Cold excitons

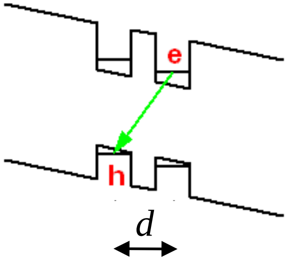
Introduction
- **Excitons and electron-hole plasma in semiconductors**
- **Exciton condensation**
- **Experimental systems**
- **Indirect excitons in coupled quantum wells**

Phenomena in cold exciton gases
- **Stimulated scattering**
- **Pattern formation and transport**
- **Coherence and condensation**

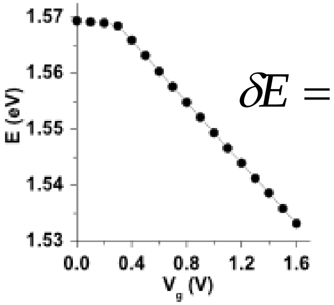
Control of excitons, excitons in potential landscapes
- **Optical traps**
- **Excitonic circuits**
- **Excitons in traps**
- **Excitons in lattices**

Spin transport of excitons

Most recent studies
- **Topological defects in interference pattern**
- **Spin pattern formation**



indirect excitons



$\delta E = edF$

have long lifetimes

have built-in dipole moment *ed*

can cool down to 0.1 K well below T_{dB} ~ 3K

can travel over large distances

energy can be controlled by gate voltage

condensation
pattern formation

transport
spin transport

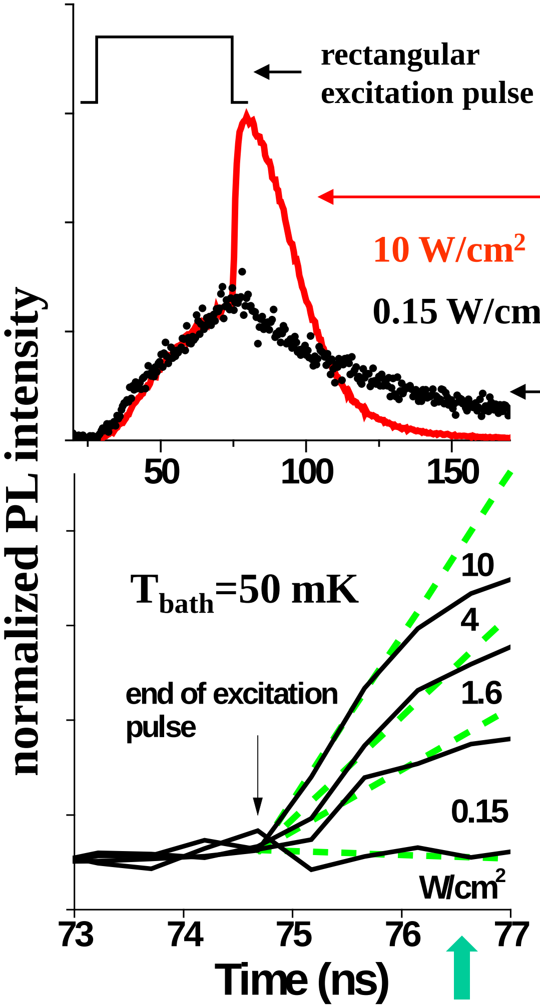
potential landscapes
can be created and *in situ* controlled

<u>cold Bose gases</u> in solid-state materials

<u>excitonic devices</u>

optical methods → <u>local probe</u> of excitons

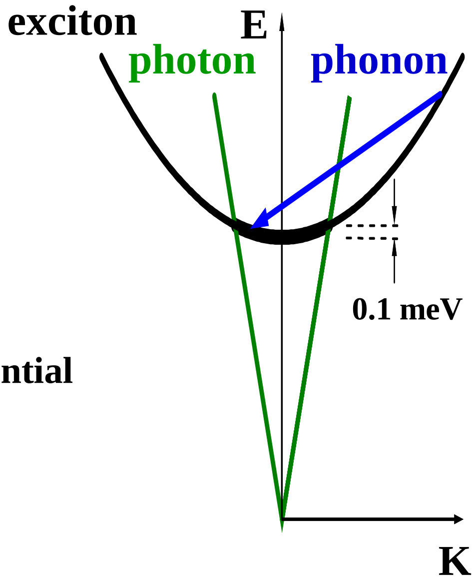
Bosonic stimulation of exciton scattering



rectangular excitation pulse

PL jump

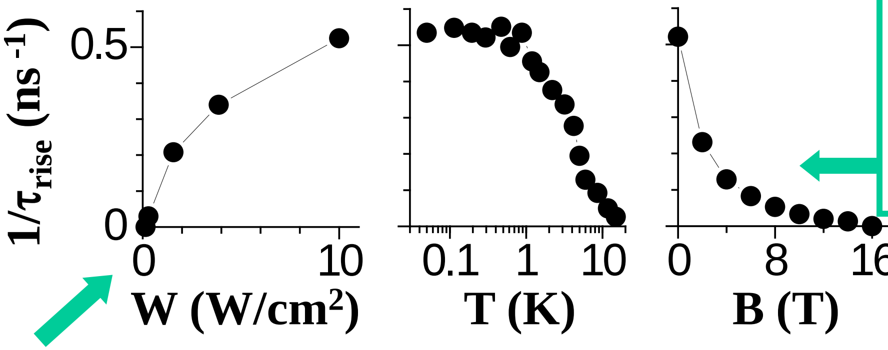
monoexponential PL kinetics



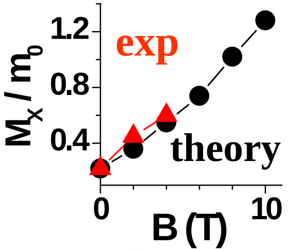
exciton PL kinetics

↕

occupation kinetics of optically active exciton states



exciton mass is controlled in situ



Butov et al. PRL 87, 26804 (2001)

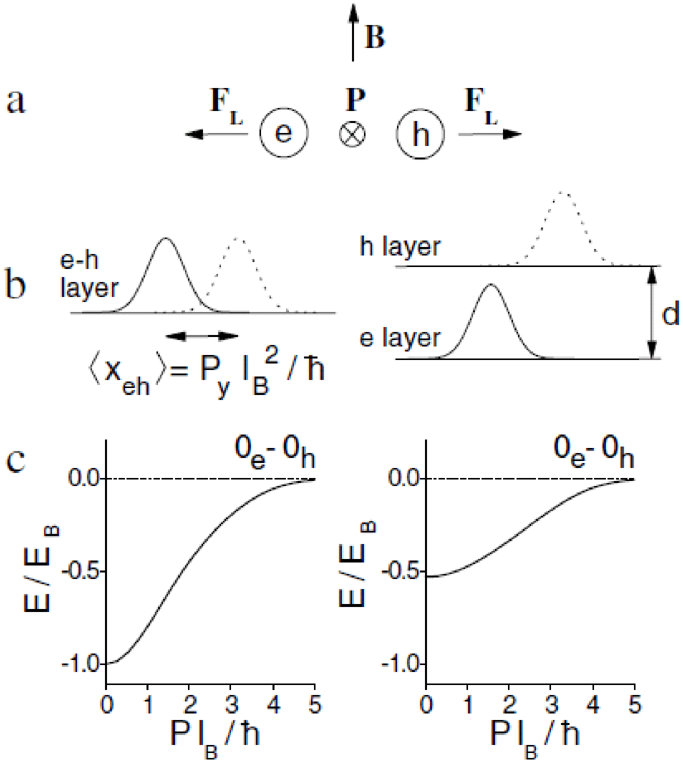
enhancement of exciton scattering rate to low energy states with increasing exciton concentration reveals bosonic stimulation of exciton scattering

scattering rate of bosons to a state p is $\propto 1 + N_p$

signature of degenerate Bose-gas of excitons

L.V. Butov, A.L. Ivanov, A. Imamoglu, P.B. Littlewood, A.A. Shashkin, V.T. Dolgopolov, K.L. Campman, A.C. Gossard, PRL 86, 5608 (2001)

Magnetoexciton

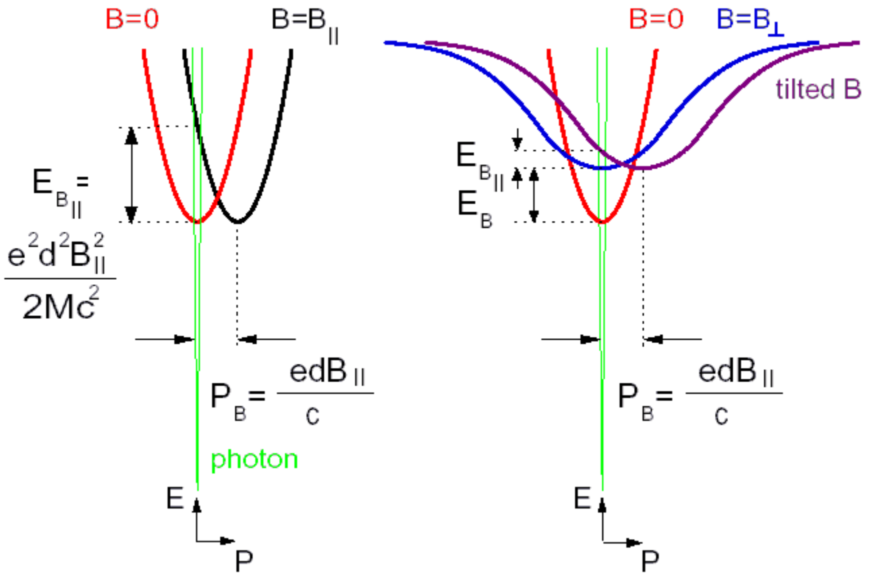


coupling between the internal structure and center of mass motion for magnetoexciton

$$\hbar\omega_c = \hbar\frac{eH}{mc} \qquad Ry_{ex} = \frac{\mu e^4}{2\varepsilon^2\hbar^2}$$

high magnetic field limit: $\hbar\omega_c \gg Ry_{ex}$ →
at H ~ 10 T for exciton
at H ~ 10^6 T for hydrogen atom

Magnetic fields as a tool for measurements and control of quasi-2D exciton effective mass and dispersion relation



when $B_\parallel$ is applied (magneto)exciton dispersion surface shifts by $P_B = edB_\parallel/c$
optically active exciton states are within photon cone

PL energy vs $B_\parallel$ → indirect exciton dispersion

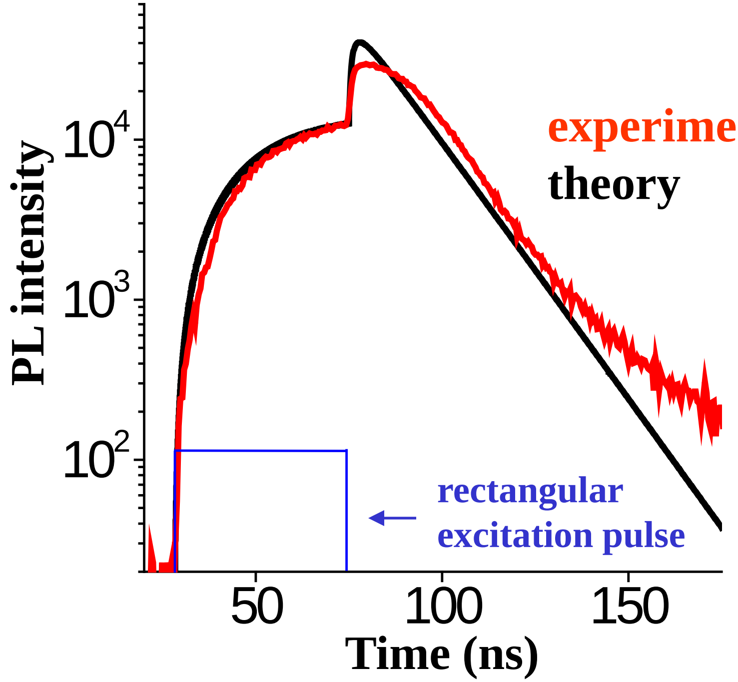
$$E_{B0-0} = \sqrt{\frac{\pi}{2}}\frac{e^2}{\varepsilon l_H} \propto \sqrt{H}$$

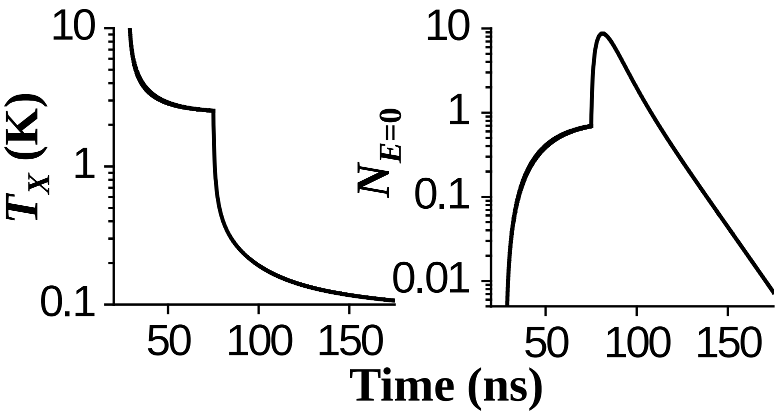
$$M_H = \frac{2^{3/2}\varepsilon\hbar^2}{\pi^{1/2}e^2 l_H} \propto \sqrt{H}$$

$$l_H = \sqrt{\hbar c/(eH)}$$

L.P. Gor’kov, I.E. Dzyaloshinskii, JETP 26, 449 (1968); I.V. Lerner, Yu.E. Lozovik, JETP 51, 588 (1980);
Yu.E. Lozovik, I.V. Ovchinnikov, S.Yu. Volkov, L.V. Butov, D.S. Chemla, PRB 65, 235304 (2002)

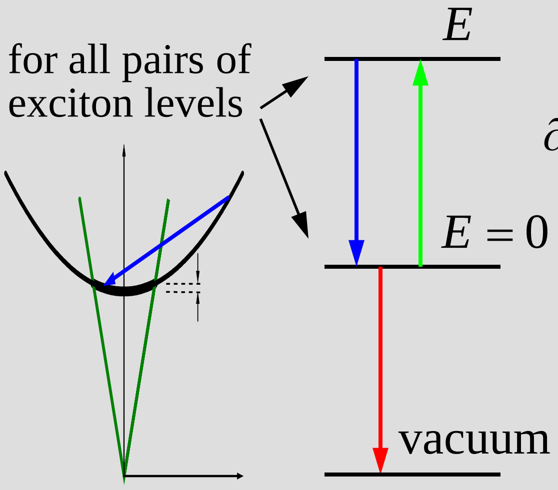
Experiment vs theory





$$N_{E=0} = e^{T_{dB}/T_X} - 1$$

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



phonon emission — phonon absorption — recombination

$$\partial N_{E=0}/\partial t = \boxed{\Gamma_{ph} N_E (1+N_{E=0})(1+n_E{}^{ph})} - \boxed{\Gamma_{ph}(1+N_E)N_{E=0}n_E{}^{ph}} - \boxed{N_{E=0}/\tau} =$$

$$= \Gamma_{ph}(N_E - n_E{}^{ph})N_{E=0} + \Gamma_{ph}(1+n_E{}^{ph})N_E - N_{E=0}/\tau$$

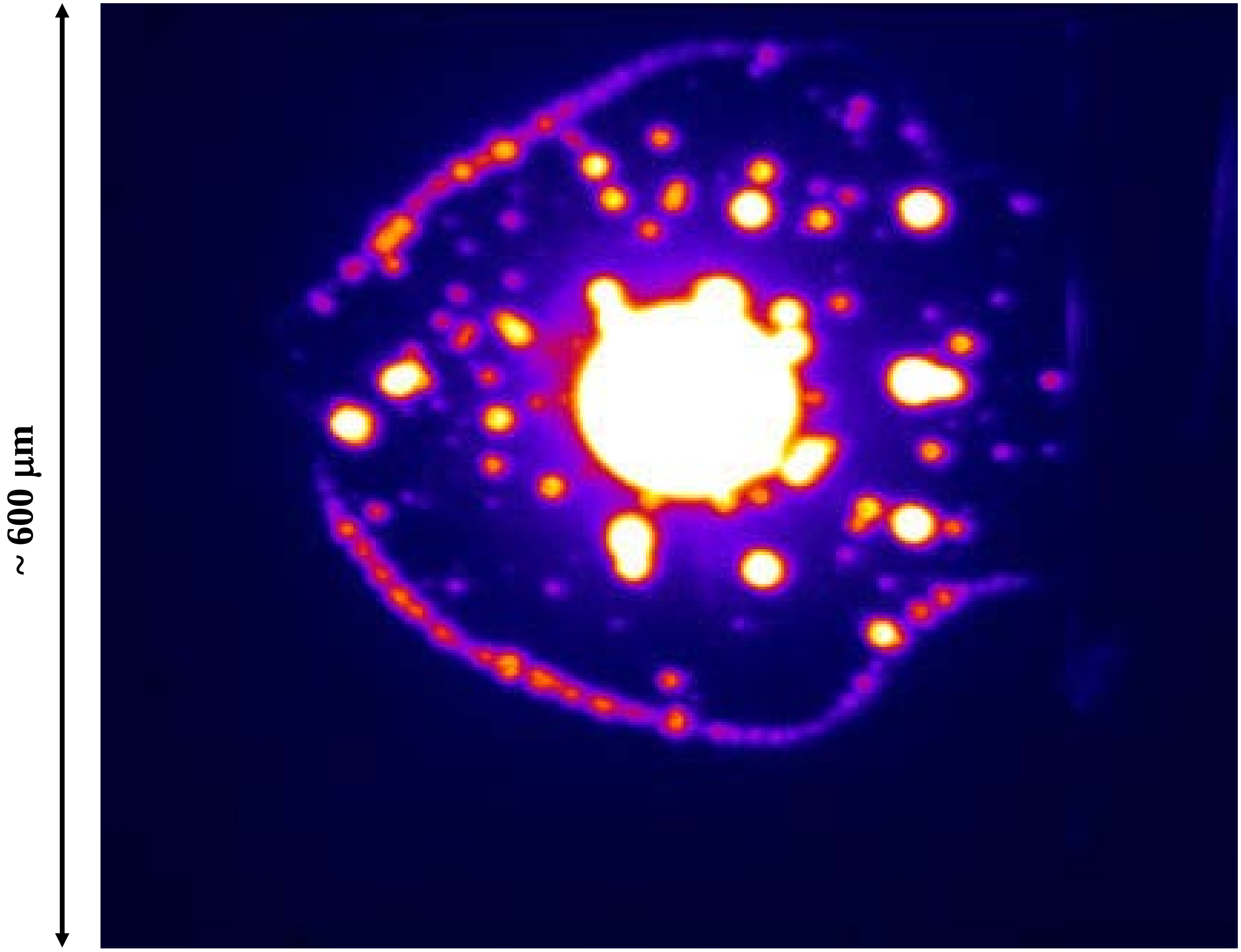
at low $T_{lattice}$ and in presence of generation of hot excitons

$N_E - n_E{}^{ph} > 0$ ←

Frolich inversion condition counterpart of population inversion condition for lasers

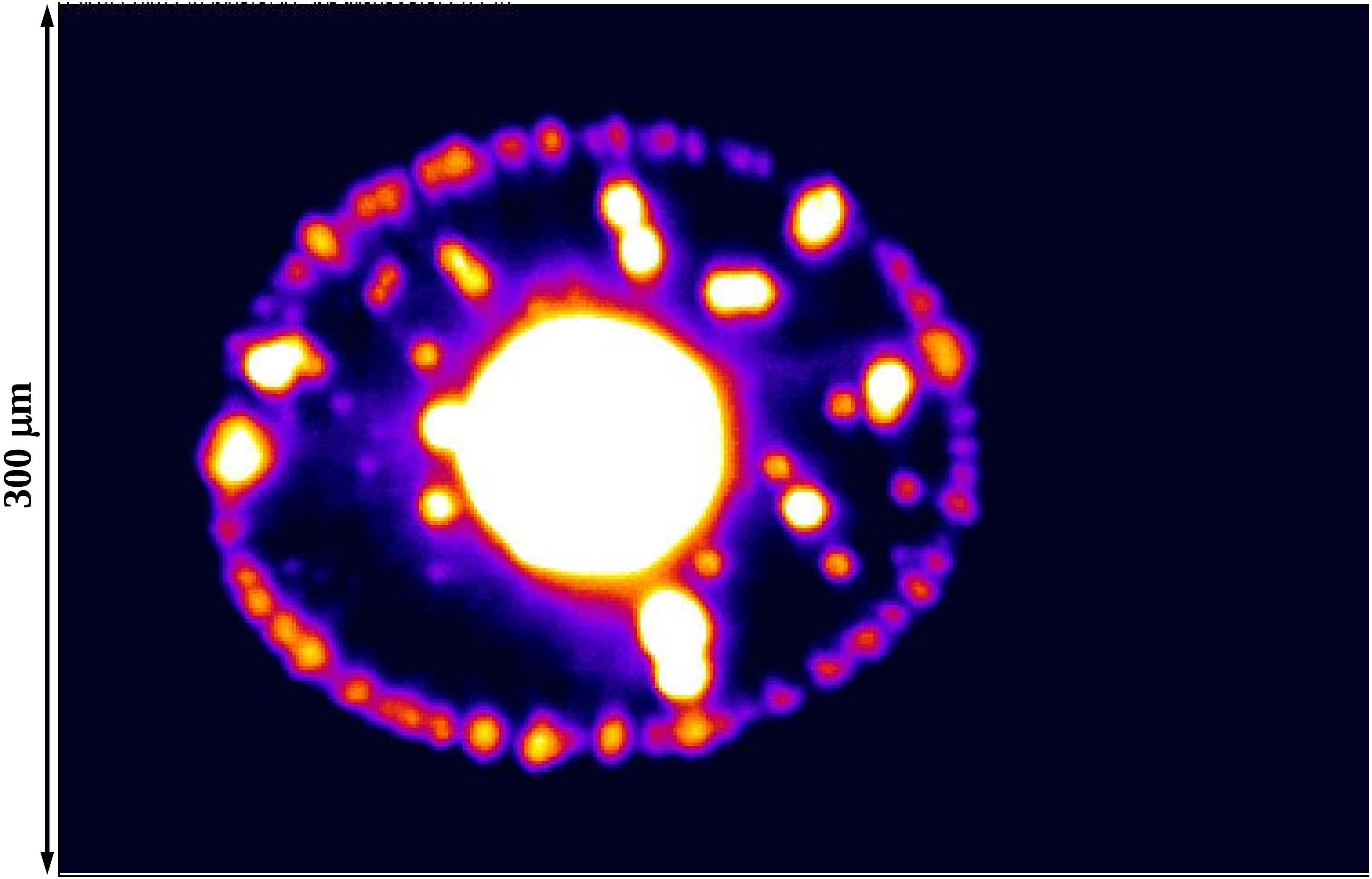
Pattern formation, coherence and condensation in cold exciton gases

2D image of indirect exciton PL vs P_{ex}



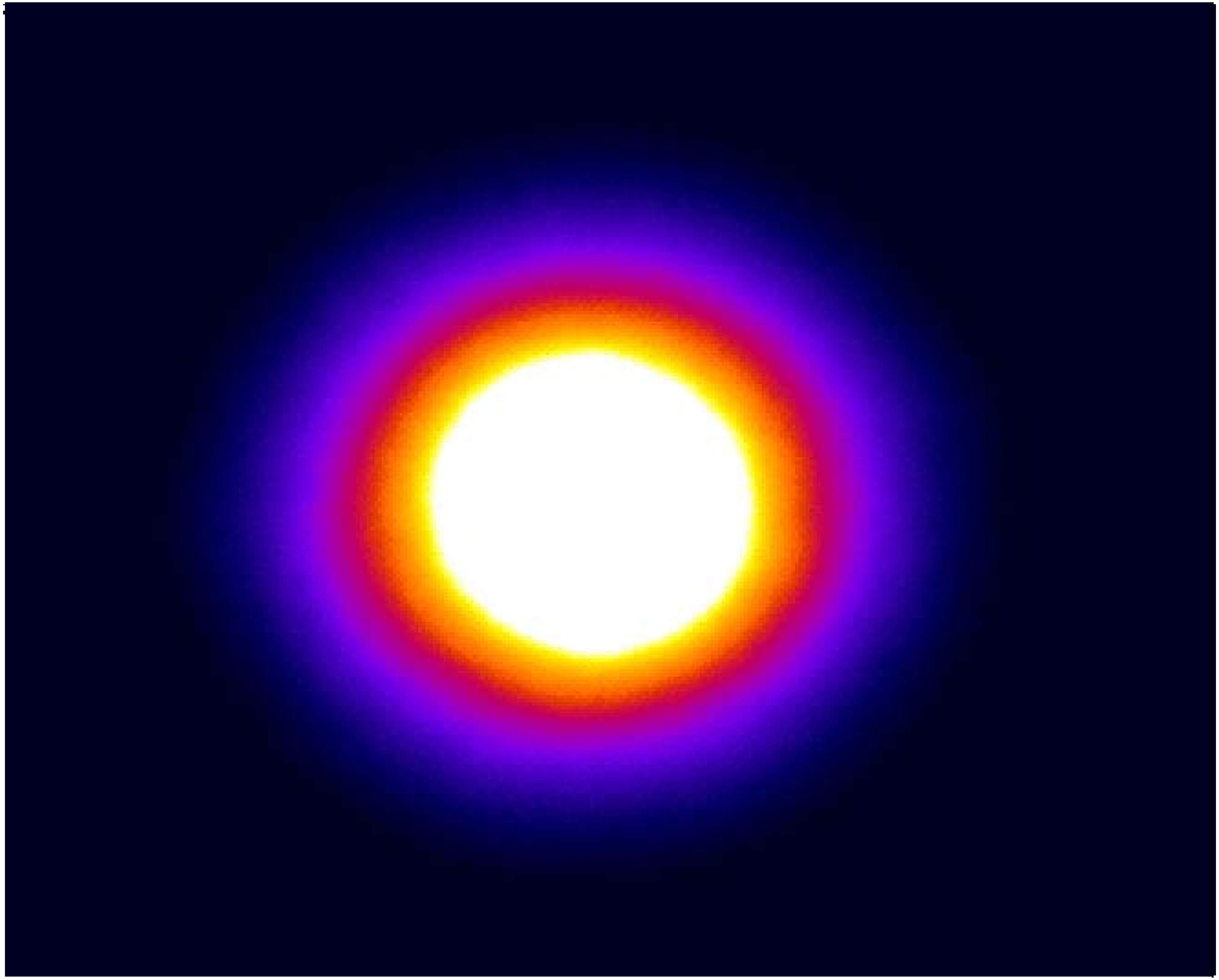
L.V. Butov, A.C. Gossard, D.S. Chemla, cond-mat/0204482 [Nature 418, 751 (2002)]

Indirect exciton PL vs excitation spot position

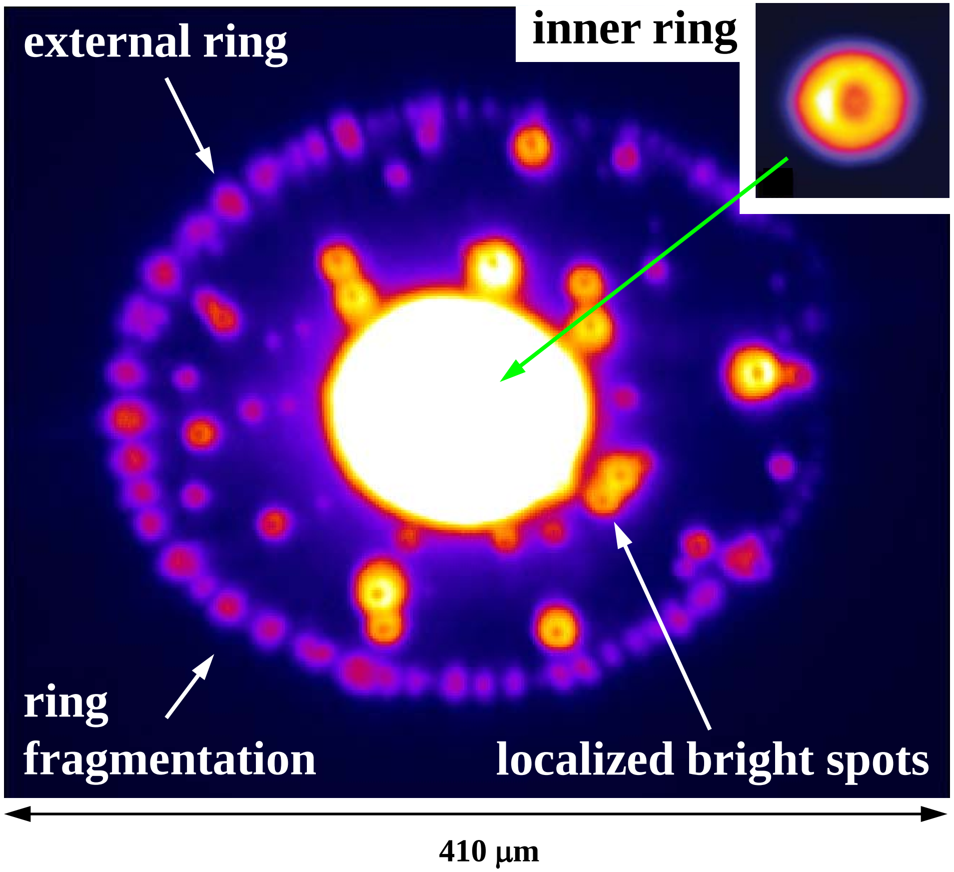


2D image of indirect exciton PL vs temperature

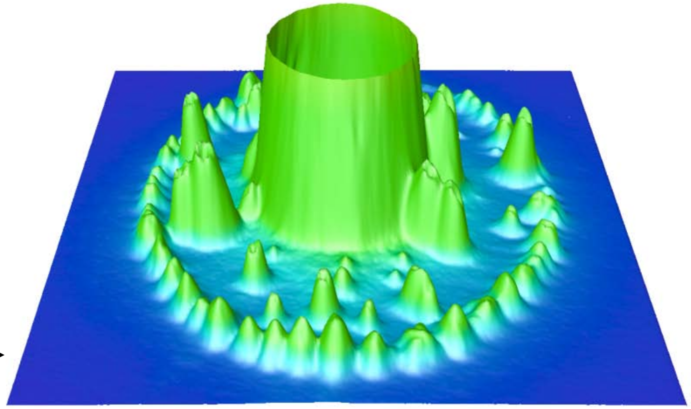
T=0.38-20 K

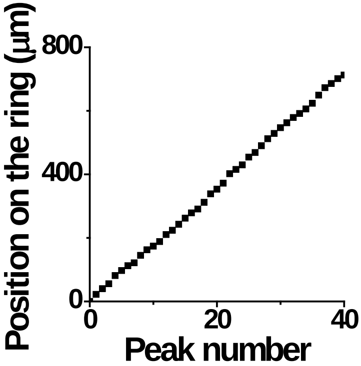


Pattern Formation: Exciton Rings and Macroscopically Ordered Exciton State

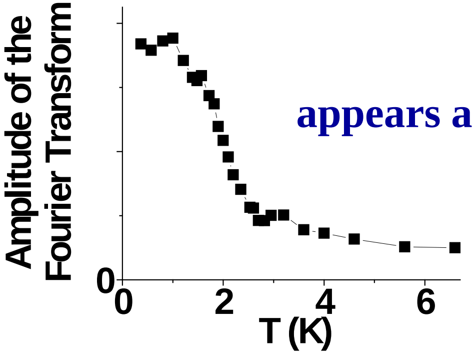


same

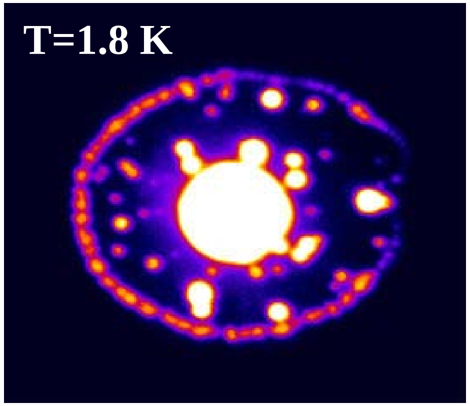


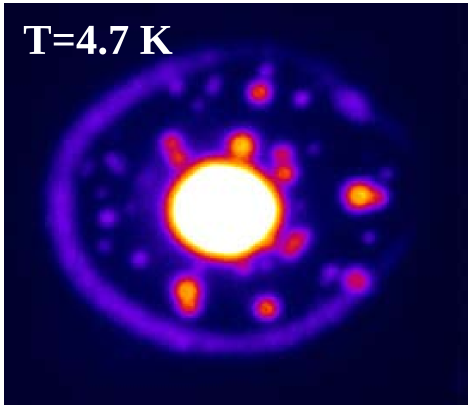


spatial order on macroscopic lengths



appears abruptly at low *T*

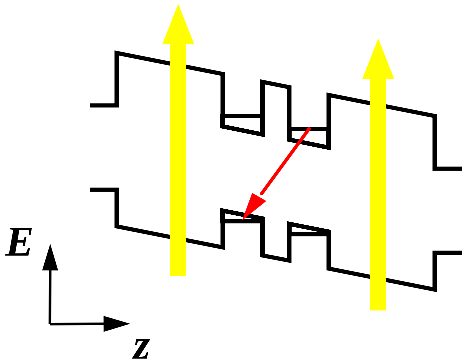




L.V. Butov, A.C. Gossard, D.S. Chemla,
Nature 418, 751 (2002)

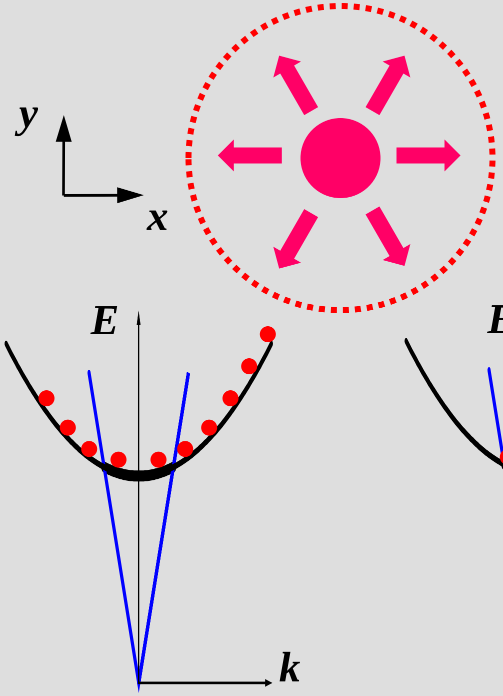
Inner ring

laser excitation creates excitons in CQW



inner ring forms due to exciton transport and cooling

flow of excitons out of excitation spot due to exciton drift, diffusion, etc.



exciton transport

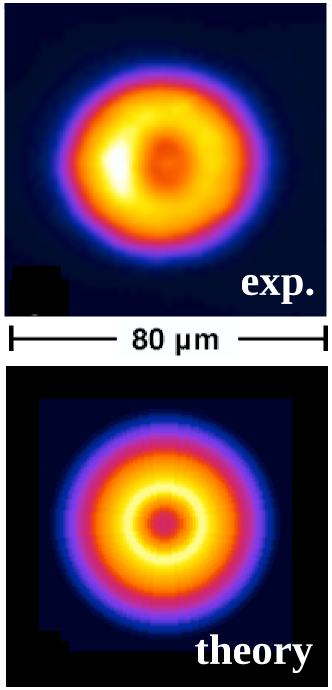
<u>**excitation spot**</u>
high T_X
⬇
lower occupation of radiative zone

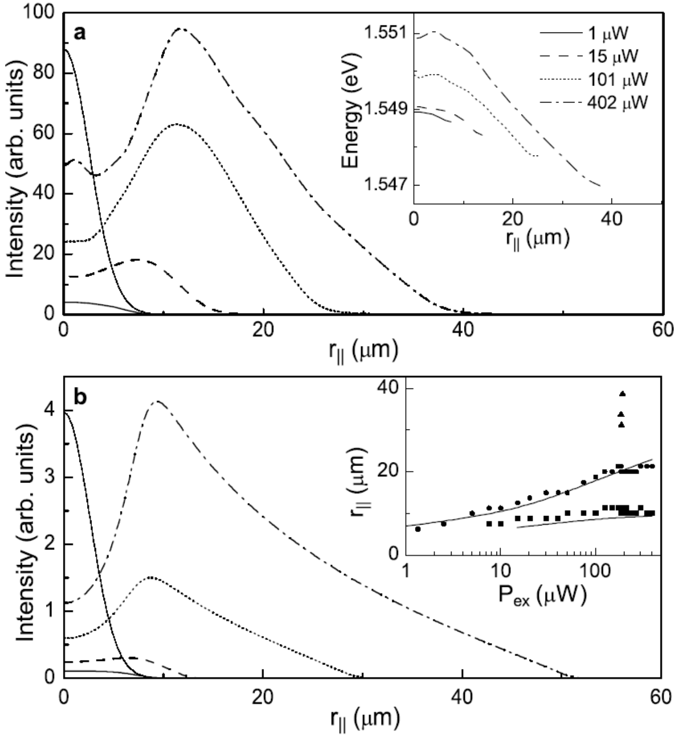
<u>**inner ring**</u>
lower T_X
⬇
higher occupation of radiative zone

L.V. Butov, A.C. Gossard, D.S. Chemla, Nature 418, 751 (2002)

A.L. Ivanov, L. Smallwood, A. Hammack, Sen Yang, L.V. Butov, A.C. Gossard, EPL 73, 920 (2006)

Localization-delocalization transition for exciton transport in random potential





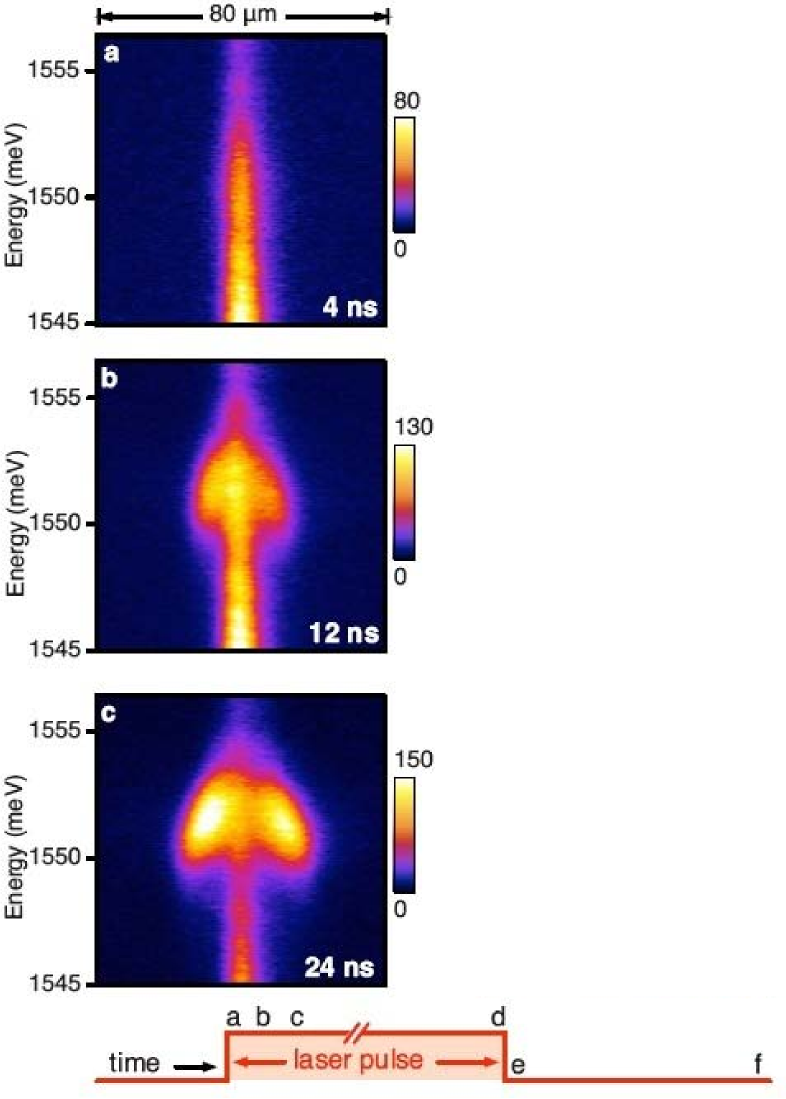
exp.

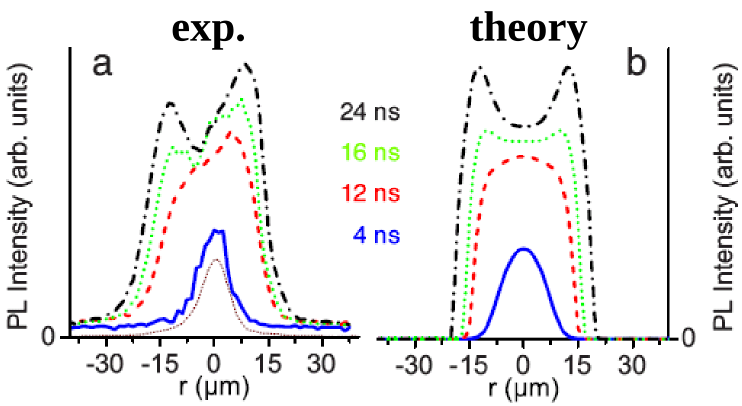
theory

low densities:
emission profile follows excitation spot
excitons are localized in random potential

high densities:
emission extends well beyond excitation spot
excitons screen random potential, travel away from excitation spot and form inner ring

Kinetics of inner ring. Exciton transport.





time-resolved imaging

↓

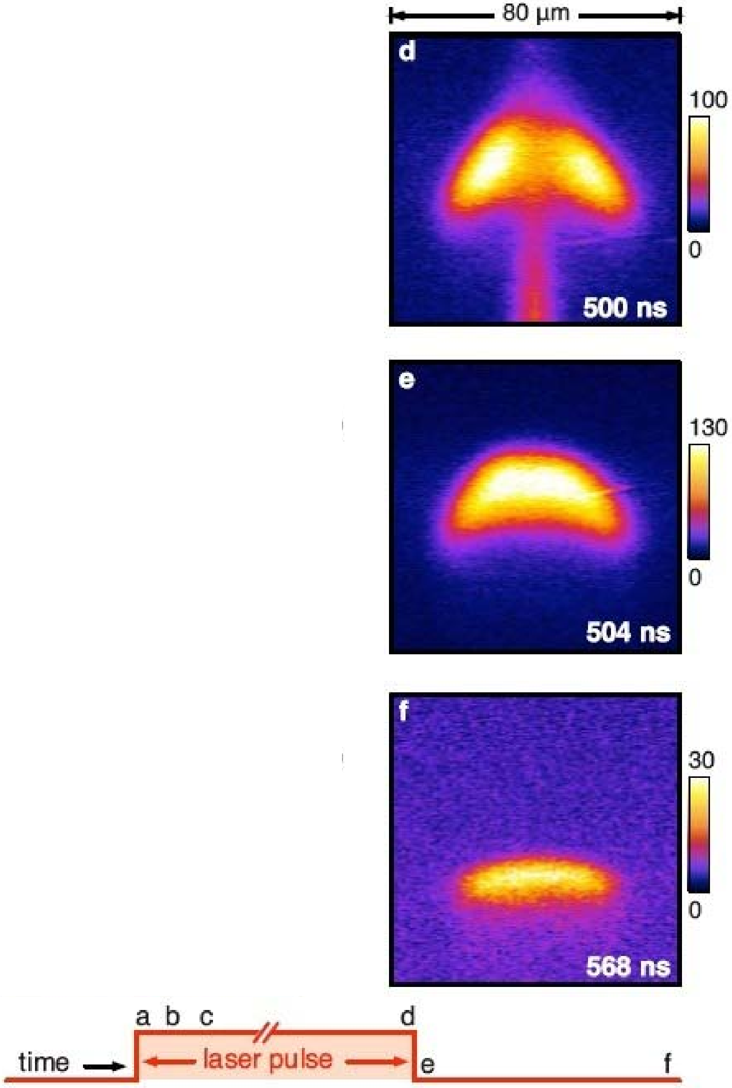
kinetics of inner ring

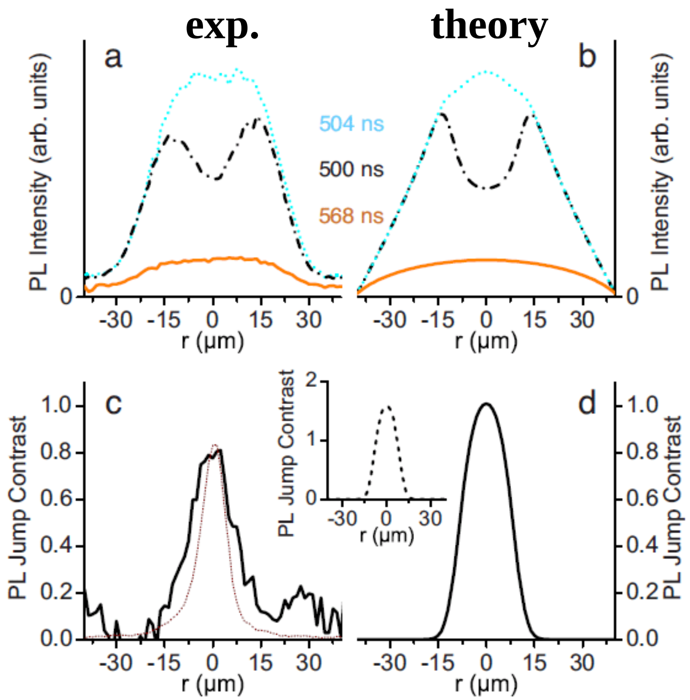
↓

probe of exciton transport

A.T. Hammack, L.V. Butov, J. Wilkes, L. Mouchliadis, E.A. Muljarov, A.L. Ivanov, A.C. Gossard, PRB 80, 155331 (2009)

Kinetics of inner ring. Exciton cooling.





PL jump vs *r* → excitons outside laser spot including inner ring region are cooled to $T_{lattice}$ even during laser excitation

A.T. Hammack, L.V. Butov, J. Wilkes, L. Mouchliadis, E.A. Muljarov, A.L. Ivanov, A.C. Gossard, PRB 80, 155331 (2009)

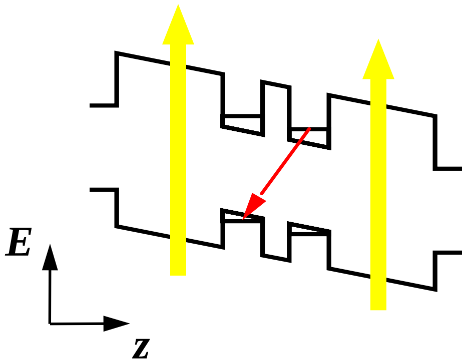
movie

External ring

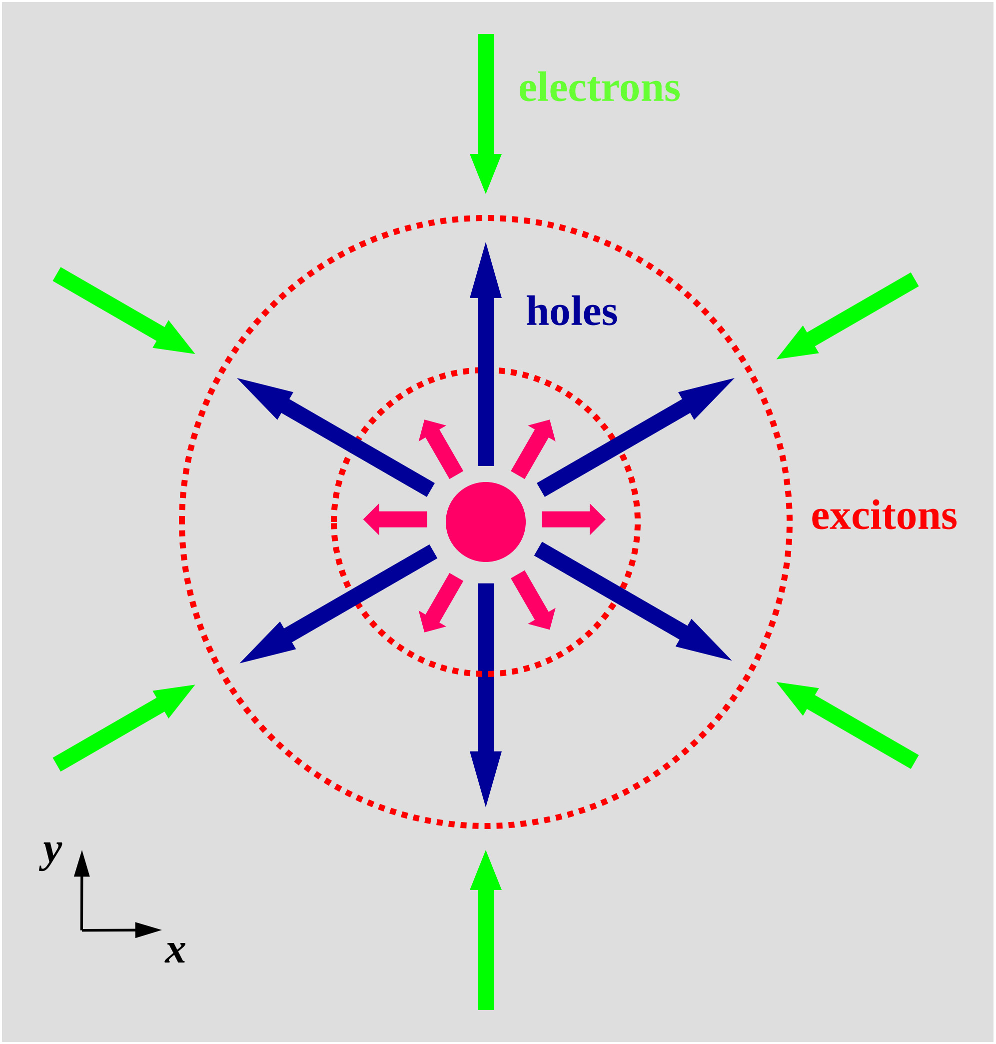
above barrier laser excitation creates additional number of holes in CQW

↑

heavier holes have higher collection efficiency to CQW



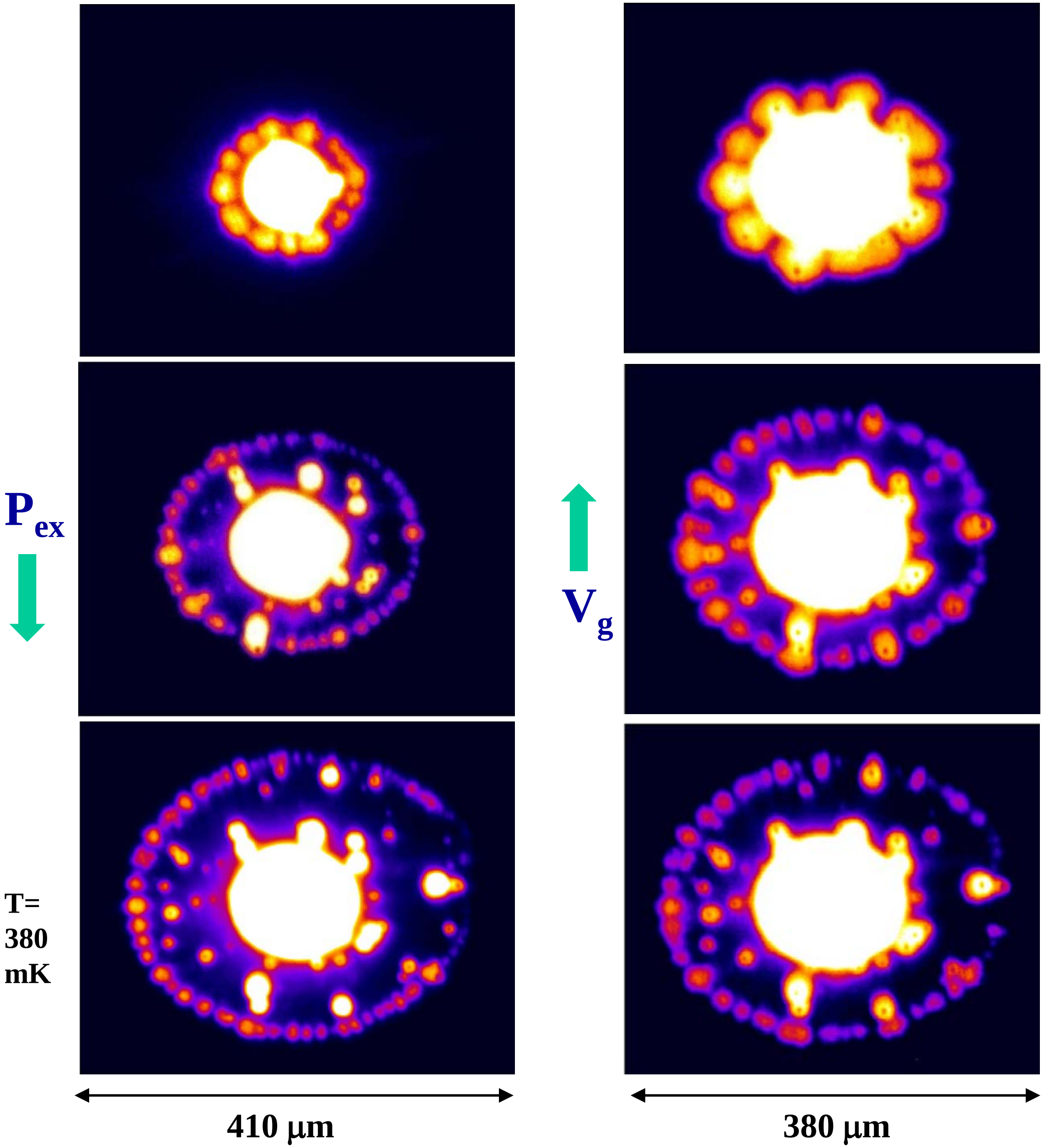
external ring forms at interface between electron-rich and hole-rich regions



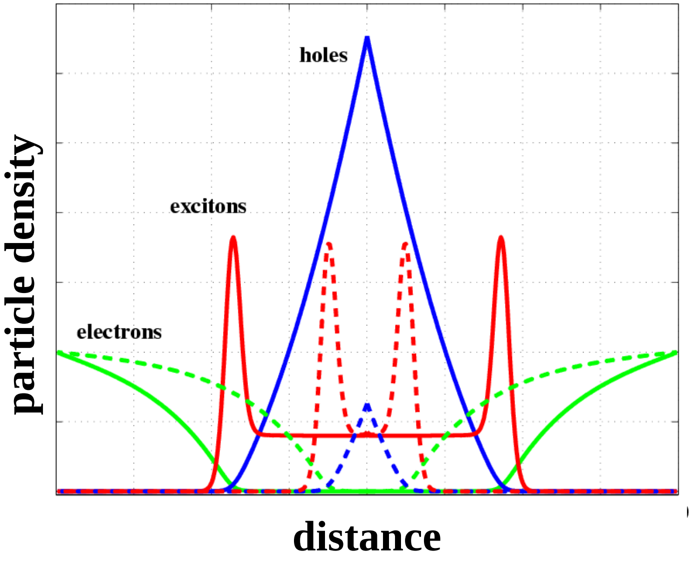
L.V. Butov, L.S. Levitov, B.D. Simons, A.V. Mintsev, A.C. Gossard, D.S. Chemla, PRL 92, 117404 (2004)

R. Rapaport, G. Chen, D. Snoke, S.H. Simon, L. Pfeiffer, K.West, Y.Liu, S.Denev, PRL 92, 117405 (2004)

Optical and electronic control of the ring radius



Theoretical model



$$\frac{\partial n_e}{\partial t} = D_e \nabla^2 n_e - w n_e n_h + J_e$$

$$\frac{\partial n_h}{\partial t} = D_h \nabla^2 n_h - w n_e n_h + J_h$$

$$J_h = P_{ex} \delta(r)$$

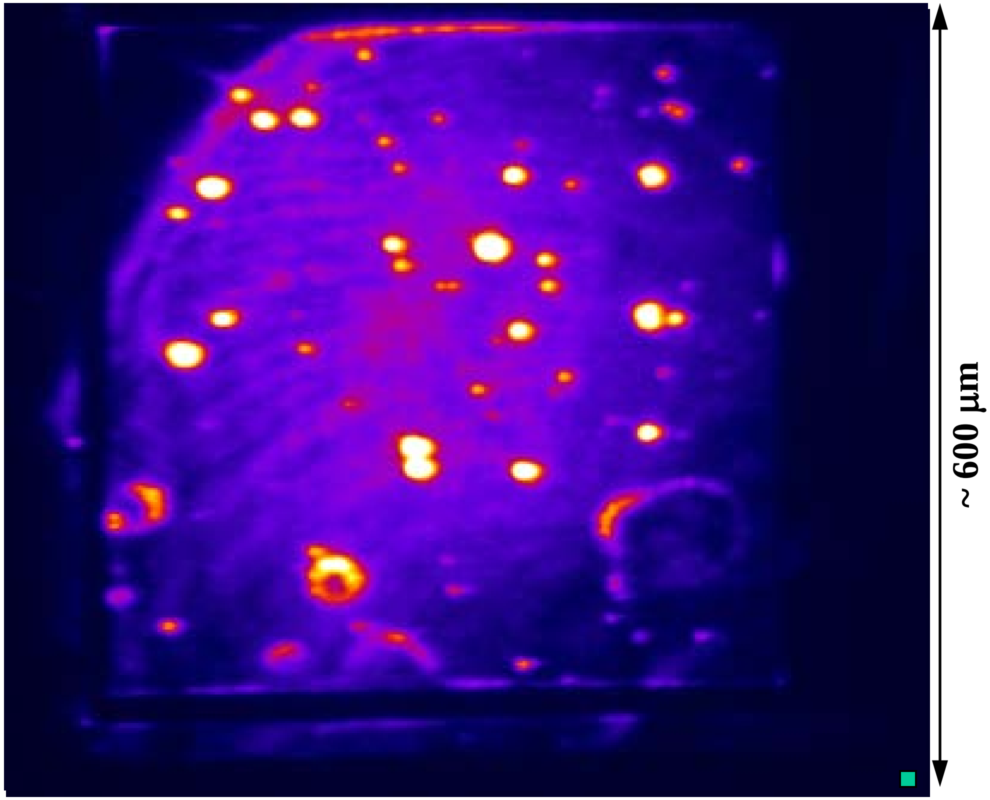
$$J_e = I_{in} - \gamma_{out} n_e$$

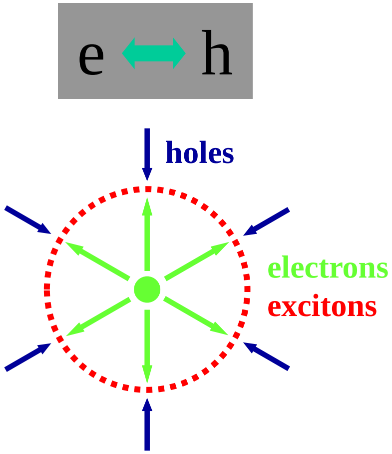
L.V. Butov, L.S. Levitov, B.D. Simons,
A.V. Mintsev, A.C. Gossard, D.S. Chemla,
PRL 92, 117404 (2004)

Localized bright spots (LBS)

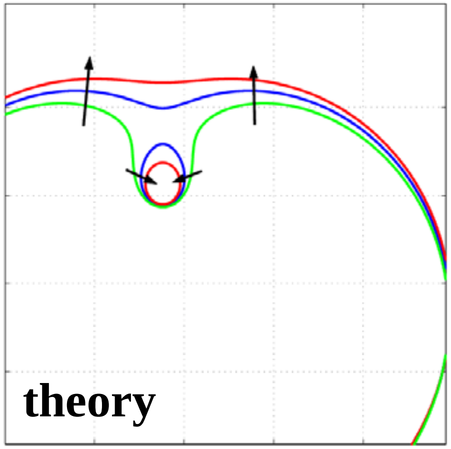
2D image of indirect exciton PL vs P_{ex}

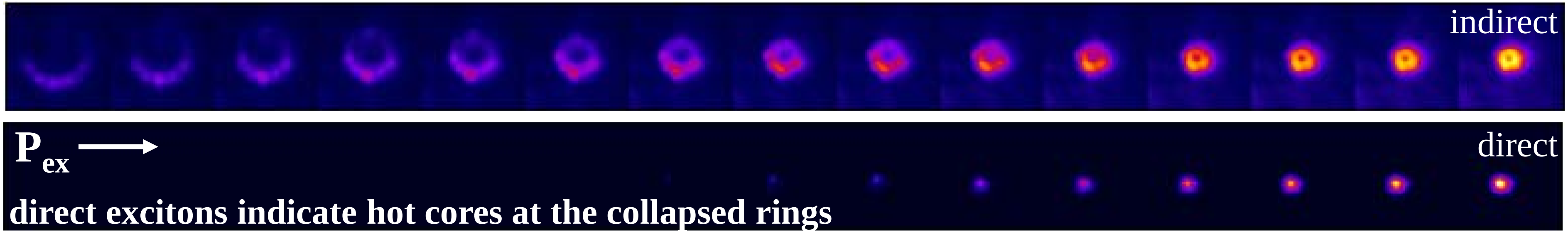
collapse of
exciton rings
to LBS
with
increasing P_{ex}





LBS are due to localized sources of electrons at current filaments crossing CQW embedded in the hole rich illuminated area

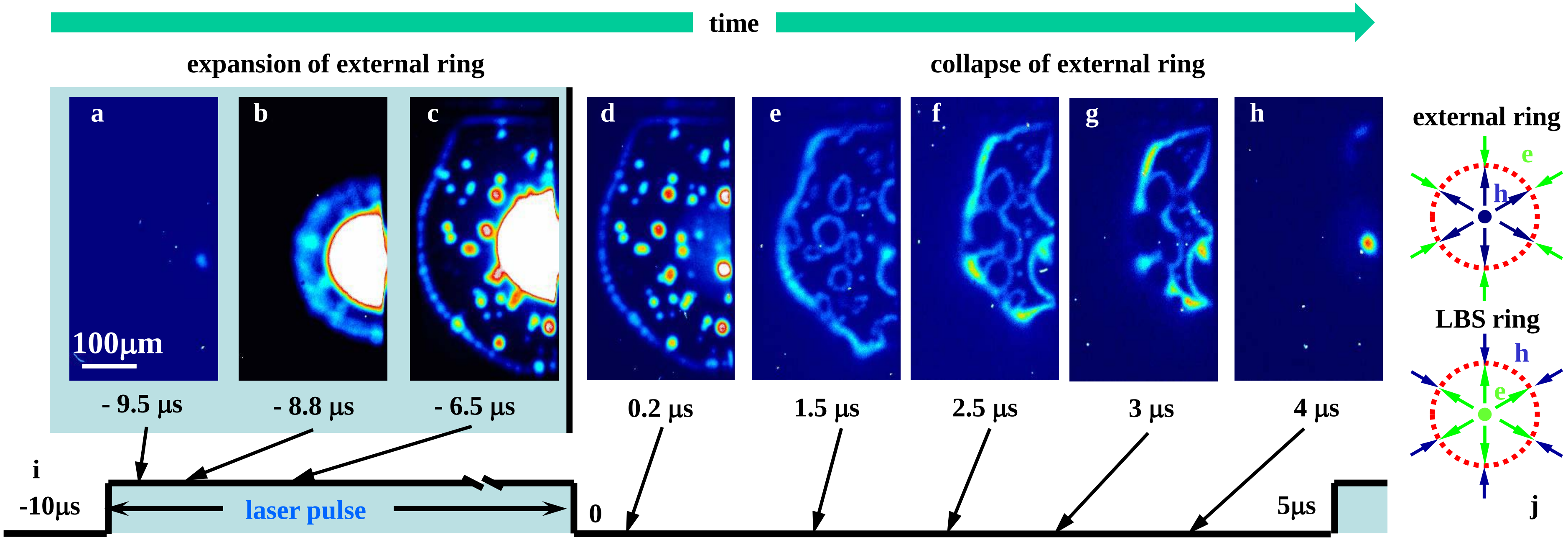




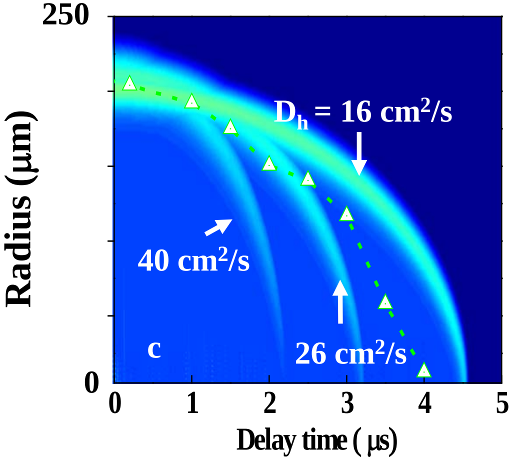
direct excitons indicate hot cores at the collapsed rings

L.V. Butov, L.S. Levitov, B.D. Simons, A.V. Mintsev, A.C. Gossard, D.S. Chemla, PRL 92, 117404 (2004)

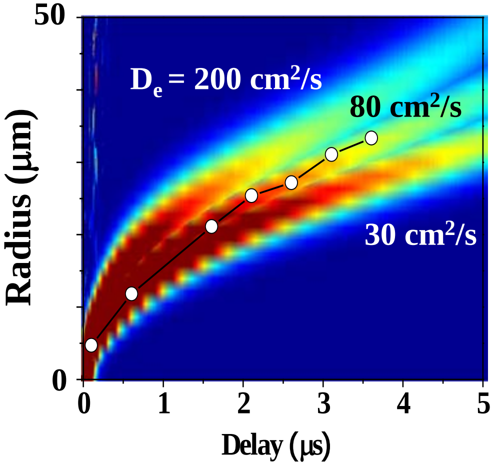
Kinetics of external ring and LBS rings. Exciton front propagation.



collapse of external ring



expansion of LBS rings



time-resolved imaging

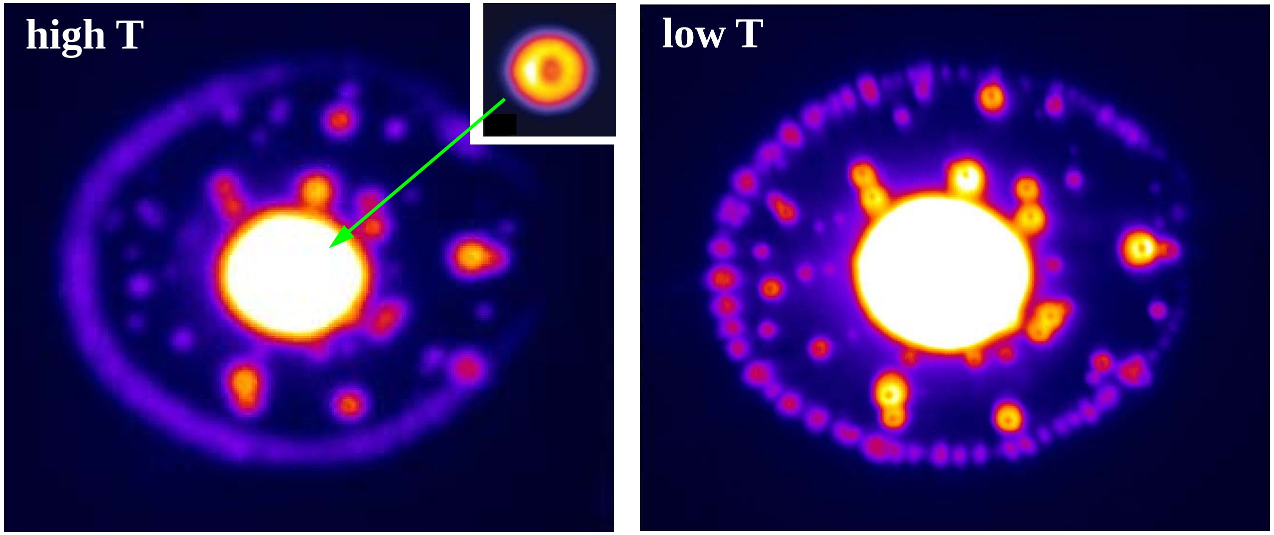
⬇

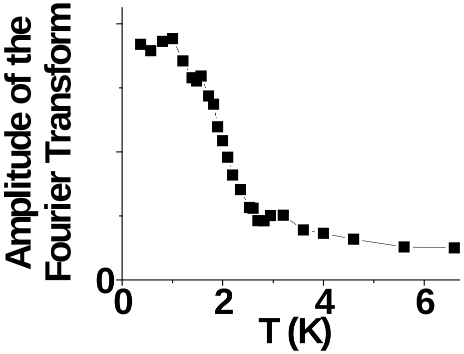
kinetics of external and LBS rings

⬇

probe of electron and hole transport

Sen Yang, L.V. Butov, L.S. Levitov, B.D. Simons, A.C. Gossard, PRB 81, 115320 (2010)





L.V. Butov, A.C. Gossard,
D.S. Chemla, cond-mat/0204482
[Nature 418, 751 (2002)]

observed features in exciton PL pattern

- **inner ring**
- **external ring**
- **localized bright spots**

- **MOES**

low-T phenomenon

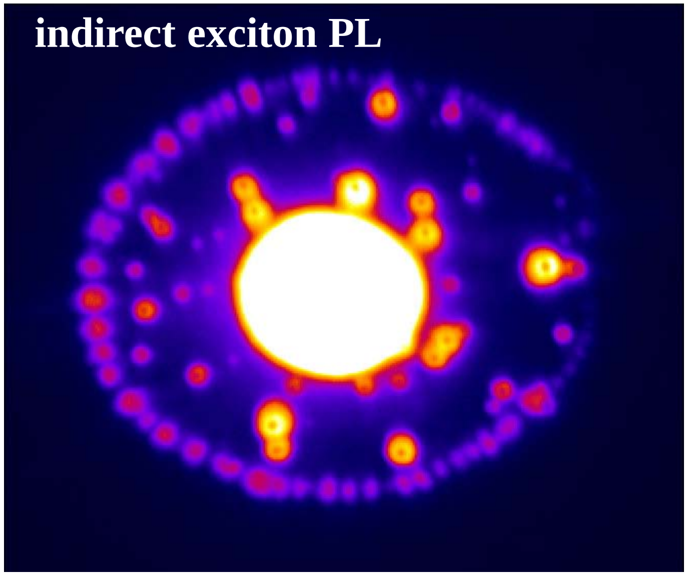
observed below a few K where exciton gas is degenerate

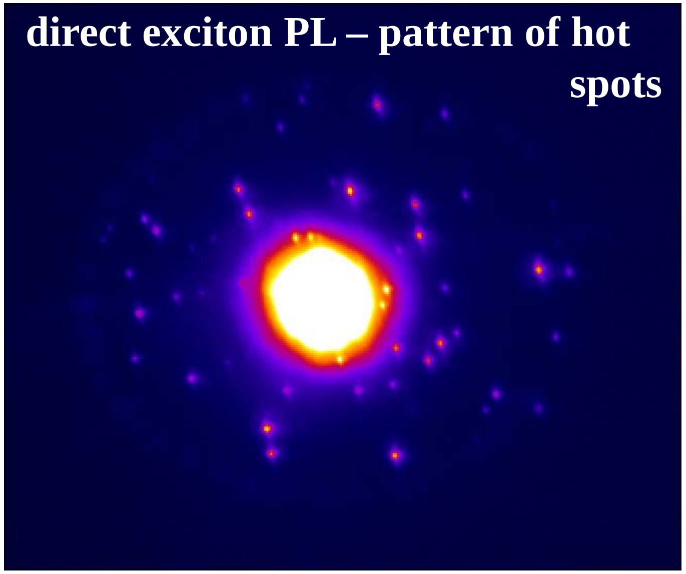
high-T phenomena

observed up to tens of K where exciton gas is classical

↓

their origin is classical





localized bright spots
have hot cores

no hot spots
in external ring
and LBS rings

rings are far from hot spots
due to long lifetimes of indirect excitons $T_X \approx T_{lattice}$

rings form is <u>region</u> where <u>cold and dense exciton gas</u> is created

⬇

macroscopically ordered exciton state (MOES)

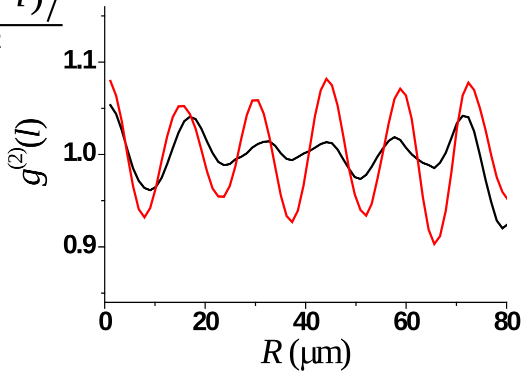
phase fluctuation of the macroscopic exciton density wave

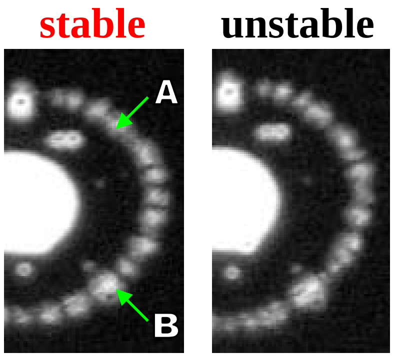
real time movie
at fixed parameters

the phase of the macroscopic exciton density wave is locked at LBS defects and fluctuates in between of them

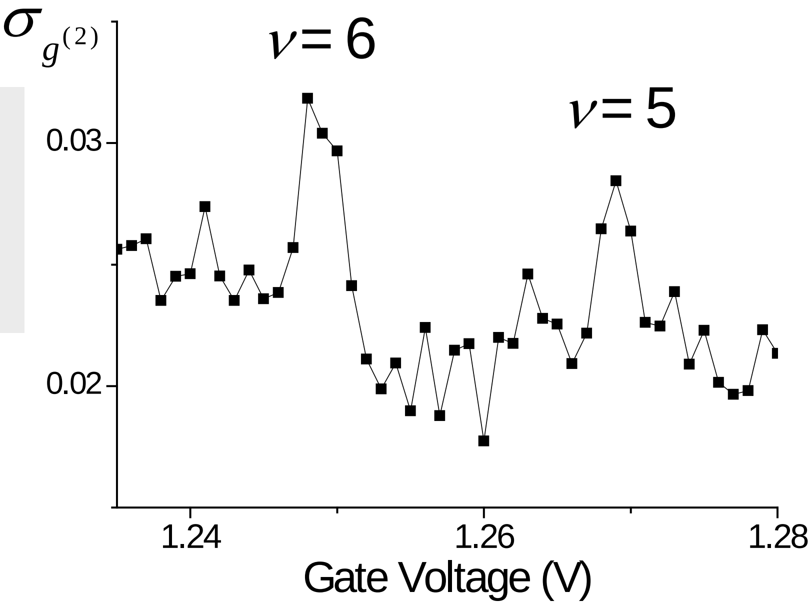
Commensurability effect for the macroscopic exciton density wave

$$g^{(2)}(l)=\frac{\langle I(l')I(l'+l)\rangle}{\langle I(l')\rangle^{2}}$$





← 30 ms integration time



phase of macroscopic exciton density wave

is unstable if ν is not integer ← incommensurate

is stabilized if ν is integer ← commensurate

$$\nu = L/\lambda_{MOES}$$

is the number of MOES wavelengths in between the LBS defects

commensurability is a common phenomenon for waves: e.g. EM waves in Fabry Perot cavity

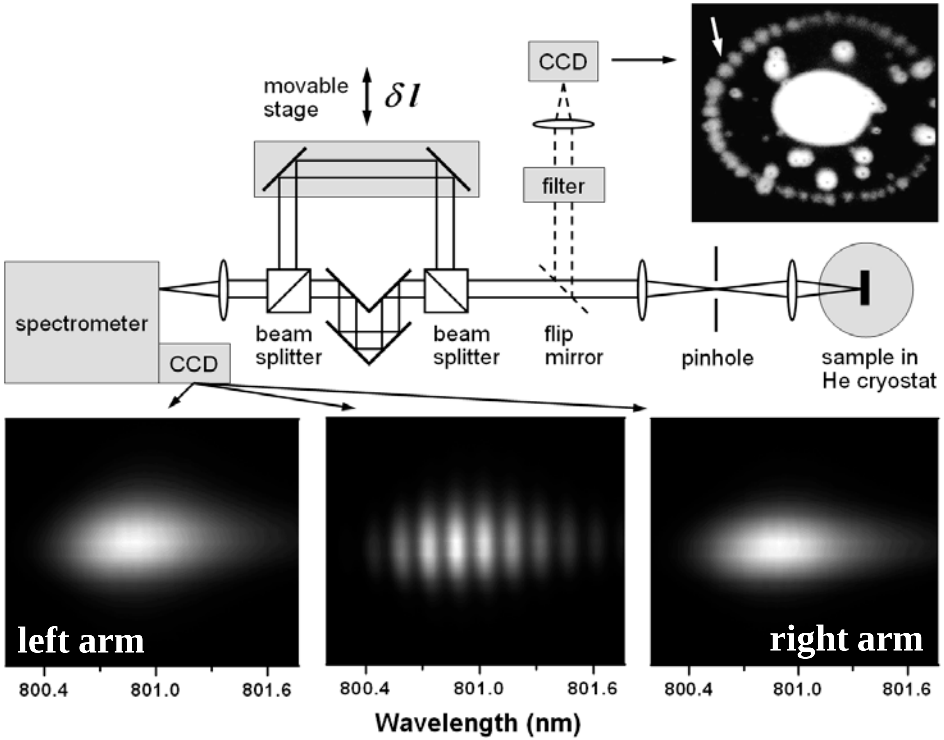
specific property of MOES: it is a collective state of many excitons ~ 10^5 excitons in the MOES between LBS A and B

Sen Yang, A. Hammack, L.V. Butov, L.S. Levitov, B.D. Simons, A.C. Gossard, unpublished

Probe of spontaneous coherence (not driven by laser excitation)

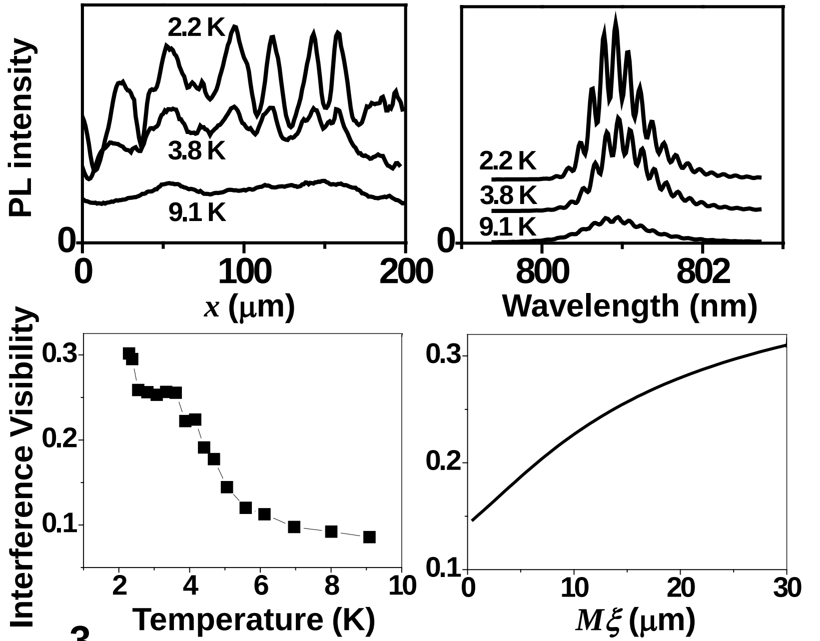
**Mach-Zehnder interferometry
with spatial and spectral resolution**

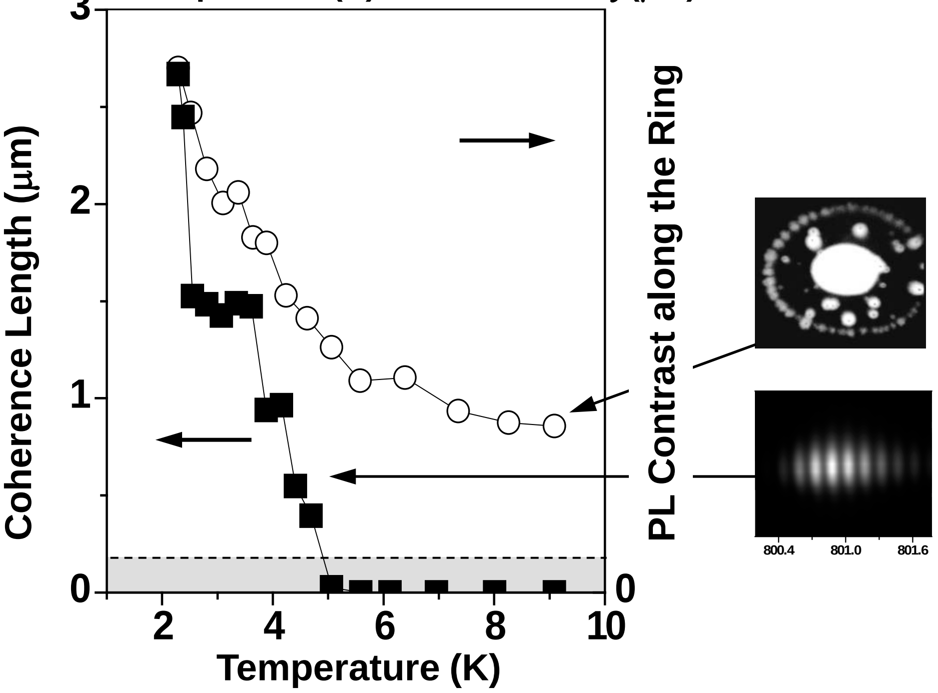
**probing coherence far from laser both in
space and energy: coherence is spontaneous**



Sen Yang, A. Hammack, M.M. Fogler, L.V. Butov, A.C. Gossard, cond-mat/0606683 [PRL 97, 187402 (2006)]

Emergence of spontaneous coherence of excitons at low temperatures





the increase of the coherence length ξ
is correlated with
the macroscopic spatial ordering of excitons

$\xi \sim 2$ μm >> the classical value ~ $\lambda_{dB} \sim 0.1$ μm

$$n_k = \int d^2 r e^{-i\mathbf{kr}} \cdot g^{(1)}(r)$$

$$\delta k \cdot \xi \sim 1$$

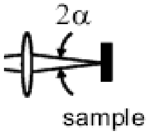
spontaneous coherence =
= condensation in *k*-space

MOES is a state with:

- **macroscopic spatial ordering and**
- **large coherence length**
  → a condensate in *k*-space

Effect of finite spatial resolution

Finite spatial resolution * = *k*-filtering effect @



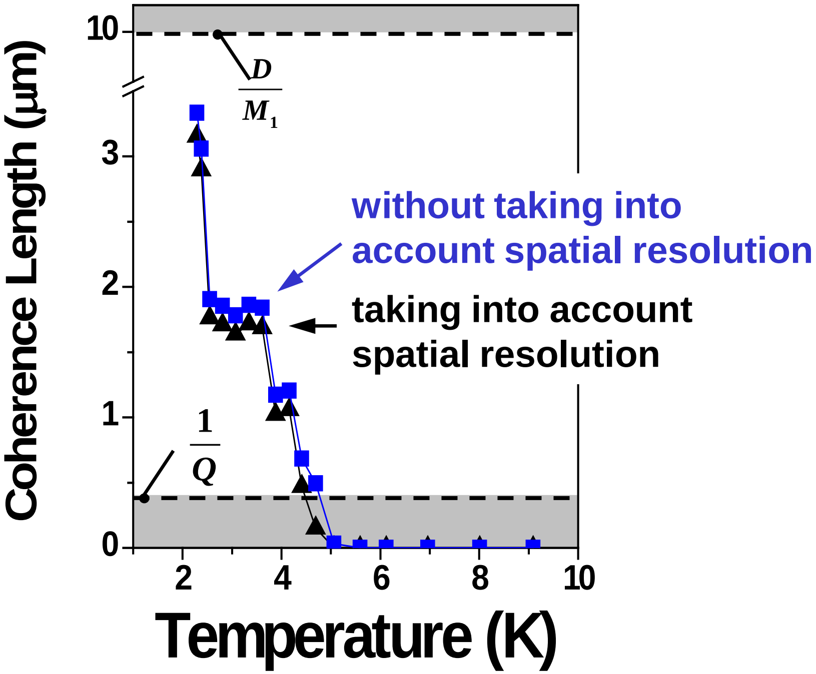
$\mathrm{NA}=\sin\alpha$

$$\xi = \sqrt{\xi_x^2 + \frac{1}{Q^2}}$$

ξ optical coherence length

ξ_x exciton coherence length

$\frac{1}{Q} = \frac{\text{Abbe limit}}{\pi} = \frac{\lambda_0}{2\pi NA}$ spatial resolution



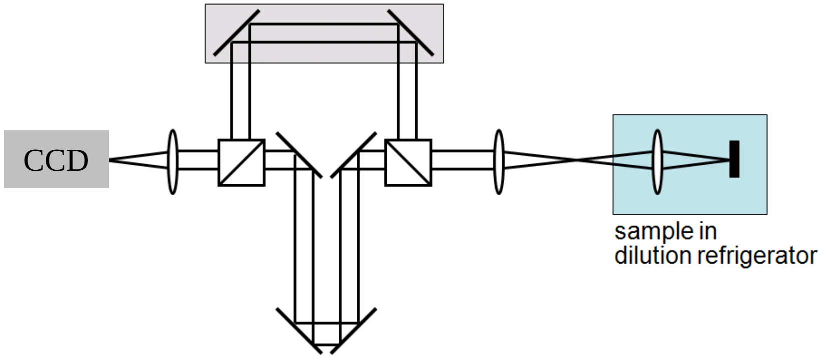
without taking into account spatial resolution

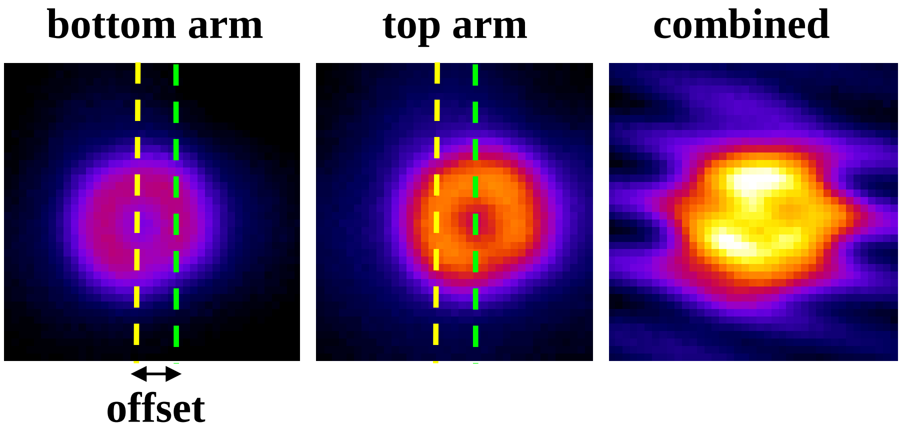
taking into account spatial resolution

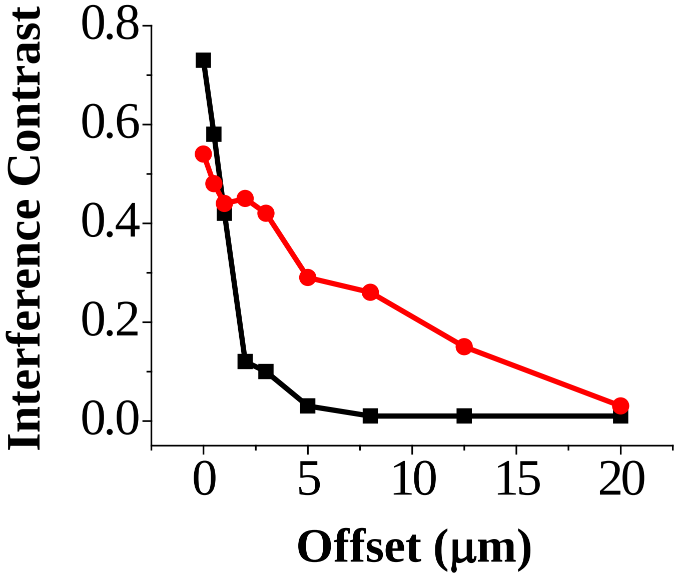
[@] L. Mouchliadis, A. L. Ivanov, arXiv:0802.4454 [PRB 78, 033306 (2008)]

[*] M.M. Fogler, Sen Yang, A.T. Hammack, L.V. Butov, A.C. Gossard, arXiv:0804.2686 [PRB 78, 035411 (2008)]

Probe of exciton coherence length in different regions of pattern formation







work in progress

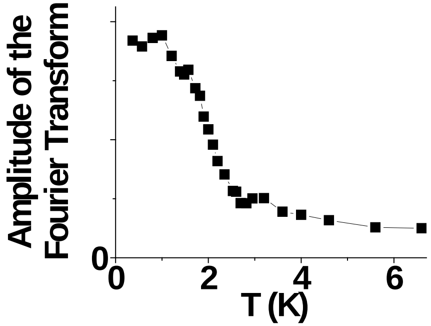
What we know about the macroscopically ordered exciton state

MOES is a state with:

- **macroscopic spatial ordering**
- **large coherence length → a condensate in *k*-space**

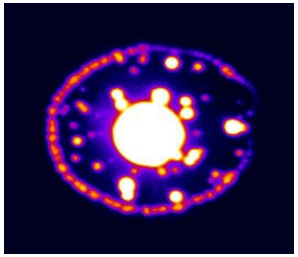
observed <u>in a cold exciton gas</u>

- at low temperatures below a few K
- in a system of indirect excitons
- in the external ring far from hot excitation spot

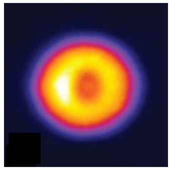


observed <u>in external ring</u>

- on interface between hole-rich area
  and electron-rich area

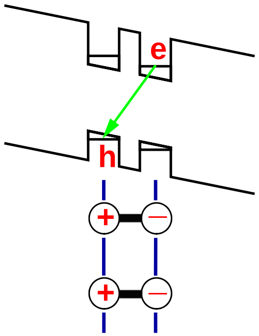


not observed for inner ring



characterized by <u>repulsive interaction</u>

(→ not driven by attractive interaction)



repulsive interaction of oriented dipoles

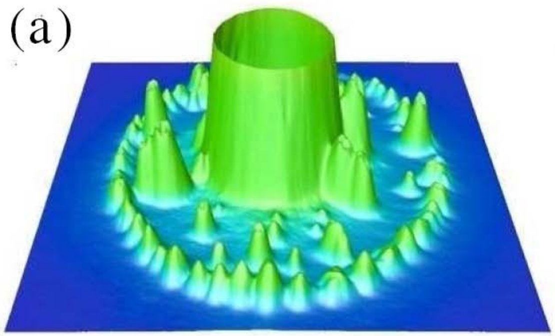
Sen Yang et al.,
PRB 75, 033311 (2007)

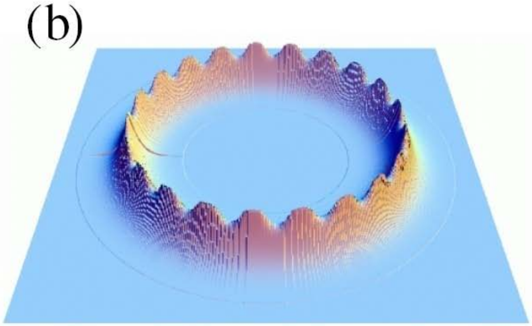
Theoretical model for MOES consistent with the experimental observations

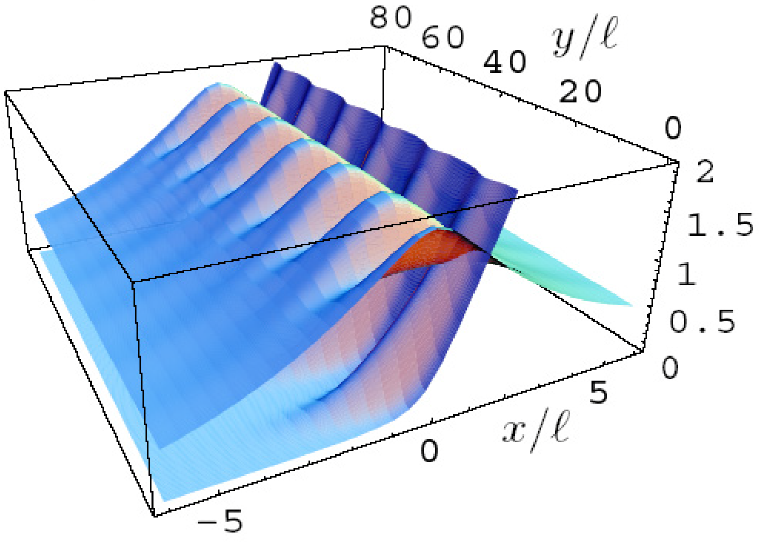
instability requires positive feedback to density variations

↕

instability can result from quantum degeneracy in a cold exciton system due to stimulated kinetics of exciton formation







$$\frac{\partial n_e}{\partial t} = D_e \nabla^2 n_e - w n_e n_h + J_e$$

$$\frac{\partial n_h}{\partial t} = D_h \nabla^2 n_h - w n_e n_h + J_h$$

$$\frac{\partial n_X}{\partial t} = D_X \nabla^2 n_X + \underline{w n_e n_h} - n_X / \tau_{opt}$$

$$\underline{w \sim 1 + N_{E=0} = e^{\frac{T_{dB}}{T}} = e^{\frac{2\pi\hbar^2}{mgk_BT} n_x}}$$

L.S. Levitov, B.D. Simons, L.V. Butov, PRL 94, 176404 (2005)