Condensation and pattern formation in cold exciton gases

L.V. Butov[1,2], L.S. Levitov[3], A.V. Mintsev[1,2], B.D. Simons[4], A.L. Ivanov[5], A. Imamoglu[6], P.B. Littlewood[4], Y.E. Lozovik[7], A.A. Shashkin[1], V.T. Dolgopolov[1], K.L. Campman[6], A.C. Gossard[6], D.S. Chemla[2,8]

[1] Institute of Solid State Physics RAS, Chernogolovka
[2] E.O. Lawrence Berkeley National Laboratory
[3] MIT
[4] Cavendish Laboratory, Cambridge
[5] Cardiff University
[6] University of California at Santa Barbara
[7] Institute of Spectroscopy RAS, Troitsk
[8] University of California at Berkeley

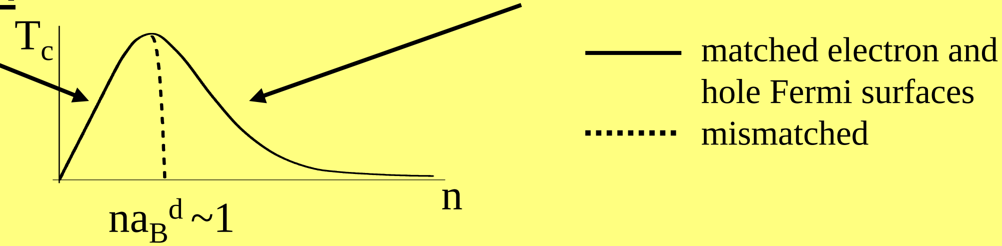
Work supported by the Office of Energy Research, Office of Basic Energy Sciences, Division of Material Sciences of the U. S. DoE

and by Russian Foundation of Basic Research

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

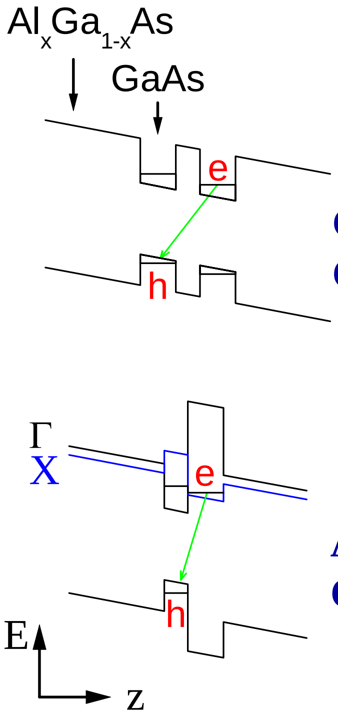
Kelvin for excitons ⇕ microKelvin for atoms

how to get cold exciton gas?

$T_{lattice} \ll 1$ K in He refrigerators
finite lifetime of excitons could result to high exciton temperature: $T_X > T_{lattice}$
T_X is determined by the ratio of the exciton lifetime and cooling time

lifetime >> cooling time ⟹ $T_X \sim T_{lattice}$

Why indirect excitons in CQWs?



GaAs/AlGaAs CQW

AlAs/GaAs CQW

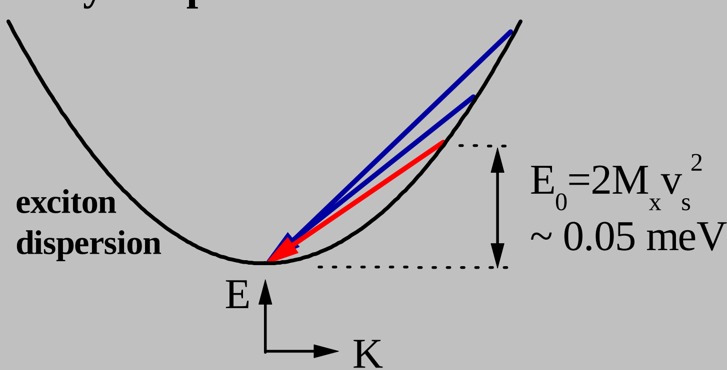
<u>long exciton lifetime</u> due to separation between electron and hole layers

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

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

potential candidate for realization of exciton condensation

exciton energy relaxation by LA-phonon emission



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

$< T_c$ << lifetime

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

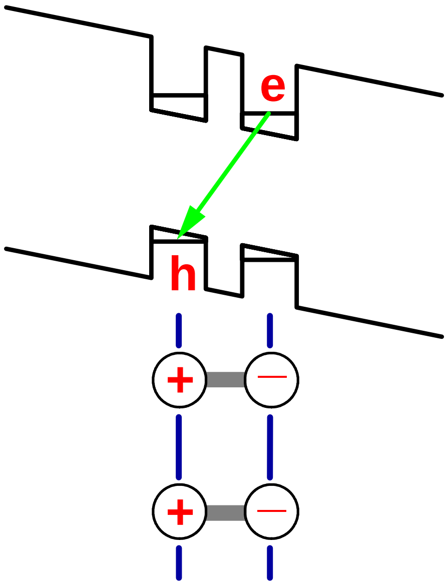
discrimination in time

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

discrimination in space

study indirect excitons excitons beyond photoexcitation spot

Repulsive interaction between indirect excitons



indirect excitons are oriented dipoles

<u>dipole-dipole repulsive interaction</u>

stabilizes exciton state against formation of metallic electron-hole droplets

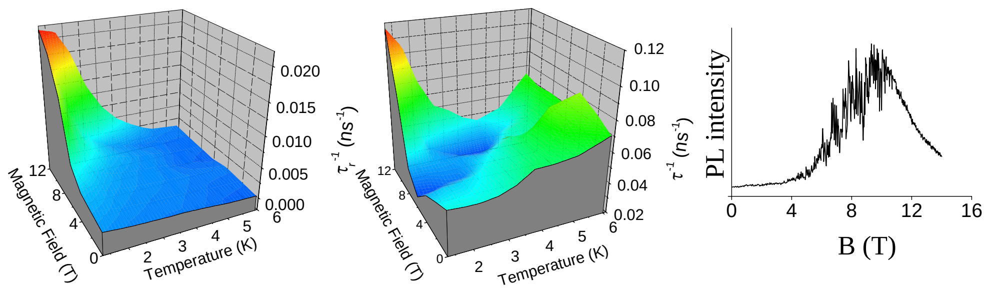
D. Yoshioka, A.H. MacDonald, J. Phys. Soc. Jpn. 59, 4211 (1990)
X. Zhu, P.B. Littlewood, M. Hybertsen, T. Rice, PRL 74, 1633 (1995)

the ground state of the system is excitonic

results in effective screening of in-plane disorder

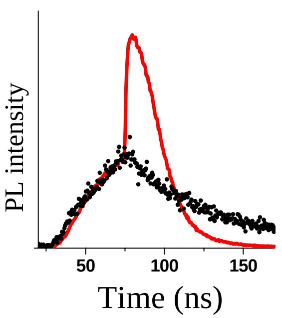
A.L. Ivanov, EPL (2002)

Experiments on exciton condensation in CQW nanostructures



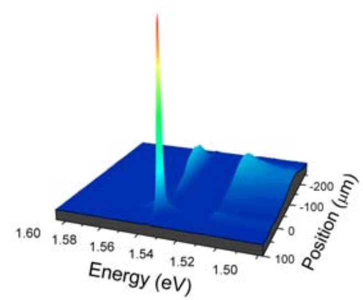
effects indicating exciton condensate superradiance (macroscopic dipole), onset of exciton superfluidity, and fluctuations near phase transition

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



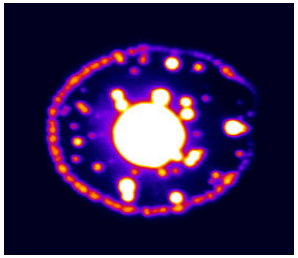
bosonic stimulation of exciton scattering - signature of degenerate Bose-gas of excitons

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)



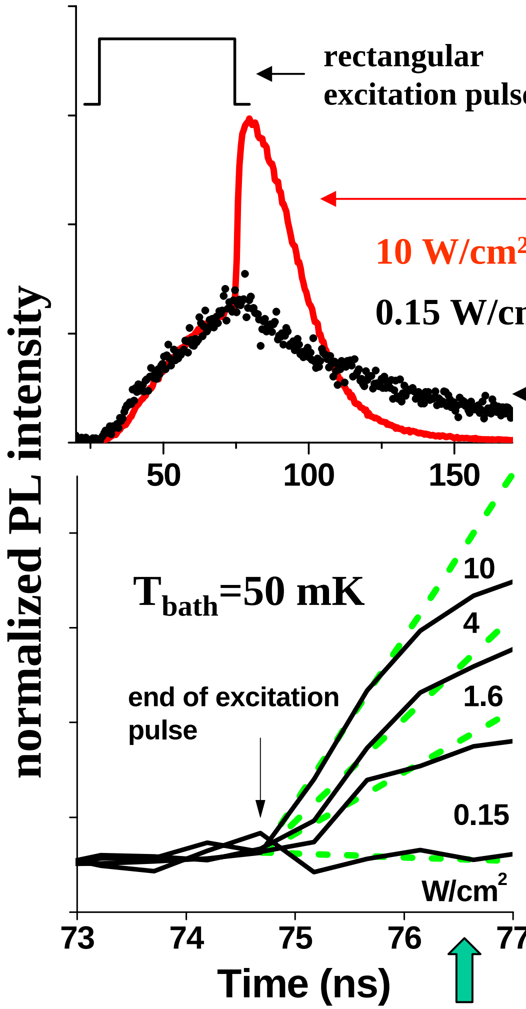
macroscopically ordered exciton state

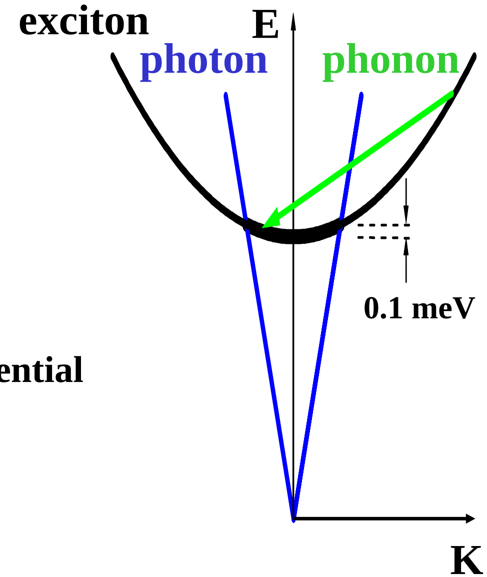
Butov et al. Nature, 418, 751 (2002)

difference between quasi-condensate – macroscopic occupation of low energy states and BEC – macroscopic occupation of ground state – is not essential for most experiments [V.N. Popov (1972)] and unambiguous distinguishing between them in experiments is hard (if possible)

http://www.lbl.gov/~butov/
http://www.issp.ac.ru/butov/

Bosonic stimulation of exciton scattering

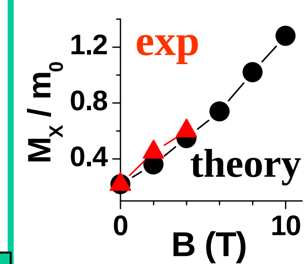




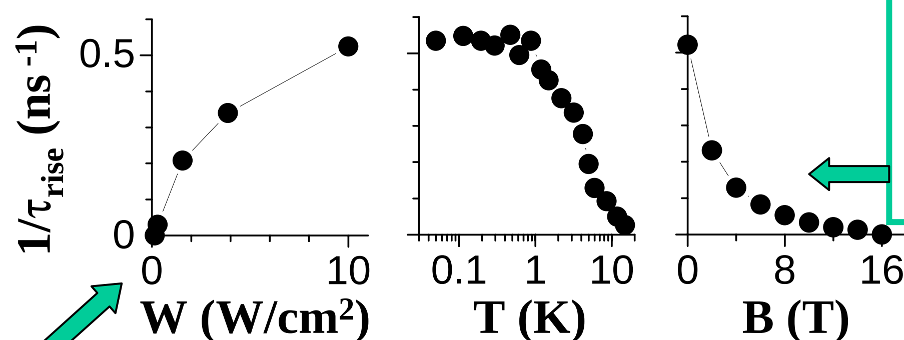
exciton PL kinetics

occupation kinetics of optically active exciton states

exciton mass is controlled in situ



PRL 87, 26804 (2001)



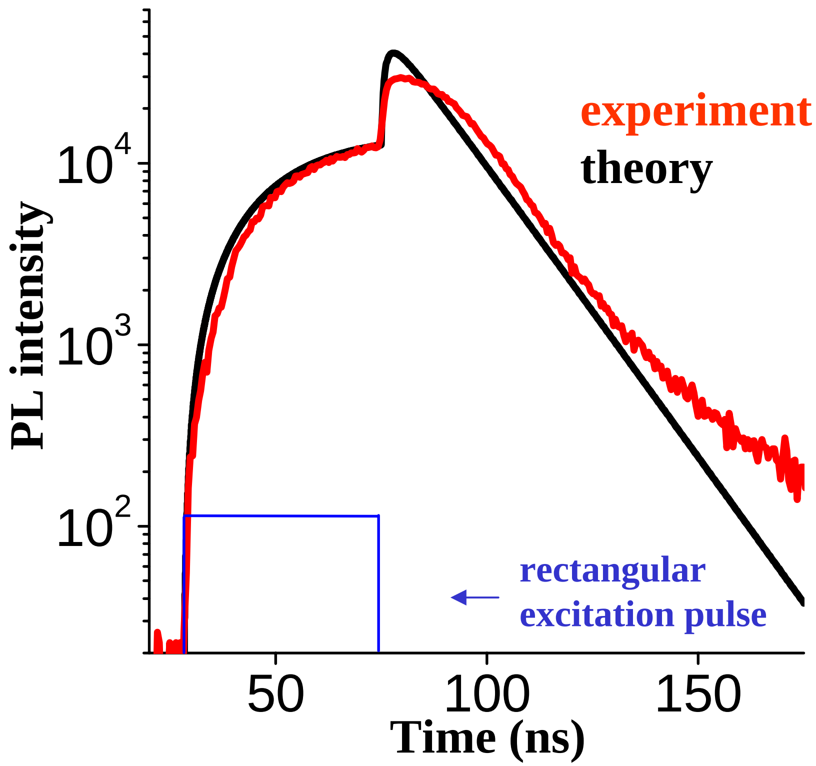
enhancement of exciton scattering rate to low energy states with increasing exciton concentration reveals <u>bosonic stimulation of exciton scattering</u>

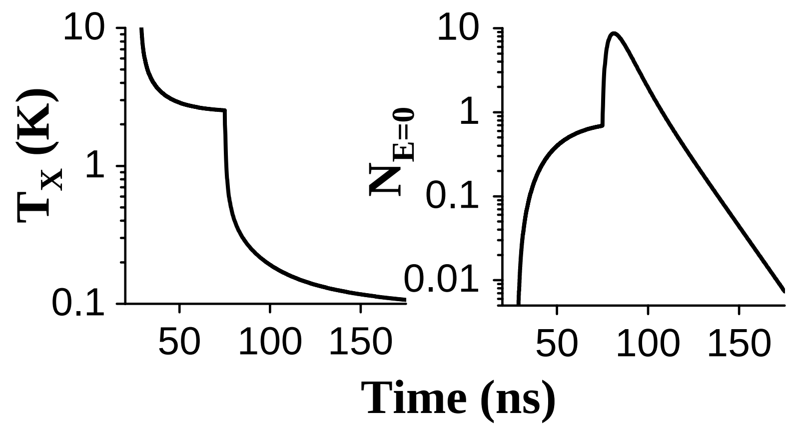
signature of <u>degenerate Bose-gas of excitons</u>

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





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

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

temperature of quantum degeneracy

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

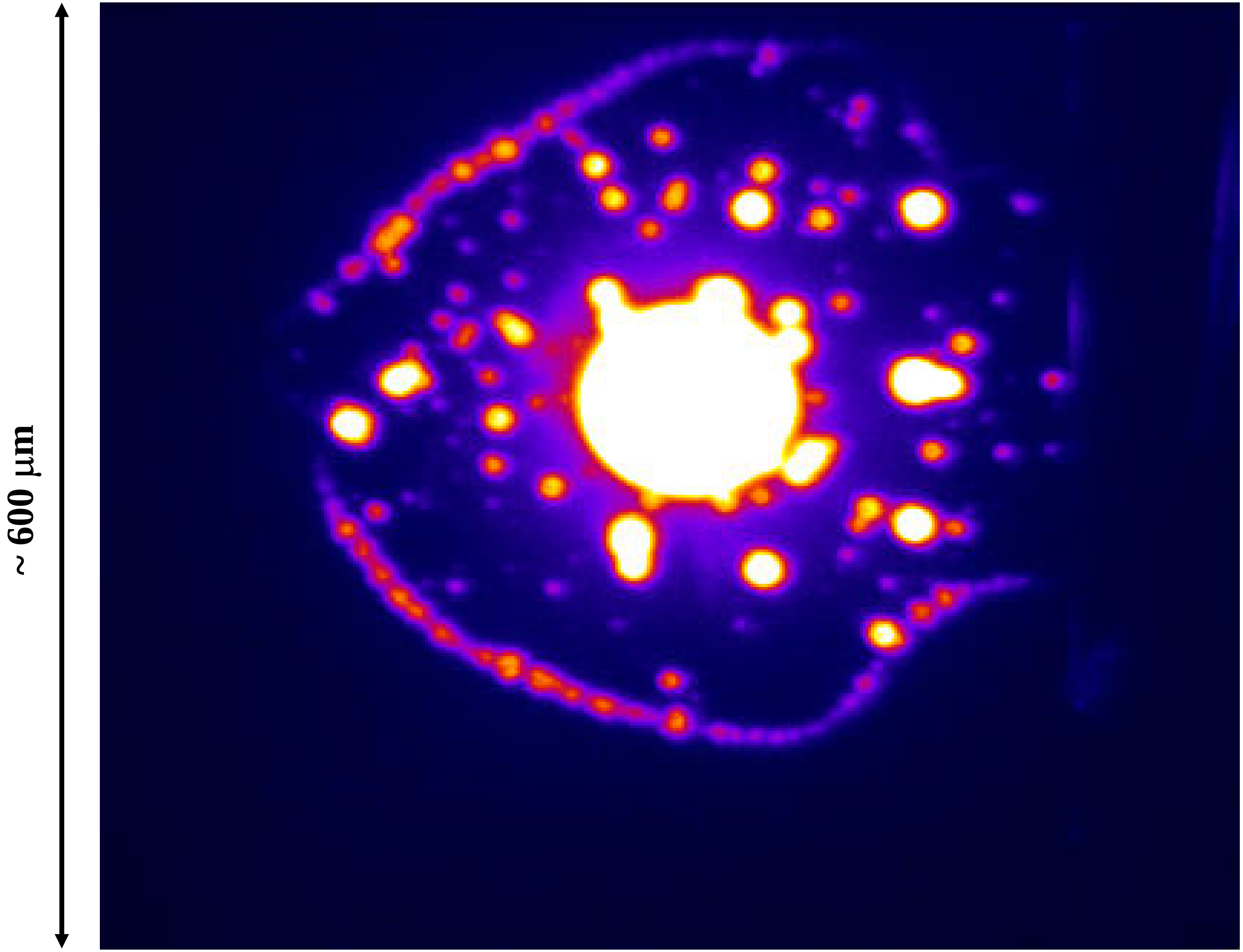
$$= \Gamma_{ph} (N_E - n_E^{ph}) N_{E=0} + \Gamma_{ph} (1 + n_E^{ph}) N_E - N_{E=0} / \tau$$

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

$N_E - n_E^{ph} > 0$

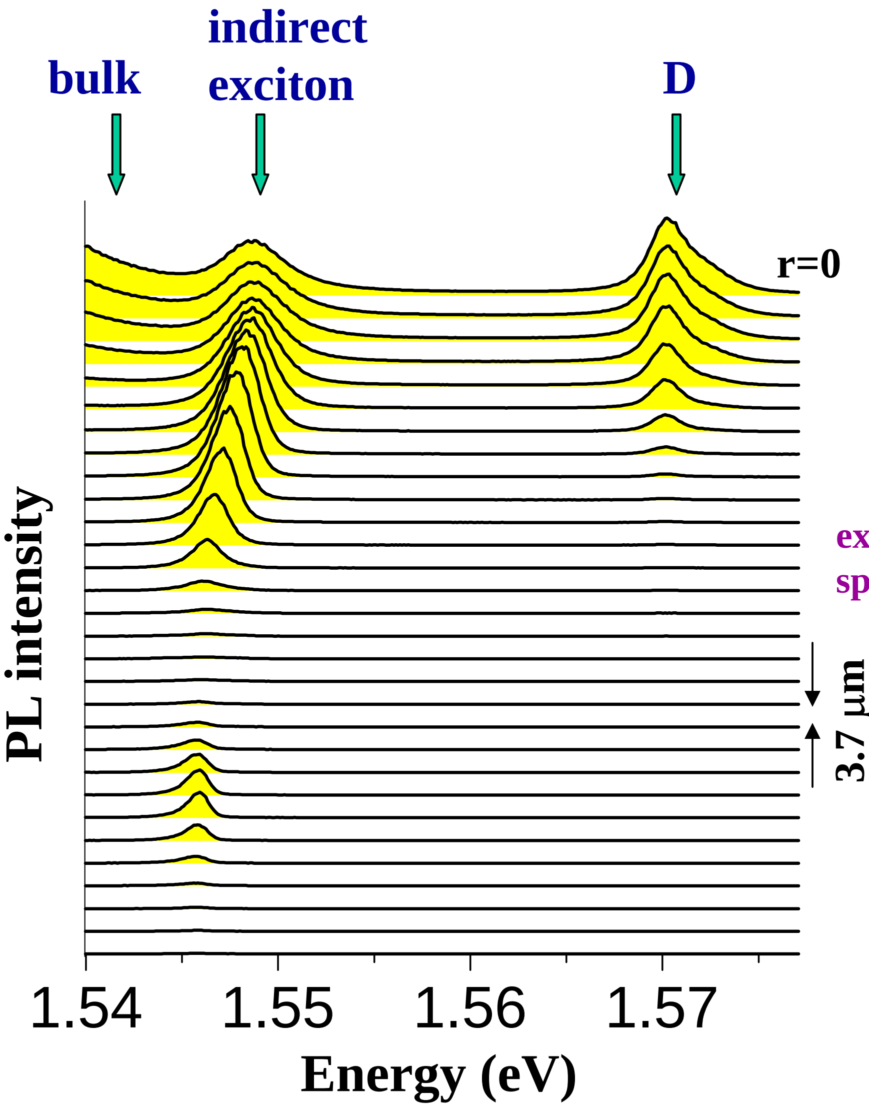
Frolich inversion condition counterpart of population inversion condition for lasers

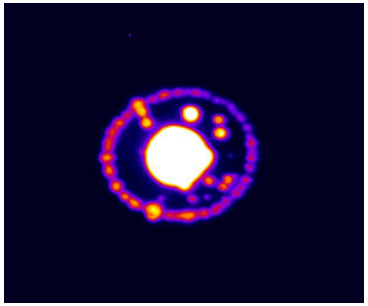
2D image of indirect exciton PL vs P_{ex}

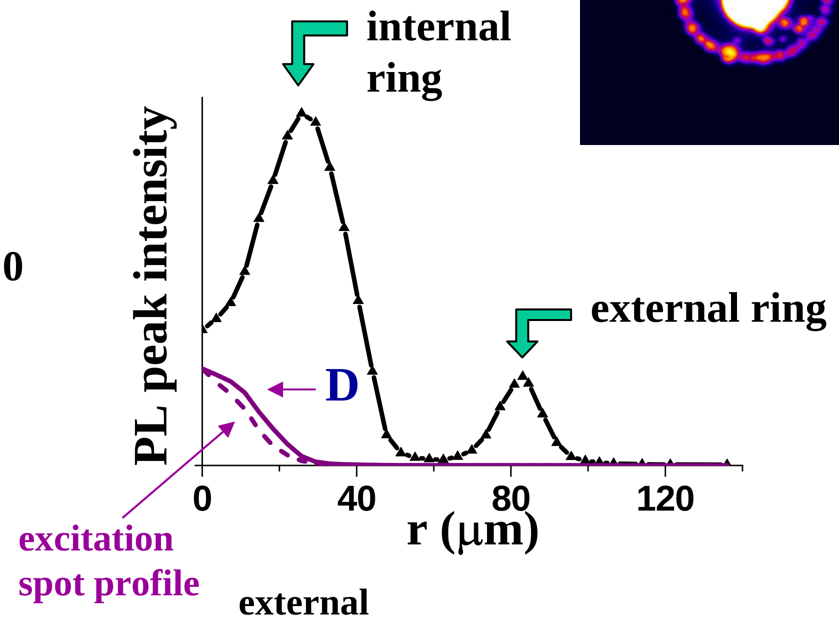


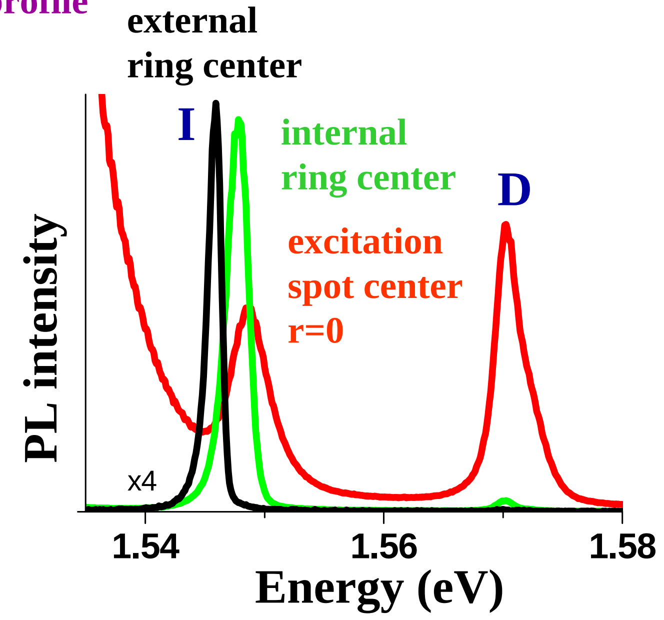
L.V. Butov, A.C. Gossard, and D.S. Chemla, cond-mat/0204482 [Nature 418, 751 (2002)]

Radial dependence of indirect exciton PL

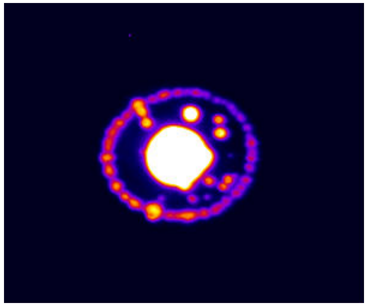


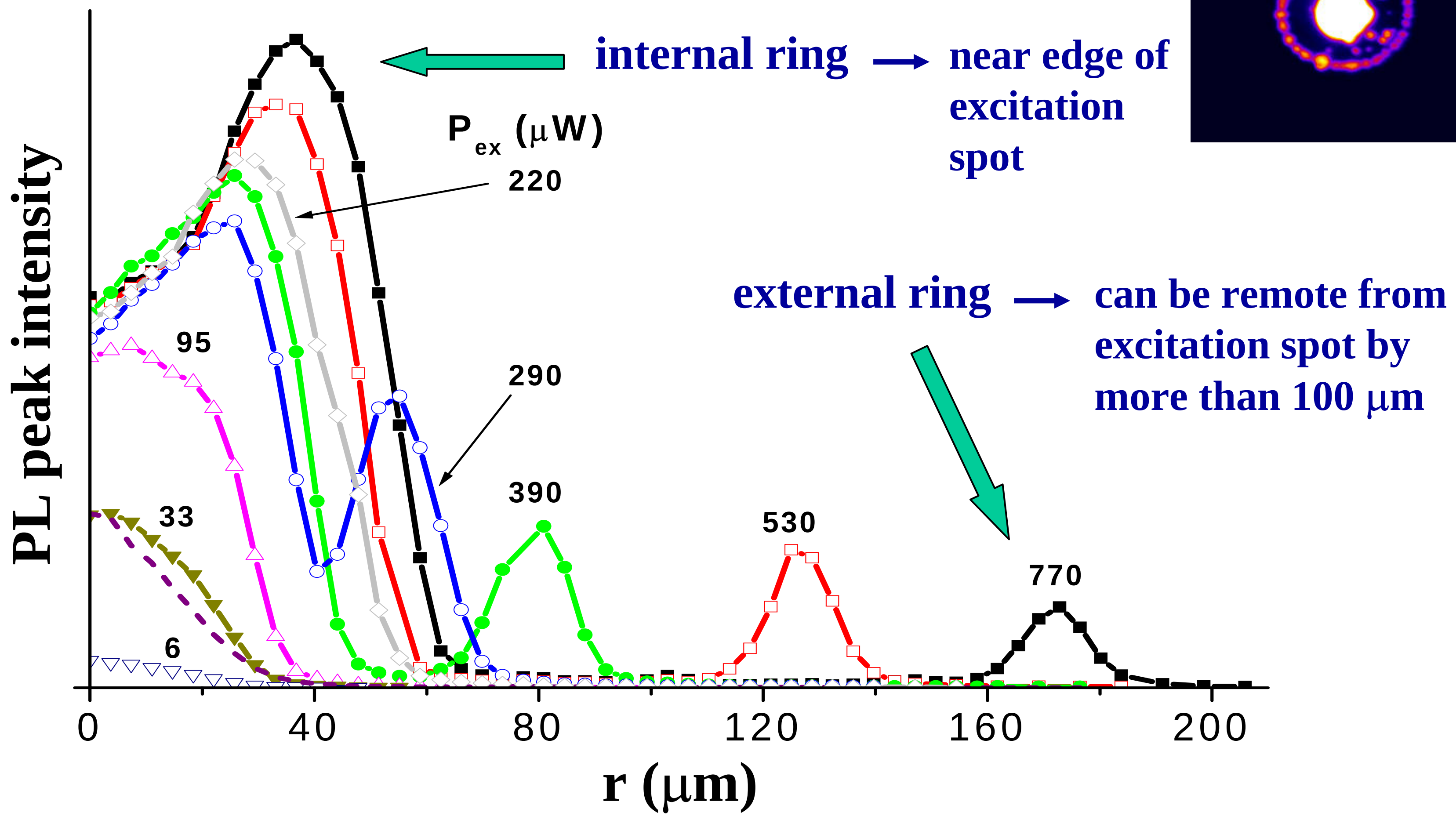






Ring structure of indirect exciton PL

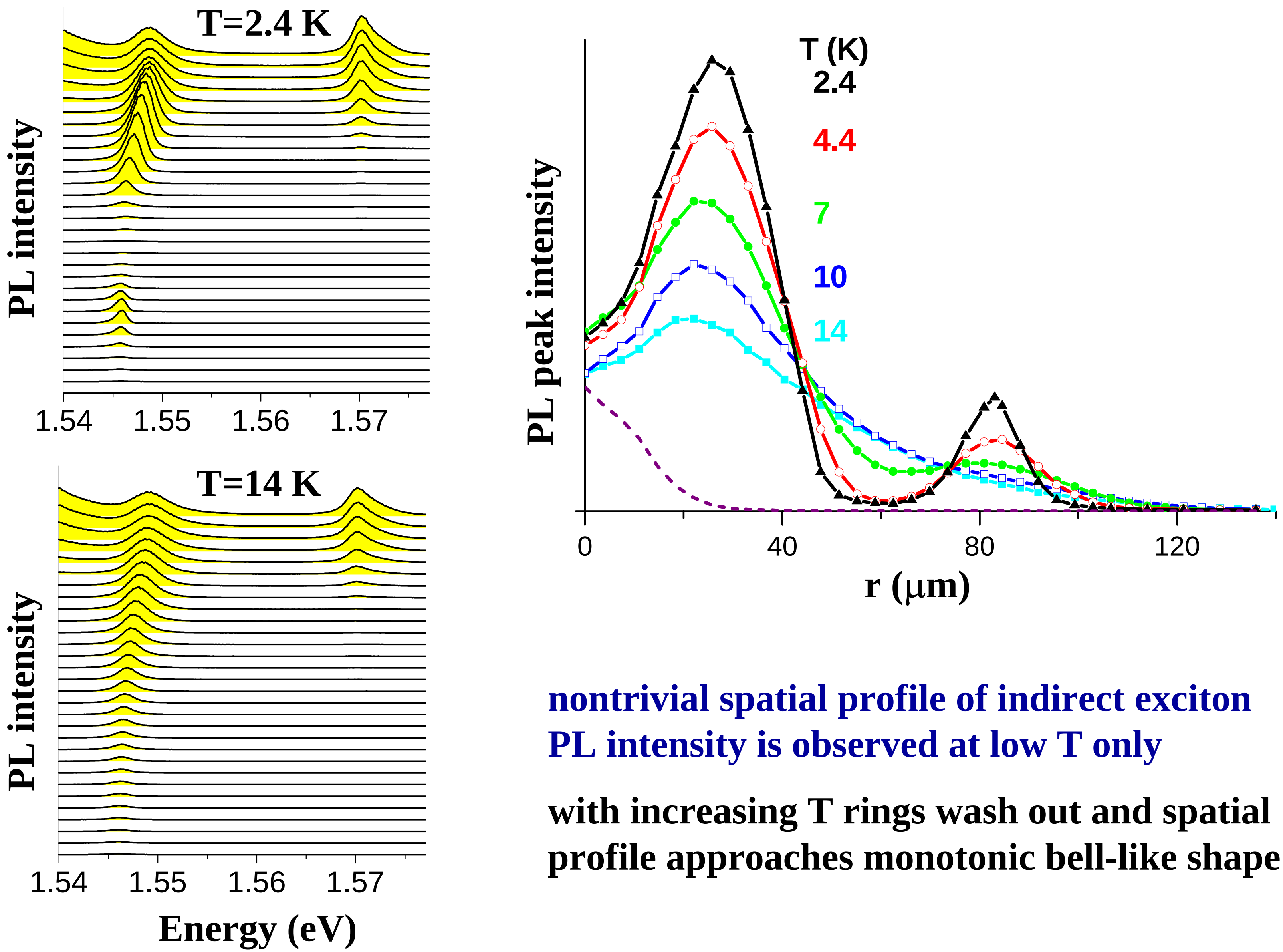




at low densities:
spatial profile of indirect exciton PL intensity follows laser excitation intensity

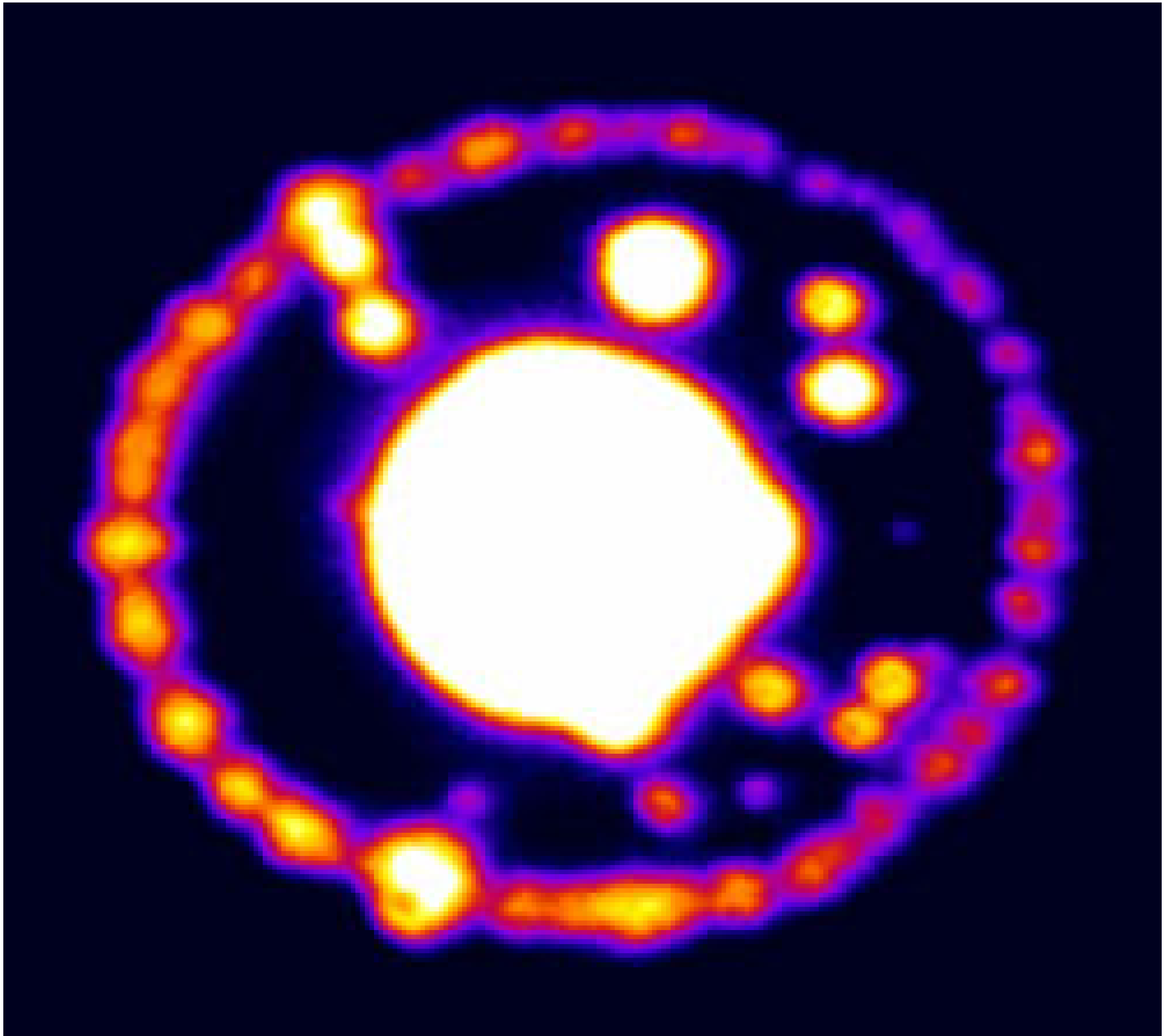
at high densities:
spatial profile of indirect exciton PL intensity is nontrivial ← ring structure

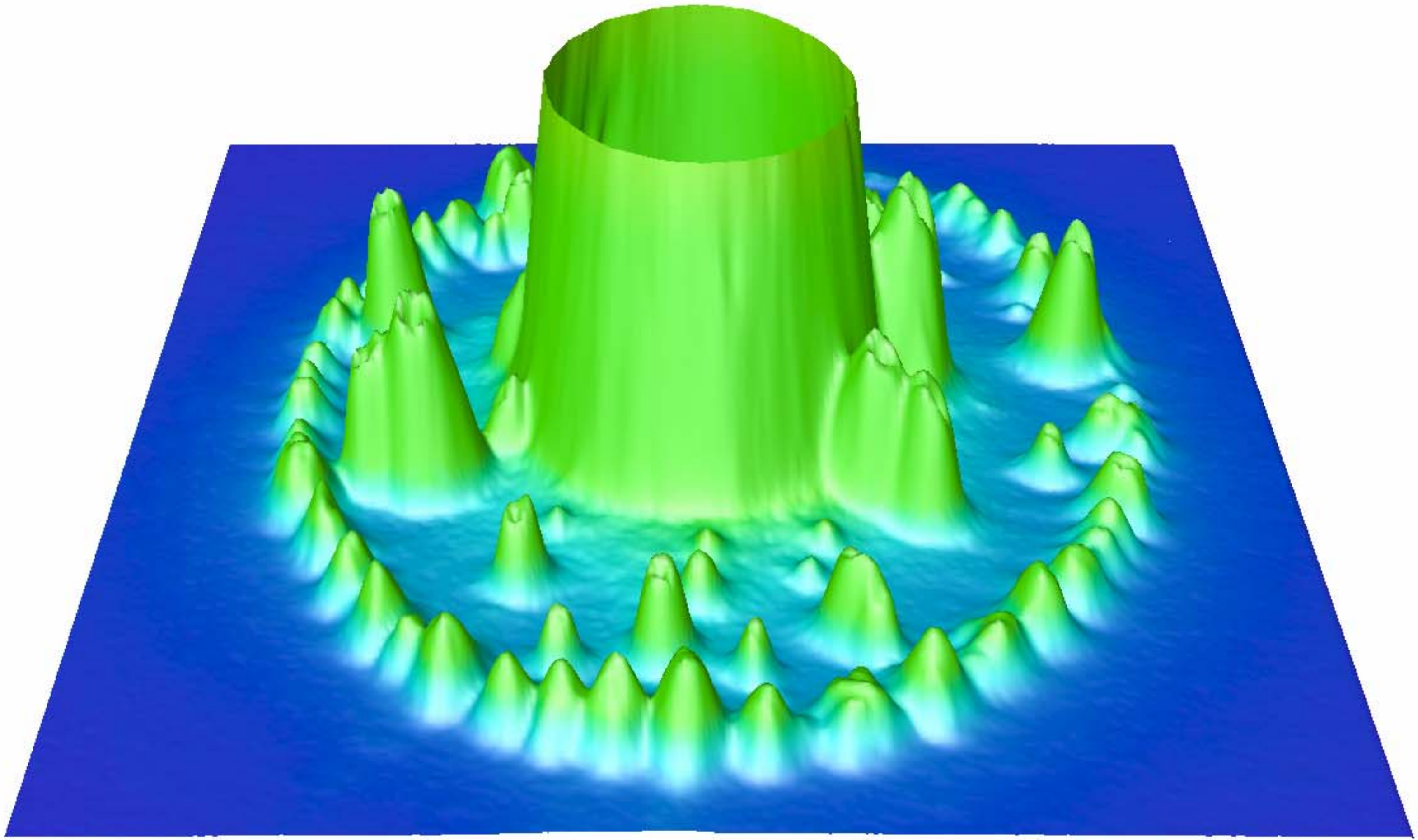
Temperature dependence of ring-shaped PL structure



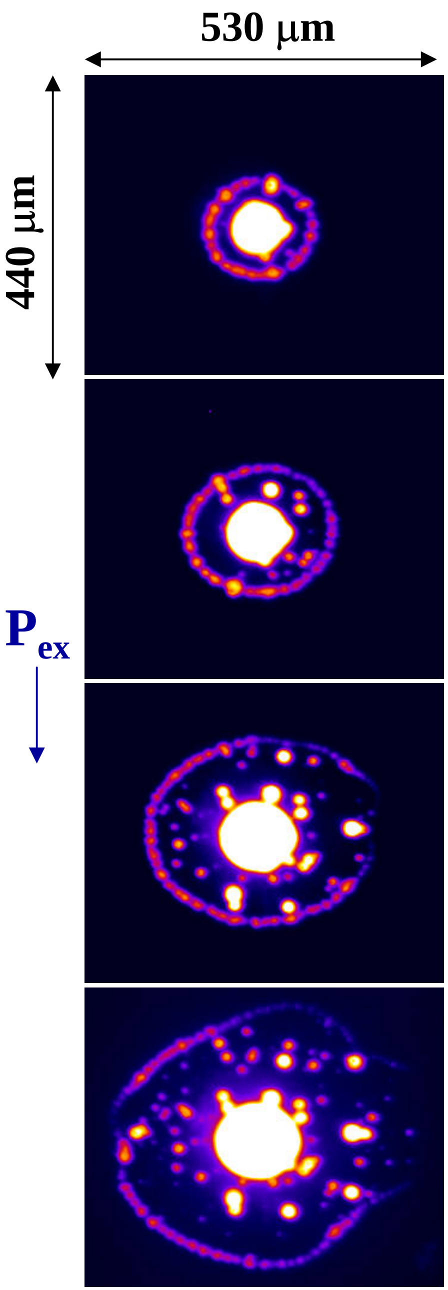
nontrivial spatial profile of indirect exciton PL intensity is observed at low T only

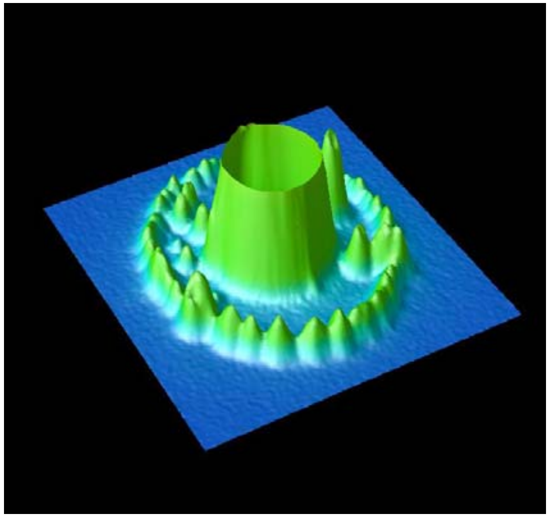
with increasing T rings wash out and spatial profile approaches monotonic bell-like shape

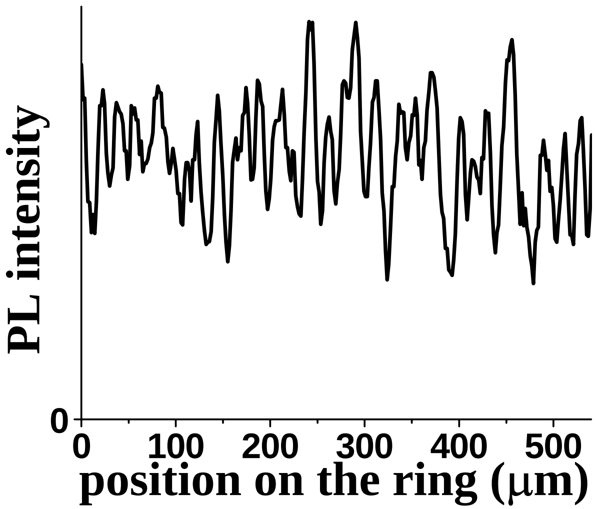


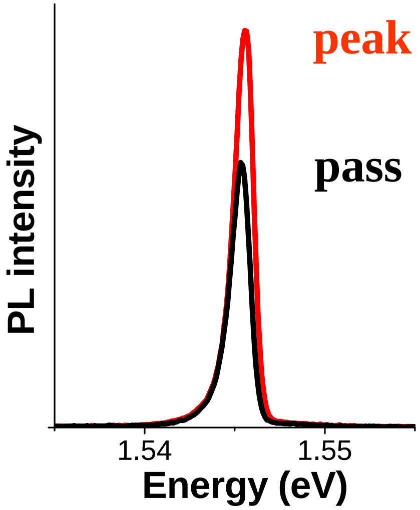


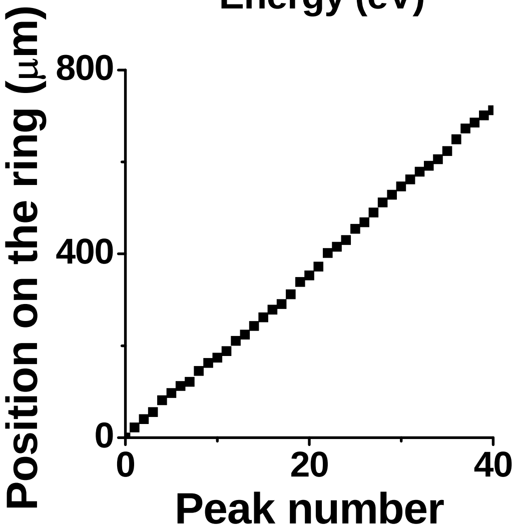
Ring fragmentation





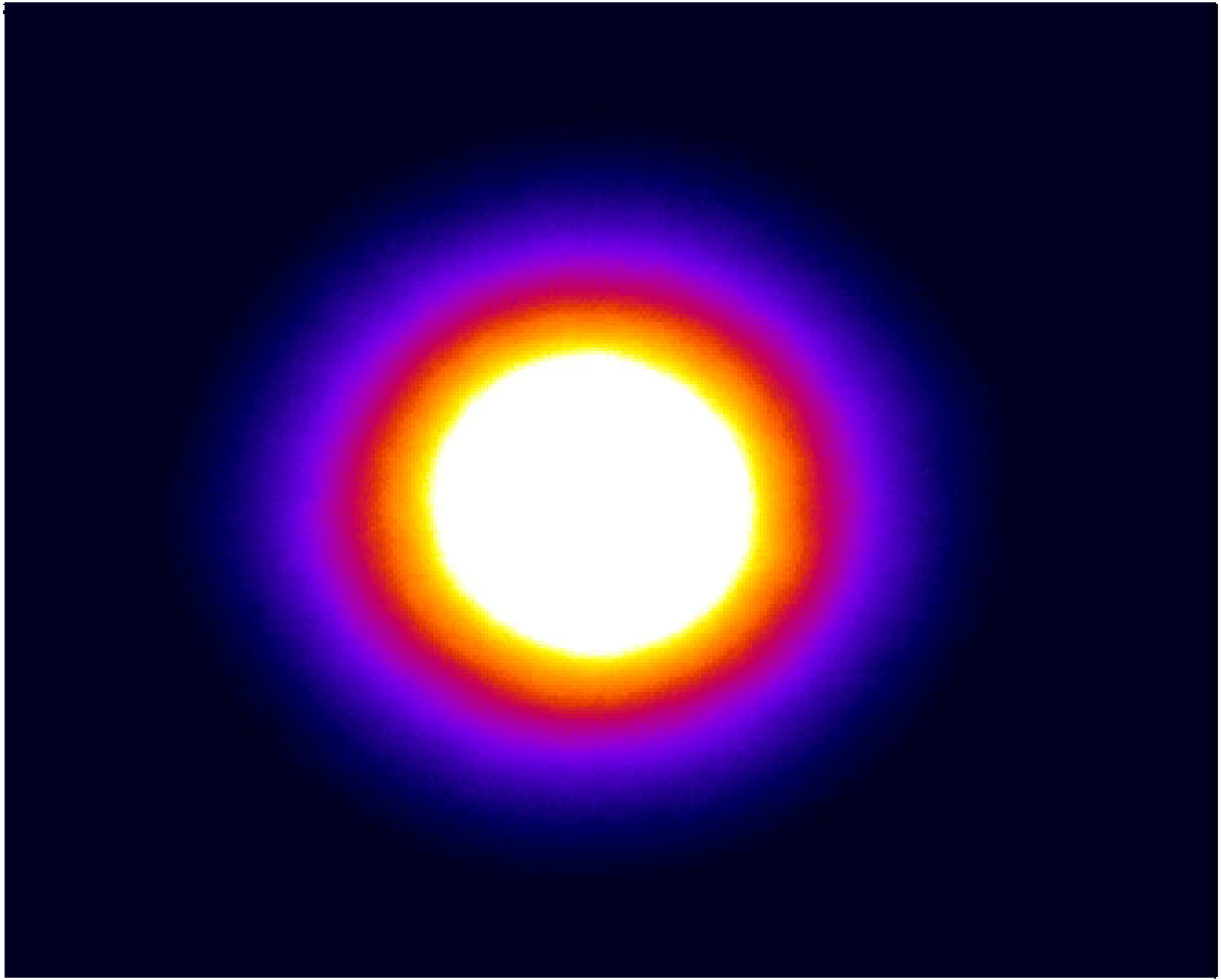






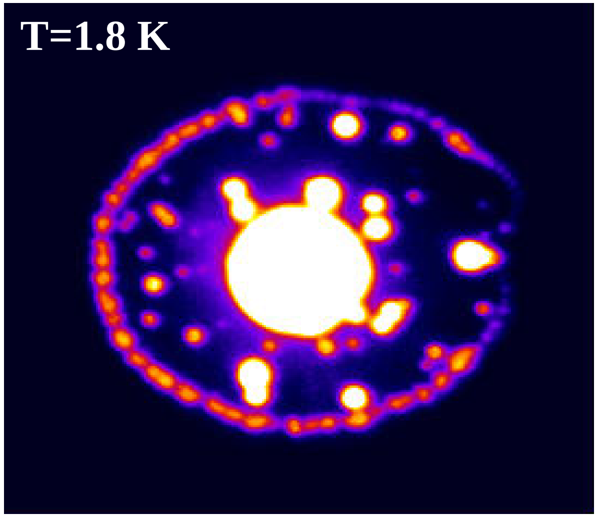
external ring is fragmented into circular-shaped structures that form periodic array over macroscopic lengths, up to ~ 1 mm

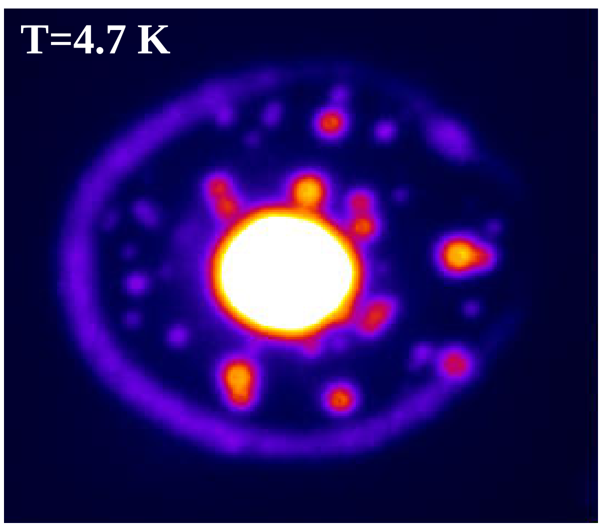
2D image of indirect exciton PL vs temperature

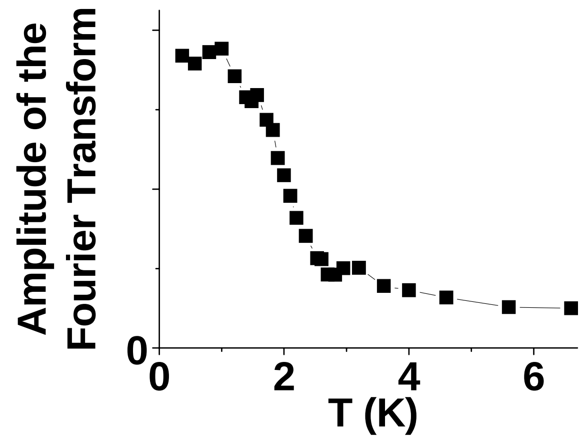


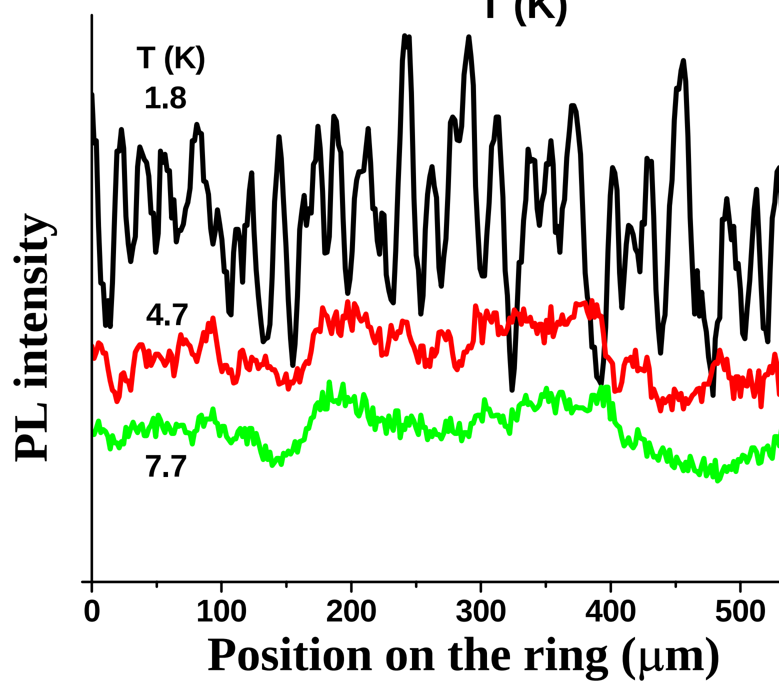
T=0.38-20 K

Temperature dependence of ring fragmentation into spatially ordered array of beads



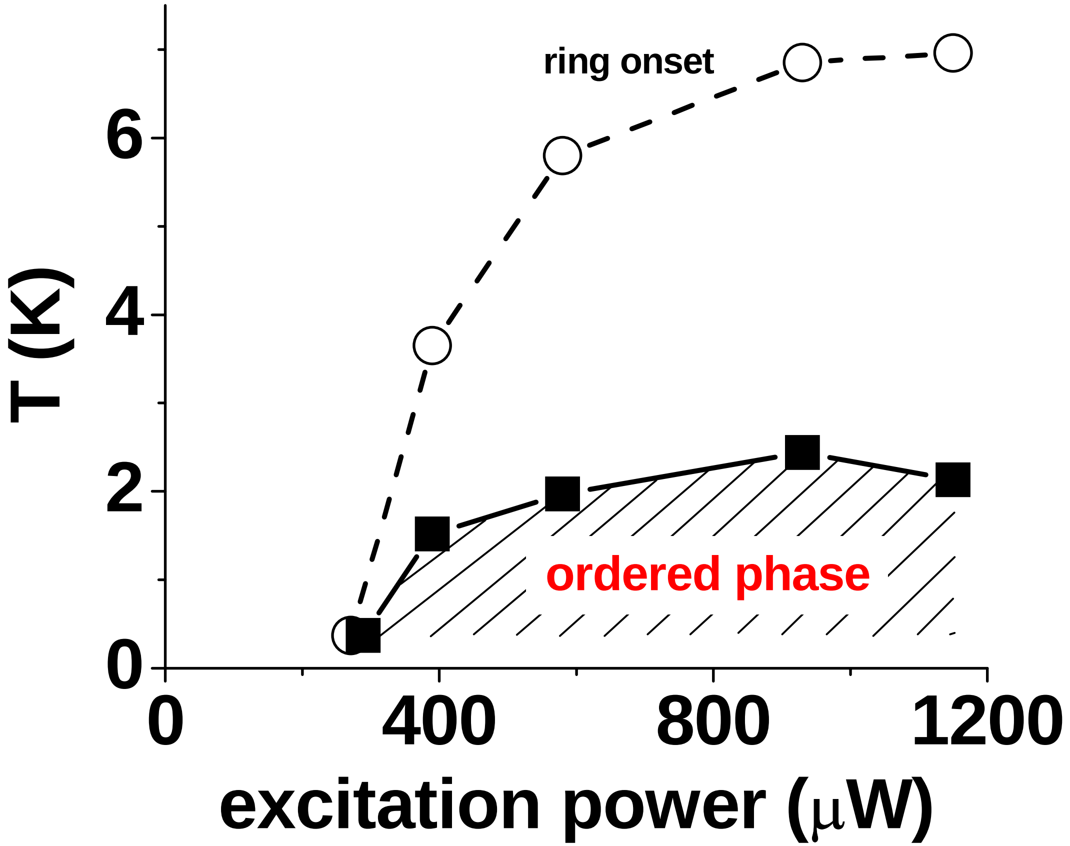






ring fragmentation into spatially ordered array of beads appears abruptly at low T

Ordered phase



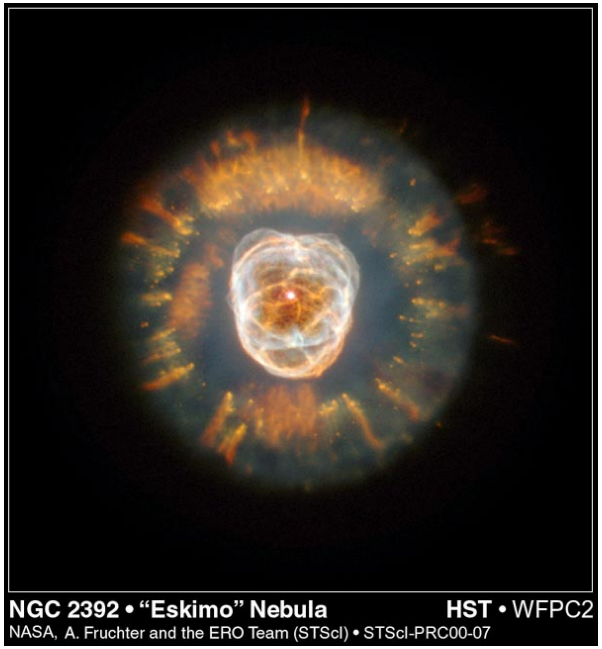
Discussion

origin of the rings

on origin of the macroscopically ordered exciton phase

L.V. Butov, L.S. Levitov, A.V. Mintsev, B.D. Simons, A.C. Gossard, D.S. Chemla, unpublished

Similarities in astrophysics: ring structure of expanding matter

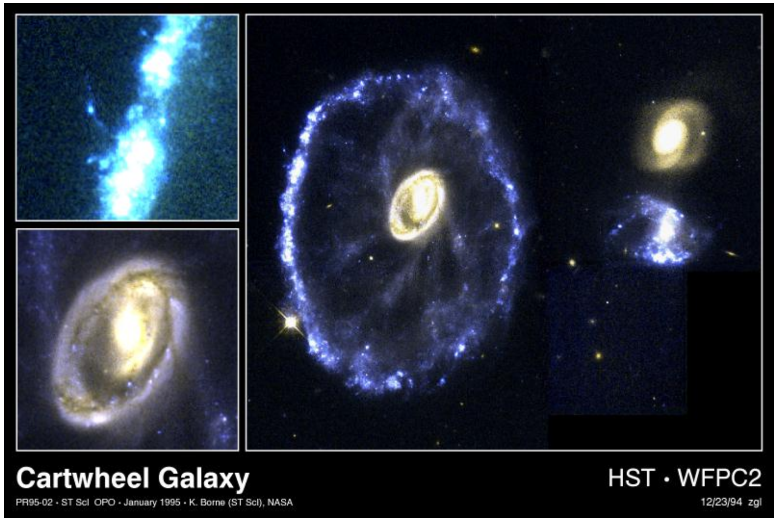


ring structures are generic for systems with centrally symmetric mass flow

a planetary nebula - represents the final stage in the evolution of a Sun-like star

the nebular shells with textures are formed by the wind of material ejected by the star

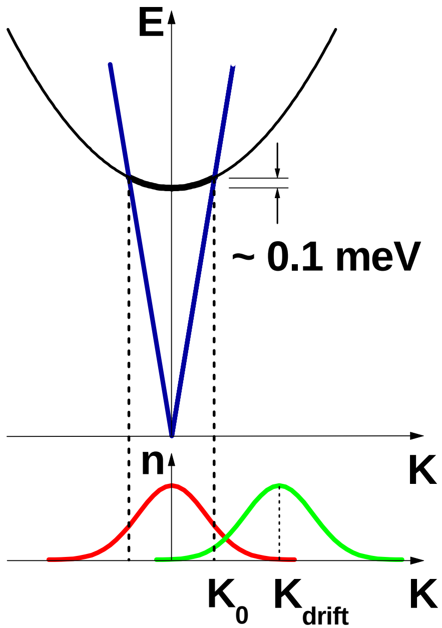
Rayleigh-Taylor instability ?

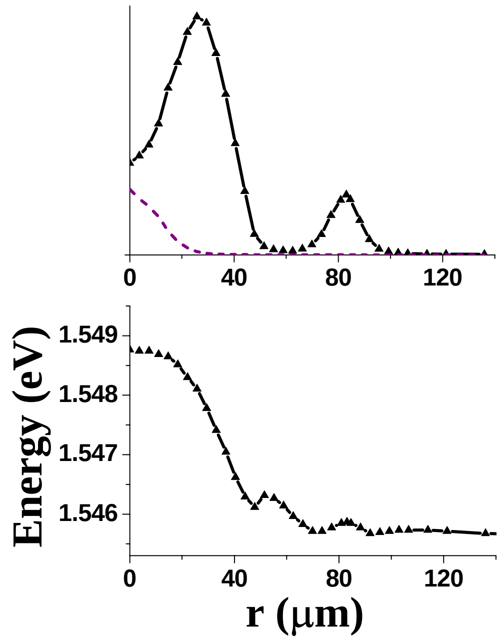


"…head-on collision between two galaxies."
"Like a rock tossed into a lake, the collision sent a ripple of energy into space, plowing gas and dust in front of it … this cosmic tsunami leaves in its wake a firestorm of new star creation … in large fragmented gas clouds."

from http://hubblesite.org

PL pattern ⟺ spatial distribution of optically active low energy excitons





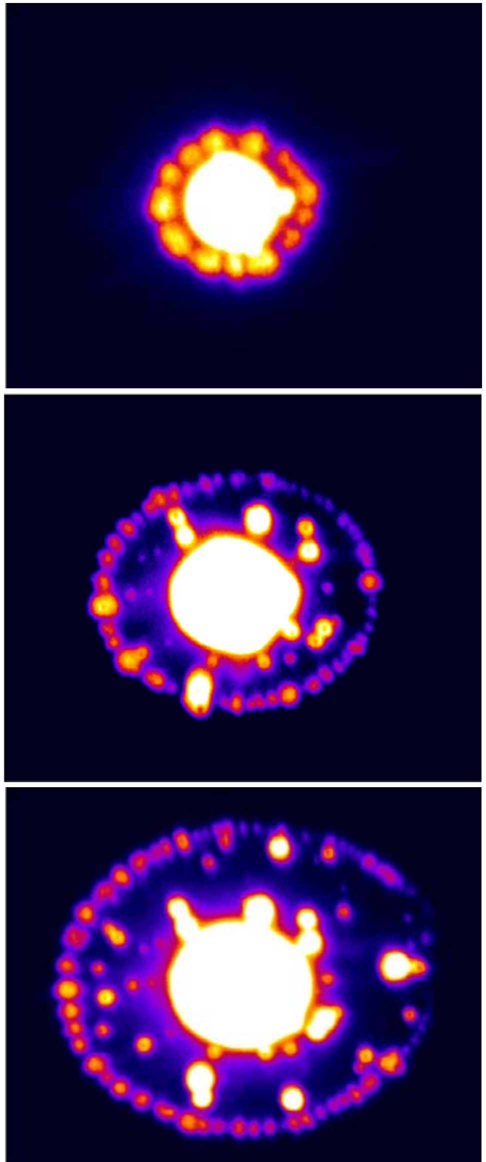
continuous flow of excitons out of excitation spot due to exciton drift, diffusion, phonon wind, carrier wind etc.

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 ⟶ **internal ring**

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

Excitons are generated within the external ring

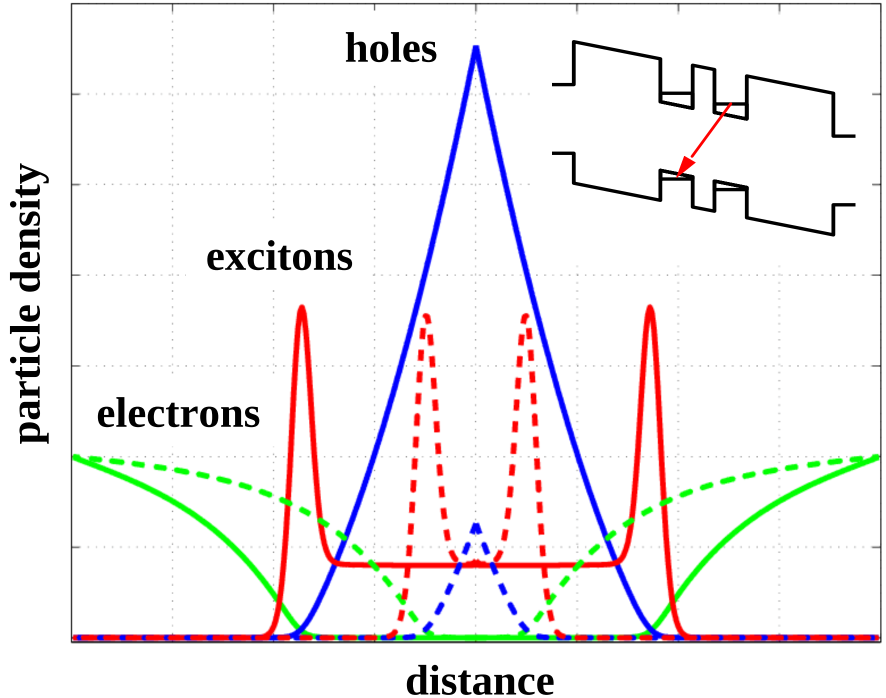


P_{ex}

T= 380 mK

410 μm

off-resonance laser excitation creates charge imbalance in CQW
electrons and holes have different collection efficiency to CQW



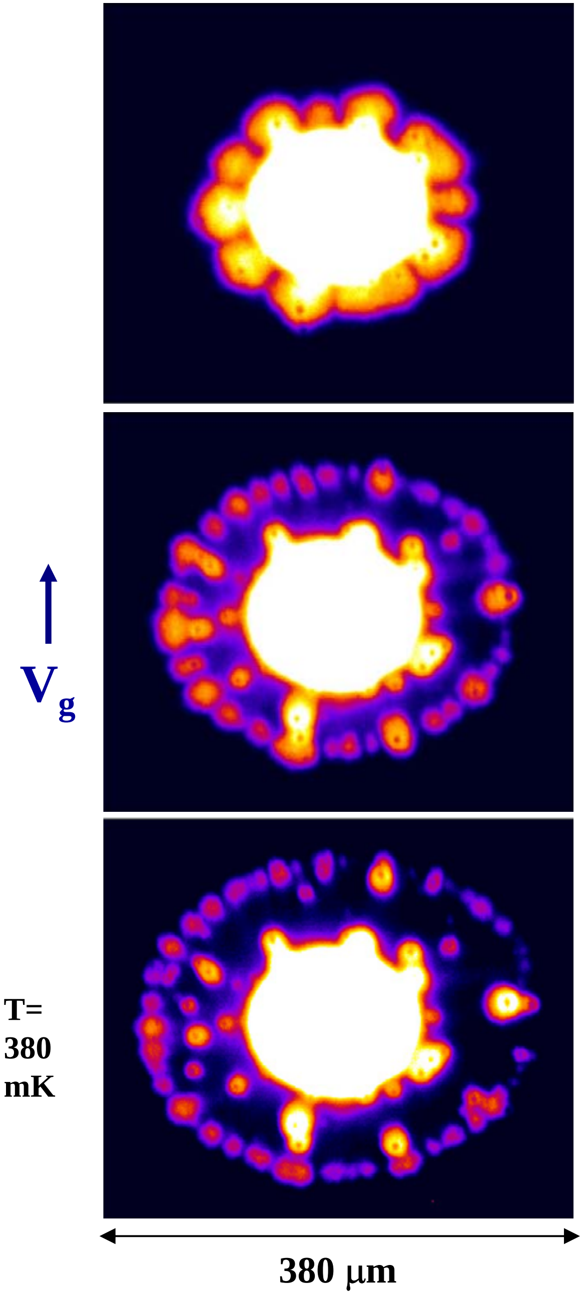
same for
e ⟷ h

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

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

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

External control of exciton rings



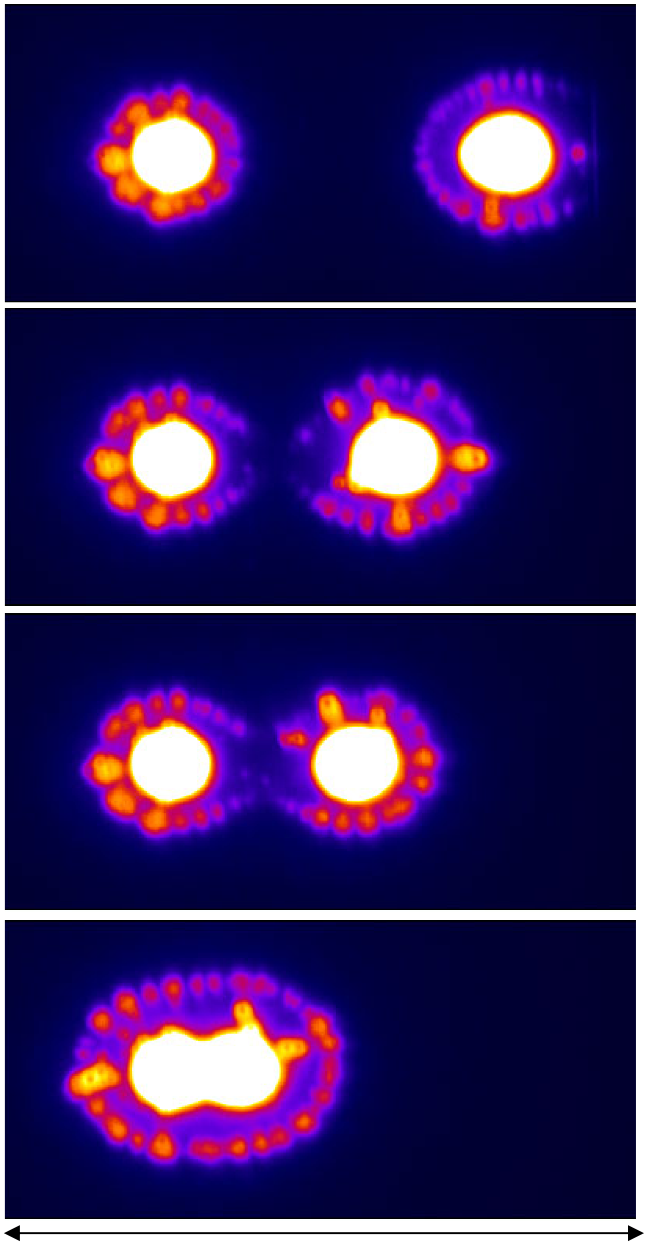
expansion of the ring with decreasing gate voltage

⇕

a reduction of transverse electric field, and hence of the current *I(r)*, depletes electrons in CQWs

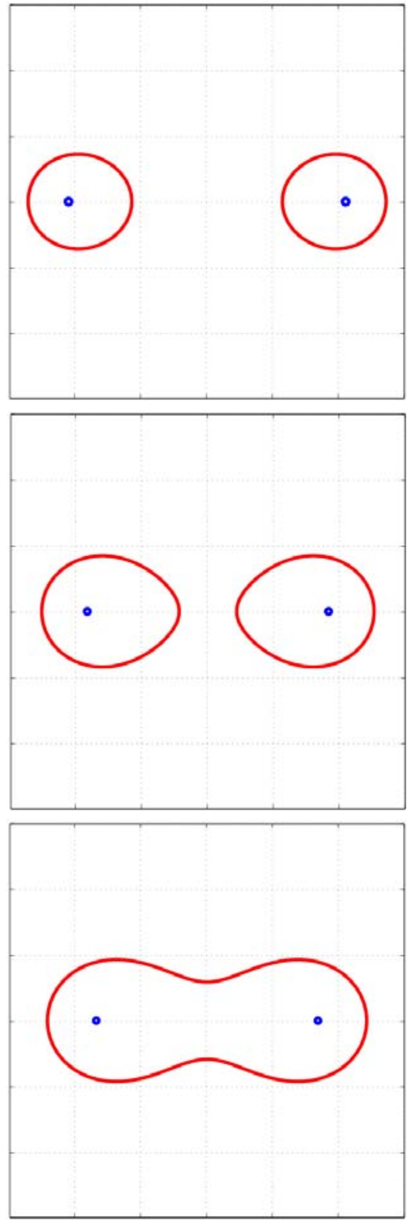
$$\dot{n} = D\Delta n - \gamma np + J(r)$$
$$\dot{p} = D'\Delta p - \gamma np + J'(r)$$
$$J(r) = \underline{I(r)} - a(r)n(r)$$
$$J'(r) = P_{ex}\delta(r)$$
$$n_X \propto np$$

Interaction of two exciton rings



T= 380 mK

520 μm



rings attract one another at large distances

⇕

the existence of ``dark matter'' outside the rings that mediates the interaction

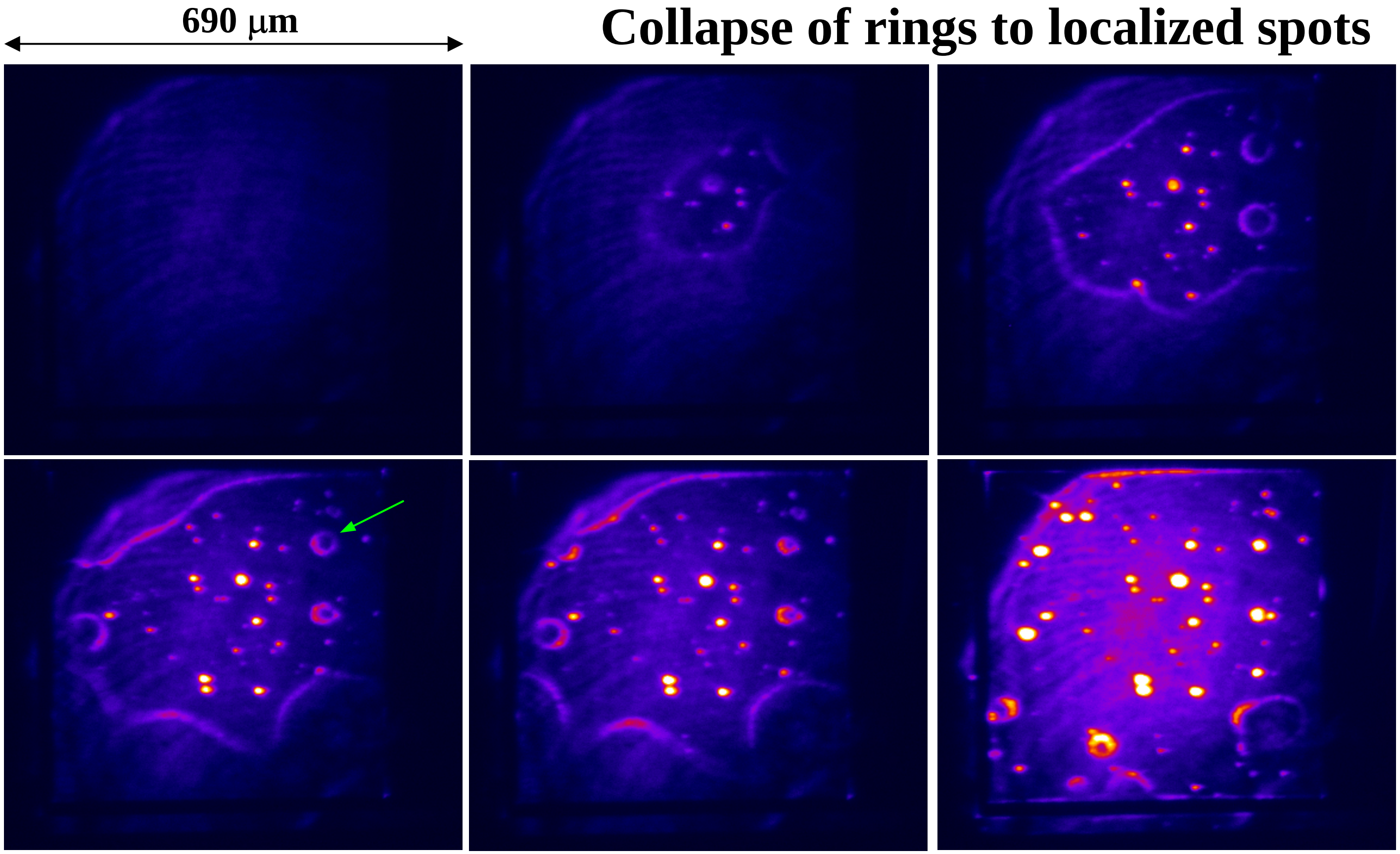
electron flow outside each ring which is perturbed by the presence of another ring

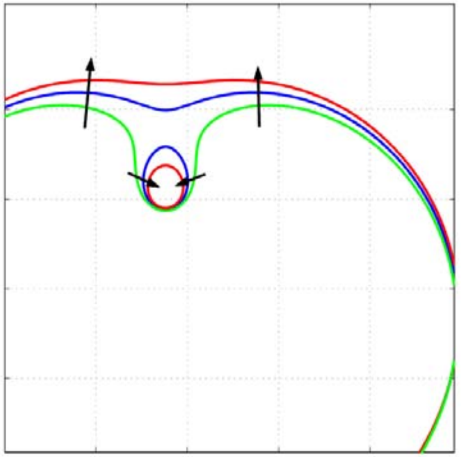
electrons in the area between the rings are depleted more strongly

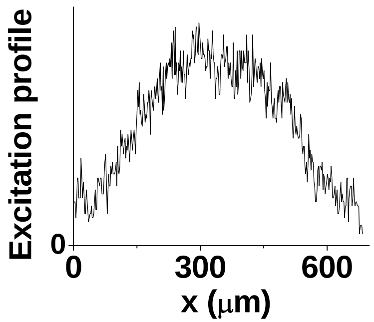
⇓

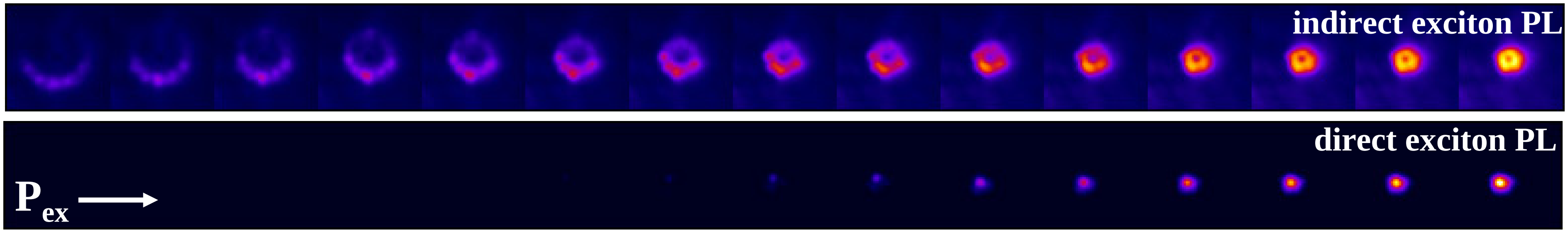
attraction of the rings

Collapse of rings to localized spots









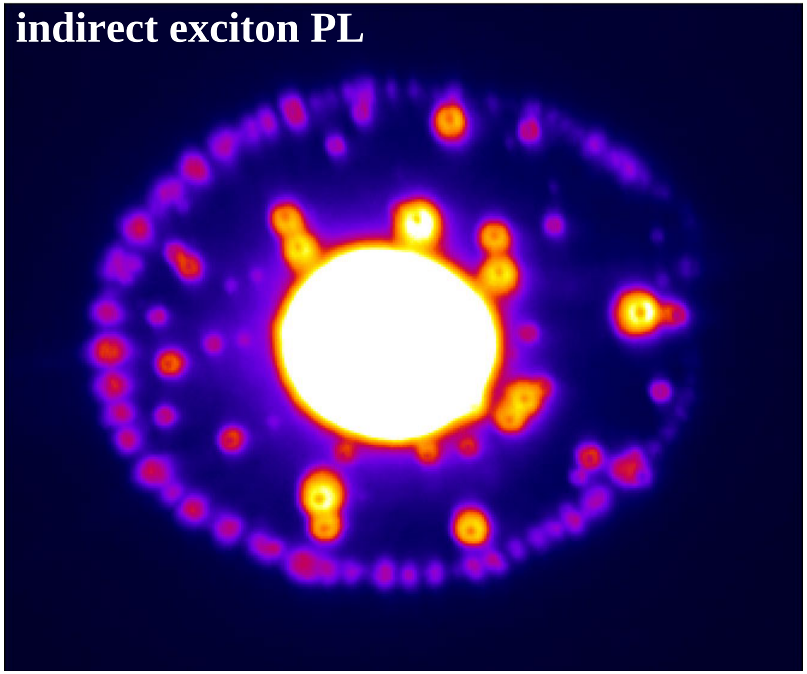
around the localized spots, small rings appear which shrink at increasing P_{ex}

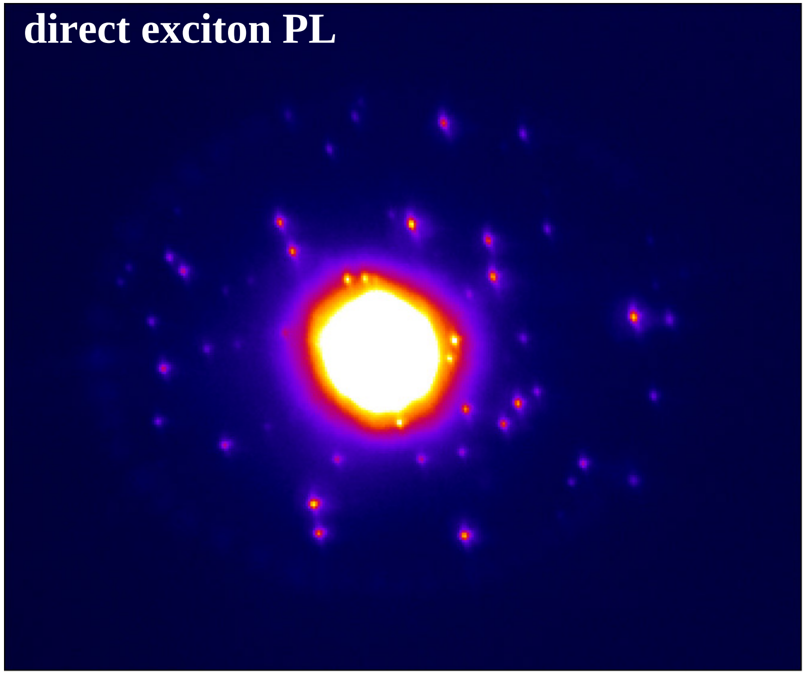
e ⟺ h

localized sources of electrons (due to pinholes) embedded in the hole rich illuminated area

direct exciton emission indicates hot cores at the center of the collapsed rings

Ordered phase

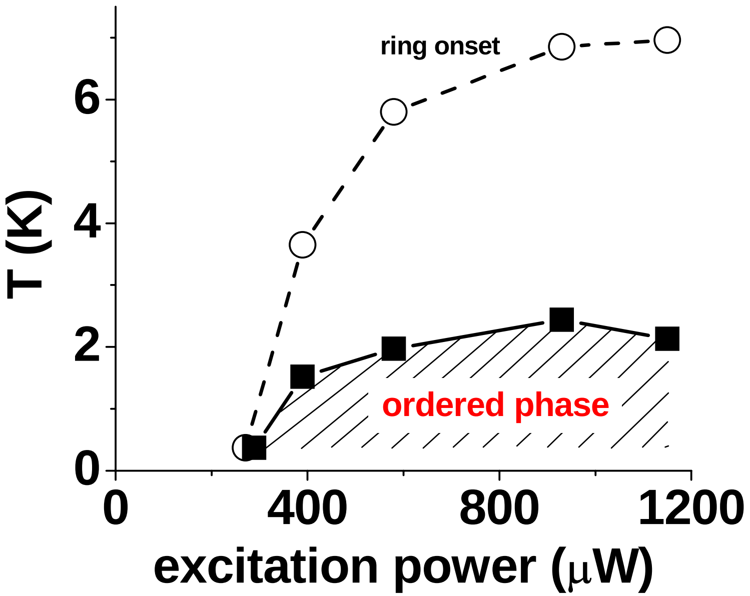




410 μm

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



the rings represent a source of cold excitons
with a temperature close to that of the lattice
in external ring heating sources vanish → exciton gas is the coldest

macroscopically ordered exciton state

new state, not predicted

microscopic nature 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

statistically degenerate Bose-gas of excitons

the macroscopic ordering is an intrinsic
property of exciton condensate ?

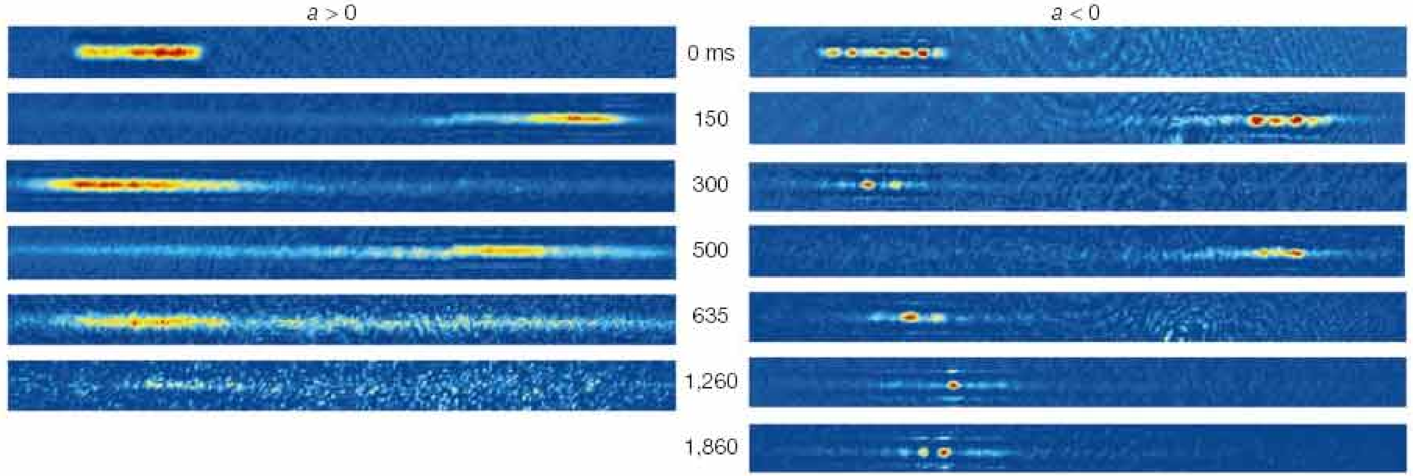
Similarities with known phenomena: Modulational instabilities

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)



<u>soliton train</u>
is observed below T_c only

intrinsic property of atom BEC

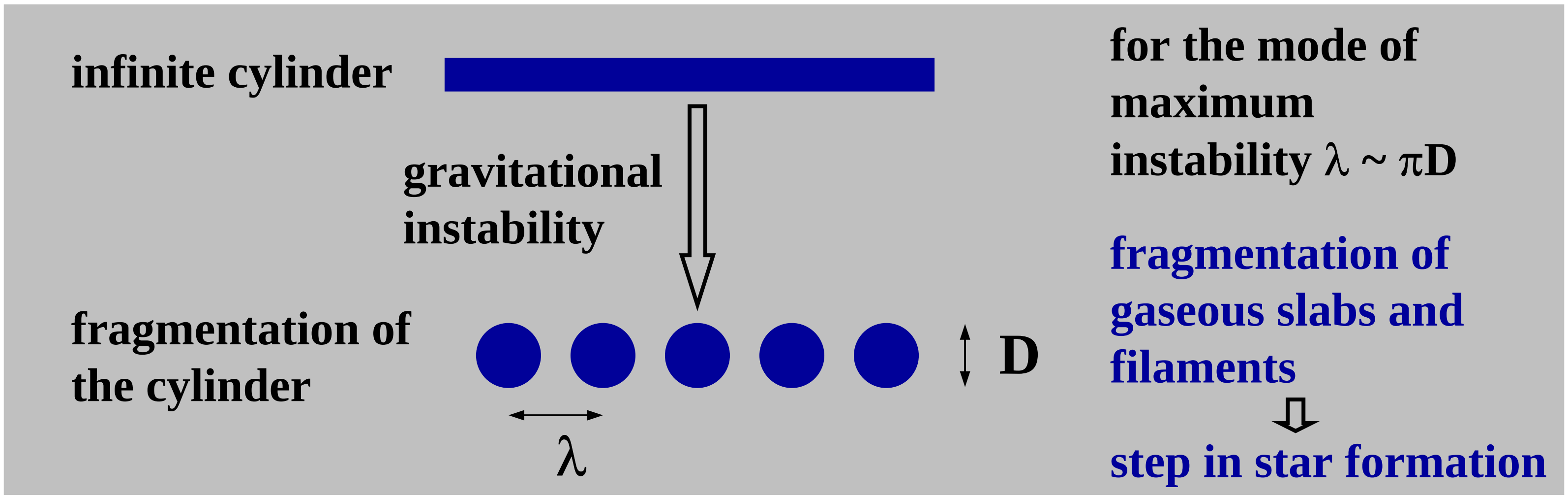
repulsion between beads of soliton train is wave interference phenomenon

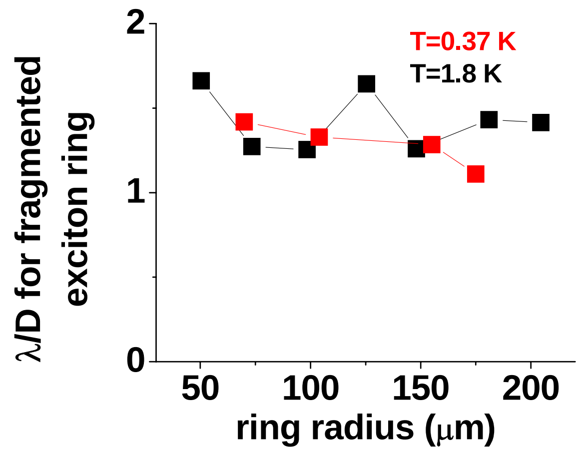
the macroscopic ordering is an intrinsic property of exciton condensate ?

attractive interaction for indirect excitons ?

Similarities in astrophysics

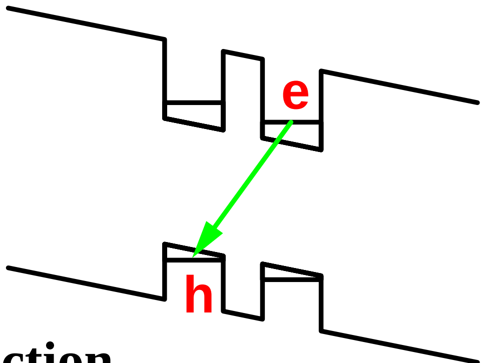
S. Chandrasekhar and E. Fermi (1953)
<u>gravitational instability</u> of an infinite cylinder:
the cylinder is unstable for all modes of deformation with wavelengths exceeding a certain critical value



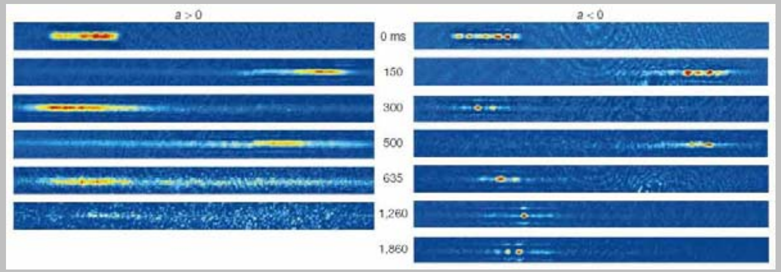


attractive interaction for indirect excitons ?

attractive interaction ?



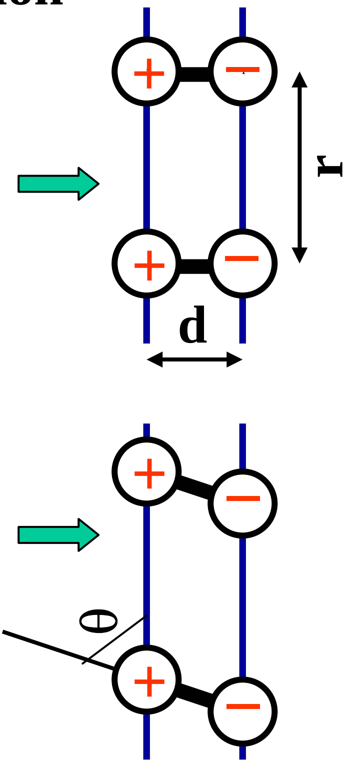
soliton train in atom BEC appears when the interaction is switched from repulsive to attractive
K.E. Strecker et al., Nature 417, 150 (2002)



dipole-dipole interaction
$U \sim d^2/r^3\,(1-3\cos^2\theta)$

repulsive interaction

attractive interaction
(for $\cos^2\theta < 1/3$)



when in-plane electric field exceeds the threshold the interaction switches from repulsive to attractive ?

indirect excitons with spatially separated electrons and holes, d_{eh}~10 nm

↓

strong dipole-dipole interaction

large in-plane polarizability

⬇

spontaneous in plane dipole alignment at $T<T_c$

⬇

instability due to attractive interaction

?