Indirect excitons

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Introduction:

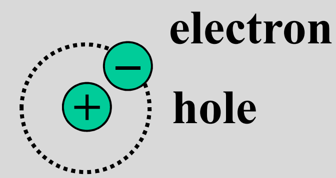
- **Cold exciton gas**
- **Indirect excitons**

Data:

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

exciton – bound pair of electron and hole

light bosonic particle in semiconductor



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

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

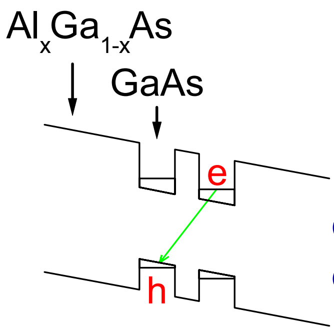
how to realize cold exciton gas ?

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

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

find excitons with <u>lifetime</u> >> <u>cooling time</u> → **$T_{exciton} \sim T_{lattice}$**

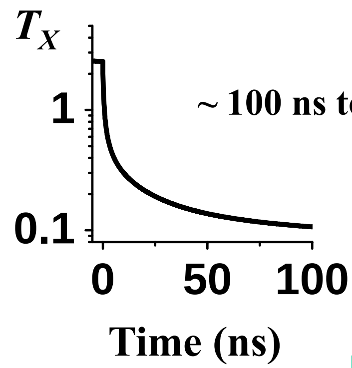
Indirect excitons in CQW



GaAs/AlGaAs CQW

<u>10^3 – 10^6 times longer exciton lifetime</u> due to separation between electron and hole layers

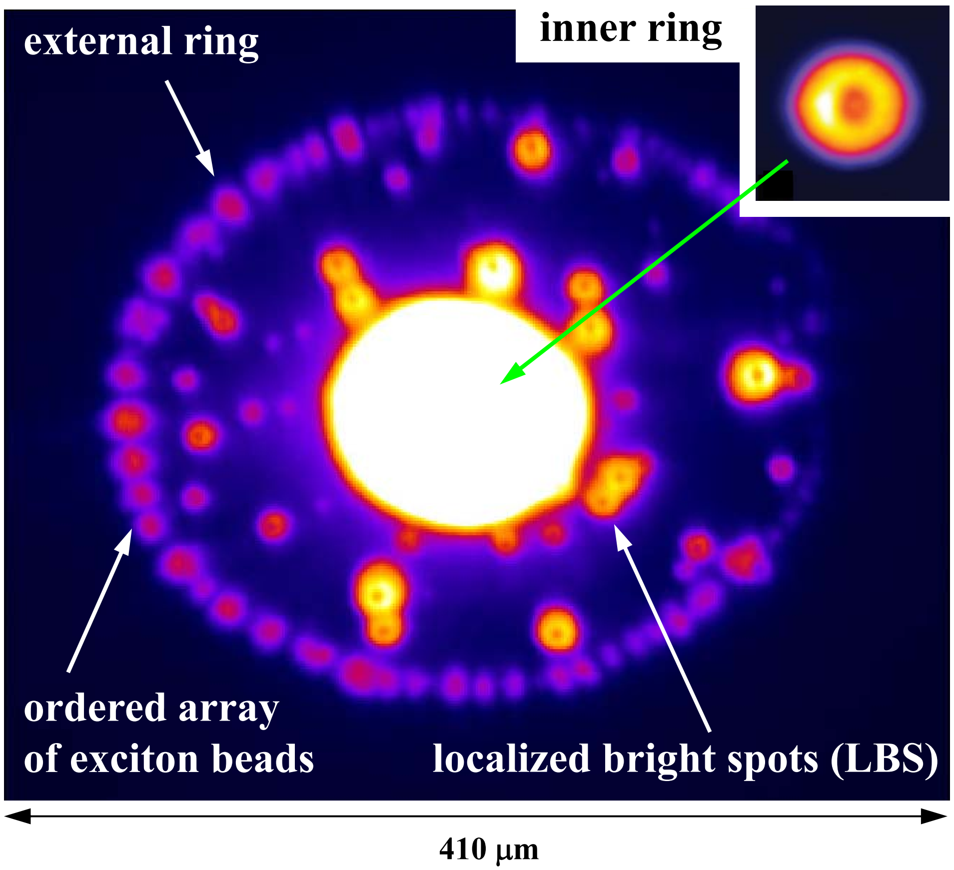
realization of cold exciton gas in separated layers was proposed by Yu.E. Lozovik, V.I. Yudson (1975); S. I. Shevchenko (1976); T. Fukuzawa, S.S. Kano, T.K. Gustafson, T. Ogawa (1990)

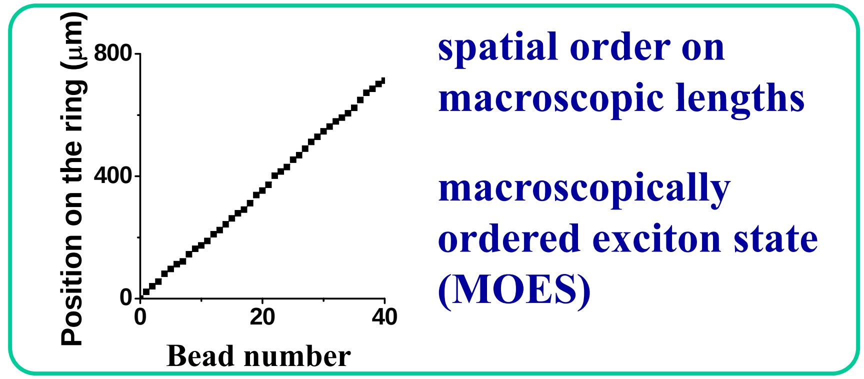


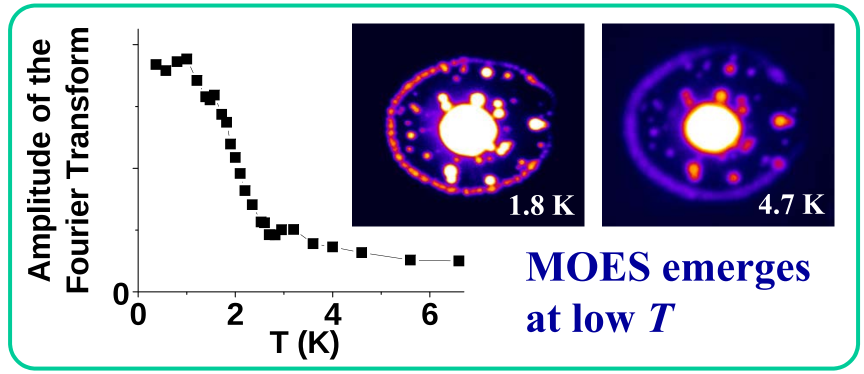
A.L. Ivanov et al.
in PRL 86, 5608 (2001)

$T_X \sim 100$ mK << T_{dB}
is realized for indirect excitons

Exciton rings and macroscopically ordered exciton state





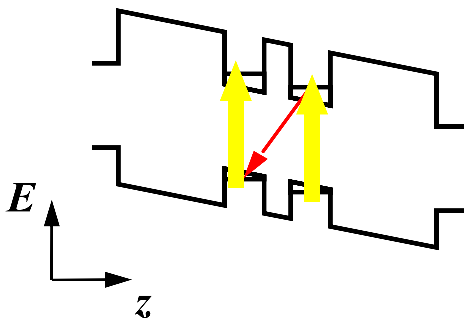


L.V. Butov, A.C. Gossard, D.S. Chemla,
Nature 418, 751 (2002)

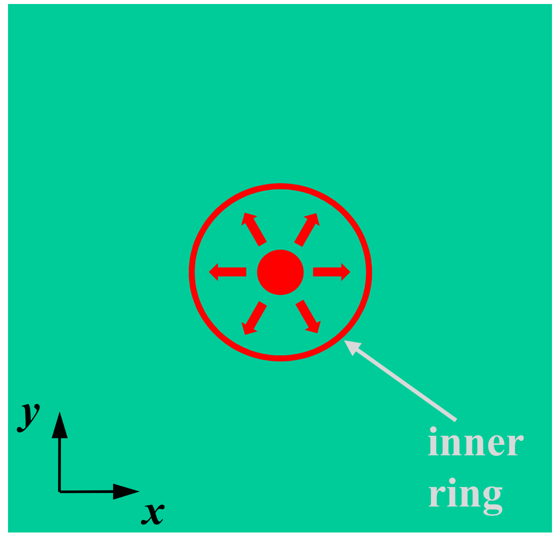
model of

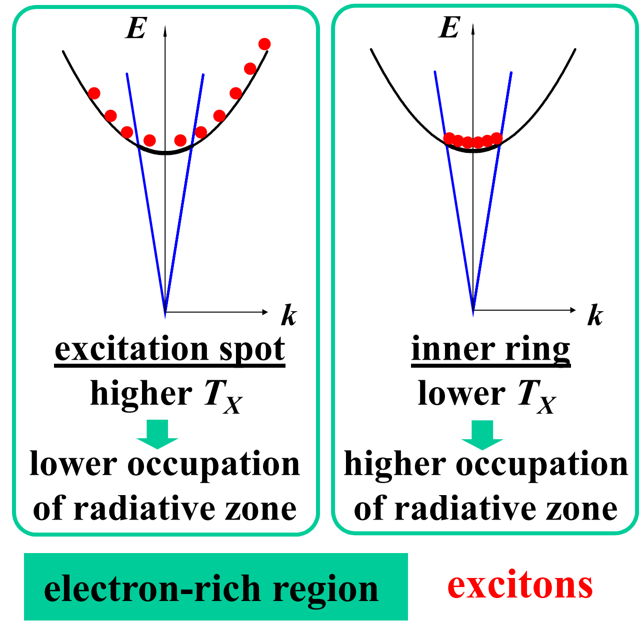
- **inner ring:** A.L. Ivanov, L. Smallwood, A. Hammack, Sen Yang, L.V. Butov, A.C. Gossard, EPL 73, 920 (2006)
- **external ring:** L.V. Butov, L.S. Levitov, B.D. Simons, A.V. Mintsev, A.C. Gossard, D.S. Chemla, PRL 92, 117404 (2004)
  R. Rapaport, G. Chen, D. Snoke, S.H. Simon, L. Pfeiffer, K.West, 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

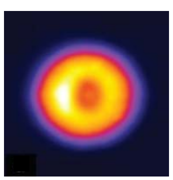


inner ring



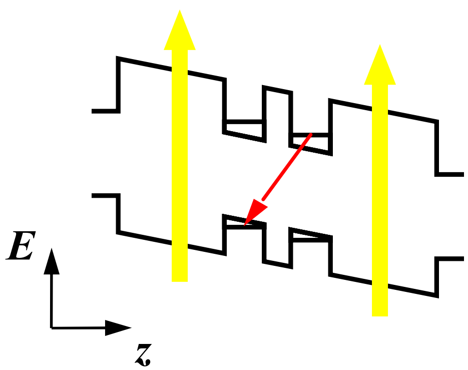


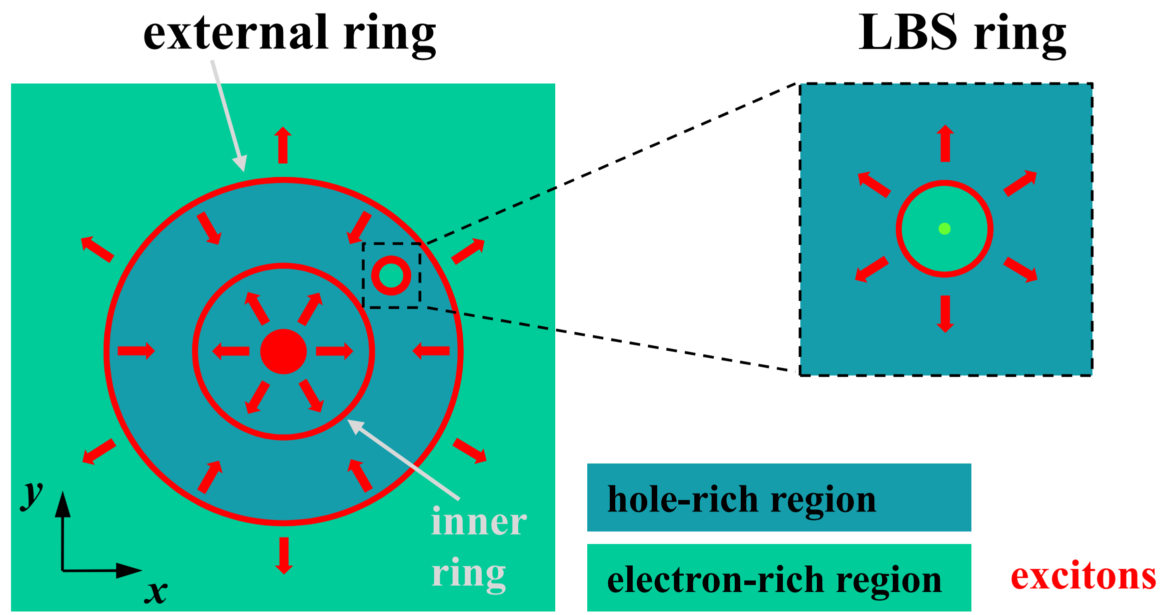
inner ring forms due to transport and cooling of optically generated excitons



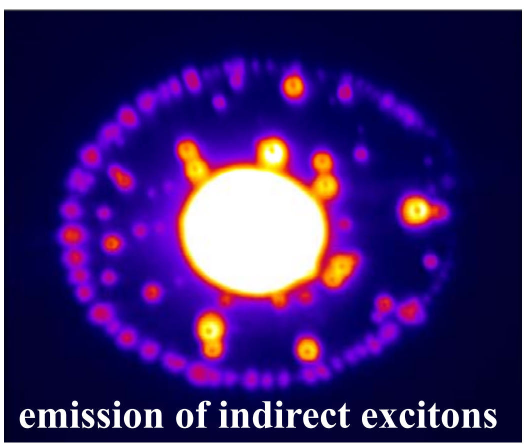
emission of indirect excitons

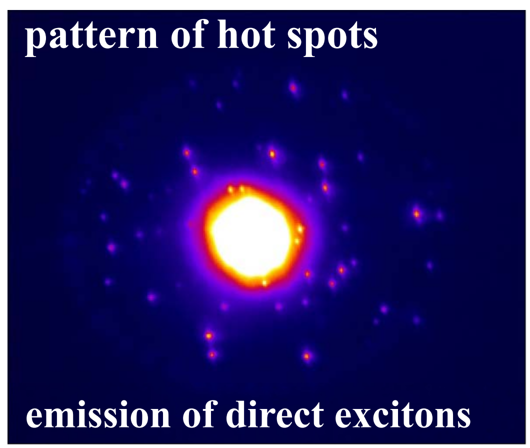
above barrier laser excitation
creates excitons + holes
in CQW





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





external rings and LBS rings form sources of cold excitons

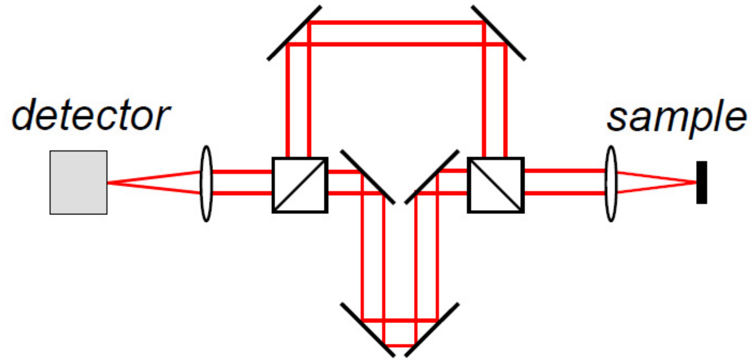
exciton gas
is hot in LBS centers
is cold in external ring and LBS rings

measured by
shift-interferometry

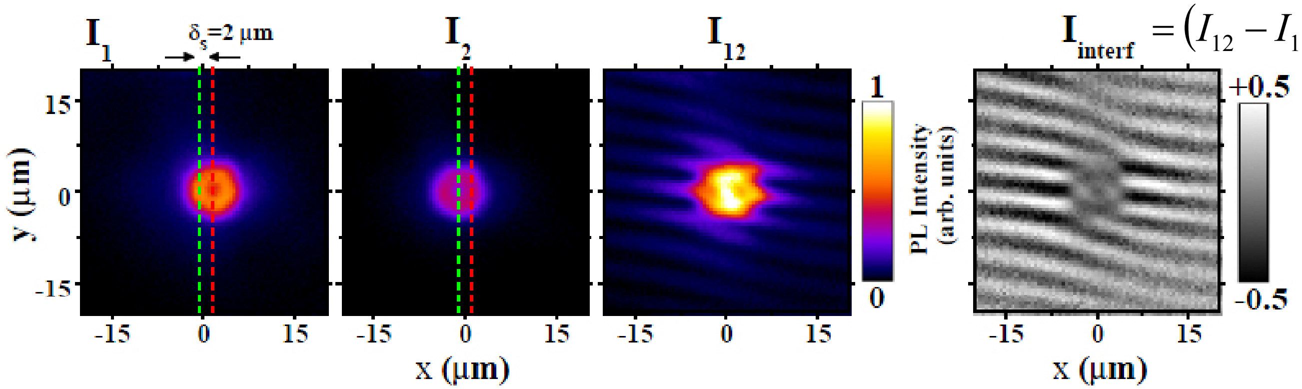
spontaneous coherence
and
spin polarization textures

measured by
polarization resolved imaging

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



$$I_{interf} = (I_{12} - I_1 - I_2)/(2\sqrt{I_1 I_2})$$

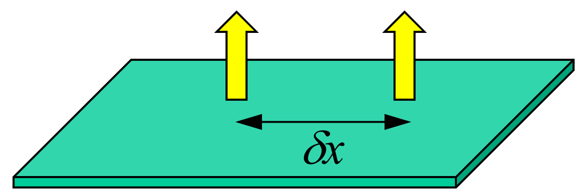


Pattern of $g_1(\delta x)$ is measured by shift-interferometry

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

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

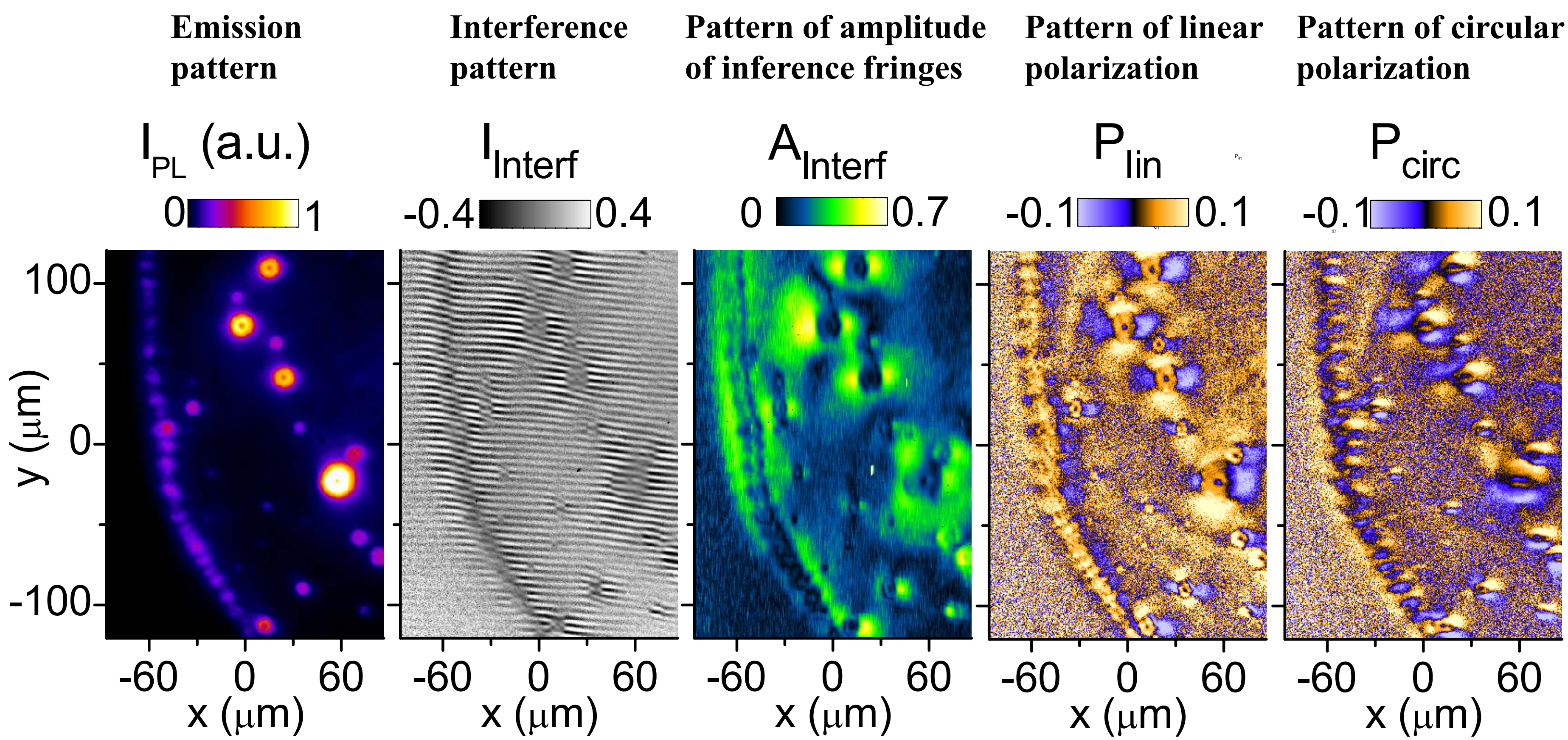
Contrast of interference fringes $A_{interf}(\delta x) \rightarrow g_1(\delta x)$



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



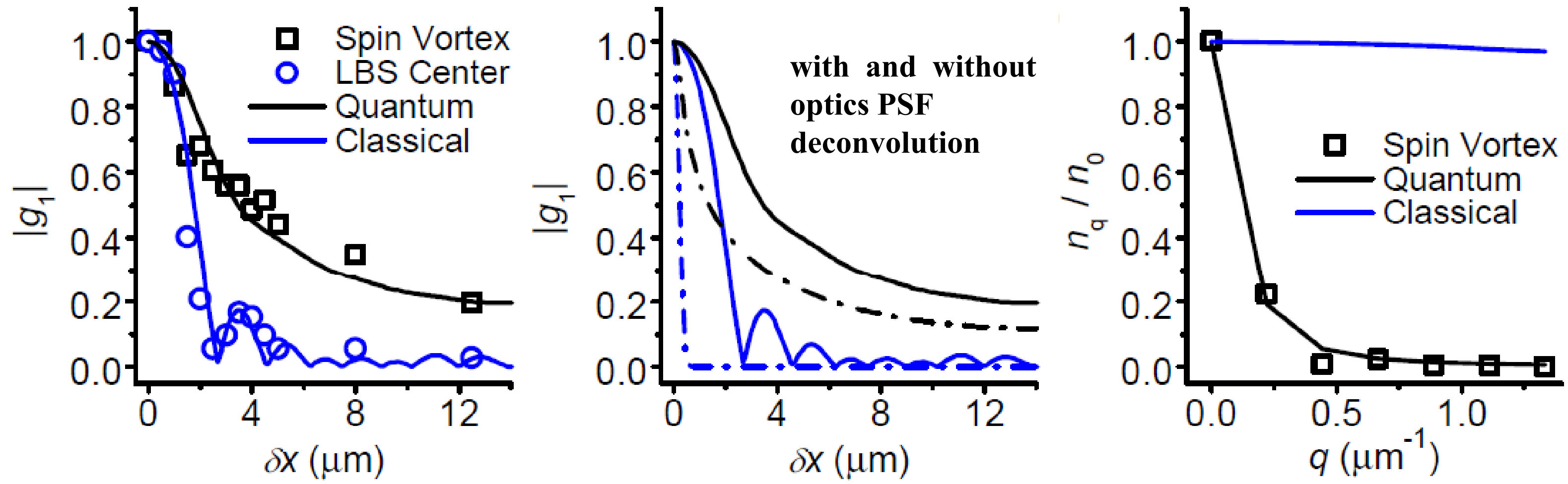
A.A. High, J.R. Leonard, A.T. Hammack, M.M. Fogler, L.V. Butov, A.V. Kavokin, K.L. Campman, A.C. Gossard, Nature 483, 584 (2012)

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, M. Vladimirova, A.V. Kavokin, K.L. Campman, A.C. Gossard, unpublished

First order coherence function $g_1(\delta x)$ **Distribution in q-space n_q**



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

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

$\xi >> \xi_{classical}$

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

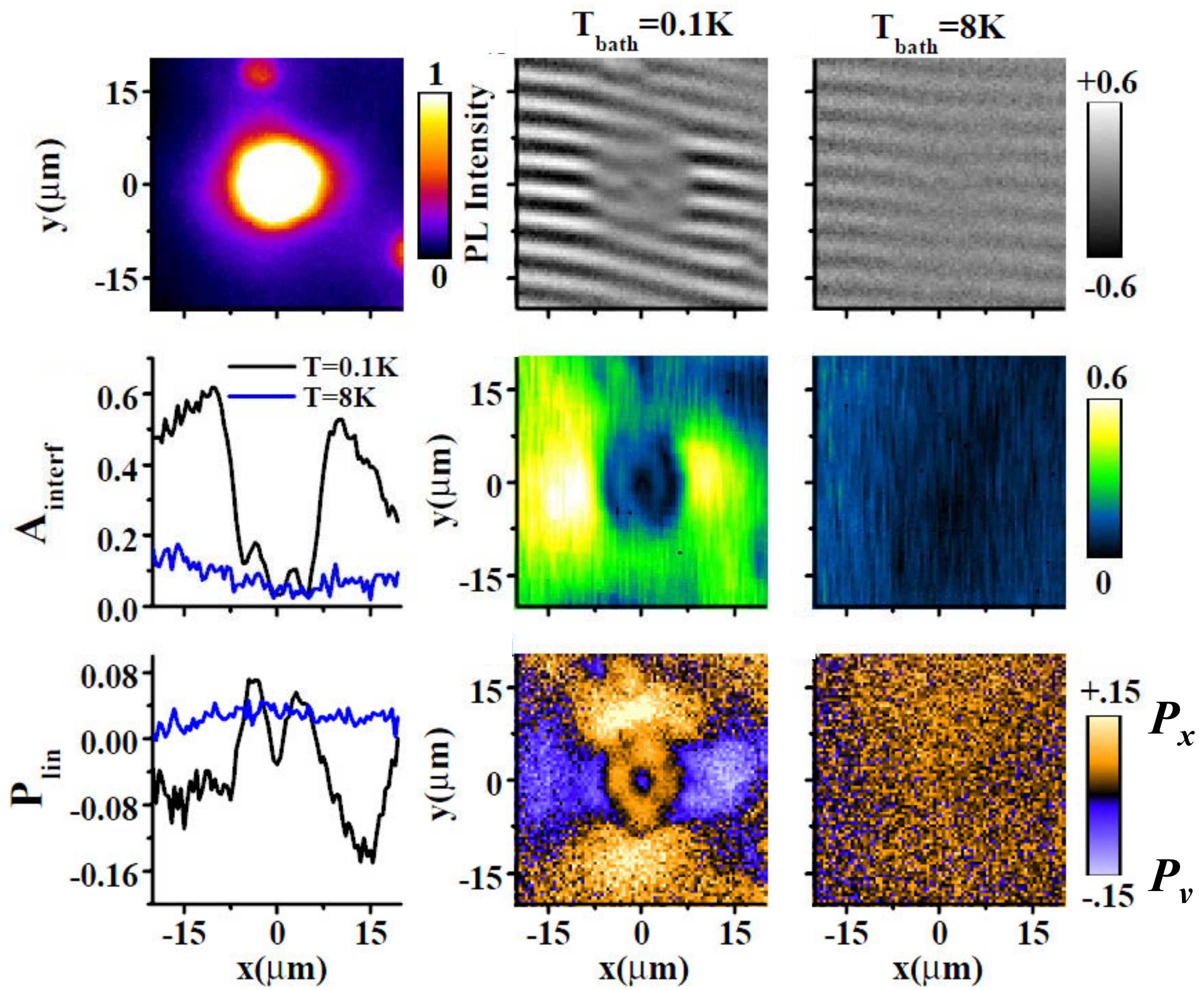
characteristic of a condensate

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

talk of
Michael Fogler

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 $r > r_0$

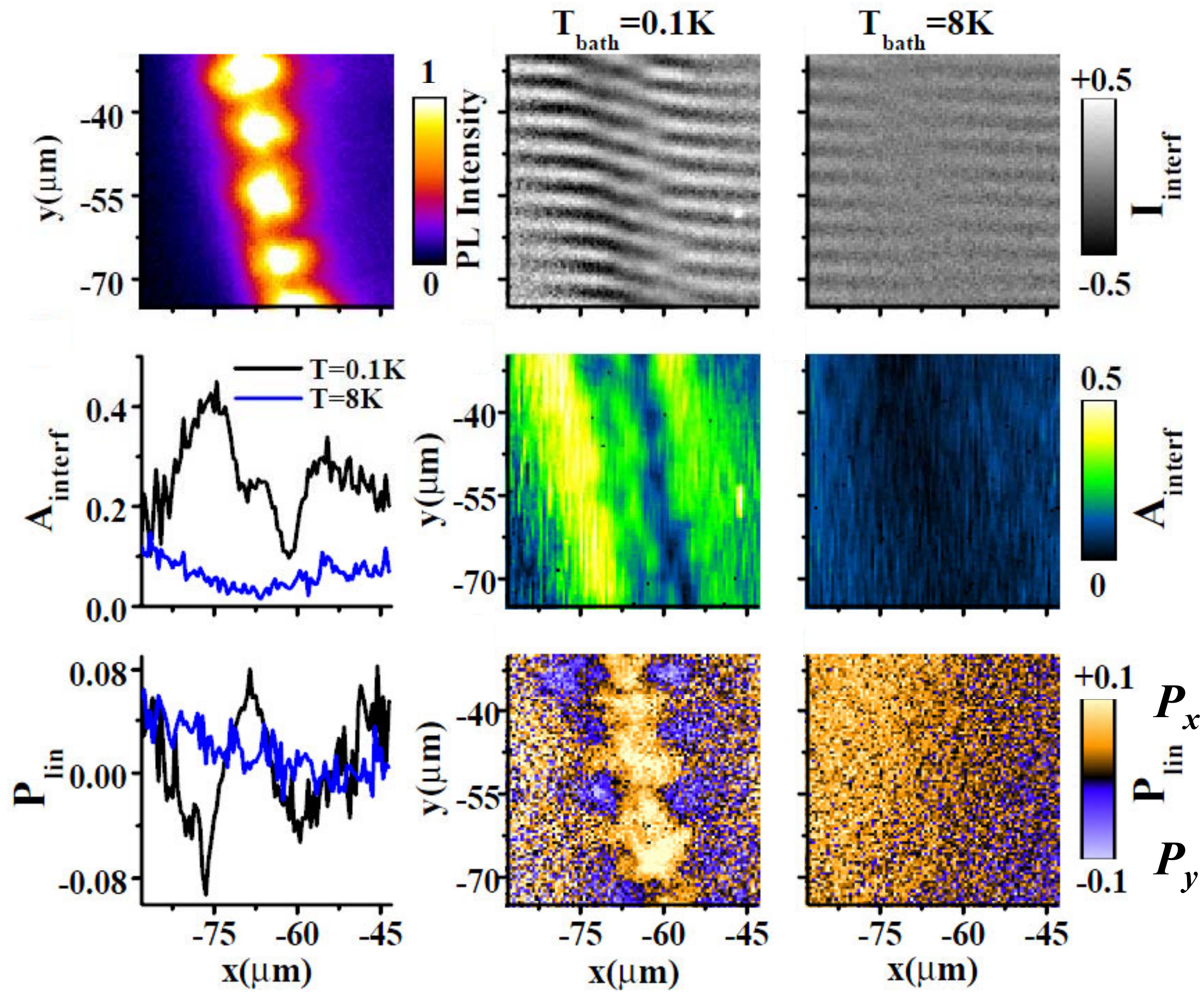
at $r = r_0$

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

enhancement of amplitude of interference fringes

shift in phase of interference fringes

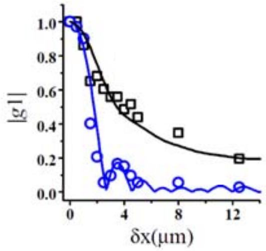
Exciton coherence and spin texture around external ring



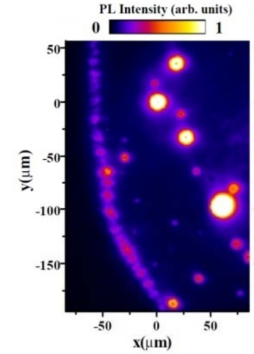
Emergence of

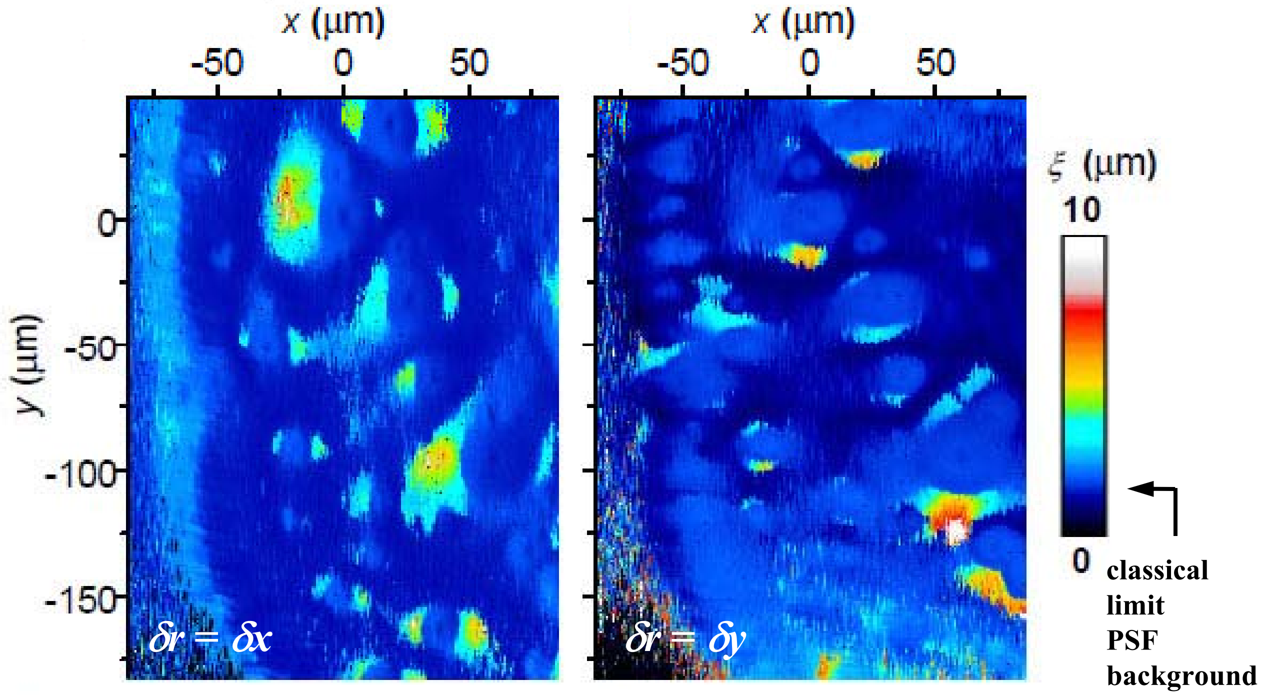
- **Spontaneous coherence**
- **Periodic spin texture**

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**

$\xi >> \xi_{classical}$

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

directional property of exciton coherence:

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

Pattern formation and coherence: Experiment

<table>
<tr><th>inner ring</th><th>LBS</th><th>external ring</th><th>fragmentation / ordering</th><th>coherence</th></tr>
<tr><td colspan="4">L.V. Butov, A.C. Gossard, D.S. Chemla, Nature 418, 751 (2002)</td><td></td></tr>
<tr><td></td><td></td><td>D. Snoke et al, Nature 418, 754 (2002)
R. Rapaport et al, PRL 92, 117405 (2004)</td><td></td><td></td></tr>
<tr><td></td><td></td><td colspan="3">Sen Yang et al, PRL 97, 187402 (2006)
A.A. High et al, Nature 483, 584 (2012)
M. Alloing D. Fuster, Y. Gonzalez, L. Gonzalez, F. Dubin, arXiv:1210.3176</td></tr>
<tr><td>M. Stern et al, PRL 101, 257402 (2008)
A.V. Gorbunov et al, JETP Lett 94,800 (2011)
M. Alloing et al, PRB 85, 245106 (2012)</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td>L.V. Butov et al, Nature 417, 47 (2002)
C.W. Lai et al, Science 303, 503 (2004)</td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="2">B. Fluegel et al, PRB 83, 195320 (2011)</td><td></td><td></td></tr>
</table>

Fragmentation and coherence
Barcelona group

Observation of macroscopic coherence in self-organized dipolar excitons

M. Alloing[1], D. Fuster[2], Y. González[2], L. González[2] and F. Dubin[1]
[1] *ICFO-The Institut of Photonic Sciences, Av. Carl Friedrich Gauss, num. 3, 08860 Castelldefels (Barcelona), Spain and*
[2] *IMM-Instituto de Microelectrónica de Madrid (CNM-CSIC), Isaac Newton 8, PTM, E-28760 Tres Cantos, Madrid, Spain*
(Dated: October 12, 2012)

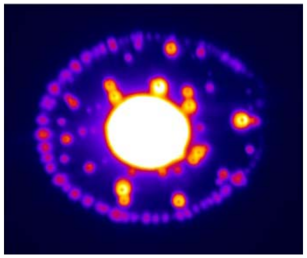
We report experiments showing that spatially indirect excitons confined in a wide single quantum well can exhibit macroscopic spatial coherence. Extended coherence is spontaneously established in the regime where indirect excitons form a distinctive ring shaped pattern fragmented into microscopic beads. These contain a large concentration of indirect excitons at sub-Kelvin temperatures, the excitons spatial coherence being the greatest in the vicinity of the fragments.

arXiv:1210.3176v1 [cond-mat.mes-hall] 11 Oct 2012

What we know about the macroscopically ordered exciton state

MOES is a state with:

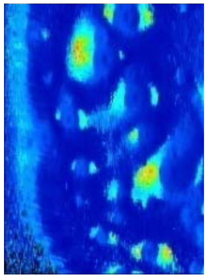
- **macroscopic <u>spatial ordering</u>**



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

- **<u>spontaneous coherence</u>** (coherence length >> classical)

  → a <u>condensate</u> in *k*-space



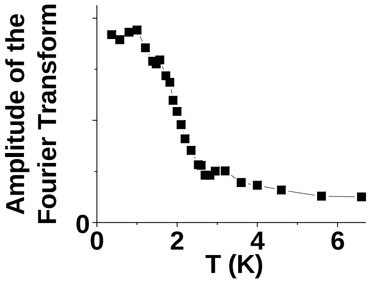
Sen Yang et al., PRL 97, 187402 (2006)

M.M. Fogler et al., PRB 78, 035411 (2008)

A.A. High et al., Nature 483, 584 (2012)

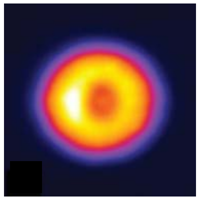
observed <u>in a cold exciton gas</u>

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



observed <u>in external ring</u>

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

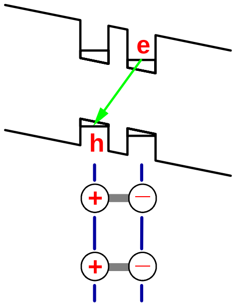


not observed in inner ring

A.L. Ivanov et al., EPL 73, 920 (2006)

characterized by <u>repulsive interaction</u>

(→ not driven by attractive interaction)



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

IX: L.V. Butov et al., PRL 73, 304 (1994)

dipolar matter

Theoretical model for MOES

consistent with experimental data

instability requires
<u>positive feedback</u>
to density variations

→

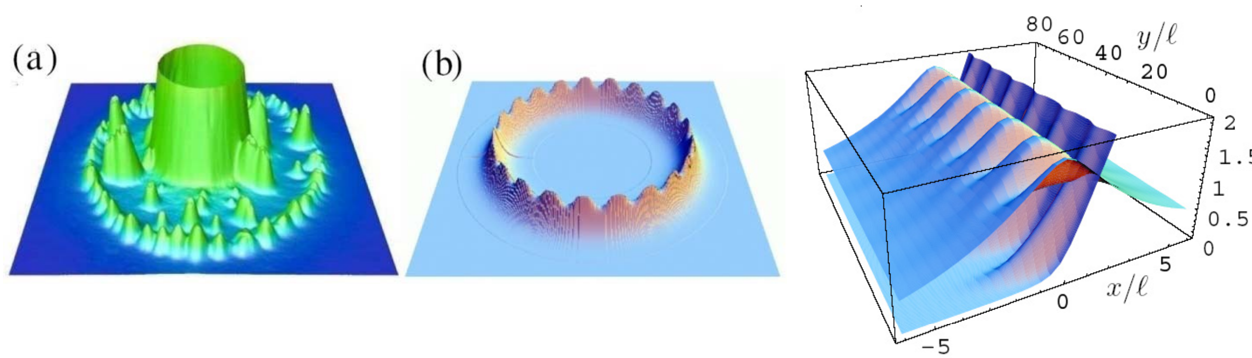
instability results from quantum degeneracy in a cold exciton system due to <u>stimulated kinetics of exciton formation</u>

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

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

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

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



L.S. Levitov et al., PRL 94, 176404 (2005)

A.A. Chernyuk, V.I. Sugakov,
PRB 74, 085303 (2006)

C.S. Liu et al.,
PRB 80, 125317 (2009)

<u>inconsistency with experiment:</u>

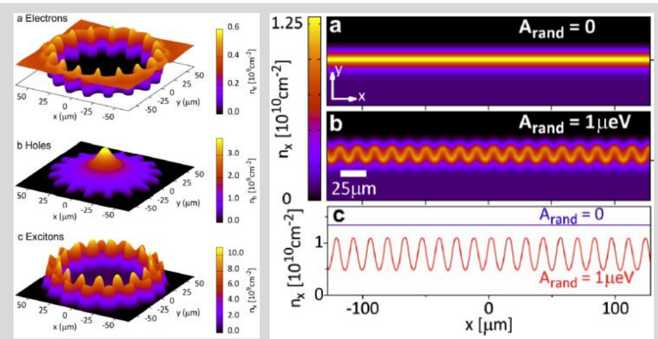
models are for **attractive** interaction while experiment shows **repulsive** interaction

A.V. Paraskevov, T.V. Khabarova,
Phys. Lett. A 368, 151 (2007)

1D GP: fragmentation

Other theoretical models

J. Wilkes et al.,
PRL 109, 187402 (2012)



<u>inconsistency with experiment:</u>

- model is for **classical** gas while experiment shows that modulation forms in **coherent gas**
- model gives modulation of **interface position (ring radius)** while experiment shows modulation of **density**
- in model, modulation appears when $D_X \ll D_e, D_h, D_{X\text{-}exp}$?

phase singularities

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

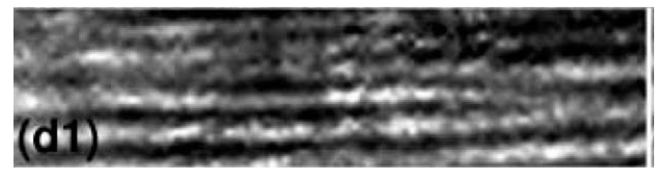
fork-like defect in phase pattern can be signature of quantized vortex

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)

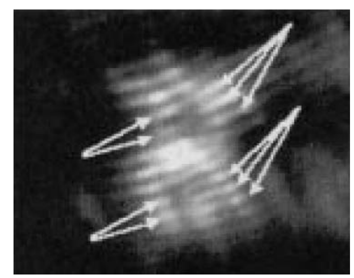
F. Chevy, K.W. Madison, V. Bretin, J. Dalibard, PRA 64, 031601(R) (2001)

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



optical vortices

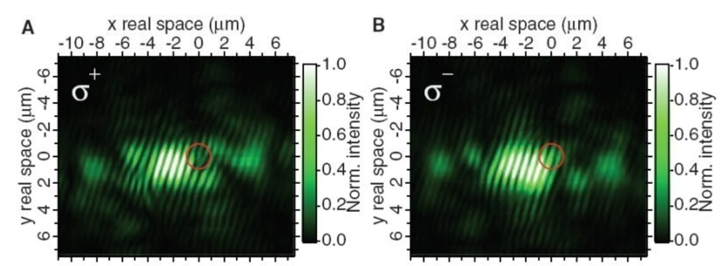
J. Scheuer, M. Orenstein, Science 285, 230 (1999)
and references therein



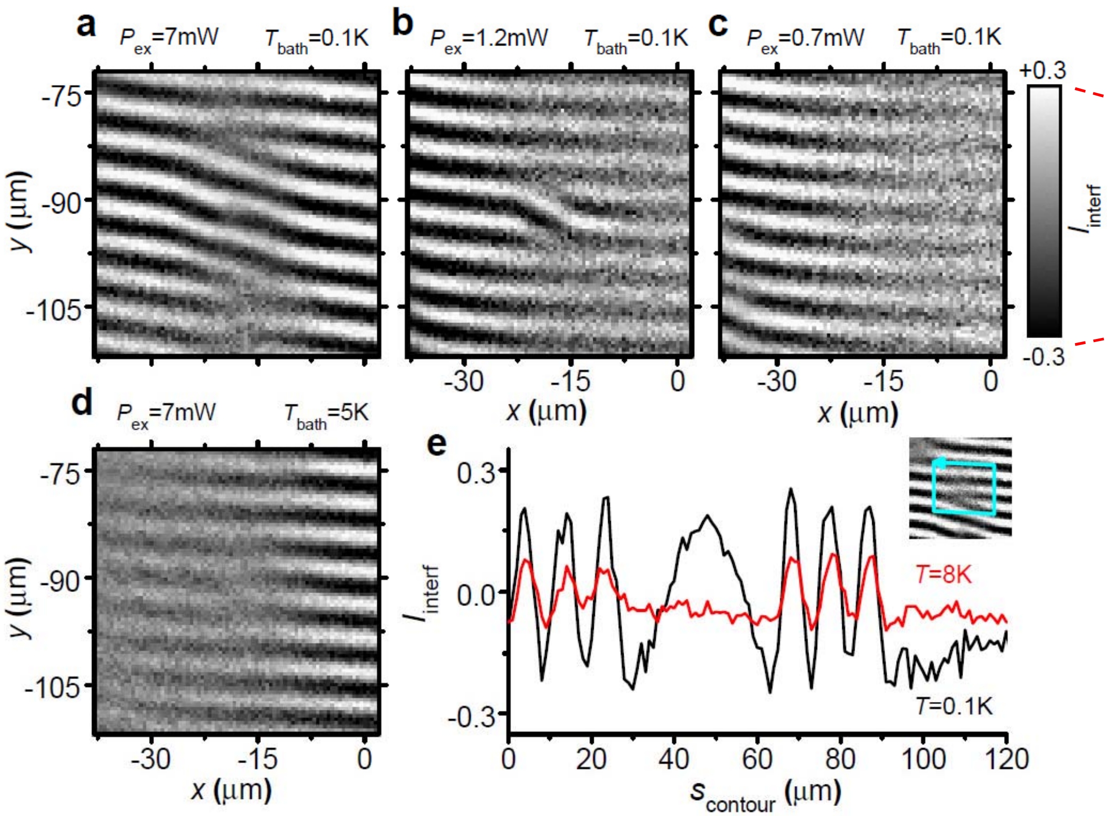
polariton vortices

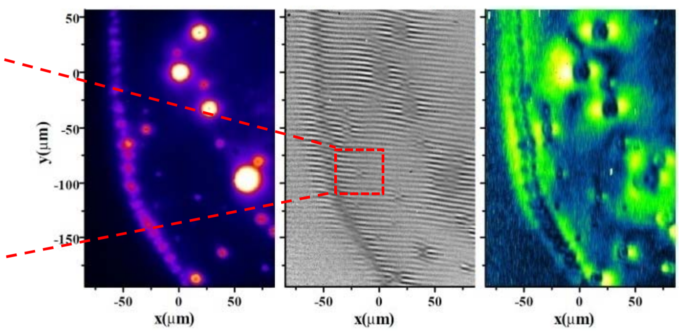
K.G. Lagoudakis, M. Wouters, M. Richard, A. Baas, I. Carusotto, R. André, Le Si Dang, B. Deveaud-Plédran, Nature Physics 4, 706 (2008)

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



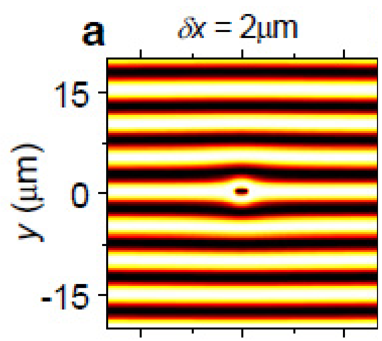


Forks are observed at low T in quantum exciton gas, vanish at high T in classical gas

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

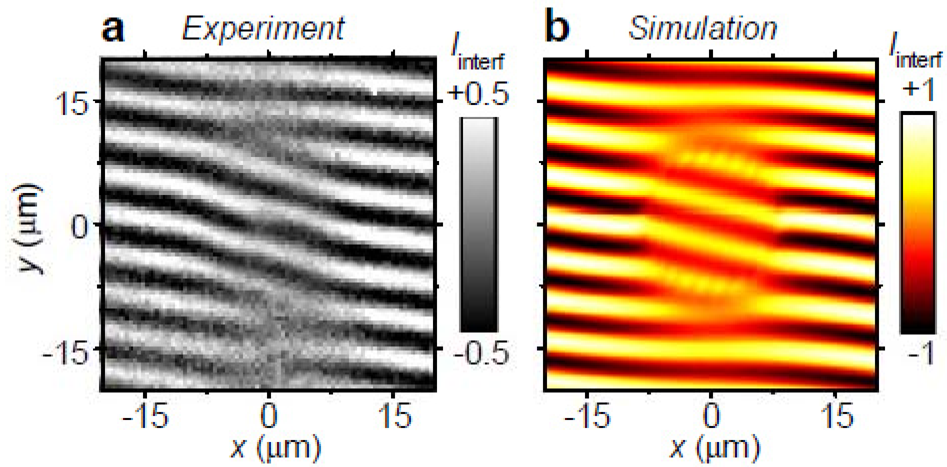
Distance between left- and right-facing forks ≠ shift in shift-interferometry

Observed phase singularity is different from a regular quantized vortex



Modeling

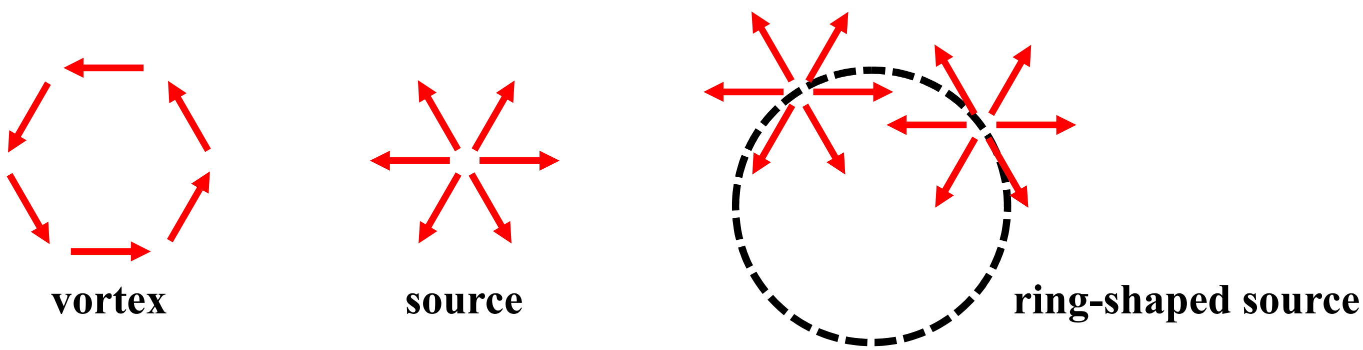
Fork-like defects in interference pattern



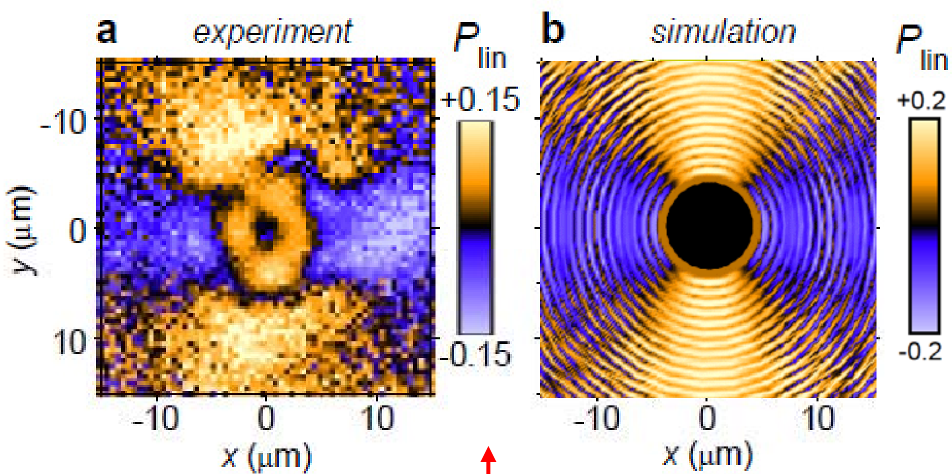
Ring-shaped source → interference pattern with left- and right-facing forks with distance between them >> shift

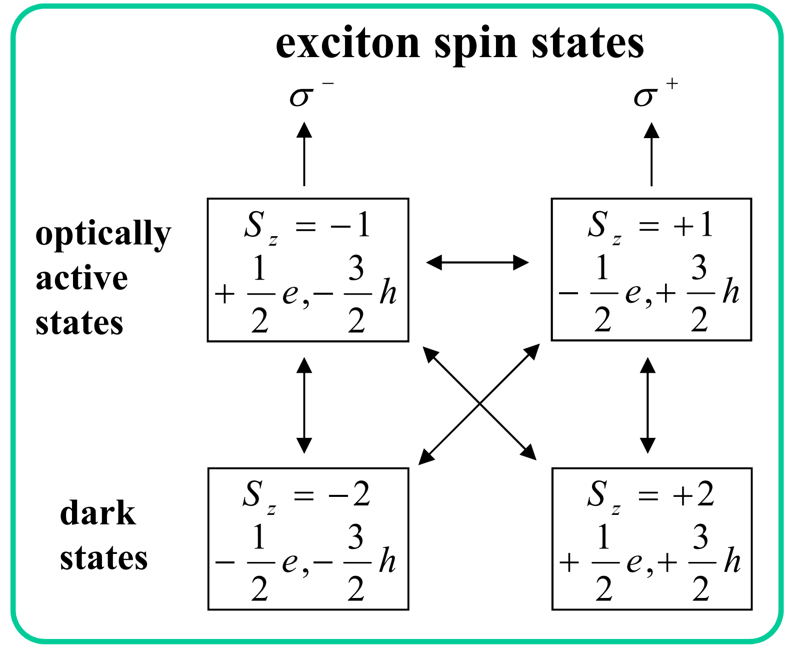
Ring-shaped source produces more complicated phase pattern than vortex.

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

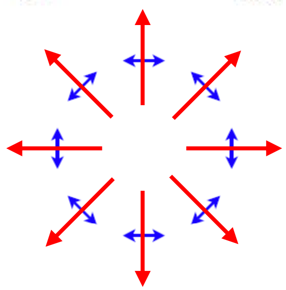


Spin polarization texture around LBS – radial source of cold excitons





within coherence length



ballistic exciton transport with **coherent spin precession** ➡ **vortex of linear polarization**

due to SO interaction, splitting of exciton states, and Zeeman effect

---

talk of Alexey Kavokin:
in the basis of 4 exciton states with spins $J_z = +1,-1,+2,-2$ the coherent spin dynamics is governed by

$$\hat{H} = \begin{bmatrix} E_b - (g_h - g_e)\mu_B B/2 & -\delta_b & k_e\beta_e e^{-i\phi} & k_h\beta_h e^{-i\phi} \\ -\delta_b & E_b + (g_h - g_e)\mu_B B/2 & k_h\beta_h e^{i\phi} & k_e\beta_e e^{i\phi} \\ k_e\beta_e e^{i\phi} & k_h\beta_h e^{-i\phi} & E_d - (g_h + g_e)\mu_B B/2 & -\delta_d \\ k_h\beta_h e^{i\phi} & k_e\beta_e e^{-i\phi} & -\delta_d & E_d + (g_h + g_e)\mu_B B/2 \end{bmatrix}$$

measured by polarization resolved imaging

control of spin currents

by magnetic field

condensation of indirect excitons → suppression of exciton scattering → suppression of Dyakonov-Perel and Elliott-Yafet mechanisms of spin relaxation

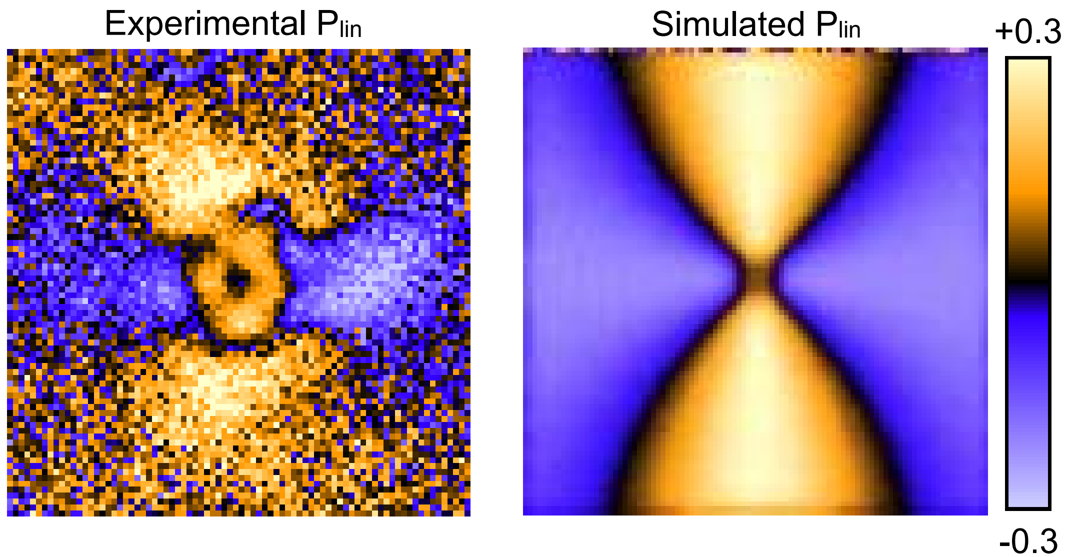
exp: strong enhancement of coherence length

separation between electron and hole → suppression of Bir-Aronov-Pikus mechanism of spin relaxation for indirect excitons

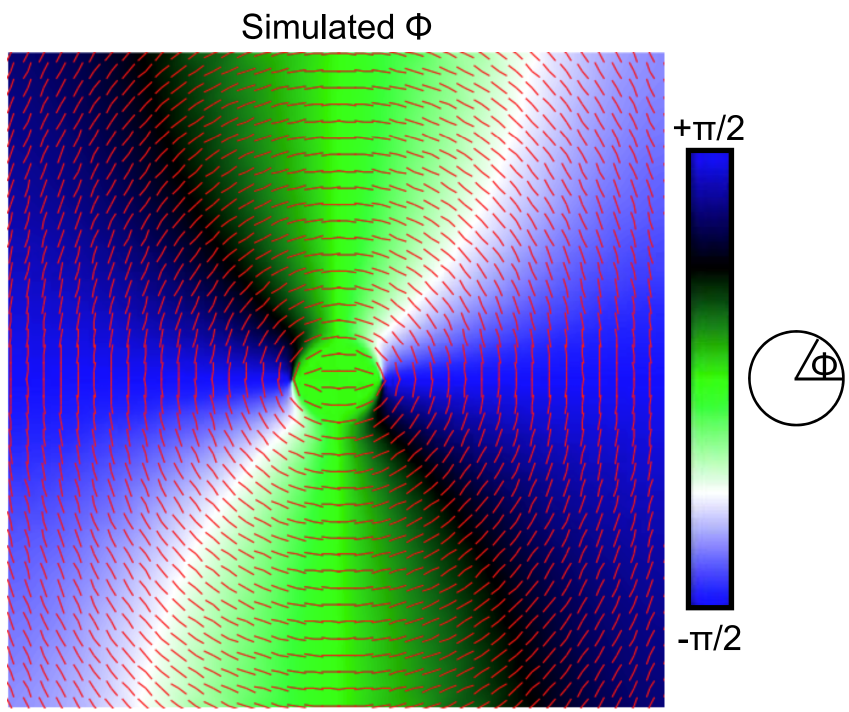
strong enhancement of the spin relaxation time in a condensate of indirect excitons

while the spin relaxation times of free electrons and holes can be short,
the formation of a coherent gas of their bosonic pairs
results in a strong enhancement of their spin relaxation times,
facilitating long-range spin currents

B=0T

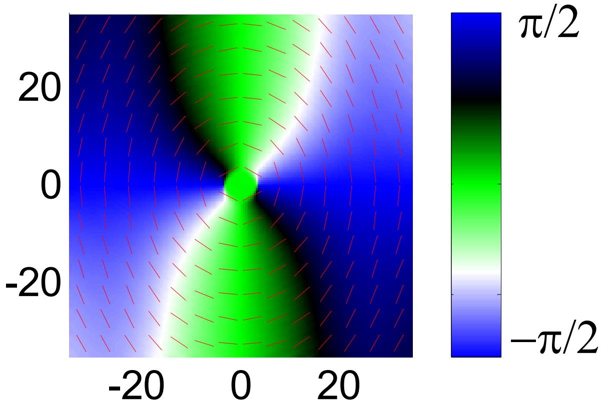


radial exciton polarization currents are associated with spin currents carried by electrons and holes bound into excitons

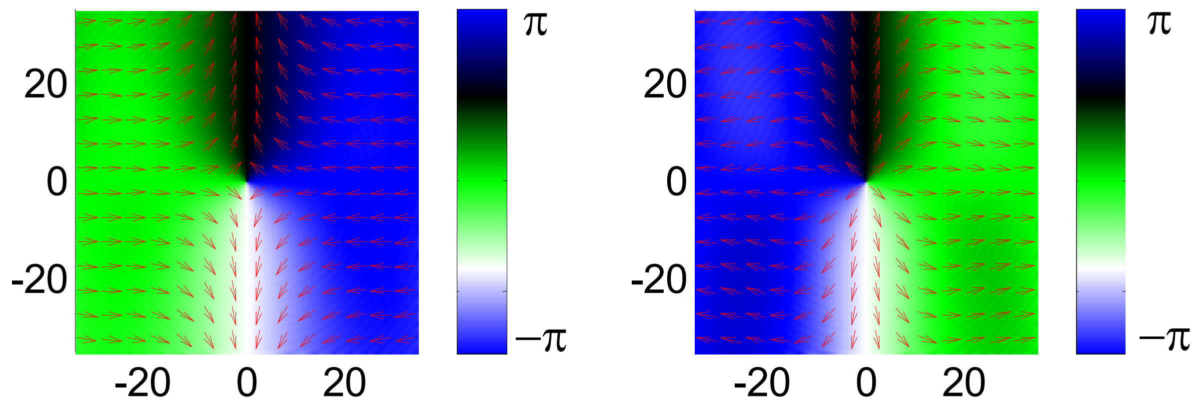


A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov, T. Ostatnický, M. Vladimirova, A.V. Kavokin, K.L. Campman, A.C. Gossard,
unpublished

exciton polarization



electron and hole spin patterns



radial exciton polarization currents are associated with spin currents carried by electrons and holes bound into excitons

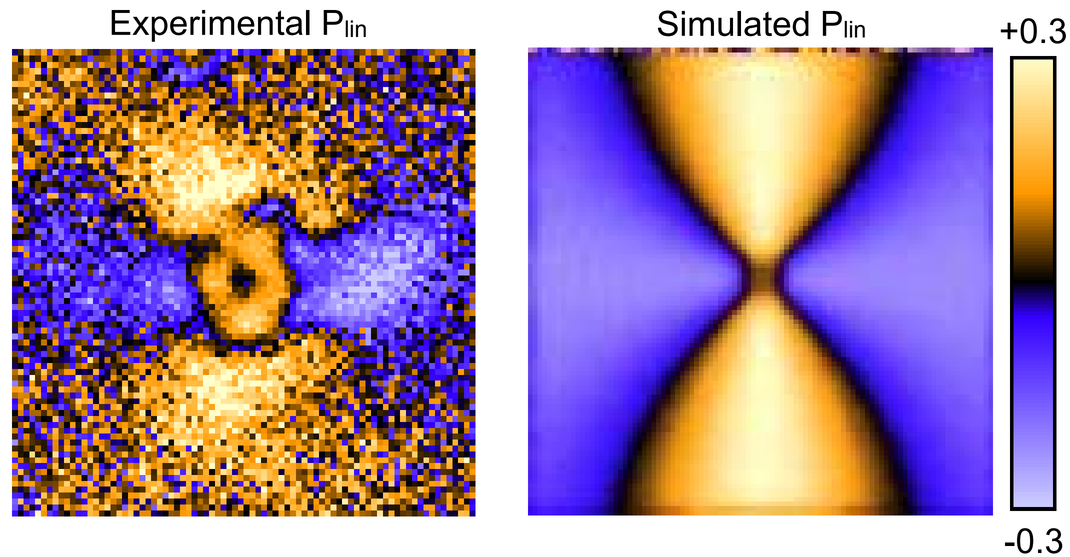
A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov, T. Ostatnický, M. Vladimirova, A.V. Kavokin, K.L. Campman, A.C. Gossard, unpublished

measured polarization pattern —(exciton spin density matrix)→ spin currents carried by electrons and holes bound to excitons

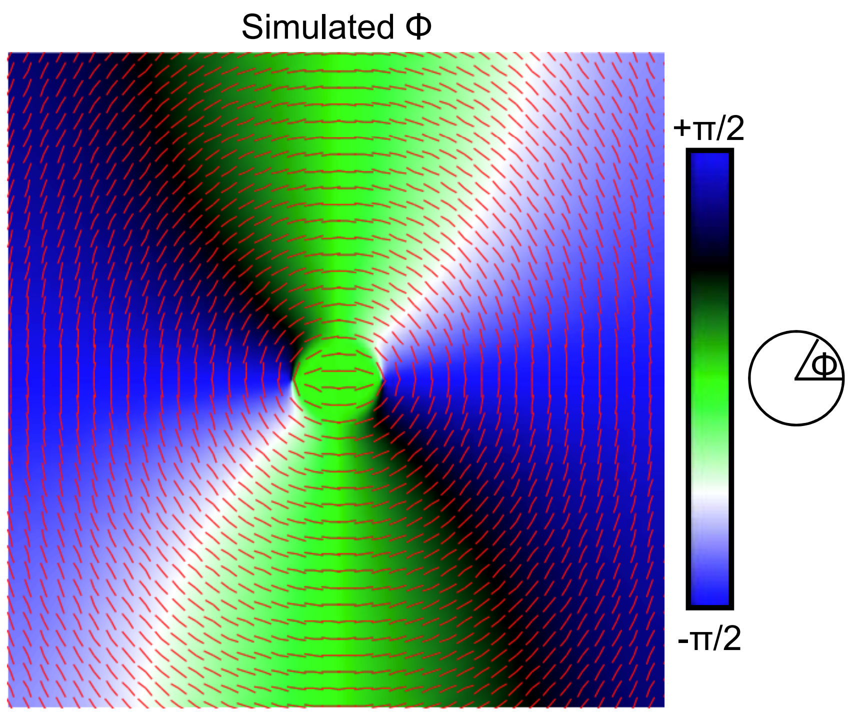
electron and hole spin tend to align along the effective magnetic fields given by the Dresselhaus SO interaction

talk of Alexey Kavokin

B=0T

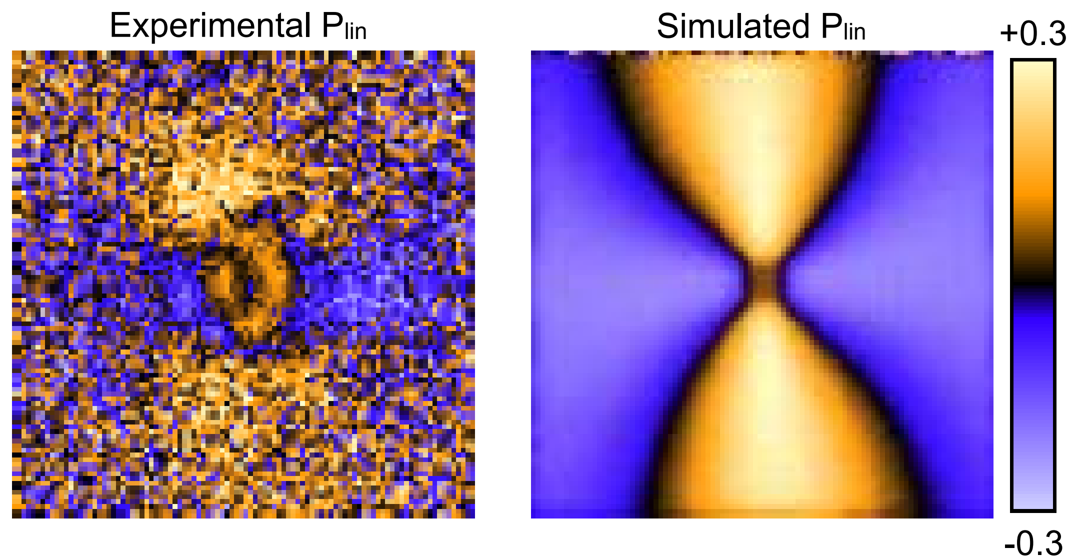


radial exciton polarization currents are associated with spin currents carried by electrons and holes bound into excitons



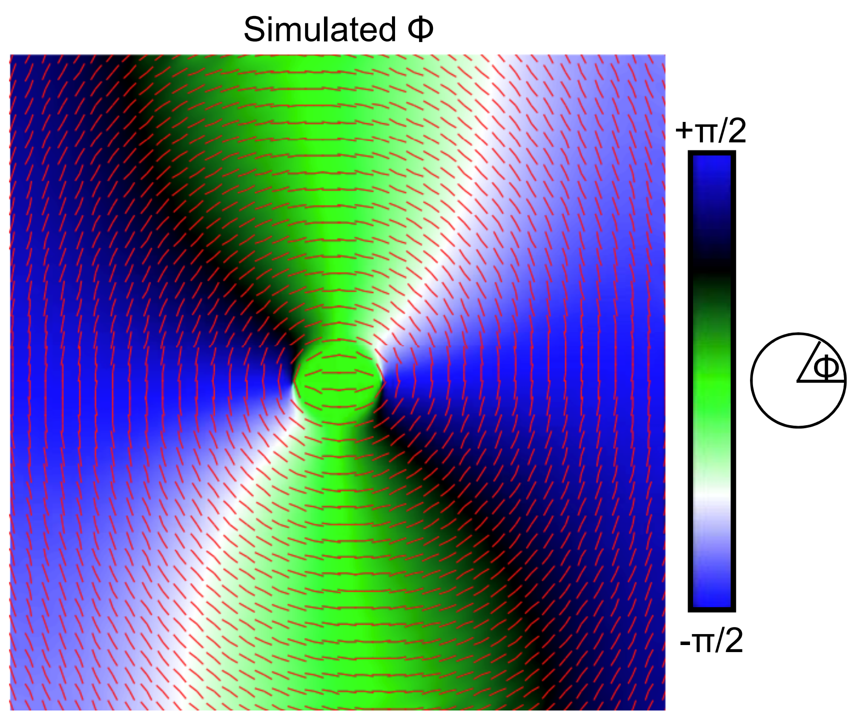
A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov, T. Ostatnický, M. Vladimirova, A.V. Kavokin, K.L. Campman, A.C. Gossard, unpublished

B=1T

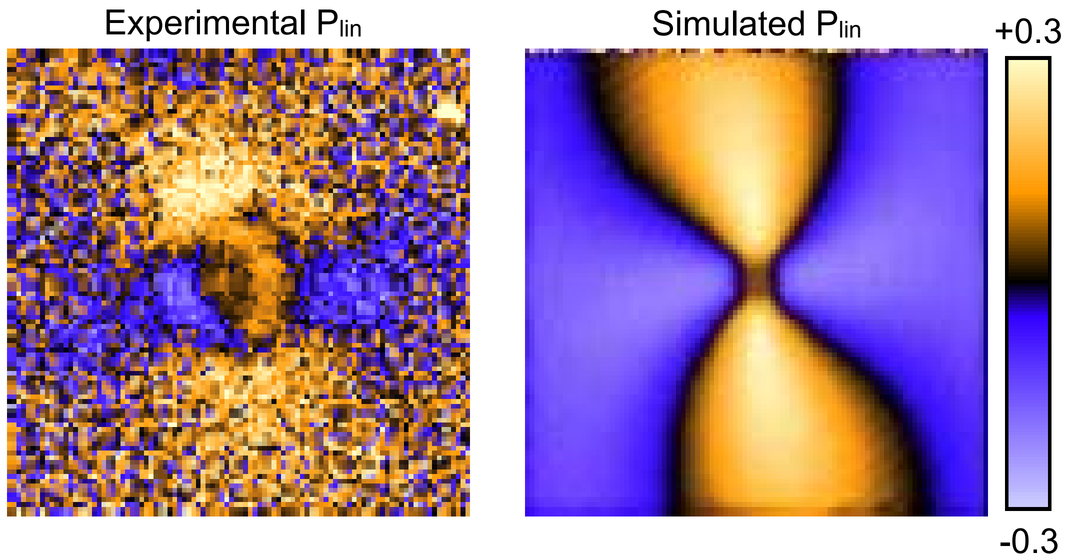


applied magnetic fields bend spin current trajectories

spiral patterns of linear polarization



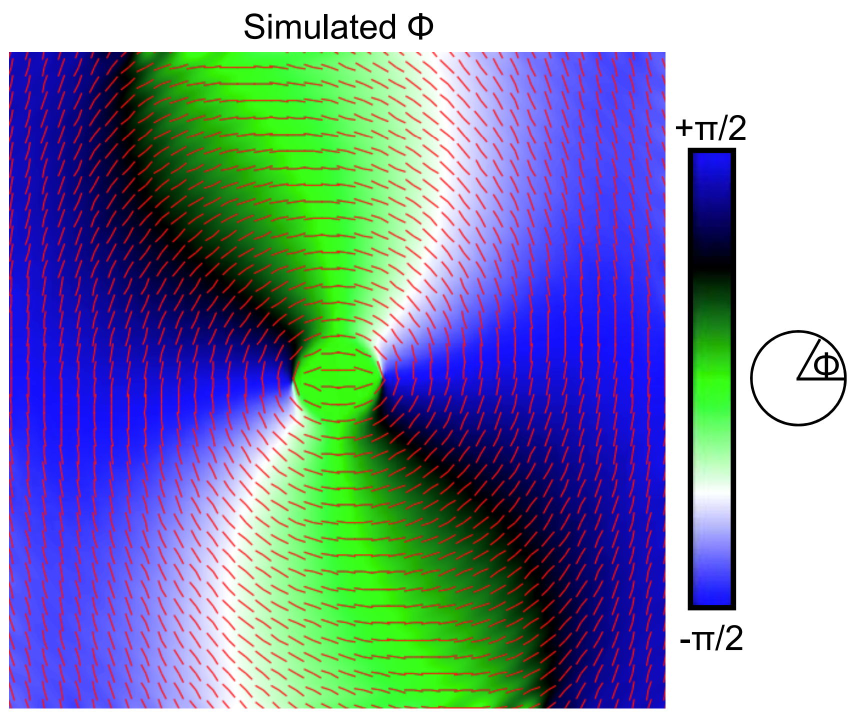
B=2T



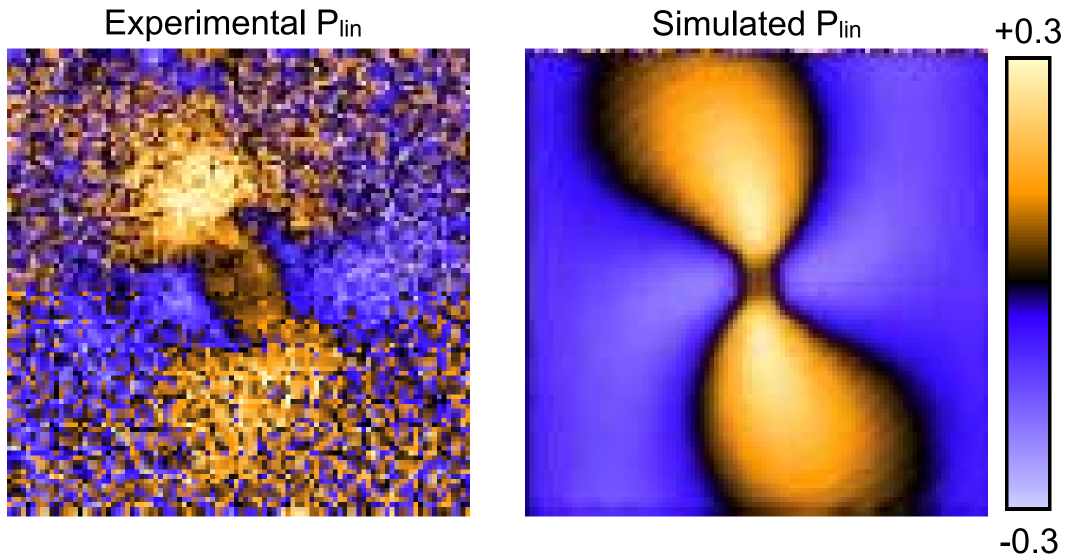
applied magnetic fields bend spin current trajectories

↓

spiral patterns of linear polarization

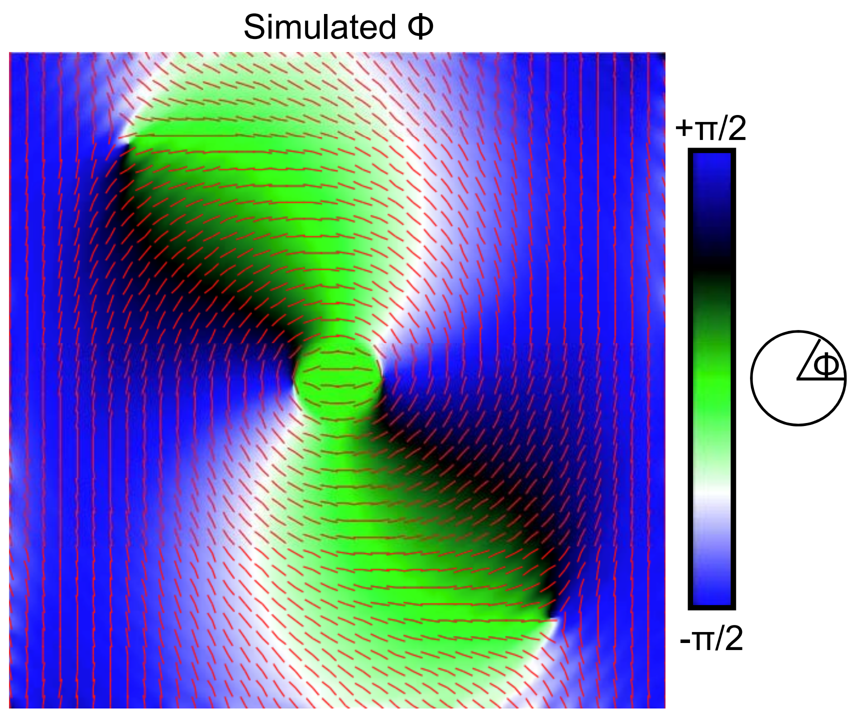


B=3T

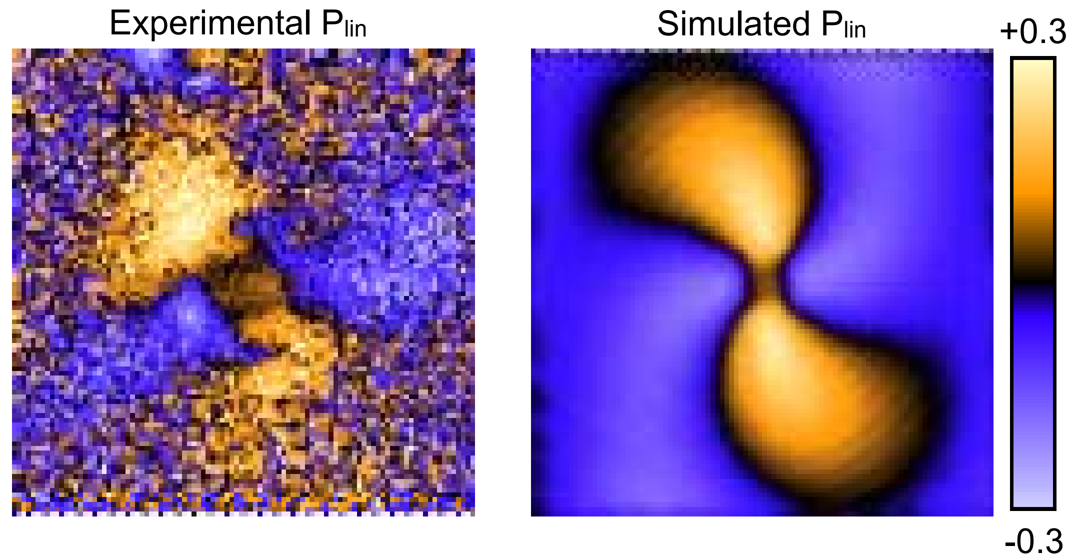


applied magnetic fields bend spin current trajectories

spiral patterns of linear polarization

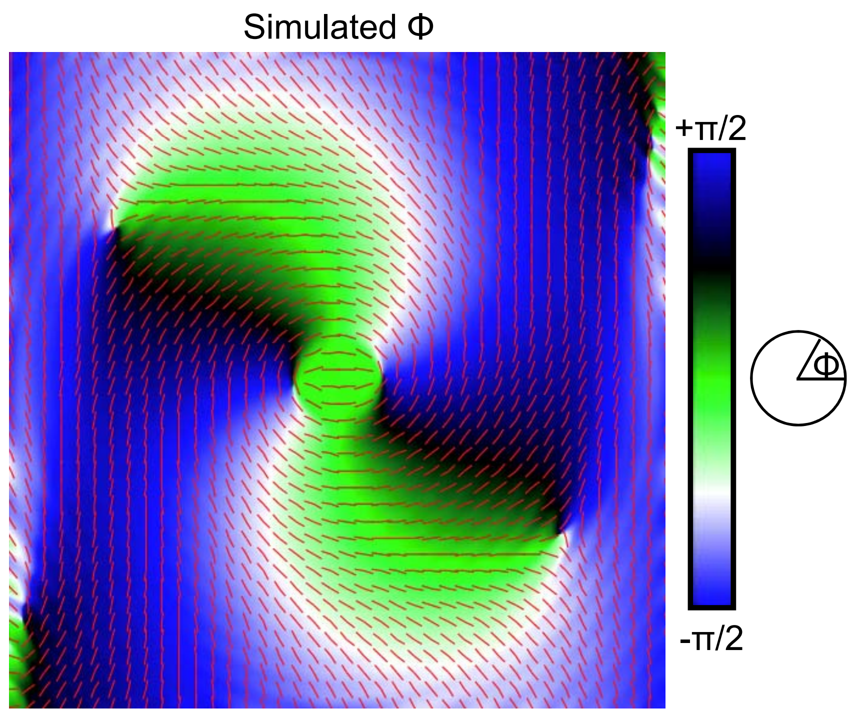


B=4T

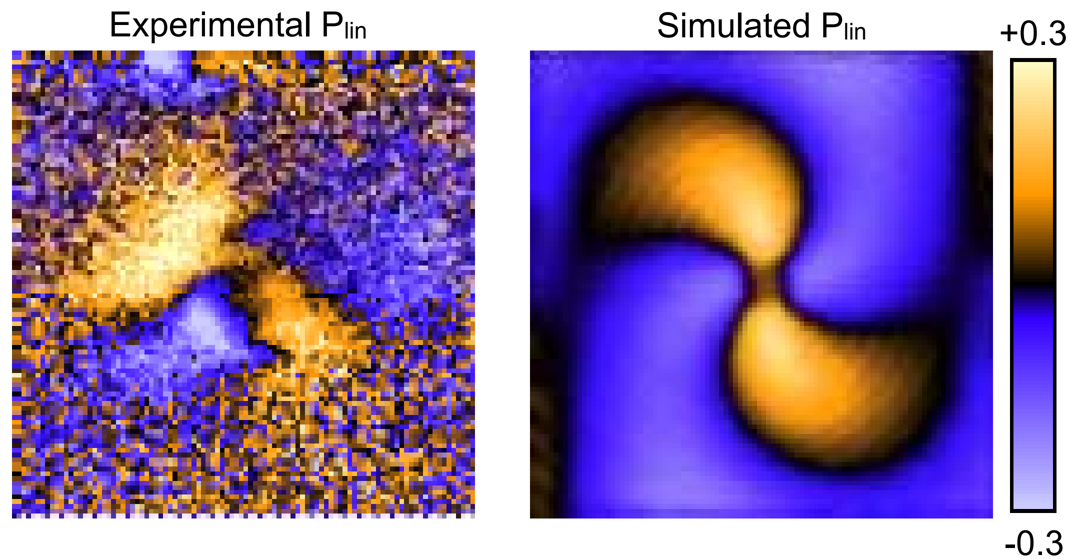


applied magnetic fields bend spin current trajectories

spiral patterns of linear polarization

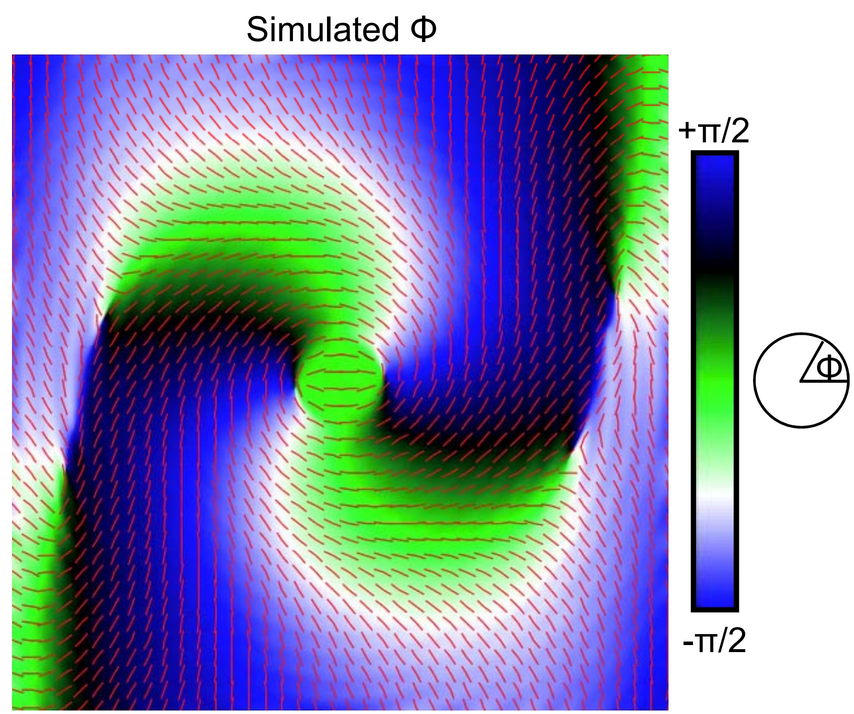


B=5T

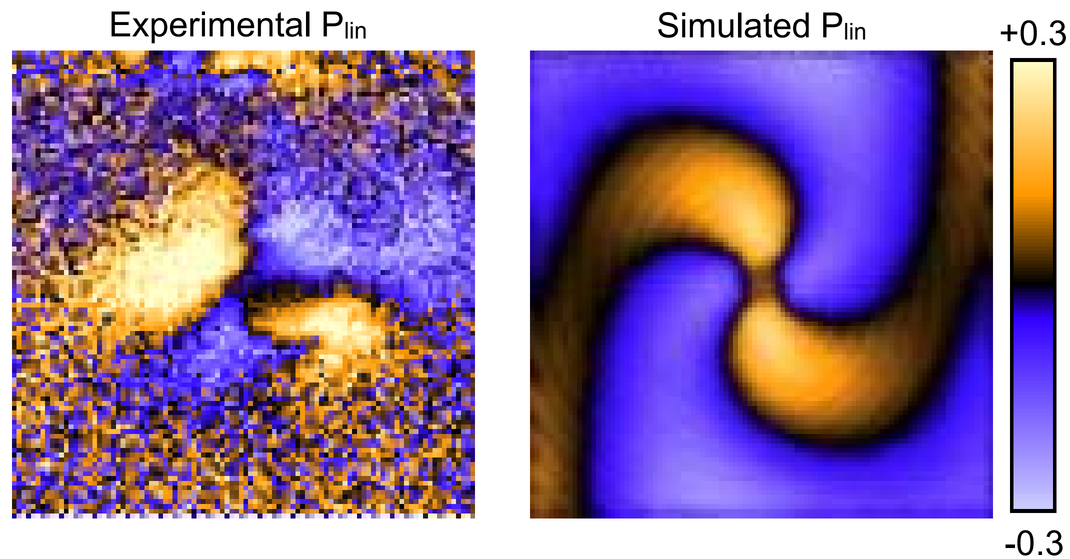


applied magnetic fields bend spin current trajectories

spiral patterns of linear polarization



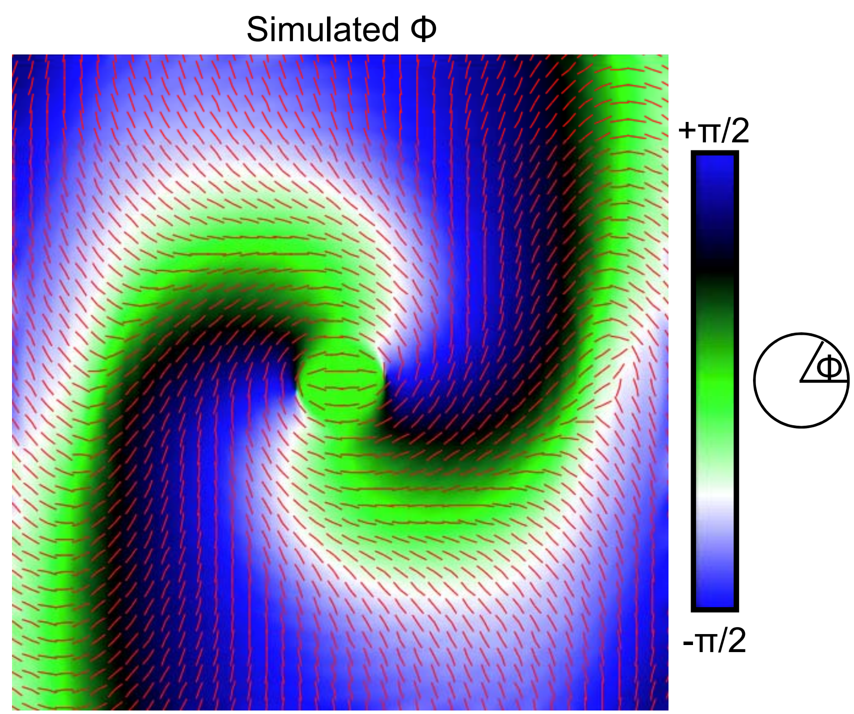
B=6T



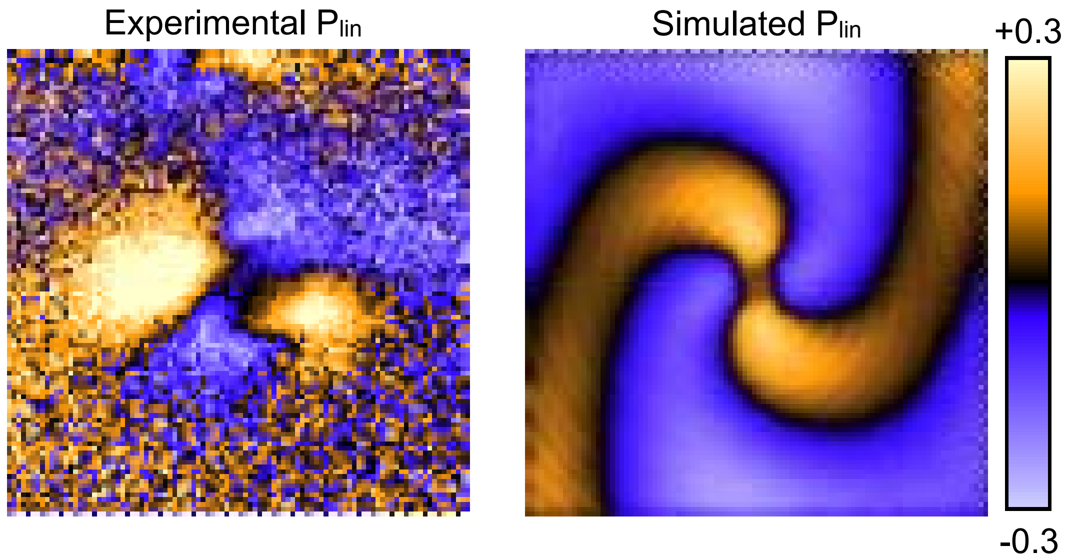
applied magnetic fields bend spin current trajectories

↓

spiral patterns of linear polarization



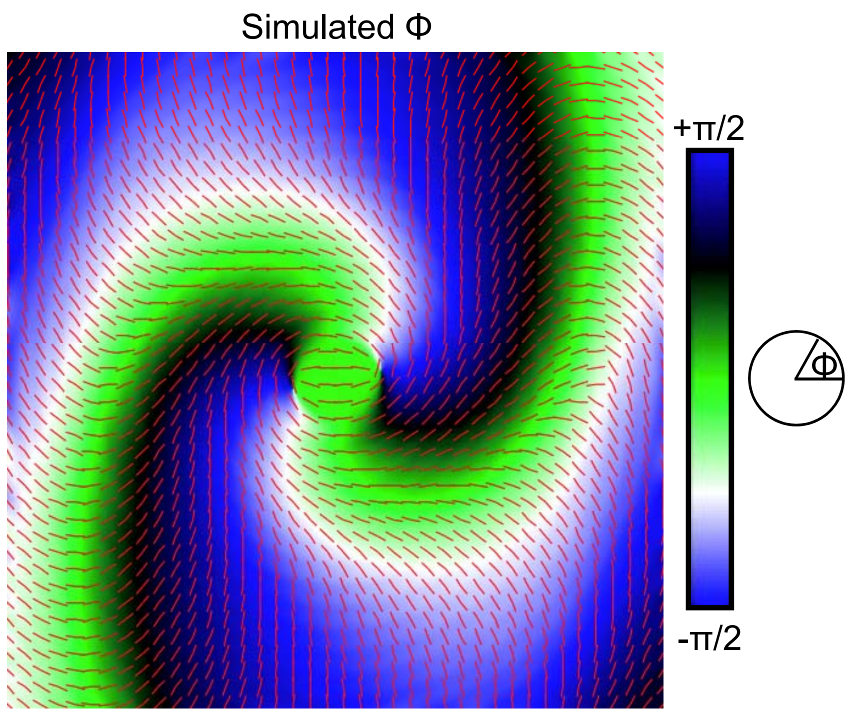
B=7T



applied magnetic fields bend spin current trajectories

⬇

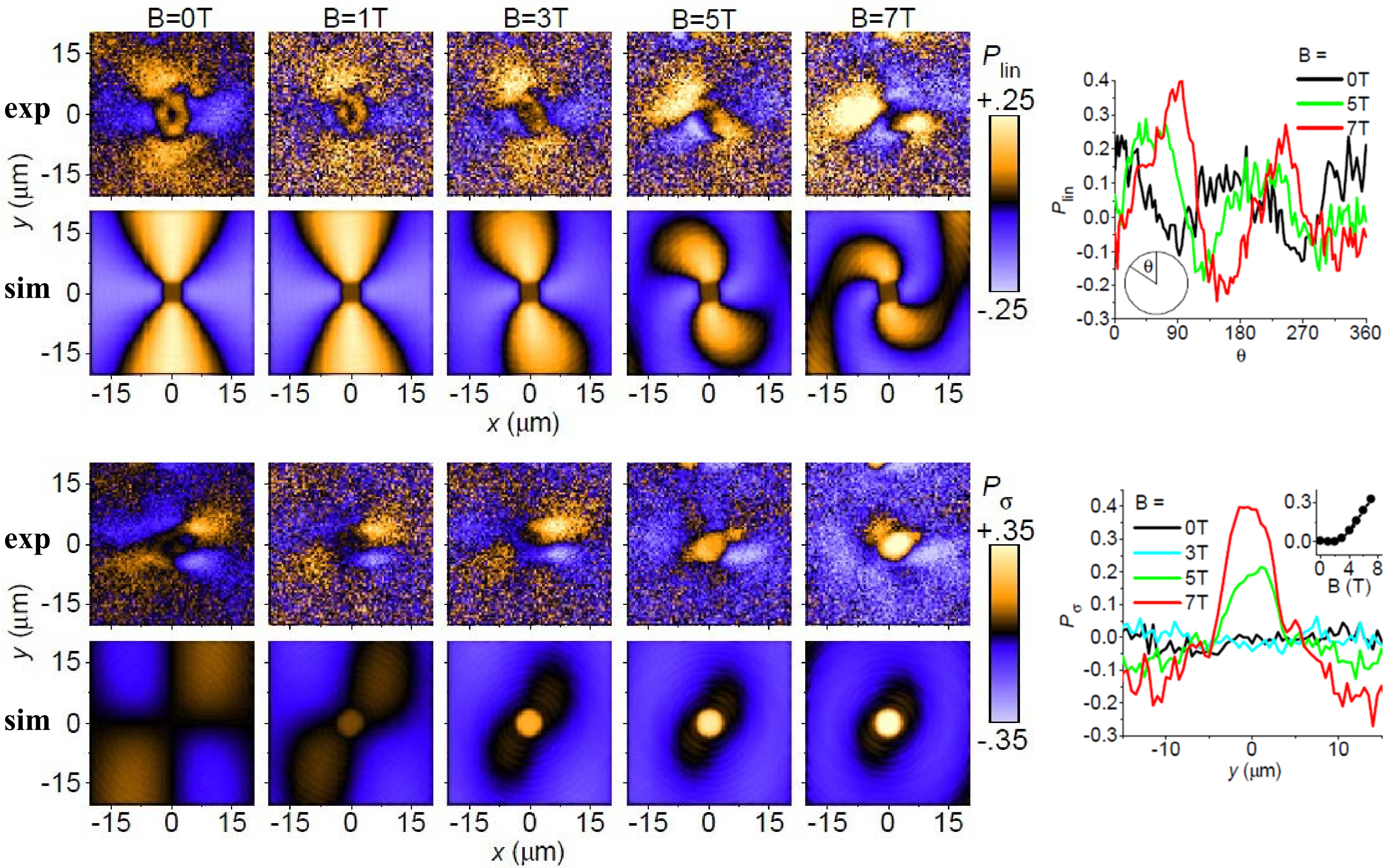
spiral patterns of linear polarization



spiral direction of exciton polarization current

≠

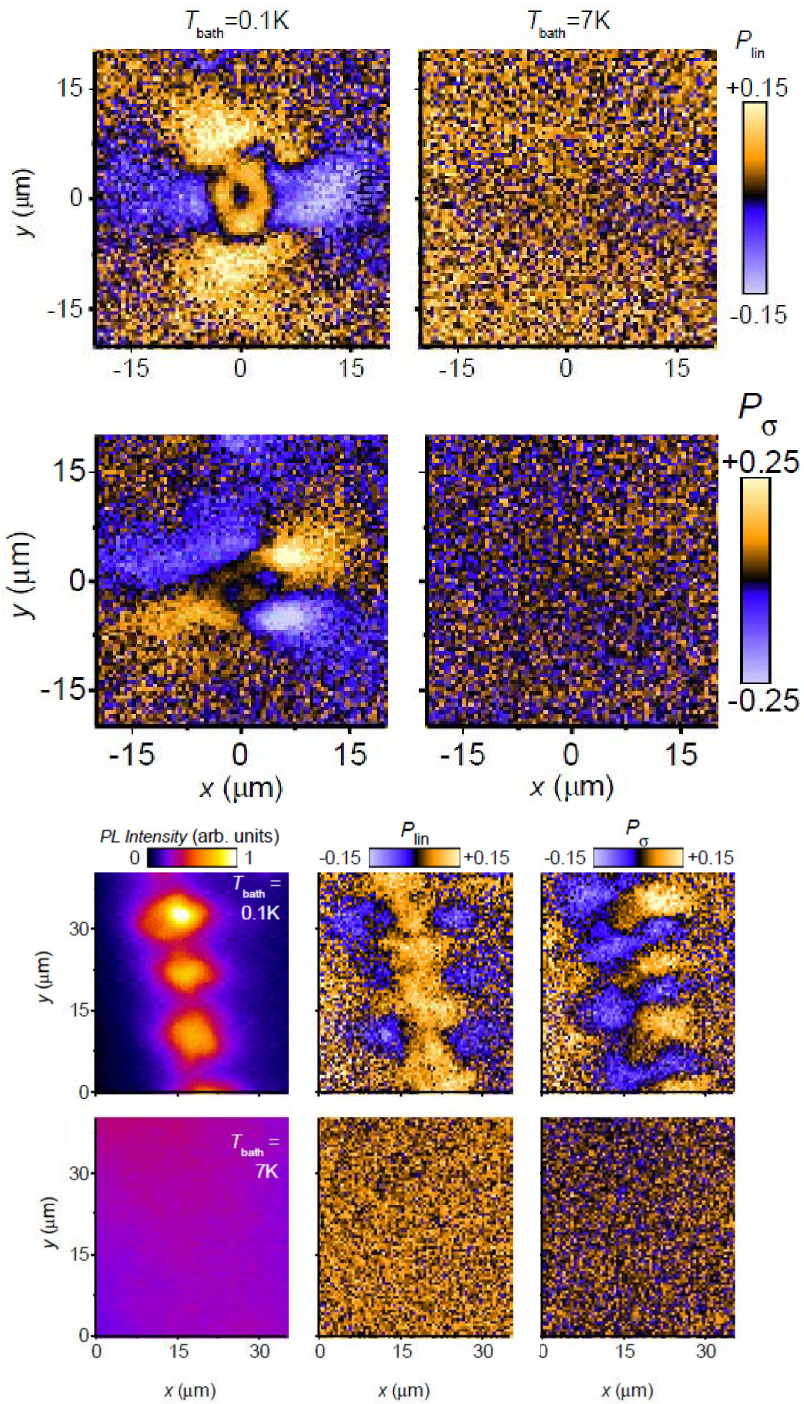
radial direction of exciton density current

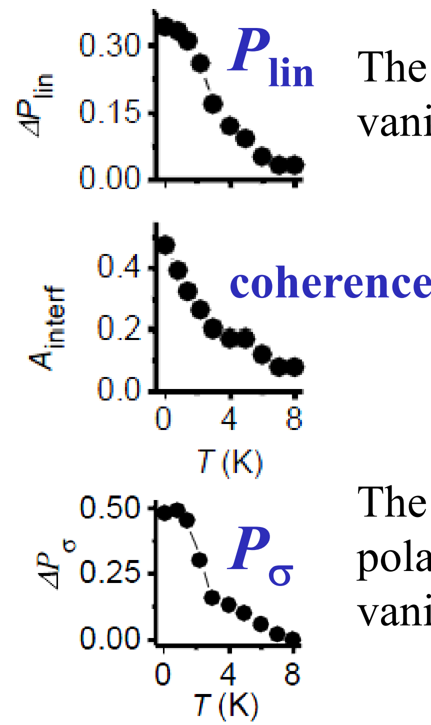


radial source of excitons with hedgehog momentum distribution generates

	linear polarization	circular polarization
B = 0	**helical (vortex) pattern**	**four-leaf pattern**
finite B	**spiral pattern**	**bell-like with inversion pattern**

Temperature dependence





The vortex of linear polarization vanishes with increasing temperature

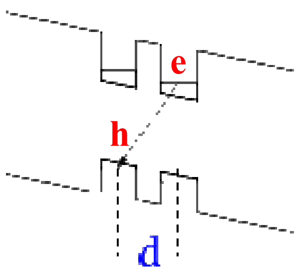
The four-leaf pattern of circular polarization
vanishes with increasing temperature

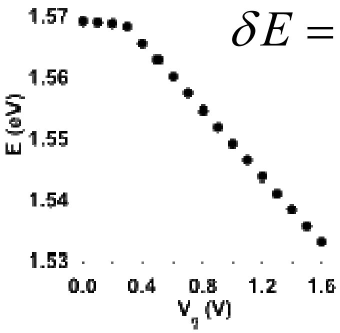
A periodic array of beads in the MOES creates periodic polarization textures

The periodic polarization textures vanish above the critical temperature of the MOES

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**
- **sub-wavelength footprint**

traps for excitons

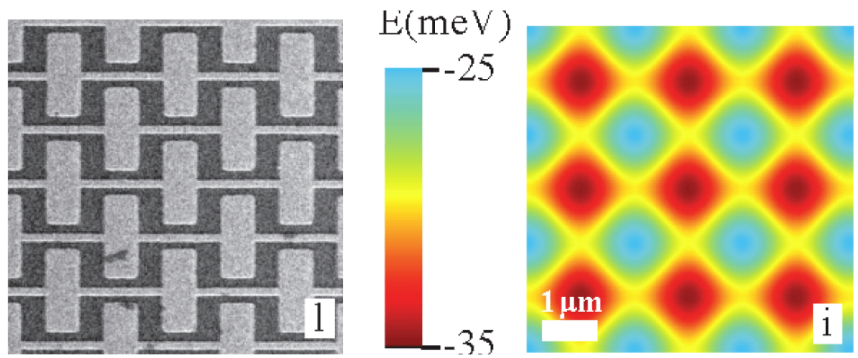
and other potential landscapes

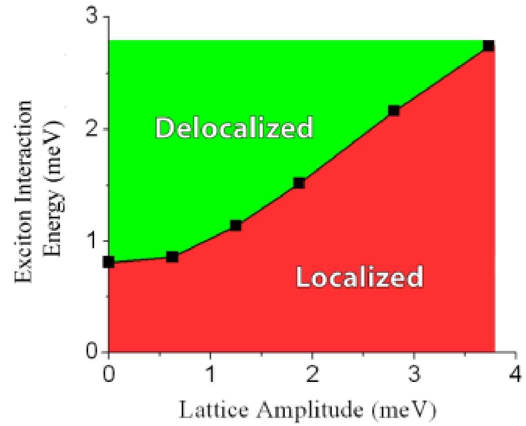
control of shape and depth of potential landscape

→ tool for studying basic properties

traps and lattices are effectively used in studies of cold atoms

Lattices for excitons



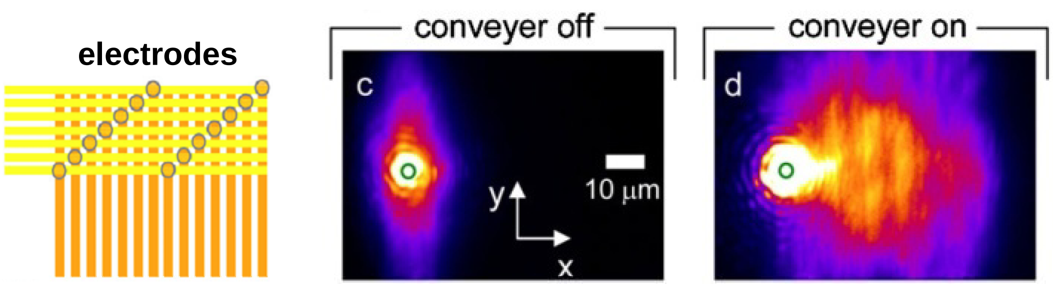


exciton localization
– delocalization
in a lattice

talk of
Michael Fogler

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)

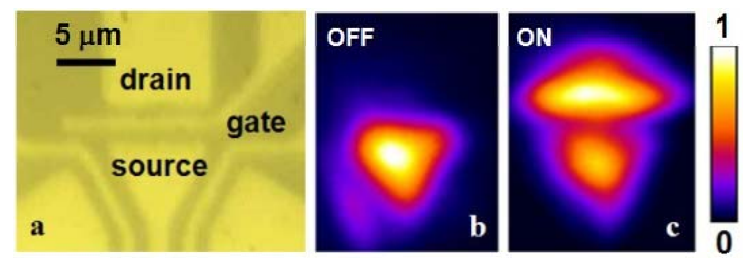
M. Remeika, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, *Appl. Phys. Lett.* 100, 061103 (2012)



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

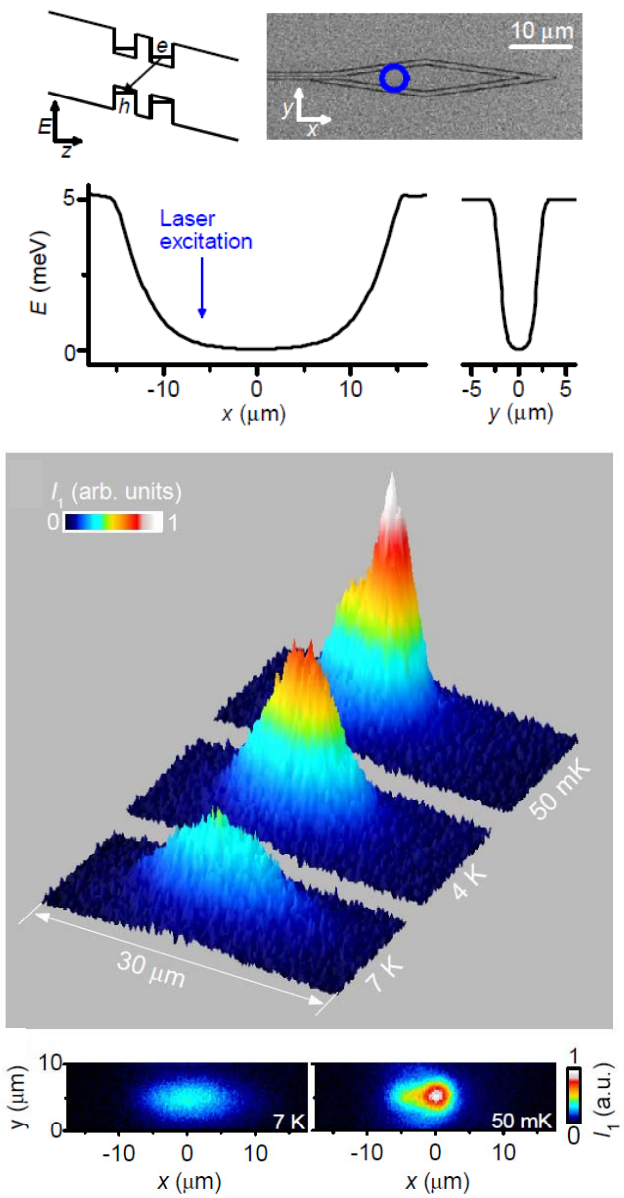
Science 321, 229 (2008)

Nature Photonics 3, 577 (2009)

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

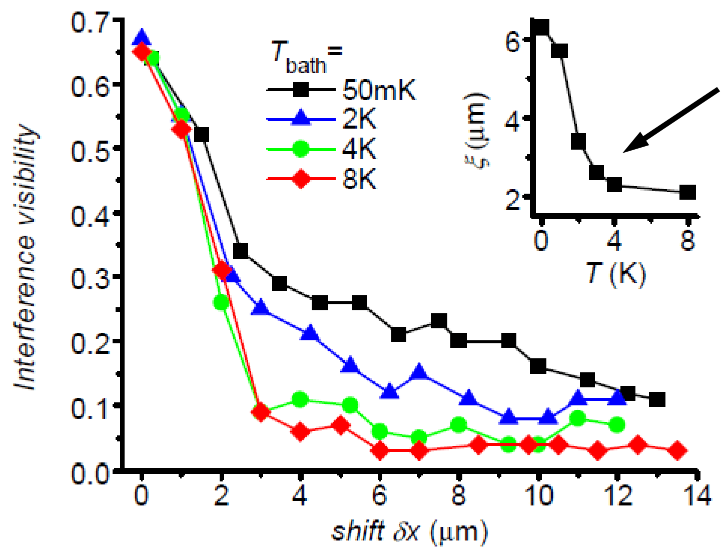
condensation of excitons in a trap

Condensation of excitons in diamond trap



with lowering temperature

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



measured transition temperature ~2 K

rough estimate of the temperature of exciton BEC

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

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

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

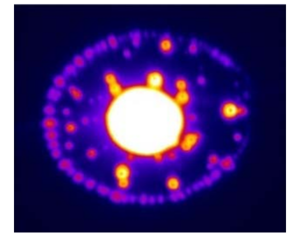
A.A. High, J.R. Leonard, M. Remeika, L.V. Butov, M. Hanson, A.C. Gossard, Nano Lett. 12, 2605 (2012)

summary

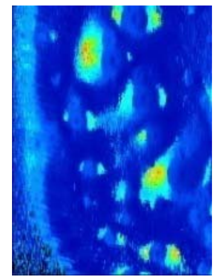
Cold indirect excitons (recent results):

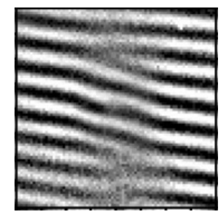
- **Macroscopically ordered exciton state (MOES)**

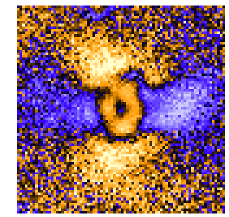
L.V. Butov, A.C. Gossard, D.S. Chemla, Nature 418, 751 (2002)

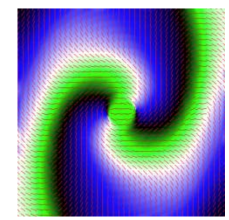


- **Spontaneous coherence in MOES and pol. vortex**
- **Phase singularities in interference pattern**
- **Spin textures and spin currents**









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)