Spin Currents in a Coherent Exciton Gas

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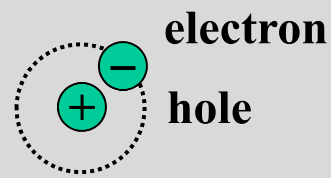
- **Cold exciton gas**
- **Indirect excitons**
- **Exciton rings**
- **Spontaneous coherence**
- **Spin currents**

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

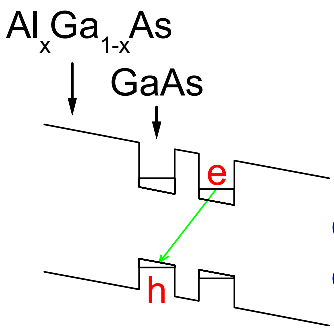
how to realize cold exciton gas ?

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

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

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

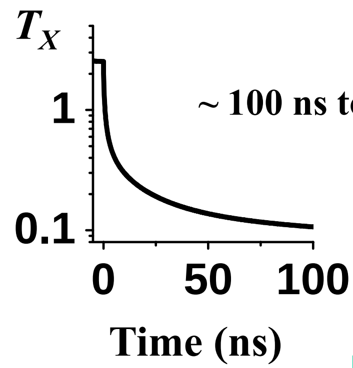
Indirect excitons in CQW



GaAs/AlGaAs CQW

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

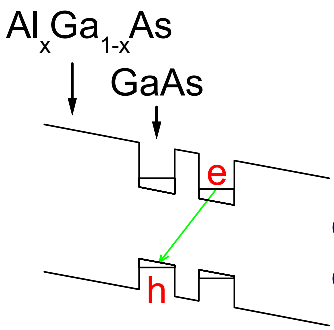
realization of cold exciton gas in separated layers was proposed by
Yu.E. Lozovik, V.I. Yudson (1975)
T. Fukuzawa, S.S. Kano, T.K. Gustafson, T. Ogawa (1990)



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

T_X ~ 100 mK << T_{dB}
is realized for indirect excitons

Indirect excitons in CQW



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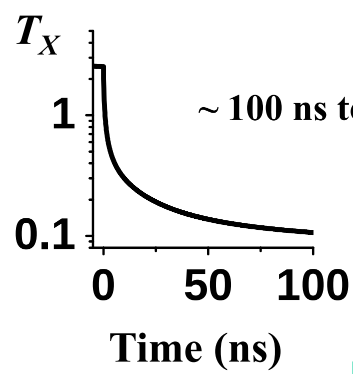

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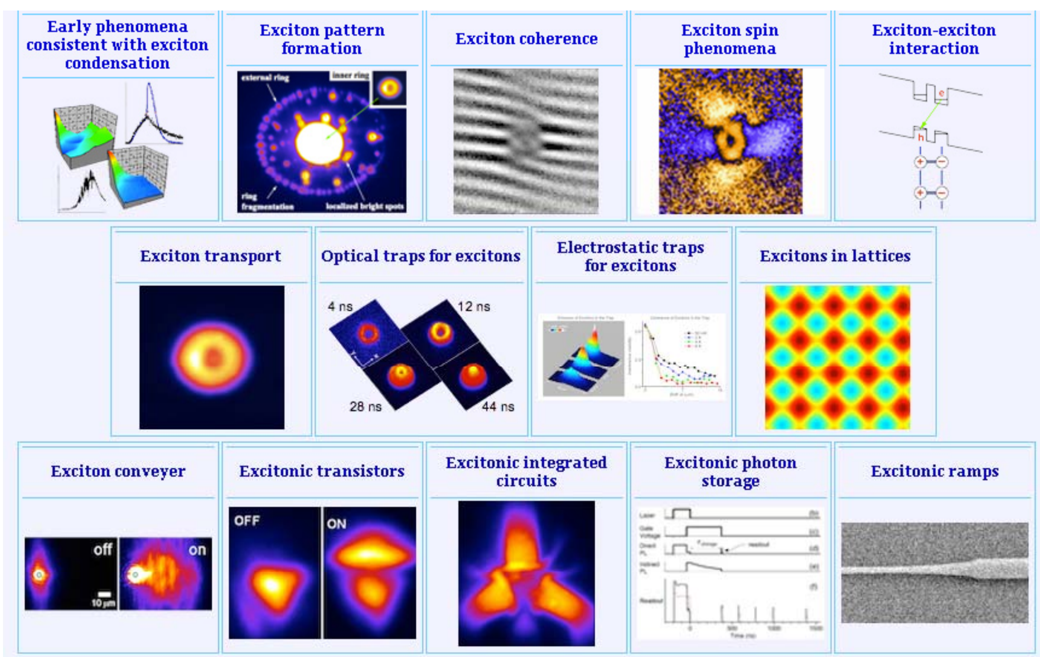
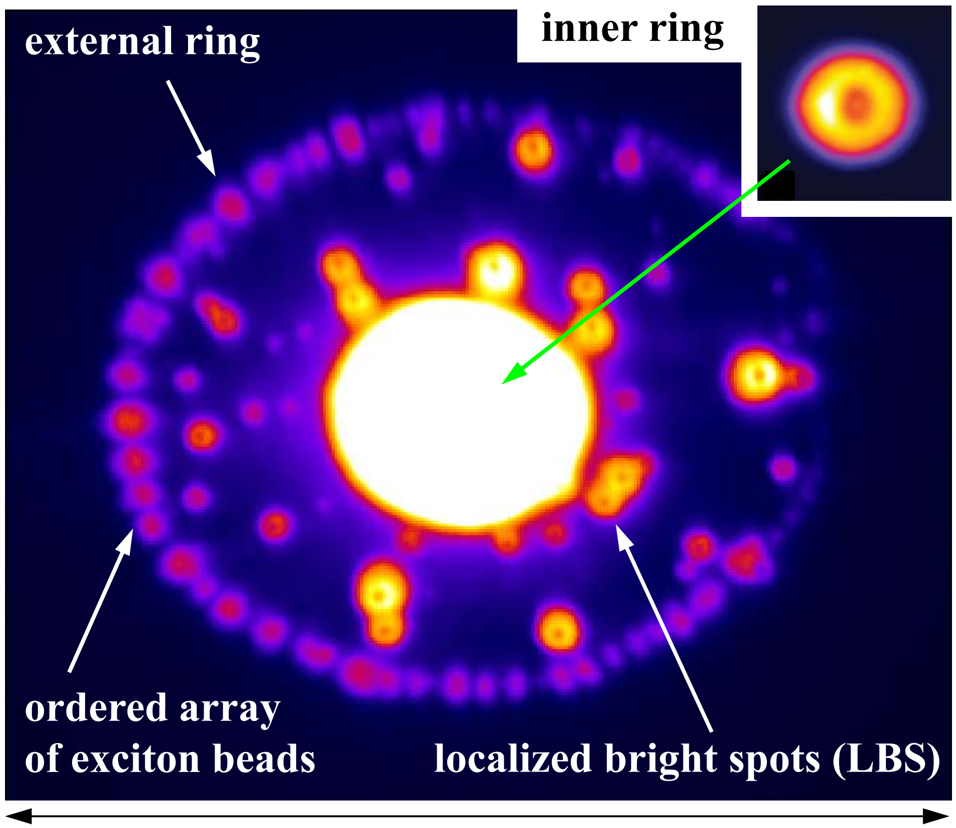
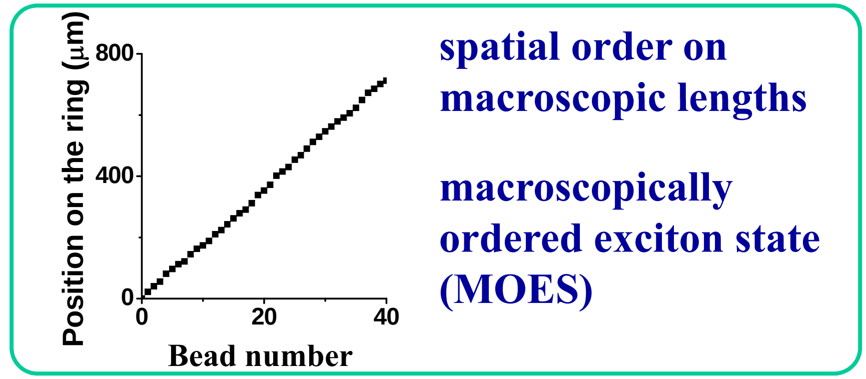
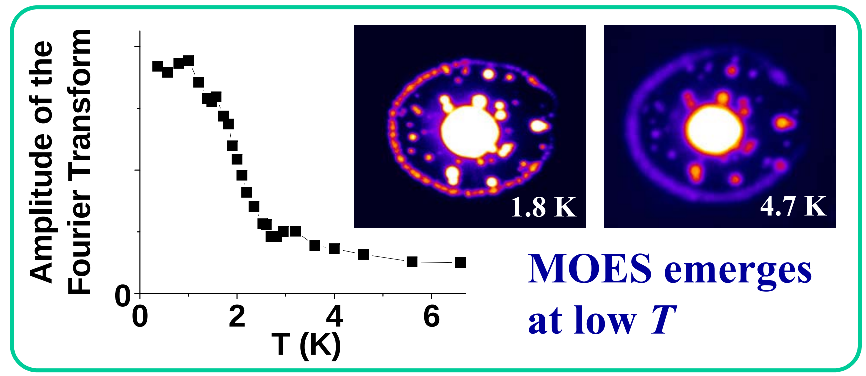


http://physics.ucsd.edu/~lvbutov/

Exciton rings and macroscopically ordered exciton state





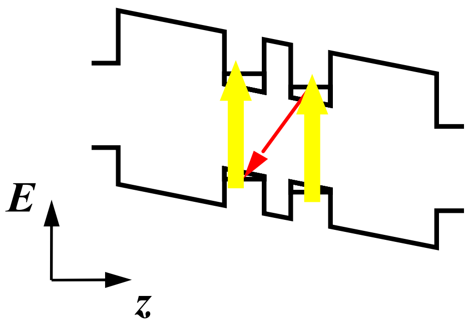


L.V. Butov, A.C. Gossard, D.S. Chemla,
Nature 418, 751 (2002)

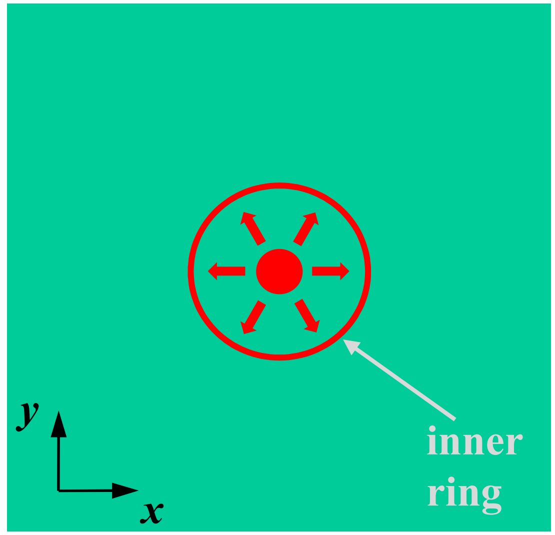
model of

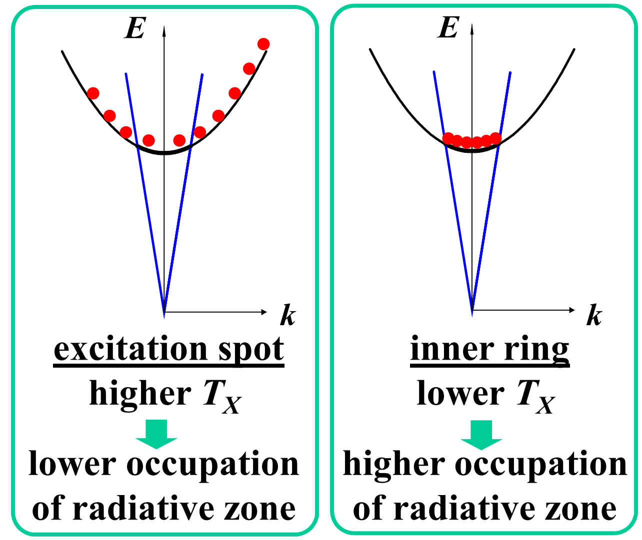
- **inner ring:** A.L. Ivanov, L. Smallwood, A. Hammack, Sen Yang, L.V. Butov, A.C. Gossard, EPL 73, 920 (2006)
- **external ring:** L.V. Butov, L.S. Levitov, B.D. Simons, A.V. Mintsev, A.C. Gossard, D.S. Chemla, PRL 92, 117404 (2004)
  R. Rapaport, G. Chen, D. Snoke, S.H. Simon, L. Pfeiffer, K.West,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

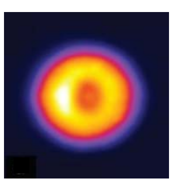




electron-rich region

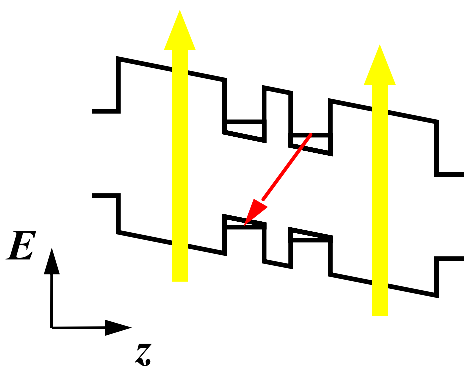
excitons

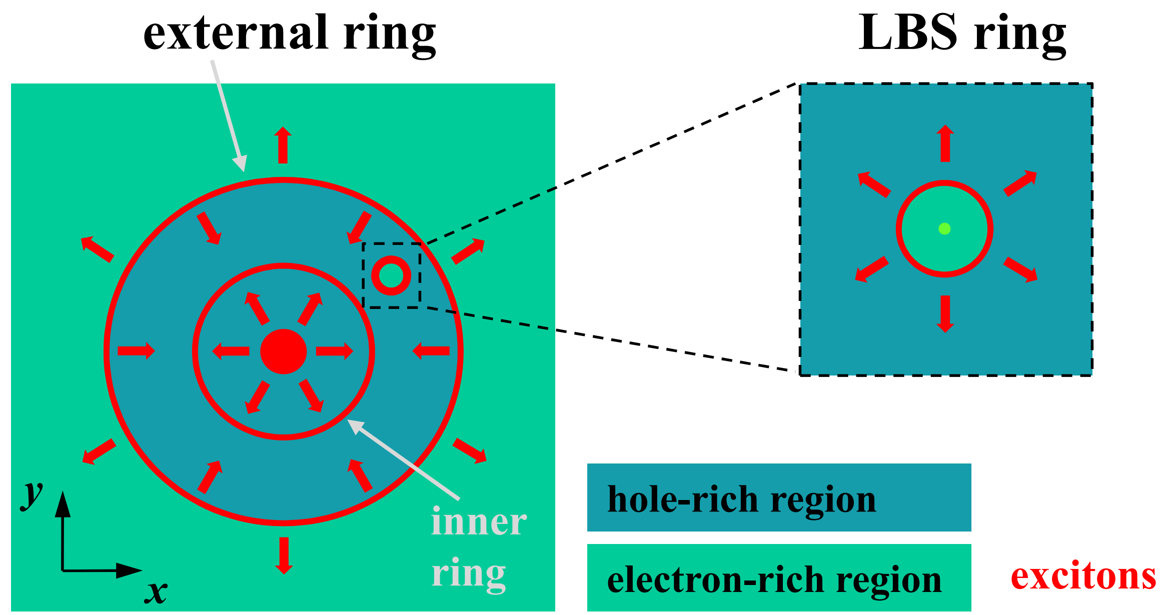
inner ring forms due to transport and cooling of optically generated excitons



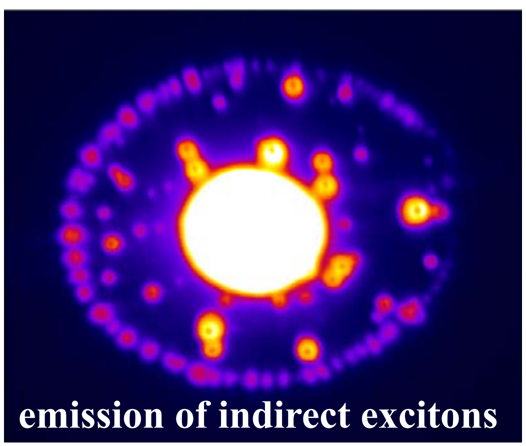
emission of indirect excitons

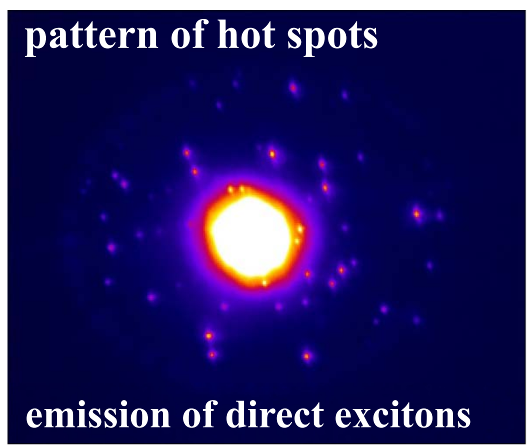
above barrier laser excitation creates excitons + holes in CQW





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

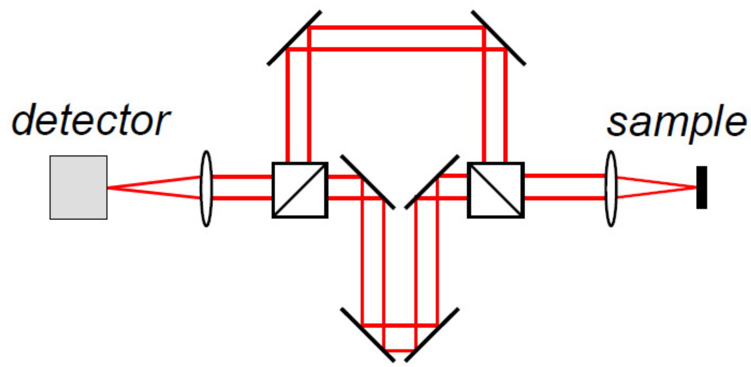
exciton gas
is hot in LBS centers
is cold in external ring and LBS rings

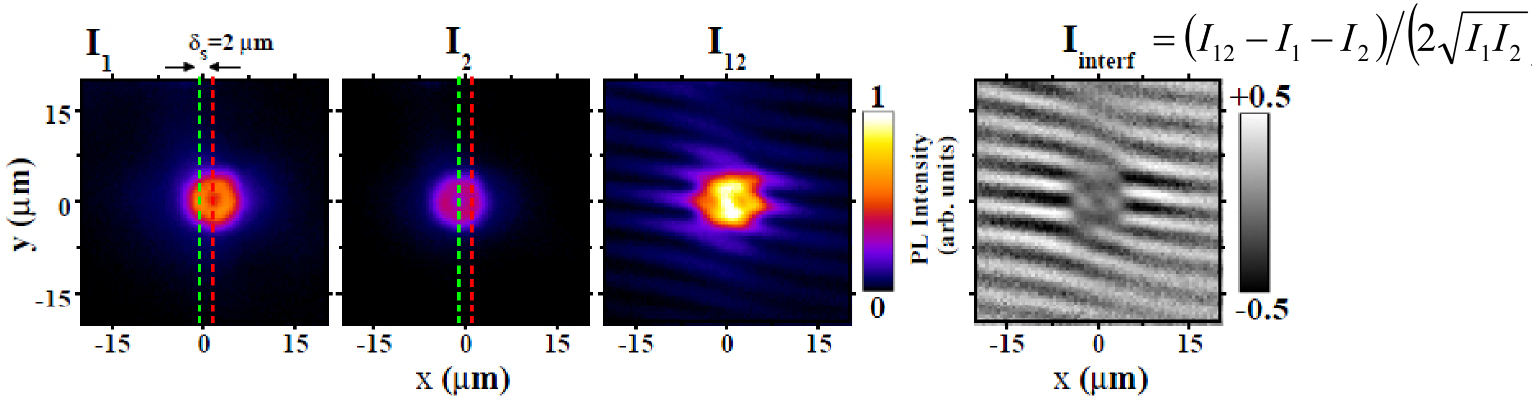
measured by
shift-interferometry

spontaneous coherence
and
spin polarization textures

measured by
polarization resolved imaging

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



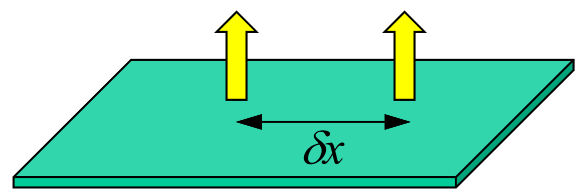


Pattern of $g_1(\delta x)$ is measured by shift-interferometry

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

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

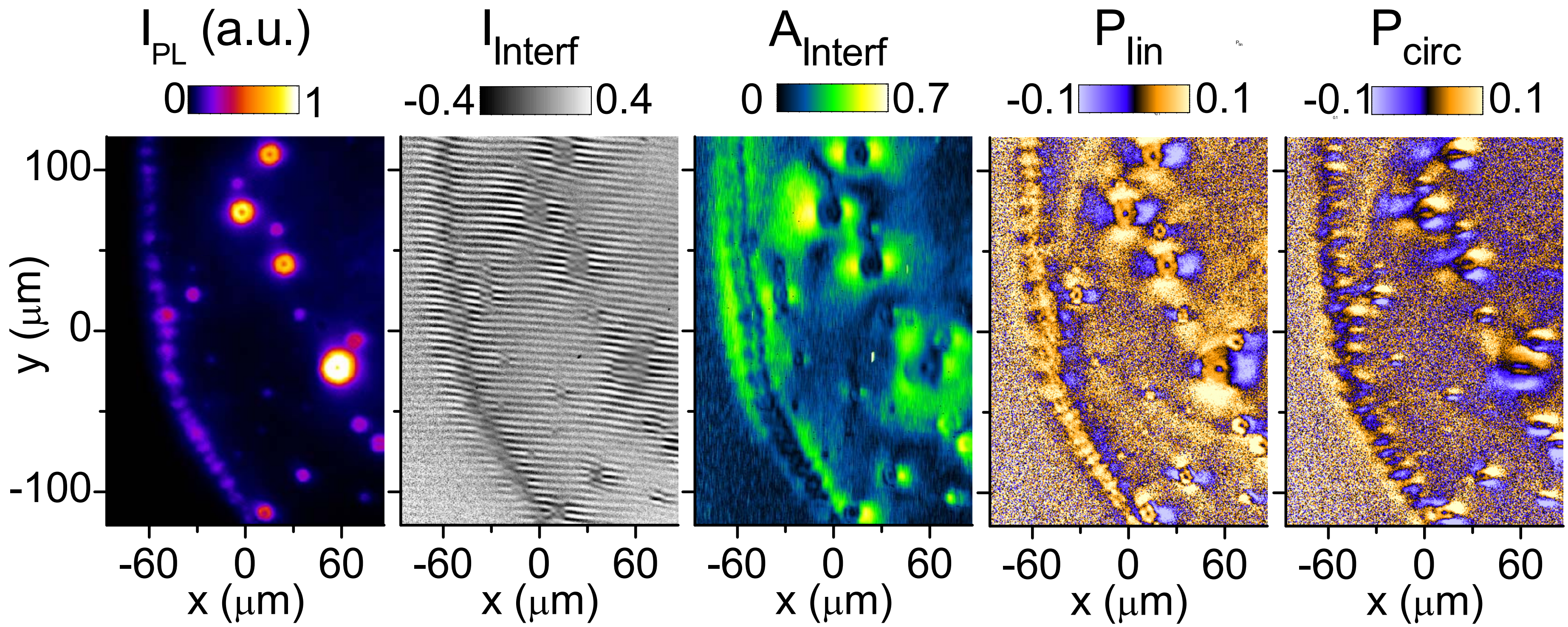
Contrast of interference fringes $A_{interf}(\delta x) \rightarrow g_1(\delta x)$



exciton coherence is imprinted on coherence of their light emission

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**



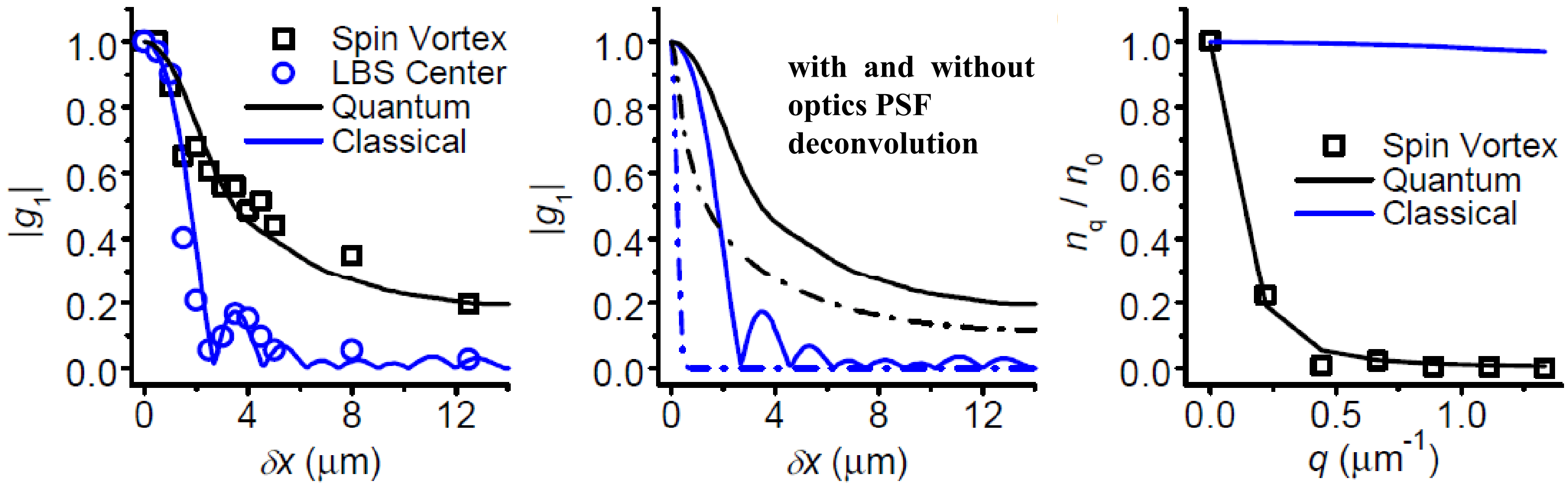
A.A. High, J.R. Leonard, A.T. Hammack, M.M. Fogler, L.V. Butov, A.V. Kavokin, K.L. Campman, A.C. Gossard, Nature 483, 584 (2012)

map of coherence degree

coherence is not induced by pumping light and, instead, is spontaneous

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, PRL 110, 246403 (2013)

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

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

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

$\xi >> \xi_{classical}$

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

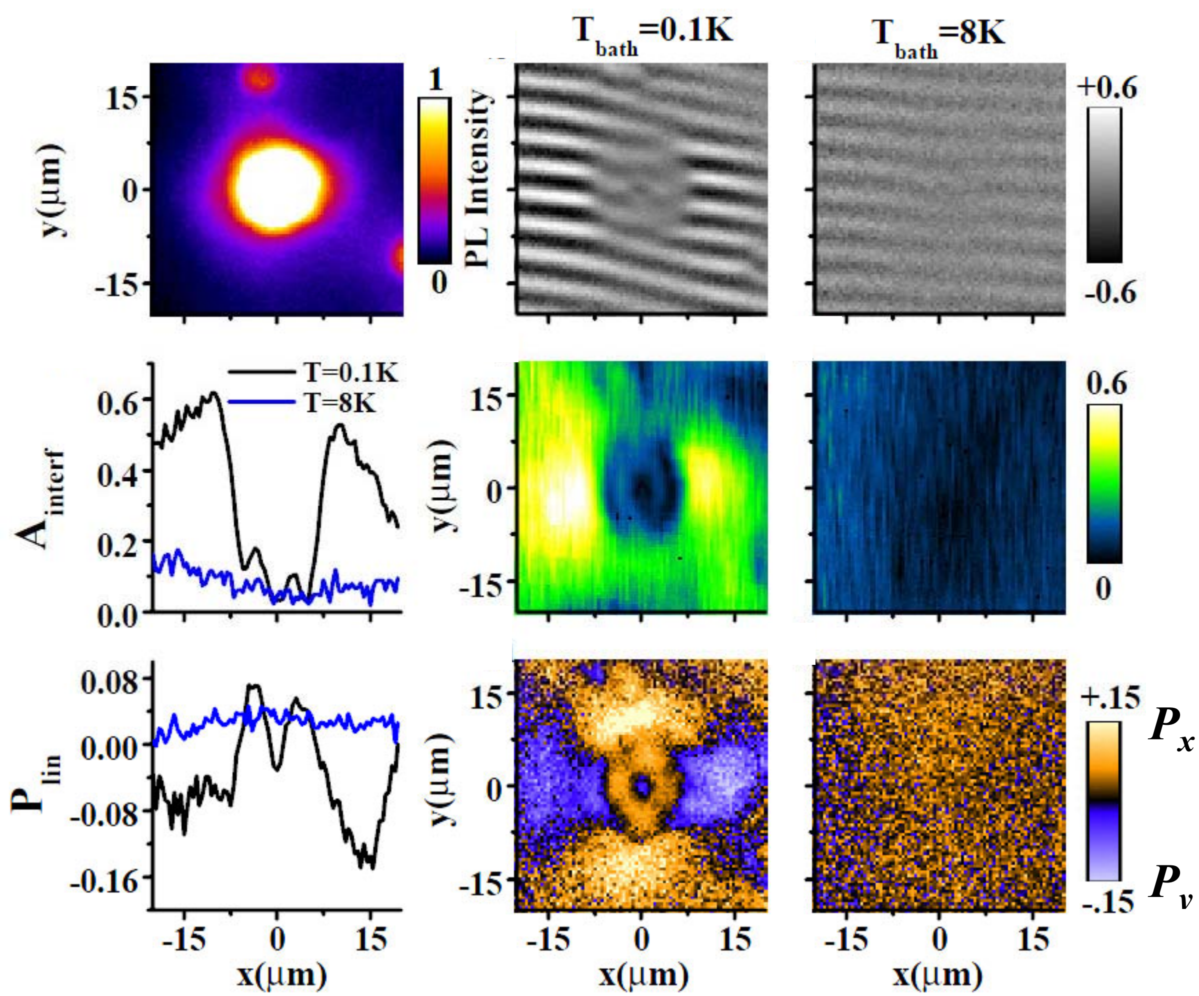
characteristic of a condensate

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

resolution of optics and exciton cloud geometry matter

$\xi, \ l_{sys}, l_{res}$

Exciton coherence and spin texture around LBS-ring



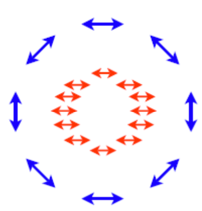
Emergence of

- Spontaneous coherence
- Spin polarization vortex

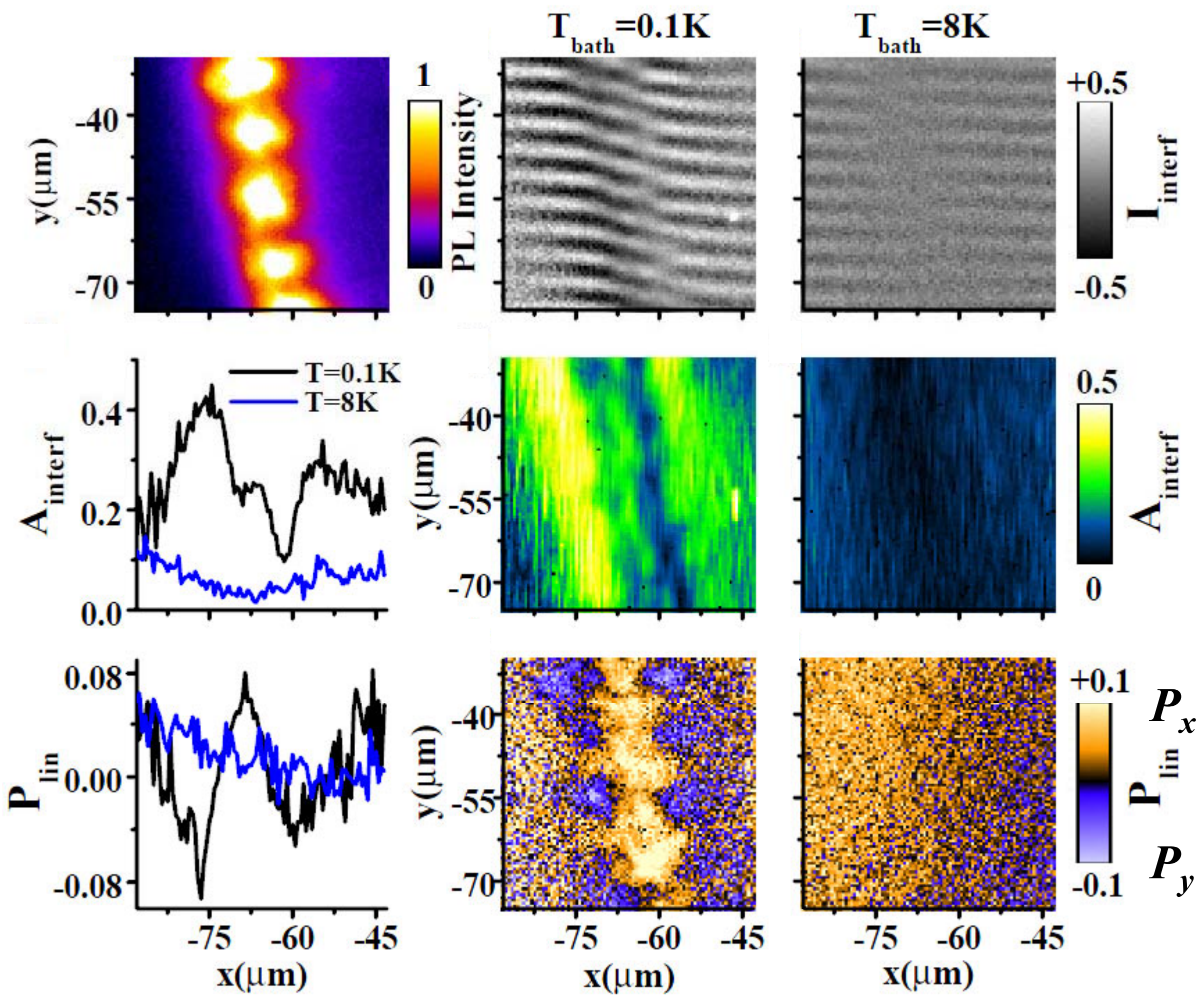
at low T at $r > r_0$

vortex of linear polarization

ring of linear polarization



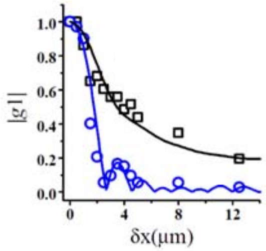
Exciton coherence and spin texture around external ring



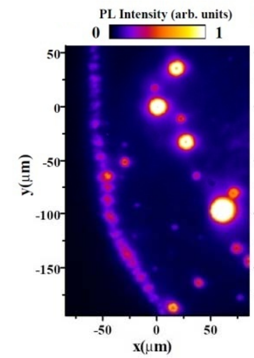
Emergence of

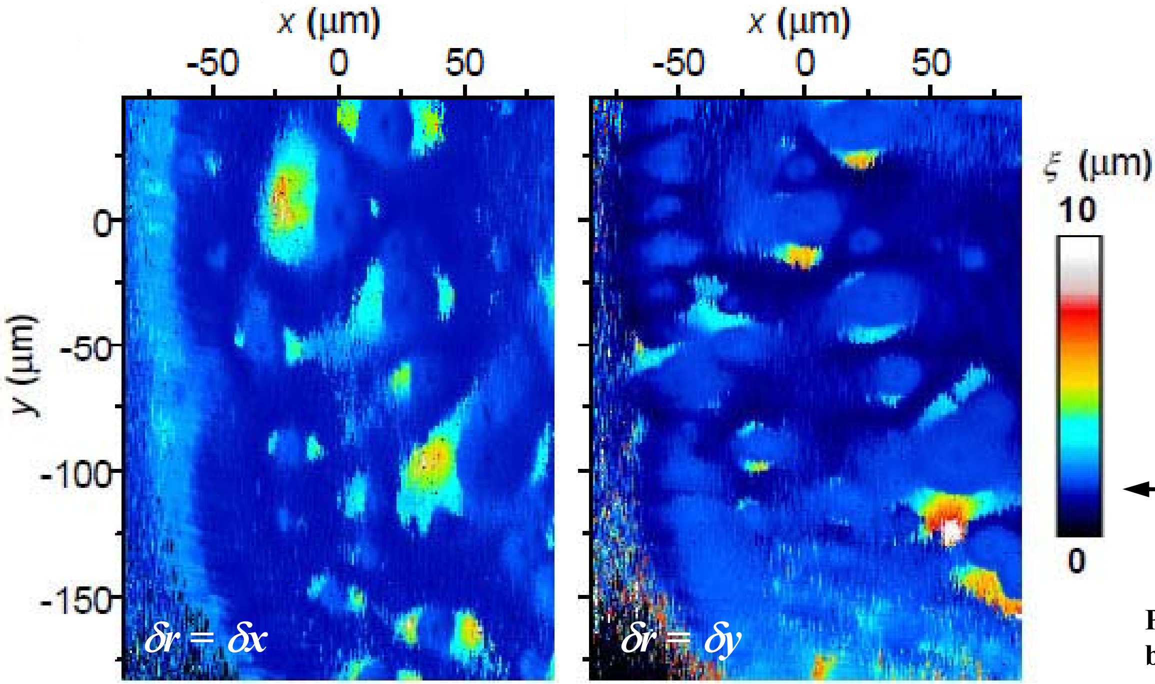
- **Spontaneous coherence**
- **Periodic spin texture**

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**

$\xi >> \xi_{classical}$

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

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>
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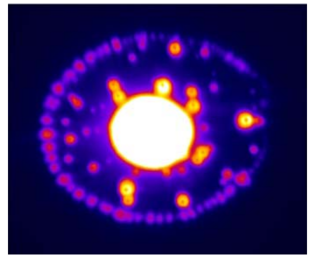
What we know about the macroscopically ordered exciton state

MOES is a state with:

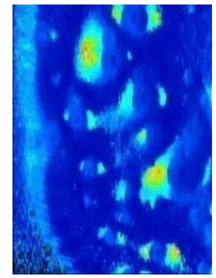
- **macroscopic <u>spatial ordering</u>**



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



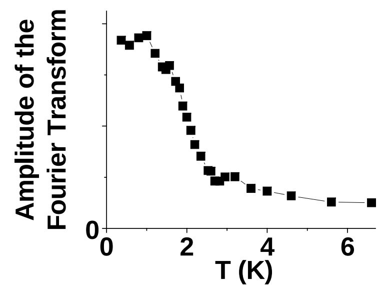
Sen Yang et al., PRL 97, 187402 (2006)

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

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

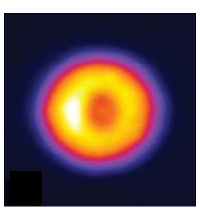
observed <u>in a cold exciton gas</u>

- 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

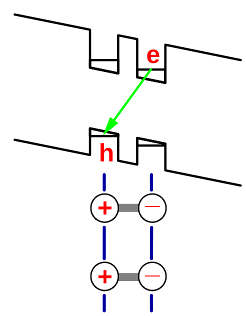


not observed in inner ring

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**

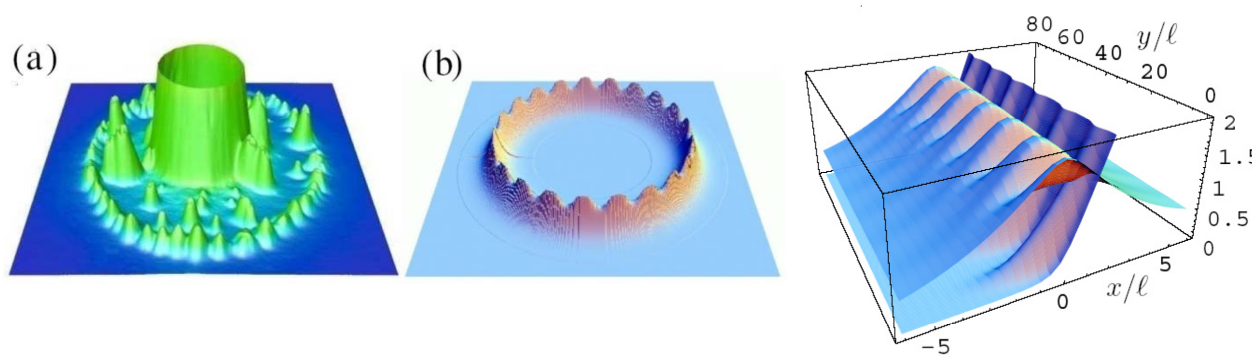
➡ **instability results from quantum degeneracy in a cold exciton system due to** <u>**stimulated kinetics of exciton formation**</u>

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

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

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

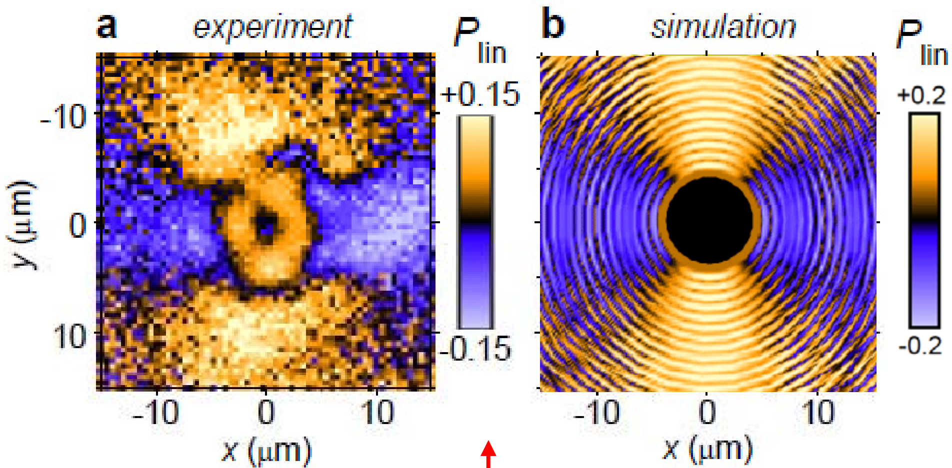
$$w \sim 1 + N_{E=0} = e^{\frac{T_{dB}}{T}} = e^{\frac{2\pi\hbar^2}{m g k_B T} n_x}$$

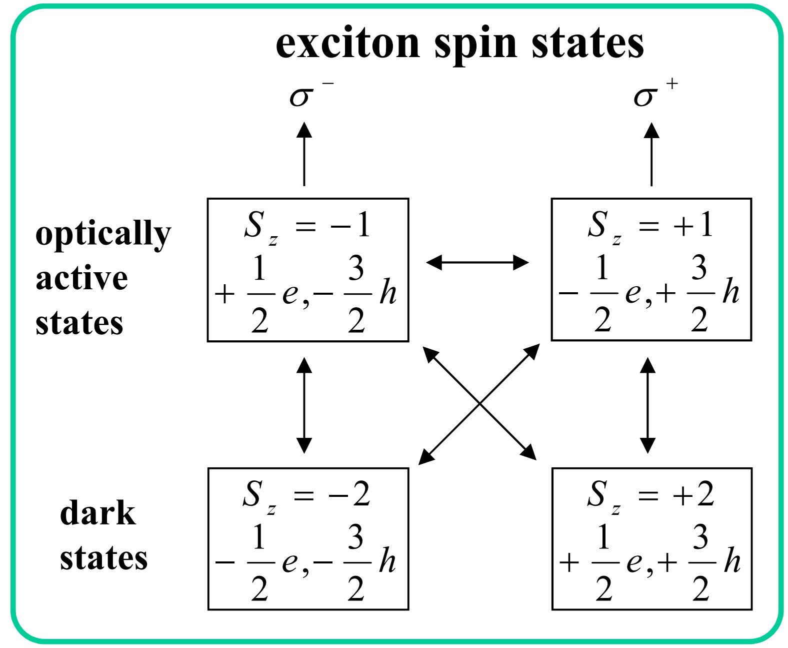


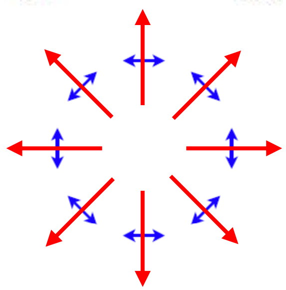
L.S. Levitov et al., PRL 94, 176404 (2005)

spin textures and spin currents

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

theory 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

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

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

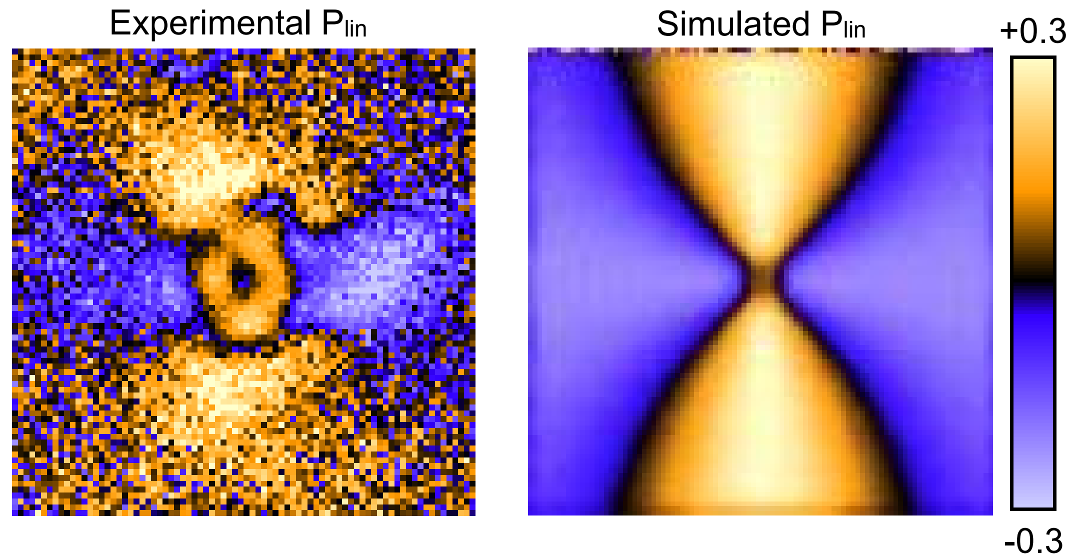
while the spin relaxation times of free electrons and holes can be short,
the formation of a coherent gas of their bosonic pairs
results in a strong enhancement of their spin relaxation times → long-range spin currents

measured by polarization resolved imaging

control of spin currents

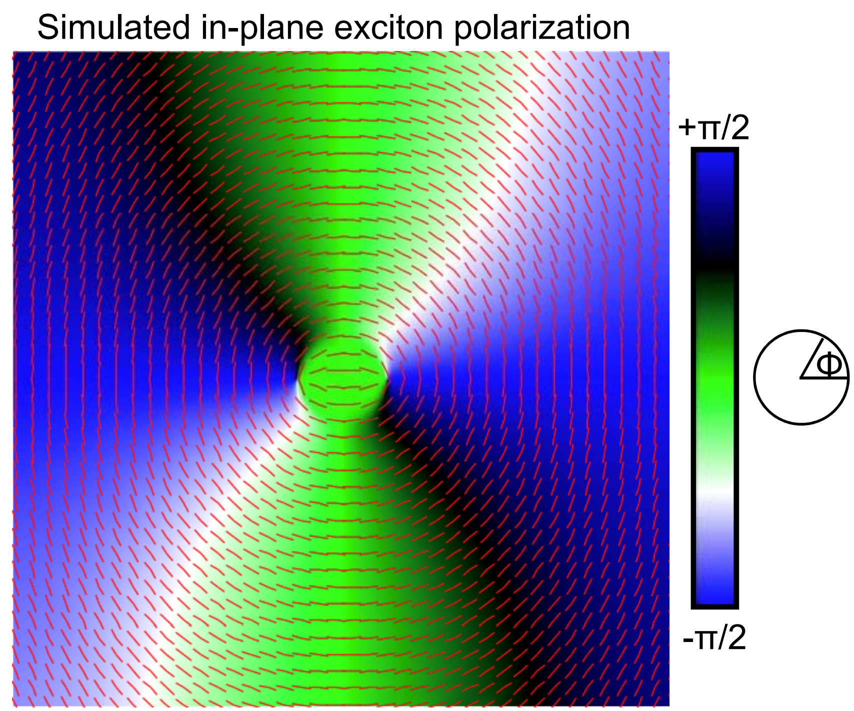
by magnetic field

B=0T



$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

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



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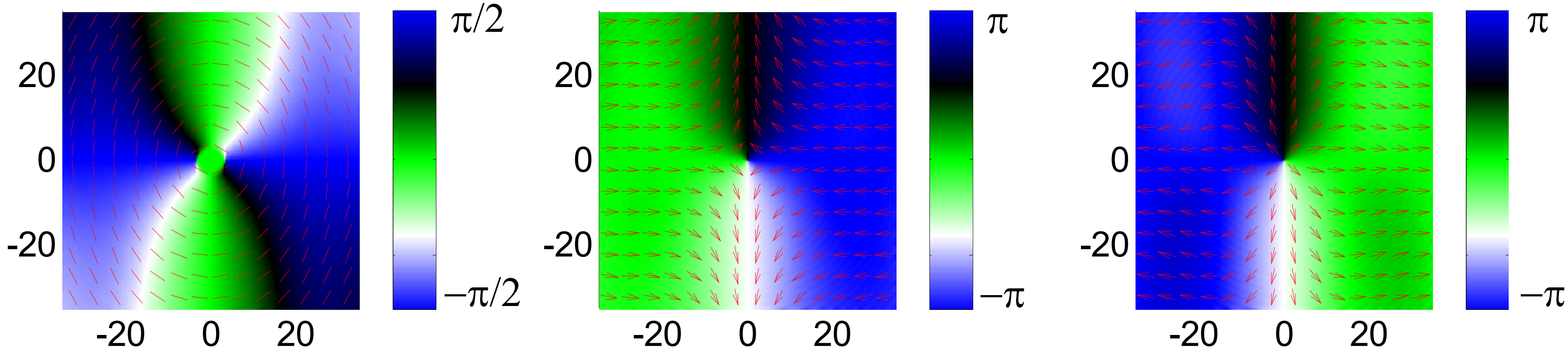
exciton polarization **electron and hole spin patterns**



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

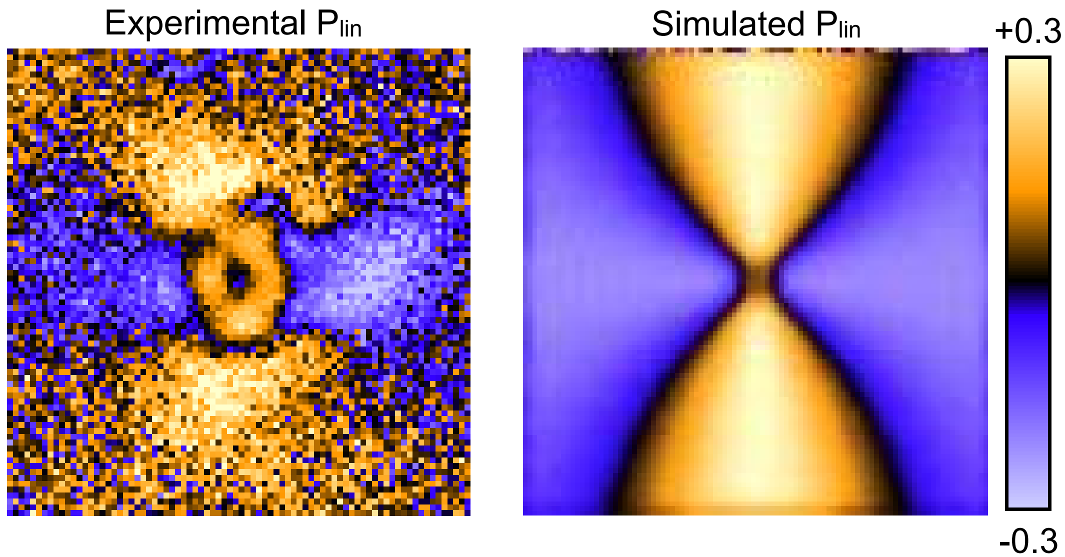
measured polarization pattern → (exciton spin density matrix) → spin currents carried by electrons and holes bound to excitons

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

theory of Alexey Kavokin

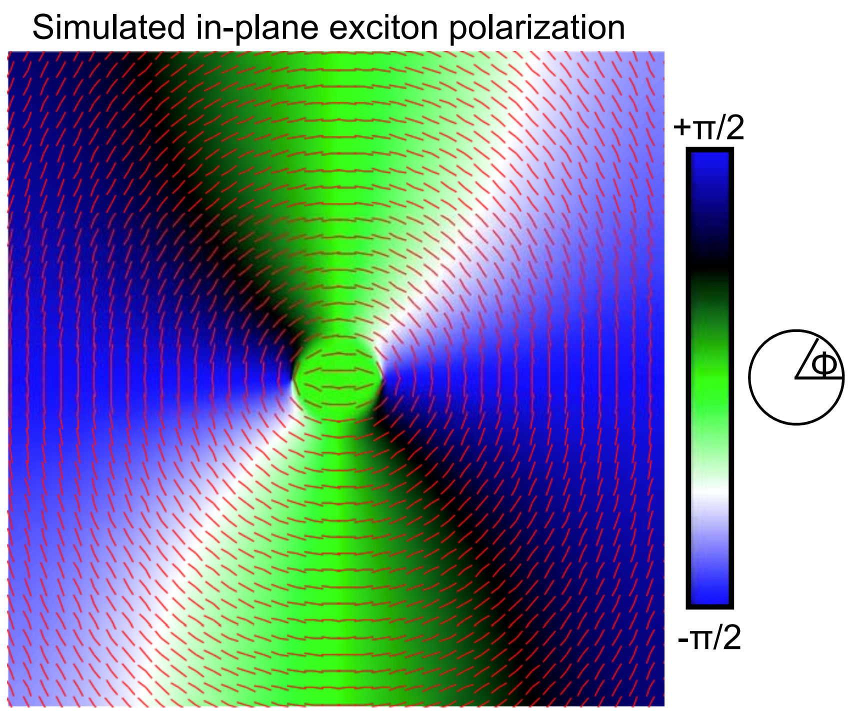
A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov, T. Ostatnický, M. Vladimirova, A.V. Kavokin, K.L. Campman, A.C. Gossard, PRL 110, 246403 (2013)

B=0T



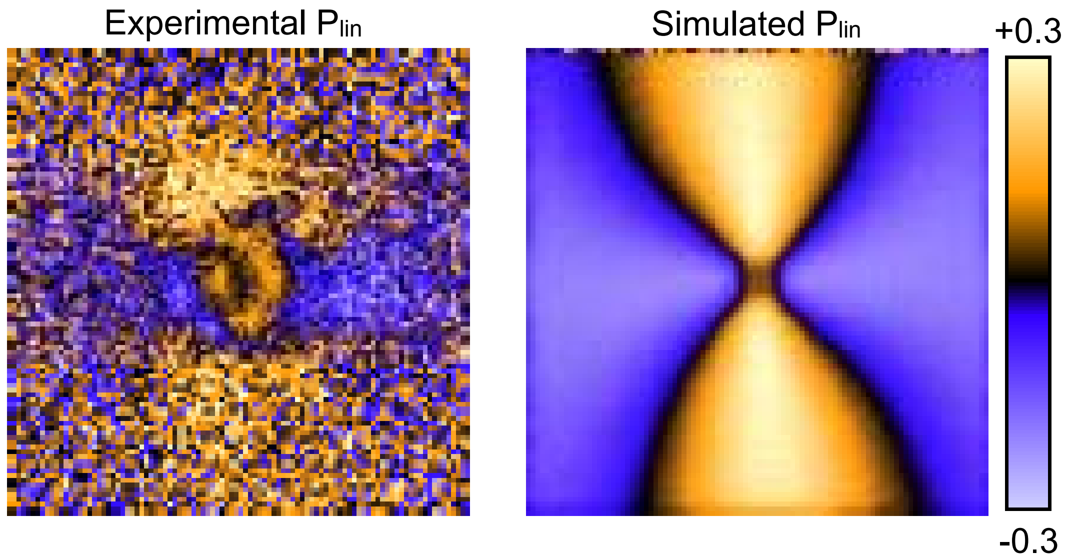
$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

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, PRL 110, 246403 (2013)

B=1T

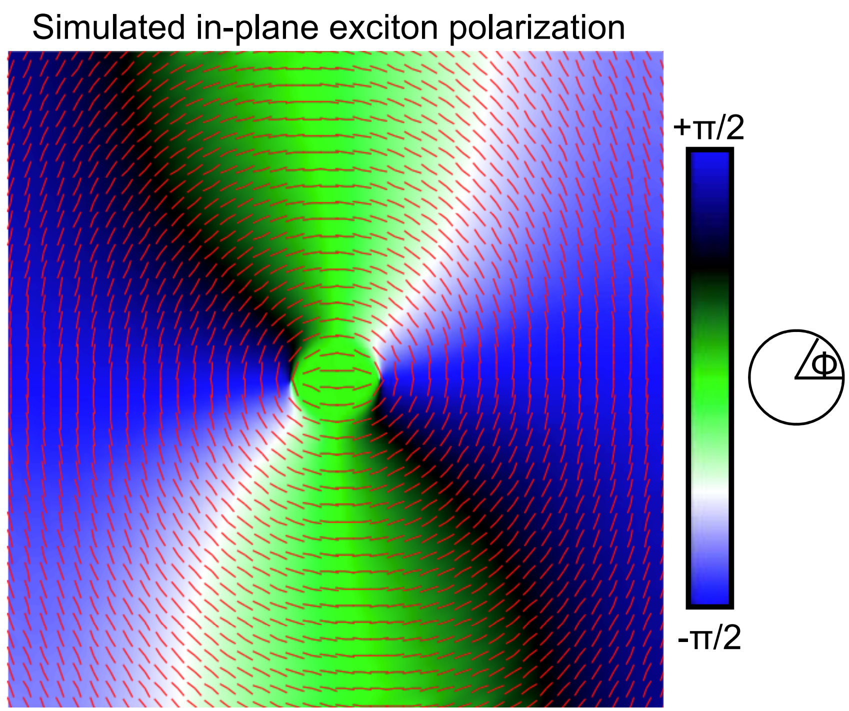


$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

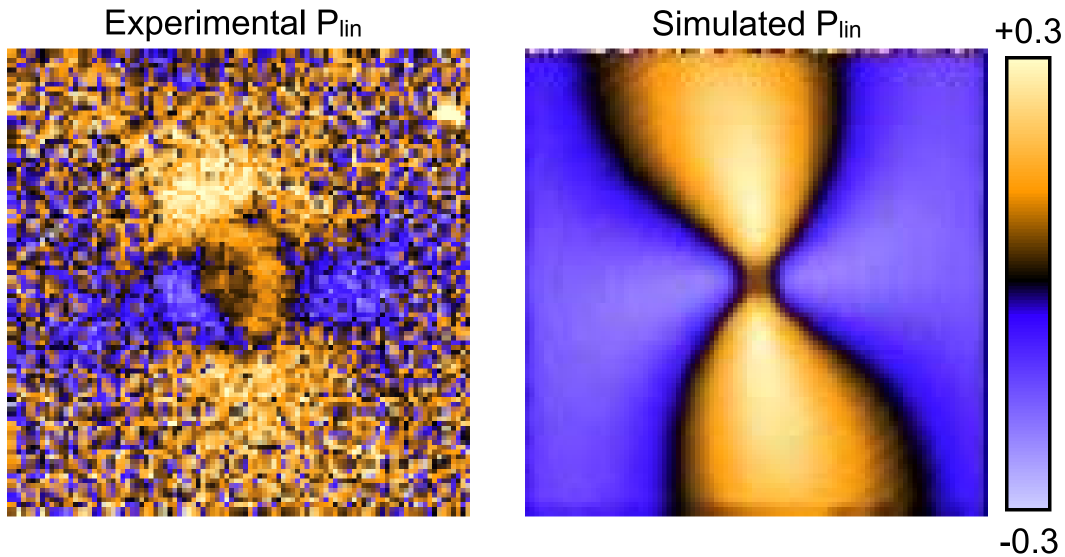
applied magnetic fields bend spin current trajectories

↓

spiral patterns of linear polarization



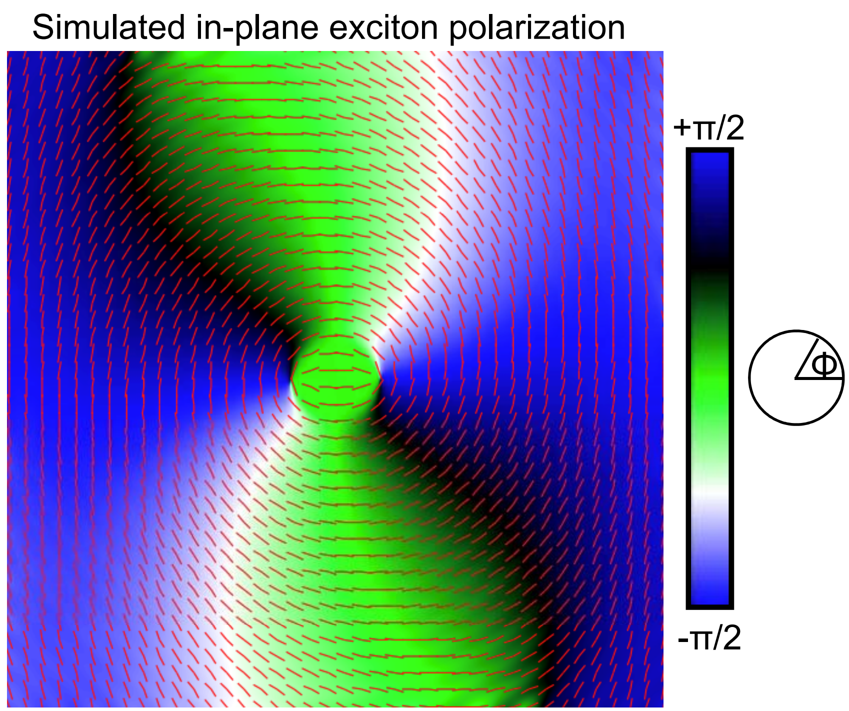
B=2T



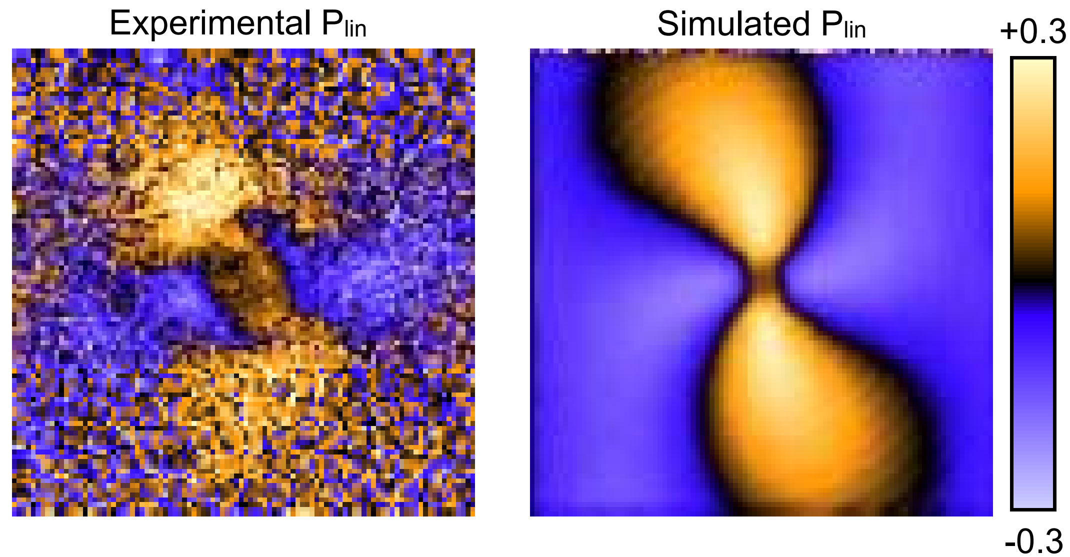
$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

applied magnetic fields bend spin current trajectories

spiral patterns of linear polarization



B=3T

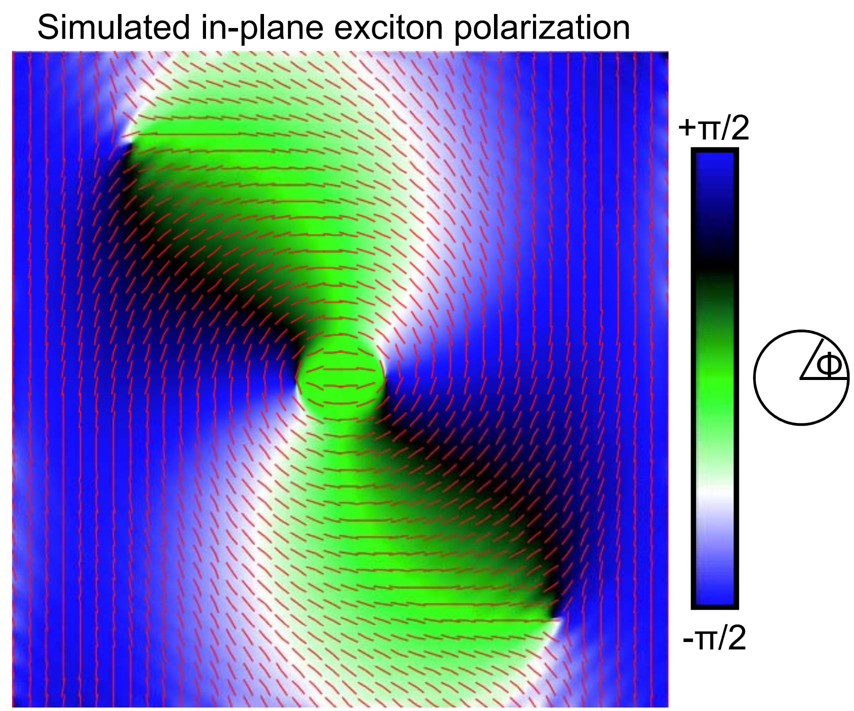


$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

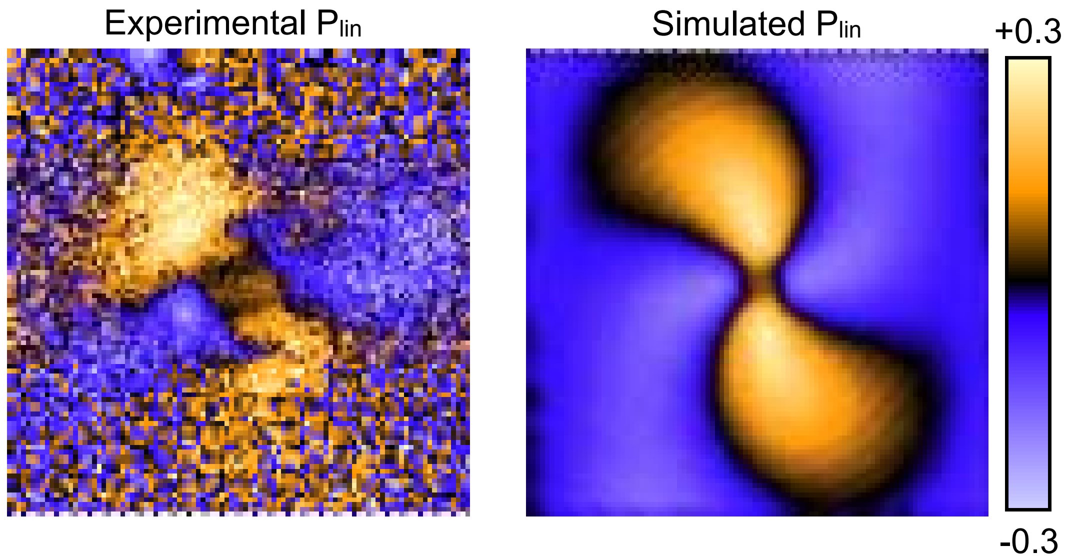
applied magnetic fields bend spin current trajectories

⬇

spiral patterns of linear polarization



B=4T

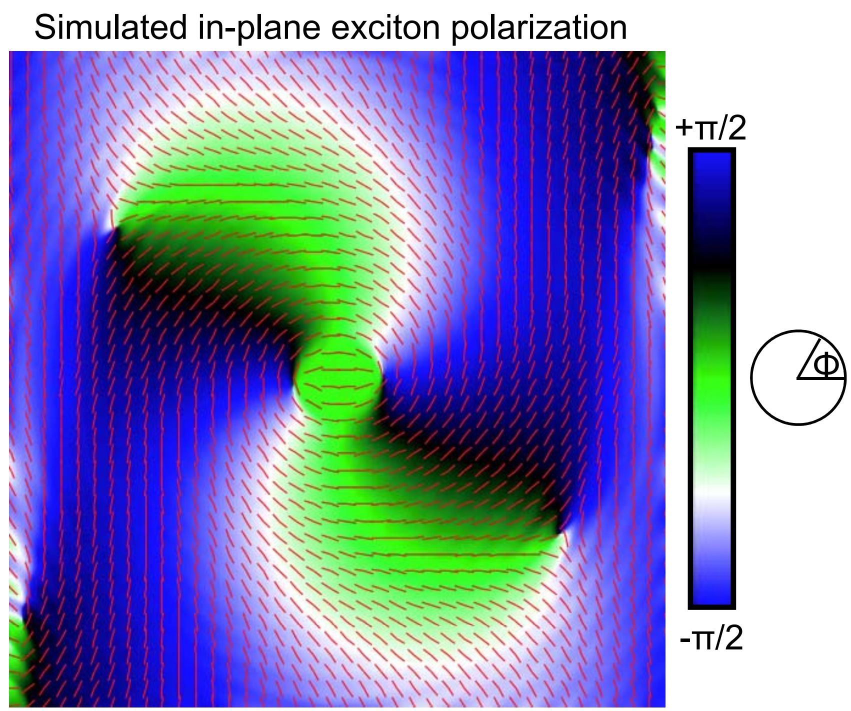


$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

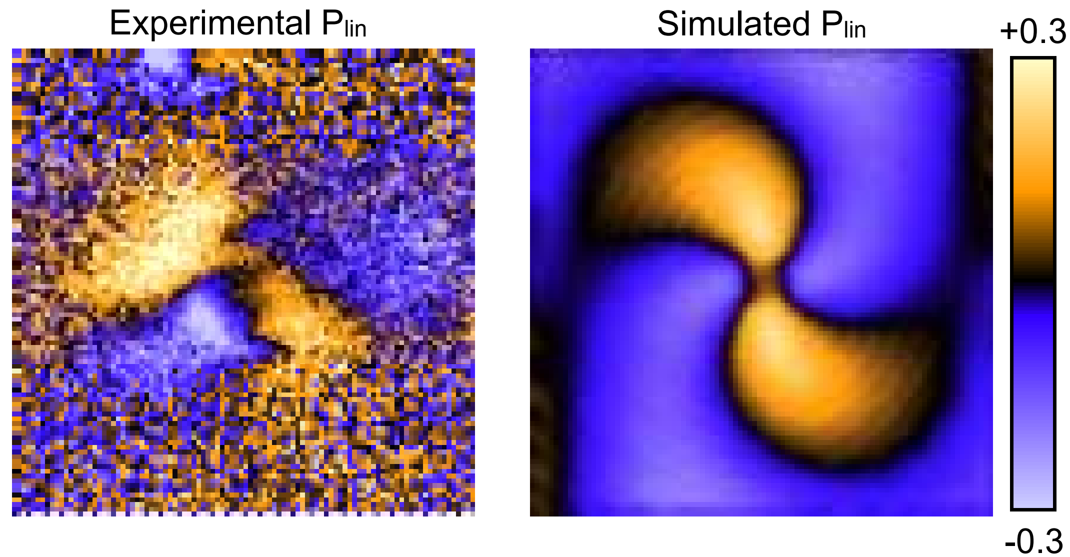
applied magnetic fields bend spin current trajectories

↓

spiral patterns of linear polarization



B=5T

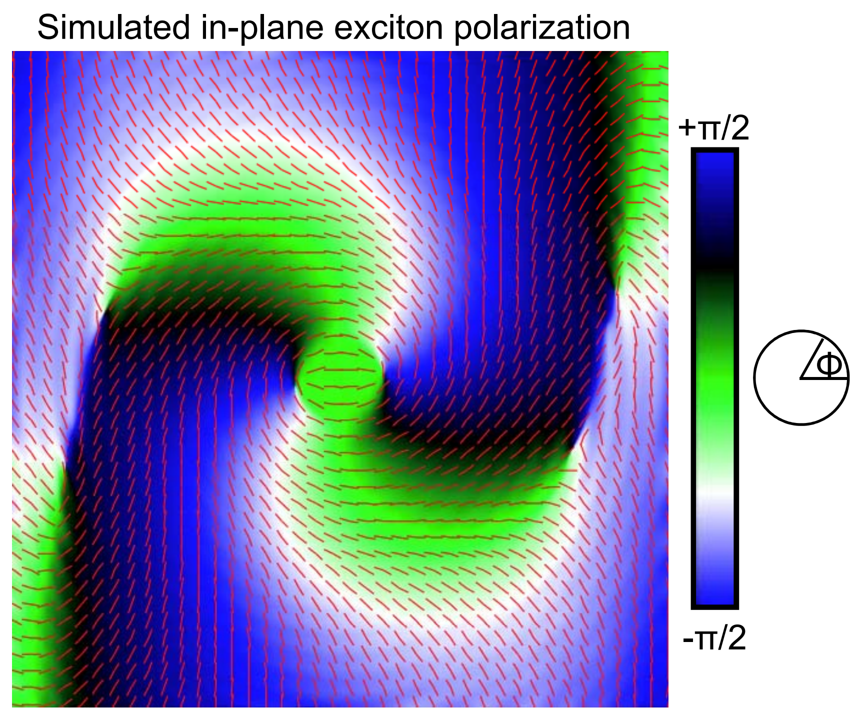


$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

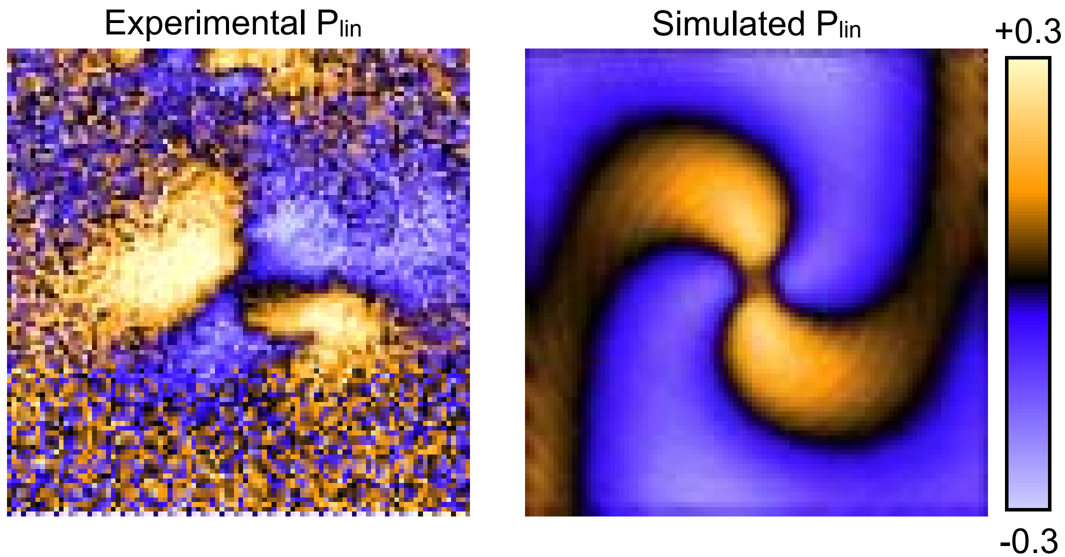
applied magnetic fields bend spin current trajectories

↓

spiral patterns of linear polarization



B=6T

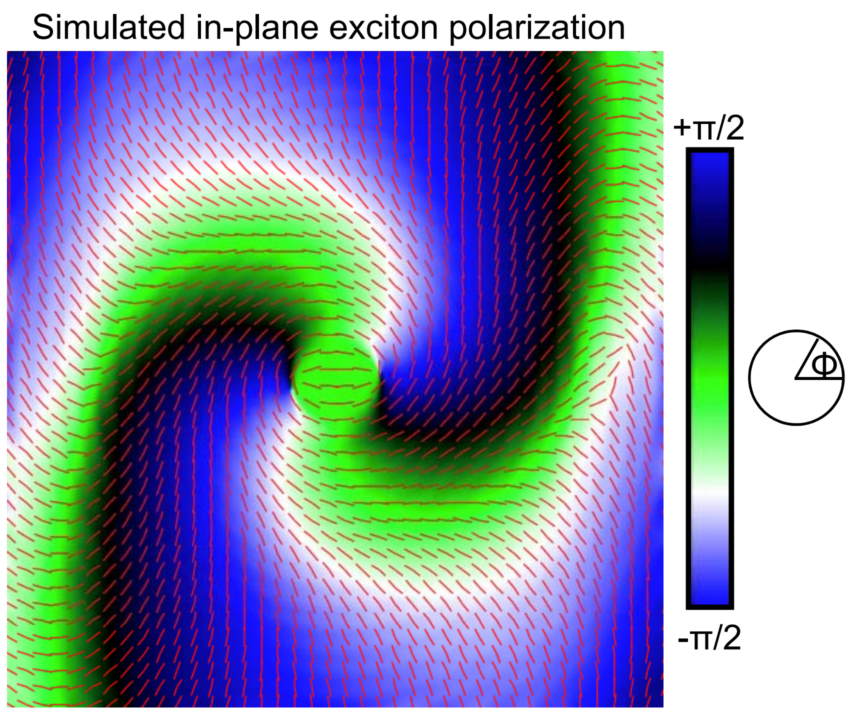


$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

applied magnetic fields bend spin current trajectories

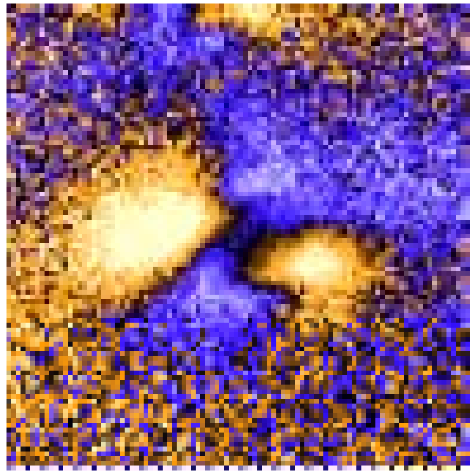
↓

spiral patterns of linear polarization

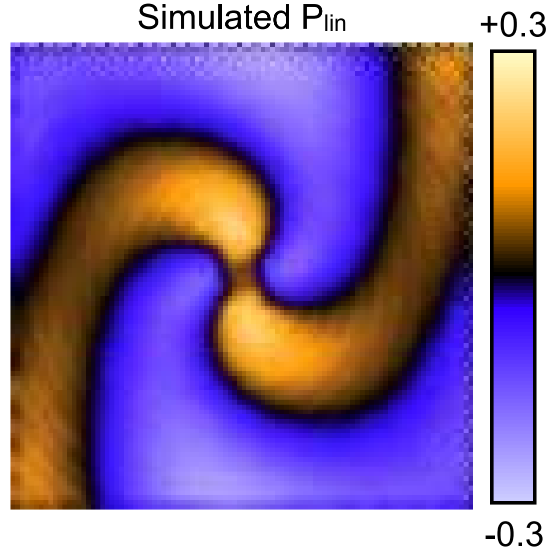


B=7T

Experimental P_{lin}



Simulated P_{lin}



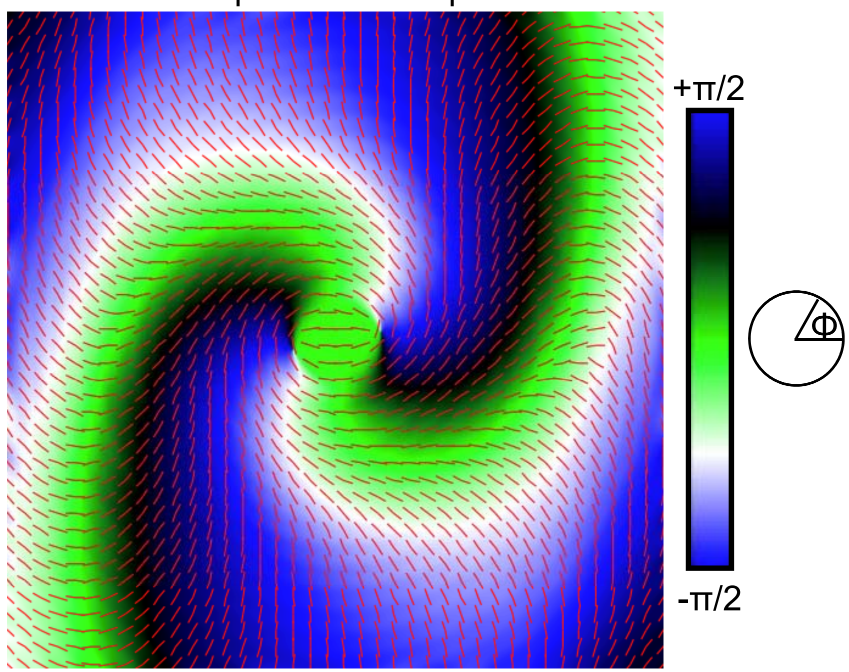
$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

applied magnetic fields bend spin current trajectories

⬇

spiral patterns of linear polarization

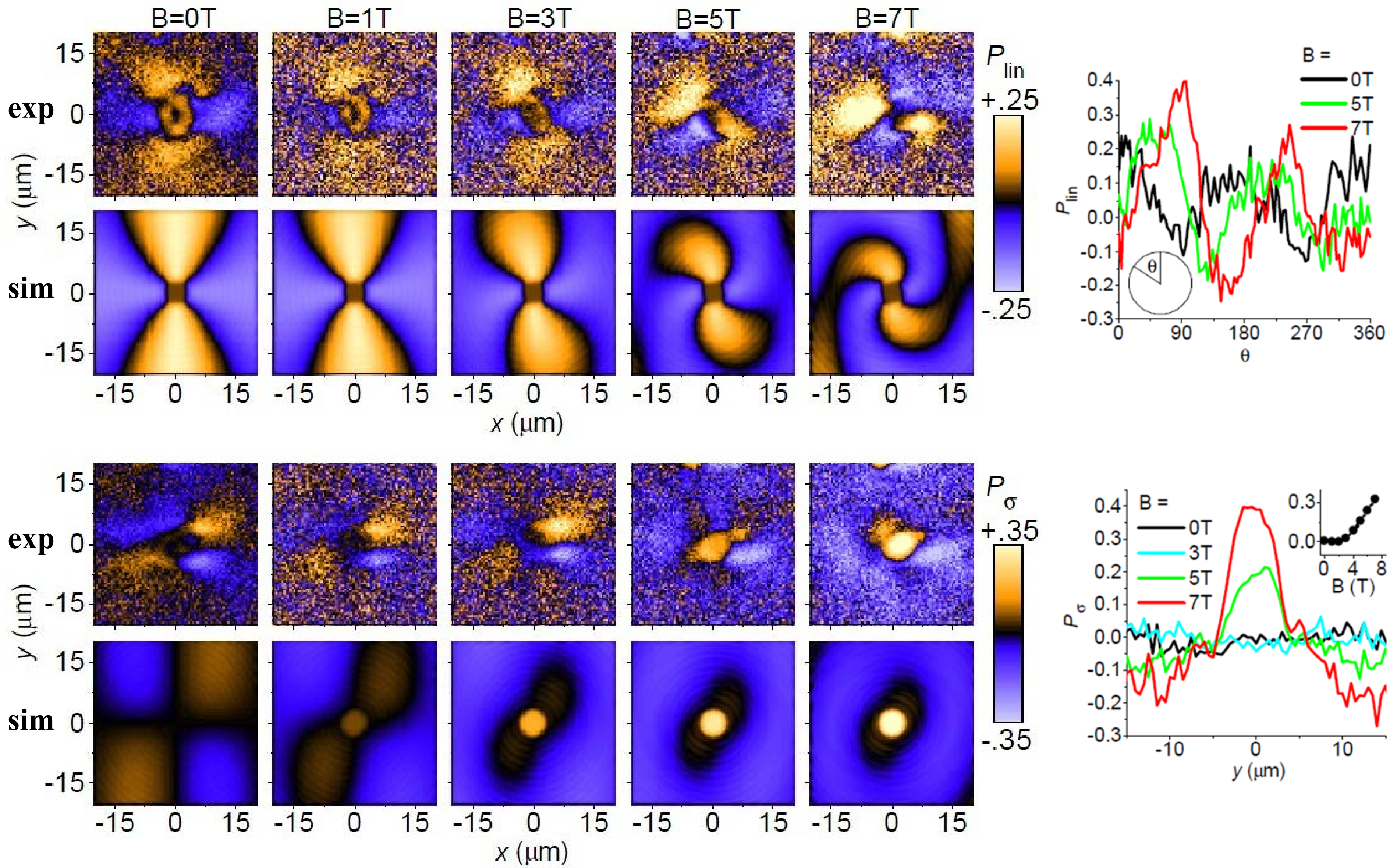
Simulated in-plane exciton polarization



spiral direction of exciton polarization current

$\neq$

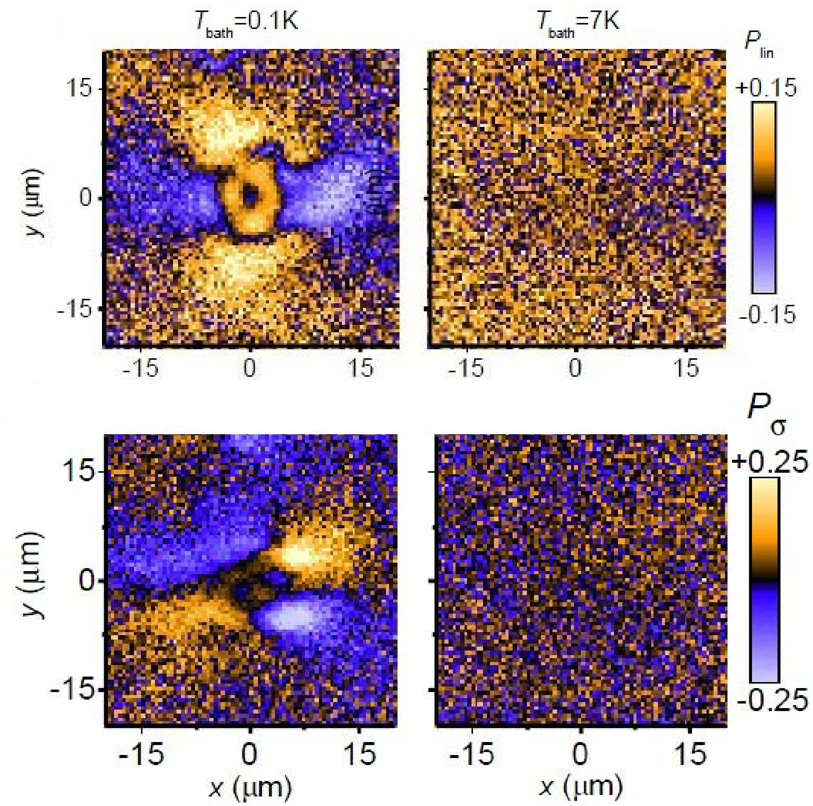
radial direction of exciton density current

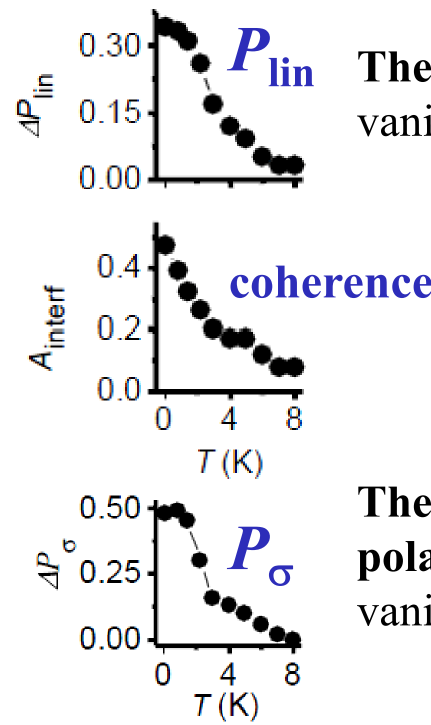


radial source of excitons with hedgehog momentum distribution generates

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

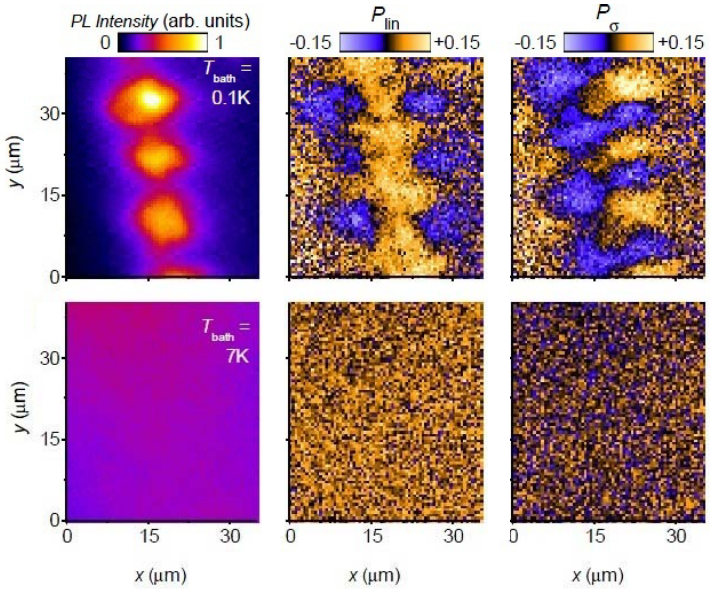
Temperature dependence





The vortex of linear polarization
vanishes with increasing temperature

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



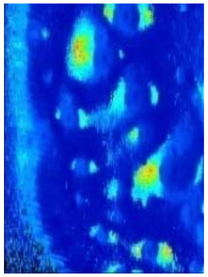
A periodic array of beads in the MOES creates
periodic polarization textures

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

Summary

- **Spontaneous coherence in a cold exciton gas**

  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)



- **Spin currents and spin textures in a coherent exciton gas**

  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, PRL 110, 246403 (2013)