Cold excitons

Introduction

- Excitons and electron-hole plasma in semiconductors
- Exciton condensation
- Experimental systems
- Indirect excitons in coupled quantum wells

Phenomena in cold exciton gases

- Stimulated scattering
- Pattern formation and transport
- Coherence and condensation

Control of excitons, excitons in potential landscapes

- Optical traps
- Excitonic circuits
- Excitons in traps
- Excitons in lattices

Spin transport of excitons

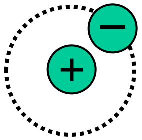
Most recent studies

- Topological defects in interference pattern
- Spin pattern formation

exciton – bound pair of electron and hole

$$M = m_e + m_h << m_{atom}$$

light bosonic particle in semiconductor



$$e^2 \to \frac{e^2}{\varepsilon}$$

$$m \to \mu$$

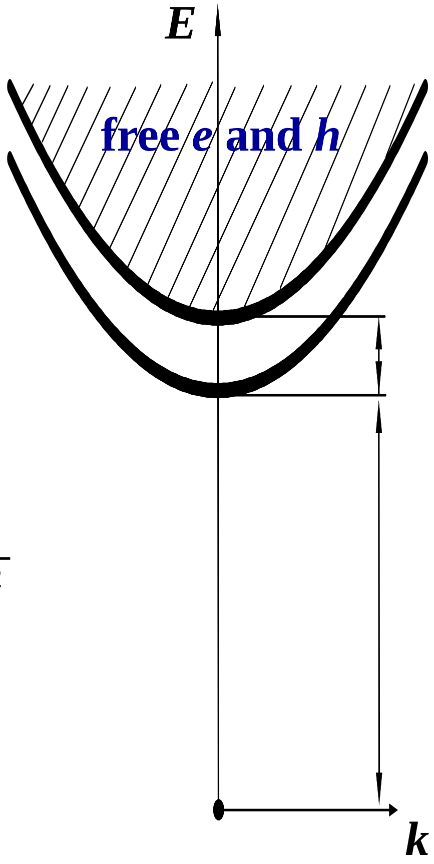
Hydrogen atom → exciton

$$\boxed{\begin{aligned} a_0 &= \frac{\hbar^2}{me^2} \\ Ry &= \frac{me^4}{2\hbar^2} \end{aligned}} \begin{aligned} &\to \\ &\to \end{aligned} \boxed{\begin{aligned} a_{ex} &= \frac{\hbar^2 \varepsilon}{\mu e^2} \\ Ry_{ex} &= \frac{\mu e^4}{2\varepsilon^2 \hbar^2} \end{aligned}}$$

$$E_n(k) = E_g + \frac{\hbar^2 k^2}{2M} - \frac{\mu e^4}{2\varepsilon^2 \hbar^2 n^2}$$

$$M = m_e + m_h$$

$$\mu^{-1} = m_e^{-1} + m_h^{-1}$$



← **exciton dispersion**

← **exciton binding energy**

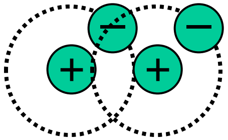
exciton density is controlled by excitation $n = G\tau$

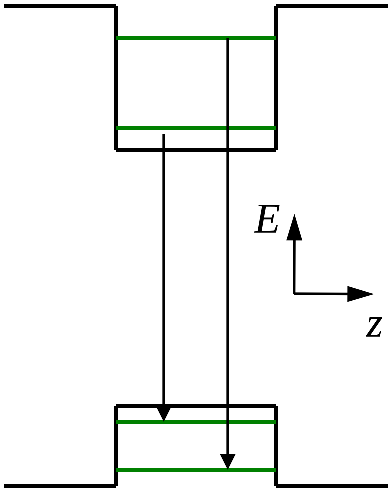
← **photon energy ~ E_g**

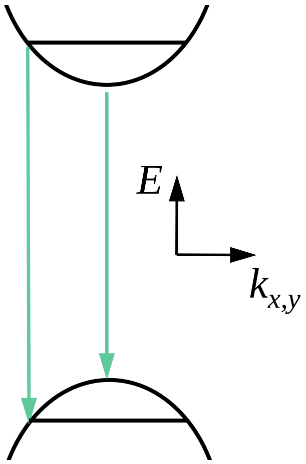
Hydrogen-like excitons at low densities

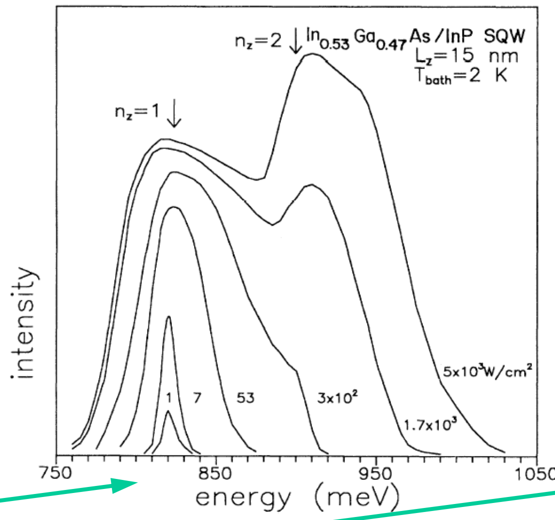
_e-h_ plasma at high densities

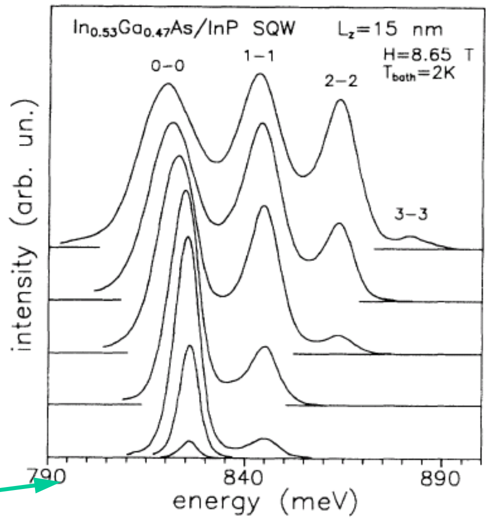
Mott transition at $na_B^D \sim 1$











Emission of <u>_e-h_ plasma and magnetoplasma</u> in QW:

linewidth → Fermi energy

energy shift → band gap renormalization

shift of Landau levels → mass renormalization

excitons in dense magnetoplasma

broadening of Landau levels → damping of one-particle states

many-body effects

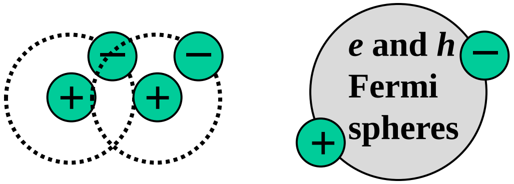
L.V. Butov, V.D. Kulakovskii, E.Lach, A. Forchel, D. Grutzmacher, PRB 44, 10680 (1991)
L.V. Butov, V.D. Kulakovskii, E.I. Rashba, JETP Lett. 53, 109 (1991)
L.V. Butov, V.D. Kulakovskii,G.E.W. Bauer, A. Forchel, D. Grutzmacher, PRB 46, 12765 (1992)

Types of exciton:

Hydrogen-like excitons

in dilute gases ($na_B^D \ll 1$)

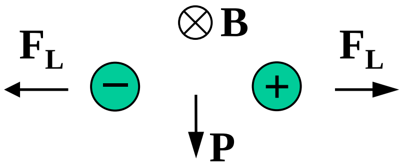
Cooper pair-like excitons



in dense *e*-*h* system ($na_B^D \gg 1$)

require matched *e* and *h* Fermi surfaces

Magnetoexcitons



in high magnetic fields

internal structure and
center of mass motion are coupled

Types of exciton condensate

electron-hole liquid

condensation in real space to
electron-hole droplets (EHL) forming
degenerate Fermi gas of electrons and holes

L.V. Keldysh (1968)

polariton laser

macroscopic occupation of
coupled exciton-photon mode

thermal equilibrium is not required

A. Imamoglu, R.J. Ram, S. Pau, Y. Yamamoto (1996)

Bose Einstein condensate

in dilute exciton gas ($na_B^D << 1$)
excitons are (interacting)
Bose particles similar to hydrogen atoms

below T_c thermal distribution of excitons
leads to their condensation in *k*-space

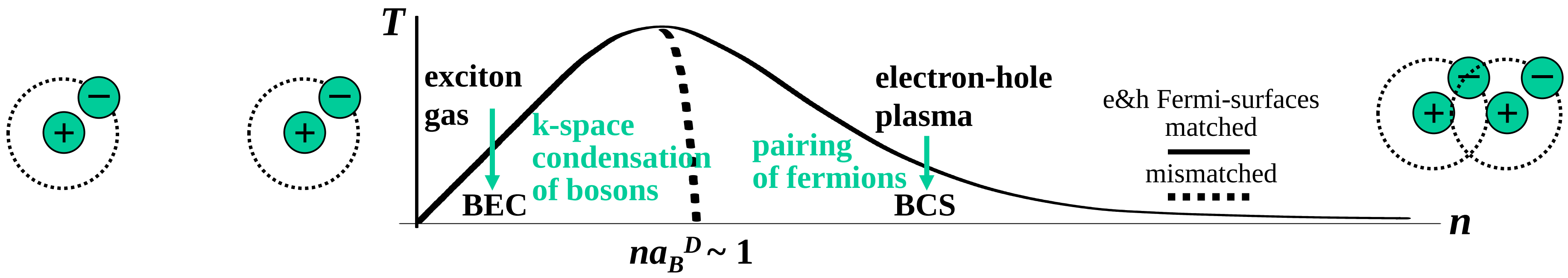
L.V. Keldysh, A.N. Kozlov (1968)

excitonic insulator (BCS-like condensate)

in dense electron-hole system ($na_B^D >> 1$)
excitons are similar to Cooper pairs

below T_c electrons and holes bind to pairs –
excitons – forming BCS-like condensate

L.V. Keldysh, Yu.E. Kopaev (1964)



Experimental systems

electron-hole liquid

Ge
Si

polariton laser

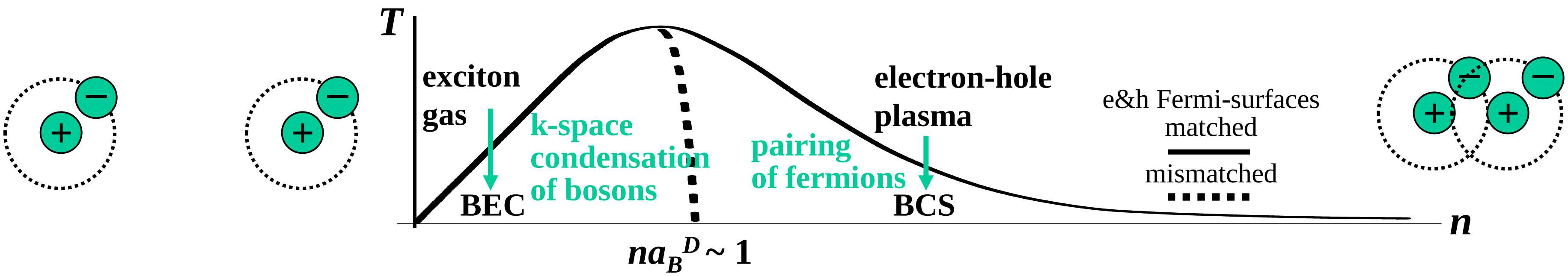
Microcavity polaritons

Bose Einstein condensate

Cu_2O
Indirect excitons in CQW

excitonic insulator (BCS-like condensate)

Electron bilayers
in high magnetic fields at $\nu=1$



What temperature is “cold” for exciton gas?

$$\lambda_{dB} = \left(\frac{2\pi\hbar^2}{mk_BT}\right)^{1/2}$$

transition from classical to quantum gas takes place when thermal de Broglie wavelength is comparable to interparticle separation

3D: $\lambda_{dB} = n^{-1/3}$

$$T_{dB} = \frac{2\pi\hbar^2}{mk_B} n^{2/3}$$

$$T_{BEC} = 0.527 T_{dB}$$

$m_{exciton} \sim 10^{-6}\, m_{atom}$

Kelvin for excitons
is like
microKelvin for atoms

2D: $\lambda_{dB} = n^{-1/2}$

$$T_{dB} = \frac{2\pi\hbar^2}{mk_B} n$$

3D gas of Rb atoms:
$n = 10^{15}$ cm^{-3}, $m_{atom} = 10^5 m_e \rightarrow T_{dB} \sim 5\times10^{-6}$ K

2D gas of excitons in GaAs QW
$n = 10^{10}$ cm^{-2}, $m_{exciton} = 0.2\, m_e \rightarrow T_{dB} \sim 3$ K

estimates for characteristic temperatures for cold 2D Bose gases

for $n = 10^{10}$ cm^{-2} per spin state ($< n_{Mott} \sim 1/a_B^2 \sim 10^{11}$ cm^{-2}), $M = 0.22\ m_0$

λ_{dB} is comparable to interexcitonic separation

$$T_{dB} = \frac{2\pi\hbar^2 n}{M k_B} \approx 3K$$

$$\lambda_{dB}^2 n = 1$$

thermal de Broglie wavelength

$$\lambda_{dB} = \left(\frac{2\pi\hbar^2}{M k_B T}\right)^{1/2} \approx 160 nm$$

at $T = 1$ K

temperature of quantum degeneracy

$$T_0 = T_{dB} \approx 3K$$

$$N_{E=0} = \exp\left(T_{dB}/T\right) - 1$$

A.L. Ivanov, P.B. Littlewood, H. Haug,
PRB 59, 5032 (1999)

BEC in finite 2D system

$$T_{cS} = T_{dB}\frac{1}{\ln\left(nS\right)} \approx 0.3K$$

for $N=nS\sim10^5$

Y.M. Kagan, lectures
W. Ketterle, N.J. van Drutten, PRA 54, 656 (1996)

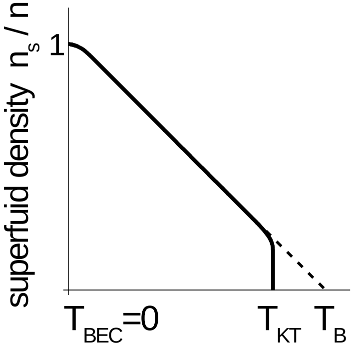
temperature of onset of local superfluidity

$$T_c = T_{dB}\frac{1}{\ln\ln(1/na^2)} \approx 1.7K$$

Bogoliubov temperature onset of nonzero order parameter

$\ln\ln(1/na^2)=1$–3 for $1/na^2=10$-10^8 for $\ln\ln(1/na^2)=1.5$

V.N. Popov, Theor. Math. Phys. 11, 565 (1972)
D.S. Fisher, P.C. Hohenberg, PRB 37, 4936 (1988)



Kosterlitz-Thouless temperature

$$T_{KT} \approx T_{dB}\frac{\ln\ln(1/na^2)}{1+\ln\ln(1/na^2)} \approx 1K$$

pairing of vortices = onset of macroscopic superfluidity which is not destroyed by vortices

for not so dilute gas

$$T_c \approx T_{dB}\frac{1}{\ln(\xi/4\pi)+\ln\ln(1/na^2)} \approx 0.6K$$

$$\xi \approx 380$$

N. Prokof’ev, O. Ruebenacker, B. Svistunov,
PRL 87, 270402 (2001)

How to realize cold exciton gases ?

$T_{lattice}$ << 1 K in He refrigerators

finite lifetime of excitons could result to high exciton temperature: $T_{exciton} > T_{lattice}$

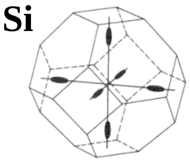
find excitons with lifetime >> cooling time $\longrightarrow$ $T_{exciton} \sim T_{lattice}$

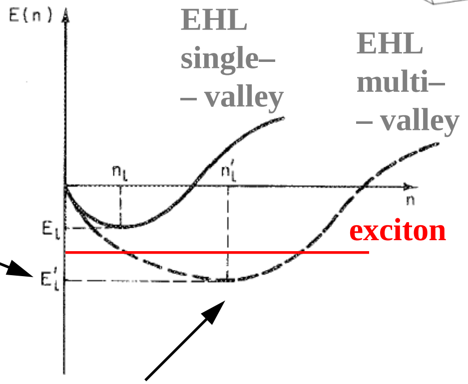
Challenges for realization of exciton condensates	To solve: Find or design semiconductor structures where
short lifetime	excitons have long lifetimes >> cooling times
competing ground states, e.g. EHL	excitons form the lowest energy state
exciton destruction, e.g. due to Mott transition	excitons have large binding energy
disorder	disorder is weak

Excitons in bulk semiconductors

materials with low *e-h* recombination rate	**challenges for experimental realization of cold exciton gases**
Ge, Si	**ground state – metallic *e-h* liquid (EHL) rather than exciton**
Cu_2O	**slow cooling** **high rate of Auger recombination** K.E. O'Hara, L.O. Suilleabhain, J.P. Wolfe, PRB 60, 10565 (1999)

$$E = E_{kin} + E_{exc} + E_{cor}$$





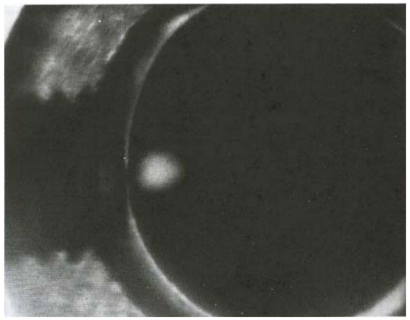
EHL density corresponds to degenerate Fermi gases of electrons and holes: *e-h* plasma

$$E_{kin}(n) = \frac{3}{5}E_F \sim n^{2/3}$$

$$E_{exc}(n) = -\frac{3}{4}\frac{e^2 k_F}{\pi} \sim -n^{1/3}$$

$$E_{cor} \sim -n^{1/4}$$

Review: L.V. Keldysh,
Contemp. Phys. 27, 395 (1986)



two elements of the *e-h* droplet repel each other due to the phonon wind generated in each of the elements → explosion of large droplets → $R_{c\text{-}Si} \sim 1$ μm, $R_{c\text{-}Ge} \sim 10$ μm

huge droplets with $R \sim 200$ μm can be created due to confinement

J.P. Wolfe, W.L. Hansen, E.E. Haller, R.S. Markiewicz, C. Kittel, C.D. Jeffries, PRL 34, 1292 (1975)

Search for exciton BEC in Cu_2O

exciton transport

expansion of exciton cloud front at near sonic velocity → exciton condensate superfluidity

D.W. Snoke, J.P. Wolfe, A. Mysyrowicz,
PRL 64, 2543 (1990)

reduction in velocity dispersion → quasistable wave packet of exciton superfluid

E. Fortin, S. Fafard, A. Mysyrowicz, PRL 70, 3951 (1993)

amplification of directed beam of excitons → stimulated exciton scattering

A. Mysyrowicz, E. Benson, E. Fortin, PRL 77, 896 (1996)

PL lineshape

enhanced PL intensity at low energies → BE distribution of excitons

D. Hulin, A. Mysyrowicz, C.B. à la Guillaume, PRL 45, 1970 (1980)
D. Snoke, J.P. Wolfe, A. Mysyrowicz, PRL 59, 827 (1987)

→ PL of exciton BEC

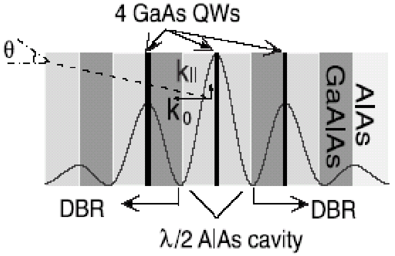
J.L. Lin, J.P. Wolfe, PRL 71, 1222 (1993)

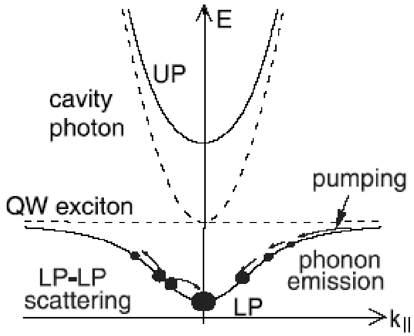
S.G. Tikhodeev et al. (1992-1998):
exciton transport data are quantitatively explained by phonon wind effect

K.E. O'Hara, J.P. Wolfe et al. (1999-2000):
PL lineshape data are quantitatively explained with inhomogeneous classical exciton gas,
exciton densities reached in Cu_2O are ~ 100 times below that required to achieve BEC
presumably due to the high Auger recombination rate in Cu_2O

Excitons in Cu_2O form a very interesting system and
search for exciton BEC in Cu_2O is in progress

Microcavity polaritons





from H. Deng, G. Weihs, C. Santori, J. Bloch, Y. Yamamoto, Science 298, 199 (2002)

Types of coherent state in MC

- **weak coupling regime**

polaritons are destroyed → cavity photons and *e–h* pairs

because of dephasing, screening and phase space filling owing to carrier Coulomb interaction

analogous to a conventional laser (VCSEL)

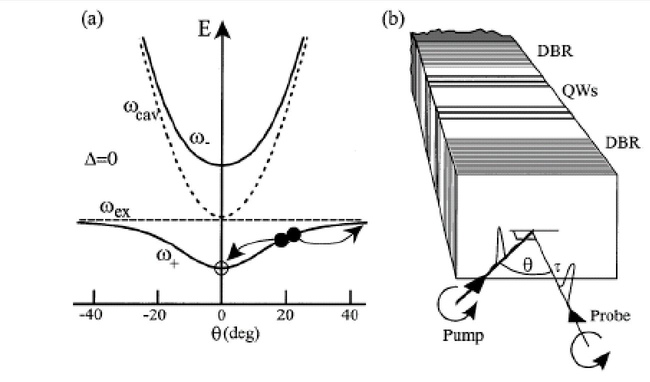
review: G. Khitrova, et al. RMP 71, 1591 (1999)

- **strong-coupling, or polariton, regime**

a) resonant pumping with photons at specific angle

polariton parametric amplifier

P.G. Savvidis, et al. PRL 84, 1547 (2000)



b) non-resonant pumping

such coherent state
has been realized in GaAs and CdTe MC

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

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

proposed in A. Imamoglu, R.J. Ram, Phys. Lett. A 214, 193 (1996); A. Imamoglu, R.J. Ram, S. Pau, Y. Yamamoto, PRA 53, 4250 (1996).

interesting new
type of condensate

Polariton laser

a coherent state of e-m waves – a laser
a coherent state of matter waves – a BEC

a polariton is a mixture of an e-m wave and matter

Is this polariton coherent state similar to a laser, to a BEC, or somehow to both?

in a system of bare excitons

the coherent states of MC polaritons disappear when the *photon* component vanishes

but remain strong when the *exciton* component vanishes

in the weak-coupling regime

⬇

implies that the coherence of the MC polaritons arises from the coherence of an e-m field

as in a laser

Nature 447, 540 (2007)

interesting new
type of condensate

Thermal equilibrium

essential property of BEC

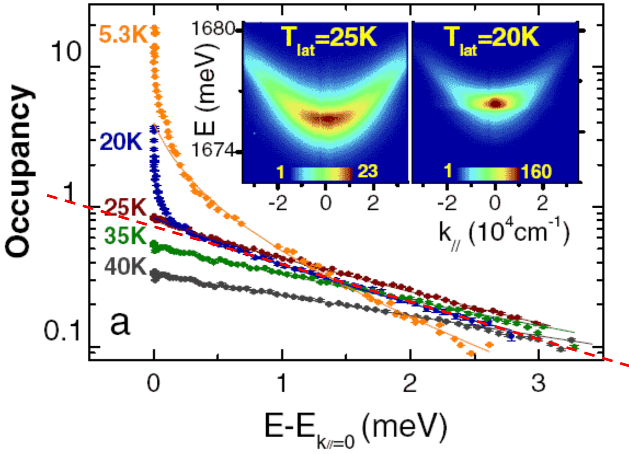
is not required for lasers

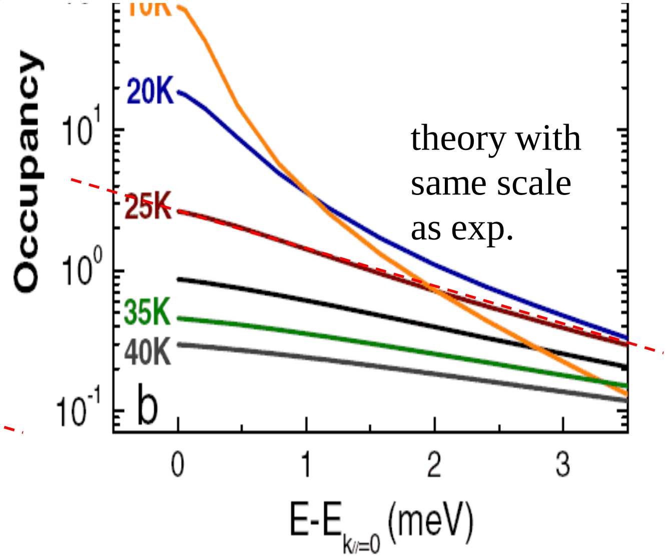
Lifetime of MC polaritons is short: 1-3 ps

Can thermal equilibrium be established within such short lifetime ?

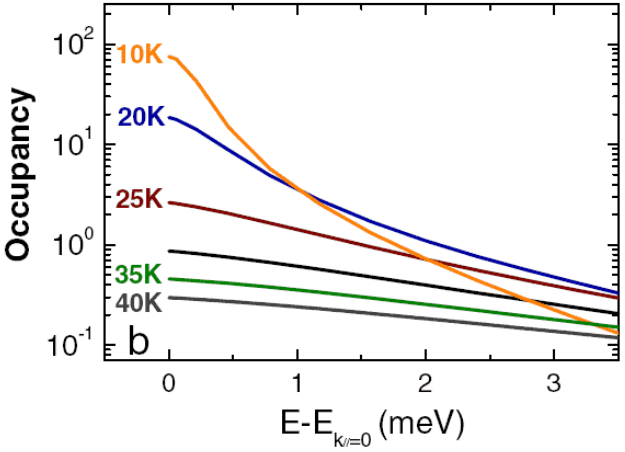
Is it required for formation of polariton condensate ?

is not required for polariton lasers





theory with same scale as exp.



Dashed line fits exp. distribution marked 20 K and theor. distribution marked 25 K at high *E*.

Exp. distribution at *E* > 0 gives much stronger occupancy enhancement at *E* = 0 (left) than that corresponding to thermal distribution (right).

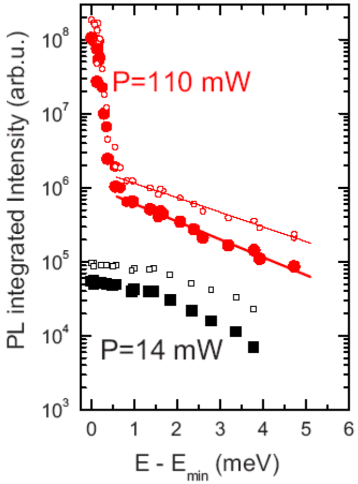
⬇

<u>no thermal equilibrium</u> between condensate and noncondensed cloud

From Fig. 1 in J. Kasprzak, D. D. Solnyshkov, R. Andre´, Le Si Dang, G. Malpuech, PRL 101, 146404 (2008)

weak coupling regime, regular photon laser regime:

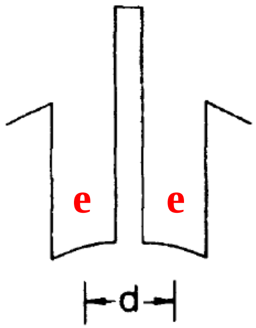
sharp peak near *E* = 0 and Boltzmann distribution at higher energies



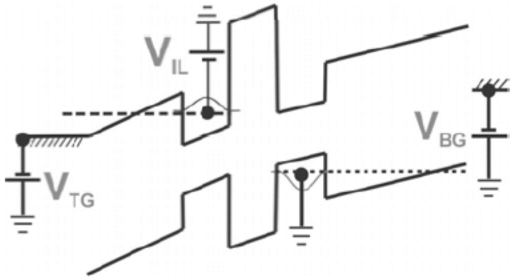
D. Bajoni, P. Senellart, A. Lemaître, J. Bloch, PRB 76, 201305R (2007)

Indirect excitons in coupled quantum wells

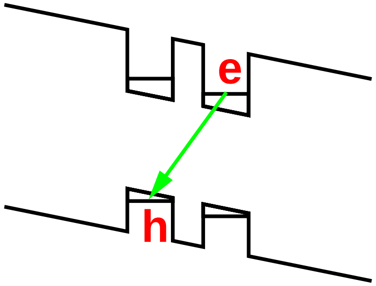
Electron-electron bilayers in magnetic fields at ν=1



Electron-hole bilayers with gate-induced carriers



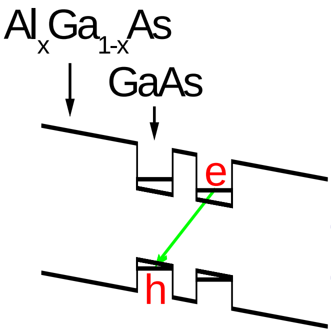
Electron-hole bilayers with photoexcited carriers



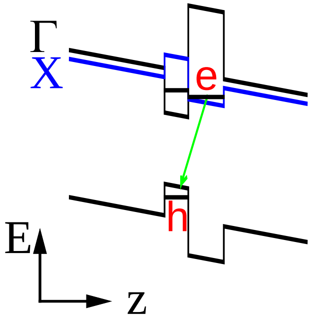
Experiments:

Caltech	Bell Labs	Bell Labs
Columbia	Cambridge	Berkeley
Pisa	IBM	Chernogolovka
Princeton	Sandia	Hebrew
Stuttgart		IBM
		Munich
		St. Peterburg
		Weizmann
		UCSB
		UCSD

Why indirect excitons in CQW ?



GaAs/AlGaAs CQW



AlAs/GaAs CQW

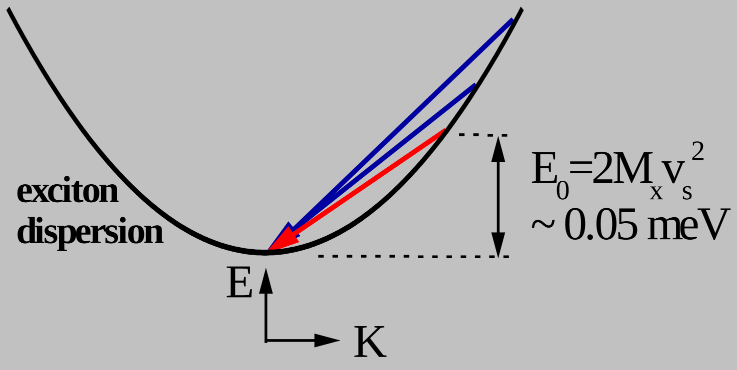
<u>10^3-10^6 times longer exciton lifetime</u> due to separation between electron and hole layers

realization of cold exciton gas in separated layers was proposed by
Yu.E. Lozovik, V.I. Yudson (1975); S. I. Shevchenko (1976);
T. Fukuzawa, S.S. Kano, T.K. Gustafson, T. Ogawa (1990)

<u>10^3 times shorter exciton cooling time</u> than that in bulk semiconductors

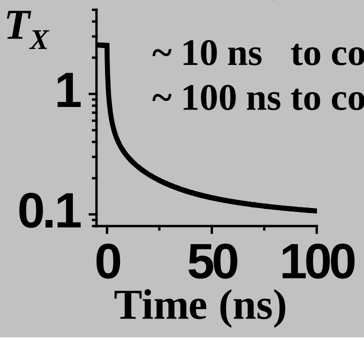
$T_X \sim 100$ mK
has been realized experimentally
30 times below T_{dB}

exciton energy relaxation by LA-phonon emission



$E_0 = 2M_x v_s^2$
~ 0.05 meV

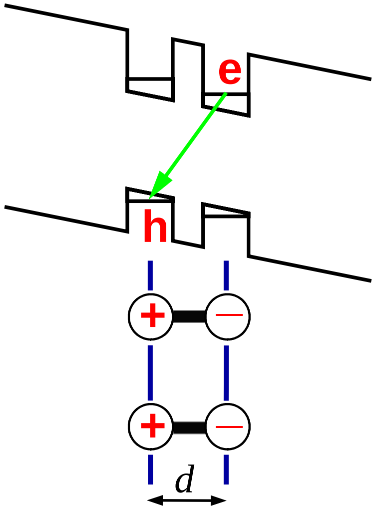
3D: coupling of $E=0$ state to single state $E=E_0$
2D: coupling of $E=0$ state to continuum of energy states $E > E_0$
effective cooling of 2D excitons by bulk phonons



~ 10 ns to cool to 300 mK
~ 100 ns to cool to 100 mK

A.L. Ivanov et al
in PRL 86, 5608 (2001)

Interaction between indirect excitons



indirect excitons are oriented dipoles

Repulsive dipole-dipole interaction

- **stabilizes exciton state against formation of metallic EHL**

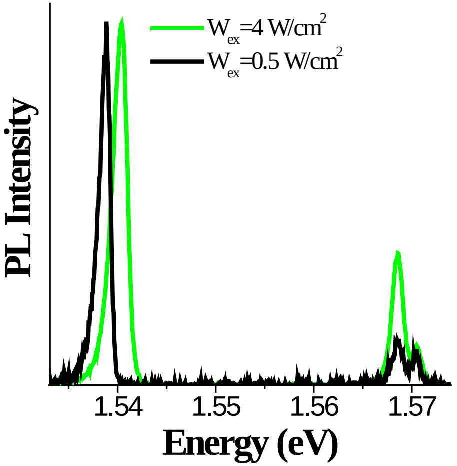
D. Yoshioka, A.H. MacDonald, J. Phys. Soc. Jpn. 59, 4211 (1990)
X. Zhu, P.B. Littlewood, M. Hybertsen, T. Rice, PRL 74, 1633 (1995)
Yu. E. Lozovik, O. L. Berman, JETP Lett. 64, 573 (1996)

the ground state is excitonic

- **results in effective screening of in-plane disorder**

A.L. Ivanov, EPL 59, 586 (2002)
R. Zimmermann

also high quality CQW samples with small initial disorder are required



Repulsive interaction in experiment

exciton energy increases with density

L.V. Butov, A. Zrenner, G. Bohm, G. Weimann, J. de Physique 3, 167 (1993)

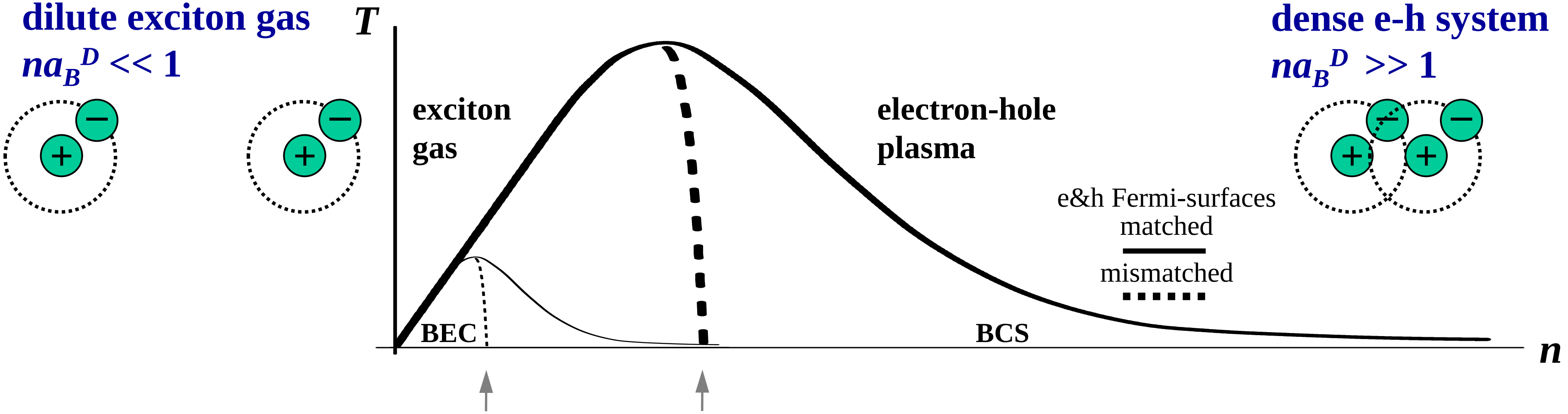
energy shift: $\delta E \sim n/C$ → **estimate for exciton density**

approximation for short-range $1/r^3$ **interaction** $C = \varepsilon/4\pi e^2 d$

C. Schindler, R. Zimmermann, PRB 78, 045313 (2008)

→ C **and** n **in experiments are higher**

How to overcome exciton dissociation due to Mott transition: Make *d* small


dilute exciton gas

$na_B^D \ll 1$

dense e-h system

$na_B^D \gg 1$

$n \sim 1/a_B^D$

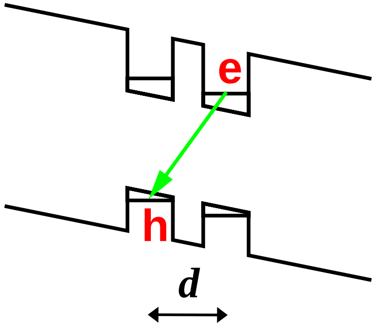
large *d*

large a_B

$n \sim 1/a_B^D$

small *d*

small a_B



smaller *d*

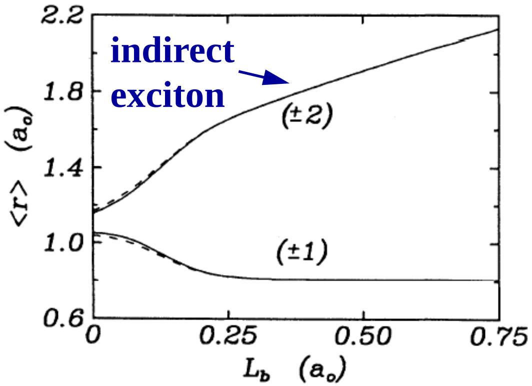
↓

smaller exciton radius

↓

larger T_c at high *n*

increase of a_B with increasing *d*



M.M. Dignam, J.E. Sipe, PRB 43, 4084 (1991)

$a_0 = \hbar^2 \varepsilon / \mu e^2 \qquad L_{QW} = 0.6 a_0$

in CQW with $L_B = 4$ nm, $L_{QW} = 8$ nm

$d \approx 12$ nm, exciton radius $a_B \approx 20$ nm

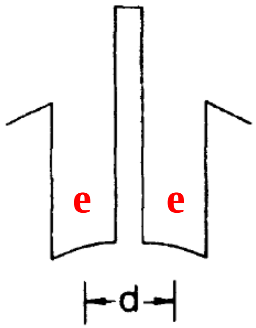
2D gas of excitons in GaAs QW

$n = 10^{10}$ cm^{-2}, $m_{exciton} = 0.2\, m_e \rightarrow T_{dB} \sim 3$ K

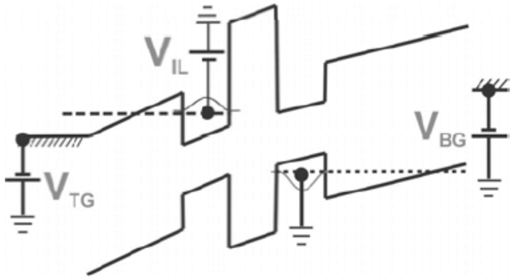
$n < n_{Mott} \sim 1/a_B^2 \sim 2 \times 10^{11}$ cm^{-2}

Indirect excitons in coupled quantum wells

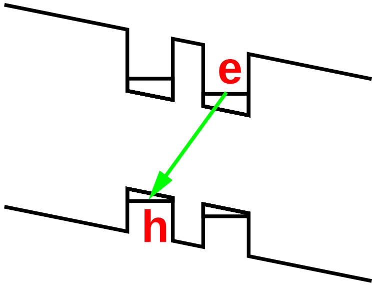
Electron-electron bilayers in magnetic fields at $\nu = 1$



Electron-hole bilayers with gate-induced carriers



Electron-hole bilayers with photoexcited carriers



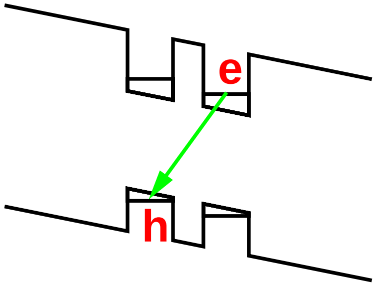
Experiments:

Caltech
Columbia
Pisa
Princeton
Stuttgart

Bell Labs
Cambridge
IBM
Sandia

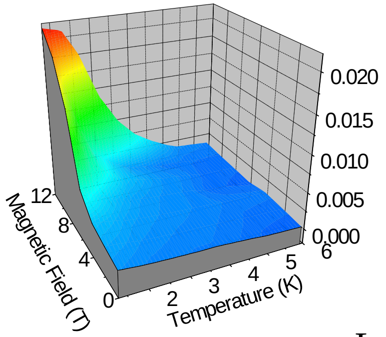
Bell Labs
Berkeley
Chernogolovka
Hebrew
IBM
Munich
St. Peterburg
Weizmann
UCSB
UCSD

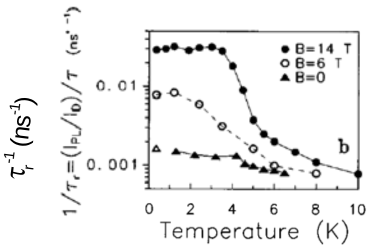
coupled electron and hole layers



exciton superradiance $\tau_r^{-1} \sim \xi^2$
($\xi < \lambda$)

enhancement of radiative decay rate of excitons

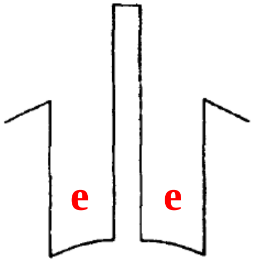




L.V. Butov, A.I. Filin,
PRB 58, 1980 (1998)

excitons above and below T_c

electron-electron bilayers in high magnetic fields at $\nu = 1$



collective electron state in QH bilayers at $\nu = 1$

J.P. Eisenstein, G.S. Boebinger, L.N. Pfeiffer,
K.W. West, S. He, PRL 68, 1383 (1992)

T.S. Lay, Y.W. Suen, H.C. Manoharan, X. Ying,
M.B. Santos, M. Shayegan, PRB 50, 17725 (1994)

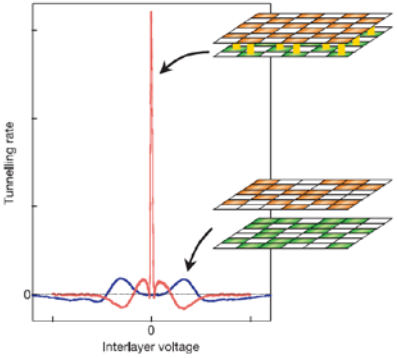
particle-hole transformation

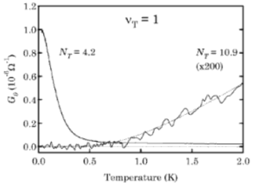
$\nu_e = 1/2 + \nu_e = 1/2 \quad \Rightarrow \quad \nu_e = 1/2 + \nu_h = 1/2$

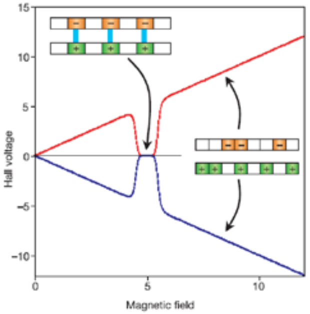
collective electron state $\Rightarrow$ exciton condensate

J.P. Eisenstein,
A.H. MacDonald,
Nature 432,
691 (2004)

enhancement of tunneling rate of electrons







I.B. Spielman, J.P. Eisenstein, L.N. Pfeiffer,
K.W. West, PRL 84, 5808 (2000)

transport of *e-h* pairs:
Hall voltage drops at
ν=1 ↔ neutral excitons

no exciton above T_c, *e-h* pairing below T_c → BCS-like condensate

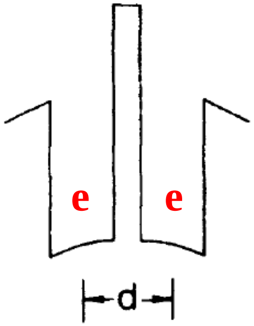
exciton recombination in *e-h* ⟷ electron tunneling in *e-e*

for both: exciton in initial state, no exciton in final state

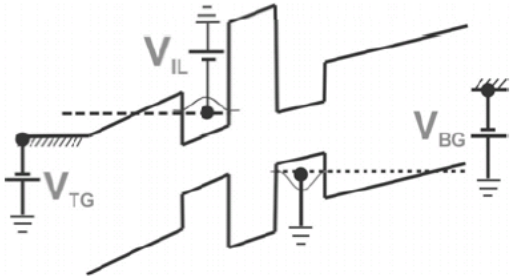
⟵ **particle – hole transformation**

Indirect excitons in coupled quantum wells

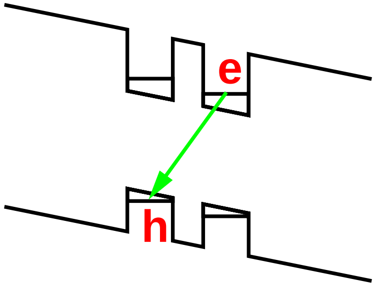
Electron-electron bilayers in magnetic fields at $\nu=1$



Electron-hole bilayers with gate-induced carriers



Electron-hole bilayers with photoexcited carriers



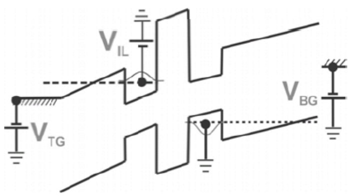
Experiments:

- Caltech
- Columbia
- Pisa
- Princeton
- Stuttgart

- Bell Labs
- Cambridge
- IBM
- Sandia

- Bell Labs
- Berkeley
- Chernogolovka
- Hebrew
- IBM
- Munich
- St. Peterburg
- Weizmann
- UCSB
- UCSD

The Coulomb drag measurement: current in one layer induces a voltage in the other



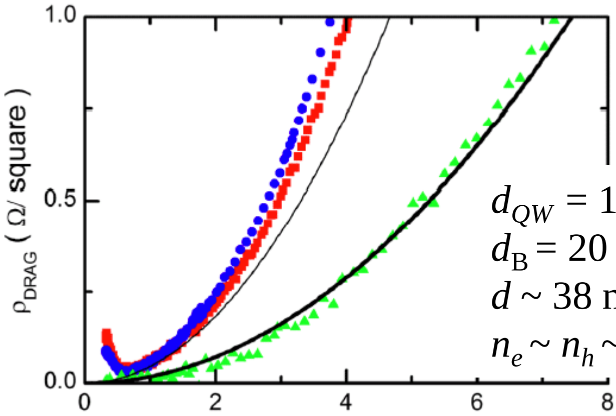
for weakly coupled Fermi liquid bilayers: the drag resistance $\rho_{drag} = V/I \sim T^2$

T.J. Gramila, J.P. Eisenstein, A.H. MacDonald, L.N. Pfeiffer, K.W. West, PRL 66, 1216 (1991)

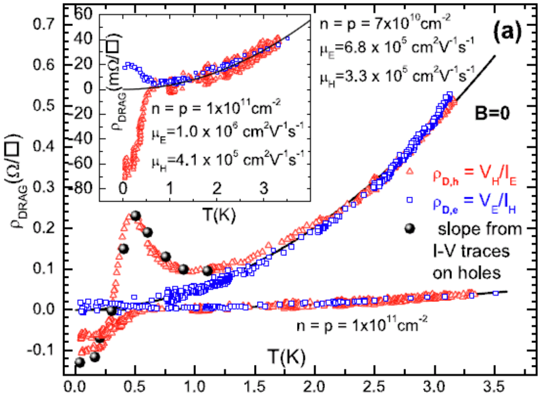
for an exciton condensate: the drag resistance will increase dramatically at T_c

G. Vignale, A.H. MacDonald, PRL 76, 2786 (1996)

an increase in the drag resistance as T is reduced



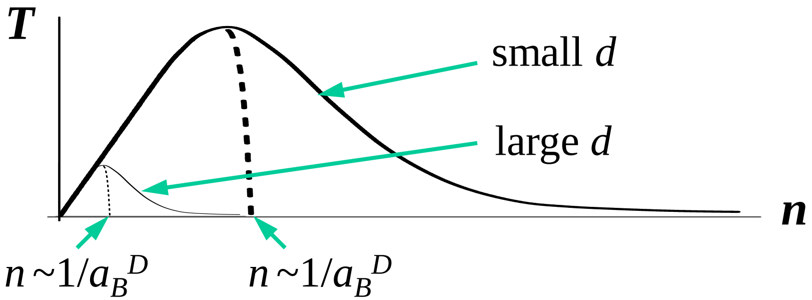
d_{QW} = 18 nm
d_B = 20 nm
d ~ 38 nm
$n_e \sim n_h \sim 10^{11}$ cm^{-2}



d_{QW} = 20 nm
d_B = 25 nm
d ~ 45 nm
$n_e \sim n_h \sim 10^{11}$ cm^{-2}

J. A. Seamons, C.P. Morath, J.L. Reno, M.P. Lilly, PRL 102, 026804 (2009)

A.F. Croxall, K. Das Gupta, C.A. Nicoll, M. Thangaraj, H.E. Beere, I. Farrer, D.A. Ritchie, M. Pepper, PRL 101, 246801 (2008)



small d

large d

$n \sim 1/a_B^D$ $n \sim 1/a_B^D$

challenge: hard to achieve condensation
large $d \longrightarrow$ large a_B, large n

$n > 1/a_B^2$?