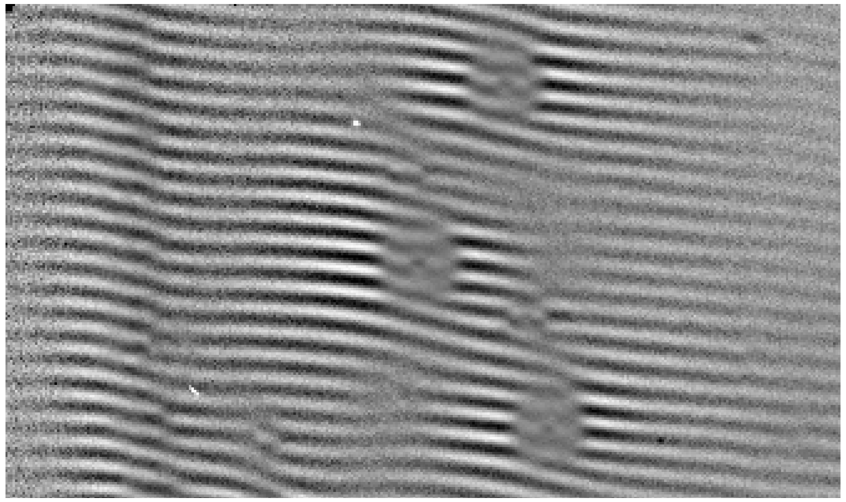
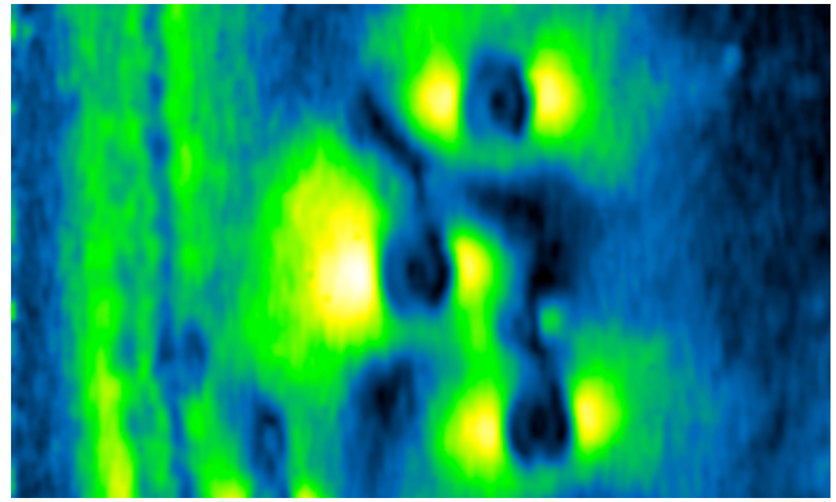
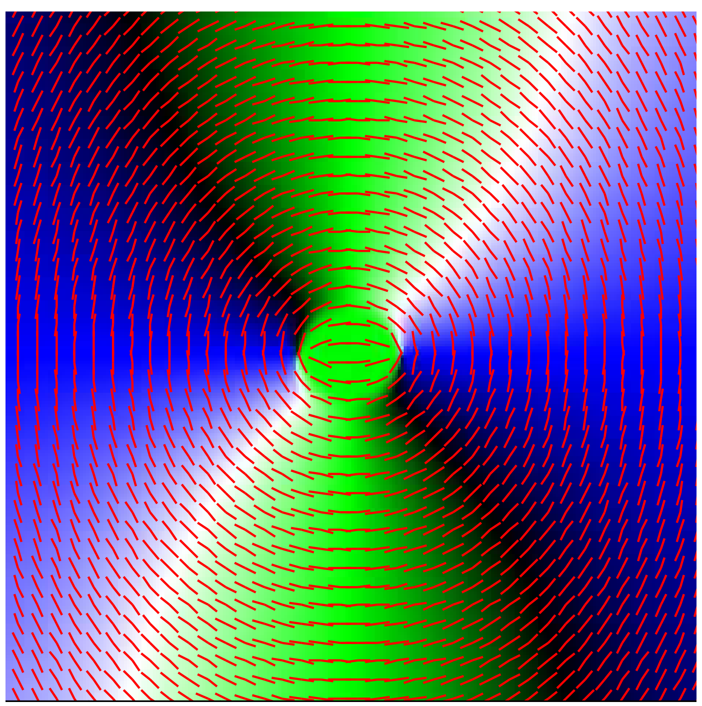
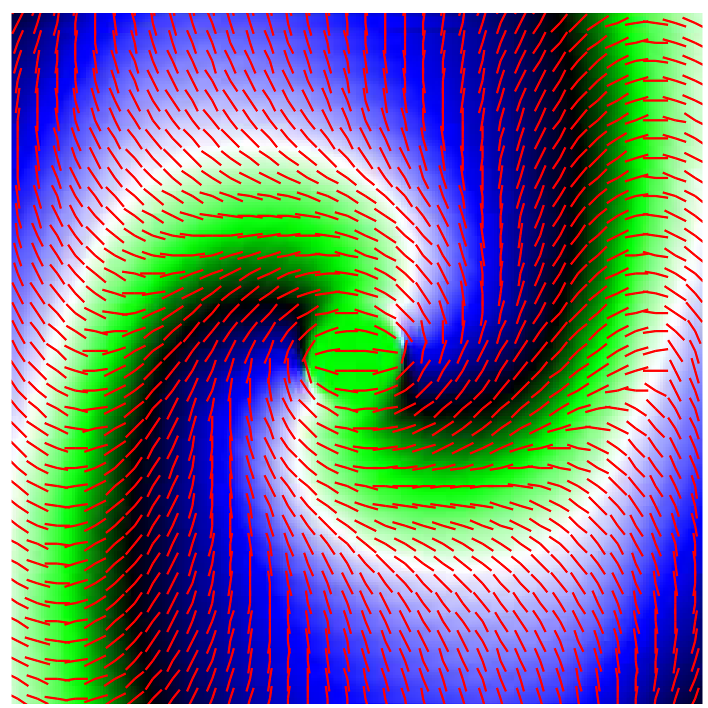
Spontaneous coherence in a cold exciton gas





Spin currents in a coherent exciton gas





Alex High, Jason Leonard, Aaron Hammack, Sen Yang, Misha Fogler & Leonid Butov

University of California at San Diego

Tomas Ostatnický

Charles University in Prague

Masha Vladimirova

Université Montpellier

Alexey Kavokin

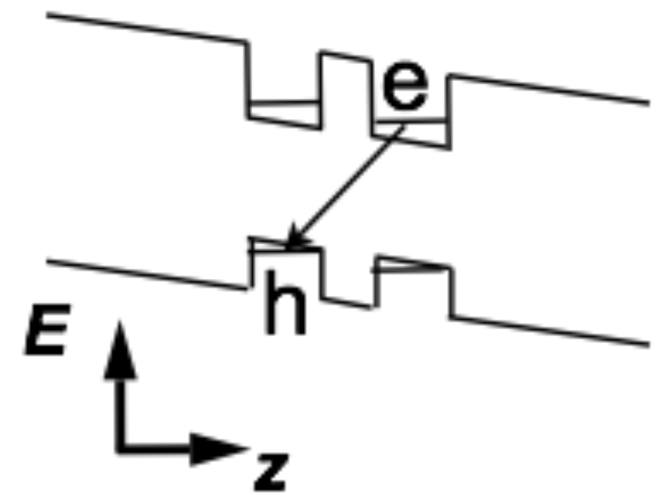
University of Southampton

Ken Campman & Art Gossard

University of California at Santa Barbara

An Introduction to Indirect Excitons

- An indirect exciton is composed of an electron and hole in separate quantum wells



Characteristics of indirect excitons

•long lifetime •bosons

⟶ model system for studies of physics of ultracold bosons in CM materials

QM1G.7: Yuliya Kuznetsova
Transport of Indirect Excitons in a Potential Energy Gradient
Monday, 9:45 AM

QM2G.7: Mikas Remeika
Electrostatic Lattices for Indirect Excitons in Coupled Quantum Wells
Monday, 12:15 PM

QTu3D.3: Alex High
Spontaneous Coherence of Indirect Excitons in a Trap
Tuesday, 5:15 PM

Onset of Quantum Degeneracy

- "Quantum gas" when thermal de Broglie wavelength comparable to separation between excitons

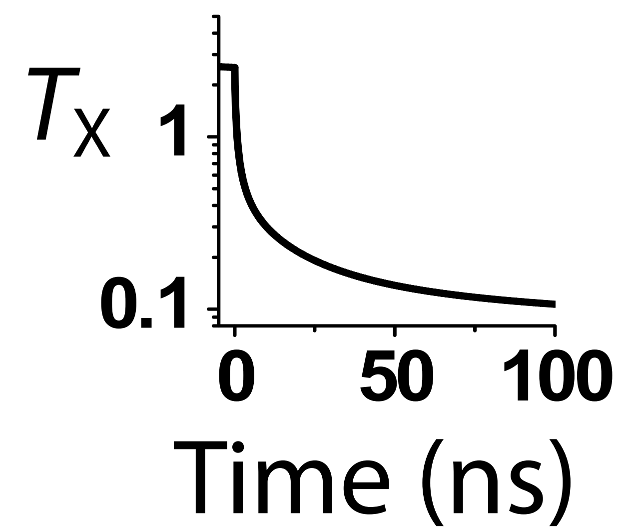
$$\lambda_{dB} = \left(\frac{2\pi\hbar^2}{mk_B T} \right)^{1/2}$$

$$\lambda_{dB} = n^{-1/2} \longrightarrow T_{dB} = \frac{2\pi\hbar^2}{mk_B} n$$

- Excitons in GaAs CQW: $n = 10^{10}$ cm^{-2}, $m_{exciton} = 0.2\ m_0$

$$\longrightarrow T_{dB} \sim 3\ \mathrm{K}$$

- Excitons can cool to 100mK within lifetime

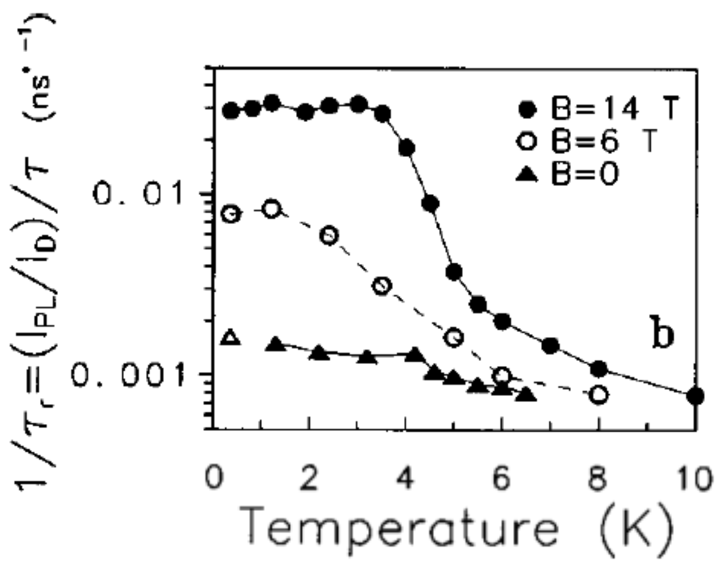


L.V. Butov, A.L. Ivanov, A. Imamoglu, P.B. Littlewood, A.A. Shashkin, V.T. Dolgopolov, K.L. Campman, and A.C. Gossard, *Phys. Rev. Lett.* **86**, 5608 (2001)

Prior Evidence for Exciton Condensation

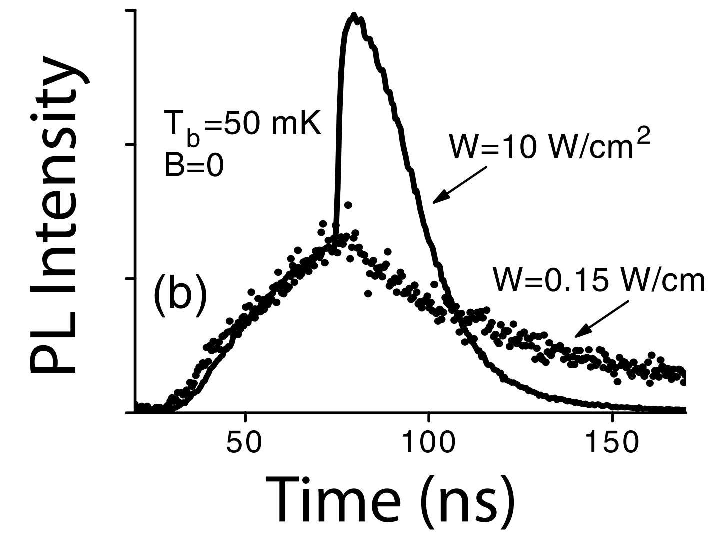
Coupled Quantum Wells

- enhancement of radiative decay rate with decreasing temperature



L.V. Butov and A.I. Filin, *Phys. Rev. B* **58**, 1980 (1998)

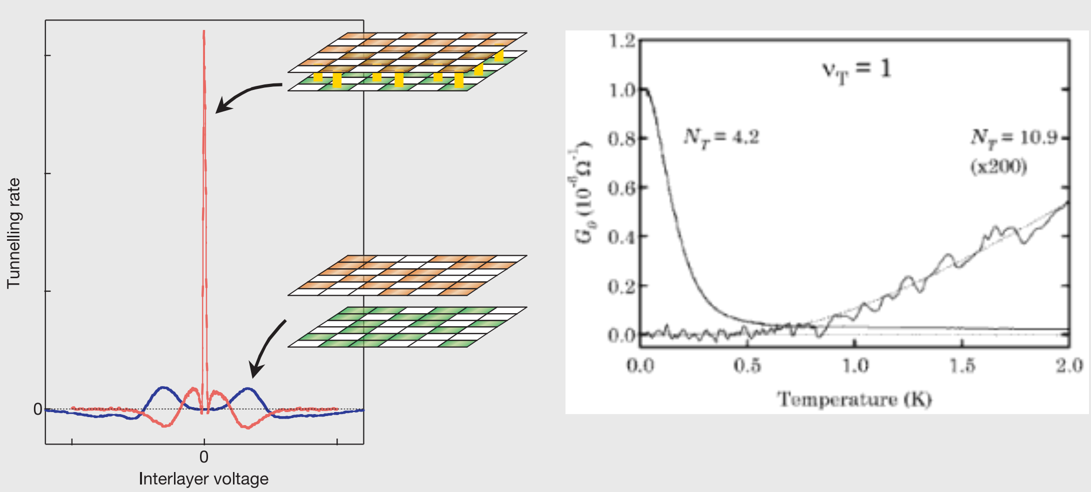
- enhancement of scattering rate with increasing density



L.V. Butov, A.L. Ivanov, A. Imamoglu, P.B. Littlewood, A.A. Shashkin, V.T. Dolgopolov, K.L. Campman, and A.C. Gossard *Phys. Rev. Lett.* **86**, 5608 (2001).

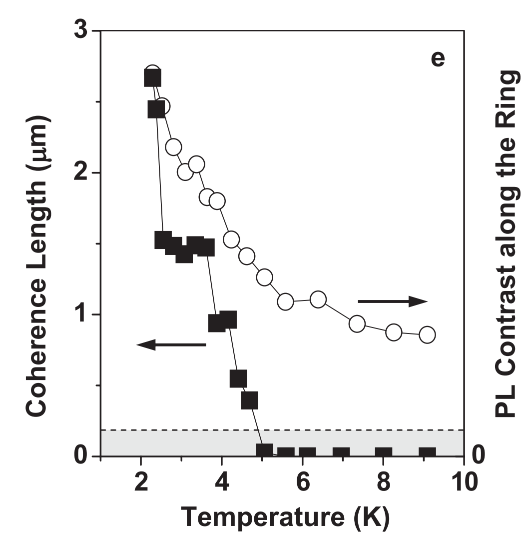
Bilayer Quantum Hall Layers

- enhancement of tunneling rate with decreasing temperature



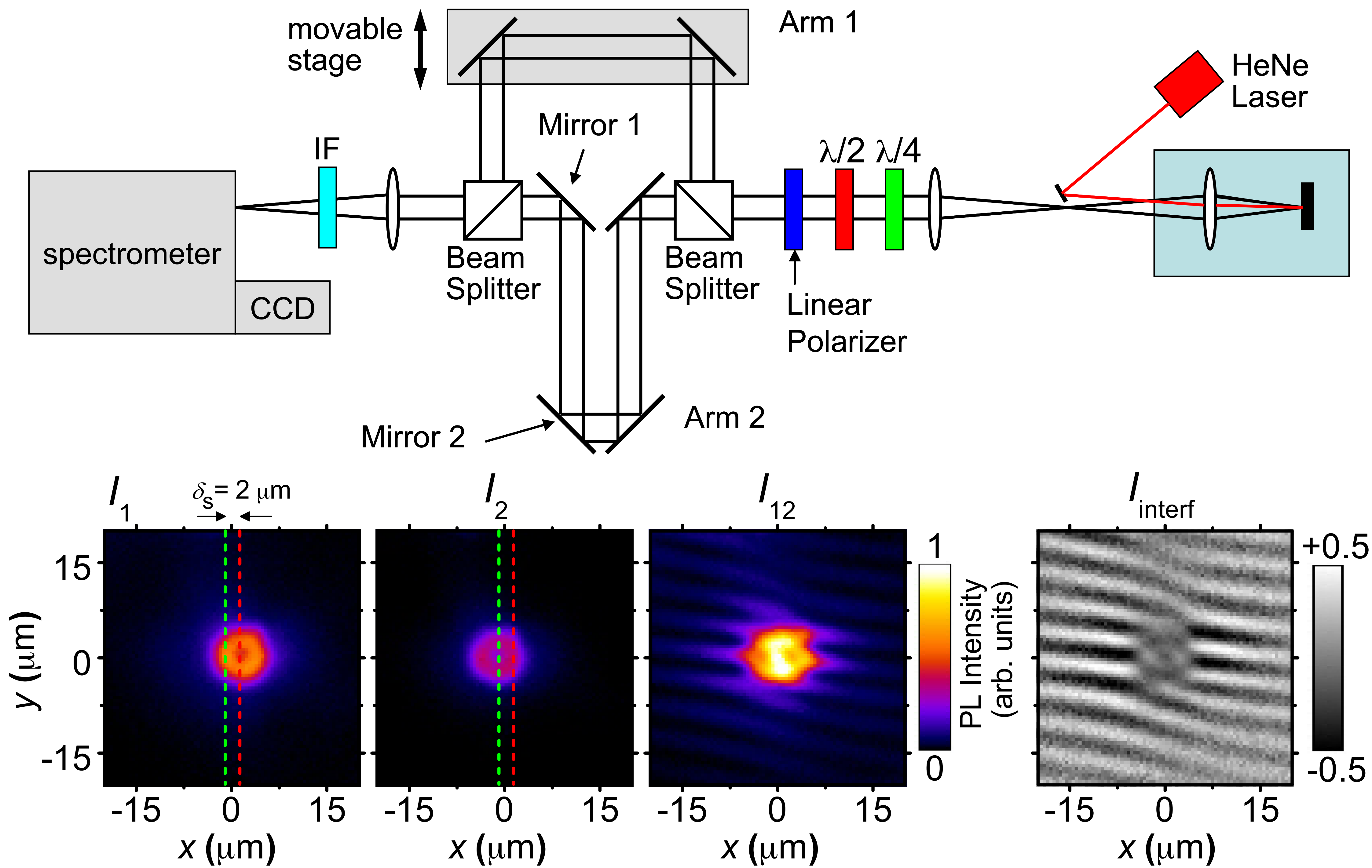
I. B. Spielman, J. P. Eisenstein, L. N. Pfeiffer, and K. W. West, *Phys. Rev. Lett.* **84**, 5808 (2000).

- enhancement of coherence length with decreasing temperature



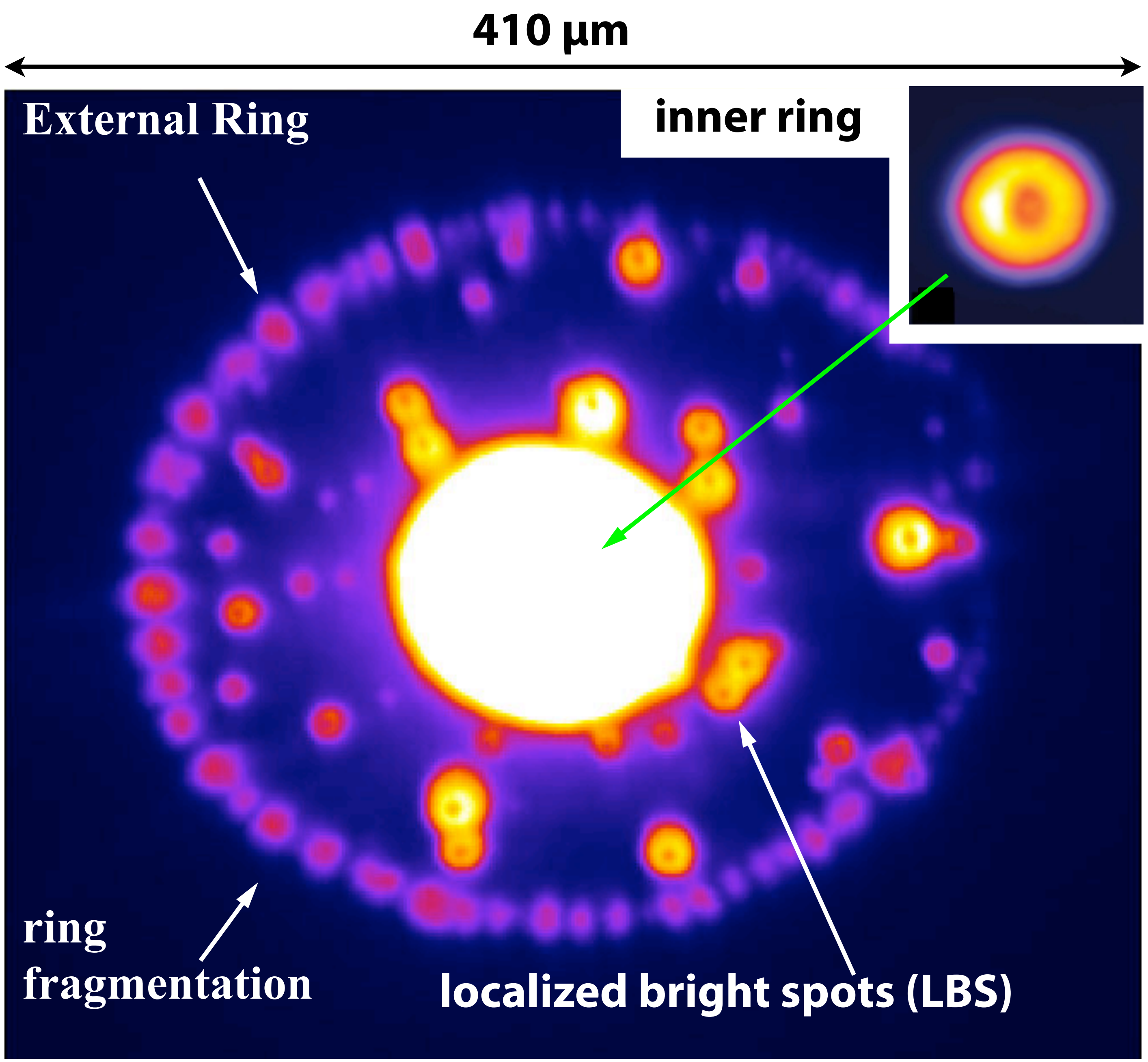
Sen Yang, A.T. Hammack, M.M. Fogler, L.V. Butov, and A.C. Gossard, *Phys. Rev. Lett.* **97**, 187402 (2006)

Shift-Interferometry with M-Z interferometer



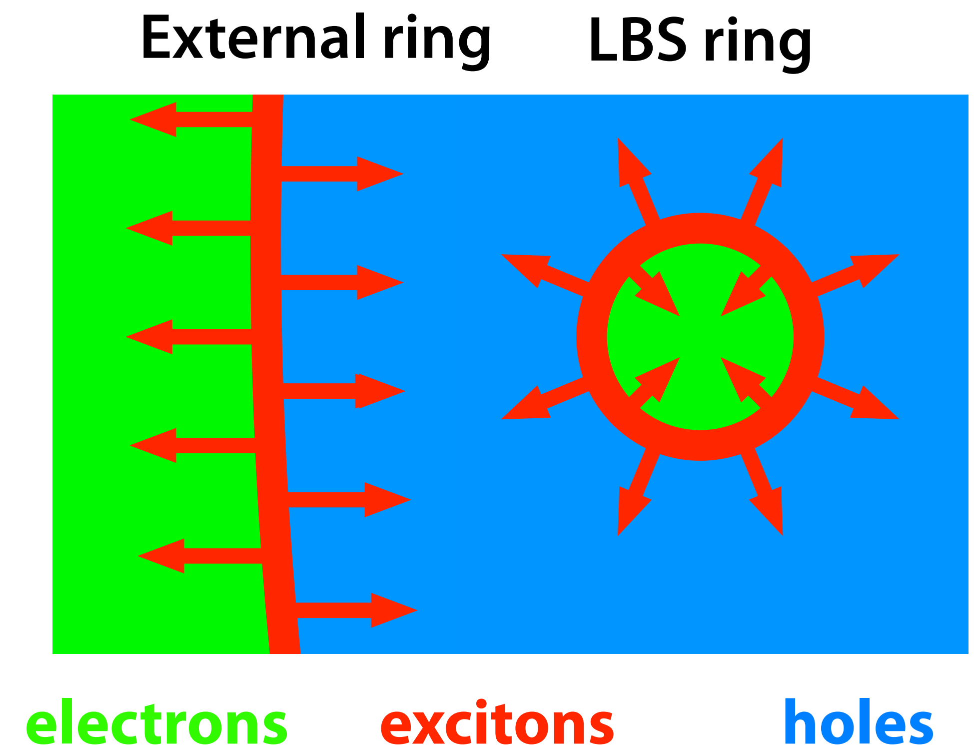
Shift interferometry directly measures the first order spatial coherence function $g_1(x)$

Exciton Pattern Formation



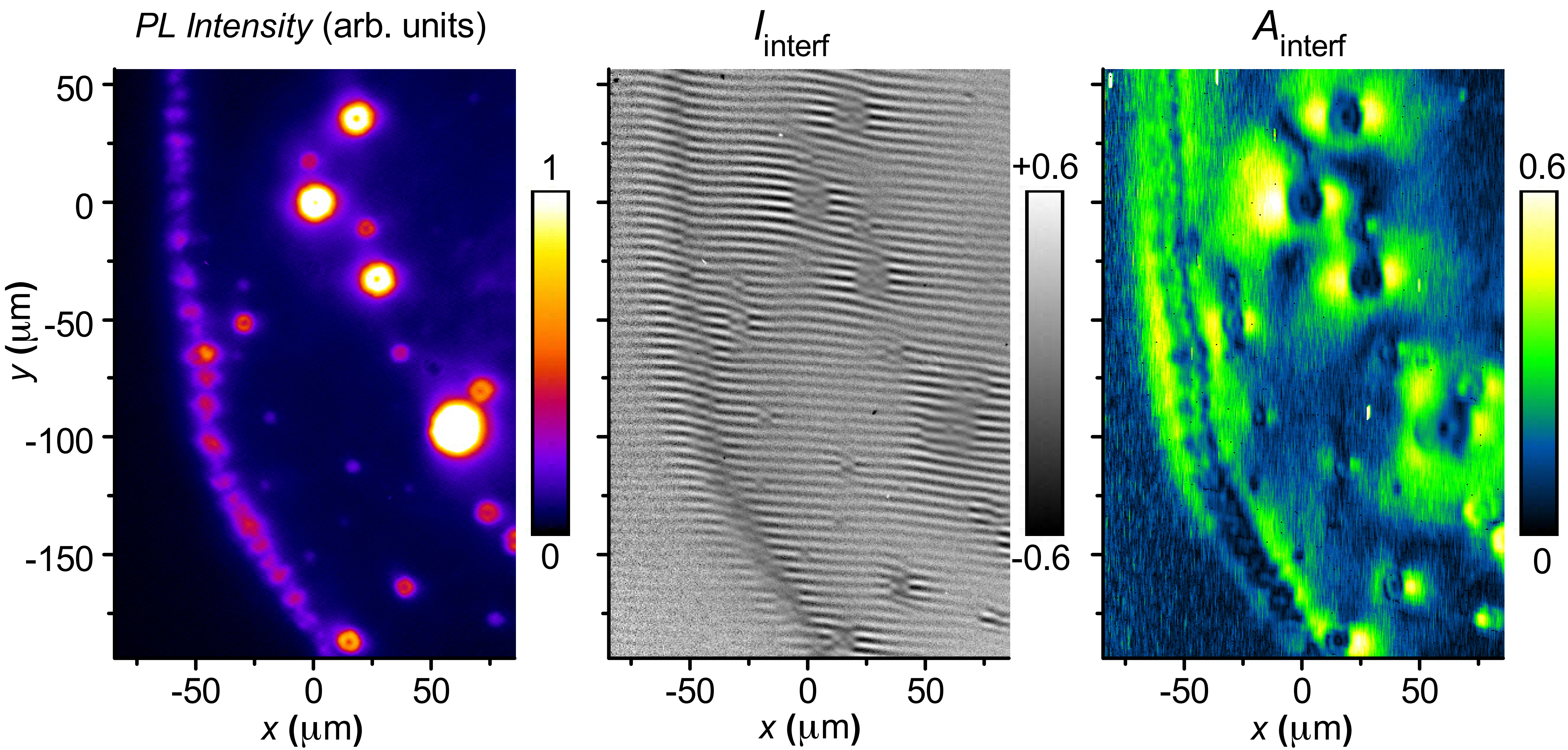
L.V. Butov, A.C. Gossard, & D.S. Chemla, Nature **418**, 751(2002)

Sources of cold excitons:



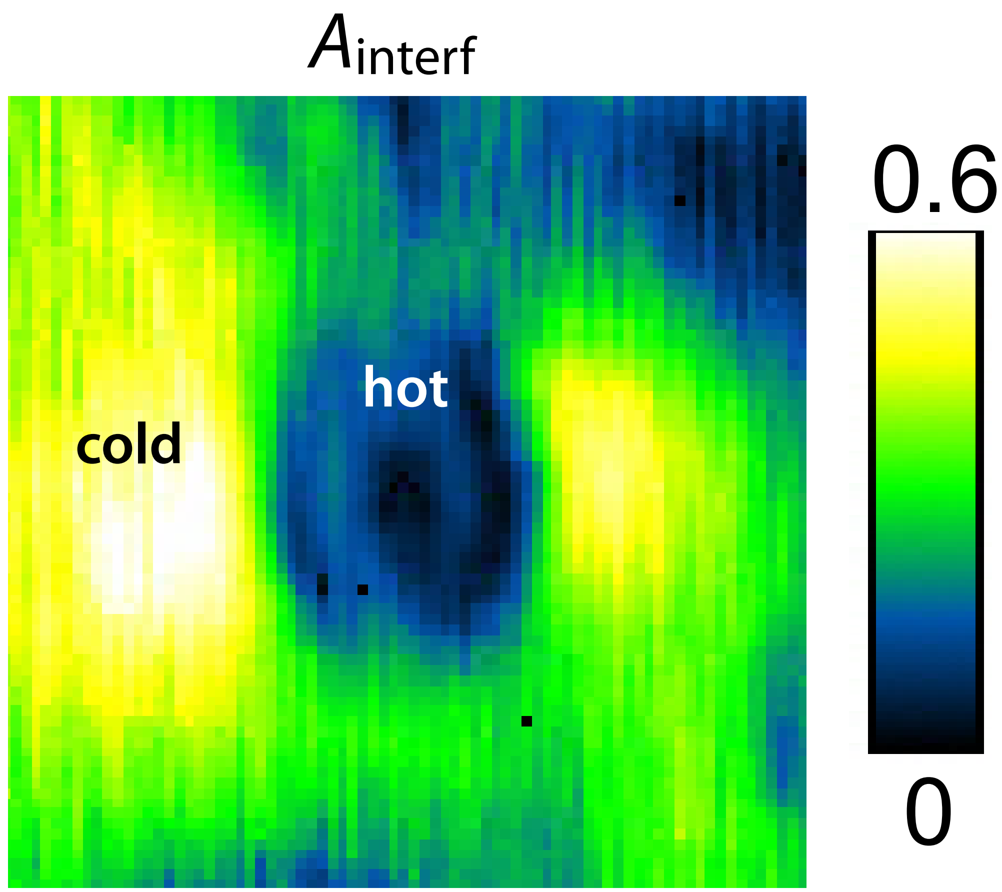
LBS ring is close to model radial source of cold excitons

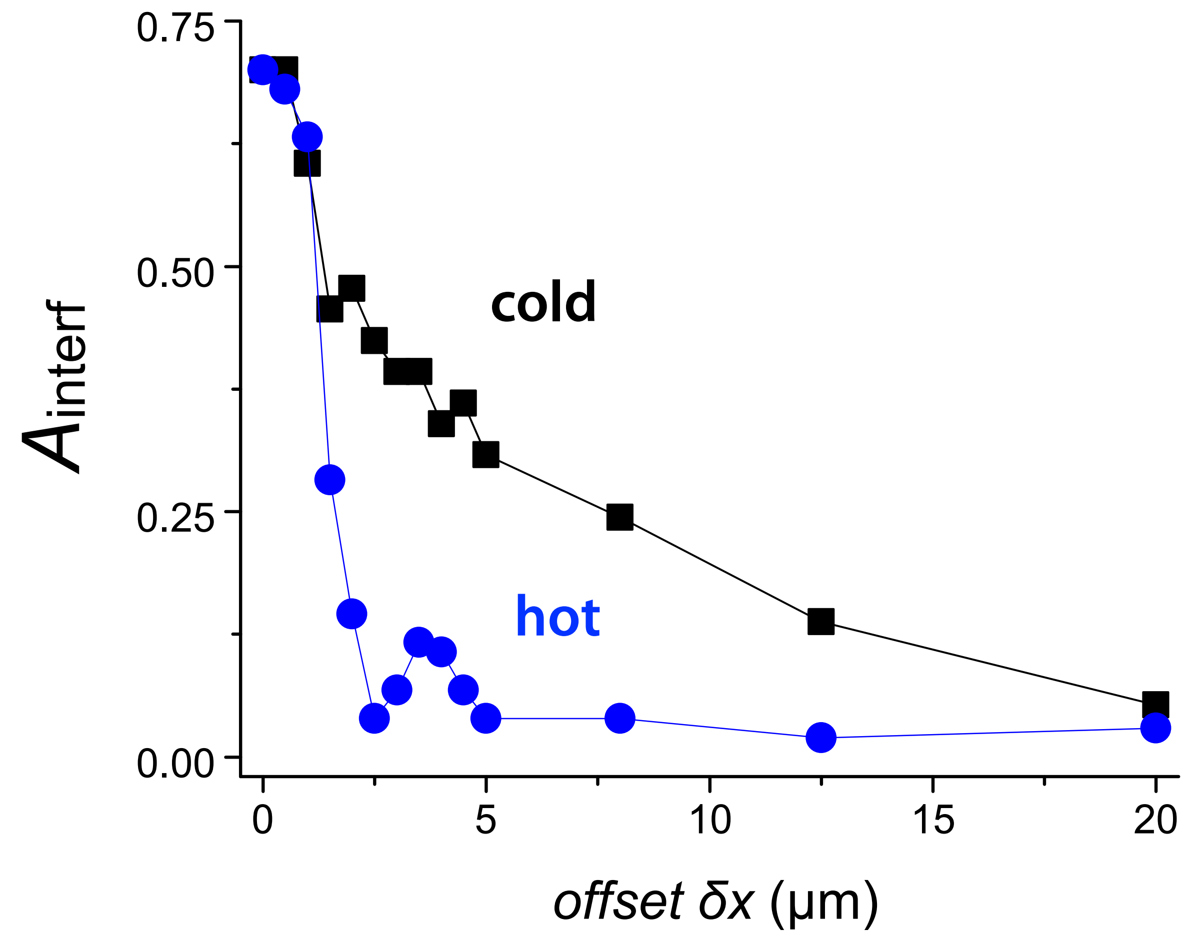
Observation of Spontaneous Coherence



- Spontaneous coherence in regions of LBS and external ring
- Phase jumps, forks

Offset Dependence of A_{interf}

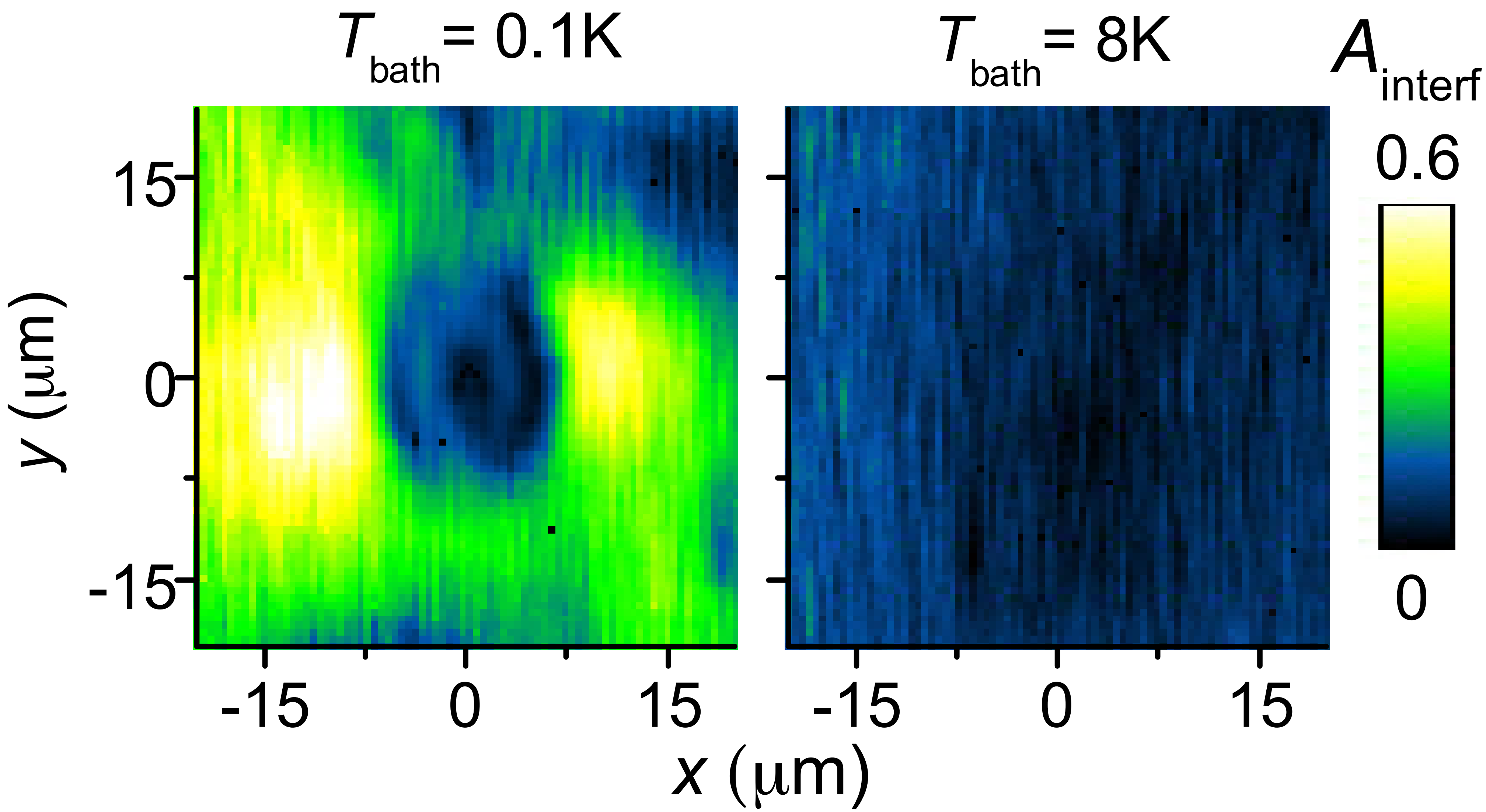




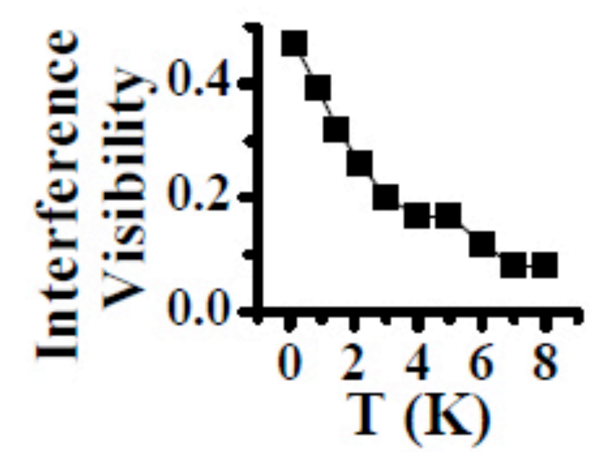
- At hot LBS center, A_{interf} decays quickly →classical
- Away from LBS center A_{interf} decays slowly →condensate
- in cold region spontaneous coherence with coherence length $\xi \approx 8$ μm
- $\xi_{classical} \approx 0.3$ μm at 0.1K

$\xi >> \xi_{classical}$ →direct measurement of a condensate

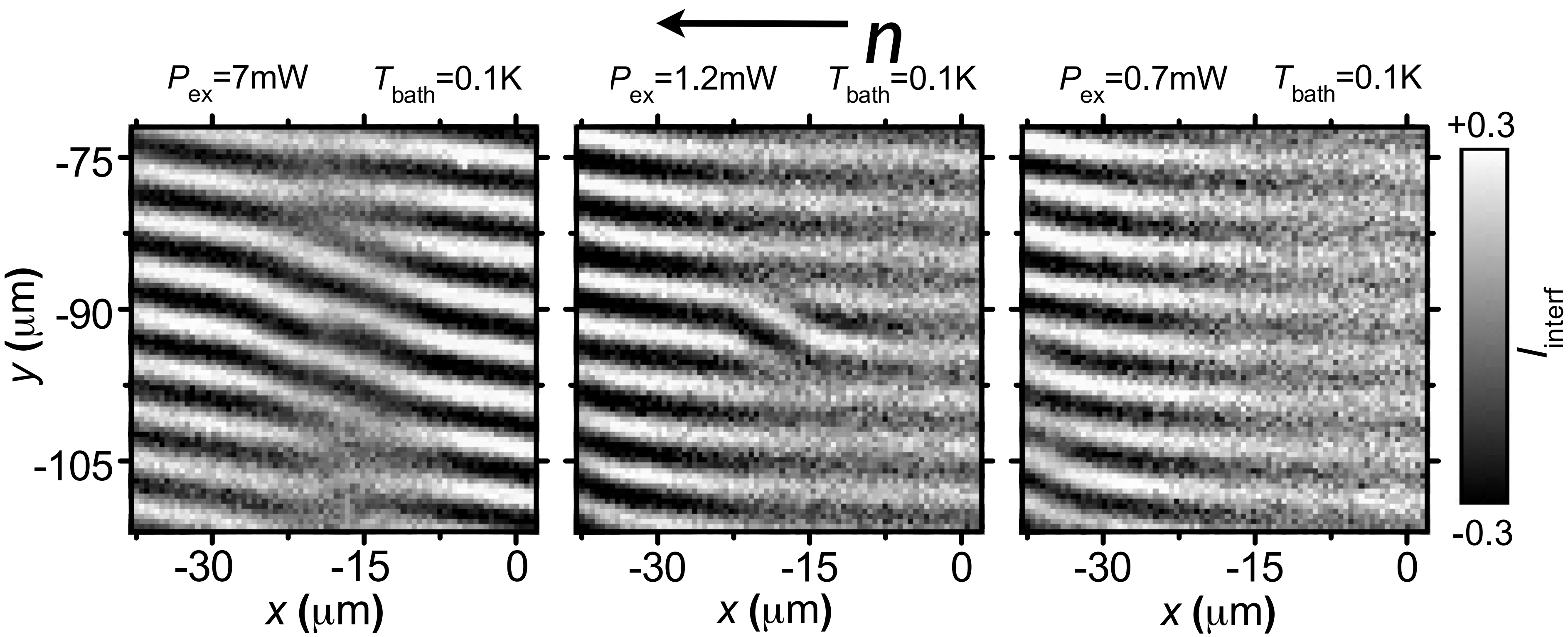
Temperature Dependence of Coherence



Coherence emerges at low temperature



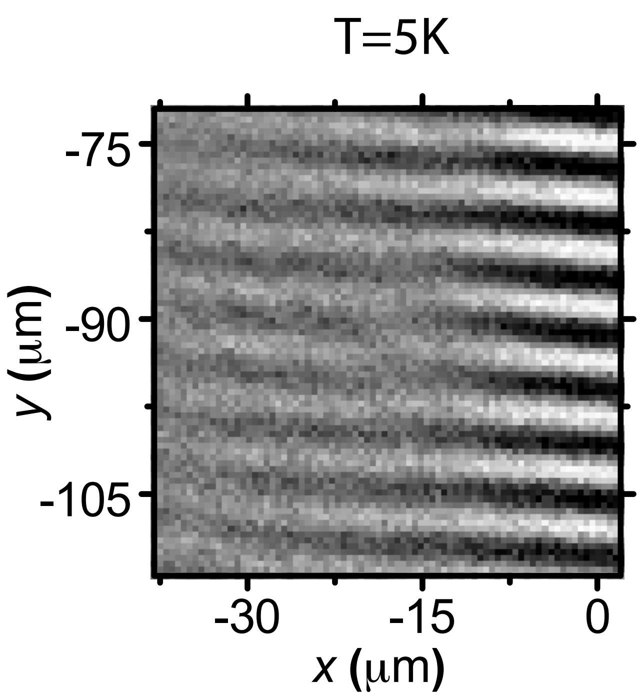
Phase Singularities in Interference Pattern



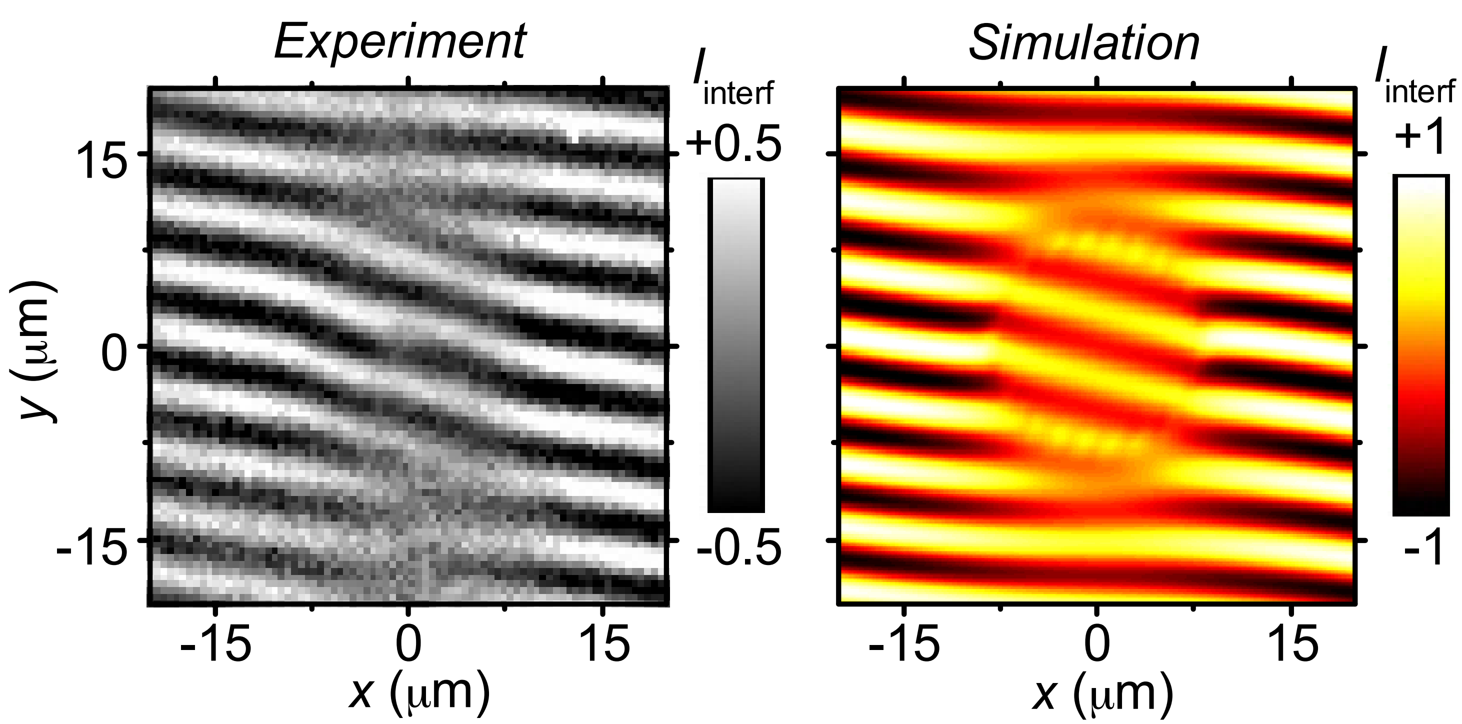
- If vortex, then separation of forks = offset dx
- Fork separation varies with density and ≠offset

➡ not a simple vortex

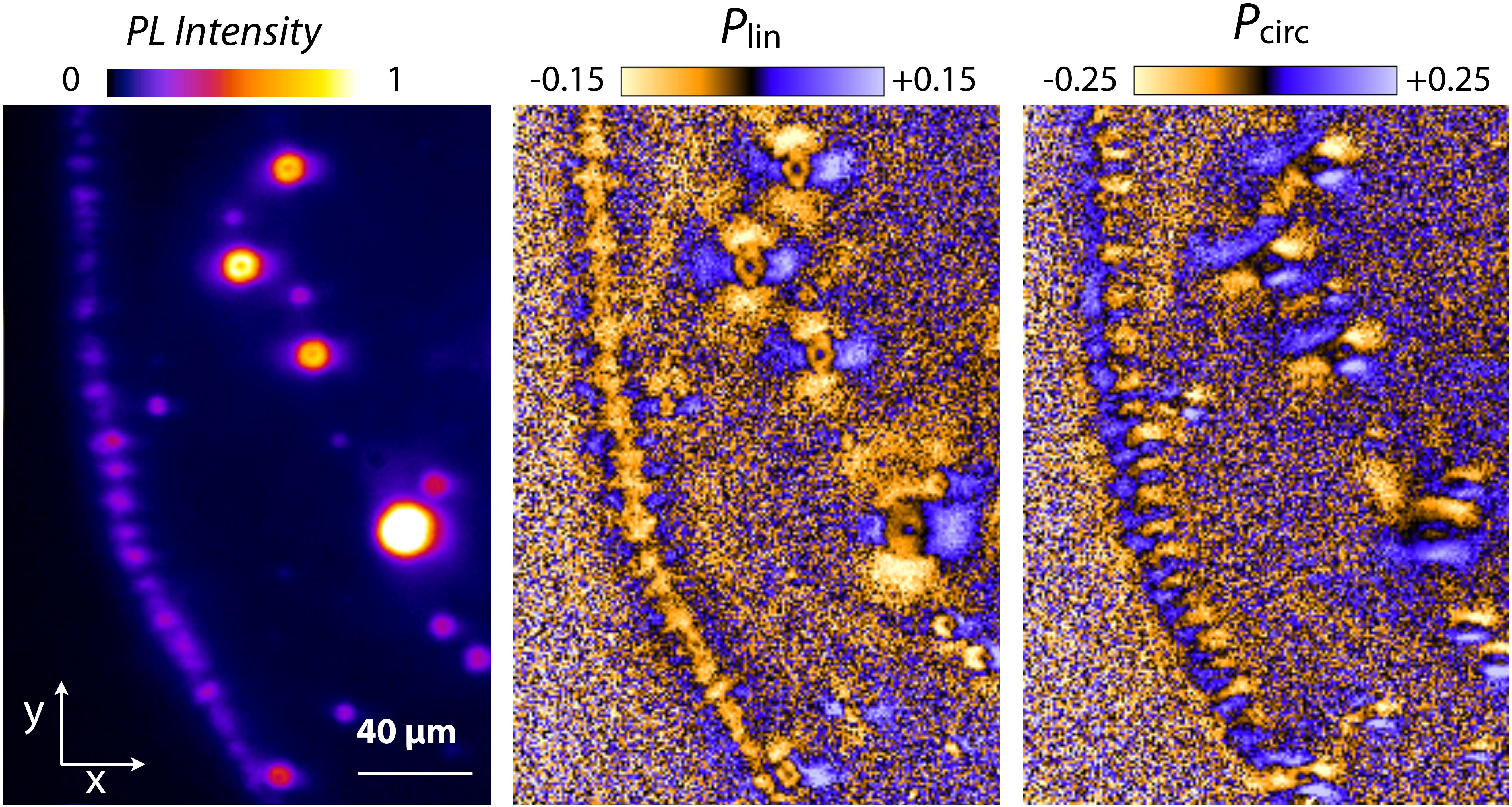
- Phase singularities appear at low temperature in a coherent exciton gas



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



Polarization of emission → Imaging of Spin Distribution



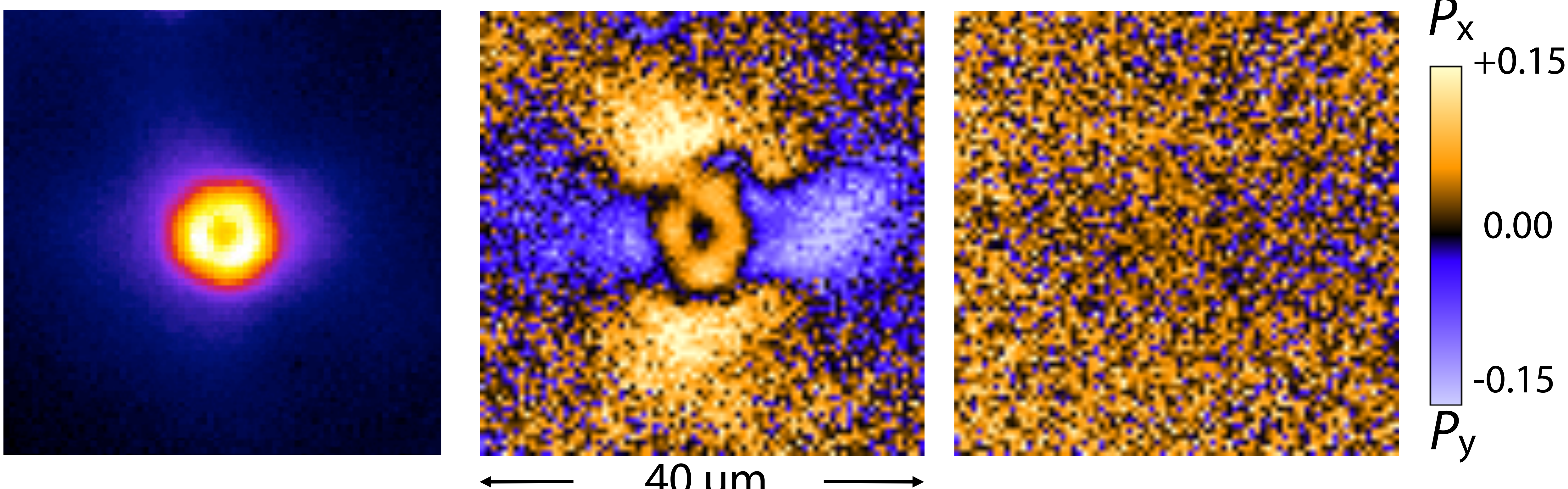
Real Space Image

Linear Polarization (in-plane spin component)

Circular Polarization (z-axis spin component)

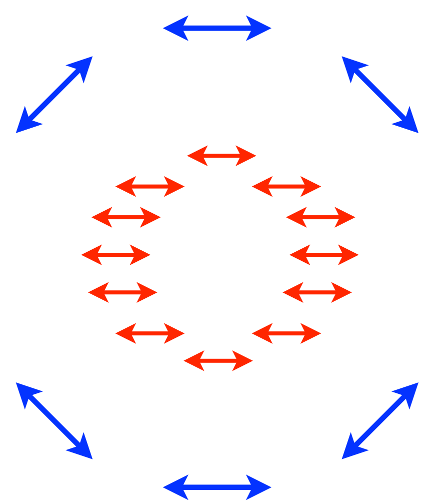
Linear Polarization → In-Plane Spin Pattern

Image of LBS $T_{bath} = 0.1$ K $T_{bath} = 7$ K

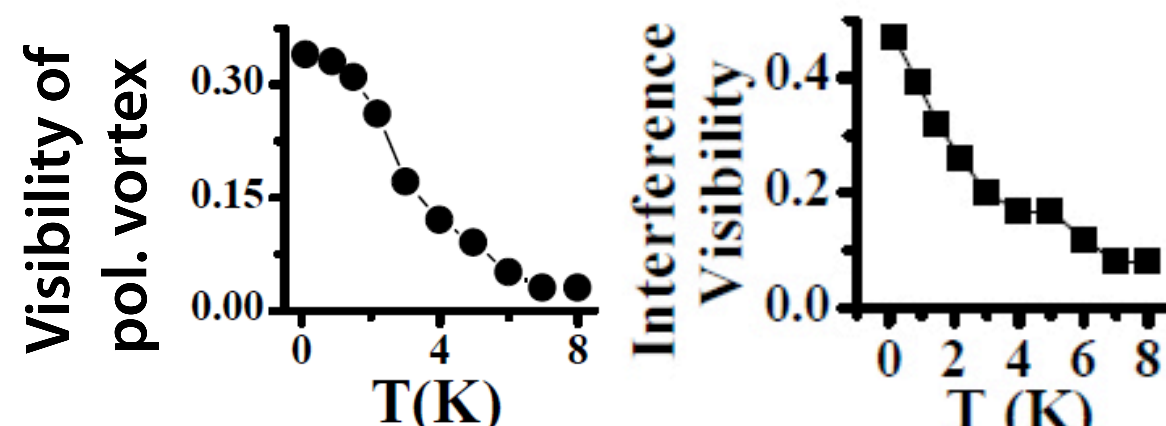


Two distinct features:

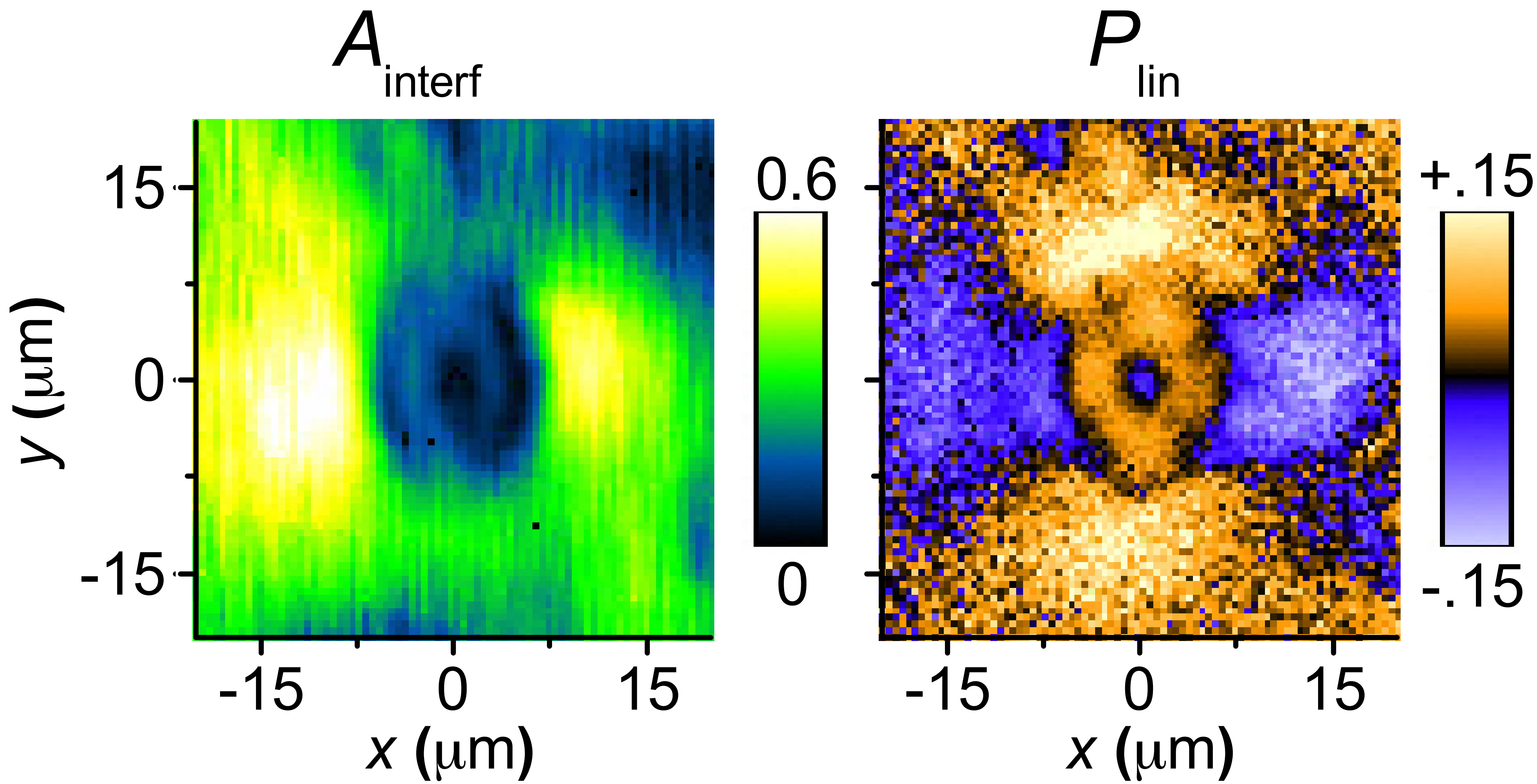
- Polarization ring
- Polarization vortex



- Spin pattern emerges with decreasing temperature in concert with coherence

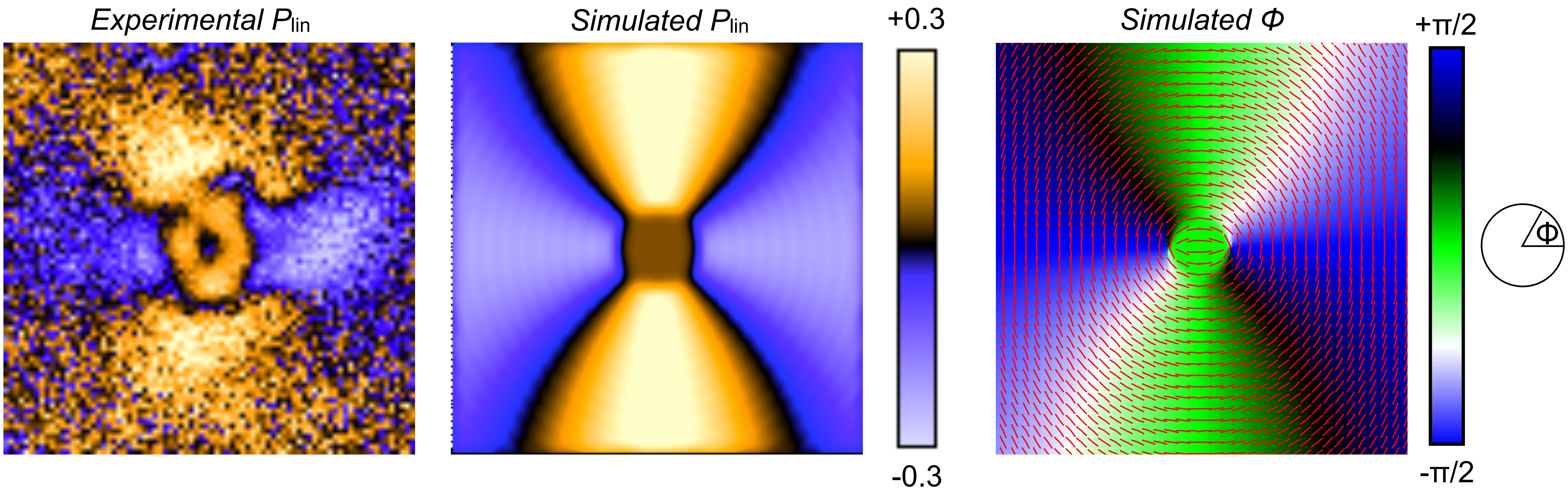


Correlation of Coherence and Spin



- Close to source, hot → no long-range coherence, polarization ring
- Away from source, cold → exciton condensate, polarization vortex

Long Range Spin Pattern → Imaging of Spin Currents



coherent transport
+
spin precession

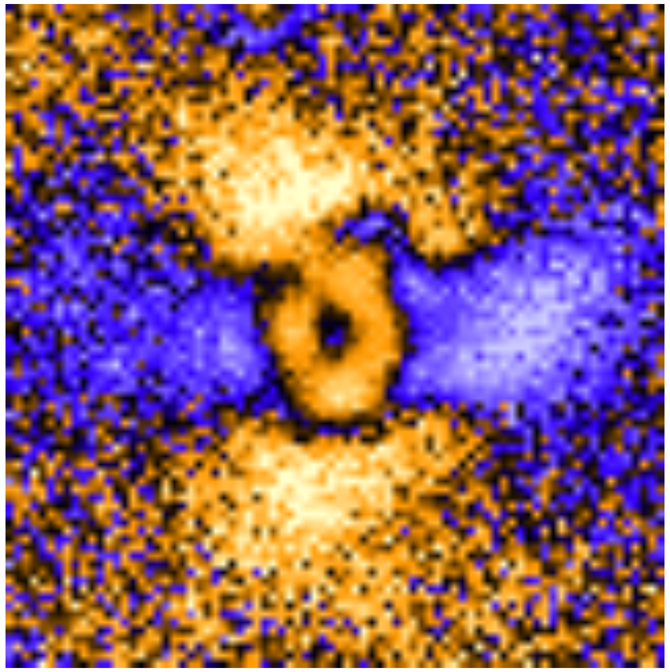
spin-orbit coupling   anisotropy

= polarization vortex

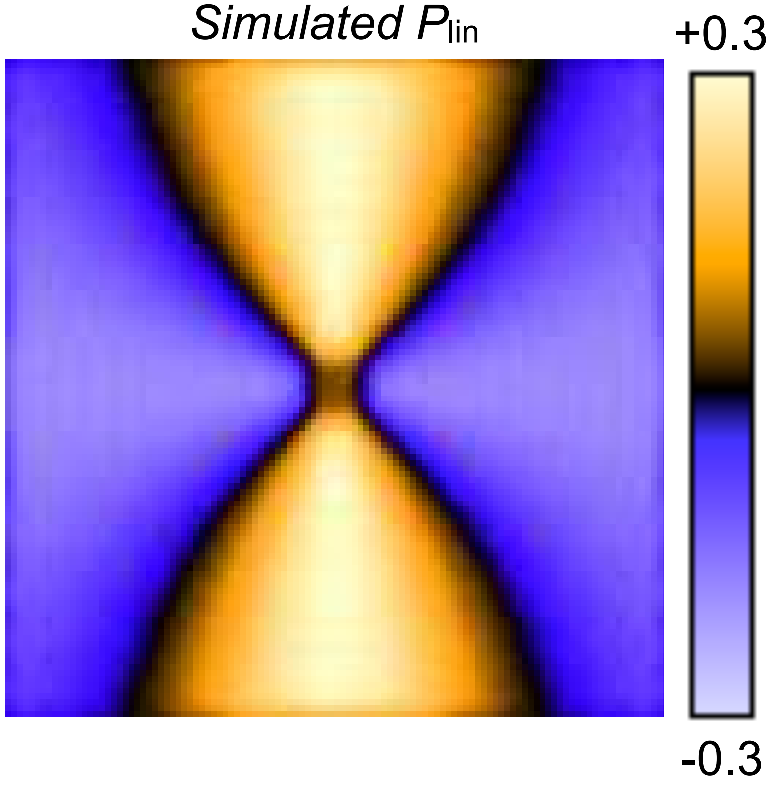
Control of spin current by magnetic field

B=0T

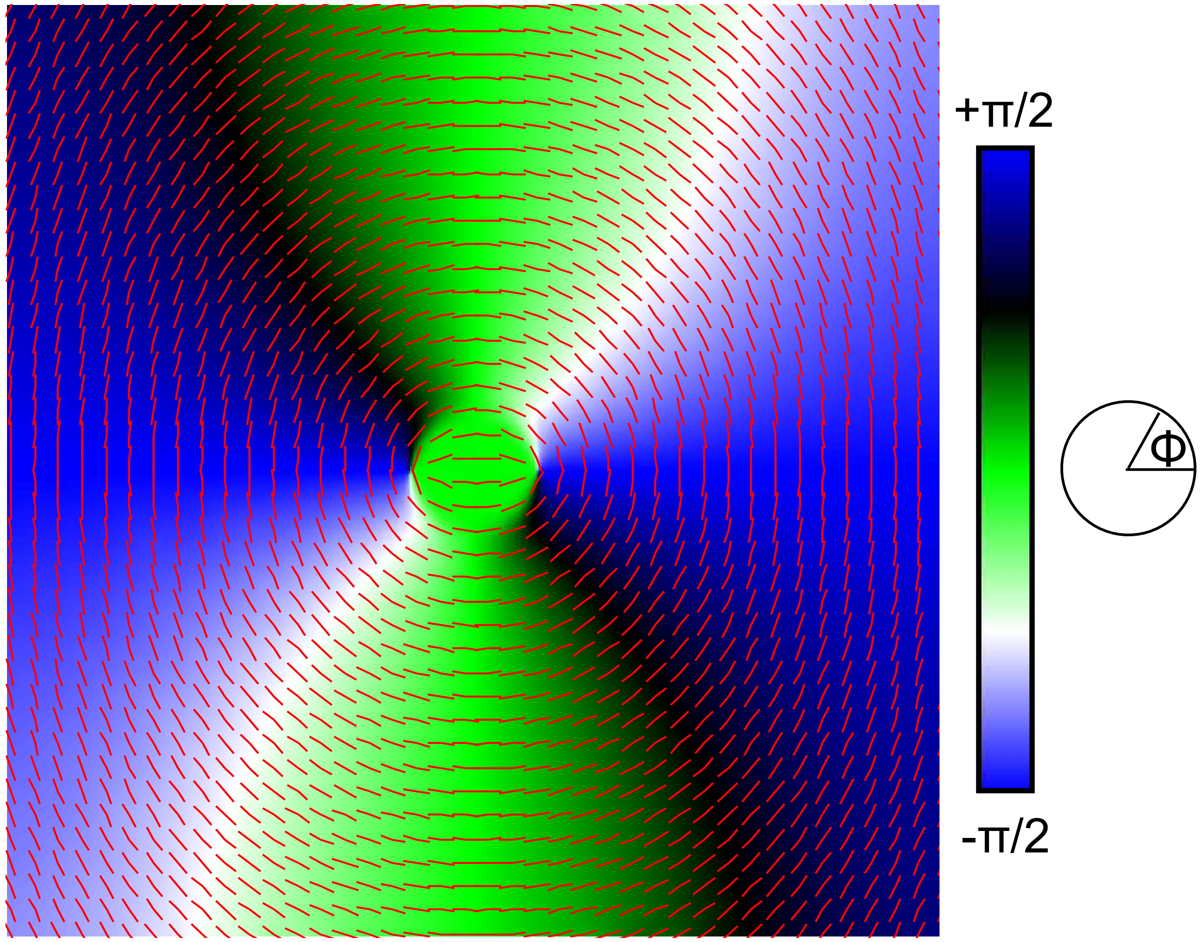
Experimental P_{lin}



Simulated P_{lin}

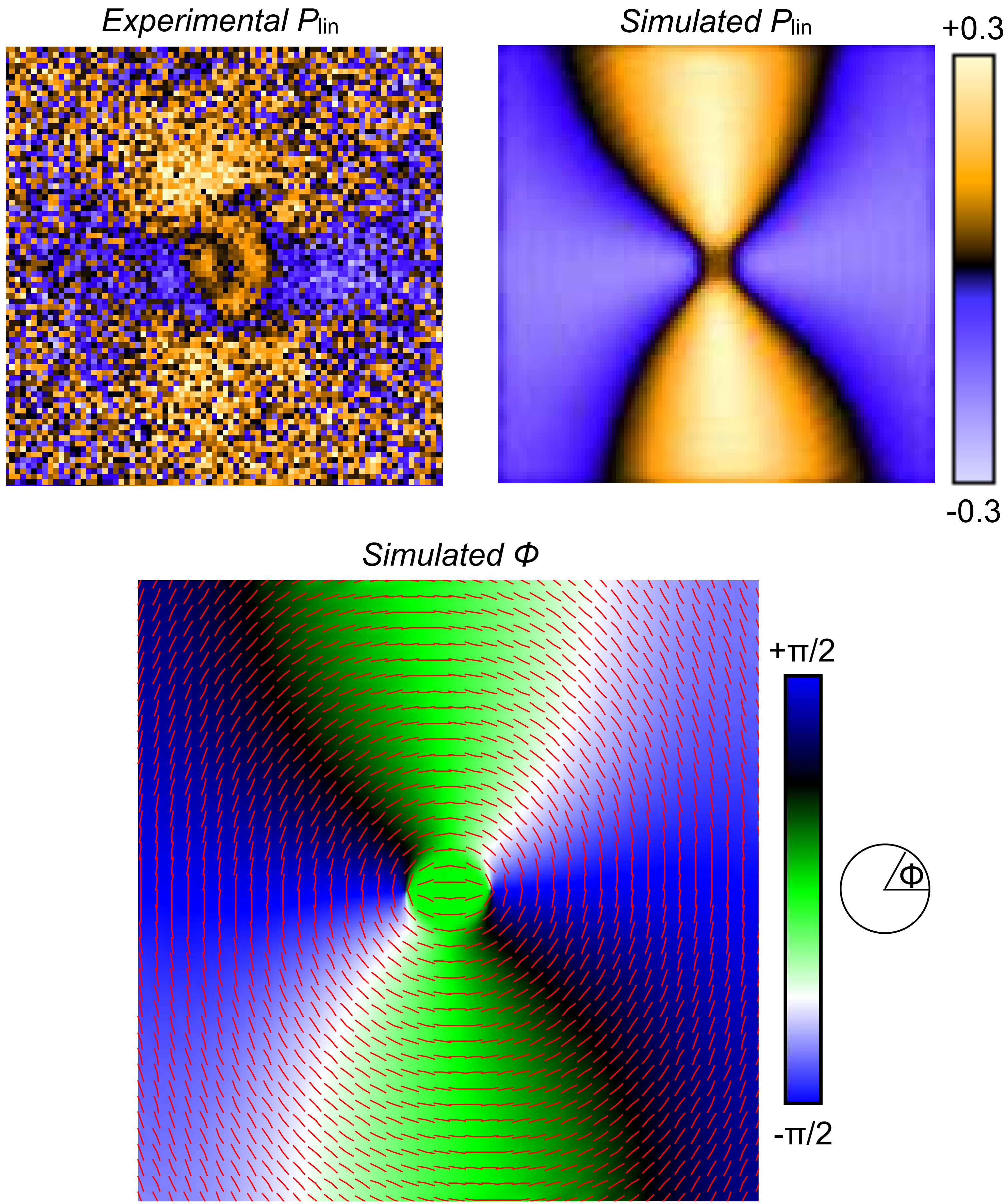


Simulated Φ



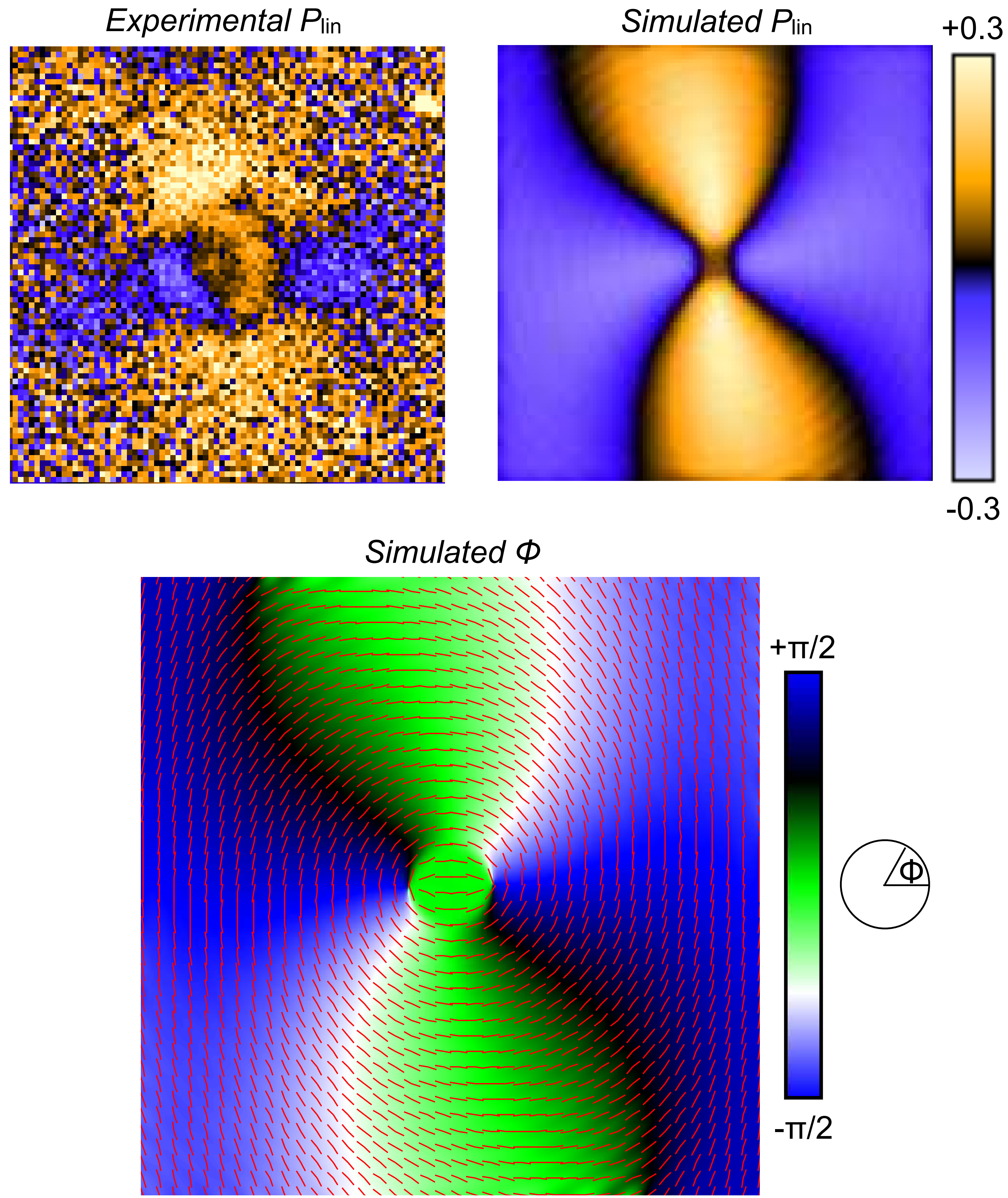
Control of spin current by magnetic field

B=1T



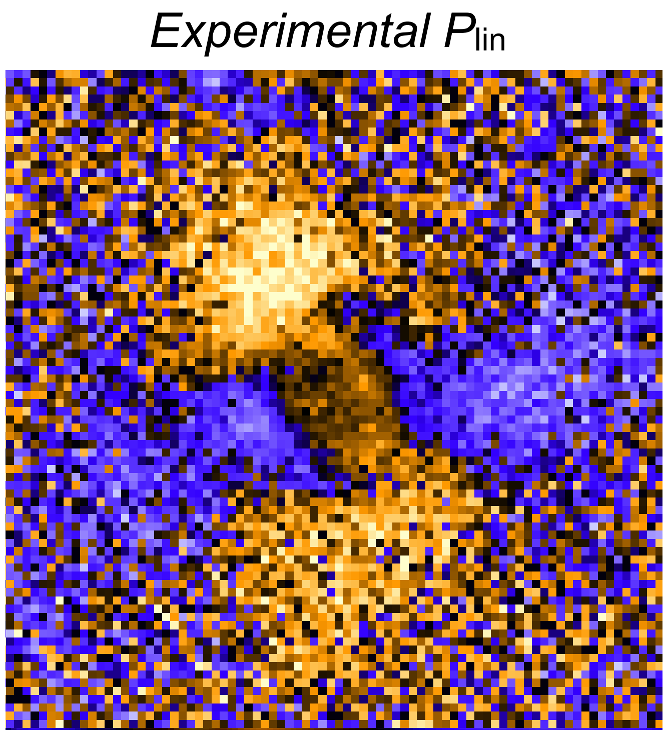
Control of spin current by magnetic field

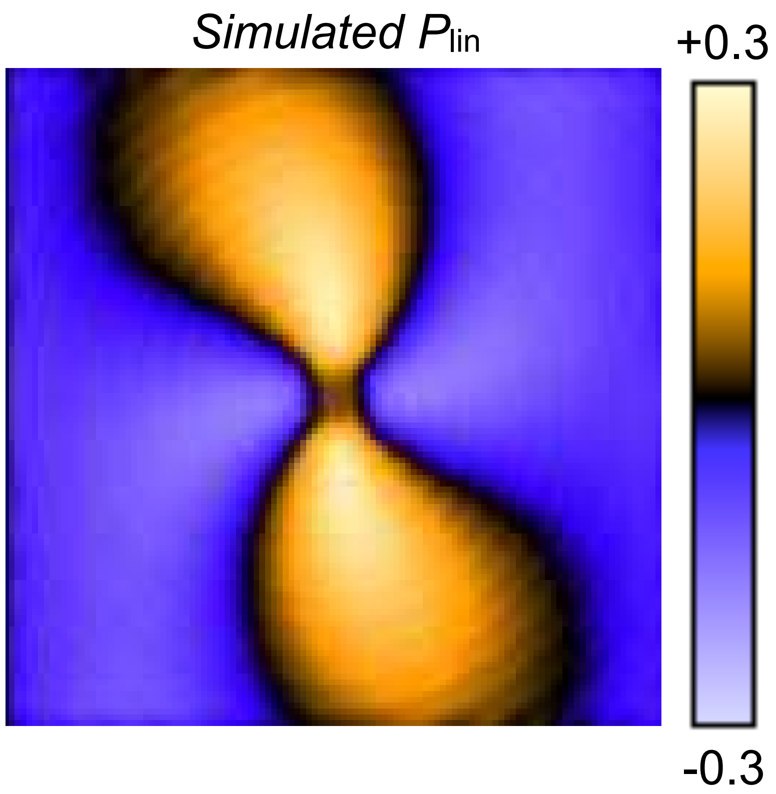
B=2T

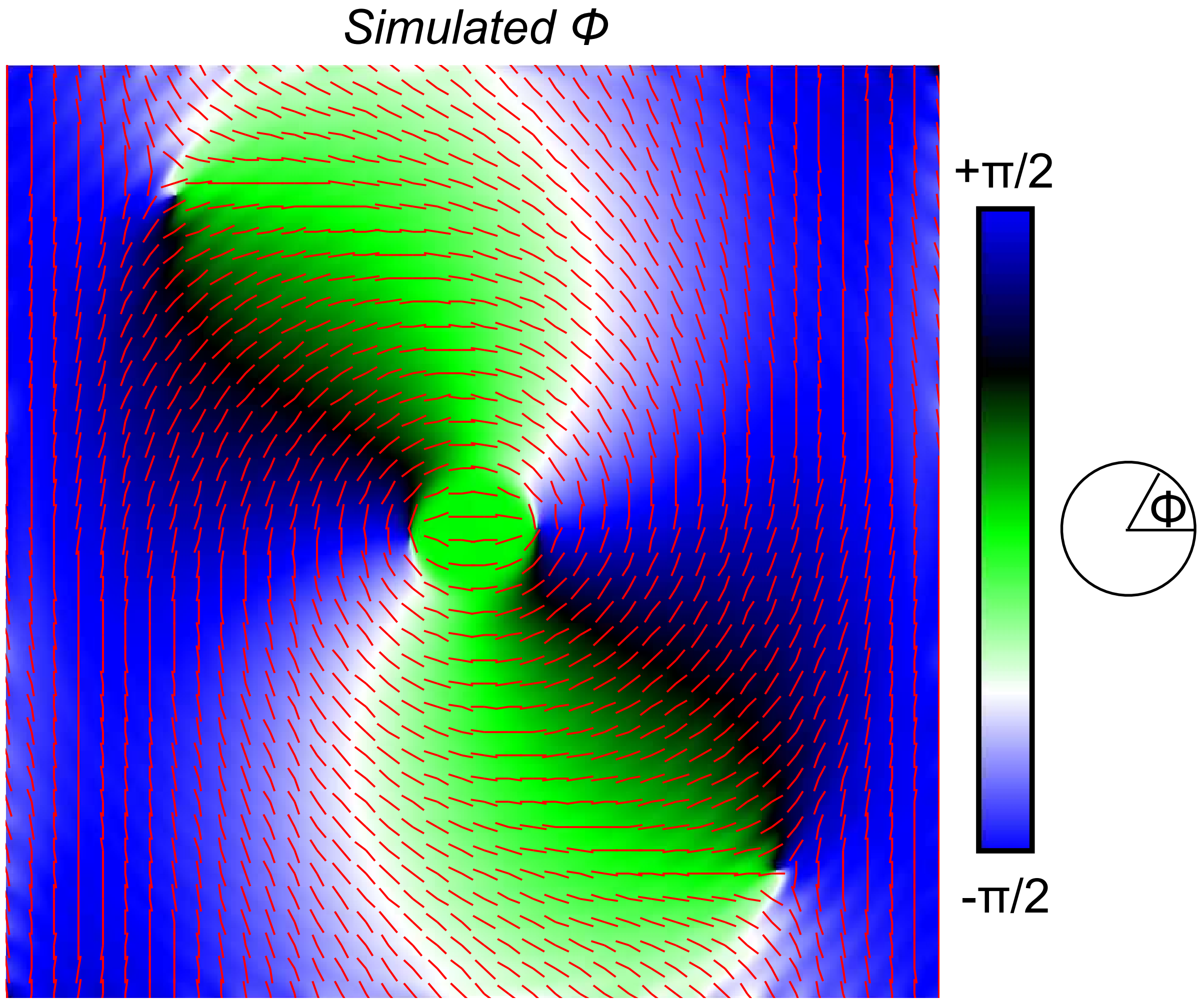


Control of spin current by magnetic field

B=3T

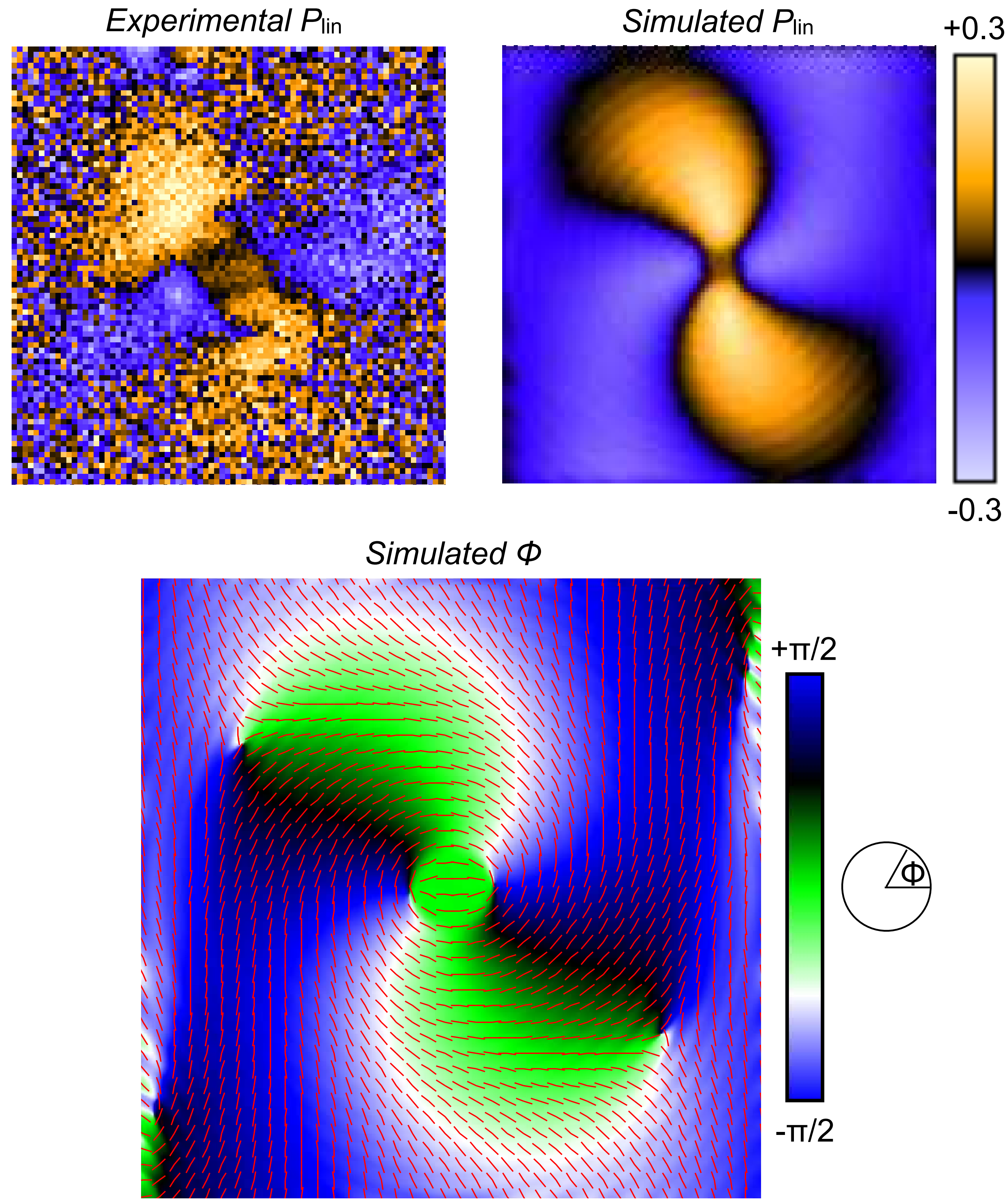






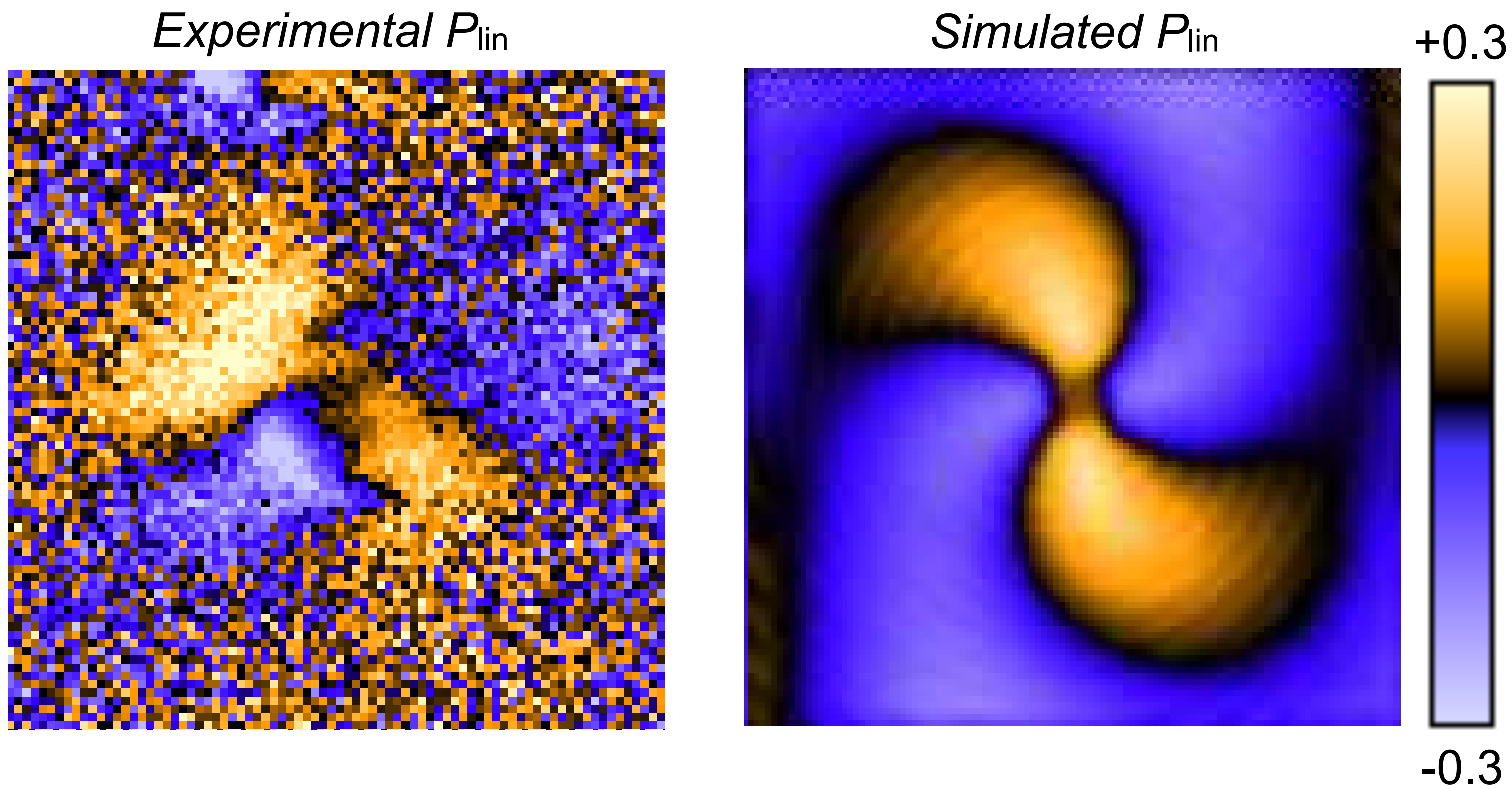
Control of spin current by magnetic field

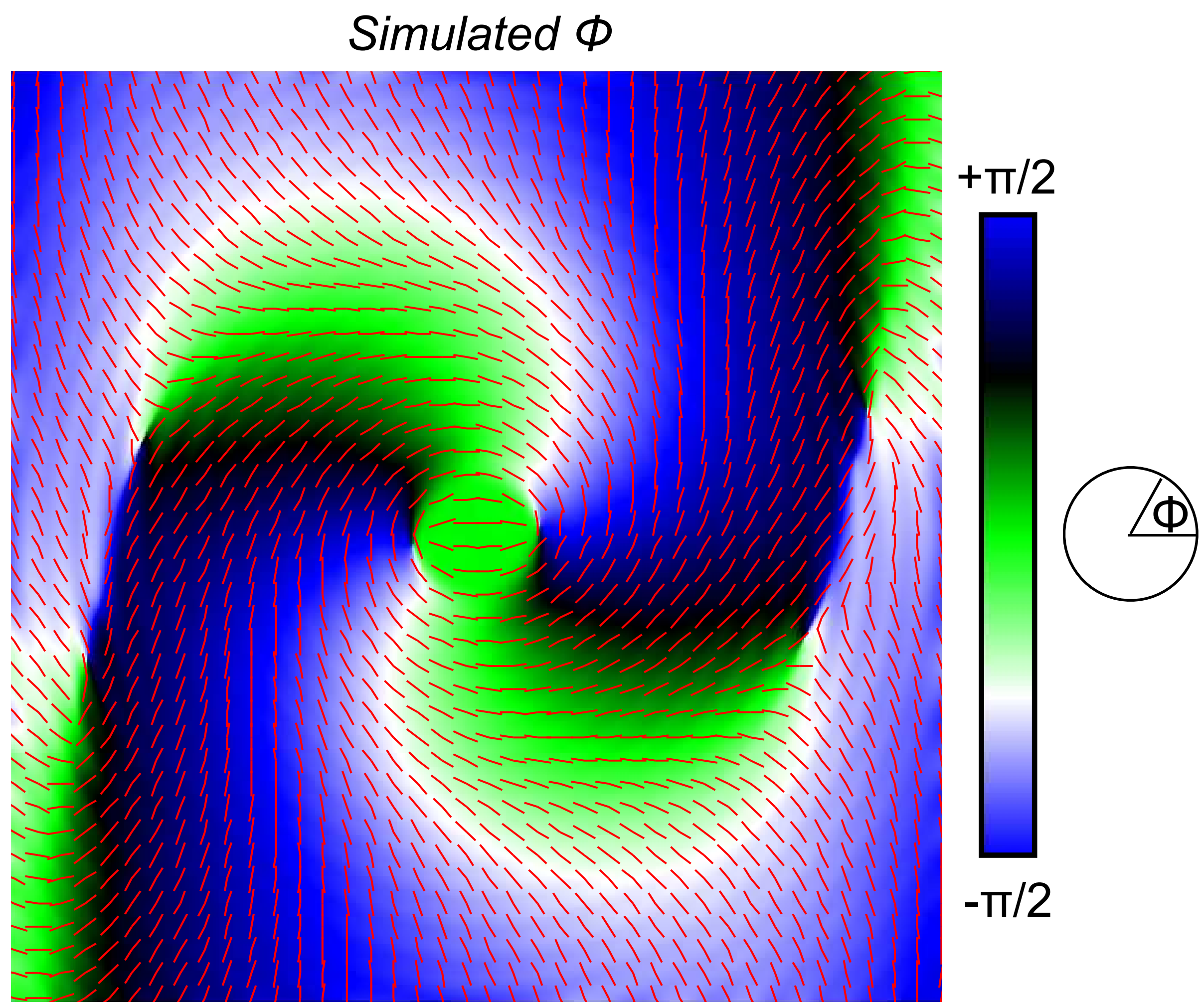
B=4T



Control of spin current by magnetic field

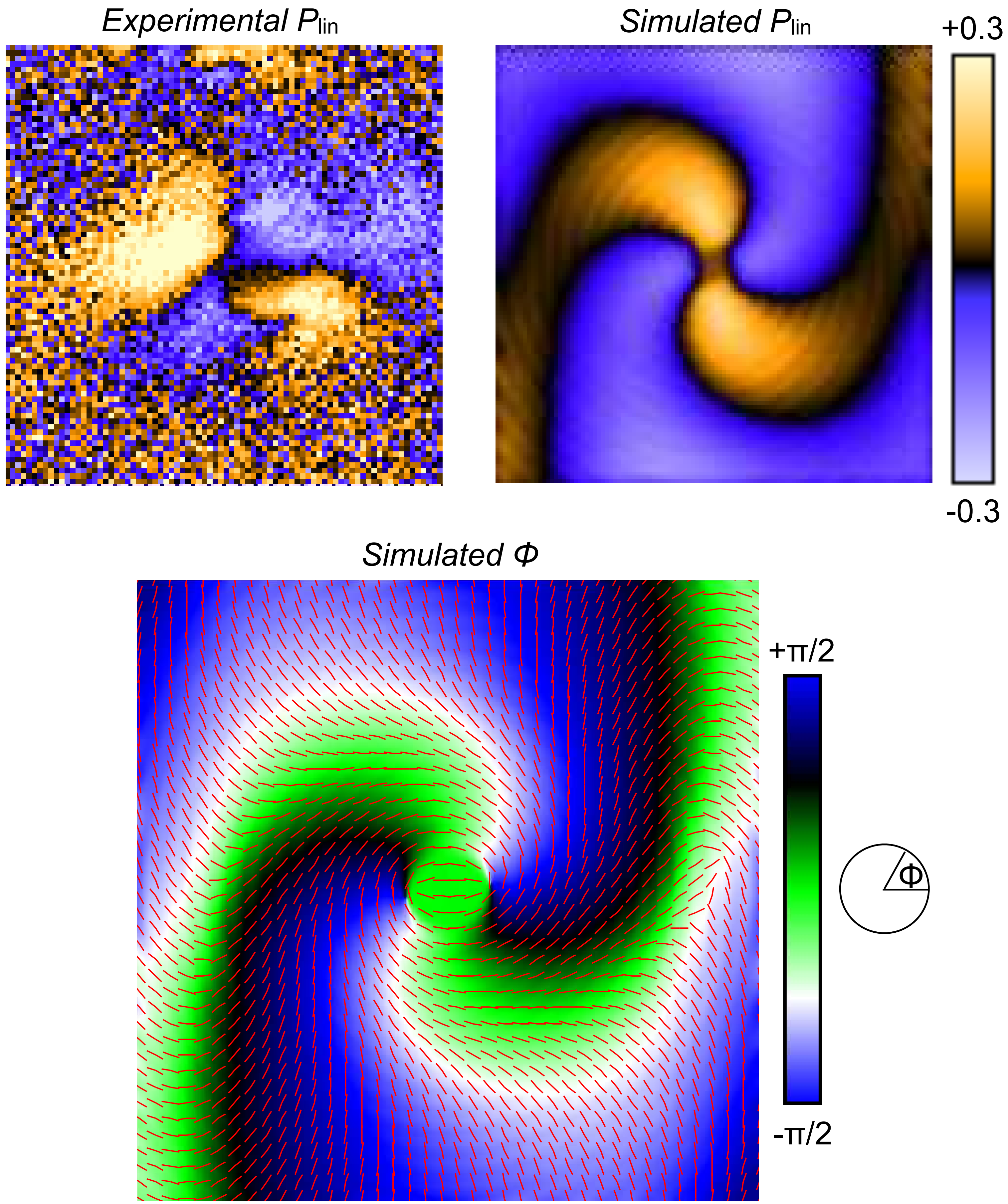
B=5T





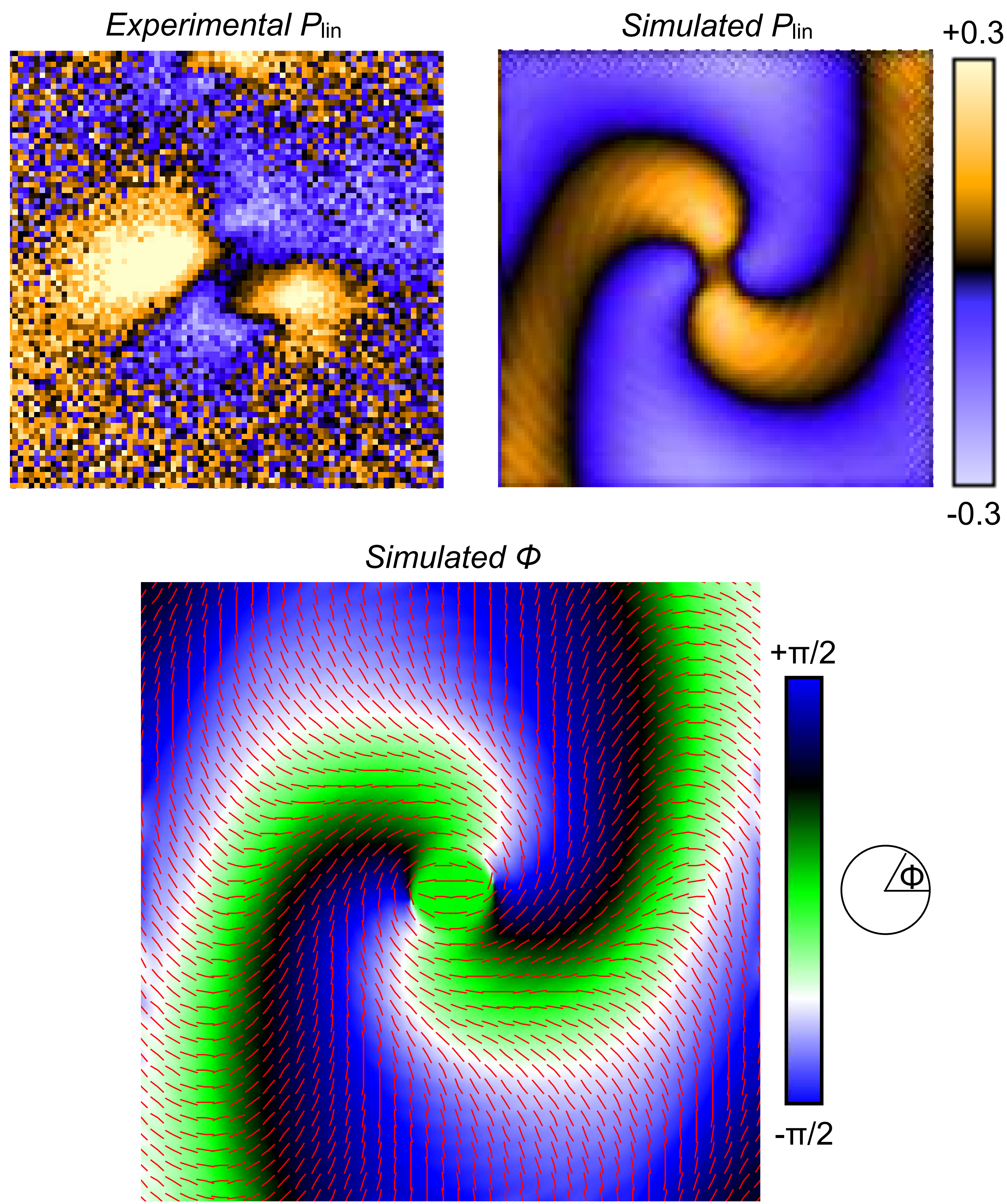
Control of spin current by magnetic field

B=6T



Control of spin current by magnetic field

B=7T

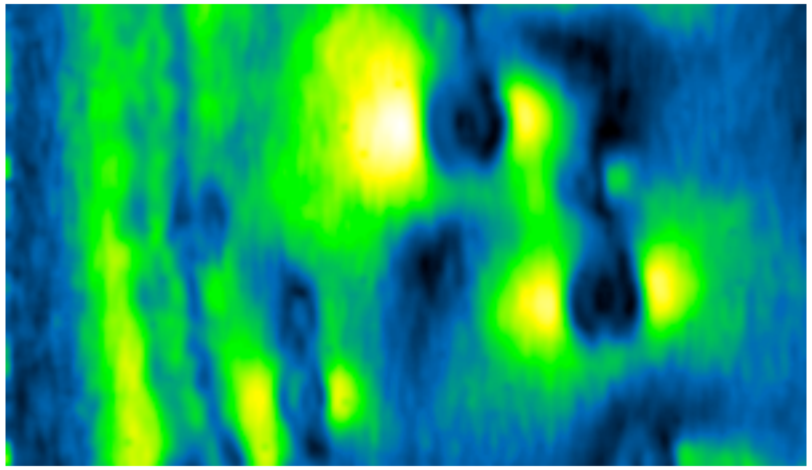


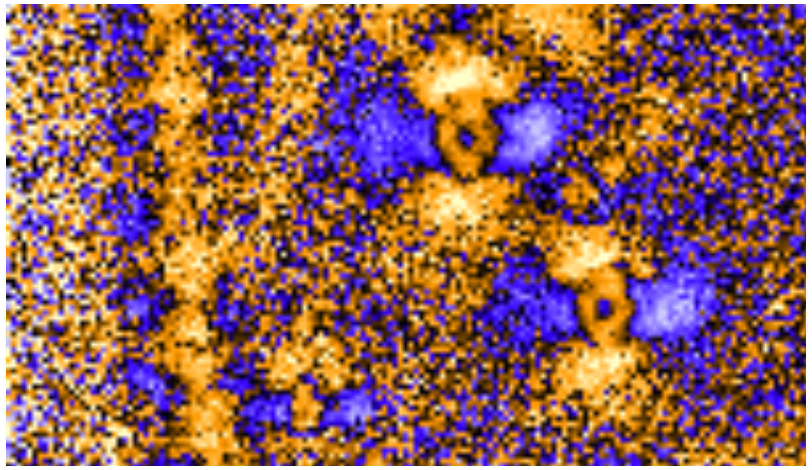
Conclusions

Observation of spontaneous exciton coherence:

- Extended coherence $\xi >> \xi_{classical}$ in polarization vortex and MOES
- Spin textures
- Phase singularities in interference

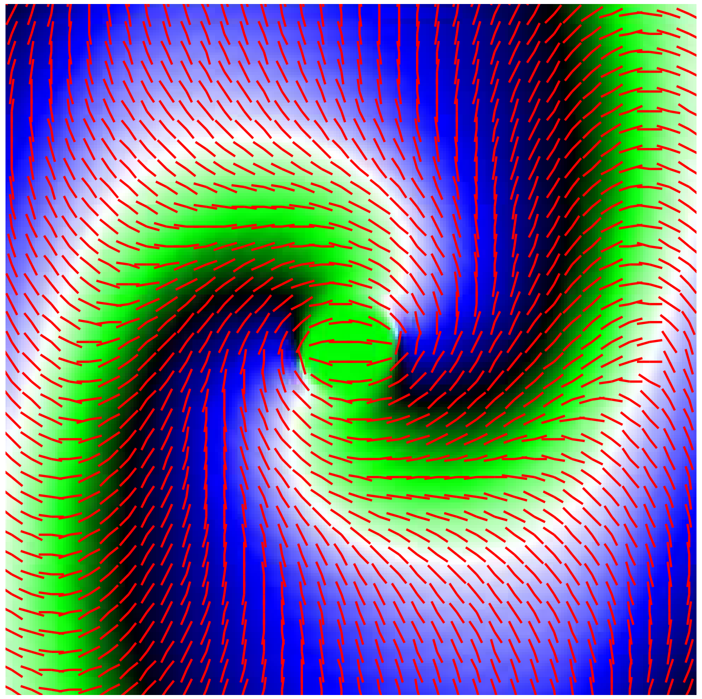
A.A. High, J.R. Leonard, A.T. Hammack, M.M. Fogler, L.V. Butov, A.V. Kavokin, K.L. Campman & A.C. Gossard, Spontaneous coherence in a cold exciton gas, *Nature* **483**, 584–588 (29 March 2012)





Imaging and control of spin currents in a coherent exciton gas:

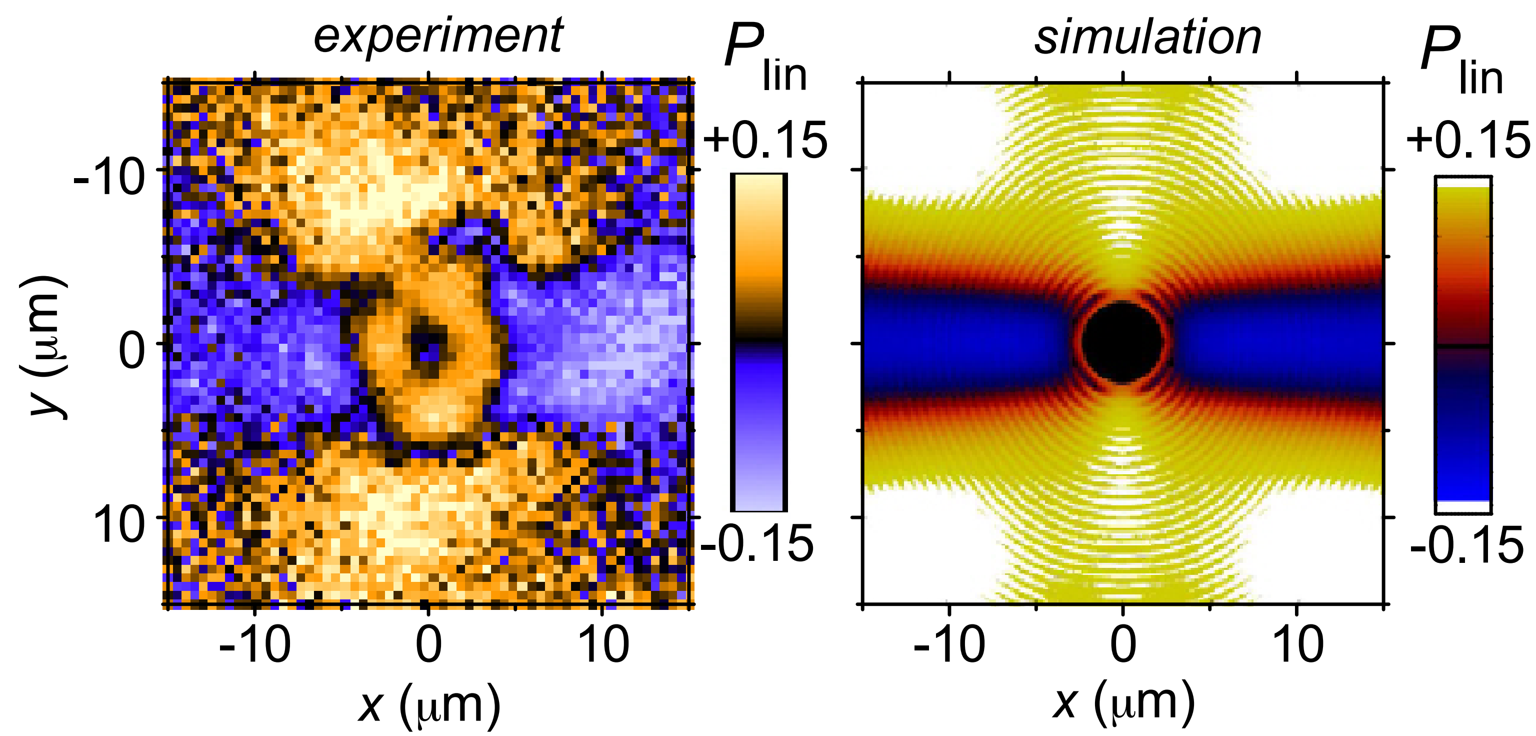
- Detection by polarization resolved imaging
- Control by magnetic field



Modeling

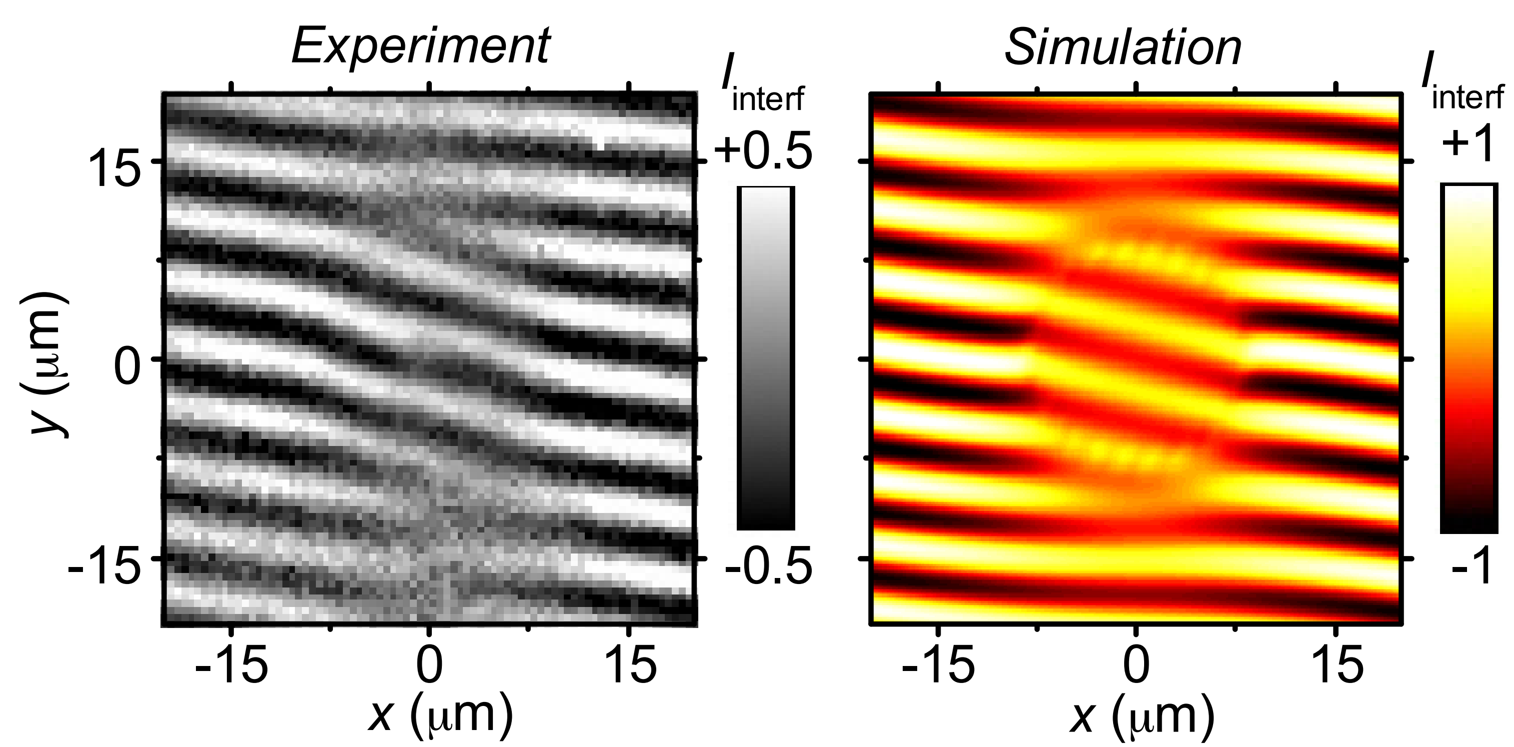
Ballistic exciton transport and spin precession → vortex of linear polarization

Spin polarization texture



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

Fork-like dislocations in interference pattern

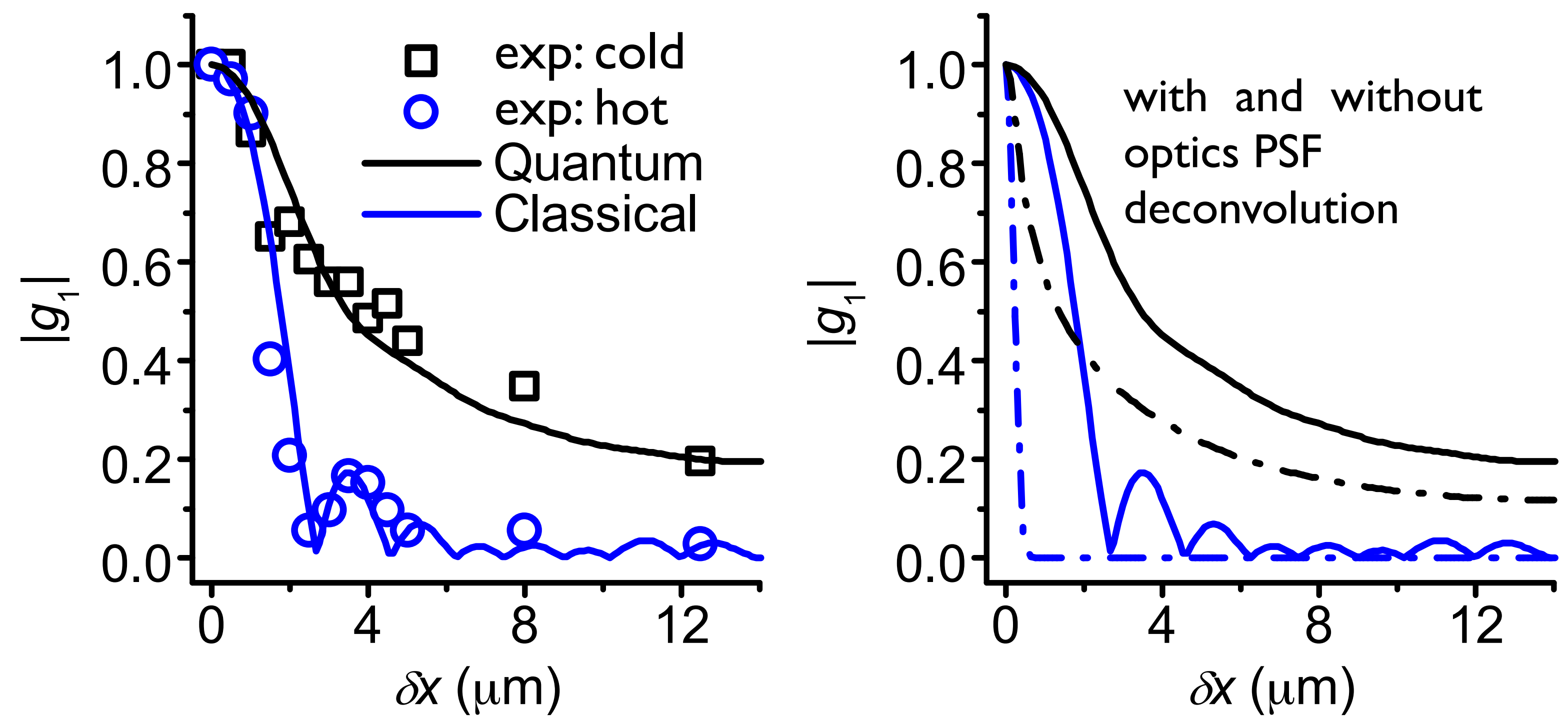


•both vortex, point source are characterized by spreading of particle velocities over all directions

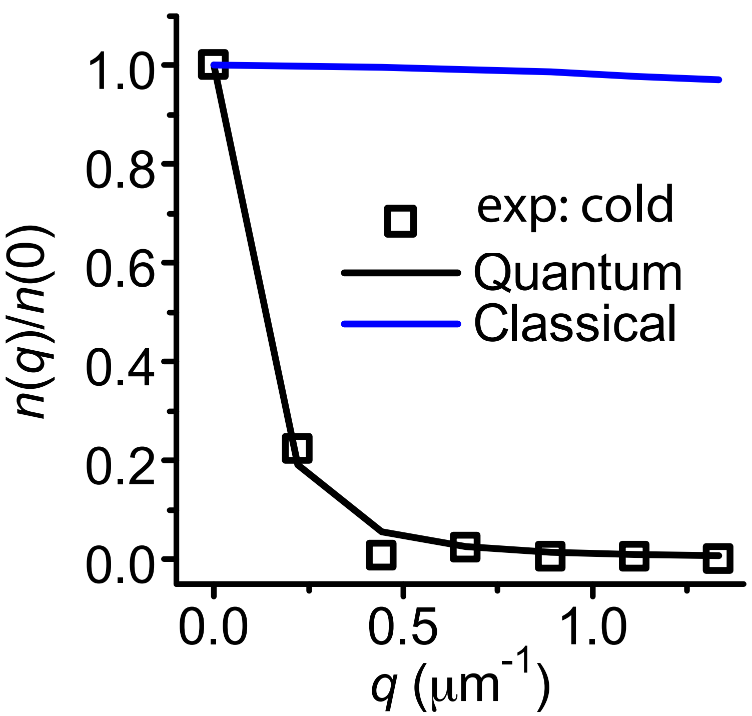
Condensate Properties

- measured g_1 is convolution of real g_1 with the point spread function (PSF) of the optics
- deconvolution gives more accurate g_1
- momentum distribution *n*(k) is fourier transform of g_1

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



Distribution in k-space, n(k)



Classical gas:
- narrow g_1(r) and broad n(k)
- $\xi_{classical}$ ~ λdB ~ 0.5 μm at 0.1 K
- n(0) ≪ 1

Quantum gas:
- extended g_1(r) and narrow n(k)
- $\xi >> \xi_{classical}$
- $\delta k << \delta k_{classical}$
- n(0) ≈ 5000

→characteristic of a condensate