Spontaneous Coherence and Spin Texture in a Cold Exciton Gas

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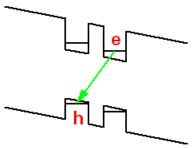
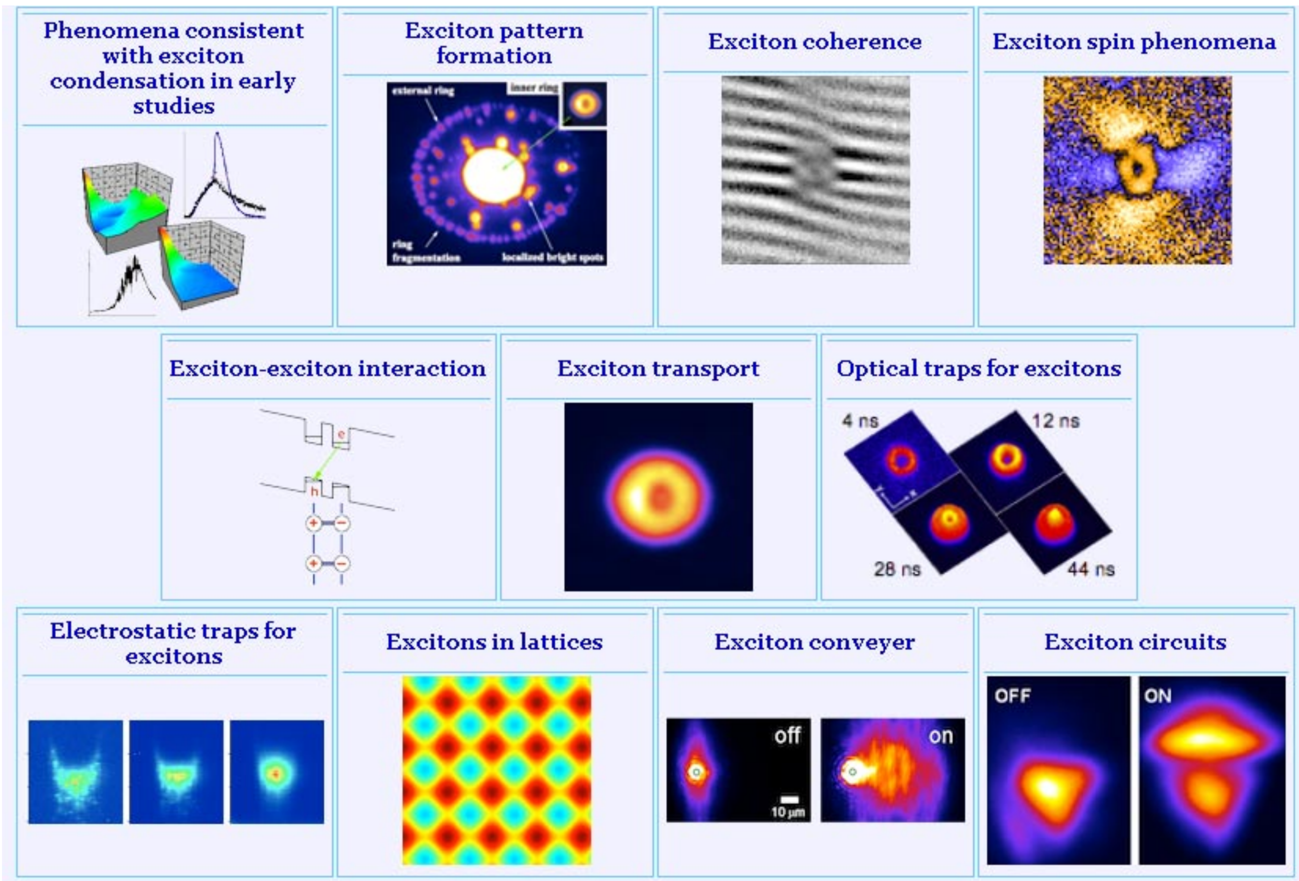


Indirect excitons

→ **Cold excitons**

→ **Excitonic signal processing**



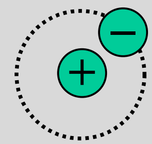
Introduction
- Cold exciton gas
- Indirect excitons
- Exciton rings
- MOES

New data
- Spontaneous coherence
- Spin textures
- Phase singularities
- Spontaneous coherence in a trap

supported by ARO, DOE, NSF

exciton – bound pair of electron and hole

light bosonic particle in semiconductor



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

Cold excitons

⬇

thermal de Broglie wavelength is comparable to separation between excitons

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

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

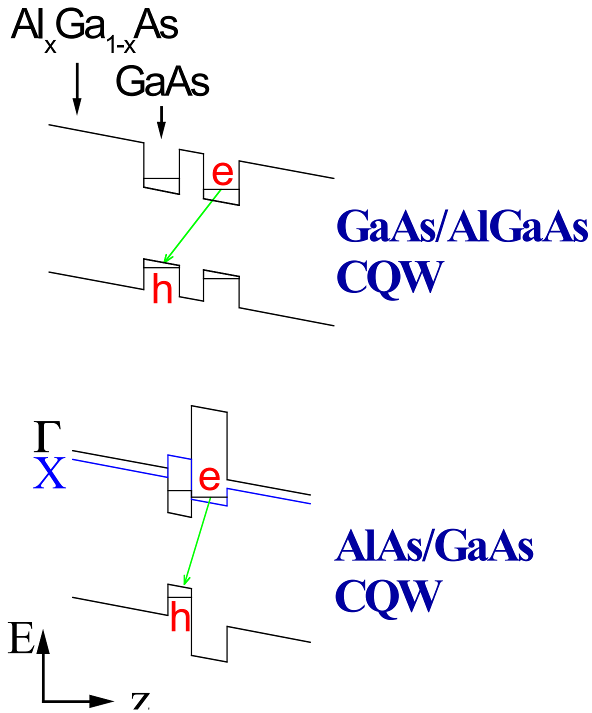
How to realize cold exciton gas ?

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

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

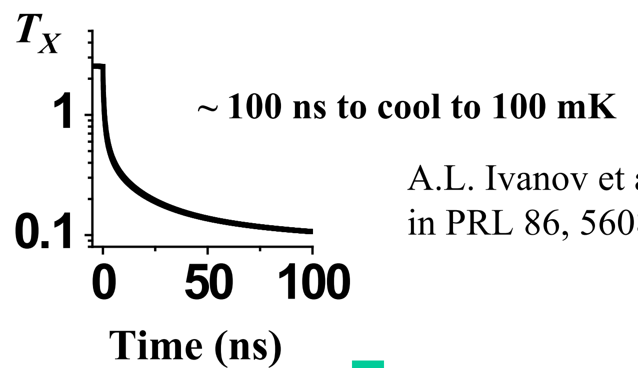
find excitons with lifetime >> cooling time ⟶ $T_{exciton} \sim T_{lattice}$

Indirect excitons in 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)



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

T_X ~ 100 mK
is realized in experiments
30 times below T_{dB}

if bosonic particles are cooled down below the temperature of quantum degeneracy they can spontaneously form a coherent state in which individual matter waves synchronize and combine

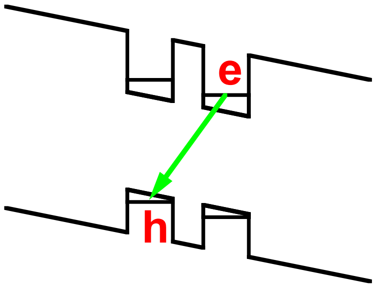
condensation in momentum space ↔ emergence of spontaneous coherence

theoretical predictions for a range of coherent states in cold exciton systems:

- **BEC** L.V. Keldysh, A.N. Kozlov, JETP 27, 521 (1968)
- **BCS-like condensation** L.V. Keldysh, Yu.V. Kopaev, Phys. Solid State 6, 2219 (1965)
- **charge-density-wave formation** X.M. Chen, J.J. Quinn, PRL 67, 895 (1991)
- **condensation with SO coupling** Congjun Wu, Ian Mondragon-Shem, arXiv:0809.3532v3

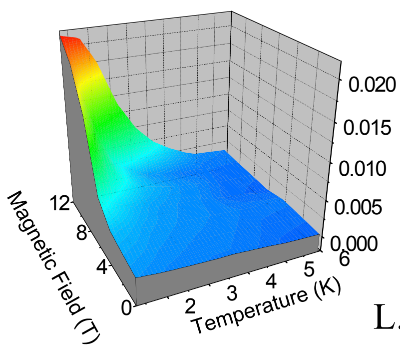
Onset of spontaneous coherence was evidenced by a strong enhancement of the recombination and tunneling rate

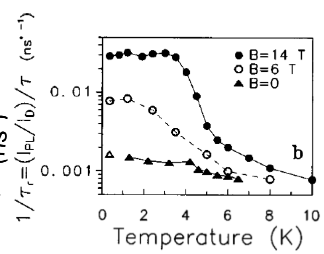
coupled electron and hole layers



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

enhancement of radiative decay rate of excitons

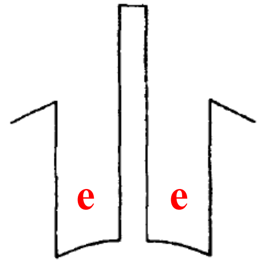




L.V. Butov, A.I. Filin, PRB 58, 1980 (1998)

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)

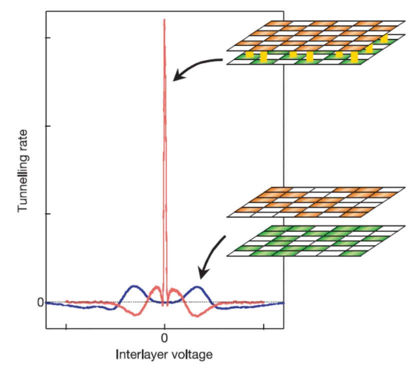
particle-hole transformation

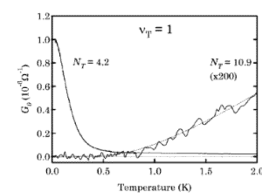
$\nu_e = 1/2 + \nu_e = 1/2 \quad \Rightarrow \quad \nu_e = 1/2 + \nu_h = 1/2$

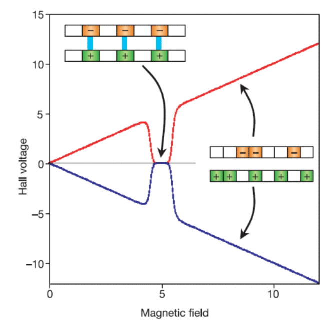
collective electron state $\Rightarrow$ exciton condensate

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 $\nu=1 \leftrightarrow$ 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**

The results of other transport and optical experiments were also consistent with spontaneous coherence of indirect excitons

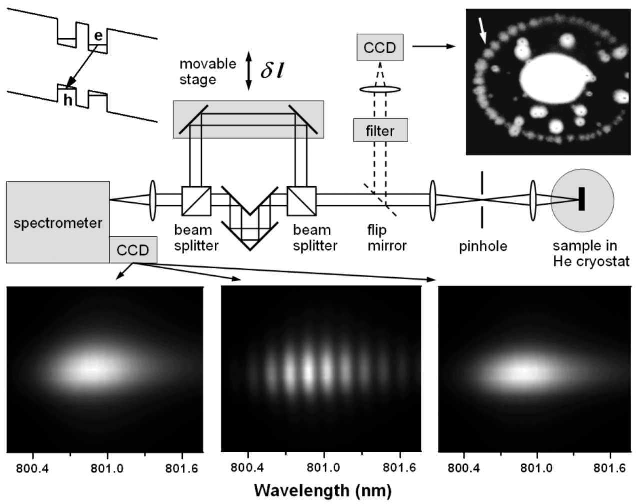
- L.V. Butov, A.L. Ivanov, A. Imamoglu, P.B. Littlewood, A.A. Shashkin, V.T. Dolgopolov, K.L, Campman, A.C. Gossard, PRL 86, 5608 (2001)
- L.V. Butov, A.I. Filin, PRB 58, 1980 (1998)
- I.B. Spielman, J.P. Eisenstein, L.N. Pfeier, K.W. West, PRL 84, 5808 (2000)
- J.P. Eisenstein, A.H. MacDonald, Nature 432, 691 (2004)
- L.V. Butov, A. Zrenner, G. Abstreiter, G. Bohm, G. Weimann, PRL 73, 304 (1994)
- E. Tutuc, M. Shayegan, D.A. Huse, PRL 93, 036802 (2004)
- L. Tiemann, J.G.S. Lok, W. Dietsche, K. von Klitzing, K. Muraki, D. Schuh, W. Wegscheider, PRB 77, 033306 (2008)
- 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)
- J.A. Seamons, C.P. Morath, J.L. Reno, M.P. Lilly, PRL 102, 026804 (2009)
- B. Karmakar, V. Pellegrini, A. Pinczuk, L.N. Pfeier, K.W. West, PRL102, 036802 (2009)

However, no direct measurement of coherence has been performed in these studies

Exciton coherence is imprinted on coherence of their light emission, which one can study by interferometry

Earlier probe of spontaneous coherence by interferometry

Mach-Zehnder interferometer with spatial and spectral resolution

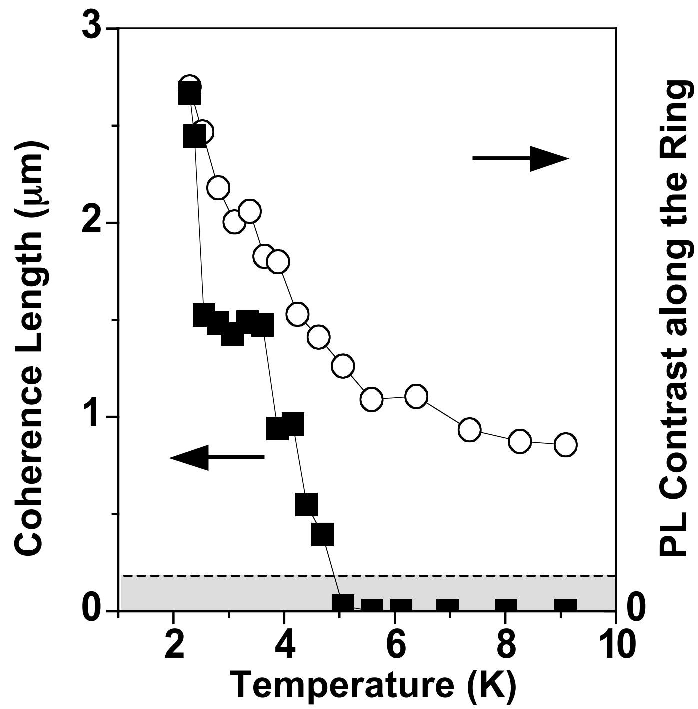


Sen Yang, A. Hammack, M.M. Fogler, L.V. Butov, A.C. Gossard, PRL 97, 187402 (2006)

M.M. Fogler, Sen Yang, A.T. Hammack, L.V. Butov, A.C. Gossard, PRB 78, 035411 (2008)

observed an enhancement of the exciton coherence length ξ in the macroscopically ordered exciton state

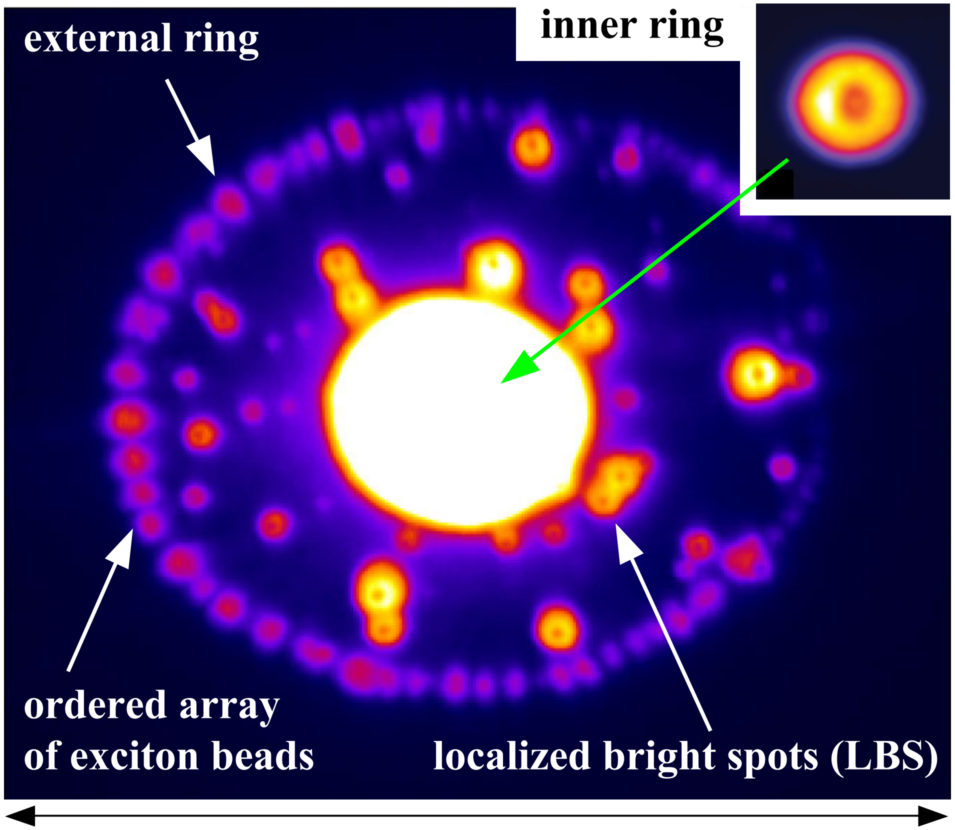
$\xi \sim 2\ \mu\text{m} >> \xi_{\text{classical}}$

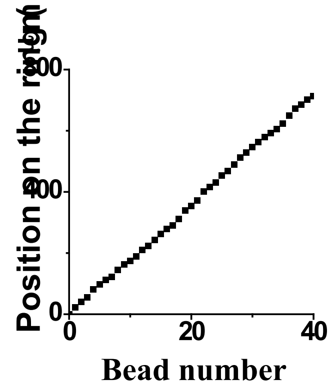


these experiments used a single-pinhole interferometric technique which does not measure $g_1(r)$ and the derivation of ξ was based on a mathematical analysis of the data

Experiment

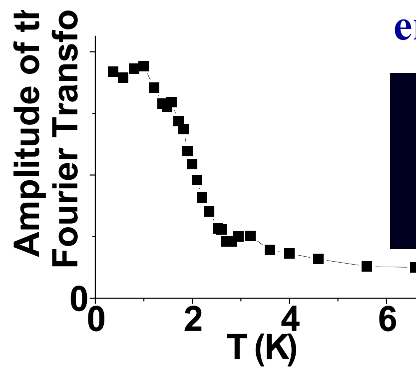
Exciton rings and macroscopically ordered exciton state



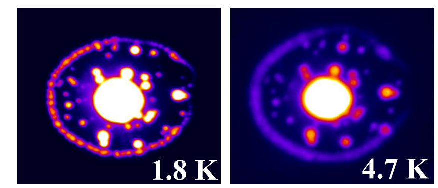


spatial order on macroscopic lengths

macroscopically ordered exciton state (MOES)



emerges at low *T*



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

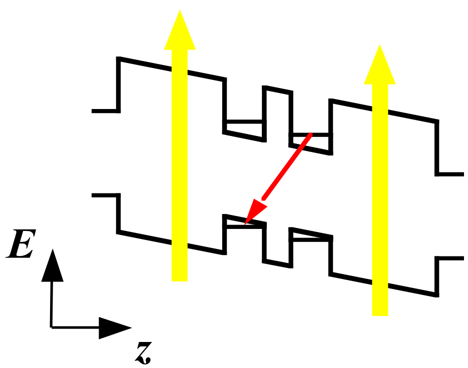
model of

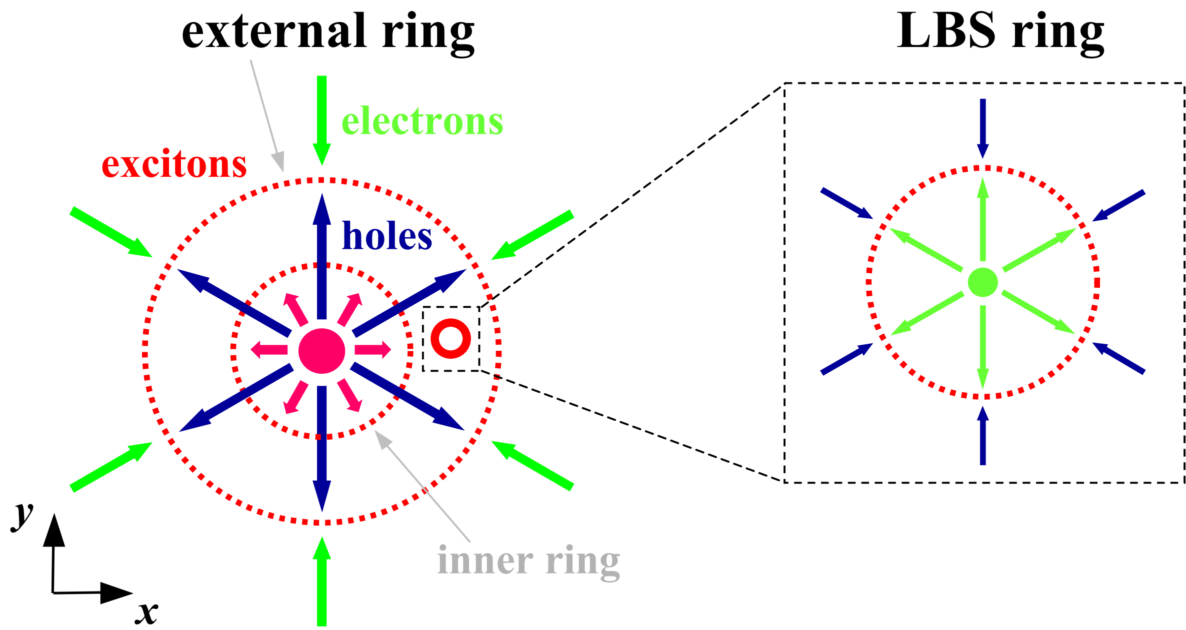
inner ring: A.L. Ivanov, L. Smallwood, A. Hammack, Sen Yang, L.V. Butov, A.C. Gossard, EPL 73, 920 (2006)

external ring: 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)

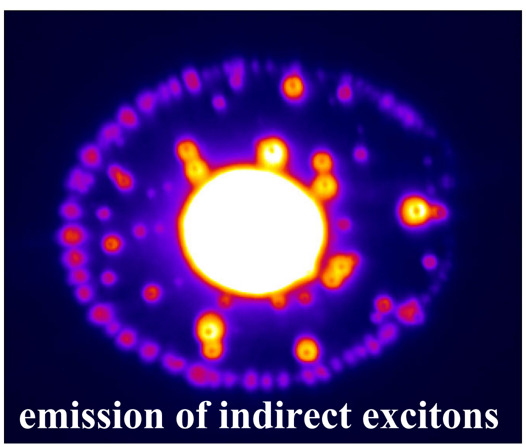
MOES: L.S. Levitov, B.D. Simons, L.V. Butov, PRL 94, 176404 (2005)

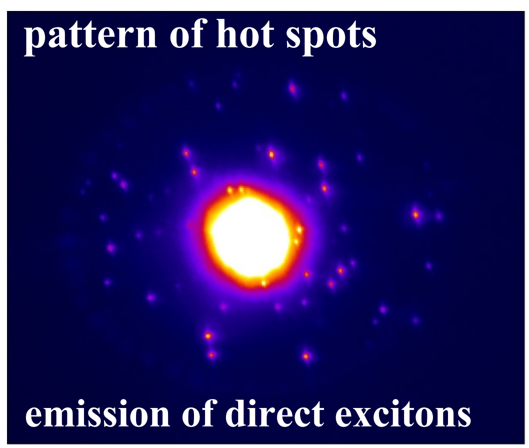
above barrier laser excitation
creates excitons + holes
in CQW





excitons are generated in external ring and LBS rings
at ring shaped interface between electron-rich and hole-rich regions





external rings and LBS rings form sources of cold excitons

exciton gas
is hot in LBS centers
is cold in external ring and LBS rings

measured by
shift-interferometry

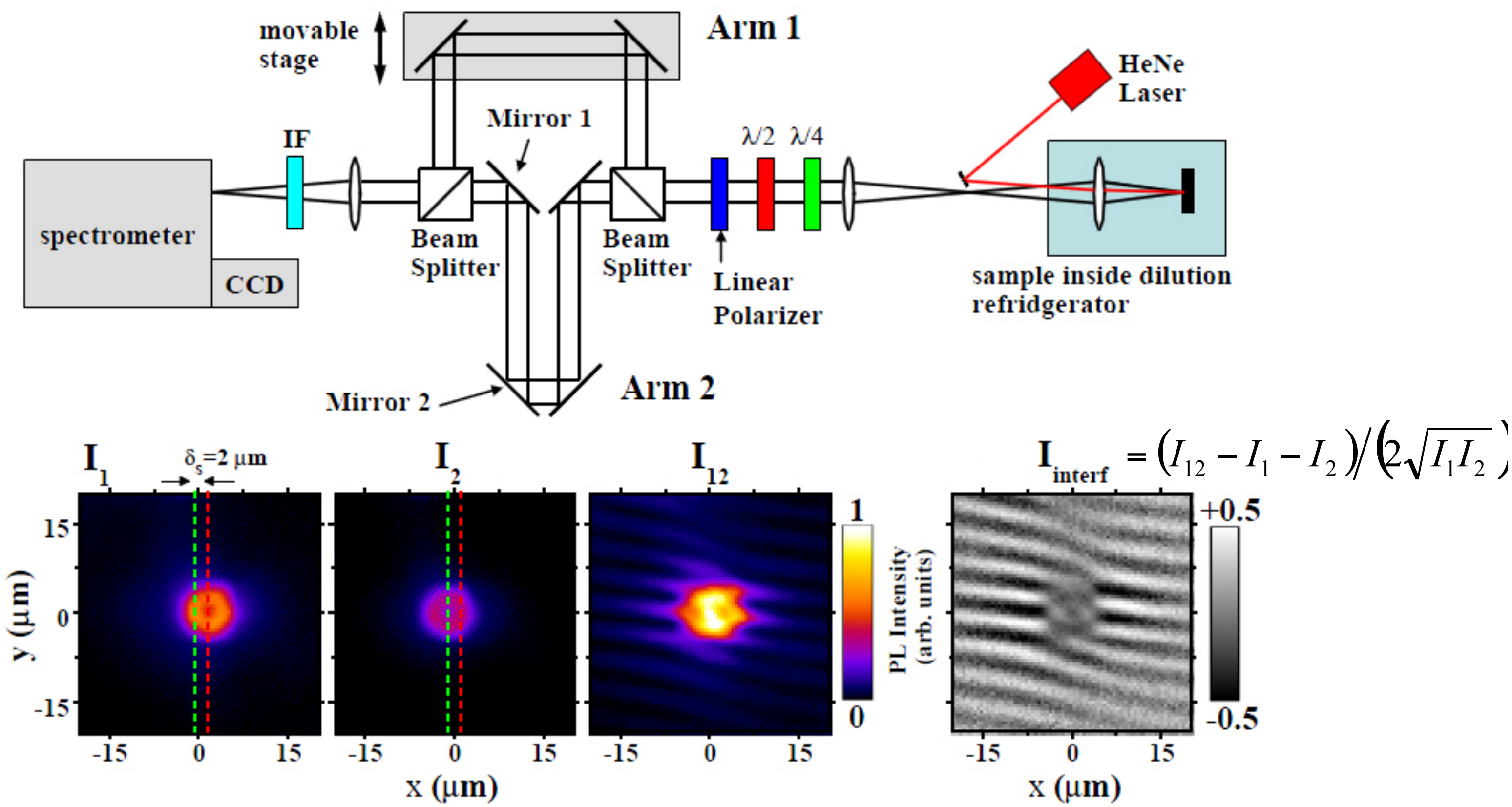
Spontaneous coherence
and
spin polarization textures

measured by
polarization resolved imaging

spin textures

- skyrmion spin textures in quantum Hall ferromagnets
- ferromagnetic domains, spin rings, and spin vortices in atom BEC
- skyrmion lattices in chiral magnets
- half-vortices in He3 and polariton condensates
- spin Hall effect and optical spin Hall effect
- spin transport with spin accumulation near contacts
- topological insulators

First order coherence function $g_1(\delta x)$



Pattern of $g_1(\delta x)$ is measured by shift-interferometry

$$g(t, \mathrm{r}) = \langle E(t' + t, \mathrm{r}' + \mathrm{r}) E(t', \mathrm{r}') \rangle / \langle E^2(t', \mathrm{r}') \rangle$$

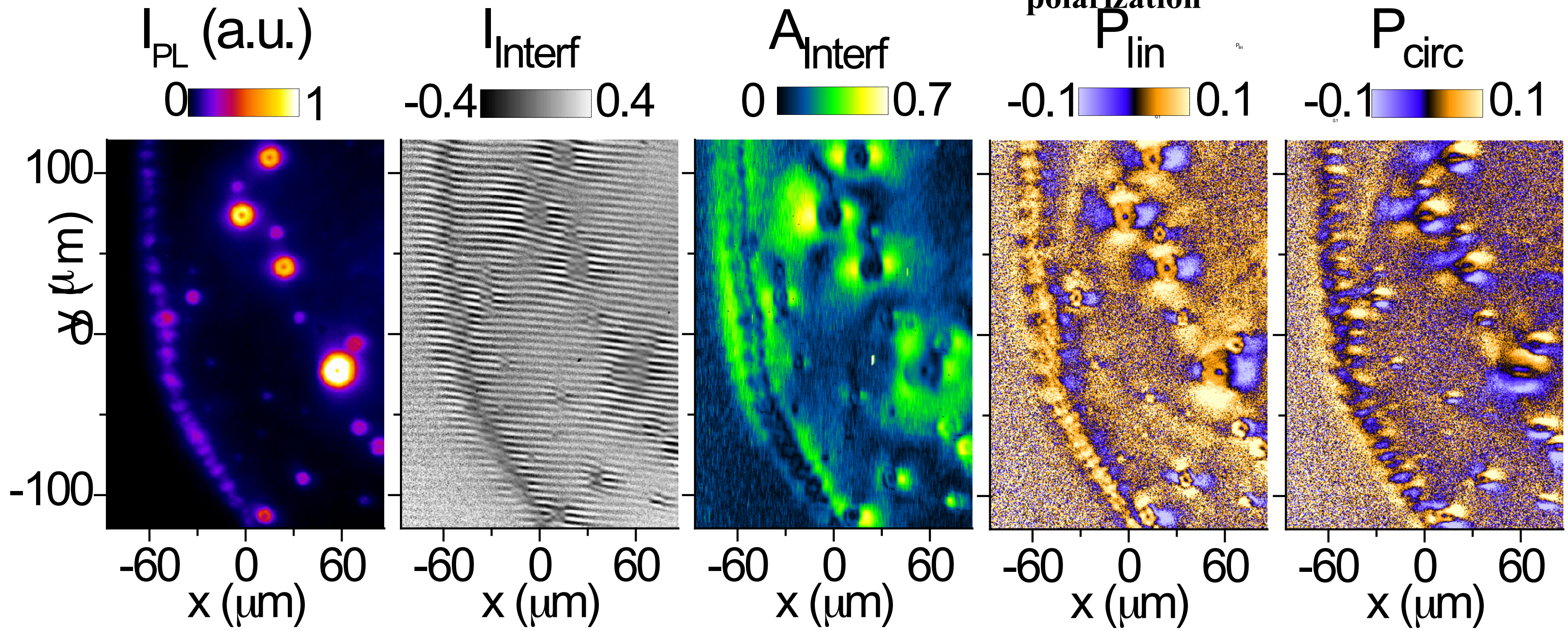
Images produced by arm 1 and 2 of MZ interferometer are shifted to measure interference between emission of excitons separated by δx

Contrast of interference fringes $A_{interf}(\delta x) \rightarrow g_1(\delta x)$

Pattern of spin polarization is measured by polarization resolved imaging

Emission, interference, coherence degree, and polarization patterns

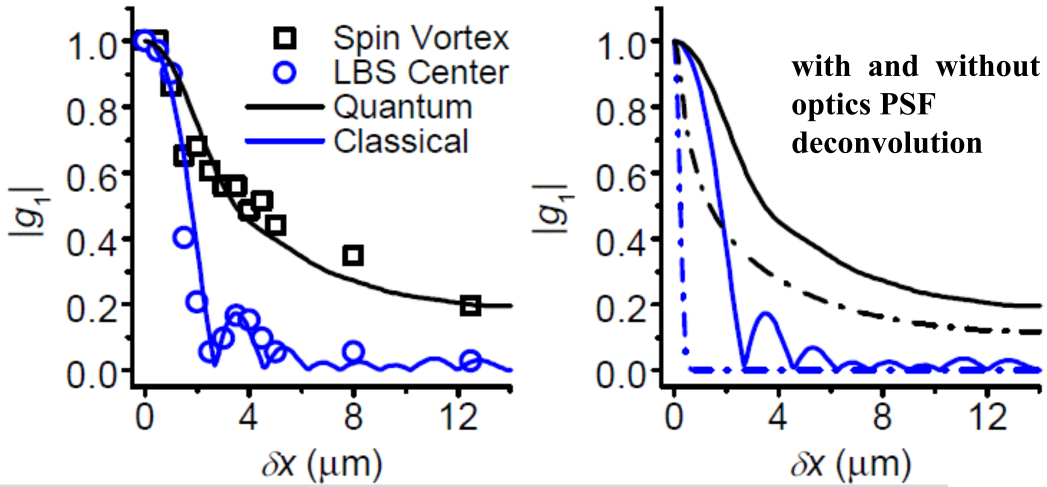
Emission pattern | **Interference pattern** | **Pattern of amplitude of inference fringes** | **Pattern of linear polarization** | **Pattern of circular polarization**



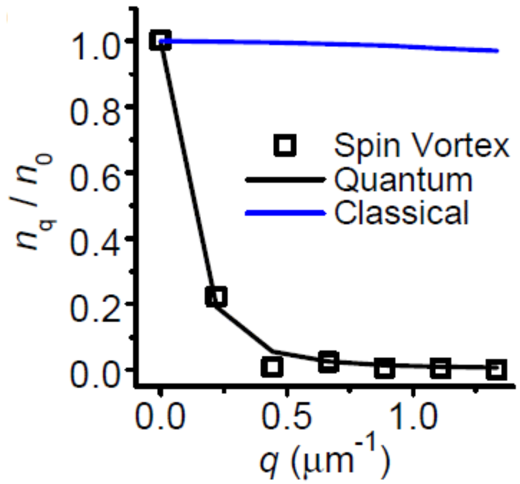
map of coherence degree

green: regions of extended spontaneous coherence of excitons

First order coherence function $g_1(\delta x)$



Distribution in q-space $n(q)$



Theory:

$g_1(r) \leftrightarrow n_q$ **Fourier transform** $\delta q \cdot \xi \sim 1$

coherence length

Classical gas: narrow $g_1(r)$ and broad n_q

$\xi_{classical} \sim \lambda_{dB} / \pi^{1/2} \sim 0.3\ \mu m$ **at 0.1 K**

Quantum gas: extended $g_1(r)$ and narrow n_q

$\xi >> \xi_{classical}$

$\delta q << \delta q_{classical}$

characteristic of a condensate

$$\xi \sim \xi_0 = \sqrt{\frac{n_0}{4\pi}}\lambda_{dB} \longleftarrow g_1(r) \sim \int d^2 q e^{iqr} n_q$$

Experiment:

Hot excitons: short-range coherence

$A_{interf}(\delta x)$ fits to PSF

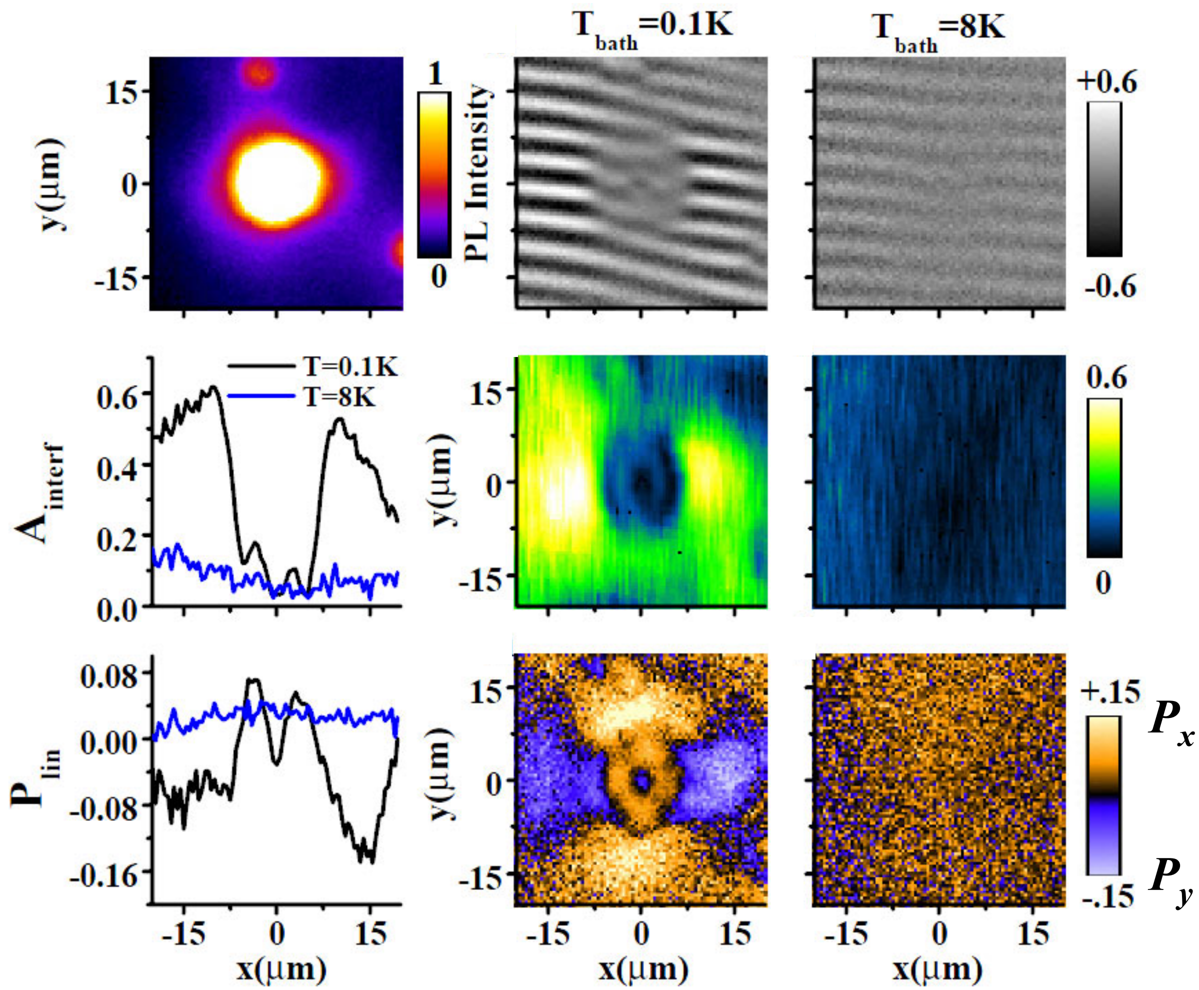
Cold excitons: extended coherence

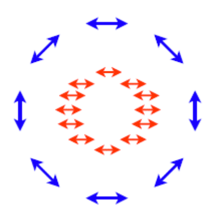
$\xi >> \xi_{classical}$

$\delta q << \delta q_{classical}$

A_{interf} is given by convolution of g_1 with point-spread function (PSF) of optics

Exciton coherence and spin texture around LBS-ring





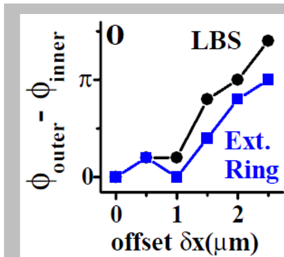
vortex of linear polarization

ring of linear polarization

Emergence of

- **Spontaneous coherence**
- **Spin polarization vortex**

at low T at $r > r_0$



$$\delta q_{r=r_0} \sim \delta\phi/\delta x$$

$$\sim 2\,\mu m^{-1}$$

phase shift → estimate of q jump

$$I_{12} = \left|\Psi(\mathbf{r}) + e^{iq_t y}\Psi(\mathbf{r}+\delta x)\right|^2$$

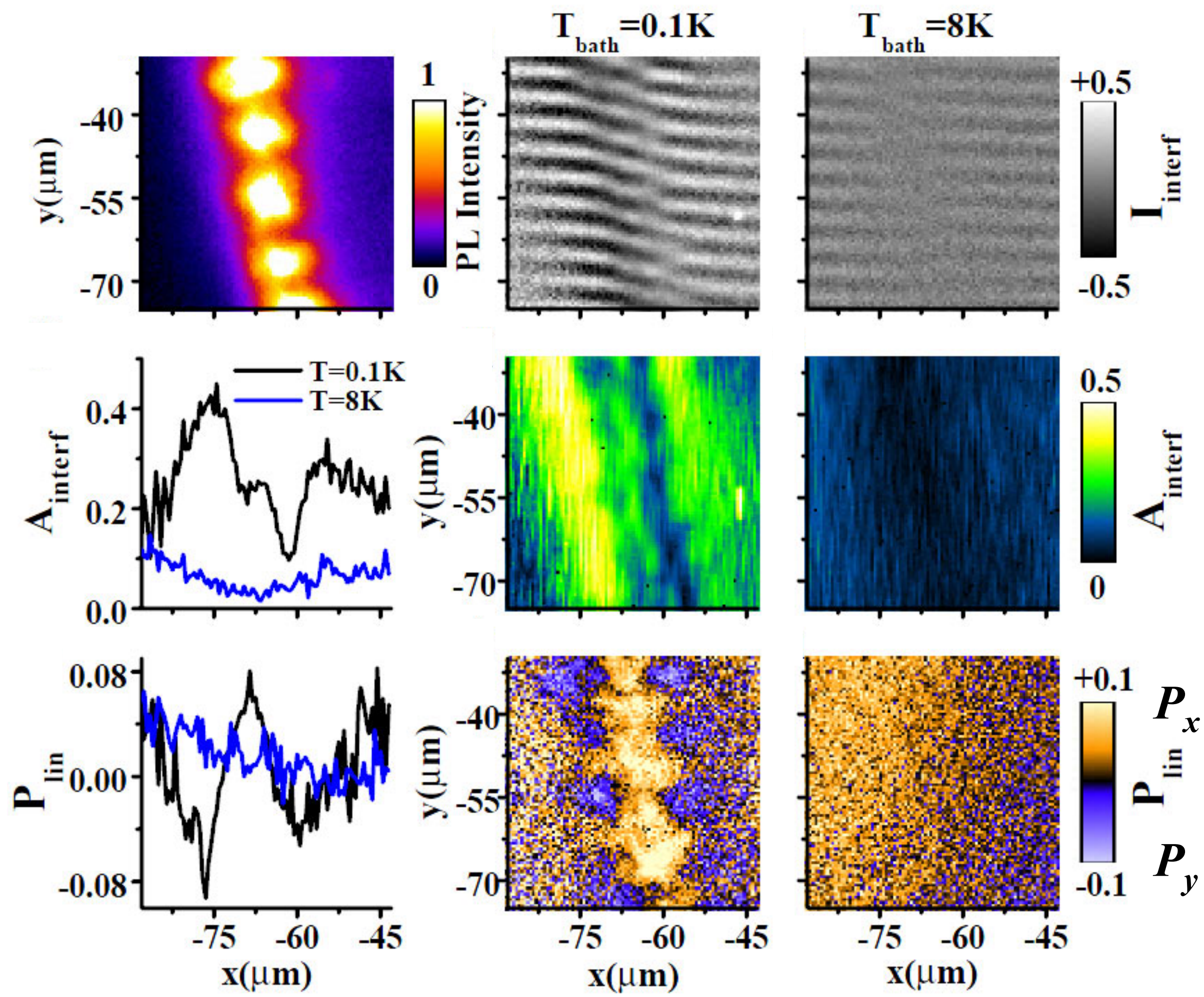
$\Psi(\mathbf{r})$ - the source amplitude at point $\mathbf{r}$

$q_t = 2\pi\alpha/\lambda$ sets the period of interference fringes.

For a uniform flow of excitons with momentum $\mathbf{q}$, $\Psi(\mathbf{r}) = e^{i\mathbf{qr}}$

$$I_{12} = 2 + 2\cos(q_t y + \mathbf{q}\delta\mathbf{x})$$

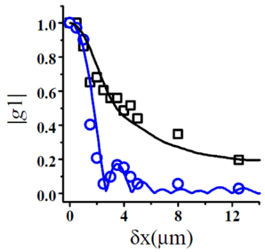
Exciton coherence and spin texture around external ring



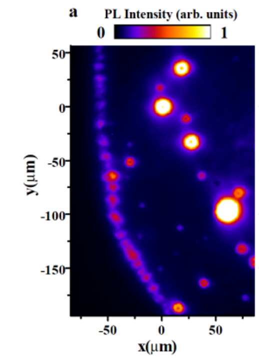
Emergence of

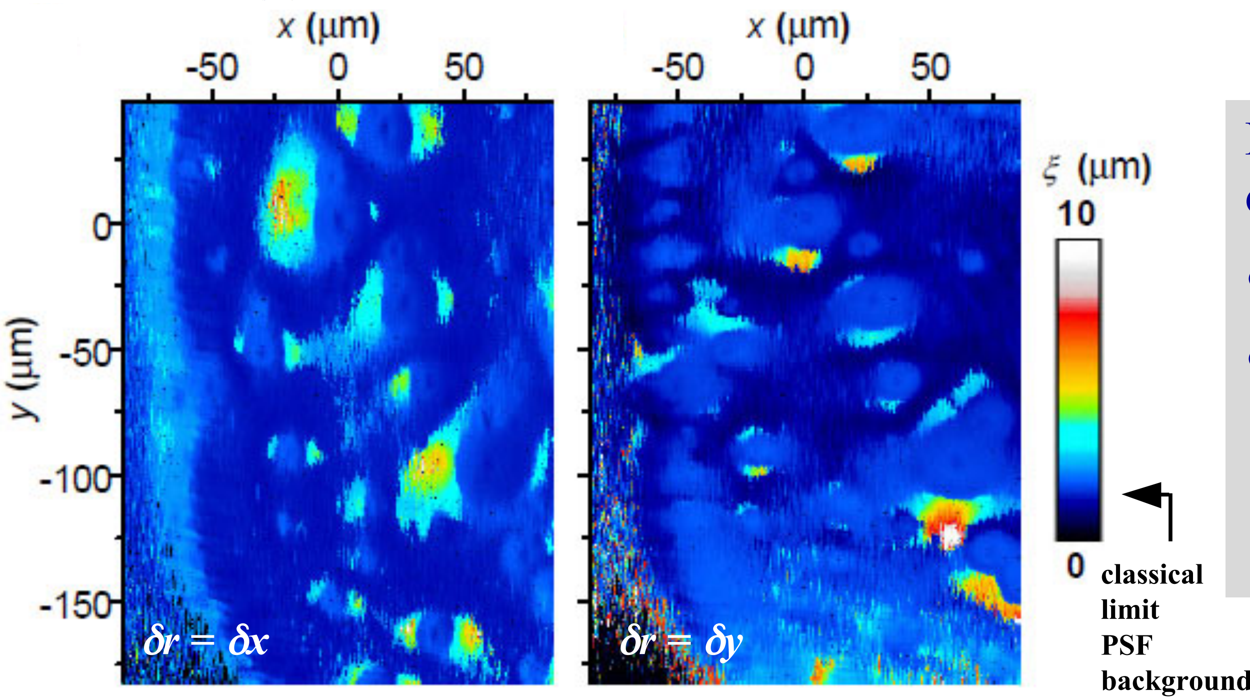
- **Spontaneous coherence**
- **Periodic spin texture**

at low *T* at $r > r_0^*$



Pattern of coherence length $\xi\,(x, y)$

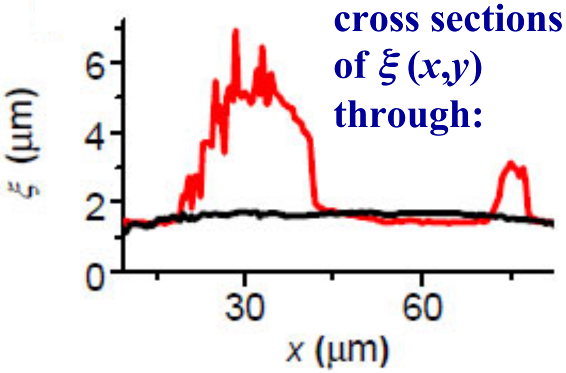




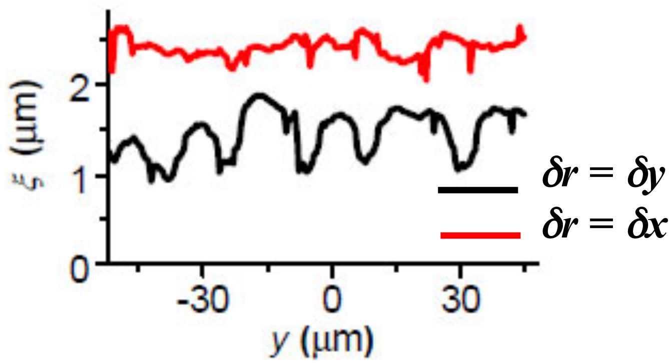
Extended spontaneous coherence of excitons emerges

- **in region of MOES**
- **in region of vortices of linear polarization**

$$\xi >> \xi_{classical}$$
$$\delta q << \delta q_{classical}$$



cross sections of $\xi\,(x,y)$ through:



vortex of linear polarization **MOES**

Directional property of exciton coherence:

extension of $g_1(r)$ is higher when exciton propagation direction is along vector *r*

Phase singularities

in singly quantized vortex
phase of wavefunction winds by 2π around singularity point

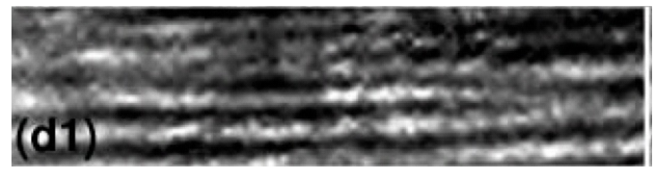
fork-like defect in phase pattern can be signature of quantized vortex

vortices in atom BEC

S. Inouye, S. Gupta, T. Rosenband, A.P. Chikkatur, A. Görlitz, T.L. Gustavson, A.E. Leanhardt, D.E. Pritchard, W. Ketterle, PRL 87, 080402 (2001)

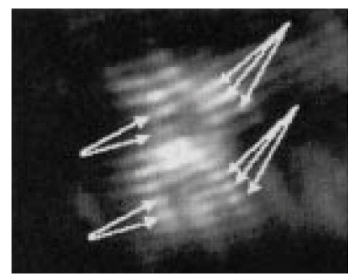
F. Chevy, K.W. Madison, V. Bretin, J. Dalibard, PRA 64, 031601(R) (2001)

Z. Hadzibabic, P. Krüger, M. Cheneau, B. Battelier, J. Dalibard, Nature 441, 1118 (2006)



optical vortices

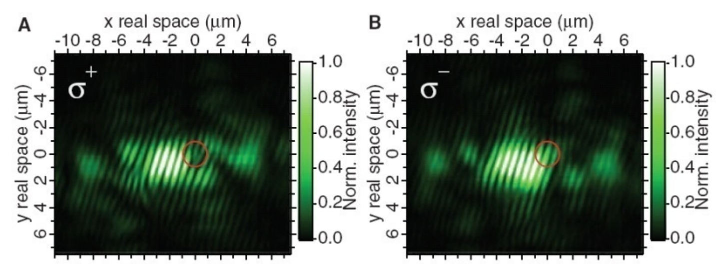
J. Scheuer, M. Orenstein, Science 285, 230 (1999)
and references therein



polariton vortices

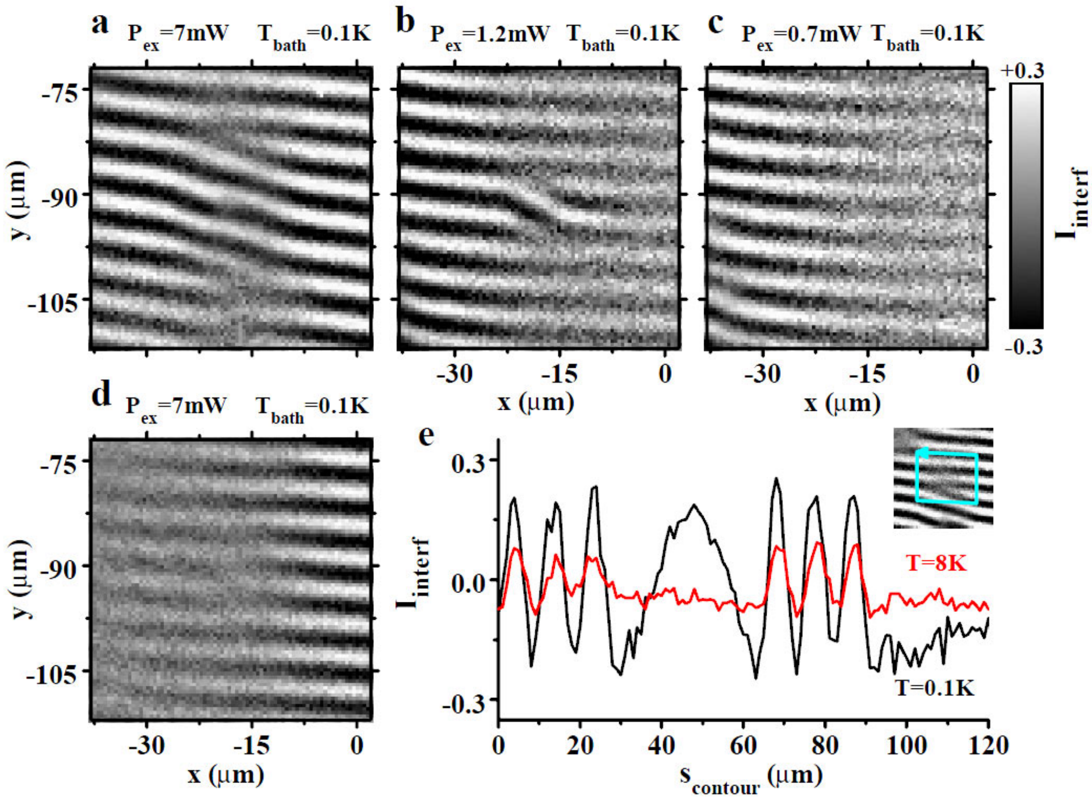
K.G. Lagoudakis, M. Wouters, M. Richard, A. Baas, I. Carusotto, R. André, Le Si Dang, B. Deveaud-Plédran, Nature Physics 4, 706 (2008)

K.G. Lagoudakis, T. Ostatnický, A.V. Kavokin, Y.G. Rubo, R. André, B. Deveaud-Plédran, Science 326, 974 (2009)



polariton half-vortices

Fork-like defects in exciton interference pattern



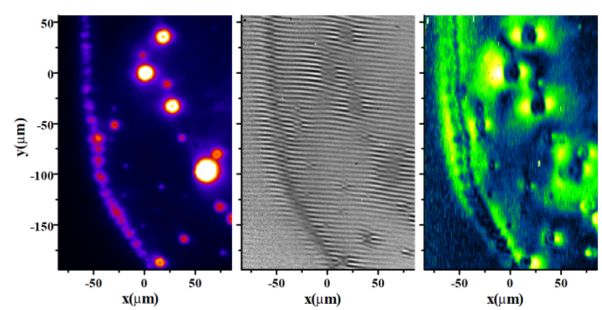
Forks are observed at low *T*
in quantum exciton gas,
vanish at high *T* in classical gas

Phase of interference fringes
on closed contour winds by 2π
indicating phase singularity

Similar properties are observed for
quantized vortices

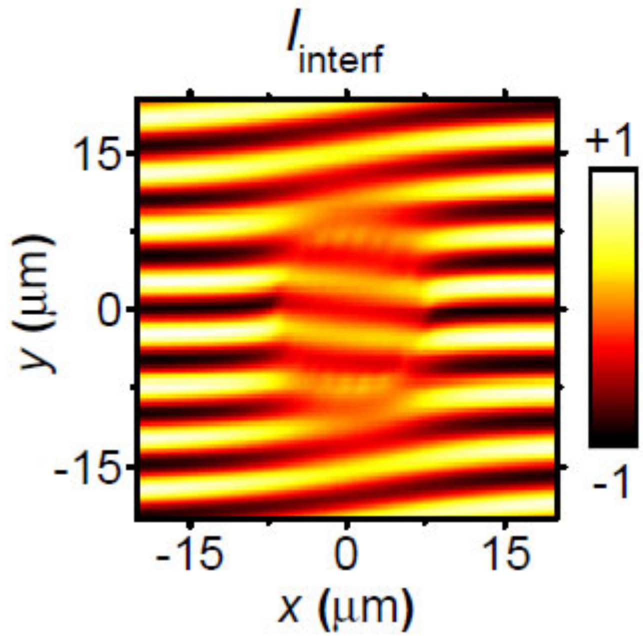
Distance between left- and right-facing forks ≠ shift in shift-interferometry

Observed phase singularity is different from a regular quantized vortex



Modeling

Fork-like defects in interference pattern



Ring-shaped source → interference pattern with left- and right-facing forks with distance between them >> shift

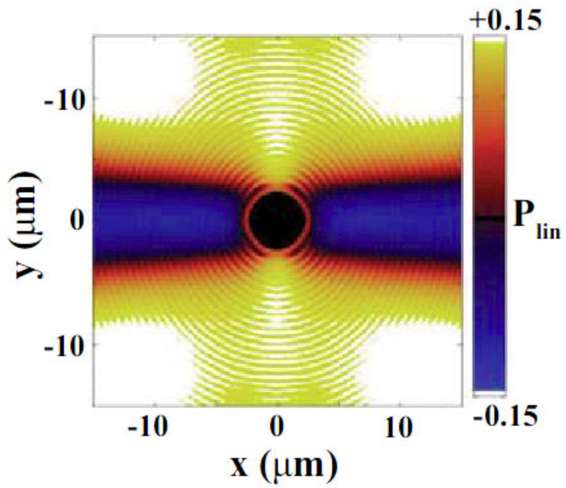
Ring-shaped source produces more complicated phase pattern than vortex

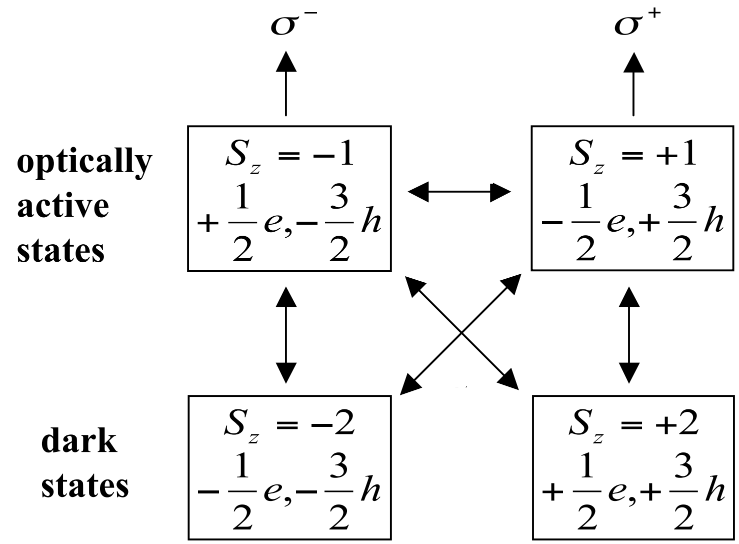
Both objects are characterized by spreading of particle velocities over all directions

A.A. High, J.R. Leonard, A.T. Hammack, M.M. Fogler, L.V. Butov, A.V. Kavokin, K.L. Campman, A.C. Gossard, arXiv:1109.0253v1

Modeling

Spin polarization texture





ballistic exciton transport and spin precession → vortex of linear polarization

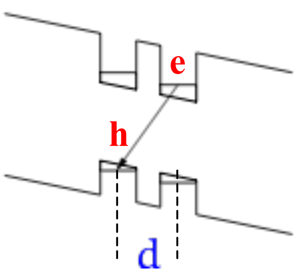
due to splitting of linearly polarized exciton states and spin-orbit interaction described by the Dresselhaus Hamiltonian

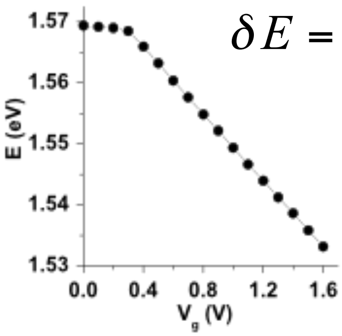
A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov, T. Ostatnicky, A.V. Kavokin, A.C. Gossard, arXiv:1103.0321v1

Spontaneous coherence of excitons in traps

Electrostatic traps for excitons

potential energy of indirect excitons can be controlled by voltage





$$\delta E = edF_z$$

in-plane potential landscapes
can be created for excitons by voltage pattern
e.g. circuit devices, traps, lattices

Early works on electrostatic trapping of indirect excitons

S. Zimmermann, A. Govorov, W. Hansen, J. Kotthaus, M. Bichler, W. Wegscheider, PRB 56, 13414 (1997)

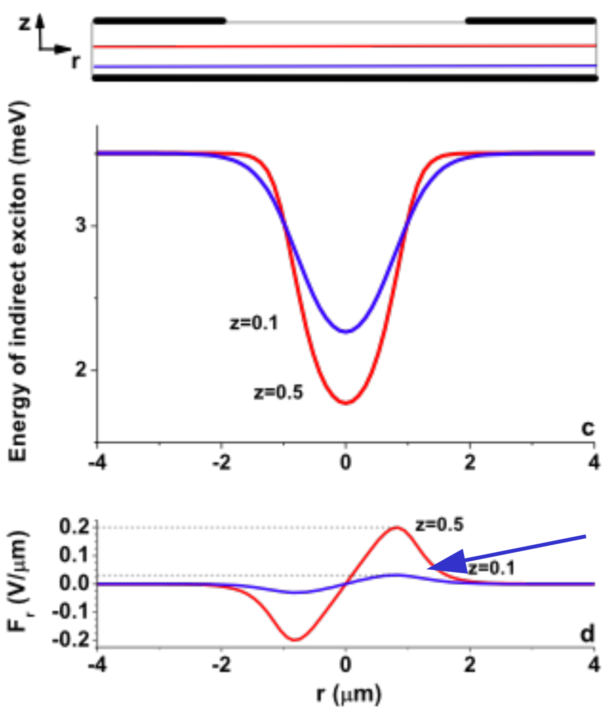
T. Huber, A. Zrenner, W. Wegscheider, M Bichler. Phys. Stat. Sol. (a) 166, R5 (1998)

Obstacle in early works → in-plane electric field dissociated excitons

Solution: to position CQW layers closer to the homogeneous bottom electrode

1999 – calculations, 2005 – experiment

A.T. Hammack, N.A. Gippius, Sen Yang, G.O. Andreev, L.V. Butov, M. Hanson, A.C. Gossard, cond-mat/0504045; JAP 99, 066104 (2006)



CQW far from top gate reduces in plane field F_r

no exciton dissociation

$eF_r a_{ex} << E_{ex}$

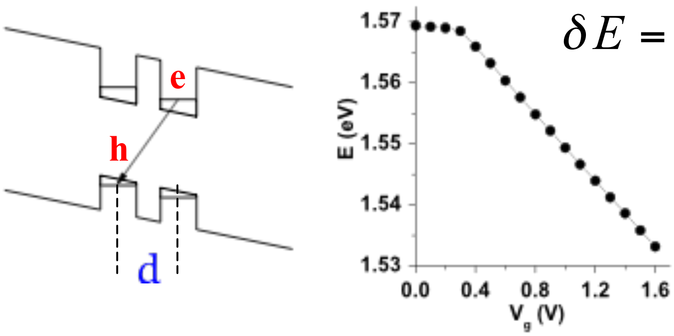
dissociation rate vs F_r

$$\frac{\Gamma_{2D}}{R_y} = \frac{64}{\sqrt{\pi}} \left[\frac{R_y}{eF_{||}a_0} \right]^{1/2} \exp\left[-\frac{32R_y}{3eF_{||}a_0} \right]$$

D.A.B. Miller, D.S. Chemla, T.C. Damen, A.C. Gossard, W. Wiegmann, T.H. Wood, C.A. Burrus, PRB 32, 1043 (1985)

Electrostatic traps for excitons

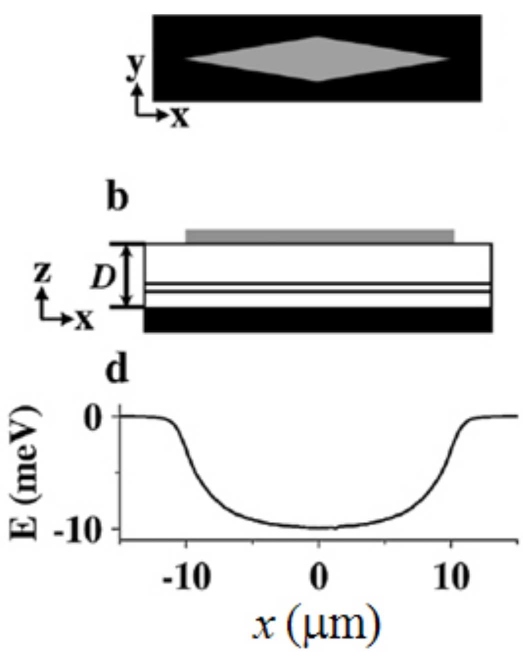
potential energy of indirect excitons can be controlled by voltage



$$\delta E = edF_z$$

in-plane potential landscapes
can be created for excitons by voltage pattern
e.g. circuit devices, traps, lattices

Diamond trap



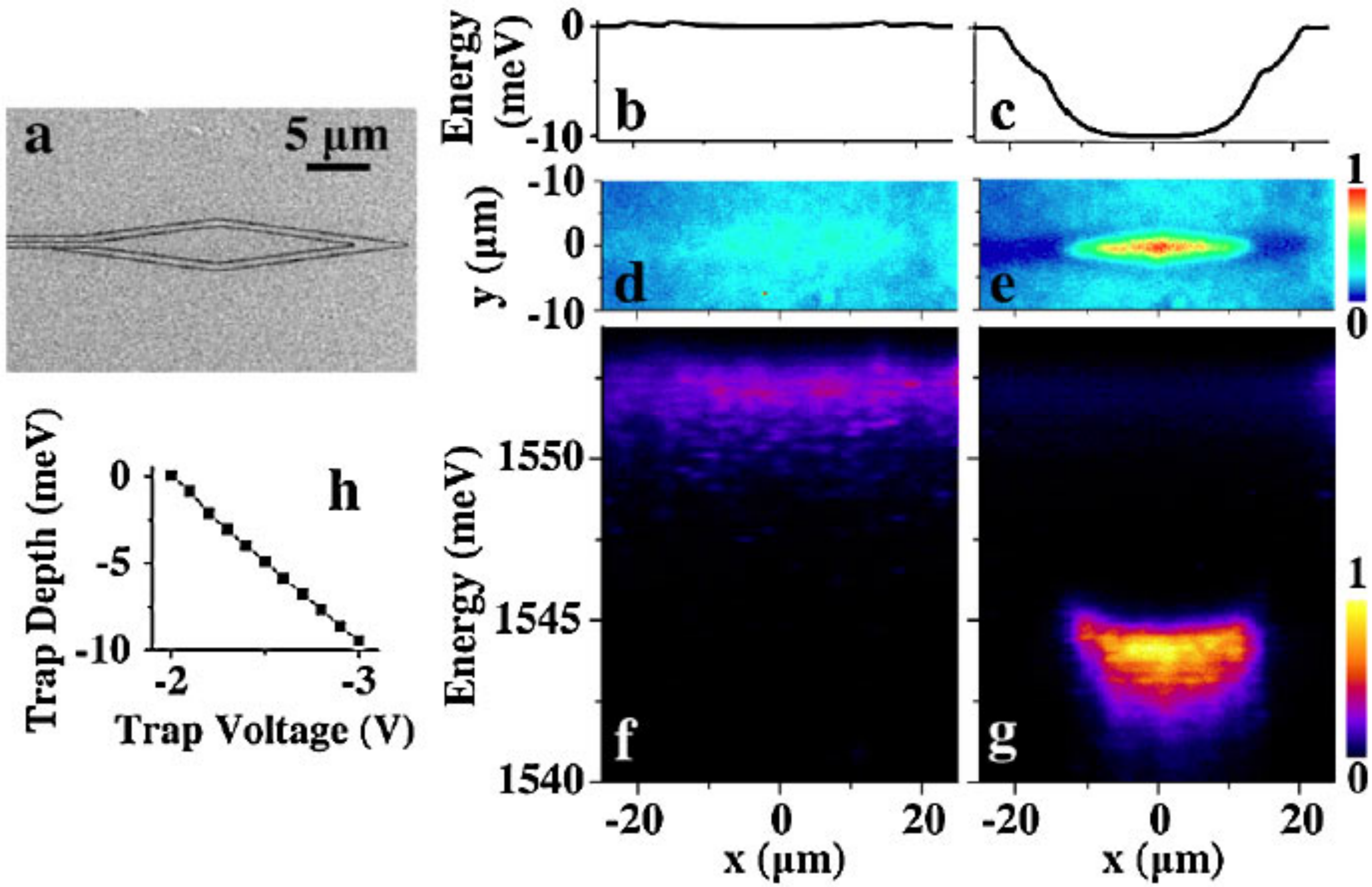
parabolic-like potential collects excitons to trap center

↓

realization of cold and dense exciton gas

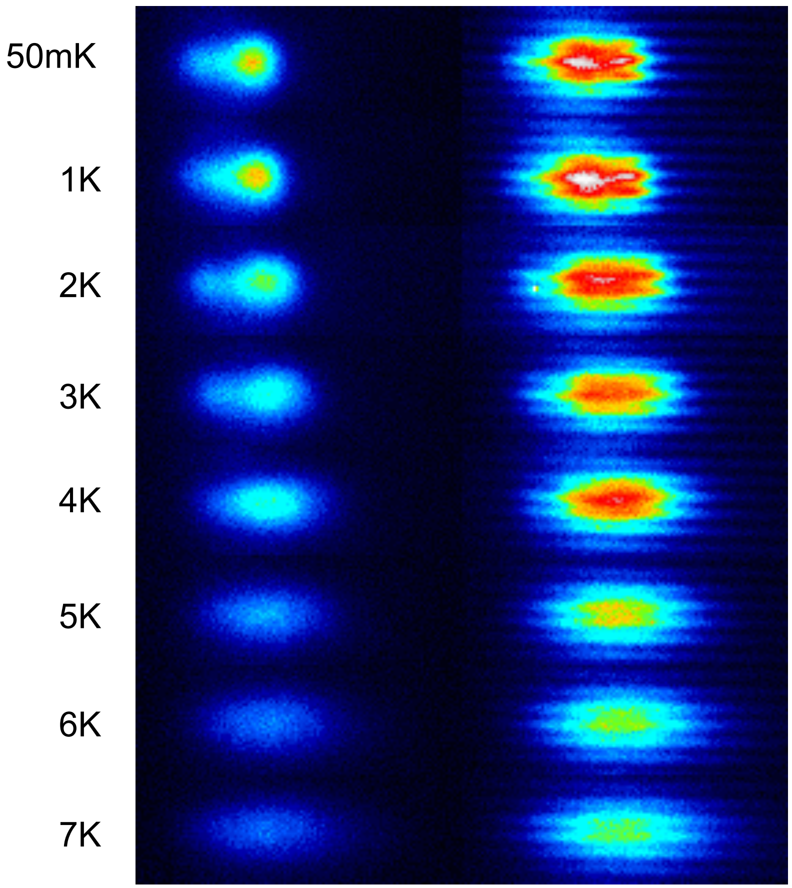
A.A. High, A.K. Thomas, G. Grosso, M. Remeika, A.T. Hammack, A.D. Meyertholen, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, PRL 103, 087403 (2009)

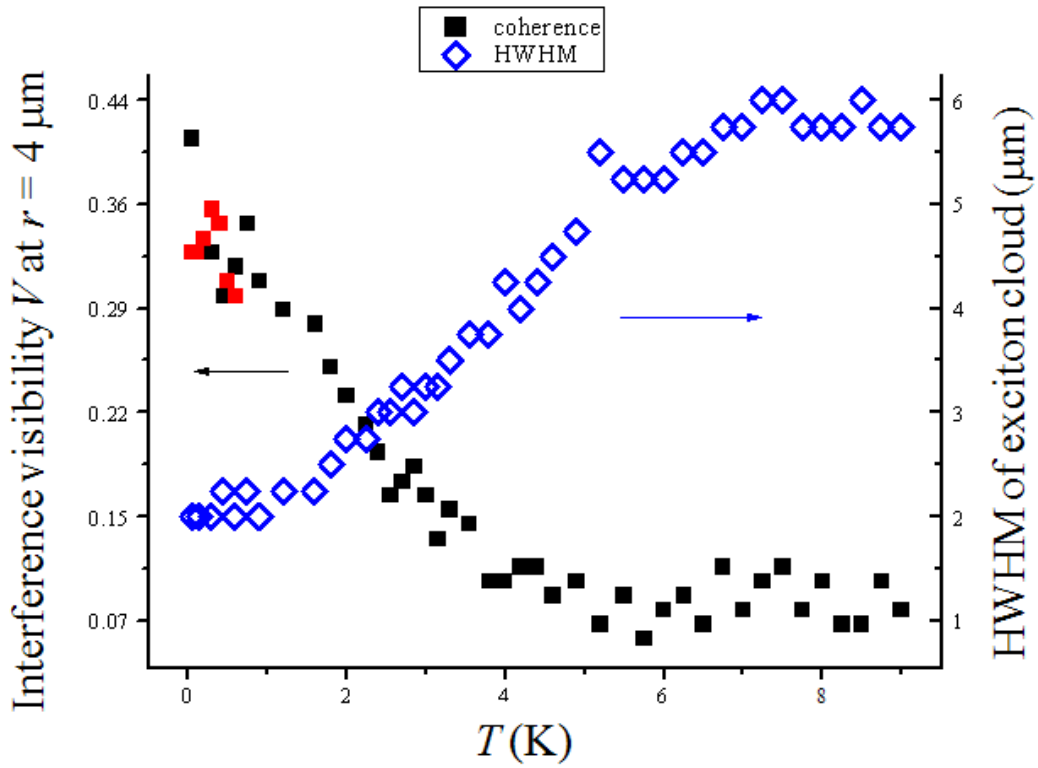
Characterization of diamond trap



A.A. High, A.K. Thomas, G. Grosso, M. Remeika, A.T. Hammack, A.D. Meyertholen, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, PRL 103, 087403 (2009)

Spontaneous coherence of indirect excitons in diamond trap





with lowering temperature

- **size of exciton cloud in trap reduces**
- **interference visibility increases**

work in progress

Density dependence

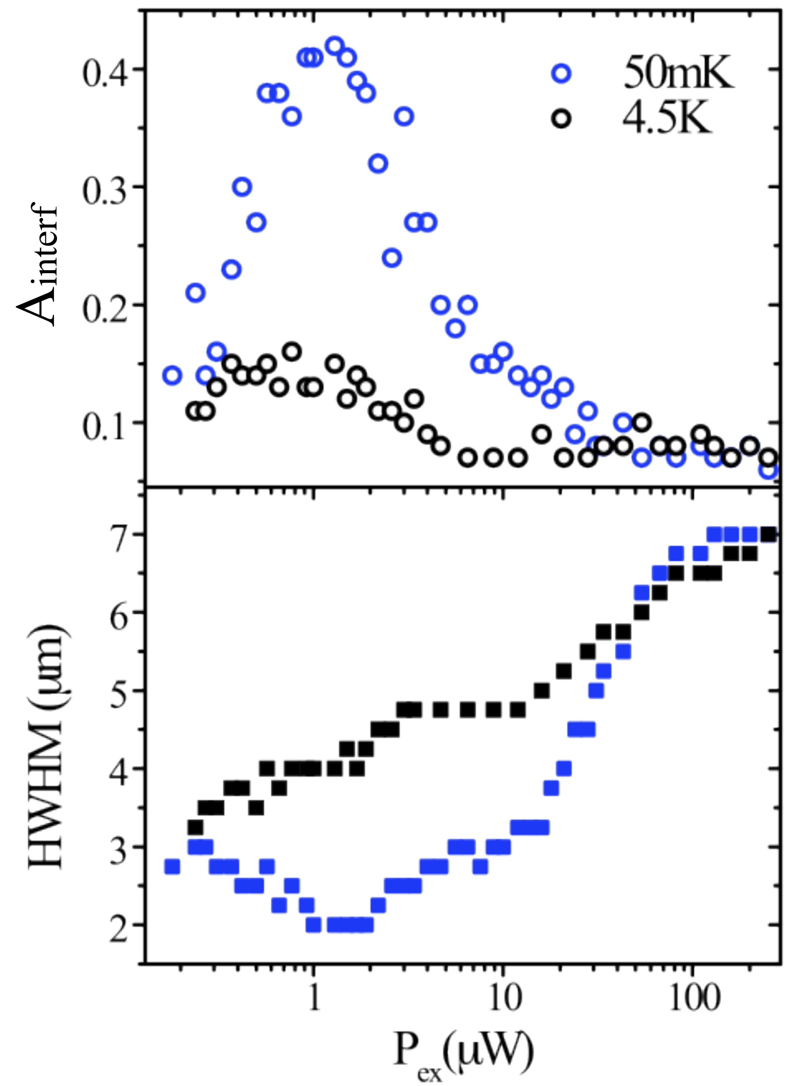
with increasing density

***T* = 50 mK:**
coherence degree and
spatial width of exciton cloud
change non-monotonically

maximum coherence corresponds to
minimum spatial width

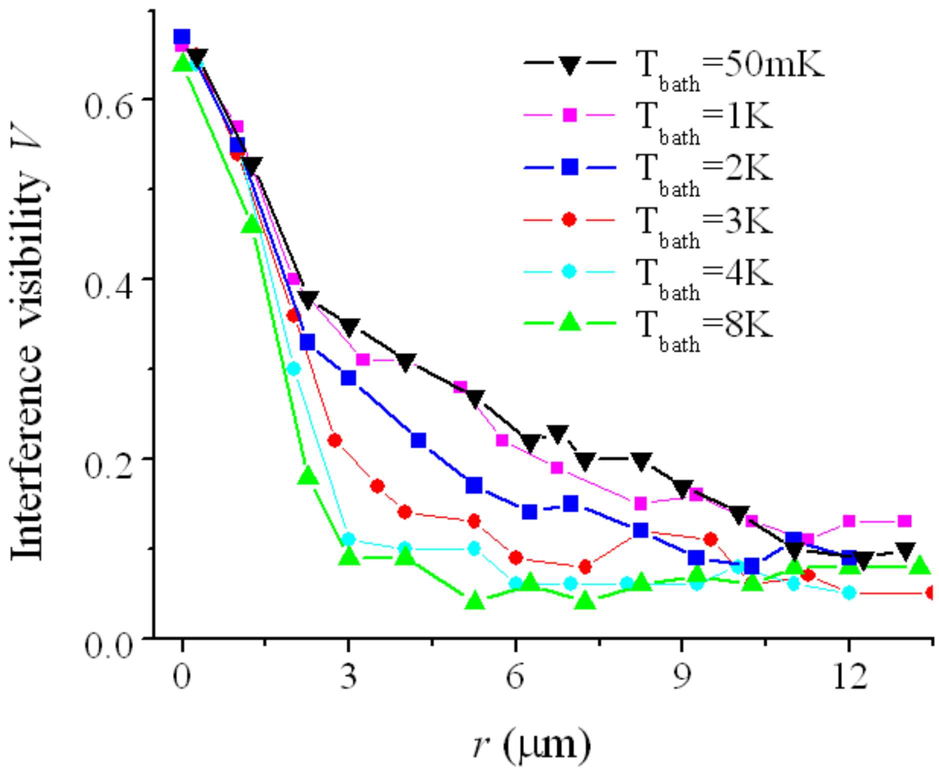
***T* = 4 K:**
coherence degree is low

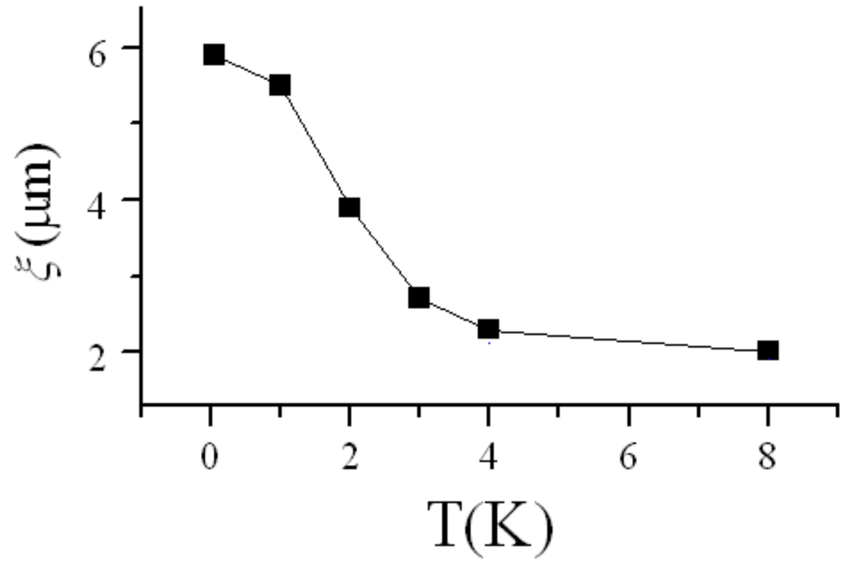
spatial width of exciton cloud increases



work in progress

$g_1(r)$ vs temperature





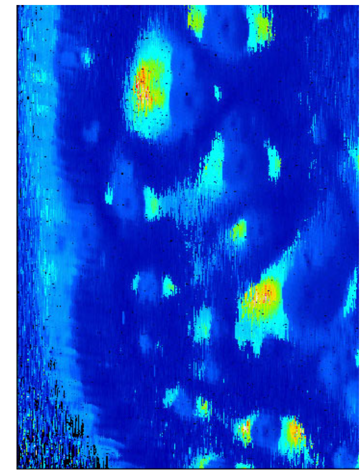
High $T > 4$ K: $V(r)$ quickly drops with r and vanishes at PSF width, as expected for a classical gas

A strong enhancement of coherence is observed at low temperatures

Low T: $\xi >> \lambda_{dB}$
ξ reaches size of entire exciton cloud

work in progress

Summary



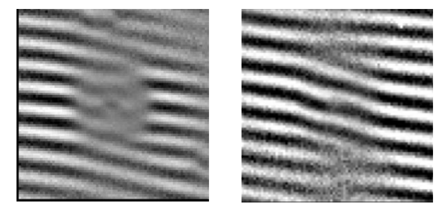
Extended spontaneous coherence of excitons is observed

- **in the macroscopically ordered exciton state**
- **in the vortices of linear polarization**

The coherence length in these regions $\xi >> \xi_{\mathrm{classical}}$ indicating a coherent state with a much narrower than classical exciton distribution in *q*-space, characteristic of a condensate

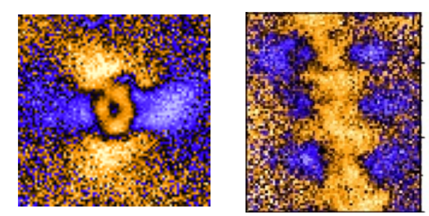
A pattern of extended spontaneous coherence is correlated with a pattern of spontaneous polarization, revealing the properties of a multi-component coherent state

Phase singularities



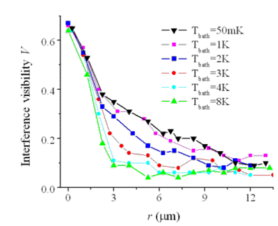
- **phase domains**
- **fork-like defects in the interference pattern**

Spin textures



- **vortex of linear polarization**
- **periodic spin texture**
- **ring of linear polarization**
- **skew of exciton fluxes in orthogonal circular polarizations and four-leaf pattern of circular polarization**

Spontaneous coherence of excitons in a trap



The exciton coherence length reaches the size of the entire exciton cloud

arXiv:1109.0253v1 **arXiv:1103.0321v1**

Experiments on cold gases of indirect excitons in CQW

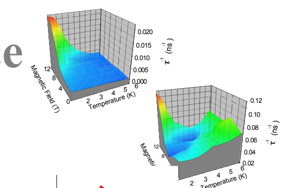
- **Realized cold exciton gases with $T << T_{dB}$**

- **Observed in cold exciton gases:**
  - **Evidence for phenomena expected for exciton condensation**

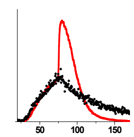
consistent with onset of

enhancement of exciton:

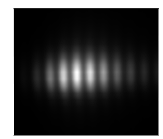
- radiative decay rate → superradiance
- mobility → superfluidity
- scattering rate with increasing density → stimulated scattering
- coherence length → spontaneous coherence



PRL 73, 304 (1994)
PRB 58, 1980 (1998)

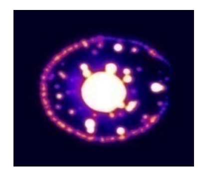


PRL 86, 5608 (2001)



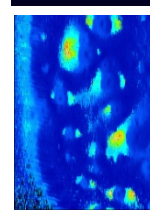
PRL 97, 187402 (2006)

  - **Macroscopically ordered exciton state**



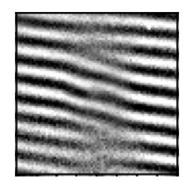
Nature 418, 751 (2002)

  - **Extended spontaneous coherence with $\xi >> \xi_{classical}$**

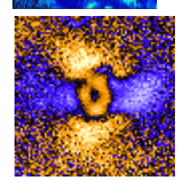


arXiv:1109.0253v1

  - **Phase singularities in interference pattern**



  - **Spin textures**



arXiv:1103.0321v1