ICSCE10

CONFERENCE ABSTRACT BOOK

28-31 January 2020

10TH INTERNATIONAL CONFERENCE ON SPONTANEOUS COHERENCE IN EXCITONIC SYSTEMS

ARTS CENTRE MELBOURNE AUSTRALIA

icsce10.org

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Welcome

Thank you for joining us at the **10th International Conference on Spontaneous Coherence in Excitonic Systems (ICSCE10).** ICSCE10 is a great opportunity for Australian and international scientists to discuss the latest progress in the study of quantum collective phenomena in various kinds of excitations in solids and other physical systems.

ICSCE10 will be hosted at the Arts Centre Melbourne on 28-31 January 2020. Continuing with the ICSCE series with previous conferences held in Edinburgh (ICSCE8 2018) and Montreal (ICSCE9 2019), ICSCE10 will be taking a broader perspective on spontaneous coherence effects, with topics on excitons, novel materials, exciton-polaritons, quantum dots and spontaneous coherence in cold atomic, plasmonic and other systems.

We hope this will be a fruitful meeting for you. Enjoy your time in Melbourne!

Kind regards,

ICSCE10 Organising Committee

Elena Ostrovskaya, Australian National University, co-chair

Timothy Liew, Nanyang Technological University Singapore, co-chair

Matthew Davis, University of Queensland

Yuerui Lu, Australian National University

Tich-Lam Nguyen, FLEET

Host Organisation

ARC Centre of Excellence in Future Low-Energy Electronics Technologies (FLEET)

FLEET is developing electronic devices that operate at ultra-low energy, enabling revolutionary new technologies to drive future electronics and computing, while meeting society's demand for reduced energy consumption.

FLEET addresses a grand challenge: reducing the energy used in information and communication technology (ICT), which already accounts for up to 8% of the electricity use on Earth and is doubling every 10 years. The "internet of things" would drive this energy demand even higher. Within a decade, the financial and environmental cost of electricity use will limit the growth of computing. The current, silicon-based technology (CMOS) is 40 years old, and reaching the limits of its efficiency.

FLEET is linking a highly interdisciplinary team of high-profile Australian and international researchers in atomic physics, condensed matter physics, materials science, electronics, nanofabrication and atomically-thin materials.

FLEET's solution will be a new generation of ultra-low energy electronics that will allow computing to continue to grow. FLEET will develop electronic devices in which electrical current can flow with near-zero resistance and dissipation of heat. The work is built on the science of atomically-thin two-dimensional materials and nanofabrication.

www.fleet.org.au

Invited Speakers

A/Prof Hui Deng – University of Michigan, USA

Dr Johannes Feist – Universidad Autónoma de Madrid, Spain

Dr Sebastien Klembt – University of Würzburg, Germany / University of St. Andrews, UK

Prof Junichiro Kono – Rice University, USA

Prof Dmitry Krizhanovskii – University of Sheffield, UK

A/Prof Francesca Marchetti – The Autonomous University of Madrid, Spain

Dr Carlos Sanchez Munoz – University of Oxford, UK

A/Prof Elena Ostrovskaya – The Australian National University, Australia

A/Prof Meera Parish – Monash University, Australia

Dr Barbara Piętka – University of Warsaw, Poland

Prof Sylvain Ravets – Centre de Nanosciences et de Nanotechnologies, France

Prof Daniele Sanvitto – Institute of Nanotechnology – CNR Lecce, Italy

Prof Vincenzo Savona – EPFL, Switzerland

Dr Christian Schneider – University of Würzburg, Germany

Prof Marzena Szymanska – University College London, UK

Prof Päivi Törmä – Aalto University, Finland

Prof Emanuel Tutuc – University of Texas Austin, USA

Prof Chris Vale – Swinburne University of Technology, Australia

Program Outline

Note: Program details subject to change at any time

Tuesday 28 January 2020	
0800-1030	Registration
1000-1900	Exhibition Open
1030-1700	Conference day 1
1700-1900	Poster presentations
Wednesday 29 January 2020	
0900-1715	Exhibition Open
0900-1715	Conference day 2
Thursday 30 January 2020	
0900-1715	Exhibition Open
0900-1715	Conference day 3
1800-2100	Conference Dinner
Friday 31 January 2020	
0900-1500	Exhibition Open
0900-1545	Conference day 4
1500-1700	Exhibition pack down
1545	Conference Close

ORAL PRESENTERS:

Save presentation file as: Day_Time_LastName, for example: Tue_1545_Ostrovskaya

Both pptx and pdf formats are acceptable.

Please bring your presentation file on a USB stick and submit to the technician in the "Speaker Room"

Presentations before lunch to be uploaded by 08:00

Presentations after lunch to be uploaded by 13:00

POSTER PRESENTERS:

Posters are to be displayed on designated boards from noon Tuesday 28 Jan 2020 until noon Friday 31 Jan 2020

The official poster presentation time is 17:00-19:00 Tuesday 28 Jan

Venue

Sitting beneath the iconic spire right in the heart of Victoria's arts precinct, Arts Centre Melbourne brings style and sophistication in art-filled event spaces.

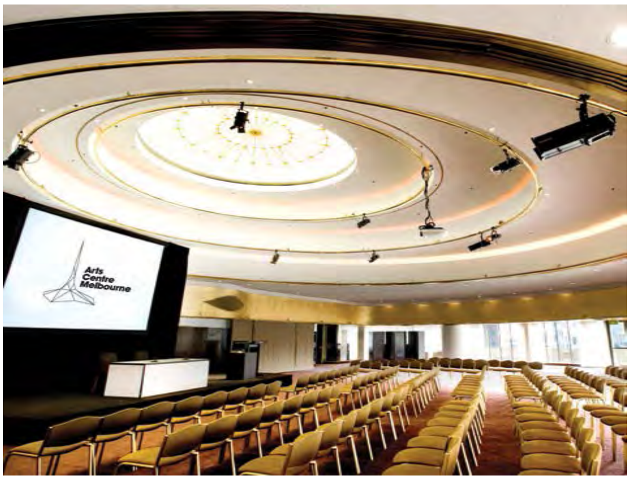
Located in the CBD and only a stone's throw from the Yarra River, Arts Centre Melbourne is not just a defining landmark, it is also Australia's largest performing arts centre. Complimented by local restaurants and bars, extended foyers, open gardens and galleries.

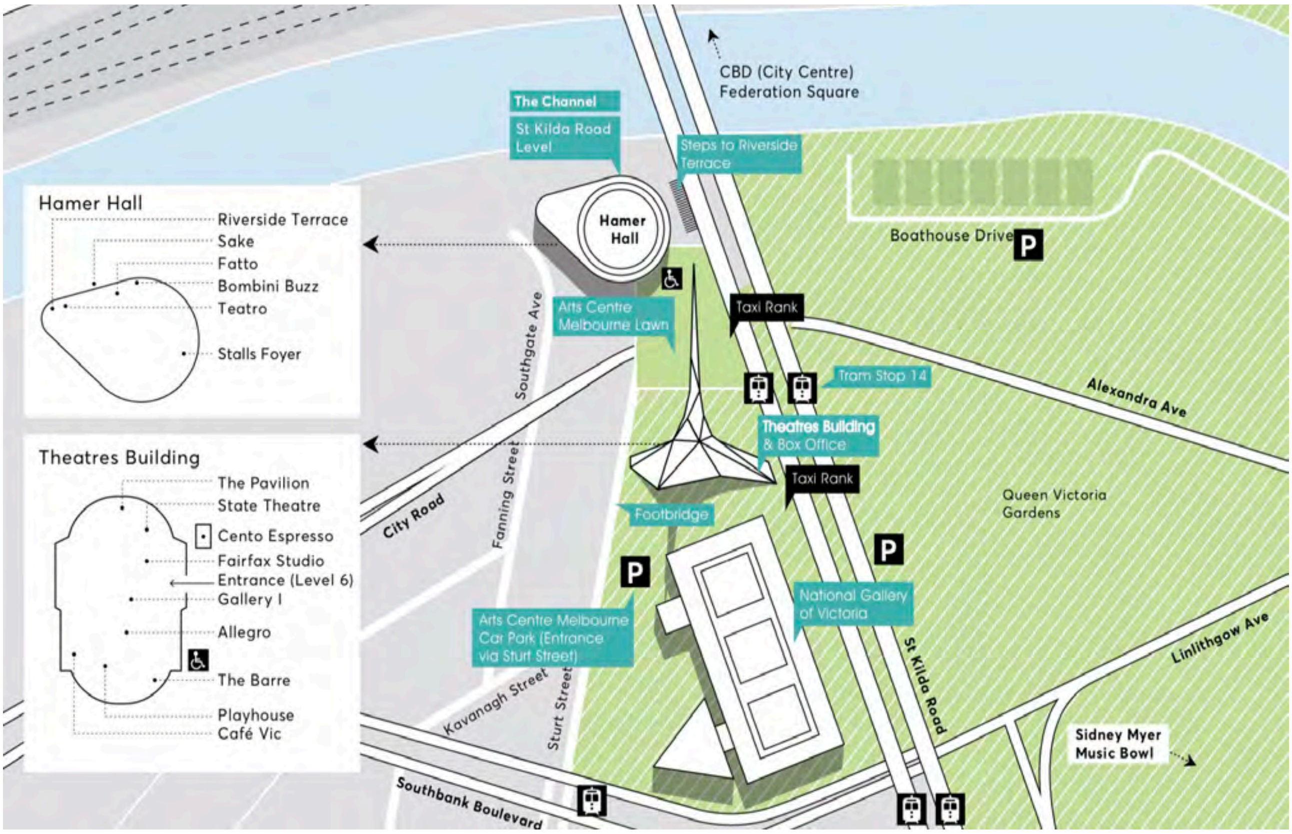
ICSCE10 will be held in the Pavilion. All lunch and break sessions and the poster presentation will be served in the foyer areas.

Delegate Profile

ICSCE10 provides a unique environment, dedicated to bringing 150 international and national scientists working on light-matter interaction in various systems.

40% of our delegates to come from Australia and 60% from overseas. The majority are in academia, government or federally funded employment.





Conference Program

TUESDAY 28 JANUARY 2020	
08:00	Registration
10:30	Morning Tea
11:00	Opening Ceremony
11:15	Emanuel Tutuc – Observation of an emerging equilibrium indirect exciton condensate in double bilayer graphene-WSe_2 heterostructures
11:45	Andrew Joe – Gate tunable spin-singlet/-triplet charged interlayer excitons in atomically thin hetero-structures
12:00	Nina Voronova – Superfluidity in a driven-dissipative cold exciton gas
12:15	Andres Mier Valdivia – Enhanced interlayer exciton lifetime in atomically thin semiconducting van der Waals hetetrostructures
12:30	Lunch
13:30	Dmitry Krizhanovskii – Nonlinear polariton effects in photonic structures based on III-nitrides and monolayers of transition metal dichalcogenides
14:00	Yuerui Lu – Super-transport of excitons in atomically thin organic semiconductors at the 2D quantum limit
14:15	Jiaxin Zhao – Strong light-matter interaction in multiple quantum-wells system based on monolayer tungsten disulfide
14:30	Guan-Hao Peng – Distinctive signatures of the spin- and momentum-forbidden dark exciton states underlying in the temperature dependent photoluminescence of WSe_2 monolayers
14:45	Peter Gruenwald – Electromagnetically-induced transparency with Cu_2O Rydberg excitons in the pres-ence of phonon coupling
15:00	Pierre Gilliot – Ultrafast relaxation path due to colliding coherent excitons in the strong coupling re-gime
15:15	Afternoon Tea
15:45	Elena Ostrovskaya – Measurements of polariton-polariton interaction strength and quantum depletion in optically trapped exciton-polariton condensates
16:15	Lorenzo Scarpelli – Towards quantum polaritonics with fibre-cavity polaritons
16:30	David Snoke – Assessing the various measurements of the polariton-polariton interaction strength in GaAs microcavities
16:45	David Colas – Self-interference effects in condensed matter systems
17:00	**POSTER PRESENTATIONS**

Conference Program

WEDNESDAY 29 JANUARY 2020	
09:00	Hui Deng – When polariton condensates have dissipations or have no excitons
09:30	Meera Parish – Microscopic theory of exciton-polaritons
10:00	Dmitry Efimkin – Exciton-polarons in doped semiconductors
10:15	Ryo Hanai – Critical exceptional point in a driven-dissipative coupled condensate
10:30	Morning Tea
11:00	Francesca Maria Marchetti – Charge-imbalanced polaritons
11:30	Hui Hu – BEC-BCS crossover in an equilibrium exciton-polariton condensate
11:45	Jesper Levinsen – Spectroscopic probes of quantum many-body correlations in polariton microcavities
12:00	Artem Strashko – Charge-imbalanced polariton condensates
12:15	Jeff Davis – Measuring exciton polariton interactions and relaxation with multidimensional coherent spectroscopy
12:30	Lunch
13:30	Paivi Torma – Bose-Einstein condensation and stimulated thermalisation in plasmonic lattices
14:00	Chris Vale – Excitations in strongly interacting Fermi gases
14:30	Maciej Pieczarka – Probing Tan's contact in an exciton-polariton Bose-Einstein condensate
14:45	Eliezer Estrecho – Collective oscillations of a trapped exciton-polariton condensate
15:00	Hirofumi Shiraki – Chirality selective enhanced correlation among quantum emitters by chiral metallic structures
15:15	Afternoon Tea
15:45	Johannes Feist – Cavity-induced modification of molecules
16:15	Anna Musial – Stand-alone quantum dot-based single-photon source operating at telecommunication wavelengths
16:30	Kevin Silverman – Inas quantum dots and surface acoustic wave cavities for quantum transduction
16:45	Michael Cosacchi – Phonon-induced quality enhancement of quantum dot-based photonic sources
17:00	Oleg Sushkov – Prediction of the spin triplet two-electron quantum dots in Si: towards controlled quantum simulations of magnetic systems

Conference Program

THURSDAY 30 JANUARY 2020	
09:00	Junichiro Kono – Ultra-strong light-matter and matter-matter coupling: Dicke phenomena
09:30	Carlos Sanchez Munoz – Ultrastrong coupling in cavity QED: exotic phenomena and their simulation
10:00	Vincenzo Savona – Emergent quantum criticality in driven-dissipative cavity arrays
10:30	Morning Tea
11:00	Marzena Szymanska – Critical and superfluid properties of polariton condensates
11:30	Oliver Stockdale – Dynamics of vortex pinning in a two-dimensional superfluid flow
11:45	Alexis Askitopoulos – Spontaneous emergence and tuning of phase coherence revivals within a quantum fluid
12:00	Anne Maitre – Soliton patterns and stationary arrays of vortex streets in a 2D polariton superfluid
12:15	Min Park – Direct transfer of light's orbital angular momentum onto a nonresonantly excited polariton superfluid
12:30	Lunch
13:30	Barbara Pietka – Real magnetic fields and artificial Hamiltonians to control exciton-polaritons' spin
14:00	Bernd Berger – Switching the topological charge of exciton polariton vortices
14:15	Matt Reeves – Relaxation to negative temperature equilibria in a chiral system of superfluid quantum vortices
14:30	Mateusz Krol – Synthetic Hamiltonians and spin-orbit engineering in tunable birefringent microcavities
14:45	Daegwang Choi – Observation of non-simultaneous rotation of exciton-polariton superfluid
15:00	Matthias Pukrop – Optical vortex core switching in polariton condensates
15:15	Afternoon Tea
15:45	Daniele Sanvitto – Polaritons as efficient and ultrafast platform for neuromorphic computing
16:15	Sanjib Ghosh – A quantum optical neuromorphic network
16:30	Julian Toepfer – Macroscopically coupled polariton condensates
16:45	Kirill Kalinin – Networks of non-equilibrium condensates for simulation of spin Hamiltonians
17:00	Helgi Sigurdsson – Engineering interactions in networks of polariton condensates and the prospect of neural architectures
18:00	**CONFERENCE DINNER & POSTER AWARD CEREMONY**

Conference Program

FRIDAY 31 JANUARY 2020	
09:00	Christian Schneider – Room temperature organic exciton-polariton condensates in tailored landscapes
09:30	Rui Su – Exciton polaritons in perovskite lattices at room temperature
10:00	James Hutchison – Applications of organic molecule-light strong coupling
10:15	Anton Zasedatelev – Atto-Joule polariton condensate switch
10:30	Morning Tea
11:00	Sebastian Klembt – Topological physics with a hybrid light-matter system
11:30	Sylvain Ravets – Artificial matter in semiconductor lattices
12:00	Toby Dowling – Observation of the optical spin hall effect in photonic graphene
12:15	Subhaskar Mandal – One way reflection free polariton spin filtering channel
12:30	Lunch
13:30	Rimi Banerjee – Coupling between exciton-polariton corner modes mediated through edge states
13:45	Johannes Beierlein – Propagating exciton-polariton condensates in coupled waveguide structures
14:00	Paolo Comaron – Topological edge mode lasing in non-Hermitian polariton systems
14:15	Luis Jauregui – Electrical control of interlayer exciton dynamics in atomically thin heterostructures
14:30	Mykhailo Klymenko – Effect of charge transport in organic semiconductors on the conductance of silicon nanowires
14:45	Dimitrie Culcer – Resonant photovoltaic effect in doped magnetic semiconductors
15:00	Holger Fehske – On the existence and nature of the excitonic insulator phase in the extended Falicov-Kimball model
15:15	**Closing Ceremony followed by Afternoon Tea**

Conference Program

POSTER PRESENTATIONS	
01	Alexander Johnston – The emergence of asymmetric steady-states in networks of polariton condensates
02	Guangyao Li – Exciton-polariton propagator with application to electron-polariton scattering and testing of quantum reference frame transformations
03	Karolina Lempicka – Tunable room-temperature exciton-polaritons in a microcavity containing 2D-perovskites
04	Marcin Syperek – Towards an (Al,Ga)As-based exciton-polariton laser operating at room temperature
05	Qingdong Ou – Engineering low-loss polaritons in 2D materials
06	Mateusz Krol – Exciton-polaritons in multilayer WSe_2 in a tunable planar microcavity
07	Matthias Wurdack – Towards all-dielectric monolithic microcavities with embedded atomically thin semiconductors for exciton-polariton research
08	Nicolo Defenu – Quantum scale anomaly and spatial coherence in a 2D Fermi superfluid
09	Nobuhiko Yokoshi – Synchronised energy transport by surface plasmons on a metallic nanofiber
10	Huawen Xu – Universal self correcting computing with driven-dissipative disordered neural networks
11	Olivier Bleu – Nonadiabatic anomalous hall effect for exciton-polaritons
12	Olivier Bleu – Quantum theory of 2D polariton condensates
13	Pierre Gilliot – Exciton fine-structure in transition-metal dichalcogenides mono-layers
14	John Philbin – Exciton-exciton annihilation and superradiance in colloidal nanocrystals
15	Shao-Yu Chen – Coulomb bound many-body excitonic states in monolayer tungsten diselenide

Observation of an emerging equilibrium indirect exciton condensate in double bilayer graphene-WSe_2 heterostructures

Burg, G. William[1], Efimkin, Dmitry[2], Prasad, Nitin[1], Taniguchi, Takashi[3], Watanbe, Kenji[3], Register, Leonard F.[1], MacDonald, Allan H.[2], Tutuc, Emanuel[1,*]

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[2]*Department of Physics, The University of Texas at Austin, Austin, Texas 78712, USA*
[3]*National Institute for Materials Science, 1-1 Namiki Tsukuba, Ibaraki 305-0044, Japan*
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Electronic double layers, consisting of two two-dimensional (2D) semiconductors separated by a dielectric, are an ideal platform for probing indirect exciton physics. When the two 2D layers are doped with equal and opposite charge densities, at a sufficiently small interlayer separation electrons and holes in opposite layers can couple and form equilibrium indirect excitons. We present here a study of rotationally aligned double bilayer graphene heterostructures, separated by bilayer WSe_2.

Rotational alignment of the graphene bilayers ensures that tunneling between layers conserves both energy and momentum, resulting in tunneling characteristics that agree well with single particle tunneling calculations. By using a dual gated structure with multiple contacts to each layer, we can electrostatically dope each graphene layer individually, and probe the intrinsic tunneling current-voltage characteristics. When the two graphene bilayers are doped with equal and opposite charge densities, the tunneling amplitude is dramatically enhanced relative to single particle expectations, showing a vertical onset at zero interlayer bias. The tunneling enhancement is strongly dependent on temperature, with the enhancement largely suppressed above T = 5 K. Furthermore, the enhancement is fully suppressed by applying an in-plane magnetic field. These experimental observations suggest the emergence of a nascent indirect exciton condensate in double bilayer graphene heterostructures (Fig. 1).

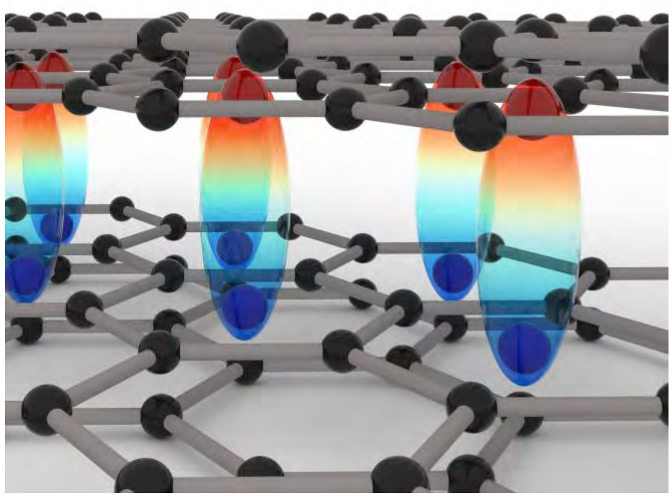

Fig. 1. Schematic illustration of indirect exciton formation in a double bilayer graphene heterostructure.

Gate tunable spin-singlet/-triplet charged interlayer excitons in atomically thin heterostructures

Joe, Andrew[1], Jauregui, Luis A.[1], Pistunova, Kateryna[1], Lu, Zhengguang[2,3], Wild, Dominik S.[1], Scuri, Giovanni[1], De Greve, Kristiaan[1,4], Gelly, Ryan J.[1], Sung, Jiho[1,4], Mier Valdivia, Andrés[5], Sushko, Andrey[1], Taniguchi, Takashi[6], Watanabe, Kenji[6], Smirnov, Dmitry[2,3], Lukin, Mikhail D.[1], Park, Hongkun[1,4], Kim, Philip[1,5]*

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[2] *National High Magnetic Field Laboratory, Tallahassee, Florida, USA*
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Abstract: Strong Coulomb interactions across the atomically separated electrons and holes can create neutral and charged excitons with long lifetimes in van der Waals (vdW) heterostructures [1]. Large spin-orbit coupling in transition metal dichalcogenides (TMD) provide helical coupling of photons and excitons with different spin states. Here, we fabricate a dual-gated $MoSe_2/WSe_2$ vdW heterostructure optoelectronic device and demonstrate electrically tunable optical helicity using spin-singlet and spin-triplet charged interlayer excitons. We use electrostatic gate doping to reach the spin-split conduction band, accessing the spin-triplet exciton state in TMDs (Fig. 1a) and show they still have lifetimes significantly longer than intralayer excitons (Fig. 1b). By applying a magnetic field, we measure the g-factors for the two states and show that they have opposite signs (Fig. 1c). Due to a non-trivial phase introduced in rotation by the in-plane displacement of the layers, the singlet and triplet interlayer excitons have opposite valley characteristics when emitting the same circular polarization. Electrically controlled and optically addressed singlet/triplet charged excitons provide a route for optoelectronic valleytronic devices that can dynamically switch between the two valley states without changing the helicity of incoming light.

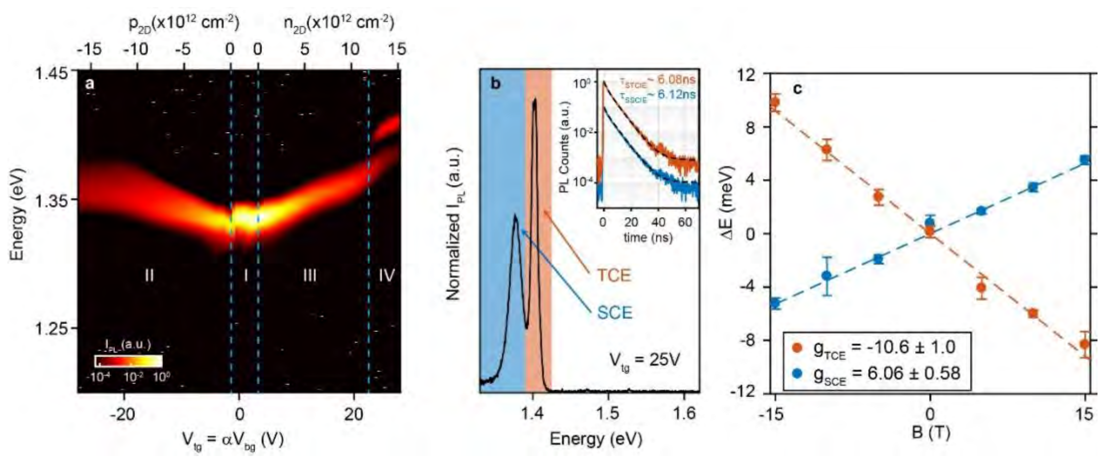

Fig. 1. (a) Electrostatic doping dependence of the photoluminescence spectra that shows spin-singlet and spin-triplet charged interlayer excitons at high *n*-doping. (b) Single spectra at V_{tg} = 25 V and lifetimes of the two peaks. (c) Energy splitting ($\Delta E = E_{\sigma+} - E_{\sigma-}$) of the photoluminescent energy for the triplet and singlet with calculated g-factors.

References

[1] L. A. Jauregui *et al.*, "Electrical control of interlayer exciton dynamics in atomically thin heterostructures," *arXiv*, p. 1812.08691, 2018.

SUPERFLUIDITY IN A DRIVEN-DISSIPATIVE COLD EXCITON GAS

Subbotin, Stanislav[1], Voronova, Nina[1,2,*], Kurbakov, Igor[3], Lozovik, Yurii[1,3]

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[2]*Russian Quantum Center, Skolkovo IC, Bolshoi Boulevard 30 bld.1, 121205 Moscow, Russia*
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Indirect excitons is a perfect solid-state platform for studying many-body effects, thanks to their long lifetimes, high critical temperatures, and the possibility to control the density by laser excitation [1]. To describe the motion of such cold excitonic systems, a formalism based on transport equations was developed in a series of works [2]. However this approach breaks down in the limit of very low temperatures where collective effects take place.

In our work, we develop a formalism based on quantum hydrodynamics approach [3], extending the description from conservative to driven-dissipative systems. Relating to the geometry of the experiment [1] with spatially-separated pumping and losses, we account for pumping as boundary conditions on density and velocity of the exciton incoming flow, while the losses are assumed present in all 2D space in consideration. We introduce the free energy functional of the system with terms describing dissipation, and study its properties in the hydrodynamic approximation. Stationary profiles of the condensate density and velocity are obtained from the applied model (Fig. 1), indicating the existence of the static superfluidity in the system. Furthermore, we derive the quadratic Hamiltonian and obtain the Bogoliubov spectrum of excitations which indicates that the excitations do not decay despite the losses in the system.

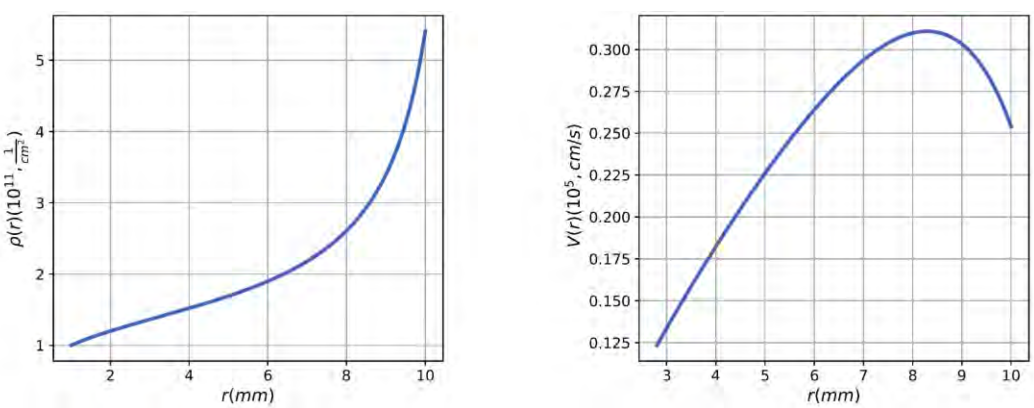

Fig. 1. Stationary profiles of the density (left) and velocity (right), with the lifetime τ = 42 ns and effective mass of the indirect exciton $m = 0.22\ m_e$ (experimental data from [1]).

References

[1] A.T. Hammack, M. Griswold, L.V. Butov et al., *Phys. Rev. Lett.*, 2006, **96**, 2227402.

[2] A.L. Ivanov*, Europhys. Lett.*, 2002, **59**(4), 586; A.L. Ivanov, *J. Phys.: Condens. Matter*, 2004, **16**, 3629.

[3] S. Stringari, *Phys. Rev. Lett.*, 1996, **77**, 2360; W.-C. Wu and A. Griffin, *Phys. Rev. A*, 1996, **54**, 4204.

TITLE: ENHANCED INTERLAYER EXCITON LIFETIME IN ATOMICALLY THIN SEMICONDUCTING VAN DER WAALS HETETROSTRUCTURES

Mier Valdivia, Andrés M.[1], Joe, Andrew Y.[2], Jauregui, Luis A.[2], Rhodes, Daniel[3], Kim, Bumho[3], Taniguchi, Takashi[4], Watanabe, Kenji[4], Hone, James[3], Kim, Philip[1,2,*]

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Interlayer excitons (IXs) in atomically thin transition metal dichalcogenide (TMD) heterostructures are a promising platform for the study of dipolar Bose-Einstein condensates (BECs) in two-dimensional solid-state systems. IXs exhibit tunable emission energies, large binding energies, and long lifetimes, allowing for the manipulation of the exciton energies and spatial position [1]. To successfully generate a BEC, long lifetimes are favorable for the IXs to thermalize with each other and potentially condense. One approach to further extending the excitonic lifetime is to place ultrathin hexagonal boron nitride (h-BN) in between two monolayers of TMDs [2]. At sufficiently high electric fields, we demonstrate the existence of two species of IXs in a system of WSe_2/monolayer h-BN/WSe_2 (Fig. 1a). We can tune their emission owing to their large dipole moments of 0.9 nm for the A-IX, and 0.5 nm for the B-IX. Further, we can use the electric field to tune the lifetime of the A-IX between 75-100 ns (Fig. 1b), a significant improvement over natural bilayer lifetimes. This technique is promising for applying to other indirect exciton systems, such as $MoSe_2$/WSe_2 heterobilayers.

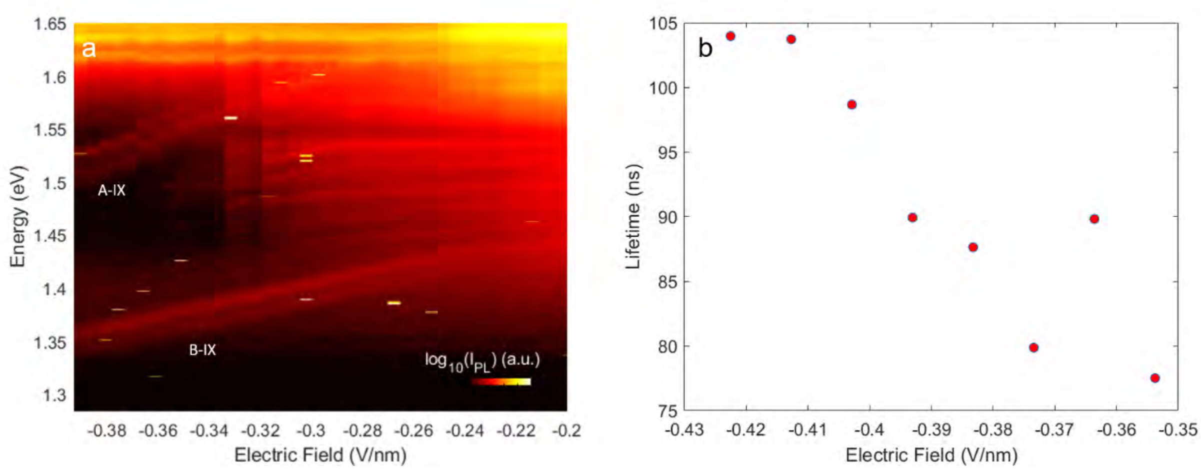

Fig. 1. (a) Electric field dependence of the photoluminescence spectra. We observe two distinct IX species: a higher energy peak starting around -0.34 V/nm labeled A-IX, and a lower energy peak appearing around -0.24 V/nm, labeled B-IX. (b) The lifetime of the A-IX is enhanced with increasing magnitude of the electric field.

References

[1] L. A. Jauregui, A. Y. Joe, K. Pistunova, D. S. Wild, A. A. High, G. Scuri, K. De Greve, A. Sushko, C. Yu, T. Taniguchi, K. Watanabe, D. J. Needleman, M. D. Lukin, H. Park, and P. Kim, *ArXiv*, 2018, 1812.08691.

[2] E. V. Calman, M. M. Fogler, L. V. Butov, S. Hu, A. Mishchenko, and A. K. Geim, *Nat. Commun.,* 2018*,* **9,** 1895.

NONLINEAR POLARITON EFFECTS IN PHOTONIC STRUCTURES BASED ON III-NITRIDES AND MONOLAYERS OF TRANSITION METAL DICHALCOGENIDES

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Strong exciton-photon coupling in semiconductor microcavities and waveguides gives rise to formation of hybrid light-matter 2D quasiparticles, so-called polaritons. Giant Kerr-like optical nonlinearity arising from the excitonic component resulted in a number of remarkable observations: superfluidity of light, bright and dark solitons, vortices limited by interactions and continuum generation have been reported in GaAs-based systems[1,2]. Very recently weak antibunching (polariton blockade) has been also observed in 0D GaAs-based microcavities.

Here I focus on polaritons in photonic structures based on III-nitrides and monolayers of transition metal dichalcogenides materials (TMDC). While in GaAs exciton-polaritons exist at T up to 50-70 K the larger exciton binding energy in these materials makes polaritons stable at temperatures up to 300 K, which is potentially useful for applications utilizing strong optical nonlinearites. Moreover, the strong oscillator strength in TMDCs enables polaritons with just a single monolayer. Remarkable compatibility of TMDCs with various semiconductor/dielectric substrates also paves the way towards development of active nanophotonic devices of new generation.

Firstly, we investigated AlGaN waveguide with 20 embedded GaN quantum wells (QWs)[3]. Strong coupling between the waveguide photonic mode and QW excitons leads to formation of UV high-velocity polaritons emitting at ~350 nm and characterized by a Rabi splitting up to 90 meV. The resonant excitation of propagating polariton fluid with a strong laser pulse results in a significant energy broadening of the injected pulse from the initial 10 meV up to ~80 meV and spatial defocussing, which is associated with self-phase modulation, modulation instability and possibly Cherenkov radiation by bright polariton solitons[4]. The strength of polariton-polariton (exciton-exciton) interactions normalized to a single QW is found to be comparable to that in GaAs. The effects persist up to 300 K and to the best of our knowledge this is the first observation of nonlinear polariton fluids in GaN system.

In the second part of my talk I will present studies of nonlinear polaritons in microcavities and photonic crystals with an embedded monolayer of $MoSe_2$. Importantly, the strong Coulomb interactions give rise to very robust 2D trions (charged excitons) in TMDCs, the large oscillator strength of which enables formation of trion-polaritons at low electron density. This leads to very pronounced phase space filling effects resulting in giant trion-polariton nonlinearity comparable to or even stronger than that in GaAs polariton system. The trion-polariton nonlinearity is also found to be 1-2 orders of magnitude stronger than that measured for neutral TMDC exciton-polaritons[5]. I will also discuss the theoretical perspective of reaching strong polariton blockade using TMDC trion-polaritons.

1 Iacopo Carusotto and Cristiano Ciuti Rev. Mod. Phys. 85, 299 (2013)
2 M Sich, et al., Comptes Rendus Physique 17 (8), 908-919 (2016)
3 J. Ciers, J. G. Roch, J.-F. Carlin, G. Jacopin, R. Butté, and N. Grandjean Phys. Rev. Applied **7**, 034019 (2017)
4 PM Walker, et al, Light: Science & Applications 8 (1), 6 (2019)
5 V Kravtsov et al., arXiv preprint arXiv:1905.13505

Super-transport of Excitons in Atomically Thin Organic Semiconductors at the 2D Quantum Limit

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Long-range and fast transport of coherent excitons is important for development of high-speed excitonic circuits and quantum computing applications [1]. However, most of these coherent excitons have only been observed in some low-dimensional semiconductors when coupled with cavities, as there are large inhomogeneous broadening and dephasing effects on the exciton transport in their native states of the materials. Here, by confining coherent excitons at the 2D quantum limit, we firstly observed molecular aggregation enabled 'super-transport' of excitons in atomically thin two-dimensional (2D) organic semiconductors between coherent states, with a measured a high effective exciton diffusion coefficient of ~346.9 cm^2/sec at room temperature. This value is one to several orders of magnitude higher than the reported values from other organic molecular aggregates and low-dimensional inorganic materials. Without coupling to any optical cavities, the monolayer pentacene sample, a very clean 2D quantum system (~1.2 nm thick) with high crystallinity (J-type aggregation) and minimal interfacial states, showed superradiant emissions from the Frenkel excitons, which was experimentally confirmed by the temperature-dependent photoluminescence (PL) emission, highly enhanced radiative decay rate, significantly narrowed PL peak width and strongly directional in-plane emission. The coherence in monolayer pentacene samples was observed to be delocalized over ~150 molecules, which is significantly larger than the values (a few molecules) observed from other organic thin films. In addition, the super-transport of excitons in monolayer pentacene samples showed highly anisotropic behaviour. Our results pave the way for the development of future high-speed excitonic circuits, quantum computing devices, fast OLEDs, and other opto-electronic devices [2].

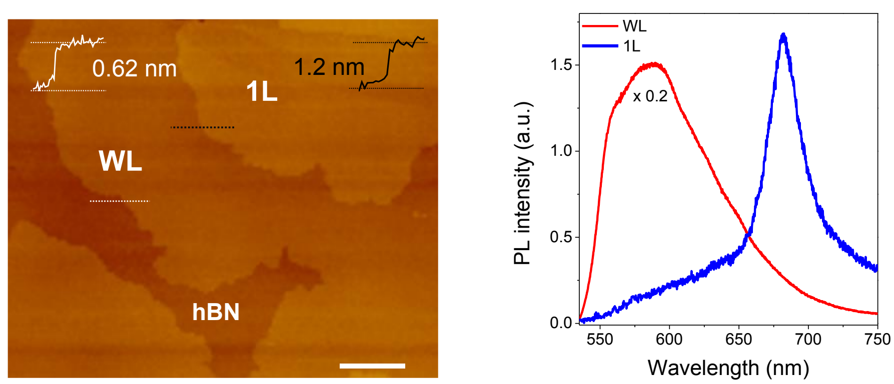

Fig. 1. a, Atomic force microscope (AFM) image of layered organic 2D materials showing the actual measured thickness of WL and 1L pentacene. The scale is 2 μm. b, Measured PL spectra from WL and 1L samples at room temperature.

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Strong Light-matter Interaction in Multiple Quantum-wells System Based on Monolayer Tungsten Disulfide

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Monolayer group-VI transition-metal dichalcogenides (TMDs) have emerged as a new class of 2D semiconductors and attracted extensive research interests due to their sizable direct bandgap, remarkable optical and electronic properties [1]. The tightly bound excitons with giant oscillator strength render monolayer TMDs as an ideal platform to investigate light-matter interaction in strong coupling regimes when they are integrated with optical cavities. The exciton-polaritons based on monolayer TMDs are stable at room temperature with considerable promise towards optoelectronic and valleytronic devices [2]. In addition, the layered structure can be assembled vertically to fabricate van der Waals heterostructure and enable new strategies for control of strong light-matter interactions [3]. Here, we report on the observation of the strong coupling regime in TMD quantum wells (QW) systems with tunability coupling-strengths. We incorporate multiple-QW structure using different numbers of tungsten disulfide (WS_2) monolayers that are separated by silicon dioxide (SiO_2) layers in a planar microcavity. The anti-crossing curve of the lower and upper polariton branches is revealed by using a home-built angle-resolved photoluminescence spectrometer. The vacuum Rabi splitting in the multiple QW microcavity is proportional to the square root of the number of QW. Our results not only provide fundamental understanding of the light-matter interaction in the integrated two-dimensional semiconductor and optical cavity system, but also show great promises for the application of polariton devices at room temperature.

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DISTINCTIVE SIGNATURES OF THE SPIN- AND MOMENTUM-FORBIDDEN DARK EXCITON STATES UNDERLYING IN THE TEMPERATURE DEPENDENT PHOTO-LUMINESCENCE OF WSe2 MONOLAYERS

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Atomically thin transition-metal dichalcogenide monolayers (TMD-MLs) have recently drawn broad attention because of the extraordinary spin-, valley- and excitonic properties. [1,2] With the combined spin- and valley-degrees of freedom, an exciton in a TMD-ML under photo-excitation exhibits the complex fine structures, composed of the bright exciton (BX) states, and spin-forbidden (SF) and momentum-forbidden (MF) dark states (DXs) as well. Because of the optical invisibility, the latter two kinds of the dark states are in principle hardly observed and even distinguished in conventional spectroscopies though their impacts on the optical and dynamical properties of TMD-MLs have been well noticed. In this work, we present a theoretical and computational investigation of the excitonic band structures and the temperature-dependent photo-luminescence (TD-PL) spectra of WSe_2-MLs under thermalization by solving the density-functional-theory (DFT)-based Bethe-Salpeter equation (BSE) with the full consideration of both electron-hole direct and exchange Coulomb interactions.[3] As main results, we reveal the distinctive signatures of the SF- and MF-DX underlying in the TD-PL, featured by the quickly rising and slowly descending PL intensities with increasing the temperature at low T~80K and high T~260K, respectively. Further, the exciton dynamics in the W-based TMD-MLs subjected to the exciton-phonon interactions is also studied by using the Lindblad quantum master equation based on the multi-exciton-level model. The computational results agree well with the existing experimental data, [4] and account for the impact of the high lying MF-DX states on the optical properties of W-based TMD-MLs.

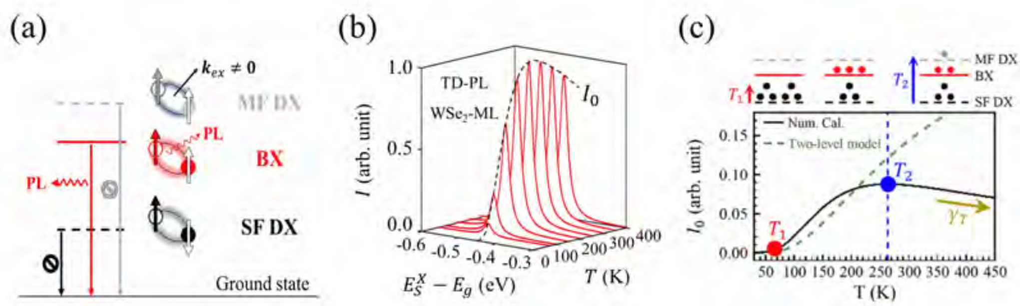

Fig. 1. (a) Schematics of the fine structure of the bright exciton (BX) states, and spin-forbidden (SF) and momentum-forbidden (MF) dark states (DX) of a WSe_2-ML. (b) The calculated temperature-dependent PL spectra and (c) the temperature-dependent PL intensities of a WSe_2-ML featured by the characteristic temperatures T_1 and T_2 as the signatures of the existing SF- and MF-DX, respectively. [3]

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ELECTROMAGNETICALLY-INDUCED TRANSPARENCY WITH CU_2O RYDBERG EXCITONS IN THE PRESENCE OF PHONON COUPLING

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Rydberg excitons in Cu_2O have emerged as a platform of strongly interacting particles with great potential for both fundamental phenomena as well as optical applications. A central problem is a strong absorptive background underlying the spectrum, stemming from the excitons' coupling to optical phonons and constricting the effect of exciton interactions [1]. Here, we analyze how and under which conditions electromangnetically-induced transparency (EIT) can suppress this background [2]. After developing a Hamiltonian theory that captures the single-photon absorption spectrum, we investigate the optical response in two-photon absorption as a function of yet unknown system parameters, see Fig. 1. Depending on these parameters, the background and exciton spectrum can partially or even fully be separated, essentially switching off the coupling to the phonon dynamics. This procedure also provides a direct handle on the experimental determination of these quantities and places limits required for optical applications. Our findings pave the way for the exploitation of Rydberg blockade with Cu_2O excitons in EIT setups.

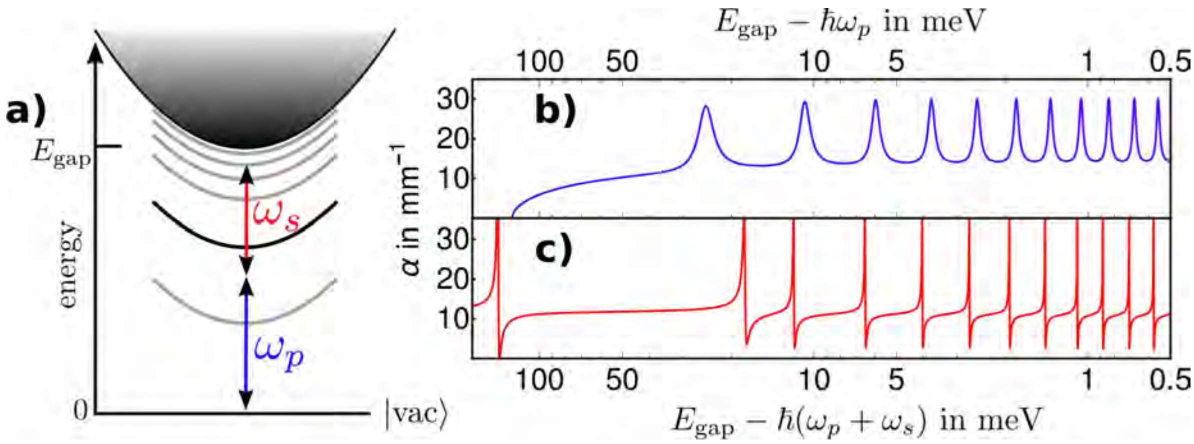

Fig. 1. a) Two-laser setup with the first laser pumping a low-lying *p*-exciton and the second coupling to a Rydberg *s*-exciton. b) single-photon absorption showing the background superimposing the *p*-states. c) adding the second laser with appropriate system parameters suppresses the resonance and the background, thus maximizing the absorption contrast.

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ULTRAFAST RELAXATION PATH DUE TO COLLIDING COHERENT EXCITONS IN THE STRONG COUPLING REGIME

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Exciton-exciton annihilation is a very essential process that governs excitation dynamics in photo-physics. For example, the efficiency of carrier generation in photovoltaic organic materials is limited by exciton-exciton annihilation that decreases their population before they have been dissociated. As well, the light-emission efficiency of carbon nanotubes is strongly reduced due to the relaxation that follows collisions between excitons [1]. Moreover these processes seem to be very efficient and very fast: An instantaneous E_{22}- to E_{11}-exciton transfer is observed in carbon nanotubes [2] and the measured very short relaxation times are incompatible with the usual processes, involving for example a cascade of phonons that would imply a minimum relaxation time for each phonon emission [3]. Furthermore, when exciting the lowest E_{11}-exciton resonance, an instantaneous change on the E_{22} resonance [4] is observed, showing a direct link between the two states.

Exciton-exciton annihilation is usually seen as an irreversible process that resembles an Auger recombination: the collision between two excitons gives rise to an annihilation of one of them, while the other one is sent to a high energy level. We show, in the present work, that, instead of being connected by a one-way irreversible process, the two-exciton state and the high-energy one-exciton state can be in a strong-coupling regime. This induces a coherent superposition of these two states that can persist up to the relaxation of one of the two components.
We describe the two-exciton states using the Schwinger representation of su(1,1) algebra as eigenstates of a pseudo-angular momentum [5]. This two-exciton manifold is coupled to the higher energy one-exciton states. In the case of carbon nanotubes for example it is enhanced by the resonance between twice the energy of the E_{11} exciton and the energy of the E_{22} exciton. Together with the high strength of the interaction, this gives then rise to a strong coupling the two manifolds.

Strong coupling has deep consequences on the exciton dynamics. First the exciton population can be coherently transferred to the high energy states in a very efficient way. Second, as in a degenerate parametric amplification process that is described by the same Hamiltonian, at high exciton densities, the E_{11} population is depleted in favor of the E_{22} level. The latter being less protected from the interaction with the environment, this favors non-radiative exciton recombination. We will discuss in this paper the efficiency of this process and relate it to the spatial features of the excitons described by their diffusion and coherence length [6] that govern the collision efficiency.

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MEASUREMENTS OF POLARITON-POLARITON INTERACTION STRENGTH AND QUANTUM DEPLETION IN OPTICALLY TRAPPED EXCITON-POLARITON CONDENSATES

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Condensates of exciton polaritons in semiconductor microcavities typically coexist and interact with an incoherent excitonic reservoir injected by an optical pump. The reservoir serves both as the gain medium and as a repulsive potential for exciton polaritons, hence directly affecting the formation, coherence, and dynamics of the condensate. Measurements of the most fundamental properties of the exciton-polariton condensate, such as the strength of polariton-polariton interactions, have been hindered by the presence of the reservoir [1], with the reported values for GaAs and InGaAs quantum well microcavities differing by up to four orders of magnitude [3].

By realising a single-shot condensation [2] in an optically-induced “box” trap, our group has successfully created an exciton-polariton condensate in the high-density Thomas-Fermi regime, spatially separated from the incoherent reservoir. This has allowed us to perform a direct measurement of the polariton-polariton interaction strength by measuring the blueshift of the condensate mean-field energy as a function of the polariton density. This measurement, performed for a range of the excitonic fractions in the exciton-polariton quasiparticle, yields values in agreement with theoretical predictions [3].

Beyond this measurement, the high-density Thomas-Fermi regime of exciton-polariton condensation in an optically-induced trap offers a platform for fundamental studies of the non-equilibrium condensate without the influence of the reservoir. In particular, by reaching this regime under continuous wave (cw) optical excitation conditions, we have successfully imaged the so-called “ghost branch” of the dispersion of the elementary excitations, which is populated by the quantum depletion process. Since quantum depletion is a direct consequence of interactions, this observation provides an opportunity for another, independent measurement of the polariton-polariton interaction strength. Our measurement of the quantum depletion in momentum space demonstrates power-law decays of the occupation numbers [4], with a clear transition from equilibrium, Bogoliubov-like behavior for more exciton-like polaritons to a highly nonequilibrium behavior for photon-like polaritons [5]. Remarkably, the polariton-polariton interaction strengths extracted from these measurements [5] are in excellent agreement with our measurements performed in a single-shot regime. The two independent measurements serve to reduce the uncertainty in the values of the polariton-polariton interaction strengths.

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Towards Quantum Polaritonics with Fibre-Cavity Polaritons

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Over the past decade, exciton-polaritons in semiconductor microcavities have attracted a great deal of interest as driven-dissipative quantum fluids [1]. They offer themselves as a versatile platform for performing Hamiltonian simulations with light as well as for experimentally realizing nontrivial out-of- equilibrium phase transitions. The key ingredient at the basis of these phenomena is the fact that polaritons interact with each other. In the regime of large two-body interactions, polaritons can be used to manipulate the quantum properties of a light field. A regime of particular interest that has remained elusive so far is the one for which the interactions are large enough to show up in the system response at the level of few quanta, signified by the presence of quantum correlations between the emitted photons [2,3].

In this talk, I will report on the experimental observation of such correlations in resonant laser light transmitted through a fiber-cavity polariton system [4], indicating the onset of the strong interaction regime [5]. We observe a dispersive shape of the photon autocorrelation function including weak antibunching around the polariton resonance which is a characteristic signature of this phenomenon. From the photon autocorrelation data, we are further able to extract a value for the polariton-polariton interaction constant. Owing to their weak amplitude, the observed quantum correlations remain far from a fully- developed Fock state of light with low photon number, but they still demonstrate the emergence of time- ordering in the photon stream.

Besides resonant measurements, we have also conducted experiments under off-resonant pumping of the fiber-cavity polaritons. Using a narrow-band filter for the emitted photons, we are able to again observe non-trivial quantum correlations from the off-resonantly pumped system. These findings, at first sight surprising, are supported by numerical simulations of the system dynamics.

Our works act as a door opener for the emerging field of quantum polaritonics [3]. With further improvements both on the photonics engineering and the materials engineering side, quantum well cavity polaritons might eventually become a platform of choice for turning laser light into single photons and for realizing strongly interacting quantum fluids of light for quantum simulations.

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Assessing the various measurements of the polariton-polariton interaction strength in GaAs microcavities

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Various experiments have measured the value of the polariton-polariton interaction constant in GaAs/AlGaAs microcavity structures, and the numbers have ranged over orders of magnitude, from the theoretically predicted[1] value of around 1 μeV-μm^2 for the pure exciton-exciton limit, to three orders of magnitude larger than that. Recalibration of the data of Ref. 2 has reduced the results of that experiment by one order of magnitude, but the implied value of those experiments is still two orders of magnitude larger than the theoretical value, even when the effects of quantum confinement due to trapping are taken into account.

In this talk we will review the various experiments on this value and present new results from numerical models of the thermalization of the polariton gas in these structures, following the same method as Ref. 3 but including the effect of dark excitons and the known calibrations for polariton and exciton density in typical experiments. As seen in Figure 1, using the theoretical value for the interaction does not allow enough thermalization of the polaritons and gives energy distributions greatly in disagreement with the experiments, while using a higher value gives agreement. We will also discuss the theory of line broadening of the polariton emission, which is another constraint on the interaction strength.

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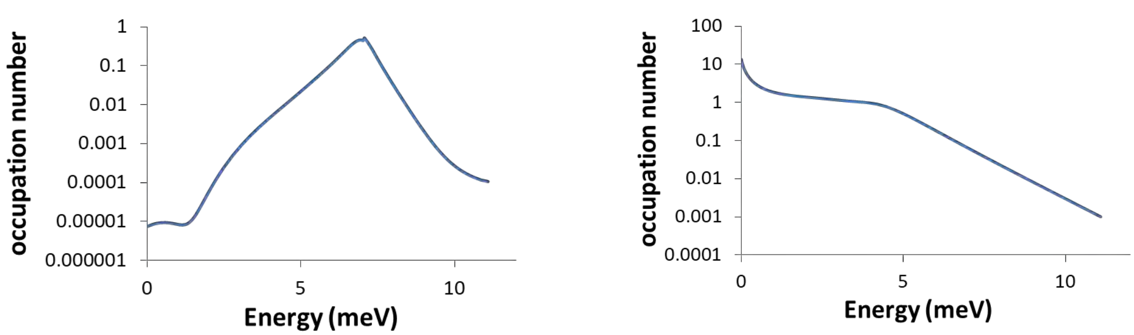

Figure 1. a) Numerically predicted polariton and exciton distribution for a cavity lifetime of 1.3 ps, with non-resonant pumping, using the theoretically predicted value for the exciton-exciton interaction constant, for total polariton density 7.4×10^9 cm^{-2}. b) The same simulation but with density 3.4×10^9 cm^{-2} and interaction constant 100 times larger.

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Self-interference effects in condensed matter systems

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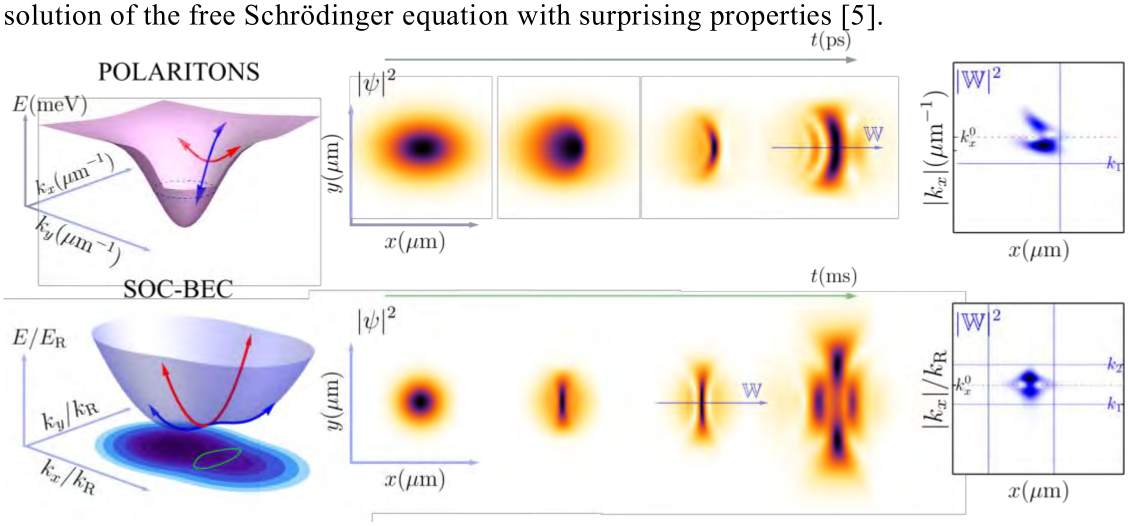
The phenomenon of interference is one of the main manifestations of the wave-like nature of quantum particles. In the Schrödinger picture, particles are well-described by wave packets, and their interference naturally follows from the principle of superposition. The self-interference of a single packet can occur, *e.g.* when bouncing against a potential wall. However, a wide range of quantum systems allow for dispersion engineering, with the appearance of regions of negative effective mass permitting the free propagation of self-interfering wave packets in the absence of an external potential or applied forces. This effect was first predicted theoretically for exciton-polariton systems [1]. It was later observed in 1D atomic spin-orbit coupled Bose-Einstein condensates (SOC-BEC) [2,3] and also found to be at the origin of the formation of polariton nonlinear X-waves [4]. Here we show that self-interference can develop due to the presence of nonlinear interactions, despite being a pure linear effect of the dispersion relation. We demonstrate how the X-wave formation can be understood using the wavelet transform, a spectral decomposition that provides unique insights into the nontrivial dynamics of wave packet propagation that can fully characterize self-interfering wave packets. The wavelet transform also provides a new perspective on another well-known non-spreading wave packet: the Airy beam, a solution of the free Schrödinger equation with surprising properties [5].



<u>Figure 1</u>: Propagation of nonlinear X-waves in an exciton-polariton system (top row) and in a 2D SOC-BEC system (bottom row). The X-wave is self-generated from an initial Gaussian wave packet that is initially placed in the hyperbolic region of the dispersion relation. The wavelet analysis reveals the interference mechanism that leads to the X-wave formation.

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When polariton condensates have dissipations or have no excitons

Hui Deng

Abstract: Microcavity exciton-polaritons are formed in a semiconductor with strong exciton-photon coupling and low carrier density. They have been widely studied as a weakly interacting boson gas that can form a Bose-Einstein condensation (BEC) like many-body state in a solid. However, the cavity dissipation and fermionic nature of the electrons can lead to phenomena outside the well established framework for polariton condensation. We first examine a phenomenon unique to a dissipative, non-equilibrium condensate. We show the formation of limit cycles with two coupled condensates, as a result of dissipative coupling and polariton nonlinearity.

We then look "inside" the polaritons and reveal an electron-hole-photon condensate that share similar spectral properties as a polariton BEC but with a microscopic origin similar to a BCS-state.

TITLE: Microscopic theory of exciton-polaritons

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We present a microscopic description of exciton-polaritons that involves electrons, holes and photons within a two-dimensional microcavity. Our approach goes beyond previous work and allows us to describe the effect of the light-matter coupling on the exciton wave function. We will also explore the high-excitation regime of the microcavity, where there is the prospect of realizing a BCS state of overlapping electron-hole pairs.

BEC-BCS crossover in an equilibrium exciton-polariton condensate

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Microcavity exciton-polariton systems in two-dimensions are long anticipated to exhibit a crossover from Bose-Einstein condensate (BEC) to Bardeen-Cooper-Schrieffer (BCS) superfluid, when the carrier density is tuned to reach the Mott transition density. Yet, theoretical understanding of such a BEC-BCS crossover largely relies on the mean-field framework [1, 2] and the nature of carriers at the crossover remains unclear to some extent. Here, inspired by the recent demonstration of a BCS polariton laser [3] and based on a simplified description with contact interactions to model the attraction between electrons and holes, we investigate quantum fluctuations of an exciton-polariton condensate and determine the number of electron-hole pairs, condensed photons and polaritons at the crossover beyond mean-field. We find that the exciton-polariton condense remains in the strong-coupling regime, when the carrier density is much larger than the Mott density.

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Critical exceptional point in a driven-dissipative coupled condensate

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Critical phenomena arise ubiquitously in various context of physics. Usually, these phenomena are associated with the softening of the massive. Here, we propose a novel, nonequilibrium-induced mechanism of critical phenomena driven by the *coalescence* of the eigenmodes, that may arise in driven-dissipative many-body systems with coupled order parameters, such as polariton condensates and driven-dissipative Bose-Einstein condensates in a double-well potential.

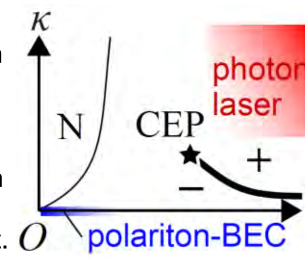

Fig. 1: Schematic phase diagram (as a function of the pump power P and photon decay rate κ) proposed in Ref. [1]. The thick solid line represents the phase boundary within the condensed phase. Here, "$-(+)$" represents the "$-(+)$"-solution phase, "N" represents the normal phase, and "CEP" is the critical exceptional point.

In our previous work, we have shown that a lower-to-upper branch condensate transition may be induced by the non-Hermitian nature of a coupled driven-dissipative condensate [1] (Fig. 1), proposing a new interpretation to the phase transition observed in some polariton experiments in the U(1)-broken phase (the so-called "second threshold" [2]). Interestingly, as shown in the figure, we have found that the phase boundary has an endpoint, marked by the so-called exceptional point (which we call the "critical exceptional point, CEP"), where the lower- and upper- branch condensate solutions coalesce.

In this work [3], we investigate the critical properties of CEP. We show that the critical fluctuations arise at the CEP due to the coalescence of the collective eigenmodes that converts all the thermal and dissipative noise activated fluctuations to the Goldstone mode, leading to anomalously giant phase fluctuations that diverge at spatial dimensions d≤4 (Fig. 2). By performing a renormalization group analysis to the coupled-KPZ-like equations, we find that this anomalous feature leads to the rise of a strong-coupling fixed point at dimensions as high as d≤8.

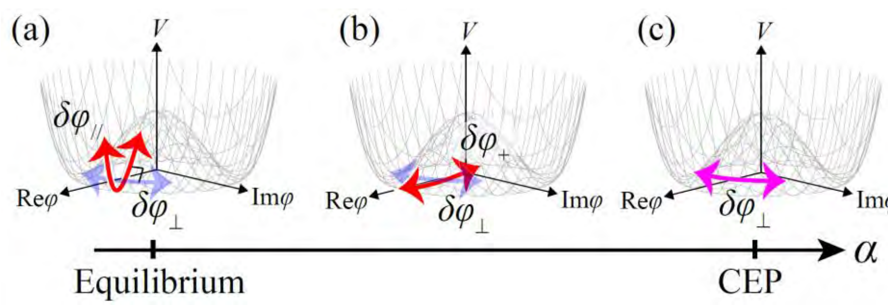

Fig. 2: Schematic explanation of the criticality of CEP. In the equilibrium limit (a), the two eigenmodes are given by the longitudinal ($\delta\varphi_{//}$) and transverse ($\delta\varphi_{\perp}$) modes. As the system approaches CEP by varying the parameter α, these modes ($\delta\varphi_{+}$ and $\delta\varphi_{\perp}$) become non-orthogonal (b), until they coalesce at CEP (c), leading to anomalously giant phase fluctuations.

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Charge-imbalanced polaritons

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Recent technological progress has led to precise and efficient manipulation of electronic and optical properties of semiconductor solid-state devices. Noticeable examples include GaAs heterostructures, while, more recently, transition metal dichalcogenide (TMDC) monolayers have emerged as ideal materials for optoelectronic devices. Crucially, these structures have been recently embedded into planar optical cavities, allowing to study the interplay between strong light-matter coupling and electronic doping. This opens the prospect to generate and control novel strongly correlated phases between exciton-polaritons and 2D electron system.

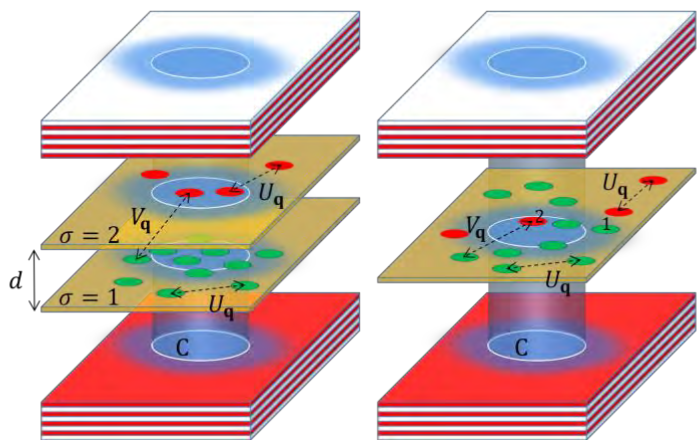

Fig. 1. Schematic representation of a charge-imbalanced bilayer (left) and single quantum well (right) embedded into a planar microcavity confining the photon mode.

In this presentation, I will consider a charge-imbalanced mixture of electrons and holes in either doped single quantum wells or bilayers, strongly coupled to a cavity mode (see schematic Fig.1). I will discuss the occurrence of different coherent phases following the competition between long-ranged Coulomb interactions, Pauli blocking and the strong coupling to light.

Exciton-polarons in doped semiconductors

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The dynamics of a quasiparticle can be significantly modified by a quantum media surrounding it. This type of phenomenon can be viewed quite generally as a polaronic effect, using the concept invented by L. Landau and S. Pekar. The Bose-polaron problem involving the quantum bath of phonons or magnons has been important historically, stimulating the development of the path integral formulation of quantum mechanics and creative new numerical tools in quantum physics. Over the past decade, the Fermi-polaron problem involving a Fermi gas as the quantum media has become experimentally accessible in cold atom systems, and considerable progress has been achieved in understanding of its rich behaviour.

In my talk, I will argue that the Fermi-polaron physics govern the optical properties of moderately doped two-dimensional semiconductors. The interactions of photoexcited excitons with Fermi sea formed by excess charge carriers split them into attractive and repulsive exciton-polarons, that manifest as two separate peaks in the absorption. The doping dependence of resonant frequencies of two peaks and their amplitudes are in a very good agreement with recent experimental results as in conventional quantum well systems, as in transition metal dichalcogenides.

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Spectroscopic probes of quantum many-body correlations in polariton microcavities

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We theoretically investigate the many-body states of exciton-polaritons that can be observed by pump-probe spectroscopy. Here, a weak-probe "spin-down" polariton is introduced into a coherent state of "spin-up" polaritons created by a strong pump. We show that the spin-down impurities become dressed by excitations of the spin-up medium, and form new polaronic quasiparticles that feature two-point and three-point many-body quantum correlations, which, in the low density regime, arise from coupling to the vacuum biexciton and triexciton states respectively. In particular, we find that these correlations generate additional branches and avoided crossings in the spin-down optical transmission spectrum that have a characteristic dependence on the spin-up polariton density. Our results thus demonstrate a way to directly observe correlated many-body states in an exciton-polariton system that go beyond classical mean-field theories.

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CHARGE-IMBALANCED POLARITON CONDENSATES

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Polariton condensation is a well-established phenomenon featuring all the signatures of an ordinary condensate: U(1) symmetry breaking, superfluidity, vortices [1]. However, in the context of polariton condensation, almost exclusively balanced systems, with equal densities of electrons and holes, have been studied. This misses a whole class of potential exotic imbalanced condensed states like an FFLO in superconductors [2,3] or a breached-pair state proposed in the QCD systems [4].

Inspired by pioneering works on imbalanced electron-hole systems (due to applied bias voltage) in TMDC monolayers strongly coupled to a cavity photon [5], we explore whether a combination of strong matter-light coupling and electric field biasing promotes imbalanced condensed states, which do not exist otherwise. To address this question, we use a variational mean-field approach [6] to construct a finite temperature phase diagram.

On top of a balanced polariton and a dark imbalanced FFLO condensates, we find novel imbalanced polaritonic states with coexisting polariton condensate and unpaired electrons with either isotropic or anisotropic Fermi surface (see Fig. 1) depending on applied bias voltage. These states arise due to combination of strong matter-light coupling and long-range Coulomb potential. Moreover, akin to a usual balanced polariton condensate, these new states are stable at high temperatures (within a mean-field approximation).

Therefore, we predict new imbalanced polariton states, which should be possible to observe in an existing experimental platform of electrically biased TMDC monolayers.

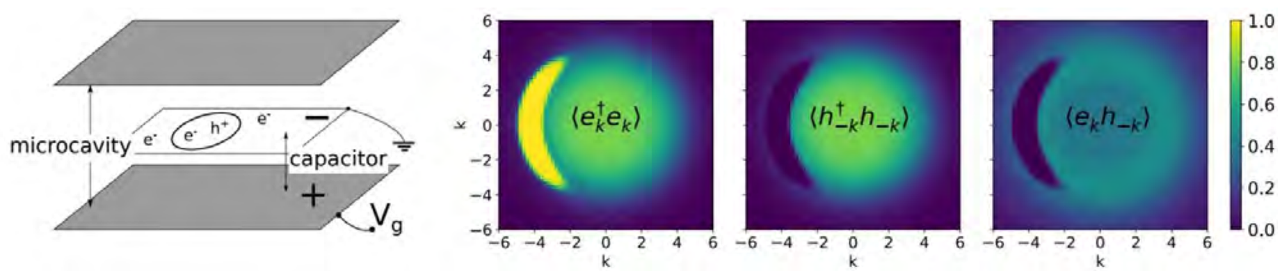

Fig. 1. Crescent state. From left to right: system cartoon, electron and hole mode populations, coherence in the momentum space.

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MEASURING EXCITON POLARITON INTERACTIONS AND RELAXATION WITH MULTIDIMENSIONAL COHERENT SPECTROSCOPY

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Multidimensional coherent spectroscopy is based on transient four-wave mixing and has been used to reveal dyanmics and interactions in a range of systems[1]. We have used this approach to reveal detail of the relaxation dynamics of exciton polaritons resonantly excited in the lower polariton branch of a GaAs-based quantum well in a cavity. Two-dimensional spectra, such as those shown below, map what is effectively the absorption energy (E_1) and emission energy (E_2), and in this case, these rephasing plots show homogeneous linewidths, even in the presence of inhomogeneous broadening.

After the initial excitation (t_2=0), the full range of energies of the lower polariton (LP) is excited, as demonstrated by the diagonal peak in the 2D spectrum at t_2=0. These polaritons rapidly (<500fs) relax, however, they do not produce cross-peaks, (see plot below at 500fs) suggesting this process may not conserve wave-vector. Finally, at longer times, the LP peak on the diagonal becomes narrower as the excitation density decreases, and a distinct diagonal peak at the exciton energy is evident. In this figure, it is also clear that there is a cross-peak between the bottom of the polariton branch and the bare exciton, without any intermediate crosspeak. This suggests the relaxation from the bare excitons (with high k) to the bottom of the LP is rather direct and different to the relaxation within the LP band. Further experiments, analysis and modelling will help to understand the relaxation mechanisms and interactions in these exciton-polariton systems.

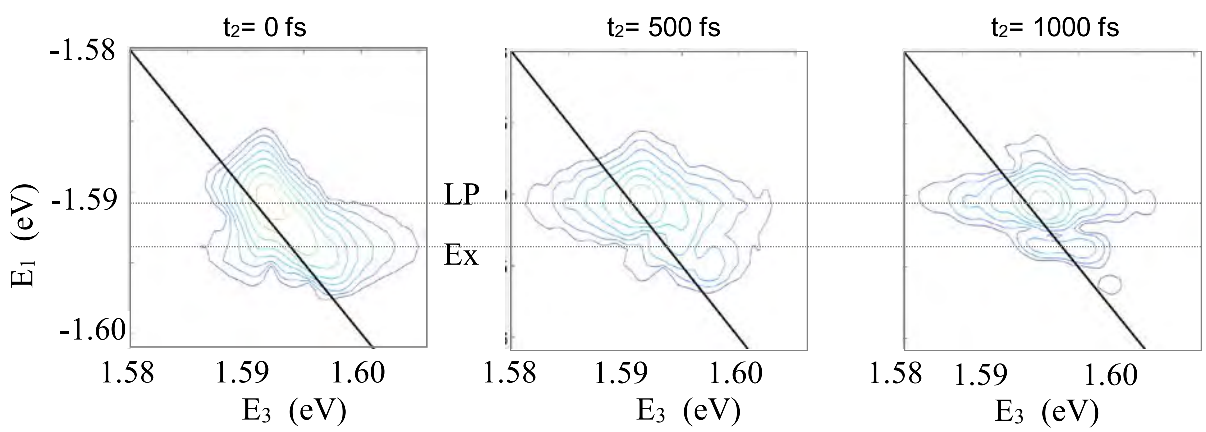

Fig. 1. Two-dimensional spectra from GaAs-based exciton-polaritons at population times t_2= 0, 500 fs, and 1000 fs. The E_1 (E_3) axis can effectively be considered the absorption (emission) energy, and the diagonal line marks the points where emission equals absorption energy. The dashed horizontal lines indicate the exciton energy (Ex) and the energy at the bottom of the lower polariton band (LP).

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BOSE-EINSTEIN CONDENSATION AND STIMULATED THERMALIZATION IN PLASMONIC LATTICES

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Bose-Einstein condensation has been realized for various particles or quasi-particles, such as atoms, molecules, photons, magnons and semiconductor exciton polaritons. We have recently experimentally realized a new type of condensate: a BEC of hybrids of surface plasmons and light in a nanoparticle array [1]. The condensate forms at room temperature and shows ultrafast dynamics. We utilized a special measurement technique, based on formation of the condensate under propagation of the plasmonic excitations, to monitor the sub-picosecond thermalization dynamics of the system. Recently, we have achieved such Bose-Einstein condensation also at the strong coupling regime, and shown by varying the lattice size that the thermalization in these systems is a simulated process that occurs in 100 femtosecond scale [2]. This new platform is ideal for studies of differences and connections between BEC and lasing [3,4,5]. While usually lasing in nanoparticle arrays occurs at the centre of the Brillouin zone, we have now demonstrated lasing also at the K-point [6]. The lasing mode can be identified with the help of group theory. Clear lasing is observed despite a narrow band gap at the K-point, which is promising considering future studies of topological photonics. Nanoparticle arrays are well suited for studies of topological phenomena due to the easy tunability of the array geometry and the system symmetries.

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EXCITATIONS IN STRONGLY INTERACTING FERMI GASES

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Dynamical processes in strongly-correlated quantum systems are central to understanding transport and dissipation. Here, we experimentally measure the excitation spectra of strongly interacting Fermi gases as a function of both the temperature and interactions. At temperatures below the superfluid transition, long wavelength excitations are dominated by the Bogoliubov-Anderson phonon mode whose frequency and width provide the sound speed and damping rate, respectively [1]. At higher energies, single particle excitations become accessible allowing a direct measurement of the pairing gap. Bragg spectra of gases at unitarity show a strong dependence on the temperature, particularly across the superfluid transition where the evolution of the phonon mode displays striking similarities to what is found in liquid helium [2]. In the high-momentum limit, studied of the excitation spectra reveal universal features, such as Tan's contact parameter which we have mapped across the superfluid transition [3]. These measurements establish quantitative benchmarks for many-body theories of fermionic matter.

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Probing Tan's contact in an exciton-polariton Bose-Einstein condensate

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The short-range behaviour of the many-body wavefunction of a quantum system with contact interactions is manifested in the momentum occupation distribution $N(k)$ as a power-law decay $\sim k^{-4}$ at large wavevectors. The asymptotic value $\lim_{k\to\infty} k^4 N(k) = C$ is referred to as "the contact" and has been linked to numerous universal thermodynamic relations in seminal papers of S.Tan [1]. The value of the contact has been successfully measured in fermionic gases at the unitary limit [2,3]. Similar studies are much more challenging in the case of bosonic quantum gases [4], where three-body Efimov resonances appear when approaching the unitary limit. Recently, the contact has been measured in a weakly interacting Bose-Einstein condensate (BEC), and significant deviations from theoretical predictions have been found [5].

Exciton polaritons are composite bosons resulting from the strong coupling between excitons and photons in a semiconductor microcavity. These quasiparticles can condense into a driven-dissipative BEC and form a macroscopically coherent many-body quantum state. We have recently observed experimental evidence of quantum depletion in a high-density exciton-polariton BEC [6], by probing the photoluminescence of the negative energy Bogoliubov excitation branch (so-called ghost branch – GB). Analysis of the asymptotic behaviour of momentum distribution in the GB allows for the extraction of the Tan's contact for various exciton-photon detunings, i.e. for different polariton-polariton interaction strengths and an excitonic fraction of the exciton-polariton quasiparticle, see exemplary data in Fig. 1. The obtained values of the contact show deviations from the theoretical predictions based on the local density approximation and Bogoliubov theory, which treats the exciton-polariton as a structure-less boson characterised by an experimentally measured contact interaction strength. We discuss the influence of the composite nature of exciton-polaritons on the short-range behaviour of the condensate wavefunction and possibility to connect the extracted Tan's contact to thermodynamical properties of exciton-polariton condensate.

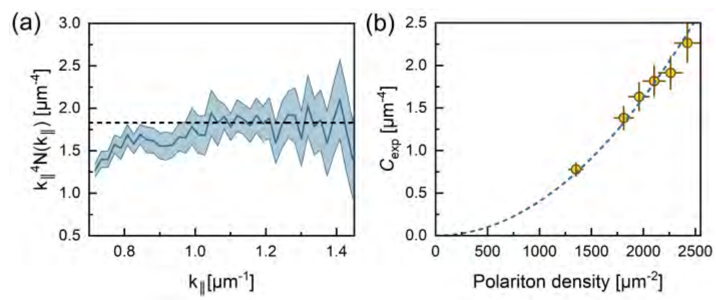

Fig. 1 (a) Measured dependence $k^4N(k)$ for extraction of the contact. (b) Tan's contact as a function of polariton density fitted with a quadratic function.

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COLLECTIVE OSCILLATIONS OF A TRAPPED EXCITON-POLARITON CONDENSATE

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Condensates of exciton-polaritons are nonequilibrium quantum fluids that exhibit an intriguing superfluid-like behavior [1], which, along with other collective properties, can be well understood by studying its elementary excitations. Recent experiments [2] measured the modified excitation spectrum but the near-zero momentum components, which are mostly affected by dissipation, were excluded. In this work, we observe collective oscillations, representing the low-energy excitations, of a high-density trapped condensate. Using an optically induced trap in the pulsed regime [3], we create condensates with long-lived sloshing that persist for the whole condensate lifetime, as shown in Figure 1. The longevity of the oscillation suggests that the damping due to friction from the normal (non-superfluid) component and the excitonic reservoir is minimal. The frequency of the oscillation, which is dominated by dipole modes, is around 10 GHz and chirps down as the density decays, confirming that the collective mode frequency depends on the mean-field energy. This work opens the way for probing and manipulating different oscillation modes which will shed light on unexplored properties of this weakly interacting system, such as the compressibility, hidden symmetry in two dimensions [4], and interaction of the first and second sounds.

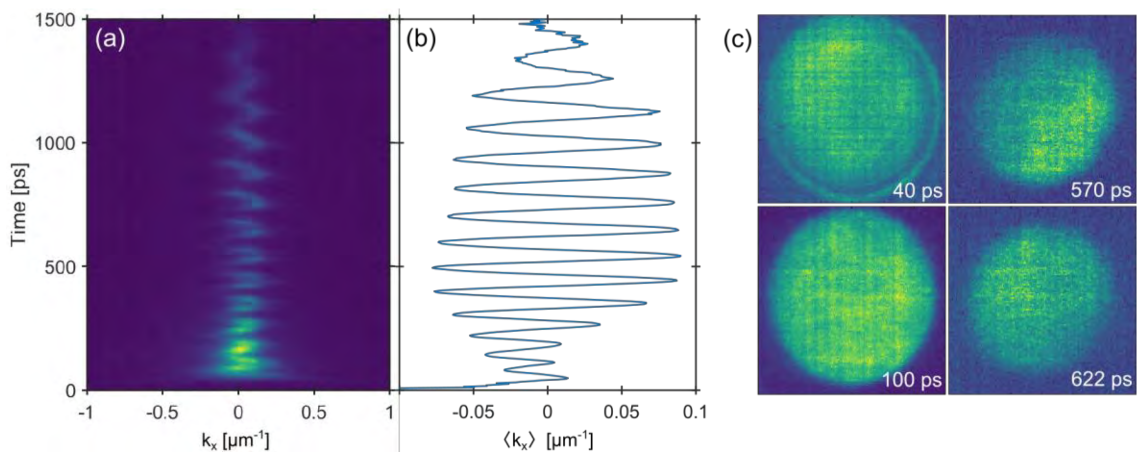

Fig. 1. Time-resolved (a) cross-section and (b) mean of the k-(momentum) space distribution of the sloshing condensate; (c) real space images of the condensate at different times.

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Chirality selective enhanced correlation among quantum emitters by chiral metallic structures

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High-density of quantum emitters in population inversion state exhibit a cooperative emission (superfluorescence) through the correlated polarizations. Superfluorescence has three main characteristics [1]: the peak of the emission intensity proportional to the square of the number N of the quantum emitters, the pulse width of the emission proportional to $1/N$, and the coherence and the directivity in the emission.

We have studied the anomalous enhancement of the cooperative effect by metallic structures sustaining the localized surface plasmons so far, where we use our theoretical method that can analyze the emission time profile of arbitrarily configurated emitters in an arbitrary dielectric environment [2]. In that study, we have revealed the enhancement of cooperative effect in superfluorescence largely depends on the metallic structure and the emitters' arrangement.

In this contribution, we consider chiral spatial structures of the metal and particle arrangements (Fig. 1), and calculate the emission intensity of superfluorescence. The result (Fig. 2) shows that a definite chiral selectivity of the enhanced correlation in a superfluorescence. Furthermore, when examining the polarization state of the radiation, there was a chiral selective change. We can expect that these results will lead to a new methodology in chiral research. In this presentation, we will discuss the details conditions of the metal and emitters' configurations for the chiral selective behavior of the time evolution of the emission intensity, including the dependence of the metal size and the emitter resonance energy.

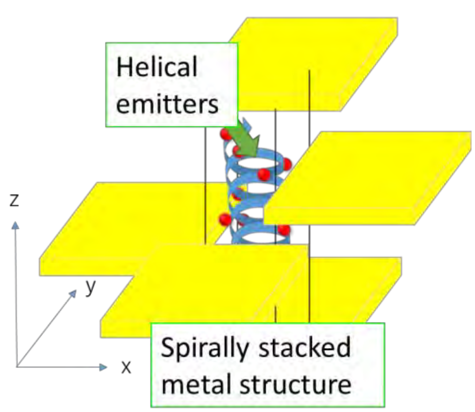

Fig. 1. Schematic diagram of metal and emitters' spatial structures with chirality.

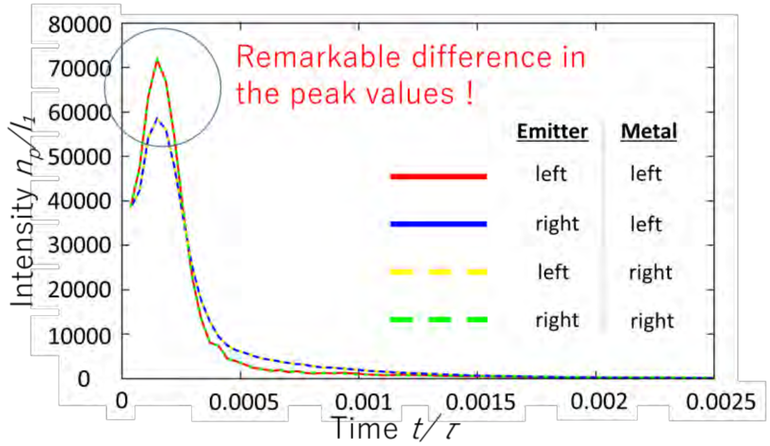

Fig. 2. The light emission intensity was calculated when the metal structures and the light emitters were arranged as shown in Fig. 1.

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CAVITY-INDUCED MODIFICATION OF MOLECULES

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Organic molecules have long been recognized as a favorable type of emitter to achieve the strong-coupling regime, i.e., exciton-polariton formation, even at room temperature due to their large dipole moments and the stability (large binding energy) of Frenkel excitons. Strong coupling creates a paradigmatic hybrid quantum system with eigenstates that have mixed light-matter character, so-called polaritons. Traditionally, this has been used to achieve new functionalities in which polaritons are thought of as dressed photons, e.g., by exploiting exciton-exciton interaction to achieve interacting polaritons. However, over the last years, it has become clear that this regime also allows to significantly modify internal material properties and dynamics. Polariton formation leads to changes in the excited-state character and energy levels (i.e., potential energy surfaces) of the involved molecules, which can affect a wide range of properties, such as energy transport, photochemical reactions, and even thermally driven ground-state chemical reactions.

At the same time, organic molecules are highly complex material systems with a large number of nuclear (vibrational) degrees of freedom. Consequently, an accurate theoretical description of such systems faces a large amount of challenges: Fundamentally, electronic, nuclear, and (quantized) photonic degrees of freedom have to be treated on an equal footing both statically and dynamically. Typical experimental systems display ultrafast femtosecond-scale dynamics in their coupled photonic, electronic, and nuclear degrees of freedom due to room-temperature molecular dynamics and (typically) femtosecond-scale lifetimes of the cavity modes and plasmonic resonances employed as the photonic components of the polaritons. A theoretical description of these systems thus requires a combination of techniques from historically separate fields such as quantum optics, quantum chemistry, and ultrafast laser science.

I will give an overview over some effects observed in these systems, focusing on ways to observe and manipulate ultrafast dynamics in these systems, as well as different proposals for steering and catalyzing (photo)chemical reactions.

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Stand-alone quantum dot-based single-photon source operating at telecommunication wavelengths

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The ultimate security of the quantum communication protocols/schemes can be ensured by laws of quantum mechanics, but realization of the quantum communication protocols requires, among others, sources of single photons. For such solutions to become practical not only the sources need to be efficient, but also compatible with existing fiber infrastructure (emission at telecom spectral range) as well as semiconductor technology. Preferentially they should be fiber-coupled and operating at room temperature. Semiconductor quantum dots (QDs) provide inherently pure single-photons and they can fulfill almost all abovementioned requirements. The fundamental limit is room-temperature operation which is fundamentally not-achievable for QDs emitting at telecom wavelengths.

In this work we present realization of stand-alone fiber-coupled QD-based single-photon source operating in the 2nd telecom window and cooled down by industrial Stirling cryocooler (T = 40 K) which does not require access to cryogenics. The active element is a single $In_{0.75}Ga_{0.25}As/In_{0.2}Ga_{0.8}As/GaAs$ QD deterministically incorporated [1] into a numerically (finite element method) optimized mesa structure [2] for enhanced extraction efficiency. The especially developed interferometric method has been used to position a specialty highly gradually Ge doped single-mode fiber (NA=0.42) with respect to mesa of a cylindrical shape [3]. The single-photon purity has been evaluated by autocorrelation measurements with superconducting NbN detectors in all-fiber Hanbury-Brown and Twiss configuration with custom-designed fiber elements to deliver the optical pumping but also to filter from the detection channel the laser line and scattering light as well as the emission from a sample except of a single QD transition. In result, there could be obtained a train of single photons at the output of the standard telecom single-mode fiber.

The single-photon rate of the source at the output is 20 kHz which corresponds to coupling efficiency into the specialty fiber of 30%. The best single-photon purity measured under non-resonant pulsed-excitation (80 MHz, 50 ps pulses) corresponds to $g^{(2)}(0) = 0.15$ proving single-photon emission from such stand-alone device at the second telecommunication window.

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Inas quantum dots and surface acoutsic wave cavities for quantum transduction

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Quantum information technology based on superconducting microwave technology is progressing rapidly and is now widely adopted by large corporations and small startup firms. These components operate at extremely cold (<20mK) temperatures requiring an isolated environment. Therefore, a critical problem is the transfer of quantum information out of and into the cryostat. Currently, the only viable method for transporting quantum information ~km distances is via optical photons. Subsequently, efficient and noise-free microwave-optical conversion is required. Recently, progress has been made by simultaneously coupling the light and microwave degrees of freedom to nanomechanical resonators. A successful approach is to place a SiN membrane in a high-Q Fabry-Perot cavity [1]. The motion of the membrane parametrically modulates the frequency of the cavity light via the index of refraction.

Here, we present progress on a new type of transducer where the optical cavity is replaced with an InAs quantum dot and the membrane is exchanged for a surface acoustic wave cavity (SAWc). Recently, hybrid quantum devices involving SAW cavities and superconducting qubits have been successfully integrated [2]. In a SAWc, phonons will parametrically modify the resonance frequency of a QD via strain [3]. In this work, we demonstrate progress in developing state-of-the-art, stable SAWc operating at ~ 3.4GHz. We demonstrate a reduction in the SAWc mode volume by using focusing SAW mirrors (Fig. 1). These devices are characterized using atomic force measurements of SAWc cavity-modes demonstrating high-quality focusing phononic wavefronts. Finally, we discuss reducing bulk scattering, theoretical coupling rates and discuss efficient photon extraction.

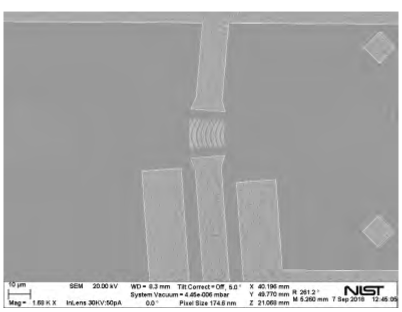

Fig. 1. SEM image of SAWc device.

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PHONON-INDUCED QUALITY ENHANCEMENT OF QUANTUM DOT-BASED PHOTONIC SOURCES

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Semiconductor quantum dot-cavity systems are widely discussed as sources of highly nonclassical photonic states, such as single photons and pairs of polarization-entangled photons. Since the pure-dephasing type coupling to longitudinal acoustic phonons has been identified as the key decoherence mechanism for quantum dot excitons one would naively expect the phononic influence on the quality of the target photonic states to be of a similar detrimental nature. But, quite unexpectedly, we were able to theoretically identify situations leading to a phonon-enhancement of single-photon purity [1] and photon entanglement [2].

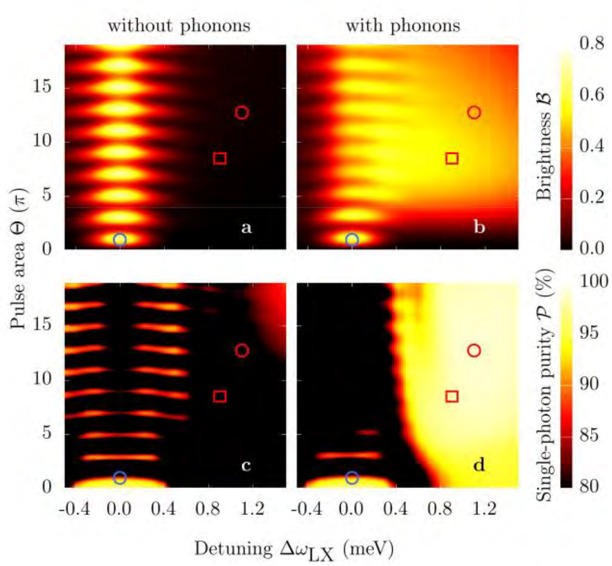

Fig. 1. Source brightness (a,b) and single-photon purity (c,d) as a function of the laser-exciton detuning and the pulse area. Image taken from Ref. [1].

Comparing the standard resonant π-pulse excitation with off-resonant phonon-assisted schemes in terms of source brightness and single-photon purity reveals a wide parameter regime, where the single-photon purity is close to or beyond the value obtained in the resonant scheme for otherwise identical parameters [1] (cf. Fig. 1 d) and the brightness does not drop significantly (cf. Fig. 1 b). Besides numerous experimental advantages, off-resonant schemes ultimately pave the way to excite two or more spatially separated dots with the same laser, which is a crucial step towards complex quantum networks.

Furthermore, we predict a phonon-induced enhancement of photon entanglement in the biexciton-exciton cascade in a certain parameter range caused by a combination of phonon-induced dephasing and renormalization of the cavity coupling strength.

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Prediction of the spin triplet two-electron quantum dots in Si: towards controlled quantum simulations of magnetic systems

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Ground state of two-electron quantum dots in single-valley materials like GaAs is always a spin singlet regardless of what the potential and interactions are. This statement cannot be generalized to the multi-valley materials like n-doped Si. Here we calculate the spectrum of a two-electron Si quantum dot analytically and numerically and show that the dot with the lateral size of several nm can have the spin triplet ground state which is impossible in the single-valley materials. Predicted singlet-triplet level crossing in two-electron Si quantum dots can potentially establish the platform for quantum simulation of magnetic many-body systems based on the triplet quantum dots. We suggest several examples of such systems that open a way to controlled quantum simulations within the condensed matter setting.

ULTRASTRONG LIGHT-MATTER AND MATTER-MATTER COUPLING: DICKE PHENOMENA

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Recent experiments have demonstrated that light and matter can mix together to an extreme degree, and previously uncharted regimes of light-matter interactions are currently being explored in a variety of settings, where new phenomena emerge through the breakdown of the rotating wave approximation [1]. This talk will summarize a series of experiments we have performed in such regimes. We will first describe our observation of ultrastrong light-matter coupling in a two-dimensional electron gas in a high-*Q* terahertz cavity in a quantizing magnetic field, demonstrating a record-high cooperativity [2]. The electron cyclotron resonance peak exhibited splitting into the lower and upper polariton branches with a magnitude that is proportional to the square-root of the electron density, a hallmark of cooperative vacuum Rabi splitting, known as Dicke cooperativity. Additionally, we have obtained clear and definitive evidence for the vacuum Bloch-Siegert shift [3], a signature of the breakdown of the rotating-wave approximation. The second part of this talk will present microcavity exciton polaritons in a thin film of aligned carbon nanotubes [4] embedded in a Fabry-Pérot cavity. This system exhibited cooperative ultrastrong light-matter coupling with unusual continuous controllability over the coupling strength through polarization rotation [5]. Finally, we have generalized the concept of Dicke cooperativity to demonstrate that it also occurs in a magnetic solid in the form of matter-matter interaction [6]. Specifically, the exchange interaction of N paramagnetic erbium(III) (Er^{3+}) spins with an iron(III) (Fe^{3+}) magnon field in erbium orthoferrite ($ErFeO_3$) exhibited a vacuum Rabi splitting whose magnitude is proportional to $N^{1/2}$. Our results provide a route for understanding, controlling, and predicting novel phases of condensed matter using concepts and tools available in quantum optics, opening up exciting possibilities to combine the traditional disciplines of many-body condensed matter physics and cavity-based quantum optics.

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ULTRASTRONG COUPLING IN CAVITY QED: EXOTIC PHENOMENA AND THEIR SIMULATION

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Recent technological developments have made it increasingly easy to access the non-perturbative regimes of cavity-QED known as ultra or deep strong coupling, where the light-matter coupling becomes comparable to the bare modal frequencies [1]. Here, we present two works that highlight the unusual phenomenology associated to the ultrastrong coupling regime, and show how these effects can be replicated even without reaching these high-values of light-matter coupling.

First, we will discuss how in the non-perturbative light-matter coupling regime, the single-mode Rabi model becomes unphysical, allowing for superluminal signalling. We show that the multi-mode description of the electromagnetic field, necessary to account for light propagation at finite speed, reveals phenomena of fundamental interest on the dynamics of the intracavity electric field, where a free photonic wavefront and a bound state of virtual photons are shown to coexist [2].

Second, we will describe how a number of analogs of well-known nonlinear-optics phenomena that can be realized in the ultrastrong coupling, such as the excitation of two atoms by a single photon, can also be simulated with coupling rates below this regime by means of strong optical drivings [3].

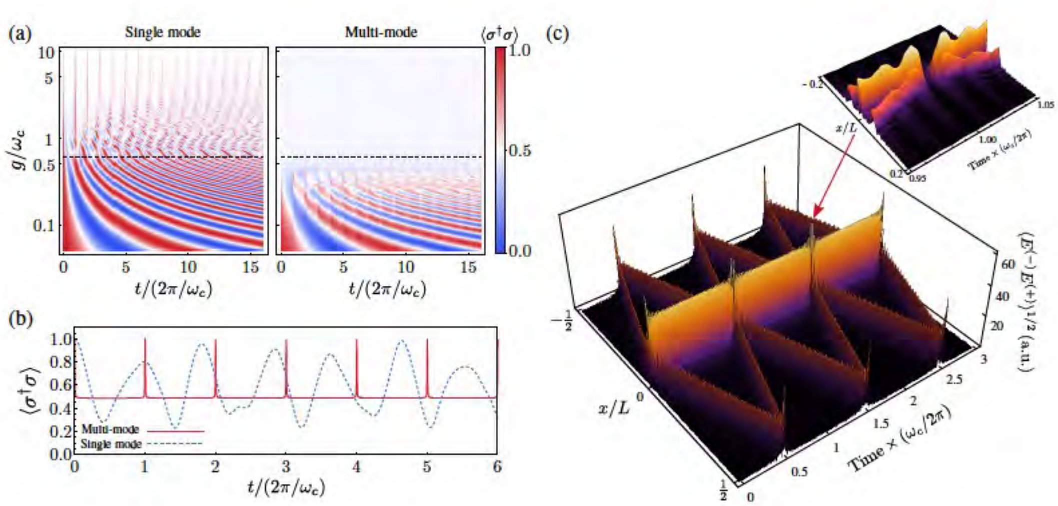

Fig. 1. Dynamics of light and matter in the ultrastrong coupling regime of the multi-mode Rabi model.

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Emergent quantum criticality in driven-dissipative cavity arrays

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The possibility of realizing strongly correlated states in photonic cavity arrays has stimulated an intense research on open quantum many-body systems, establishing a fascinating interface between condensed matter physics and quantum optics. Among the phenomena emerging in these systems, dissipative phase transitions are nowadays receiving increasing attention. Due to the competition between the coherent and incoherent dynamics, a continuous tuning of the external parameters can lead to a criticality in the non-equilibrium steady state of the open system.
Here, I will present a theoretical study of the driven-dissipative Bose-Hubbard model in the presence of two-photon driving and losses, a model that is within reach of current experimental techniques based on circuit-QED resonators [1]. The mean-field analysis of the steady state of this system reveals the occurrence of a second-order phase transition, characterized by the spontaneous breaking of the Z2 symmetry of the model [2]. The critical exponents associated to the transition are computed using a fully many-body approach, based on the corner-space renormalization method. These show that the phase transition belongs to the universality class of the quantum transverse Ising model, revealing thus the important role of quantum fluctuations and long-range entanglement at the critical point [3].
Quadratically driven-dissipative photonic arrays are feasible both on a circuit-QED platform and using microcavity polaritons, as in both cases the coherent two-photon driving process has been experimentally demonstrated. Such systems would then be suitable for the simulation of a wide range of collective phenomena, among which the emergence of the spin liquid phase in frustrated magnets [4].

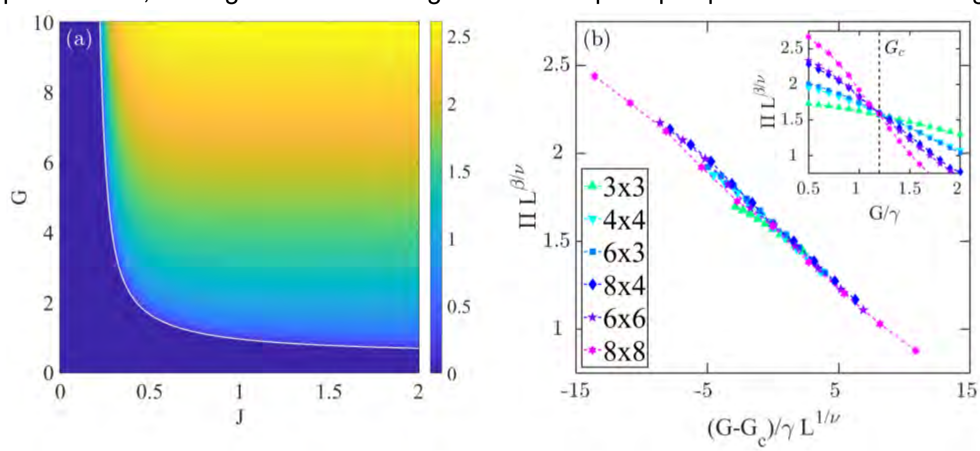

Fig. 1. Figure (a) Mean-field phase diagram of the quadratically driven-dissipative Bose-Hubbard model, as a function of the two-photon driving amplitude G and of the hopping strength J: the color plot indicates the value of the order parameter, i.e. the expectation value of the coherence. (b) Finite size scaling of the parity in a 2D lattice, using the critical exponents of the quantum 2D transverse Ising model.

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Critical and superfluid properties of polariton condensates

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Driven-dissipative polariton fluid can exhibit a novel non-equilibrium order, where superfluidity is accompanied by stretched exponential decay of correlations [1]. This celebrated Kardar-Parisi-Zhang (KPZ) phase has not been achieved in any system in 2D and even 1D realisations are not conclusive.

We show analytically [1] and confirm numerically that polaritons in the OPO configuration can be fine-tuned to realise the so far experimentally elusive KPZ phase in two dimensions for realistic experimental parameters. Further, we study the phase-ordering after a sudden quench across the critical region [2] and show that the unique interplay between non-equilibrium and the variable degree of spatial anisotropy leads to different critical regimes. By providing an analytical expression for the vortex evolution, based on scaling arguments, which is in agreement with the numerical results, we confirm the form of the interaction potential between vortices in this KPZ system.

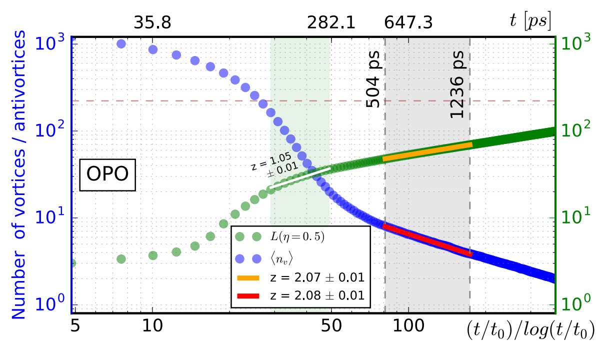
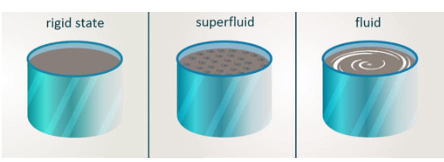


Fig1: Phase ordering kinetics after quench

At the same time, we obtain that for typical experimental conditions polariton system, despite its driven-dissipative nature, fulfils dynamical scaling hypothesis by exhibiting self-similar patterns for the two-point correlator at late times of the phase ordering [3]. We show that polaritons are characterised by the dynamical critical exponent $z \approx 2$ and that the Kibble-Zurek mechanism holds [4]. Thus, our findings reinforce the idea that the concepts of universality and critical dynamics are not restricted to systems at or close to thermodynamic equilibrium, but extend to driven-dissipative ones that do not conserve energy nor particle number, nor they satisfy a detailed balance condition.



Finally, we determine that the superfluid response—the difference between responses to longitudinal and transverse forces—is zero for *coherently* driven polaritons [5]. This is a consequence of the gapped excitation spectrum caused by external phase locking. Furthermore, while a normal component exists at finite pump momentum, the remainder forms a rigid state that is unresponsive to either longitudinal or transverse perturbations and suggests that the suppression of scattering observed in experiments should be interpreted as a sign of a new rigid state of matter and not a superfluid.

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DYNAMICS OF VORTEX PINNING IN A TWO-DIMENSIONAL SUPERFLUID FLOW

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An understanding of the turbulent behaviour of superfluid flow is important for their future development for devices such as exciton transistors. Therefore, an understanding of the dynamics of vortices and their pinning behaviour is essential. While vortex pinning is reasonably well-understood in superconductors, an understanding of the dynamics of vortex pinning is not as well developed in superfluids [1, 2]. Here we simulate the scattering of a quantised vortex off a pinning obstacle in a two-dimensional atomic superfluid using the Gross-Pitaevskii equation. We provide a framework for interpreting the numerical simulations by mapping the mean-field description of the superfluid to classical electrostatics. We show that our simulations are consistent with analytical solutions of an analogue system of a free charge interacting with a dielectric medium in regimes when the flow velocity is small (see Fig. 1). By building a phase portrait of vortex pinning we elucidate the physical mechanisms that lead to vortex pinning, as well as calculating the superfluid velocity required to unpin a vortex. We find that larger pinning sites are not always the most efficient way to pin a vortex. We will also present results for vortex pinning in driven-dissipative polariton superfluid flows.

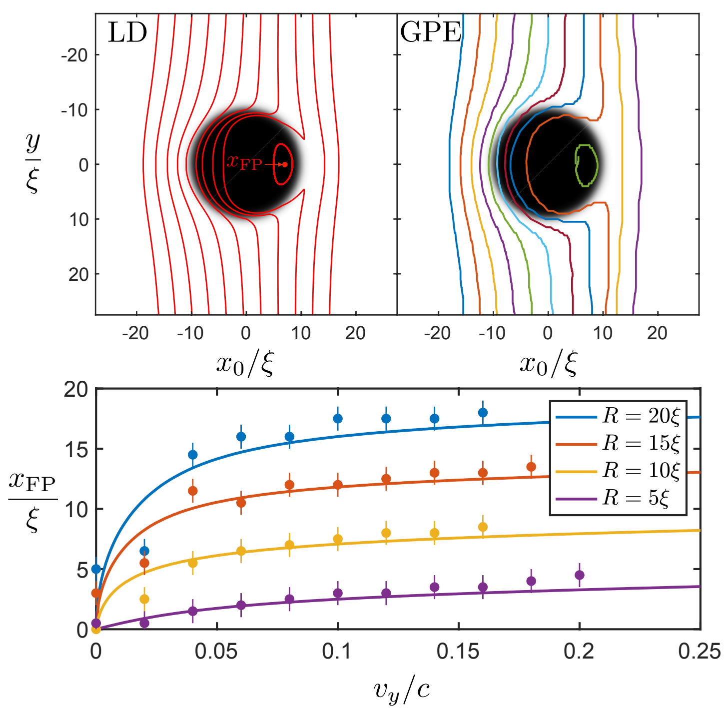

Fig. 1. Top: Comparison between linear dielectrics (LD) and the Gross-Pitaevskii equation (GPE) of vortex trajectories past a soft pinning potential in a uniform superfluid flow. **Bottom:** Position of the vortex fixed point, as shown in the upper left panel, between LD (solid line) and GPE (data points) as a function of superfluid velocity.

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Spontaneous emergence and tuning of phase coherence revivals within a quantum fluid

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Polaritons are quantum bosonic admixtures of excitons and photons, that have been shown to undergo the BEC phase transition and have been proposed as a platform for simulations of classical Hamiltonians [1]. The polariton architecture is advantageous for such endeavors, featuring extreme optical control and scalability enables straightforward realization of large scale lattices of interacting condensates limited mainly by the available optical power, while also featuring extremely efficient readout of the spin degree of freedom owing to the large number of particles populating the quantum degenerate condensation level. Additionally, we have recently demonstrated, that when the system is driven to the weak inter-particle interaction limit and interactions with the incoherent reservoir are suppressed, the coherence time of the polariton Bose gas increases to almost three orders of magnitude beyond the polariton lifetime of ~5ps, to the nanosecond range [2], underscoring the huge potential of the system should quantum effects be revealed, allowing individual spinor condensates to be treated as qubits [3]. Here we present and discuss initial experimental evidence towards the revealing of quantum coherence in spinor polariton BECs. It has been shown that in the optical trap configuration [4], the BEC tends to coalesce into one of its two spin eigenstates [5,6]. By spin polarizing the reservoir of particles (excitons) from which polaritons originate, combined with the macroscopic number of particles (N~2000) of the spinor condensate, we induce a local effective magnetic field on the system. The application of an effective field Ω will induce rotations of the spin state of the system around the Bloch sphere [3], while control of this field can serve as a means of coherent control of the BEC. By means of gated single shot delayed interferometric measurements of the condensate for the first time we uncover coherent rotations around the Bloch sphere that manifest as revivals of the first order normalized Glauber correlation function ($g^{(1)}(\tau)$) and demonstrate the extreme coherent control capabilities inherent in the system.

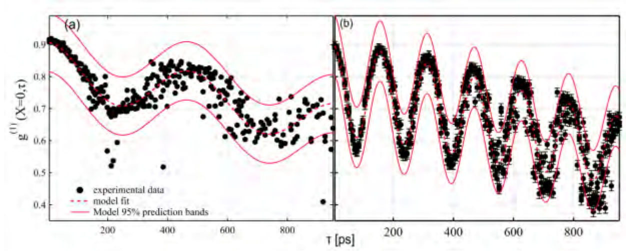

Fig. 1. Emergence of coherence revivals in a polariton BEC for increasing density. (a) For a condensate density around 1.5 times the threshold density we observe that the oscillation of the matter wave field accelerates and becomes more pronounced (b).

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SOLITON PATTERNS AND STATIONARY ARRAYS OF VORTEX STREETS IN A 2D POLARITON SUPERFLUID

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The quantum fluids of light [1] are a wide family of systems where an effective photon-photon interaction can be engineered, resulting in collective hydrodynamic effects. Exciton-Polaritons in semiconductor microcavities are a paradigmatic example of this behaviour.
In this work, we show how, in a resonantly driven 2D polariton superfluid, the combination of the bistability behaviour of the system with flexible all-optical methods allows to shape the potential polariton landscape and to control the formation and the propagation of a new class of dark solitons. Due to the onset of the snake instabilities these topological defects evolve in stationary symmetric or anti-symmetric arrays of vortex streets, straightforwardly observable in CW experiments [2]. The flexibility of this photonic platform allows implementing more complicated potentials such as maze-like channels, with the vortex streets connecting the entrances and thus solving the maze. These results open the way to the study of quantum turbulence.

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Direct transfer of light's orbital angular momentum onto a nonresonantly excited polariton superfluid

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An exciton-polariton (polariton) is a Bosonic quasiparticle formed through the strong coupling of an exciton and a photon. It can condense into a coherent ground state which behaves like a superfluid in many ways. It is an inherently driven-dissipative superfluid due to the presence of pumping and leakage. Therefore, formation of both the condensate itself and quantized vortices of the condensate has been a subject of intense research. In this experiment, we present a relatively simple method to create quantized vortices in the polariton condensate with a non-resonat Lagurre-Gaussian (LG) beam. We found that the chirality of the polariton vortex mostly depends on the orbital angular momentum of the pumping beam. [1]

No fine tuning of other parameters such as the laser beam's intensity, energy, momentum, size or shape is required Polariton condensates angular momentum follows the incident beam's angular momentum both in direction and magnitude indicating some form of angular momentum transfer occurring from the beam to the condensate. In other words, there is a one to one correspondence between the photon's angular momentum to polariton's angular momentum and photonic control of polariton's topological charge is possible. [1]

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Real magnetic fields and artificial Hamiltonians to control exciton-polaritons' spin

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The internal angular momentum, the spin of polaritons, is an important degree of freedom that can be used to control polaritons and its condensates. Polaritons inherit the spin property from excitonic component and from the point of view of spin structure are therefore bosons with a 1/2 pseudospin. Spin of polaritons is difficult to control through external parameters because polariton Zeeman splitting is usually very weak in standard semiconductor microcavities. However, spin effects can be magnified by increasing the sensitivity to magnetic field of either excitonic or photonic part of polariton in a specially designed structures.

To control the excitonic part, we propose structures based on II-VI semimagnetic semiconductors with magnetic ions incorporated into the crystal lattice. In the CdMgZnTe microcavity and CdMnTe material of the quantum well, the *s,p-d* exchange interactions between localized *d*-shell electrons of the magnetic ions and delocalized band electrons and holes allows to enhance magneto-optical properties of polaritons. I'll discuss many spectacular effect that are observed in semimagnetic exciton-polaritons and its condensates, such as giant Zeeman splitting, condensation induced by external magnetic field, giant spin Meissner effect, and spin polarized vortices. I'll demonstrate that the control over the condensate spin can be taken through external parameters such as excitation power and/or magnetic field.

The control over the polariton spin through photonic part is more difficult. Photons do not react directly to external magnetic field, so to study spin effects we propose a synthetic field resulting from H-V splitting of photonic modes which leads to the effects known as optical spin-Hall effect. I'll demonstrate a new type of a tunable birefringent microcavity filled with liquid crystal, where the H-V splitting can be tuned over extreme range from -20 meV to +50 meV. Moreover, when cavity thickness reaches the resonance condition for the photonic modes of different even-odd parities, a new coupling term becomes observable. The photon modes become circularly polarised and split, as described by the Rashba-Dresselhaus spin-orbit coupling and artificial magnetic field (Zeeman) terms in the Hamiltonian.

Our results demonstrate the wide range of method to control over polariton spins and are the first step to use the spin degree of freedom in realization of polariton simulators and logic operations based on polariton condensates.

Acknowledgment
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Switching the topological charge of exciton polariton vortices

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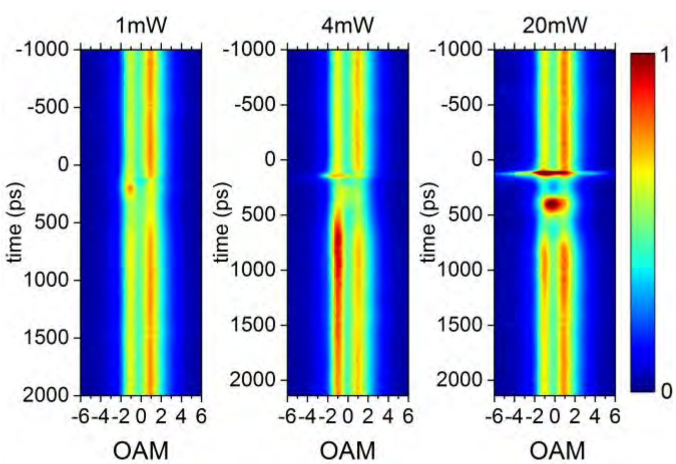
Vortices are elementary excitations arising in exciton polariton condensates [1] and consist of a $2\pi\cdot m$ radial phase shift of the polariton wavefunction, where m is the topological charge of the vortex. This topological charge translates into the orbital angular momentum (OAM) state of the emitted light field and can be detected by application of a dedicated OAM spectroscopy technique [2]. This technique gives us the opportunity to study the temporal dynamics of vortices in exciton polariton condensates without using complex interferometric techniques that also always require a phase reference. Here, we experimentally demonstrate the switching of the topological charge of a vortex due to a pulsed perturbation [3].
First, we create a stable localized m=+1 vortex inside an annular trap created all-optically by a CW laser. Then an additional non-resonant pulsed laser is switched on in addition to create a potential barrier, which interacts with the polariton vortex and may reverse its direction of rotation. Depending on the pumping power of the pulsed laser a switching to the m=-1 state is observed. This effect is shown in Fig. 1.



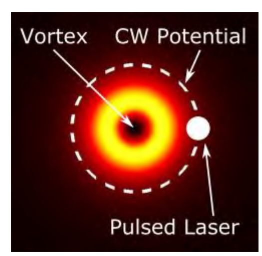


Fig. 1. Left: Vortex switching in dependence of the excitation power of the pulsed perturbation. Right: Experimental geometry.

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Relaxation to negative temperature equilibria in a chiral system of superfluid quantum vortices

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A system of N identical point-like vortices confined to a disk exhibit a symmetry-breaking phase transition, whereby they preferentially gather into an off-axis cluster at certain values of angular momentum and energy [1]. These distributions can be understood as maximum entropy states at negative absolute temperatures, a concept first put forward by Onsager to explain the emergence of coherent vortices from turbulent flow [2]. Here, we experimentally realize these non-axisymmetric vortex equilibria in an atomic superfluid containing quantized vortices, Further, we demonstrate the relaxation of a non-equilibrium initial state to negative temperature equilibrium. We find the experimental observations to be in excellent agreement with microcanonical Monte Carlo simulations of the point-vortex ensemble, evolving gradually through different equilibrium states under weak dissipation. We demonstrate that the system dynamics can be quantitatively modelled by a simple point-vortex model supplemented by a Brownian motion term. Our results establish quantum gases as a platform for quantitative studies of emergent quantum vortex phenomena, and open new directions in the study of turbulence, vortex matter [3], and statistical mechanics of systems with long-range interactions.

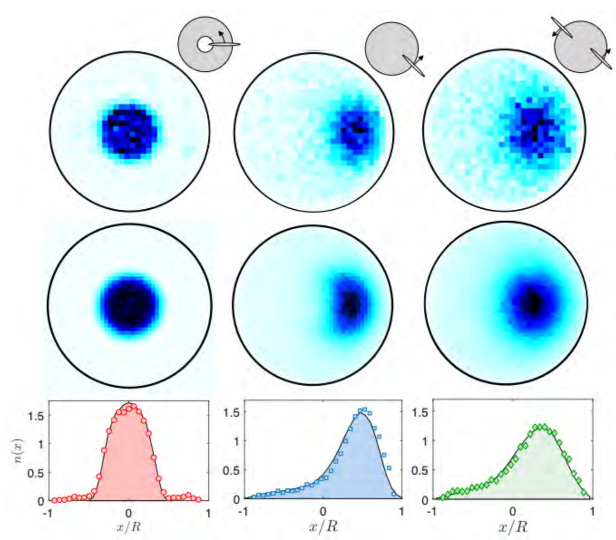

Fig. 1. Comparison of equilibrium vortex density histograms for experiment (top row) and Monte Carlo simulations (middle row). The bottom row shows column-integrated densities for experiments (data points) and simulation (black lines). The on-axis state corresponds to a positive vortex temperature, while the two off-axis states have negative absolute temperature.

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Synthetic hamiltonians and spin-orbit engineering in tunable birefringent microcavities

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Spin-orbit optical interactions in photonic systems exploit the analogy between the quantum mechanical description of electronic spin-orbit system and synthetic Hamiltonians derived for propagation of electromagnetic waves in dedicated spatial structures. We realize an artificial Rashba-Dresselhaus spin-orbit interaction (SOI) and synthetic magnetic field (Zeeman term) using a birefringent photonic microcavity.

A nematic liquid crystalline (LC) optical medium was enclosed in a typical Fabry-Perot resonator. The long-range order of elongated liquid crystals molecules results in a strong anisotropy in particular in optical properties. The liquid nature of these materials, thus freedom of molecular reorientation, allow for convenient control of these properties by relatively weak external electric fields. Significant changes in the optical properties of LC can be obtained after applying merely several volts. With the ability to manipulate the permittivity tensor and, therefore, effective refractive indices for different polarizations of light it is possible to tune the energy splitting between cavity modes which strongly influences the reflectivity and transmission of the microcavity (Fig. 1).

When two linearly polarized modes of different parity are brought into resonance theoretical analysis of birefringent electromagnetic waveguide results in SOI effects of light which stem directly from the solutions of Maxwell equations, in the form of $\widehat{H}_{RD} = -2\alpha\hat{\sigma}_z k_y$, where $\hat{\sigma}_z$ is the Pauli matrix describing polarization ("spin") of light and k_y is light's direction of propagation. The Rashba parameter α depends on the properties of LC and cavity dimension. We performed three-dimensional tomography in energy-momentum space to directly observe the spin-split photon dispersion relation in the presence artificial spin-orbit coupling. Engineering of spin-orbit synthetic Hamiltonians in cavities opens the way to photonic emulators of quantum Hamiltonians with internal degrees of freedom.

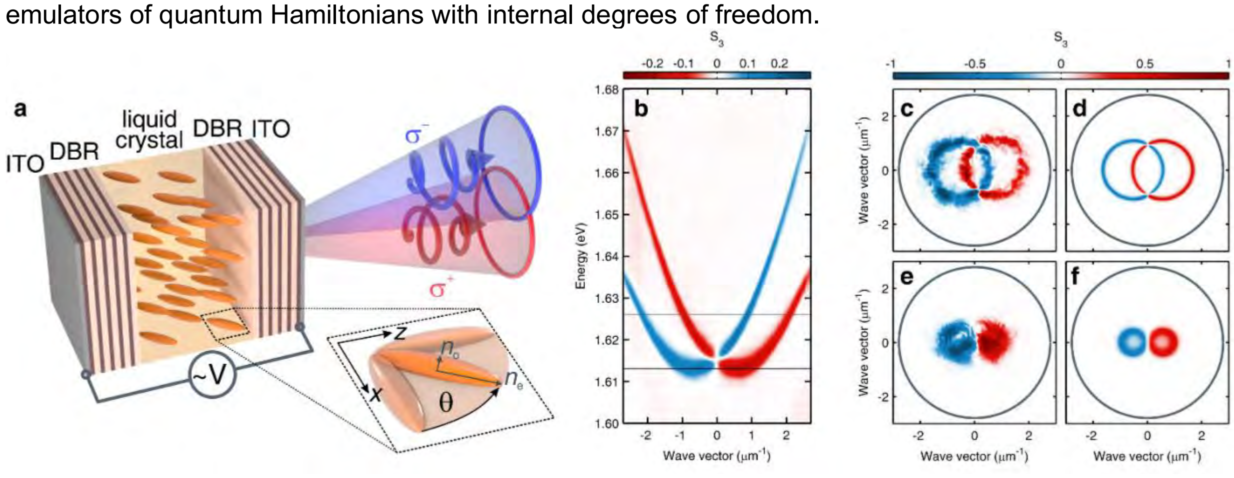

Fig 1. a Scheme of the birefringent microcavity and degree of circular polarization (S3 Stokes parameter) of **b** reflected and **c-f** transmitted light in momentum space. **b,c,e** experiment **d,f** modeling for different energies marked in **b**.

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OBSERVATION OF NON-SIMULTANEOUS ROTATION OF EXCITON-POALRITON SUPERFLUID

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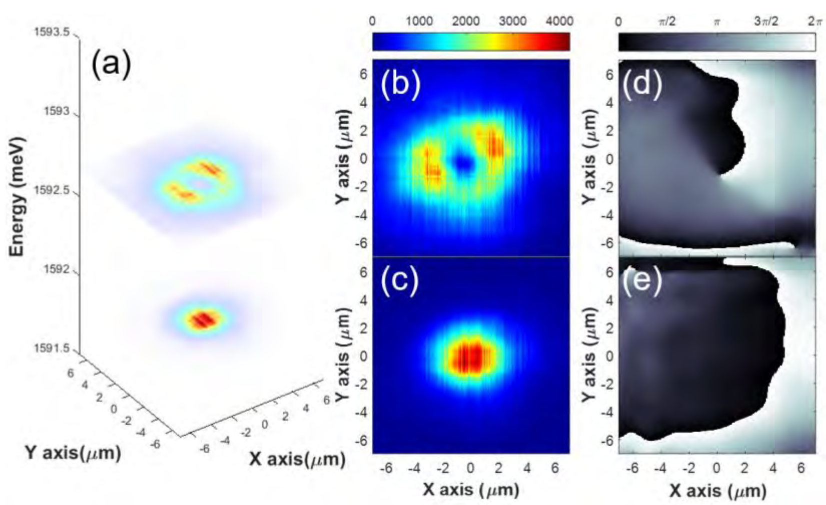
Exciton-polaritons (polaritons) in a semiconductor based 2D microcavity are bosonic quasiparticles, which are formed as a result of strong coupling between quantum well excitons and cavity photons. Polaritons condense to macroscopic coherent states, called polariton condensates due to their bosonic characteristics. A quantum vortex state, which has quantized angular moment in a superfluid, can be created by non-resonant Laguerre-Gaussian excitation in GaAs based planar microcavity.[1] Traditional superfluids have been described as a single wave function with all particles have the same angular momentum. However, we show that total angular momentum of polariton superfluid need not be quantized in the same way. We observed the photoluminescence of two distinguished polariton states in energy spectrum as shown in Fig. 1(a). Figs. 1(b) and 1(d) show that the higher energy state has a ring shaped intensity distribution and a 2π phase winding around the core of polariton distribution, indicating the presence of a quantized vortex. Figs. 1(c) and 1(e), however, show that the lower energy state has Gaussian distribution and zero angular momentum. So, the polariton superfluid has both the rotational and irrotational parts simultaneously. This phenomenon most likely resulted from non-equilibrium dynamics of polariton condensates and relaxation process of condensation. This result will be helpful for understanding superfluidity of polariton condensates and non-equilibrium superfluid in general.



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OPTICAL VORTEX CORE SWITCHING IN POLARITON CONDENSATES

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Vortices are topological objects carrying quantized orbital angular momentum, also known as topological charge, and have been widely studied in many physical systems. In those with spin degree of freedom the elementary excitations are so called half-vortices (HVs), referring to a vortex state carrying a topological charge in only one circular polarization component of a spinor system. We demonstrate the spontaneous formation of localized half-vortices in spinor polariton condensates, non-resonantly excited by a linearly polarized ring-shaped pump [1,2]. In the core region of the half-vortex the condensate is circularly polarized, while it is linearly polarized elsewhere. With TE-TM splitting, the pseudospin structure of the condensate gives rise to solutions with broken cylindrical symmetry. The attractive cross-interaction between different spin components can be used to realize optical vortex core switching between left- and right-circularly polarized HV states [1]. This switching process (Fig. 1) results in the reversal of the circular polarization state in the HV core. It can be easily detected by measuring the polarization resolved intensity in the vortex core region, and the same method can also be applied to higher order states.

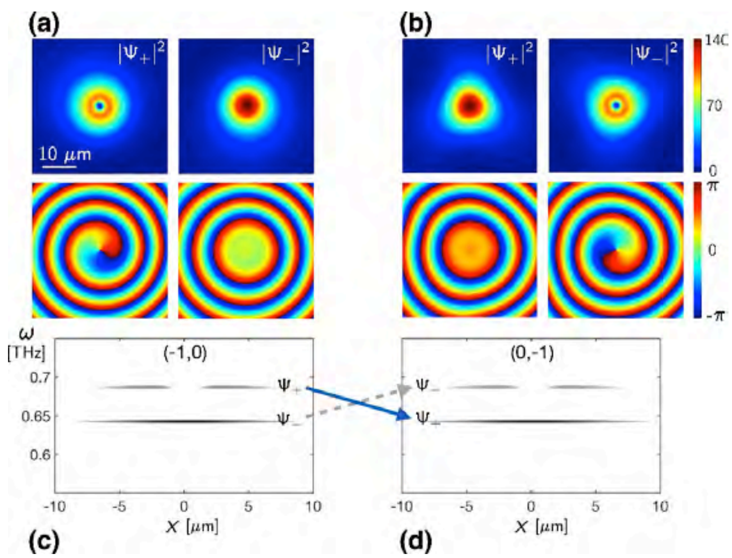

Fig. 1 (a,b) Densities and phase profiles of the initial and final states in the two circular polarization components Ψ+ and Ψ−. (c,d) Corresponding condensate spectra in real space. The grey dashed arrow represents imprinting of a vortex state in the Ψ− component due to the resonant control beam, while the blue arrow shows the simultaneous transition into the ground state (non-vortex) of the Ψ+ component, induced by the attractive cross-interaction leading to a redshift.

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Polaritons as efficient and ultrafast platform for neuromorphic computing

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Exciton-polaritons, mixed states of photons and excitons, have attracted a great deal of interest both from a fundamental point of view, with the observation of quantum macroscopic phenomena, and, given the possibilities they can offer, for the realisation of all-optical devices with limitless advantages in terms of energy consumption, dissipation-less operation and high clock frequencies [1].

After showing some of the most intriguing characteristics of polaritons in semiconductor microcavities, we will focus on the use of polariton systems as semiconductor-based platforms for the realisation of an image recognition system based on a reservoir computing array of polariton nodes [2].

We have studied several schemes to best exploiting the strong polariton nonlinearities in a network of almost degenerate polariton states. We used the MNIST database of handwritten numbers as a benchmark to test the efficiency of the network against the number of training dataset as well as the network dimension.

Using quasi-resonant excitation schemes, we obtained extremely unexpected and startling results. Compared to previous works on hardware implementation of neuronal network schemes we could show a higher success rate in a system that offers the fastest computational speeds. Moreover, despite a smaller set of training data, such an exciton-polariton-based platform demonstrated to outperform even linear classification algorithms working with the full MNIST database.

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A quantum optical neuromorphic network

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We introduce *quantum reservoir processing* as a platform for quantum information processing developed on the principle of a neural network. A quantum reservoir processor can efficiently perform qualitative quantum tasks like recognising entangled states or quantitative quantum tasks like estimating entropy, purity and negativity (see Ref[1, 2] for more details). This platform can be implemented in a variety of systems, e.g., arrays of semiconductor quantum dots, superconducting qubits, cold atoms and NV centres in diamond. Exciton-polaritons in semiconducting microcavities are yet another promising alternative system which are recently shown to operate in the quantum regime [3, 4].

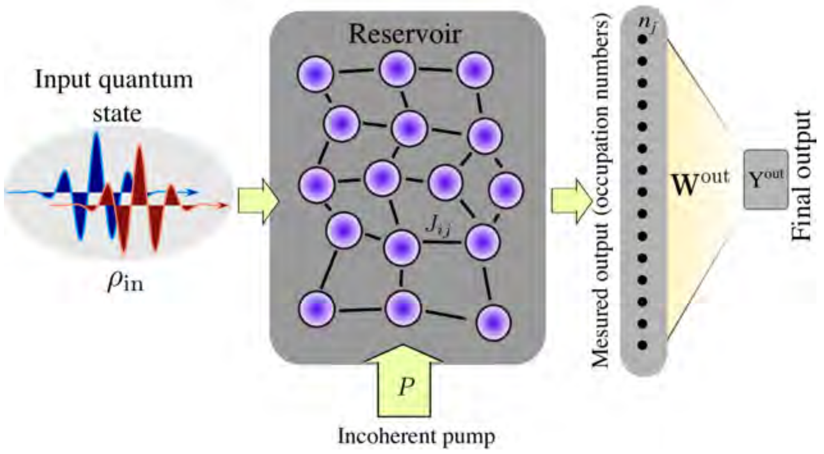

Figure 1: Schematic representation of a quantum reservoir processor. A quantum state in the form of an optical field excites a lattice with random coupling J_{ij} in an effective Hubbard model. The occupation numbers of the sites are extracted and combined to give a final output. This generic architecture can perform various tasks, such as identifying a quantum state and simultaneously estimating its various properties.

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Engineering interactions in networks of polariton condensates and the prospect of neural architectures

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Exciton-polariton condensation has now been demonstrated as a flexible platform to study light-matter wave physics with transients in the order of picoseconds. Here, I will discuss the all-optical engineering of polariton condensate networks and the corresponding potential landscape of non-condensed exciton reservoirs induced by the nonresonant beams. We show that one can deterministically tune the interaction strength between different condensates by using another set of intruding nonresonant optical beams [1]. This allows switching of the phase arrangement between individual as well clusters of condensates (see Fig.1a,b). Such control enables us to study the physics of synchronous phases in large networks of nonlinear oscillators and intermediate regimes where chaotic trajectories reside.

I will present results on how the band structure of such all-optical lattice systems can be engineered to support polariton modes unique to the geometry in question. Of interest are polyacetylene-like lattices where the staggered interactions between condensates split the bands and a multimodal condensate appears. Implanting lattice defects leads to the appearance of *dark* and *bright* condensate defect states reminiscent of solitonic solutions. For polygon structures, characterized by discrete rotational symmetry, we find modes supporting persistent circulating currents along the polygon edges. Lastly I will discuss the prospect and challenges of using polariton condensate networks as neuromorphic hardware. Specifically, the advantage of time-delay interactions [2] over Josephson interactions between condensate nodes and how it suits a neural network strategy known as *Reservoir Computing* [3] (see Fig.1c).

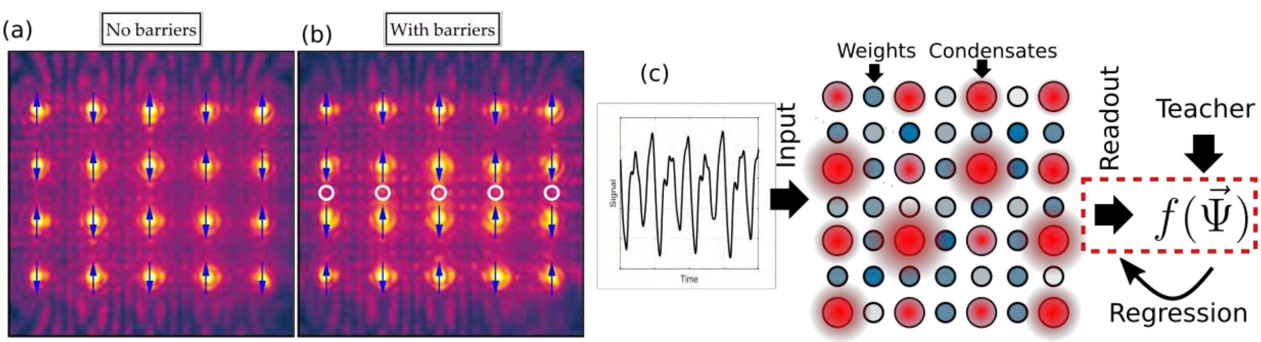

Fig. 1. A real space photoluminescence of a 4x4 polariton condensate lattice without (a) and with (b) nonresonant optical barriers [white circles] switching the parity of the upper and lower half denoted by the blue arrows. (c) Schematic of a reservoir computer where a resonant analogue signal is fed into a condensate network undergoing linear regression training in the same spirit as recurrent neural networks.

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Networks of non-equilibrium condensates for simulation of spin Hamiltonians

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There is a growing interest in investigating the potential of various physical systems to solve hard optimisation problems. One promising class of optimisers can be based on a driven-dissipative physical platform, namely gain-dissipative simulators. The underlying operational principle of such simulators depends on the gain (pumping) mechanism. As the gain increases from below threshold until a nonzero occupation appears, the system becomes globally coherent. Such a phase transition to a coherent state of matter occurs at the minimum of an associated spin Hamiltonian that describes the maximum occupation of the state for the given gain. Examples of such spin Hamiltonians include Ising, XY, Potts, and Heisenberg models. Finding the global minimum of such spin Hamiltonian problems is known to be strongly NP-complete, meaning that an efficient way of solving them can be used to solve all problems in the complexity class NP. We have developed a general framework for the operation of the gain-dissipative analogue simulators [1] and demonstrated how the minimization of the Ising and XY models can be tackled with polariton graphs [2]. Moreover, motivated by the operation of such physical systems, we have developed a novel class of classical optimisation algorithms that can outperform standard built-in methods [3]. We have also shown recently that other models, including Kuramoto and Stuart-Landau, can be realised with polaritonic networks under different conditions [4]. Together with an individual control of pairwise interactions via spatially varying the dissipation profile [5], the networks of polariton condensates offer great potential for an efficient analogue Hamiltonian optimiser and for reservoir computing.

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Macroscopically coupled polariton condensates

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Networks of interacting polariton condensates have been shown to offer a versatile platform for engineering and studying complex systems such as phase or spin-synchronized lattices [1, 2]. In this work we present an in-depth study of the nature of interaction and synchronization between two spatially separated, non-trapped and ballistically expanding polariton condensates. We show that this system differs from a conventional Josephson-junction of trapped condensates since the coupling is not mediated by a tunneling current but by radiative coupling inherently connected with finite time of particle transfer [3]. Synchronization is observed over macroscopic distances as large as d = 114 μm (Fig.1a) for two tightly-pumped condensates, which is more than 50x larger than the FWHM of each condensate (~2 μm). We demonstrate that interactions in-between condensates can be optically controlled (Fig.1b) [4] and are described by delay-differential equations which makes networks of non-trapped polariton condensates a promising platform to study time-delay coupled systems [5], that arise in many areas of nature, and can be attractive for implementing artificial neural networks.

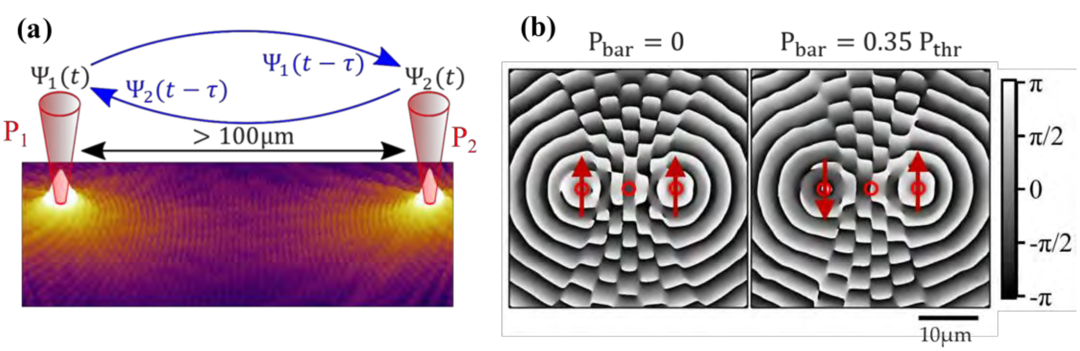

Fig. 1. (a) Two macroscopically separated and ballistically expanding polariton condensates. Interference fringes visualize the synchronization of both condensates. (b) Optical control of synchronization between two condensates locked in-phase (left) and anti-phase (right) by modulation of the optical-pump intensity of an additional potential barrier in-between the two condensates (middle red circle).

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ROOM TEMPERATURE ORGANIC EXCITON-POLARITON CONDENSATES IN TAILORED LANDSCAPES

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Interacting Bosonic condensates, loaded in periodic potentials have emerged as a prime system for on-chip quantum simulation, exploration of exotic quantum phases, and topological photonics. However, such experiments, which rely on a well-defined shaping of the potential landscape of the condensates, have been restricted to ultra-cold temperatures in atomic systems in laser traps, or cryogenic temperatures for exciton-polaritons in the mature GaAs platform. In our work, we present first experiments conducted on a condensate of exciton-polaritons in a lattice at ambient conditions. We utilize fluorescent proteins as an excitonic gain material, providing ultra-stable Frenkel excitons, and directly take advantage of their soft nature by mechanically shaping them in the photonic lattice environment.

I will discuss the following observations:

- The high quality of our device allows us to generate a close-to ideal bandstructure of the lattice, arranged by tightly bound polaritonic traps [1].
- The high structural quality of our material allows us to enter the regime of bosonic condensation at ambient condition in this lattice [1,2].
- Microscopic modelling allows us to establish the fundamental understanding about polaritonic non-linearities based on Frenkel-Excitons [2]
- By shaping the pump spot, we can load the condensate into distinct lattice modes and symmetries at will. This capability is a powerful tool for any sort of advanced experiments relying on collective transitions of coherent bosonic states.

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Exciton polaritons in perovskite lattices at room temperature

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Microcavity exciton polaritons are part-light, part-matter quasiparticles emerging from the quantum hybridization of excitons and microcavity photons. As strong-interacting bosons, they have been exhibited rich quantum dynamics in the past decades. With the development of microfabrication techniques, polariton condensates can be precisely trapped in periodical potentials to form artificial lattices, which have led to a wide range of important applications, such as ultrafast simulators of the X-Y Hamiltonian[1], topological Chern insulators[2] and topological lasers[3]. However, such realizations have been limited in GaAs system, which can only work at liquid helium temperatures. Here, we demonstrate our latest results on perovskite microcavities, which serve as a promising system to realize artificial polariton lattices operating at room temperature. Specifically, we demonstrate the observation of exciton polariton condensation in a one-dimensional strong lead halide perovskite lattice at room temperature. Modulated by deep periodic potentials, the strong lead halide perovskite lattice exhibits a large forbidden bandgap opening up to 13.3 meV and a lattice band up to 8.5 meV wide (Fig.1), which are at least 10 times larger than previous systems. Above a critical density, we observe exciton polariton condensation into p_y orbital states with long-range spatial coherence at room temperature. In addition, we also demonstrate the realization of a perovskite zigzag lattice with topological protected edge states Our results pave the way to implement artificial polariton lattices for quantum simulation and topology at room temperature.

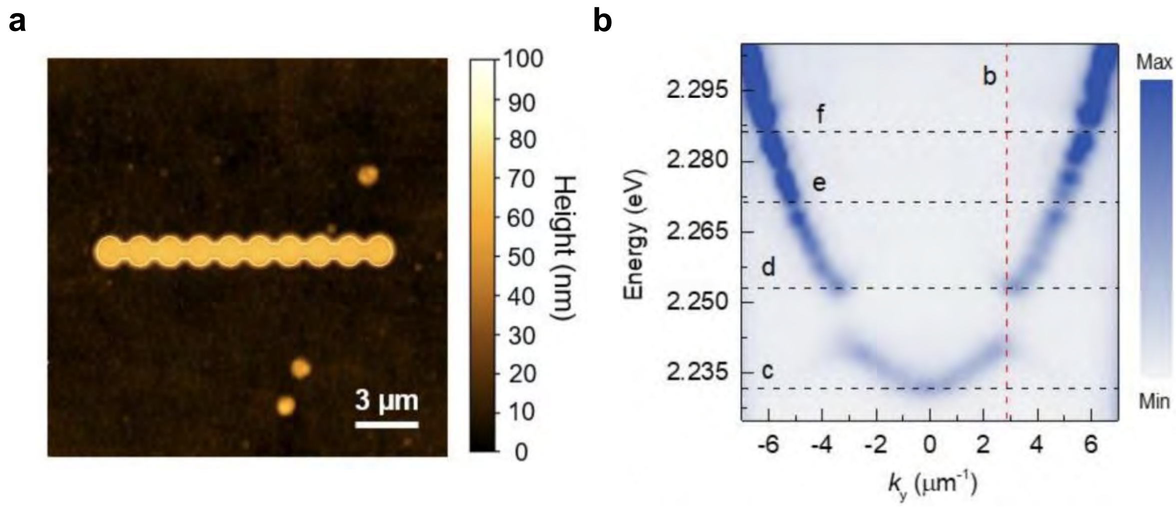

Fig.1. **a**, Atomic microscopy image of the perovskite lattice. **b**, Energy-resolved dispersion of the perovskite lattice.

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Applications of organic molecule-light strong coupling

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The typical tools utilized by chemists to control the rate of a chemical reaction include temperature, concentration of reactants, presence of catalysts, solvent, etc. In recent years a less intuitive notion has been explored: that the electromagnetic environment of the reactants one can perturb the reaction potential energy surface, much like the action of a catalyst, and thereby influence chemical reactivity. Work over the last decade shows that this becomes possible in the strong coupling limit of molecular interactions with light, where the new collective polaritonic states have very different energies to the unbound system. We have shown that reactivity is influenced in both photochemical reactions (coupling electronic transitions) and for thermal reactions (coupling vibrational transitions).[1]

Our other recent work has examined strong light-molecule coupling effects on electrical conductivity [2], energy transfer [3], non-linear optics [4], and in biological systems targeting protein vibrational modes [5], further evidence that exciton-polaritons are worthy of study in the context of the molecular sciences.

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ATTO-JOULE POLARITON CONDENSATE SWITCH

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Recent progress in polaritonics makes fascinating polariton physics possible at room-temperature [1–3]. Exciton-polaritons obey Bose-statistics and therefore undergo well-known bosonic stimulation in case a state is occupied with N>1 bosons. Exploiting the principle, we have managed driving a strongly coupled organic system towards the regime of dynamic polariton condensation where a transition from incoherent exciton reservoir to a massively occupied polariton state becomes stimulated by a weak resonant seed pulse [4]. We fabricated a strongly coupled microcavity consisting of 35 nm layer of ladder-type conjugated polymer (MeLPPP), sandwiched between SiO_2/Ta_2O_5 DBRs and study dynamic polariton condensation through the direct exciton-to-polariton vibron-mediated relaxation at very low energies of the seed pulse. We observe significant contrast of the ground polariton state occupancy by resonantly seeding the state with a few atto-joules pulse. Figure 1a shows dispersion images recorded for the unseeded (upper) and seeded (bottom) polariton condensates. In particular, seeding of the ground state by 40 aJ pulse drastically changes the total occupancy of the polariton condensate as shown in Figure 1b. Our results reveal extreme nonlinearity of dynamic condensation in Frenkel exciton-polariton systems allowing for microscopic control over macroscopic polariton wave-functions.

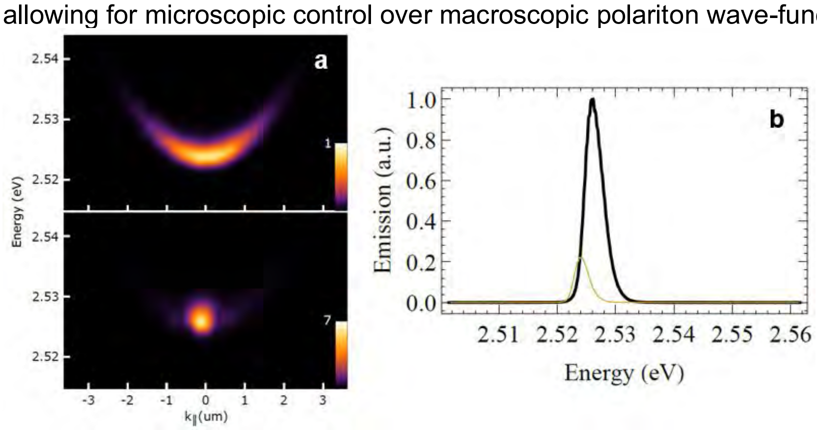

Fig. 1. (a) Dispersion images of unseeded (*upper*) and seeded (*bottom*) polariton condensates. (b) Norm. emission spectra of unseeded (*orange*) and seeded (*black*) condensates integrated over ±0.4 μm^{-1}

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Topological physics with a hybrid light-matter system

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Topological insulators (TIs) are a striking example of materials in which topological invariants are manifested in robustness against perturbations, as originally observed in the integer quantum Hall effect. However, during the past decade the concepts of topological physics have been introduced into numerous fields beyond condensed matter, ranging from microwaves, photonic and polaritonic systems to cold atoms, acoustics, mechanics and electrical circuits. Topology has emerged as an abstract, yet surprisingly powerful, new paradigm for controlling the flow of an excitation, e.g. the flow of light. As such, it holds great promise for a wide range of advanced applications.
Topological phenomena in polaritons are fundamentally different from all topological effects demonstrated experimentally thus far: exciton-polaritons are part-light part-matter quasiparticles emerging from the strong coupling of quantum well excitons and microcavity photons. We show that by placing exciton-polaritons in artificial lattices that emulate two-dimensional materials, we can engineer a wide range of exotic band structures hosting flat bands as well as Dirac cone dispersions. Based on this precise technological control, we have demonstrated experimentally the first exciton-polariton TI [1]. Due to the strong interactions and a large nonlinearity displayed by the exciton-polariton system, this platform promises a wide range of novel many-body effects and resulting functionalities. Here, we will briefly discuss the progress towards a topological polariton laser [2-4].

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Artificial matter in semiconductor lattices

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Semiconductor microcavities have recently emerged as a powerful platform to implement artificial photonic materials based on the use of exciton-polaritons [1], which are hybrid quasiparticles resulting from the strong coupling of cavity photons and quantum well excitons. Polaritons are particularly attractive since they combine the best of two worlds: (i) they are photonic excitations that can conveniently be excited and read-out using optical spectroscopy; (ii) their interactions can be tuned and reinforced *via* their matter component. Moreover, at C2N, we are able to sculpt the microcavities into micron-scale photonic materials with a great variety of geometries, in order to emulate different Hamiltonians.

After a general introduction, I will describe two examples that illustrate the potential of this non-linear photonic platform to address diverse physical questions. (i) We recently explored the localization properties of waves in synthetic quasiperiodic lattices [2]. Using both a theoretical analysis and experiments on our devices, we evidenced the existence of a series of delocalization-localization transitions in a novel family of quasiperiodic chains. (ii) In another study, we investigated the nonlinear properties of polaritons in the gapped flatband of a 1D Lieb lattice [3]. We observed the formation of gap solitons with quantized size and abrupt edges, a signature of frozen propagation due to the quenching of kinetic energy in a flatband. Our experiments also reveal a complex multistable behavior, which is a direct consequence of the driven-dissipative nature of the platform. I will finally discuss perspectives of this work for quantum simulation.

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OBSERVATION OF THE OPTICAL SPIN HALL EFFECT IN PHOTONIC GRAPHENE

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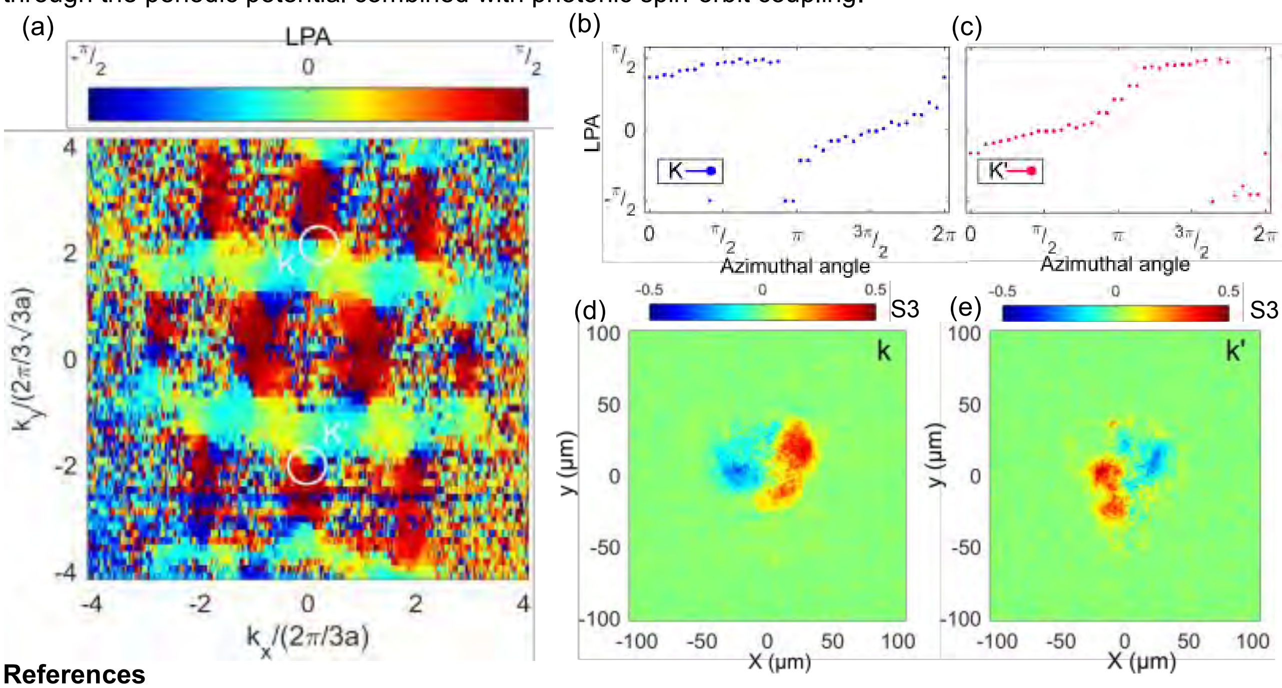
Exciton-polariton (polariton) gases confined in lattice potentials have emerged as an attractive candidate for emulating nonlinear lattice Hamiltonians, where 2D arrays of micropillars whose photonic energy bands have strong analogy with the electronic energy bands of real world 2D (or quasi-2D) materials. Results such as the demonstration of Dirac cones [1] and more recently a topological insulator [2], have only furthered research into this ever growing field of research.

The spin hall effect is the spin current generated from the interplay between spin-orbit coupling and the TE-TM modes in a photonic system. We report on the experimental observation of the optical spin Hall effect in a patterned microcavity with a honeycomb lattice geometry, so-called photonic graphene. TE-TM splitting native to microcavities, which acts as an effective magnetic field with a double azimuthal winding, in the neighborhood of the dirac point energies K-K' point is transformed into a Dresselhaus-type field with a single winding around these points, figure 1a ,b, c. This reduced symmetry is revealed in the optical spin hall effect pattern, figure 1d, e. The precession of the pseudospin of a resonantly injected photonic wave packet, which leads to the formation of the two spin domains, confirming the artificial gauge field created through the periodic potential combined with photonic spin-orbit coupling.



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One way reflection free polariton spin filtering channel

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Topological polariton systems are characterized by the appearance of chiral edge states, which travel in a particular direction at an edge of a topological lattice where time reversal symmetry is broken [1, 2]. In a strip geometry, chiral edge states always appear in pairs, which propagate in opposite directions on opposite edges of the strip. While there has been a very clear fundamental interest in these states, the suggestion that they can act as information carriers is hindered by this fact that they appear in pairs, as it means that in any system there will be an unwanted counter-propagating signal, potentially leading to detrimental feedback effects.

Here we consider polaritons in a strip of honeycomb lattice with zigzag edges. It is shown that the interplay between the TE-TM splitting, Zeeman splitting and an onsite potential can give rise to a band structure where one of the edge states vanishes completely while the other one resides with the gap-less bulk having opposite spin. Being surrounded by opposite spin states and the absence of one of the edge states ensures both reflection free and feedback suppressed one-way flow for polaritons with one particular spin in the system. This paves the way for feedback free polariton channels, which can be useful in transferring information in polariton networks.

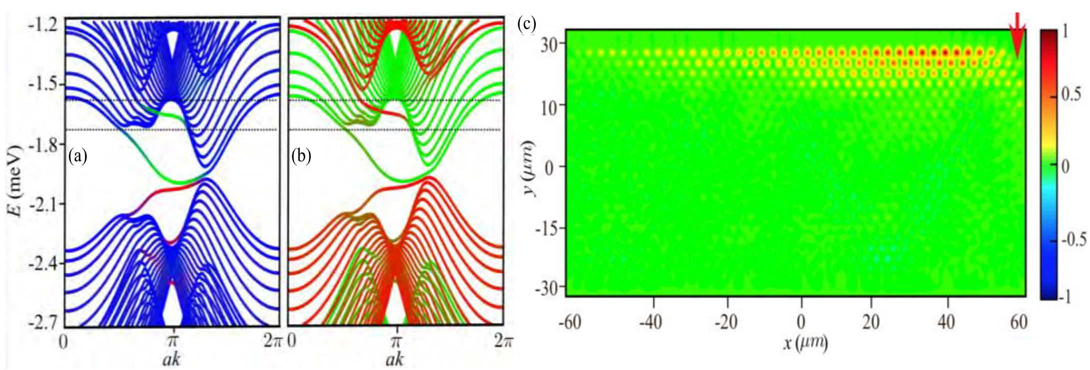

Fig. 1. (a) Band structure of the system under consideration with the edge states shown in red and green. (b) Same band structure plotted with colour coding corresponding to the spin degree of freedom. (c) Spatial distribution of the spin degree when the system is subjected to a linearly polarized coherent pump whose position is indicated with the red arrow.

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Coupling between exciton-polariton corner modes mediated through edge states

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In recent years there has been a surge of interest in using exciton-polaritons to realize first order topological bandstructures [1-2]. These topological states are well-isolated from disorder and so seem ideal candidates for preserving information. However, this also means that they are well-isolated from each other and so it is hard to imagine coupling together multiple topological states, which would likely be prerequisite for some information processing elements (e.g., two-input logic gates).

Here we consider theoretically the realization of a second order topological polariton bandstructure, which gives rise to zero-dimensional localized corner states in a polariton lattice (Fig. 1). Due to the topological nature, information can be trapped in the corner even in the presence of disorder. We show that in the presence of polariton-polariton scattering, polaritons can scatter from a pumped corner state into an edge state, which again scatter back to another adjacent corner. In this way, we find that as a nonlinear driven-dissipative system exciton-polaritons offer a unique opportunity for realizing spatially localized topological states that can be coupled together.

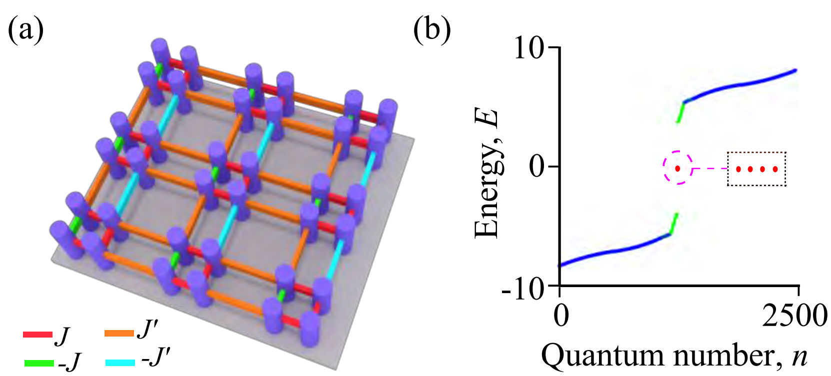

Fig. 1. (a) Schematic diagram of a square lattice formed by coupled exciton polariton micropillars with four different hopping *J, -J, J'*, and *-J'* indicated by four colors. (b) Energy eigen-values of the system consisting of 50 × 50 micropillars, as a function of the quantum number *n*. The modes corresponding to *n*=1249-1252 are the corner states appearing at *E=0*, denoted by red. The bulk and edge states are shown in blue and green respectively.

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Propagating exciton-polariton condensates in coupled waveguide structures

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In the past decades, exciton-polaritons (polaritons) have emerged as a new scientific field due to its light-matter nature. In addition, polaritons show a strong non-linearity when reaching the condensation threshold. Using a variety of etching techniques to create microcavity waveguides (WGs), long-range propagation and interference effects of polaritons have been demonstrated [1,2].
In this paper, we study coupling phenomena in two microcavity WGs, which are realized by etching the top and bottom DBRs. Due to pronounced evanescent coupling the condensate oscillates between the waveguides. This transfer of energy is clearly displayed in real-space due to the propagating nature of the condensate.(Fig 1) Depending on the device parameters a different phase at the end of the coupling area can be reached, resulting in different routing ratios. We study this two WG coupling as a building block for larger coupled WG arrays.
This arrays are manufactured using a well developed etch-and-overgrowth technique. Here, the barrier height and thus the WG coupling is highly controllable. In homogenous coupling WG arrays we clearly observe discrete diffraction patterns of polaritons propagating. Furthermore, we show that the precise control of the coupling parameters opens the way to study topologically non-trivial band structures and complex propagation behaviors such as Bloch oscillations and Zener-tunneling.

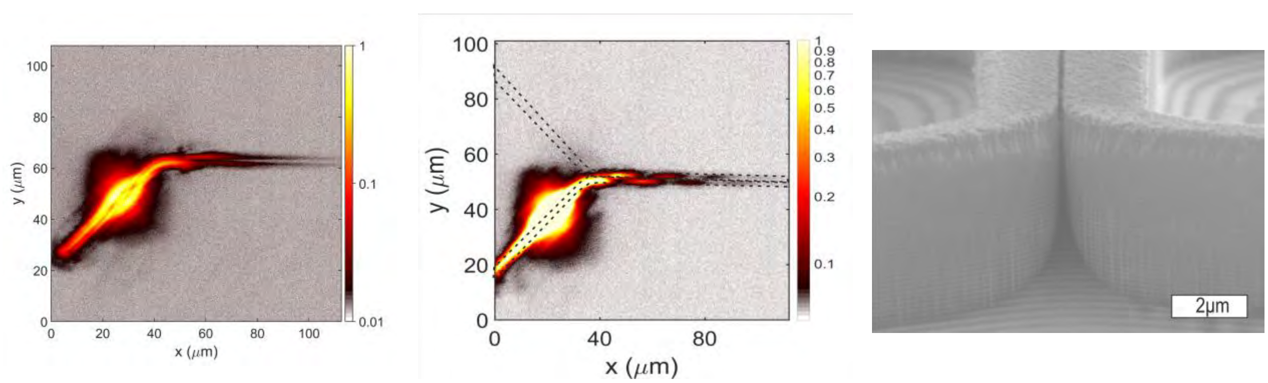

Fig. 1.a,b) Real space image of a propagating polariton condensate in a codirectional coupler with different coupling strength. **c)** SEM image of a codirectional coupler at an angle along the coupling propagation direction.

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TOPOLOGICAL EDGE-MODE LASING IN NON-HERMITIAN POLARITON SYSTEMS

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The control of topological properties in optical systems is a contemporary attracting objective from both experimental and theoretical perspective. Recently, topological insulators were suggested to be realizable in the strong matter-light coupling regime [1] and lately experimentally probed in exciton-polaritons lattices of coupled microcavities [2]. Here, the edge mode populated by a polariton condensate presents novel topological effects which differ from those demonstrated so far. Motivated by this recent achievements, in this work we investigate the properties of topological edge states and topological phase transition in a four-site unit-cell one-dimensional chain (Fig.1, left). Here the topological band-gap is generated by the gain and loss mechanisms rather than the different hopping ratio between the individual cells [3].
We theoretically analyse the system in general terms, allowing to address relevant physical structures well beyond polaritonic setups and investigating the transition from Hermitian to non-Hermitian topological insulators. Our results clearly indicate the presence of different topological phases with diverse number of topological edge modes which are characterised by a well defined topological invariant. We then numerically study the physically stable solutions of the system in the presence of nonlinear terms by solving the temporal evolution of the tight-binding model considered. Our results predict an establishment of single edge-mode lasing in microcavity arrays (Fig.1, right). Investigation of the proposed system is within the current experimental reachability.

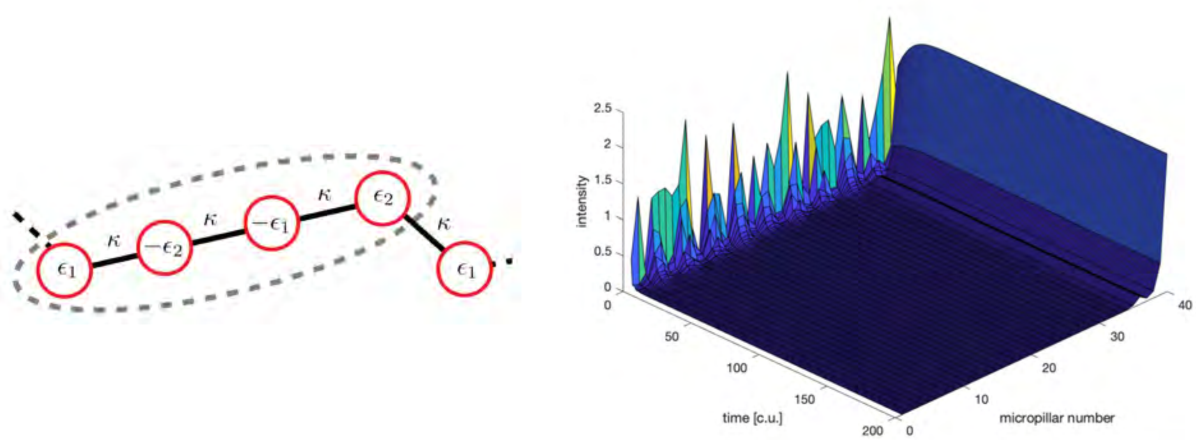

Fig. 1. Left: Schematic of the system considered, with single-cavity coupling κ and on-site potential $\epsilon_n = g_n e^{i\theta}$ where $n = 1, 2$ and $\theta = (0, 2\pi)$. Right: Temporal evolution of the field intensity in a N=10 unit-cells structure of microcavities showing stable single edge-mode lasing.

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Electrical control of interlayer exciton dynamics in atomically thin heterostructures

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Excitons in semiconductors, bound pairs of excited electrons and holes, can form the basis for new classes of quantum optoelectronic devices. A van der Waals heterostructure built from atomically thin semiconducting transition metal dichalcogenides (TMDs) enables the formation of excitons from electrons and holes in distinct layers, producing interlayer excitons with large binding energy and a long lifetime. Employing heterostructures of monolayer TMDs WSe_2/$MoSe_2$, we realize optical and electrical generation of long-lived neutral and charged interlayer excitons. We demonstrate the transport of neutral interlayer excitons across the whole sample that can be controlled by excitation power and gate electrodes. We also realize the drift motion of charged interlayer excitons using Ohmic-contacted devices. The electrical generation and control of excitons provides a new route for realizing quantum manipulation of bosonic composite particles with complete electrical tunability.

Fig. 1

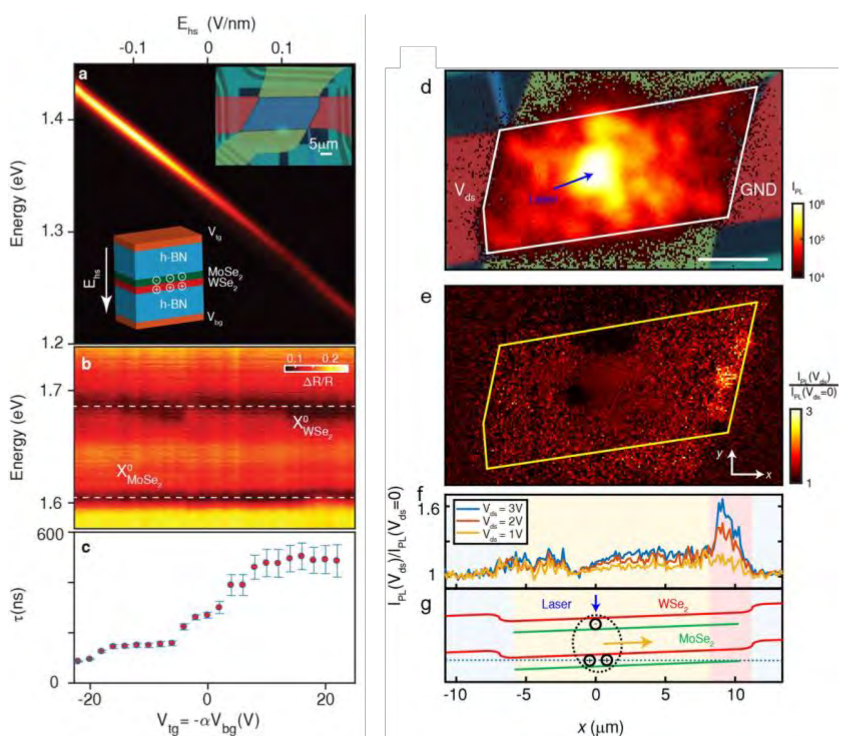

Fig. 1. (a) IE PL spectra vs. electric field applied to the heterostructure ($E_{hs} = (V_{tg} - V_{bg})/t_{total} * (\varepsilon_{h-BN}/\varepsilon_{TMD})$). Here the top ($V_{tg}$) and bottom ($V_{bg}$) gate voltages are swept together with a voltage ratio ($\alpha = t_{top}^{h-BN}/t_{bottom}^{h-BN} = 0.614$, $t_{top}^{h-BN} = 70$ nm and $t_{bottom}^{h-BN} = 114$ nm are the top and bottom *h*-BN thicknesses, respectively), t_{total} is the total *h*-BN thickness, and $\varepsilon_{h-BN} = 3.9$ and $\varepsilon_{TMD} = 7.2$ are the *h*-BN and TMD permittivity, respectively. Right inset: optical image of a representative device with the top-gates false colored. Left inset: schematic of the heterostructure cross section, showing electrons (holes) accumulate on the $MoSe_2$ (WSe_2) layers, forming IEs. The white arrow represents the positive direction of E_{hs}. **(b)** Normalized reflectance vs. E_{hs}. **(c)** IE lifetime τ vs. E_{hs}. **(d)** Spatial dependence of I_{PL} with the laser excitation fixed at the center of the heterostructure (laser position labeled as laser). An optical image of the device with false colored top gates that cover the WSe_2 and $MoSe_2$ contacts is overlaid. An in-plane electric field is applied by a voltage in one of the WSe_2 contacts (V_{ds}) while keeping the other contact grounded. **(e)** Spatial dependence of I_{PL} normalized according to $I_{PL}(V_{ds})/I_{PL}(V_{ds} = 0)$ for V_{ds} = 3 V. We observe a larger population of charged IEs near the right WSe_2 electrode by increasing V_{ds}. The yellow arrow in (d) represents the current direction. **(f)** Average of the normalized I_{PL} along the y-axis vs. *x* (depicted in Figure 3b) for different V_{ds}. **(g)** Schematic of the heterostructure bands with applied V_{ds}. The red (green) bands correspond to WSe_2 ($MoSe_2$). A positive V_{ds} is applied, while the chemical potential (indicated by a blue dotted line) is kept inside the WSe_2 valence band to form positively charged IEs. Under positive V_{ds}, the CIEs drift towards the grounded contact. The emission mainly occurs near the grounded contact, because the charged exciton cannot move beyond the heterostructure.

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Effect of charge transport in organic semiconductors on the conductance of silicon nanowires

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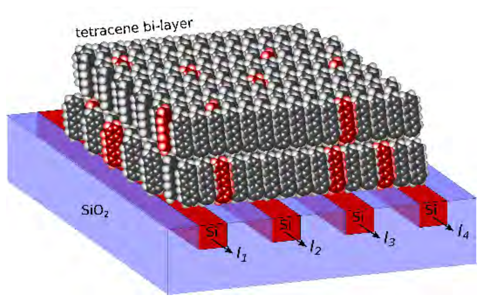
We study electron transport processes in a silicon nanowire covered by an organic semiconductor (see Fig. 1 a) [1]. We propose a mathematical model that estimates the effect of charge carriers in organic semiconductor (tetracene in this work) on the conductance of the nanowire. The model is based on the non-equilibrium Green's function approach [2] with the semi-empirical $sp^3d^5s^*$ tight-binding model for the electronic structure of the nanowire [3]. The scattering potential has been computed using a combination of the polarizable continuum model and density functional theory with the range-separated exchange-correlation functional for organic molecules [4].
Moving charge carriers in the organic semiconductor distort the electrostatic environment of the nanowire, introducing an additional source of elastic scatterings that suppresses the coherent transport of electrons. The computed conductance change caused by scattering on a single molecule is shown in Fig. 1b both for positive and negative charge carriers for a range of Fermi energies. There is also a possibility to observe the exciton and charge transfer across the interface between silicon and tetracene. In this case the organic semiconductor acts as a source of electrons and/or holes. A steady-state injection of additional charge carriers into the nanowire redefines the quasi-equilibrium thermodynamic variables such as temperature and Fermi energy level. In Fig. 1 b we have schematically shown the corresponding shift of the Fermi level, E_f, caused by the electron injection. As a result of such shift the conductance of the nanowire increases. Thus, in the considered case the movement of charge carriers in tetracene reduces the conductance of the nanowire introducing an additional source of scatterings, while the charge transfer across the interface enhances it. Both effects can be quantified from experimental measurement of the conductance.



a) b)

Fig. 1. a) an array of silicon nanowires covered by a bilayer of crystalline tetracene and b) conductance change in a silicon nanowire caused by scatterings on a single charge carrier.

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Resonant photovoltaic effect in doped magnetic semiconductors

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The non-linear optical response of clean undoped semiconductors contains a static intrinsic term – the shift current. We show that when Kramers degeneracy is lifted, the second order DC response of doped semiconductors or semimetals to an AC electric field becomes large at the interband absorption threshold in clean nearly isotropic materials. We refer to this effect, which results from an interesting interplay between inter-band coherence and intra-band occupation number response, as the resonant photovoltaic effect (RPE). We evaluate the RPE for a model of the surface states of a Bi_2Te_3 coupled to in-plane magnetic order due to either bulk doping or proximity coupling.

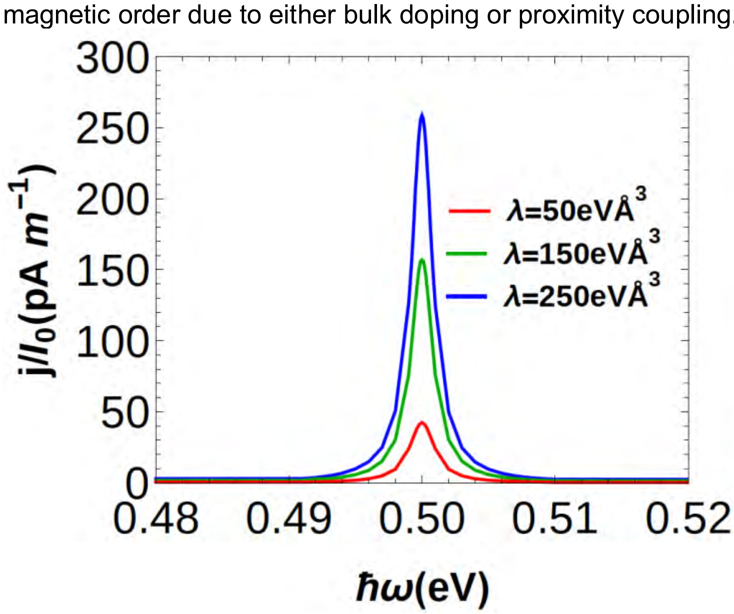

Fig. 1. RPE resonance for a topological insulator with warping coefficient λ, with I_0 the intensity in W/m^2. The blue curve corresponds to known values for Bi_2Te_3.

On the existence and nature of the excitonic insulator phase in the extended Falicov-Kimball model

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We act on the suggestion that an excitonic insulator (EI) state might separate — at very low critical temperatures — a semimetal (SM) from a semiconductor (SC) and ask for the nature of these transitions. Thereby the EI constitutes an exciton condensate in equilibrium. To analyze the EI instability, triggered by the Coulomb interaction between conduction band electrons and valence band holes, we study the half-filled Falicov-Kimball model extended by a finite f-bandwidth, by means of various analytical and numerical methods. For the 1D extended Falicov-Kimball model, we present exact DMRG results for the ground-state phase diagram and show that the criticality of the EI state with power-law correlations shows up in the von Neumann entropy [1]. In 3D, the momentum-resolved exciton numbers clearly reveal the BCS-like mechanism at the SM-EI transition, whereas at the SC-EI transition a Bose-Einstein condensation (BEC) of preformed electron-hole pairs occurs [2]. Thus, the composite nature of the excitons is of vital importance. We furthermore calculate the bound-state fractions and the exciton density to characterize the composition of the normal phase and to identify the so-called halo phase (surrounding the EI above the critical temperature), which realizes a three-component plasma consisting of electrons, holes, and excitons. The coherence length and the single-particle spectral functions show the continuous crossover from a BCS- to a BEC-type pairing by tuning the Coulomb attraction within the EI phase. The precursor of this crossover in the normal phase might cause the transport anomalies observed in several mixed-valence compounds. We also comment on spontaneous coherence in double-layer exciton systems [3].

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THE EMERGENCE OF ASYMMETRIC STEADY-STATES IN NETWORKS OF POLARITON CONDENSATES

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The rich physics of systems of interacting polariton condensates has sparked much interest in their behaviour. For example, recent work has demonstrated their potential to shed light on the nature of systems of coupled oscillators [1]. Despite extensive theoretical [2] and experimental [3] investigations into polaritonic networks, most of the literature assumes that only ferro and antiferro stationary states exist. In this study, the rate equations described in [1] are implemented on various lattices to reveal that asymmetric stationary states are possible. In such states, the condensates have unequal densities and their phase differences do not correspond to those of ferro or antiferro states (Fig. 1). We found one type of asymmetric state in systems consisting of two and three condensates, and four distinct types of asymmetric states in systems with four condensates. This study presents an investigation into the nature of such states, providing a more complete picture of the possible ground states of polaritonic networks.

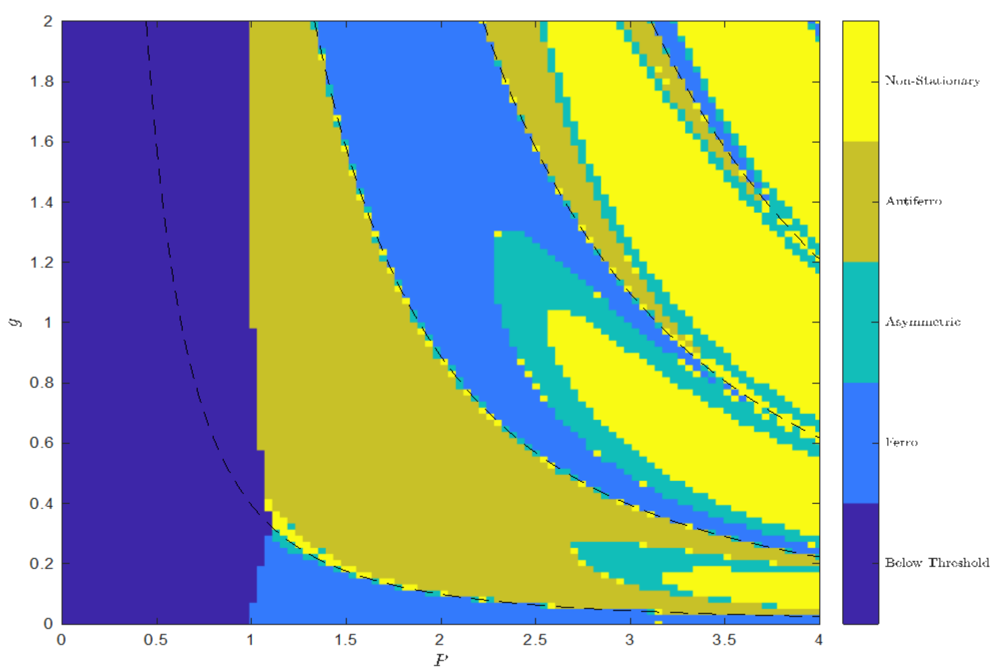

Fig. 1. Bifurcation diagram for a polariton dyad showing ferro, antiferro, asymmetric, and non-stationary states. The diagram is plotted in $P-g$ parameter space, where P is the pump intensity and $g = 2g_R/R_R$ (g_R is the polariton-exciton interaction strength and R_R is the rate of scattering from the hot reservoir).

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Exciton-polariton propagator with application to electron-polariton scattering and testing of quantum reference frame transformations

Guangyao Li

Abstract: We obtain via diagrammatic method the propagator of exciton-polariton for a $2D$ quantum well microcavity system with screened Coulomb interaction. The polariton propagator carries information about the renormalization of the exciton-photon interaction strength and the nonparabolic polariton dispersion. As an application, we calculate the electron-polariton s-wave scattering cross section and find that the effective mass approximation works very well in excitonic regime and photonic regime. However, since the polariton dispersion is nonparabolic, a gemeral momentum-dependent calculation brings up the issue of quantum reference frame transformation. Conversely, our results can provide an experimentally testable scenario for verification of existing quantum reference frame transformation proposals.

Tunable Room-Temperature Exciton-Polaritons in a Microcavity Containing 2D-Perovskites

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Very promising materials, that are attracting growing interest in optical devices and photonic applications, are hybrid organic-inorganic perovskites. In particular, great attention is recently devoted to the two-dimensional (2D) perovskites. In the two-dimensional crystalline form these materials behave as multiple quantum-well heterostructures with stable excitonic resonances up to room temperature.

We report the realization of tunable planar dielectric microcavities containing a 2D-layered perovskite-type semiconductor: $CH_3NH_3PbI_3$, showing the strong-coupling regime at both room and liquid helium temperatures. We synthesized 2D-layered perovskite structure from the organic solution which was deposited by spin-coating on a dielectric mirror. One of the main advantages of selected 2D-layered perovskite is that excitons in such material are characterized by a high binding energy which leads to a great stability even at room temperatures, as well as exhibit strong non-linearities.

We constructed a tunable cavity from two dielectric mirrors. The distance between the mirrors was controlled through piezo positioners. It allow, at the same time, for the realization of high fineness open micro-cavities (high Q) with tunable photonic mode and to avoid deterioration of perovskite crystals caused by the growth of the upper mirror. A strong coupling regime between the perovskite exciton and the confined photon mode is evidenced at room (Fig.1) and liquid-helium temperatures from angular-resolved reflectivity and photoluminescence experiments. The observed exciton-photon coupling strength is of Ω~110 meV and photonic mode can be tuned over the range of 100 meV.

The scientific significance of this work is based on the realization of a room-temperature new material platform allowing for the observation of phenomena previously carried out at cryogenic temperatures.

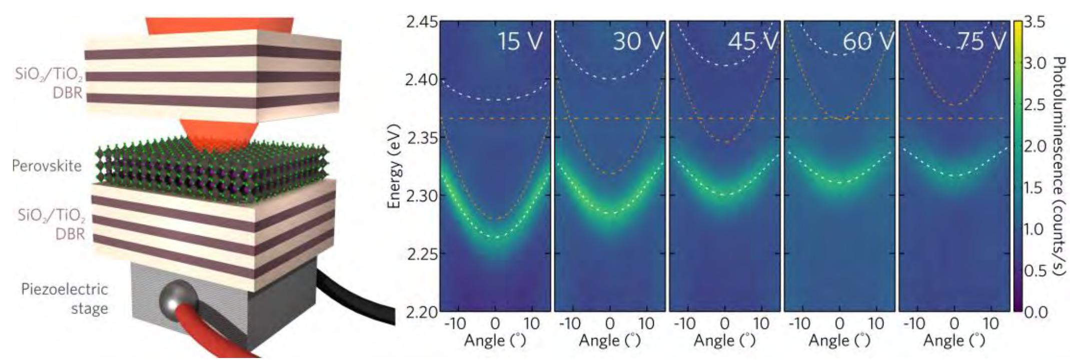

Fig. 1. (Left) Schematic image of the structure. Cavity is formed from two DBR mirrors with the perovskite layer deposited on top of bottom mirror. A free space between the mirrors allows for cavity tunability by shifting one of the mirrors with piezoelectric stage. (Right) Emission from 2D-layered perovskite in strong light-matter coupling regime at room temperature tuned by bias applied to the piezoelectric chip.

TOWARDS AN (AL,GA)AS-BASED EXCITON-POLARITON LASER OPERATING AT ROOM TEMPERATURE

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Exciton-polaritons are quasiparticles emerging from the strong coupling between excitons and photons in a semiconductor optical microcavity. They can form a macroscopically coherent state, a Bose-Einstein Condensate which can be the source of laser emission. In the case of (Al,Ga)As-based monolithic microcavities, with an (Al,Ga)As/AlAs quantum well (QW), the QW-confined excitons dissociate above cryogenic temperatures due to their binding energy (~10 meV), preventing the formation of the condensate at high temperatures. Here, we propose a strategy to enhance the exciton binding energy (E_B) and to increase the stability of the condensate up to 300 K in GaAs-based structures. The E_B is reached >30 meV through band engineering of the $Al_{0.2}Ga_{0.8}As/AlAs$ QW, exploiting the Γ-X valley mixing [1]. It preserves strong exciton-photon coupling up to 300 K. Additionally, we employ a modified excitation scheme with the pump laser beam structuring to diminish the influence of incoherent excitonic reservoir on coherent properties of the condensate at high T.

Preliminary experimental studies on the proposed polaritonic structure show the low-temperature polaritonic lasing after employing a standard pumping scheme with a focused pump beam. Polaritonic emission is indicated by a deviation from the parabolic dispersion of the cavity mode, a spectral blueshift with the pumping power, and narrowing of the emission band above the lasing threshold. We investigate the possibility of polariton lasing at elevated temperatures and test whether the strong coupling is preserved under high particle densities. The results give hope for reaching polariton emission and lasing at much higher temperature up to 300 K, after implementing an optimized excitation scheme.

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Exciton-polaritons in multilayer WSe_2 in a tunable planar microcavity

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Due to high exciton biding energy and oscillator strength transition metal dichalcogenides (TMDs) have recently gained significant attention in a field of light-matter interactions. A unique characteristic of this group of materials is strong dependence of optical properties on their thickness. Single layer flakes are of special interest to study light-matter interactions due to their direct bandgap. Significantly less explored are multi-layer flakes, which, in contrast to monolayers, exhibit an indirect bandgap.

We investigated 1 to 4 WSe_2 monolayer flakes, which were encapsulated in high quality hBN to ensure the best optical properties [1]. In case of the monolayer, excitonic transition is visible in both luminescence and reflectance spectra. For thicker layers, weak emission comes mostly from the indirect transition between Q and K points in reciprocal space. However, strong absorption at energies corresponding to direct excitonic transition in K point in the Brillouin zone are still observable in the reflectance spectra.

Few-layer flakes under investigation were embedded inside a tunable cavity made of two SiO_2/TiO_2 distributed Bragg reflectors (DBRs). Angle-resolved reflectance spectra, performed at 10 K, revealed strong light-matter coupling regime for all of the investigated WSe_2 flakes. When cavity mode energy approaches direct excitonic resonance in given WSe_2 flake, spectrum consists of two anticrossing branches: lower and upper polariton (Fig. 1**b–e**). Observed Rabi splitting increases with thickness of WSe_2 flake, which is well reproduced with our transfer matrix simulations, based on measurements of the flakes outside the cavity.

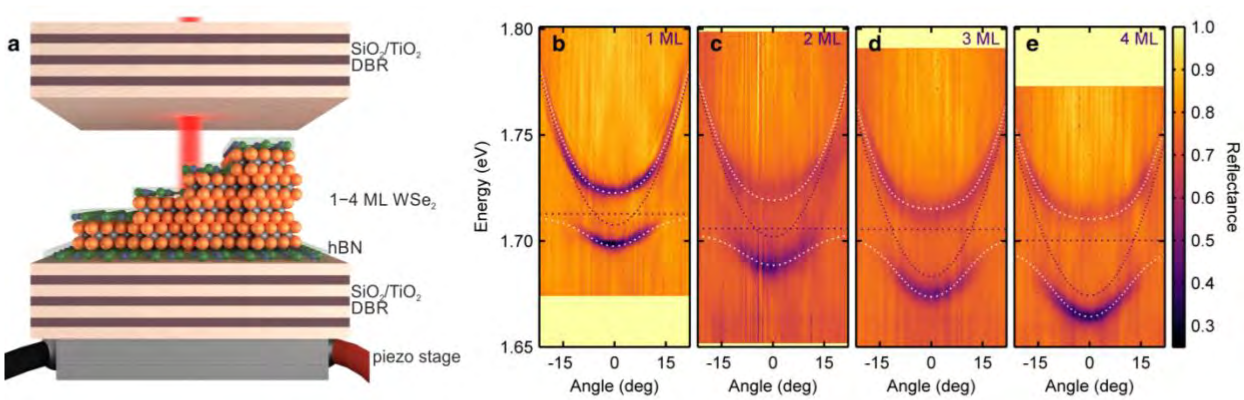

Fig 1. a Scheme of tunable microcavity with few-layer thick WSe_2 flakes encapsulated in hBN. Angle-resolved reflectance spectra for **b** 1 ML, **c** 2 ML, **d** 3 ML and **e** 4 ML flakes. White dashed lines marks fitted exciton-polariton dispersion relations.

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Towards all-dielectric monolithic microcavities with embedded atomically thin semiconductors for exciton-polariton research

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Since their first experimental observation [1], exciton polaritons in high-quality GaAs-based microcavities have become a platform for studies of collective quantum effects, such as Bose-Einstein condensation and superfluidity. However, polaritons in GaAs quantum wells exist only at cryogenic temperatures, which limits their future applications. Room temperature regime can be achieved by utilising excitons with larger binding energies, e.g., in transition metal dichalcogenide (TMDC) monolayers [2]. Although exciton polaritons in TMDCs have been demonstrated, the polariton condensation has not been observed so far.

We are working towards polariton condensation in TMDCs by fabricating a monolithic cavity with an embedded stack of monolayers (Fig. 1a). This design should enable the crucial combination of long photon lifetimes and high densities of excitons interacting with the photon. An essential component of the stack is the spacer material, which should a) protect the monolayer from the subsequent fabrication steps, and b) have a controllable nm-scale thickness and a wafer-scale size. Here, we demonstrate a method to protect fragile WS_2 and WSe_2 monolayers by wafer-scale nanosheets of Ga_2O_3 [3], which can be fabricated with a reproducible thickness. We show that Ga_2O_3 both preserves the excitonic properties of the TMDCs (Fig. 1b) and protects them against further deposition of dielectric materials (Fig. 1c). Our results demonstrate a scalable alternative to hBN for embedding TMDCs in a monolithic microcavity.

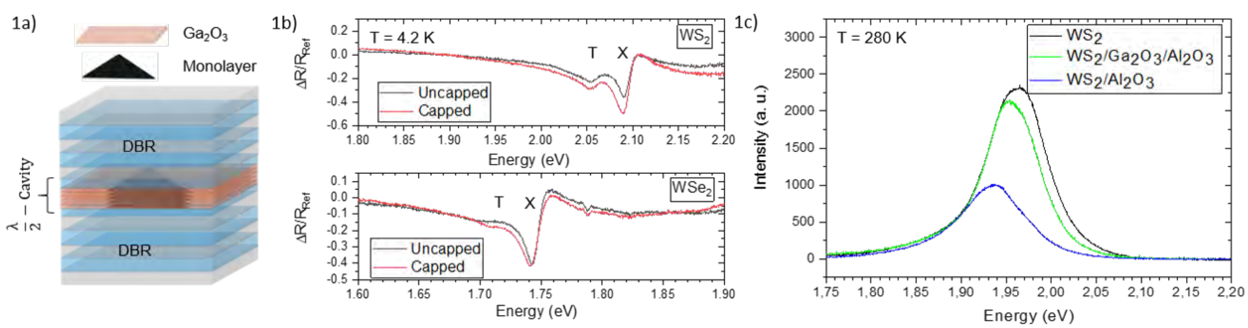

Fig. 1. (a) Schematics of the microcavity design, (b) Reflectivity spectra of exfoliated WS_2/Ga_2O_3 and WSe_2/Ga_2O_3 stacks at T = 4.2 K. Here, the exciton is labeled with X and the trion with T, (c) PL-spectra of protected and unprotected CVD-grown WS_2 after Al_2O_3 deposition via electron-beam evaporation.

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Quantum scale anomaly and spatial coherence in a 2D Fermi superfluid

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Quantum anomalies are violations of classical scaling symmetries caused by quantum fluctuations. Although they appear prominently in quantum field theory to regularize divergent physical quantities, their influence on experimental observables is difficult to discern. Here, we discovered a striking manifestation of a quantum anomaly in the momentum-space dynamics of a 2D Fermi superfluid of ultracold atoms. We measured the position and pair momentum distribution of the superfluid during a breathing mode cycle for different interaction strengths across the BEC-BCS crossover. Whereas the system exhibits self-similar evolution in the weakly interacting BEC and BCS limits, we found a violation in the strongly interacting regime. The signature of scale-invariance breaking is enhanced in the first-order coherence function. In particular, the power-law exponents that characterize long-range phase correlations in the system are modified due to this effect, indicating that the quantum anomaly has a significant influence on the critical properties of 2D superfluids [1].

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Synchronized energy transport by surface plasmons on a metallic nanofiber

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Many-particle system, which is coupled to cavities or waveguides, forms a nonlinear correlated state through the exchange of photons. Such a correlation is a key element of quantum devices such as quantum gate [1] and single photon transistor [2]. The performance of the devices depends on the efficiency of the photon energy transport between the particles. However, the temporal behavior of the inter-particle correlations is highly complicated because it should strongly depend on the spatial configurations and the environment of the plural particles.

In this work, we calculate the temporal evolution of the spontaneously-formed correlation and excited population of two particles, which are coupled with a surface plasmon on a infinite silver nanofiber. Here we use the equation of motion for two-particle correlation in arbitrary environments [3]. The figure below illustrates the temporal evolution from the initial state in which only one particle is excited. By adjusting the particle position so that the electric field phase of the surface plasmon at each particle position matches, a synchronization can be seen in the excited populations and the transport efficiency becomes enhanced. These results can introduce a guideline for constructing future quantum devices.

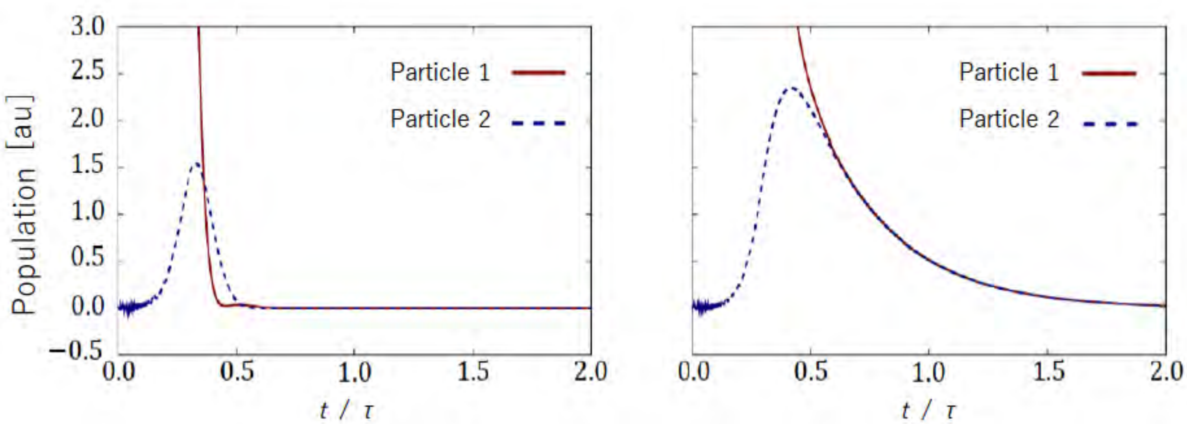

Fig. 1. Time evolution of excited populations of two two-level particles on a silver nanofiber. Here τ *i*s the radiation decay time of each particle. (Left) Case: the particles are set so that the electric field phase of the surface plasmon mode at each particle position does not match. (Right) Case: the particles are set so that the electric field phase at each particle position matches.

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Engineering low-loss polaritons in 2D materials

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Main text: This talk will introduce our recent progress on engineering highly confined low-loss polaritons in 2D materials and heterostructures [1,2]. Firstly, plasmonic excitations in graphene/Bi_2Te_3, topological insulator Bi_2Te_3, graphene nanoribbon and 3D graphene were investigated using either spectroscopic or real space imaging techniques [3-6]. We show how the plasmonic coupling happens in two Dirac materials, how high-order plasmonic modes are observed in 3D graphene structure, how multiple plasmonic modes at sub-wavelength are achieved in graphene nanoribbon and how edge chirality controls the plasmonic shift [3-6].

Secondly, we update our recent work on the observation of anisotropic and ultra-low-loss polariton propagation along the surface of a natural van der Waals crystal α-MoO_3 [7]. We visualized and verified phonon polaritons with elliptic and hyperbolic in-plane dispersion, which have been theoretically predicted but never experimentally observed in natural materials before. Furthermore, we show our recently developed strategies (e.g., chemical intercalation [8], dielectric control, and nanopatterning) to manipulate these low-loss polartions towards future low-energy photonic and optoelectronic device applications.

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UNIVERSAL SELF CORRECTING COMPUTING WITH DRIVEN-DISSIPATIVE DISORDERED NEURAL NETWORKS

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We show theoretically that neural networks based on driven-dissipative disordered systems [1] allow the realization of Toffoli gates. A Toffoli gate is a binary logic gate with three inputs and three outputs, which flips the third input if and only if the first two inputs are 1. One of the most remarkable features of neural networks is their ability to operate with noisy data. Noise in input signals is self corrected for by the networks, such that the obtained Toffoli gates are in principle cascadable, where their universality would allow for arbitrary circuits without the need of additional error correcting codes. We further find that the networks can directly simulate composite circuits, such that they are a highly efficient platform allowing circuits to operate in a single step, minimizing the delay of signal transport between elements and error correction overhead. As an example, we consider the full adder circuit. The architecture is generic, with potential applications in ultracold atomtronic systems, nonlinear optical cavities, and exciton-polariton systems. These findings suggest that small scale neural networks based on driven-dissipative disordered systems can be used as building blocks (e.g., Toffoli gates and composite modules like full adders) for efficient universal self correcting computing.

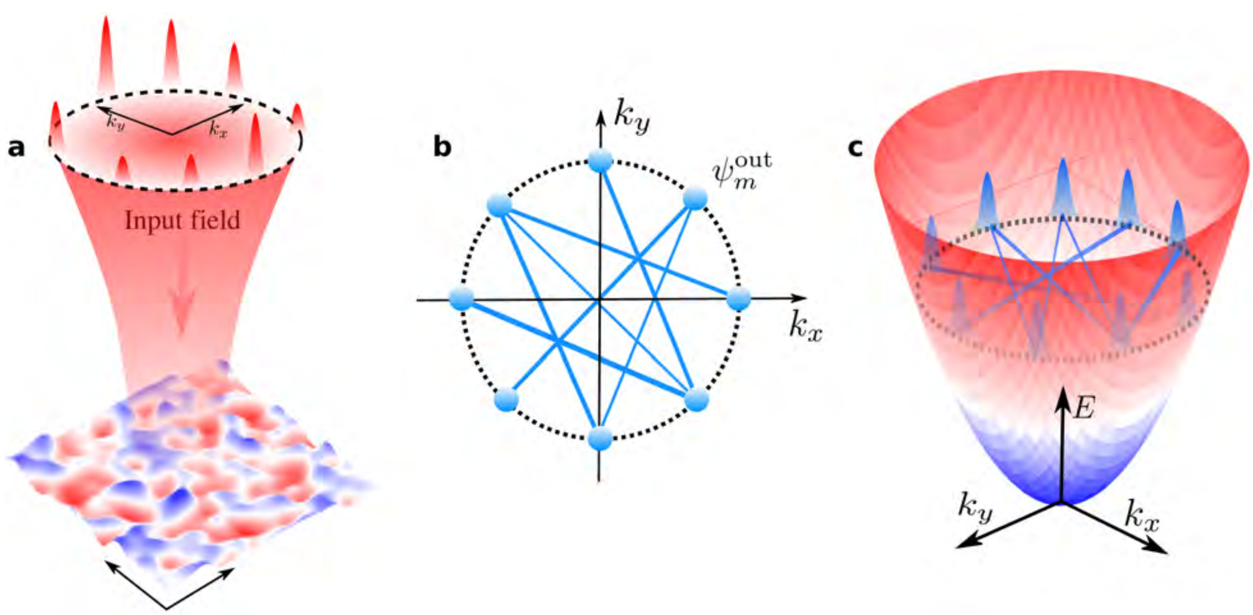

Fig. 1. Figure caption: a, A monochromatic optical field excites a driven-dissipative disordered system with components at different angles of incidence. b, The presence of disorder allows elastic collisions that effectively couple the different modes in reciprocal space. c, In-plane dispersion. The monochromatic excitation has excited only modes along an equal energy circle in reciprocal space. These modes form the nodes of our network.

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Nonadiabatic anomalous hall effect for exciton-polaritons

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We derive non-adiabatic corrections to the semiclassical equations of motion of an accelerated wavepacket in a two-band system. We underline the role of the quantum geometric tensor (QGT) [1] and show that all its components play an important role on the extra phase acquired by a spinor and on the trajectory of an accelerated wavepacket in finite-duration experiment [2]. While the adiabatic anomalous Hall effect is determined by the Berry curvature [3] (the imaginary part of the tensor), the non-adiabaticity is determined by the quantum metric g_{ij} (the real part of the tensor) and allows us to determine corrections in the regimes where the Landau-Zener approach is inapplicable.

The particular case of a planar microcavity in the strong coupling regime, in presence of a non-zero Zeeman field and TE-TM splitting, allows to extract the QGT components by direct light polarization measurements and to check their effects on the quantum evolution of a propagating polariton wave packet through the polariton anomalous Hall effect. Experimental measurement of all the QGT components have been reported for the first time in a high-quality GaAs planar cavity recently [4]. This technique can be extended to measure Bloch band geometries in artificial photonic lattices [5].

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QUANTUM THEORY OF 2D POLARITON CONDENSATES

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We consider a dilute interacting gas of 2D cavity-polaritons at equilibrium and T=0 within Bogoliubov theory. Our model allows to include both the non-parabolic kinetic energy and the k-dependent excitonic fraction. We obtain analytical results for the equation of state and the elementary excitation spectrum, allowing a comparison with theoretical predictions for 2D elementary bosons [1-3].

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Exciton fine-structure in transition-metal dichalcogenides mono-layers

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Transition metal dichacogenides have emerged recently because of their very peculiar properties, opening a new domain between optics, spintronics, and electron transport: valleytronics. Indeed, those compounds, like MoS_2, can be reduced to perfect 2D layers. They show then a direct gap, with a hexagonal crystal structure. The band extrema are located at the 6 so-called K-points. But two interactions play then a major role to define the electronic structure: Spin-orbit coupling splits the valence and conduction bands in a reversed way for each half of those K-points. This allows to excite selectively the corresponding valleys in the band structure using polarized light. We get thus a tool to couple the light polarization, the spin of the photoexcited carriers, and their transport properties. The second interaction is the electron-hole exchange that not only shifts those different levels but also gives rise to their mixing and thus to a relaxation of their spin.

We use a method based on the invariant expansion of the Hamiltonian to precisely describe the effects of spin-orbit and exchange interactions that are usually only approximately treated. In order to discuss their fine structure, we define excitons in the product space of electron- and hole states, including the lowest conduction band (LCB) and the uppermost valence band (UVB) where, at the Γ-point, they are both spin degenerate. All other states are neglected. On this basis exciton states are constructed and analyzed in the framework of a model Hamiltonian: The spin-orbit coupling in the conduction- and valence band is first simulated by introducing an effective magnetic field, giving rise to a splitting of the electron- and hole states outside the Γ-point. Then the Coulomb electron-hole exchange-interaction is introduced into the exciton Hamiltonian. It is due to the fact that electron and hole are indistinguishable particles in the exciton problem. In D_{3h} crystal symmetry this electron-hole exchange-interaction (named "intra-valley exchange") has two different contributions: A first term accounts for an energy re-normalization of the different dark- and bright-exciton states in both series. A second term does not influence the bright states but affects only the dark states of both series, which become mixed. The importance of this mixing depends also on the spin-orbit coupling within the bands. As a result, exchange interaction and spin-orbit coupling of the conduction-band electrons lift together by different amounts the degeneracy of the bright- and dark states.

These calculations (starting from the Γ-point) can be extended up to the $K_\pm$- points at the edges of the Brillouin zone. In transition-metal dichalcogenides mono-layers the wave-vector group at the $K_\pm$ points is C_{3h}. K_+ and K_- points being separated by a reciprocal lattice vector, they are equivalent points of the Brillouin zone. Their corresponding wave-vectors are connected to each other by time-reversal symmetry. In this situation, the exchange interaction introduced above leads also to exchange interaction between electrons and holes from different $K_\pm$ valleys. The latter is called "inter-valley exchange interaction". Outside the $K_\pm$ points this results into a mixing of exciton states belonging to different valleys and leads to an inter-valley transfer of electron-hole excitation that has been studied e. g. in the framework of k.p perturbation theory. (See Ref. [1])

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Exciton-exciton annihilation and superradiance in colloidal nanocrystals

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Abstract

The fast nonradiative decay of multiexcitonic states via exciton-exciton annihilation (i.e. Auger recombination) is a fundamental process affecting a variety of applications based on semiconductor nanostructures. From a theoretical perspective, the description of exciton-exciton annihilation in confined semiconductor nanostructures is a challenging task due to the large number of valence electrons and exponentially growing number of excited excitonic and biexcitonic states that are coupled by the Coulomb interaction. These challenges have restricted the treatment of Auger recombination to simple, noninteracting electron–hole models. Herein, I present a new approach for calculating Auger recombination lifetimes in confined nanostructures having thousands to tens of thousands of electrons, explicitly including electron–hole interactions. I demonstrate that the inclusion of electron–hole correlations is imperative to capture the correct scaling of the Auger recombination lifetime with the size and shape of the nanostructure. Neglecting such correlations can result in lifetimes that are 2 orders of magnitude too long. This new approach is the first theoretical method to postdict the experimentally known "universal volume scaling law" for quantum dots. Additionally, I present a few recent advances in designing nanosystems with slow exciton-exciton annihilation rates based on coupled nanocrystals: core/shell quantum dot dimers, core/shell quantum dot superlattices and nanoplatelet faces. These nanosystems have the potential to display a range of exotic physics. For example, I discuss recent joint theoretical and experimental work on the optical properties of these nanosystems in relation to superradiance.

Coulomb Bound Many-body Excitonic States in Monolayer Tungsten Diselenide

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Excitons in 2D-TMDC have sub-eV binding energy because of the lacking of dielectric screening, providing an ideal platform to investigate the many-body Coulomb interaction.

We observed the four and five-particle excitonic states in a high quality hBN-sandwiched 1L-WSe_2. We assigned these states as intervalley biexciton and the exciton-trion composite. In addition, we have assigned a new mode at 60 meV below bright exciton as the intervalley exciton. We found this the intervalley exciton exhibits superior valley polarization and unusual magneto-optical properties.