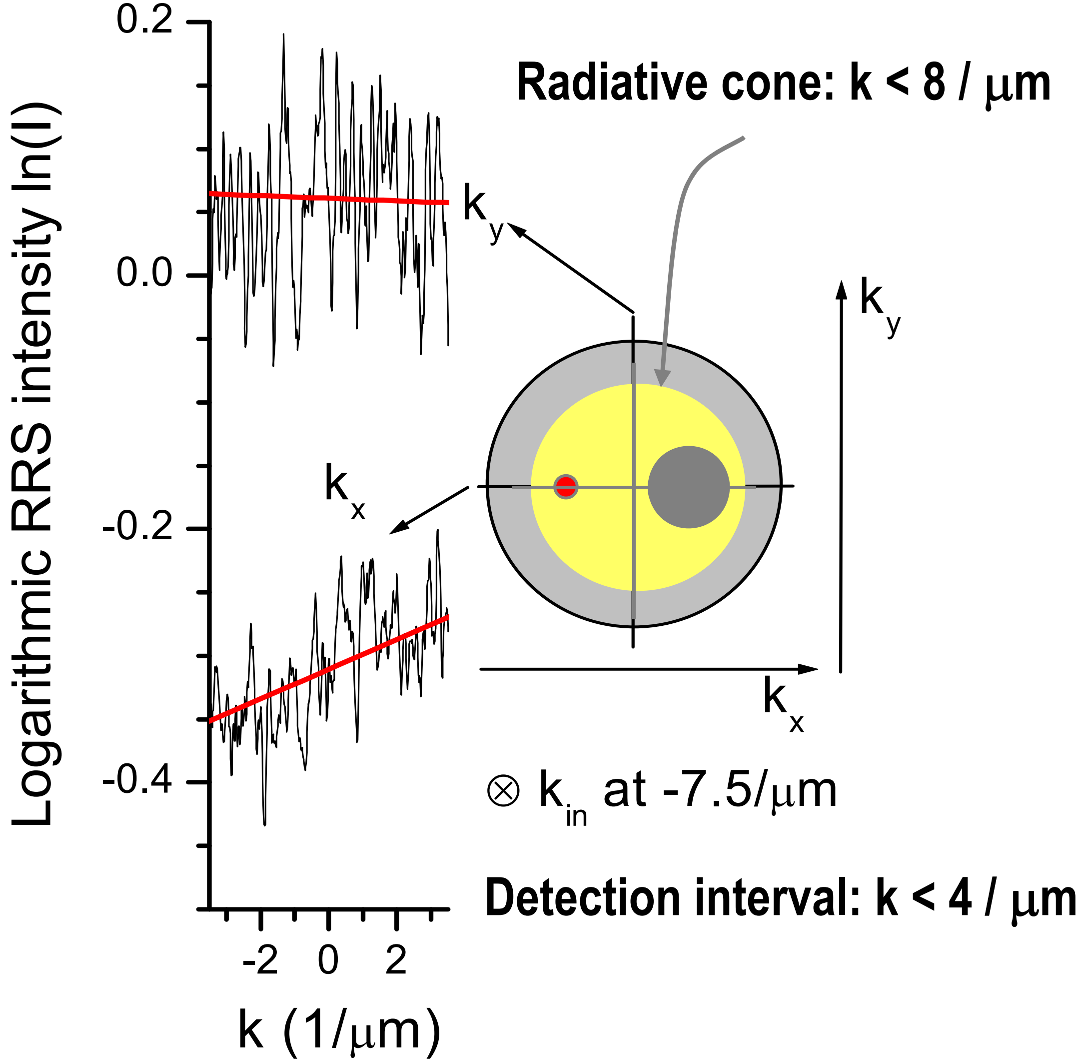
$$q\,l_0 \ll 1 \;\rightarrow\; 2I$$

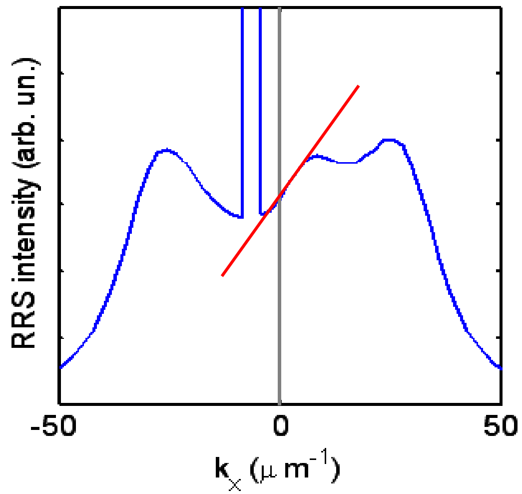
l_0: Mean free path

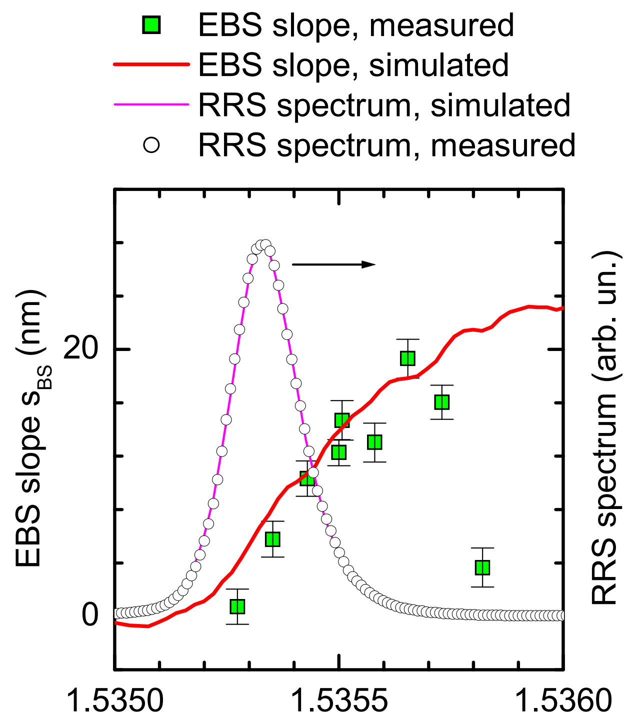
- **Enhancement by a factor 2, if single-scattering events do not contribute**
- **Argument does not apply if $\mathbf{k}l_0 \ll 1$**



Enhanced backscattering of the exciton wavefunction







V. Savona et al., PRB **62**, R4805 (2000)
W. Langbein et al., PRL **89**, 157401 (2002)

Disorder effects on polaritons in planar MCs

For a review:
V. Savona, J. Phys.: Cond. Mat. **19**, 295208 (2007)

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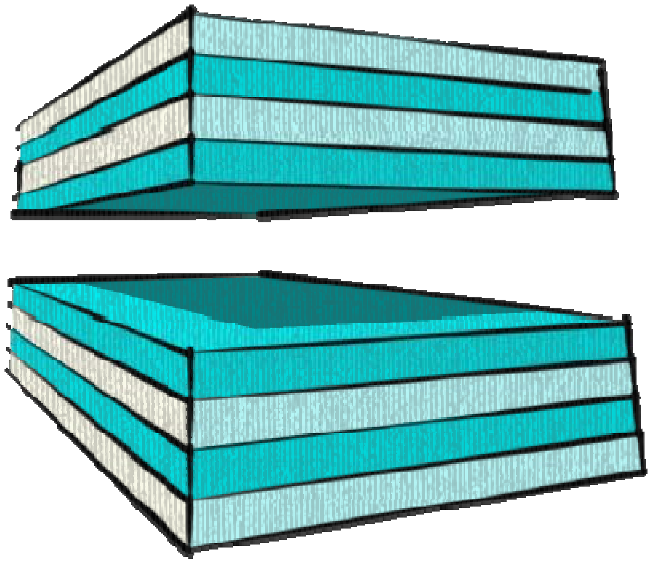
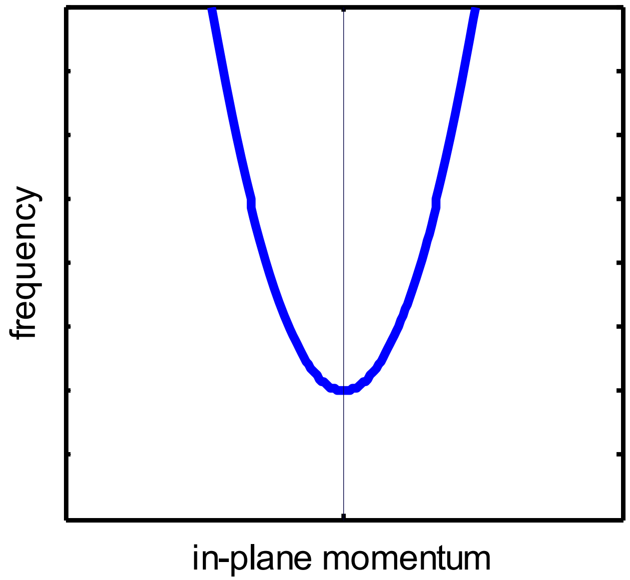
Motional narrowing in a semiconductor microcavity



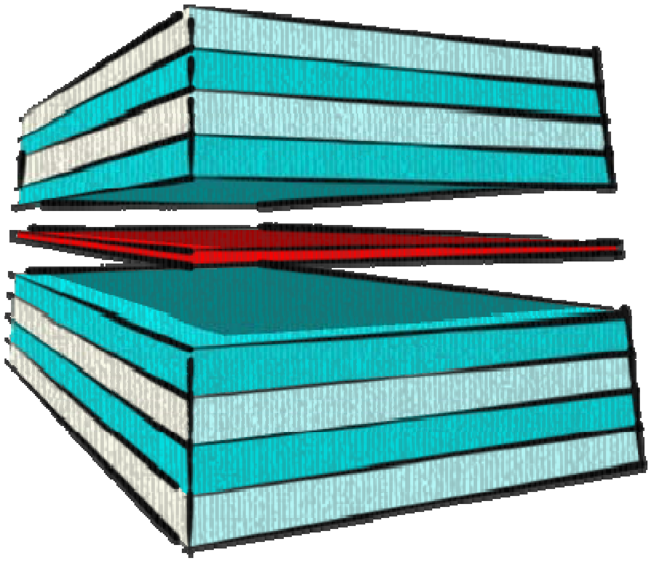


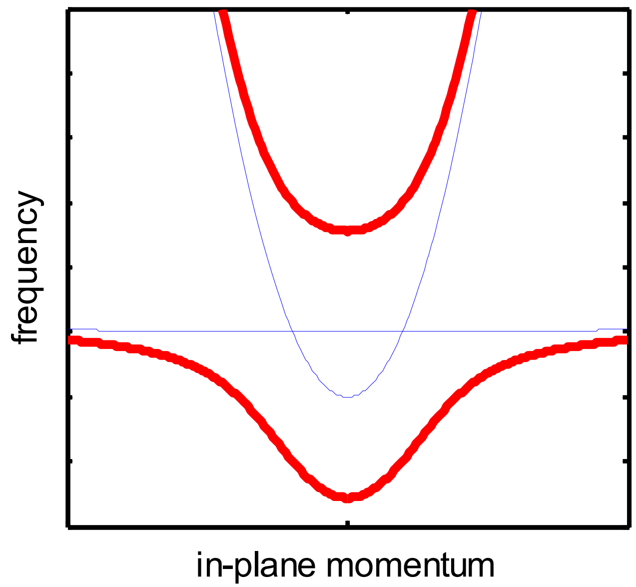
$$\frac{\sigma}{E_c^{s-r}} \sim 10^{-4}$$

: Short-range disorder does not affect the e-m field

Same for polaritons?

Motional narrowing for polaritons?





Non-parabolic dispersion of the LP: Scaling no longer applies!

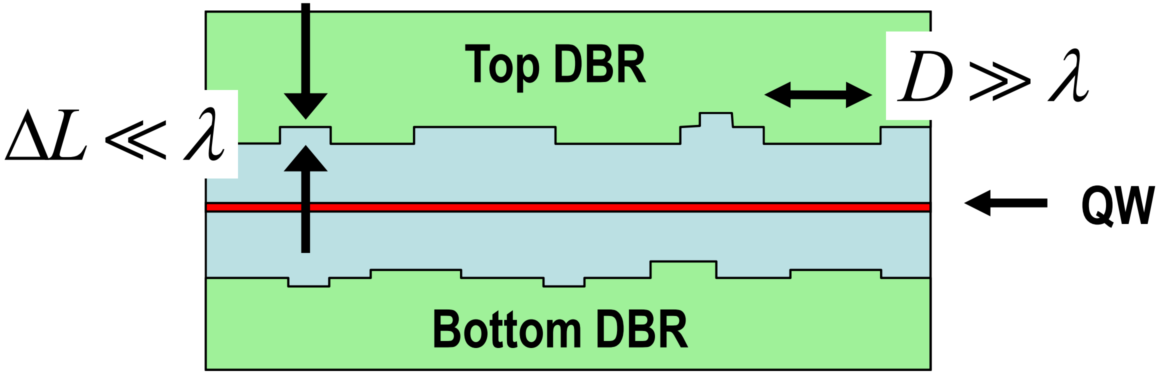
See: D. Whittaker et al., PRL **77**, 4792 (1996)
D. Whittaker, PRL **80**, 4791 (1998)
C. Ell. et al., PRL **80**, 4795 (1998)
V. Savona, J. Phys.: Cond. Mat. **19**, 295208 (2007)

Motional narrowing still present, but quantitatively less effective

Exciton mass is irrelevant (can approximate to infinite mass, i.e. local oscillators)

See: D. Whittaker, PRB **61**, R2433 (2000)
R. Houdré et al., PRA **53**, 2711 (1996)

Model the effect of MC thickness variation



- assume locally planar cavity mode

$$\mathbf{E}(\mathbf{r}) = \mathbf{E}(\boldsymbol{\rho}) \exp\left(i k_z(\boldsymbol{\rho}) z\right)$$

- Maxwell equation results in a Schrödinger-like equation with disorder potential

$$\nabla_\rho^2 \mathbf{E}(\boldsymbol{\rho}) + \left(\frac{\omega^2}{c^2}\varepsilon_0 - k_z^2(\boldsymbol{\rho})\right)\mathbf{E}(\boldsymbol{\rho}) = 0$$

- set $L_c = \lambda_c + \Delta L$ and the resonant frequency variation is

$$\Delta\omega_c = -\omega_c \frac{\Delta L}{\lambda_c + L_{DBR}} \qquad \Delta k_z = \frac{n_c}{c}\Delta\omega_c$$

V. Savona, J. Phys.: Cond. Mat. **19**, 295208 (2007)

Model of polaritons in inhomogeneous systems

- **Maxwell equation with spatial dielectric fluctuations**

$$\nabla_\rho^2 \mathbf{E}(\boldsymbol{\rho}) + \left(\frac{\omega^2}{c^2}\varepsilon_0 - k_z^2(\boldsymbol{\rho}) \right) \mathbf{E}(\boldsymbol{\rho}) + 4\pi \frac{\omega^2}{c^2} \mathbf{P}(\boldsymbol{\rho}) = 0$$

- **Schrödinger equation for the exciton center-of-mass polarization**

$$-\frac{\hbar^2 \nabla_\rho^2}{2M} \mathbf{P}(\boldsymbol{\rho}) + \left(V_X(\boldsymbol{\rho}) + \hbar\omega \right) \mathbf{P}(\boldsymbol{\rho}) + \mu \mathbf{E}(\boldsymbol{\rho}) = 0$$

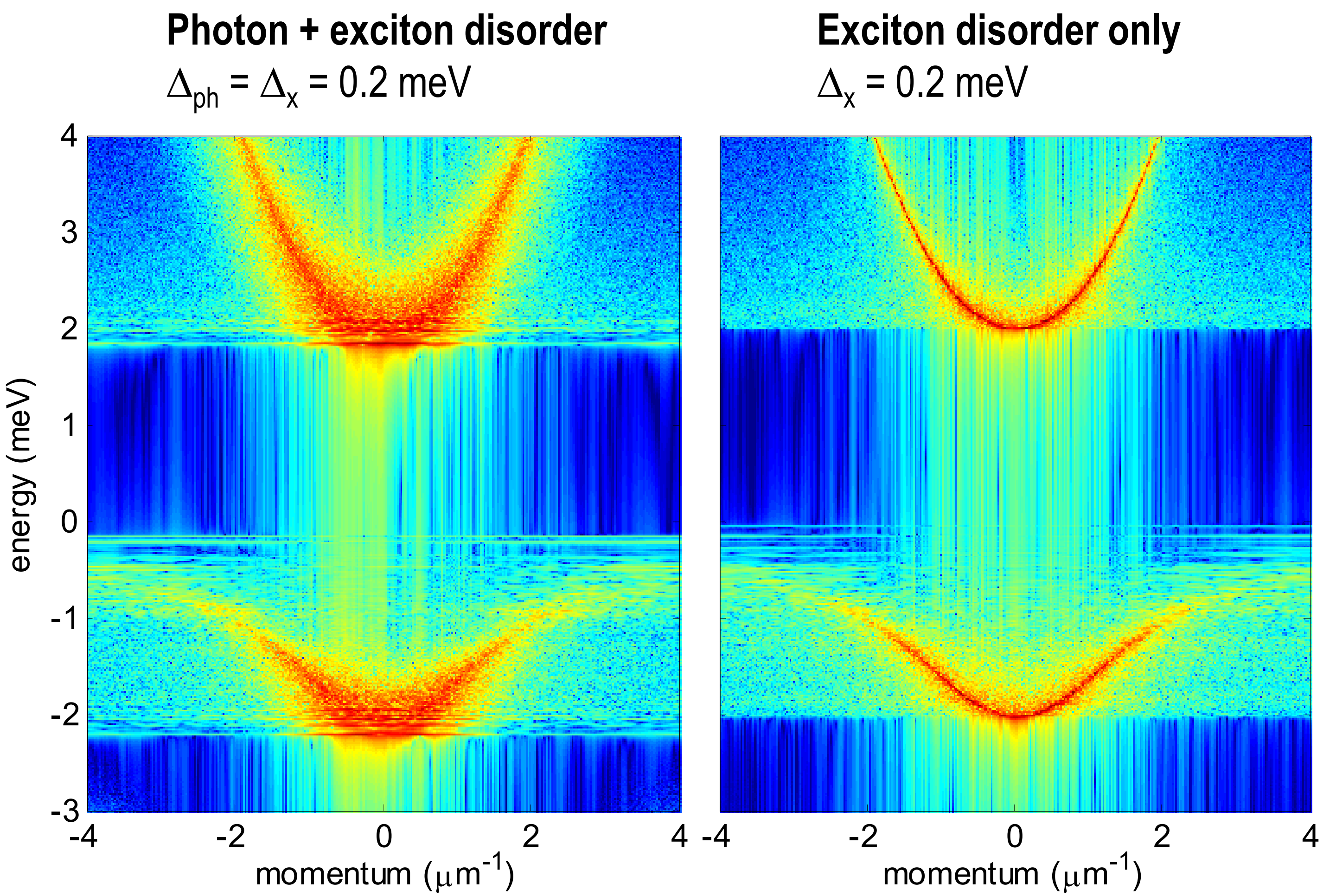
Disorder on photons effective over large length scales: > 1 μm

Disorder on excitons mostly effective over smaller lengths: ~ 10 nm

V. Savona, J. Phys.: Cond. Mat. **19**, 295208 (2007)

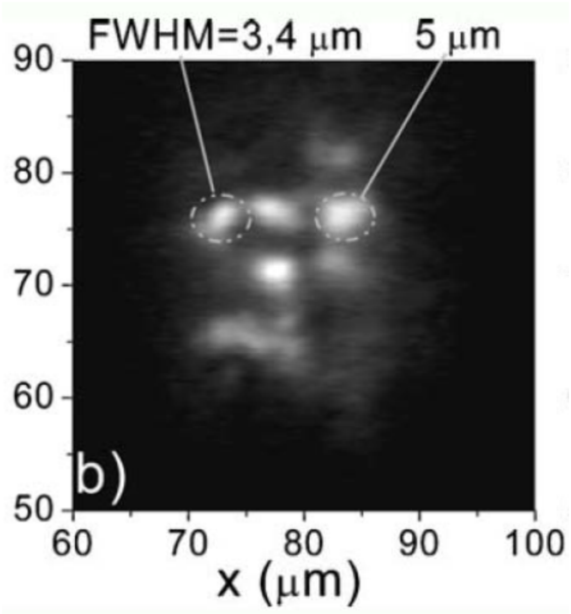
Photon vs exciton disorder

Polariton RRS spectrum mostly affected by photon disorder (long range).
Exciton disorder (short range) has marginal effect in the strong coupling region

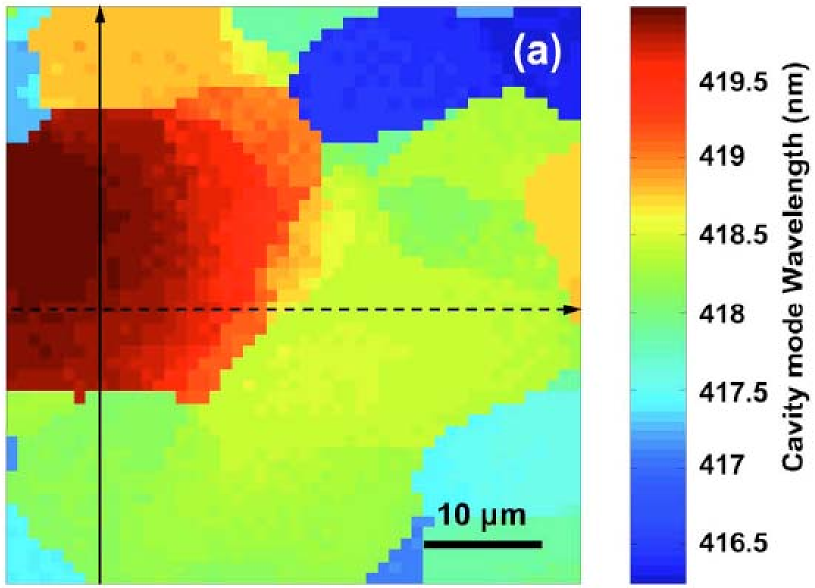


V. Savona, J. Phys.: Cond. Mat. **19**, 295208 (2007)

Long-range disorder in semiconductor MCs



Localized polariton states actually visible in a CdTe-based MC
M. Richard et al., PRB **72,** 201301 (2005)

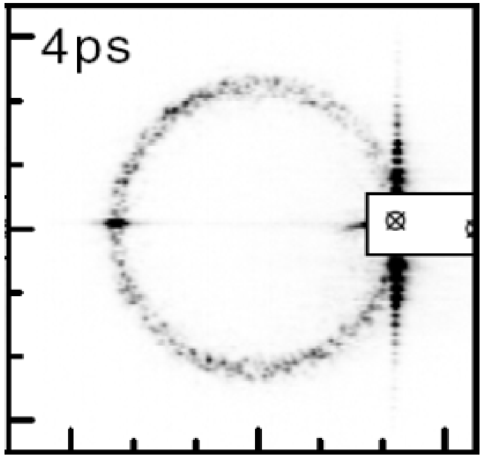


Map of cavity resonant frequency in a GaN-based MC
G. Christmann et al., APL **89,** 261101 (2006)

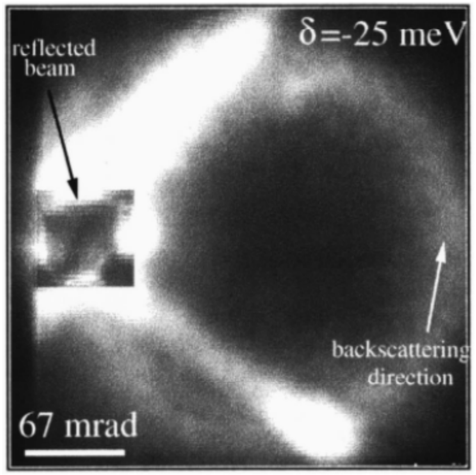
Lower polariton localization length of about 30 micron at the band bottom
W. Langbein and J. M. Hvam, PRL **88** 047401 (2002)

Crosshatch disorder for strained heterostructures

Typical cross-shaped pattern in RRS

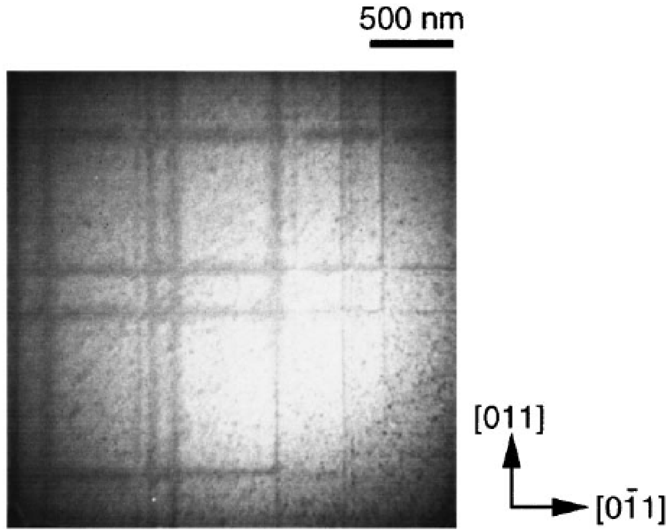


W. Langbein, J. Phys: C. M. **16**, S3645 (2004)

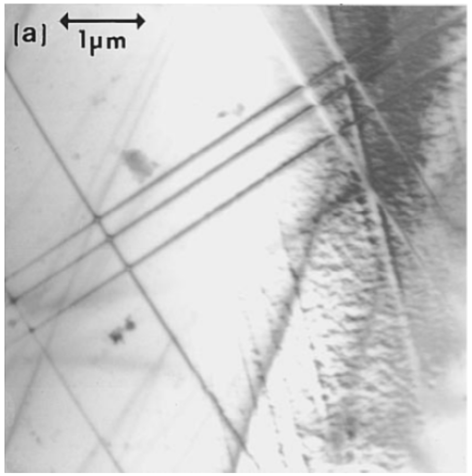


M. Gurioli et al., PRB **64,** 165309 (2001)
See also: M. Abbarchi et al., PRB **85**, 045316 (2012)

Crosshatch defects on strained heterointerfaces



K. Samonji et al., J. Appl. Phys. **86**, 1331 (1999)



C. Lavoie et al., APL **67**, 3744 (1995)

Modeling crosshatch pattern

Crosshatch p
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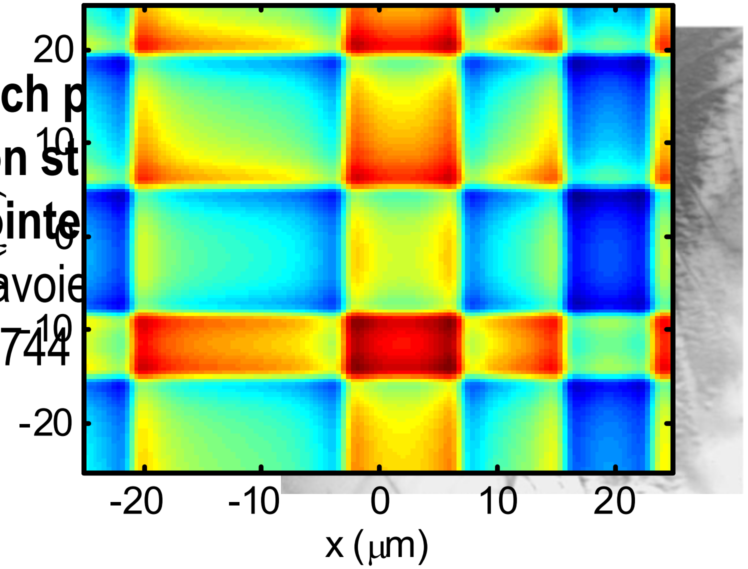
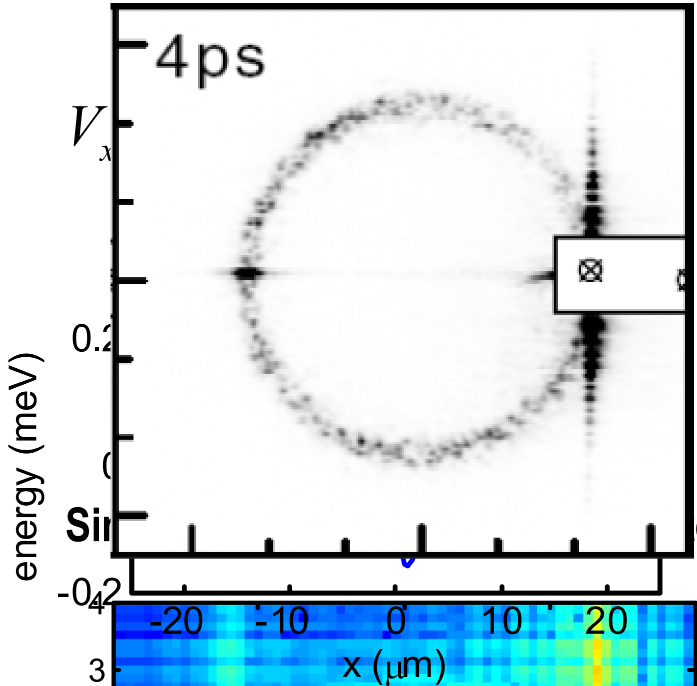
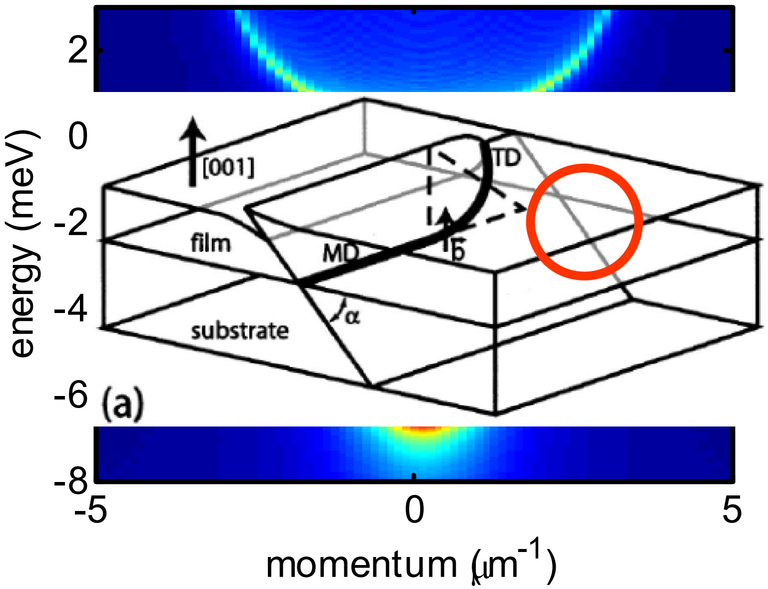
heterointe
From: C. Lavoie
APL **67**, 3744



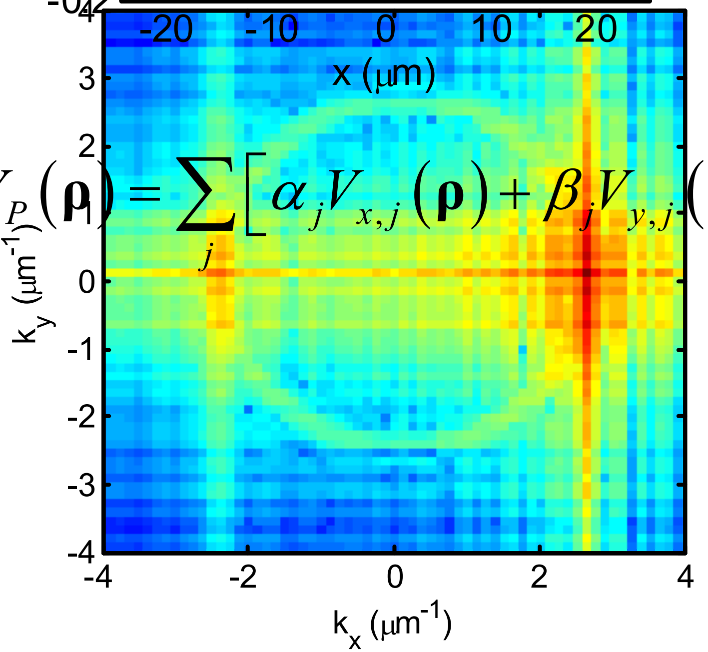
W. Langbein, J. Phys: C. M. **16**, S3645 (2004)

Effective photon crosshatch potential



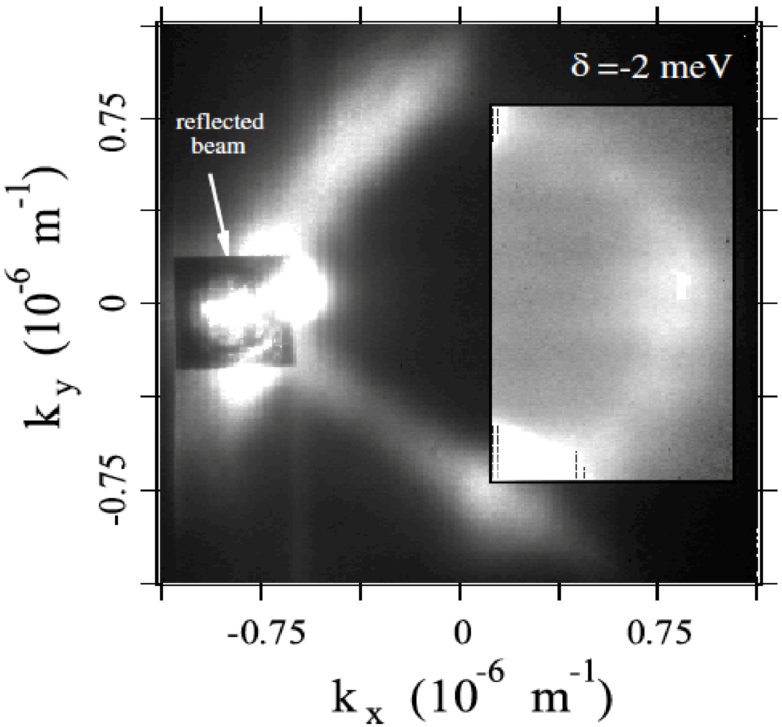


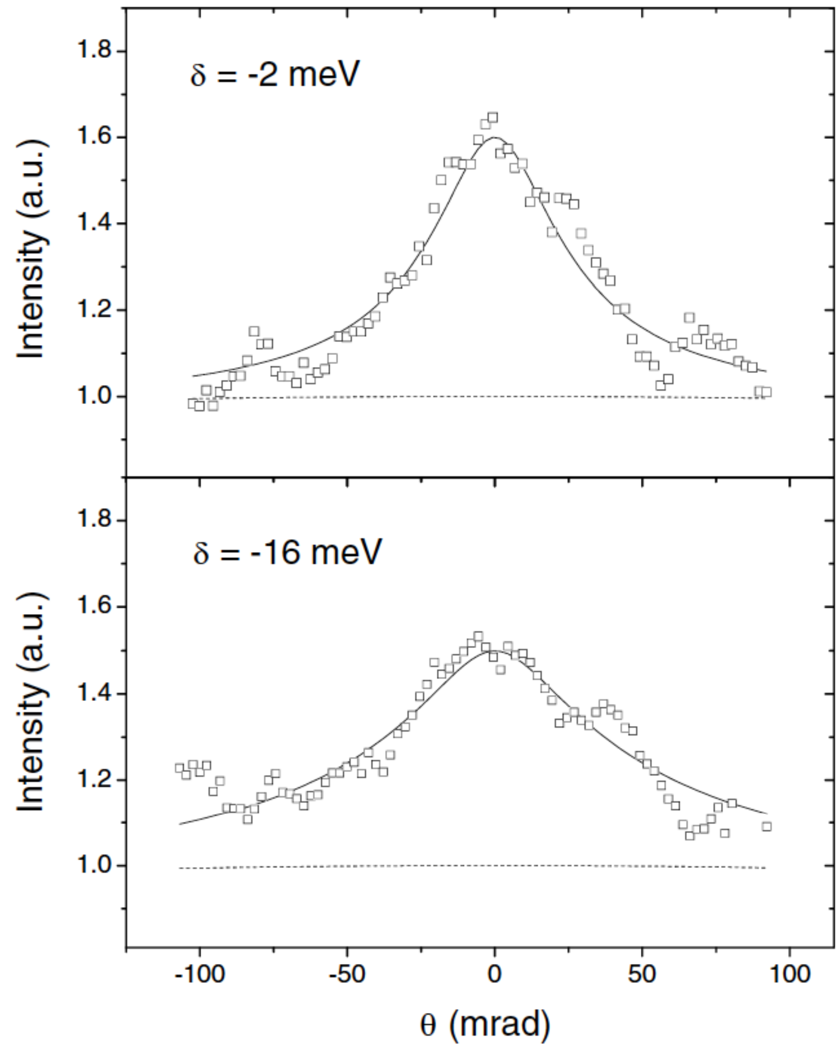
$$V_P(\boldsymbol{\rho}) = \sum_j \left[\alpha_j V_{x,j}(\boldsymbol{\rho}) + \beta_j V_{y,j}(\boldsymbol{\rho})\right]$$



Weak localization and polariton enhanced backscattering

In addition to crosshatch feature, angle-resolved resonant scattering shows enhanced backscattering, typical of weak localization



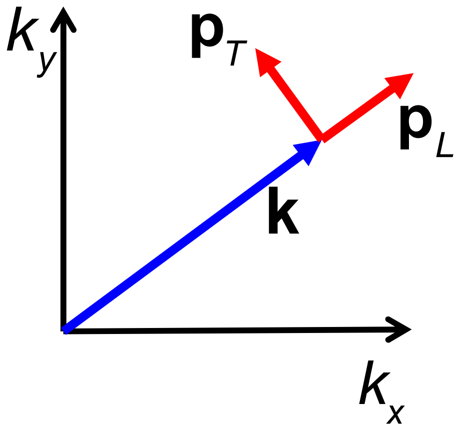


M. Gurioli et al., PRB **64,** 165309 (2001)
M. Gurioli et al., PRL **94,** 183901 (2005)
R. Houdré et al., PRB **61**, R13 333 (2000)

Polariton polarization and spin

Exciton: **Spin=1 boson (2-D)**

Material polarization



Intrinsic L-T energy splitting

$$\hat{H} \simeq \frac{\hbar^2 k^2}{2m^*} + \mu_B g \left(\sigma \cdot \mathbf{H}_{eff} \right)$$

$$\mathbf{H}_{eff} = \frac{\Delta_{LT}}{\mu_B g k^2} \begin{pmatrix} k_x^2 - k_y^2 \\ 2 k_x k_y \end{pmatrix}$$

A. Kavokin et al., PRL **95**, 136601 (2005)

Polarization – field selection rules:

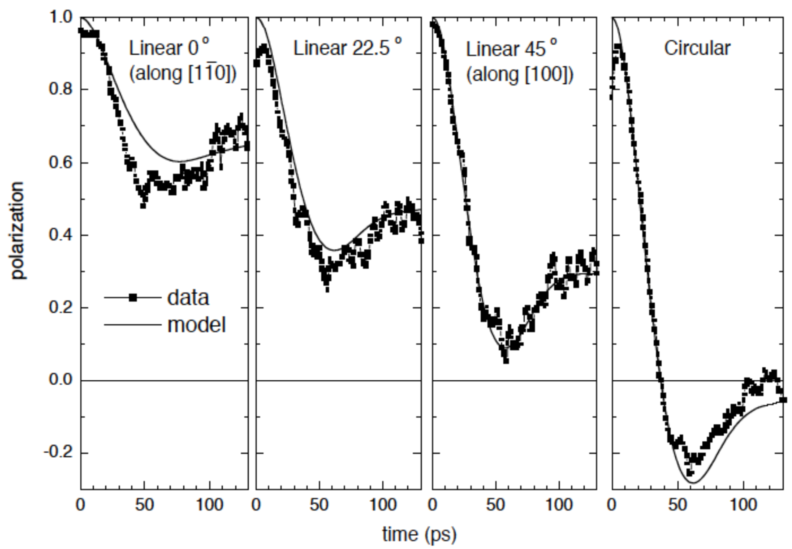
$\mathbf{p}_T \leftrightarrow$ **TE-field**

$\mathbf{p}_L \leftrightarrow$ **TM-field**

Polarization – spin selection rules:

$$S = \pm 1 \leftrightarrow \mathbf{p}_x \pm i\,\mathbf{p}_y$$

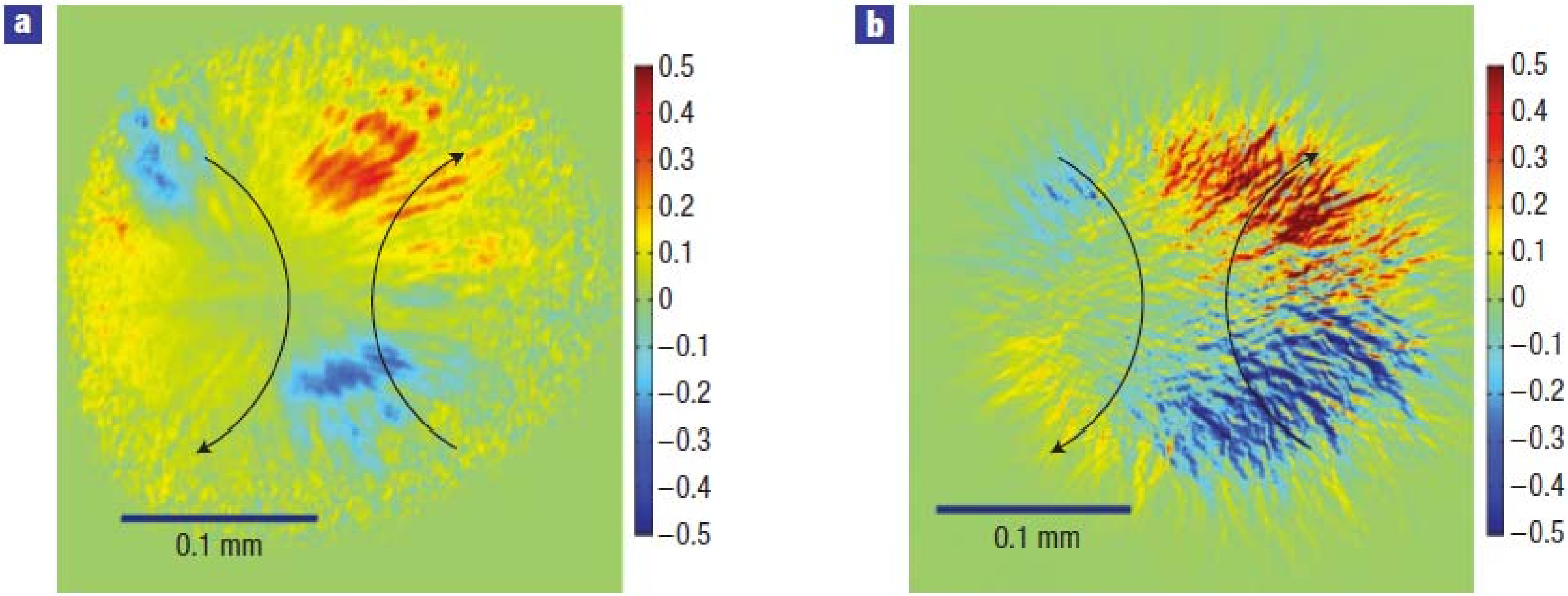
Localization: disorder-induced spin splitting



W. Langbein et al., phys. stat. sol. (b) **221**, 349 (2000)

Disorder and spin

When injecting a linearly-polarized polariton field, scattering off disorder and LT-splitting produce the "optical spin-Hall effect"



A. Kavokin et al., PRL **95**, 136601 (2005)
C. Leyder et al., Nature Physics **3**, 628 (2007)

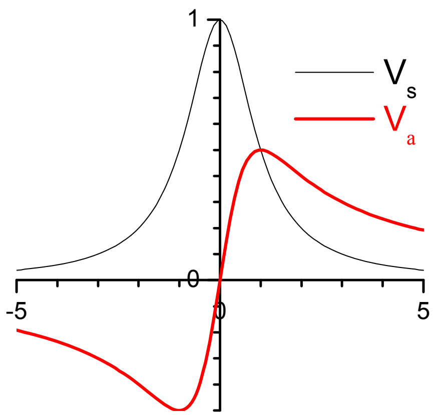
Disorder and birefringence in MCs

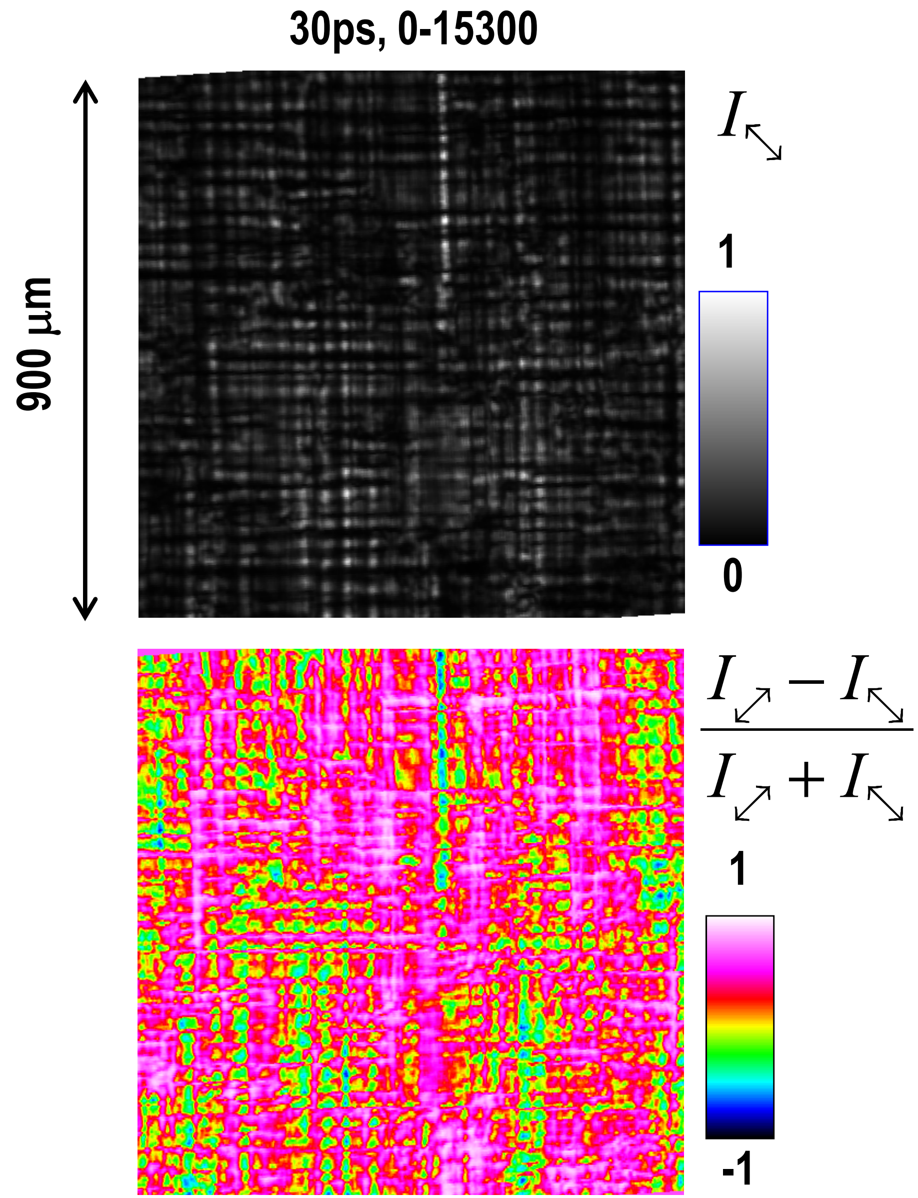
Disorder in MCs can affect polariton polarization (spin), through spatially inhomogeneous birefringence

Courtesy of W. Langbein (unpublished)

$$V_a(r) = \frac{r r_0}{r_0^2 + r^2}$$

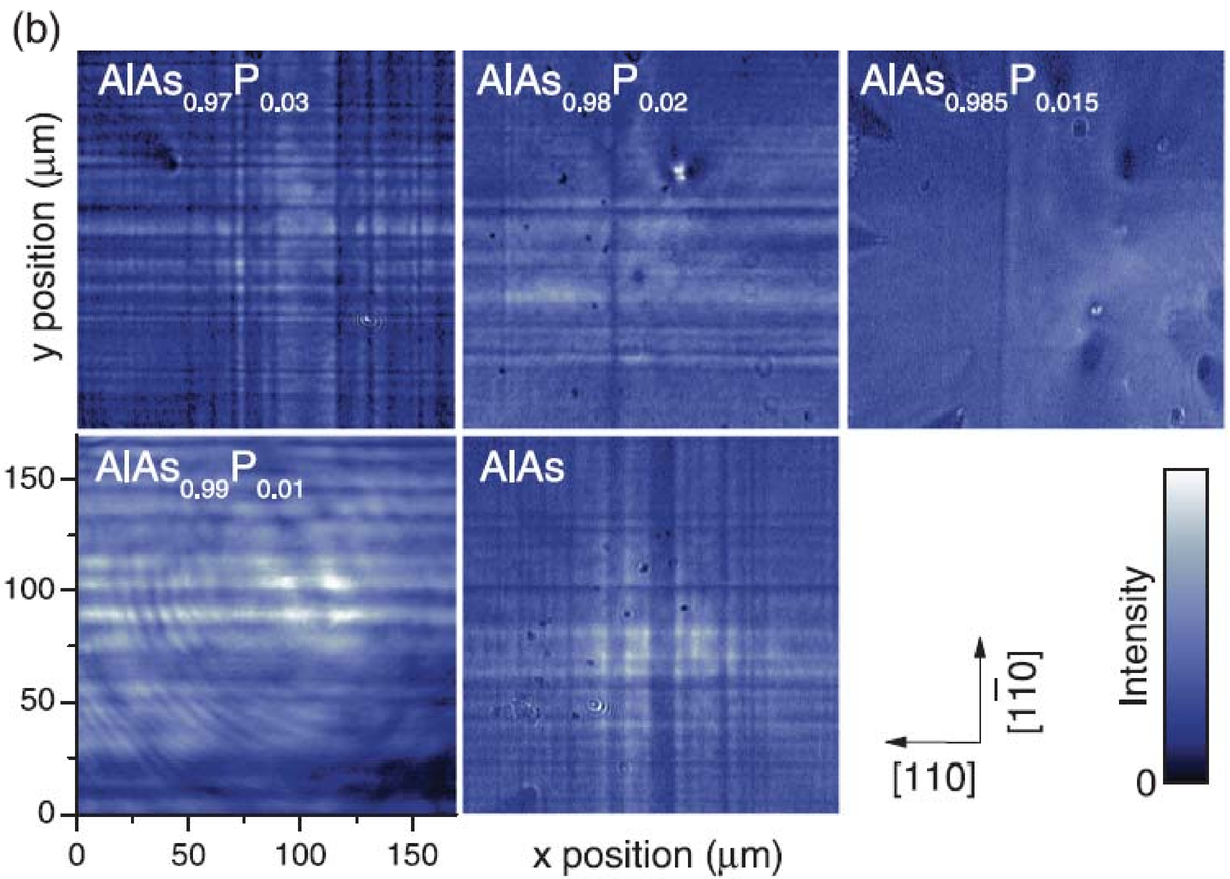
$$V_s(r) = \frac{1}{1 + r^2/r_0^2}$$





Suppressing crosshatch disorder in the growth

A small amount of phosphorous alloyed to AlAs can reestablish full lattice match



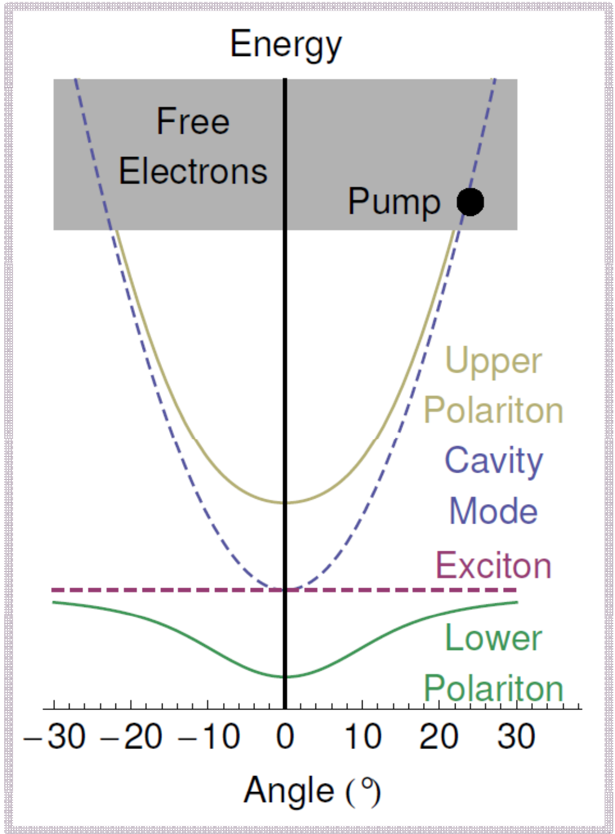
J. M. Zajac et al., APL **101**, 041114 (2012)

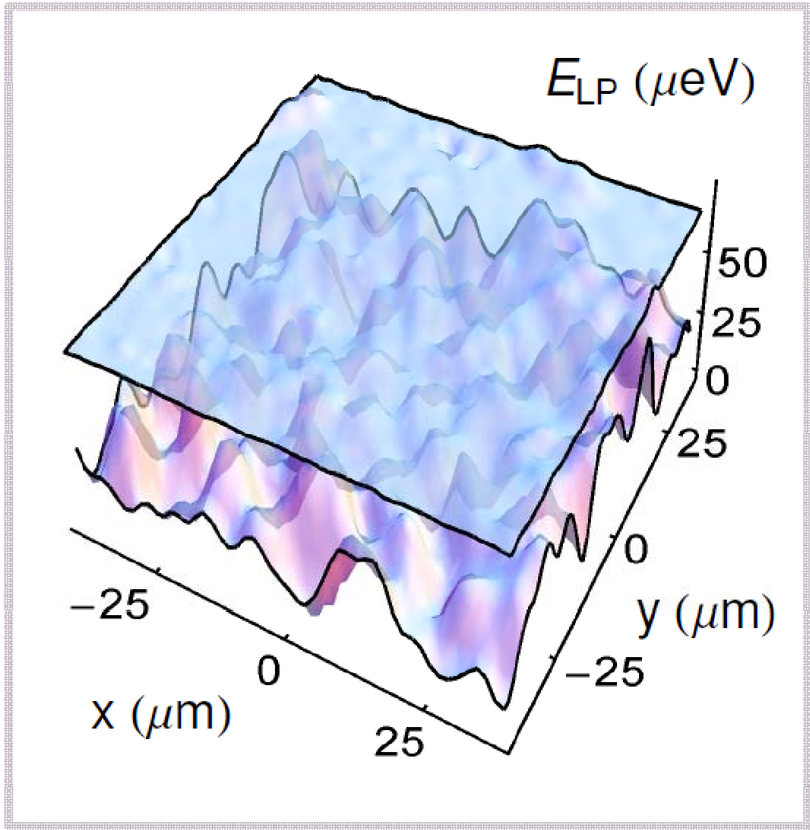
Suppressing disorder with dynamical nuclear spin polarization

Spin-polarized electrons injected resonantly, transfer the polarization to the Ga and As nuclei.

The electron density follows the disorder profile, thanks to the sharp cavity resonance.

The resulting Overhauser field counters the local disorder potential for one polariton spin.

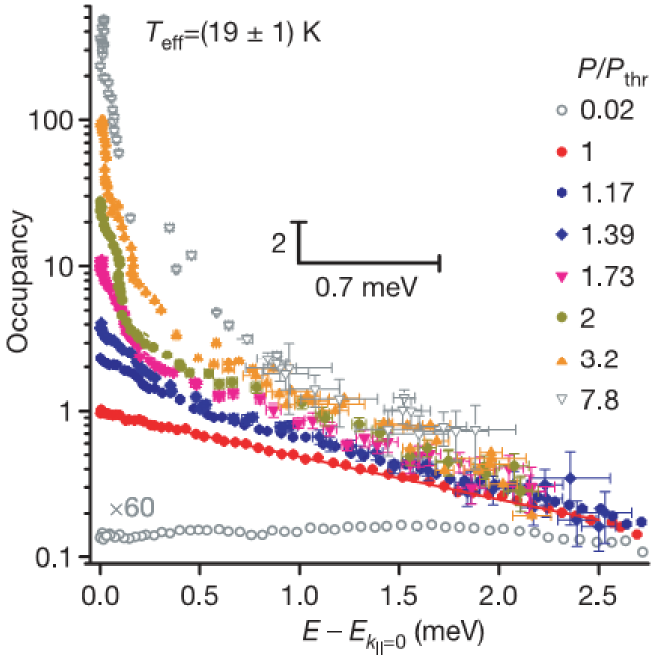


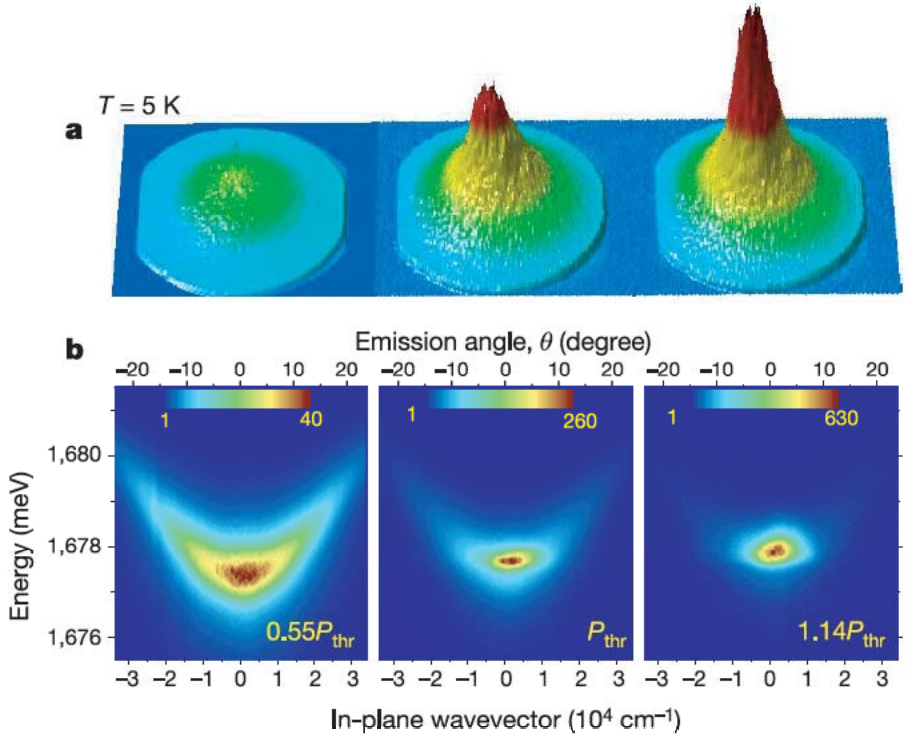


T. H. C. Liew and V. Savona, PRL **106**, 146404 (2011)

Disorder and polariton BEC

Polariton BEC: Macroscopic ground-state occupation





J. Kasprzak, et al., Nature **443**, 409 (2006)

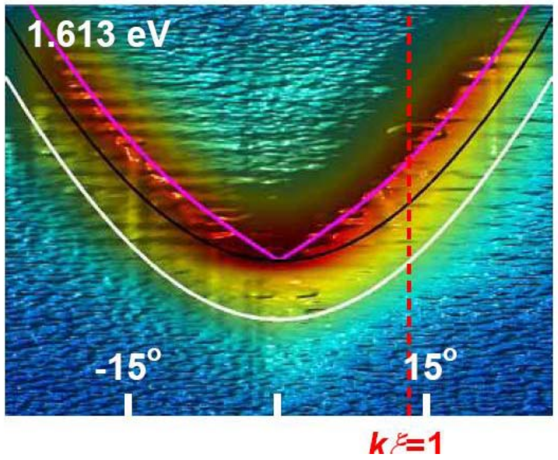
Also…

Le Si Dang et al., PRL **81**, 3920 (1998)
J. Bleuse et al., J. Crystal Growth **184/185**, 750 (1998)
H. Deng, et al., PNAS **100**, 15318 (2003)
R. Balili, et al., Science **316**, 1007 (2007)
S. Christopoulos, et al., PRL **98**, 126405 (2007)
S. Utsunomiya et al., Nature Physics **4**, 700 (2008)
E. Wertz et al., APL **95**, 051108 (2009)

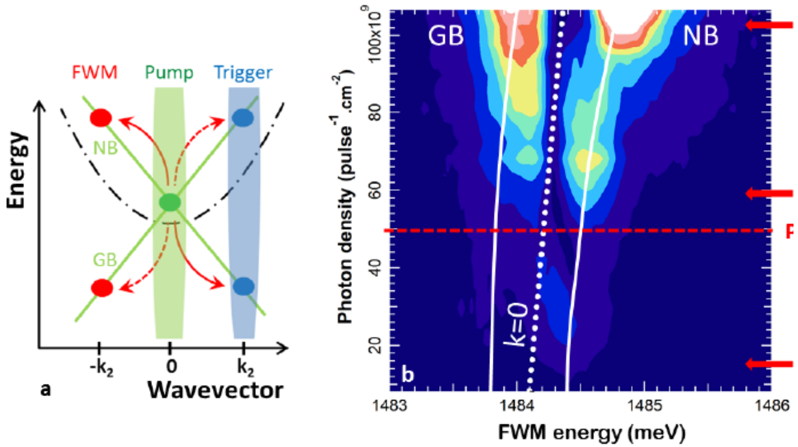
For a review:

I. Carusotto and C. Ciuti, RMP **85**, 299 (2013)
J. Keeling et al., Semicond. Sci. Technol. **22**, R1 (2007)

Polariton BEC: Collective excitation spectrum

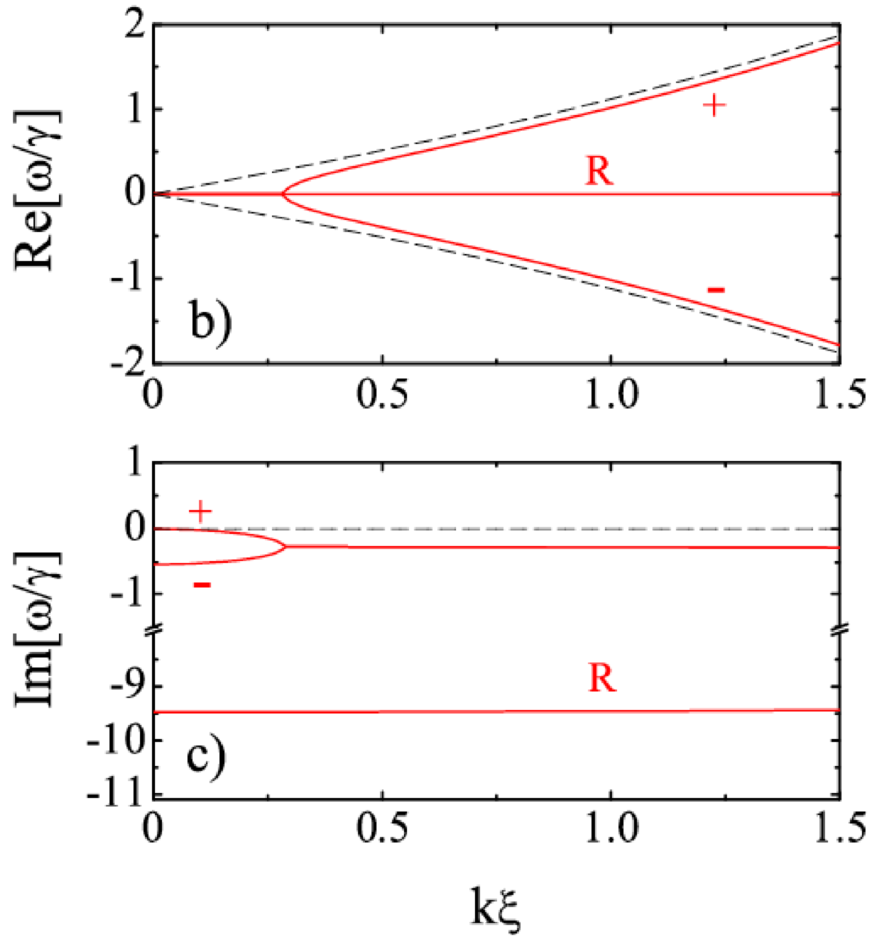


S. Utsunomiya et al., Nature Physics **4**, 700 (2008)



V. Kohnle et al., PRL **106**, 255302 (2011)

Driven-dissipative system: Diffusive Goldstone mode

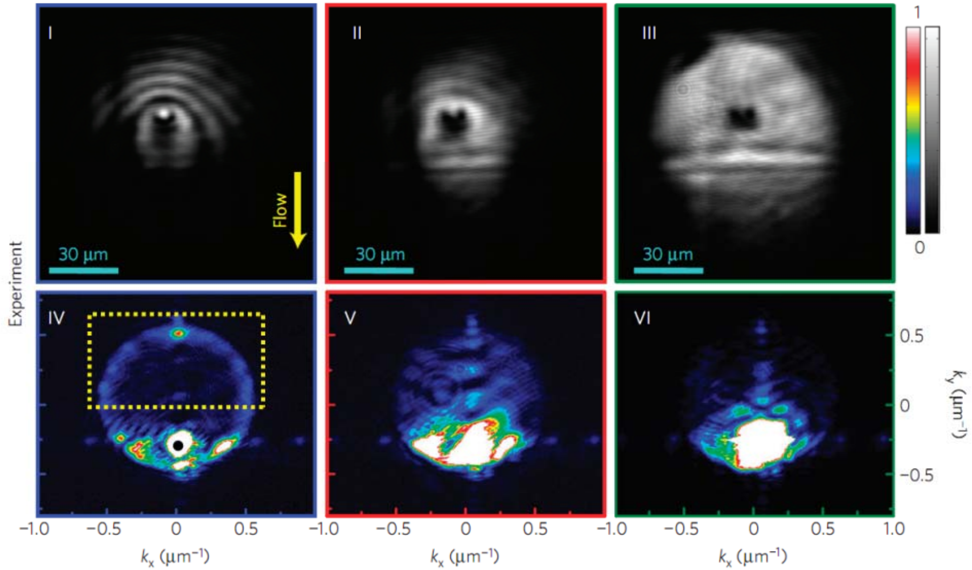


M. Wouters and I. Carusotto, PRL **99**, 140402 (2007)
M. H. Szymanska, et al., PRL **96** 230602 (2006)
J. Keeling et al., Semicond. Sci. Technol. **22**, R1 (2007)

Disorder and polariton superfluidity

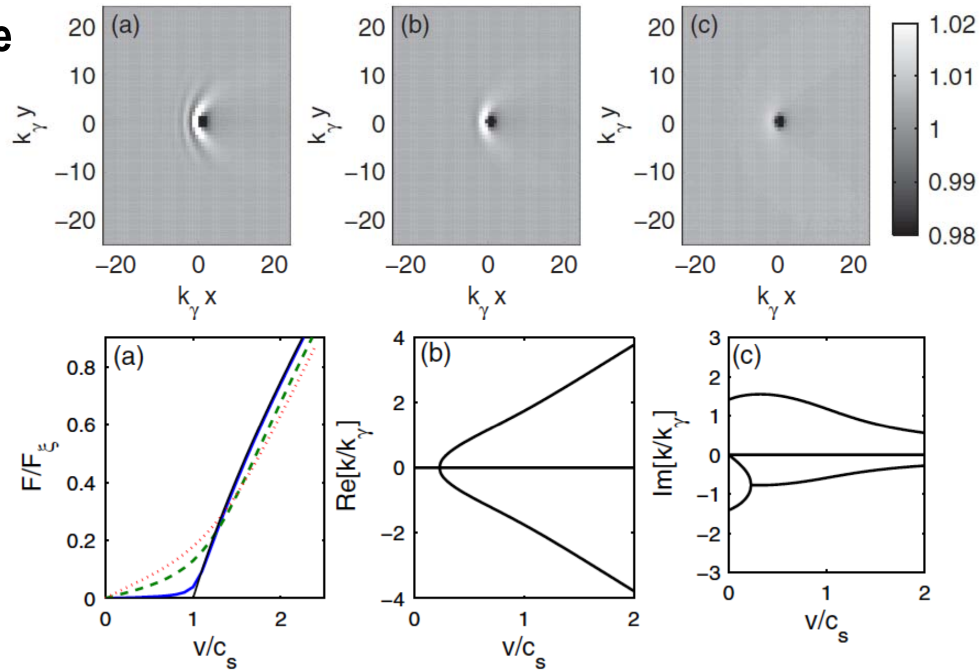
Polariton flow through disorder as a test of superfluidity

I. Carusotto and C. Ciuti, PRL **93**, 166401 (2004)
A. Amo et al., Nature **457**, 291 (2009)
A. Amo et al., Nat. Phys. **5**, 805 (2009)

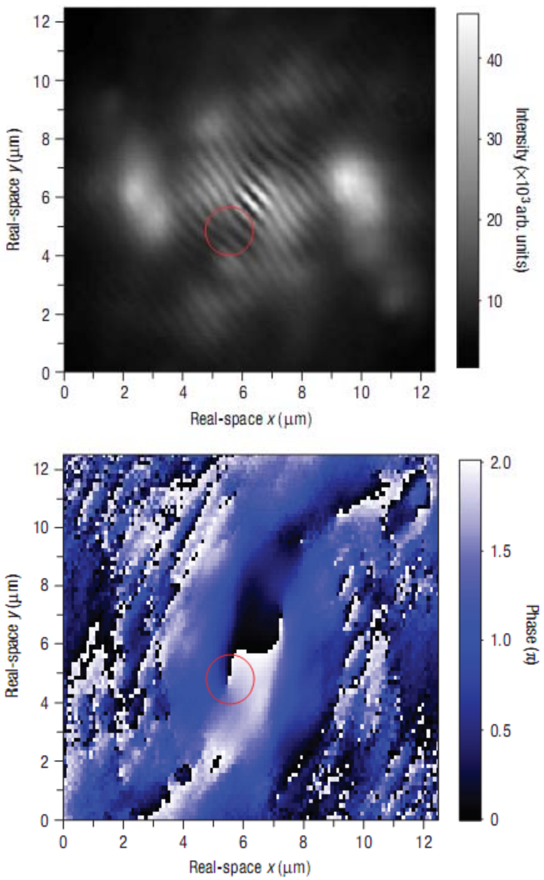


Driven-dissipative superfluid flow past a defect. Diffusive Goldstone mode would imply vanishing critical velocity. However, damped excitations are unable to carry energy away from the superfluid.

M. Wouters and I. Carusotto, PRL **105**, 020602 (2010)



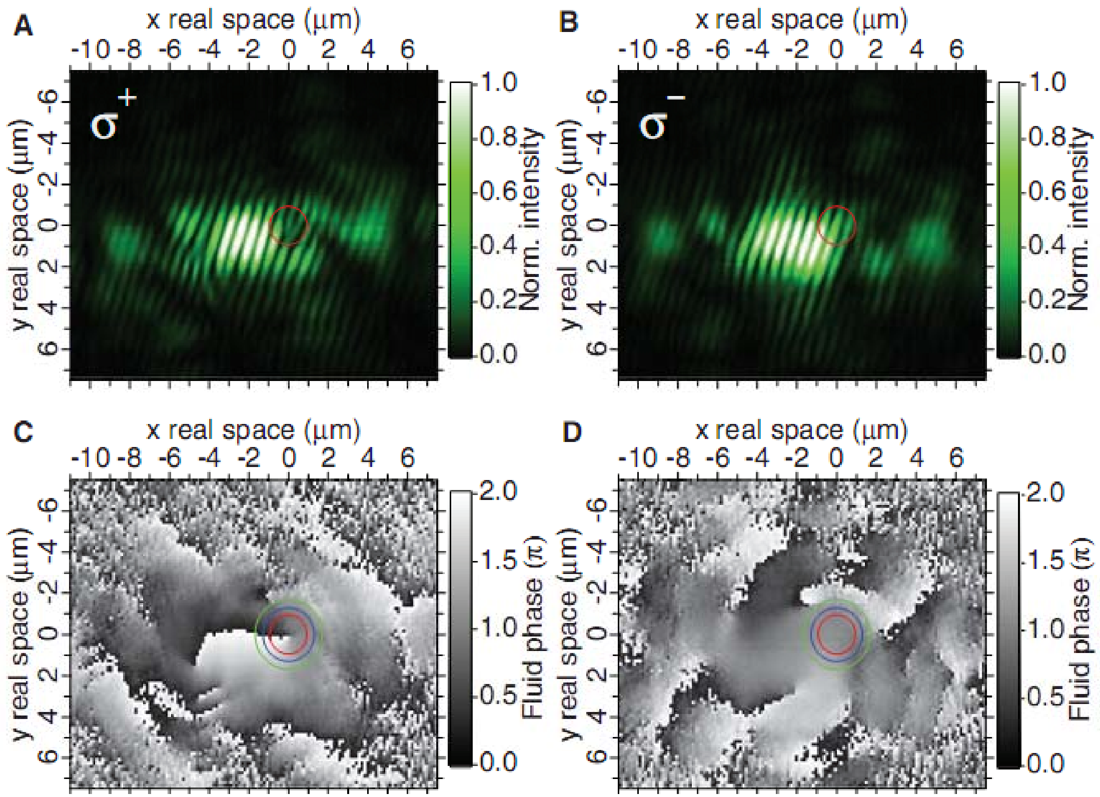
Quantized vortices and half-vortices in a polariton superfluid



K. G. Lagoudakis, et al., Nature Physics **4**, 706 (2008)
D. Sanvitto et al., Nat Phys. **6**, 527 (2010)
G. Roumpos et al., Nat. Phys **7**, 129 (2011)

Polaritons are spinor-bosons: $\psi_{lin}(\boldsymbol{r}) = \sqrt{n}e^{i\theta(\boldsymbol{r})}\begin{pmatrix}\cos\eta(\boldsymbol{r})\\ \sin\eta(\boldsymbol{r})\end{pmatrix}$

Direct observation of polariton half-vortices

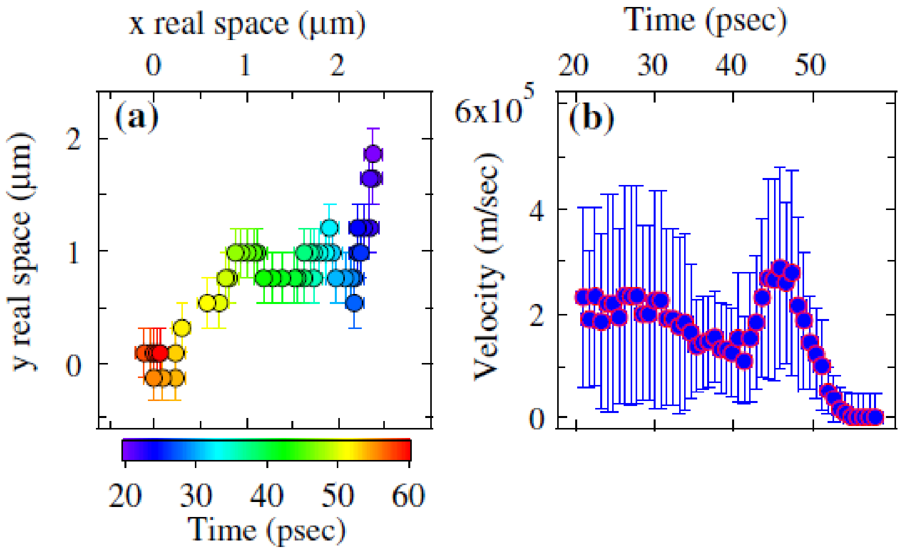


K. G. Lagoudakis, et al.,
Science **326**, 974 (2009)

Physics of the polariton quantum fluid

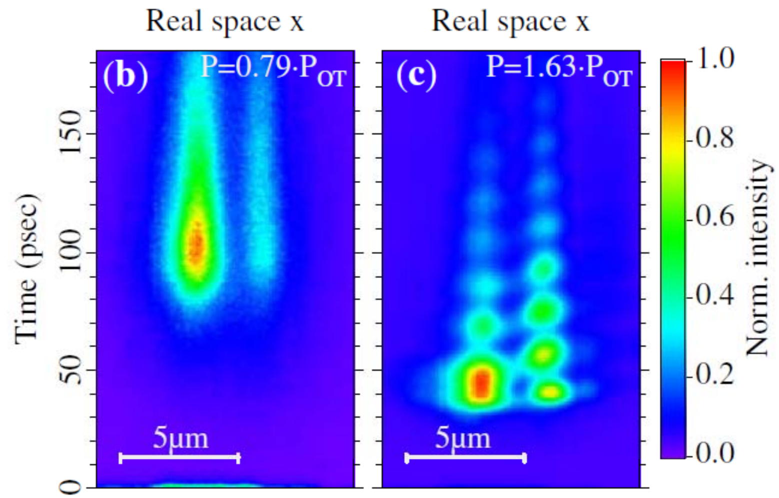
Migrating vortices

K. Lagoudakis et al., PRL **106**, 115301 (2011)



Josephson oscillations

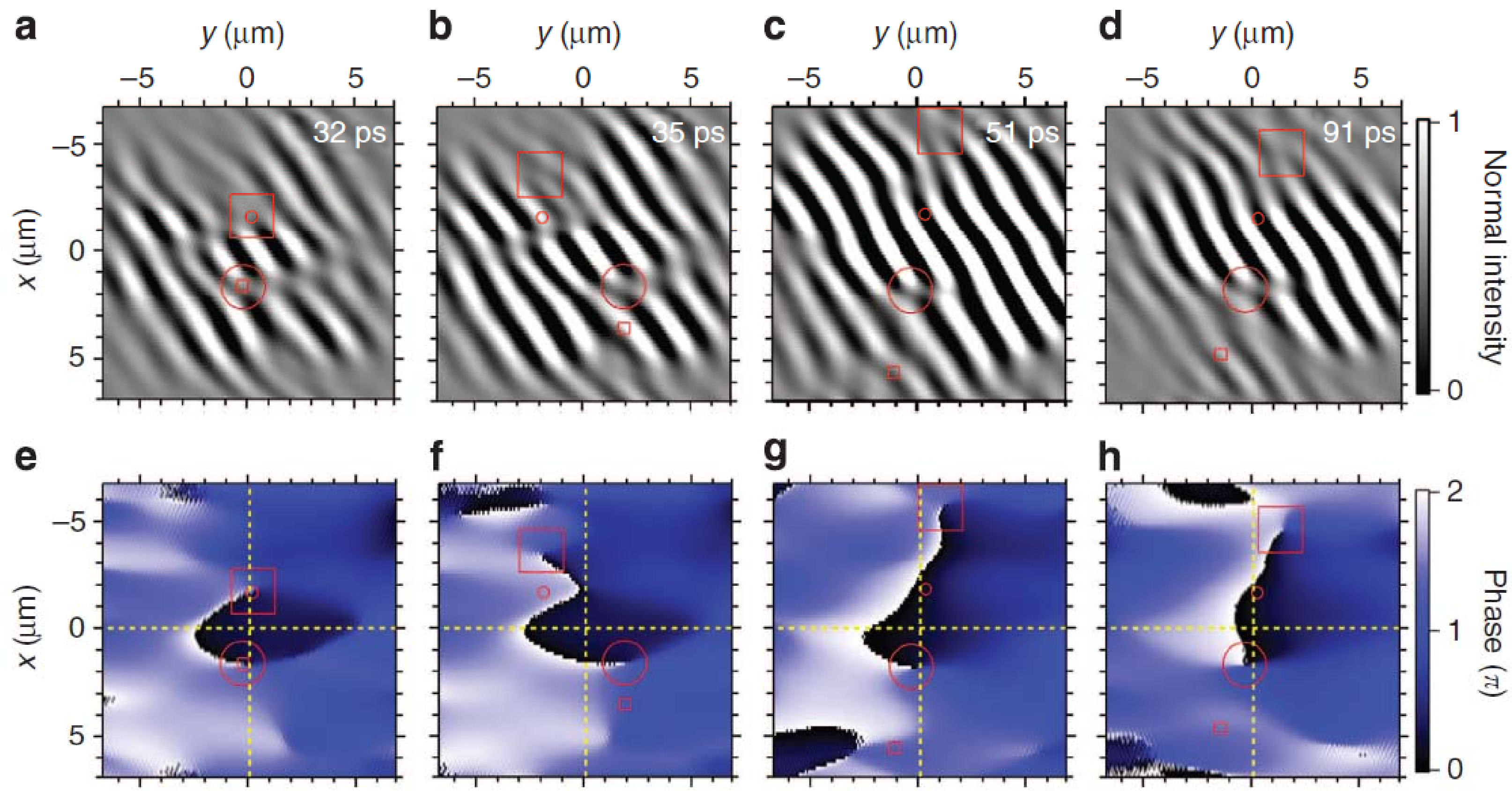
K. Lagoudakis et al., PRL **105**, 120403 (2010)



Disorder-induced half-vortex separation

A quantised vortex in a polariton superfluid separated into a pair of half vortices (the polariton superfluid is a spinor boson superfluid).

The two half-vortices are subject to different disorder potentials (birefringence) and follow different paths after dissociation



F. Manni et al., Nat. Comm. **3**, 1309 (2012)

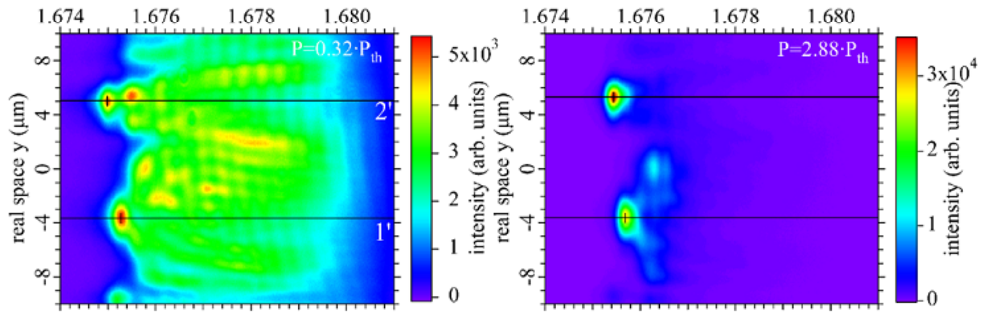
A quantum phase transition for polaritons?

Non-equilibrium and the gain-loss kinetics seem to favor condensation into an extended state. All experiments suggest a transition from a nondegenerate gas directly to the superfluid phase, without an intermediate Bose-glass phase.

E. Wertz et al., Nat. Phys. **6**, 860 (2010)
F. Manni et al., PRL **106**, 176401 (2011)

Some strong-disorder situations may show independent (nondegenerate) condensates

A. Baas et al., PRL **100**, 170401 (2008)
M. Wouters et al., PRB **77**, 121302 (2008)



A theory of a QPT under nonequilibrium must include quantum fluctuations beyond mean field.

M. Wouters and V. Savona, PRB **79**, 165302 (2009)

A systematic investigation of a possible BG-superfluid phase transition under nonequilibrium is still lacking.

Summary

- **Polaritons are the ideal system, if you wish to study the "universal" properties of a**
  driven-dissipative
  disordered
  interacting
  composite
  spinor boson field
  with unconventional energy-momentum dispersion

- **Few truly universal effects have been actually observed: e.g. enhanced backscattering. No superfluid-glass transition (yet).**

- **Still, it can be a model system for studying 2-D disorder + interactions (but the polariton lifetime should be increased and larger areas addressed)**

The bibliography of this talk can be found at: **https://www.zotero.org/groups/savonatrieste**