Коллективные явления в холодных непрямых экситонах

Collective phenomena in cold indirect excitons

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

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

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

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

D.E. Nikonov, I.A. Young (Intel)

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

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

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

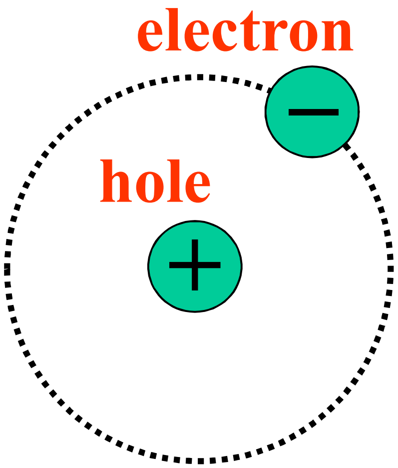
S. Hu, A. Mishchenko, A.K. Geim, K.S. Novoselov (*Manchester*)

- Indirect excitons (IXs) aka interlayer excitons

- Spontaneous coherence and condensation of IXs
- Phenomena in IX condensate
    - Density wave, commensurability effect
    - Spin textures
    - Pancharatnam-Berry phase, coherent spin transport
    - Phase singularities, interference dislocations

- IXs in van der Waals heterostructures
    - Opportunity to realize high-T IX condensation
    - IXs at room temperature
    - Indirect trions

exciton – bound pair of electron and hole



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

exciton – light bosonic particle in semiconductor

Indirect excitons (IXs) aka interlayer excitons

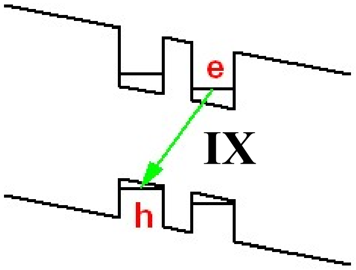
$$\lambda_{dB} = \left(\frac{2\pi\hbar^2}{m k_B T} \right)^{1/2}$$

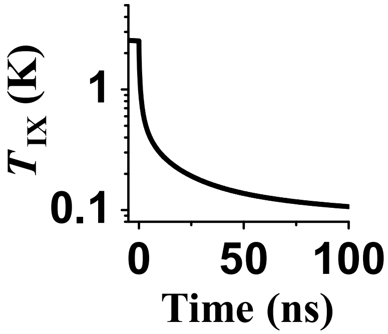
Degenerate Bose gas of excitons: thermal de Broglie wavelength ← λ_{dB}
~ separation between excitons

Temperature of quantum degeneracy $T_0 = \frac{2\pi\hbar^2}{m_x} n \sim 3\,\mathrm{K}$

↑ excitons in GaAs QW
$n = 10^{10}\ \mathrm{cm}^{-2}$, $m_x = 0.2\ m_e$

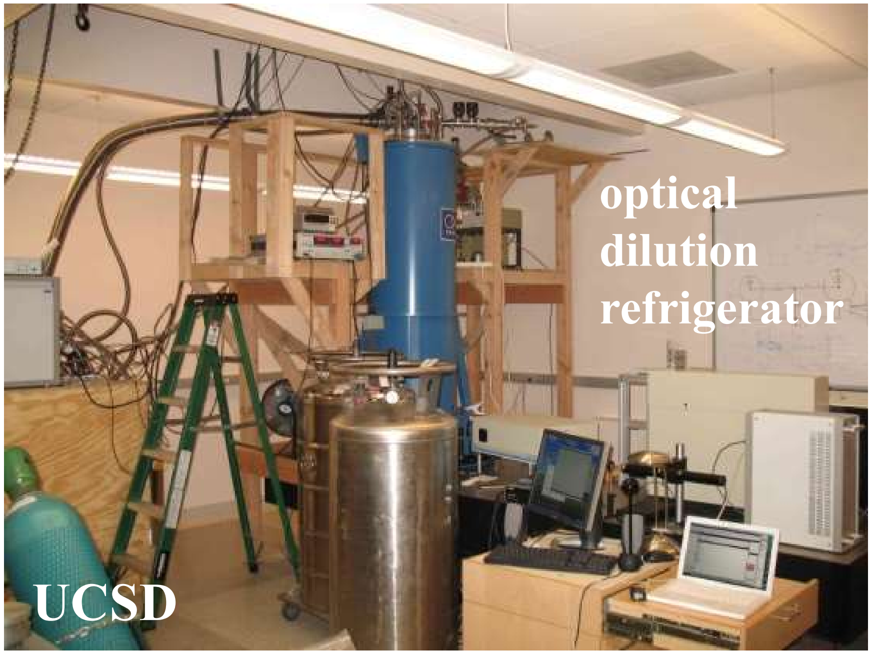
IXs in CQW





IXs cool to 100 mK within ~ 100 ns lifetime
PRL 86, 5608 (2001)

$T_{\mathrm{IX}} \sim 100\ \mathrm{mK} \ll T_0$
is realized for IXs



Spontaneous coherence and condensation of IXs

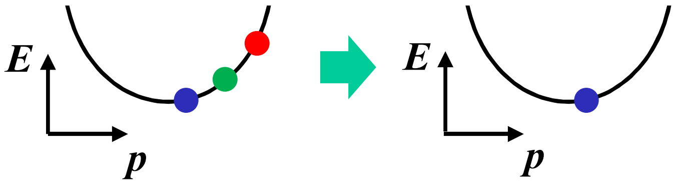
Sen Yang, A.T. Hammack, M.M. Fogler, L.V. Butov, A.C. Gossard,
PRL 97, 187402 (2006)

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)

Below the temperature of quantum degeneracy
bosonic particles can form **a coherent state ↔ BEC**

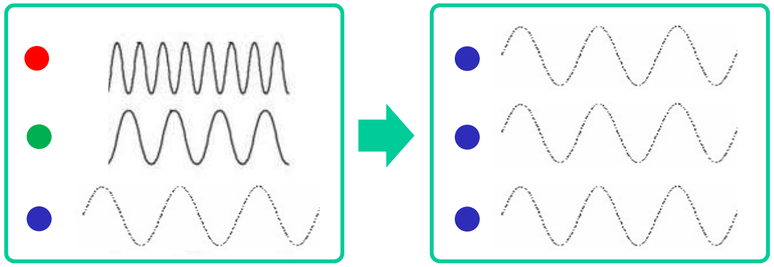
Condensation in momentum space = Spontaneous coherence of matter waves

particles (in momentum space)



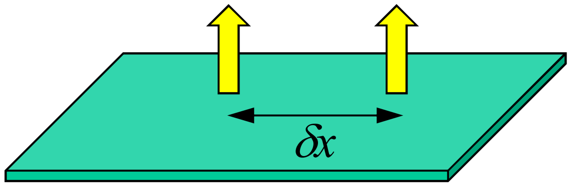
high *T* **low *T***

matter waves (in real space) $\lambda = h/p$



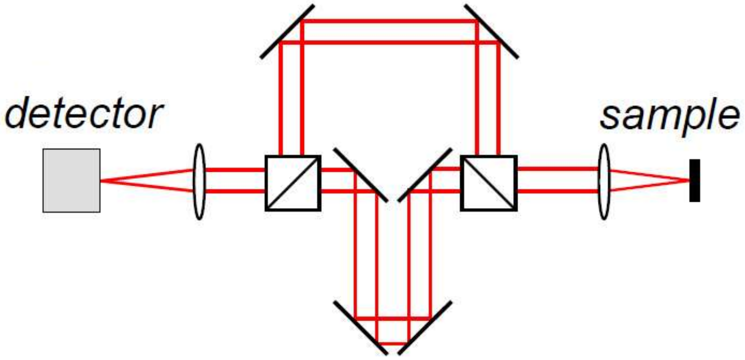
high *T* **low *T***

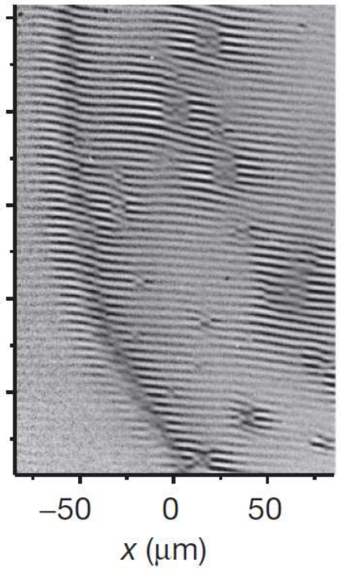
Direct measurement of spontaneous coherence and condensation



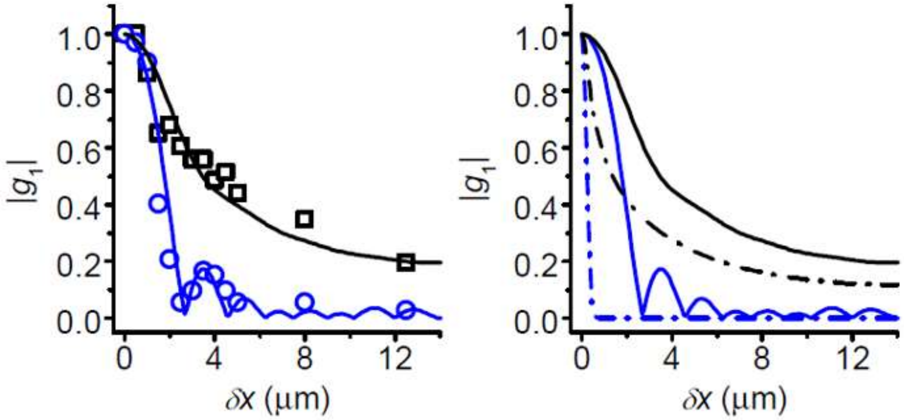
exciton coherence
is imprinted on coherence
of their light emission

measured by shift-interferometry

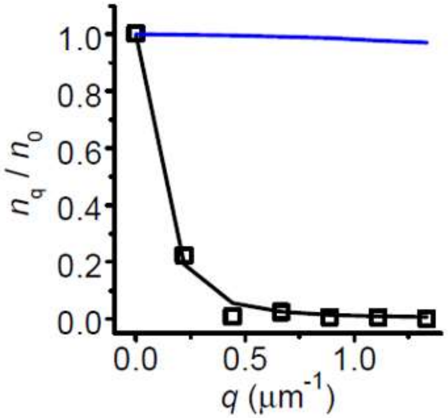




First order coherence function $g_1(\delta x)$



Distribution in q-space n_q

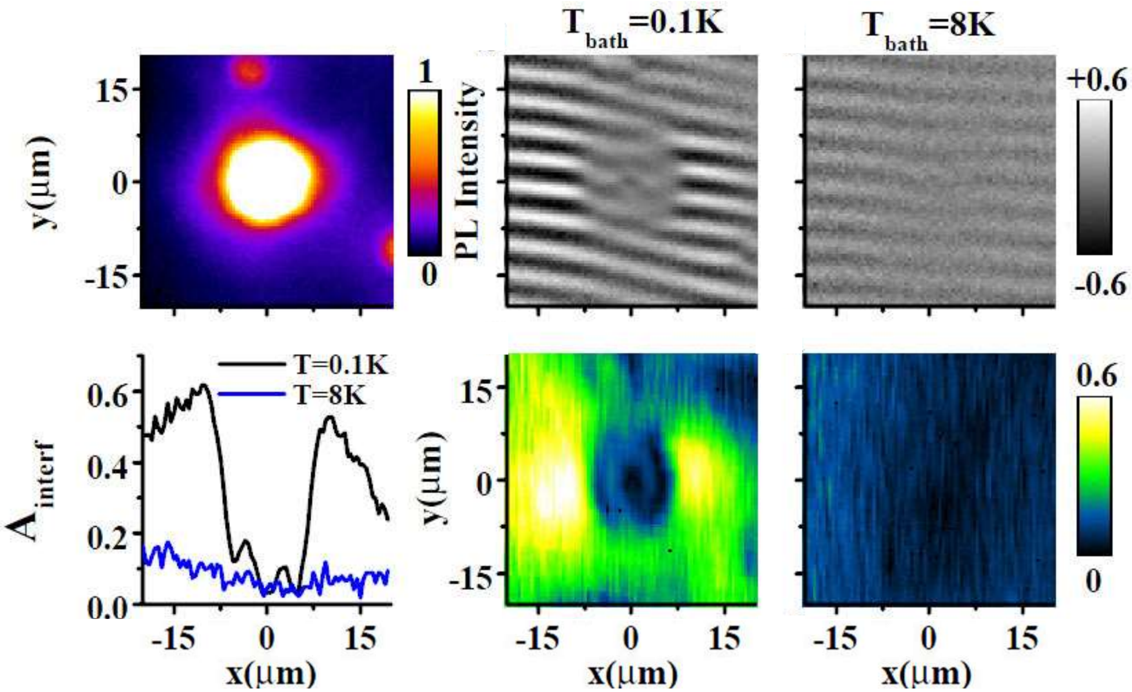


spontaneous
coherence of exciton
matter waves =

exciton condensation
in momentum space

$$g_1(r) \sim \int d^2 q e^{iqr} n_q$$

IX spontaneous coherence



emergence of
spontaneous coherence
around source of IXs
at low T at $r > r_{coh}$

Phenomena in IX condensate

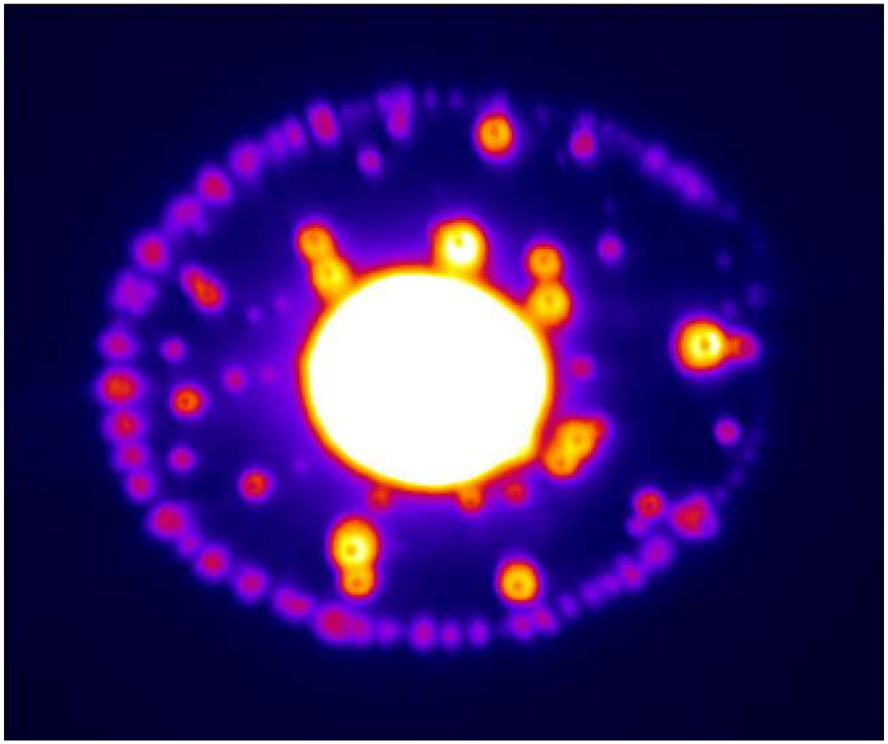
Density wave
and commensurability effect
in IX condensate

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

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

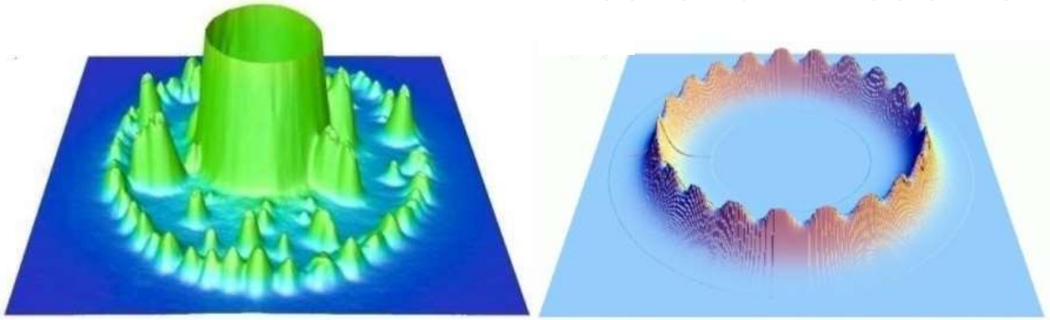
Sen Yang, L.V. Butov, B.D. Simons, K.L. Campman, A.C. Gossard, *PRB* 91, 245302 (2015)

macroscopically ordered exciton state (MOES) or **exciton density wave**



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

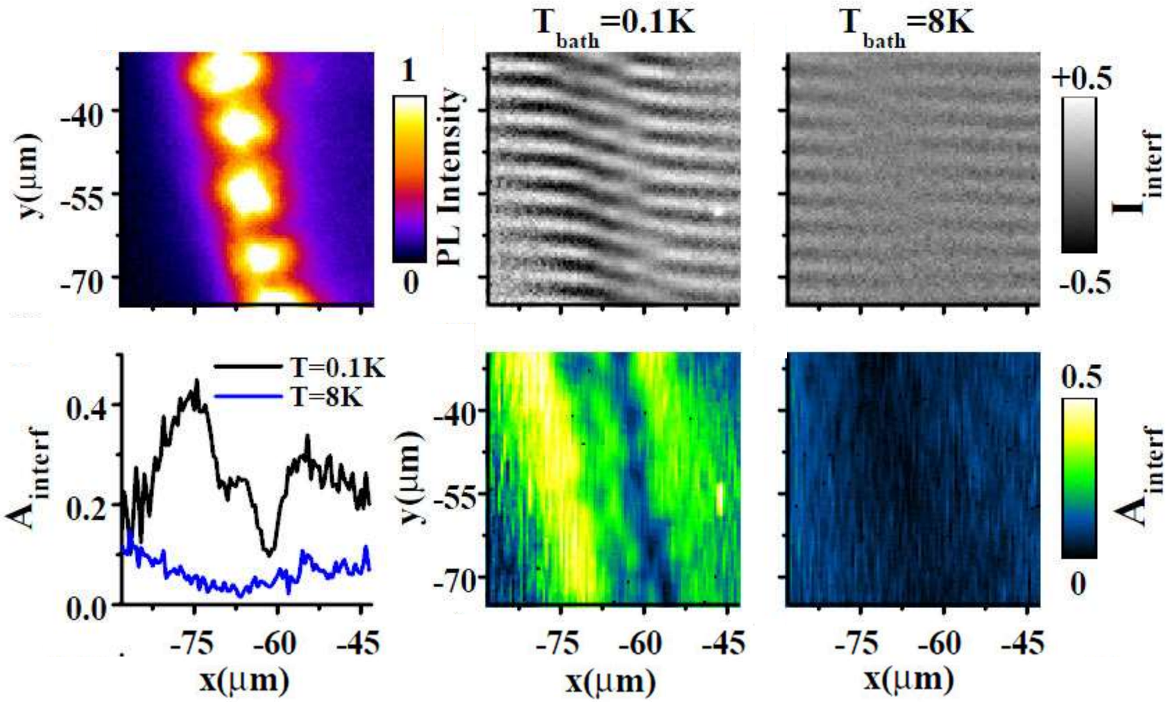
theoretical model for MOES



instability results from
quantum degeneracy due to
stimulated kinetics of exciton formation

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

IX spontaneous coherence in MOES



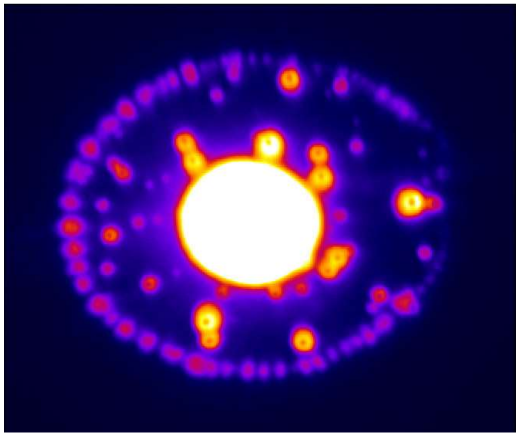
emergence of spontaneous coherence in MOES (in IX density wave) at low *T* at $r > r_{coh}{}^{*}$

MOES is **condensate in k-space** with macroscopic **spatial order**

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

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)

Commensurability effect of IX density wave



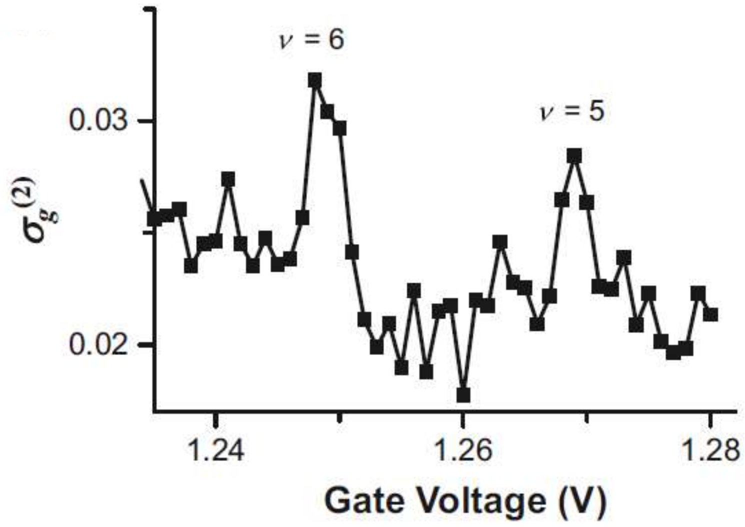
fluctuations of exciton density wave

are suppressed when

number of wavelength on wave

confinement length is integer

$\nu = L / \lambda_{\text{IX-wave}} = N$



commensurability effect: macroscopic system of IXs of length ~100 μm behaves collectively: MOES is collective phenomenon

↑

$$l_{\text{commensurability}} \gg \lambda_{\text{IX-wave}} > \xi_{\text{coh}} \gg \lambda_{\text{dB}}$$

↓

MOES is condensate

in momentum space

IX density wave and commensurability effect

↑

instability due to stimulated processes

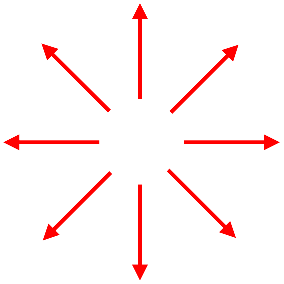
Pancharatnam-Berry phase,
spin textures,
and long-range coherent spin transport
in IX condensate

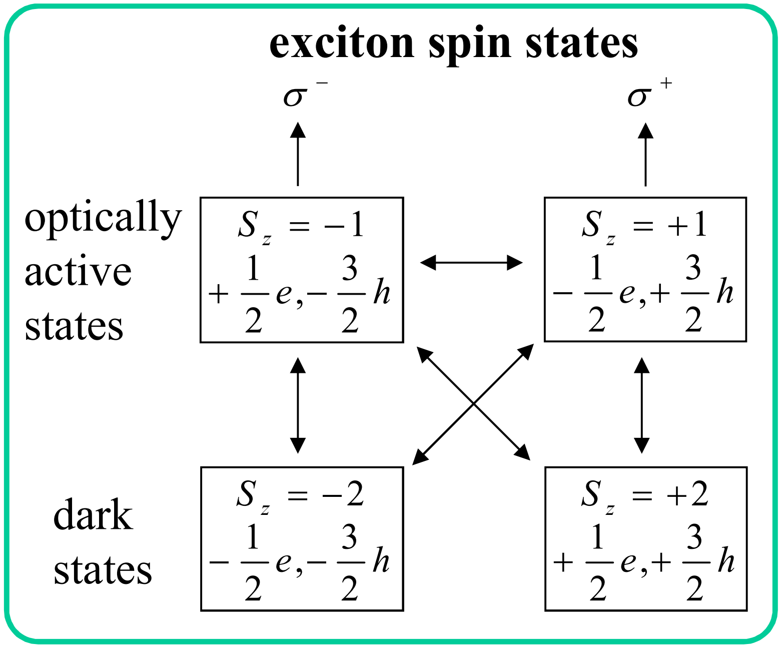
A.A. High, A.T. Hammack, J.R. Leonard, Sen Yang, L.V. Butov,
T. Ostatnický, M. Vladimirova, A.V. Kavokin, K.L. Campman,
A.C. Gossard, *PRL* 110, 246403 (2013)

J.R. Leonard, A.A. High, A.T. Hammack, M.M Fogler, L.V. Butov,
K.L. Campman, A.C. Gossard, *Nature Commun* 9, 2158 (2018)

IX transport and spin precession

IX transport from radial source of cold IXs





exciton spin states

σ^-

σ^+

optically active states

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

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

dark states

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

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

within coherence length

↓

ballistic IX transport with **spin precession**

→ **polarization textures**

→ **Pancharatnam-Berry phase**

↑

due to spin-orbit interaction,
splitting of exciton states,
Zeeman effect

discovered
by Pancharatnam for light

The **Pancharatnam-Berry phase** is a geometric phase

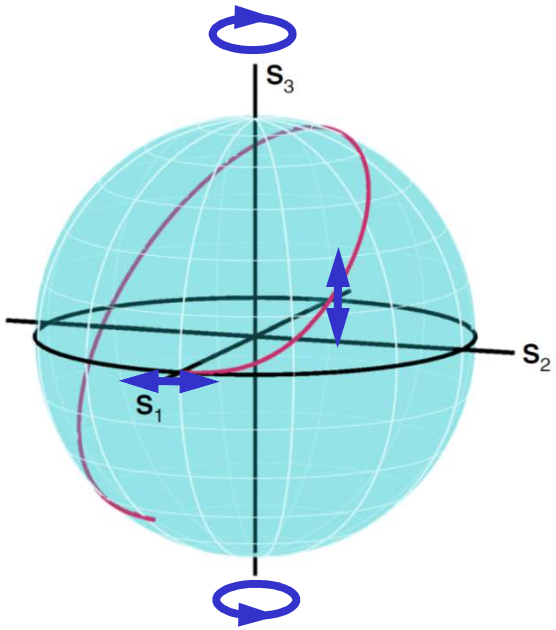
- appearing when the polarization state of light changes
- acquired over a cycle of parameters in the Hamiltonian governing the system

by Berry for matter waves

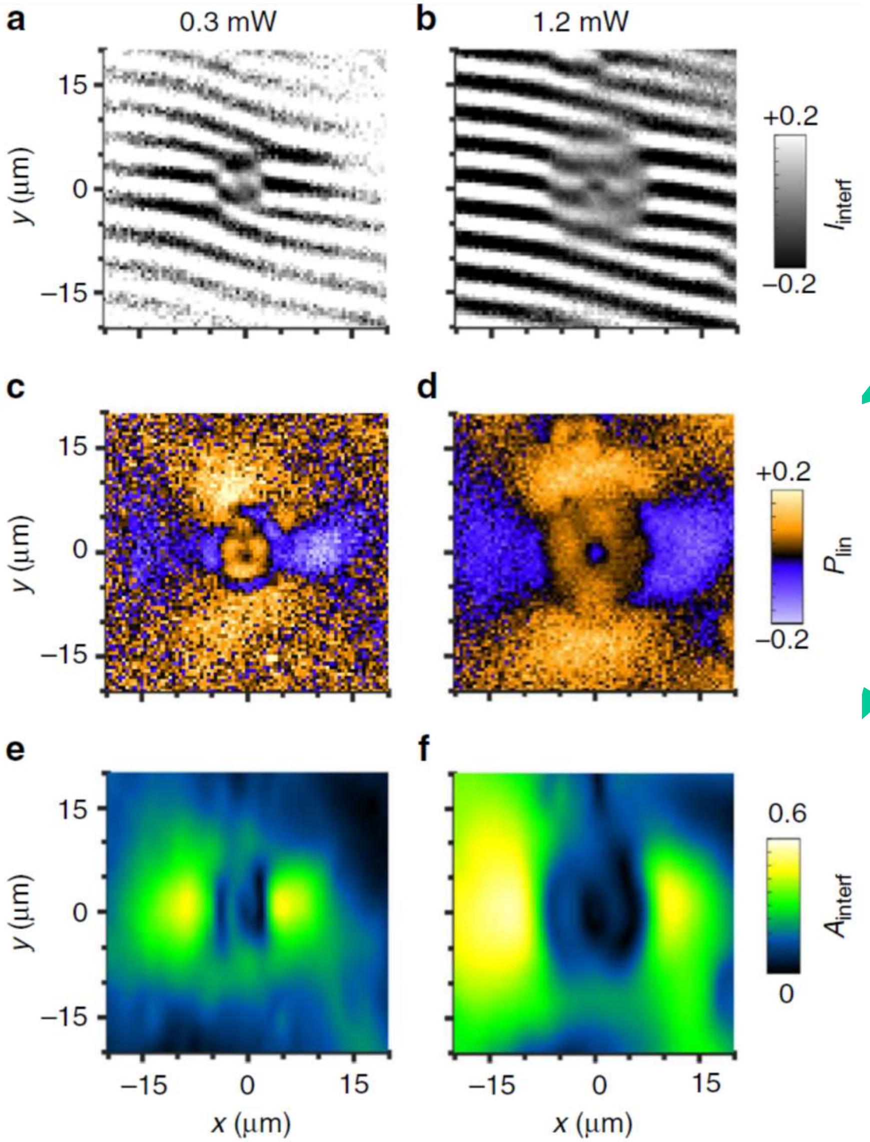
polarization state of light
goes along closed contour
on Poincaré sphere

↓

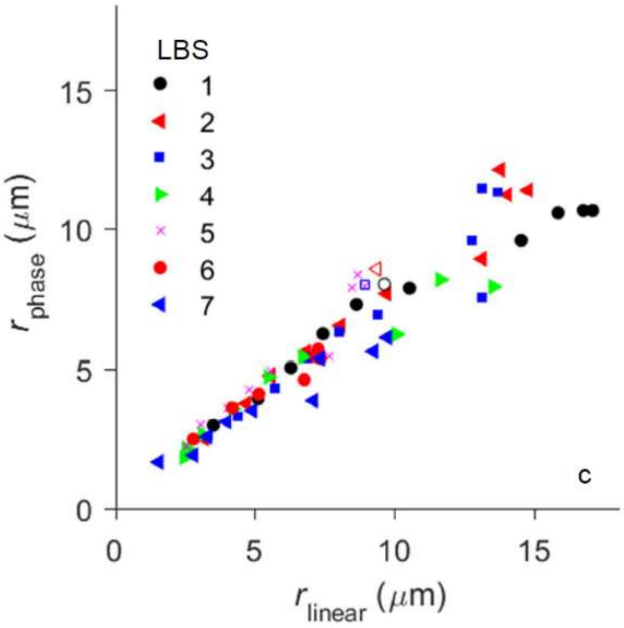
acquired Pancharatnam-Berry
phase $\phi_{PB} = 1/2\ \Omega$



correlations between
phase shifts,
polarization pattern, and
onset of **spontaneous coherence**



correlation with polarization
identifies the phase as PB phase



data for different sources
and different source powers
collapse on universal line $r_{\text{phase}} = r_{\text{linear}}$

IX condensation

suppression of scattering

suppression of Dyakonov-Perel mechanism of spin relaxation

coherent spin precession in IX condensate

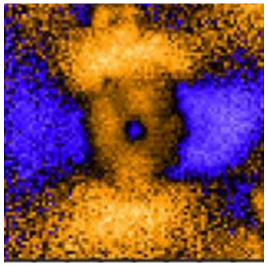
precession of polarization state of IX emission

long coherent spin transport > 10 μm

acquired Pancharatnam-Berry phase $\phi_{PB} = 1/2\ \Omega$

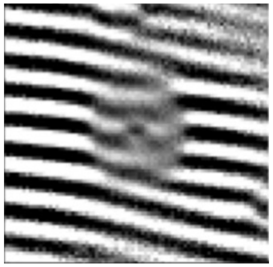
slow long-length component

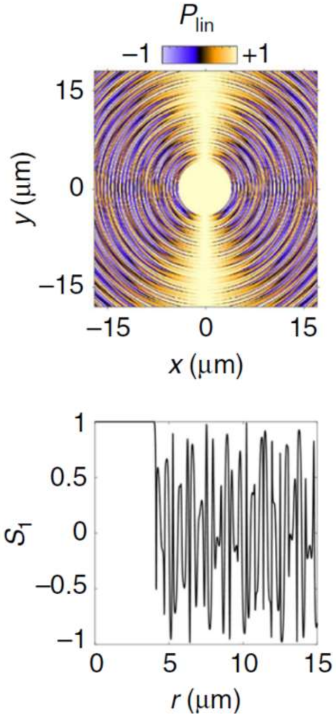
polarization pattern

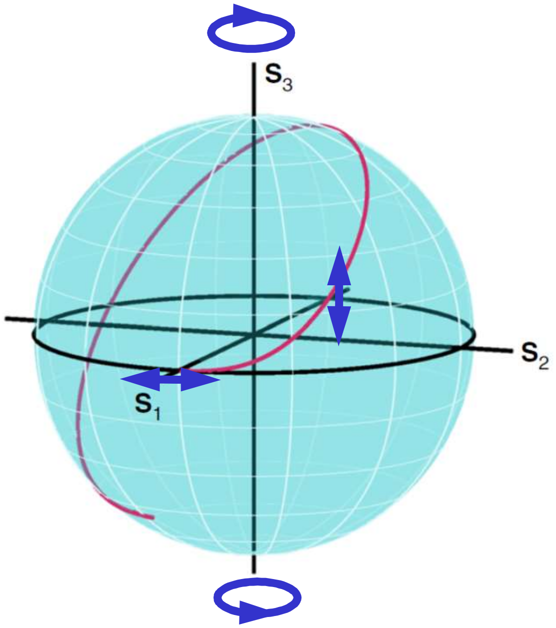


fast short-length component

PB phase



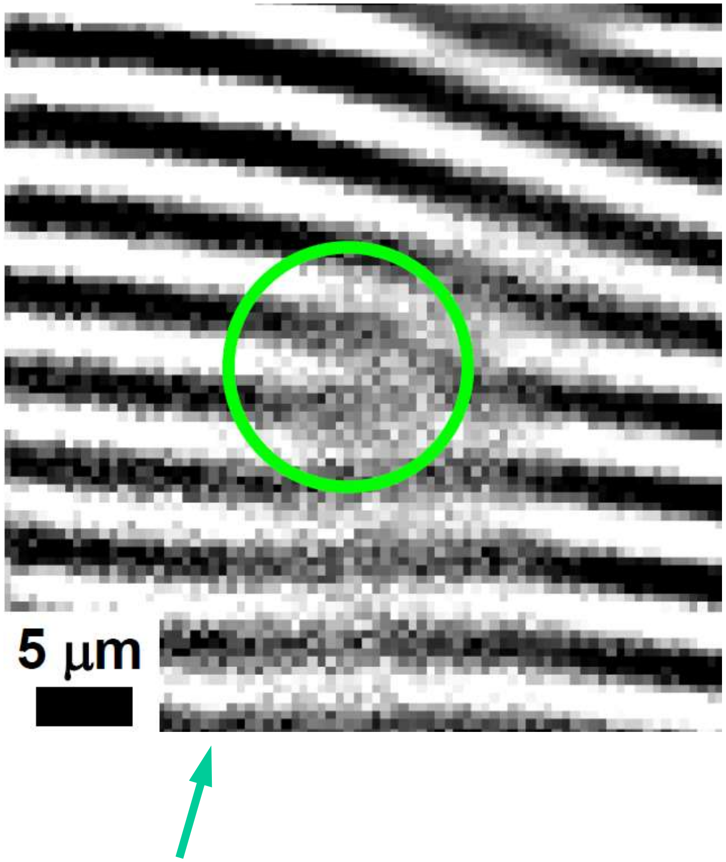




Phase singularities, interference dislocations in IX condensate

J.R. Leonard, Lunhui Hu, A.A. High, A.T. Hammack, Congjun Wu,
L.V. Butov, K.L. Campman, A.C. Gossard, arXiv:1910.06387

Dislocations (forks) in IX interference patterns



forks in interference patters are commonly associated with **vortices** in quantum systems

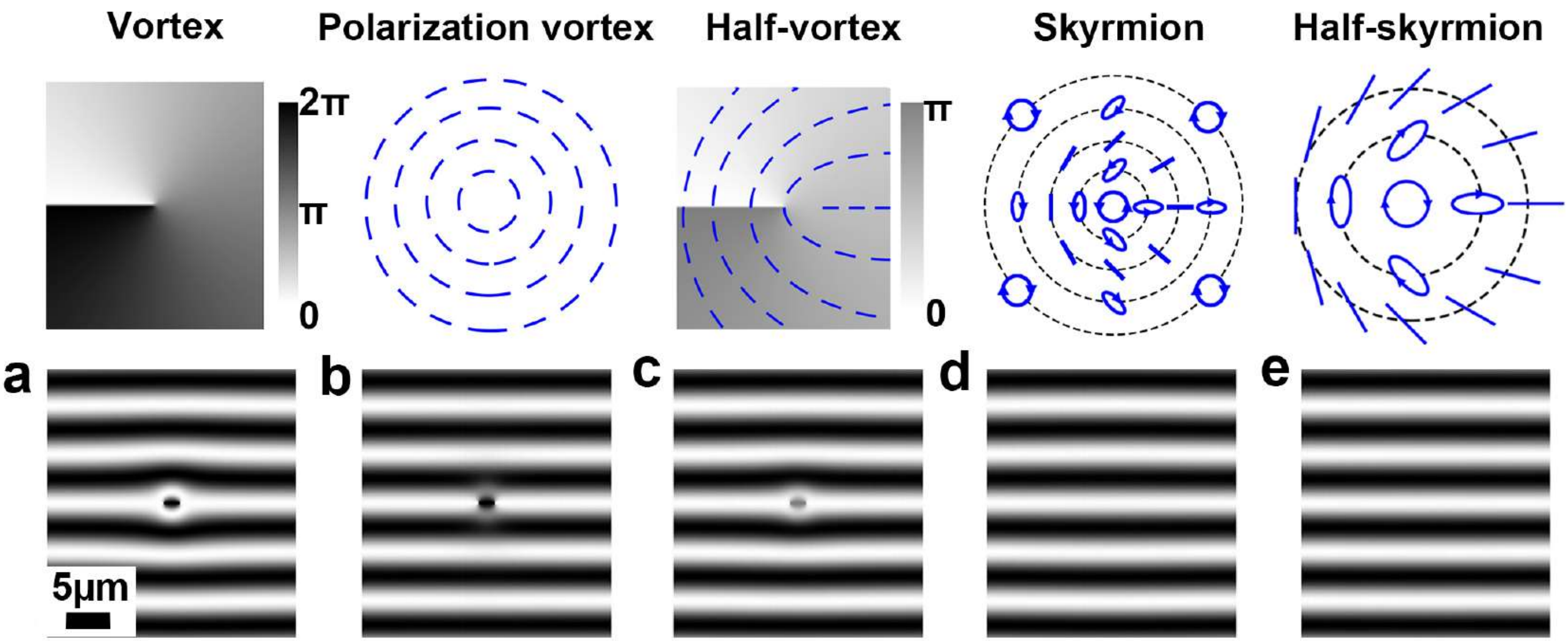
quantized vortex: phase winds by 2π around singularity point ← can be revealed as fork in interference pattern

↑

explored for vortices in **atom** condensates, **optical** vortices, and **polariton** vortices

observed dislocations in interference pattern are not associated with conventional phase defects:

not vortices, not polarization vortices, not half-vortices, not skyrmions, not half-skyrmions



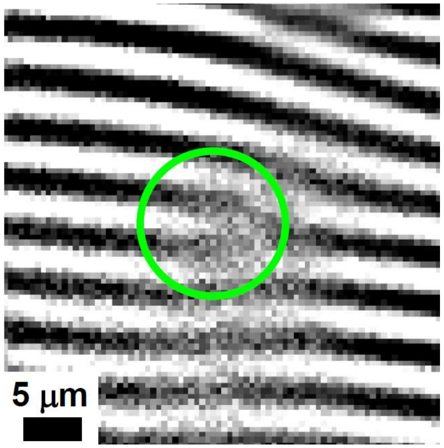
none of these simulated interference patterns is similar to experiment

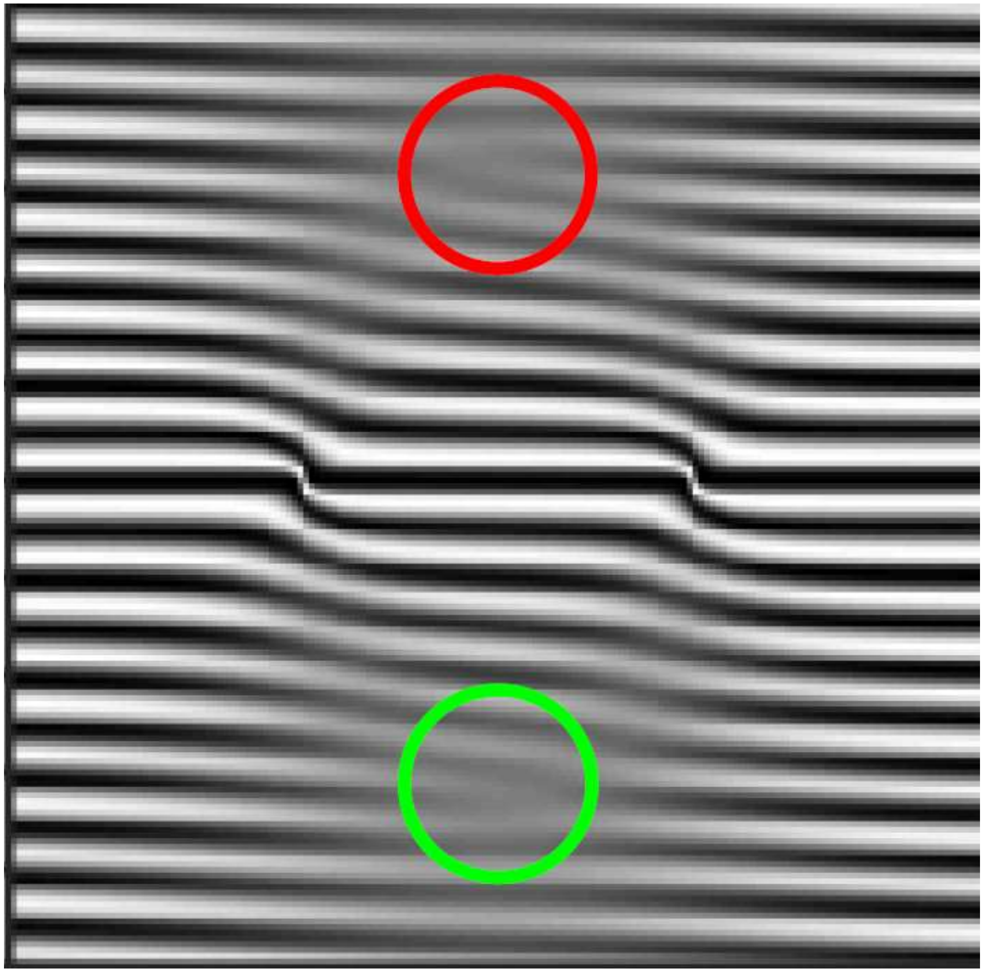
observed singularity in interference pattern is not associated with
vortex, or polarization vortex, or half-vortex, or skyrmion, or half-skyrmion

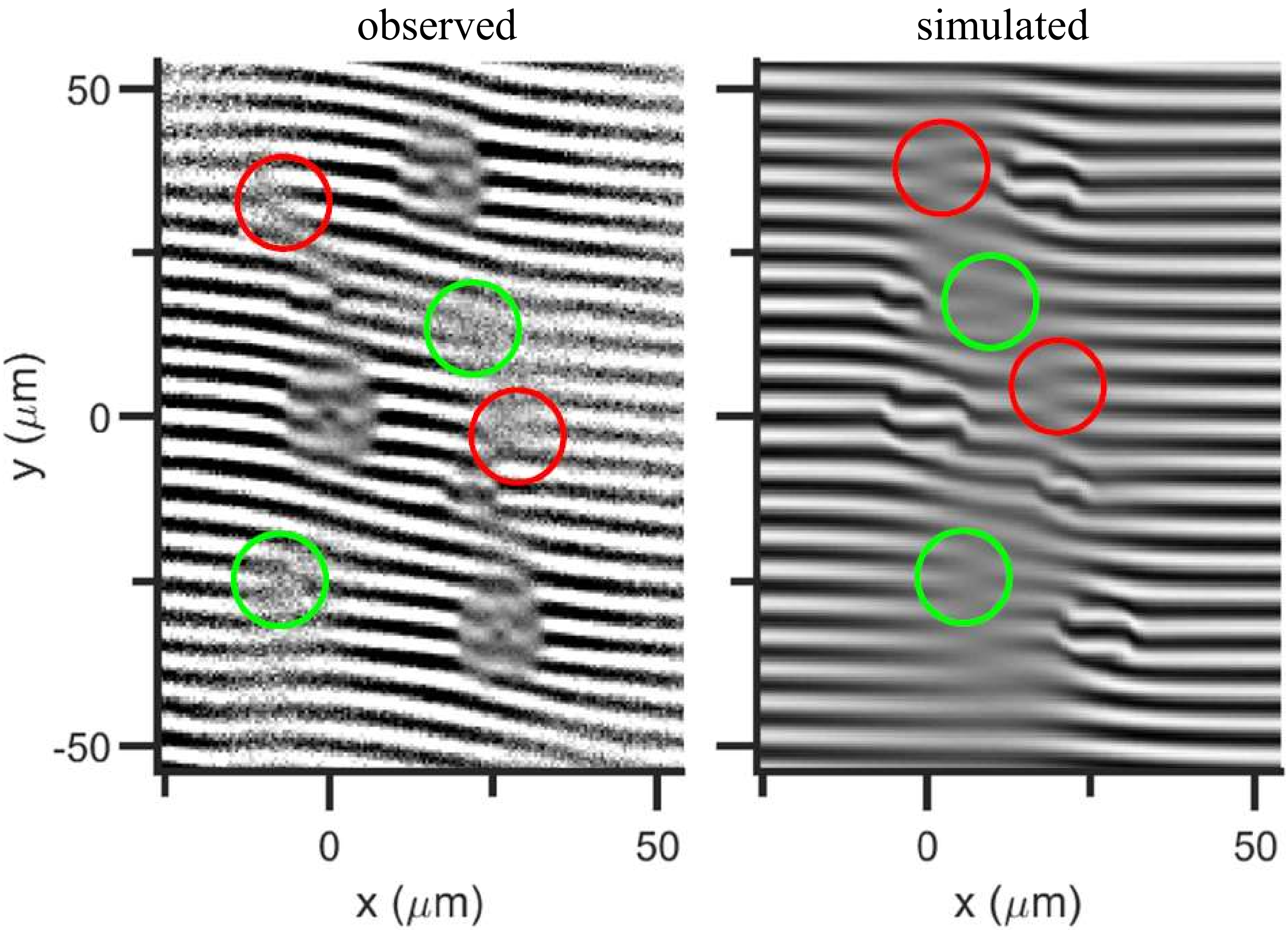
origin of observed phase singularities in IX condensate interference patterns:

observed interference dislocations originate from converging of condensate matter waves

simulations reproduce observed "isolated" interference dislocations



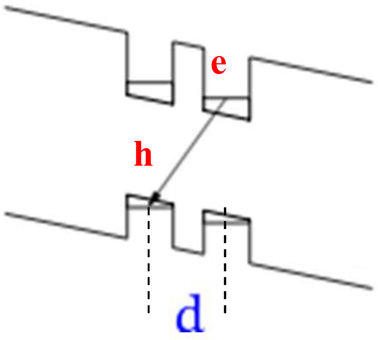


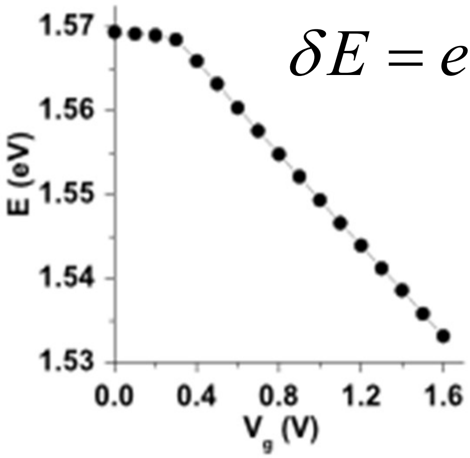


observed and simulated complex interference patterns with multiple interference dislocations ↔ converging of condensate matter waves and phase domains ↔ Pancharatnam-Berry phase

Excitonic devices

Potential energy of IXs can be controlled by voltage





$$\delta E = edF_z$$

in-plane potential landscapes
for IXs can be created
and controlled by voltage

excitonic devices
operate with excitons
in place of electrons

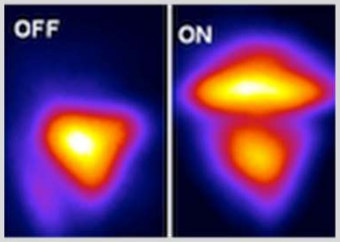
Proof of principle demonstration of excitonic devices

Excitonic Circuit Devices

- low-energy
- seamless coupling to optical communication

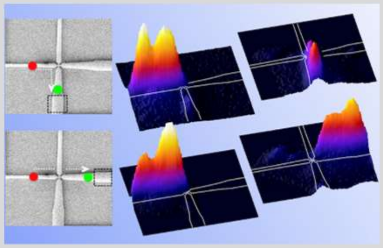
Excitonic transistors

Optoelectronic



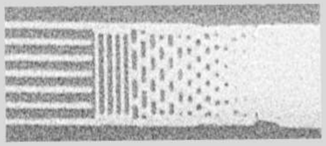
Opt. Lett. 32, 2466 (2007)

All-optical



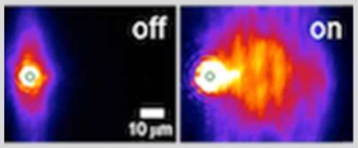
APL 104, 091101 (2014)

Excitonic diodes



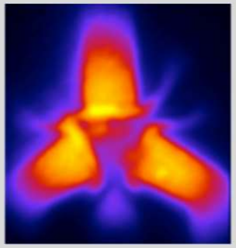
APL 108, 073502 (2016)

Excitonic CCD

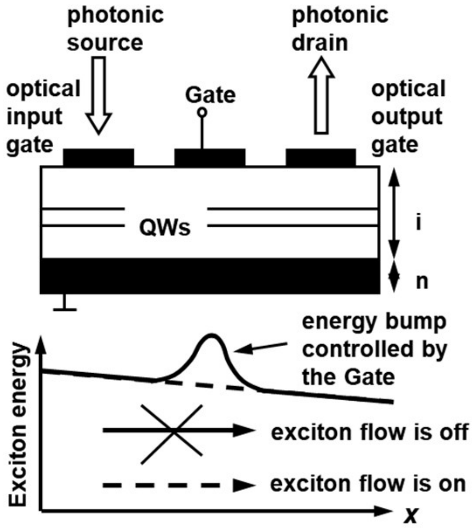


PRL 106, 196806 (2011)

Excitonic IC



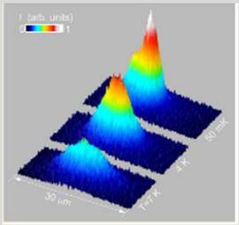
Science 321, 229 (2008)



Excitonic devices for basic study

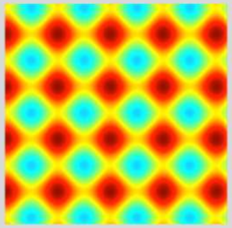
- mesoscopisc of bosons

Excitonic trap



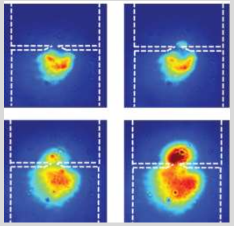
Nano Lett. 12, 2605 (2012)

Excitonic lattice



PRB 92, 115311 (2015)

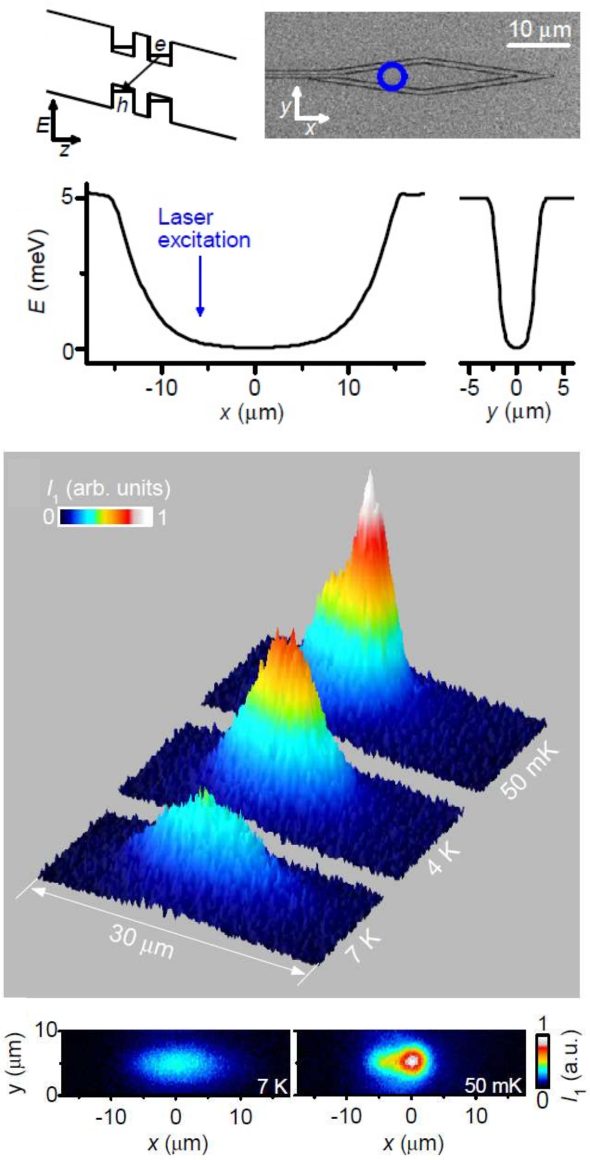
Excitonic split gate



APL 112, 183501 (2018)

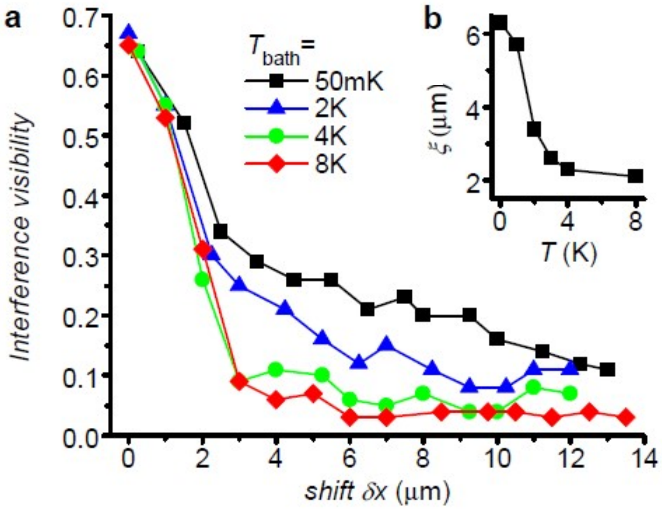
Condensation of IXs in a trap

diamond-shaped trap



With lowering *T*

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



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

Theory: S.V. Lobanov, N.A. Gippius, L.V. Butov, *Phys. Rev. B* 94, 245401 (2016)

Agreement between experiment and theory:
measured IX condensation is adequately described by
(quasi)equilibrium BEC of interacting bosons

IXs in van der Waals TMD heterostructures

IX is composed of an electron and a hole confined in separated layers

IX heterostructures (HS)

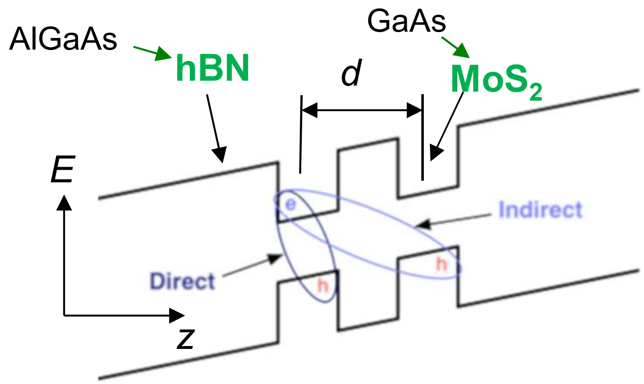
GaAs HS

Low-disorder system

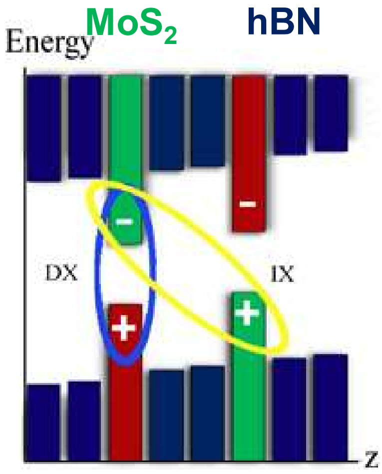
Van der Waals TMD HS

IXs are robust at room T

Type I

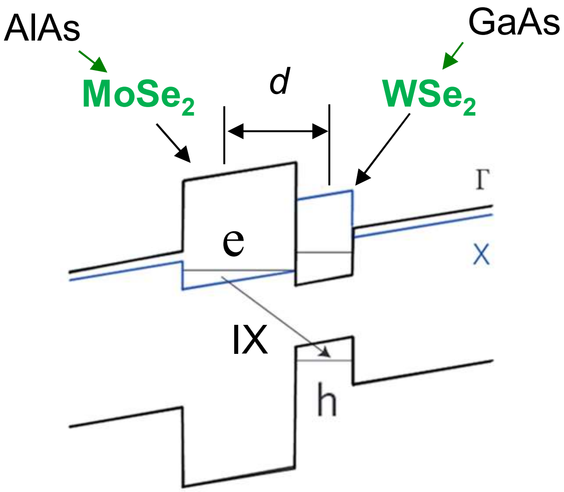


GaAs/AlGaAs HS

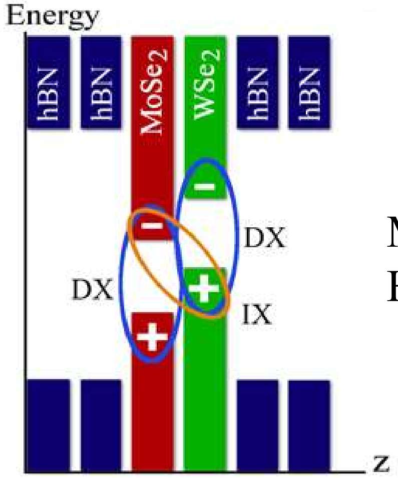


MoS_2/hBN HS

Type II

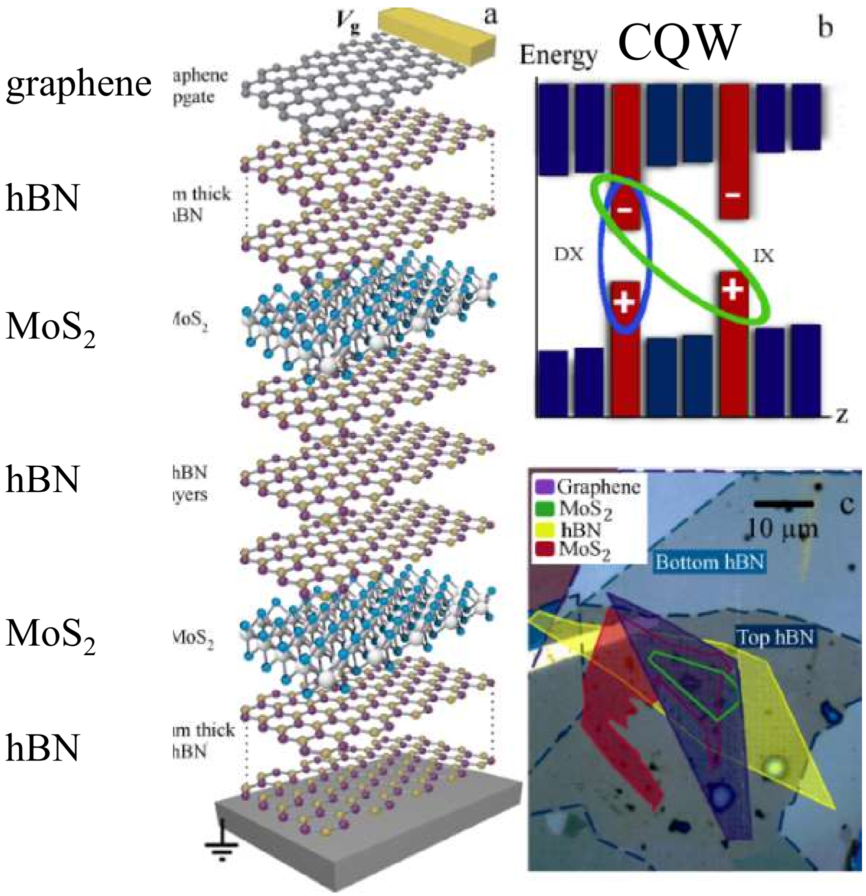


AlAs/GaAs HS



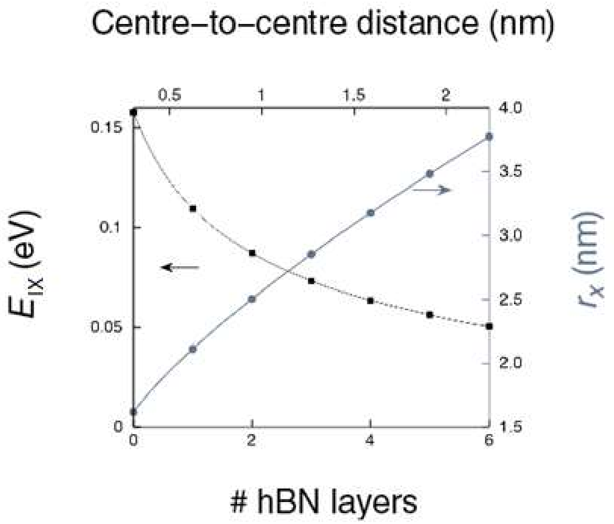
$MoSe_2$/WSe_2 HS

Van der Waals TMD heterostructures for high-T IX condensation



Recent calculations: E$_b$ ~ 350 meV > 10 T$_{room}$

Deilmann, Thygesen, *Nano Lett.* 18, 1460 (2018)



IXs are robust at room T

↓

room-T IX devices

predicted high-T superfluidity in IXs in TMD heterostructures

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

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

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

high Ry_x → high T_0

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

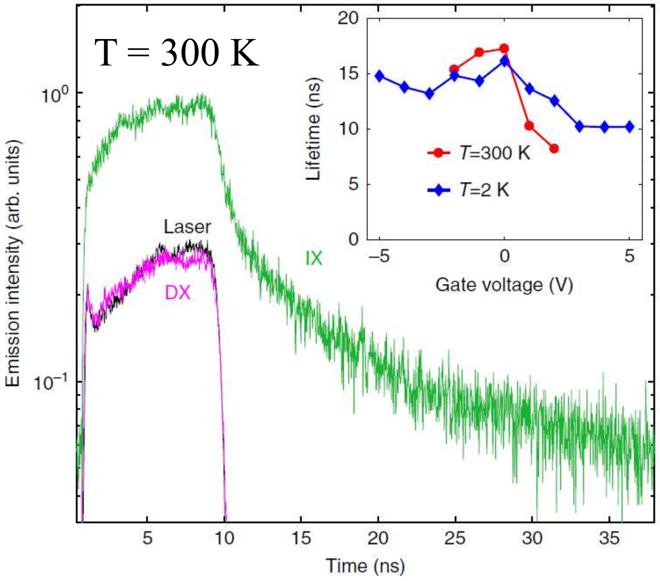
IXs at room temperature in van der Waals TMD heterostructures

E.V. Calman, M.M. Fogler, L.V. Butov,
S. Hu, A. Mishchenko, A.K. Geim,
Nature Commun. 9, 1895 (2018)

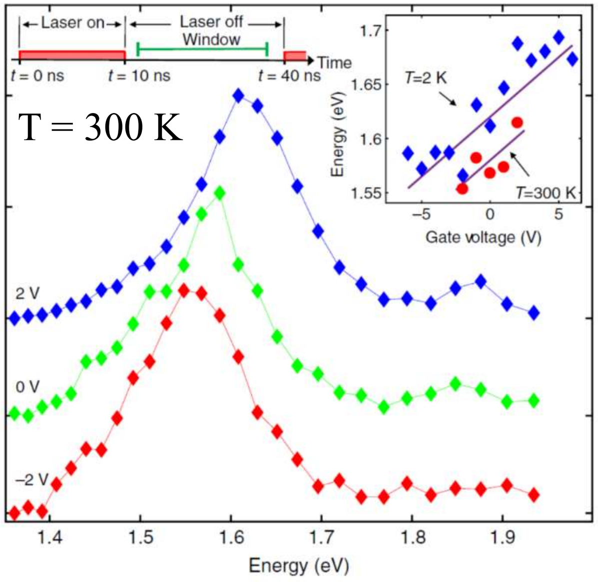
IXs in MoS_2/hBN van der Waals TMD heterostructures

basic IX properties:

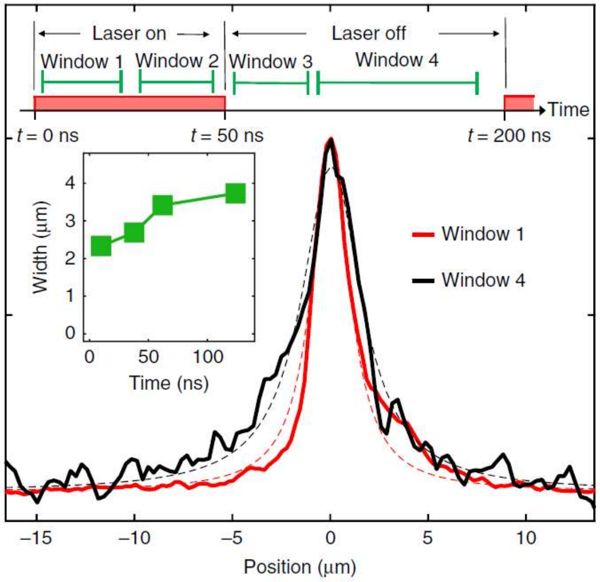
long lifetime



control of energy by voltage



transport



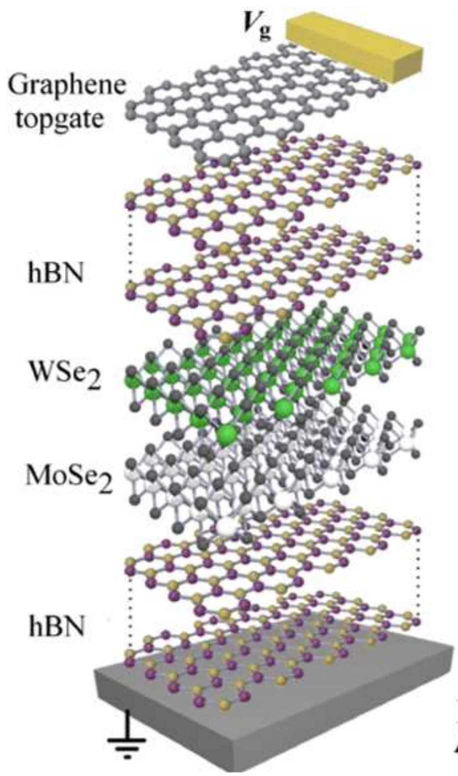
problems: ~ 100 meV broad line

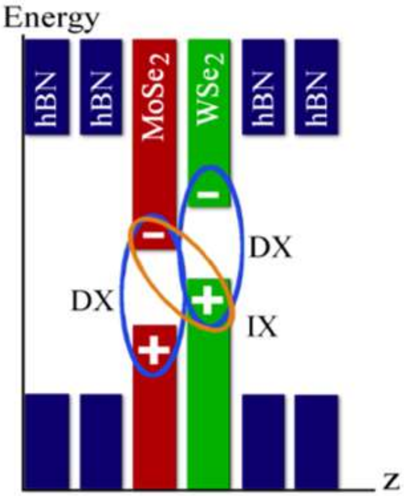
few μm short-range transport

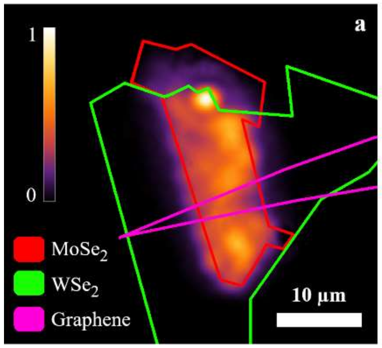
IXs in $MoSe_2$/WSe_2 van der Waals TMD heterostructures

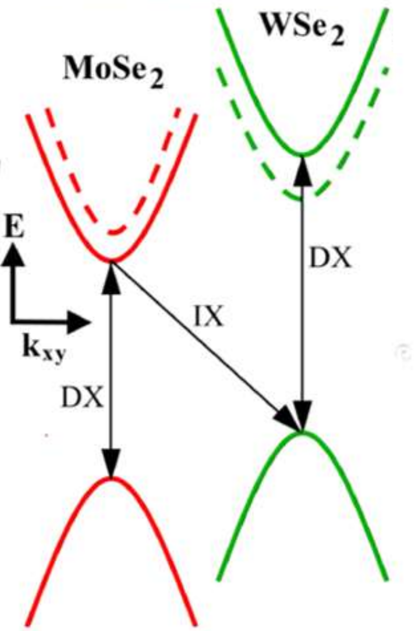
E.V. Calman, L.H. Fowler-Gerace, D.J. Choksy, L.V. Butov,
D.E. Nikonov, I.A. Young, S. Hu, A. Mishchenko, A.K. Geim,
Nano Lett. (2020)

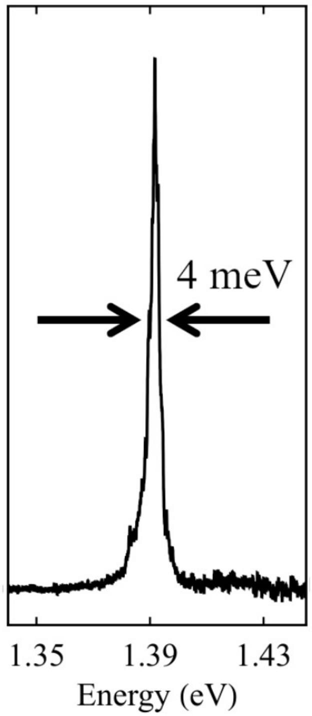
IXs in $MoSe_2/WSe_2$ van der Waals TMD heterostructures





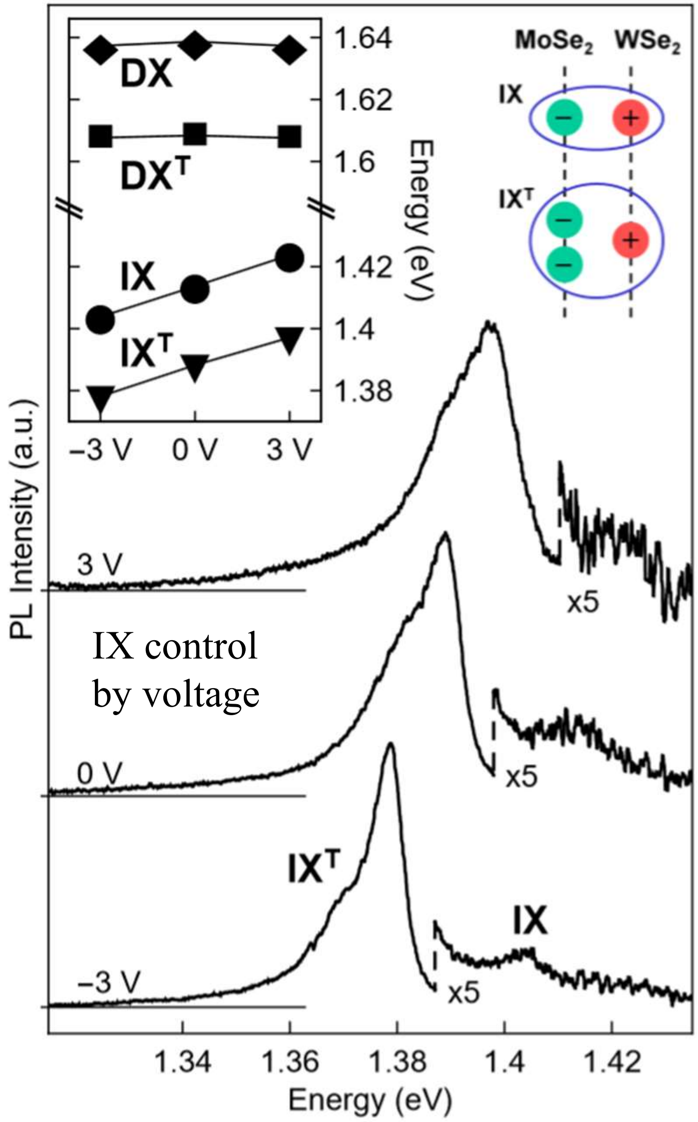






narrow IX linewidth
down to 4 meV

Indirect trions

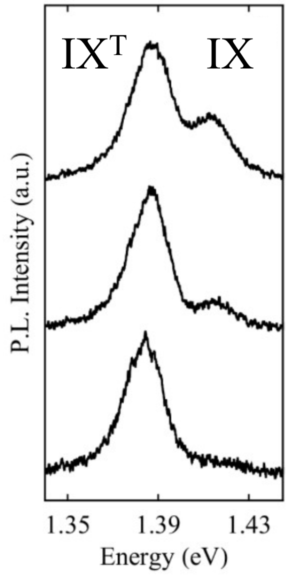


IX control by voltage

narrow linewidth

↓

resolve **two peaks** of indirect luminescence



- high energy peak – neutral indirect exciton (IX)
- low energy peak – charged indirect exciton, i.e. indirect trion (IX^T)

measured binding energy of indirect trion is in agreement with theory

E_b = 28 meV

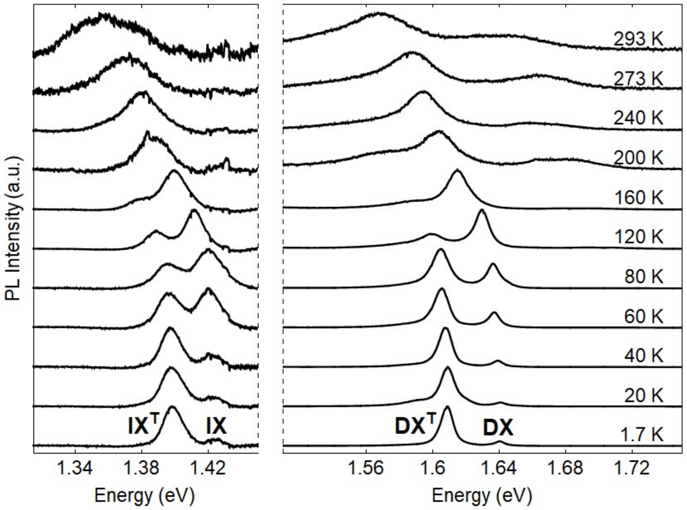
theory: Deilmann, Thygesen, *Nano Lett.* 18, 1460 (2018)

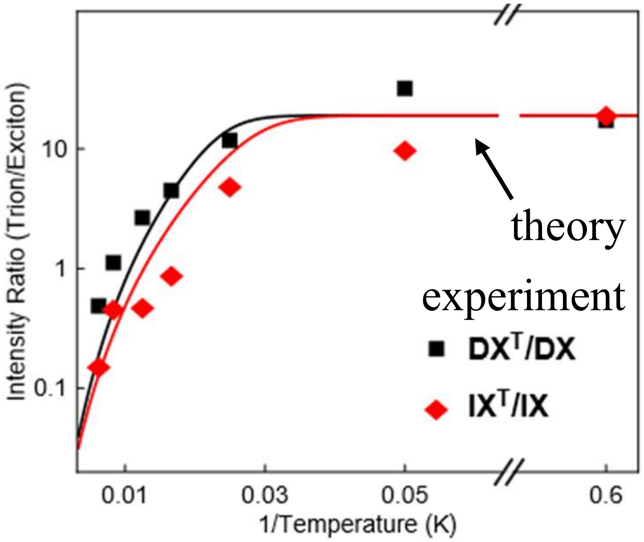
Temperature dependence

observed

IX up to

room T

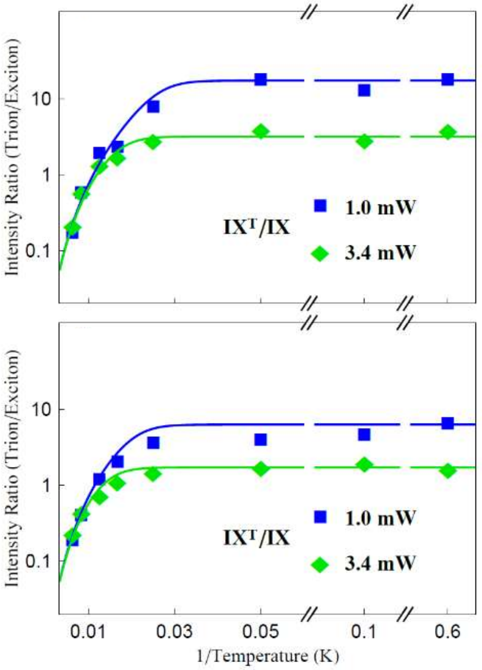




measured exciton/trion temperature dependence

is in agreement with theory of trions

checked in different samples,
spots, excitation powers



key feature of trion luminescence

is saturation at low T $\leftarrow$ observed

↑

at low T: $n_{\text{trion}} \rightarrow n_{\text{background e}}$

Summary

- Spontaneous coherence and condensation of IXs
- Phenomena in IX condensate
    - Density wave, commensurability effect
    - Spin textures
    - Pancharatnam-Berry phase, coherent spin transport
    - Phase singularities, interference dislocations

- IXs in van der Waals heterostructures
    - Opportunity to realize high-T IX condensation
    - IXs at room temperature
    - Indirect trions