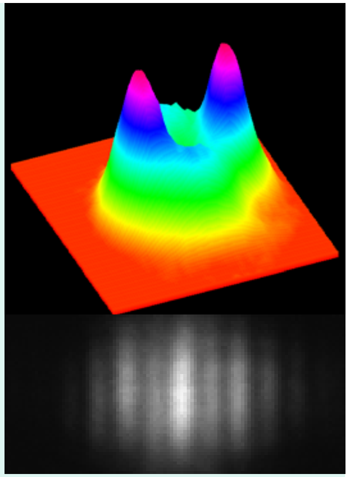
International School on Spin-Optronics

St.Petersburg
10-14 July 2012



Bose-condensation of 2D-dipolar excitons in lateral traps in heterostructures

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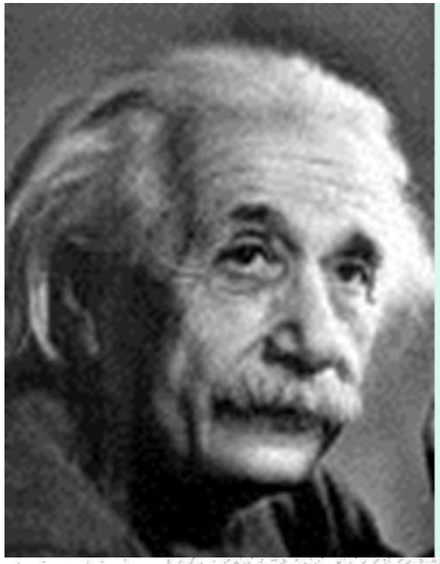
Institute of Solid State Physics RAS



A.EINSTEIN

Quantentheorie des einatomigen idealen Gases
Sitzungber Preuss.Acad.Wiss., 1, 3-14 (1925)

Satyendra N.Bose

Anmerkung des Übersetzers. Boses Ableitung der Planckschen Formel bedeutet nach meiner Meinung einen wichtigen Fortschritt. Die hier benutzte Methode liefert auch die Quantentheorie des idealen Gases, wie ich an anderer Stelle ausführen will.

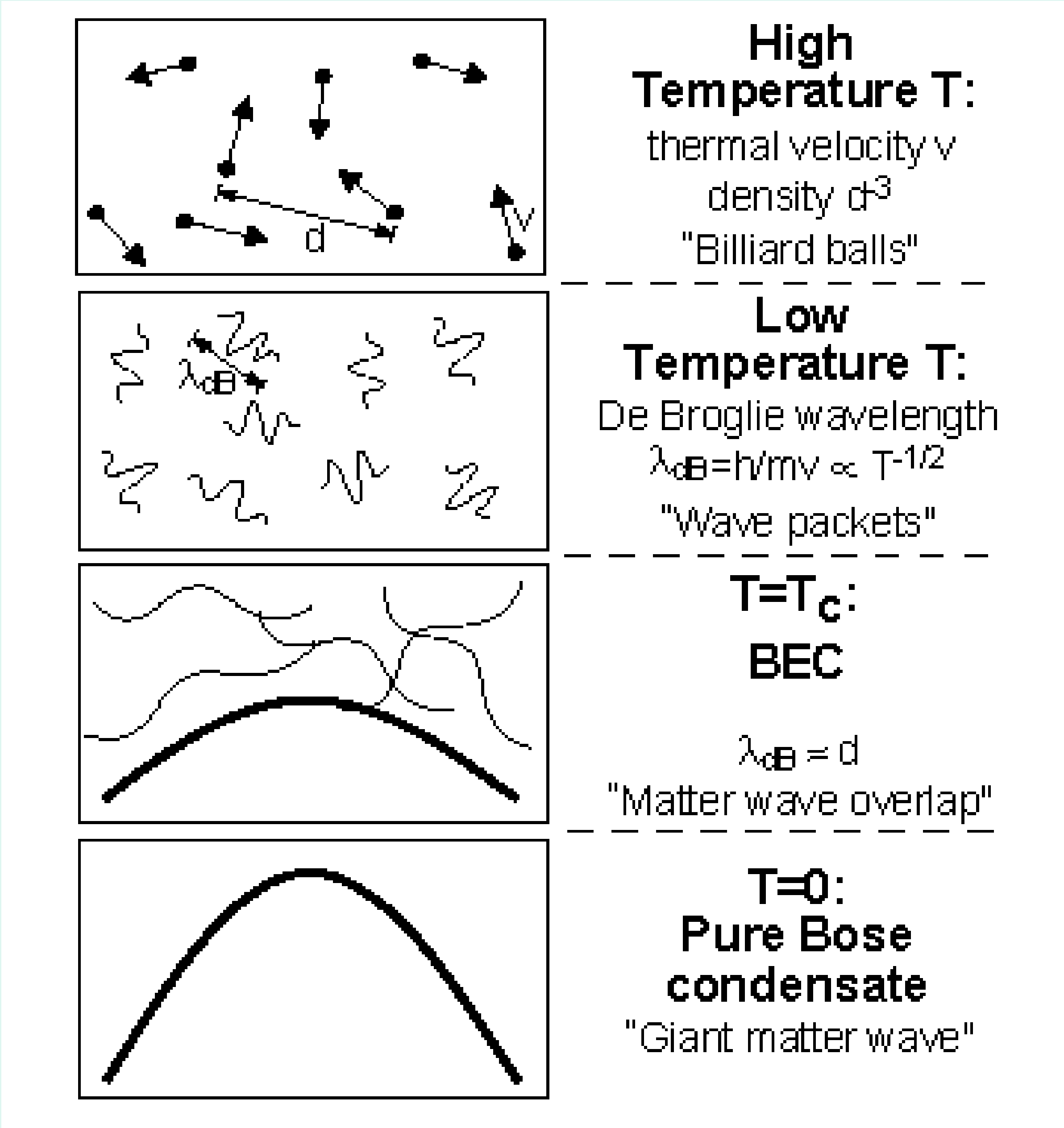
Planck's Law and the Light-Quantum Hypothesis ***Z. Physik*** **26,. 168-171 (1924)**

BEC in diluted Bose gases ($N a^d << 1$, N –density, a – linear size of Bose-particle, d – system dimensionality) occurs when thermal de Broglie wavelength $\lambda_{dB} = (h^2 / 2\pi m k_B T)^{1/2}$ exceeds the interparticles separation (1924-25)

BEC is accompanied by

1. **macroscopic occupation of the ground single partical state with momentum $p=0$ ($N \to N_o$ when $T \to 0$)**
2. **appearance of the order parameter (coherence, ξ) destroyed by fluctuations**
3. **in 3D Bose-system BEC takes place when $D \equiv N\lambda_{dB}^3 = 2.612$**

Qualitative picture of BEC



$$n\lambda_{\mathrm{T}}^{3} = n\left(\frac{2\pi\hbar^{2}}{m^{*}k_{\mathrm{B}}T}\right)^{3/2} \sim 1$$

$$\lambda_{dB} \approx (h^2 / 2\pi \text{ mkBT})^{1/2}$$

Fritz London *Nature N3571, 643 (1938)*

The λ-Phenomenon of Liquid Helium and the Bose-Einstein Degeneracy

$T_{\lambda} \cong 2.17K$ $T_{London} \cong 3.3K$

[8] Burton, E. F., NATURE, 135, 265 (1935); Kapitza, P., NATURE, 141, 74 (1938); Allen, J. F. and Misener, A. D., NATURE, 141, 75 (1938).

Superconductivity is associated with BEC of Cooper pairs (composite Bosons)

J.Bardeen, L.N.Cooper, J.R.Schrieffer *Phys.Rev. 106, 162 (1957); 108, 1175 (1957)*

In atomic Bose-gases BEC was discovered at T ≤ 1μK (1995)

E.Cornell, W.Ketterle, and C.E.Wieman (Nobel Prize 2001)

BEC of exciton gas was considered at the first time by

Moskalenko (1962), Blatt et al. (1962), Casella (1962), Keldysh, Kopaev (1965)

Excitonic scales in semiconductors

$R_{ex} = 1/\varepsilon_0^2 \, (\mu_{ex} / m_O) \, R_H$

(Ge, GaAs: $R_{ex} \approx$ 4 meV)

$a_{ex} = \varepsilon_O \, (m_O/\mu_O) \, a_H$

(Ge, GaAs : $a_{ex}^B \approx 10^{-6}$ cm)

$\mu_{ex} \approx 0.1\, m_e$; $M_{ex} \approx m_e$

$\chi_{ex}^{dia} \approx 10^5 - 10^6 \, \chi_H^{dia}$

Photoexited exciton gas is open-dissipative system

BEC discovered in various monoatomic alkali gases: 87- Rb, 23-Na, 7-Li and also 1-H at $T_C \le 10^{-6}$ K
These atoms posses an odd number of electrons , thus an even total number of Fermions, and so, as composite bosons, obey Bose statistics

In the case of GaAs/AlGaAs QWs 2D-excitons reaches a value $T_C \approx 1K$ for exciton density per spin
$N / g = 10^{10}$ cm^{-2}
($a_B \approx 15$ nm, $m_{ex} \approx 0.25\, m_0$, spin degeneracy $g = 4$)

Uniform Noninterracting 2D Bose Gas

The total Bose-partical numbers is $$N = N_0 + \frac{m^* L^2}{2\pi\hbar^2}\int_{\epsilon_0}^{\infty}\frac{\mathrm{d}\epsilon}{\mathrm{e}^{\beta(\epsilon-\mu)}-1}$$

1.When **μ > $\boldsymbol{\varepsilon_o}$** (the lowest energy), the Taylor expansion of the integrand shows a nonintegrable infrared (low energy) divergence.
Therefore, the critical number $\mathbf{N_c}$ is infinite, so always $\mathbf{N_o/N \ll 1}$,
and **no BEC occurs (!)**

2.Acccording *Hohenberg-Mermin-Wagner* theorem long-range order (LRO) in noninterracting 2D Bose gas is distroyed (!) by long-wavelenfth thermal fluctuations.
Therefore there are only short-range correlations and correlation function n(1)(s)

has a Gaussian form: n(**s**)Ξn(**Δr**) = $$n^{(1)}(s) = n\mathrm{e}^{-\pi s^2/\lambda_T^2}$$

Let us difine the 2D *phase-space density* $D=n\lambda_T^2$
(n-density, the thermal de -Broglie wavelength $\lambda_T = h/\sqrt{2\pi m^* k_B T}$

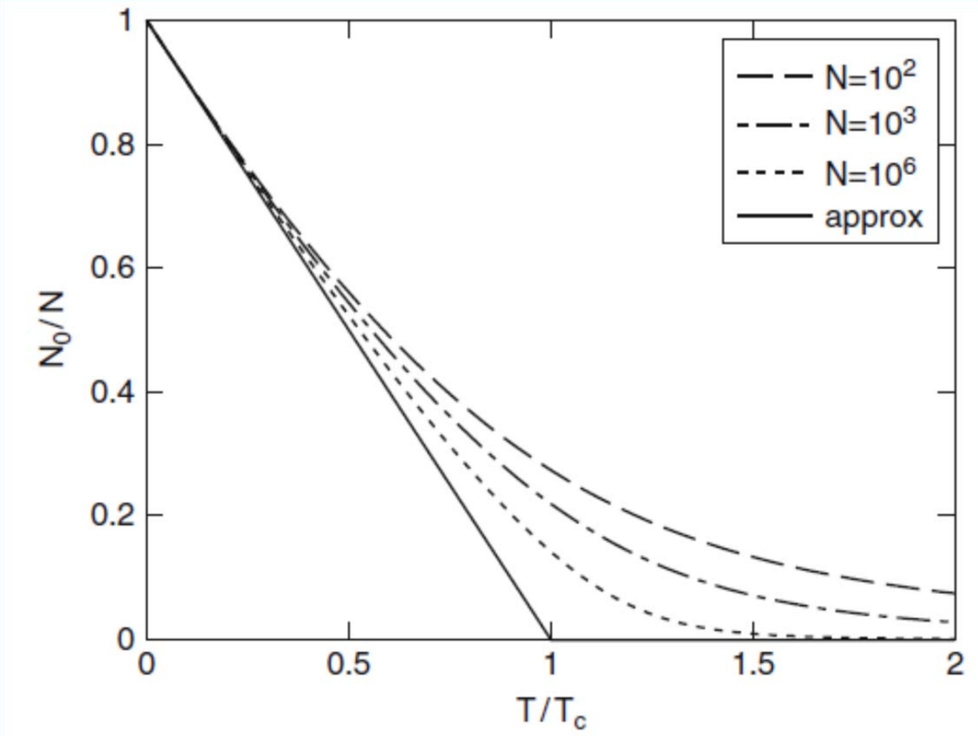
When D<<1 a gas is *nongenerate and classical*
When D > 1 a gas is degenerate and quantum effects are expected

Trapped Noninterracting 2D Bose Gas

1.In finite system, when correlation length is of the same order as system size, $k_c \approx L$, the population *No* of the ground single particle state can be a considerable fraction of the total particle number N and the system can show BEC- like features (!)

Using Bose-Einstein distribution one can receive:

$$N = N_0 + \frac{2m^* L^2}{\pi \hbar^2} k_B T \left[\ln(N_0) + \ln\left(1 + \frac{1}{N_0}\right) \right]$$



Assuming N>>1 and low enough T, when $N \approx N_o$, one can get:

$$N_0 = N\left(1 - \frac{T}{T_c}\right), \qquad k_B T_c = \frac{\pi \hbar^2 N}{2m^* L^2 \ln(N)}$$

2.In a finite geometry considerable coherence can be established across the whole system (!)

2D trapped BEC. Ground state fraction N_o/N *vs* temperature T in a 2D trapped Bose gas in an ifinitely deep QW. As total number of particles increases the exact expression for N_o converges: $No = N\,(1 - T/T_c)$ ***(From Roumpos, 2012)***

Outline

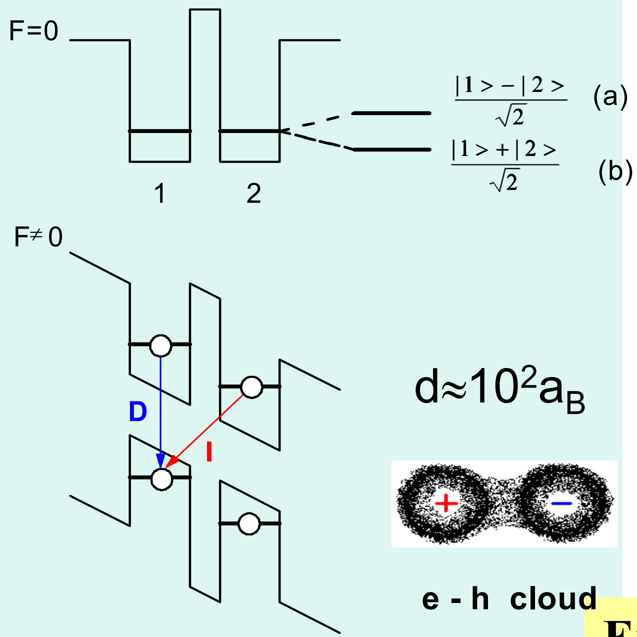
- Introduction

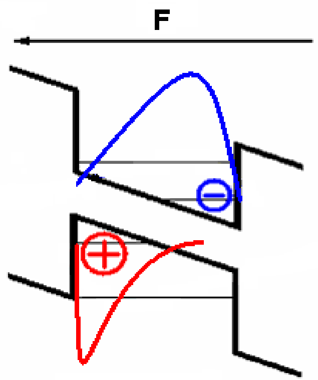
- Schottky-diode heterostructures with double and single QWs
- Electrostatic lateral traps for dipolar excitons and compensation of extra charges in traps
- Bose-Einstein condensation of dipolar excitons in lateral trap exhibited in bimodal luminescence spectra
- Phase diagram
- Patterned photoluminescence structure of BEC in circular traps (vortices?)
- Coherence of dipolar exciton Bose-condensate: $g^{(1)}$ and $g^{(2)}$ correlators
- Spin-related phenomena of dipolar excitons Bose-condensate:

  1. linear polarization of photoluminescence of dipolar excitons Bose-condensate and spontaneous symmetry breaking
- 2. suppression of spin splitting of dipolar exciton Bose condensate – direct consequence of Bose-Einstein degeneracy

- Some remarks in conclusion and perspectives

Double Quantum Well   Wide Single Quantum Well





Solov'ev, Kukushkin et al (2006)
Gorbunov, Timofeev (2006)

Space separation of electrons and holes under applied electrical bias

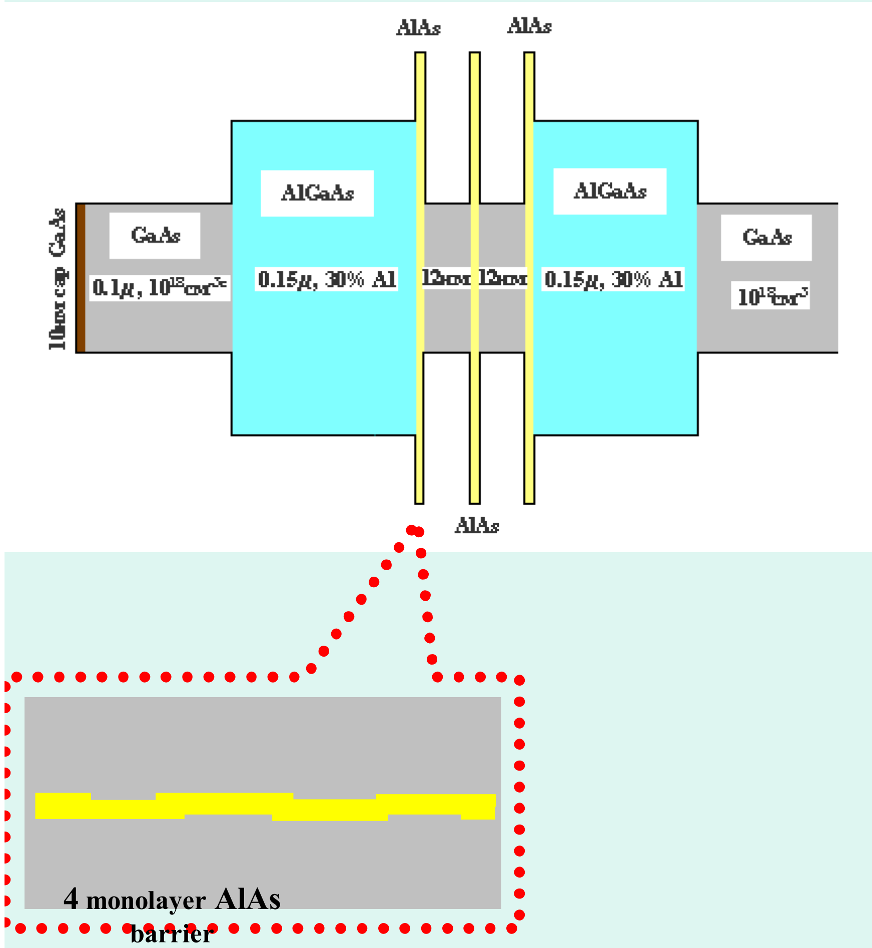
Creation of spatially indirect (or dipolar) excitons with large dipole momentum in the ground state

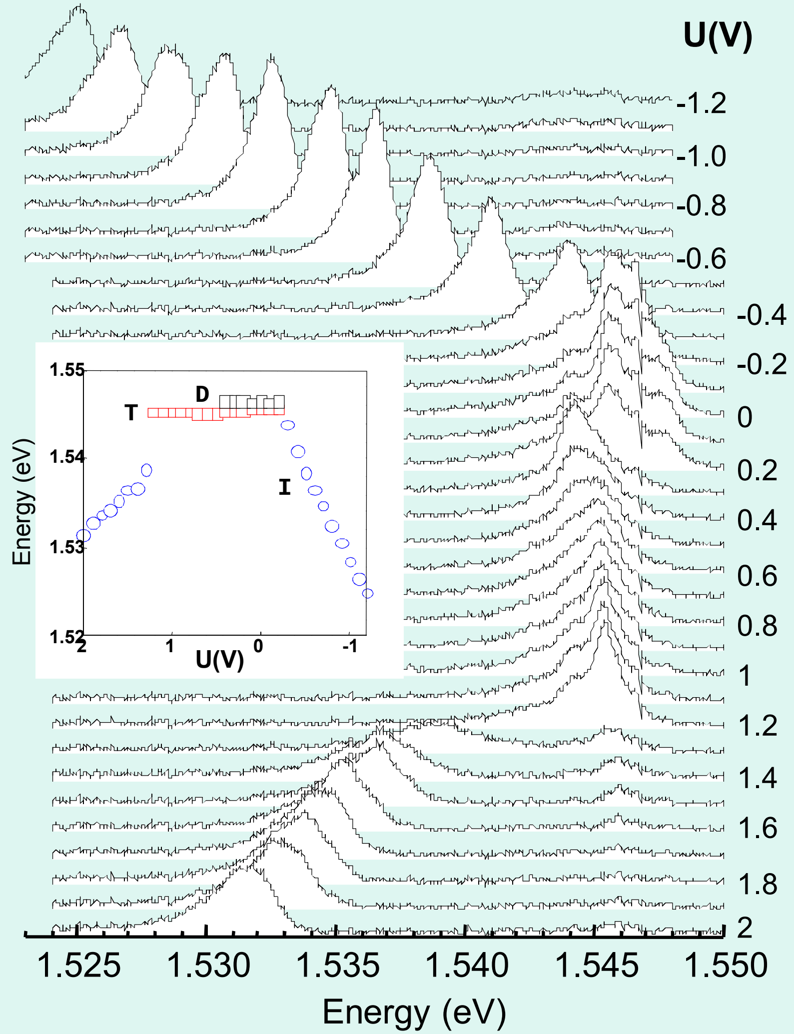
Enhanced radiative decay time is due to reduced electron-hole overlap in the direction of applied bias. It open opportunity to accumulate such excitons to high density and cool them down to low enough temperatures

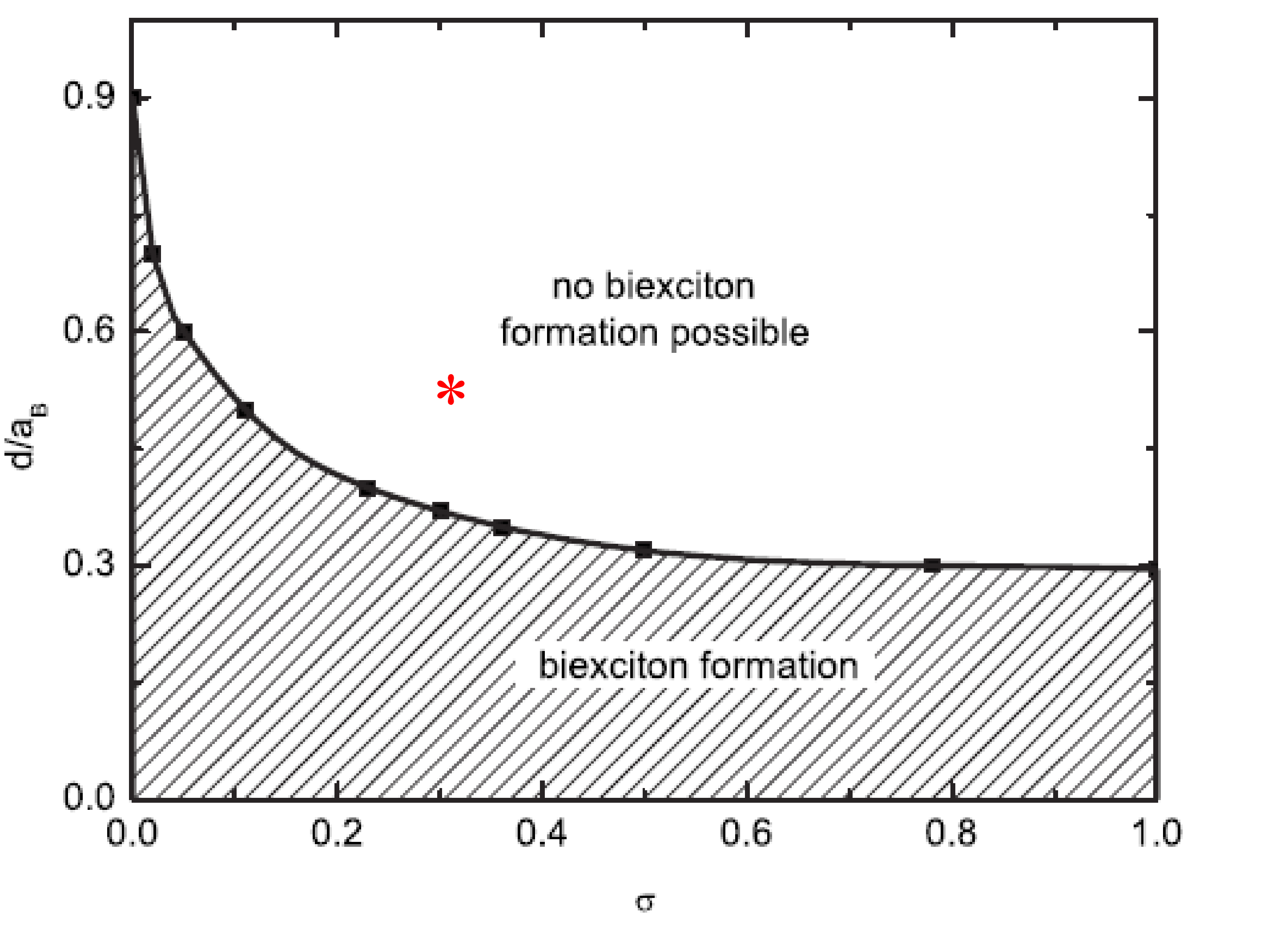
Lozovik and Yudson (1976),
Shevchenko (1976)
Fukuzawa et al. (1990),
Kash et al. (1992)
Butov et al. (1994-2005),
Snoke et al. (2002-2006))
Rapaport et al. (2003-2006)

BEC of 2D excitons can occur only (!) under spatial restriction (in lateral potential traps)

(n-i-n) - diod GaAs/AlGaAs heterostructure with DQW



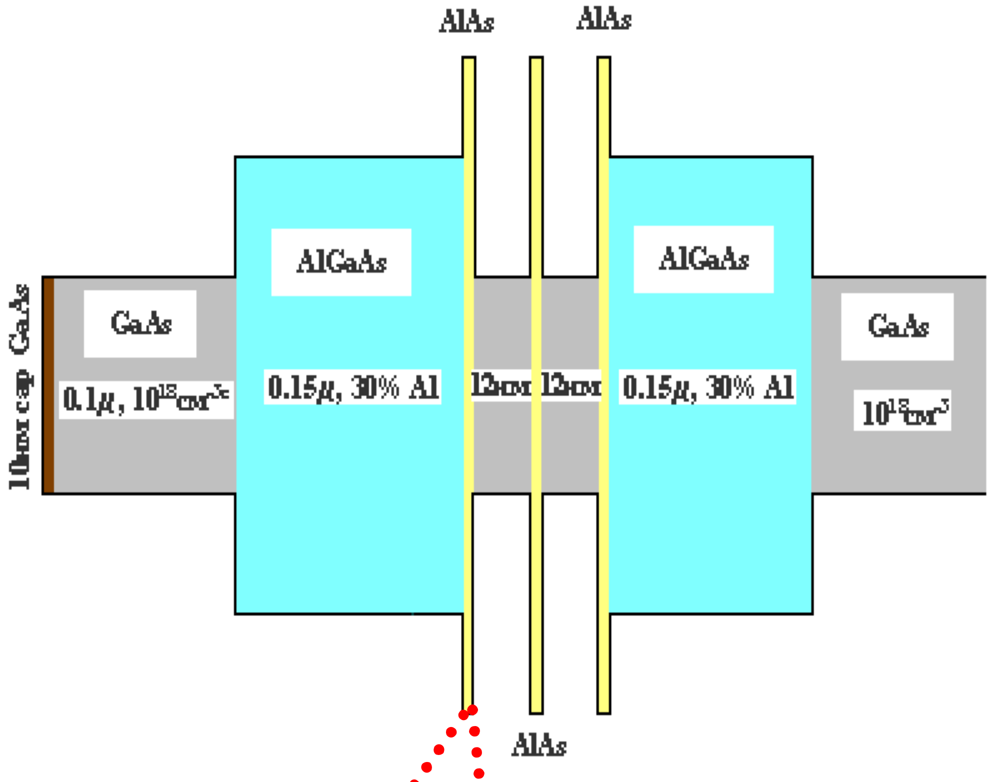


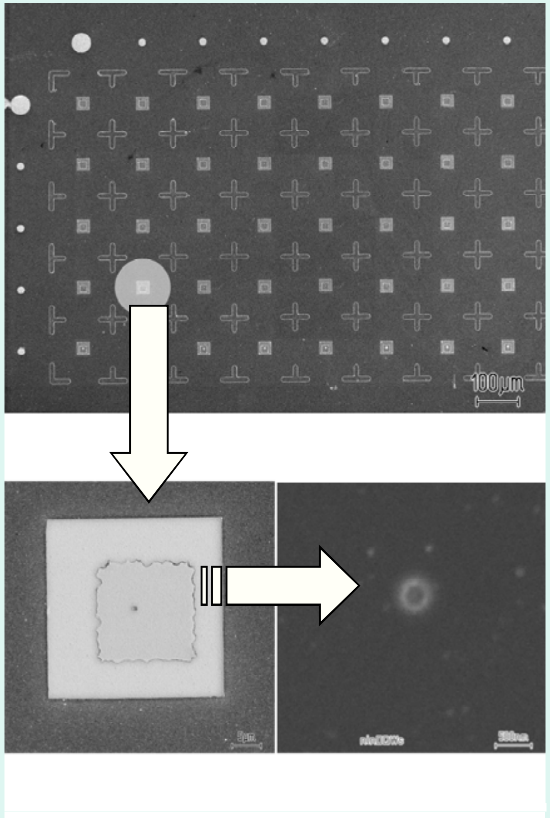


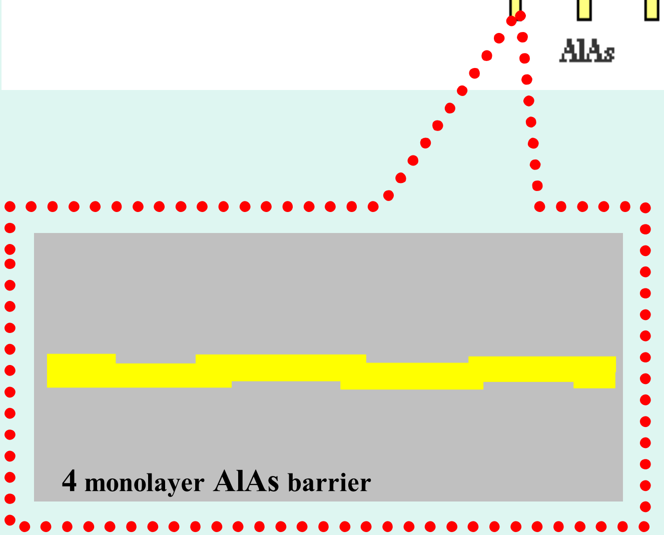
Critical charge separation in units of the bulk exciton Bohr radius $\mathbf{a_B}$ plotted vs mass ratio $\sigma = m_e/m_h$ *Schindler and Zimmermann (PR B, 2008)*

We investigate dipolar exciton systems where biexciton formation is impossible

($\sigma \equiv m_e/m_h = 0.32$ $d/a_B = 0.53$)





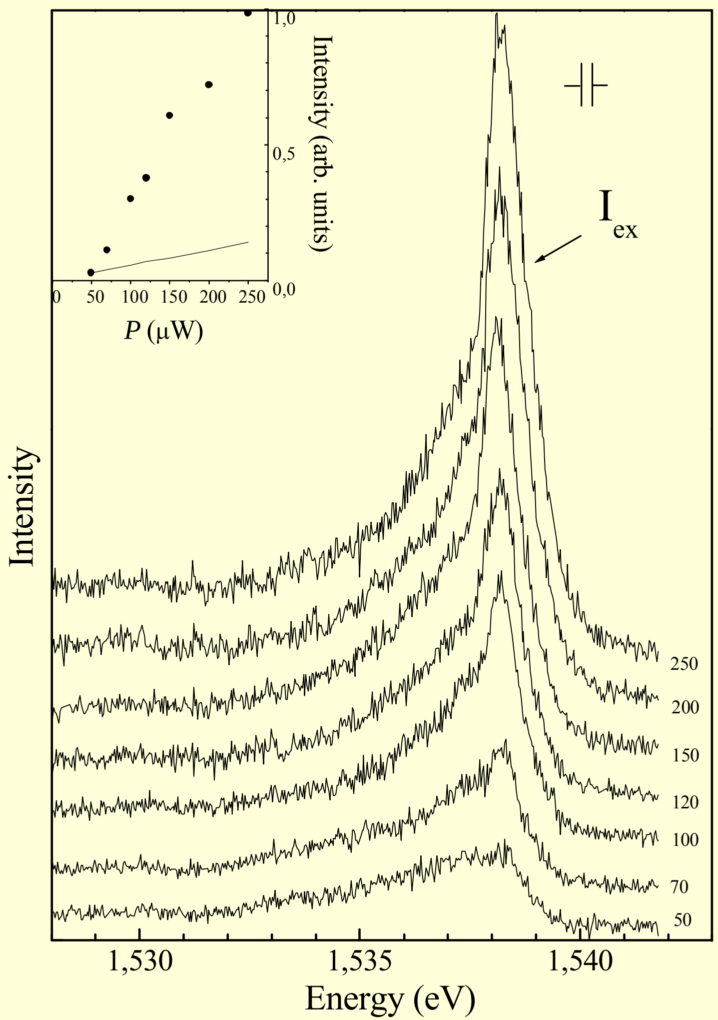


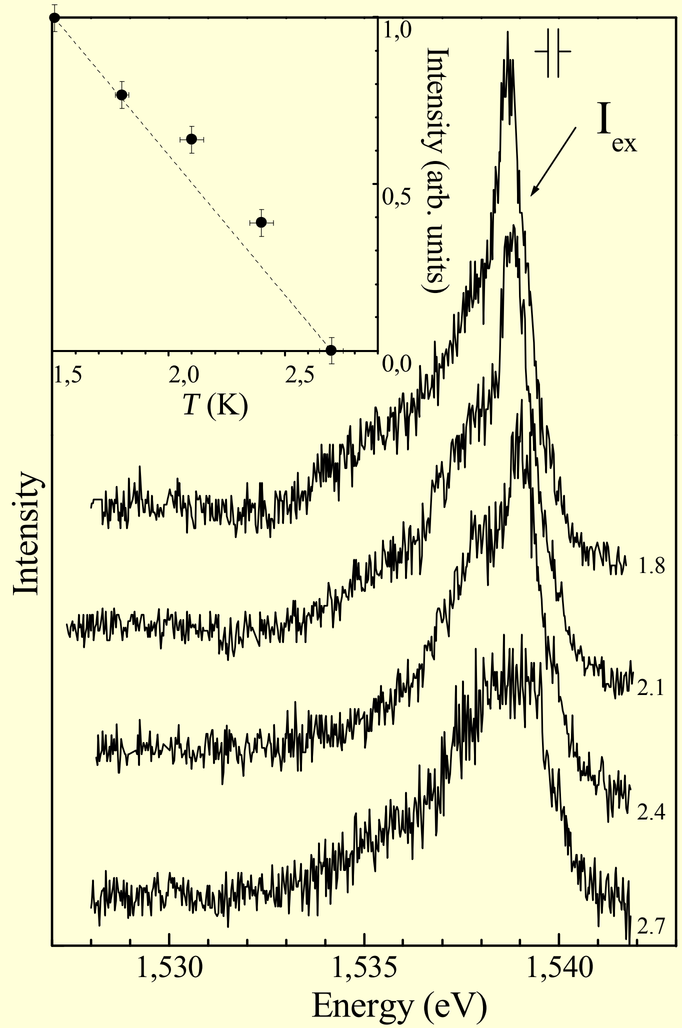
The epitaxial growth interruption technique ⇒

- to decrease a scattering on the interface roughness
- the large-scale fluctuations at the QW heteroboundaries (interfaces) - useful for effective indirect excitons accumulation

JETP Letters, Vol. 71, No. 3, 2000, pp. 117–122, A. Larionov, V. Timofeev, J. Hvam, C. Soerensen.

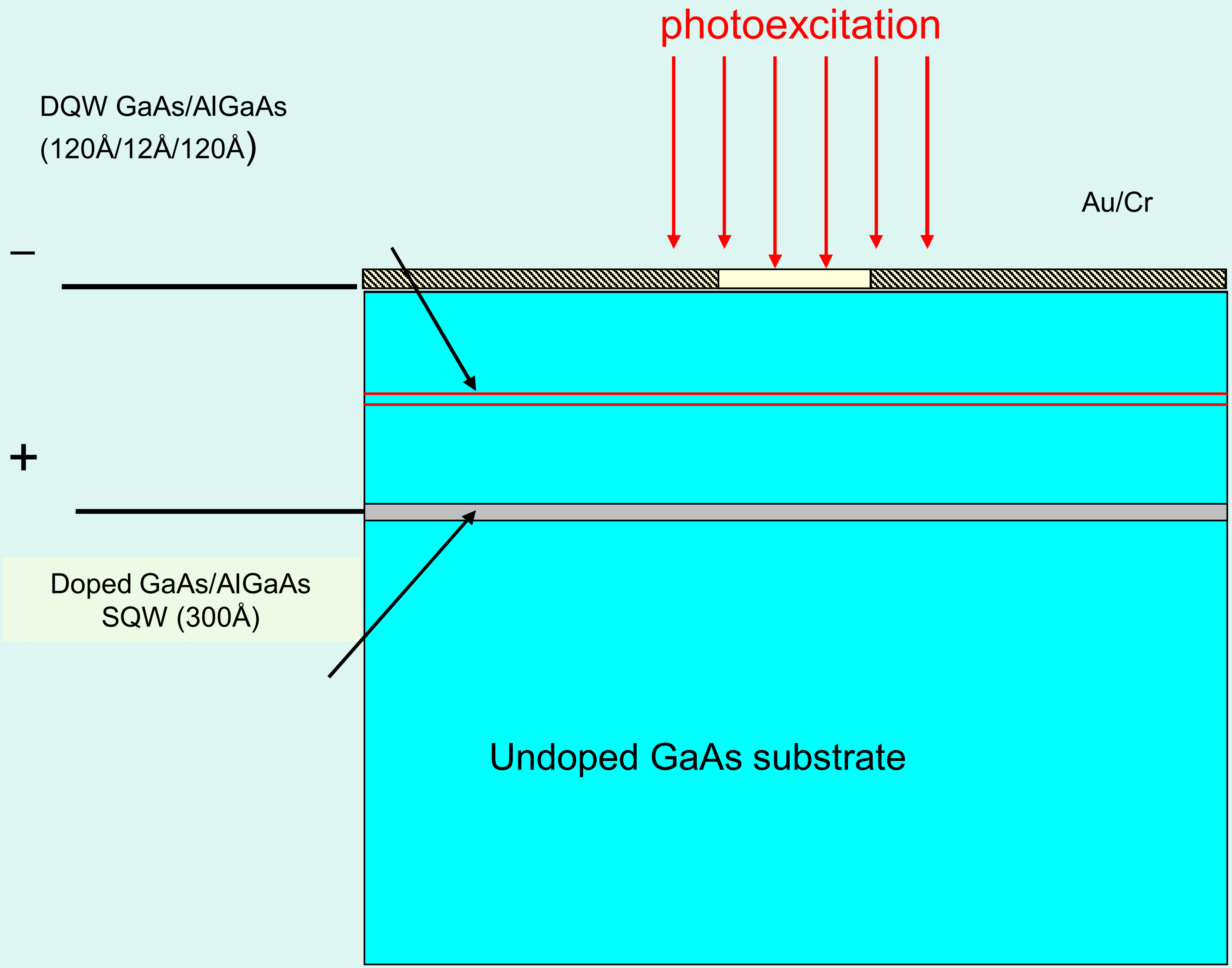
Luminescence spectra of interwell (dipolar) excitons in DQW from 2 μm window under excitation power and temperature variations





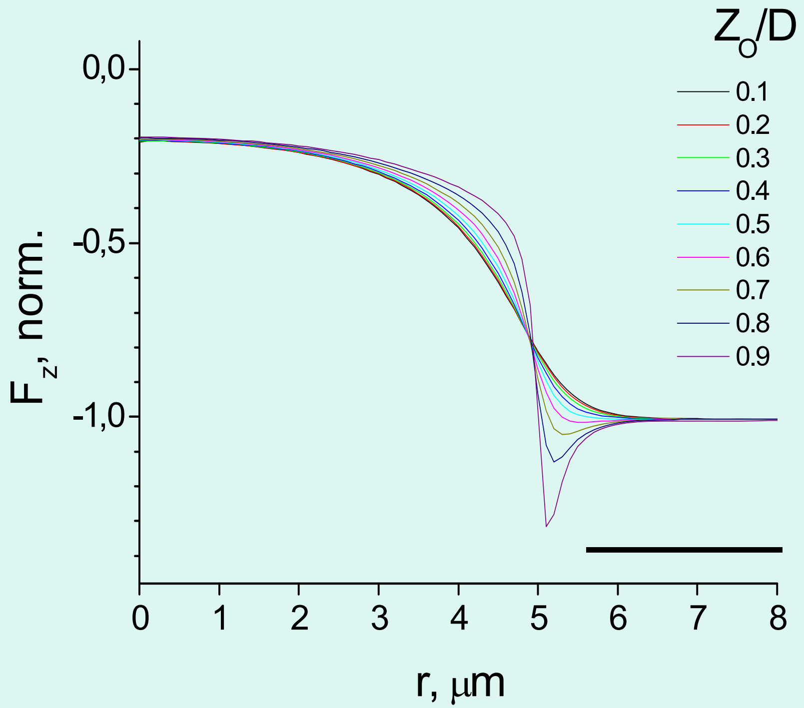
I ~ (1 – T/Tc)

Circular lateral trap for dipolar excitons appears within perimeter of the circle window in Schottky gate (heterostructures with DQW or SQW).



Gippius et al. 2005

Calculated radial profiles of the potential circular trap for dipolar excitons (potential trap along perimeter of a circle window in Schottky gate)



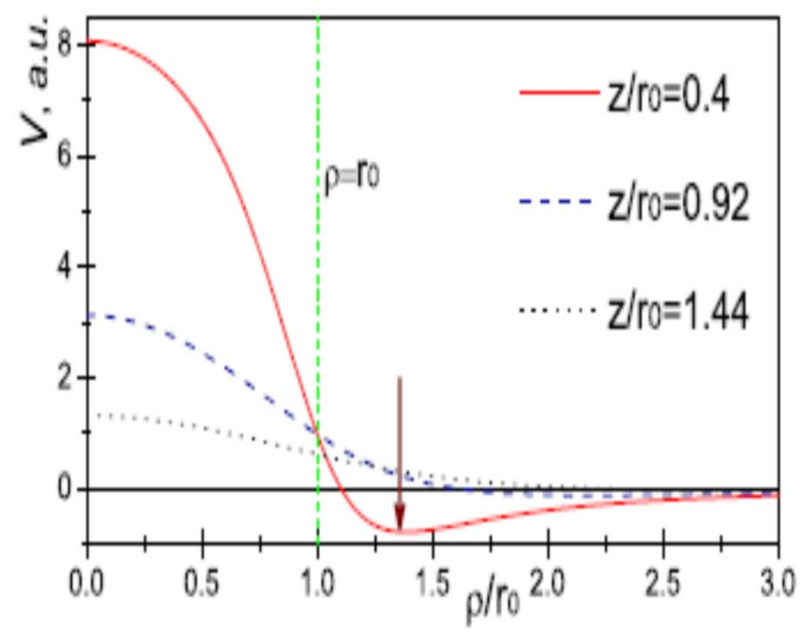


Fig. 2. A radial profile of the exciton potential energy V in nonuniform electric field as a function of the ratio ρ/r_0 at different values of the parameter z/r_0. The pulling force $\lambda = 30$ is for all curves

N.A.Gippius (2005)

V.I.Sugakov, A.A.Chernyuk JETP Lett. (2006)
A.Maksimov, Khabarova (2006)

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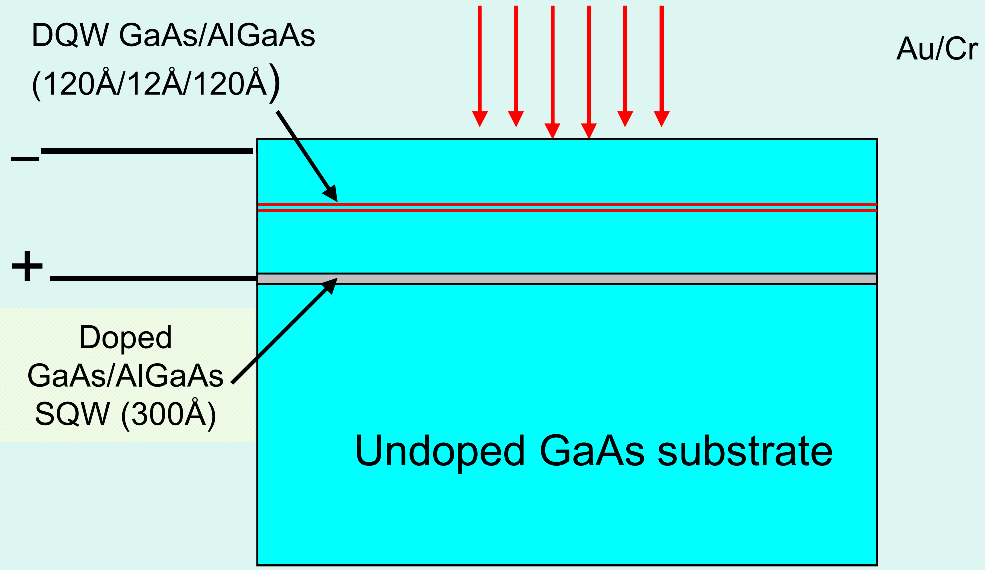
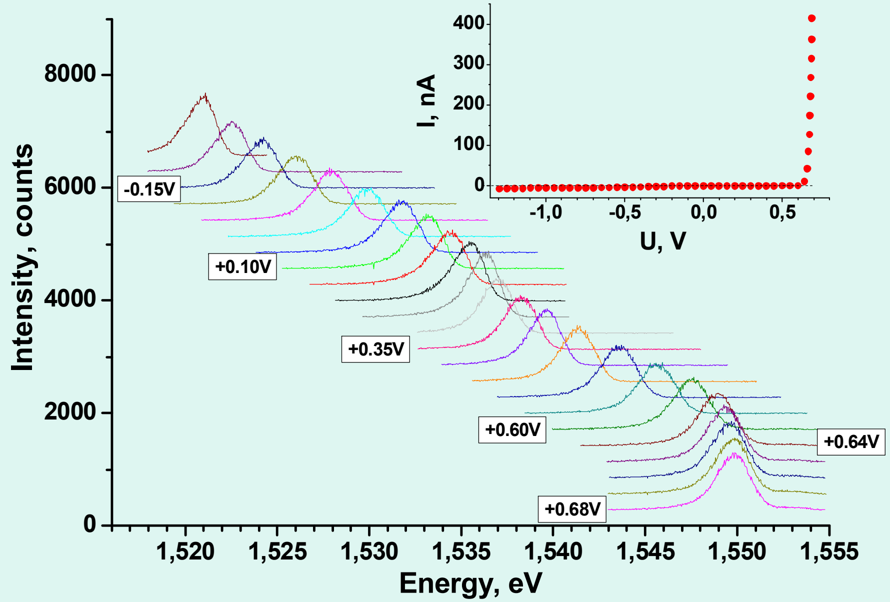
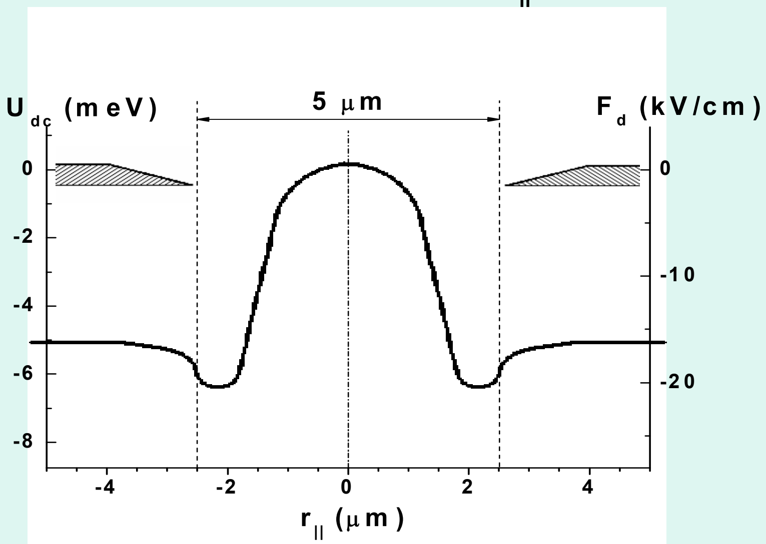
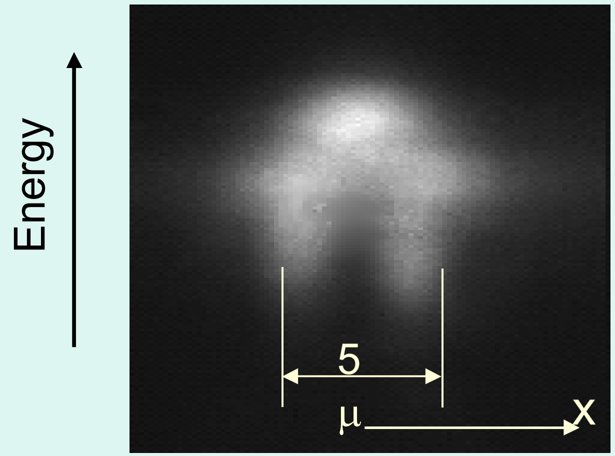


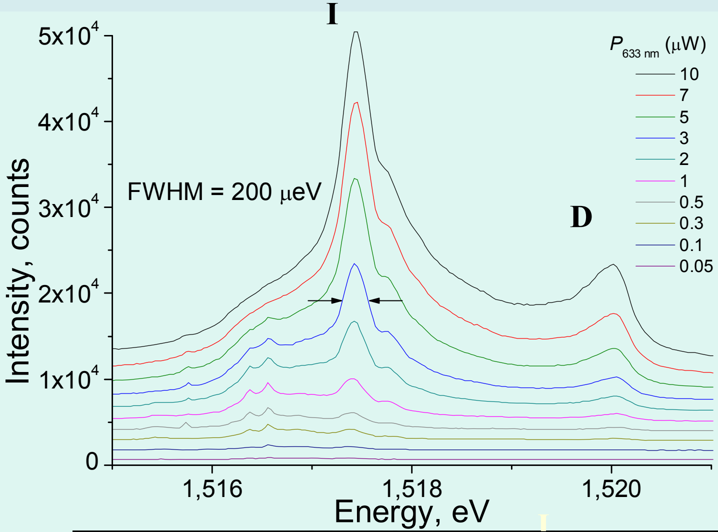


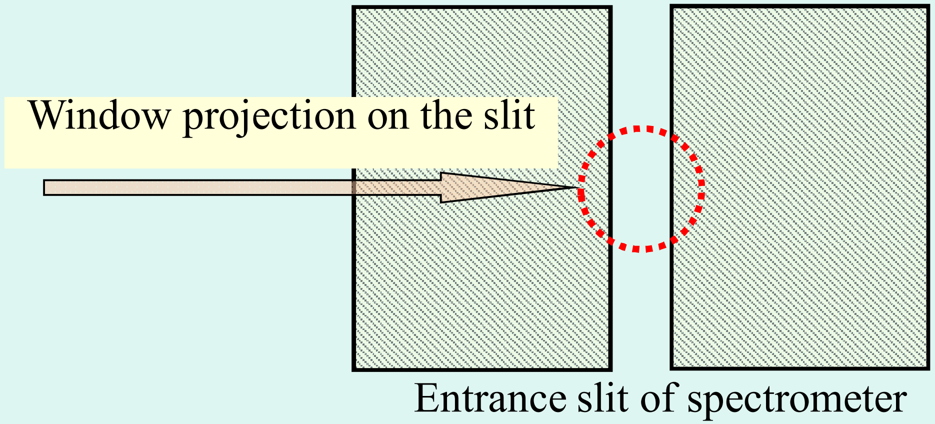
Confining energy $U_{dc}(r_{\|})$for dipolar excitons in a a ring lateral trap

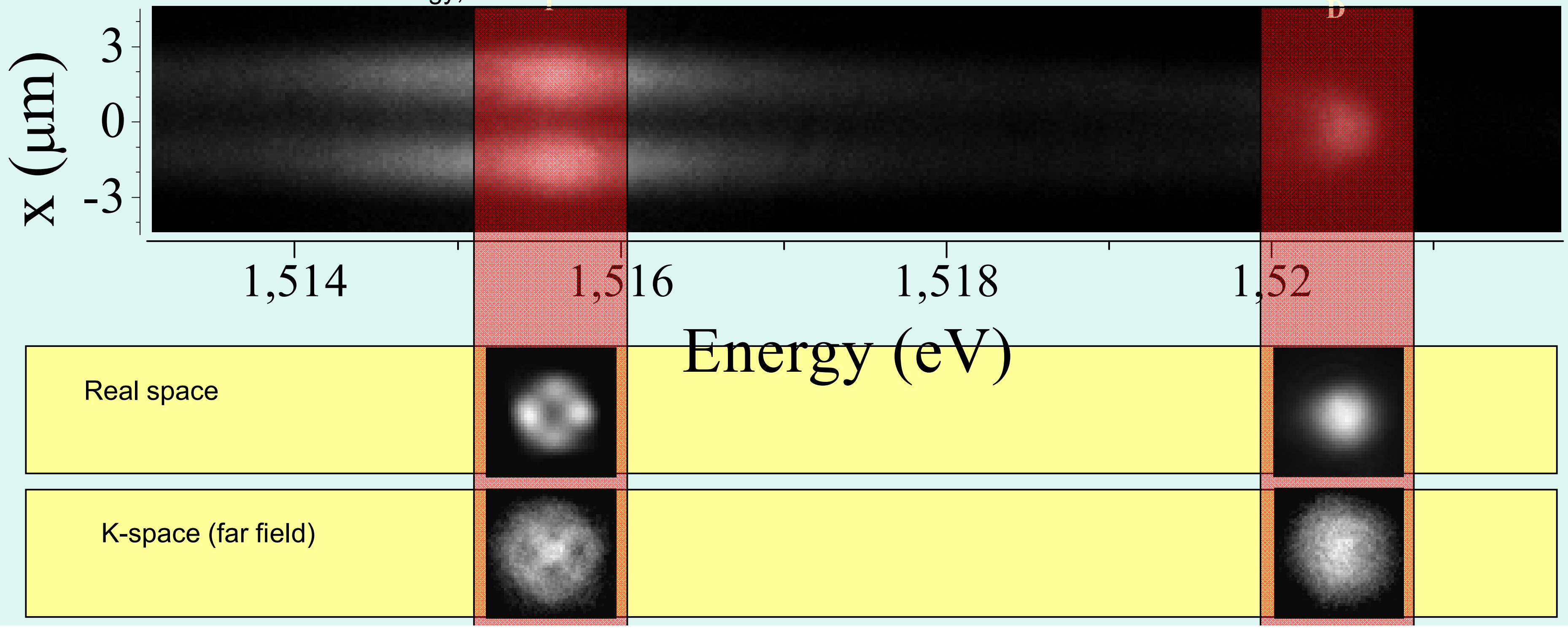




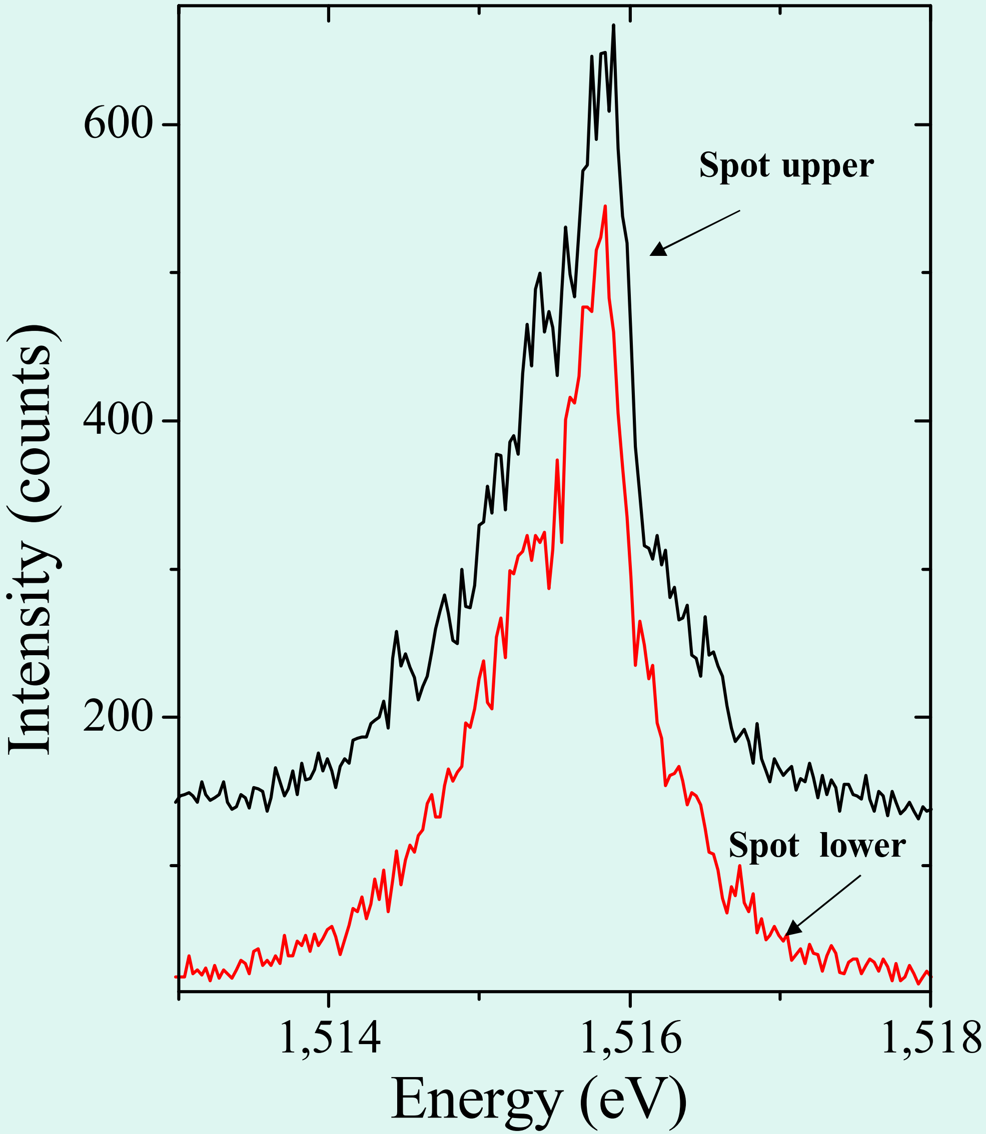
Luminescence spectra measured under projection of circular window (ø5 μm) on the entrance spectrometer slit for DQW and SQW

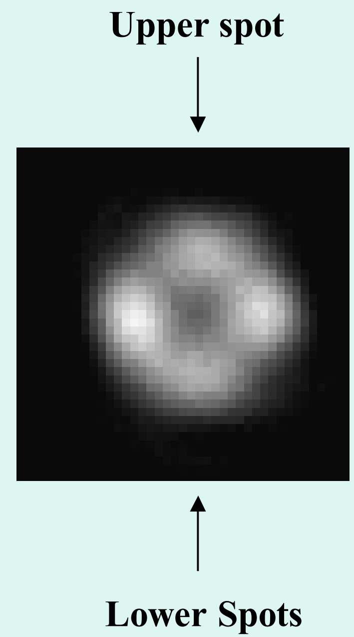




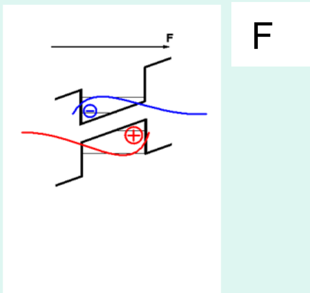


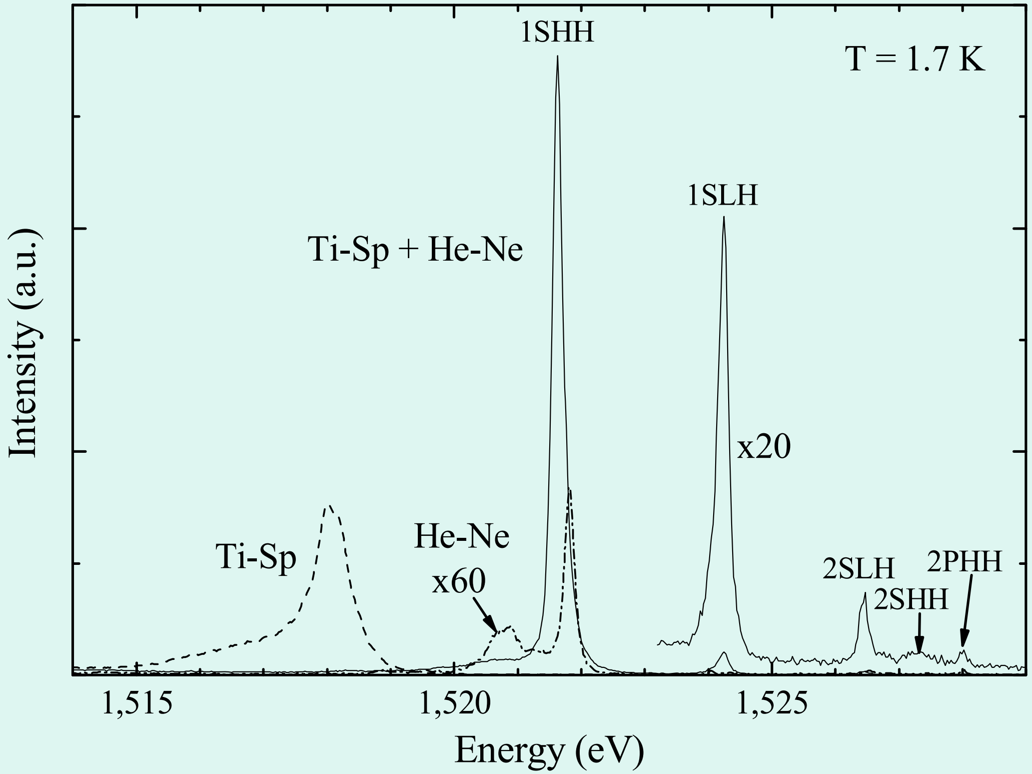
Dipolar excitons from different luminescence spots in pattern are identical



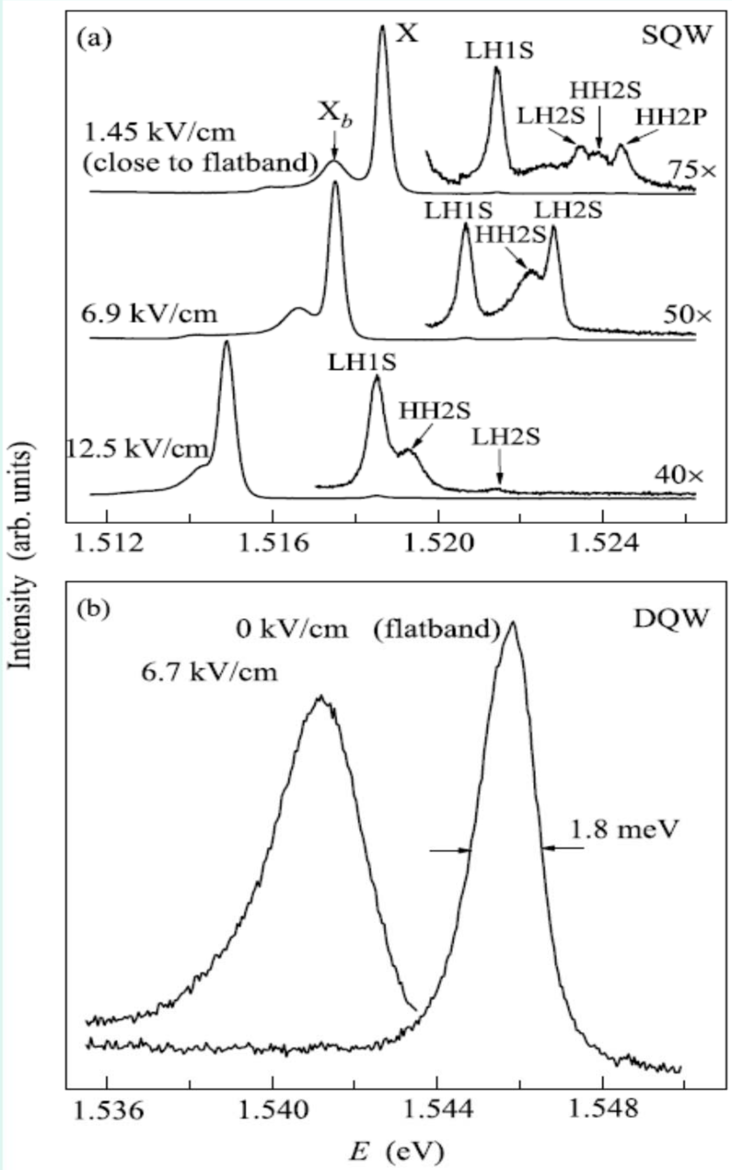


Compensation of extra charges in SQW with the use of in- and above barrier photoexcitations



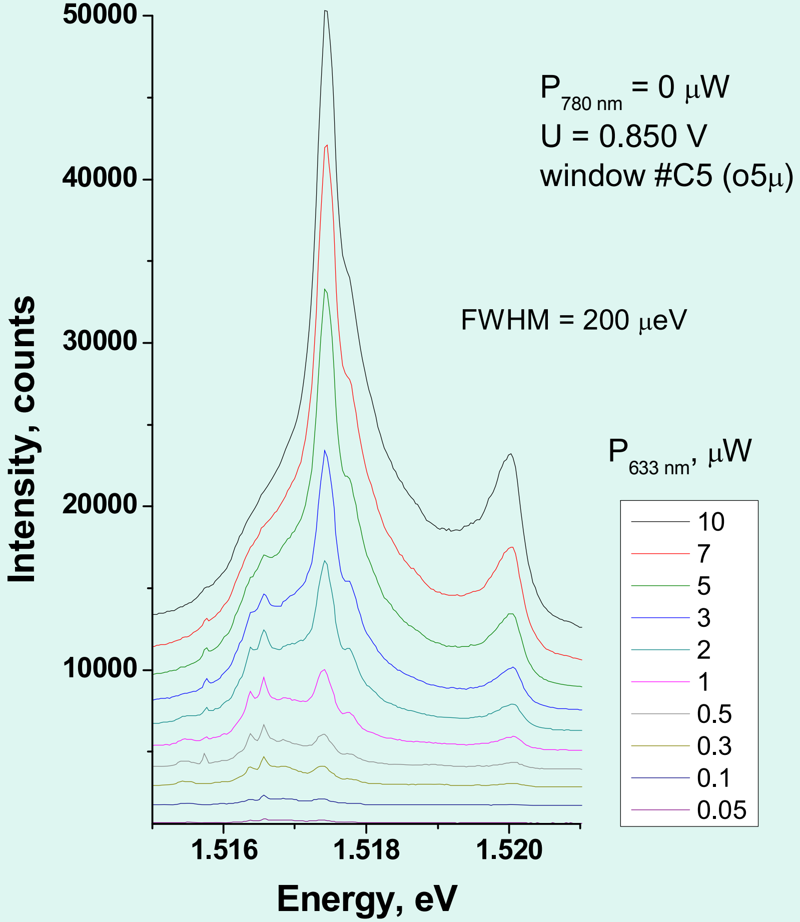


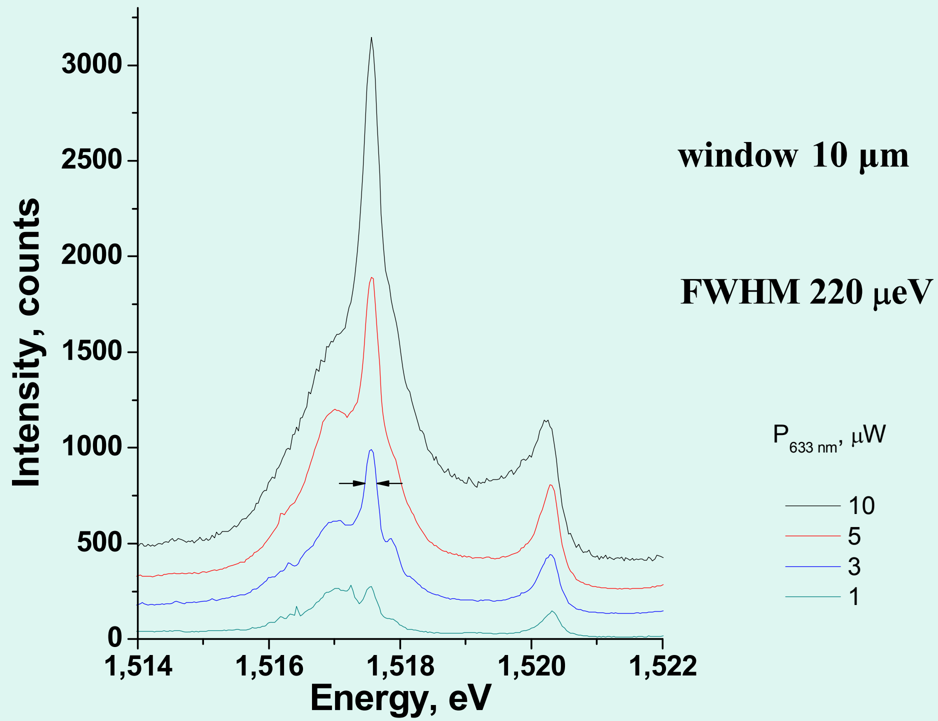
Gorbunov and Timofeev (2006)



Solov'ev, Kukushkin et al. (2006)

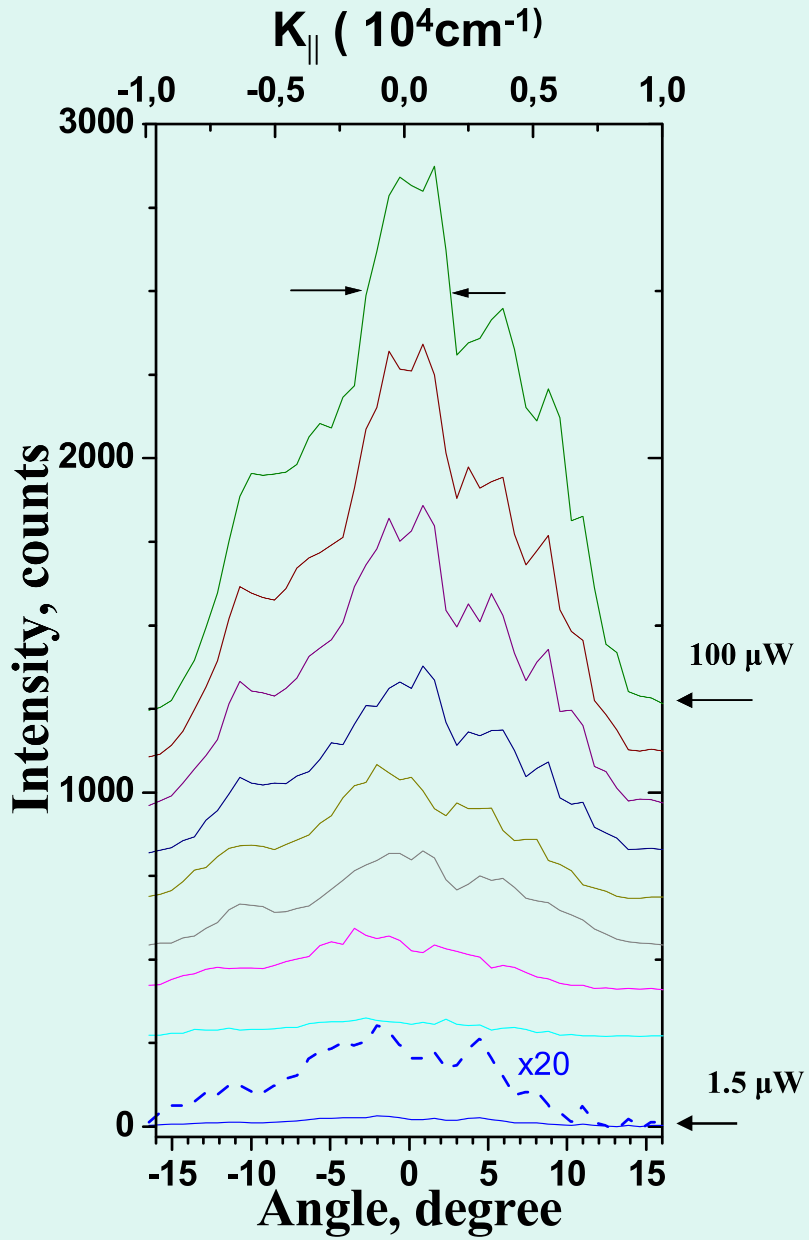
BEC of dipolar excitons in ring lateral traps of 5μm and 10 μm exhibited in luminescence spectra, T = 1.6K





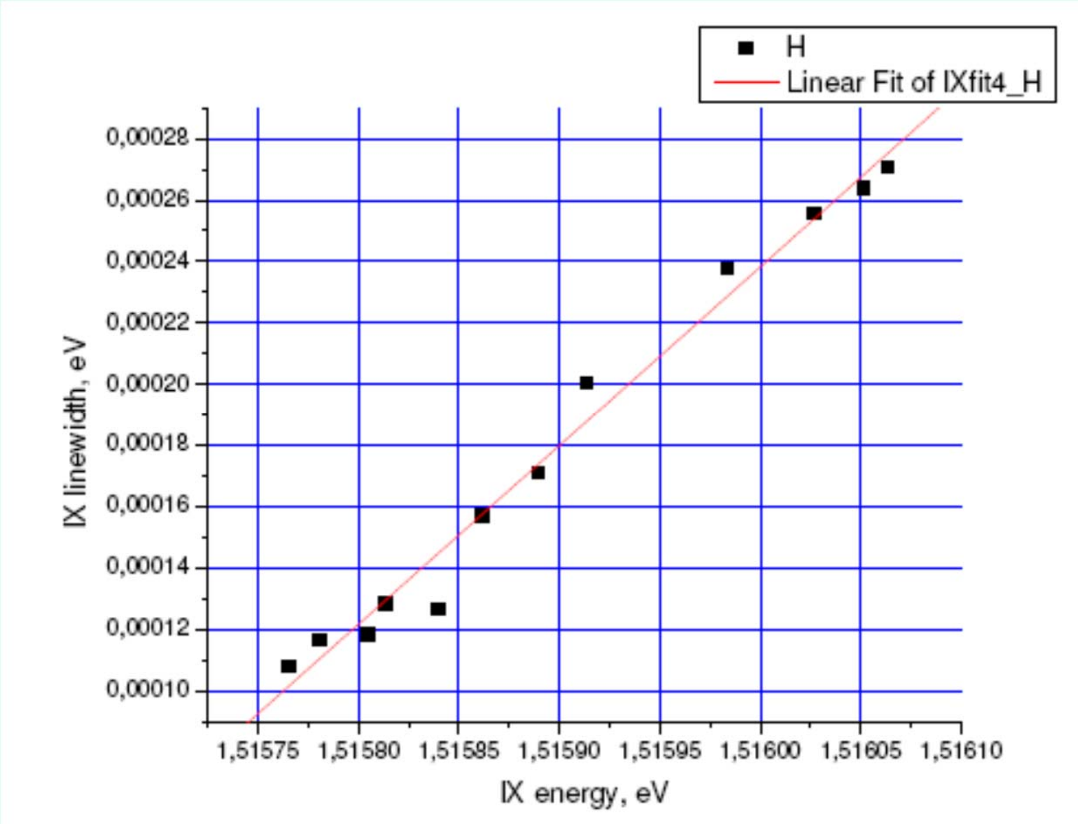
mobility edge corresponds $N_m \approx 2\cdot10^9$ cm^{-2}, exciton density of Bose-condensate $N_C \approx 5\cdot10^{10}$ cm^{-2}

Narrowing of exciton distribution in K-space



- Excitons are condensed at $K \approx 0$
- Uncertainty $\Delta K_{\|} \approx 10^4$ cm^{-1} corresponds to the radial width of the circular trap, $\Delta r \approx 1 \mu m$ ($\Delta K_{\|} \Delta r \sim 1$)

FWHM (M_2) versus spectral shift of BC luminescence line (ΔM_1) under variation of pumping power



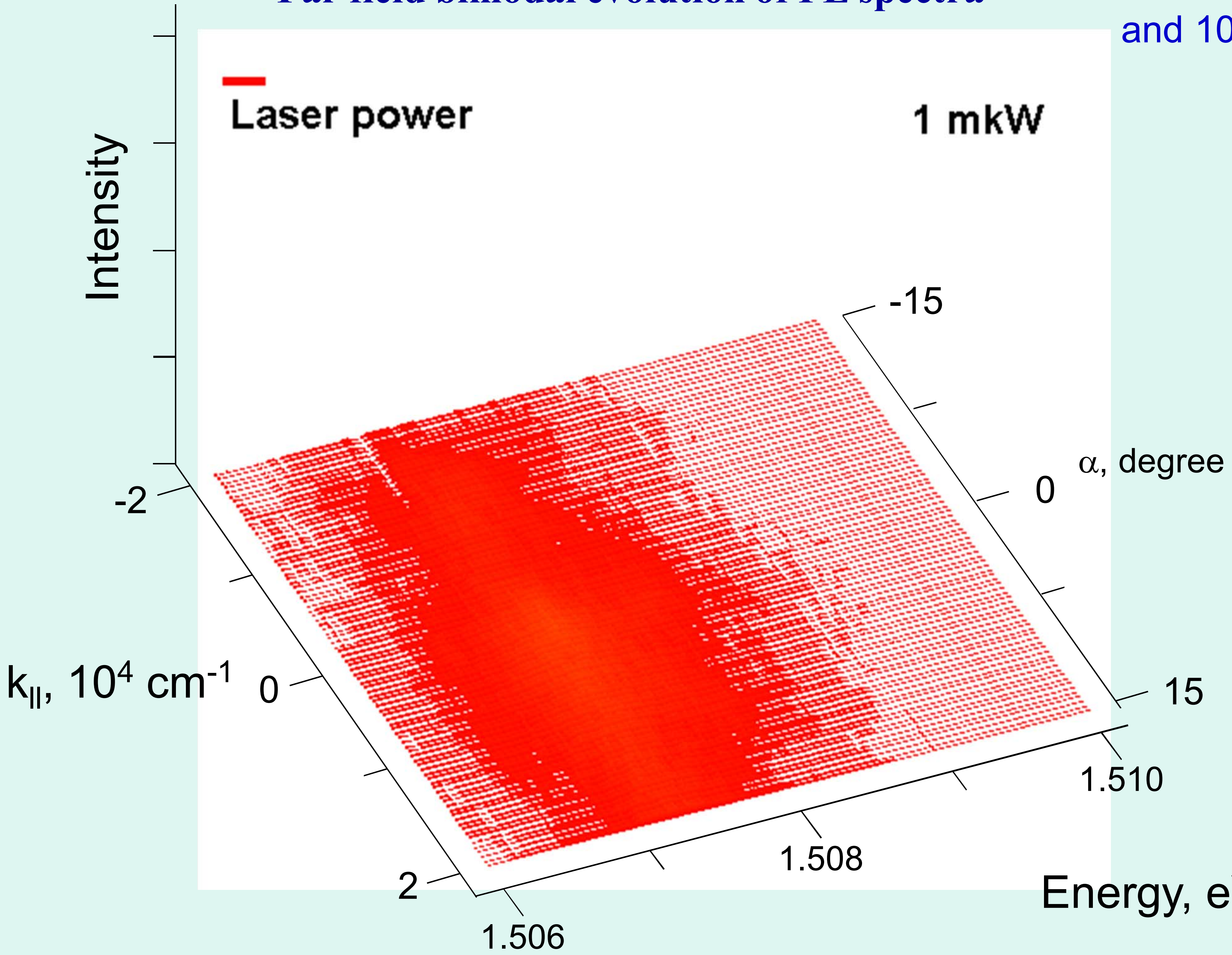
$$M_2/M_1 \cong 0.8$$

Spectral shift ΔE≈0.5 meV corresponds to n_c≈5·10^{10} cm^{-10}

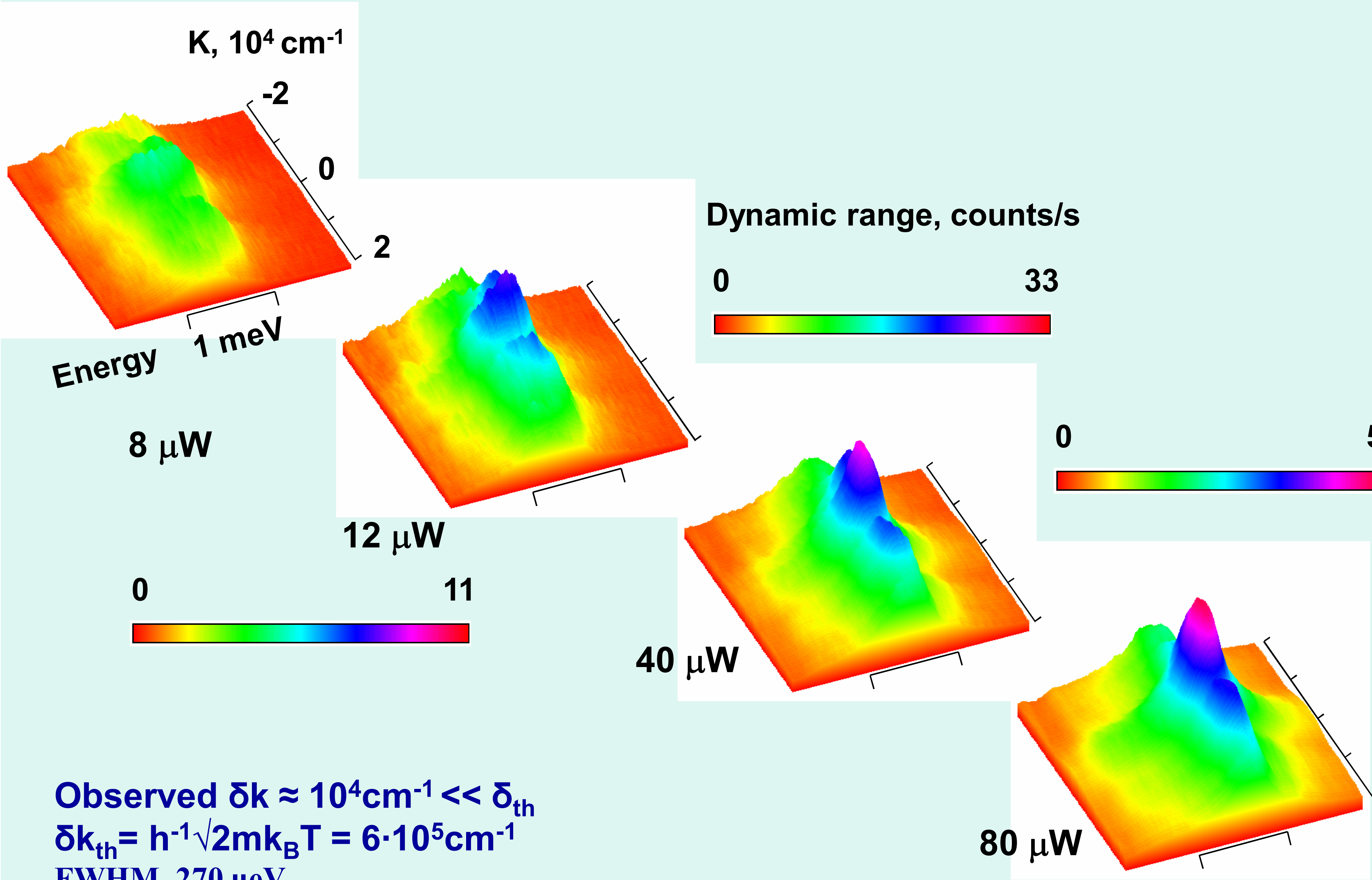
C. Schindler and R. Zimmermann, *Phys. Rev.* **B78**, 045313 (2008).

Far field bimodal evolution of PL spectra

1 – 20 μW
and 100 μW



Far field bimodal evolution of PL spectra of exciton Bose-condensate

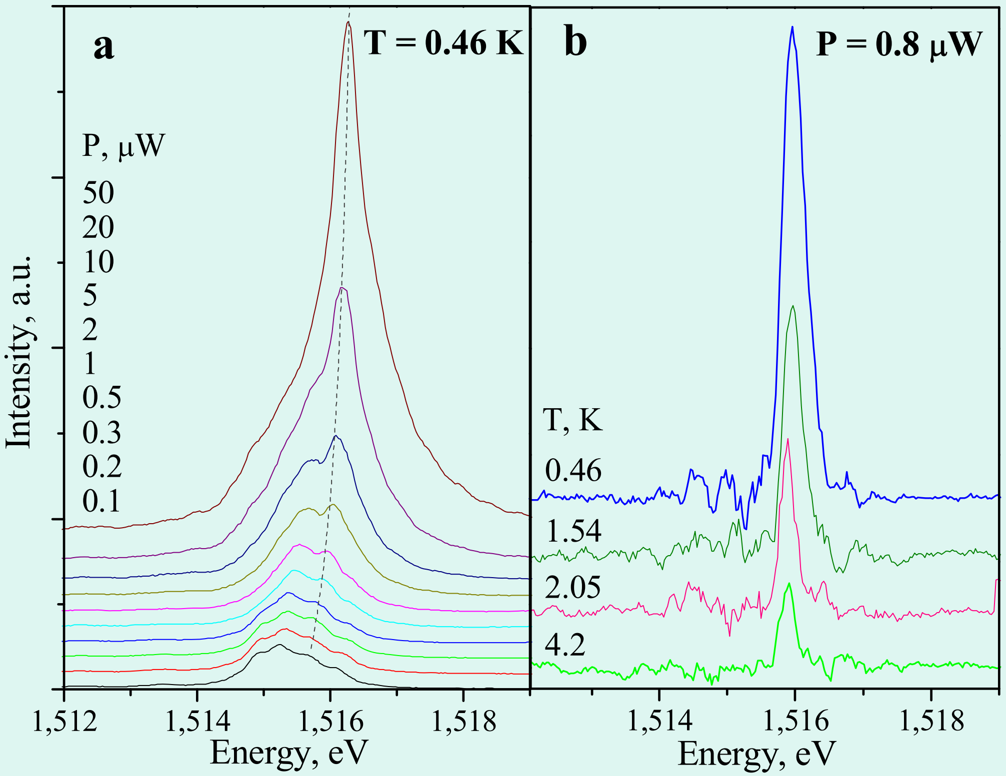


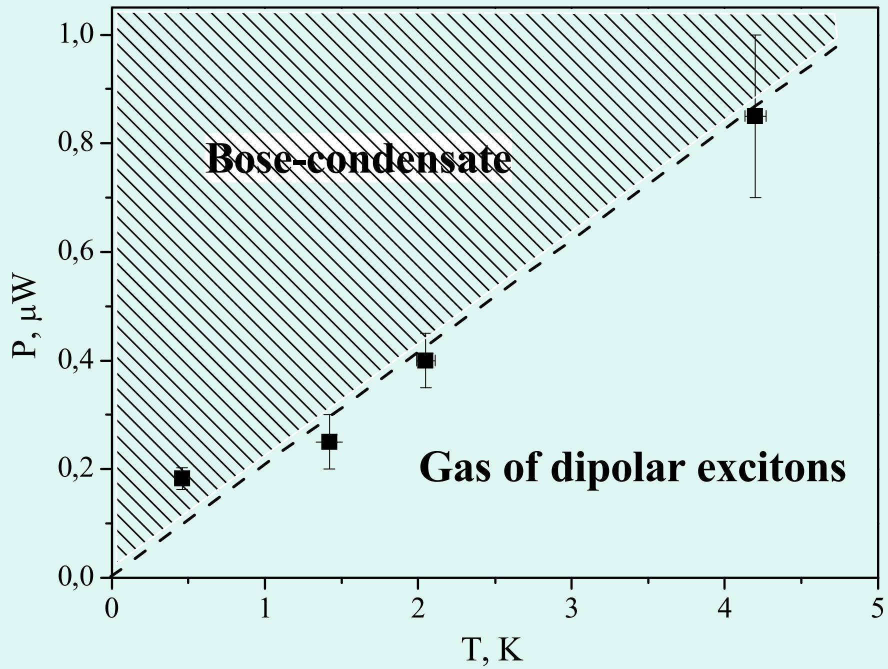
Observed $\delta k \approx 10^4 cm^{-1} << \delta_{th}$

$\delta k_{th} = h^{-1}\sqrt{2mk_BT} = 6 \cdot 10^5 cm^{-1}$

FWHM 270 µeV

The Phase Diagram of BEC of Dipolar Excitons

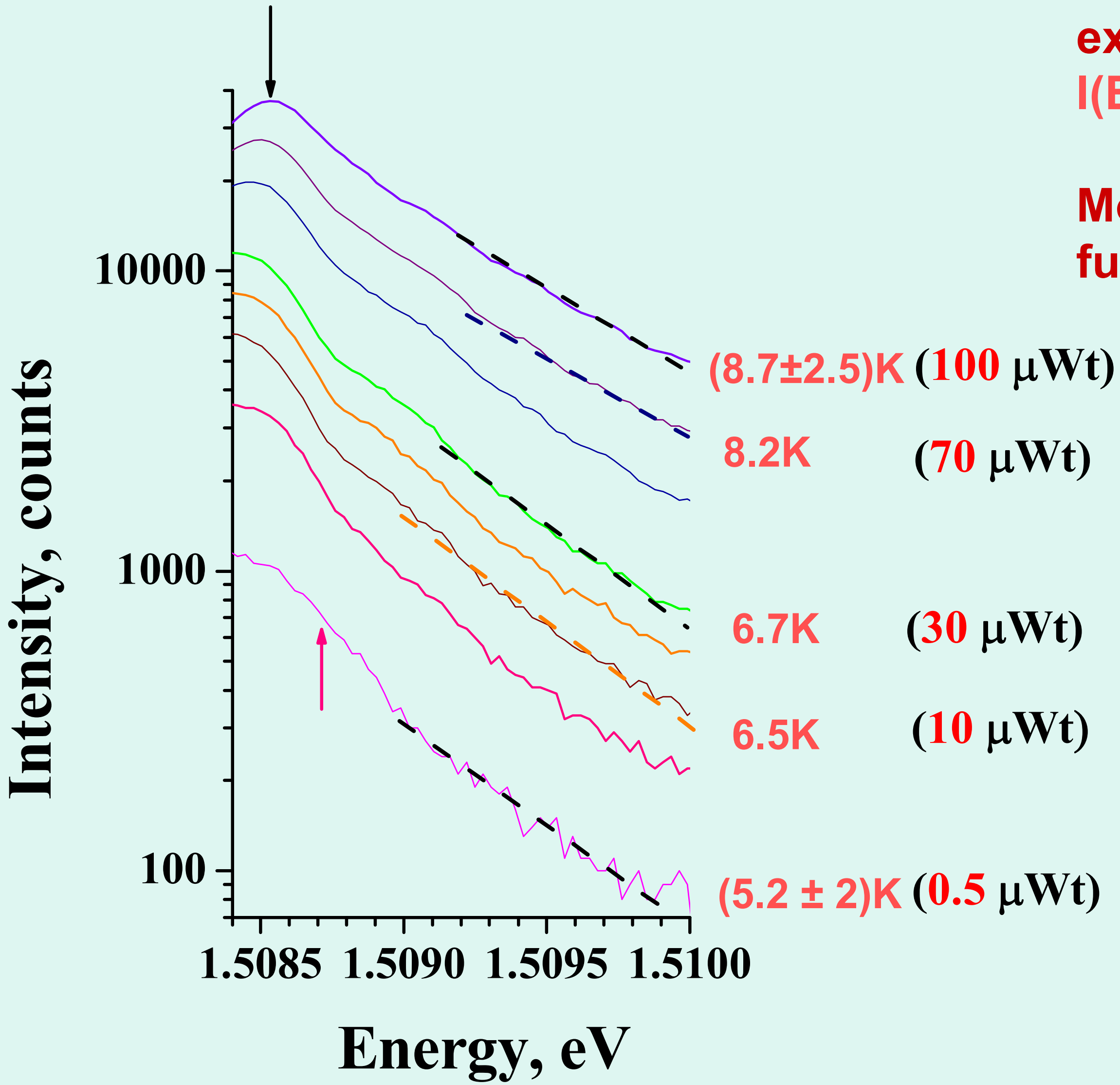




$I_T \sim (1 - T/T_C)$ $M_1/M_2 \approx 1.25$

A. V. Gorbunov, V. B. Timofeev, D. A. Demin, A. A. Dremin JETP Letters 90, 146 (2009)

Excitations of BEC are under thermal quasi equilibrium



The temperature of excitations can be found from high energy exponential tail of exciton line

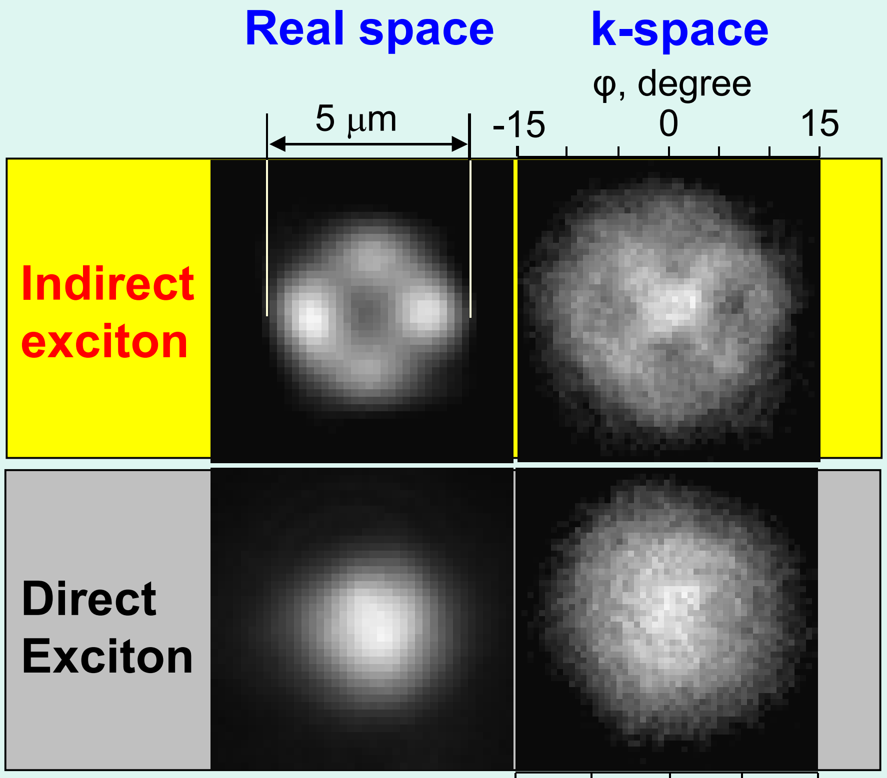
$I(E) \sim N_q \sim \exp(-E/kT)$, at $E>kT$

Momentum conservation is fulfilled due to collisions and recoil processes

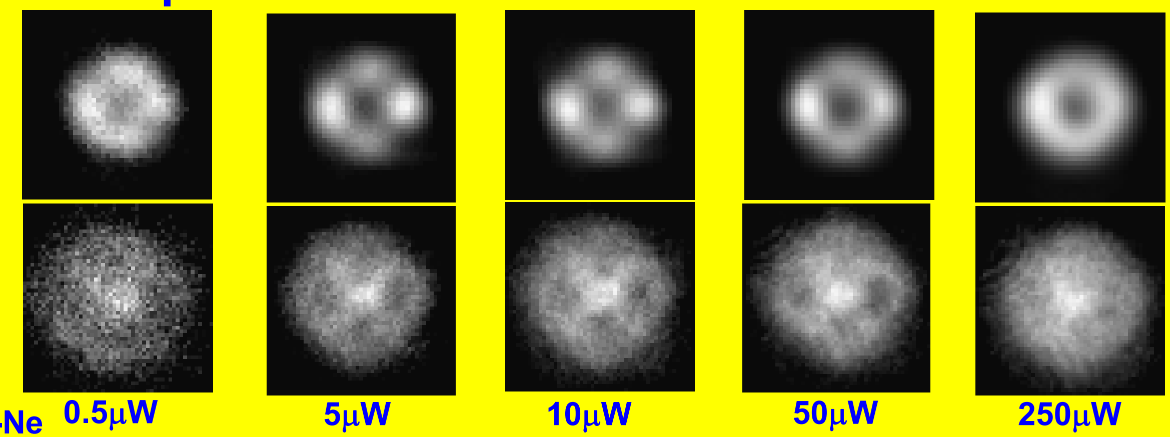
Condensation occurs under thermal quasi equilibrium

Bath T = 1.9K

Patterning of dipolar exciton luminescence both in real and k-space: optical Fourier-transform



Power dependence

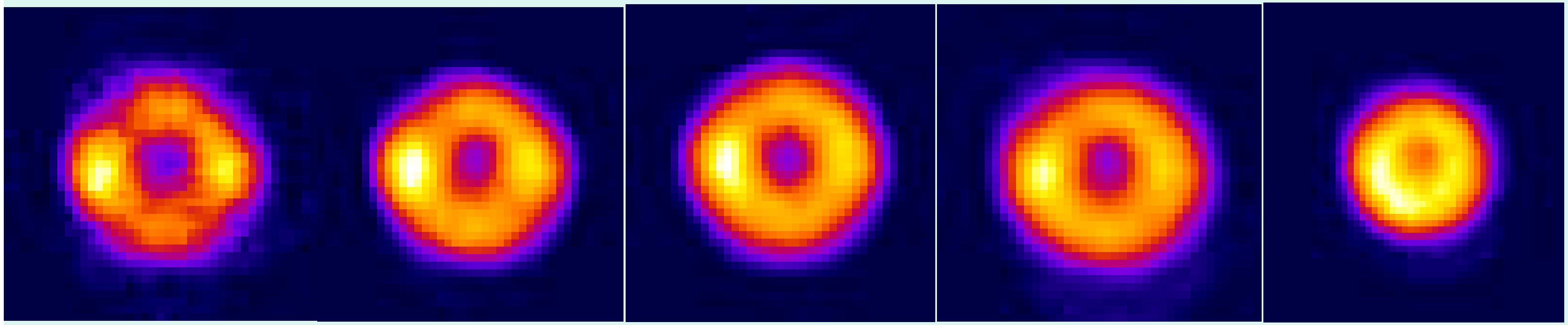


This collective state of dipolar excitons is spatially coherent.

The luminescent ring pattern with equidistant bright spots is described by a common wave function.

BEC emission concentrates close to the normal within angular cone:
$\Delta\varphi \approx \lambda/D \approx 0.23 \approx 28^{o}$.

Temperature behavior of the luminescence spatial structure in the ring lateral trap of 5 μm size (P= 20mWt) (in plane pseudo images)



4.6K 5.15K 6.0K 7.2K 10K

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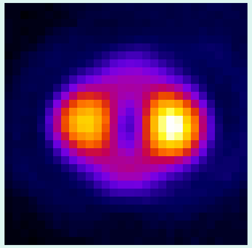
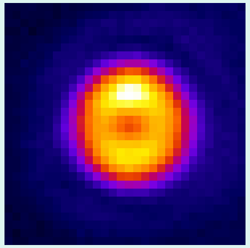
Institute of Solid State Physics RAS

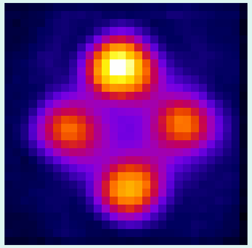
Pseudo images of patterned luminescence structure of dipolar exciton BEC in single and coupled lateral traps of different shapes



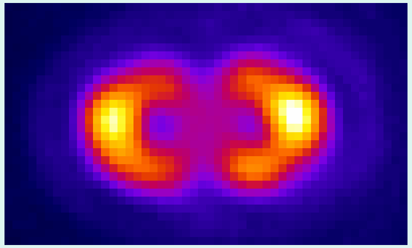
5 μm
(ellipse)



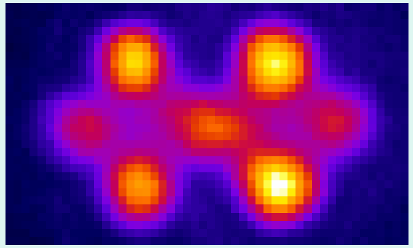
4μm
(ring)



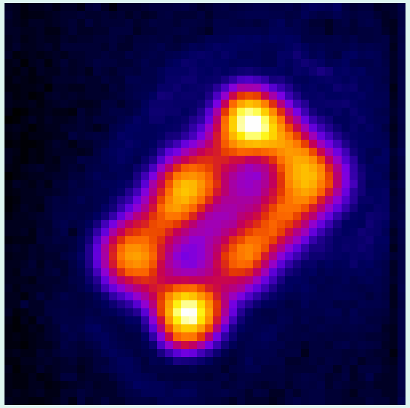
5 μm
(square)



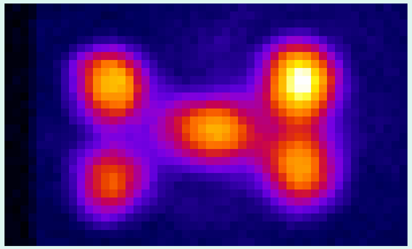
5 μm
(coupled ings)



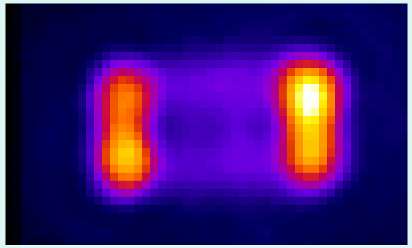
5 μm
(coupled squares)



5x10 μm
(rectangular)

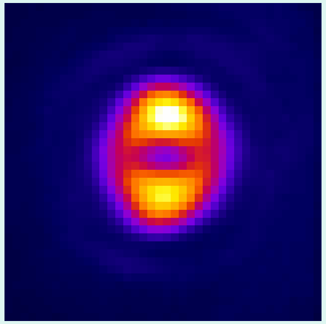


7 μm
(coupled triangular)

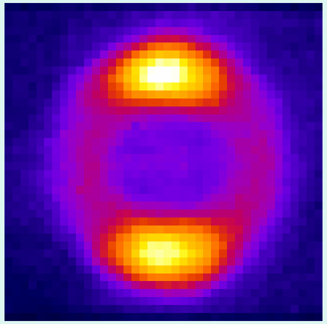


5x10 μm
(rectangular)

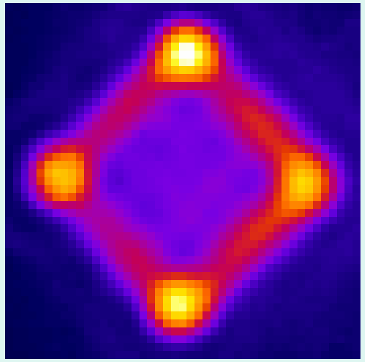
Pseudo images of patterned luminescence structure of dipolar exciton BEC in single and coupled lateral traps of different shapes



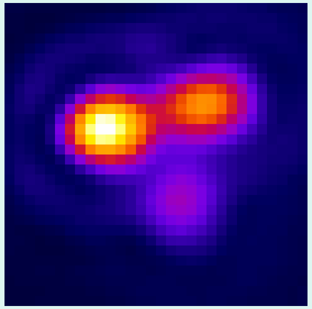
(5 μm)



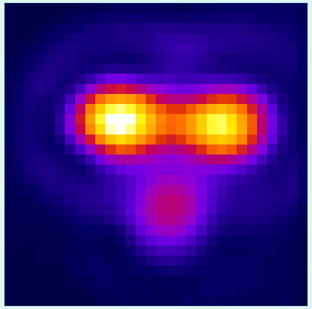
(10 μm)



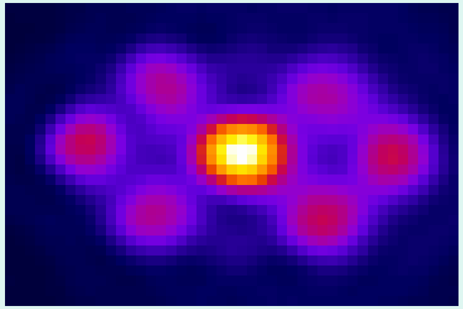
(10 μm)



7 μm



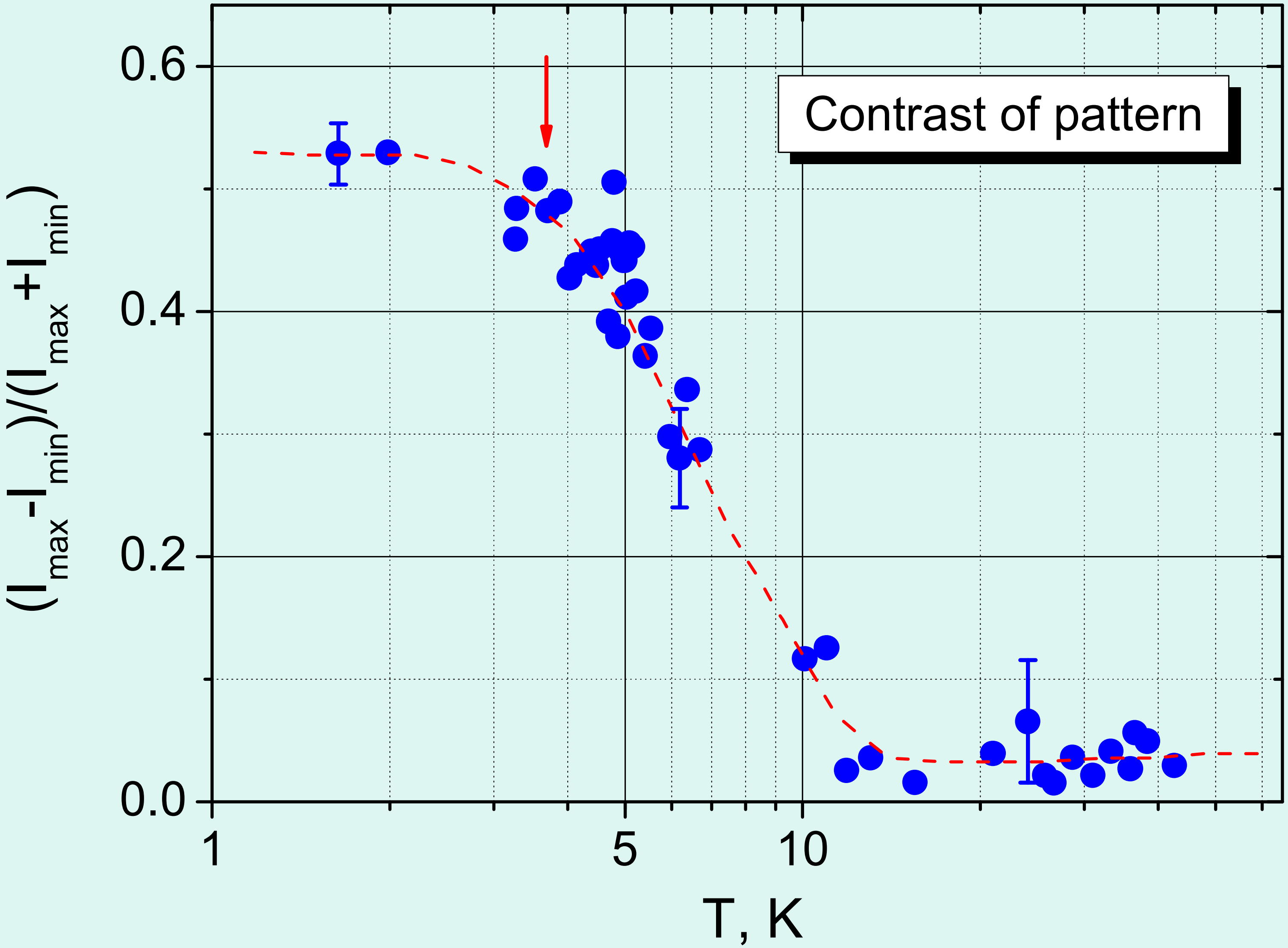
7 μm



7 μm

coupled squares

Visibility (contrast) of PL pattern structure demonstrates critical behavior on temperature



Origin of periodically patterned structure of Bose-condensed state of dipolar exciton

- **Vorteces structure of condensed dipolar exciton state confined in a trap (Keeling, Littlewood, Levitov 2004)**

(estimated *healing length* is around micron)

$$\xi = \frac{\hbar}{\sqrt{2m^* n_0 g}}$$

- **Fluctuation model of Bose-condensation in inhomogeneous systems, *instanton model* (Iordansky et al. 2006-2007)**

- **Phenomenological *gas-dielectric liquid* phase transition in inhomogeneous system of dipolar exciton with finite time decay (Sugakov – 2005-2007)**

- ***The role of random potential fluctuation which pin a discrete periodic structure in crystallographic direction still call for consideration***

Angular Distribution of Photoluminescence as a Probe of Bose Condensation of Trapped Excitons

Jonathan Keeling, L. S. Levitov, and P. B. Littlewood

PHYSICAL REVIEW LETTERS **92**, 176402, 2004

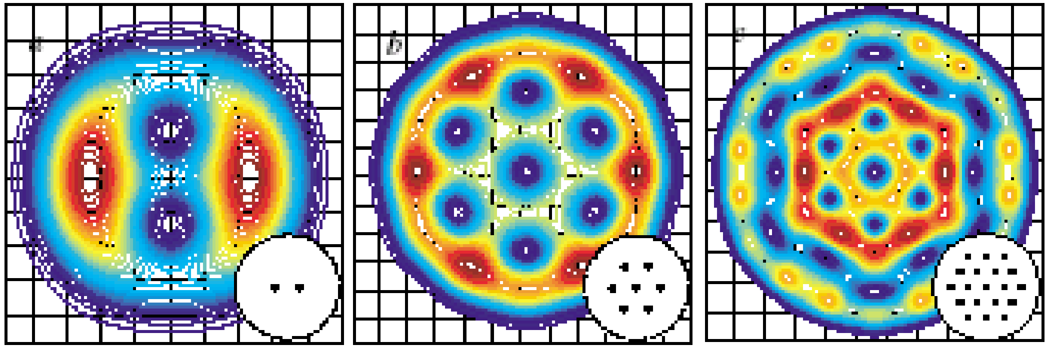
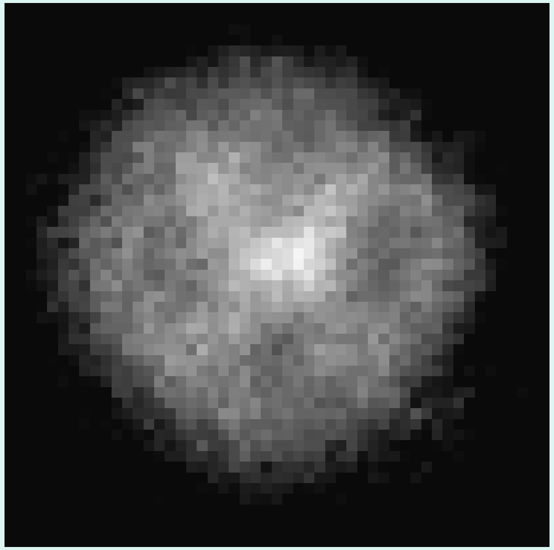
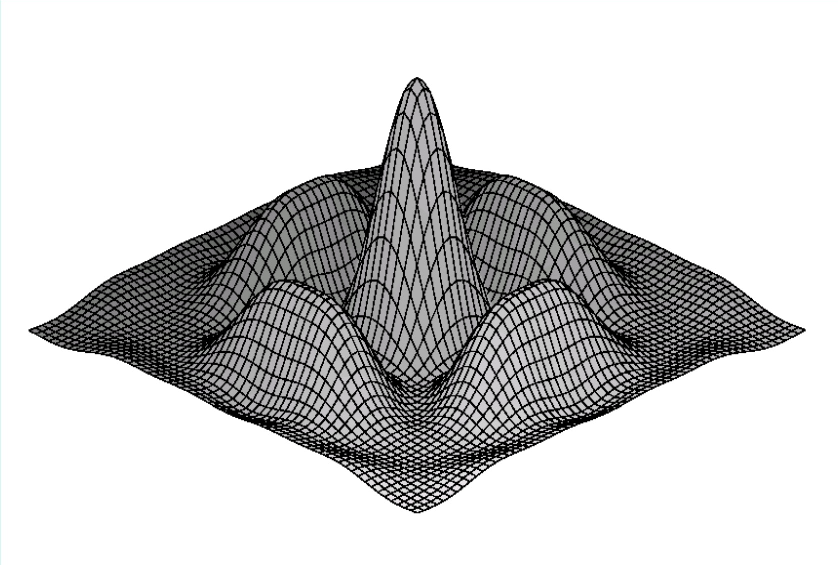


FIG. 3 (color online). (a) PL profile for 2 vortices placed at $x/R = \pm 0.2$; (b),(c) PL profile for hexagonal arrays of 7 and 19 vortices. The insets show the configuration of vortices in real space.

$$H[\psi] = \int \left[\psi^* \left(-\frac{\nabla^2}{2m} + V(\mathbf{r}) - \mu \right) \psi + \frac{\lambda}{2} |\psi|^4 \right] d^2\mathbf{r}$$

Gross-Pitaevskii



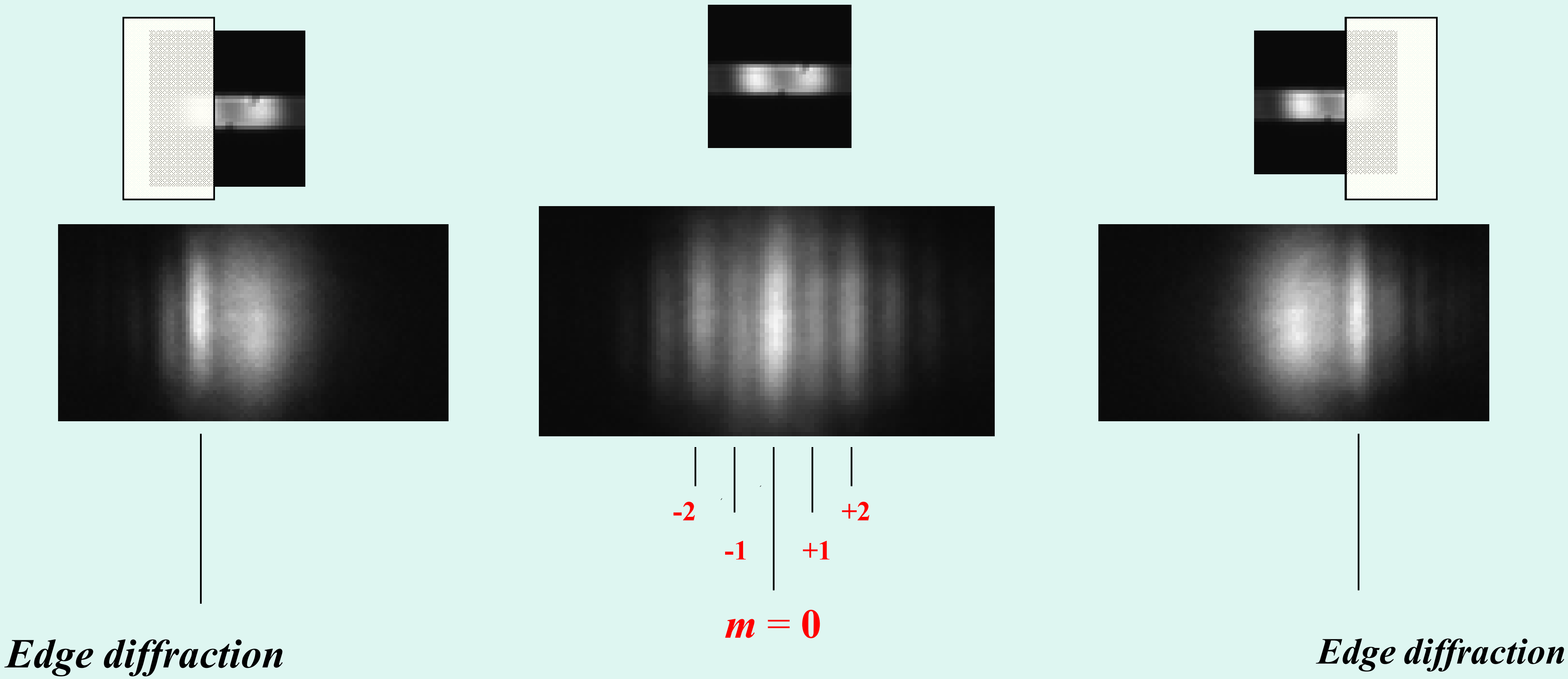


Condensed dipolar exciton system confined in a ring trap with 4 vortexes. Theoretical calculations of angular profile of luminescence – I(K), which is proportional to the momentum distribution of excitons (i.e. to Fourier-transformed density matrix within Thomas-Fermi approximation).

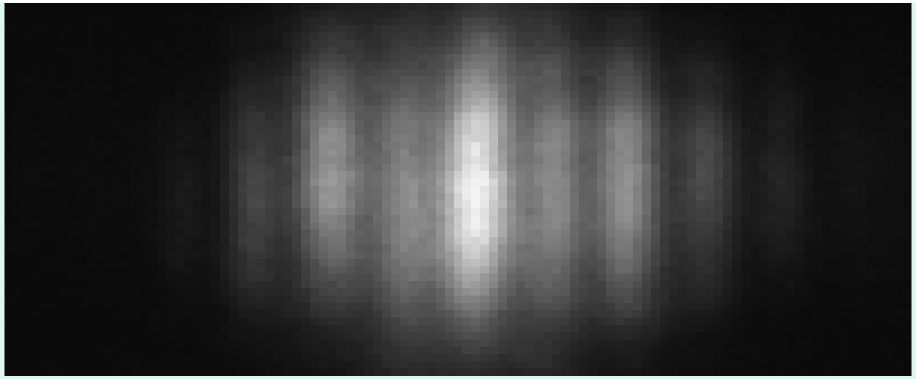
By Yu.E.Lozovik and A.G.Semenov (2006)

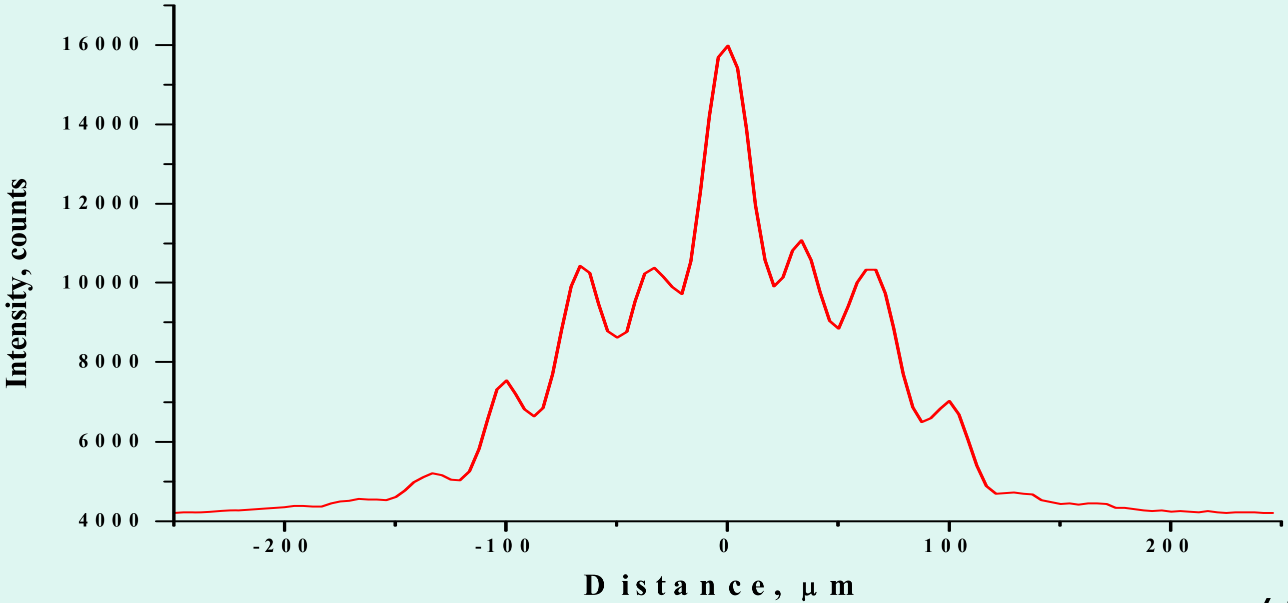
Coherence of dipolar exciton Bose-condensate

Interference from two selected spots in the frame (Young experiment)



Interference of two coherent sources





$$g^{(1)}(r,r') = \frac{\langle E^*(r)E(r')\rangle}{\langle E^*(r)\rangle\langle E(r')\rangle}$$

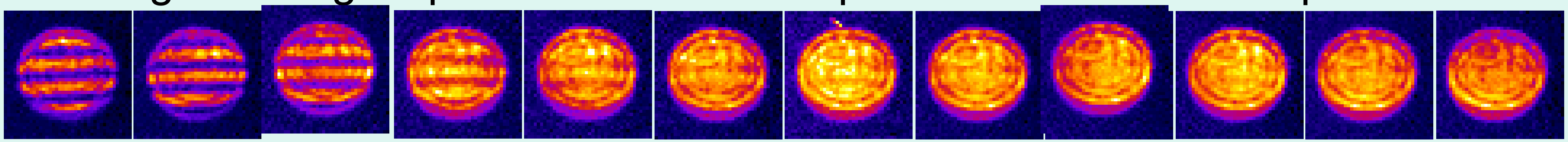
$g^{(1)}(\Delta r) \approx 0.35$

$\Delta r = 2.5$ mm

Autocorrelator and coherence length

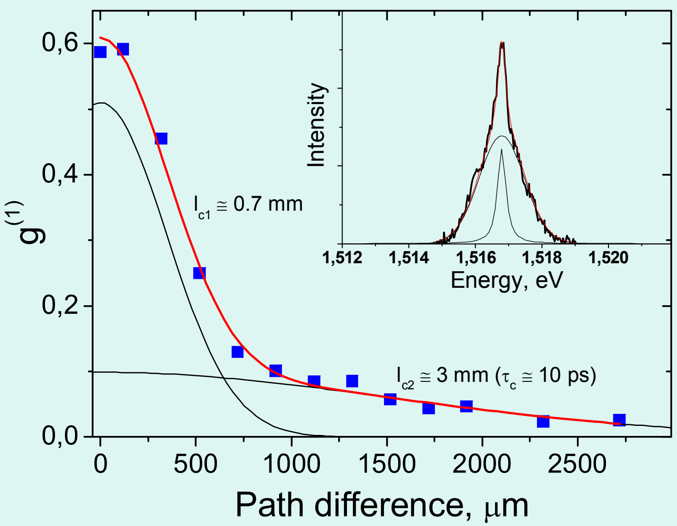
(measured with modified Michelson interferometer)

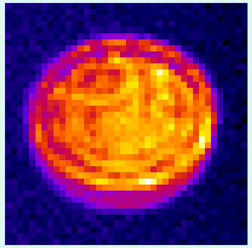
Light of single spot in luminescence pattern selected with a pinhole



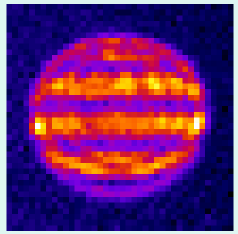
0 120 320 520 720 920 1120 1320 1520 1720 1920 2320

Path difference, μm





Below threshold

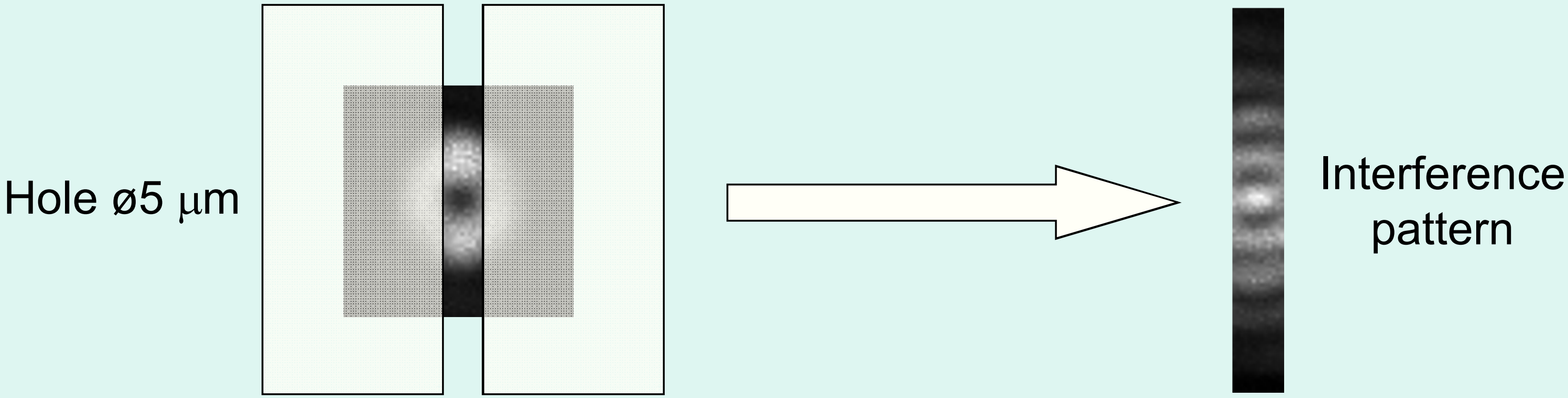


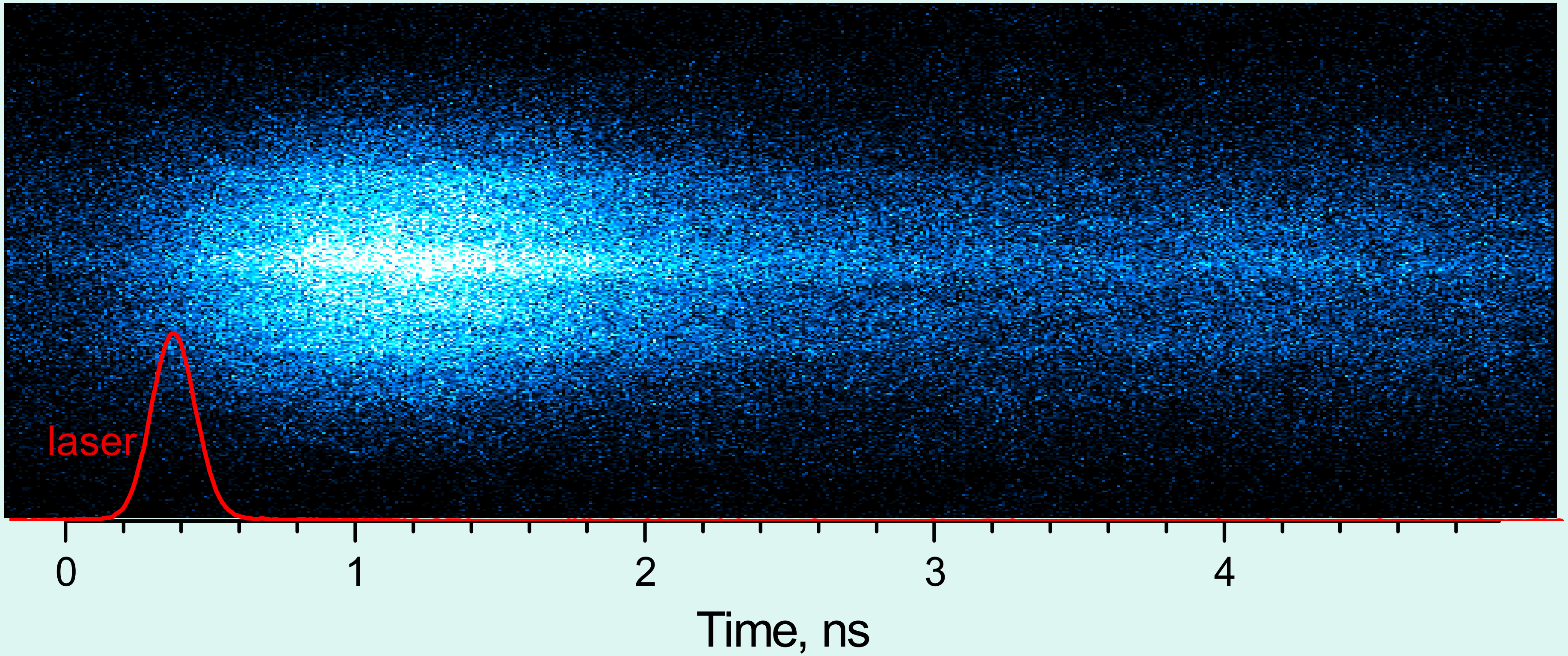
30% above threshold

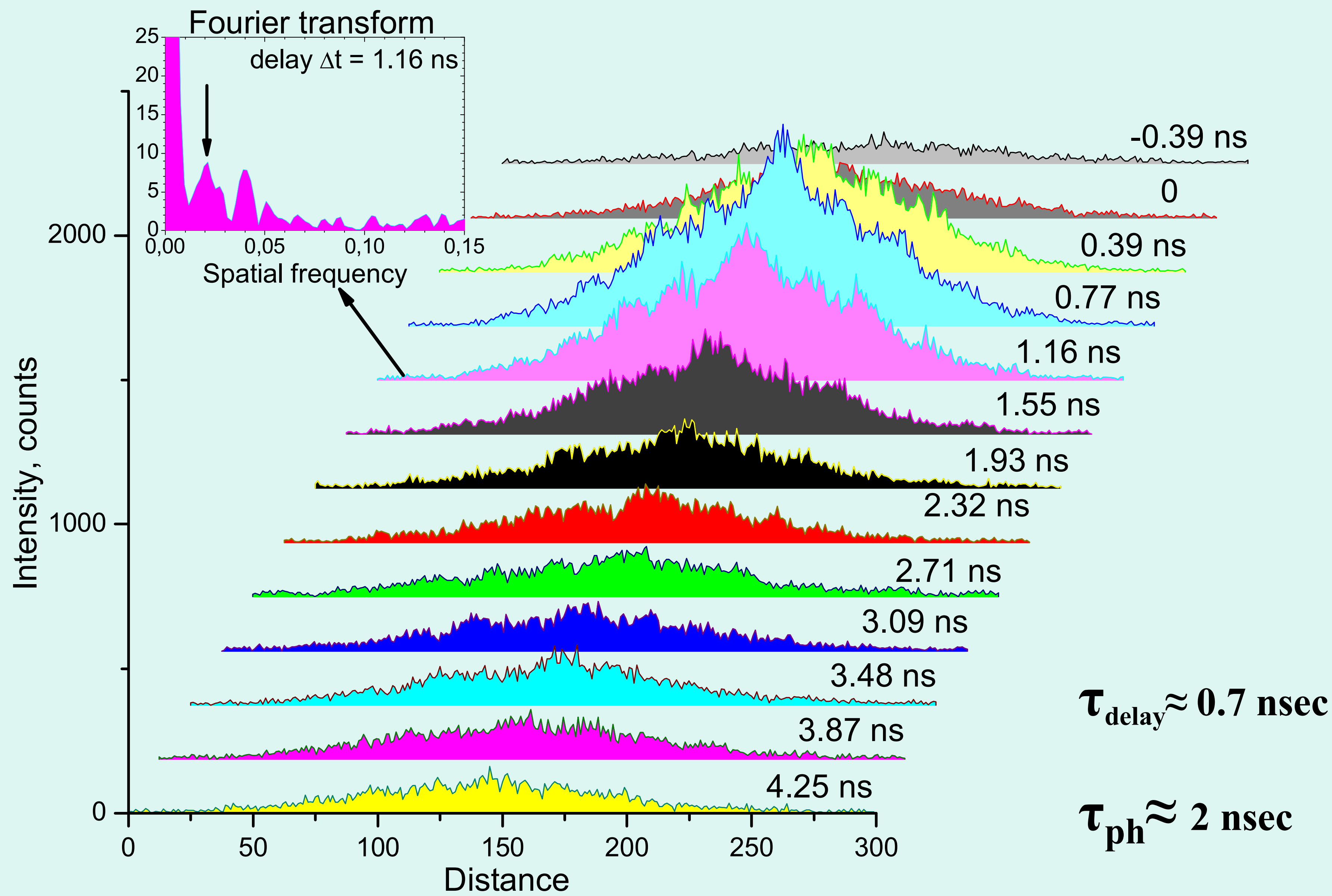
Measured coherence length $l_c \approx 3$ mm and coherence time $\tau_c \approx 20$ ps correspond well to the dipolar exciton linewidth ≈0.2-0.25 meV. (with direct correspodence to Wigner-Khinchin theorem)

Temporal coherence under pulsed photoexcitation

Pulsed Laser (t_p=100ps, f=10 MHz, λ=659nm, P=6.5μW) and
Continuous Wave Laser (λ=782nm, P=60μW), T=1.7K

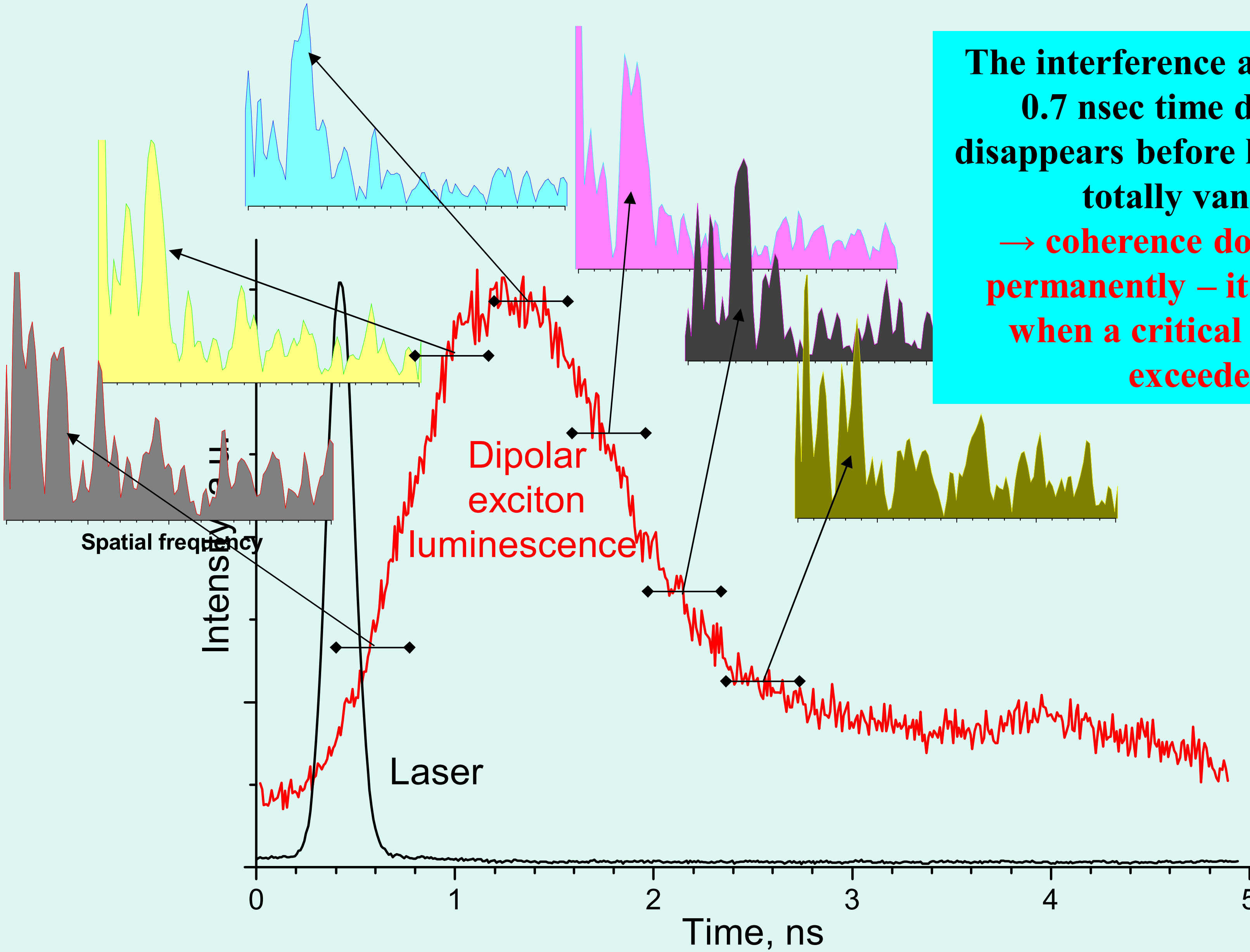






Fourier transform
delay Δt = 1.16 ns
Spatial frequency
0,00
0,05
0,10
0,15
0
5
10
15
20
25
Intensity, counts
0
1000
2000
Distance
0
50
100
150
200
250
300
-0.39 ns
0
0.39 ns
0.77 ns
1.16 ns
1.55 ns
1.93 ns
2.32 ns
2.71 ns
3.09 ns
3.48 ns
3.87 ns
4.25 ns
$\tau_{delay} \approx 0.7$ nsec
$\tau_{ph} \approx 2$ nsec

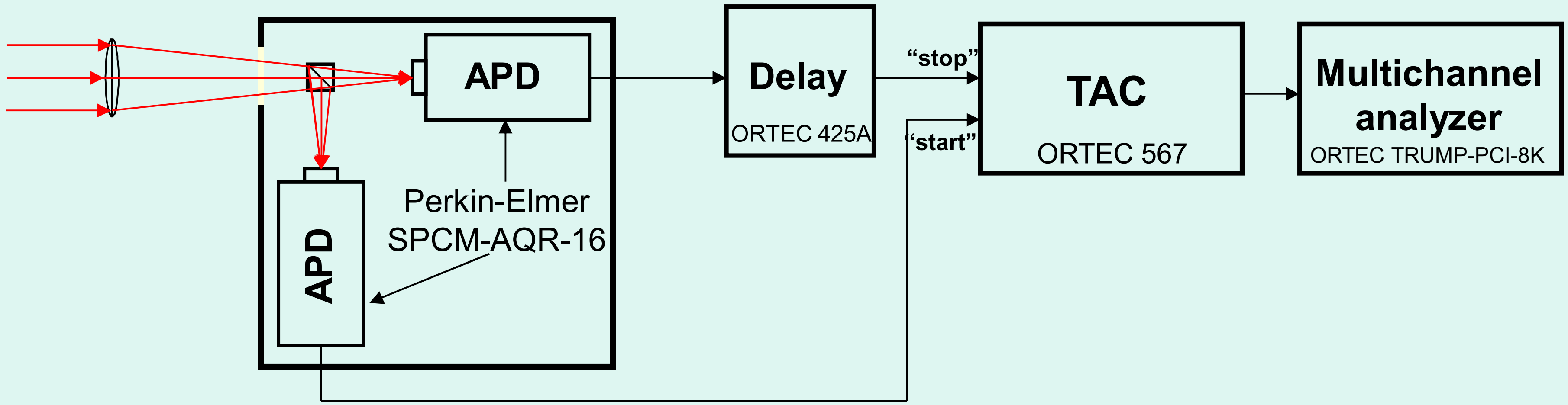
Time-resolved interference (Young experiment): Fourier-spectra

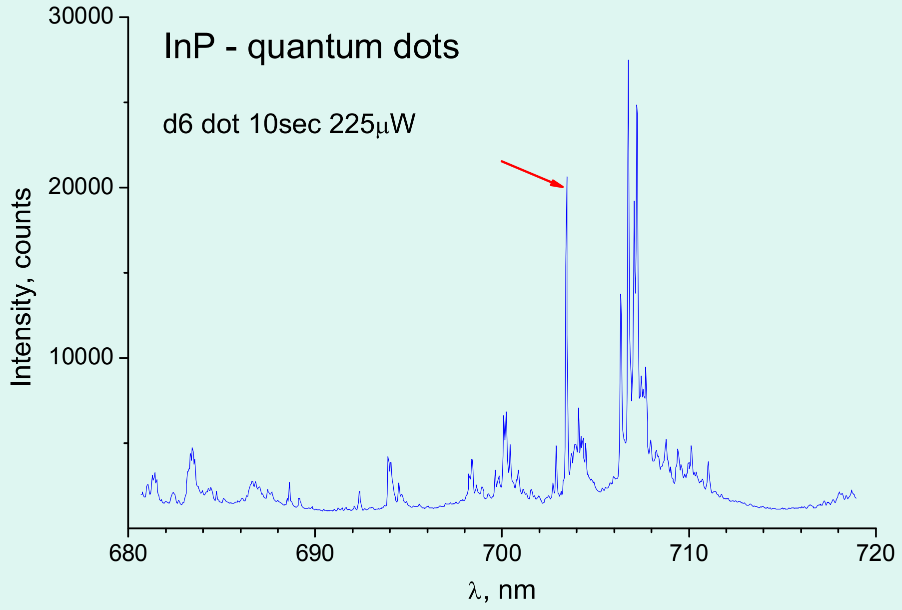


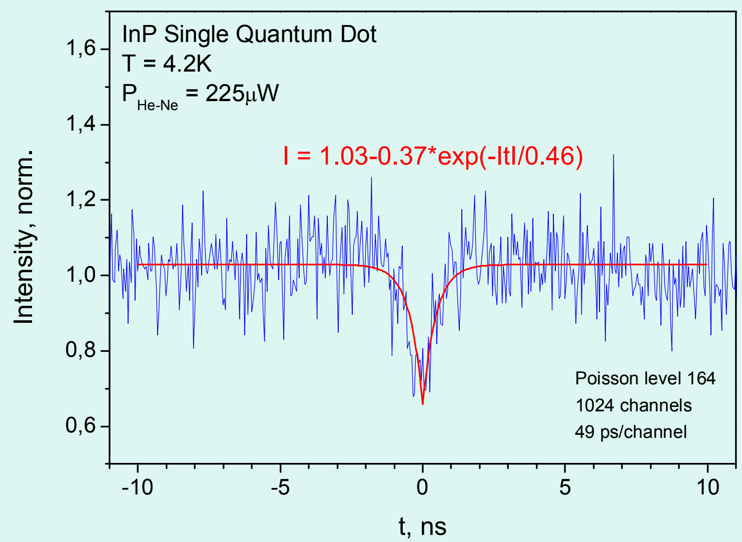
The interference appears with 0.7 nsec time delay and disappears before luminescence totally vanishes

→ coherence does not live permanently – it exists only when a critical density is exceeded.

Measurements of two-photon correlation, $g^{(2)}(\tau)$
(Hanbury Brown-Twiss – interferometer)

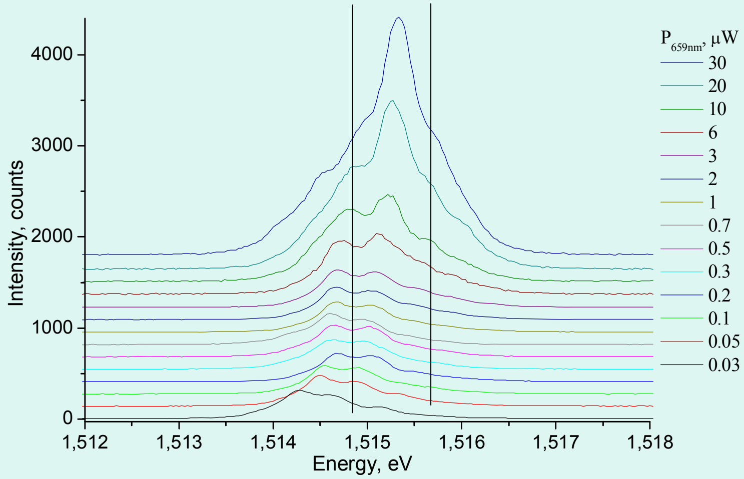


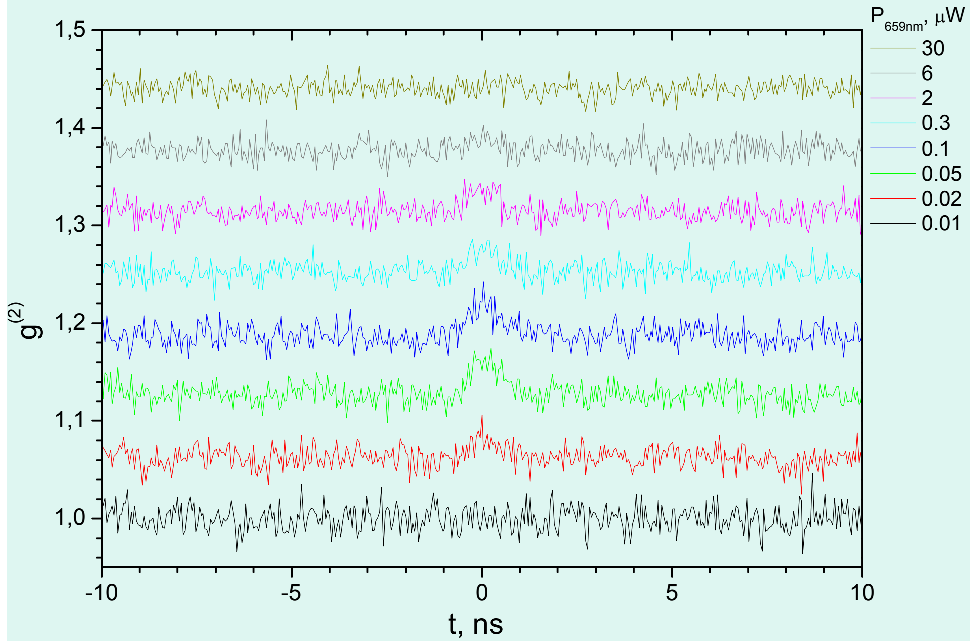


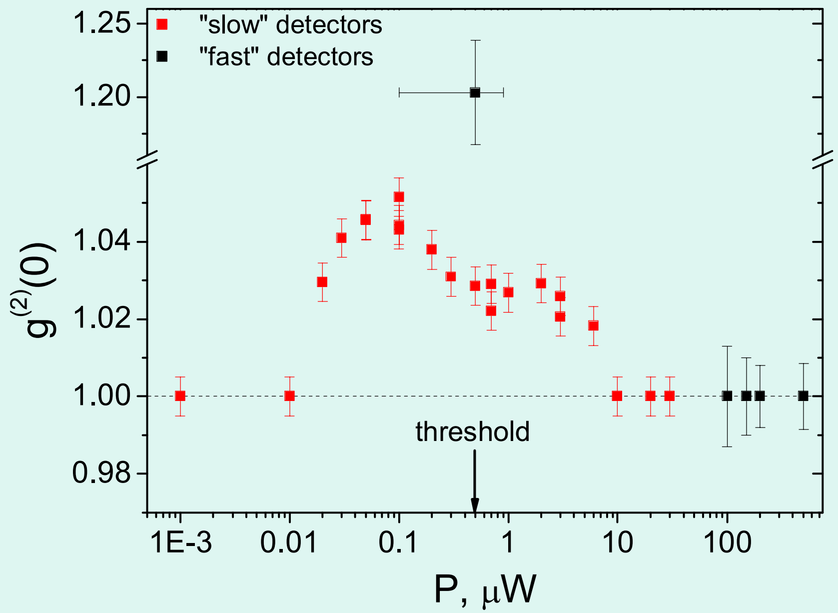


PL two-photon correlator, $g^2(t)$, as a function of pumping power
T = 0.45 K

P_{782nm} = 10 μW

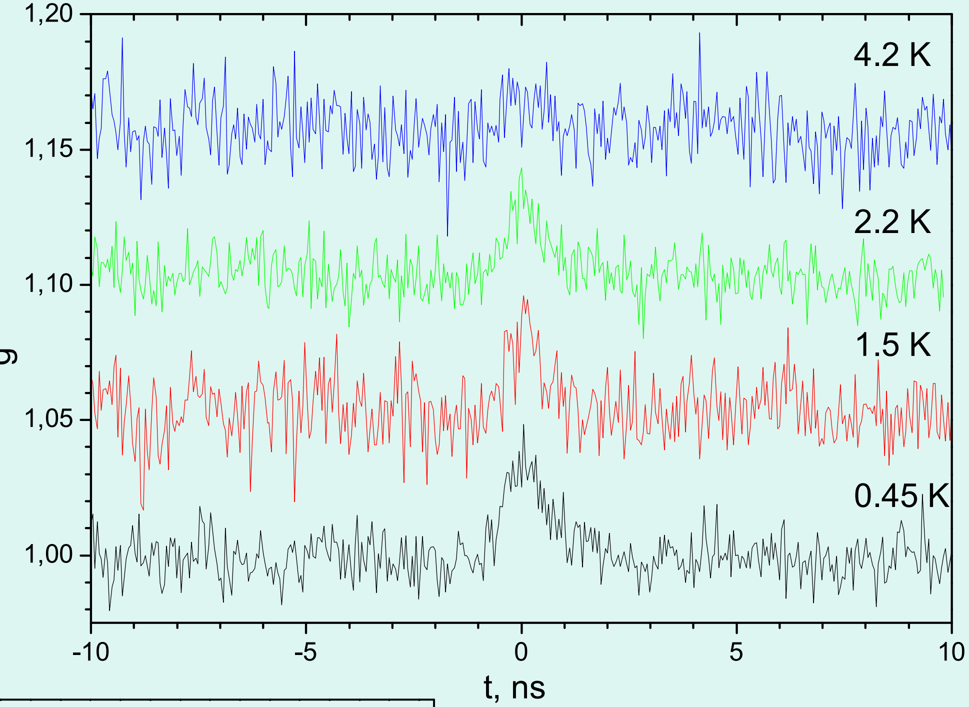


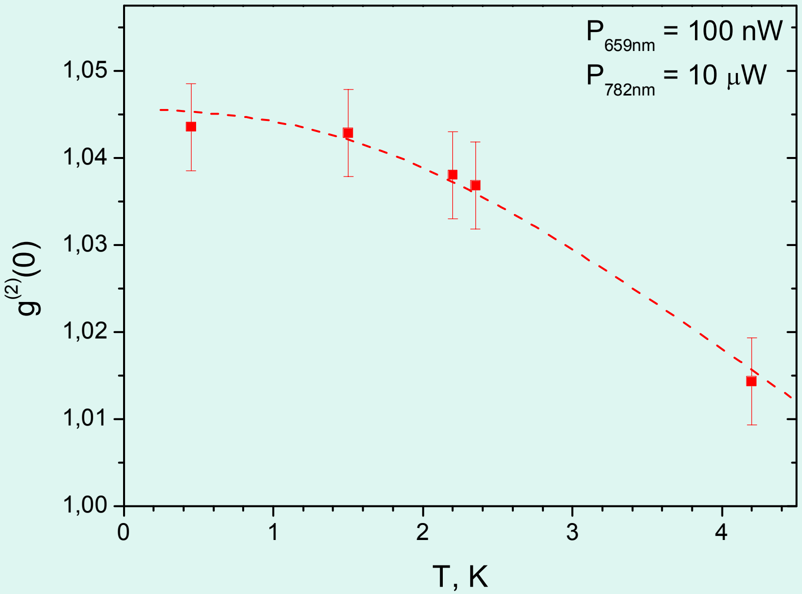


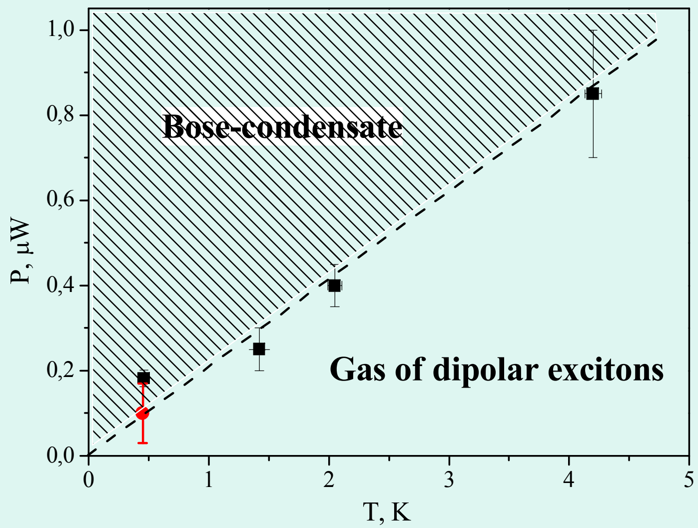


Two-photon correlator, $g^2(t)$, on the temperature variation

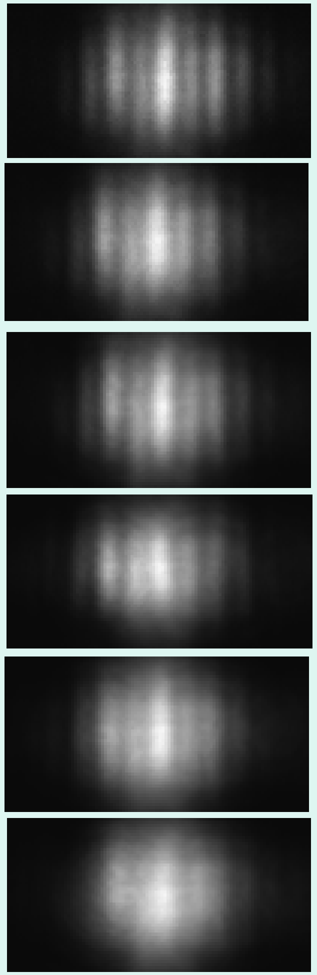
P_{782nm}=10mW
P_{659nm}=100nW

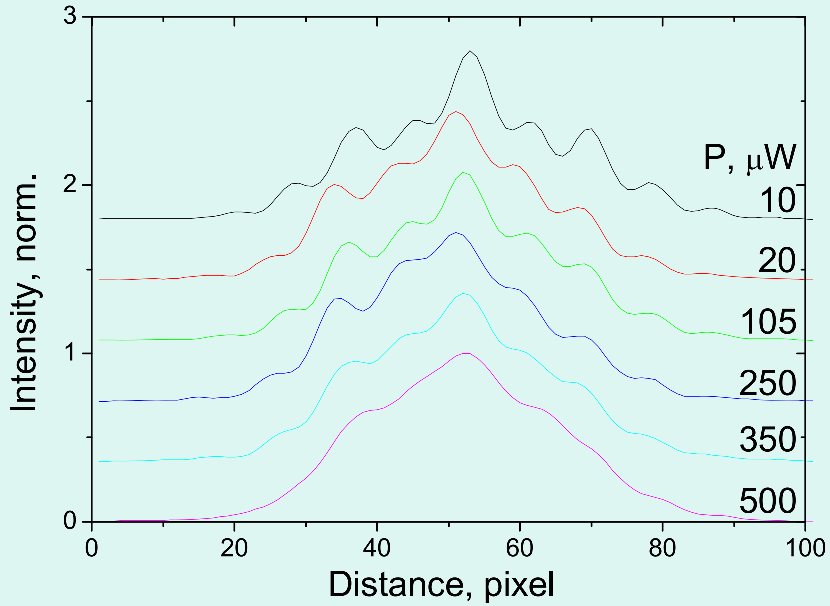






Two-beam interference from pair of spots in the frame on excitation power increase , T = 1.7 K.





Interference is seen in the region where BEC is observed: $g^{(1)}(r) = 0{,}28$.

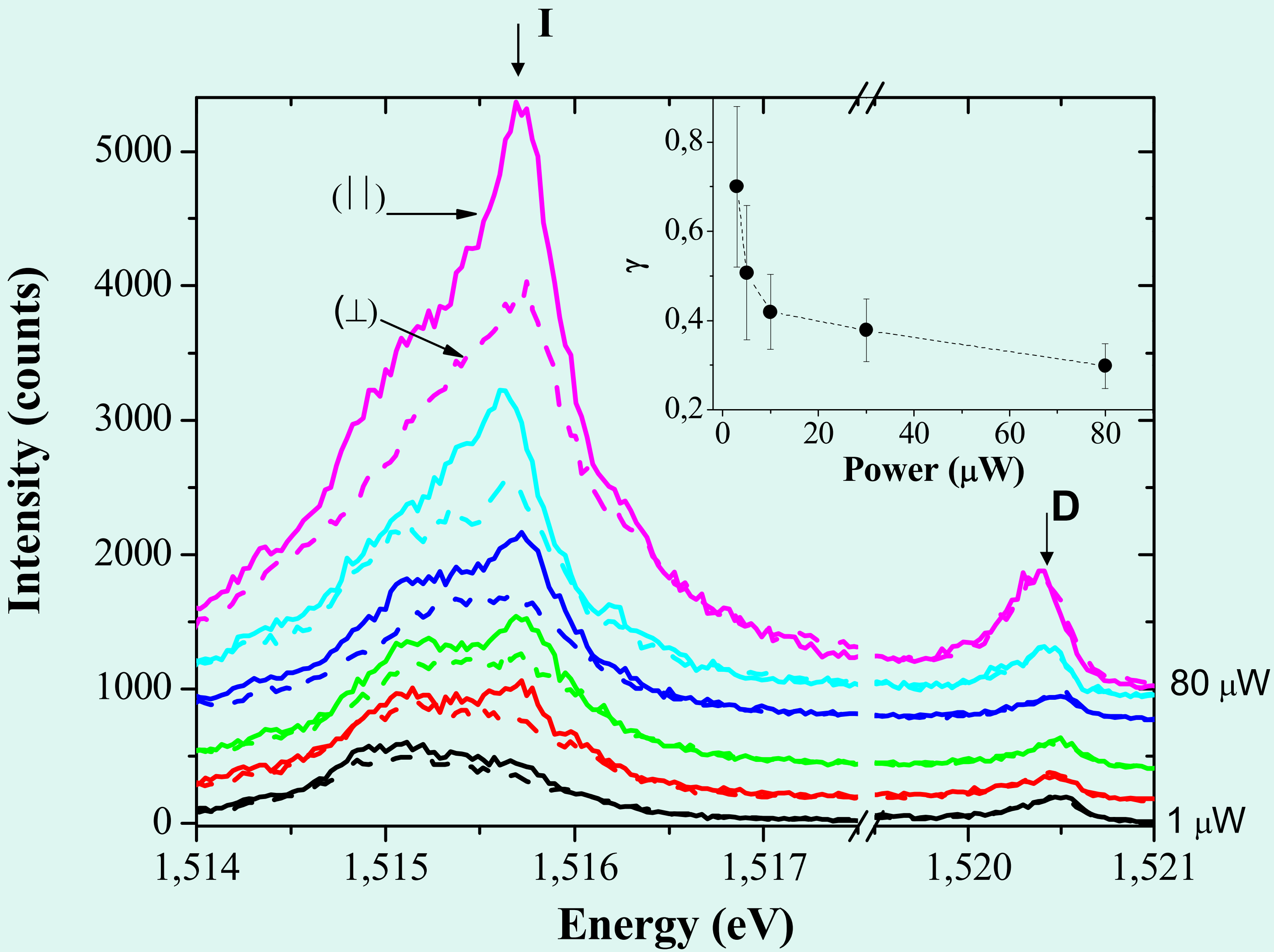
Only in the region of high excitation, where excitons are destroyed, $g^{(1)}(r) \rightarrow 0$.

Decoherence of exciton Bose-condensate is due to the increased electron-hole scattering on exciton density growth

Upper limit of decoherence time $\tau_d \leq 10$ psec at 350 μW ($\geq 5 \cdot 10^{10}$ cm $^{-2}$)

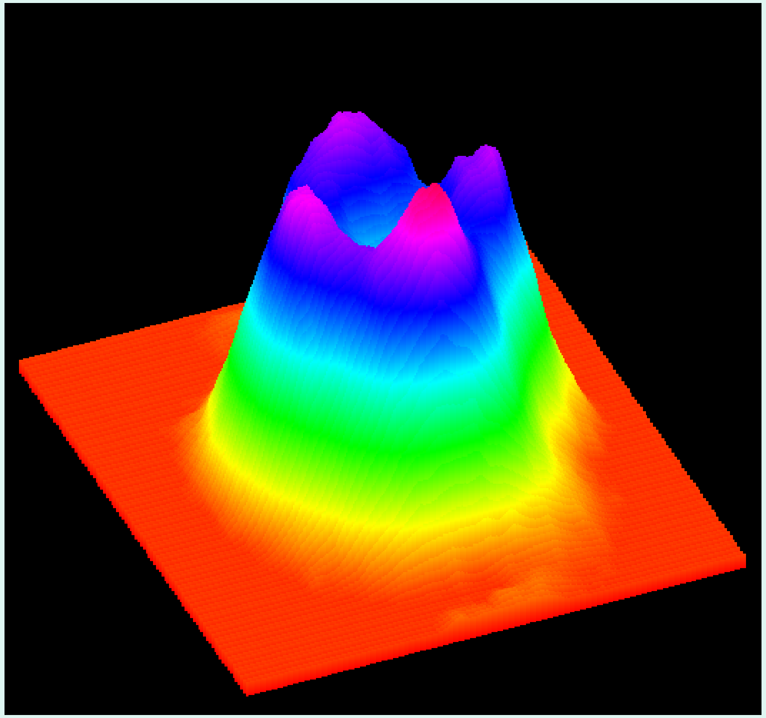
V.B.Timofeev and A.V.Gorbunov Journal of Physics, Cond.Mat. 148, 012048 (2009)

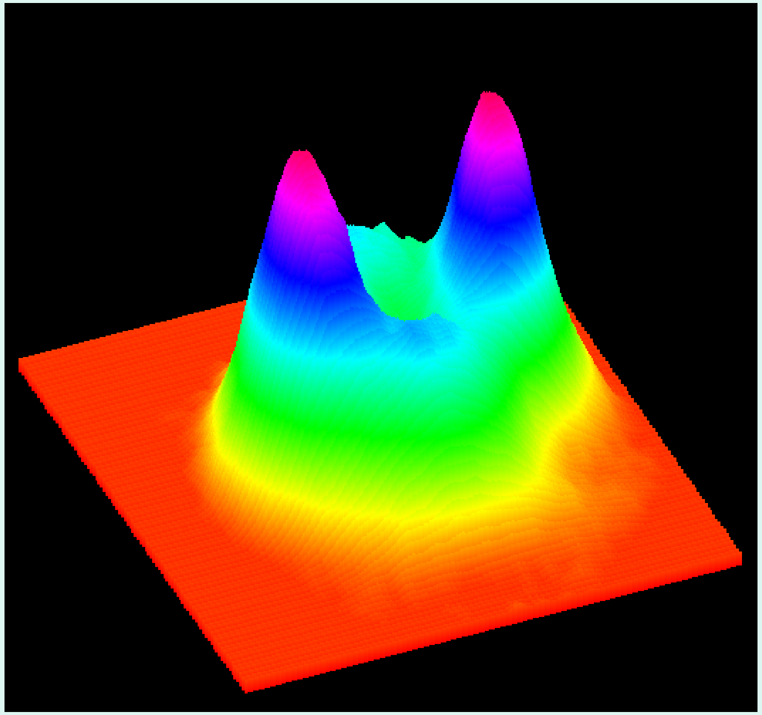
Linear polarization of BEC photoluminescence in 5μm circular trap



FWHM 270 μeV

Linear polarization of BEC PL in 5μm circular trap





E‖<011>

E‖<0-11>

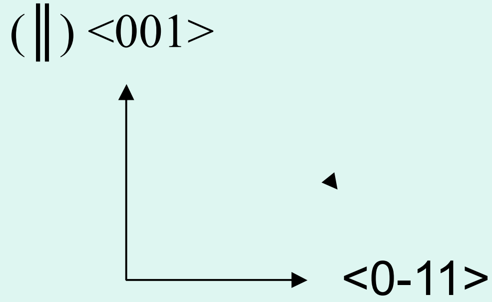
Anisotropic e-h exchange interaction

Heavy hole dipolar exciton ground state is fourfold degenerate:

$$m = S_{e,Z} + J_{h,Z} = \pm 1, \pm 2$$

$$\mathcal{H} = a_Z J_{h,Z} \, x \, S_{e,Z} + \Sigma \, b_i J^{3}_{h,I} \, x \, S_{e,I}$$

States $m = \pm 1$ and $m = \pm 2$ are splitted by $E_{ex} = 1.5\, a_Z + 3.375\, b_Z$



An asymmetry of the confinement potential leads to anisotropic e-h exchange ($b_x \neq b_y$)

$\Delta exc \leq 50\mu eV << k_B T$

The spin states are the linear combination of the $m = \pm 1$ exciton states:

$$|L_{1/2}\rangle = 1/\sqrt{2}\,(\alpha|+1\rangle \pm \beta|-1\rangle), \quad \alpha / \beta \approx 1$$

The mixing finally results in the splitting of the dipolar exciton ground state with orthogonal linear polarization of spin splitted components in photoluminescence spectra. Splitted components are pinned by random potential fluctuations

Observed phenomenon is an exhibition of *spontaneous symmetry breaking* under BEC condensation of dipolar excitons.

Spin effect in Bose-condensate of dipolar excitons: suppression of Zeeman splitting

•A key property of equilibrium exciton Bose-condensate in an external magnetic field is ***the suppression of the paramagnetic splitting.*** The theory was developed for *spinor exciton-polariton Bose-condensate* (***Yu.Rubo et al. Phys.Lett.A (2006)***).

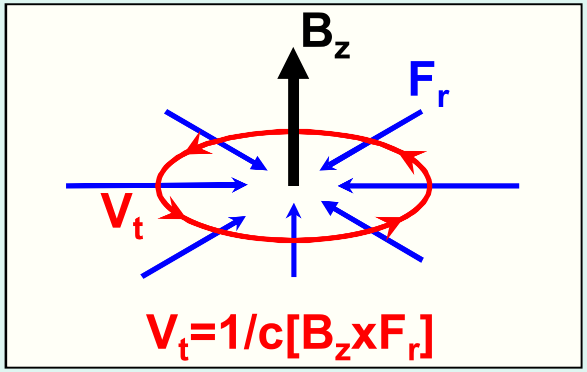
•For $B < B_c$ the Zeeman splitting of the ground exciton state is exactly compensated by exciton-exciton interaction, namely: repulsion for spins with same orientation **(α_1)**, and attraction for spins with opposite orientation **(α_2)** in the elliptically polarized Bose-condensate **(T=0,** chemical potential **$\mu \to 0$).** Therefore, up to some critical field

$$B_c = (\alpha_1 - \alpha_2)N / \mu_B g$$

Bose-condensate remains partially spin polarized and emits elliptically polarized light.

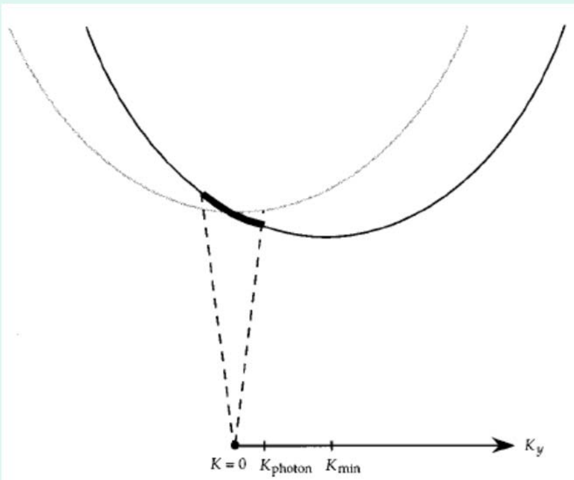
Above the critical point **($B > B_c$)**, the spin degeneracy is lifted, the circularly polarized splitted lower state appears and Zeeman splitting is recovered and is proportional to Increment of magnetic field, **($B - B_c$)**

•Predicted effect of the spin-splitting suppression was experimentally observed at the first time by ***Larionov et al. PRL (2011)***, ***(see also Walker et al. PRL (2011))*** but for exciton-polariton Bose-condensate under ***nonequilibrium conditions***



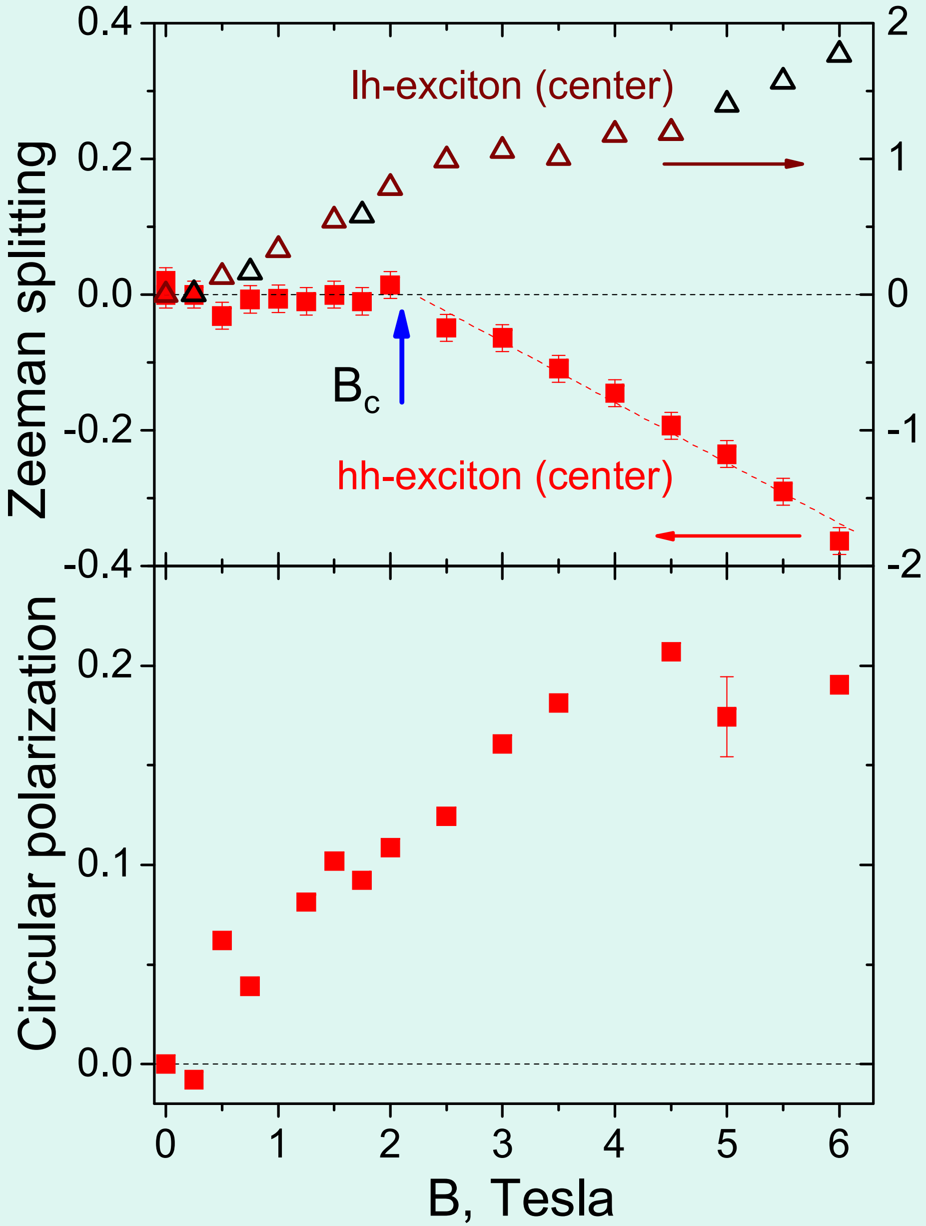
A.Imamoglu (1996)

L.Butov, Yu.Lozovik (1998)



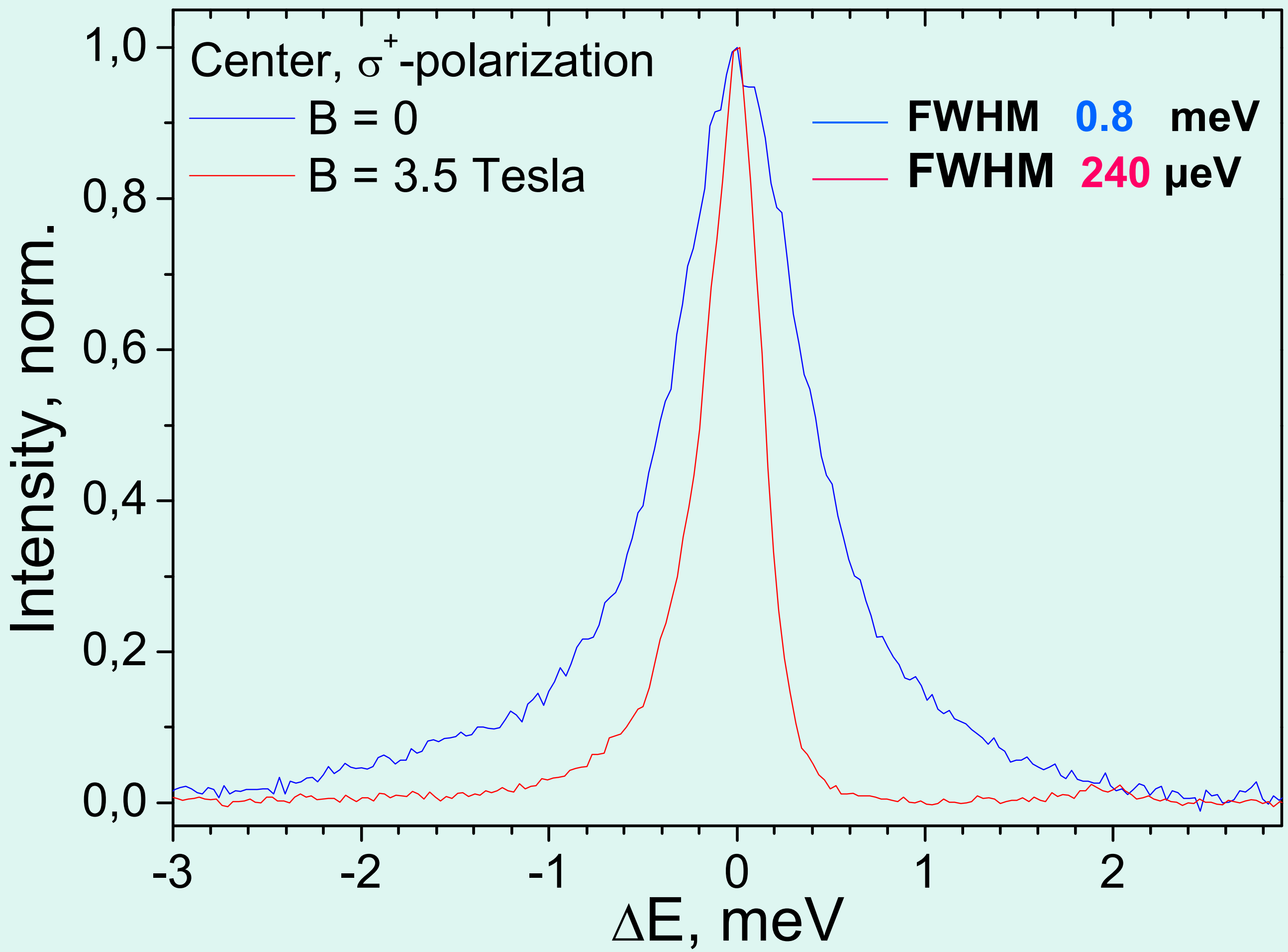
g_{ex} (light hole) ≈ +7.0
g_{ex} (heavy hole, center ≈ -1.5

Snelling et al. 1992

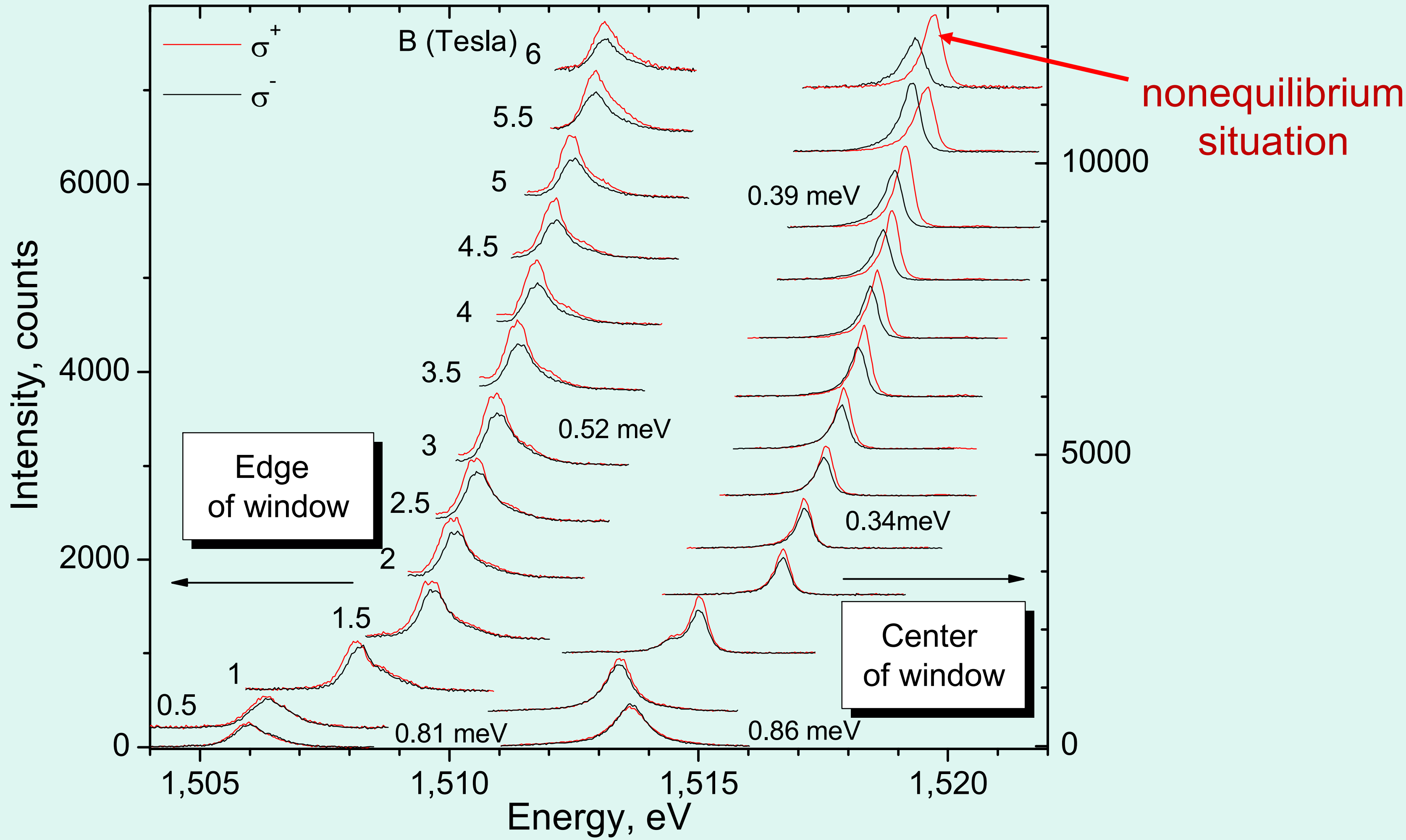


A.V. Gorbunov, V. B. Timofeev, in press (2012)

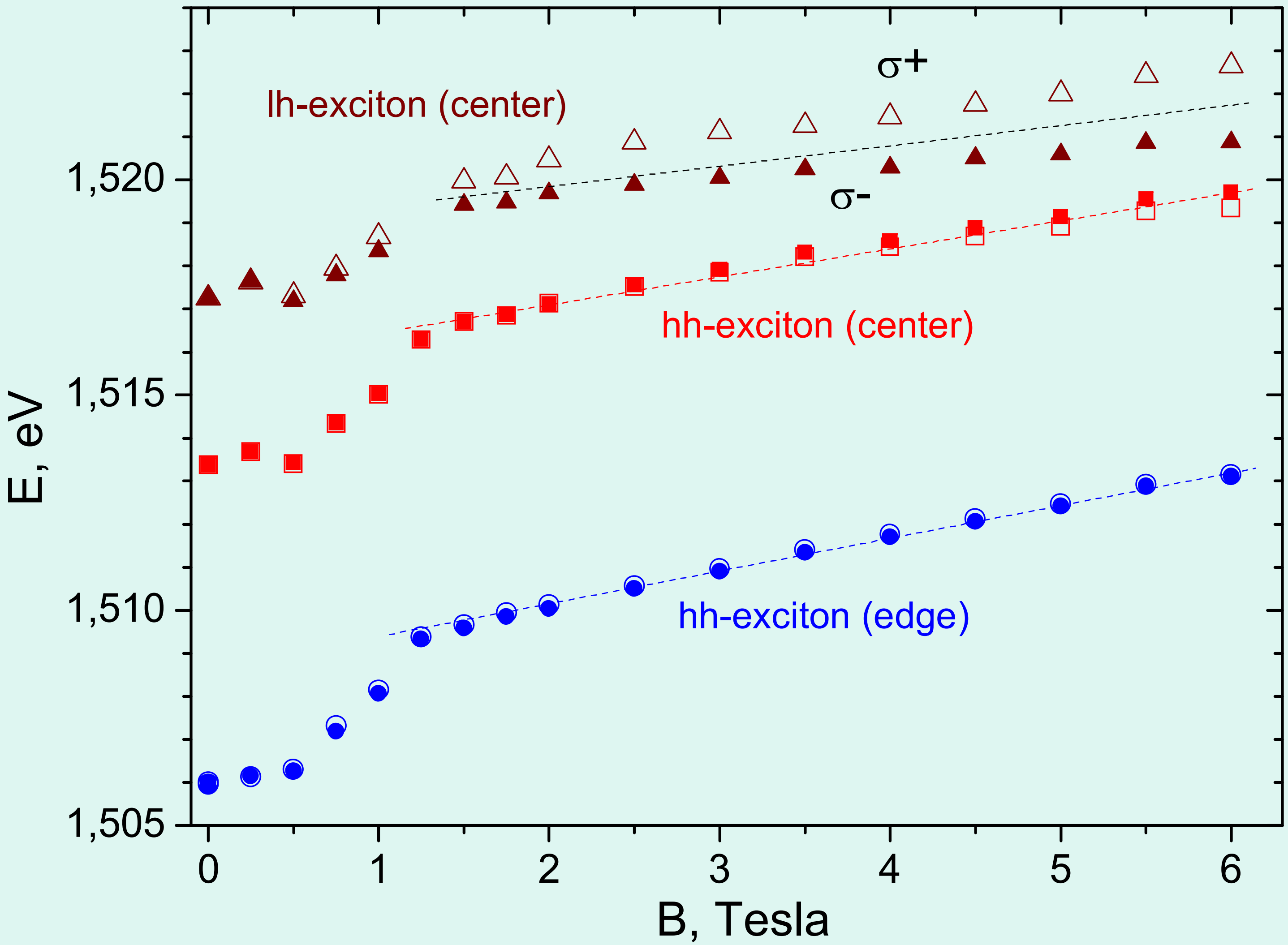
Shape of PL line of dipolar hh-excitons condensate in magneto-optical trap



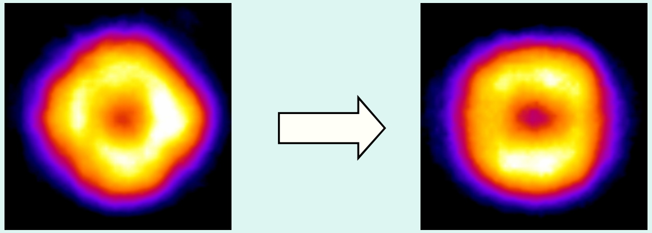
PL spectra of dipolar excitons in a trap vs perpendicular magnetic field



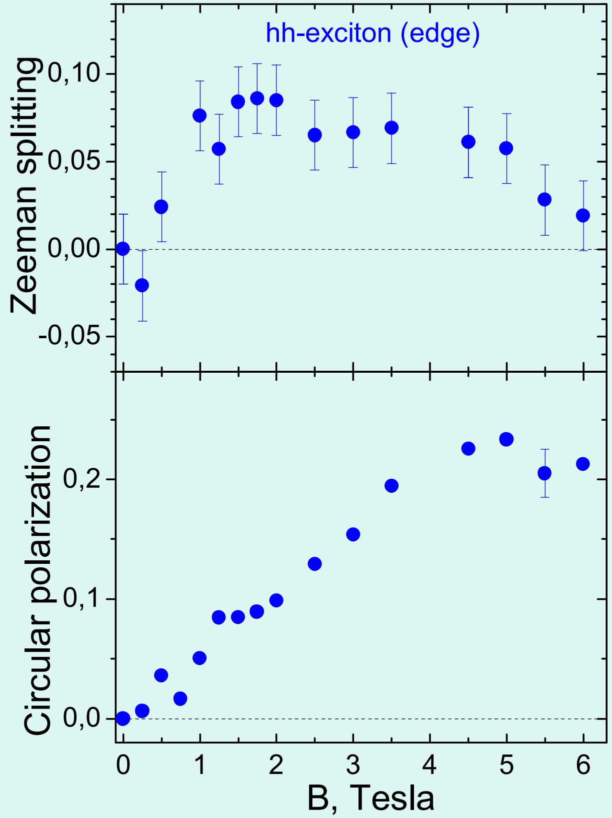
Variation of the spectral position of dipolar excitons in traps on magnetic field



- In the region of $B \leq 1.3$ T enormously large quadratic diamagnetic shift has been observed: ≈2.2 meV/T^2 for excitons in the trap close to the window edge , ≈1.9 meV/T^2 – for hh-excitons and ≈0.9 meV/T^2 – for lh-excitons in the centre of the window (in GaAs-structures typical value of diamagnetic shift is approximately <0.1 meV/T^2)



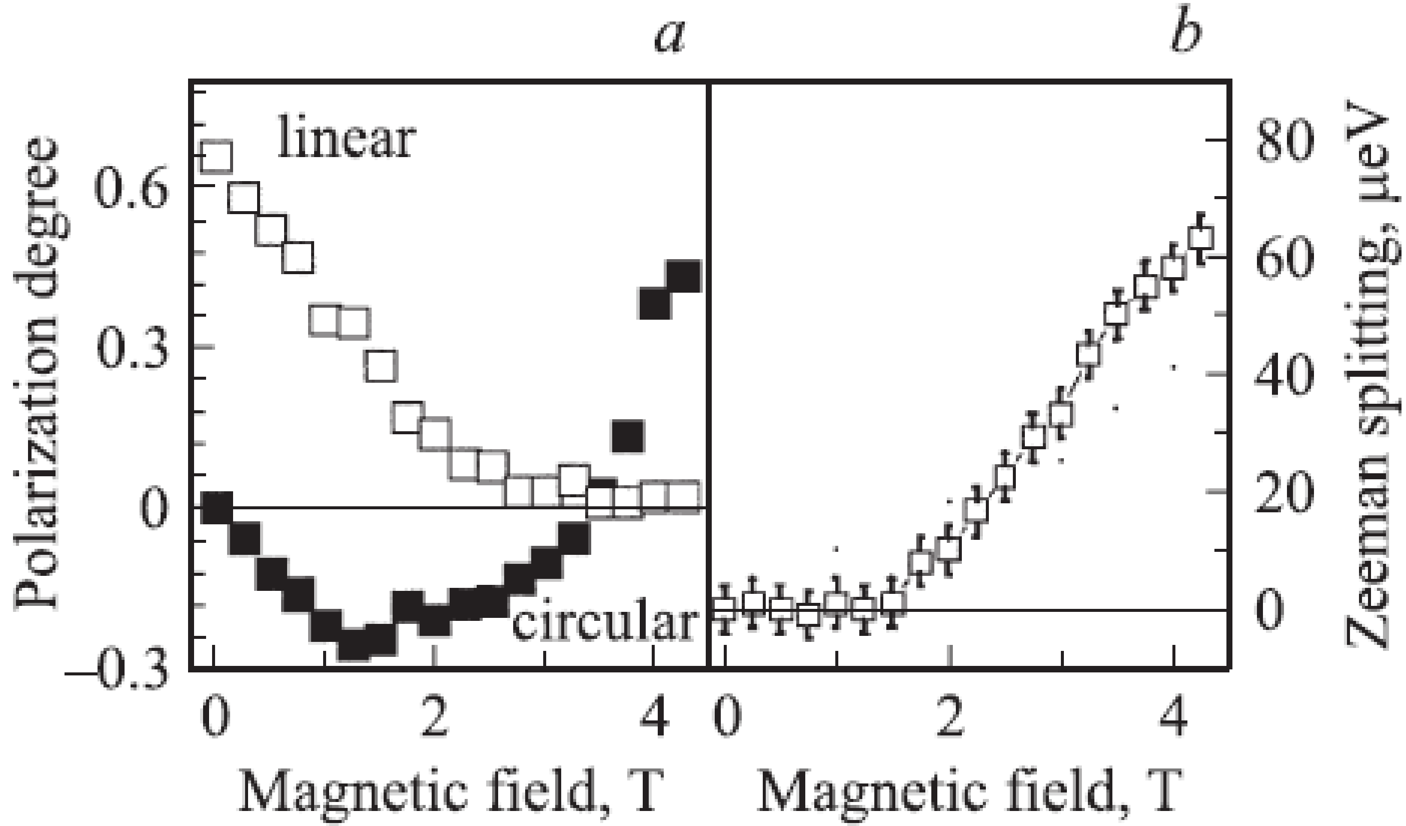
B=0 **B>0**



g_{ex} (heavy hole, edge) ≈ +0.9

A.V. Gorbunov, V. B. Timofeev, in press (2012)

Spin Meissner effect for exciton polaritons in mcrocavities (From A.Larionov, V.Kulakovskii et al. PRL (2010))



C o n c l u s i o n

BEC of interacting Bose gas of dipolar laterally trapped excitons is manifested by

1. **macroscopic accumulation of condensed excitons at K ≈ 0: appearance of a sharp PL line of condensed part of excitons;**
2. **observation in real space the patterned structure of equidistant luminescence spots of exciton condensate**
3. **coherent Bose-condensate of dipolar exciton appears *spontaneously* in the reservoir of interacting excitons;**
4. **found collective state is coherent (the large-scale spatial coherence is equal to the perimeter of a ring trap,   we assume that this state is described by a common wave function**
5. **observation of linear polarization of PL dipolar exciton Bose-condensate is an exhibition of *spontaneous symmetry breaking***
6. **suppression of a paramagnetic splitting in magnetic field is a direct sequence of Bose-Einstein degeneracy and interaction of spin-aligned excitons**

Acknowledgements

I'm grateful to acknowledge very fruitful collaboration in the course of this work to

A.V.Gorbunov, A.V.Larionov, D.A.Demin, A.A.Dremin, S.V.Dubonos, J.M.Hvam, C.Soerensen, W.Ditsche

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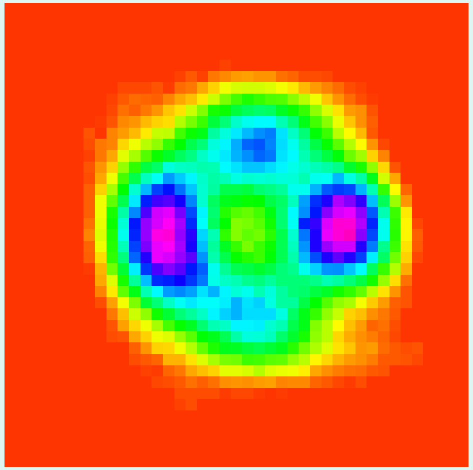

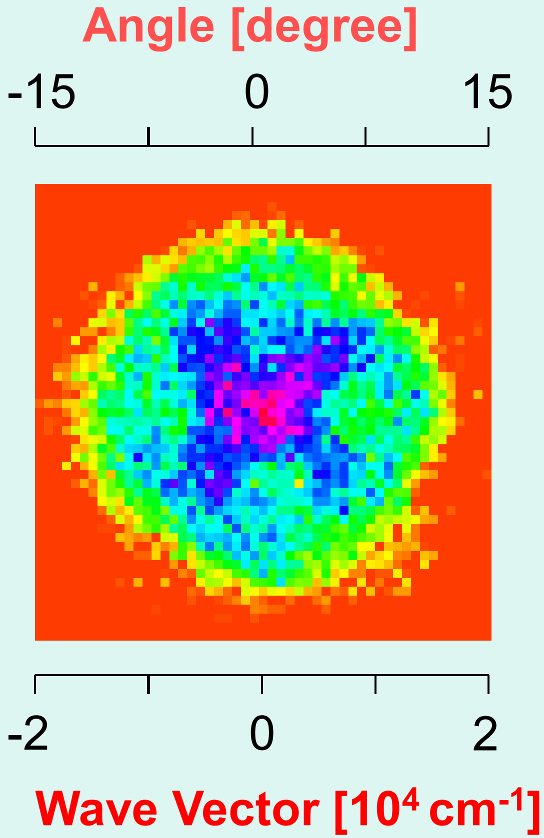

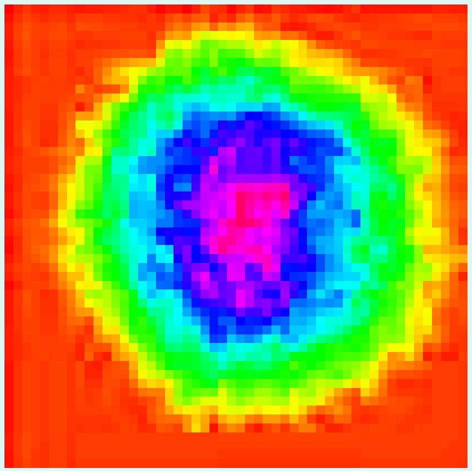

Fourier-transformations with evidence demonstrate the destructive interference.
It means that

1.collective state of dipolar excitons is spatially coherent,

2.luminescence of condensate is directed in a cone with an opening angle around

$$\Delta\varphi \approx \lambda / D \cong 0.23 rad$$

3.the whole pattern of equidistant PL spots of BEC is described by a single wave function