Phenomena in cold exciton gases: Condensation, macroscopic ordering and beyond

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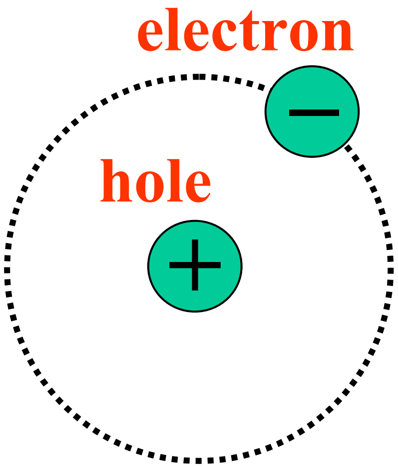
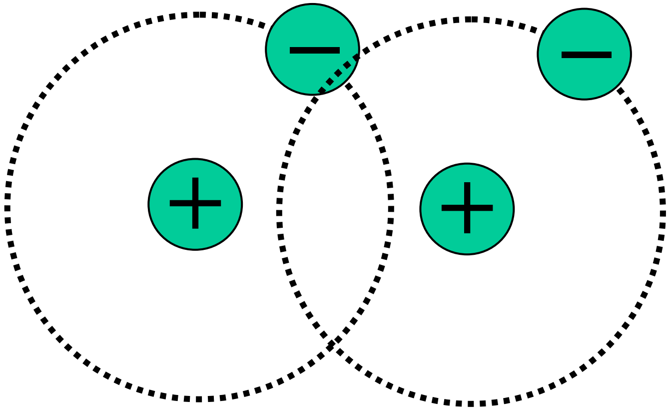
Excitons and Electron-Hole Plasma



exciton – bound pair of electron and hole

$$m_{\text{exciton}} = m_{\text{electron}} + m_{\text{hole}} \ll m_{\text{atom}}$$

exciton – light bosonic particle in semiconductor



at high densities
excitons dissociate

↓

plasma of free electrons and holes

exciton condensation

dilute exciton gas ($na_B^d \ll 1$)

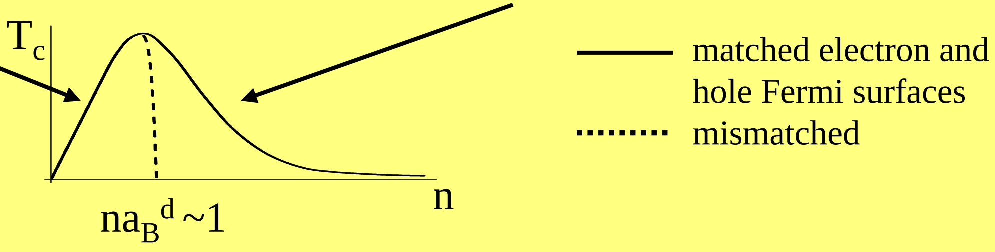
excitons are weakly interacting Bose particles

exciton condensation is analogous to Bose-Einstein condensation

dense electron-hole system ($na_B^d \gg 1$)

excitons are formed at Fermi level like Cooper pairs

exciton condensate called excitonic insulator is analogous to BCS superconductor state



L.V. Keldysh, Yu.E. Kopaev (1964)
L.V. Keldysh, A.N. Kozlov (1968)

why it's interesting?

- exciton condensate is a new form of matter
- high T_c for exciton BEC due to light exciton mass: $T_c^{exciton} \sim 1$ K →
- possibility to study crossover from BEC to BCS-like state
- possibility of manipulating condensate in microscopic semiconductor devices

Kelvin for excitons
↕
microKelvin for atoms

how to get cold exciton gas?

$T_{lattice} \ll 1$ K in He refrigerators

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

→ find excitons with lifetime >> cooling time $\Rightarrow T_X \sim T_{lattice}$

⬇

find materials with low e-h recombination rate

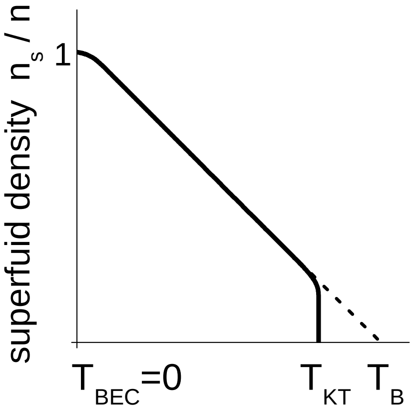
Condensation in 3D and 2D systems

BEC ⟷ Macroscopic occupation of ground state

quasi-condensate - macroscopic occupation of low energy states
difference between quasicondensate and BEC is not essential for most experiments

3D systems: BEC is possible at finite T $T_c=0.527\,\frac{2\pi\hbar^2}{M}\frac{n^{2/3}}{g^{2/3}}$

2D systems: BEC is possible at T=0 only



Bogoliubov temperature $T_B \simeq \frac{4\pi\hbar^2 n}{2Mg}\,\frac{1}{\ln[\ln(g/na^2)]}$

↑

Onset of nonzero order parameter
= onset of local superfluidity

Kosterlitz-Thouless temperature $T_{KT}=\frac{\pi^2\hbar^2 n_s(T=T_{KT}^-)}{2Mg}$

↑

pairing of vortexes = onset of macroscopic
superfluidity which is not destoyed by vortexes

Finite 2D systems: BEC is possible at finite T $T_c=\frac{4\pi\hbar^2 n}{2Mg}\,\frac{1}{\ln(nS/g)}$

include 2D systems with in-plane (random) potential
in this case S - area of local potential minimum

V.N. Popov, Theor. Math. Phys. 11, 565 (1972)
D.S. Fisher, P.C. Hohenberg, PRB 37, 4936 (1988)
W. Ketterle, N.J. van Drutten, PRA 54, 656 (1996)

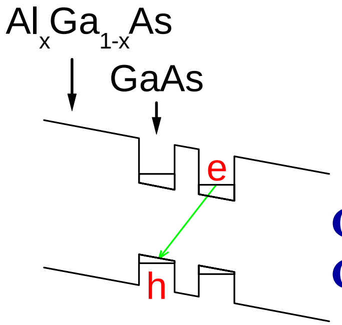
Materials with low e-h recombination rate

classical semiconductors with low e-h recombination rate	highlights	obstacles for experimental realization of cold exciton gases
Ge, Si	discovery of electron-hole liquid	ground state – metallic electron-hole liquid alternative to excitonic ground state
Cu_2O	a number of interesting effects in exciton gases	high rate of Auger recombination

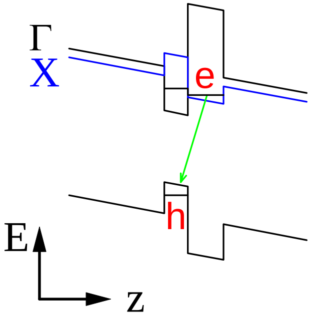
Novel systems

indirect excitons in coupled quantum wells
polaritons in microcavities
excitons in quantum-Hall bilayers

Why indirect excitons in CQWs?



GaAs/AlGaAs CQW



AlAs/GaAs CQW

<u>long exciton lifetime</u> due to separation between electron and hole layers

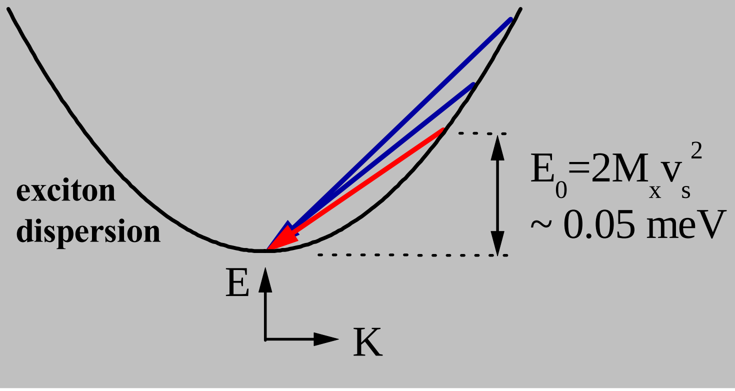
<u>10^3 times shorter exciton cooling time</u> than that in bulk semiconductors

coldest exciton gas: $T_X << 1K < T_c$

↓

potential candidate for realization of exciton condensation

exciton energy relaxation by LA-phonon emission



$E_0=2M_xv_s^2$
~ 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

How to get cold exciton gas?

excitons are generated hot and cool down to $T_{lattice}$ via phonon emission

T_X drops down to 400 mK in 5 ns

$< T_c$ $\qquad$ $\ll$ lifetime

ways to overcome the obstacle of hot generation and study cold gases of indirect excitons with $T_X \sim T_{lattice}$

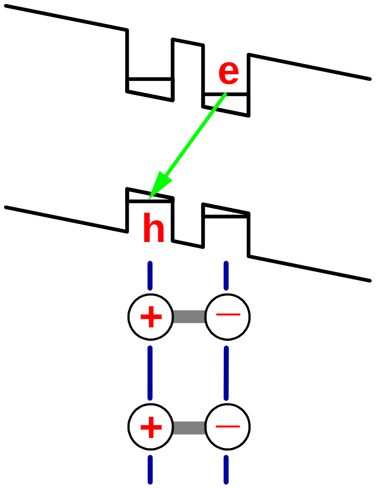
separation in time

study indirect excitons
a few ns after the end of
photoexcitation pulse

separation in space

study indirect excitons
excitons beyond
photoexcitation spot

Repulsive interaction between indirect excitons



indirect excitons
are oriented dipoles

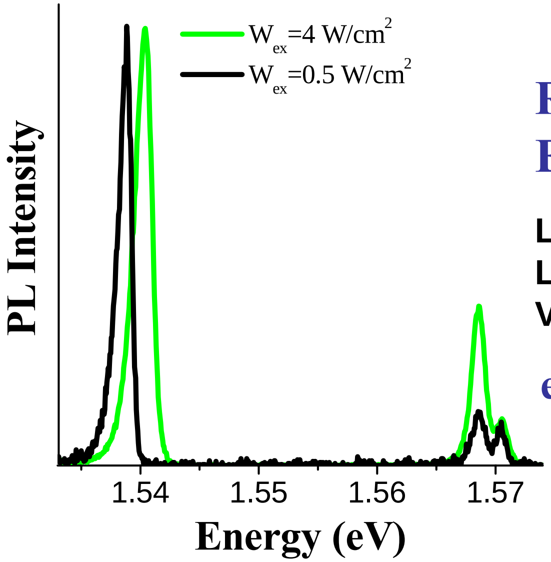
Dipole-dipole repulsive interaction
stabilizes exciton state against formation of
metallic electron-hole droplets

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)

→ the ground state of the system is excitonic

results in effective screening of in-plane disorder

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

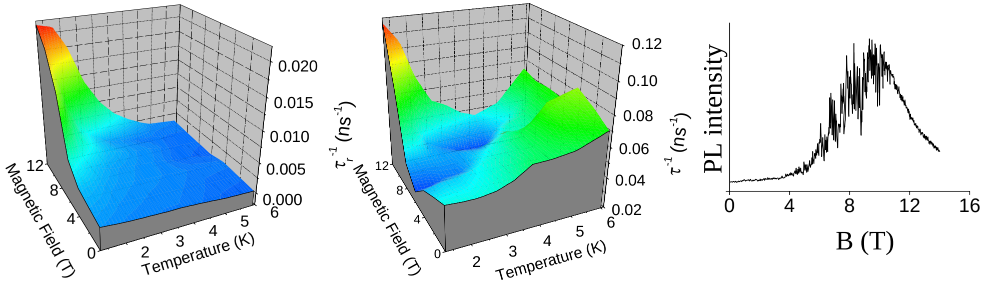


Repulsive interaction in experiment:
Exciton energy increases with density

L.V. Butov, A. Zrenner, G. Bohm, G. Weimann, J. de Physique 3, 167 (1993)
L.V. Butov, A. Zrenner, G. Abstreiter, G. Bohm, G. Weimann, PRL 73, 304 (1994)...
V. Negoita, D.W. Snoke, K. Eberl, PRB 61, 2779 (2000)

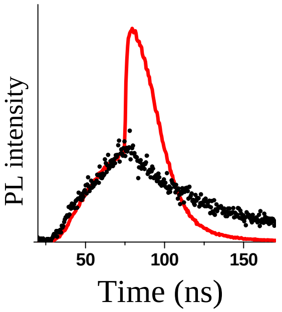
energy shift: $\delta E \sim 4\pi n e^2 d/\varepsilon$ → estimate for exciton density

Experiments on cold exciton gases in CQW nanostructures



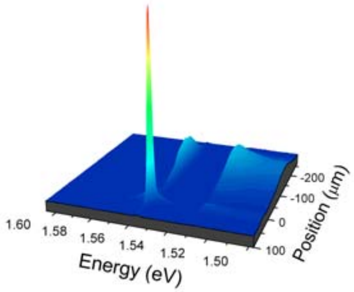
effects indicating exciton condensate superradiance (macroscopic dipole), onset of exciton superfluidity, and fluctuations near phase transition

Butov et al. *J. de Physique* 3, 167 (1993)
PRL 73, 304 (1994)
PRB 58, 1980 (1998)



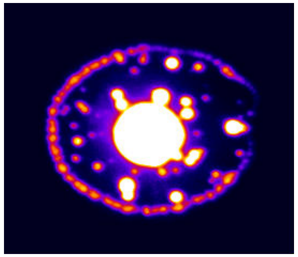
bosonic stimulation of exciton scattering - signature of degenerate Bose-gas of excitons

Butov et al. PRL 86, 5608 (2001)
PRL 87, 216804 (2001)



shrinkage of spatially localized exciton cloud with reducing T → degenerate exciton gas

Butov et al. Nature 417, 47 (2002)

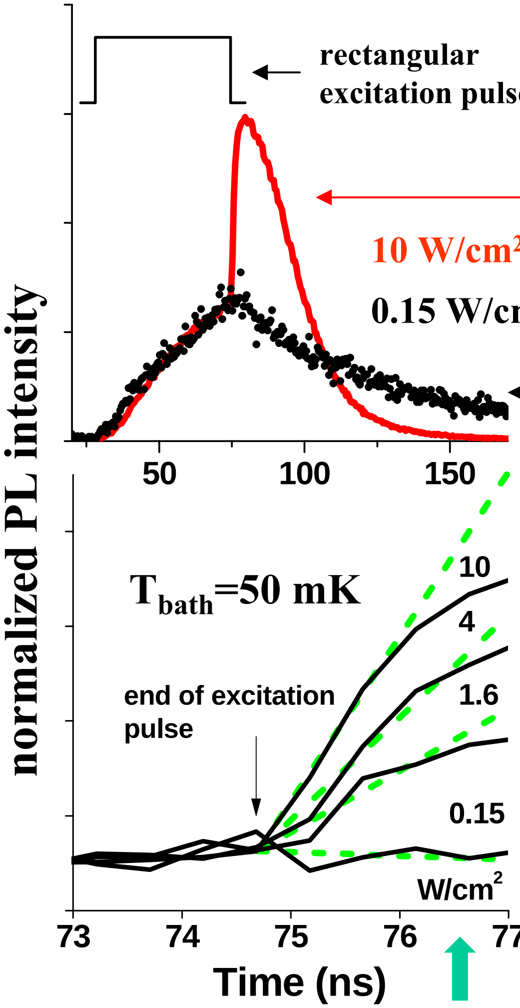


exciton rings
macroscopically ordered exciton state

Butov et al. cond-mat/0204482 [Nature, 418, 751 (2002)]
cond-mat/0308117 [PRL 92, 117404 (2004)]

SSC 127, 89 (2003)
http://physics.ucsd.edu/~lvbutov/

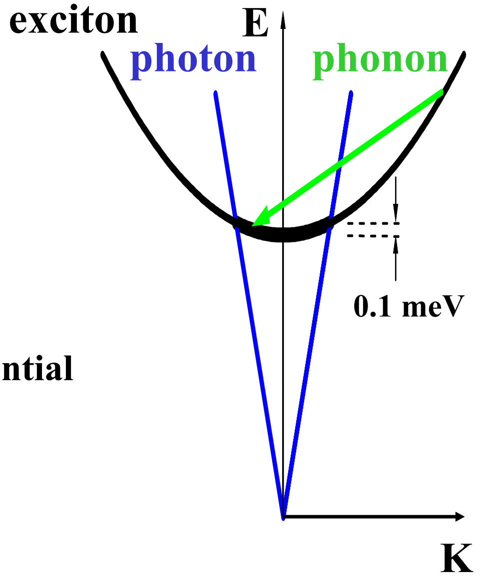
Bosonic stimulation of exciton scattering



rectangular excitation pulse

PL jump

monoexponential PL kinetics

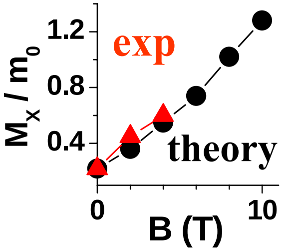


exciton PL kinetics

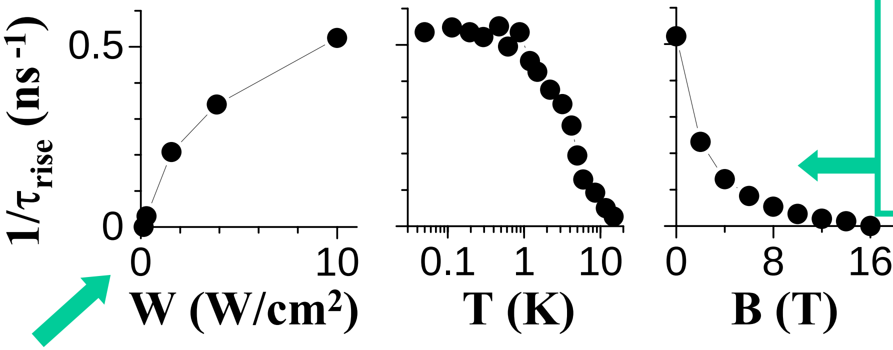
↕

occupation kinetics of optically active exciton states

exciton mass is controlled in situ



Butov et al. PRL 87, 26804 (2001)



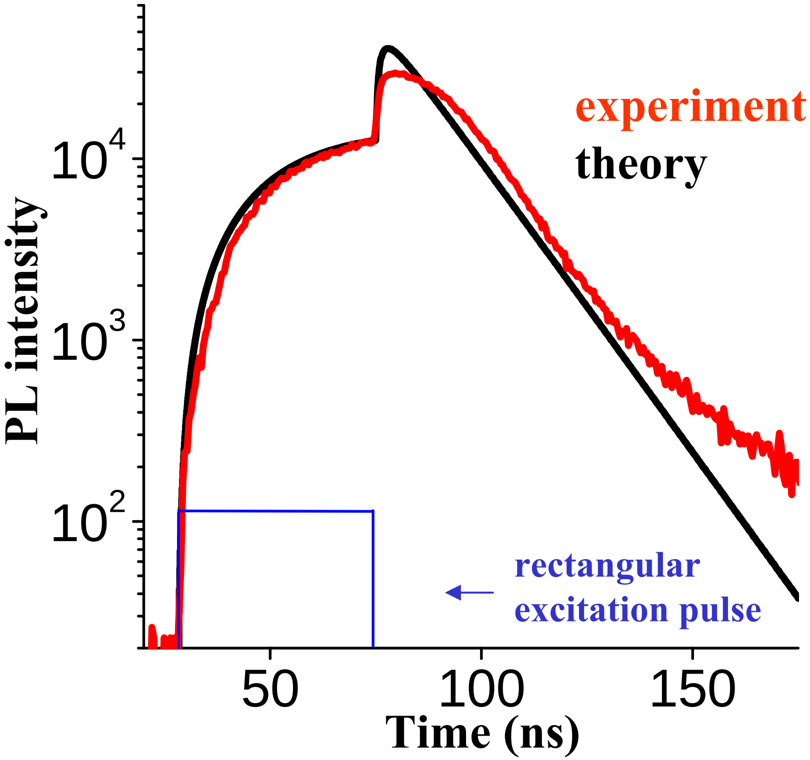
enhancement of exciton scattering rate to low energy states with increasing exciton concentration reveals bosonic stimulation of exciton scattering

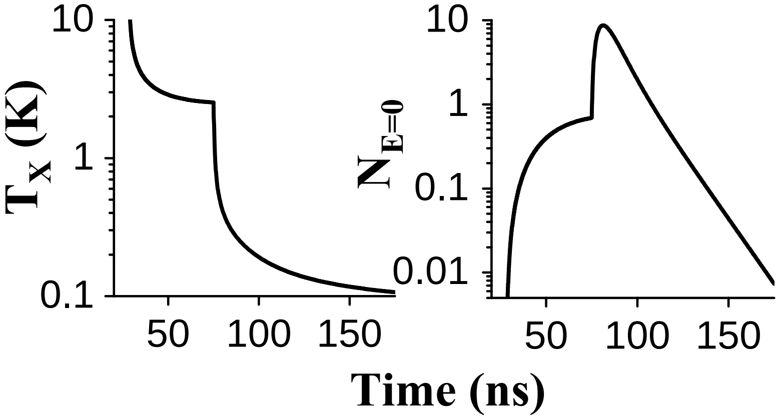
signature of degenerate Bose-gas of excitons

scattering rate of bosons to a state p is ~$(1+N_p)$

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

Experiment vs theory





$$N_{E=0} = e^{T_0/T_X} - 1$$

$$T_0 = \pi\hbar^2 n / 2gM_X k_B$$

temperature of quantum degeneracy

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

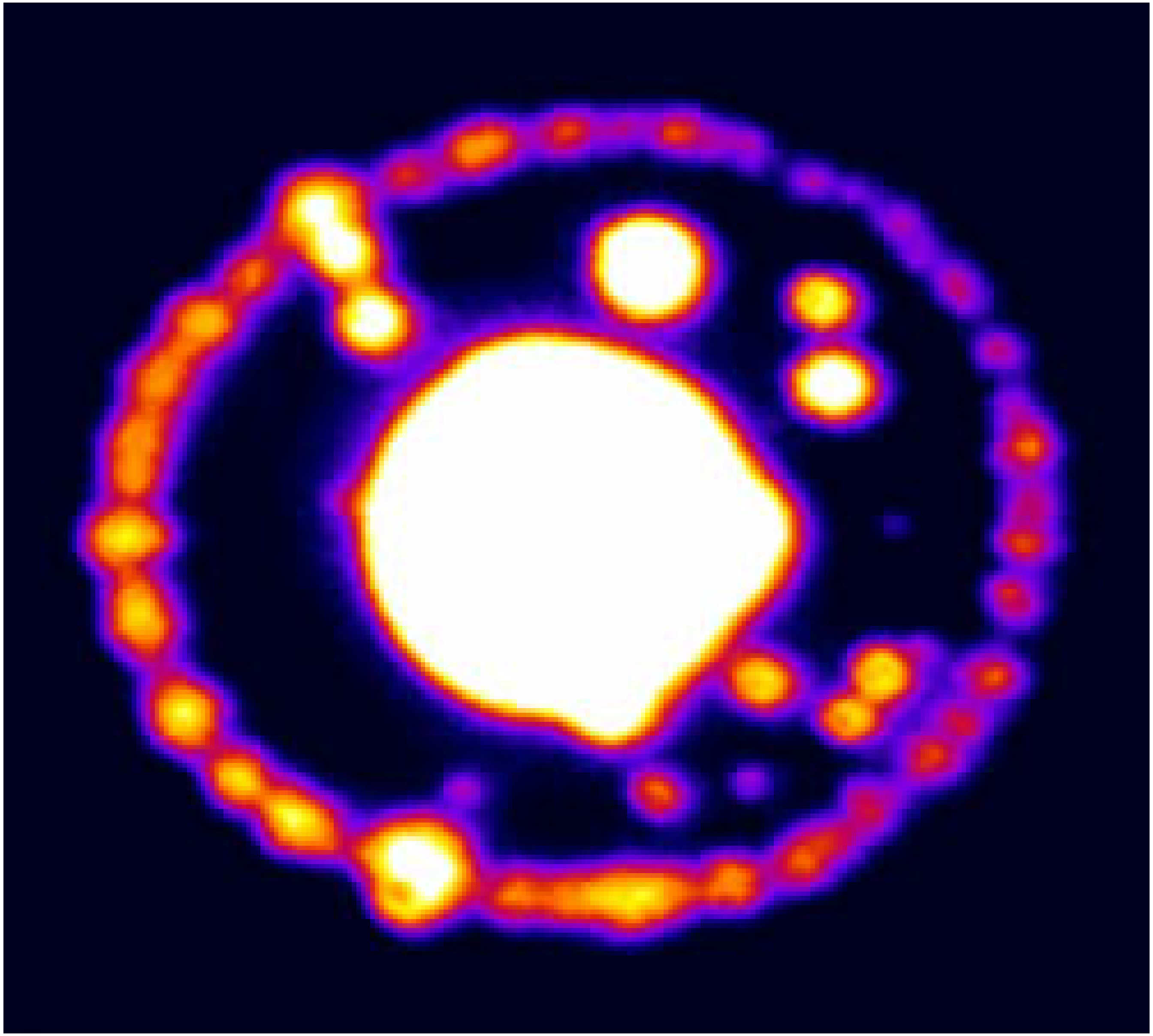
$$= \Gamma_{ph} (N_E - n_E^{ph}) N_{E=0} + \Gamma_{ph} (1 + n_E^{ph})\, N_E - N_{E=0} / \tau$$

at low $T_{lattice}$ and in presence of generation of hot excitons
$N_E - n_E^{ph} > 0$

←

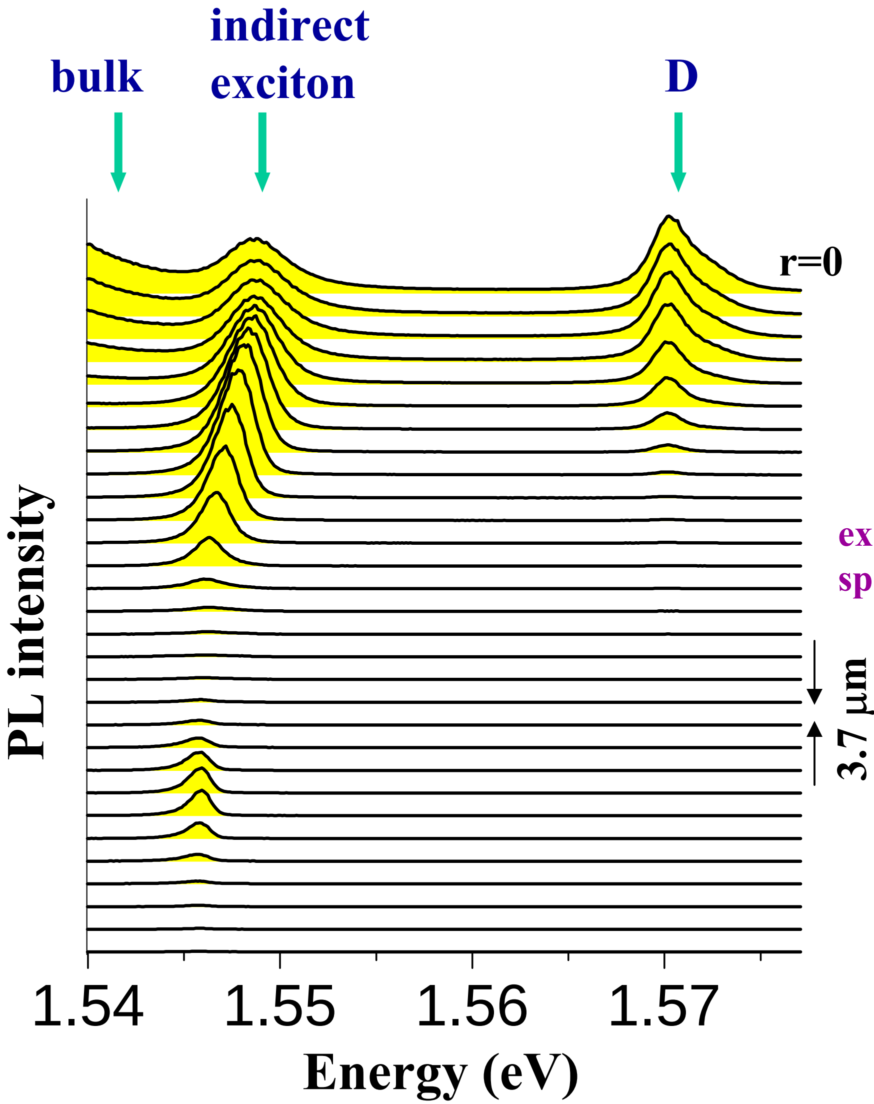
Frolich inversion condition counterpart of population inversion condition for lasers

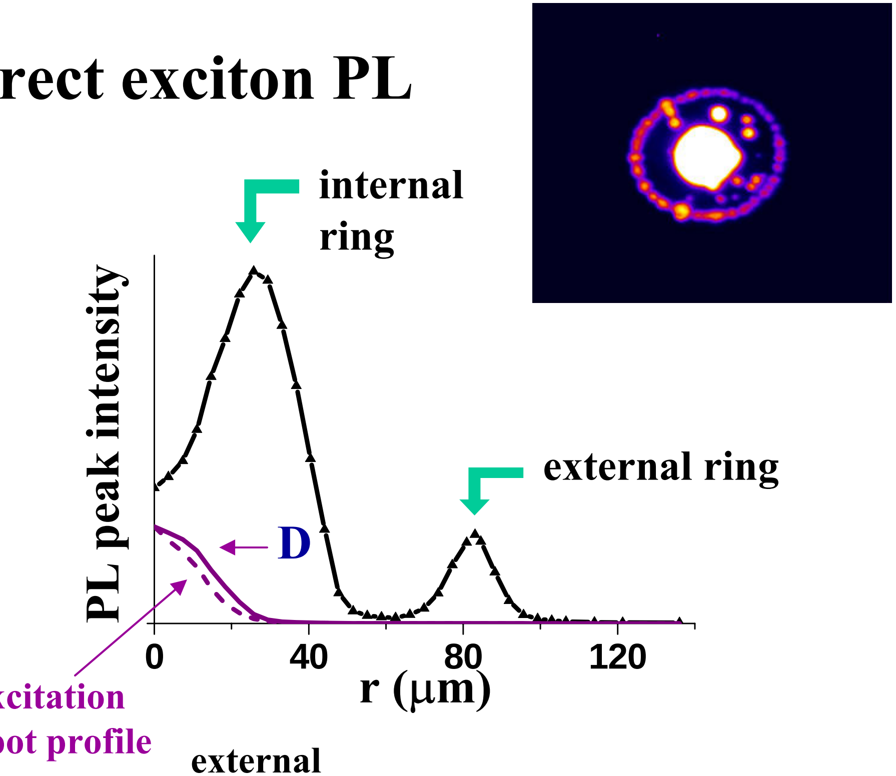
2D image of indirect exciton PL vs P_{ex}

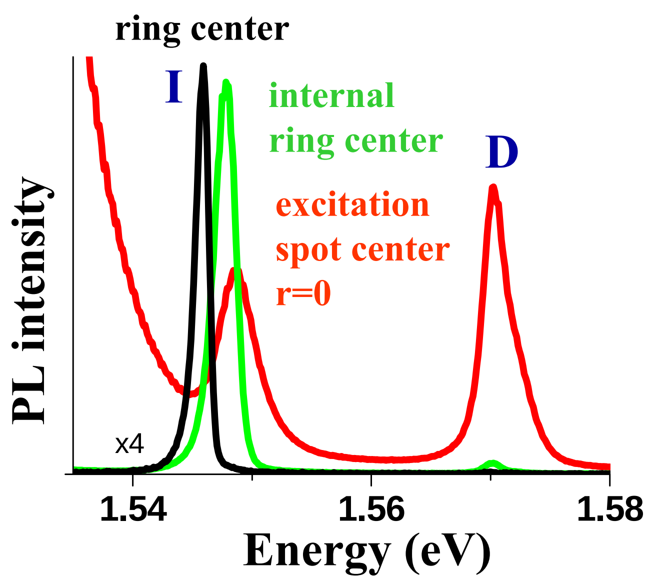


L.V. Butov, A.C. Gossard, and D.S. Chemla, cond-mat/0204482 [Nature 418, 751 (2002)]

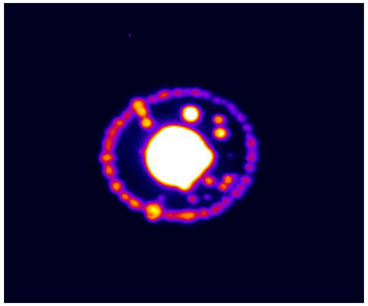
Radial dependence of indirect exciton PL

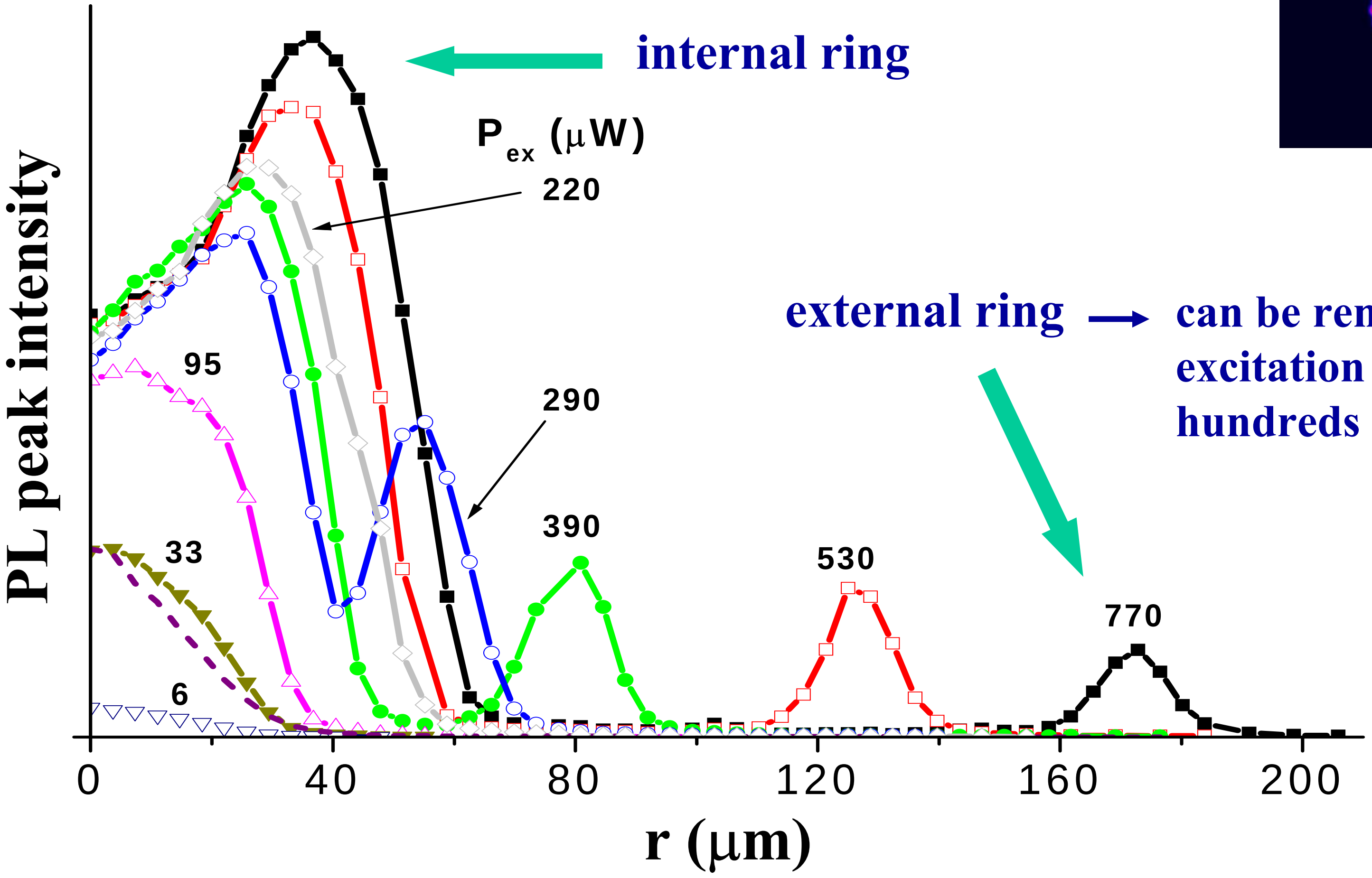






Ring structure of indirect exciton PL





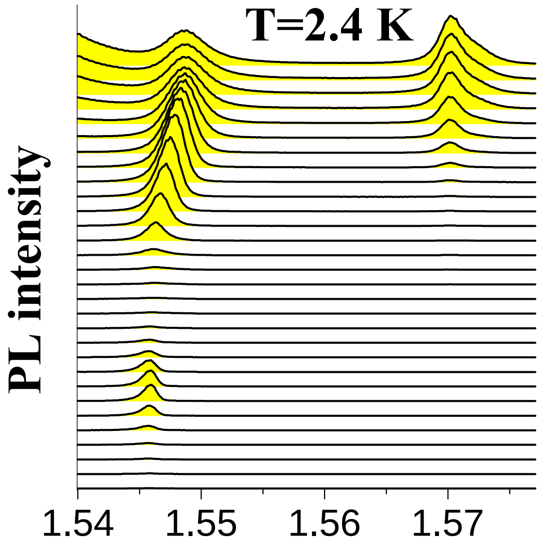
internal ring

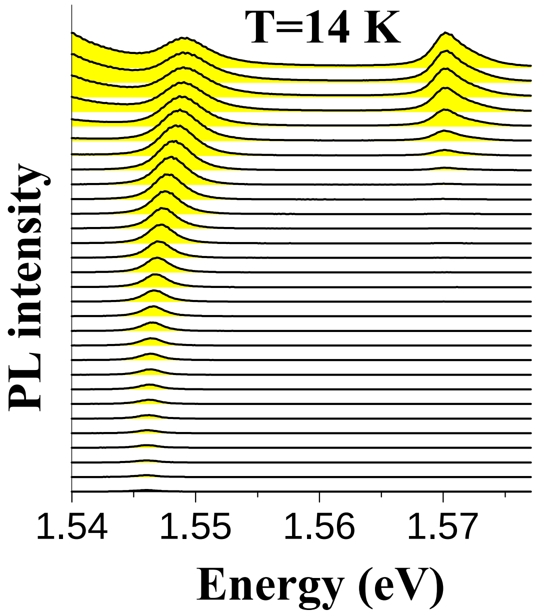
external ring → can be remote from excitation spot by hundreds of microns

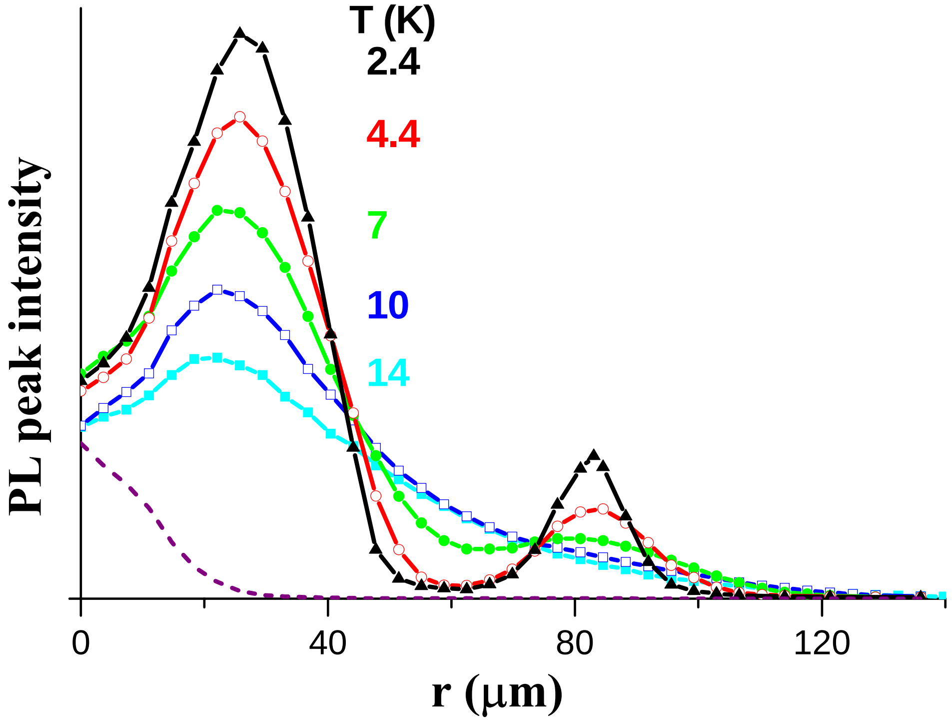
at low densities:
spatial profile of indirect exciton PL intensity follows laser excitation intensity

at high densities:
spatial profile of indirect exciton PL intensity is characterized by ring structure

Temperature dependence of ring-shaped PL structure

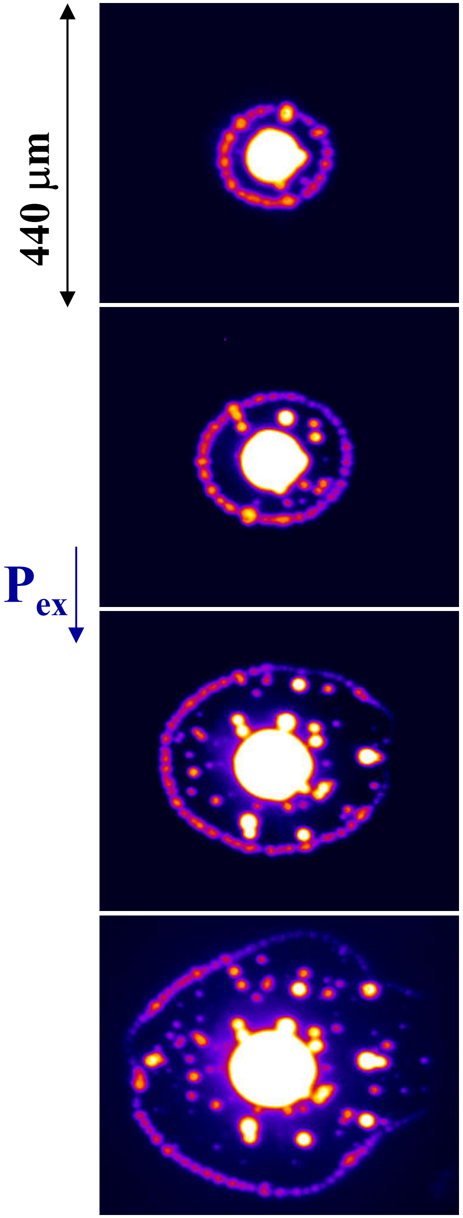


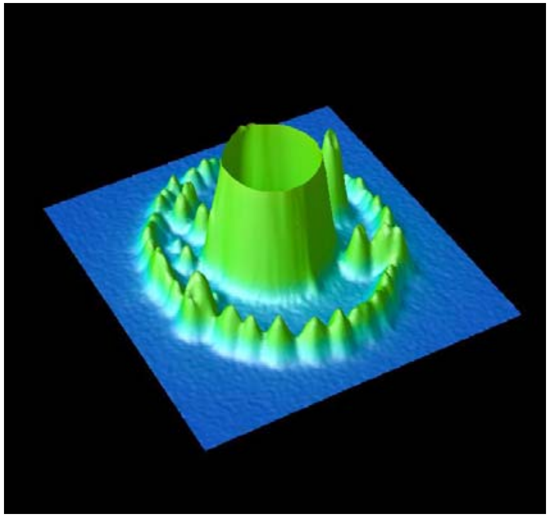


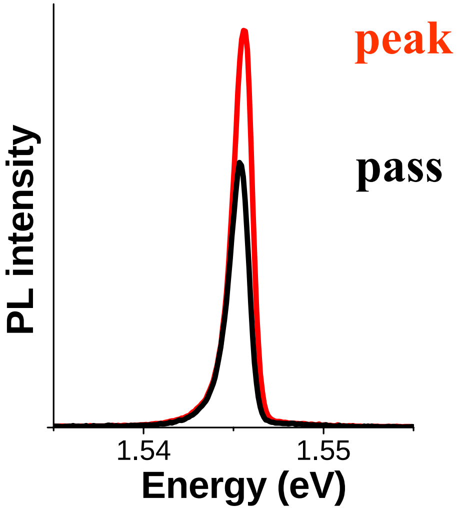


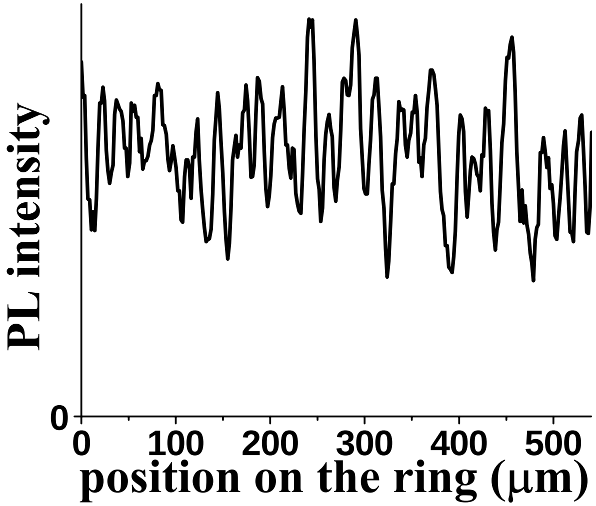
ring structure of indirect exciton PL is observed at low T

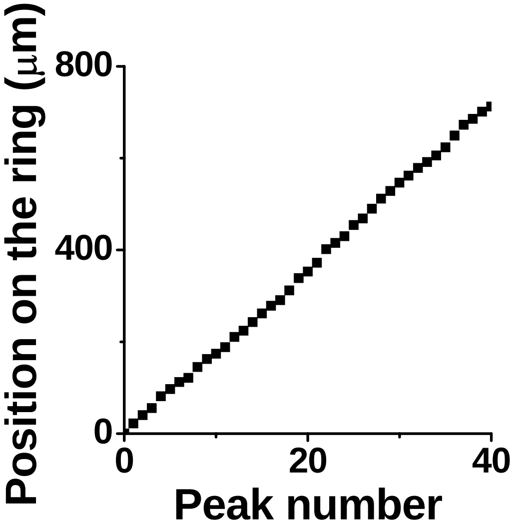
with increasing T rings wash out and spatial profile approaches monotonic bell-like shape







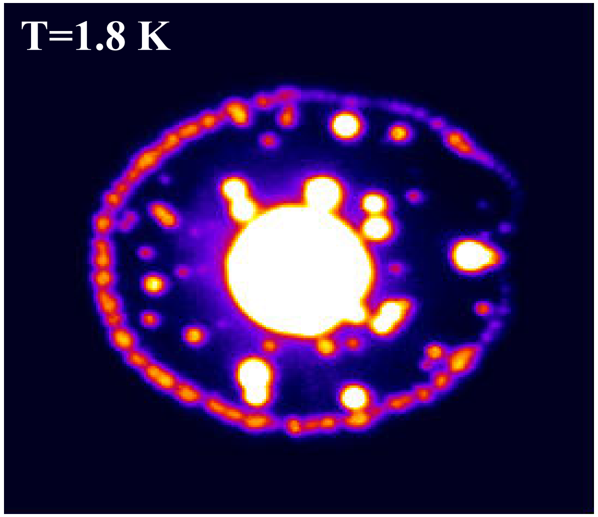


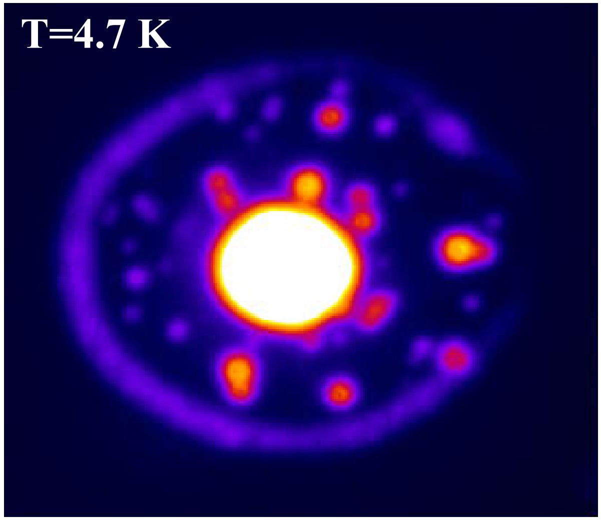


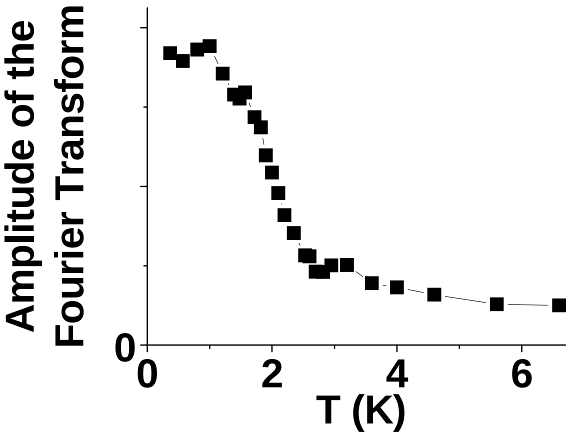
external ring is fragmented into circular structures that form a periodic array over macroscopic lengths, up to ~1 mm

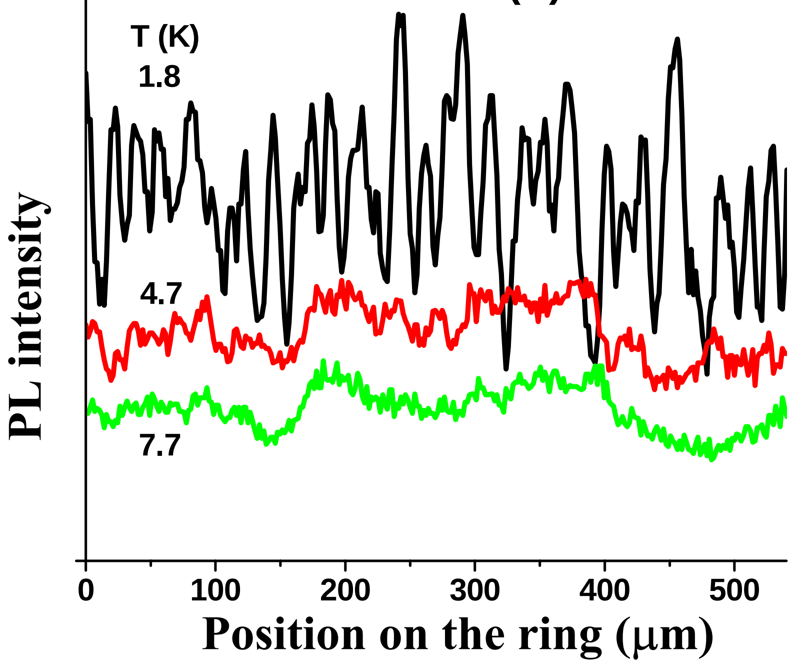
exciton state with spatial order on macroscopic lengths – macroscopically ordered exciton state

Temperature dependence of ring fragmentation into spatially ordered array of beads



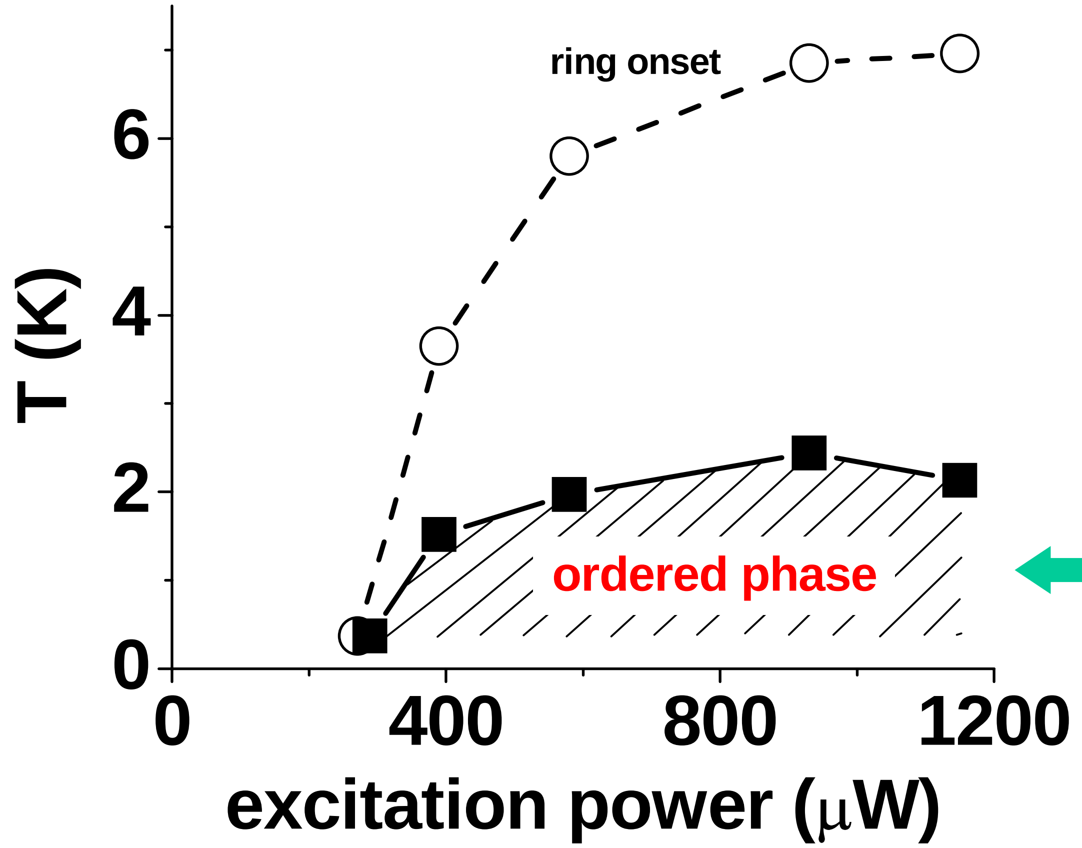






ring fragmentation into spatially ordered array of beads appears abruptly at low T

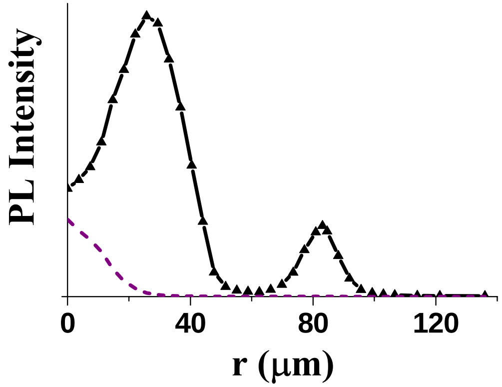
Ordered state

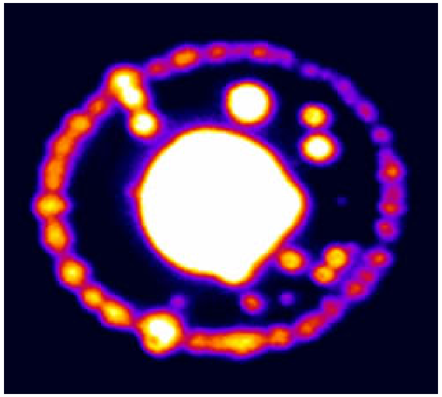


low-temperature state

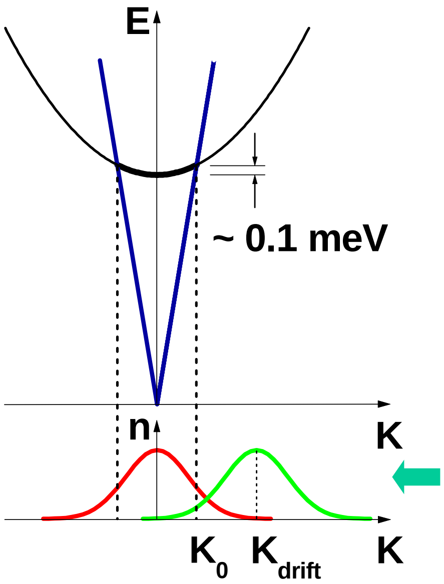
Features in exciton PL pattern

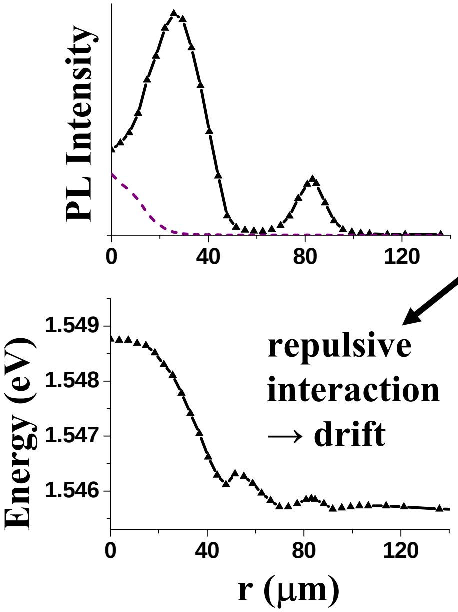
- inner rings
- external rings
- localized bright spots
- macroscopically ordered exciton phase





PL pattern ⟷ spatial distribution of optically active low energy excitons

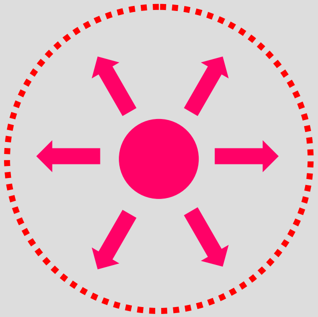




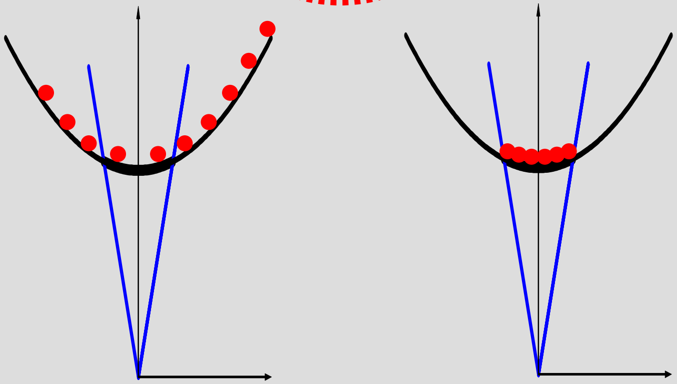
repulsive interaction → drift

origin of inner ring

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



exciton transport over tens of microns



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

<u>inner ring</u>
lower T_X
excitons relax
to radiative zone
⬇
higher occupation
of radiative zone

moving excitons are optically inactive

$K > K_0$ ➡ $v > v_s$ ➡ shock

excitons can travel in a dark state after having been excited until slowed down to a velocity below photon emission threshold, where they can decay radiatively

T_X drops outside of excitation spot
fraction of optically active excitons increases

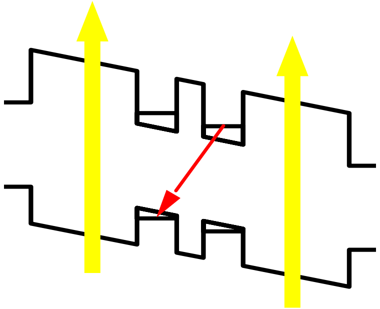
L.V. Butov, A.C. Gossard, and D.S. Chemla, cond-mat/0204482 [Nature 418, 751 (2002)]
simulations: A.L. Ivanov, unpublished

origin of external ring

off-resonance laser excitation creates
additional number of holes in CQW

↑

electrons and holes have different
collection efficiency to CQW



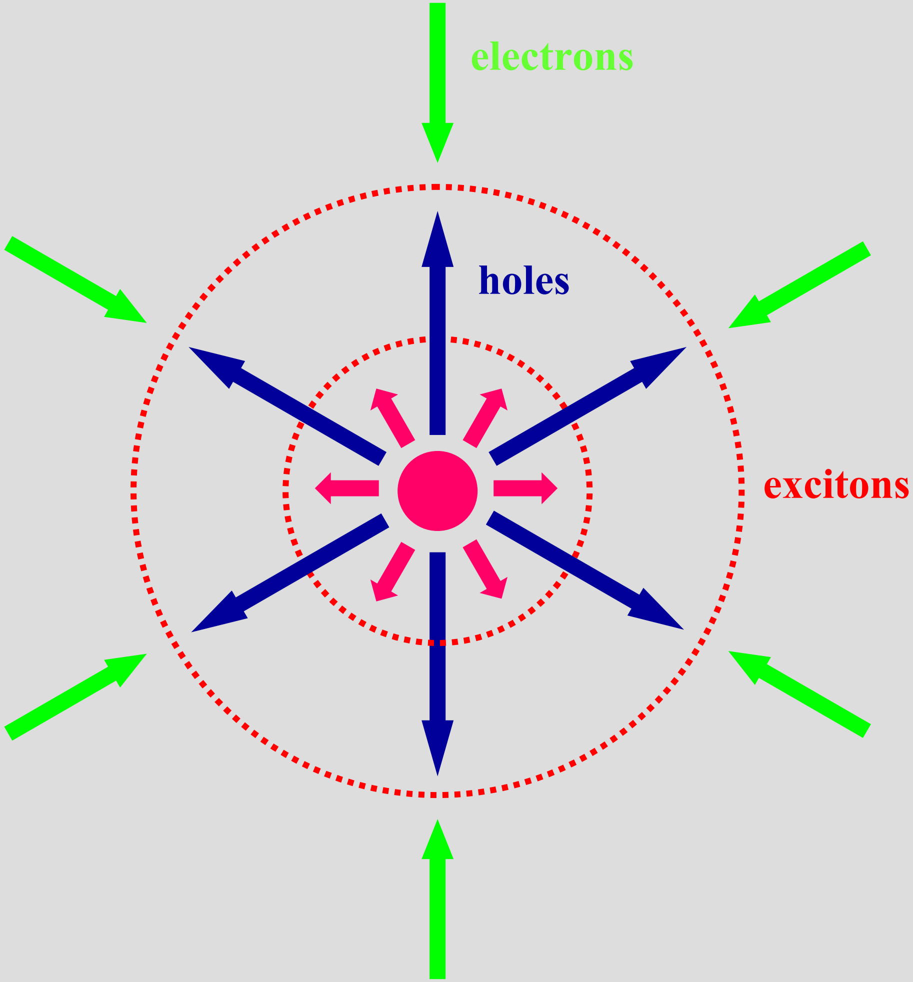
excess holes are photogenerated in the laser excitation spot

electron source is spread out over the entire plane due to current through the CQW from n-doped GaAs layers

holes created at the excitation spot diffuse out

this depletes electrons in the vicinity of the laser spot creating electron-free and hole rich region

same for
e ↔ h



excitons are generated within the external ring formed at the interface between the hole rich region and the outer electron rich area

L.V. Butov, L.S. Levitov, B.D. Simons, A.V. Mintsev, A.C. Gossard, D.S. Chemla, cond-mat/0308117 [PRL 92, 117404 (2004)]
R. Rapaport, G. Chen, D. Snoke, S.H. Simon, L. Pfeiffer, K.West, Y.Liu, S.Denev, cond-mat/0308150 [PRL 92, 117405 (2004)]

Expansion of the ring with increasing P_{ex}

an increase of P_{ex}
increases hole density in CQW

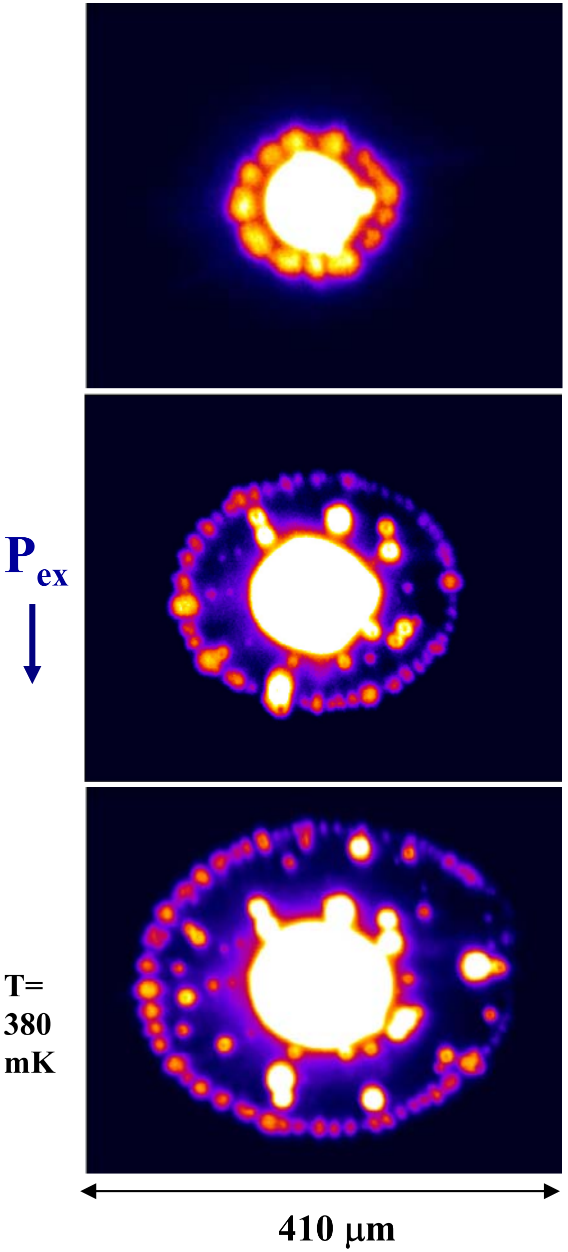
$$\dot{n} = D\Delta n - \gamma np + J(r)$$

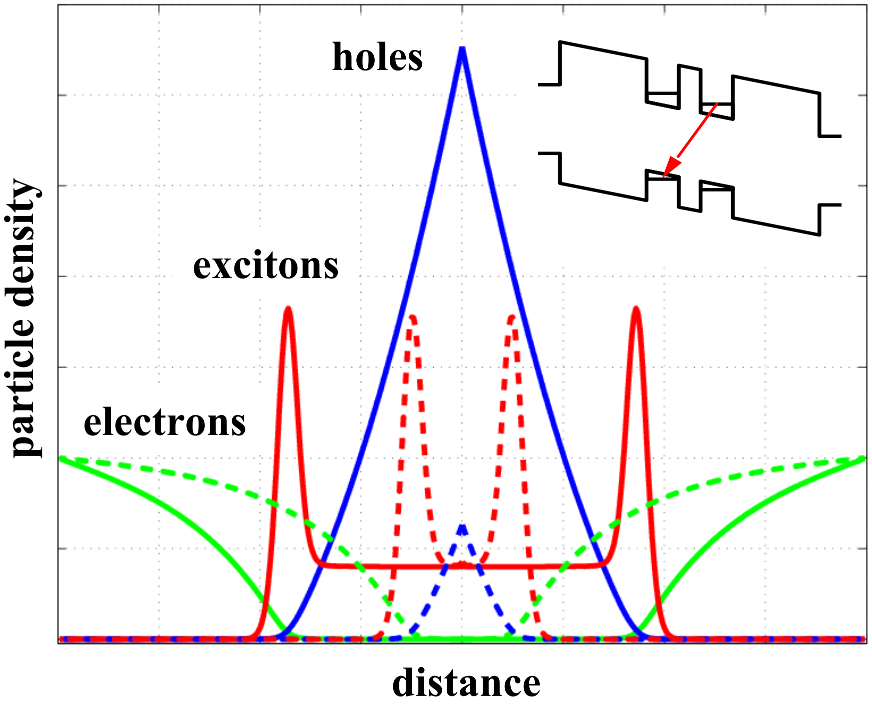
$$\dot{p} = D'\Delta p - \gamma np + J'(r)$$

$$J(r) = I(r) - a(r)n(r)$$

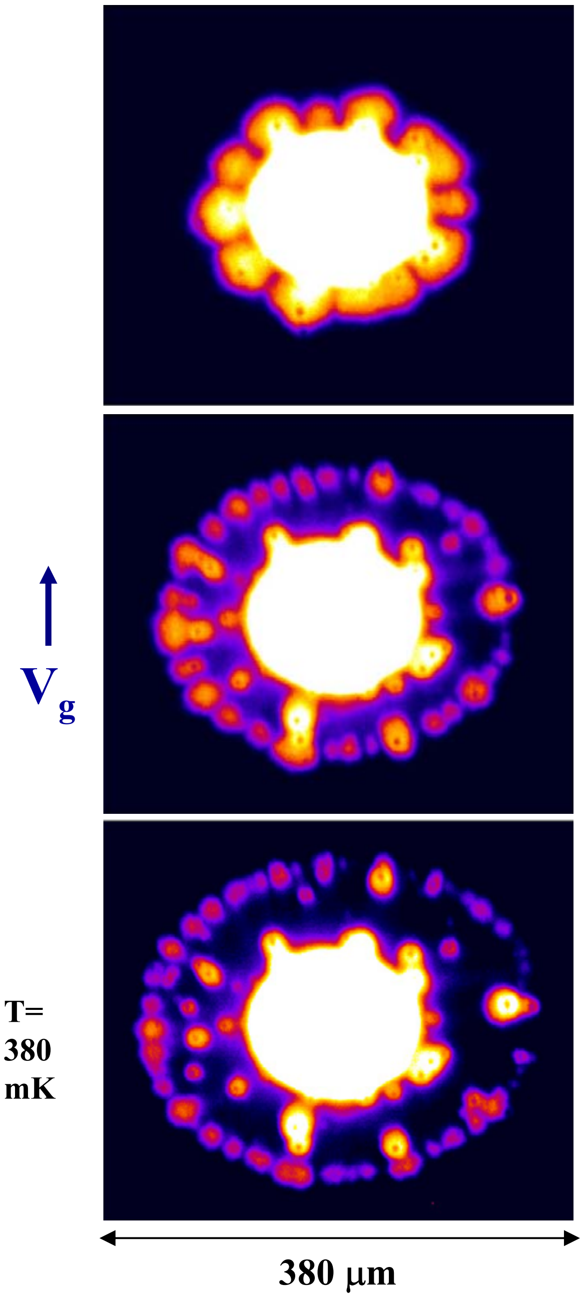
$$J'(r) = P_{ex}\delta(r)$$

$$n_X \propto np$$





optical control of the ring by excitation intensity



Shrinkage of the ring with increasing gate voltage

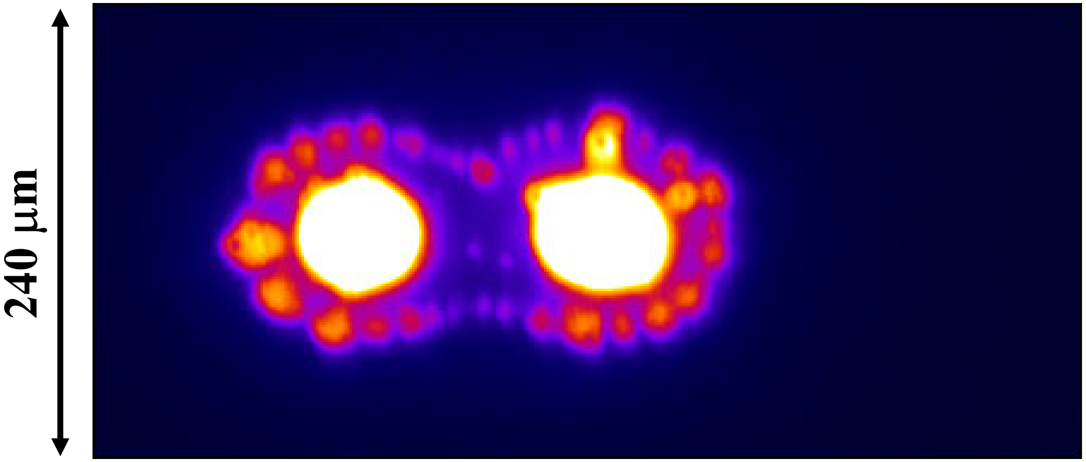
⬆

an increase of gate voltage
increases electron density in CQW

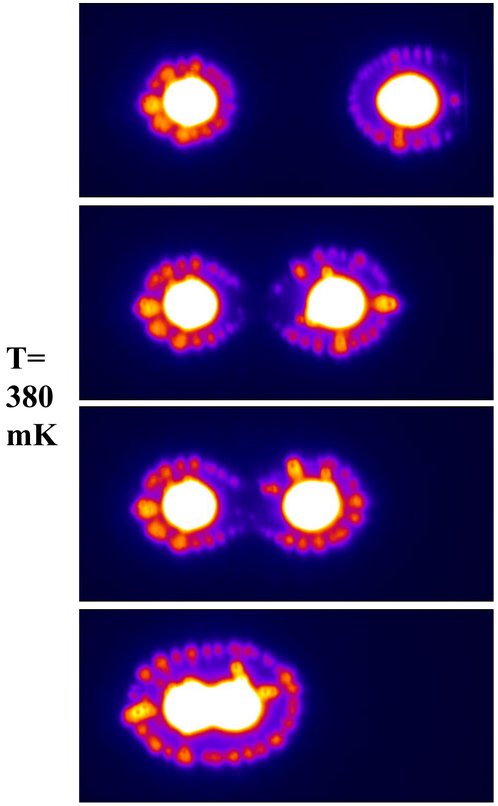
$$\dot{n} = D\Delta n - \gamma np + J(r)$$
$$\dot{p} = D'\Delta p - \gamma np + J'(r)$$
$$J(r) = \underline{I(r)} - a(r)n(r)$$
$$J'(r) = P_{ex}\delta(r)$$
$$n_X \propto np$$

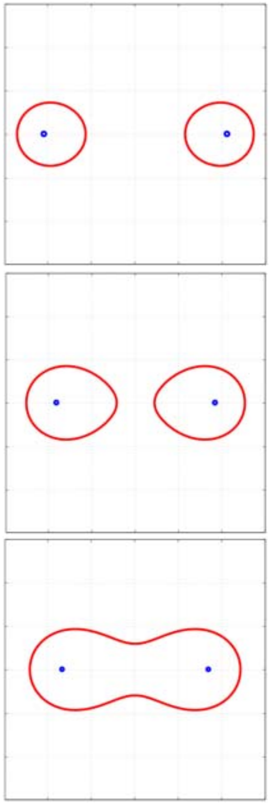
electronic control of the ring
by external gate voltage

Interaction of two exciton rings



do not mix with attractive exciton-exciton interaction!





rings attract one another at large distances

↕

the existence of “dark matter” outside the rings that mediates the interaction

↑

electron flow outside each ring which is perturbed by the presence of another ring

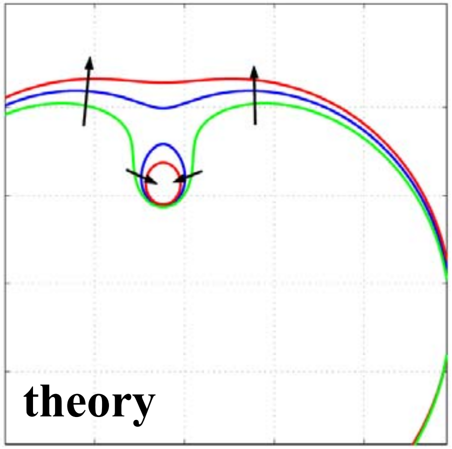
electrons in the area between the rings are depleted more strongly

↓

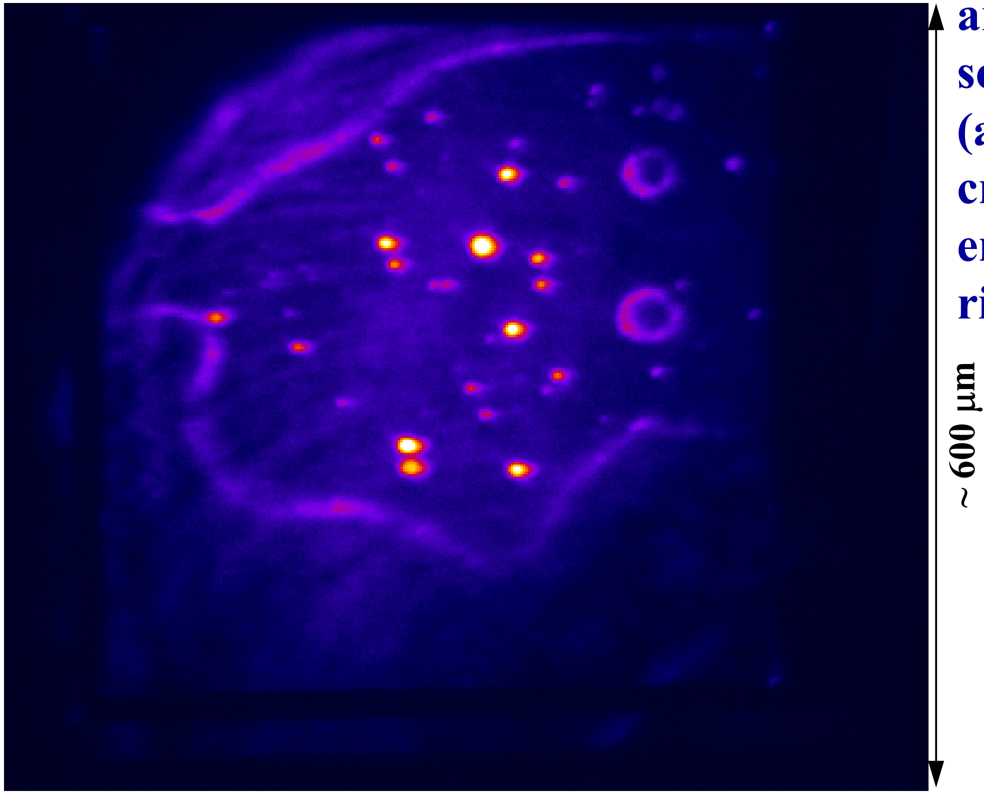
attraction of the rings

Collapse of rings to localized bright spots

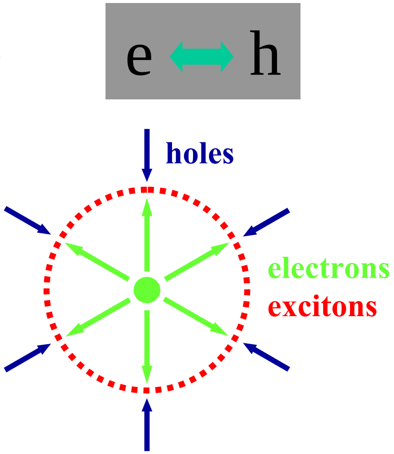
collapse of exciton rings to localized bright spots ("stars") with increasing P_{ex}

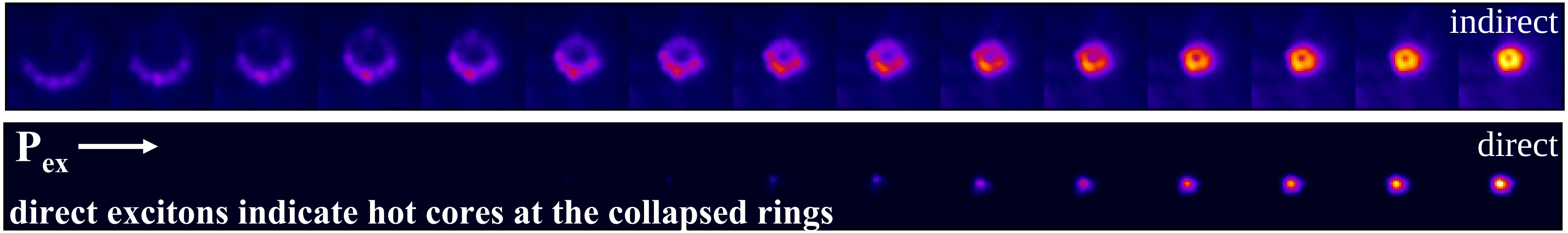


2D image of indirect exciton PL vs P_{ex}



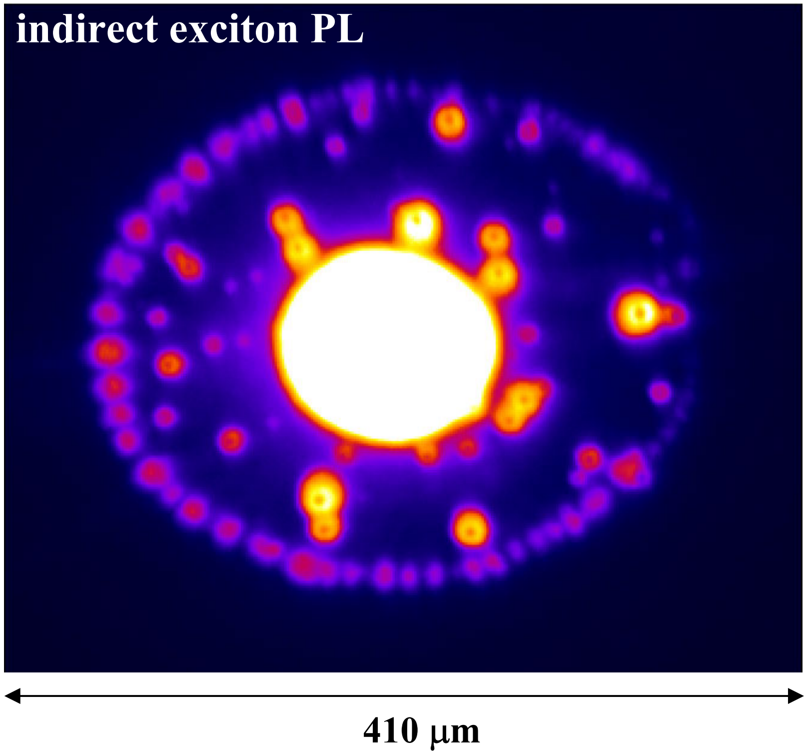
localized bright spots are due to localized sources of electrons (at current filaments crossing CQW) embedded in the hole rich illuminated area

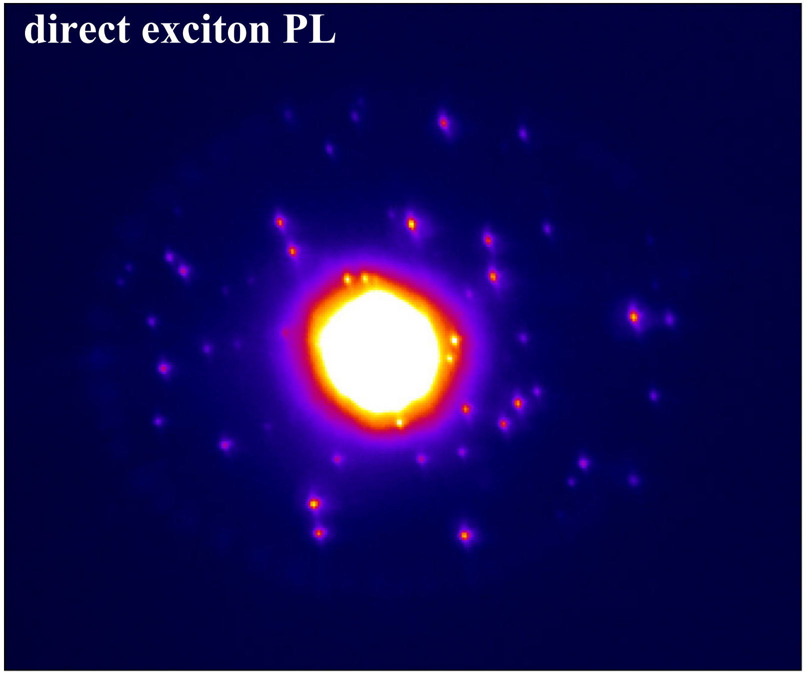




direct excitons indicate hot cores at the collapsed rings

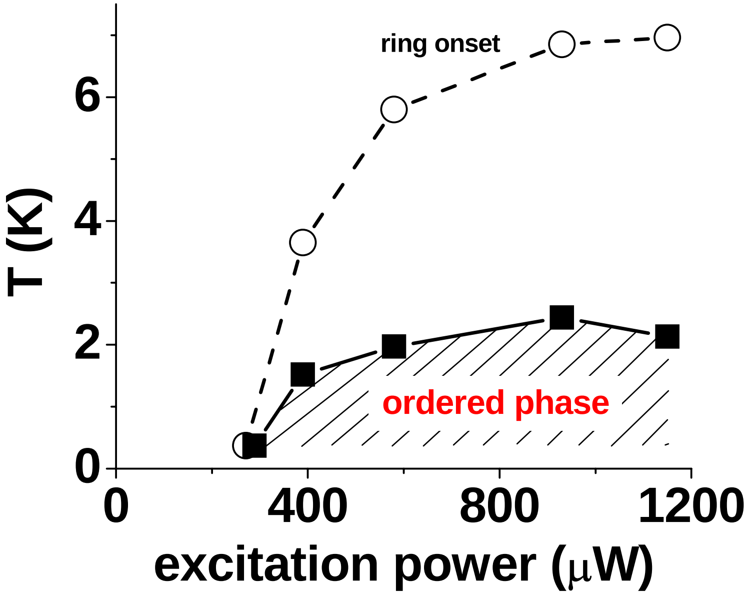
Ordered state





aggregates on the ring have no hot cores contrary to bright spots generated by the pinholes

aggregates move in concert with the ring when the position of the source is adjusted showing further that in-plane potential fluctuations are not strong enough to destroy the ordering



excitons in external ring are formed from well-thermalized carriers

heating sources in the ring - the binding energy released at exciton formation

due to long lifetimes of indirect excitons the heating has little effect on their temperature

the rings represent a source of cold excitons with temperature close to $T_{lattice}$

in external ring exciton gas is the coldest

macroscopically ordered exciton state

new state, not predicted

origin of ordered exciton state - ?

macroscopically ordered phases can be both in
quantum (e.g. atom BEC)
and classical (e.g. Taylor vortices) systems

the macroscopically ordered phase appears abruptly at low temperatures

is observed in the same temperature range as bosonic stimulation of exciton scattering (coincidence?)

statistically degenerate Bose-gas of excitons

note that the experiments on pattern formation
and PL kinetics were done at different geometries
direct comparison is not available yet

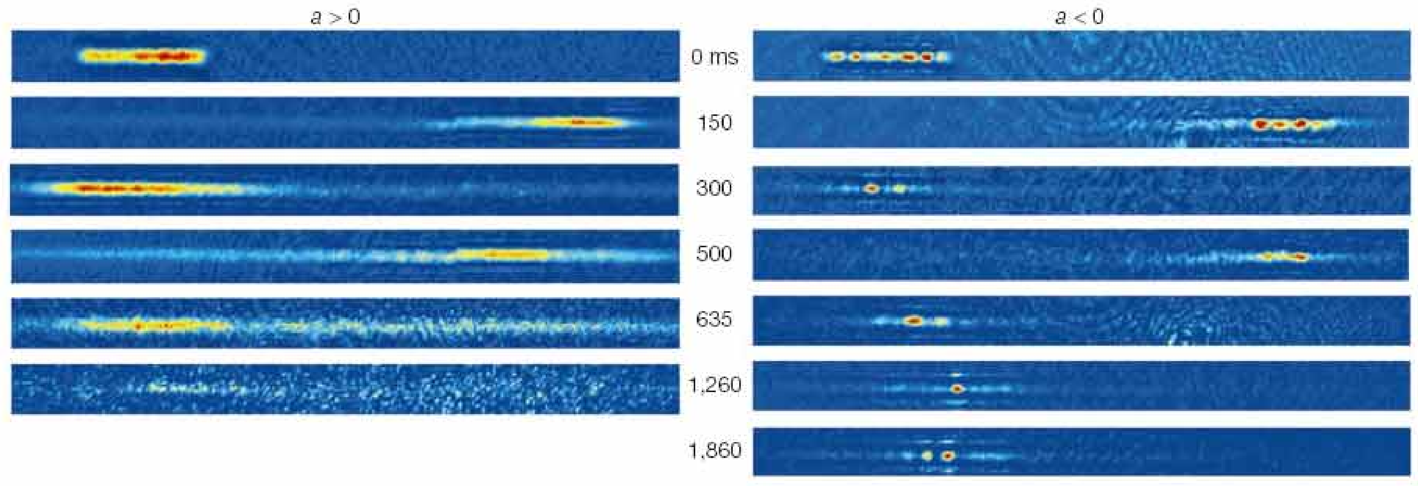
Similarities with known phenomena: Modulational instabilities

stationary solutions to 1D nonlinear Schrodinger equation under periodic boundary conditions ← on a ring

↓

stationary soliton trains

experimental example:
soliton train in atom BEC with attractive interaction
K.E. Strecker, G.B. Partridge, A.G. Truscott, R.G. Hulet, Nature 417, 150 (2002)



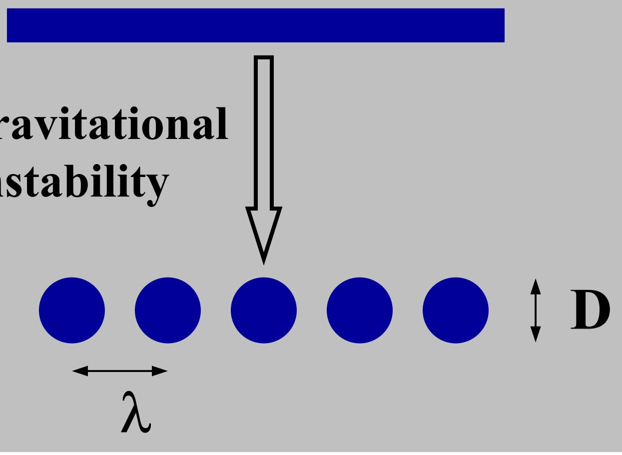
soliton train
is observed
below T_c only
↕
intrinsic
property of
atom BEC

repulsion between beads of soliton train is wave interference phenomenon

attractive interaction
for indirect excitons ?
positive feedback ?

Similarities in astrophysics ⟷ as far from BEC as possible

S. Chandrasekhar and E. Fermi (1953)
<u>gravitational instability</u> of an infinite cylinder:
the cylinder is unstable for all modes of deformation with wavelengths exceeding a certain critical value



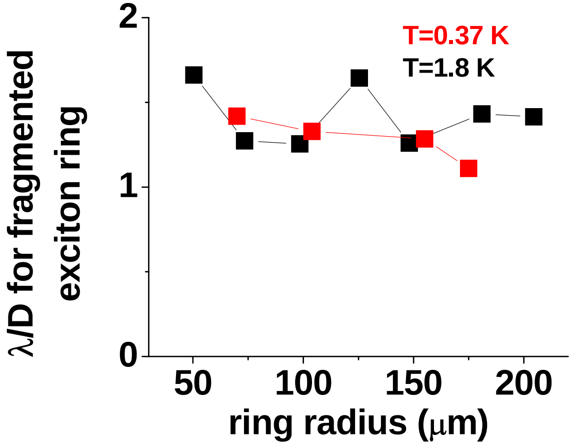
infinite cylinder

gravitational instability

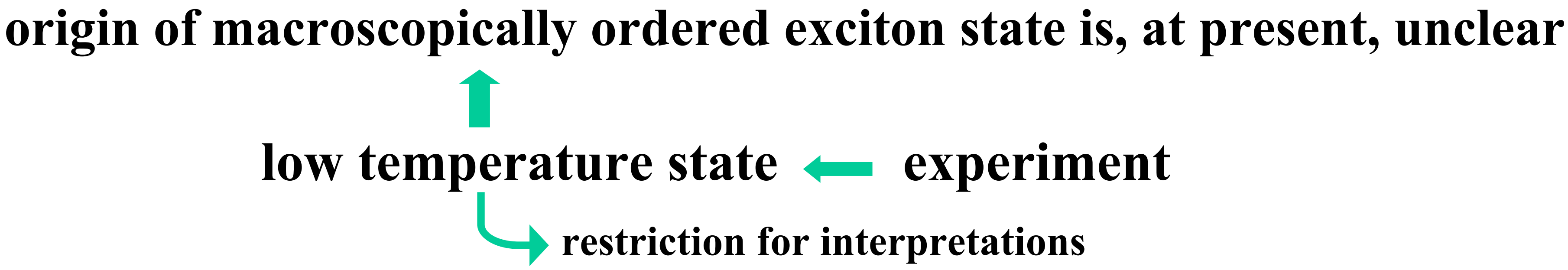
fragmentation of the cylinder

for the mode of maximum instability $\lambda \sim \pi D$

fragmentation of gaseous slabs and filaments
⇩
step in star formation



attractive interaction for indirect excitons ?
positive feedback ?



origin of macroscopically ordered exciton state is, at present, unclear

low temperature state ← experiment

restriction for interpretations