Indirect Excitons:
From the Physics of Cold Bosons to Devices and Back

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A.A. High, J.R. Leonard, Y.Y. Kuznetsova, M. Remeika, A.T. Hammack, Sen Yang, A.G. Winbow, J.C. Graves, G. Grosso, A.K. Thomas, A. V. Mintsev, P. Andreakou, S.V. Poltavtsev, E.E. Novitskaya, E.V. Calman, M.W. Hasling, C.J. Dorow (*UCSD*)

A.D. Meyertholen, M.M. Fogler (*UCSD*)

M. Vladimirova (*Montpellier*), T.C.H. Liew (Rome), T. Ostatnický, A.V. Kavokin (*Southampton*)

L.S. Levitov (*MIT*), B.D. Simons (*Cambridge*)

J. Wilkes, L. Smallwood, A.A. Guenther, A.L. Ivanov (*Cardiff*)

S. Lobanov, N. Gippius (*Skoltech*)

K.L. Campman, M. Hanson, A.C. Gossard (*UCSB*)

L.N. Pfeiffer, K.W. West (*Princeton*)

S. Hu, A. Mishchenko, A.K. Geim, K.S. Novoselov (*Manchester*)

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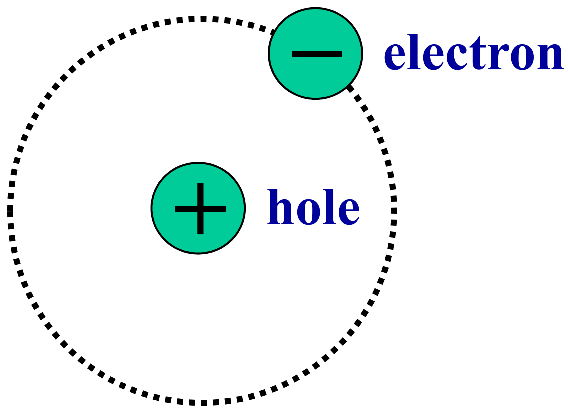
ITN INDEX

exciton – bound pair of electron and hole

$$m_{exciton} = m_{electron} + m_{hole} \ll m_{atom}$$

light bosonic particle in semiconductor



Basic physics of cold bosons:

Spontaneous coherence and condensation

Spin currents and spin textures

Transport and localization

Correlations

Pattern formation

…

excitons with designed properties

Excitonic devices:

Report of the **Semiconductor Research Corporation** and the **National Science Foundation** workshop to explore future research directions for **energy efficient computing** (Oct 2015) aligns with the Nanotechnology-inspired Grand Challenge for Future Computing and the National Strategic Computing Initiative:

"promising possibility is based on the emergence of devices for direct conversion of photons to excitons. These **excitonic devices*** might enable detection, storage, processing and transmission of data packets without the need for power-hungry electronic circuits"

*P. Andreakou *et al.*, *"Optically Controlled Excitonic Transistor," Appl. Phys. Lett. 104, 091101 (2014).*

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

How to realize quantum exciton gas ?

Transition from classical to quantum gas takes place when thermal de Broglie wavelength is comparable to interparticle separation

3D: $\lambda_{dB} = n^{-1/3}$

$$T_{dB} = \frac{2\pi\hbar^2}{mk_B} n^{2/3}$$

$$T_{BEC} = 0.527 T_{dB}$$

$m_{exciton} \sim 10^{-6}\, m_{atom}$

Kelvin for excitons is like microKelvin for atoms

2D: $\lambda_{dB} = n^{-1/2}$

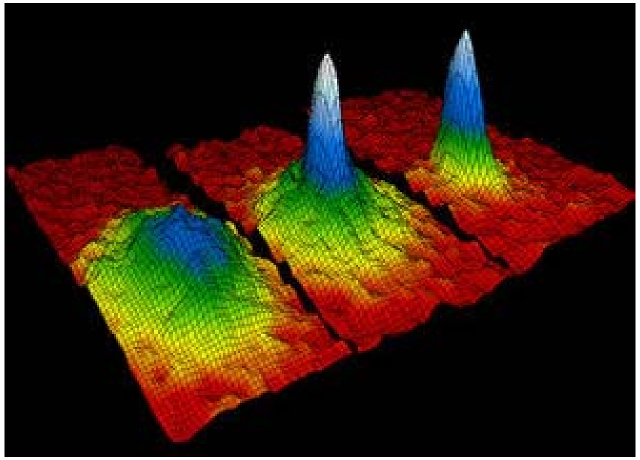
$$T_{dB} = \frac{2\pi\hbar^2}{mk_B} n$$

↑ temperature of quantum degeneracy

3D gas of Rb atoms:
$n = 10^{15}$ cm^{-3}, $m_{atom} = 10^5\, m_e \rightarrow T_{dB} \sim 5\times10^{-6}$ K

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

1995 discovery of BEC of atoms



2001

Eric A. Cornell
Wolfgang Ketterle
Carl E. Wieman

How to realize quantum exciton gas ?

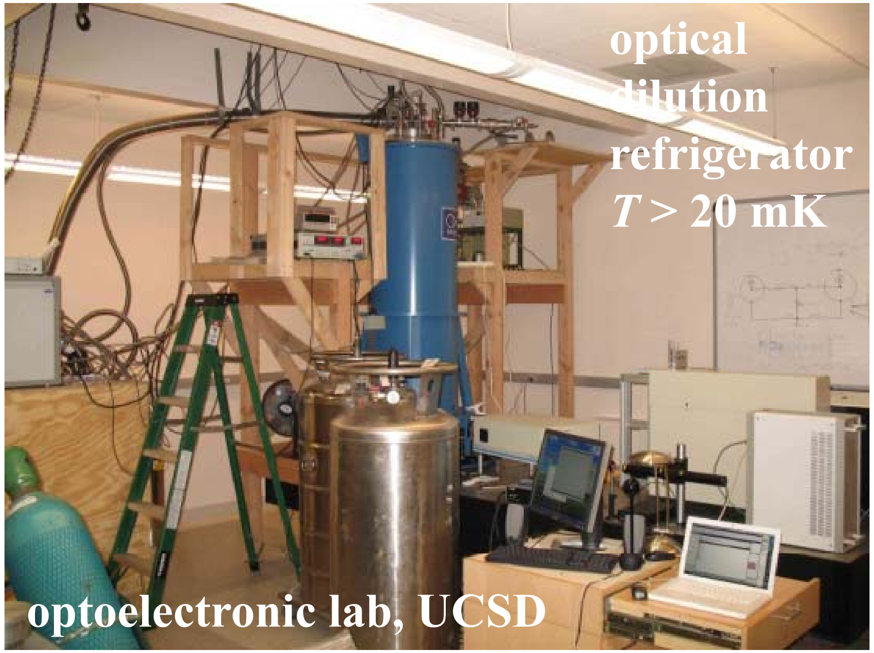
$T_{lattice} << 1$ K in He refrigerators

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

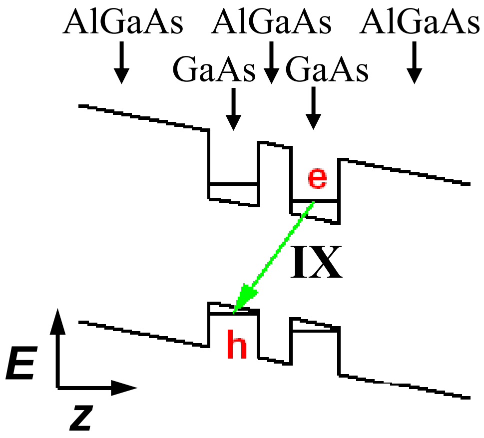
design excitons with lifetime >> cooling time

↓

$T_{exciton} \sim T_{lattice}$

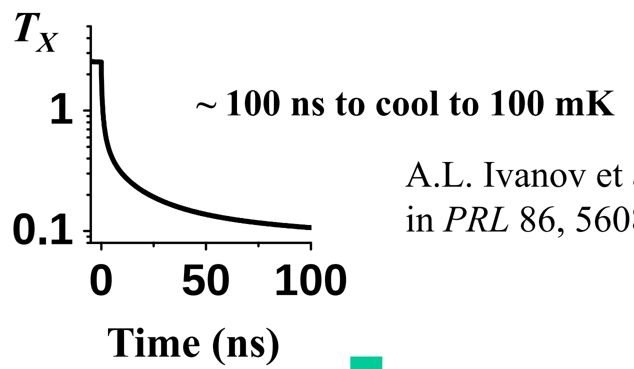


Indirect excitons in Coupled Quantum Wells



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

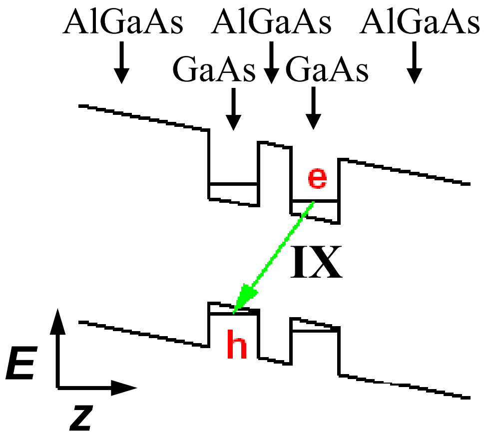
realization of cold exciton gas in separated layers was proposed by
Yu.E. Lozovik, V.I. Yudson (1975)
T. Fukuzawa, S.S. Kano, T.K. Gustafson, T. Ogawa (1990)

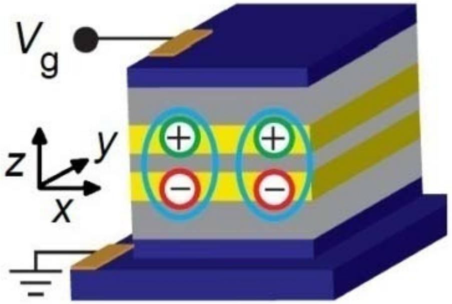


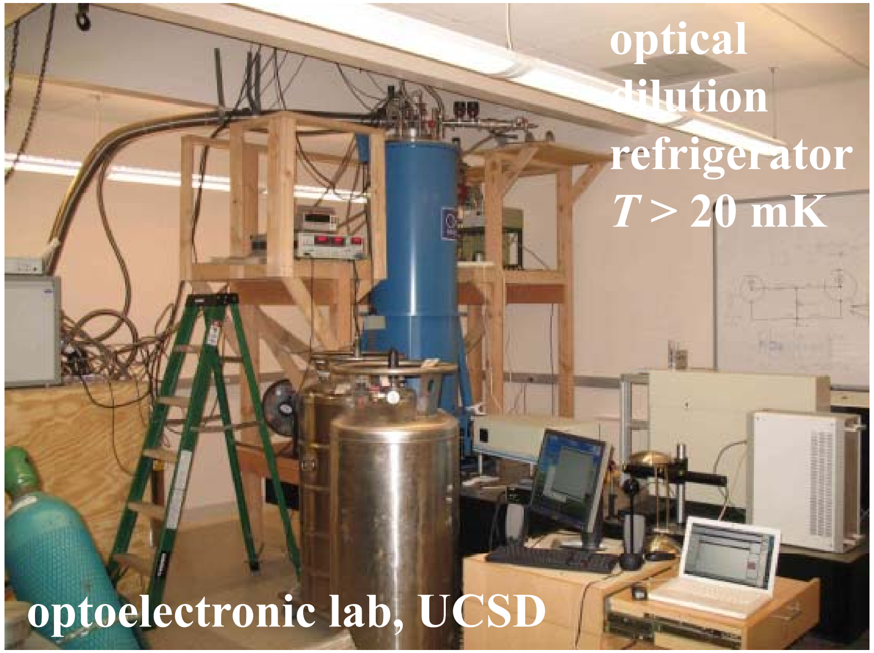
A.L. Ivanov et al.
in *PRL* 86, 5608 (2001)

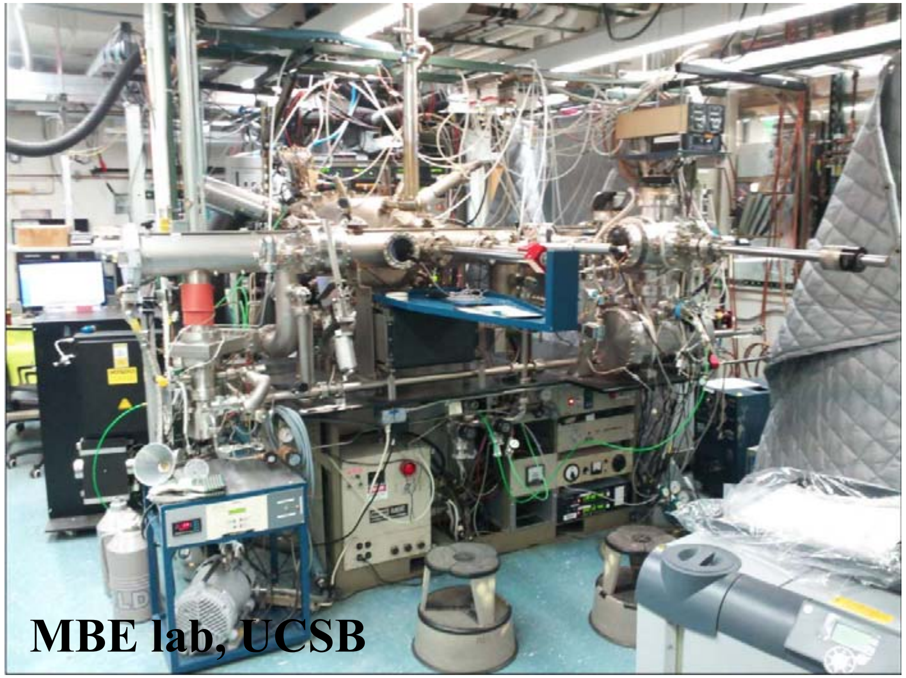
T_X ~ 100 mK << T_{dB}
is realized for indirect excitons

Indirect excitons in Coupled Quantum Wells









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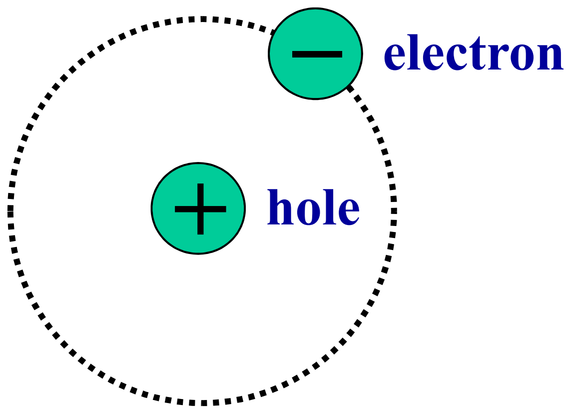

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indirect excitons

dipole excitons

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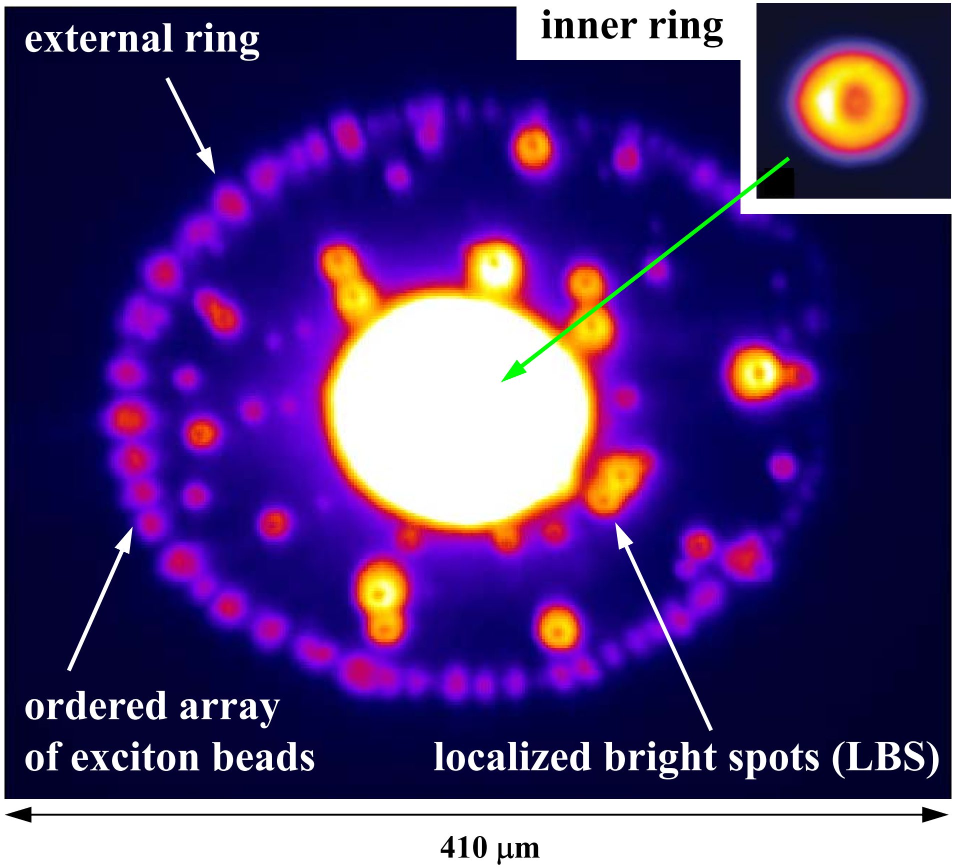
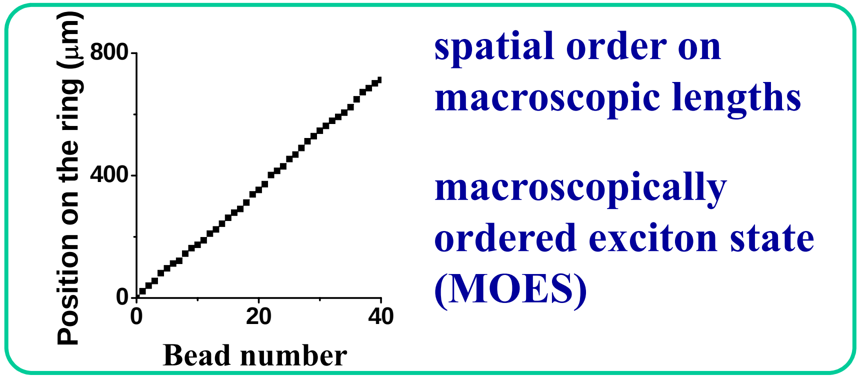
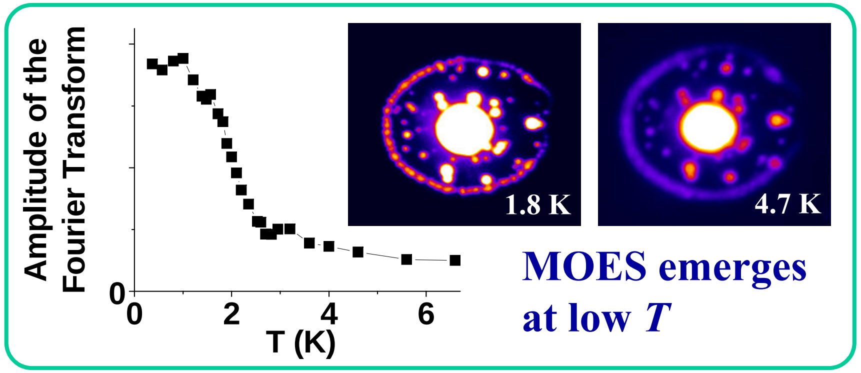
*P. Andreakou *et al.*, *"Optically Controlled Excitonic Transistor," Appl. Phys. Lett. 104, 091101 (2014).*

Pattern formation

Exciton rings and macroscopically ordered exciton state







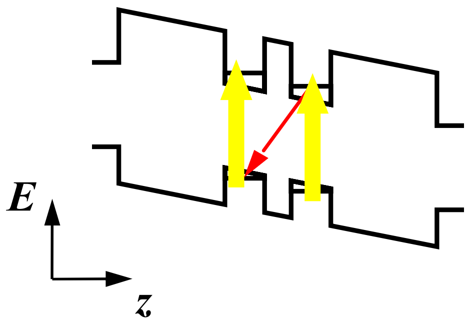
L.V. Butov, A.C. Gossard, D.S. Chemla, *Nature* 418, 751 (2002)

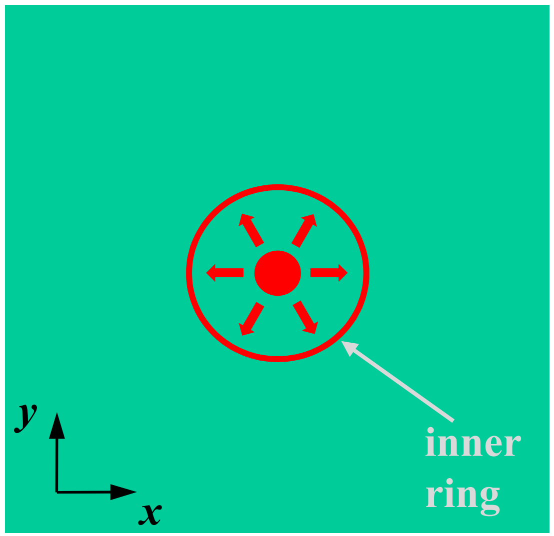
model of

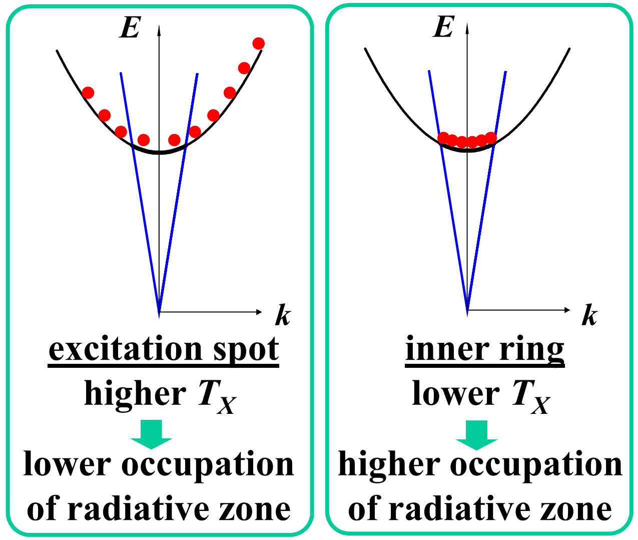
- **inner ring:** A.L. Ivanov, L. Smallwood, A. Hammack, Sen Yang, L.V. Butov, A.C. Gossard, *EPL* 73, 920 (2006)
- **external ring:** L.V. Butov, L.S. Levitov, B.D. Simons, A.V. Mintsev, A.C. Gossard, D.S. Chemla, *PRL* 92, 117404 (2004)
  R. Rapaport, G. Chen, D. Snoke, S.H. Simon, L. Pfeiffer, K.West, Y.Liu, S.Denev, *PRL* 92, 117405 (2004)
- **MOES:** L.S. Levitov, B.D. Simons, L.V. Butov, *PRL* 94, 176404 (2005)

Inner ring

laser excitation
creates excitons
in CQW

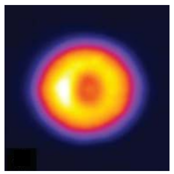






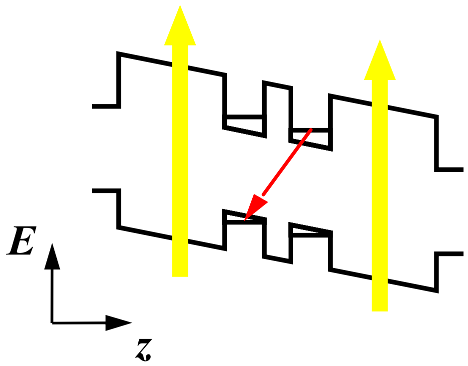
electron-rich region **excitons**

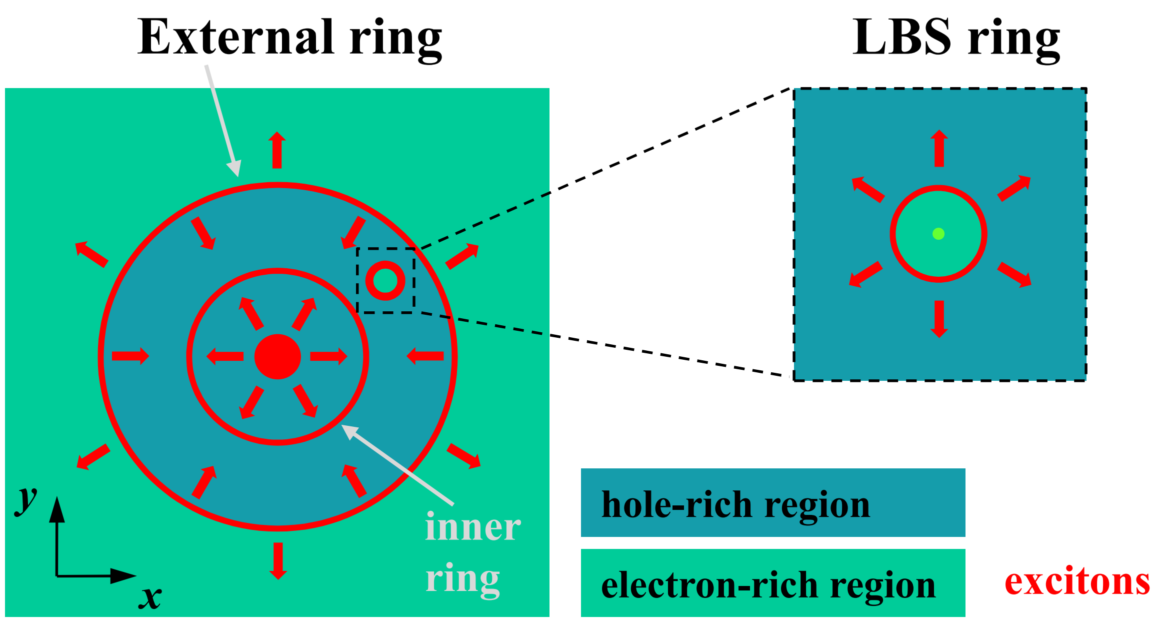
inner ring forms due to transport and cooling of optically generated excitons



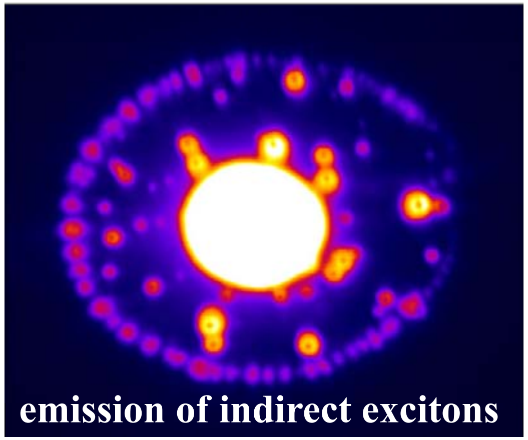
emission of indirect excitons

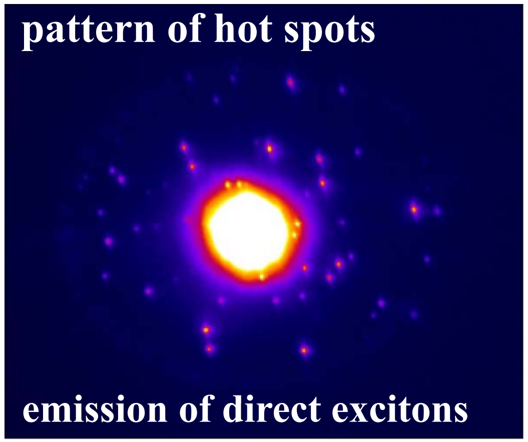
above barrier laser excitation
creates excitons + holes
in CQW





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

exciton gas
is cold in external ring and LBS rings

↓

quantum exciton gas

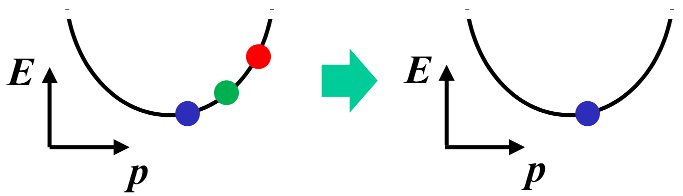
Spontaneous coherence and condensation

Condensation and spontaneous coherence

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 $\lambda = h/p$

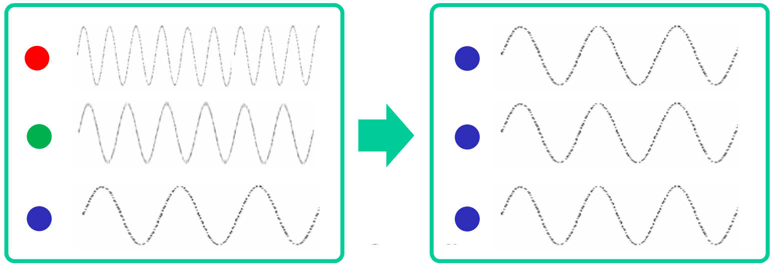
condensation in momentum space ⟷ **emergence of spontaneous coherence**

particles (in momentum space)



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

matter waves (in real space)



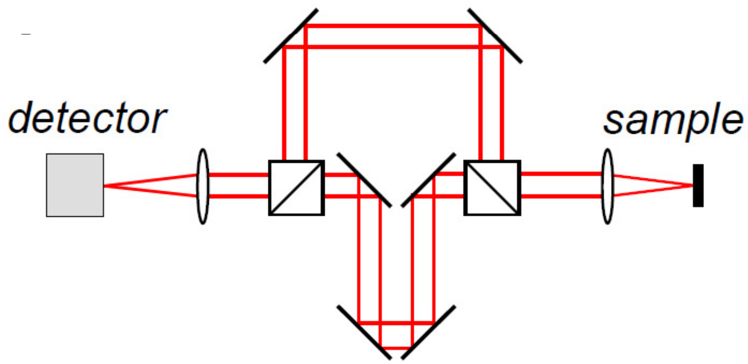
high *T* **low *T***

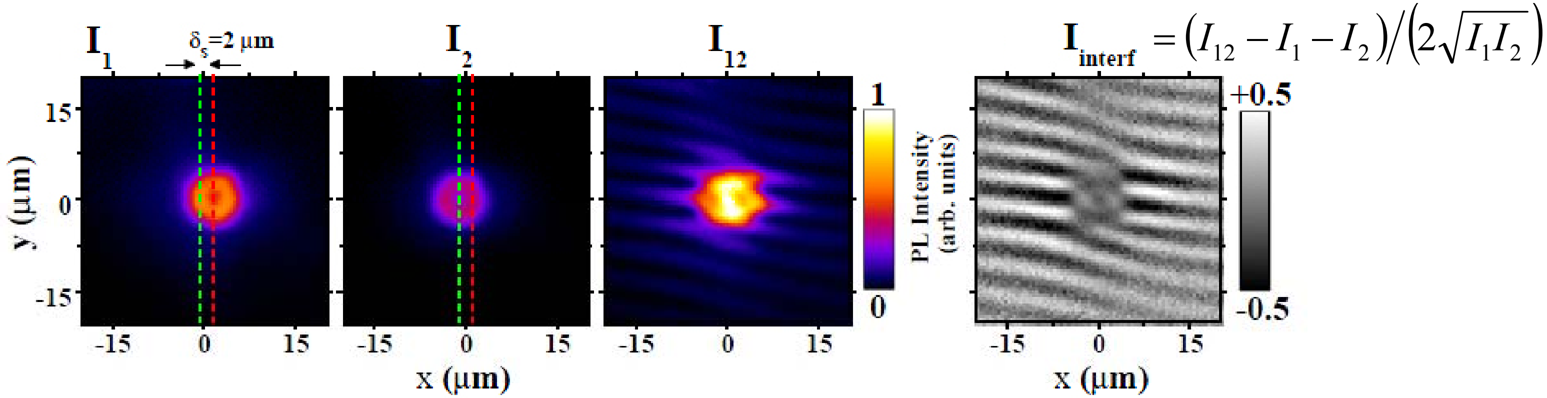
If bosonic particles are cooled down **below the temperature of quantum degeneracy**
they can spontaneously form **a coherent state**
in which **individual matter waves synchronize and combine**

Theoretical predictions for coherent states in cold exciton systems:

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

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



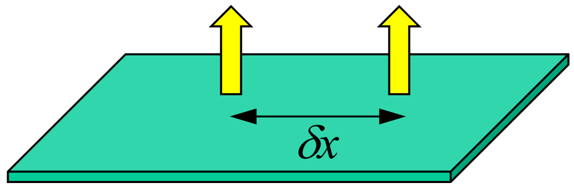


Pattern of $g_1(\delta x)$ is measured by shift-interferometry

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

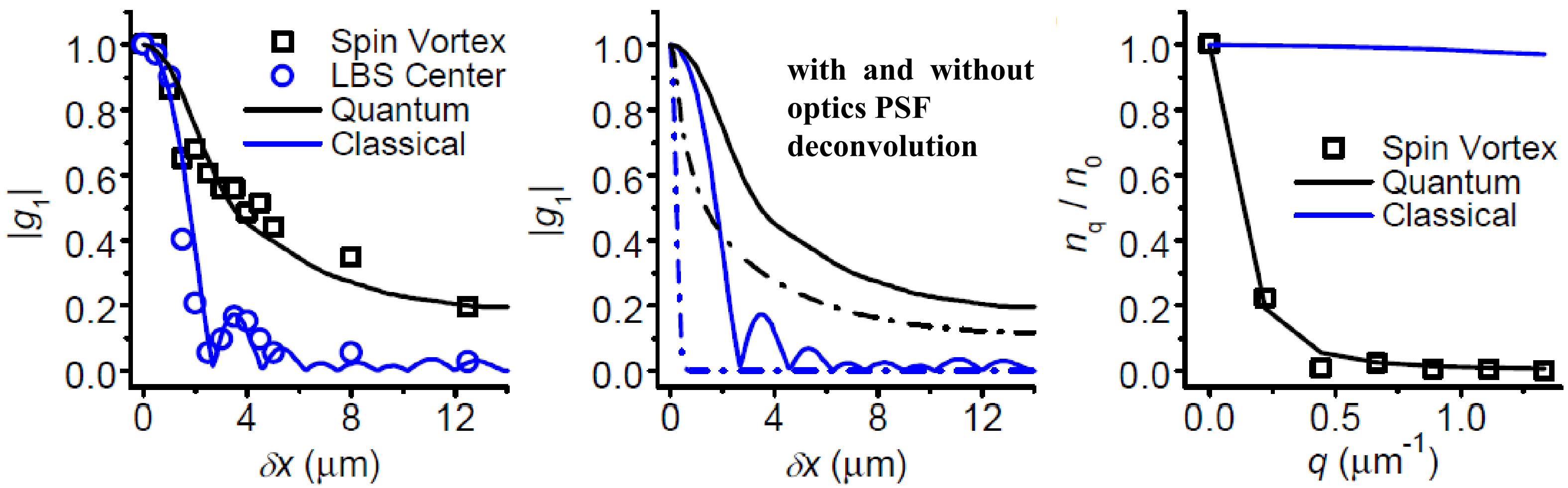
Images produced by arm 1 and 2 of MZ interferometer are shifted to measure interference between emission of excitons separated by δx

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



exciton coherence is imprinted on coherence of their light emission

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



$$g_1(r) \sim \int d^2 q e^{i\mathbf{qr}} n_q \qquad \delta q \cdot \xi \sim 1$$

coherence length

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

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

Quantum gas: extended $g_1(r)$ and narrow n_{q}

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

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

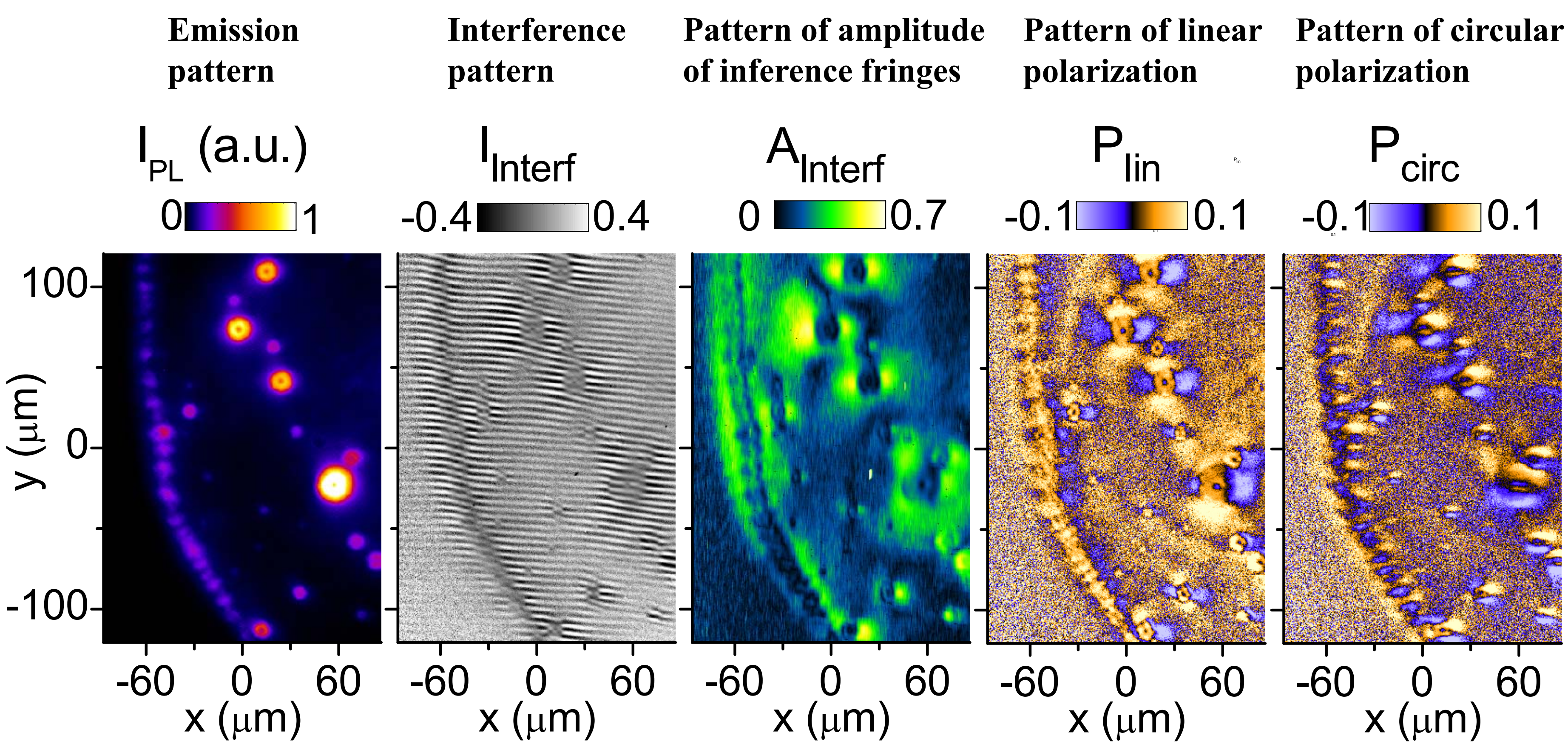
$$\xi \sim \xi_0 = \sqrt{\frac{n_0}{4\pi}} \lambda_{\text{dB}}$$

spontaneous coherence of exciton matter waves = exciton condensation in momentum space

resolution of optics and exciton cloud geometry matter

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

Emission, interference, coherence degree, and polarization patterns



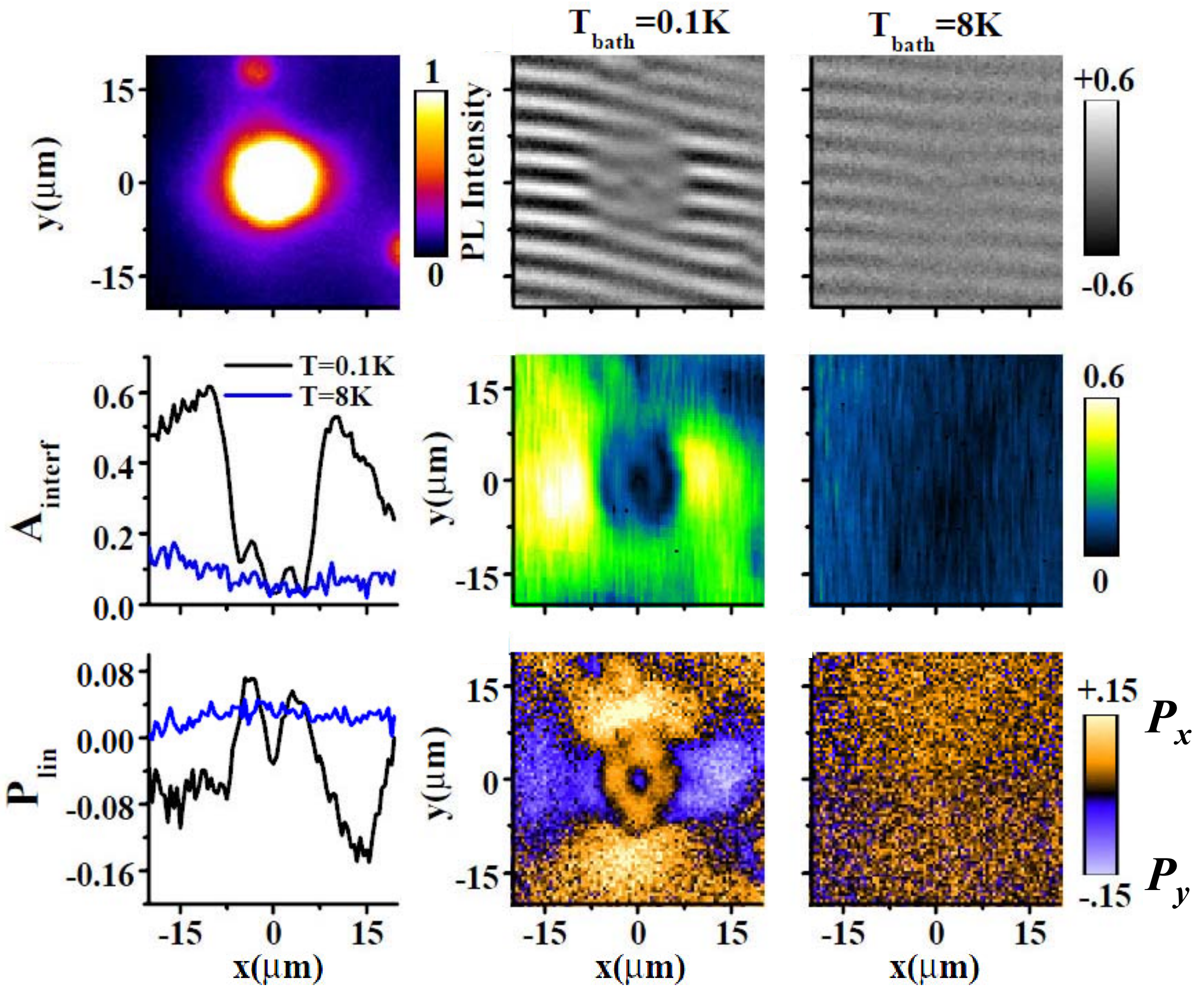
map of coherence degree

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)

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)

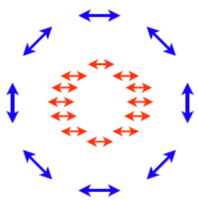
Exciton coherence and spin texture around LBS-ring



Emergence of

- Spontaneous coherence
- Spin polarization vortex

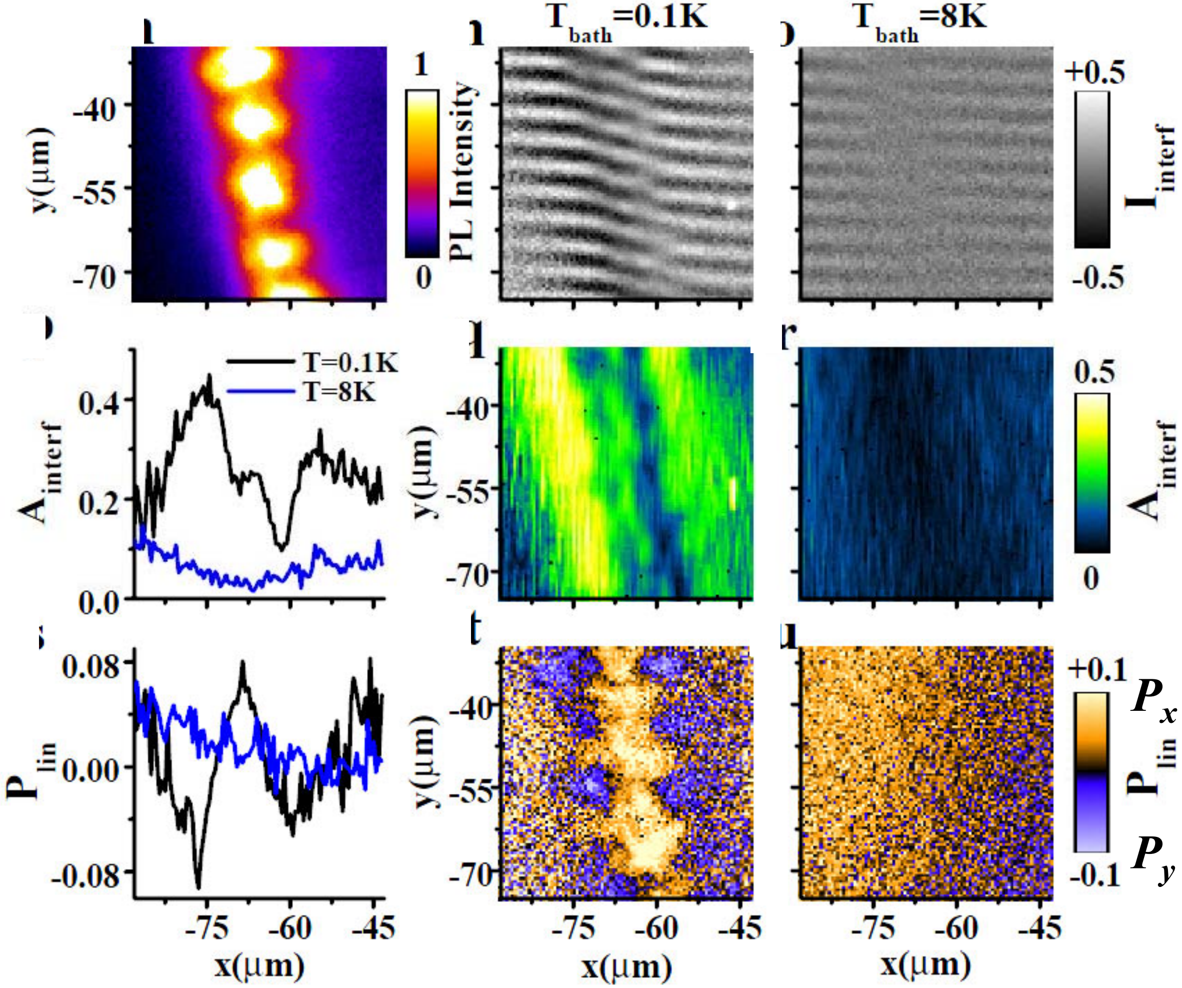
at low T at $r > r_0$



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 $r > r_0^*$

Theoretical model for MOES

consistent with experimental data

instability requires
positive feedback
to density variations

→

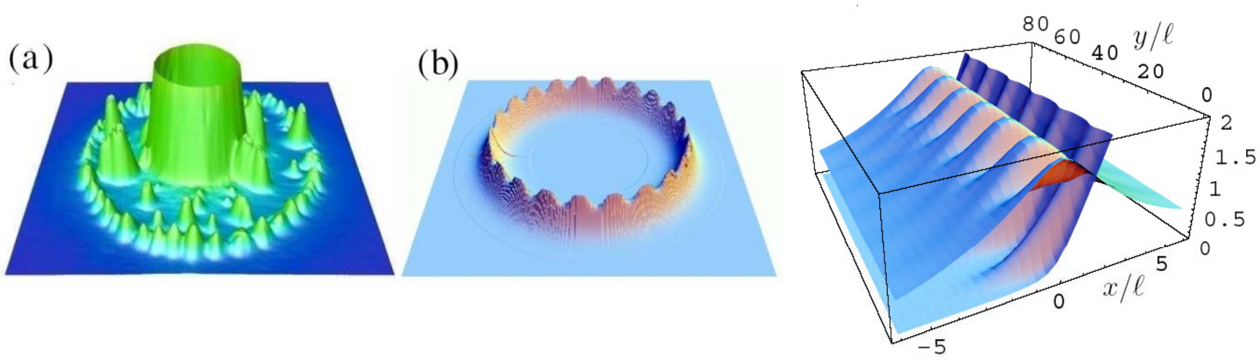
instability results from quantum degeneracy in a cold exciton system due to stimulated kinetics of exciton formation

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

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

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

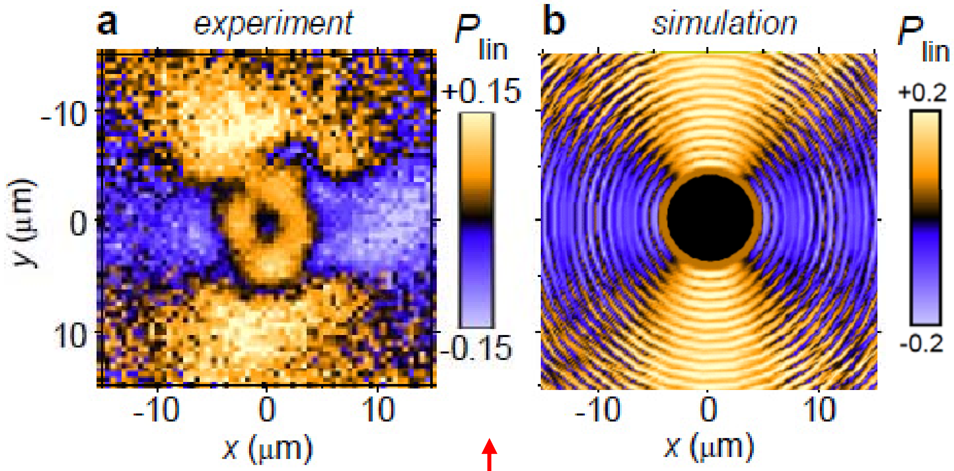
$$w \sim 1 + N_{E=0} = e^{\frac{T_{dB}}{T}} = e^{\frac{2\pi\hbar^2}{mgk_B T} n_x}$$

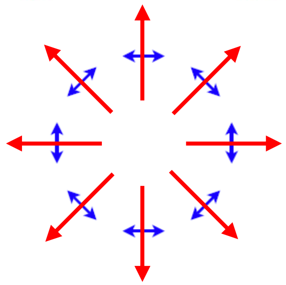


L.S. Levitov, B.D. Simons, L.V. Butov, *PRL* 94, 176404 (2005)

Spin currents and spin textures

Spin polarization texture around LBS – radial source of cold excitons



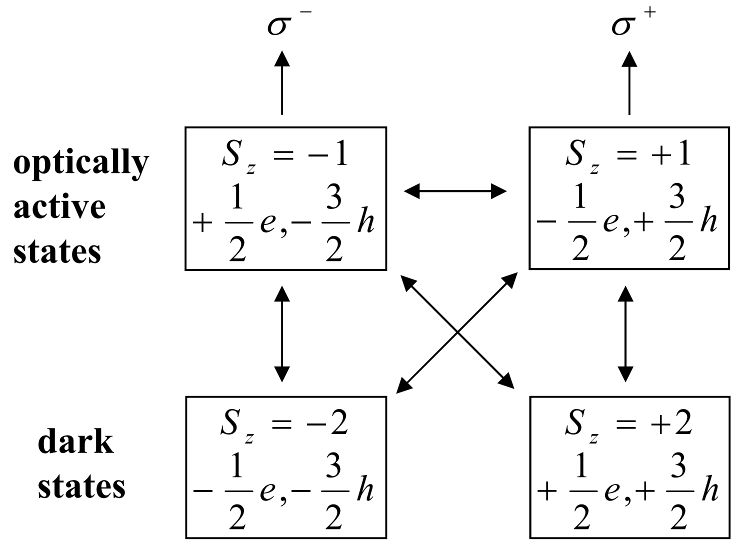


within coherence length

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

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

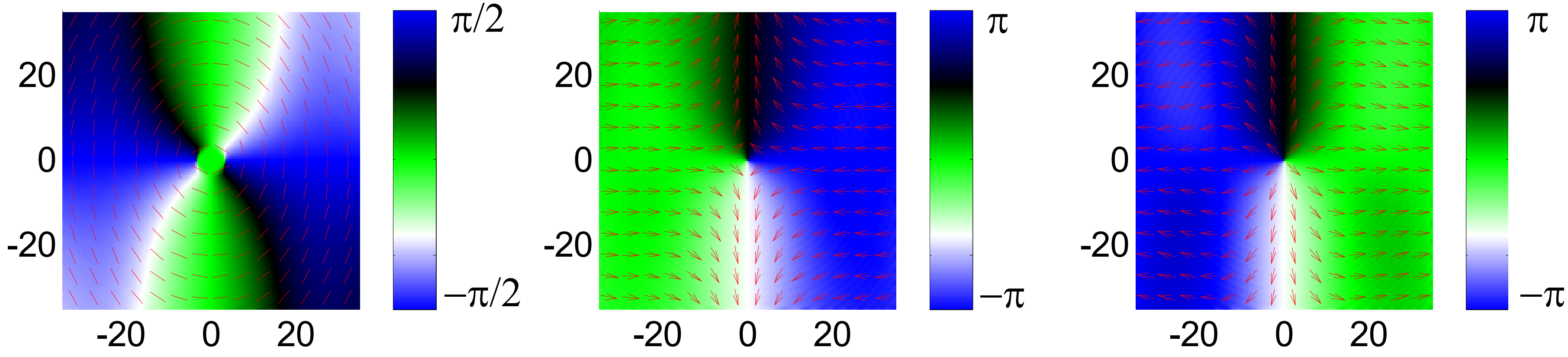
exciton spin states



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

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

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

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)

The formation of a coherent gas of bosonic pairs – a new mechanism to suppress the spin relaxation

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 (↗ suppression of exciton scattering)

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

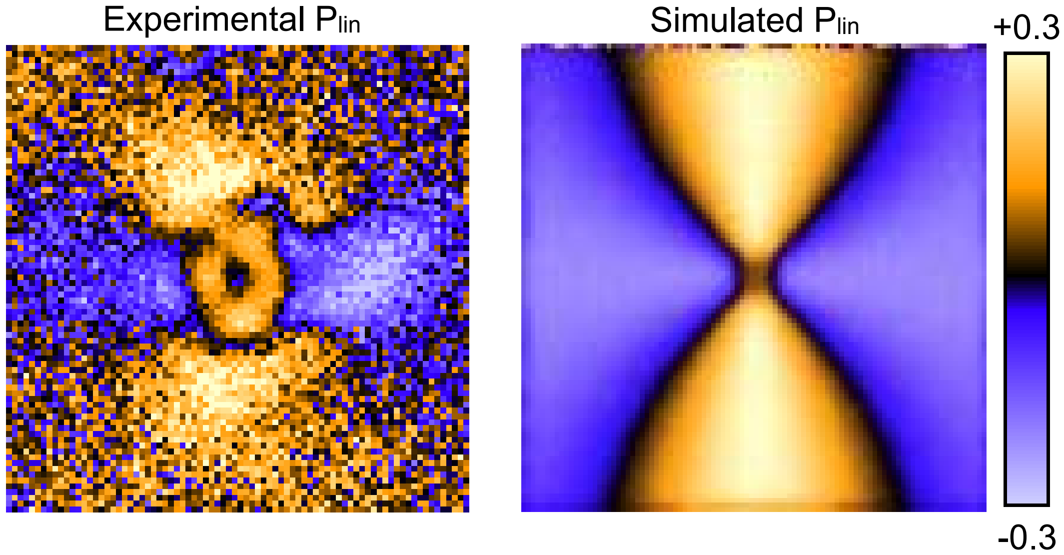
while the spin relaxation times of free electrons and holes can be short,
the formation of a coherent gas of their bosonic pairs
results in a strong enhancement of their spin relaxation times → **long-range spin currents**

measured by polarization resolved imaging

Control of spin currents

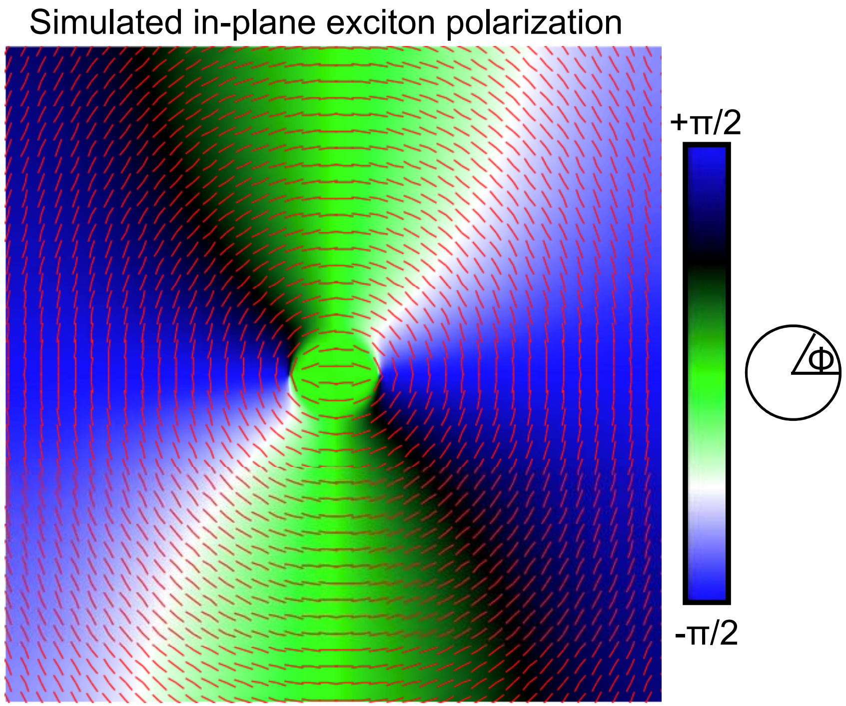
by magnetic field

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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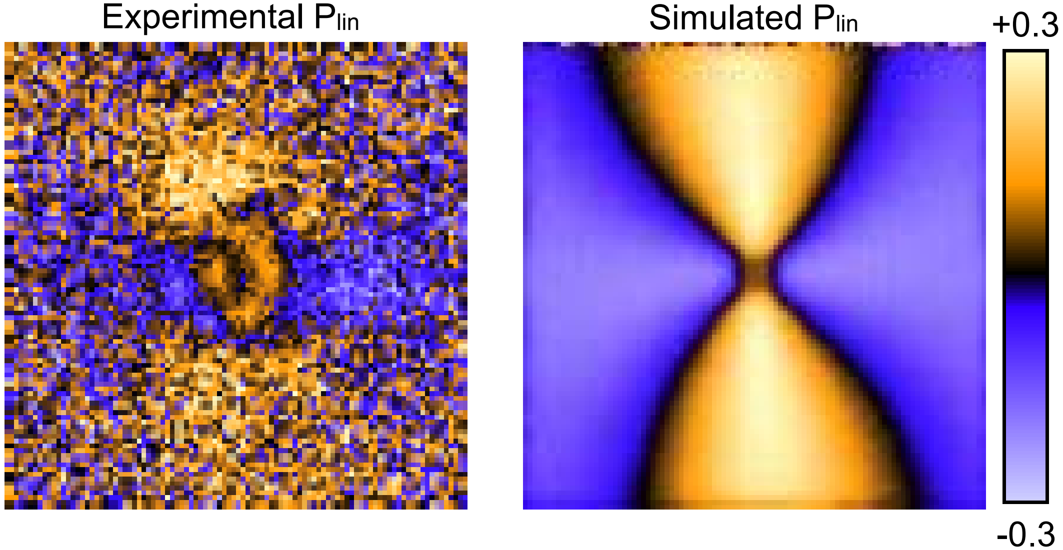
B=1T

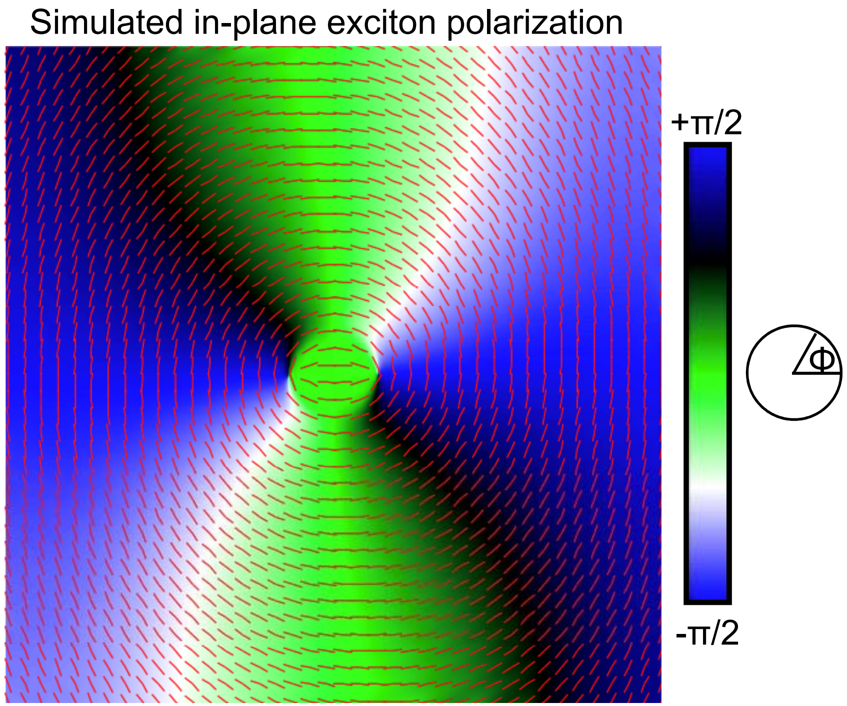


$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

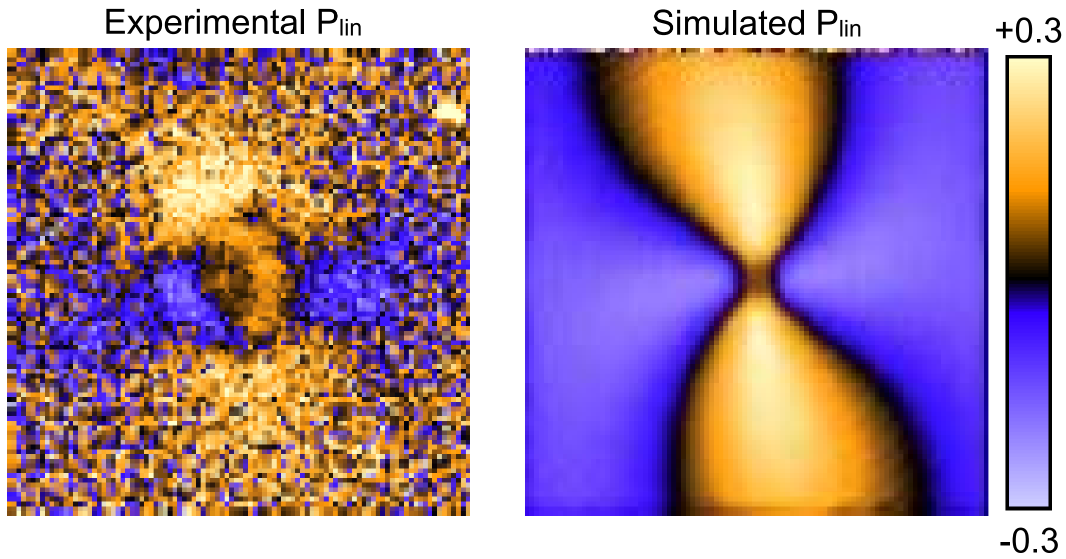
applied magnetic fields bend spin current trajectories

↓

spiral patterns of linear polarization



B=2T

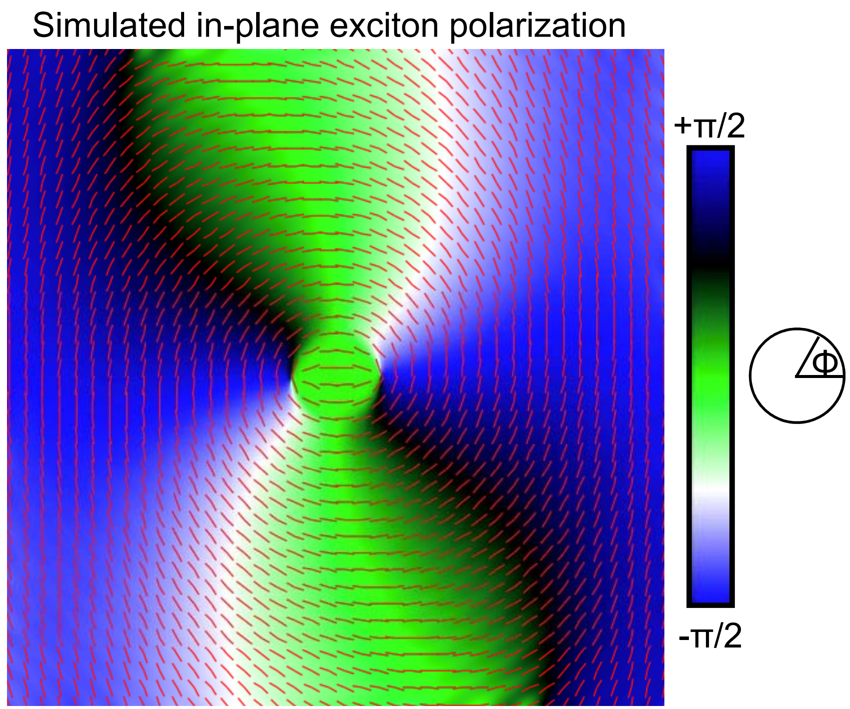


$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

applied magnetic fields bend spin current trajectories

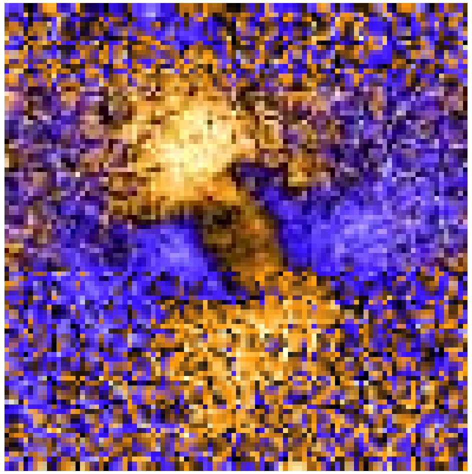
↓

spiral patterns of linear polarization

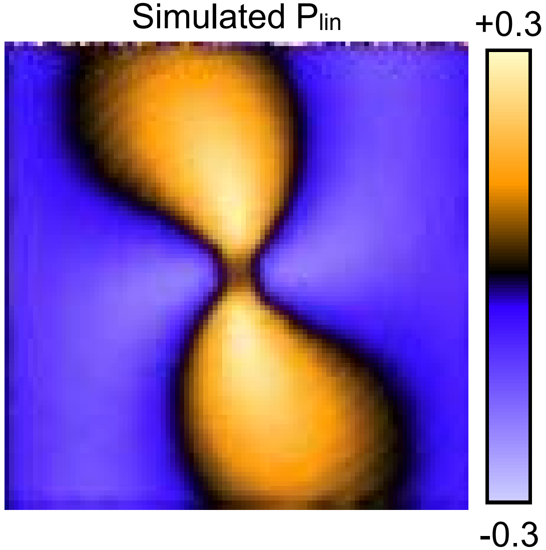


B=3T

Experimental P_{lin}



Simulated P_{lin}



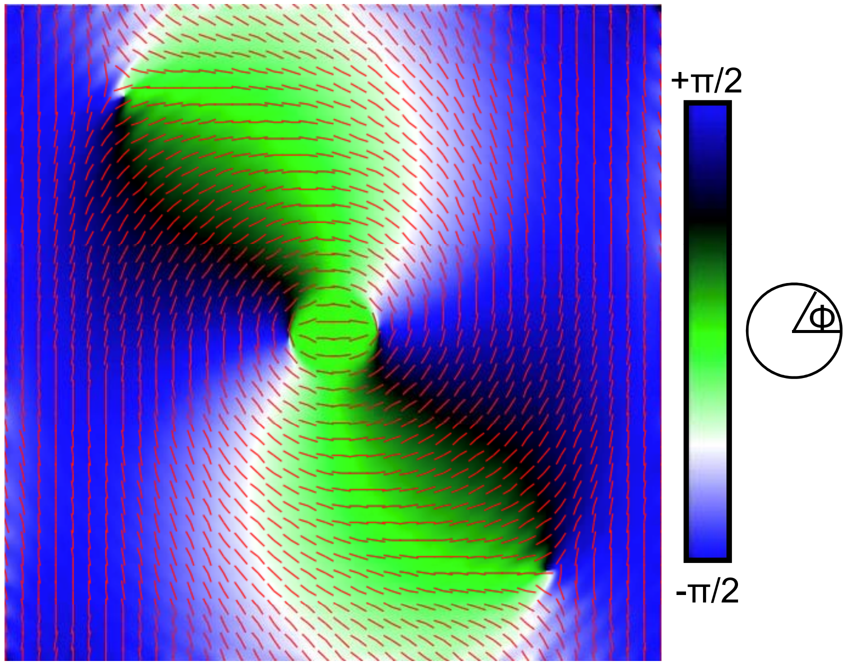
$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

applied magnetic fields bend spin current trajectories

↓

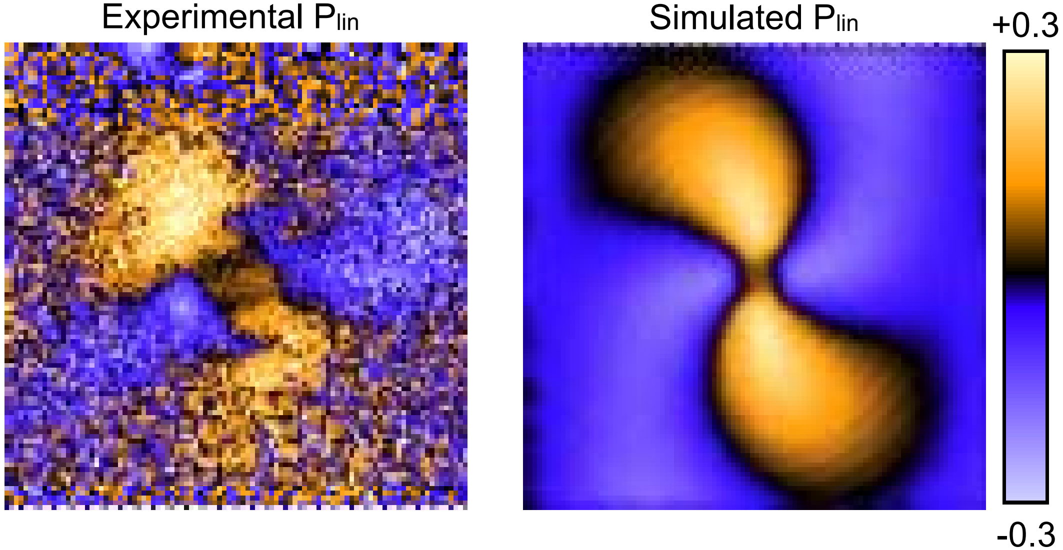
spiral patterns of linear polarization

Simulated in-plane exciton polarization



B=4T

Experimental P_{lin} Simulated P_{lin}



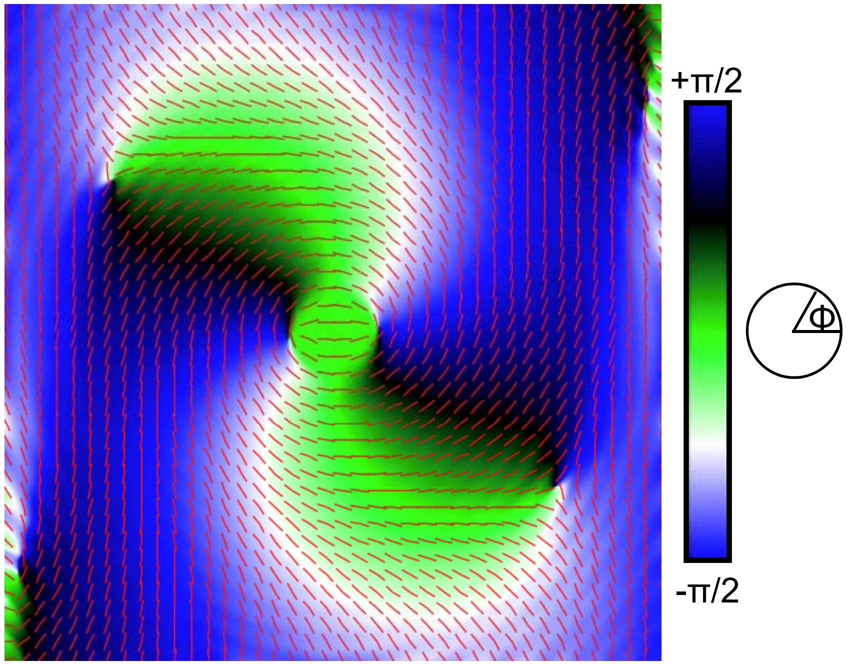
$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

applied magnetic fields bend spin current trajectories

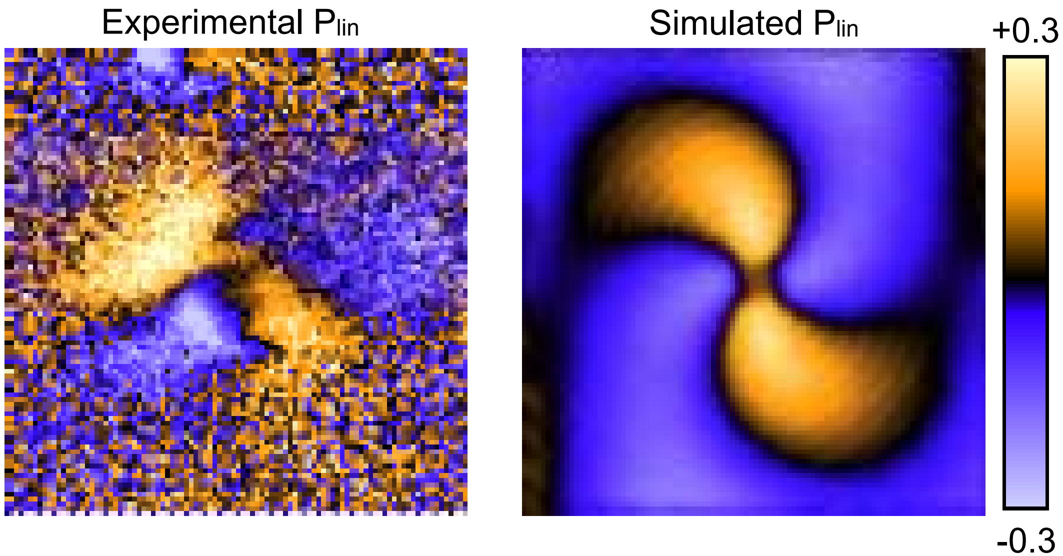
↓

spiral patterns of linear polarization

Simulated in-plane exciton polarization



B=5T

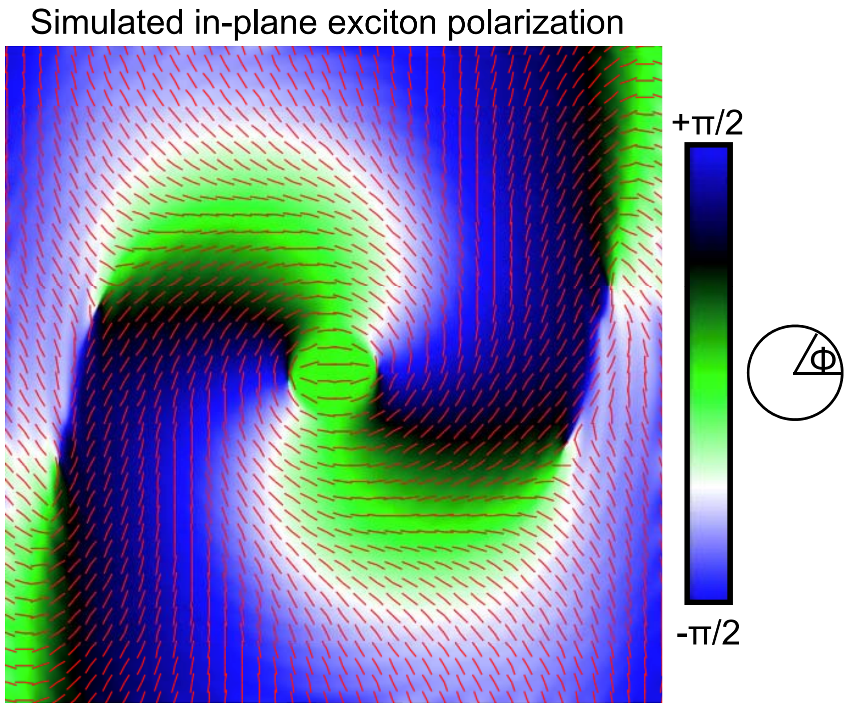


$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

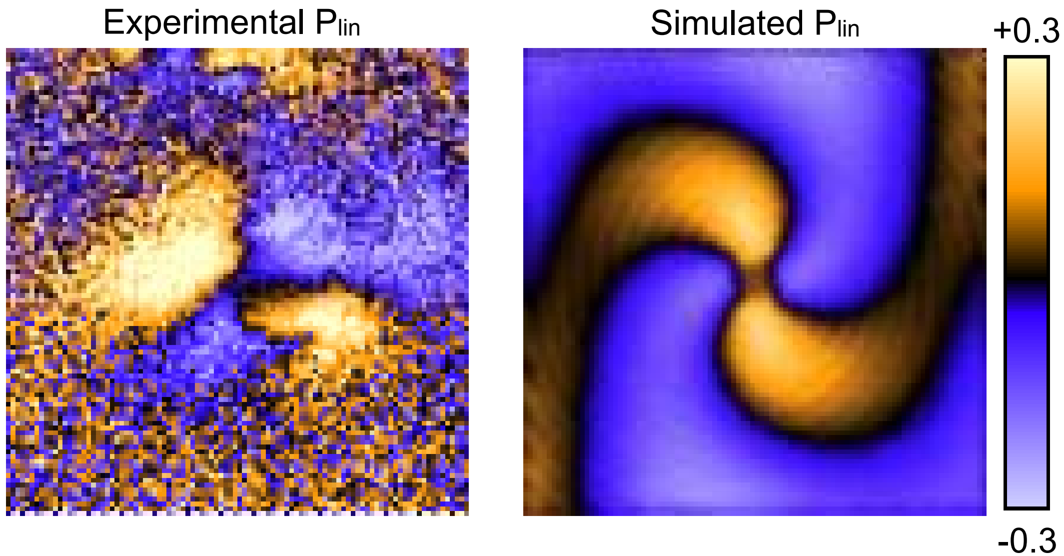
applied magnetic fields bend spin current trajectories

↓

spiral patterns of linear polarization



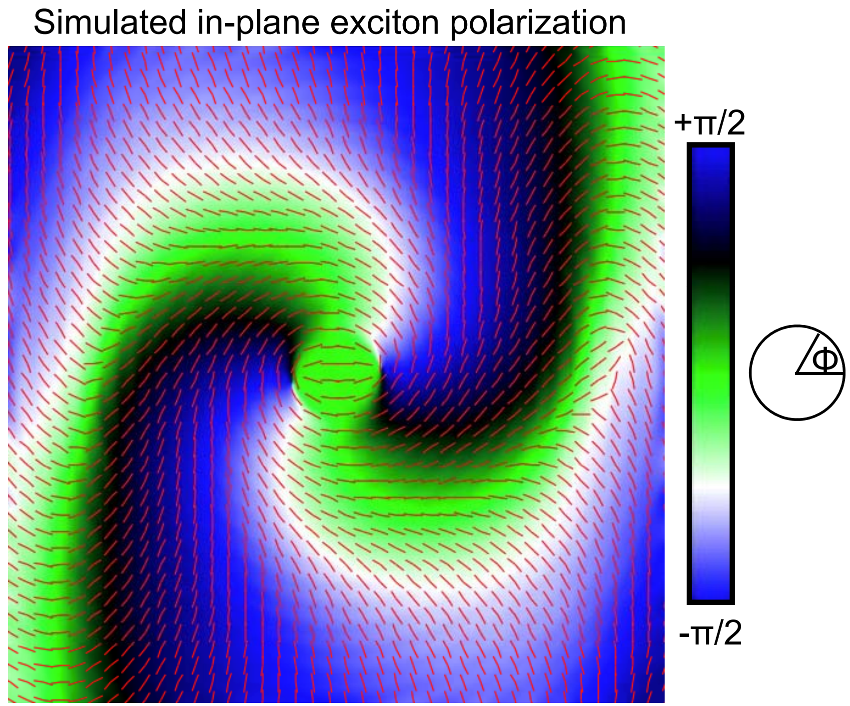
B=6T



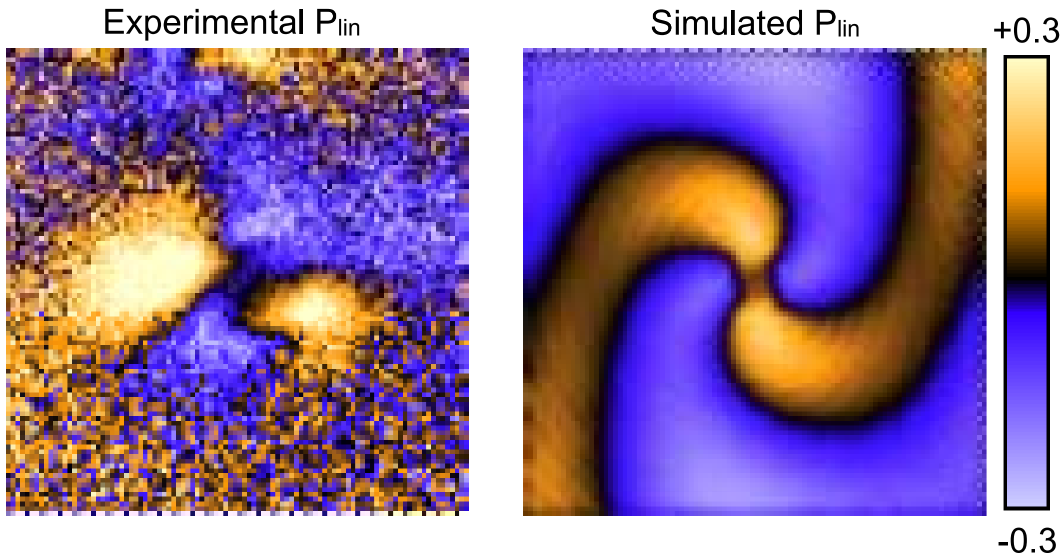
$$P_{lin} = \frac{I_x - I_y}{I_x + I_y}$$

applied magnetic fields bend spin current trajectories

spiral patterns of linear polarization



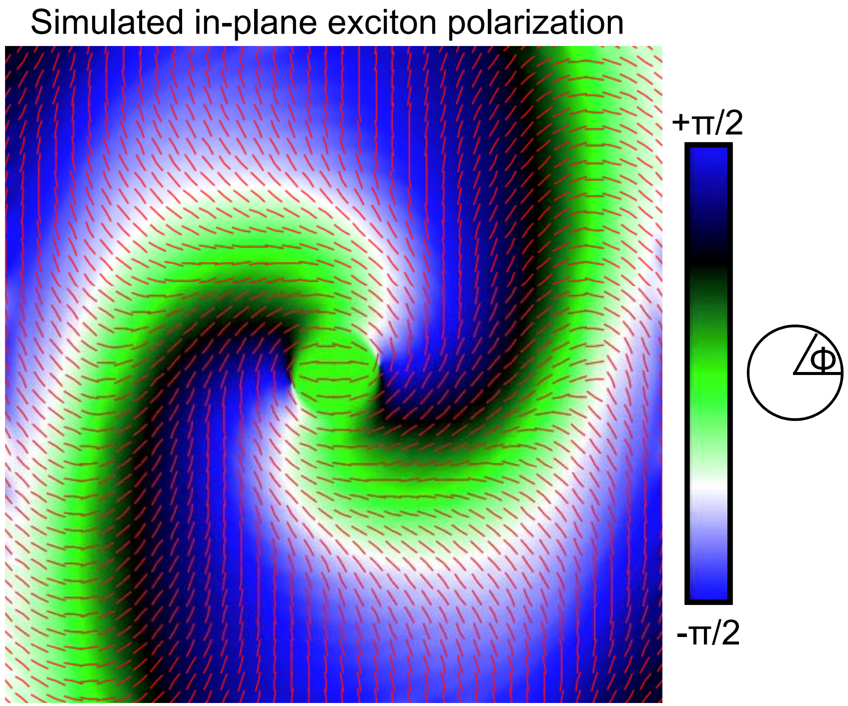
B=7T



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

applied magnetic fields bend spin current trajectories

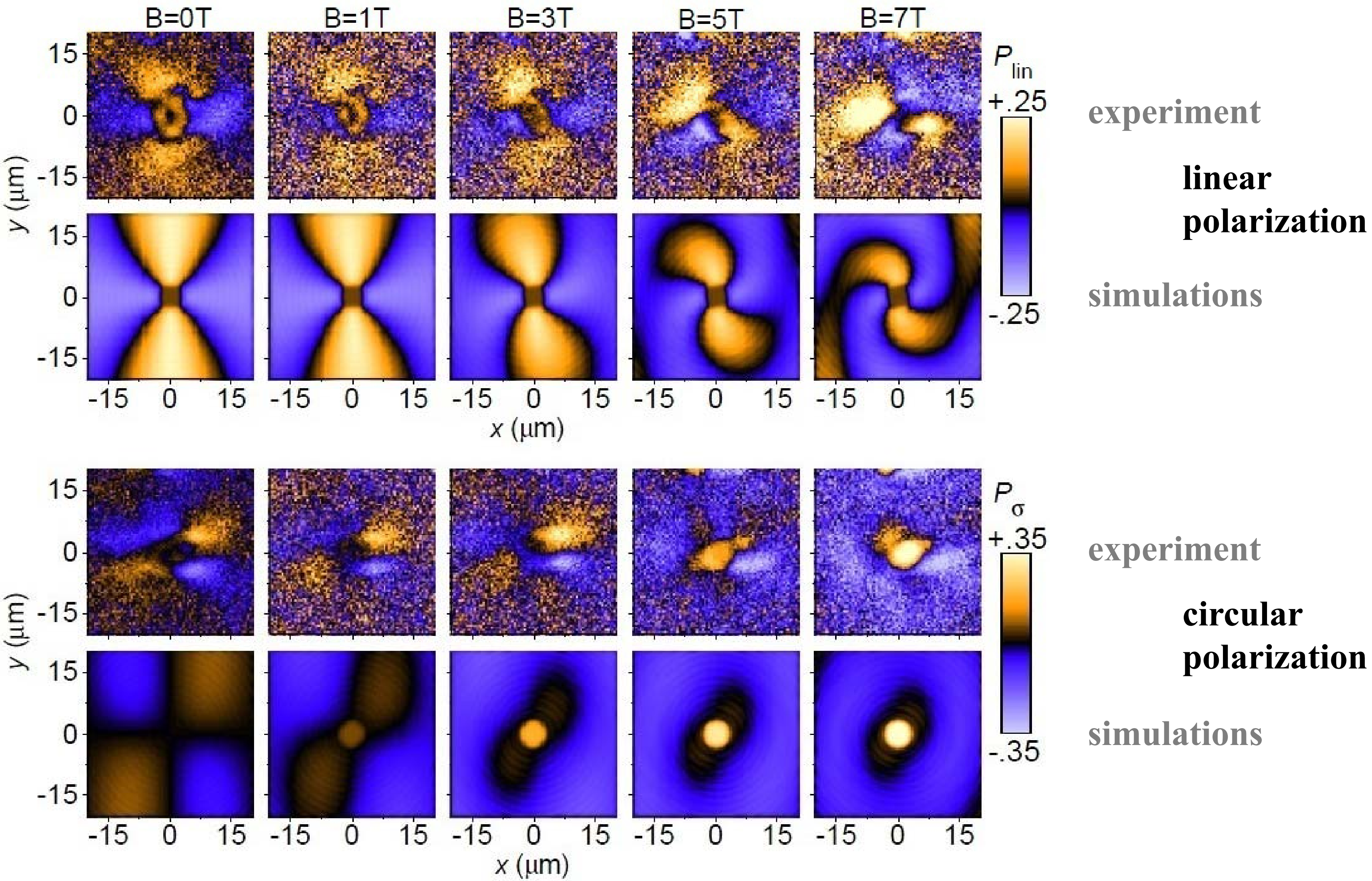
spiral patterns of linear polarization



spiral direction of exciton polarization current

$\neq$

radial direction of exciton density current

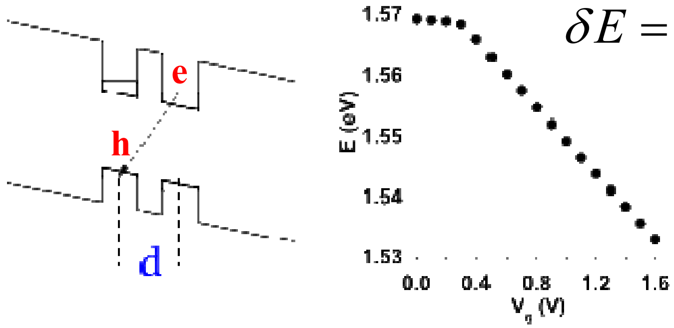


radial source of excitons with hedgehog momentum distribution generates

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

Excitonic devices

Excitonic devices



$$\delta E = edF_z$$

potential energy of indirect excitons is controlled by voltage

excitonic circuit devices

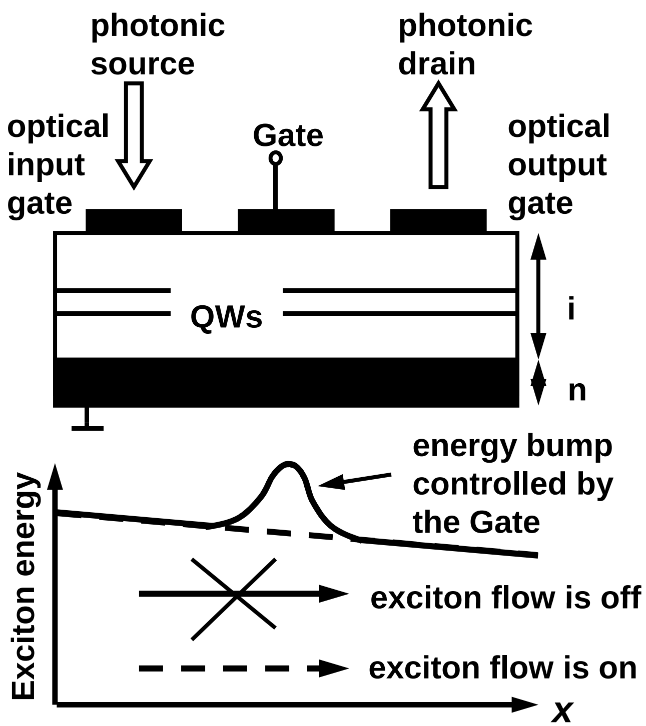
- **low-energy**
- **direct link to optical communication**
- **sub-wavelength footprint**

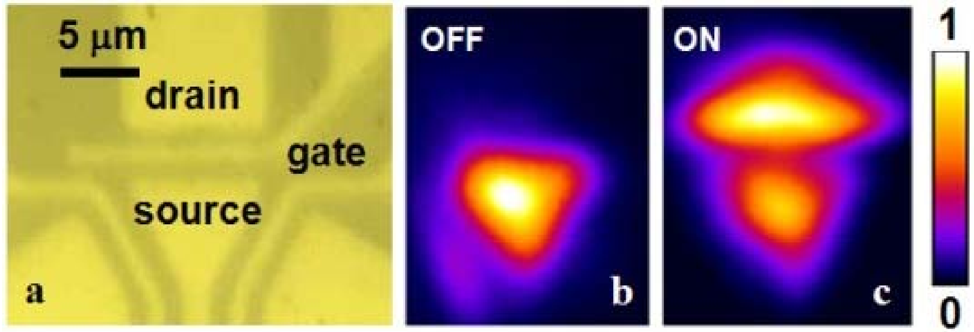
traps and lattices for excitons

and other potential landscapes

tool for studying basic properties

Proof-of-principle demonstrations of excitonic devices:

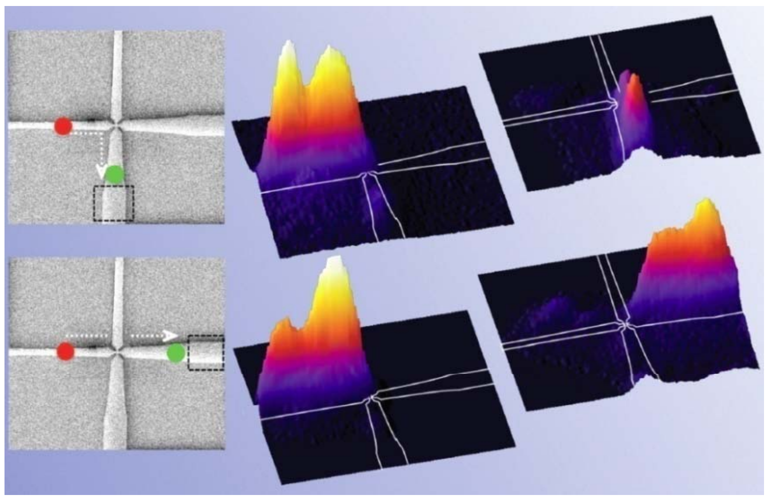




- **Excitonic transistor and IC**

A.A. High, E.E. Novitskaya, L.V. Butov, M. Hanson, A.C. Gossard, *Science* 321, 229 (2008)

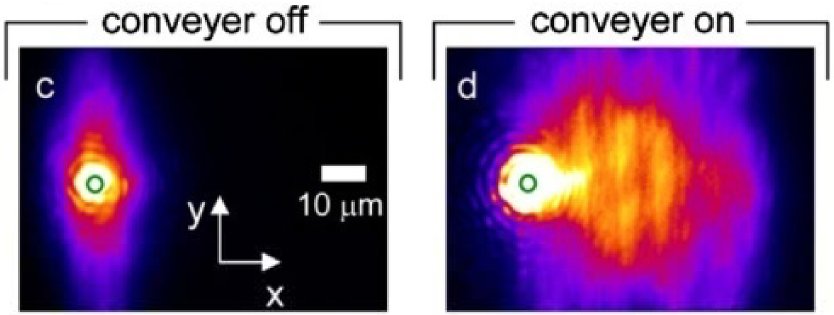
G. Grosso, J. Graves, A.T. Hammack, A.A. High, L.V. Butov, M. Hanson, A.C. Gossard, *Nature Photonics* 3, 577 (2009)



- **All-optical excitonic transistors and routers**

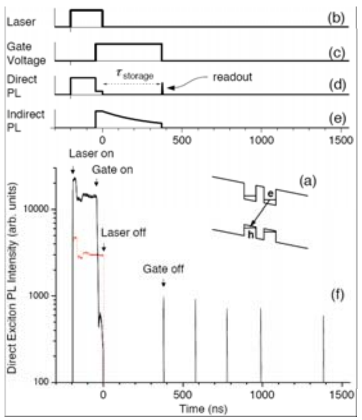
P. Andreakou, S.V. Poltavtsev, J.R. Leonard, E.V. Calman, M. Remeika, Y.Y. Kuznetsova, L.V. Butov, J. Wilkes, M. Hanson, A.C. Gossard, *Appl. Phys. Lett.* 104, 091101 (2014)

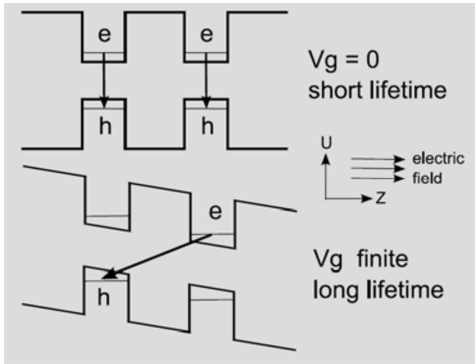
Proof-of-principle demonstrations of excitonic devices:



- **Conveyer for excitons, excitonic CCD**

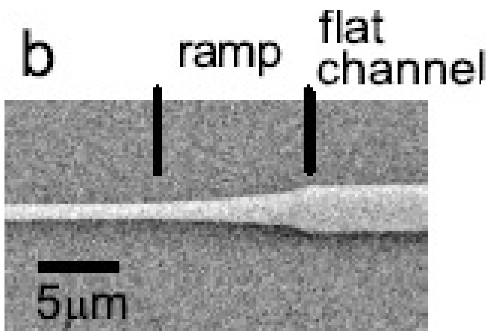
A.G. Winbow, J.R. Leonard, M. Remeika,
Y.Y. Kuznetsova, A.A. High, A.T. Hammack,
L.V. Butov, J. Wilkes, A.A. Guenther, A.L. Ivanov,
M. Hanson, A.C. Gossard, *PRL* 106, 196806 (2011)

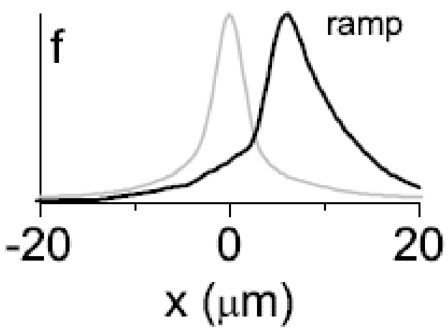




- **Excitonic photon storage**

A.G. Winbow, A.T. Hammack, L.V. Butov,
A.C. Gossard, *Nano Lett.* 7, 1349 (2007)





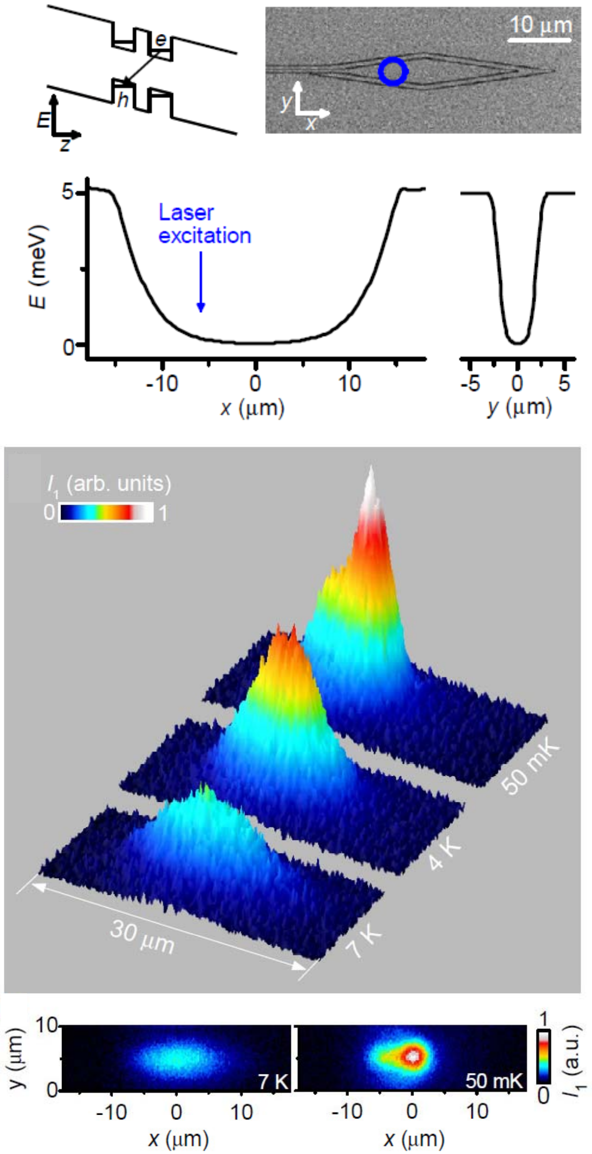
- **Ramp for excitons, excitonic diode, with no energy-dissipating voltage gradient**

J.R. Leonard, M. Remeika, M.K. Chu,
Y.Y. Kuznetsova, A.A. High, L.V. Butov,
J. Wilkes, M. Hanson, A.C. Gossard,
Appl. Phys. Lett. 100, 231106 (2012)

Indirect excitons in traps

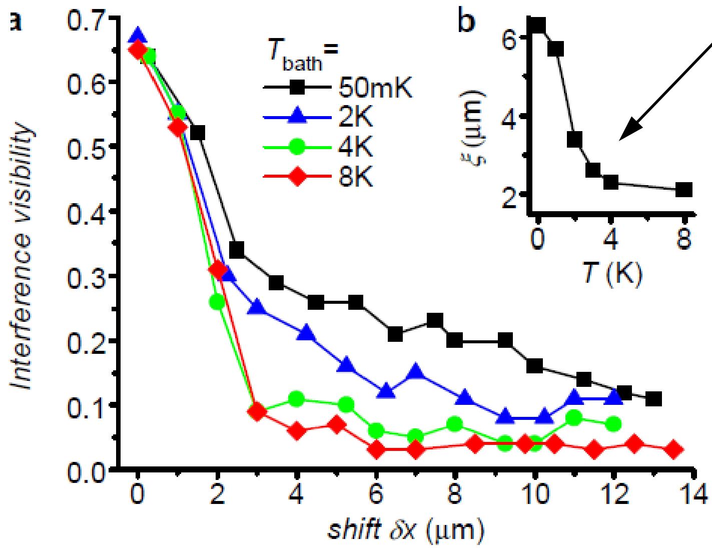
Condensation of indirect excitons in a trap

diamond-shaped trap



With lowering T

- IXs condense at the trap bottom
- IX spontaneous coherence emerges



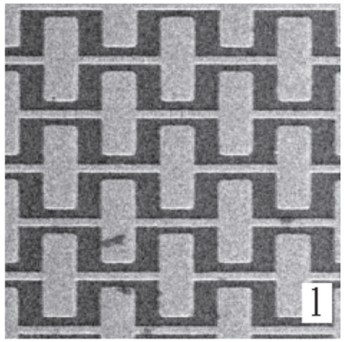
$T_c \sim 2$ K

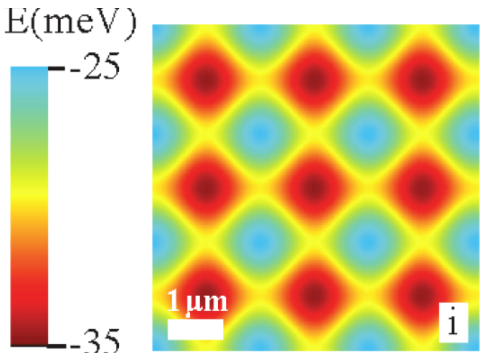
A.A. High, J.R. Leonard, M. Remeika, L.V. Butov, M. Hanson, A.C. Gossard, *Nano Lett.* 12, 2605 (2012)

Theory: S. Lobanov, N. Gippius, work in progress

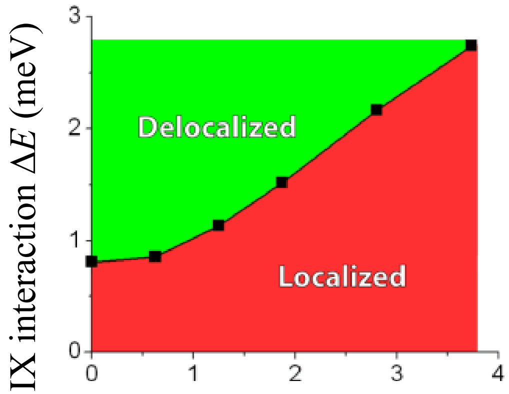
Indirect excitons in lattices

Localization-delocalization transition for excitons in lattices





IX density controlled by V



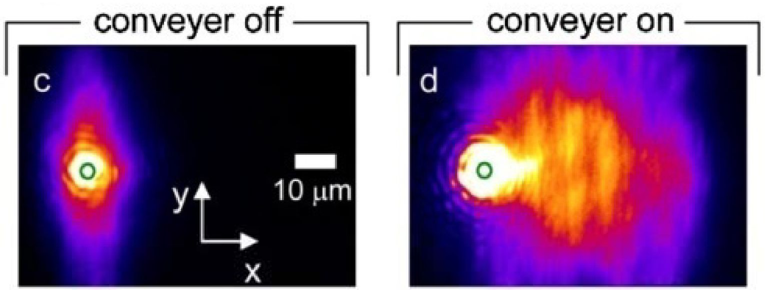
controlled by V

localization – delocalization transition
at $\Delta E \sim U$

Liner lattices: M. Remeika, J.C. Graves, A.T. Hammack, A.D. Meyertholen, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, *PRL* 102, 186803 (2009)

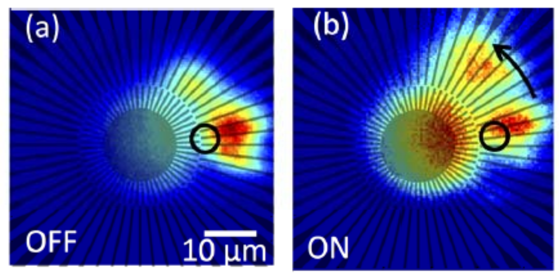
2D lattices: M. Remeika, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, *APL* 100, 061103 (2012)

Excitonic conveyers / CCD



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, *PRL* 106, 196806 (2011)

Excitonic stirring potentials

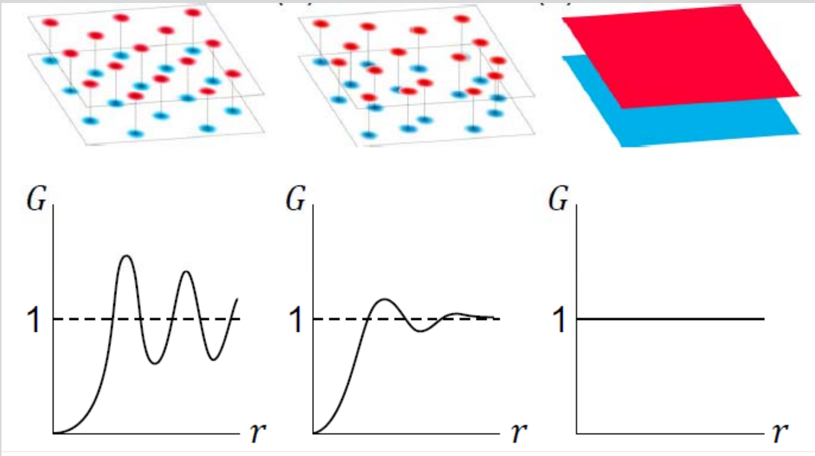


dynamical localization – delocalization transition

M.W. Hasling, Y.Y. Kuznetsova, P. Andreakou, J.R. Leonard, E.V. Calman, C.J. Dorow, L.V. Butov, M. Hanson, A.C. Gossard, *JAP* 117, 023108 (2015)

Measurement of exciton correlations using electrostatic lattices

crystal | liquid with correlations | uncorrelated liquid



'capacitor' formula

$\Delta E < \Delta E_{cap}$

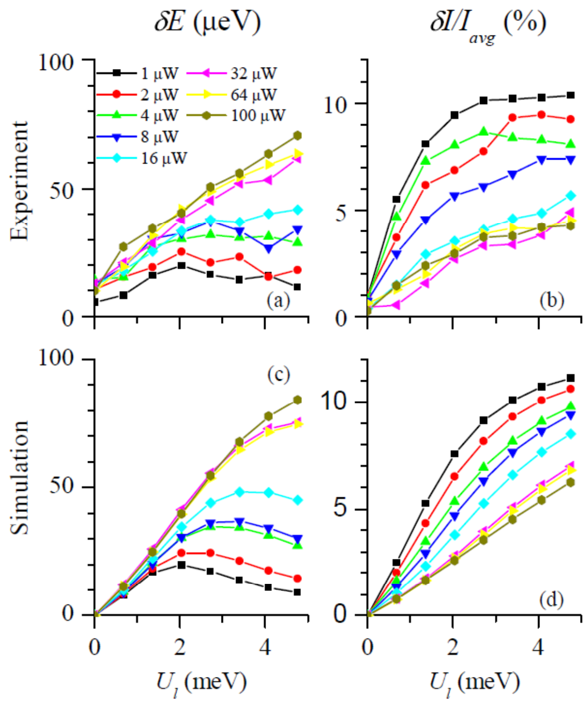
$$\Delta E_{cap} = \frac{4\pi e^2 d}{\kappa} n$$

Correlation parameter determines both the energy shift and the ability of IXs to screen an external potential perturbation

amplitudes of energy and intensity modulations of IX PL

IX correlation parameter

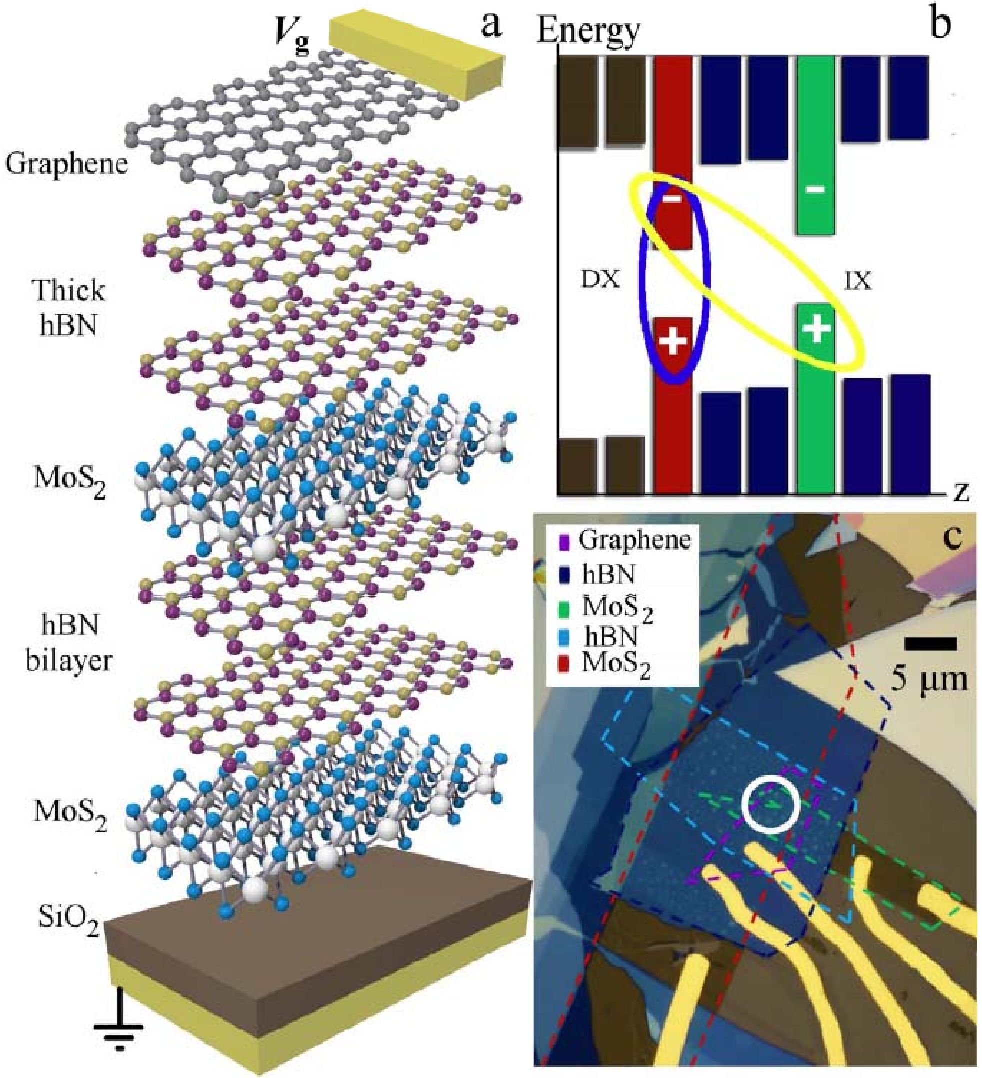
strong IX correlations: $\Delta E << \Delta E_{cap}$



M. Remeika, J.R. Leonard, C.J. Dorow, M.M. Fogler, L.V. Butov, M. Hanson, A.C. Gossard, *Phys. Rev. B* 92, 115311 (2015)

Toward high-T superfluidity with indirect excitons in van der Waals heterostructures

Double quantum well van der Waals heterostructure



E.V. Calman, C.J. Dorow, M.M. Fogler, L.V. Butov, S. Hu, A. Mishchenko, A.K. Geim, work in progress

Goal: high-T superfluidity in indirect excitons in artificially structured materials based on transition metal dichalcogenide (TMD) atomically thin layers

$$T_0 = \frac{2\pi\hbar^2}{m_x} n = \frac{4\pi m_e m_h}{m_x^2} \left(n a_x^2\right) Ry_x$$

$$n^{max} a_x^2 \sim 0.02$$

$$T_0^{max} \sim 0.06 Ry_x$$

high Ry_x → high T_0

M.M. Fogler, L.V. Butov, K.S. Novoselov, *Nature Commun*. 5, 4555 (2014)

Summary

Phenomena in a cold gas of indirect excitons

- Spontaneous coherence and condensation
- Spin currents and spin textures
- Pattern formation: Spatial ordering
- Condensation in a trap
- Localization-delocalization transitions
- Correlations

Proof-of-principle demonstrations of excitonic devices:

- Excitonic transistor and IC
- All-optical excitonic transistors and routers
- Conveyer for excitons, excitonic CCD
- Excitonic photon storage
- Ramp for excitons, excitonic diode,
  with no energy-dissipating voltage gradient

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