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COLLEGE ON

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Statistically-degenerate indirect excitons in coupled quantum wells

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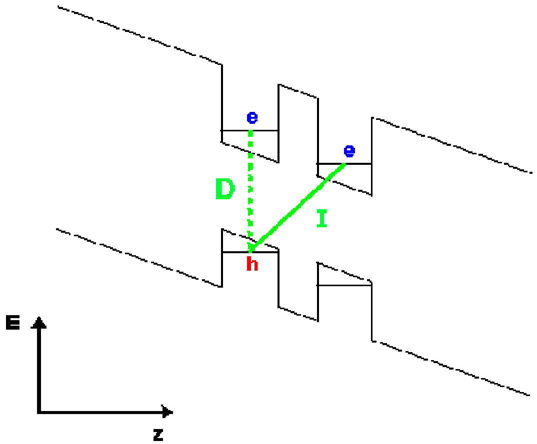
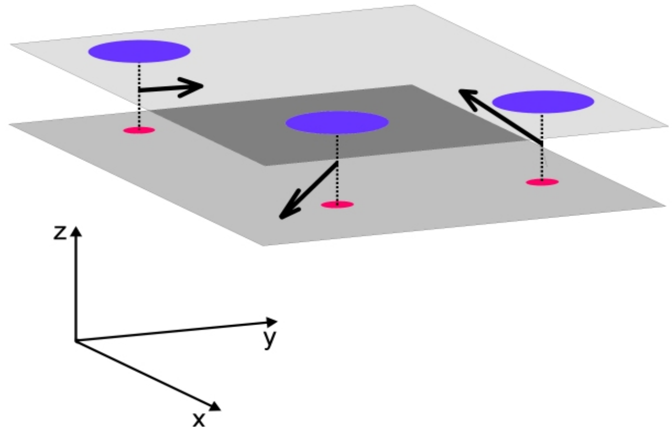
Outline

- Indirect excitons in coupled quantum wells
- Screening of QW disorder by dipole-dipole interacting indirect excitons
- Relaxation thermodynamics of indirect excitons
- Heating of indirect excitons by a laser pulse
- Recombination heating or cooling of indirect excitons
- Origin of the inner ring in PL patterns of indirect excitons
- Optical trapping of indirect excitons

Indirect excitons in GaAs/AlGaAs coupled quantum wells





- A unique object for studing the transport and collective properties of interacting quasi-2D composite bosons:

$\longrightarrow$ a well-defined dipole-dipole repulsive interaction between indirect excitons (not sensitive to the spin structure),

$\longrightarrow$ the absence of quasi-2D excitonic molecules,

$\longrightarrow$ a long radiative livetime of excitons ($\tau_{\mathrm{opt}} \sim 10 - 100\,\mathrm{ns}$),

$\longrightarrow$ effective screening of in-plane QW disorder.

Thermodynamics of quasi-2D bosons

- The degeneracy temperature: $k_B T_0 = \dfrac{2\pi}{g}\left(\dfrac{\hbar^2}{M_x}\right)\rho_{2D}$,

$\longrightarrow$ $g = 4$ and $T_0 = 0.64\,\mathrm{K}$ for $\rho_{2D} = 10^{10}\,\mathrm{cm}^{-2}$.

- Thermodynamic relationships for quasi-2D bosons:

$$\mu = k_B T \ln\left(1 - e^{-T_0/T}\right) , \quad N_E = \frac{1 - e^{-T_0/T}}{e^{E/k_B T} + e^{-T_0/T} - 1} .$$

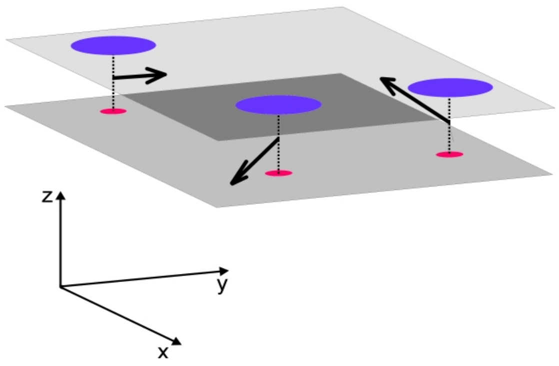
- Maxwell-Boltzmann statistics:

$$\mu = k_B T \ln\left(T_0/T\right) \quad \text{and} \quad N_{E=0} = T_0/T \ll 1 .$$

- Bose-Einstein statistics:

$$\mu = -k_B T e^{-T_0/T} \quad \text{and} \quad N_{E=0} = e^{T_0/T} \gg 1 .$$

Mean-field energy and BEC of indirect excitons



- A well-defined dipole-dipole interaction:

$$u_0 = \pi \frac{\hbar^2}{\mu_x \chi(d)}\,, \qquad \text{where} \quad \chi(d \geq a^{\mathrm{B}}_{\mathrm{2d}}) = \frac{a^{\mathrm{B}}_{\mathrm{2d}}}{2d}\,.$$

$\rightarrow$ consistent with the plate capacitor formula, $u_0 = 4\pi(e^2/\varepsilon_b)d\,.$

[S. Ben-Tabou and Boris Laikhtman (PRB, 2001)]

- **Bose-Einstein condensation of quasi-2D excitons**

Condensation temperature:

$$T_c = \frac{4\pi\hbar^2\rho_{2\mathrm{D}}}{2M_x g k_{\mathrm{B}}} \frac{1}{\ln(\rho_{2\mathrm{D}} S/g)}\,,$$

where S is the area of a meso-structure.

- Two key-questions:

$\rightarrow$ Is it possible to build up $N_E >> 1$?
$\rightarrow$ Is it possible to cool the indirect excitons down $T_b << 1\mathrm{K}$?

- The Einstein relation for degenerate quasi-2D excitons:

$$\mu^{(2D)} = \frac{D_x^{(2D)}}{k_B T_0} \left[e^{T_0/T} - 1 \right] ,$$

where $\mu^{(2d)}$ and $D_x^{(2d)}$ are the mobility and diffusion coefficient, $T_0 \propto \rho_{2D}/M_x$ is the degeneracy temperature.

- Quantum diffusion equation:

$$\frac{\partial \rho_{2D}}{\partial t} = \nabla \big[D_x^{(2D)} \nabla \rho_{2D} + \frac{2}{\pi} \left(\frac{M_x}{\hbar^2} \right) D_x^{(2D)} \left(e^{T_0/T} - 1 \right)$$

$$\times \nabla \left(u_0 \rho_{2D} + U_{QW} \right) \big] - \frac{\rho_{2D}}{\tau_{opt}} + \Lambda ,$$

where the diffusion coefficient is given by

$$D_x^{(2D)} = D_x^{(2D)}(T, T_0) = \frac{\hbar}{M_x} \left(\frac{a_{2d}^B}{2d} \right)^2 \left(\frac{\mu_x}{M_x} \right)^2 \left[\frac{1}{2k_B} \frac{\partial E_{kin}}{\partial T_0} + 2 \frac{E_{kin}}{k_B T_0} \right] ,$$

$\longrightarrow$ E_{kin} is the average thermal energy of QW excitons.

[A L Ivanov (EPL, 2002)]

- Self-thermodiffusion $\propto \nabla T$ is absent, i.e., $D_{\mathrm{T}}^{(2\mathrm{D})} = 0$.

- **Screening of long-range-correlated disorder**

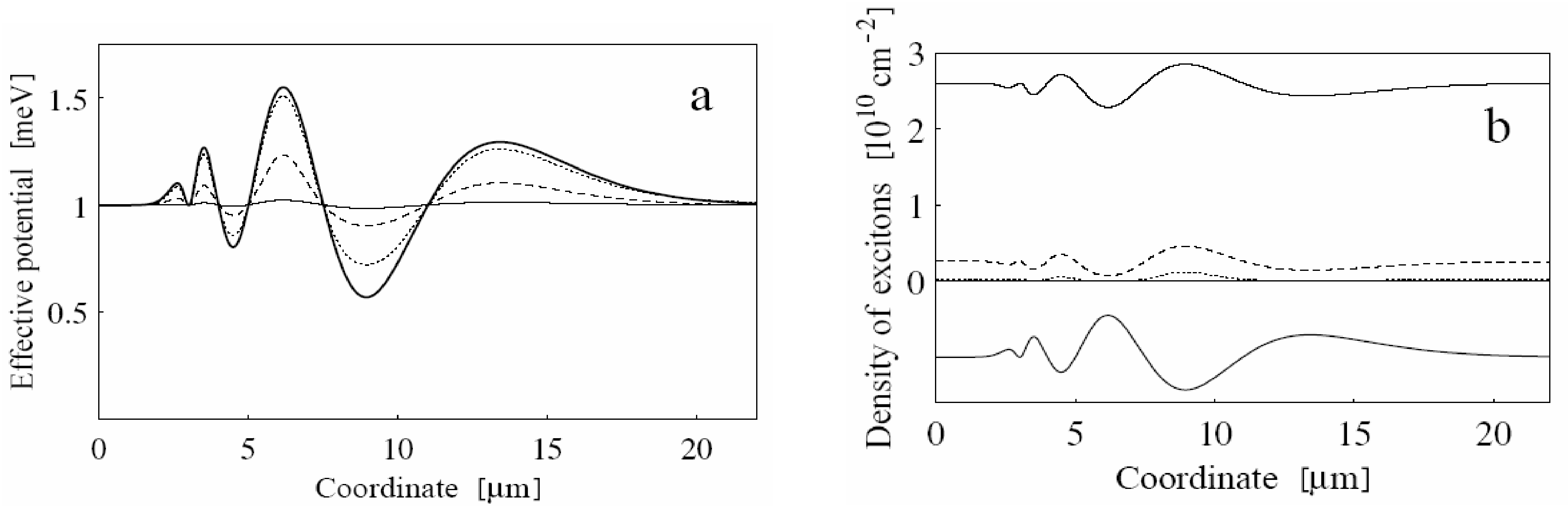
$$\delta\rho_{2\mathrm{D}}(\mathbf{r}_{\|}) \;=\; -\,\frac{U_{\mathrm{rand}}(\mathbf{r}_{\|})\rho_{2\mathrm{D}}^{(0)}}{k_{\mathrm{B}}T + u_0\rho_{2\mathrm{D}}^{(0)}}\;,$$

$$U_{\mathrm{eff}}(\mathbf{r}_{\|}) \;=\; u_0\rho_{2\mathrm{D}}^{(0)} \;+\; \frac{U_{\mathrm{rand}}(\mathbf{r}_{\|})k_{\mathrm{B}}T}{k_{\mathrm{B}}T + u_0\rho_{2\mathrm{D}}^{(0)}}\;.$$

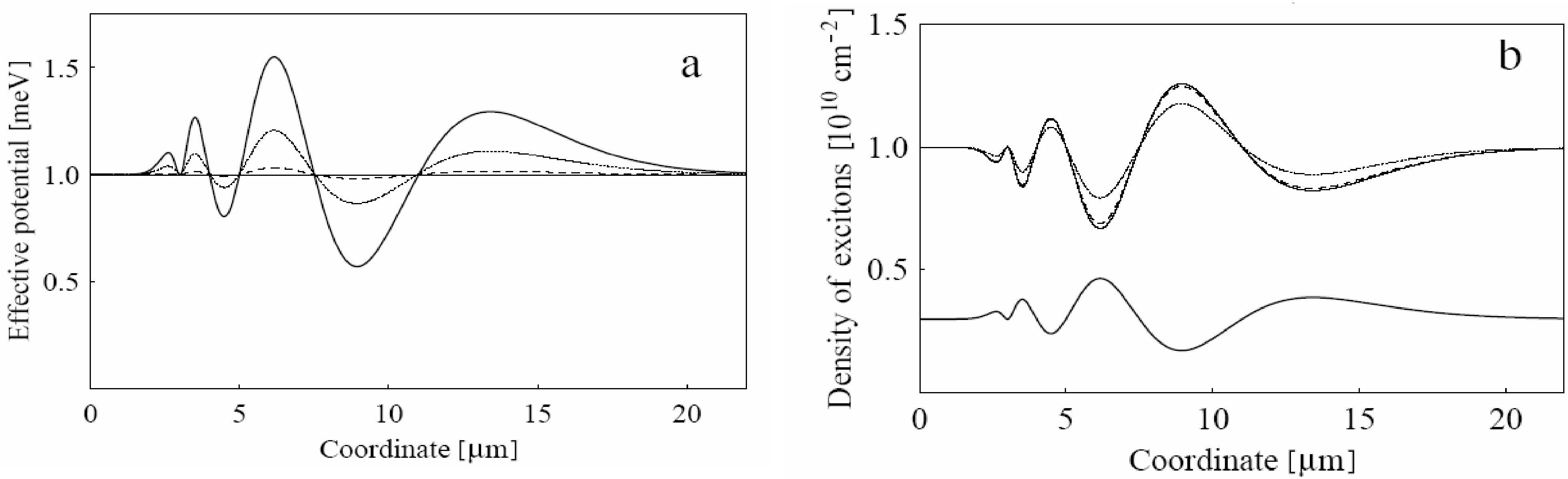
- Thermionic model: $\quad \tilde{D}_{\mathrm{x}}^{(2\mathrm{D,cl})} = D_{\mathrm{x}}^{(2\mathrm{D,cl})} \exp\left[-\frac{U_{\mathrm{rand}}(\mathbf{r}_{\|})}{k_{\mathrm{B}}T + u_0\rho_{2\mathrm{D}}^{(0)}}\right].$

$\longrightarrow$ $|U_{\mathrm{rand}}(\mathbf{r}_{\|})| \simeq 0.35\text{-}0.50\,\mathrm{meV}$ in GaAs/AlGaAs coupled QWs,

$\longrightarrow$ For $\rho_{2\mathrm{D}}^{(0)} \geq 10^{10}\,\mathrm{cm}^{-2}$ the in-plane momentum, $\mathbf{p}_{\|}$, becomes a good quantum number even for low-energy particles.



Relaxation of long-range-correlated disorder by the dipole-dipole interaction of indirect excitons in GaAs/AlGaAs coupled QWs. (a) The effective, screened potential $U_{\rm eff}(x) - u_0\rho^{(0)}_{\rm 2D}$ and (b) local concentrations of indirect excitons $\rho_{\rm 2D}(x)$ versus in-plane coordinate x. The average concentrations are $\rho^{(0)}_{\rm 2D} = 2.6 \times 10^{10}\,{\rm cm}^{-2}$ (thin solid line), $2.6 \times 10^{9}\,{\rm cm}^{-2}$ (dashed line), and $2.6 \times 10^{8}\,{\rm cm}^{-2}$ (dotted line). Temperature T=2 K, diffusion coefficient $D^{(2D)}_{\rm x} = 100\,{\rm cm}^2/{\rm s}$, and radiative lifetime $\tau_{\rm opt} = 20\,{\rm ns}$. In both figures the input, unscreened potential $U_{\rm rand}(x)$ is shown by bold solid lines.



Temperature dependence of the narrowing effect. The bold solid line shows the unscreened potential $U_{\mathrm{rand}}(x)$. (a) The effective potential $U_{\mathrm{eff}}(x)$ for $T = 10\,\mathrm{K}$ (dotted line), $T = 1\,\mathrm{K}$ (dashed line), and $T = 0.1\,\mathrm{K}$ (thin solid line). The average density of indirect excitons $\rho_{2\mathrm{D}}^{(0)} = 1.0\times10^{10}\,\mathrm{cm}^{-2}$, diffusion coefficient $D_{\mathrm{x}}^{(2\mathrm{D})} = 100\,\mathrm{cm}^2/\mathrm{s}$, and radiative lifetime $\tau_{\mathrm{opt}} = 20\,\mathrm{ns}$. (b) The local concentrations of indirect excitons, $\rho_{2\mathrm{D}} = \rho_{2\mathrm{D}}(x)$.

Quantum synergetics for indirect excitons

- *Nonlinear* quantum diffusion equation :

$$\frac{\partial \rho_{\rm 2D}}{\partial t} = \nabla\Big[D_{\rm x}^{\rm (2D)} \nabla \rho_{\rm 2D} + \frac{2}{\pi}\left(\frac{M_{\rm x}}{\hbar^2}\right) D_{\rm x}^{\rm (2D)} \left(e^{T_0/T} - 1\right)$$

$$\times \nabla \left(u_0 \rho_{\rm 2D} + U_{\rm QW}\right)\Big] - \frac{\rho_{\rm 2D}}{\tau_{\rm opt}} + \Lambda \, .$$

- *Nonlinear* LA-phonon-assisted thermalization :

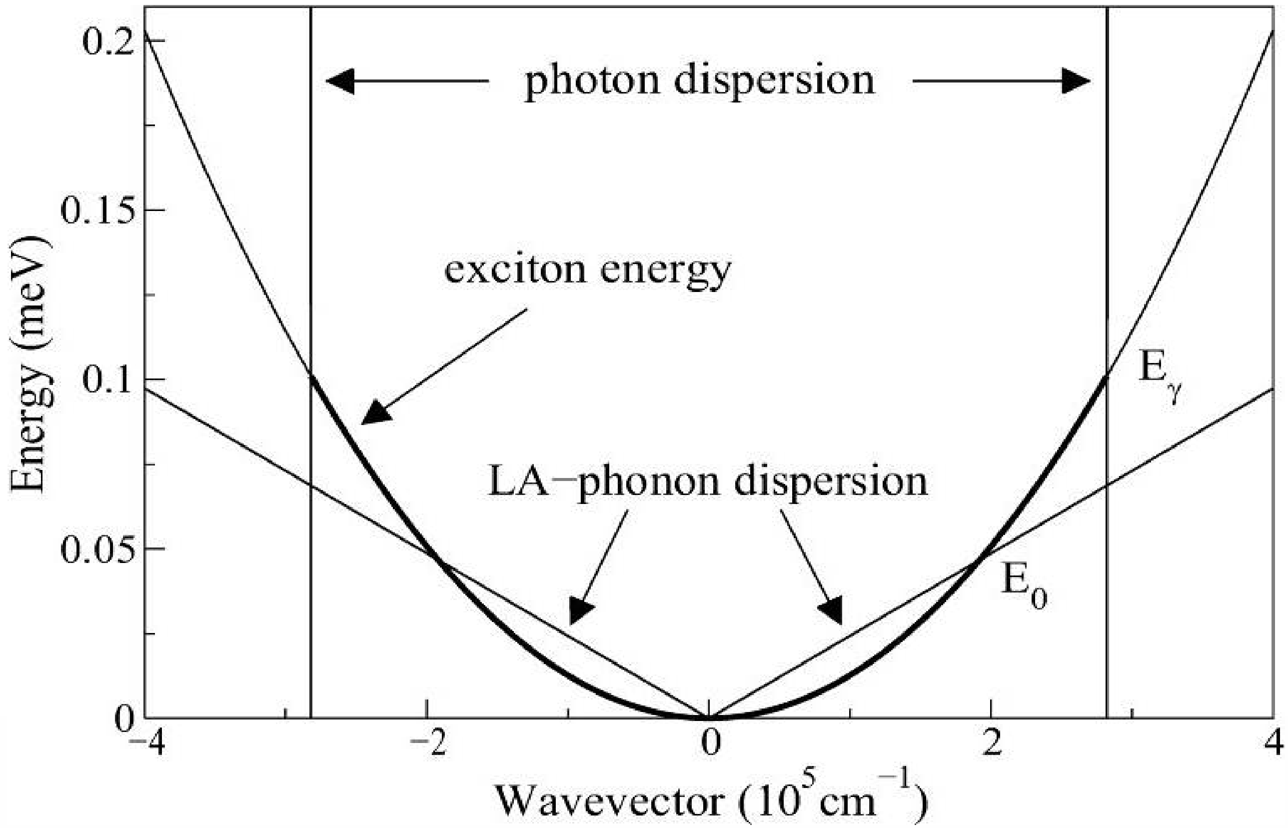
$$\frac{\partial}{\partial t} T = -\frac{2\pi}{\tau_{sc}} \left(\frac{T^2}{T_0}\right) \left(1 - e^{-T_0/T}\right) \int_1^{\infty} d\varepsilon \; \varepsilon \sqrt{\frac{\varepsilon}{\varepsilon - 1}} \; \left|F_z\big(a\sqrt{\varepsilon(\varepsilon - 1)}\big)\right|^2$$

$$\times \; \frac{e^{\varepsilon E_0/k_B T_b} - e^{\varepsilon E_0/k_B T}}{\left(e^{\varepsilon E_0/k_B T} + e^{-T_0/T} - 1\right)} \; \frac{1}{\left(e^{\varepsilon E_0/k_B T_b} - 1\right)} \; + \; \Lambda_{\rm T} \, .$$

- Intrinsically *nonlinear* optical decay :

$$I_{PL} \;=\; \hbar \omega_t \, \frac{\rho_{2D}}{\tau_{opt}(\rho_{2D}, T)} \; .$$

Energy diagram for indirect QW excitons

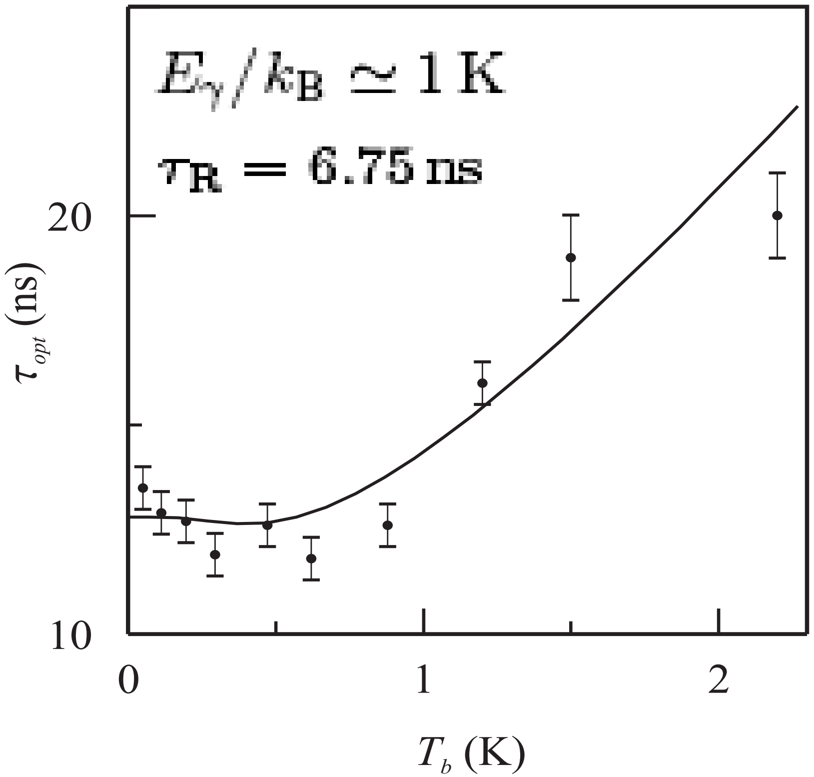


- $\longrightarrow$ the bath temperature $T_{\rm b}$;
- $\longrightarrow$ the effective temperature T ;
- $\longrightarrow$ the degeneracy temperature $T_0 \propto \rho_{\rm 2D}$;
- $\longrightarrow$ the energy $E_0 = 2M_{\rm x}v_{\rm s}^2$;
- $\longrightarrow$ the energy $E_\gamma = (\hbar k_0)^2/2M_{\rm x}$, where $k_0 = (\omega_t\sqrt{\varepsilon_{\rm b}})/c$.

Optical decay of statistically-degenerate indirect excitons

$$\Gamma_{\rm opt} \equiv \frac{1}{\tau_{\rm opt}} = \frac{1}{2\tau_{\rm R}} \left(\frac{E_\gamma}{k_{\rm B} T_0} \right) \int_0^1 \frac{1+z^2}{A e^{-z^2 E_\gamma / k_{\rm B} T} - 1}\, dz\,, \qquad A = A(T, T_0) = \frac{e^{E_\gamma / k_{\rm B} T}}{1 - e^{-T_0/T}}\,.$$

[A L Ivanov, P B Littlewood, and H Haug (PRB, 1999)]



- Well-developed classical statistics:

$$\tau^{\rm cl}_{\rm opt} = \left(\frac{3}{2} \frac{k_{\rm B} T}{E_\gamma} \right) \tau_R + \left(\frac{9}{10} - \frac{3}{4} \frac{k_B T_0}{E_\gamma} \right) \tau_{\rm R}\,.$$

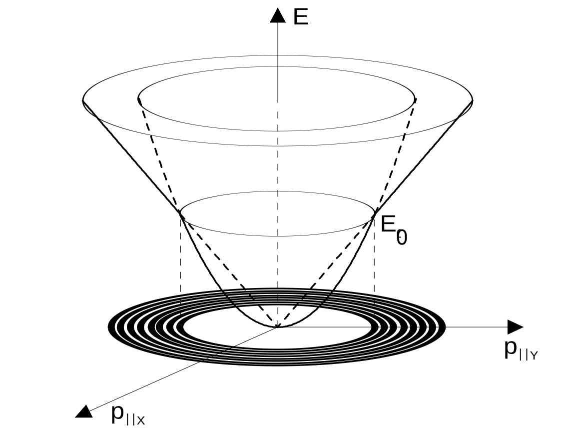
- Well-developed quantum statistics:

$$\Gamma^{\rm q}_{\rm opt} = \left[1 - \frac{T}{T_0} + \frac{T}{T_0} \ln \left(\frac{4 E_\gamma}{k_{\rm B} T} \right) \right] \frac{\Gamma_0}{2}\,,$$

where $\Gamma_0 = 1/\tau_{\rm R}$.

- Experiment (points, L V Butov et al., 2001) against theory (solid line).

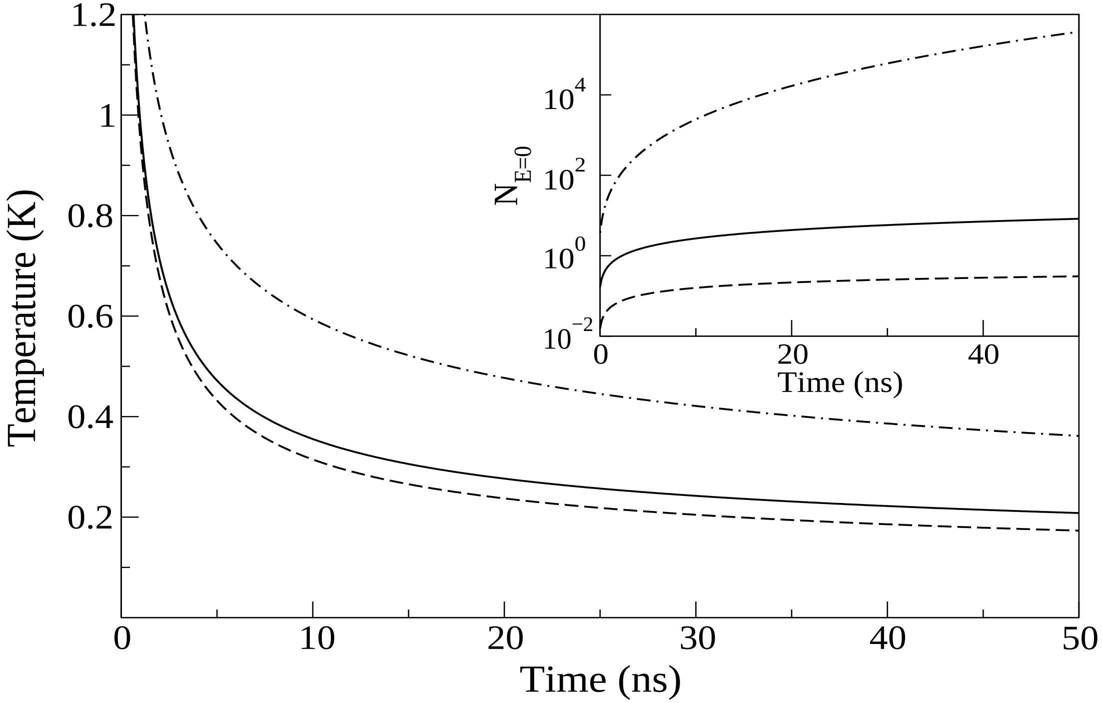
Relaxation thermodynamics of indirect excitons (high-density limit)



$$\frac{\partial}{\partial t}T = -\frac{2\pi}{\tau_{sc}}\left(\frac{T^2}{T_0}\right)\left(1 - e^{-T_0/T}\right)\int_1^\infty d\varepsilon\, \varepsilon\sqrt{\frac{\varepsilon}{\varepsilon - 1}}\,\left|F_z\left(a\sqrt{\varepsilon(\varepsilon - 1)}\right)\right|^2 \times \frac{e^{\varepsilon E_0/k_B T_b} - e^{\varepsilon E_0/k_B T}}{\left(e^{\varepsilon E_0/k_B T} + e^{-T_0/T} - 1\right)}\,\frac{1}{\left(e^{\varepsilon E_0/k_B T_b} - 1\right)},$$

where $\tau_{sc} = (\pi^2\hbar^4\rho)/(D_{dp}^2 M_x^3 v_s)$.

$\rho_{2D} \geq 10^9\,\mathrm{cm}^{-2}$;



- Classical slowing down:

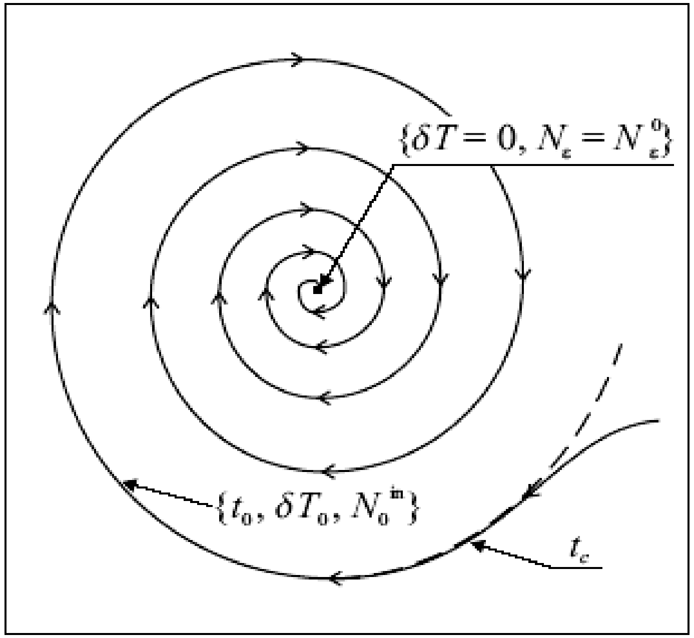
$$N_{E=0}(\tau) = \tau^{k_B T_0/E_0},$$

$$\tilde{T}(\tau) = 1/\ln(\tau) \text{ for } \tau \gg 1,$$

$$\tau = (2\pi^{3/2}E_0 t)/(k_B T_0 \tau_{sc}).$$

- Quantum slowing down.

Generic solutions for phonon-assisted kinetics of indirect excitons (low-density limit)



- Kinetic equation for QW excitons:

$$\begin{aligned}\frac{\partial}{\partial t} N_{\mathbf{k}_\|} = & -\frac{2\pi}{\hbar} \sum_{\mathbf{q}} |M(q, q_z)|^2 \{ [N_{\mathbf{k}_\|} (1 + n_{\mathbf{q}}^{\mathrm{ph}})(1 + N_{\mathbf{k}_\| - \mathbf{q}_\|}) \\ & - (1 + N_{\mathbf{k}_\|}) n_{\mathbf{q}}^{\mathrm{ph}} N_{\mathbf{k}_\| - \mathbf{q}_\|}] \, \delta(E_{\mathbf{k}_\|} - E_{\mathbf{k}_\| - \mathbf{q}_\|} - \hbar q v_s) \\ & + [N_{\mathbf{k}_\|} n_{\mathbf{q}}^{\mathrm{ph}} (1 + N_{\mathbf{k}_\| + \mathbf{q}_\|}) - (1 + N_{\mathbf{k}_\|})(1 + n_{\mathbf{q}}^{\mathrm{ph}}) N_{\mathbf{k}_\| + \mathbf{q}_\|}] \\ & \times \delta(E_{\mathbf{k}_\|} - E_{\mathbf{k}_\| + \mathbf{q}_\|} + \hbar q v_s) \} \, .\end{aligned}$$

$\longrightarrow$ low densities of QW excitons, $\rho_{2\mathrm{D}} \leq 10^9\,\mathrm{cm}^{-2}$,

$\longrightarrow$ low temperatures, $T \leq T_0$, so that $N_{\mathbf{k}_\|} \gg 1$.

- **A generic solution:**

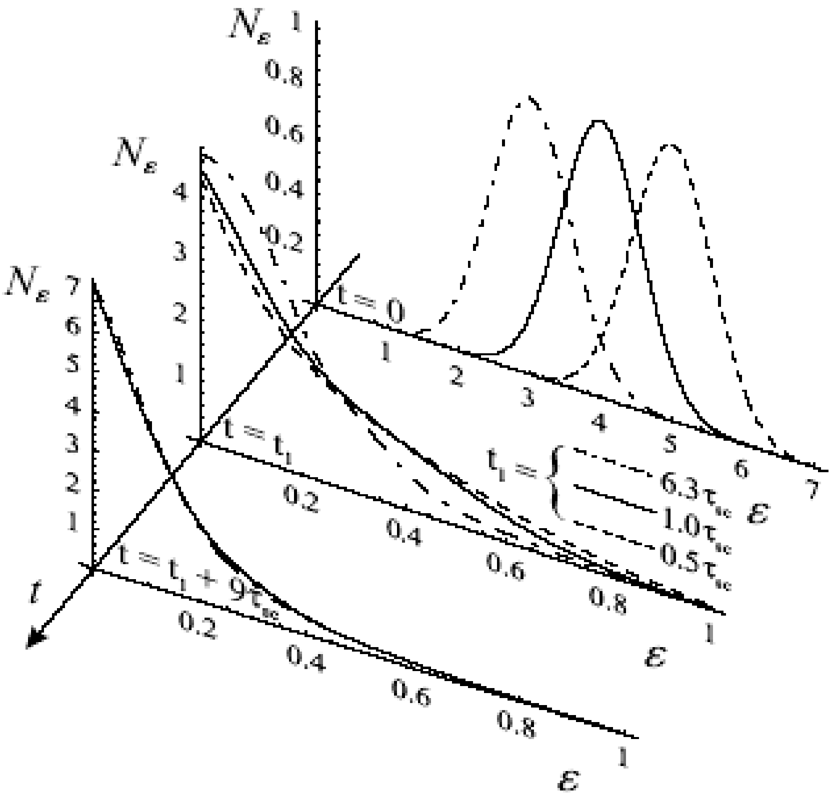
$\longrightarrow$ takes many τ_{sc},

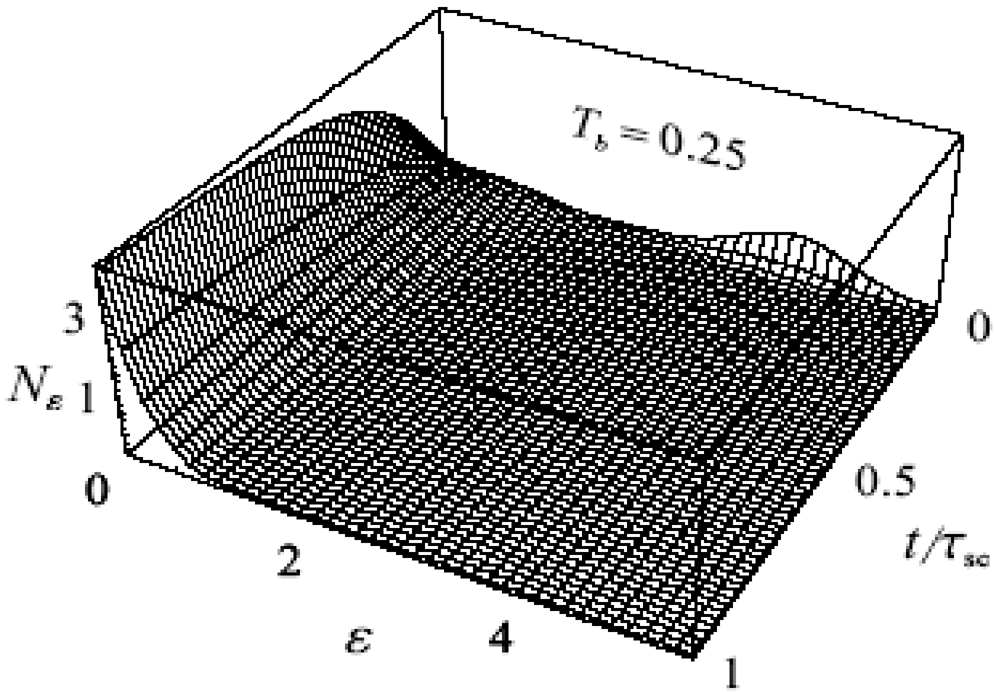
$\longrightarrow$ depends only upon two control parameters, T_b and $T_0 \propto \rho_{2\mathrm{D}}$,

$\longrightarrow$ a quasi-equilibrated distribution of high-energy QW excitons with $T = T(t)$.

[A V Soroko and A L Ivanov (PRB, 2002)]

Transient relaxation towards the adiabatic stage of evolution





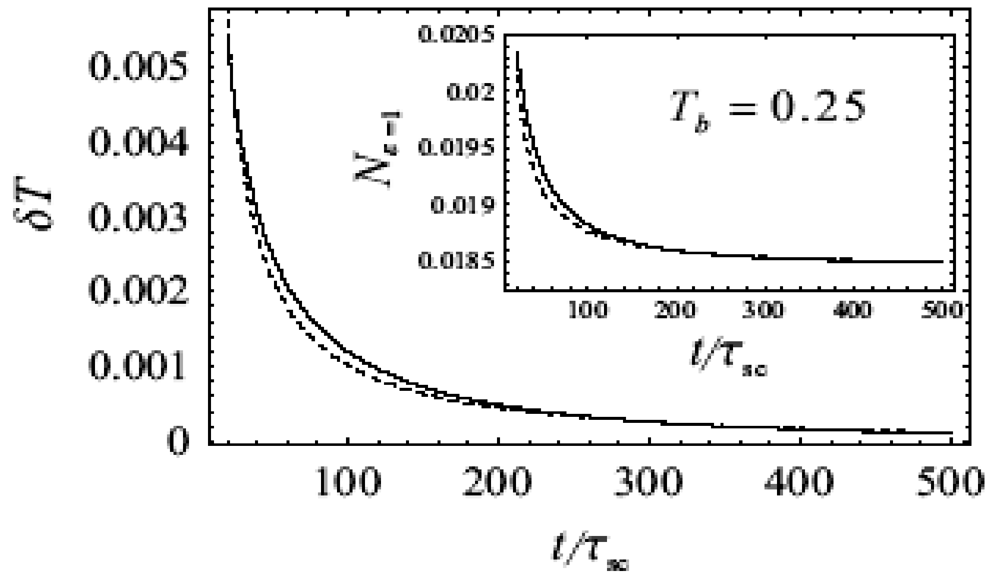
Adiabatic stage of relaxation

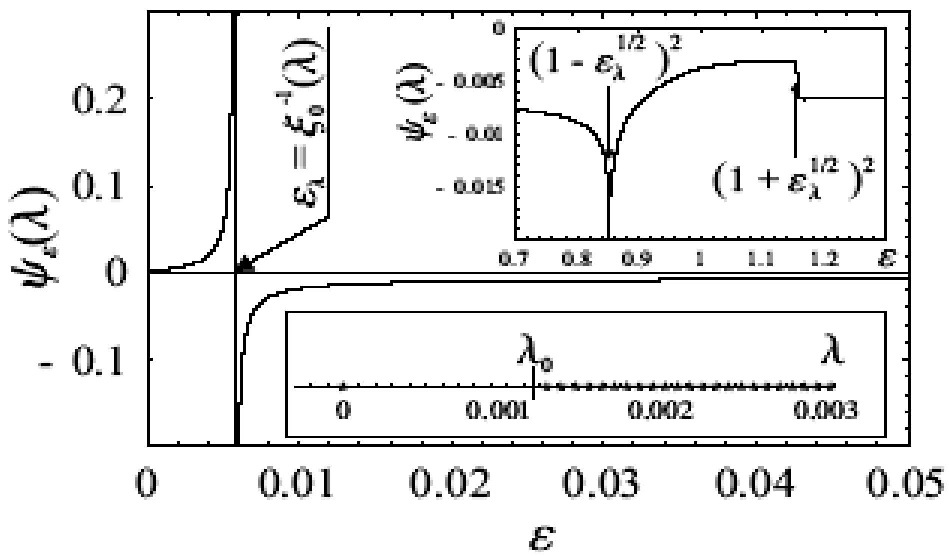
- The thermalization law is given by

$$\delta T(t) = \left(\frac{\delta T_0}{\lambda_1 - \lambda_0}\right) \frac{e^{-\lambda_0(t-t_0)} - e^{-\lambda_1(t-t_0)}}{t - t_0} ,$$

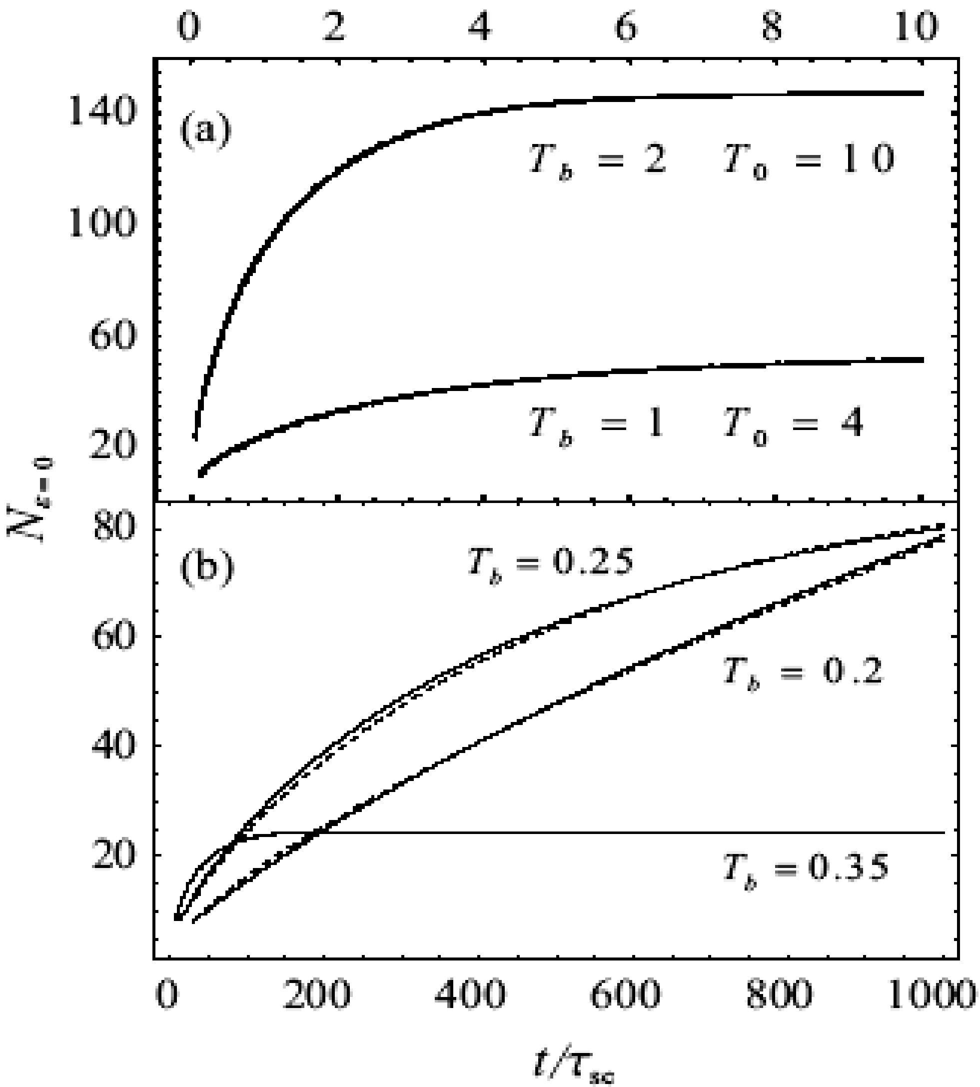
$\rightarrow$ λ_0 is a marginal value of the contunuous eigenvalue spectrum of the linearized kinetics ,

$\rightarrow$ $t_0 \sim \tau_{sc}$ and $\lambda_1 \gg \lambda_0$.





Occupation dynamics of the ground-state mode



- Nonexponential kinetics :

$$N_{\varepsilon=0}(t) = N_0^{\mathrm{in}}[1 + \chi(t - t_0)]^{\nu}\,.$$

The relaxation and photoluminescence dynamics of indirect excitons

- The relaxation and PL dynamics:

$$\frac{\partial}{\partial t}\rho_{2D} = -\frac{\rho_{2D}}{\tau_{opt}} + \Lambda(t)\,,$$
$$\frac{\partial}{\partial t}T = \left(\frac{\partial T}{\partial t}\right)_{\rho_{2D}} + S_T(t)\,.$$

- Three contributions to the relaxation thermodynamics

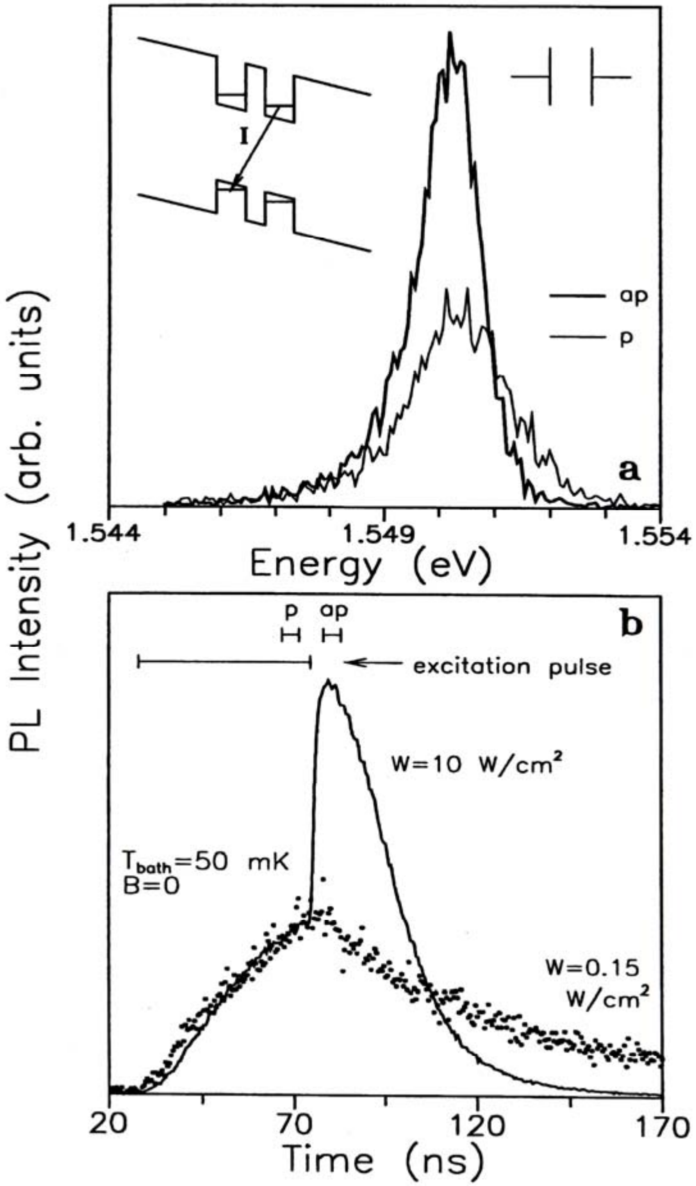
$$S_T = S_{pump} + S_{opt} + S_{diff}\,,$$

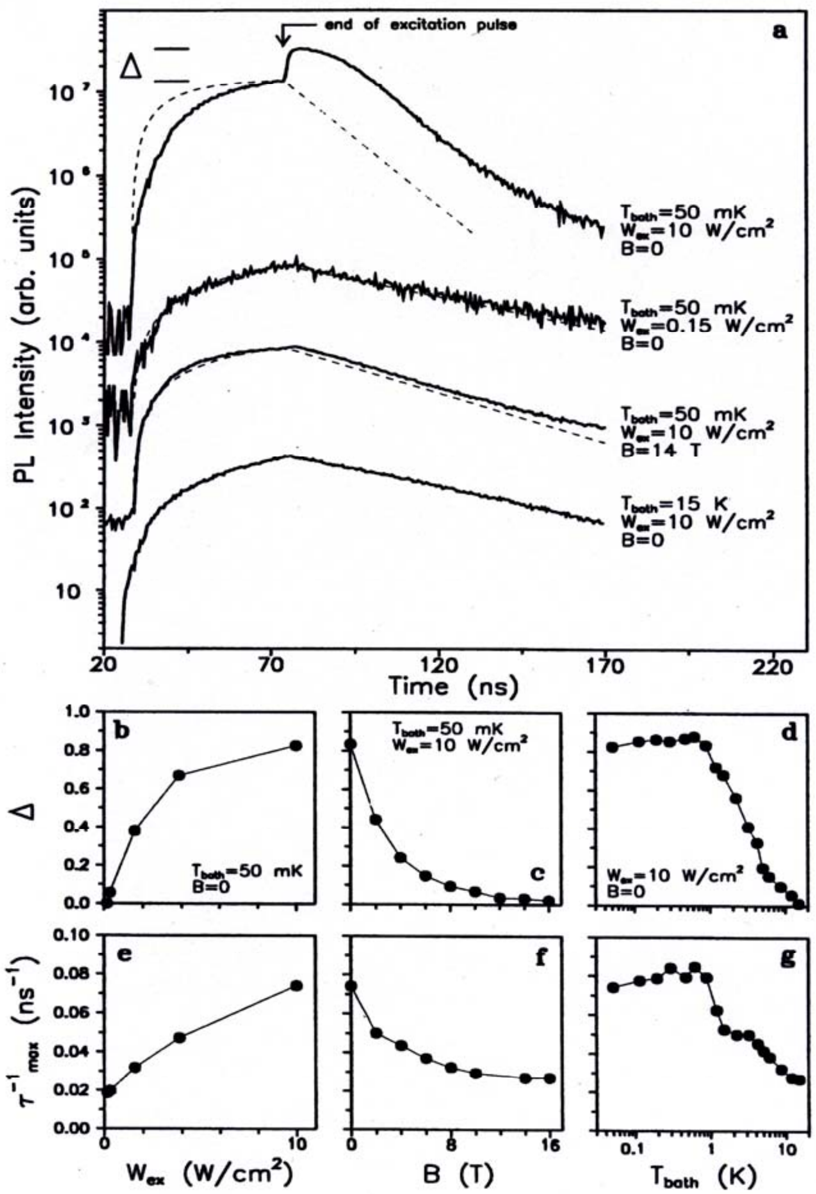
$\longrightarrow$ S_{pump} – heating of indirect excitons by the pump pulse;

$\longrightarrow$ S_{opt} – recombination heating or cooling;

$\longrightarrow$ S_{diff} – heating of indirect excitons by drift and diffusion.

PL jump



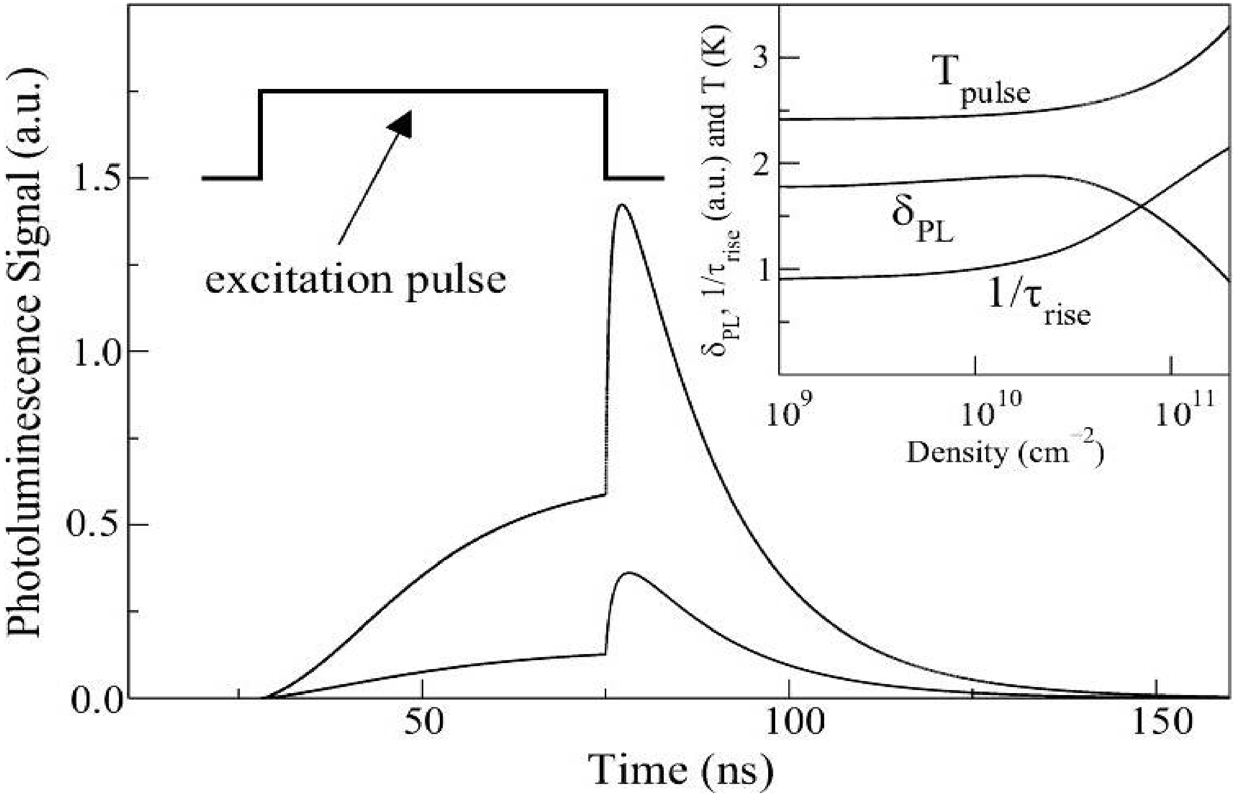


[L V Butov, A L Ivanov, A Imamoglu, P B Littlewood, A A Shashkin, V T Dolgopolov, and A Gossard (PRL, 2001)]

The PL jump: origin and modelling

- The relaxation and PL dynamics:

$$\frac{\partial}{\partial t}\rho_{2D} = -\frac{\rho_{2D}}{\tau_{opt}} + \Lambda(t)\,,$$
$$\frac{\partial}{\partial t}T = \left(\frac{\partial T}{\partial t}\right)_{\rho_{2D}} + S_T(t)\,,$$

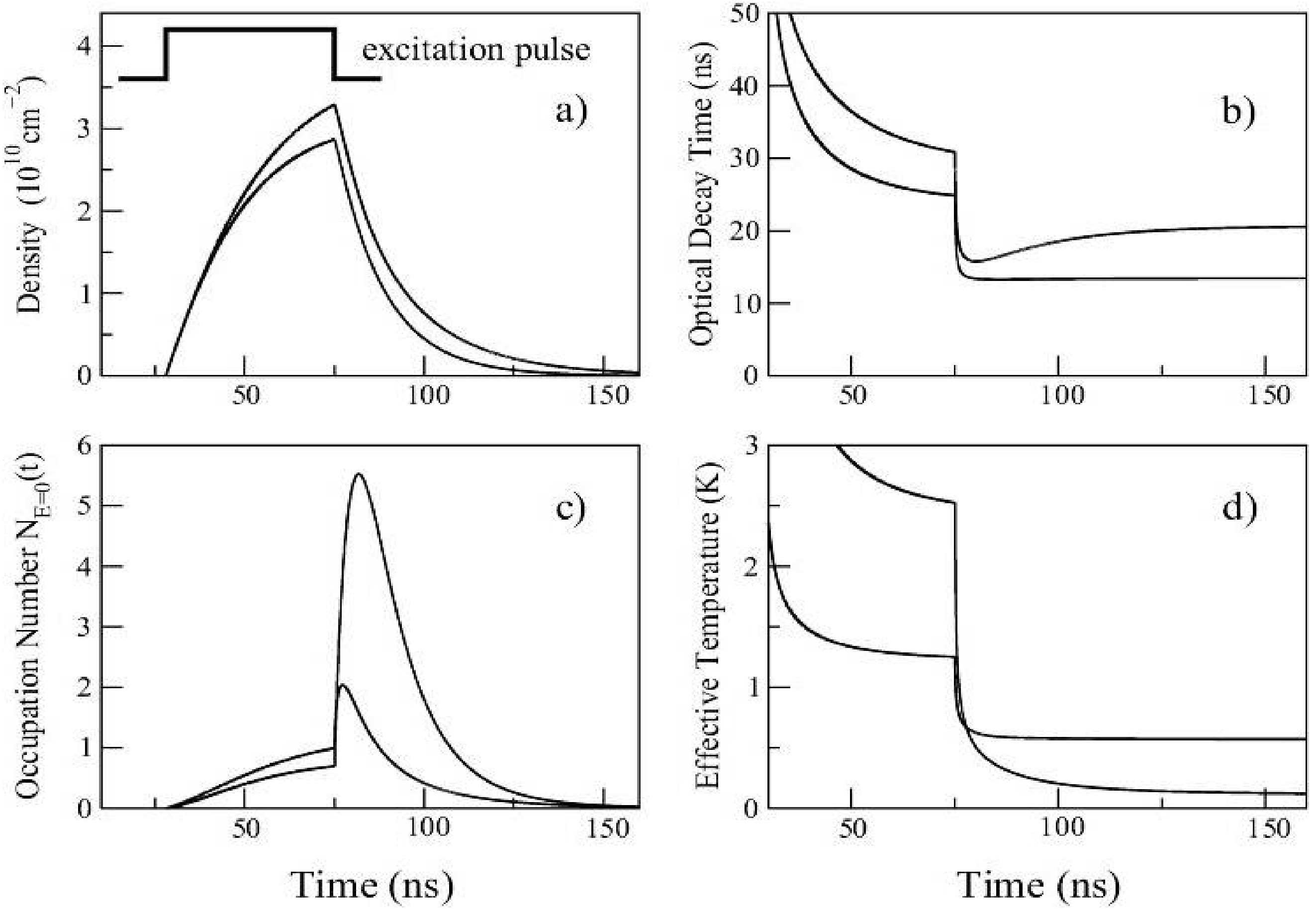


PL dynamics in the presence of $H_\perp$

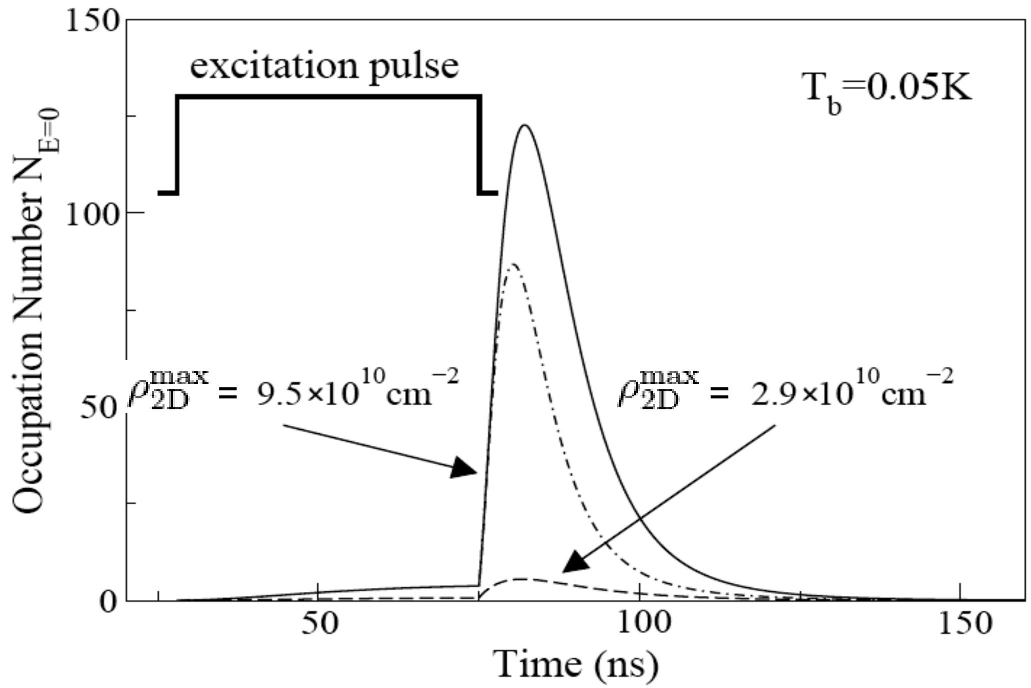
$\longrightarrow \quad H_\perp = 0 \;$ and $g = 4 \;$ (solid lines) ;

$\longrightarrow \quad H_\perp = 14\,\mathrm{T}, \; g = 1 \;$ and $\; M_x \simeq 7.1\, M_x(H_\perp\!=\!0)$ (dashed lines)

(Yu. Lozovik and A. Ruvinskii, 1997) .



Occupation dynamics of the ground-state mode



- Two contradictions in "modelling - experiment" $(10^9\,\mathrm{cm}^{-2} \leq \rho_{2D}^{max} \leq 3\times 10^{10}\,\mathrm{cm}^{-2})$:

$\longrightarrow$ strongly nonlinear increase of $1/\tau_{\mathrm{rise}}$ with ρ_{2D}^{max} (experiment)
against $1/\tau_{\mathrm{rise}}$ nearly independent of ρ_{2D}^{max} (theory);

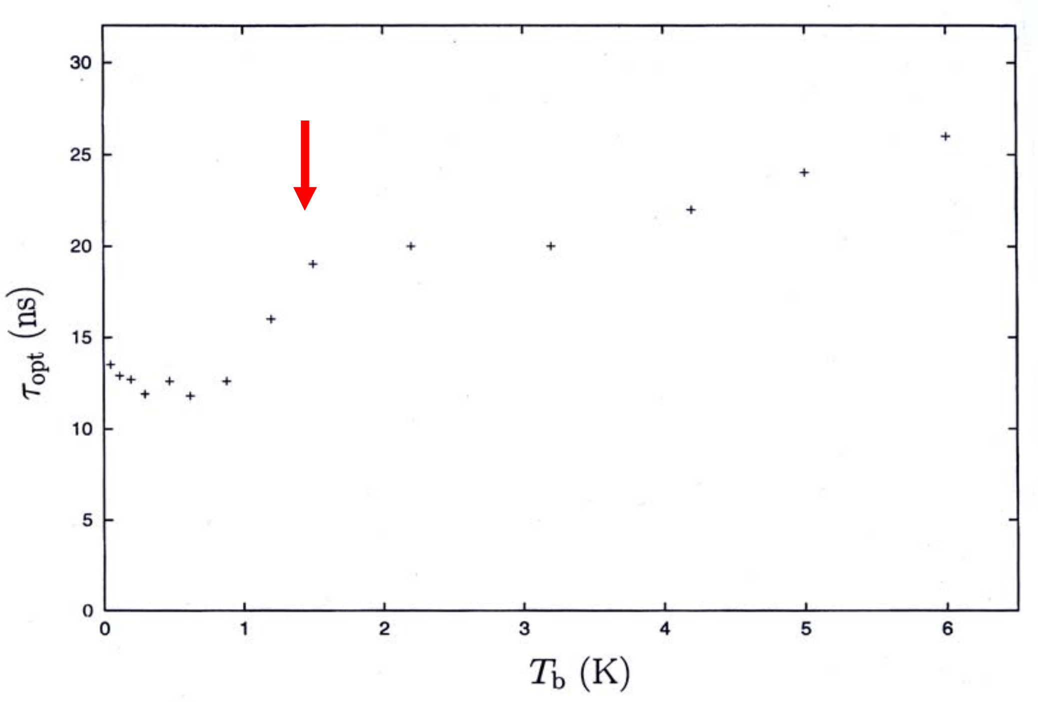
$\longrightarrow$ no PL-jump for $\rho_{2D}^{max} \simeq 10^9\,\mathrm{cm}^{-2}$ (experiment)
against a well-developed PL-jump with $\delta_{\mathrm{PL}} \simeq 2$ (theory).

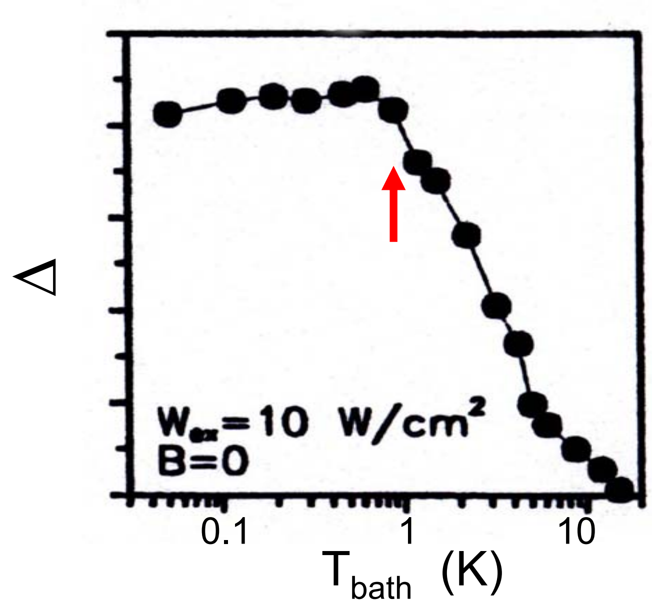
Narrowing effect due to the dipole-dipole interaction of indirect excitons

$\longrightarrow$ building up of the narrowing effect with increasing ρ_{2D} ;

$\longrightarrow$ phonon-assisted hopping against a well-defined $\mathbf{k}_{\|}$;

$\longrightarrow$ for $\rho_{2D} \leq 10^9\,\mathrm{cm}^{-2}$ the disorder effects are well-developed (S Baranovskii, E Runge and R Zimmermann) .





[L V Butov et al. (2001)]

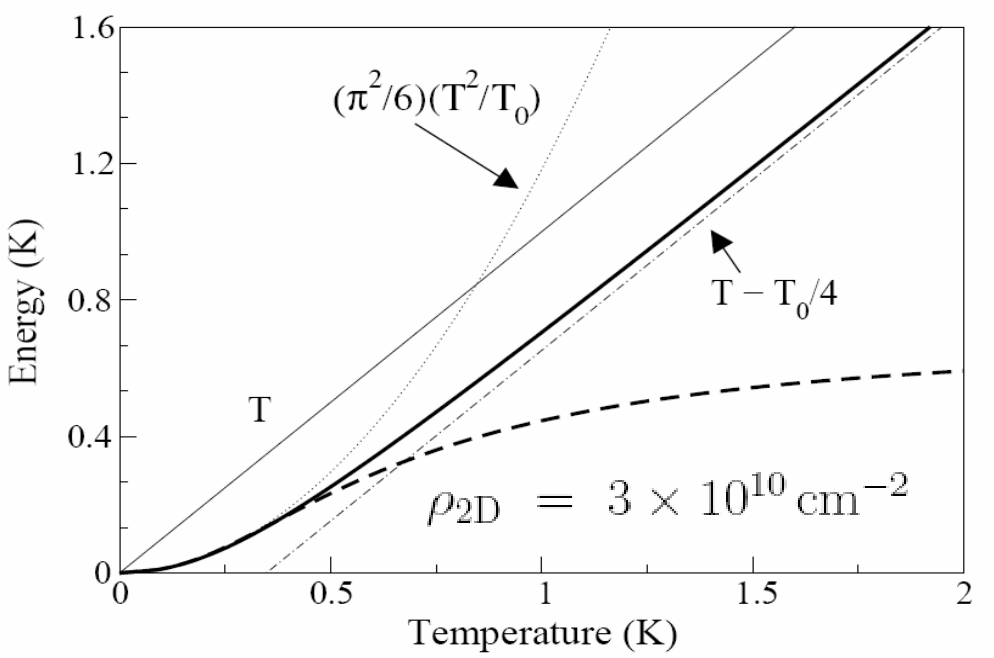
Recombination heating or cooling of indirect excitons

$$E_{\mathrm{kin}}^{(2d)} = \frac{T^2}{T_0} I_1(T, T_0) \quad \text{and} \quad E_{\mathrm{opt}}^{(2d)} = E_\gamma \frac{\tau_{\mathrm{opt}}}{\tau_{\mathrm{opt}}^{\mathrm{E}}} \, ;$$

- $k_{\mathrm{B}}T$ is much larger than $k_B T_0$ and E_γ :

$$E_{\mathrm{kin}}^{(2d)} = k_{\mathrm{B}}T \left(1 - \frac{1}{4}\frac{T_0}{T}\right) \simeq k_{\mathrm{B}}T \quad \text{and} \quad E_{\mathrm{opt}}^{(2d)} = \frac{3}{5} E_\gamma \; .$$

$\longrightarrow$ A net heating effect .



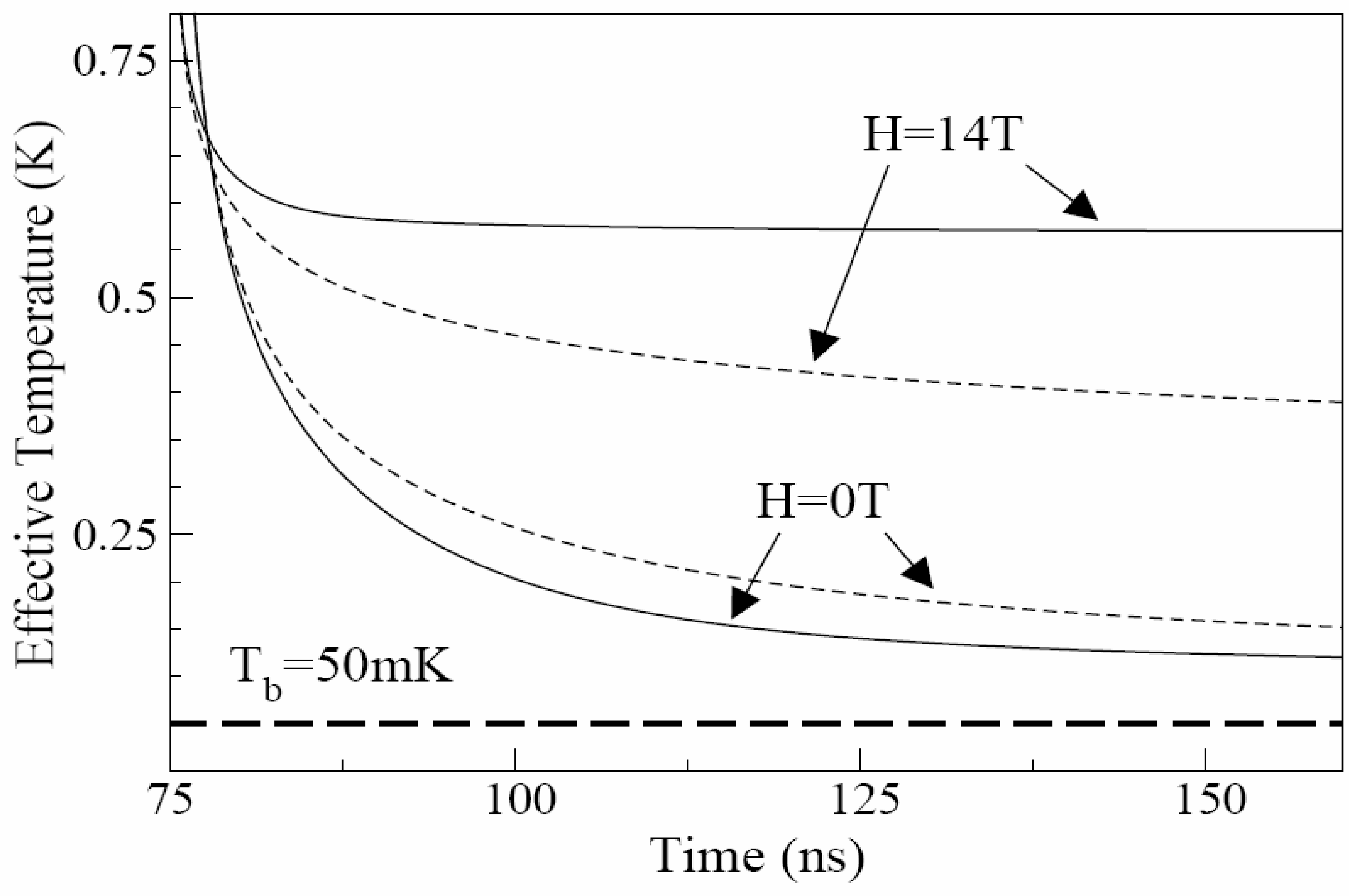
- $k_B T$ is much smaller than $k_B T_0$ and E_γ :

$$E_{\mathrm{kin}}^{(2d)} \simeq E_{\mathrm{opt}}^{(2d)} \simeq \frac{\pi^2}{6} k_{\mathrm{B}} \frac{T^2}{T_0} \; .$$

$\longrightarrow$ A net cooling effect .

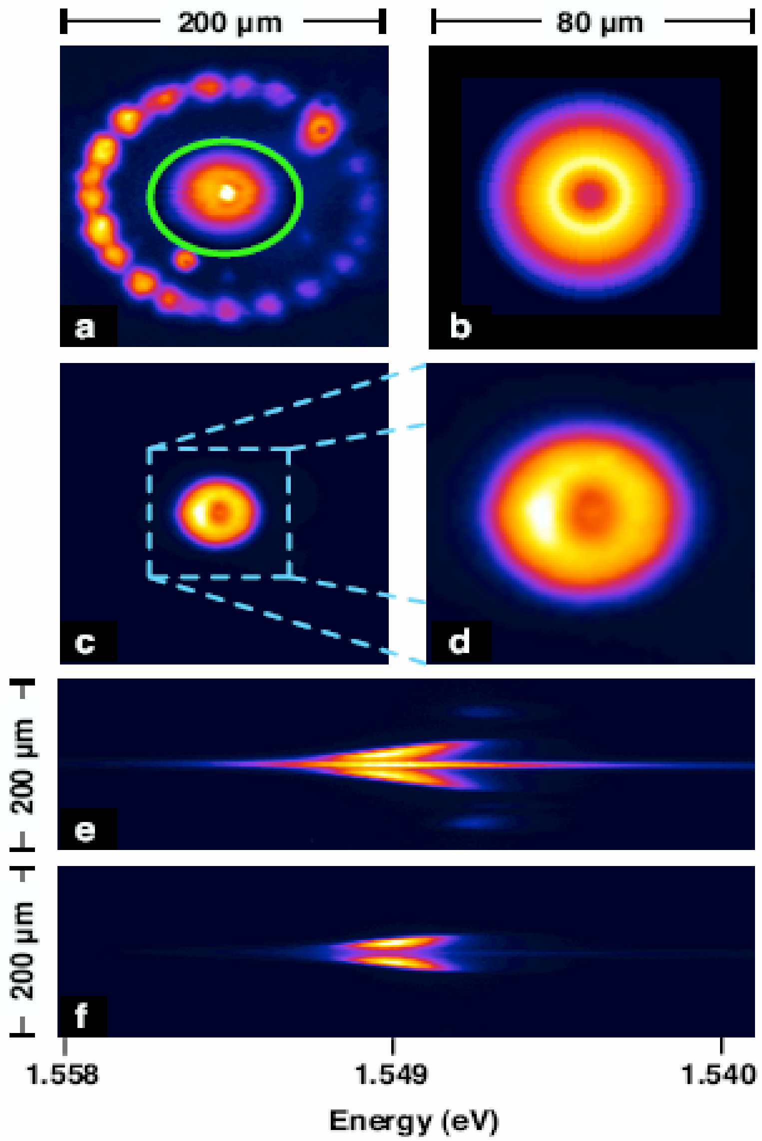
[A L Ivanov, JPCM (2004)]

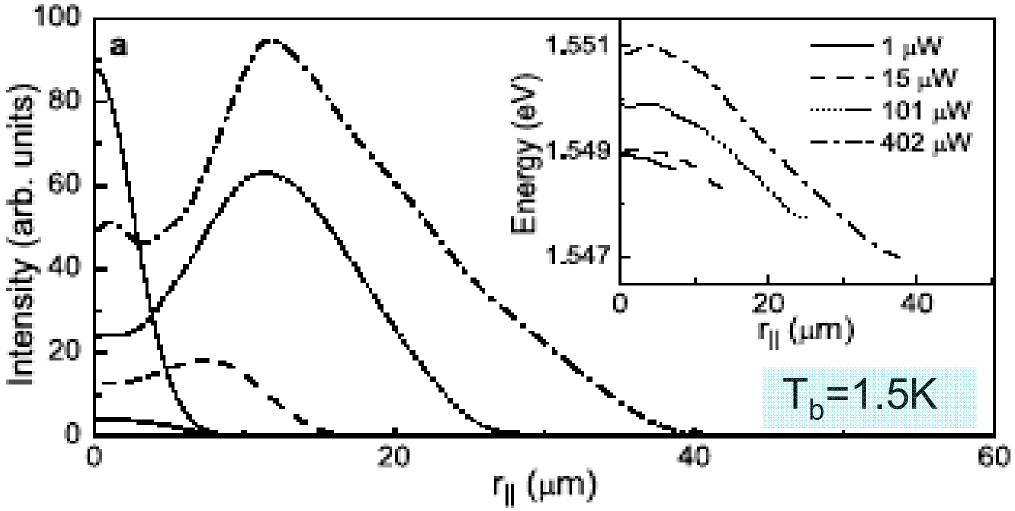
Heating/cooling of indirect excitons due to the optical evaporation



Origin of the inner ring in PL patterns of indirect excitons

[A L Ivanov, L E Smallwood, A T Hammack, S Yang, L V Butov and A C Gossard, EPL (2006)]

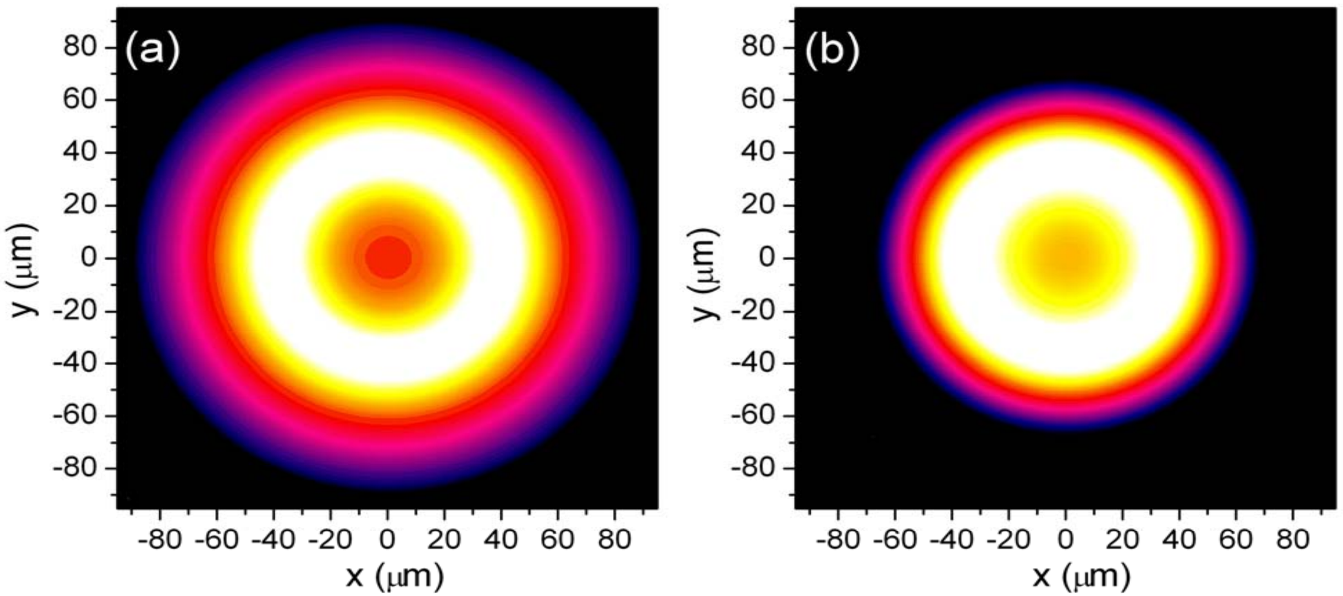




- The first, inner PL ring is akin to the PL jump.
- Spatial pinning of the PL signal: importance of the disorder effects.

Spatial pinning of the PL signal

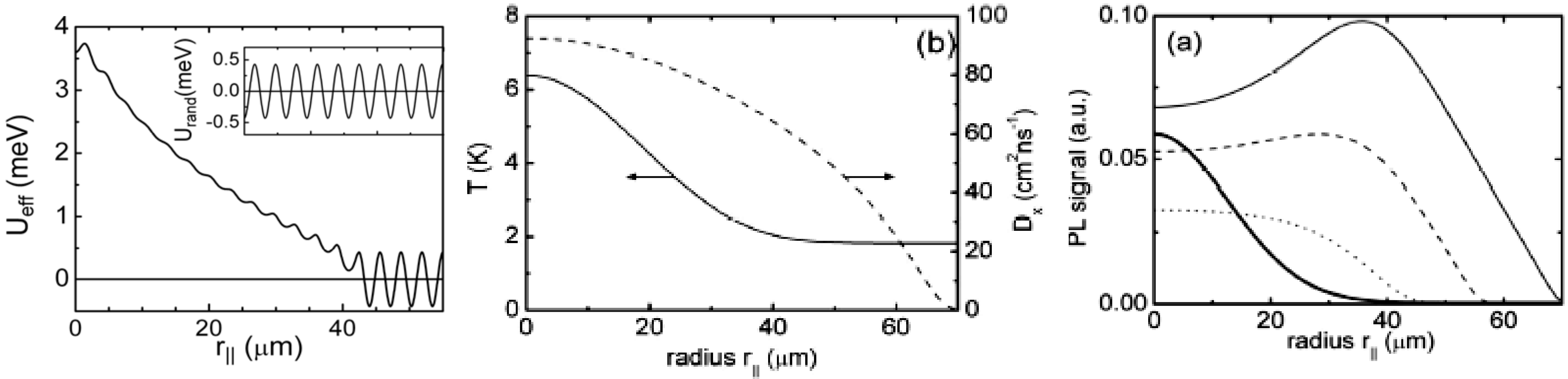
$$I_{\rm PL} \;\propto\; \exp\left[-(\Gamma_{\rm opt}/D_{\rm x}^{(2D)})^{1/2} r_{\|}\right] \; ;$$



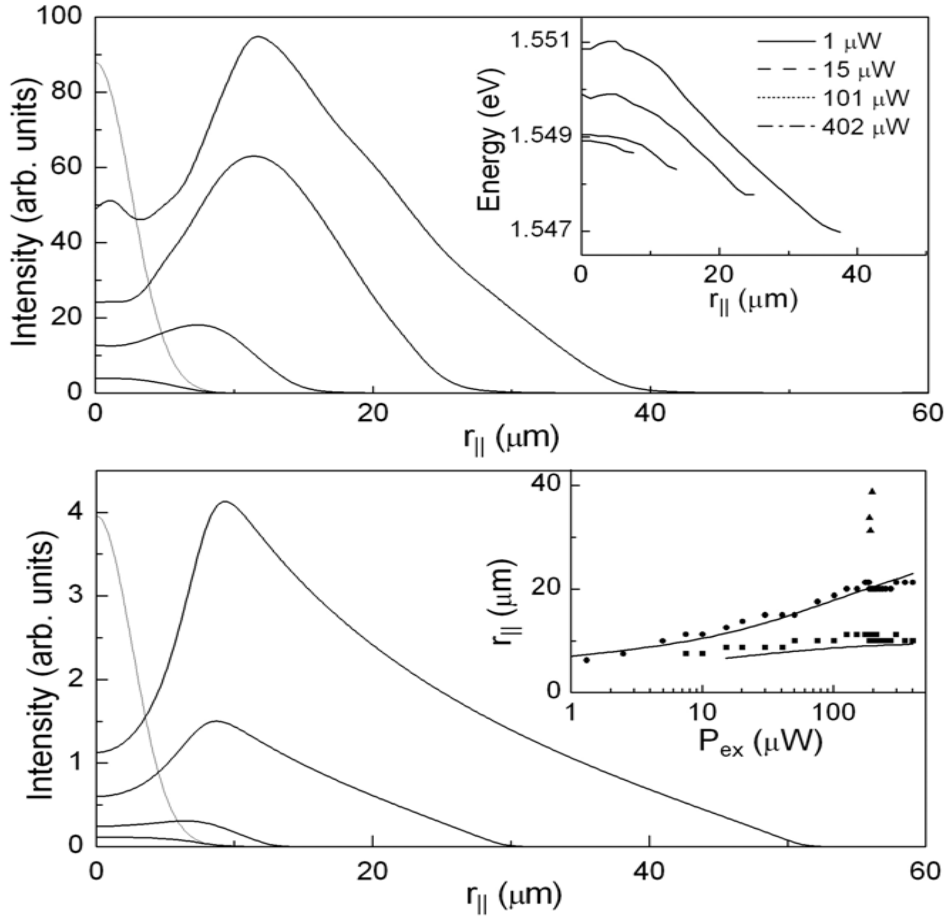
- Thermionic model :

$$\tilde{D}_{\rm x}^{(2D)} = D_{\rm x}^{(2D)} \exp\left[-\frac{U_{\rm rand}(\mathbf{r}_{\|})}{k_{\rm B}T + u_0 \rho_{\rm 2D}^{(0)}}\right] .$$

$$D_{\rm x}^{(2D)} = 100\,{\rm cm}^2/{\rm s}$$



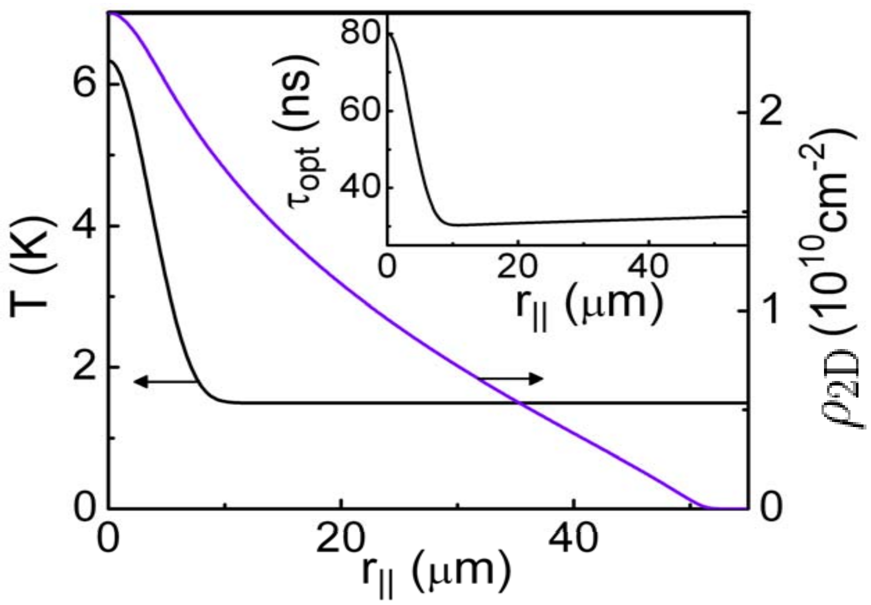
Modelling of the inner ring



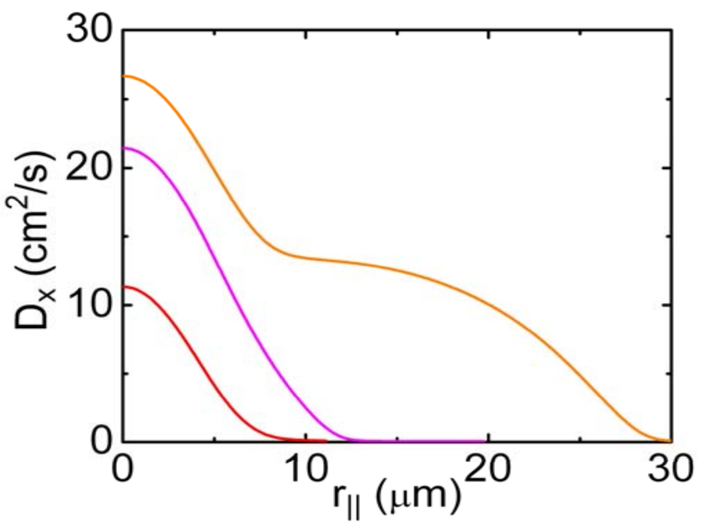
Disorder potential:

$U_0/2 = 0.45$ meV.

Effective temperature and radiative lifetime against radius



Diffusion coefficient against radius



$$D_{\mathrm{x}}^{(2\mathrm{D})} = \frac{D_{\mathrm{x-x}}^{(2\mathrm{D})} D_{\mathrm{x-imp}}^{(2\mathrm{D})}}{D_{\mathrm{x-x}}^{(2\mathrm{D})} + D_{\mathrm{x-imp}}^{(2\mathrm{D})}} ;$$

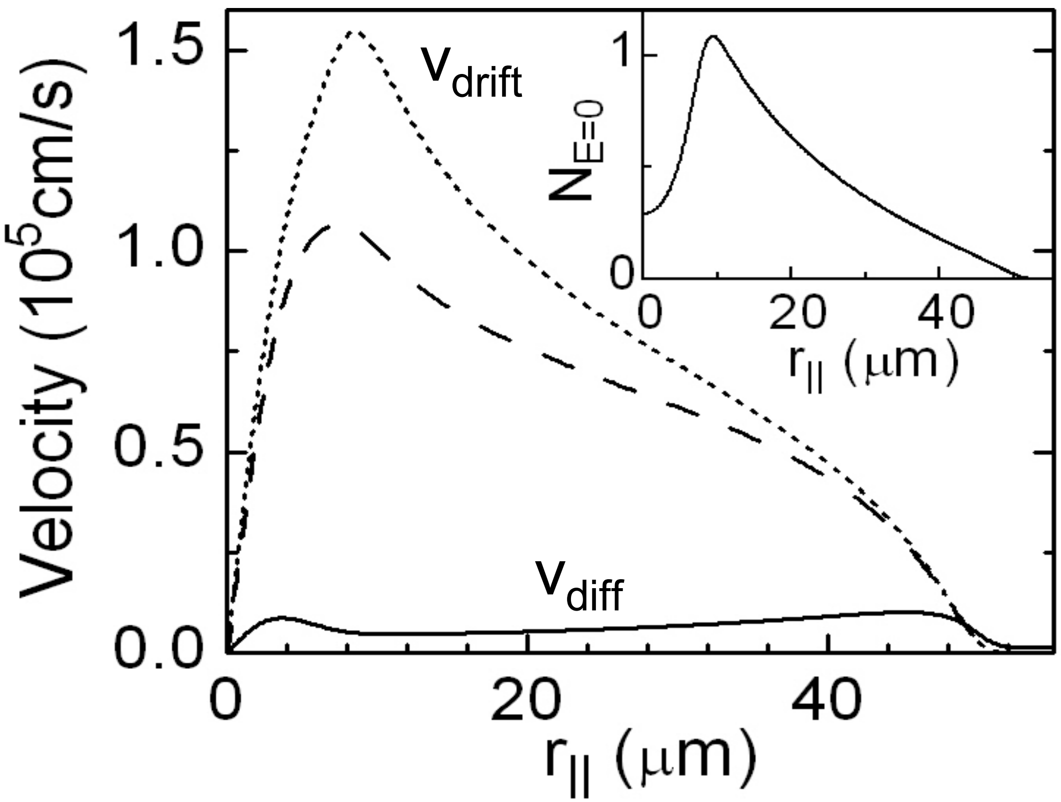
$\longrightarrow$ $D_{\mathrm{x-x}}^{(2\mathrm{D})} = C_{\mathrm{x-x}}(T/T_0)$ – self-diffusion coefficient ,

$\longrightarrow$ $D_{\mathrm{x-imp}}^{(2\mathrm{D})}$ – diffusion due to scattering by imperfections .

[consistent with Z Voros, R Balili, D Snoke et al., PRL (2005)]

In-plane drift and diffusion velocities

$$\rho_{2D}^{\max} = 2.5 \times 10^{10}\,\mathrm{cm}^{-2}$$



- Drift and diffusion velocities:

$$\mathbf{v}_{\mathrm{drift}} \;=\; -\,D_{\mathrm{x}}^{(2\mathrm{D})}\,\frac{(e^{T/T_0}-1)}{k_{\mathrm{B}}T_0}\,u_0\,\nabla\rho_{2\mathrm{D}}\,;$$

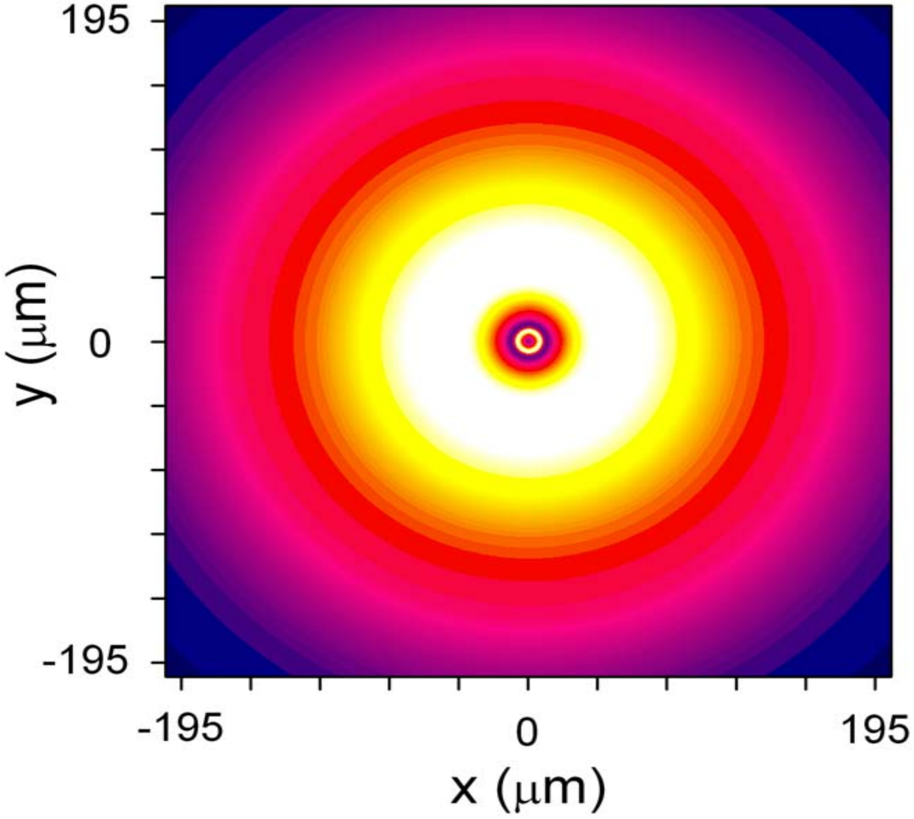
$$\mathbf{v}_{\mathrm{diff}} \;=\; -\,D_{\mathrm{x}}^{(2\mathrm{D})}\,\frac{\nabla\rho_{2\mathrm{D}}}{\rho_{2\mathrm{D}}}\,.$$

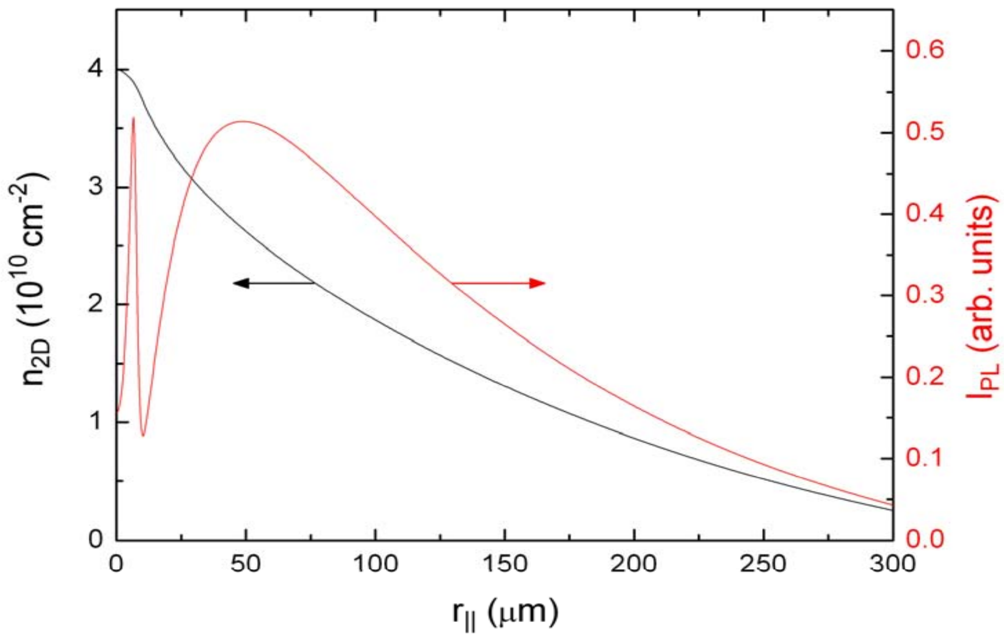
- The mean-field energy gradient:

$$u_0\,|\nabla\rho_{2\mathrm{D}}(r_{\|}\simeq r_{\|}^{\mathrm{rg}})| \;\simeq\; 1.6\,\mathrm{eV/cm}\,.$$

Second inner ring in spatially-resolved photoluminescence

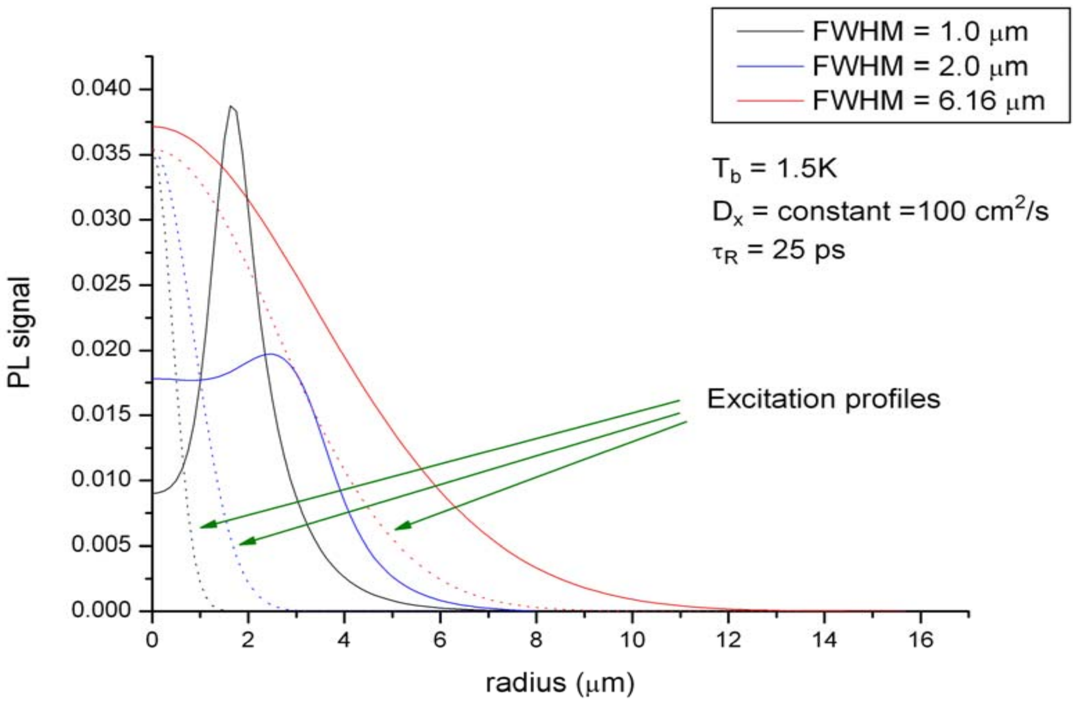
[L Smallwood, PhD, 2006]

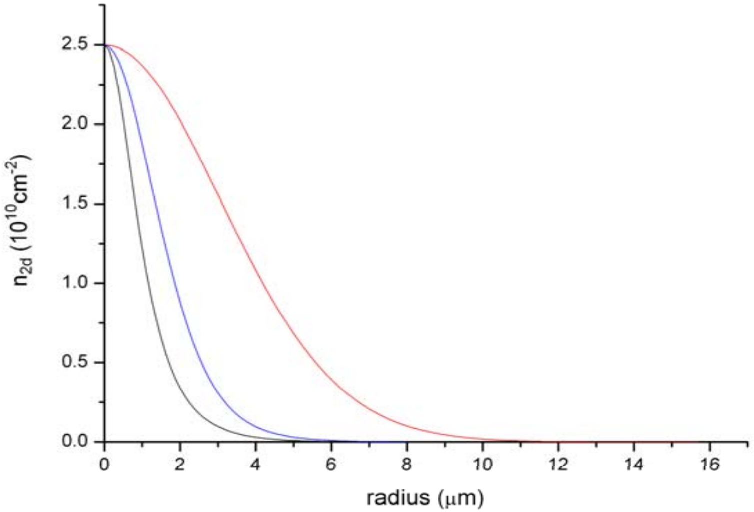


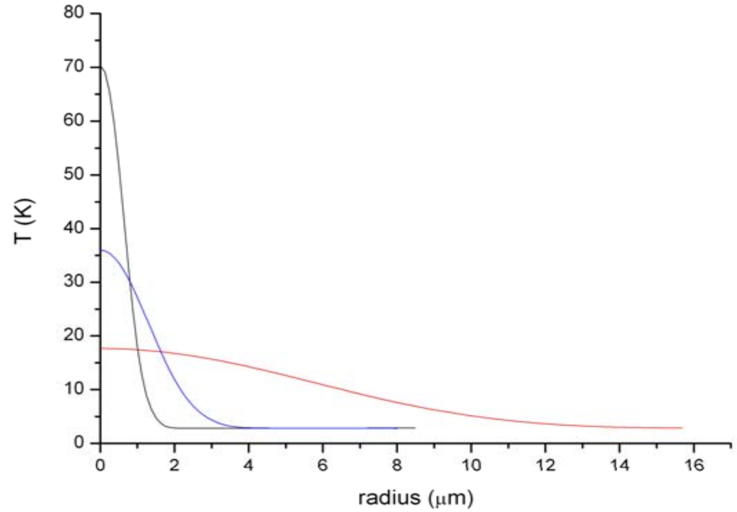


D_x= 250 cm^2/s,   FWHM = 6.16 microns,
T_b = 1.5K, U_0 = 0.9 meV, τ_R = 13 ns.

Inner ring in spatially-resolved photoluminescence from direct excitons in a single quantum well



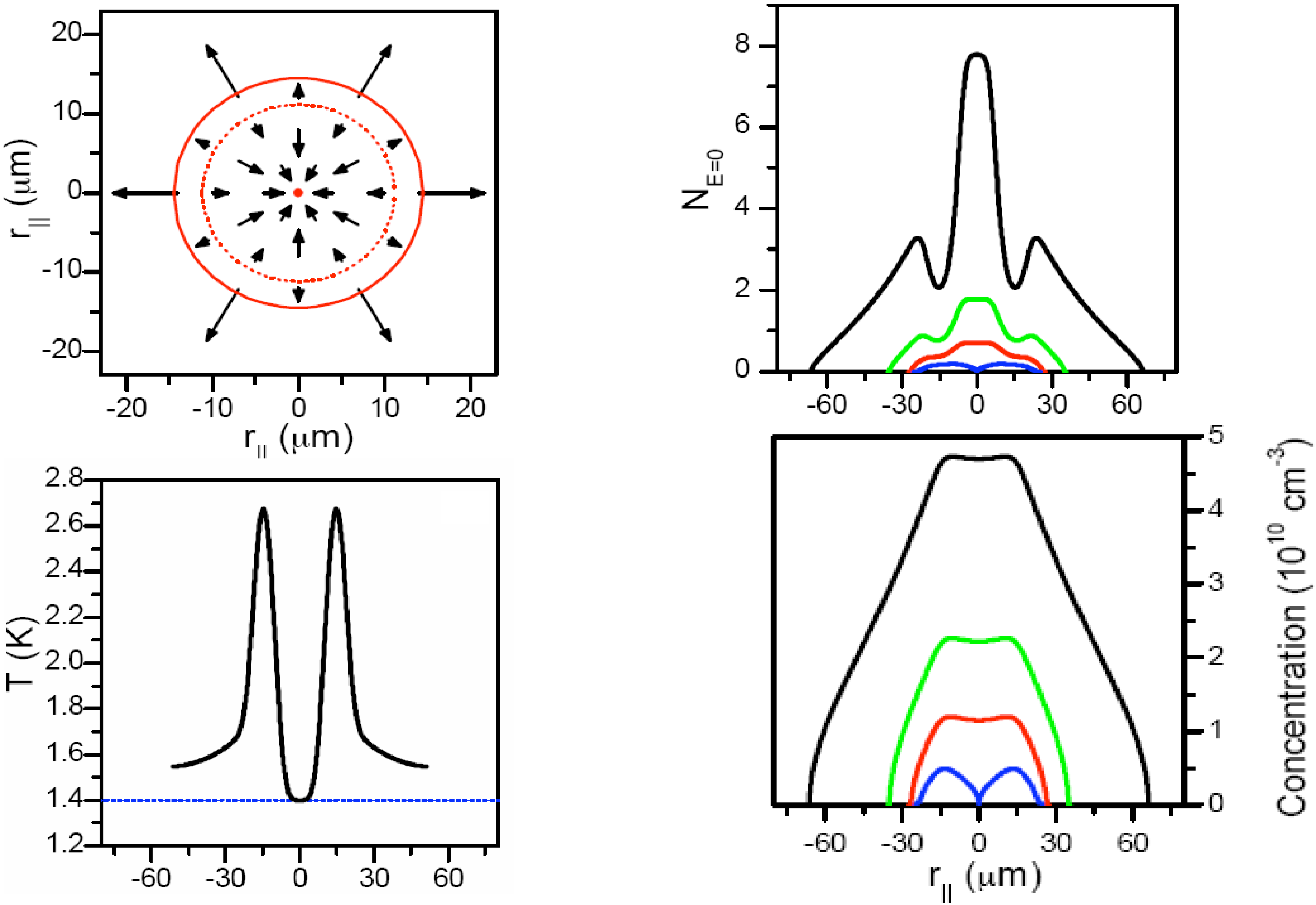




No mean-field energy and no drift

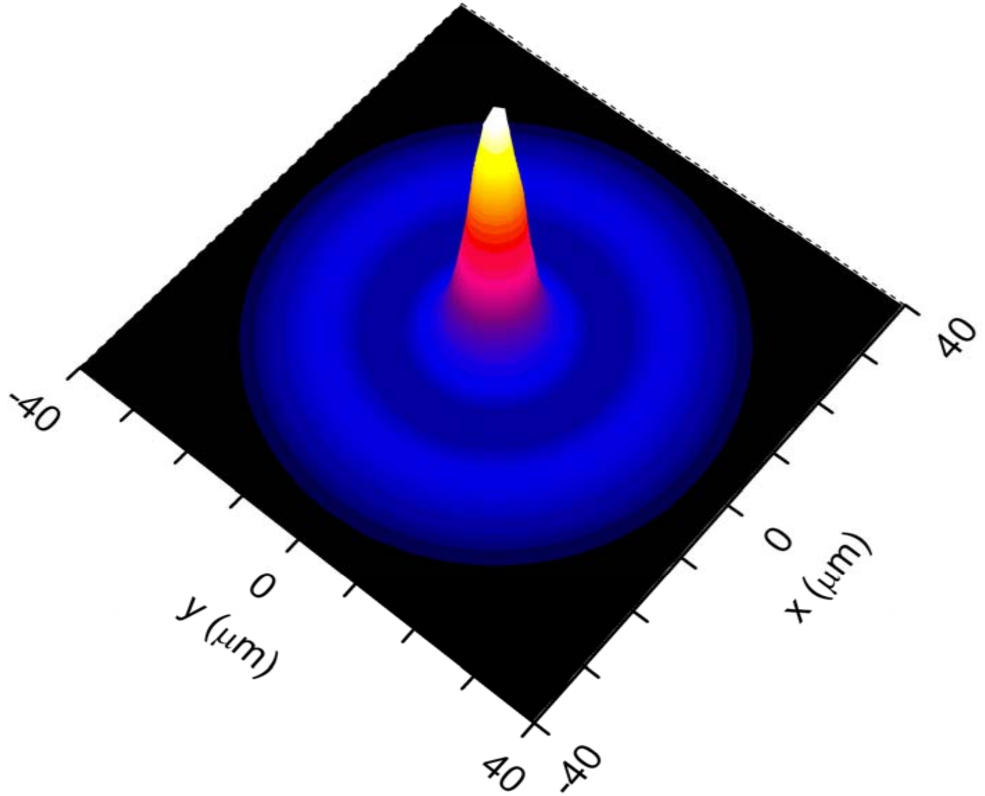
Optically-induced traps for indirect excitons

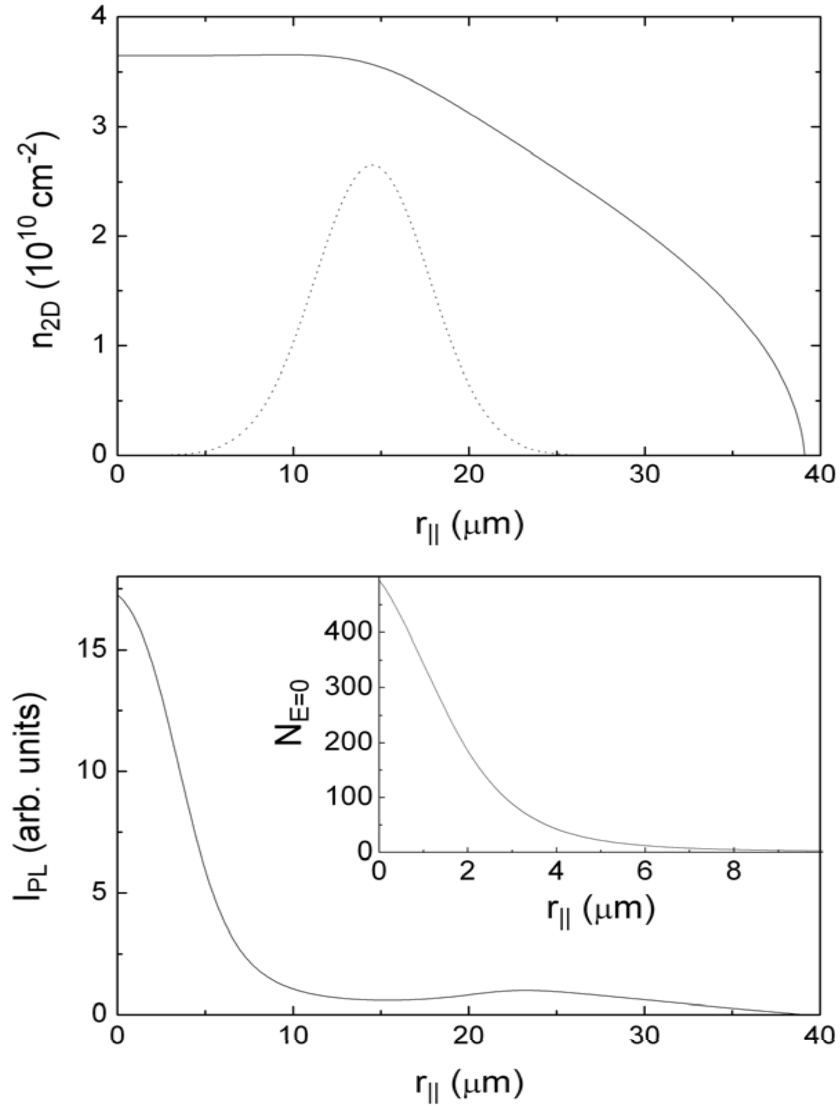
[A T Hammack, M Griswold, L V Butov, L E Smallwood, A L Ivanov and A C Gossard, PRL (2006)]



Ultra-cold indirect excitons

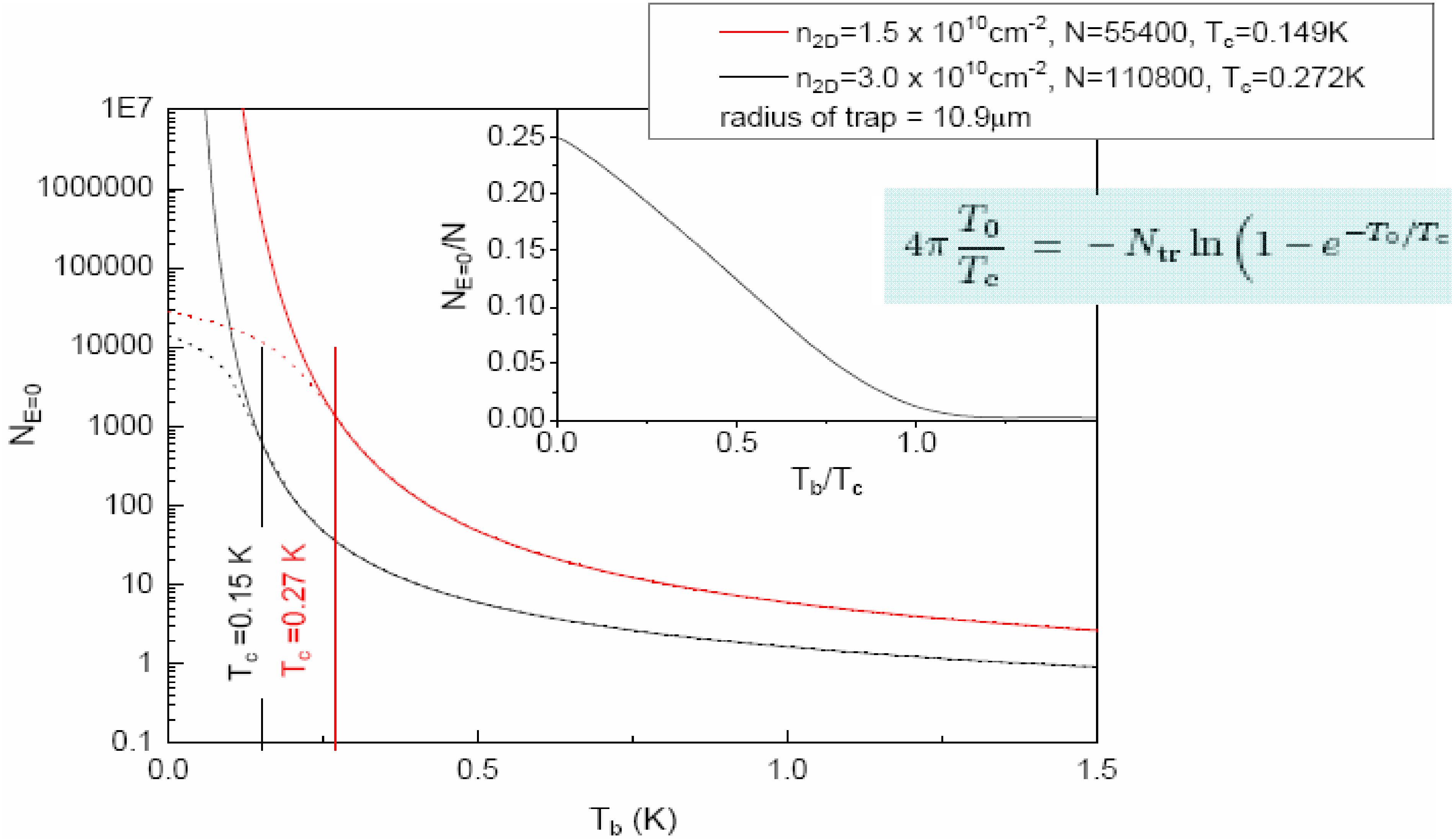
[L Smallwood, PhD, 2006]





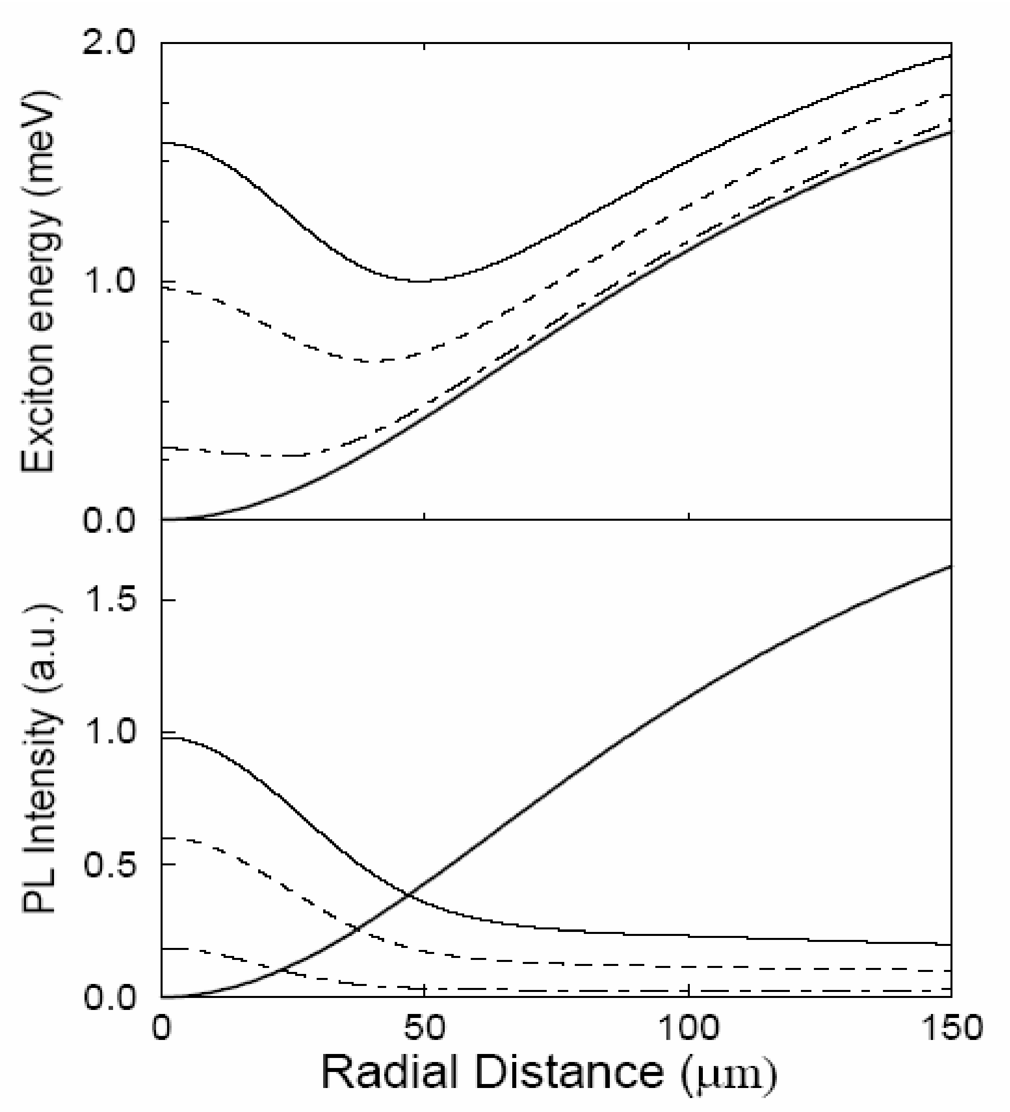
T_b = 0.4K,
FWHM = 7.7 microns,
U_0 = 1.8 meV, τ_R = 21 ns.

Towards BEC of indirect excitons



$$4\pi\frac{T_0}{T_c} = -N_{\mathbf{tr}}\ln\left(1-e^{-T_0/T_c}\right).$$

Photoluminescence of indirect excitons in an in-plane trap



- An in-plane trap:

$$U_{\text{trap}}(r_\parallel) \;=\; \frac{k r_\parallel^2}{2(1 + r_\parallel^2/r_0^2)},$$

$$\rightarrow \quad r_0 = 110\,\mu\text{m and } k = 0.4\,\mu\text{eV}/\mu\text{m}^2$$

so that $U^{\max}_{\text{trap}} = 2.5\,\text{meV}$;

$$\rightarrow \quad \rho^{\max}_{2D} \;\simeq\; 10^{10}\,\text{cm}^{-2}.$$

[L V Butov, C W Lai, A L Ivanov, A C Gossard, and D Chemla (Nature, 2002)]

Hydrodynamics of statistically-degenerate indirect excitons

$$v\frac{\partial \rho_{2\mathrm{D}}}{\partial r_{\|}} \; + \; \rho_{2\mathrm{D}}\frac{\partial v}{\partial r_{\|}} \; + \; \frac{1}{r_{\|}}\rho_{2\mathrm{D}}v \; + \; \frac{\rho_{2\mathrm{D}}}{\tau_{\mathrm{opt}}} \; = \; \Lambda(r_{\|})\,,$$

$$\begin{aligned}(M_x v^2 + T I_0 + \rho_{2\mathrm{D}} B)\frac{\partial \rho_{2\mathrm{D}}}{\partial r_{\|}} + 2M_x \rho_{2\mathrm{D}} v \frac{\partial v}{\partial r_{\|}} + \rho_{2\mathrm{D}}\left(2\frac{T}{T_0}I_1 - I_0\right)\frac{\partial T}{\partial r_{\|}} \\ + \; M_x \rho_{2\mathrm{D}}\frac{v^2}{r_{\|}} \; = \; -\rho_{2\mathrm{D}}\frac{\partial U_{\mathrm{QW}}}{\partial r_{\|}}\,,\end{aligned}$$

$$\begin{aligned}\left(v\frac{M_x v^2}{2} + 2vTI_0 + B\rho_{2\mathrm{D}}v\right)\frac{\partial \rho_{2\mathrm{D}}}{\partial r_{\|}} \; + \; \left(\frac{3}{2}M_x v^2 + 2E_{\mathrm{kin}}\right)\rho_{2\mathrm{D}}\frac{\partial v}{\partial r_{\|}} \\ + \; 2v\left(2\frac{T}{T_0}I_1 - I_0\right)\rho_{2\mathrm{D}}\frac{\partial T}{\partial r_{\|}} \; + \; \frac{1}{r_{\|}}v\rho_{2\mathrm{D}}\left(\frac{M_x v^2}{2} + 2E_{\mathrm{kin}}\right) \\ = \; -\rho_{2\mathrm{D}}v\frac{\partial U_{\mathrm{QW}}}{\partial r_{\|}} \; + \; \Lambda(r_{\|})\Omega_0\,.\end{aligned}$$

Conclusions

- In-plane diffusion of statistically-degenerate indirect excitons:

  a) Quantum diffusion equation and generalized Einstein relationship.
  b) Mean-field energy gives rise to effective screening of QW disorder.
  c) Large drift velocities, $v_{drift} \geq 10^5$ cm/s.

- Relaxation thermodynamics of indirect excitons:

  a) Heating of indirect excitons by the laser pulse (T can be much large T_b).
  b) Recombination heating or cooling of indirect excitons.
  c) Heating due to conversion of the MF energy to the internal one.
  d) It is extremely difficult, but still possible, to get T < 1K and $N_{E=0} > 10$.

- Modelling of the inner ring in the PL patterns of indirect excitons:

  a) The ring is due to cooling of excitons in their propagation from the laser spot.
  b) Diffusion coefficient D_x = 10-30 cm^2/s and amplitude of disorder $U_0/2$ = 0.5 meV.

- Synergetics of indirect excitons:

  Three coupled nonlinear equations for ρ_{2D}, T and Γ_{opt}.