Indirect Excitons

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Introduction:

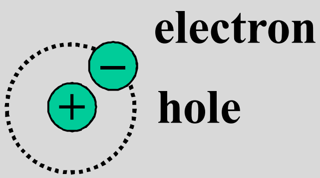
- **Cold exciton gas**
- **Indirect excitons**

Data:

- **Spatial ordering**
- **Spontaneous coherence**
- **Spin textures**
- **Phase singularities**
- **Condensation in a trap**

exciton – bound pair of electron and hole

light bosonic particle in semiconductor



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

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 <u>lifetime</u> >> <u>cooling time</u> ⟶ $T_{exciton} \sim T_{lattice}$

estimates for characteristic temperatures for cold 2D Bose gases

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

λ_{dB} is comparable to interexcitonic separation

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

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

thermal de Broglie wavelength

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

at $T = 1$ K

temperature of quantum degeneracy

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

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

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

BEC in finite 2D system

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

for $N = nS \sim 10^5$

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

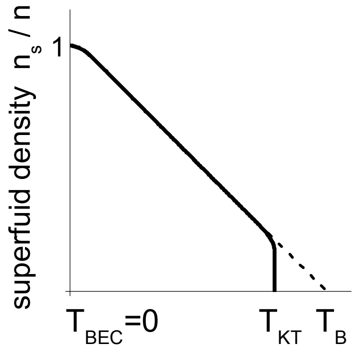
temperature of onset of local superfluidity

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

Bogoliubov temperature
onset of nonzero order parameter

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

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



Kosterlitz-Thouless temperature

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

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

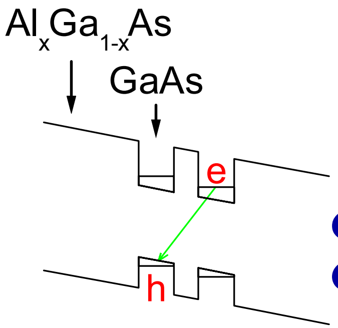
for not so dilute gas

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

$\xi \approx 380$

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

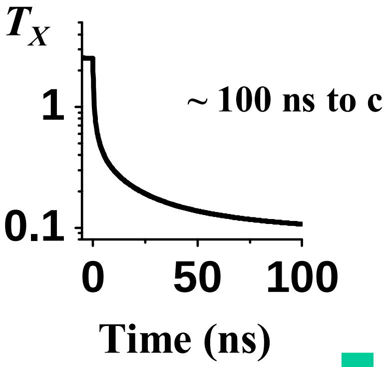
Indirect excitons in CQW



GaAs/AlGaAs CQW

$10^3 - 10^6$ times longer exciton lifetime 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)



~ 100 ns to cool to 100 mK

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

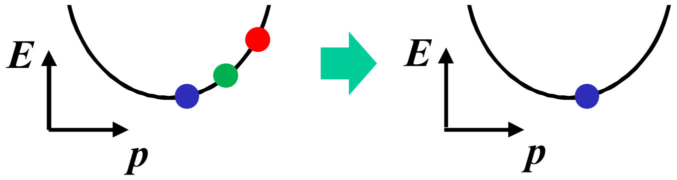
$T_X \sim 100$ mK
is realized in experiments
30 times below T_{dB}

Louis de Broglie, 1923: all forms of matter have wave as well as particle properties. The wavelength of a matter wave associated with any moving object $\lambda = h/p$

below the temperature of quantum degeneracy bosonic particles can form **a coherent state**

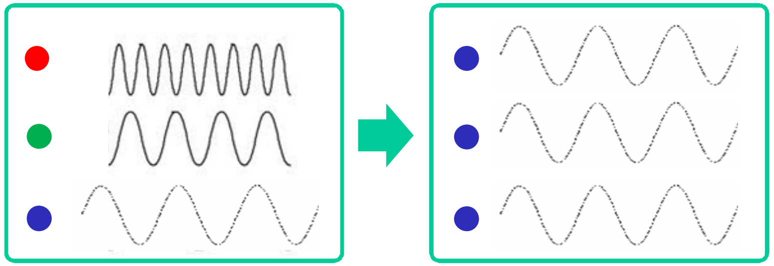
condensation in momentum space ↔ spontaneous coherence of matter waves

particles (in momentum space)



high *T* **low *T***

matter waves (in real space)

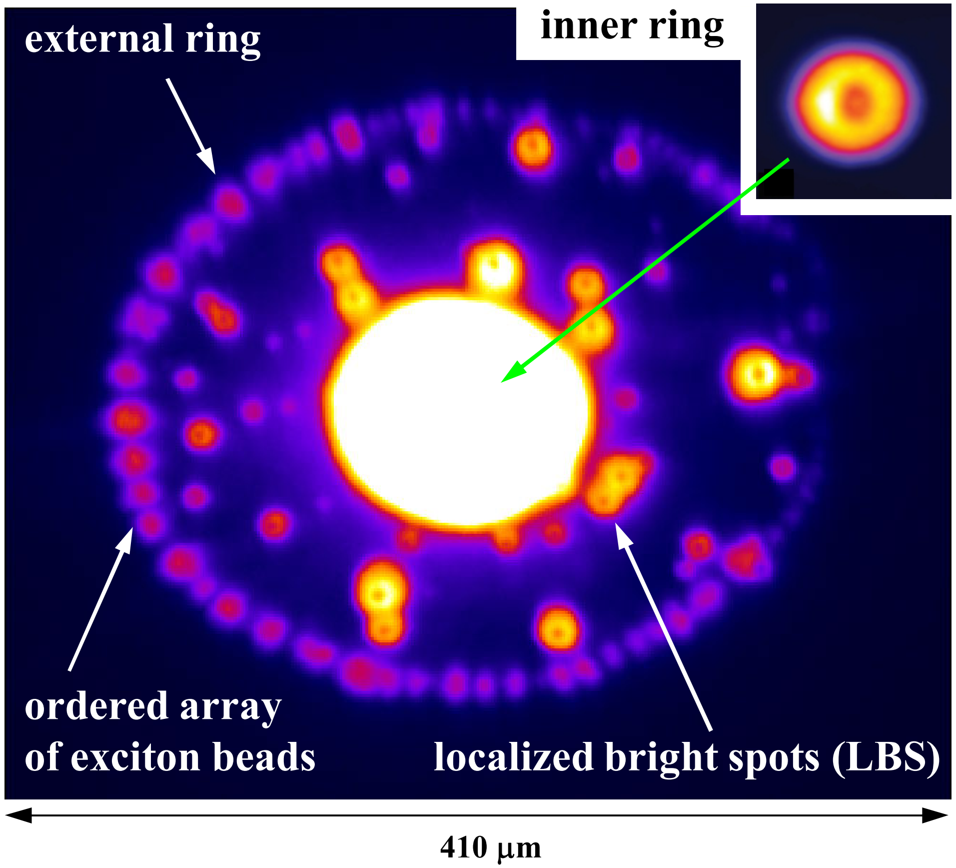


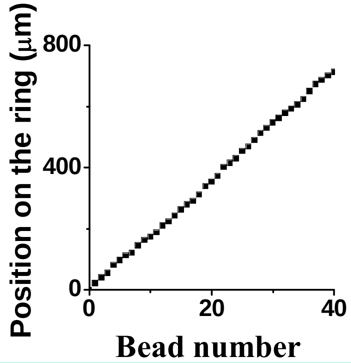
high *T* **low *T***

theoretical predictions for **coherent states in cold exciton systems:**

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

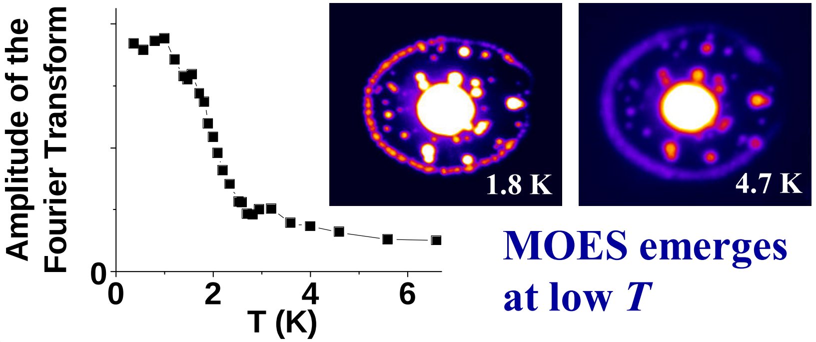
Exciton rings and macroscopically ordered exciton state





spatial order on macroscopic lengths

macroscopically ordered exciton state (MOES)



MOES emerges at low *T*

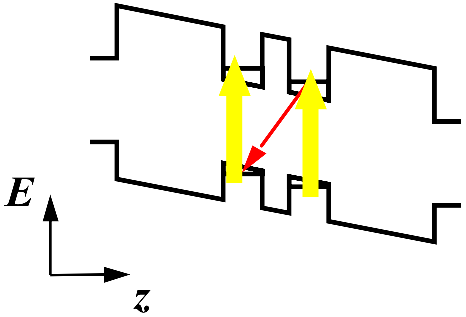
L.V. Butov, A.C. Gossard, D.S. Chemla,
Nature 418, 751 (2002)

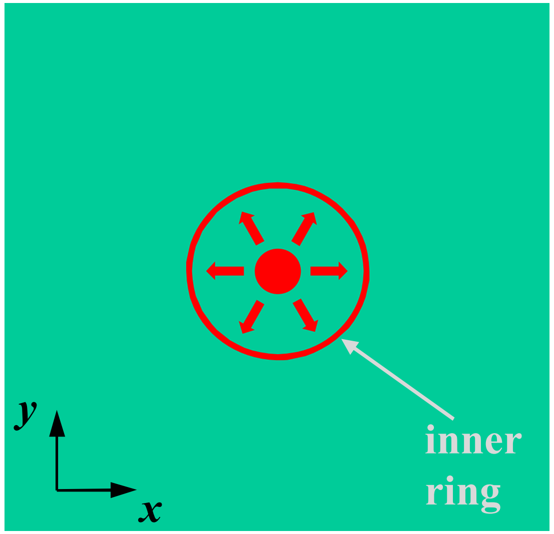
model of

- **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)

laser excitation

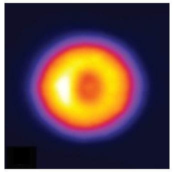
creates excitons
in CQW





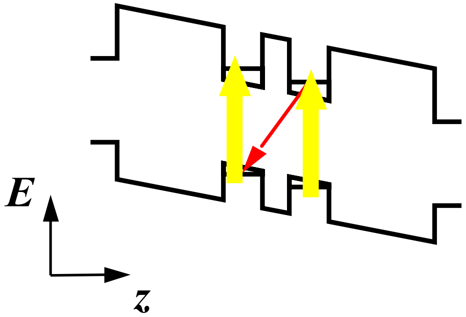
electron-rich region **excitons**

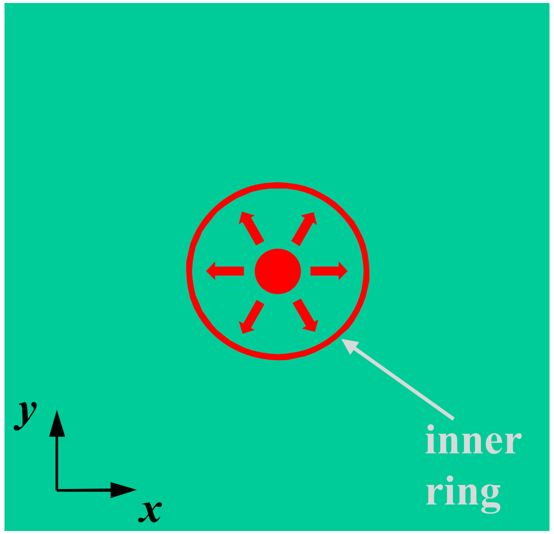
inner ring forms due to transport and cooling of optically generated excitons

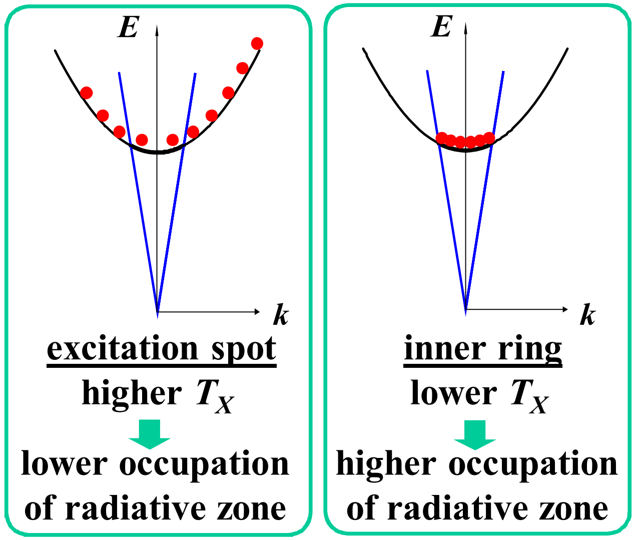


emission of indirect excitons

laser excitation
creates excitons
in CQW





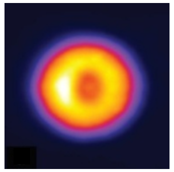


excitation spot
higher T_X
lower occupation of radiative zone

inner ring
lower T_X
higher occupation of radiative zone

🟩 **electron-rich region** **excitons**

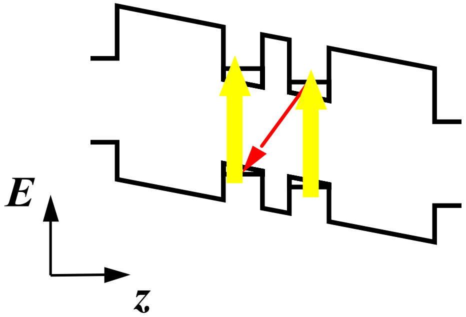
inner ring forms due to transport and cooling of optically generated excitons

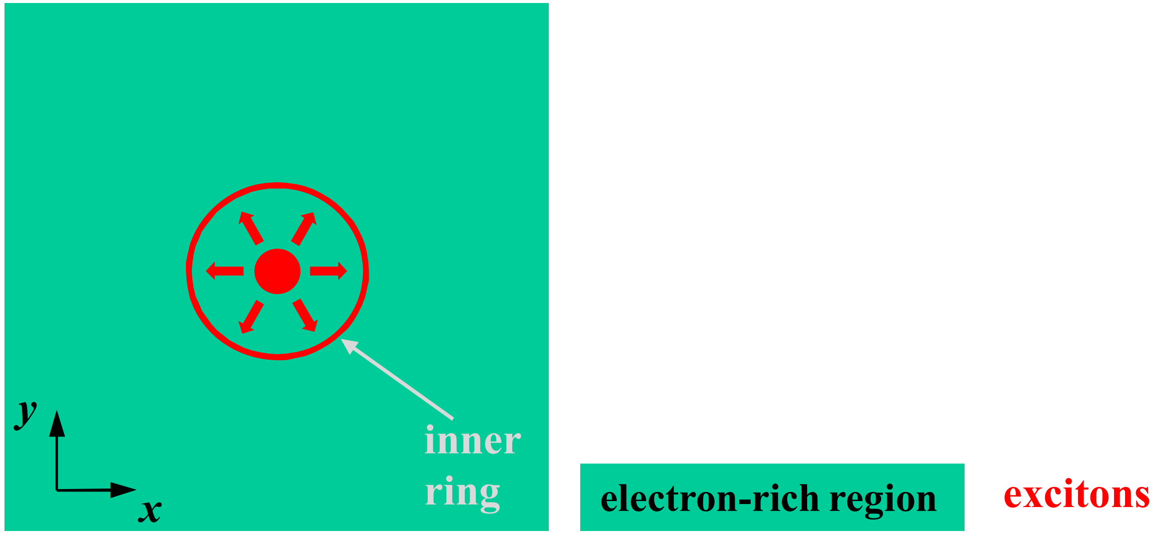


emission of indirect excitons

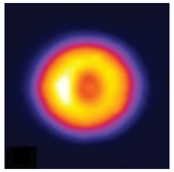
laser excitation

creates excitons
in CQW



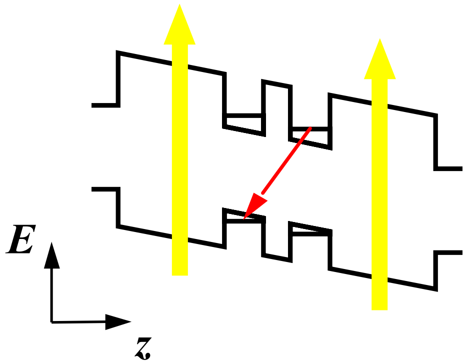


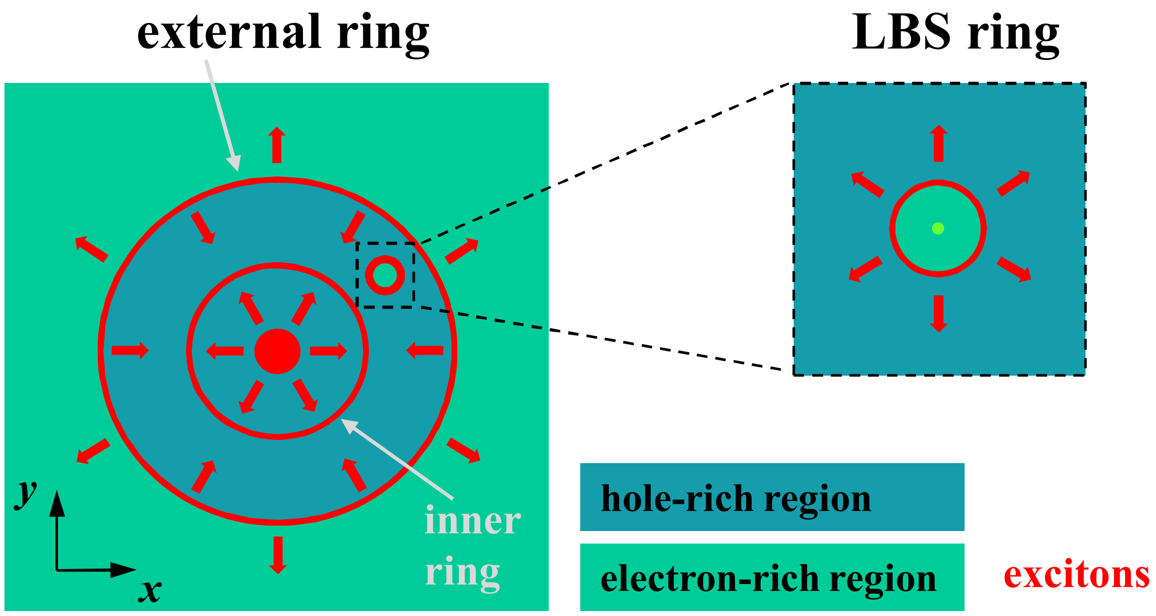
inner ring forms due to transport and cooling of optically generated excitons



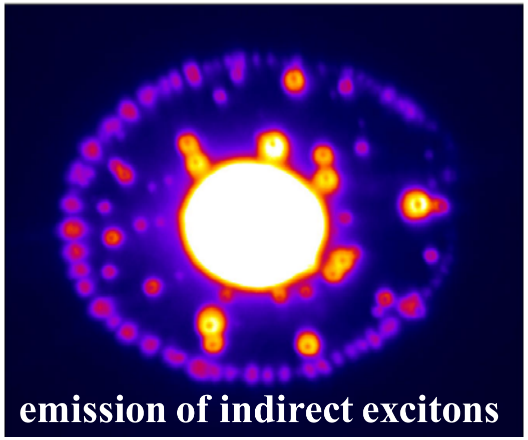
emission of indirect excitons

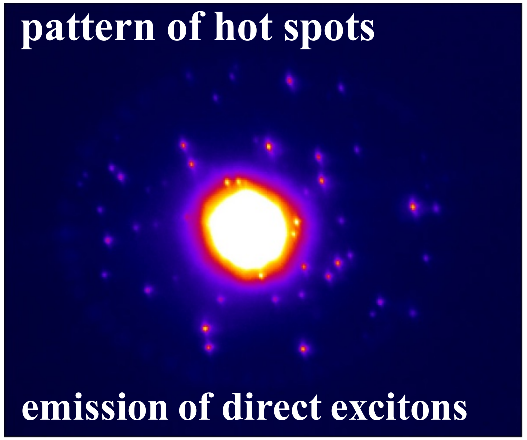
above barrier laser excitation
creates excitons + holes
in CQW





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


emission of indirect excitons


pattern of hot spots
emission of direct excitons

external rings and LBS rings form sources of cold excitons

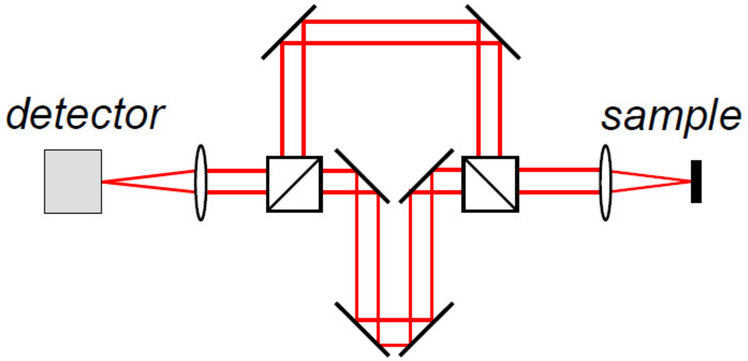
exciton gas
is hot in LBS centers
is cold in external ring and LBS rings

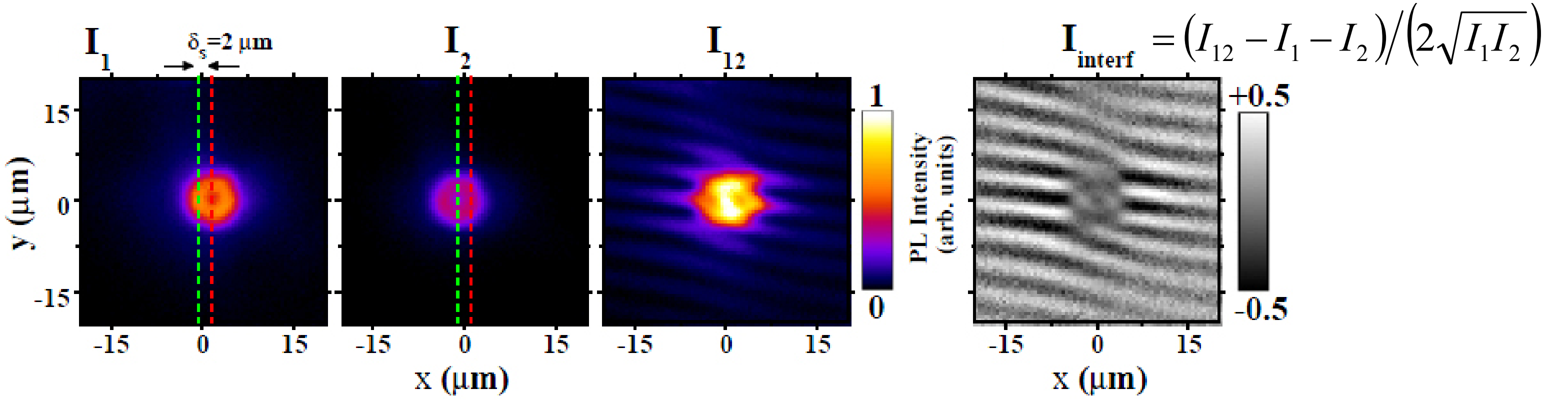
measured by
shift-interferometry

spontaneous coherence
and
spin polarization textures

measured by
polarization resolved imaging

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



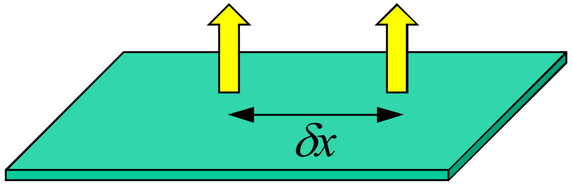


Pattern of $g_1(\delta x)$ is measured by shift-interferometry

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

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

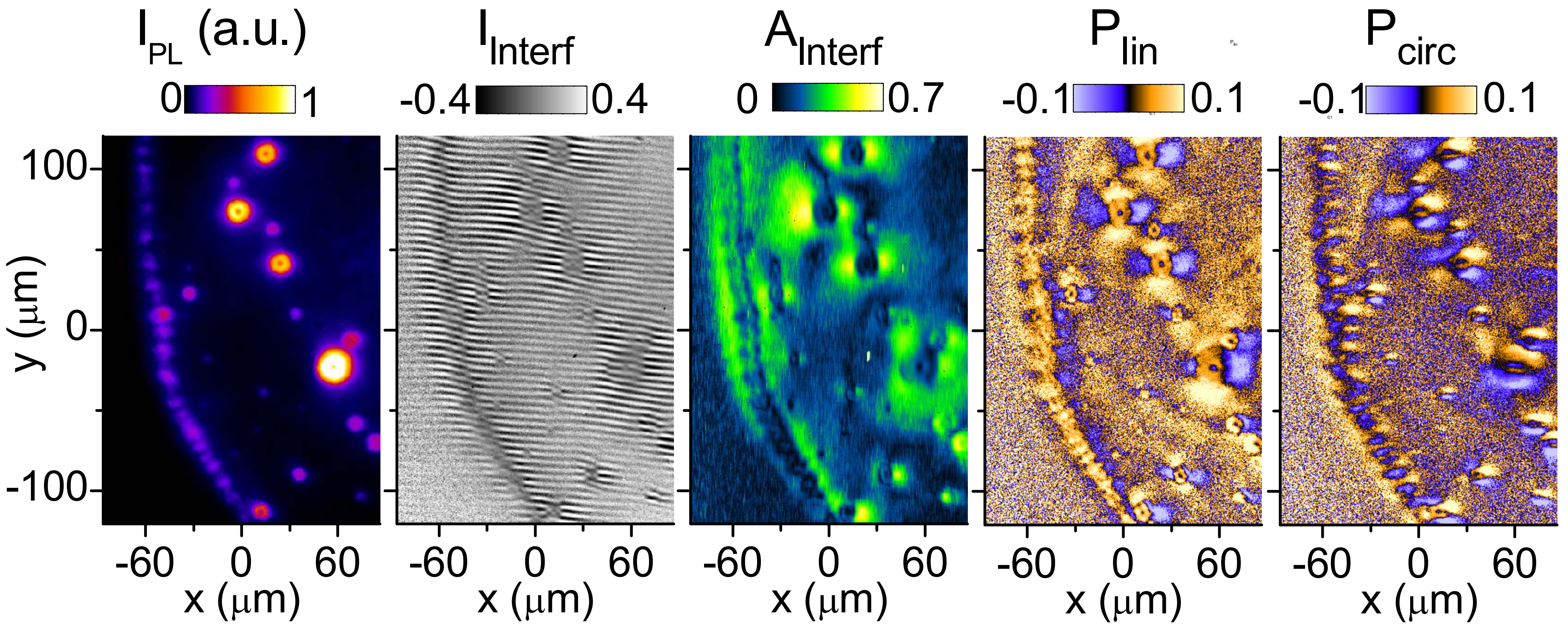
Contrast of interference fringes $A_{\text{interf}}(\delta x) \rightarrow g_1(\delta x)$



exciton coherence
is imprinted on coherence
of their light emission

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

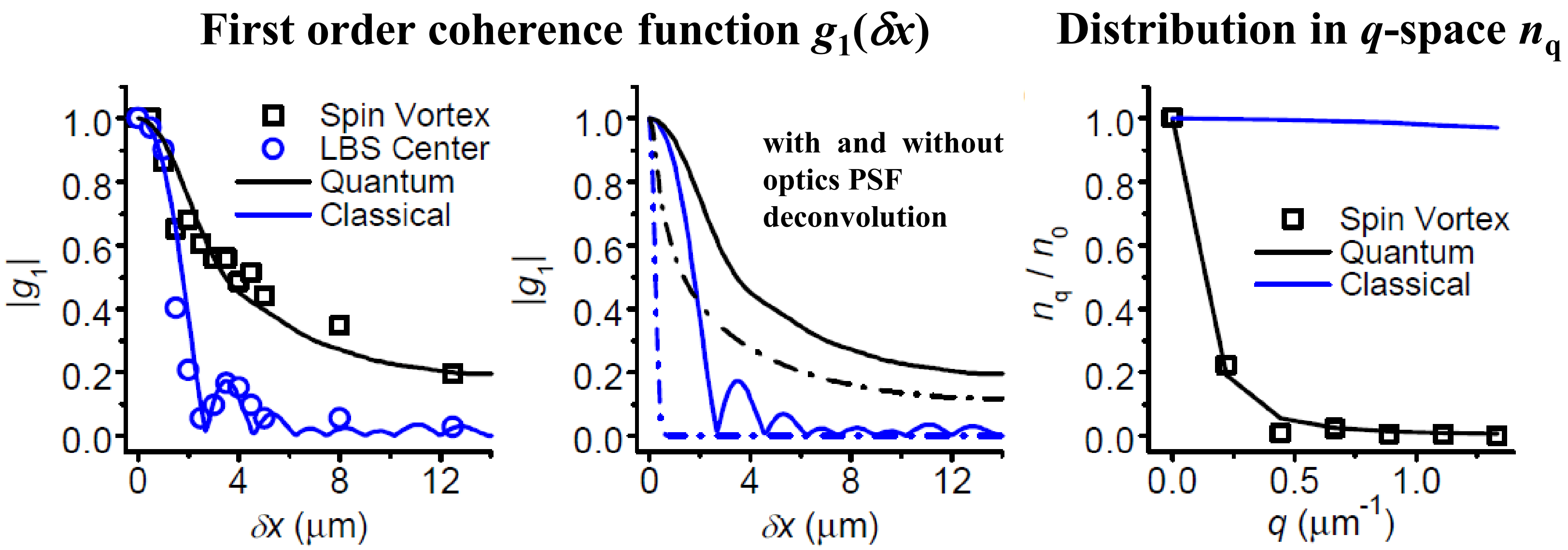
Pattern of circular polarization

A.A. High, J.R. Leonard, A.T. Hammack,
M.M. Fogler, L.V. Butov, A.V. Kavokin,
K.L. Campman, A.C. Gossard,
Nature 483, 584 (2012)

map of coherence degree

green: regions of spontaneous coherence of excitons

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


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

Distribution in q-space n_q

$g_1(r) \xleftrightarrow{\text{Fourier transform}} n_q$ $\quad \delta q \cdot \xi \sim 1$

coherence length

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

$\xi_{\text{classical}} \sim \lambda_{\text{dB}} / \pi^{1/2} \sim 0.3$ μm at 0.1 K

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

$\xi >> \xi_{\text{classical}}$

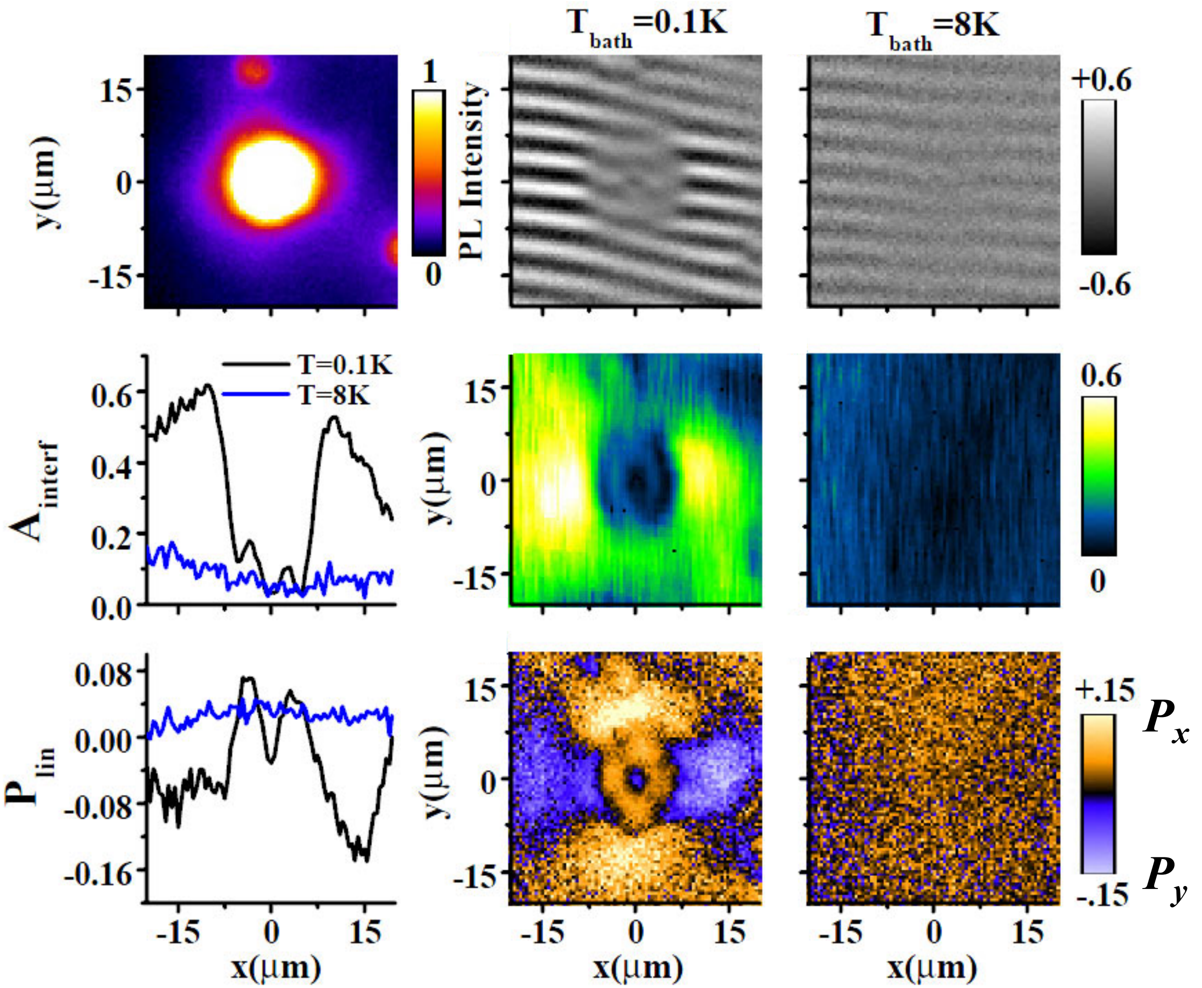
$\delta q << \delta q_{\text{classical}}$

characteristic of a condensate

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

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

Exciton coherence and spin texture around LBS-ring



Emergence of

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

at low *T* at $r > r_0$

at $r = r_0$

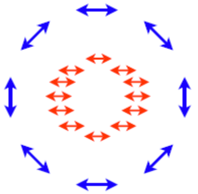
- **average momentum drops**
- **coherence degree rises**

enhancement of amplitude of interference fringes

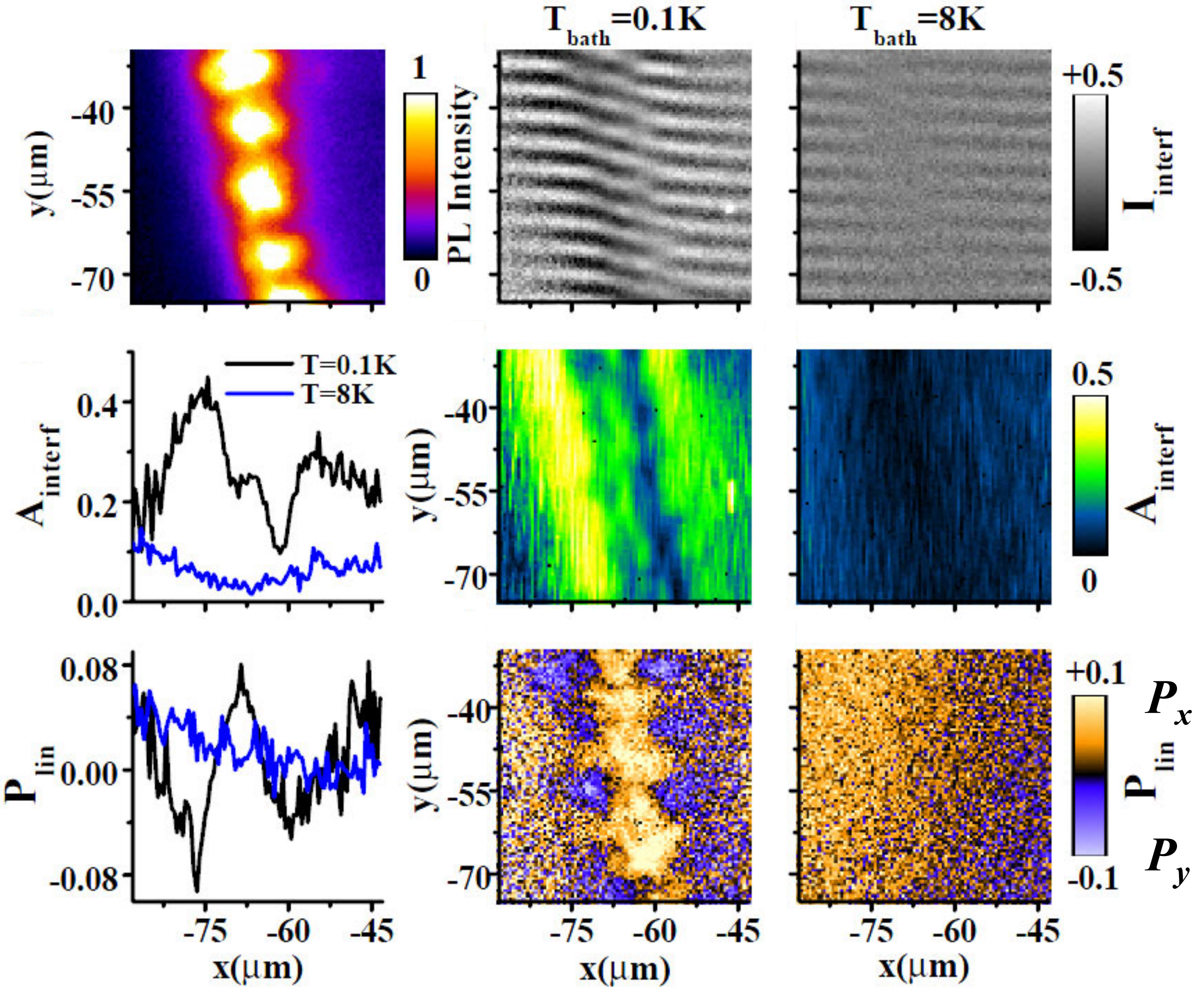
shift in phase of interference fringes

vortex of linear polarization

ring of linear polarization



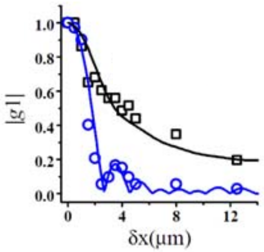
Exciton coherence and spin texture around external ring



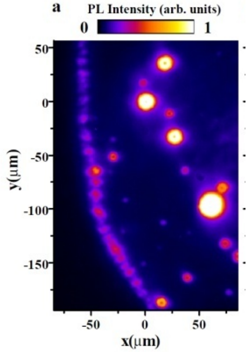
Emergence of

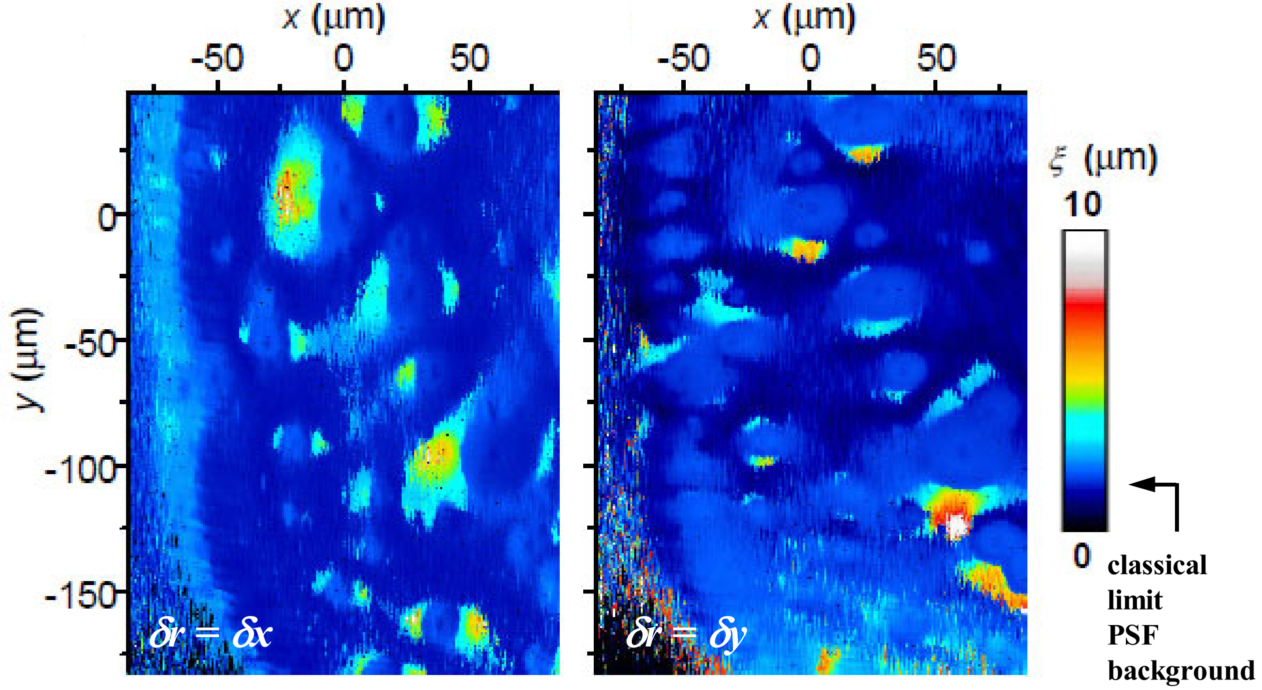
- **Spontaneous coherence**
- **Periodic spin texture**

at low T at $r > r_0^*$



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





spontaneous coherence of excitons emerges

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

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

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

⬇

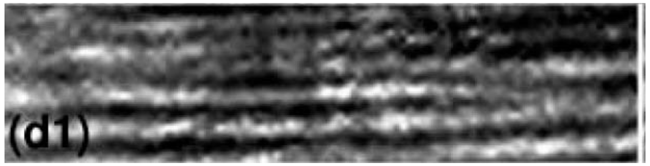
fork-like defect in phase pattern can be signature of quantized vortex

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)

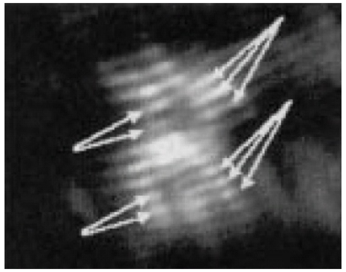
F. Chevy, K.W. Madison, V. Bretin, J. Dalibard, PRA 64, 031601(R) (2001)

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



optical vortices

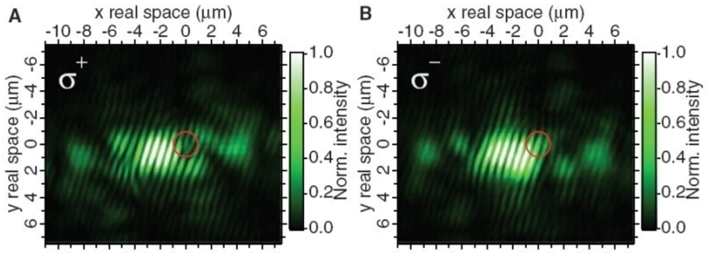
J. Scheuer, M. Orenstein, Science 285, 230 (1999)
and references therein



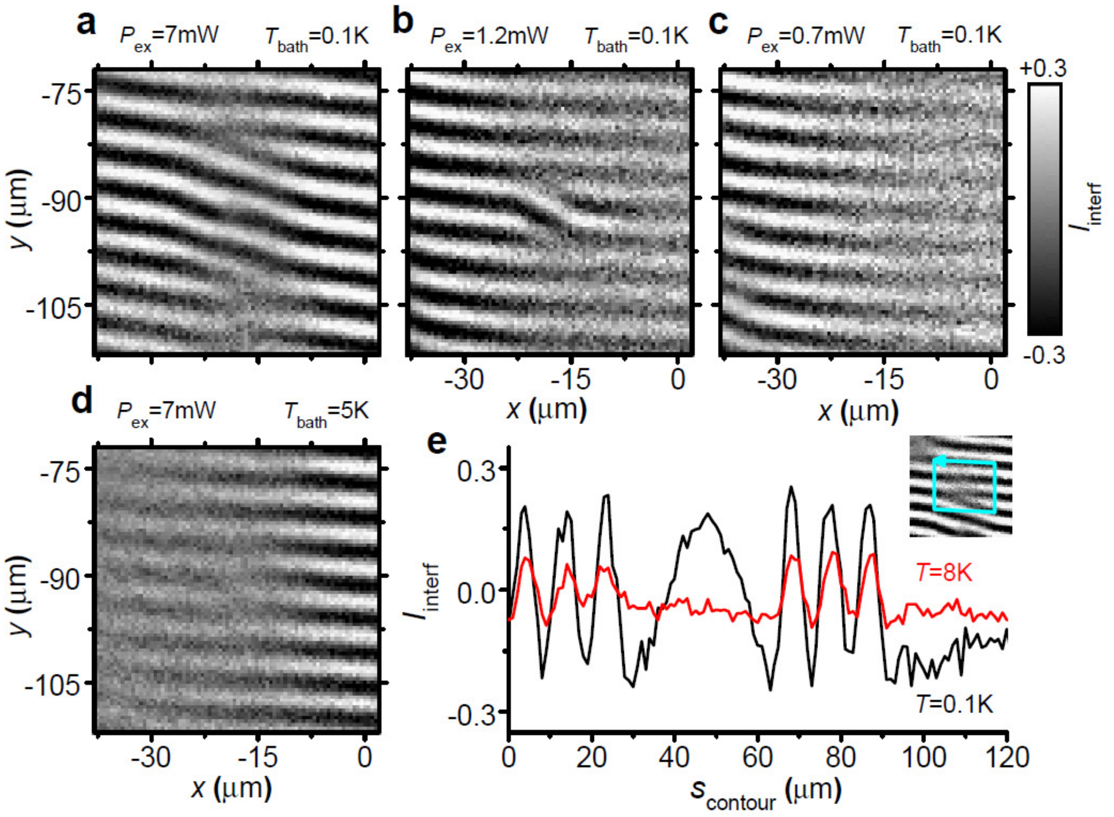
polariton vortices

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)



Fork-like defects in exciton interference pattern



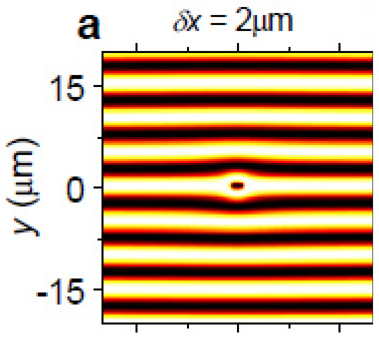
Forks are observed at low *T*
in quantum exciton gas,
vanish at high *T* in classical gas

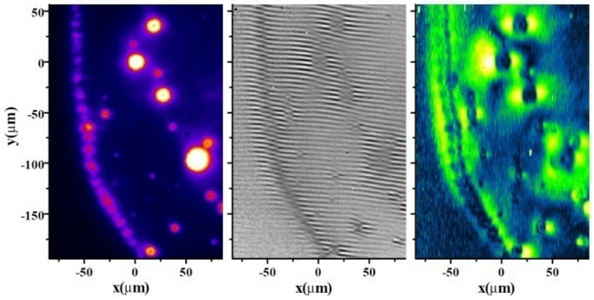
Phase of interference fringes
on closed contour winds by 2π
indicating phase singularity

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

⬇

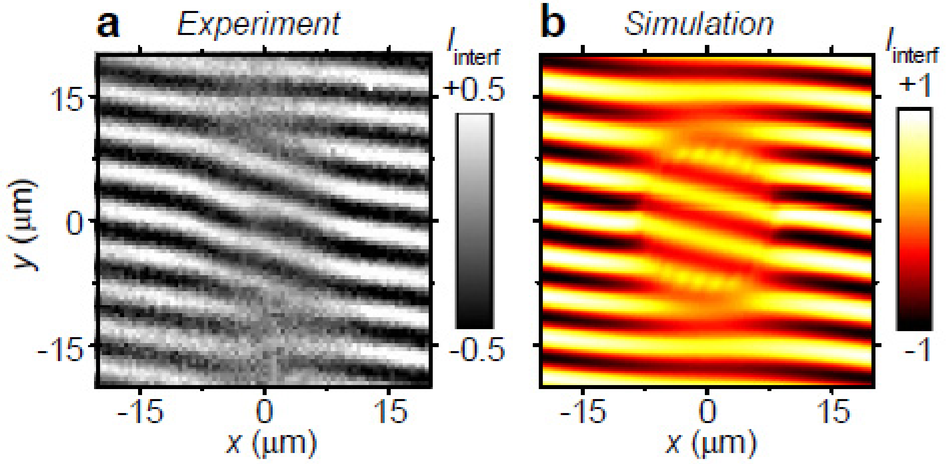
Observed phase singularity is different from a regular quantized vortex





Modeling

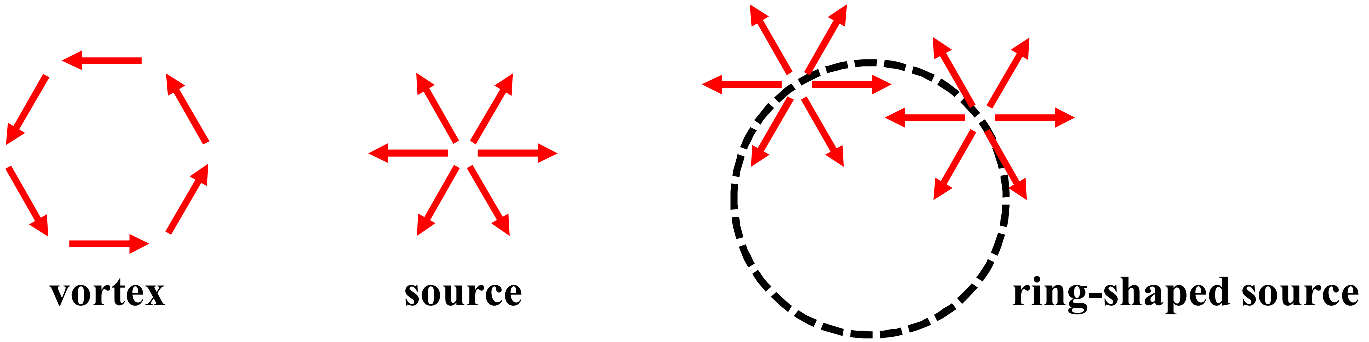
Fork-like defects in interference pattern



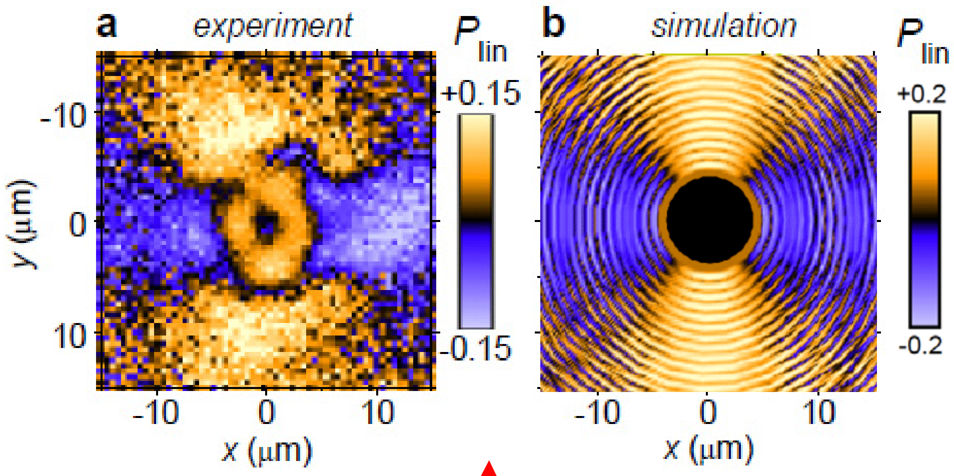
Ring-shaped source → interference pattern with left- and right-facing forks with distance between them >> shift

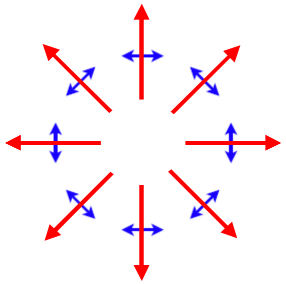
Ring-shaped source produces more complicated phase pattern than vortex.

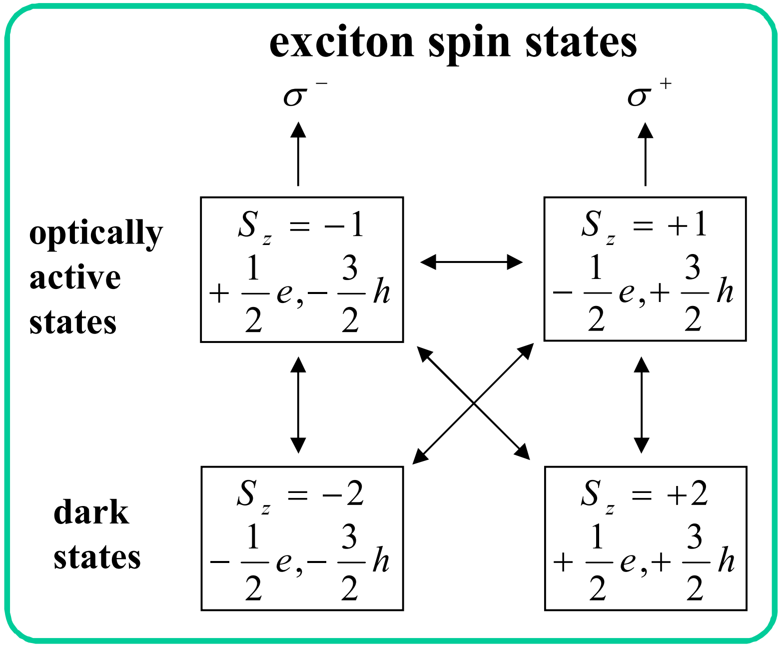
Both objects are characterized by spreading of particle velocities over all directions.



Spin polarization texture around LBS – radial source of cold excitons







exciton spin states

σ^- σ^+

optically active states

$S_z = -1$
$+\frac{1}{2}e, -\frac{3}{2}h$

$S_z = +1$
$-\frac{1}{2}e, +\frac{3}{2}h$

dark states

$S_z = -2$
$-\frac{1}{2}e, -\frac{3}{2}h$

$S_z = +2$
$+\frac{1}{2}e, +\frac{3}{2}h$

coherent exciton transport with suppressed scattering
and **precession of spins** of electrons and holes
due to splitting of exciton states with different spins ← due to splitting of linearly polarized exciton states and spin-orbit interaction

⬇

vortex of linear polarization

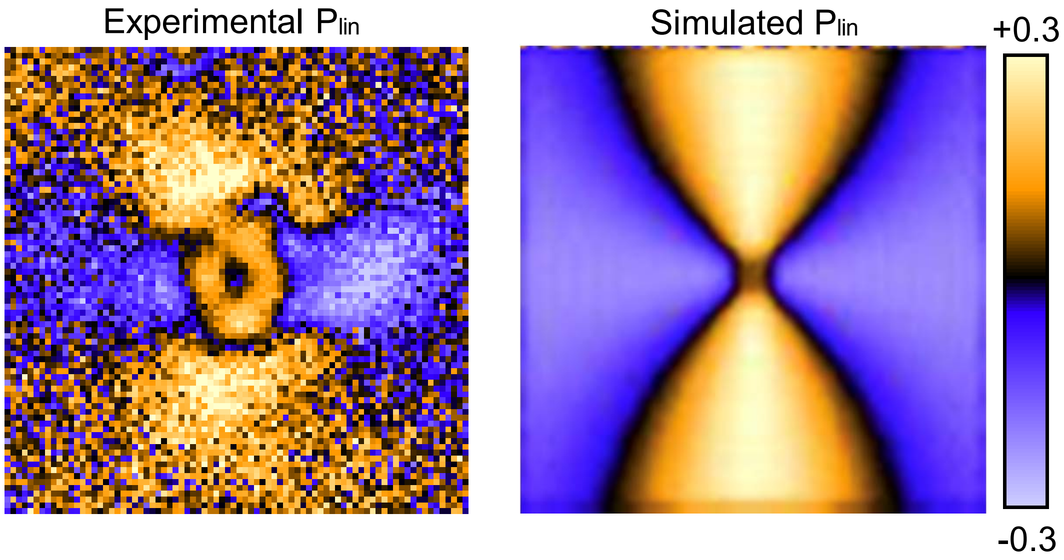
measured by
polarization resolved imaging

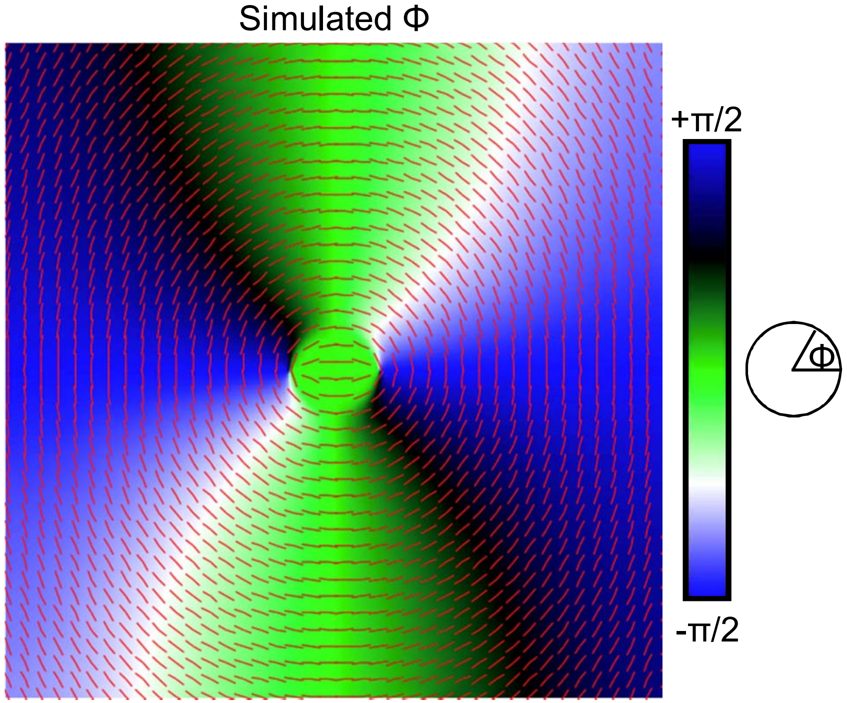
control of spin currents

by magnetic field

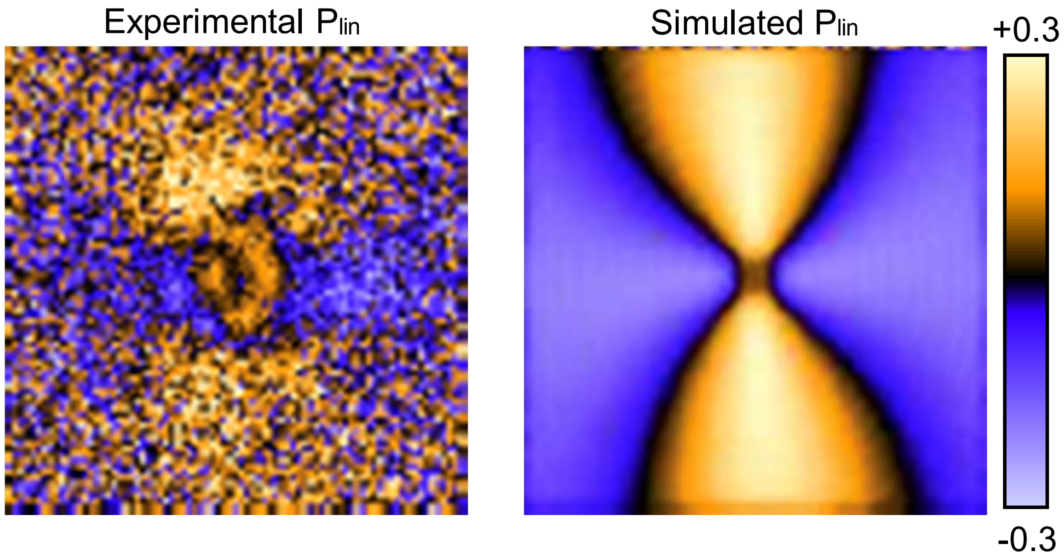
work in progress

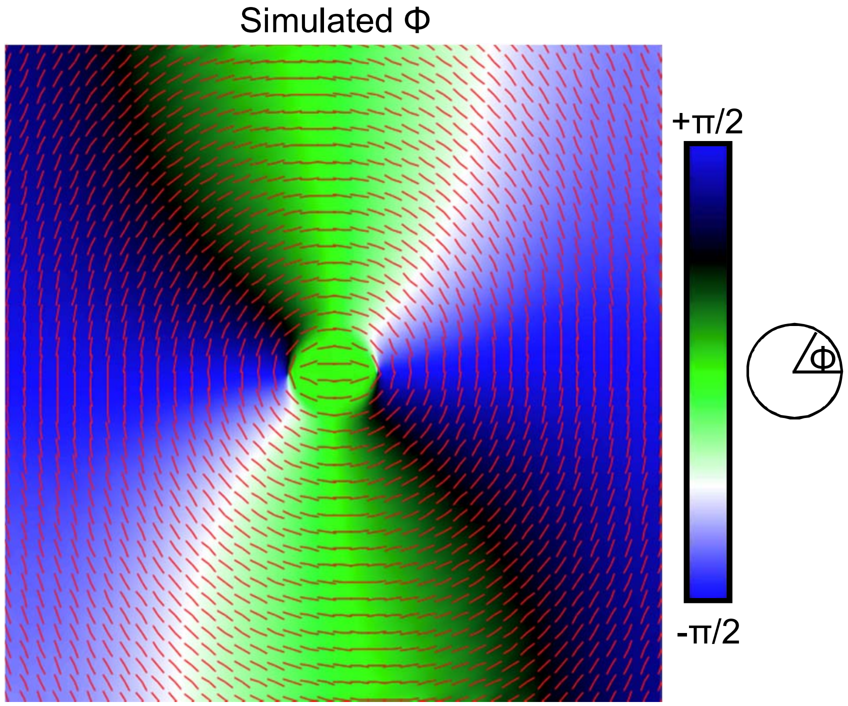
B=0T



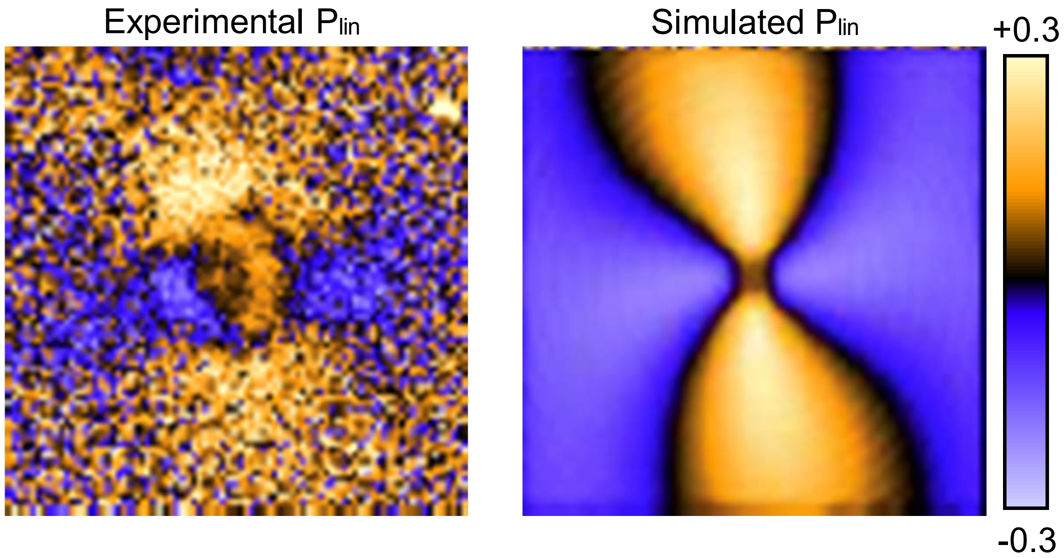


B=1T

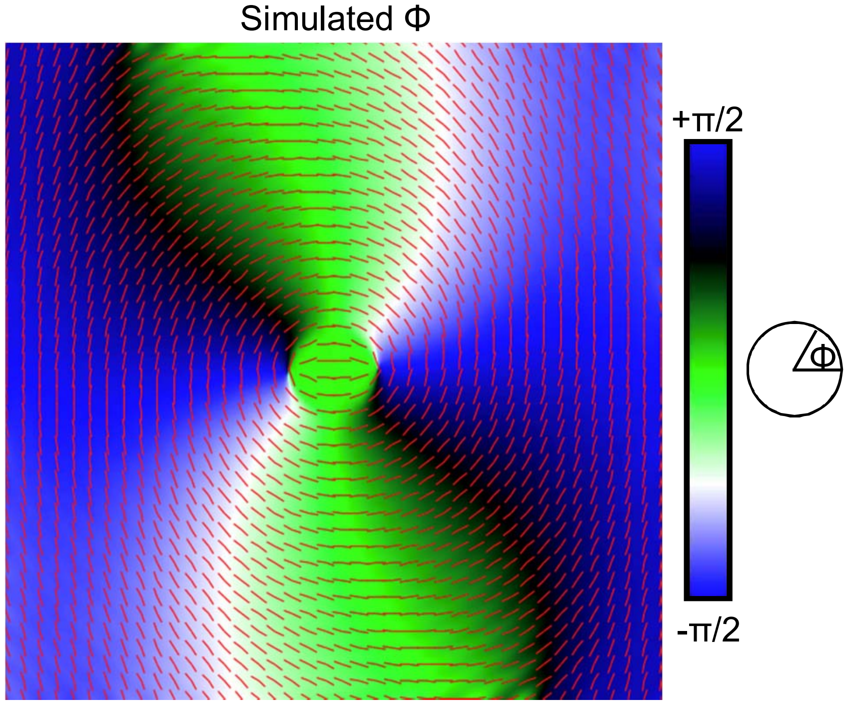




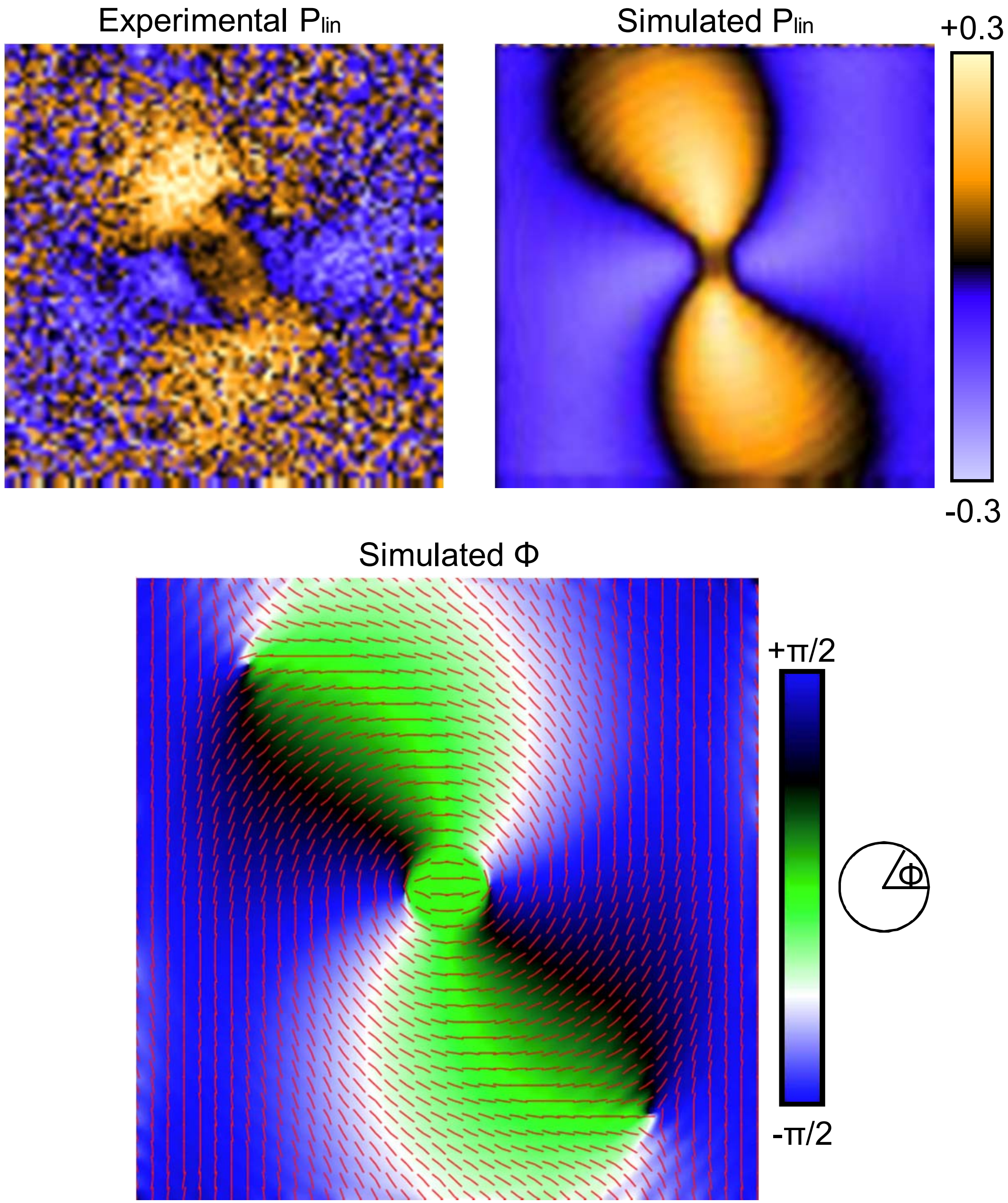
B=2T


Experimental P_{lin}

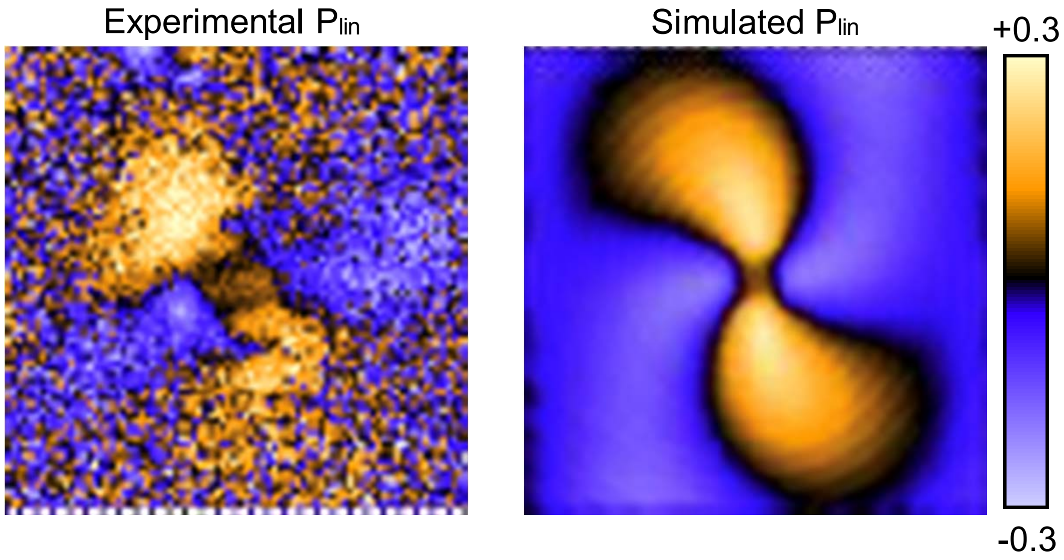
Simulated P_{lin}

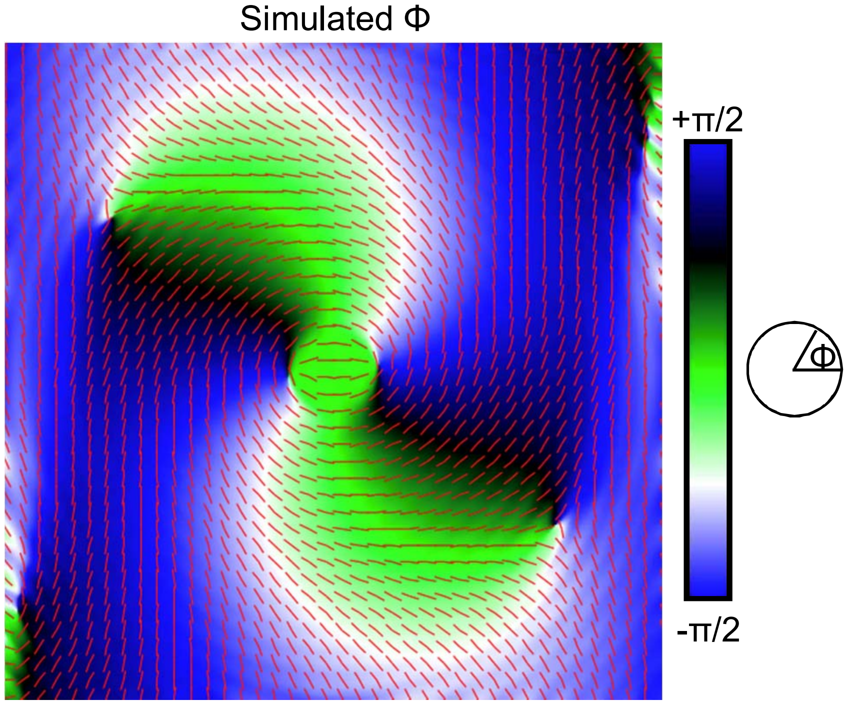

Simulated Φ

B=3T

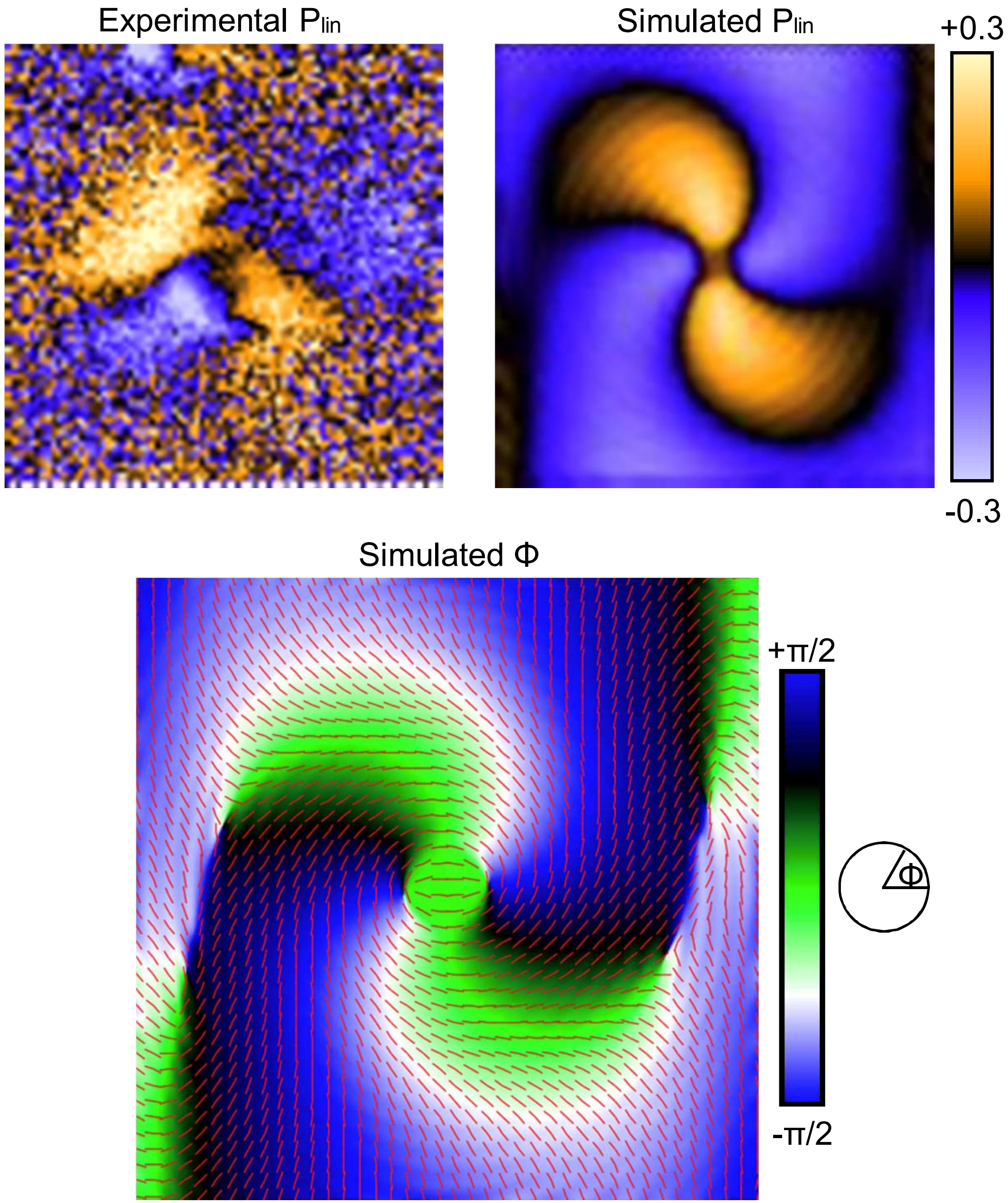


B=4T

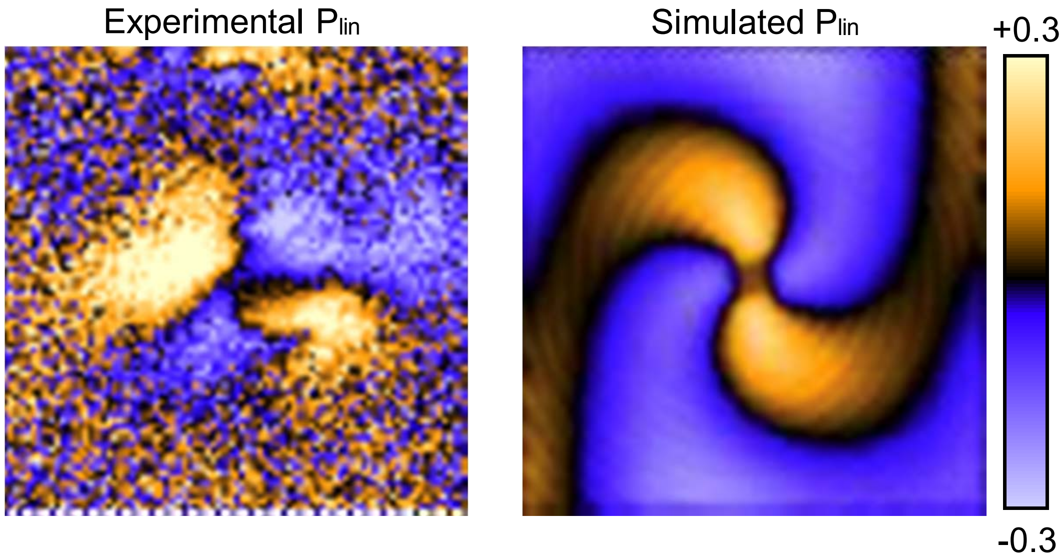




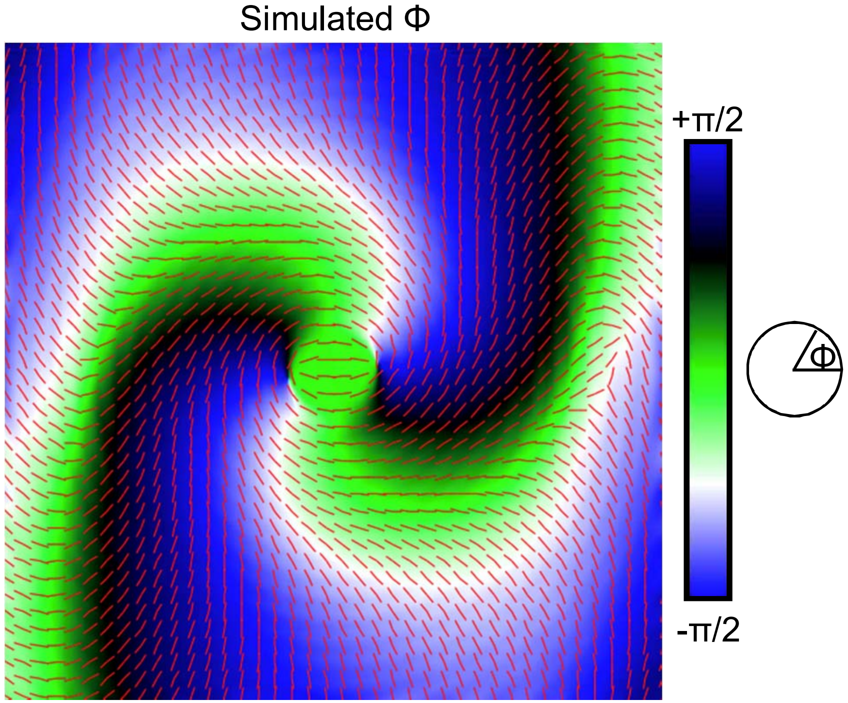
B=5T



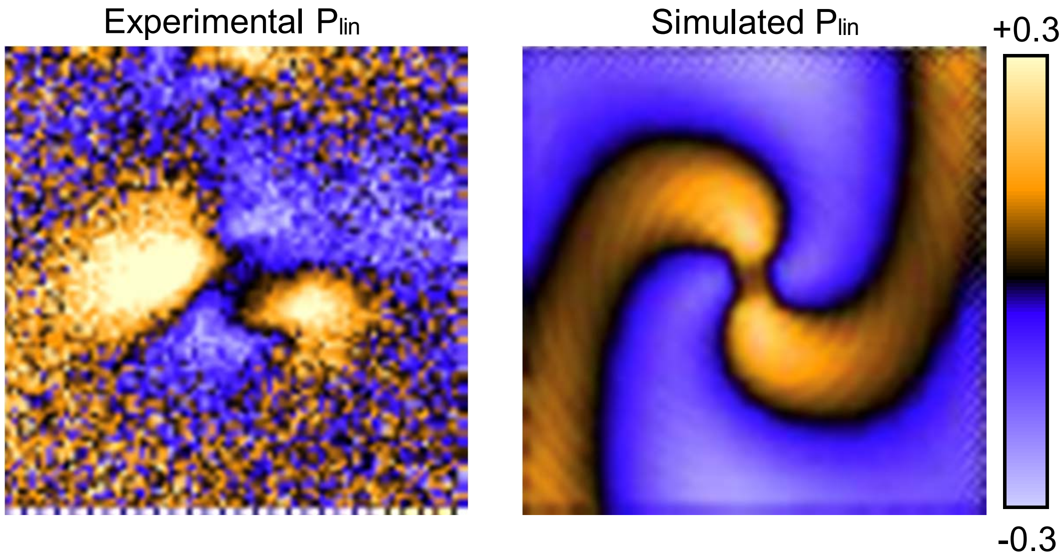
B=6T


Experimental P_{lin}

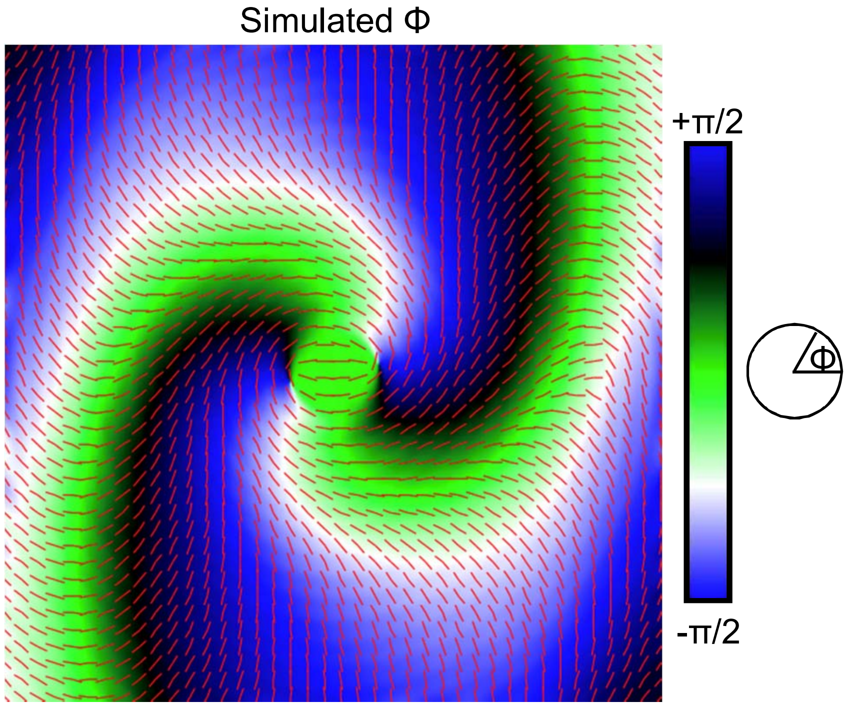
Simulated P_{lin}


Simulated Φ

B=7T



direction of spin current
≠
direction of density current

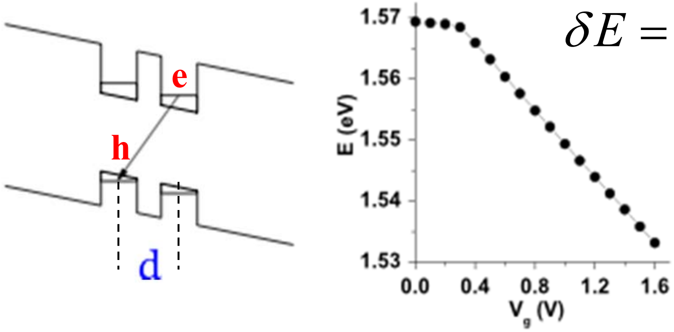


A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov, T. Ostatnický, M. Vladimirova, A.V. Kavokin, K.L. Campman, A.C. Gossard, unpublished

work in progress

excitonic devices

potential energy of indirect excitons can be controlled by an applied gate voltage



$$\delta E = edF_z$$

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

the ability to control <u>exciton</u> fluxes by an applied gate voltage

excitonic devices

delay between signal processing and optical communication is effectively eliminated in excitonic devices

→ advantage in applications where interconnection speed is important

traps for excitons

and other potential landscapes

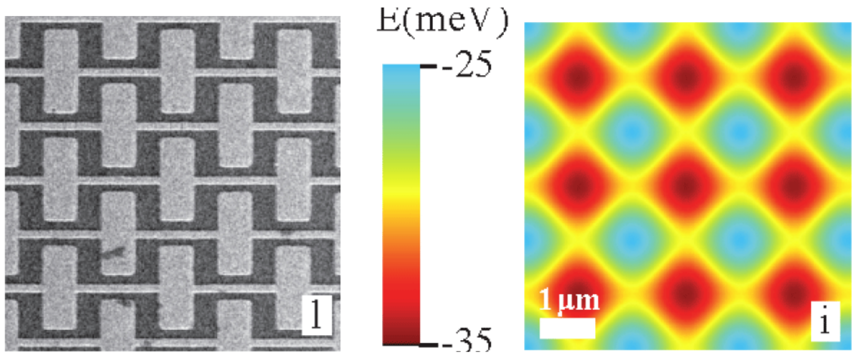
control of shape and depth of a trap, lattice, or another potential landscape

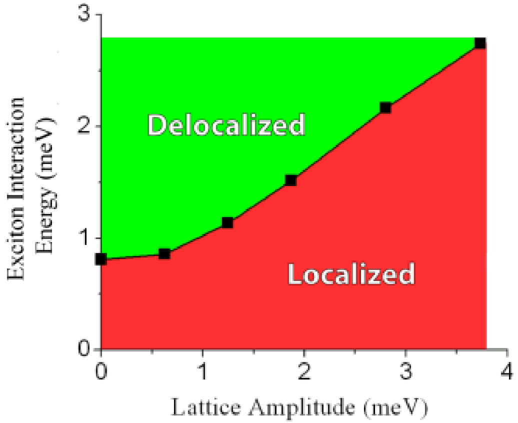
→ tool for studying basic properties of excitons

↑

traps and lattices
are effectively used in
studies of cold atoms

Lattices for excitons

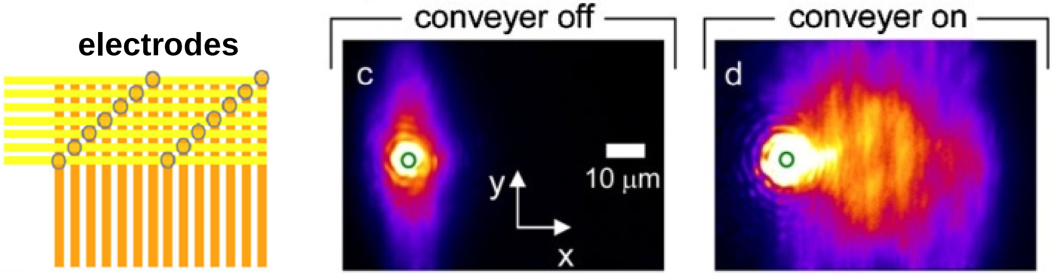




exciton localization
– delocalization
in a lattice

M. Remeika, J.C. Graves, A.T. Hammack, A.D. Meyertholen, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, *Phys. Rev. Lett.* 102, 186803 (2009)

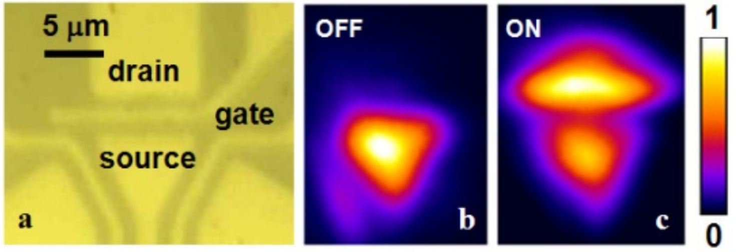
M. Remeika, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, *Appl. Phys. Lett.* 100, 061103 (2012)



Excitonic conveyers / CCD

realize controlled transport of excitons

A.G. Winbow, J.R. Leonard, M. Remeika, Y.Y. Kuznetsova, A.A. High, A.T. Hammack, L.V. Butov, J. Wilkes, A.A. Guenther, A.L. Ivanov, M. Hanson, A.C. Gossard, *Phys. Rev. Lett.* 106, 196806 (2011)



Excitonic transistors / circuits

realise excitonic signal processing

Science 321, 229 (2008)

Nature Photonics 3, 577 (2009)

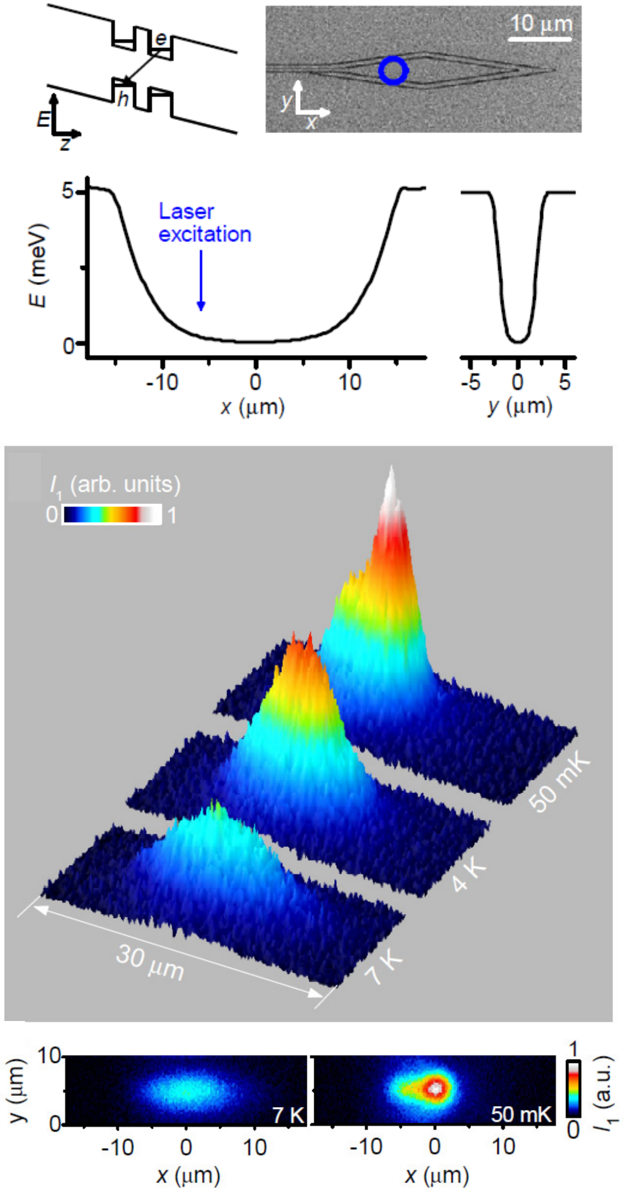
Appl. Phys. Lett. 100, 231106 (2012)

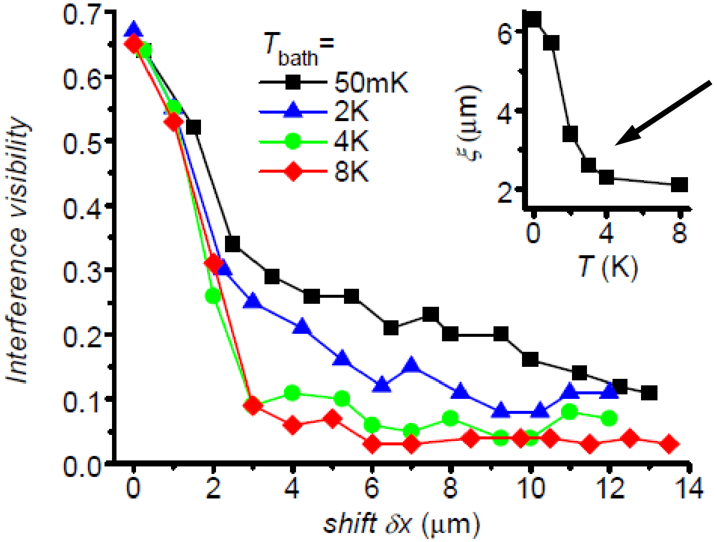
condensation of excitons in a trap

Condensation of excitons in diamond trap

with lowering temperature

- **excitons condense at the trap bottom**
- **exciton spontaneous coherence emerges**





measured transition temperature ~2 K

estimates of the temperature of exciton BEC

$$T_c = \frac{\sqrt{6}}{\pi}\hbar\omega_{2D}\sqrt{N/g} \sim 2\ \text{K}$$

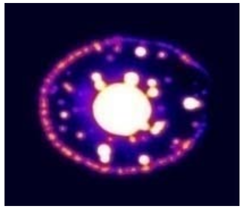
High $T > 4$ K: $V(r)$ quickly drops with r and vanishes at PSF width ← signature of a **classical gas**

Low T: $\xi >> \lambda_{\text{dB}}$, below $T \sim 1$ K, coherence extends over the entire trapped cloud ← signature of a **condensate**

A.A. High, J.R. Leonard, M. Remeika, L.V. Butov, M. Hanson, A.C. Gossard, Nano Lett. 12, 2605 (2012)

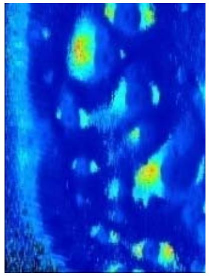
Cold indirect excitons:

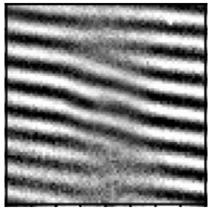
summary

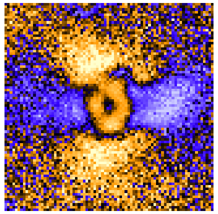


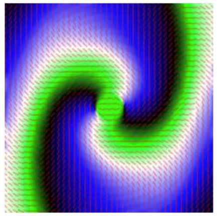
- **Macroscopically ordered exciton state (MOES)**

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









- **Spontaneous coherence in MOES and pol. vortex**
- **Phase singularities in interference pattern**
- **Spin textures and spin currents**

A.A. High, J.R. Leonard, A.T. Hammack, M.M. Fogler, L.V. Butov, A.V. Kavokin, K.L. Campman, A.C. Gossard, Nature 483, 584 (2012)

A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov, T. Ostatnický, M. Vladimirova, A.V. Kavokin, K.L. Campman, A.C. Gossard, unpublished

- **Condensation in a trap**

A.A. High, J.R. Leonard, M. Remeika, L.V. Butov, M. Hanson, A.C. Gossard, Nano Lett. 12, 2605 (2012)