

Controlling Strong Light Matter Coupling with Photonic Crystals

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Collaborators:

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Rolf Binder, University of Arizona

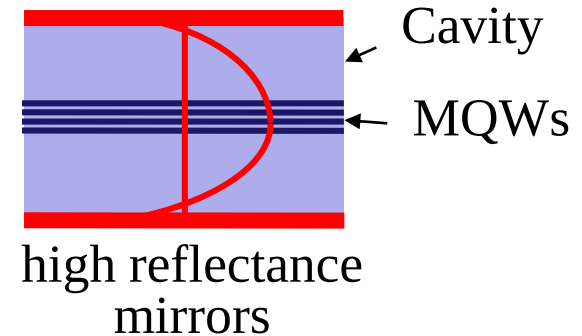
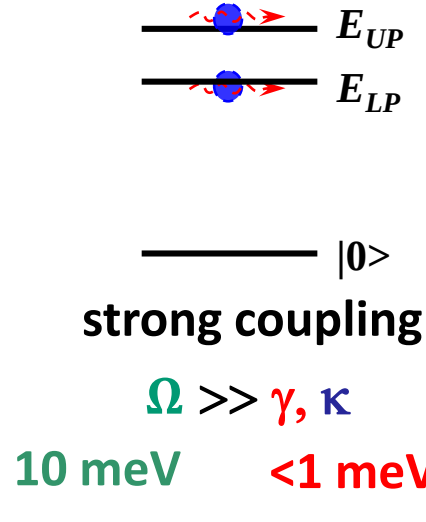
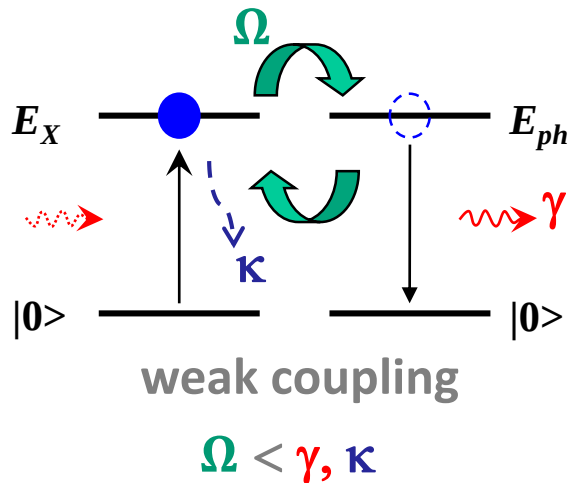
Yura Rubo, Universidad Nacional Autonoma de Mexico

Timothy Liew, Nanyang Technological University

Emanuel Tutuc, University of Texas, Austin



Strong Coupling Regime



Polariton: $\hat{p}_k = v_k \hat{e}_k + u_k \hat{a}_k$

- strong nonlinearity
- rich many-body physics

Semiconductor Platform:

→ photonic devices

- very light: $m^* \sim 10^{-5} m_e$
 → quantum features at high T
- built-in optical interface
 → experimental accessibility
 → open many-body system

Polariton Condensates

Polariton BEC/Laser

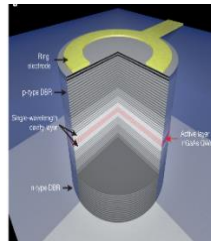
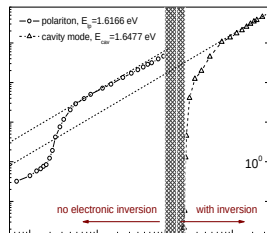
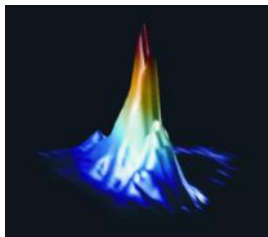
Condensation physics,
laser without band inversion

Deng et al, Science 298, 5591 (2002);

Deng et al, PNAS 100, 15318 (2003);

Kasprzak et al, Nature 443, 409 (2006);

Schneider et al, Nature 497, 348 (2013)... ..



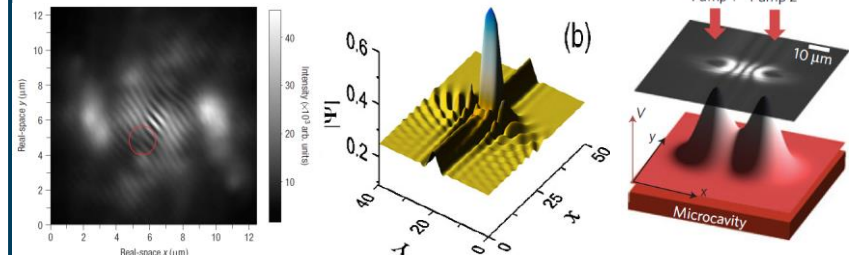
Coherent Nonlinear Fluid

Long-Range Transport, Solitons
Vortices, Josephson Oscillations,
Pattern formation

Lagoudakis, et al, Nat Phys 4, 706 (2008);

Egorov, et al, PRL 102, 153904 (2009);

Tosi, et al, Nat Phys 8, 190 (2012) ...



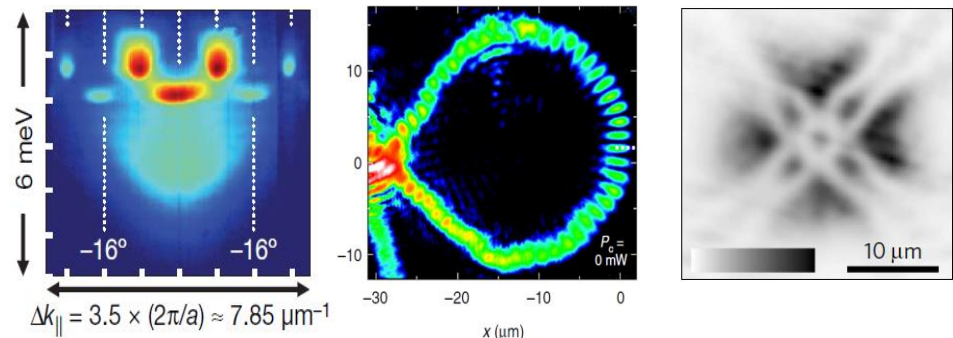
Coupled 1D/0D Condensates

Matter-wave devices &
Hamiltonian simulators

Lai et al, Nature 450, 529 (2007)

Sturm et al, Nat. Comm 5, 3278 (2014)

Berloff et al, Nat. Mat. 16, 1120 (2017)



Controlling Strong Light Matter Coupling with Photonic Crystals

Many-body physics with GaAs-microcavity polaritons

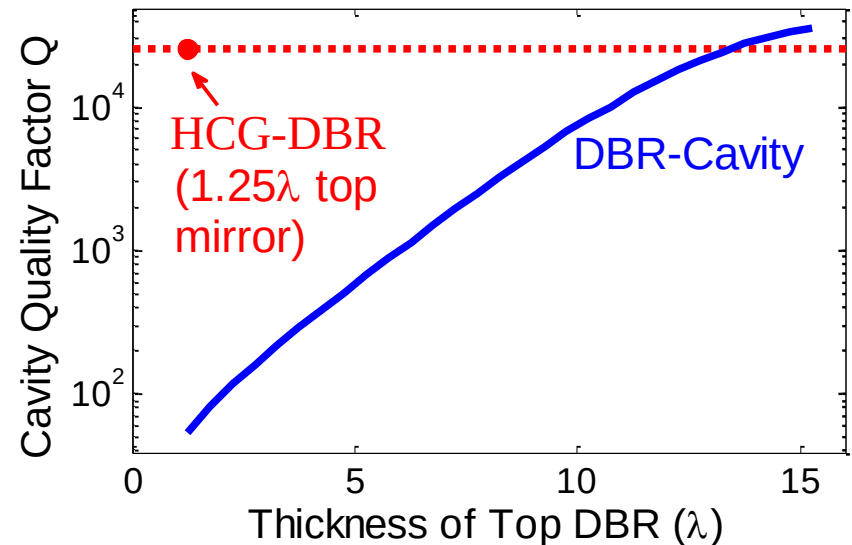
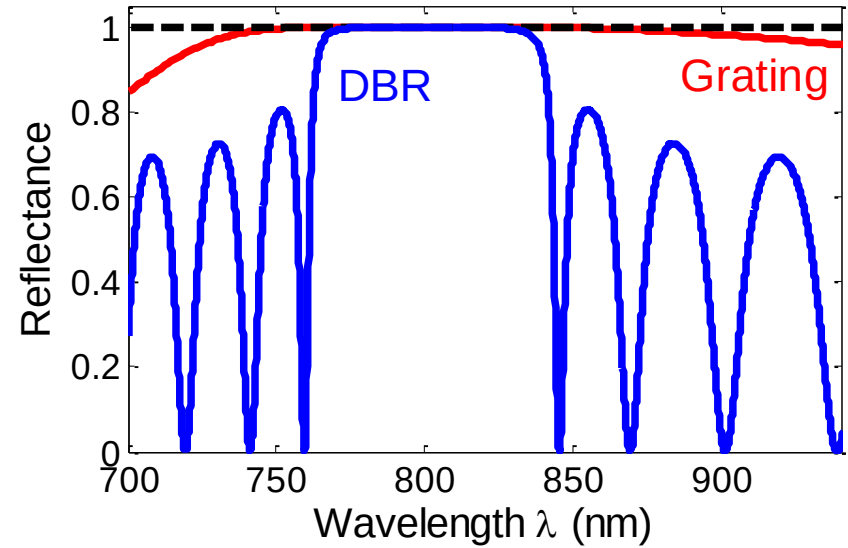
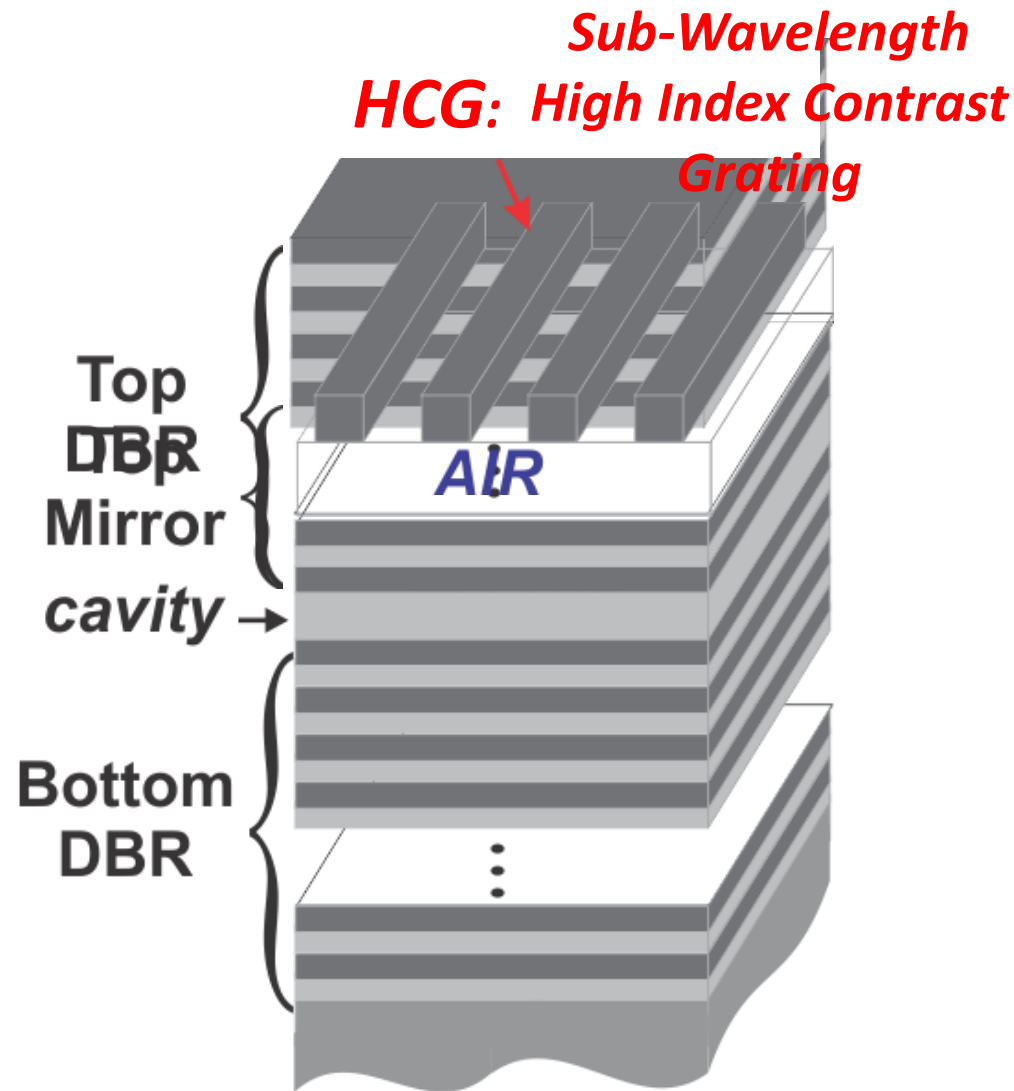
- A designer polariton system with a photonic crystal mirror
- The nonlinear polariton laser

Coherent light-matter coupling in 2D materials

- Polaritons in 1D photonic crystals
- From perfect reflection to perfect absorption

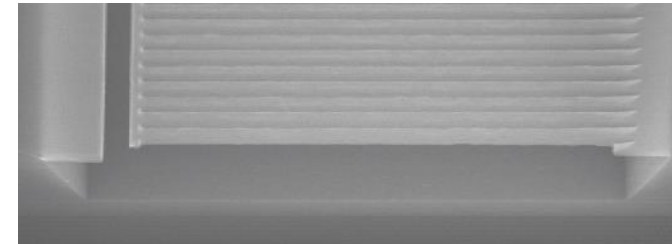
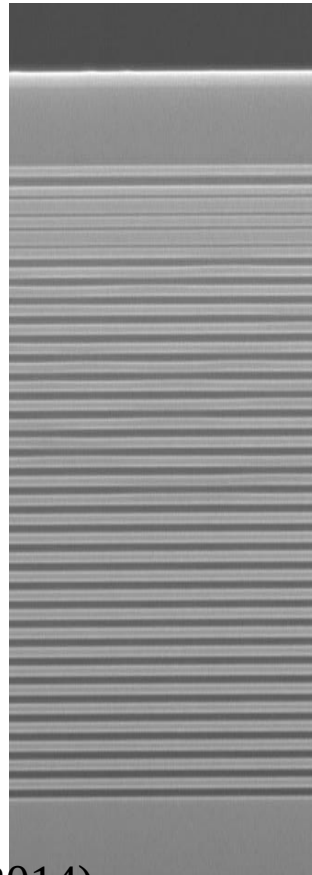
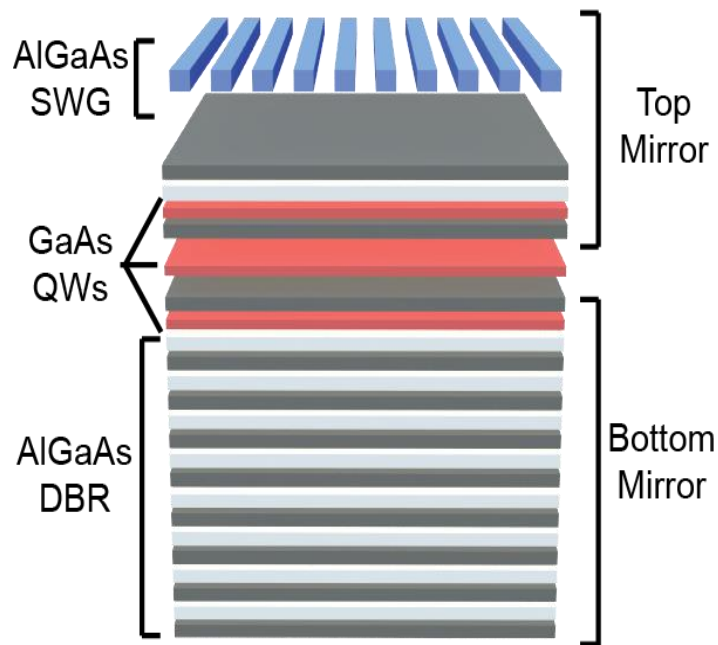
A Designer Polariton System with a Photonic-Crystal Mirror

A Different Cavity Architecture

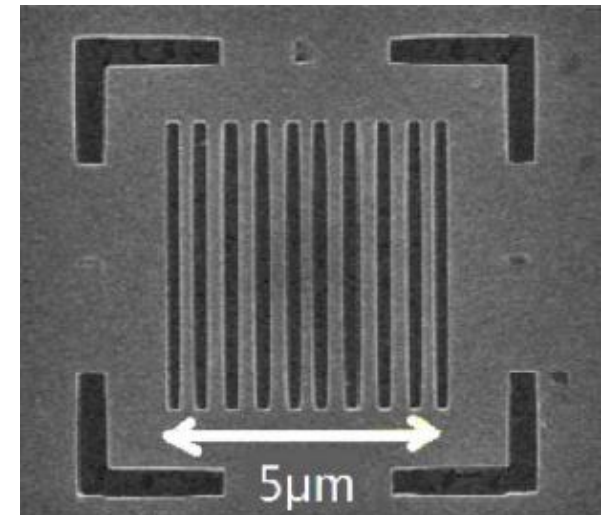


A 0D HCG-DBR Cavity

- Monolithic MBE-grown crystal
- HCG-mirror by e-beam lithography, plasma-tech, wet-etch
- Quantum wells untouched



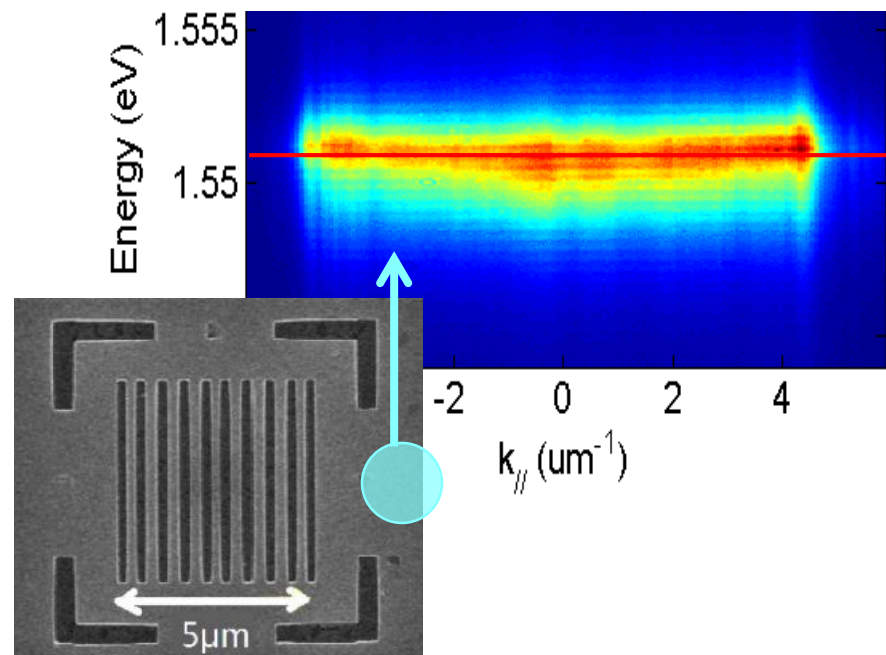
SEM cross section



SEM Top view

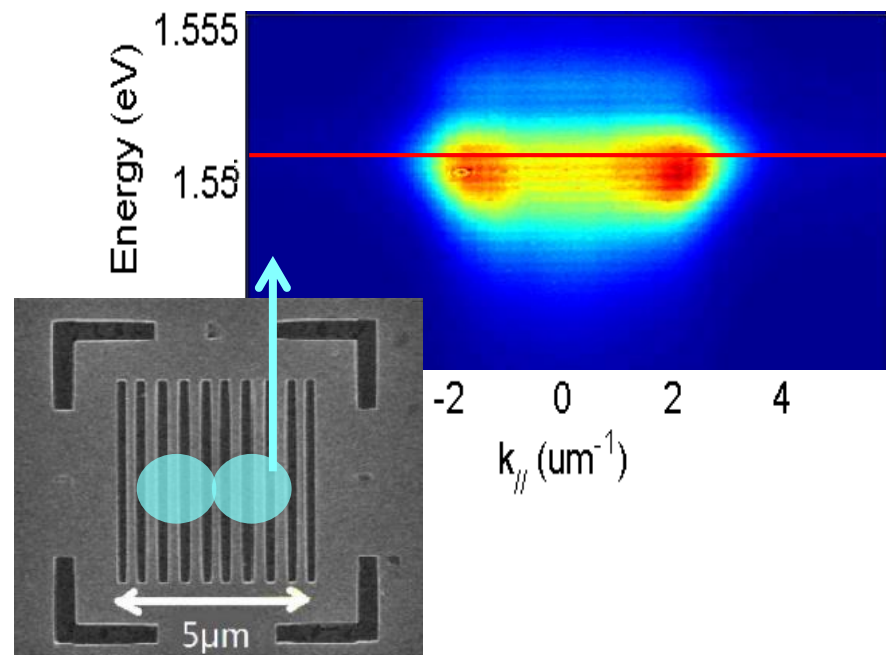
Strong-Coupling: Polariton Dispersion

Flat-Band Exciton



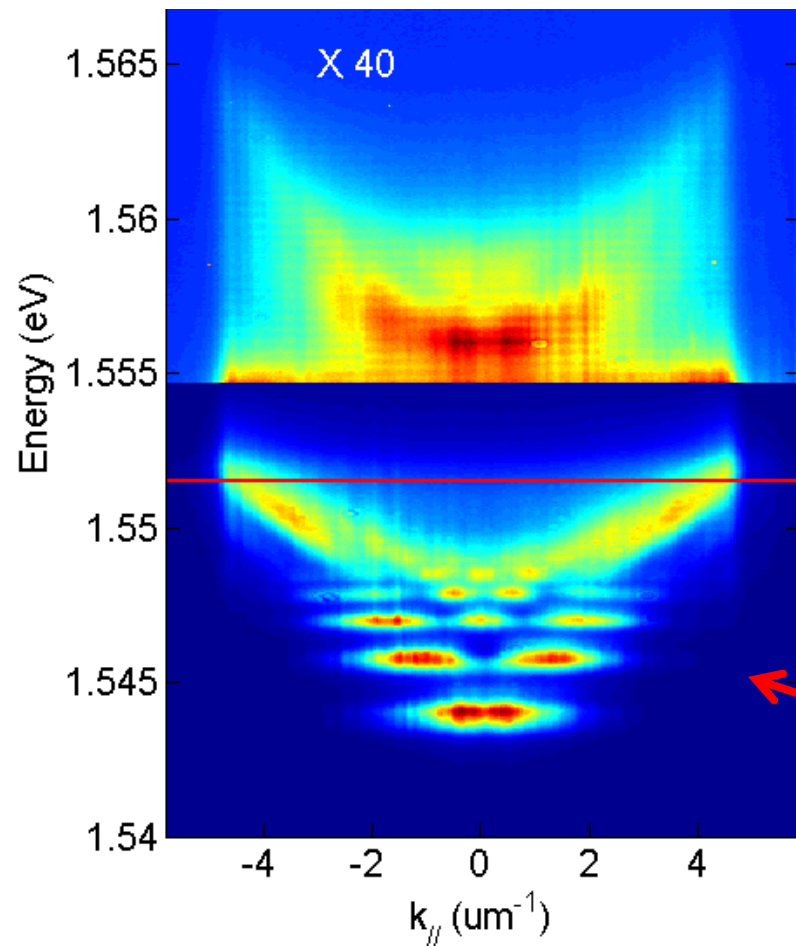
Strong-Coupling: Polariton Dispersion

TM Flat-Band Exciton

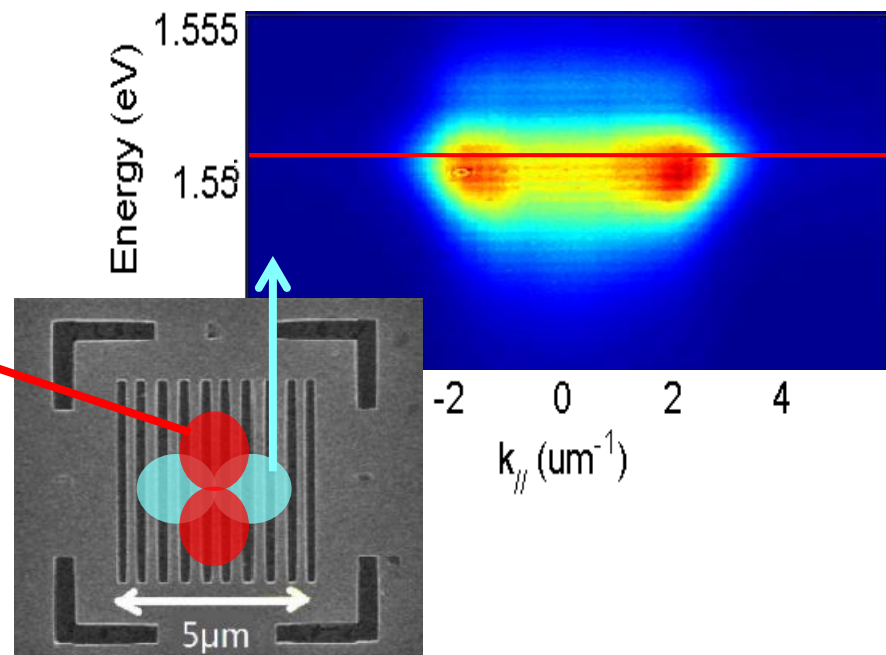


Strong-Coupling: Polariton Dispersion

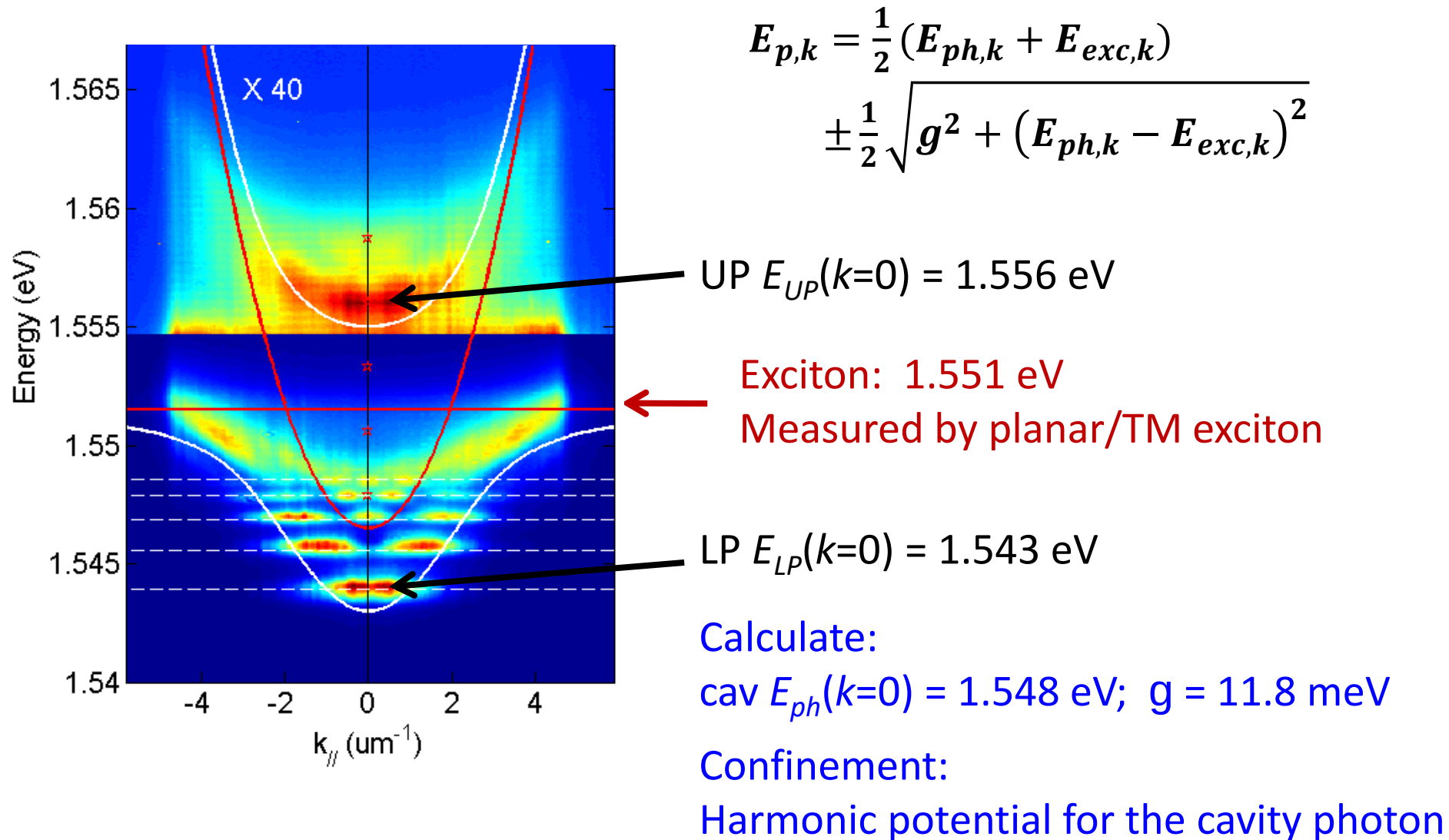
TE Discrete LP



TM Flat-Band Exciton

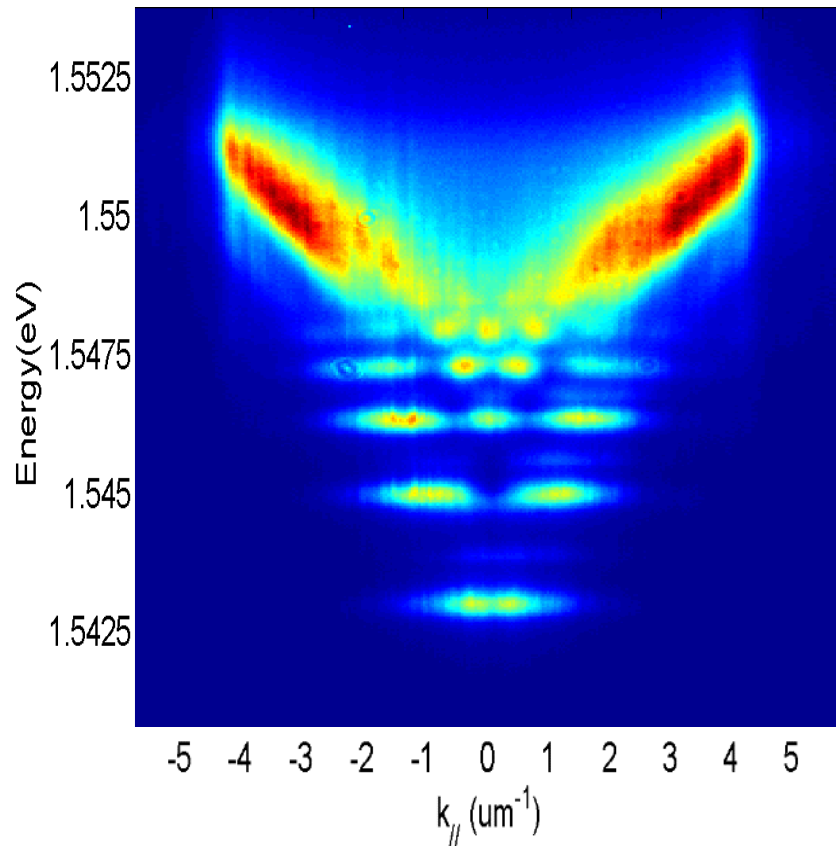


Strong-Coupling: Polariton Dispersion

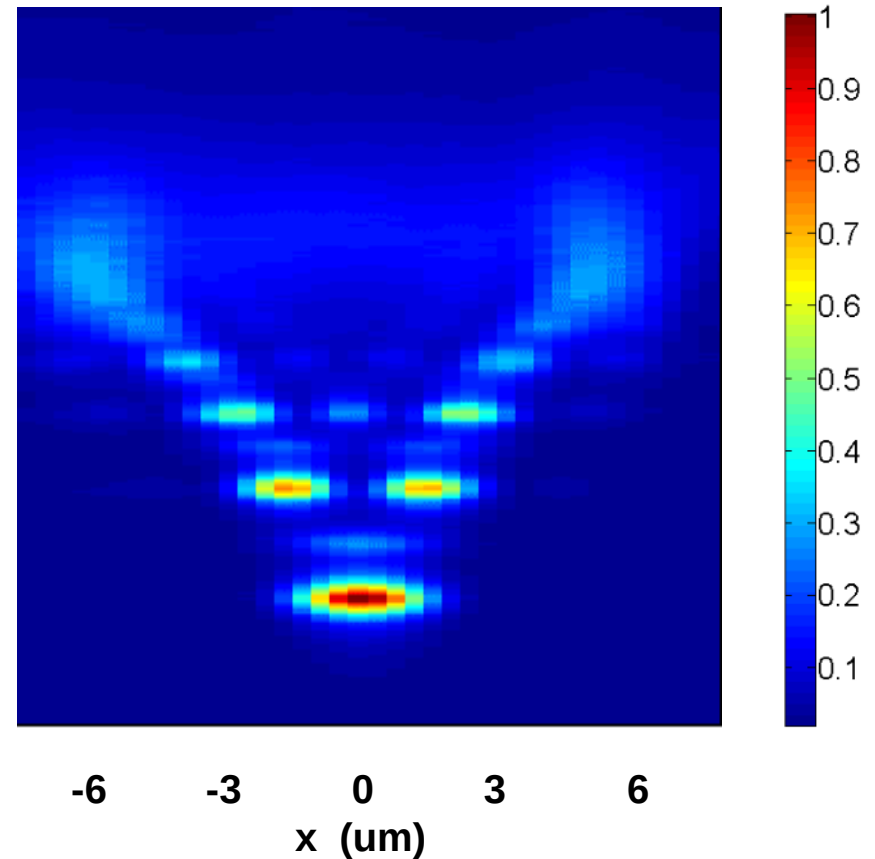


k & r wavefunctions

**k-space
mode structure**



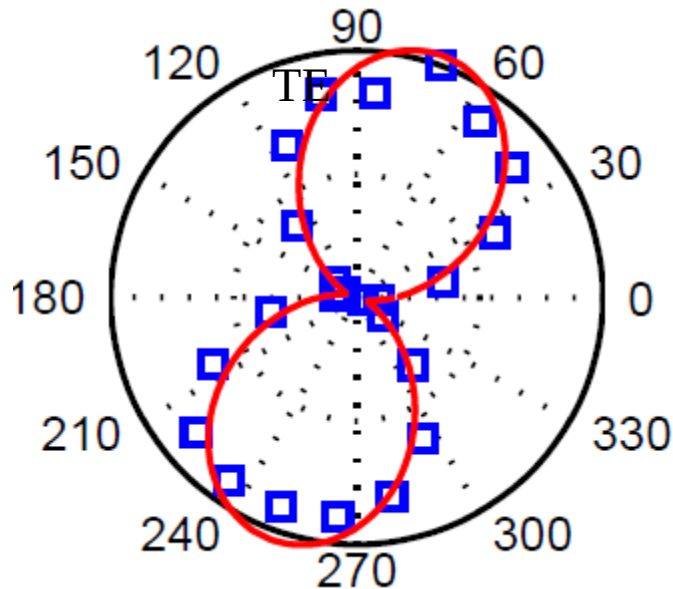
**r-space
mode structure**



Polarization Selectivity

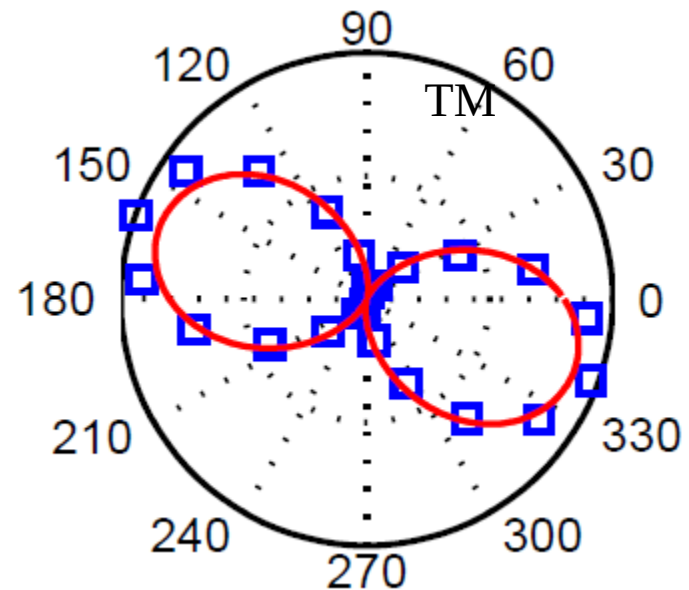
TE LP @ $k=0$

$$DOP_{LP} = 91.9\%$$



TM Exciton @ $k=0$

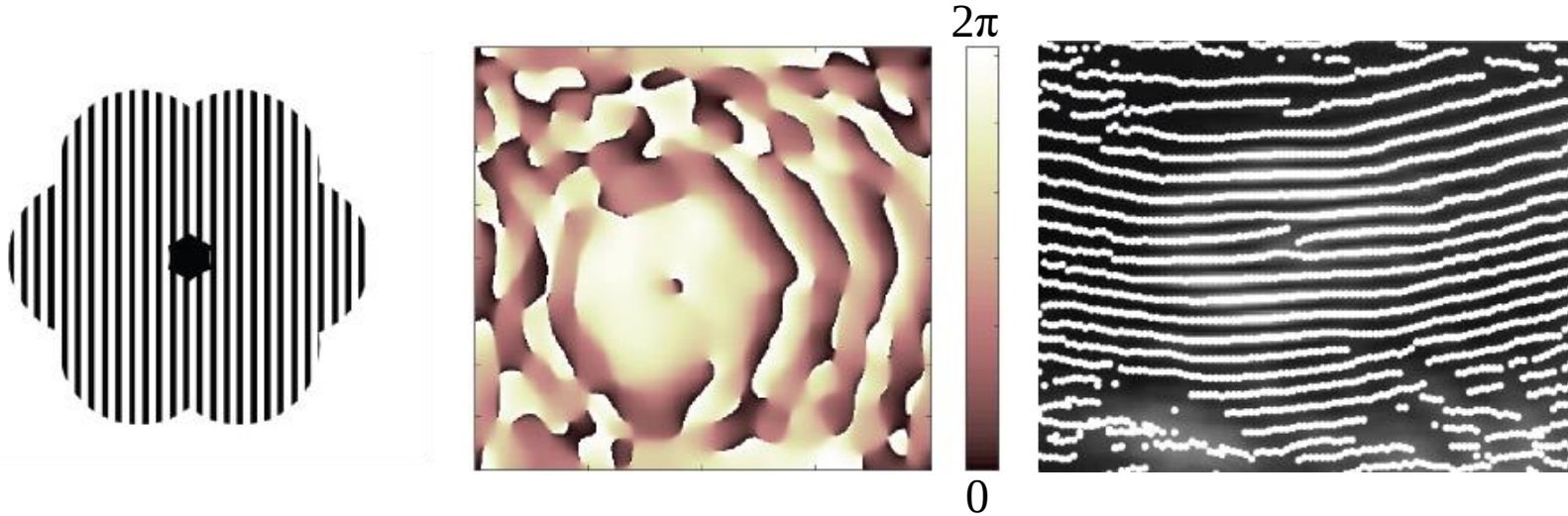
$$DOP_{exc} = 98.2\%$$



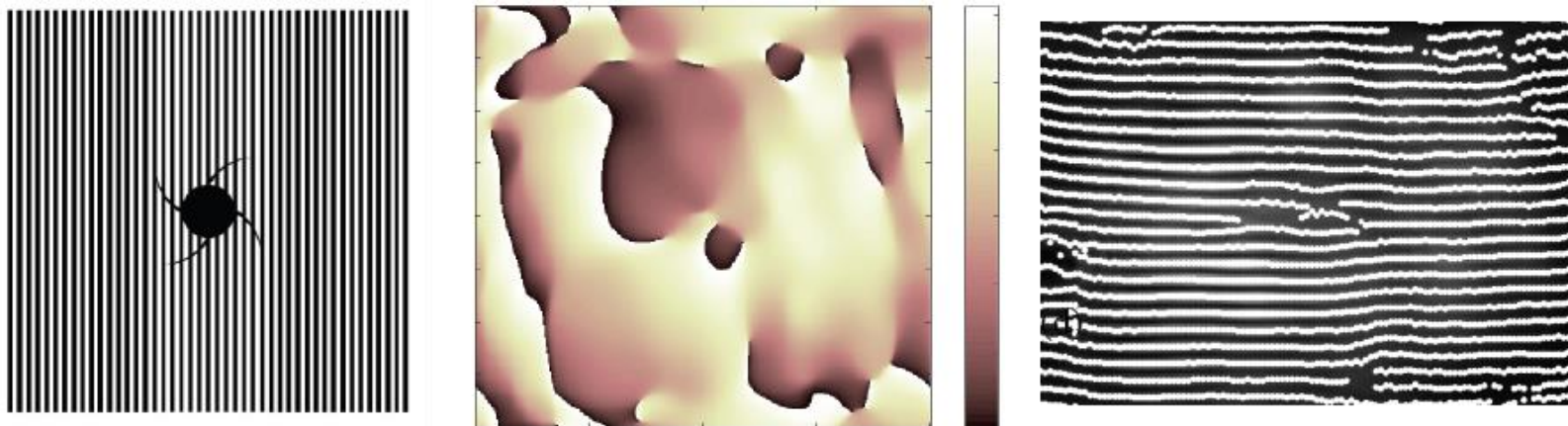
Fitting models: $I = A \cos(\theta - \phi)^2 + B$, $DOP = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{A}{A + 2B}$

Creating Phase Singularities

Preserve rotation symmetry $\rightarrow$ vortex + anti-vortex laser

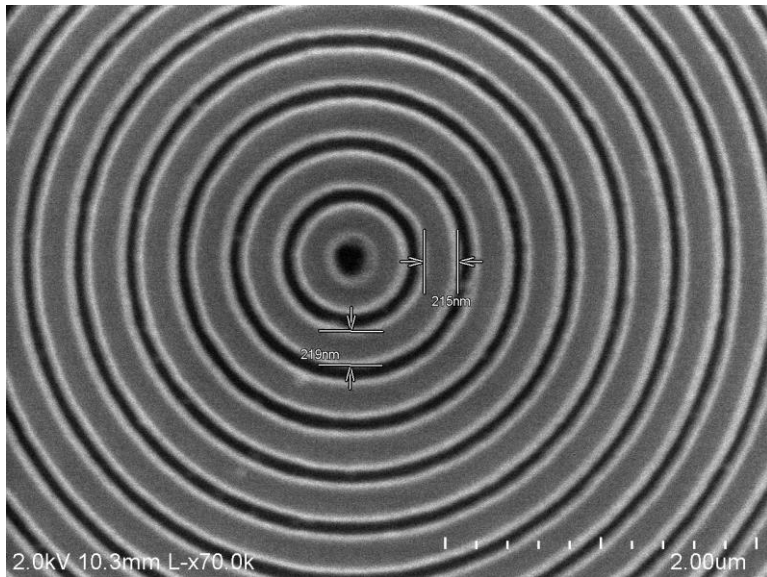


Break rotation symmetry $\rightarrow$ vortex laser (OAM=1)

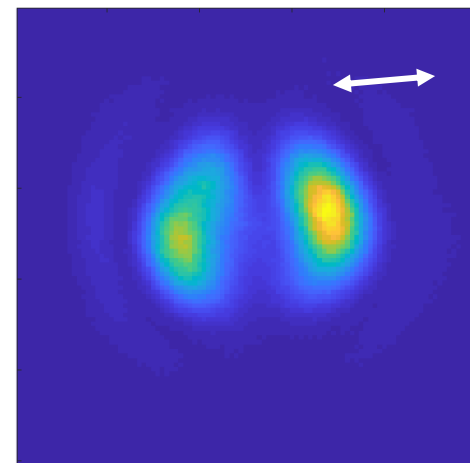
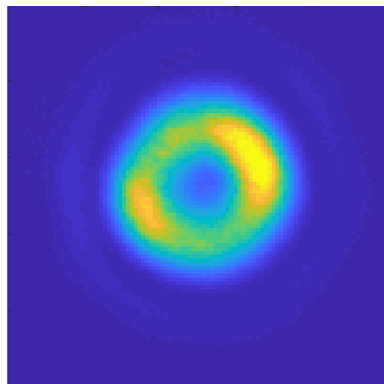
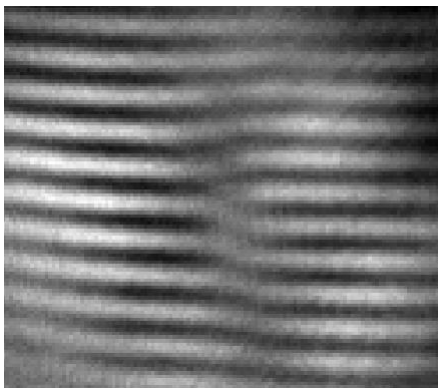
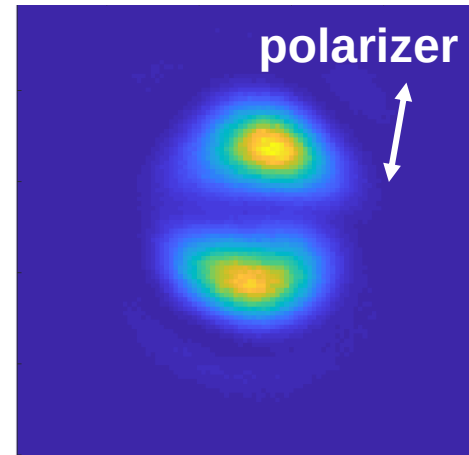


Vector Beam (OAM $l=1$)

SEM top view



Radially polarized



k-Space Dispersion

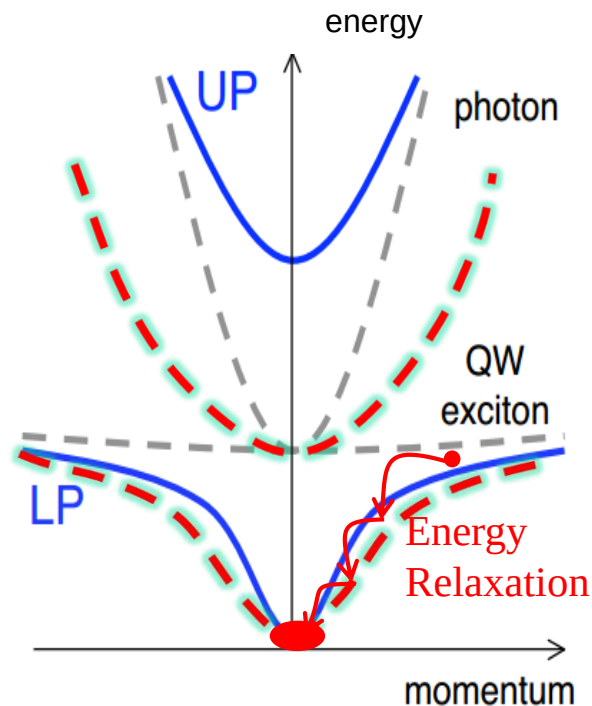
Energy
Dispersion



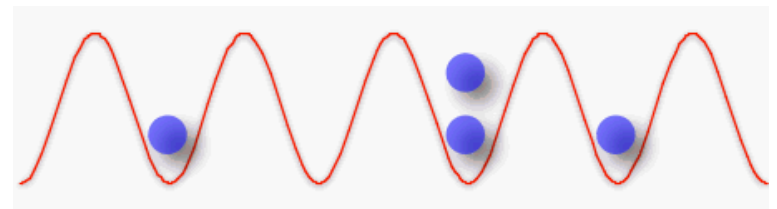
- Phase/Group Velocity
- Density of State
- Effective Mass



- Dynamics
- Transport
- Coupling & interactions
- Critical phenomena

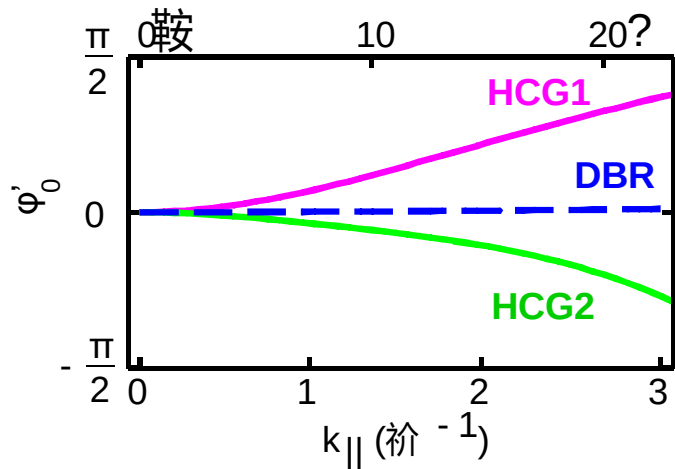
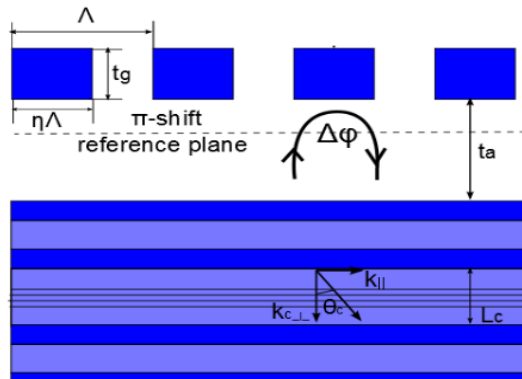


Kinetic energy vs. Interactions

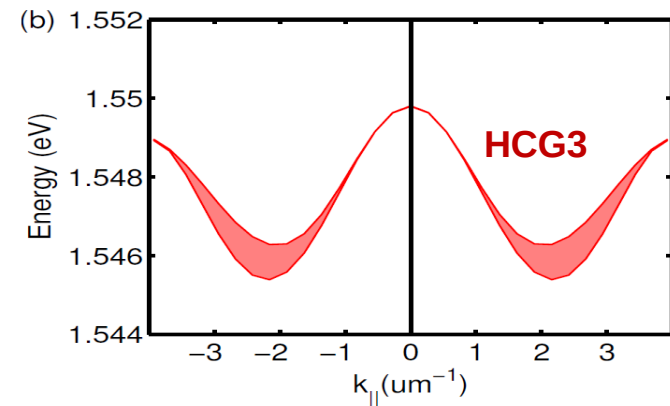
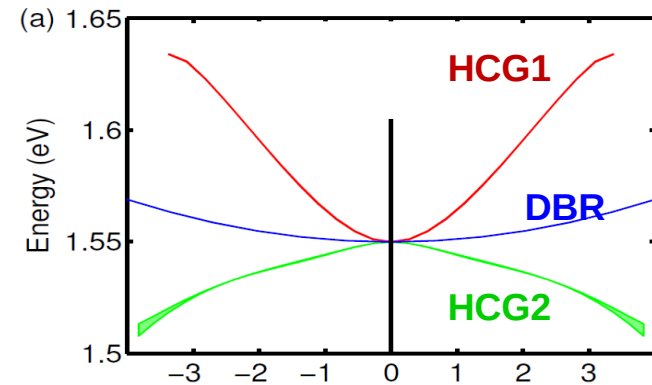


Dispersion Engineering

Angular Dependence of Reflection Phase

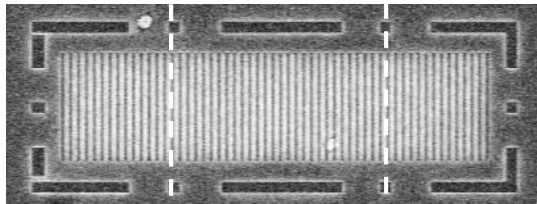


Dispersion $E(k_{||})$

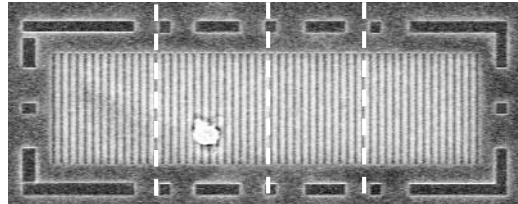


from Localization to Coupling

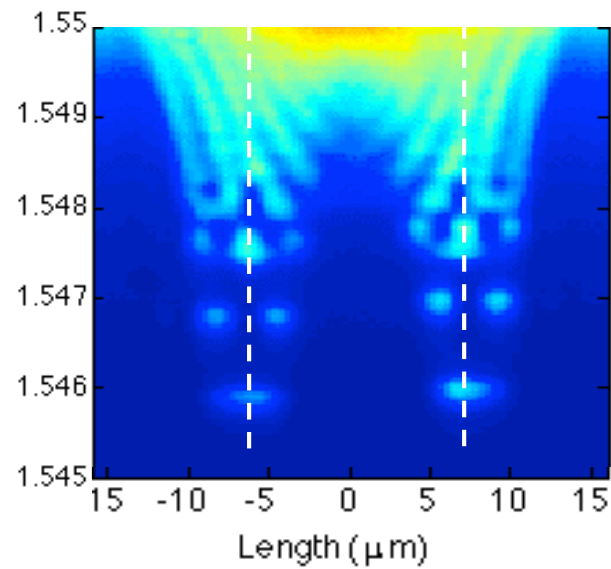
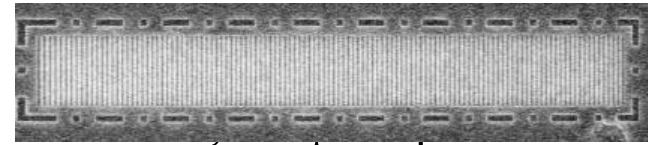
Decoupled Cavities
Localized Mode



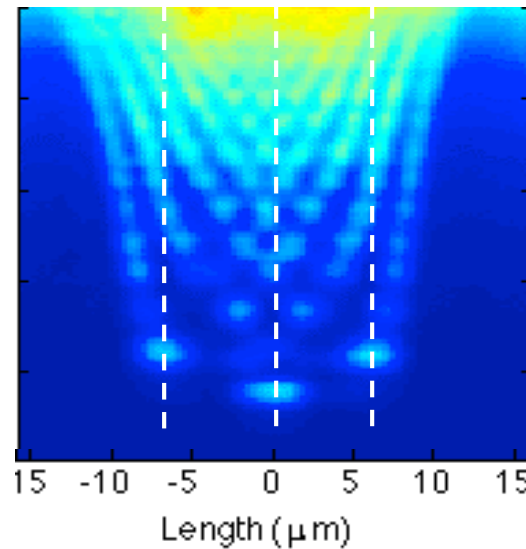
Coupled Cavities
Discrete Modes



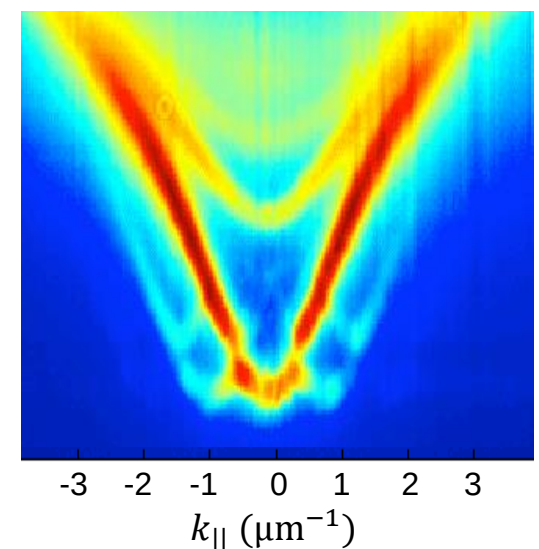
Coupled Cavities
Band Structures



x



x

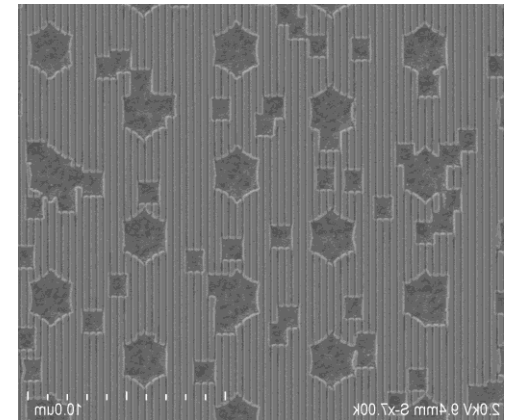
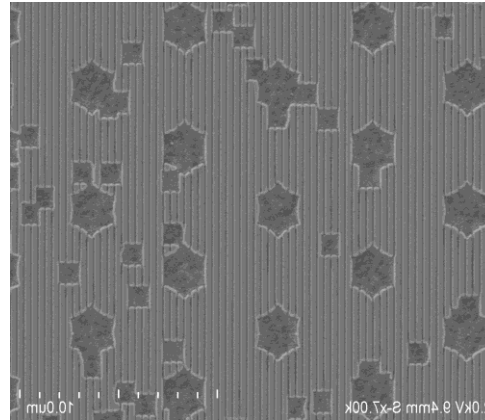
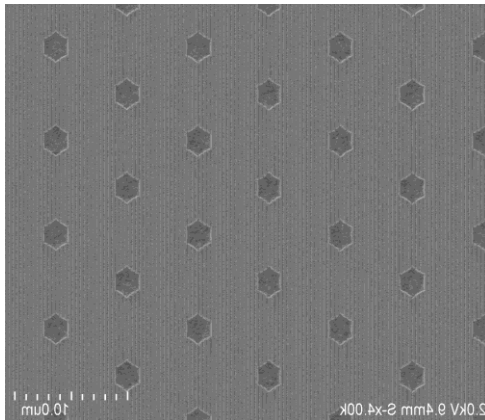


$k_{||}$

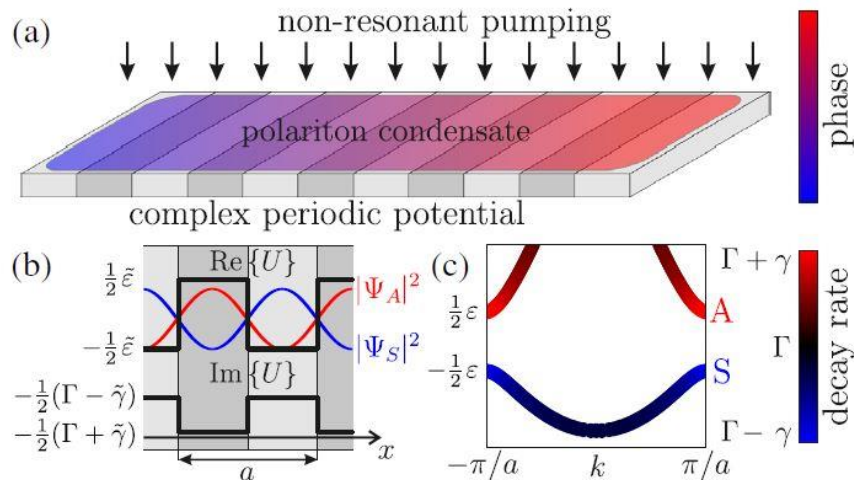
Periodic chain & more

increasing defect density $\longrightarrow$

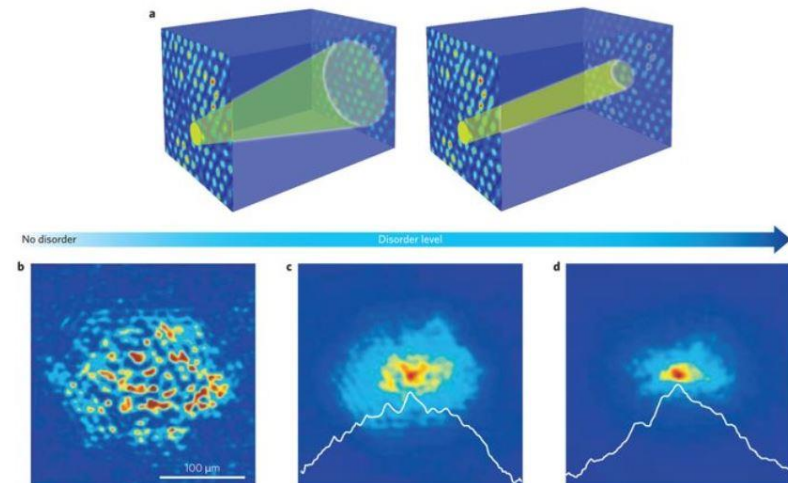
- Lattices
- Defects
- ...



Nalitov et al., Phys Rev Lett **119** 067406 (2017)



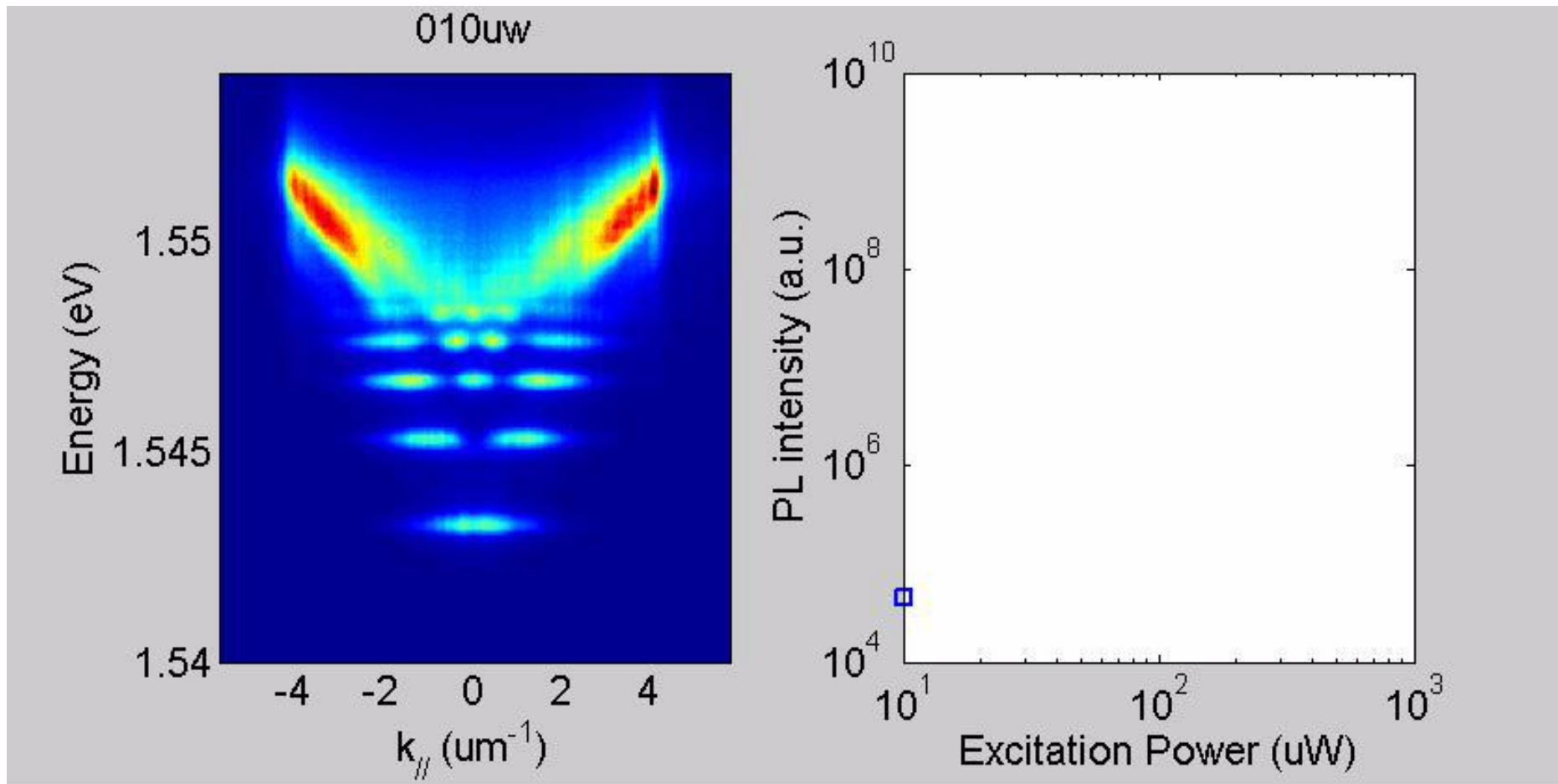
Segev et al., Nat Photon **7** 197 (2013)



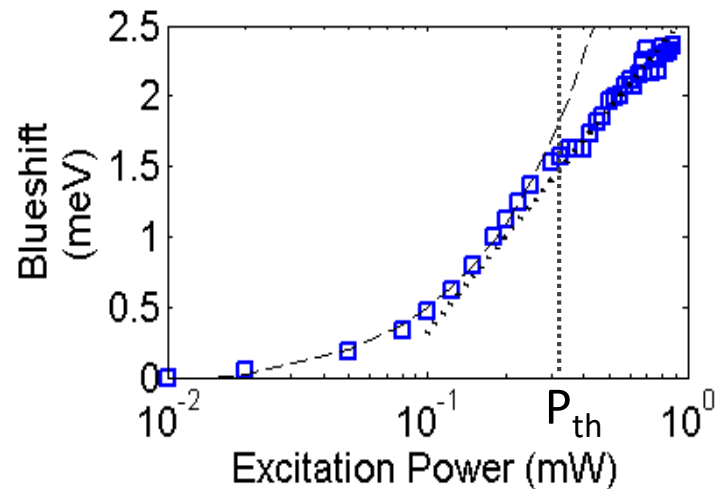
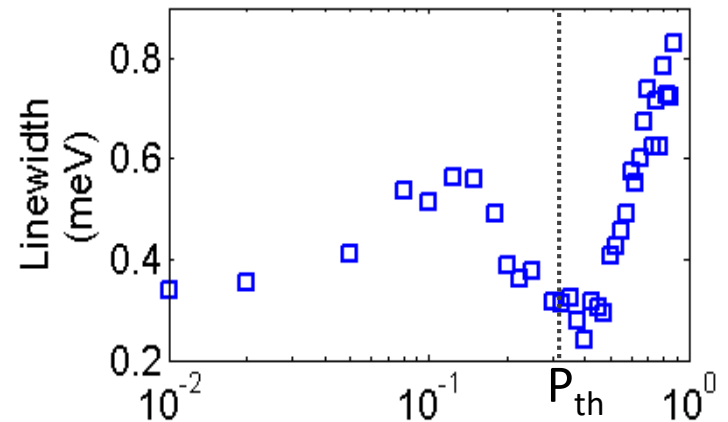
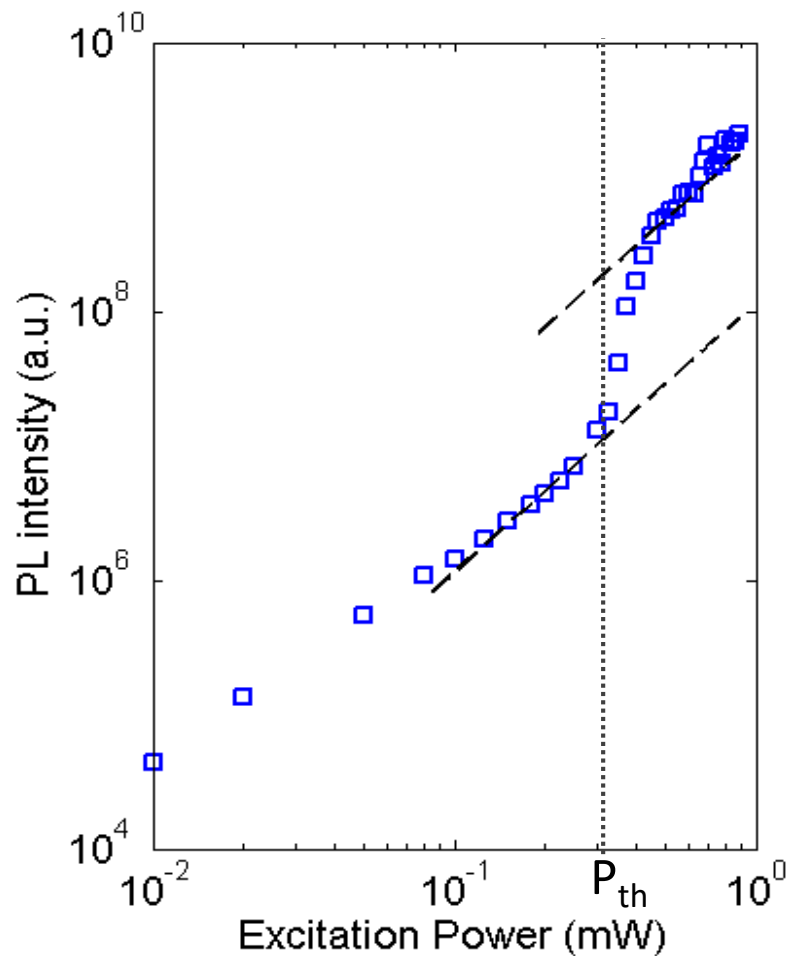
The Nonlinear Polariton Laser

- Coherent, single-mode polariton laser
- A “polariton” laser without excitons
– the high density regime
- Frequency comb by limit cycles from
dissipatively coupled polariton lasers

0D Polariton Lasing

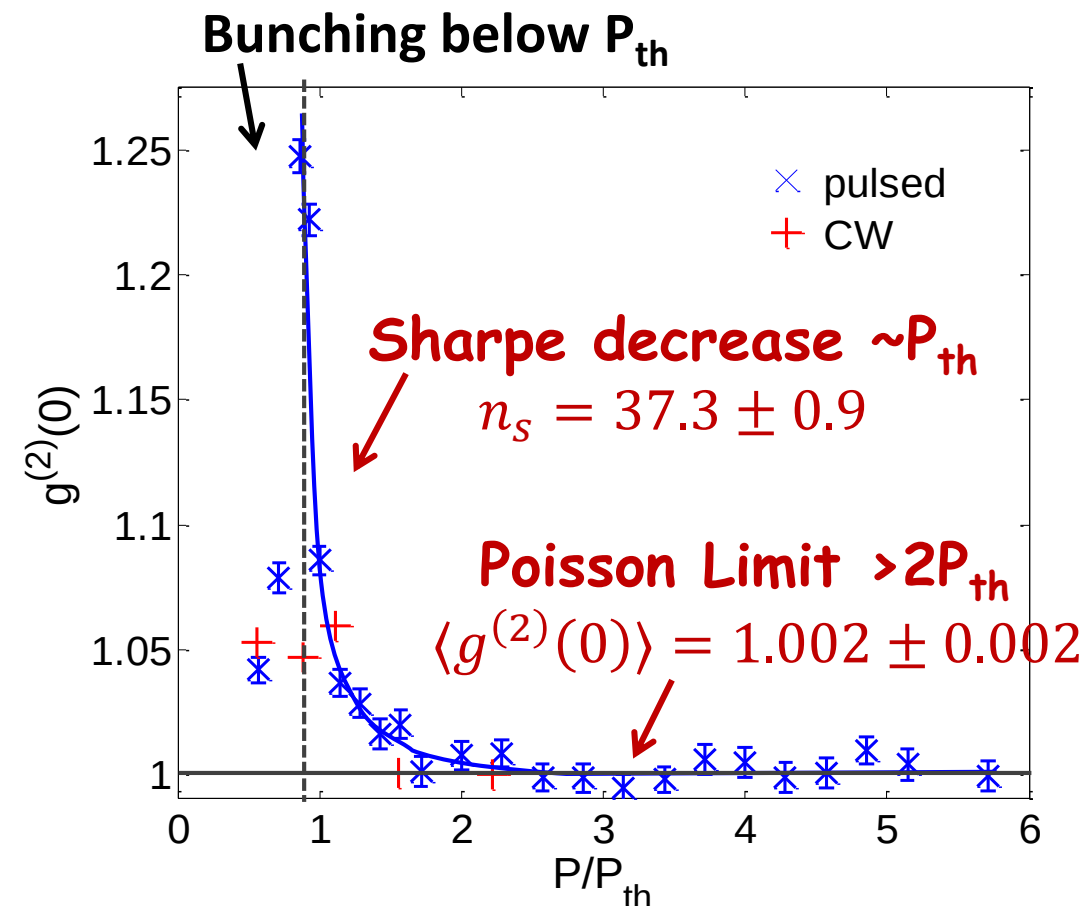
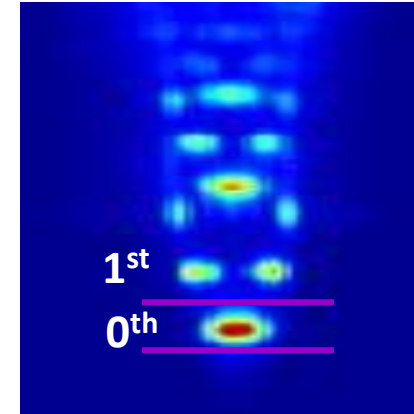


0D Polariton Lasing



$g^{(2)}$ of a Single-Mode Polariton Laser

$$g^{(2)}(0) = 1 + \frac{n_s}{\bar{n}^2}, n_s = \sigma_n^2 - \bar{n}$$

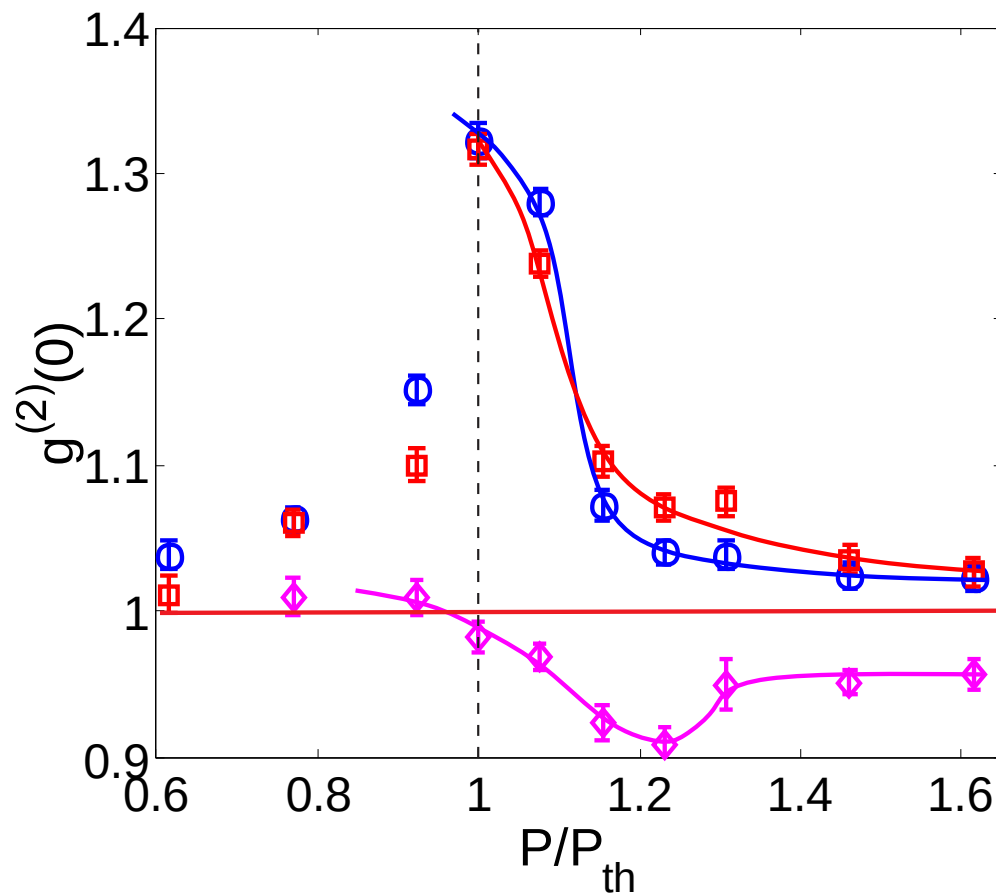


- ✓ Discrete modes
- ✓ Single polarization
- ✓ Small mode-size
- ❖ NO mode-competition or condensate fragmentation
- ❖ Suppressed condensate depletion
- ❖ Small gain saturation n_s

With Two-Mode Competition

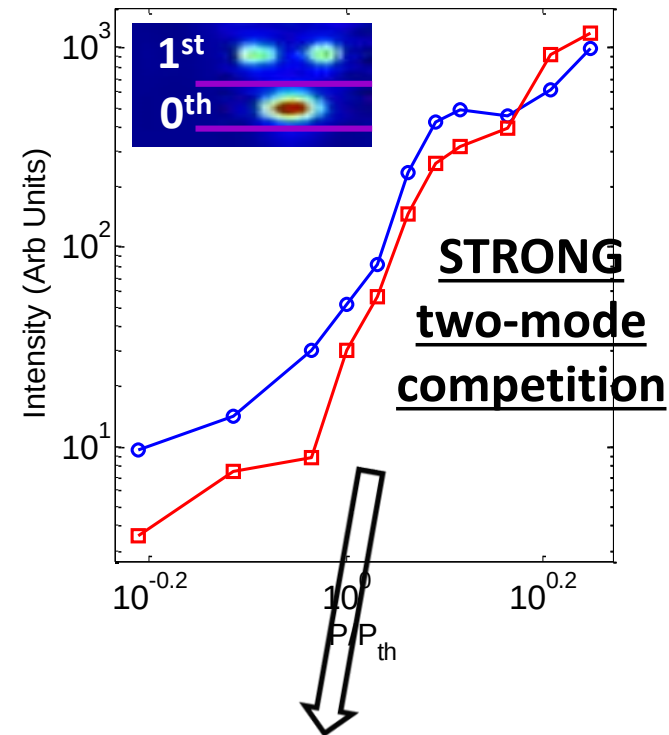
Ground state

1st excited state

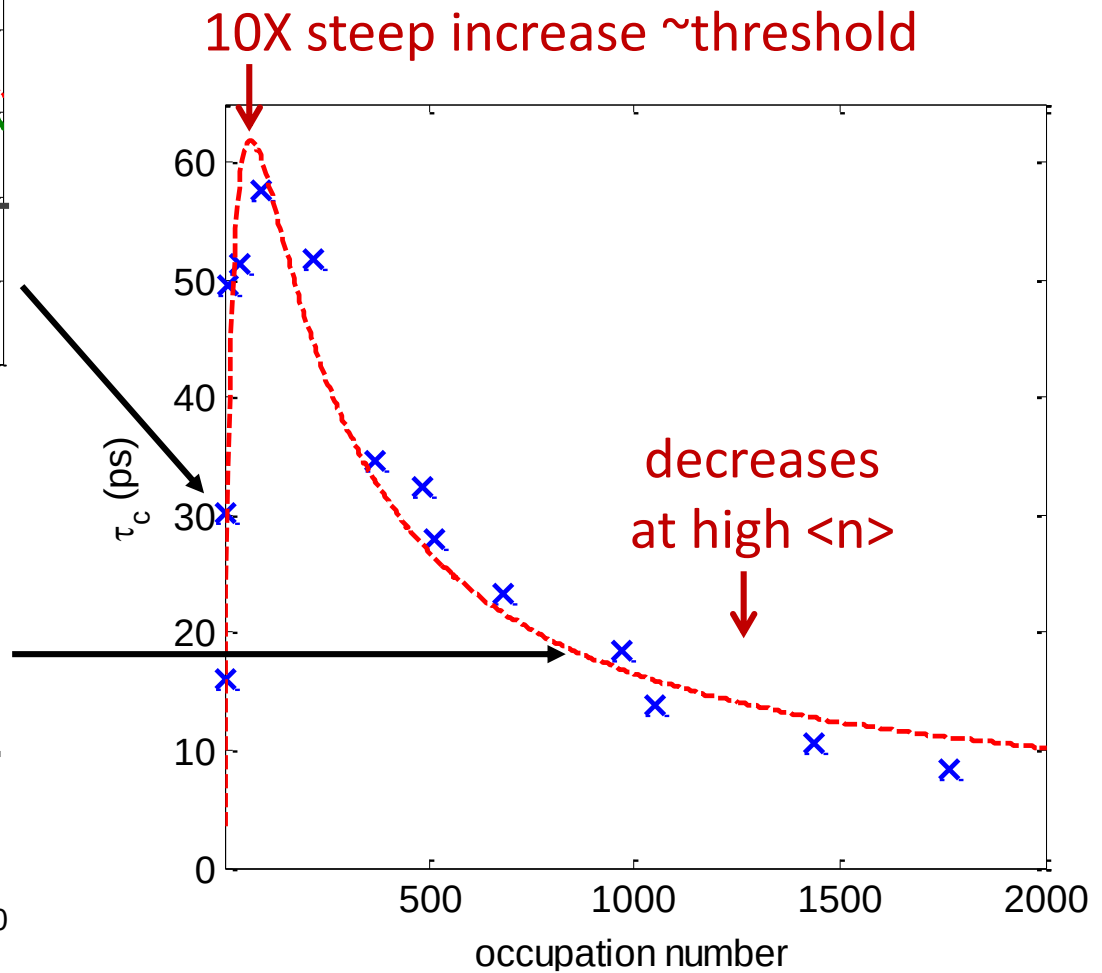
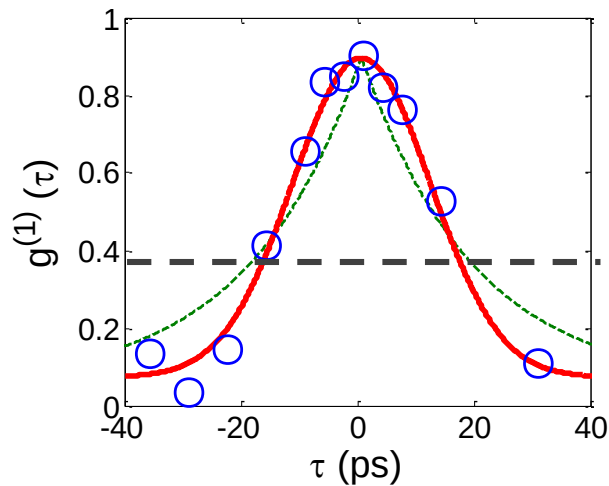
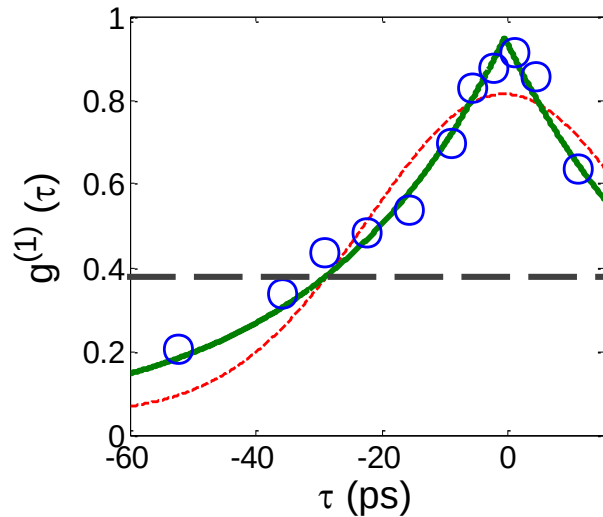


← increase of $g^{(2)}$

← Anti-correlation in $g_c^{(2)}$



Coherence Time from $g^{(1)}(\tau)$



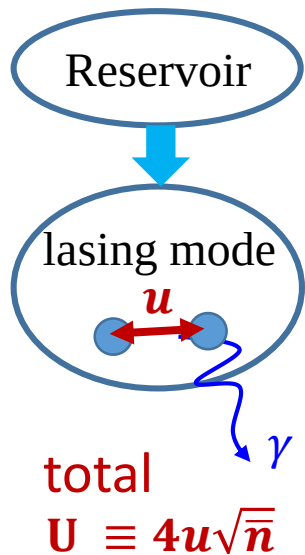
Single-Mode Matter-Wave Laser Theory

Single-mode Atom Laser Theory (*Thomsen & Wiseman 2002; Whittaker 2009*):

$\bar{n}$: mean occupancy, γ : polariton decay rate, u : LP-LP interaction constant

$n_c = \bar{n} + n_s$, $\bar{\gamma} = \gamma n/n_c$ n_s : saturation occupancy

$$g^{(1)}(\tau) = \underbrace{\exp\left(-\frac{n_c}{4\bar{n}^2}(\exp(-\bar{\gamma}\tau) - \bar{\gamma}\tau - 1)\right)}_{\text{Low occup. Weak Inter.}} \underbrace{\exp\left(-\frac{4n_c u^2}{\bar{\gamma}^2}(\exp(-\bar{\gamma}\tau) + \bar{\gamma}\tau - 1)\right)}_{\text{High occup. Strong Inter.}}$$



Low occup. Weak Inter.

$$\bar{n} \ll (\gamma/u)^2, \quad U \ll \gamma:$$

$$g^{(1)}(\tau) \approx \exp\left(-\frac{\gamma}{2\bar{n}}\tau\right)$$

Schawlow-Townes

High occup. Strong Inter.

$$\bar{n} \ll (\gamma/u)^2, \quad U \gg \gamma:$$

$$g^{(1)}(\tau) \approx \exp(-2\bar{n}u^2\tau^2)$$

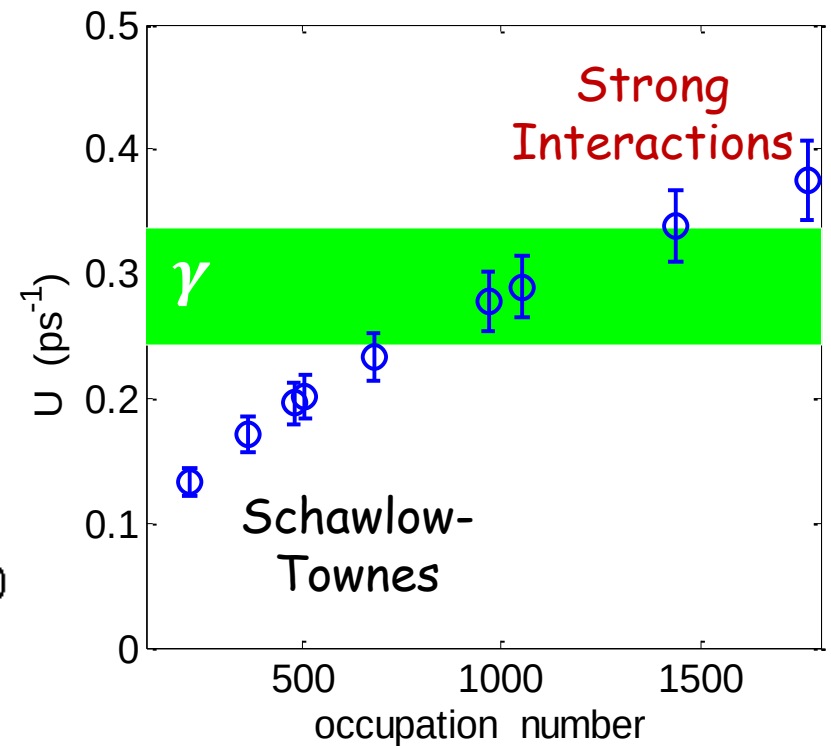
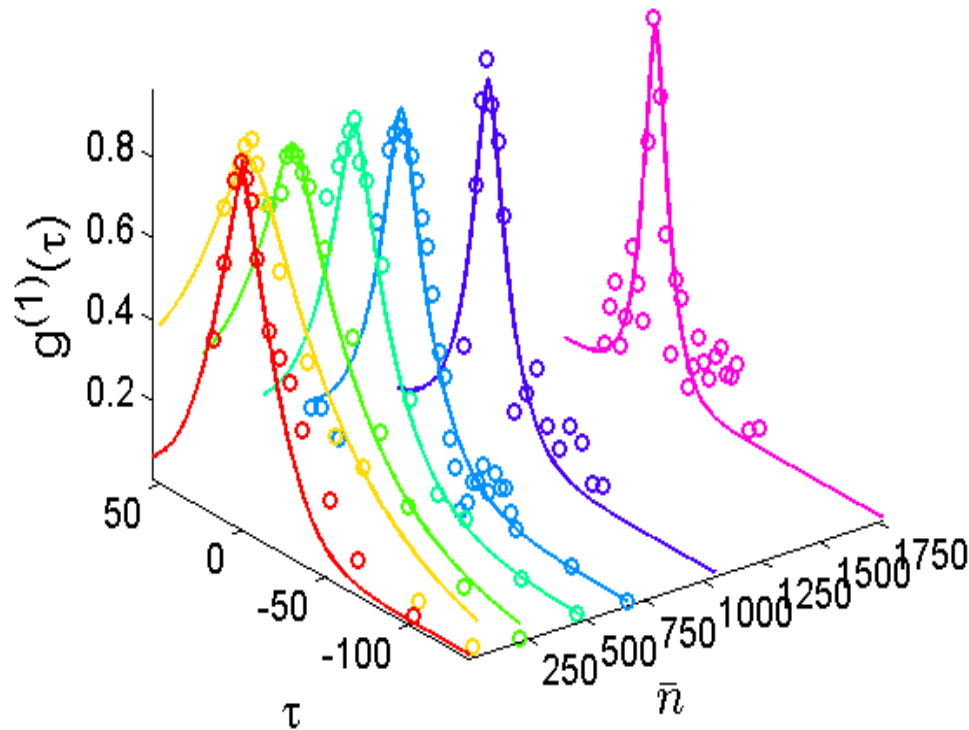
Strong Interactions

Interaction Strength vs. Occupation

$$\begin{aligned}n_s &= 61, \\ \gamma &= 0.29 \text{ ps}^{-1}, \\ u &= 2.2 \times 10^{-3} \text{ ps}^{-1}\end{aligned}$$



$$U \equiv 4u\sqrt{\bar{n}} \sim \gamma @ \bar{n} \sim 10^3$$



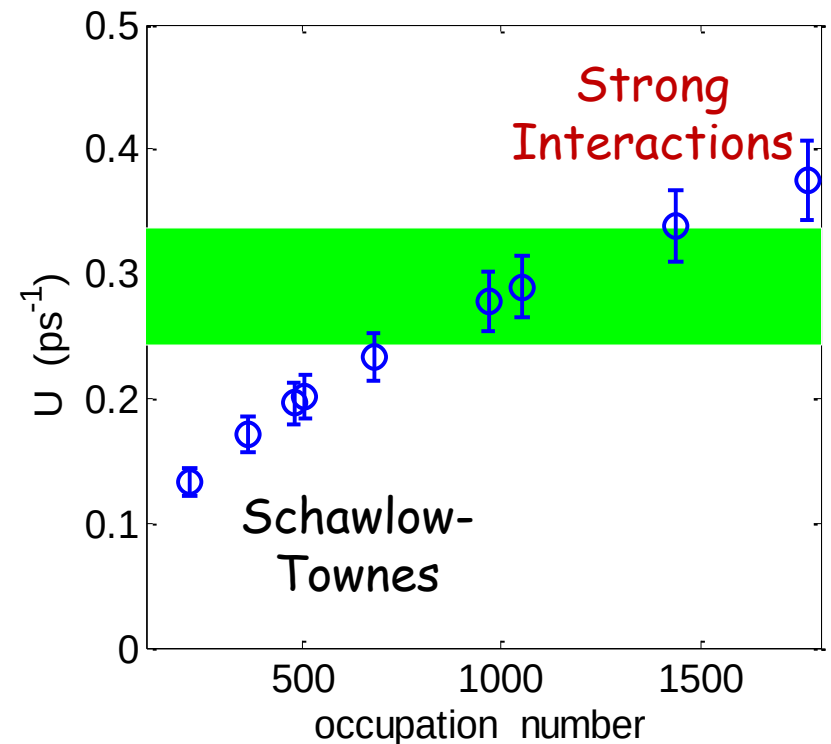
Interaction Strength vs. Occupation

$$\begin{aligned}n_s &= 61, \\ \gamma &= 0.29 \text{ ps}^{-1}, \\ u &= 2.2 \times 10^{-3} \text{ ps}^{-1}\end{aligned}$$



$$\mathbf{U} \equiv 4u\sqrt{\bar{n}} \sim \gamma @ \bar{n} \sim 10^3$$

- Strong-interactions manifested in Gaussian line-broadening
- Measurable under Poisson intensity noise
- Unique to matter-wave laser

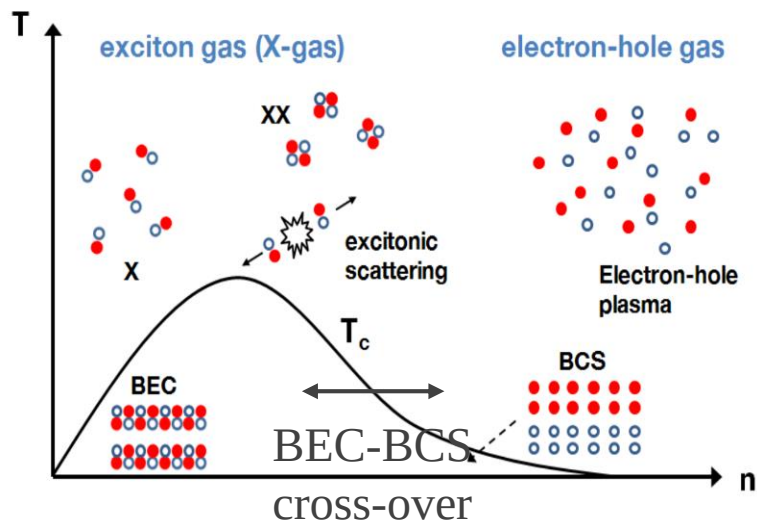


Uniquely Polaritonic

BEC-BCS Crossover

Particle-Hole-Photon Liquid

*Keldysh, Nozier, Littlewood,
Ogawa, Yamamoto ...*

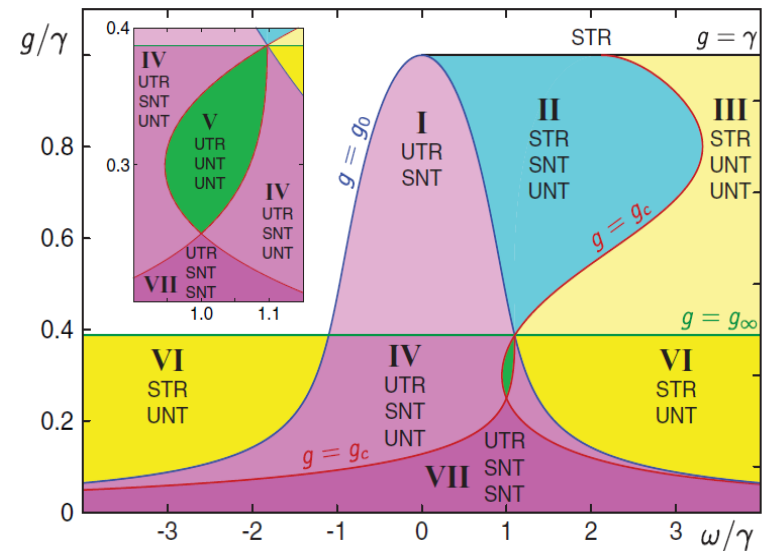


Signatures of a Bardeen-Cooper-Schrieffer Polariton Laser.

J. Hu et al. arXiv:1902.00142

Dissipation Induced Nonlinear Dynamic Phases

Rubo, Kavokin, Liew ...



Emergence Of **Micro-frequency Comb** via **Limit Cycles** in **Dissipatively Coupled Condensates**

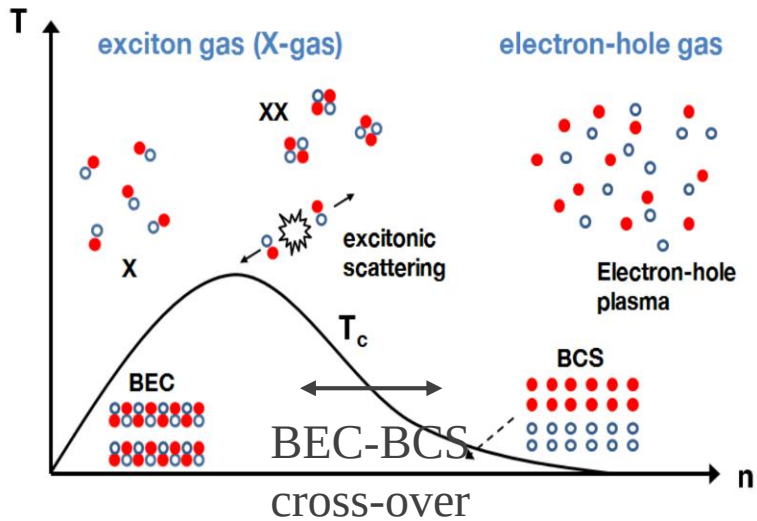
Kim et. al., arXiv:1809.04641

Uniquely Polaritonic

BEC-BCS Crossover

Particle-Hole-Photon Liquid

*Keldysh, Nozier, Littlewood,
Ogawa, Yamamoto ...*



Signatures of a Bardeen-Cooper-Schrieffer Polariton Laser.

J. Hu et al. arXiv:1902.00142

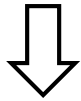
A “Polariton” Laser With No Excitons

Polariton BCS

Superconductor BCS: e-e Cooper pair



Exciton BEC to BCS crossover: e-h pair



Polariton BCS: plus photon coupling

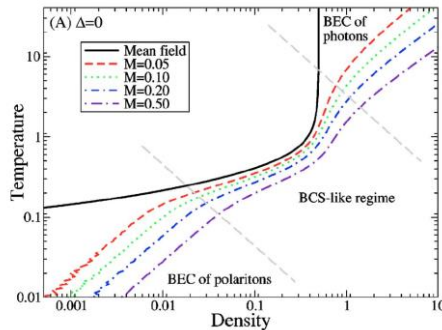
Bardeen et al. 1957 *Phys. Rev.* **108** 1175

Keldysh & Kozlov 1968 *Sov. Phys. JETP* **27** 521

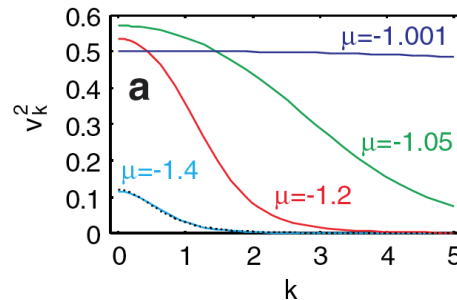
Comte & Nozières 1982 *J. Physique* **43** 1069

Littlewood et al. 2004 *J. Phys.: Condens. Matter* **16** S3597

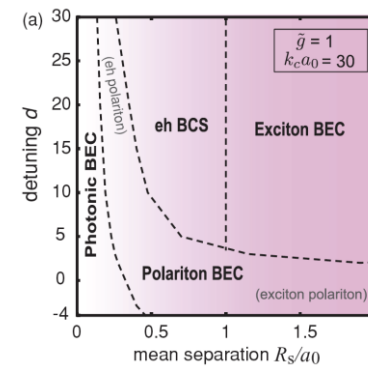
Kremp et al. 2008 *Phys. Rev. B* **78** 125315



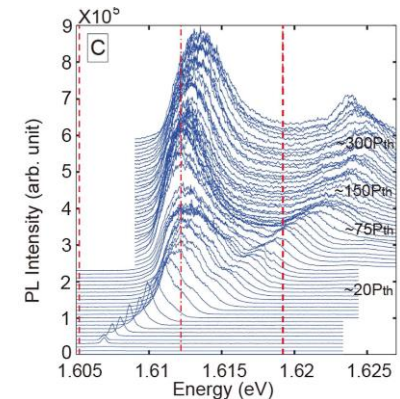
Keeling et al. 2005
Phys. Rev. B **72** 115320



Byrnes et al. 2010
Phys. Rev. Lett. **105** 186402

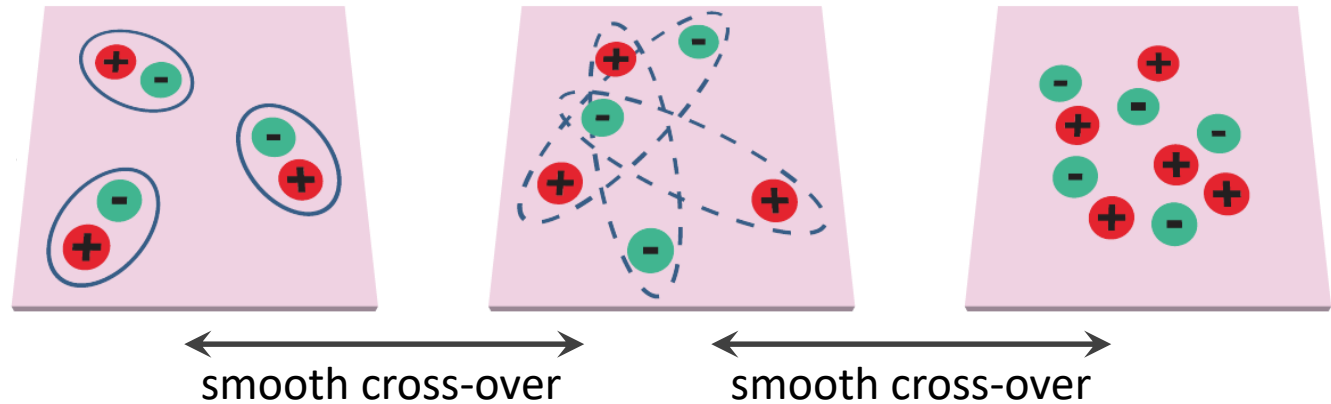


Kamide et al. 2010
Phys. Rev. Lett. **105** 056401



Horikiri et al. 2016 *Scientific Reports* **6** 25655

Polariton BEC Polariton BCS Photon Laser

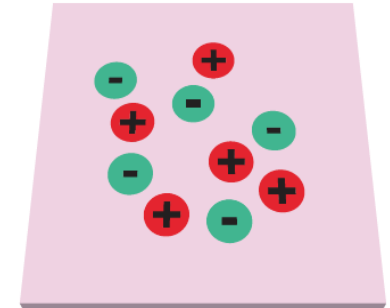
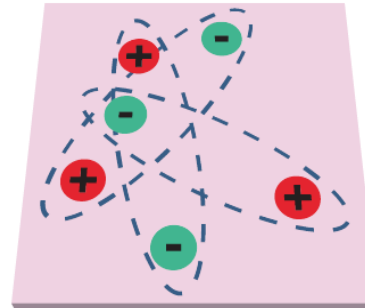
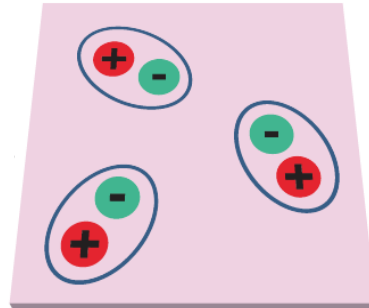


Carrier density	$n \ll n_{Mott}$	$n \geq n_{Mott}$	$n \gg n_{Mott}$
Electron, hole distribution	far below degeneracy, no inversion	below Fermi degeneracy, small inversion	Fermi degenerate, strong inversion
Quasi-particle	exciton-polariton with bound exciton	e-h-polariton with bound e-h pair	e-h plasma, unbound
Gain type	bosonic	fermionic	fermionic
Gain process	stimulated scattering into exciton-polariton	stimulated emission from BCS-like e-h-polariton	stimulated emission from unbound e-h pair

Polariton BEC

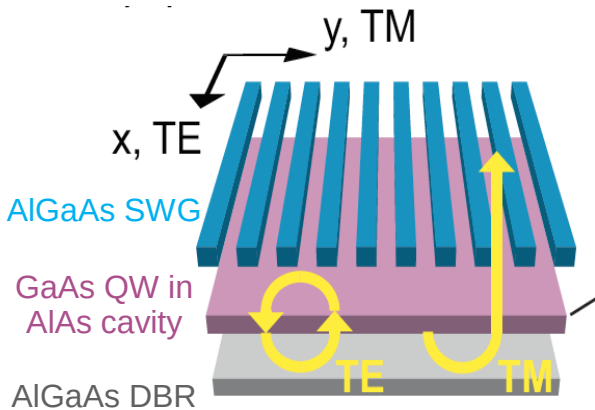
Polariton BCS

Photon Laser

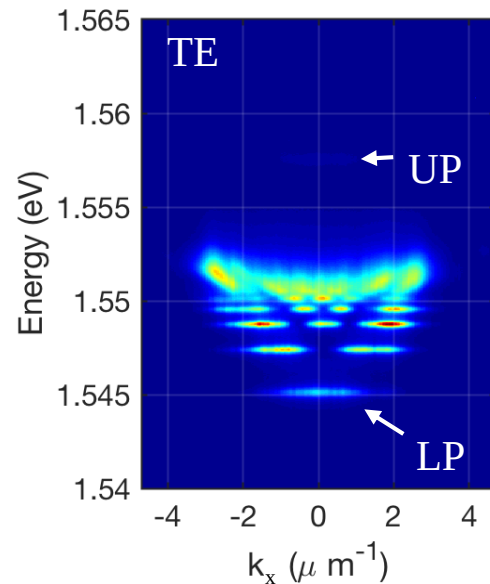


- How to identify these states experimentally?
 - All expected to have coherent light emission
 - Spectral features like frequency shift may be used to identify photon laser but not BCS
- => Need to probe the matter component of the microcavity system
- Polarization selective cavity for observing weakly-coupled (reservoir) and strongly-coupled (polariton) modes simultaneously

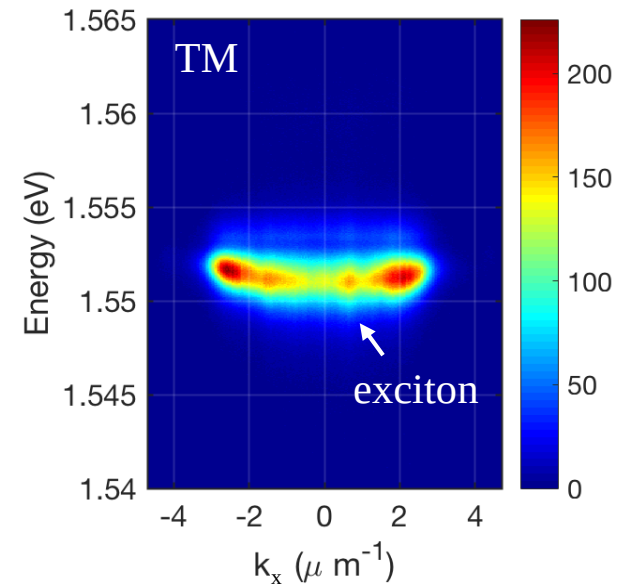
A Look “Inside” the Polariton Laser



Zhang et. al., Light Sci
Appl 3, e135 (2014)



Strong-coupling for TE



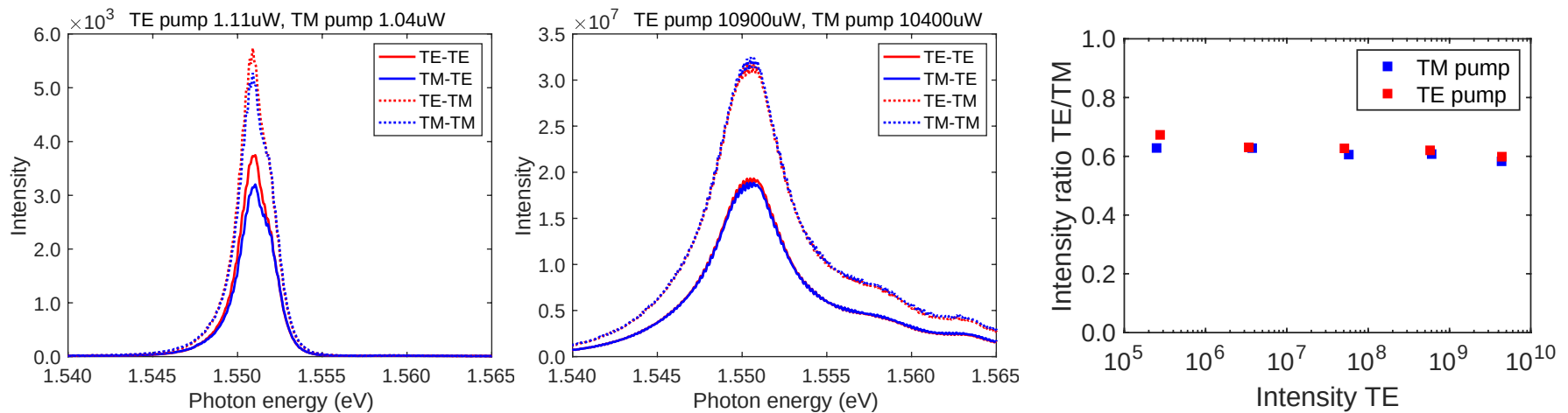
Weak-coupling for TM

- Simultaneous access to both the coupled mode and its matter component
- Linear polarization ensures spin balance

Shared Electron-Hole Reservoir

Emission from un-etched part

Non-resonant CW pump about 30meV above resonance



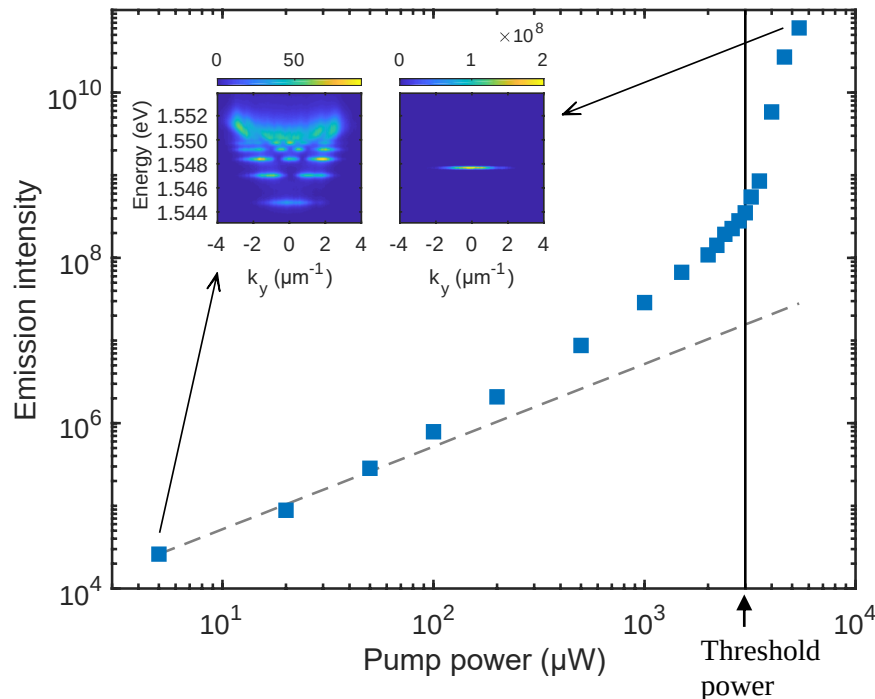
- Same intensity with TE or TM pump for given emission polarization
- Collection efficiency different for TE or TM emission, corresponding to a constant TE/TM intensities ratio
- On grating: Dispersion modified only near $k_{||} \sim 0$, where polariton density $\sim 10^{-5} - 10^{-2}$ total density

TE Polariton Lasing

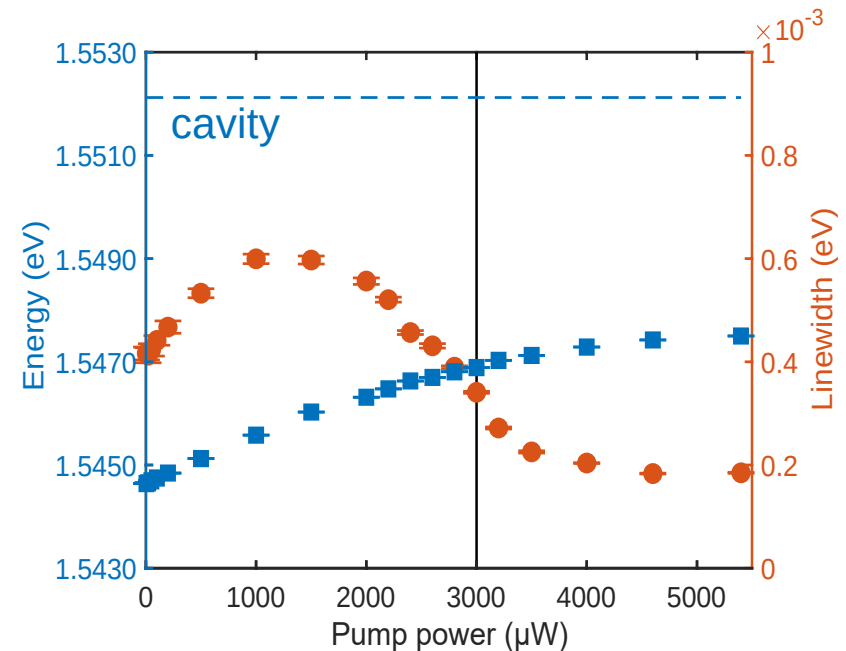
Identical emission properties & spectral features as a polariton (BEC) laser

Zhang et. al. “Zero-dimensional polariton laser in a subwavelength grating-based vertical microcavity.” *Light Sci Appl* **3**, e135 (2014).

Kim et al. “Coherent Polariton Laser.” *Phys. Rev. X* **6**, 011026 (2016).



- Super-linear increase of emission intensity from the $k_{||} = 0$ mode
- “Condensation” of emission to $k_{||} = 0$

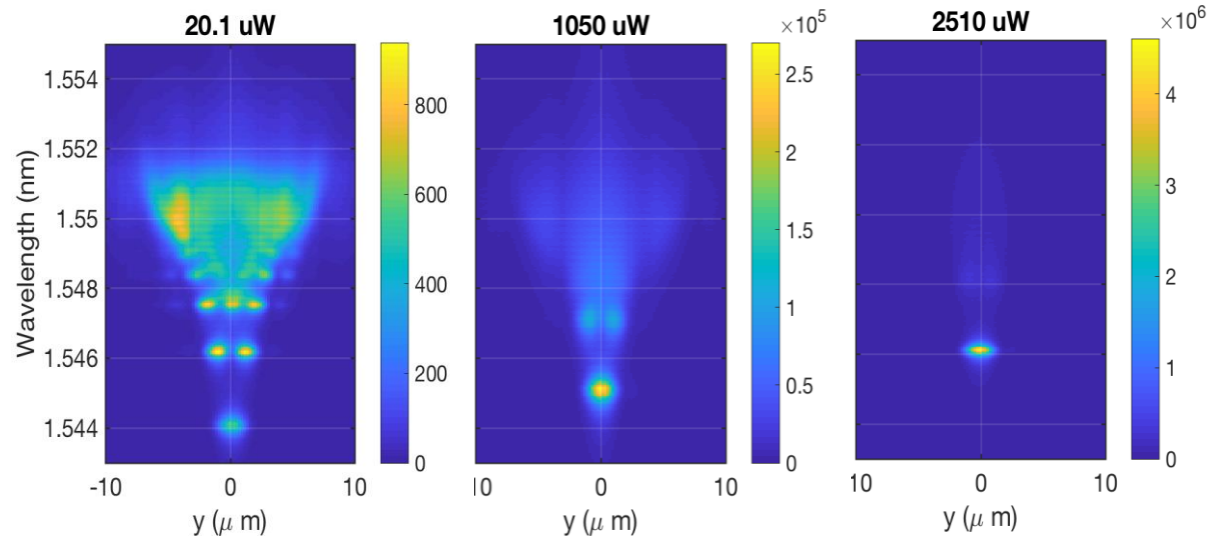


- Emission energy $\ll$ cavity
- Blue-shift small and continuous
- Linewidth $< 0.6 \text{ meV}$ and drops to resolution limit above P_{th}

Not a Photon Laser

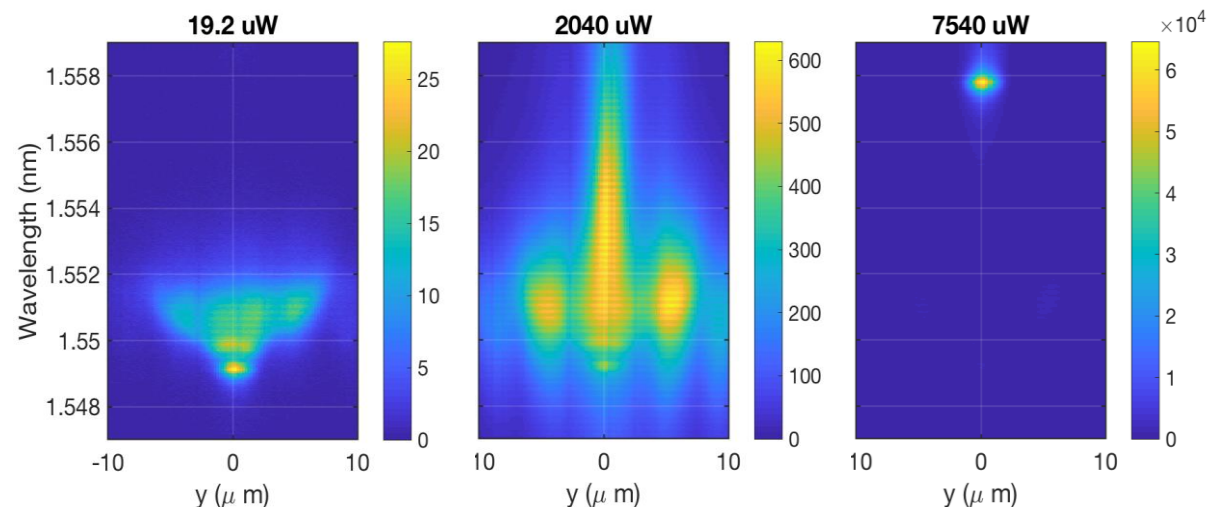
Polariton BCS

- Distinct polariton ground state
- Narrow linewidth
- Blue shift small & continuous



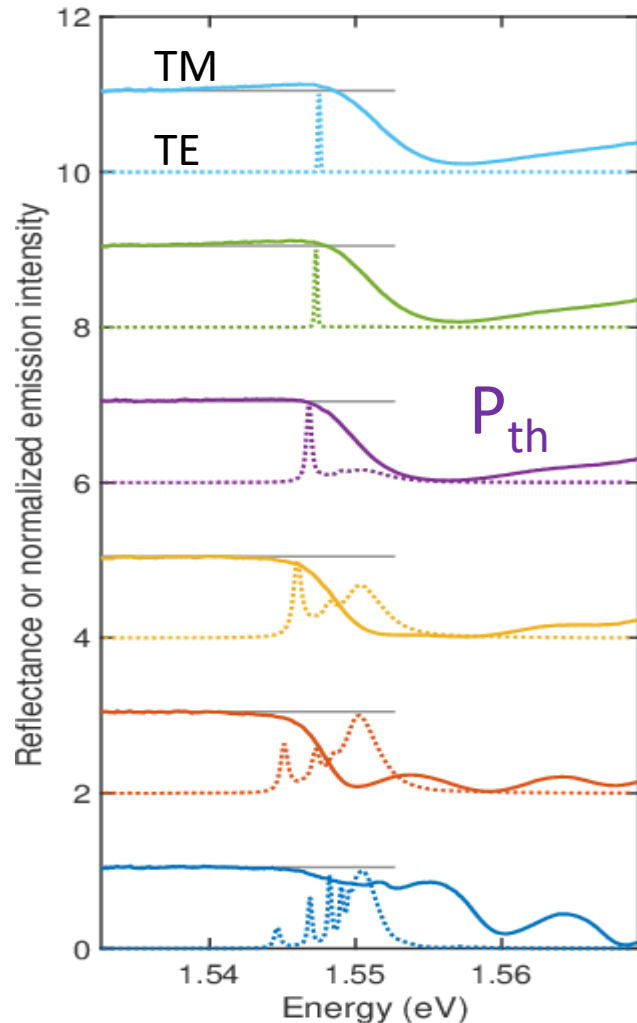
Photon laser

- Polariton ground state disappears
- Drastic broadening before threshold
- Lasing @ $E_{cav} \gg E_{LP0}$

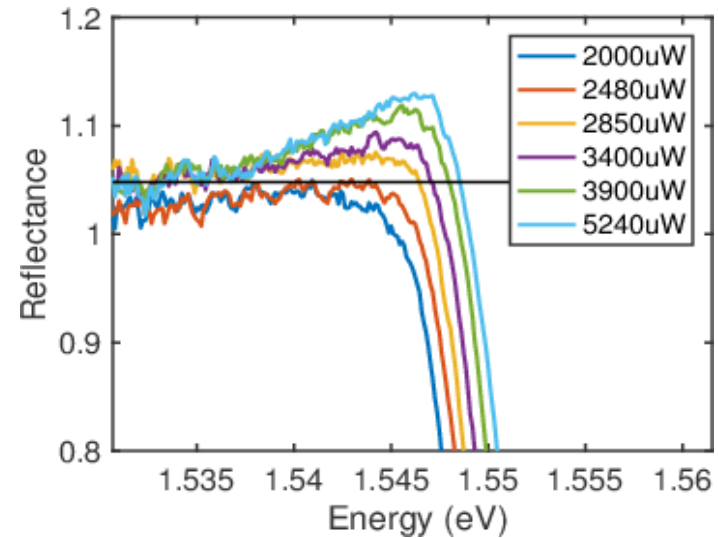


Fermionic Gain: *NOT* a Polariton BEC

TM reflection cf. TE emission



TM gain above threshold

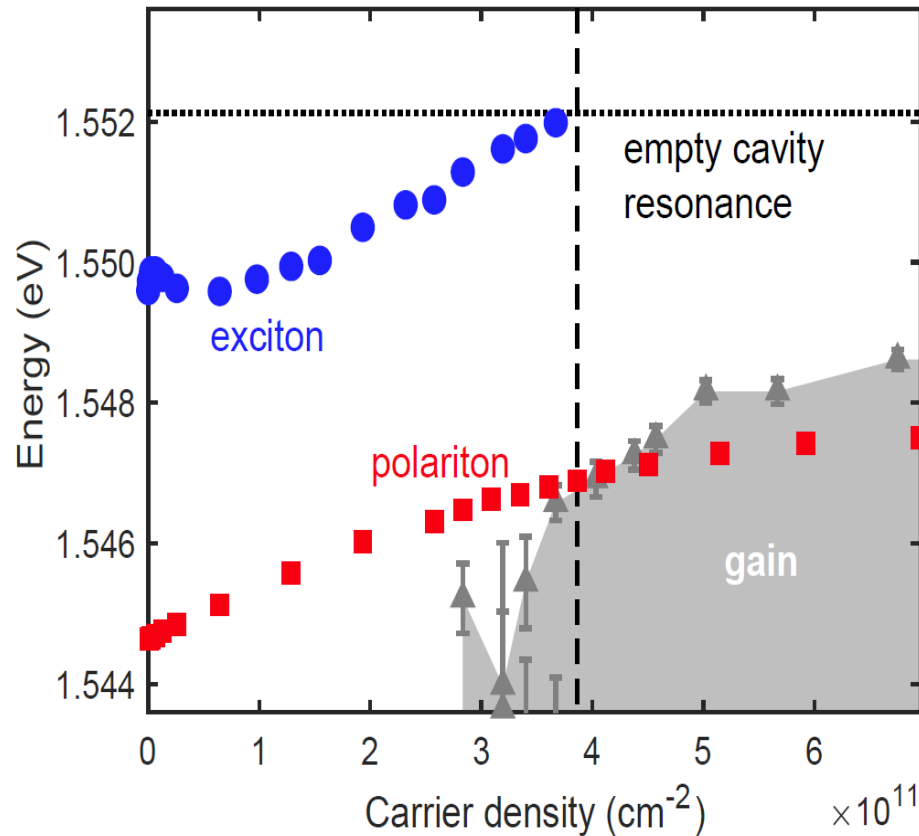


- Discrete TM exciton $\rightarrow$ continuum absorption even below P_{th}
- TM gain near and above threshold
- TE emission within gain spectra and well below cavity

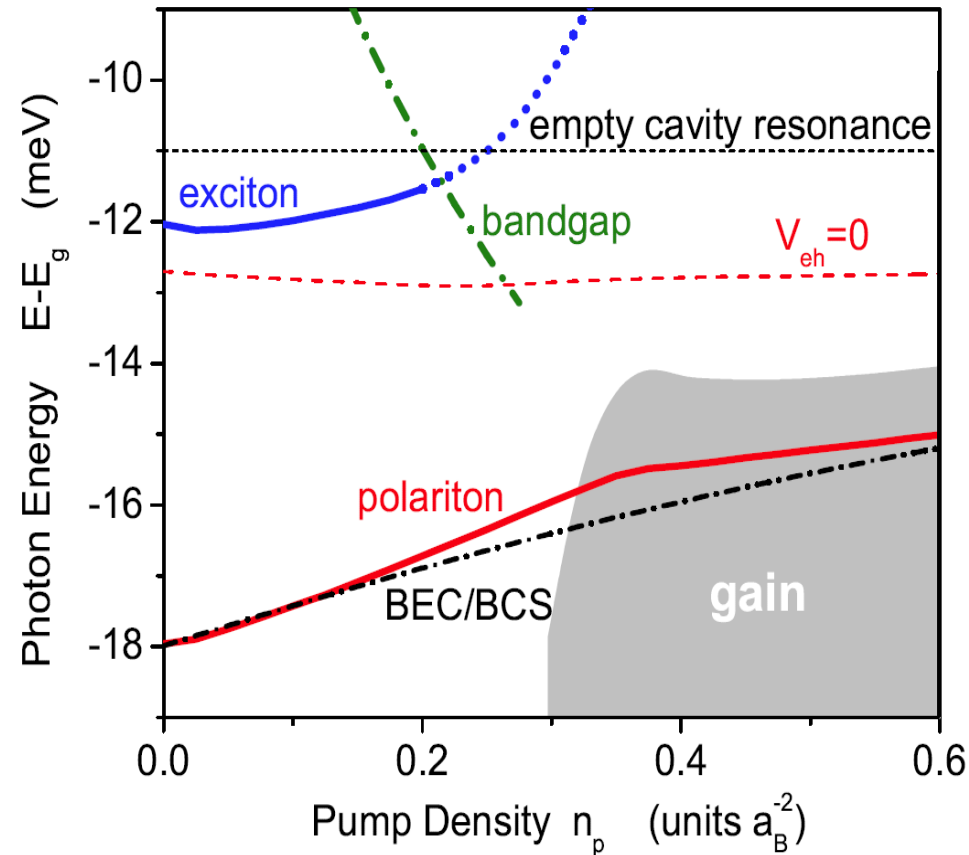
NOT polariton BEC NOR photon laser

BCS-Like Polariton laser: Exp & Theory

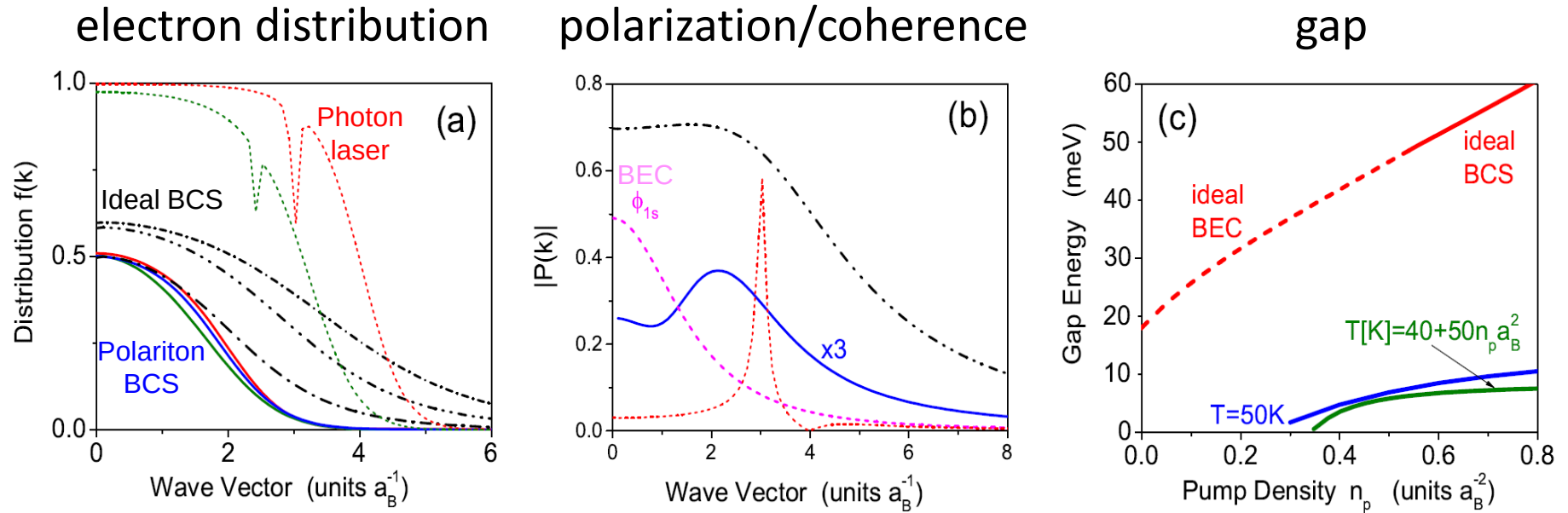
Experiment



Theory (Rolf Binder, Arizona)



BEC vs BCS vs Photon Lasers

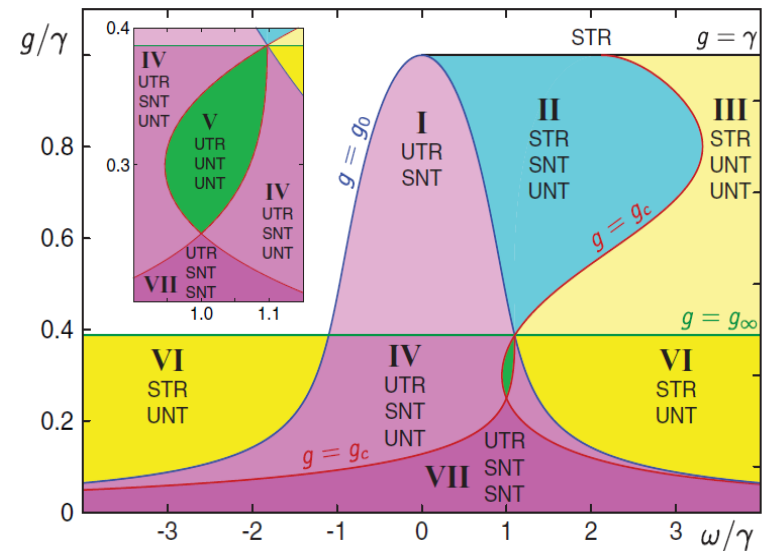


	Electron distribution $f(k)$	Polarization/Coherence	Gap
BEC	ϕ_{1s} , far below inversion	$\phi_{1s}(k)$	LP-UP
Ideal BCS	Inverted, 0.5 – 1	Broadly distributed	Large
Polariton BCS	Inverted, < ideal BCS	Reduced than ideal BCS	Small
Photon Laser	Fermi degenerate	$ p \sim \delta(k_{cav})$	Spectral hole burning

Uniquely Polaritonic

Dissipation Induced Nonlinear Dynamic Phases

Rubo, Kavokin, Liew ...

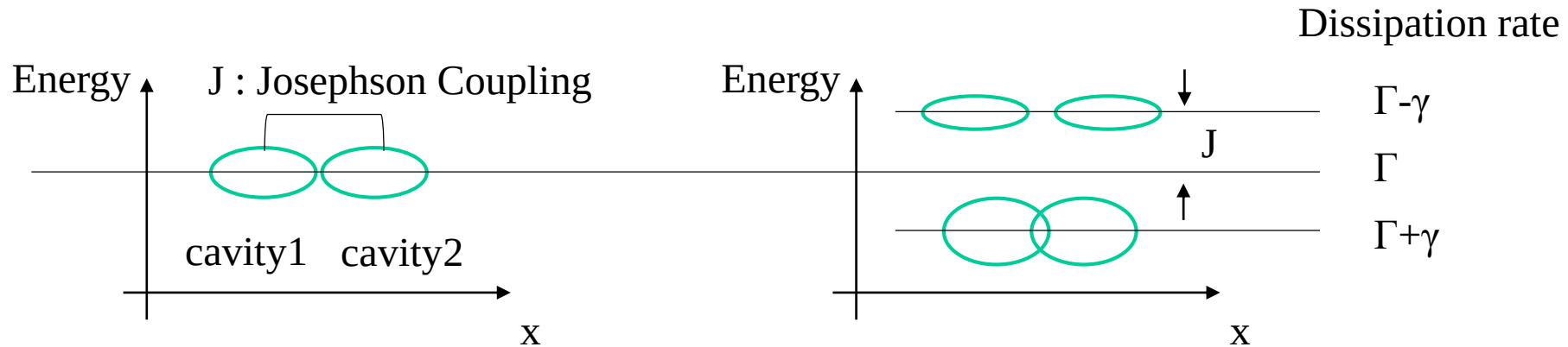


Emergence Of **Micro-frequency Comb**
via **Limit Cycles**
in **Dissipatively Coupled Condensates**

Kim et. al., arXiv:1809.04641

A “Polariton” Laser With No Excitons

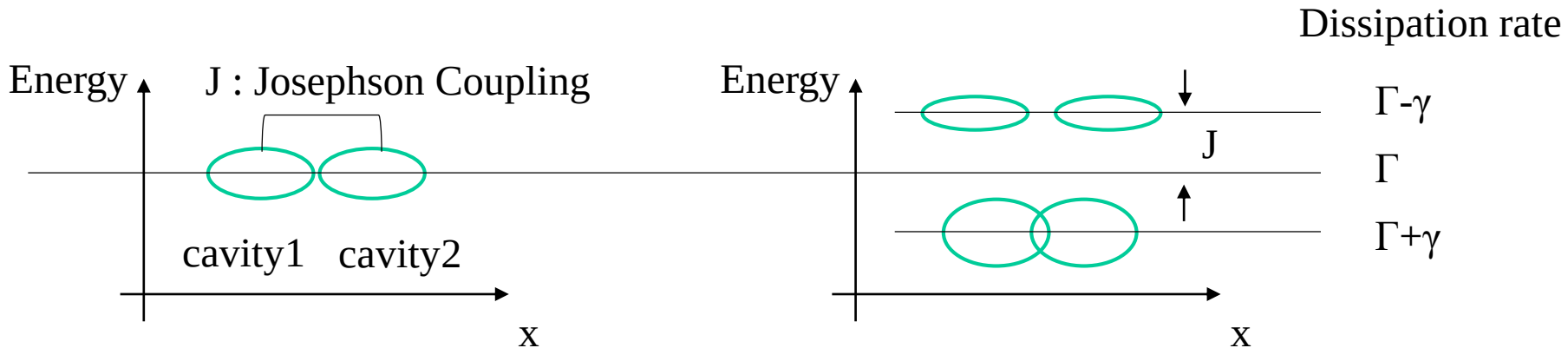
Theoretical proposal: Dissipative coupling



Complex coupling: $V_{12} = \gamma + iJ$

Rayanov PRL **114**, 193901 (2015)

Theoretical proposal: Dissipative coupling



Complex coupling: $V_{12} = \gamma + iJ$

Rayanov PRL **114**, 193901 (2015)

$$\frac{d\psi_1}{dt} = -\frac{1}{2}(g\psi_1 + \gamma\psi_2 - \mu|\psi_1|^2\psi_1) - \frac{i}{2}(2\omega_1\psi_1 - J\psi_2 + \alpha|\psi_1|^2\psi_1)$$

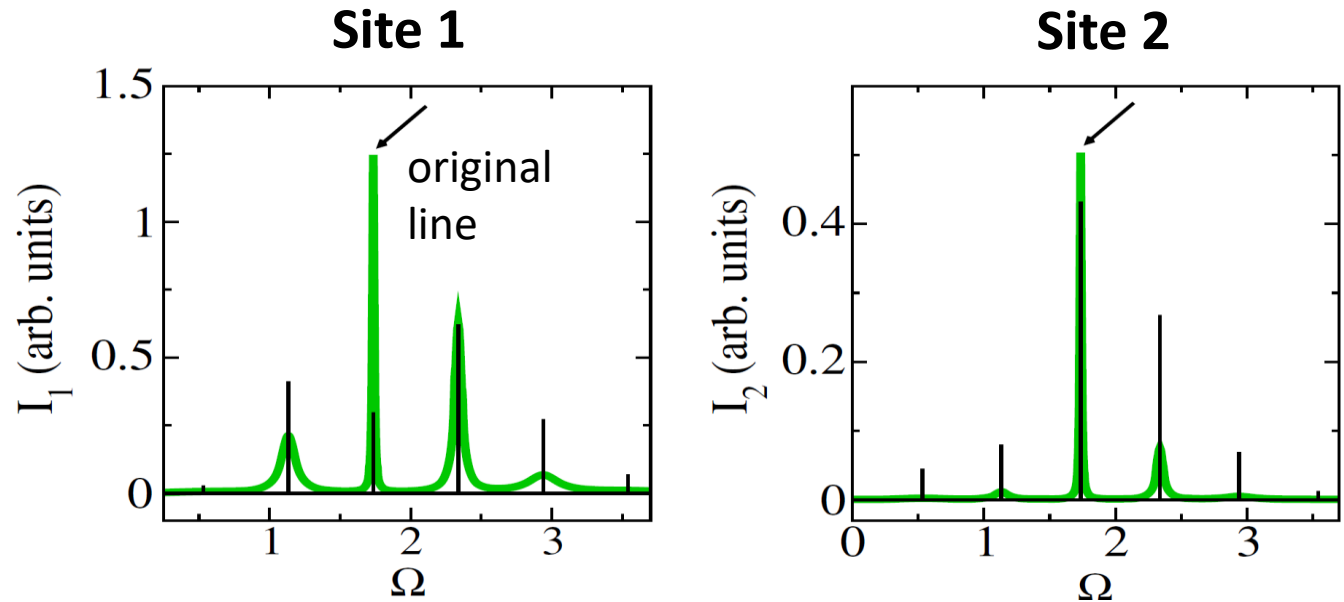
$$\frac{d\psi_2}{dt} = -\frac{1}{2}(g\psi_2 + \gamma\psi_1 - \mu|\psi_2|^2\psi_2) - \frac{i}{2}(2\omega_2\psi_2 - J\psi_1 + \alpha|\psi_2|^2\psi_2)$$

ψ : order parameter, $g = \Gamma - P$, Γ : uncoupled decay rate, P : pump strength, γ : dissipative coupling
 μ : gain saturation, ω : frequency, J : Josephson coupling, α : on-site interaction

Frequency Comb by Dissipative-Coupling

Theory

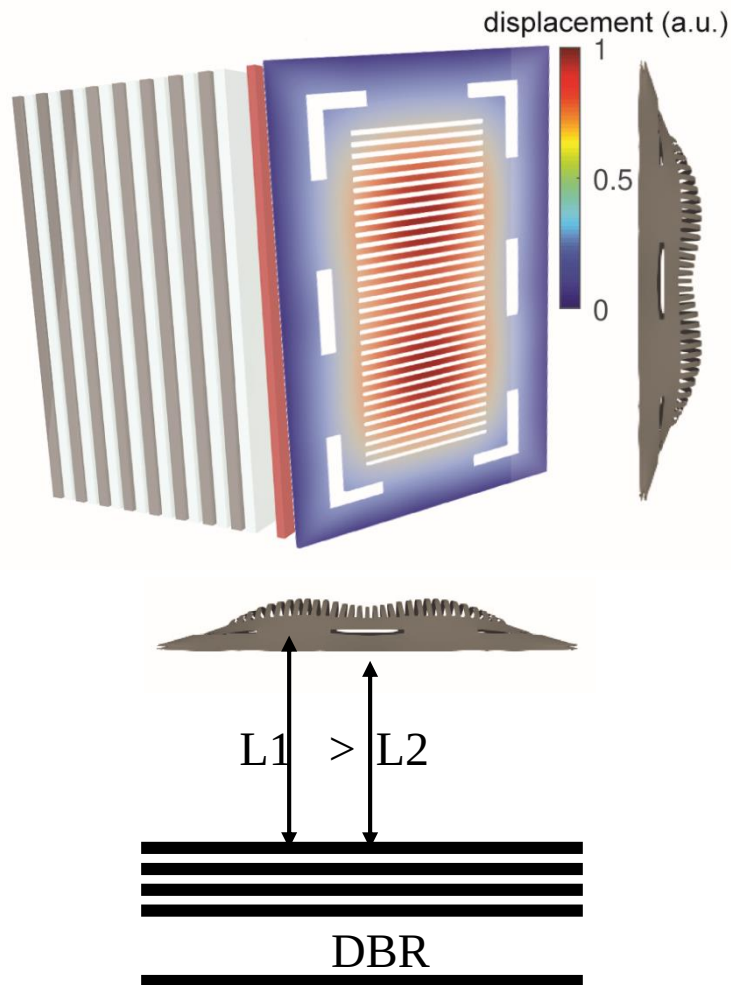
Rayanov
PRL **114**,
193901
(2015)



- Spontaneous symmetry breaking
 - Formation of a specific many-body state
 - Relative phase between sites $\phi \neq 0$ or π
 - Spontaneous current: asymmetry in k-distribution and different occupations of the sites.
- Spontaneous period doubling due to limit cycles
 - Equidistant frequency lines
 - Asymmetric comb intensity

Engineering coupled polariton

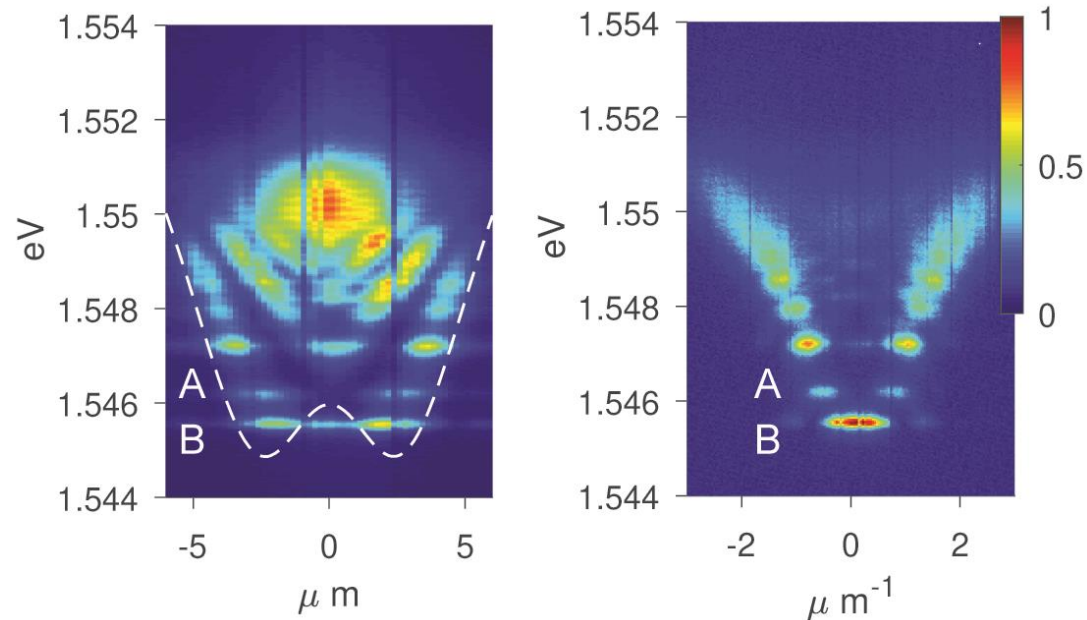
Josephson coupling strength



on-site interaction strength

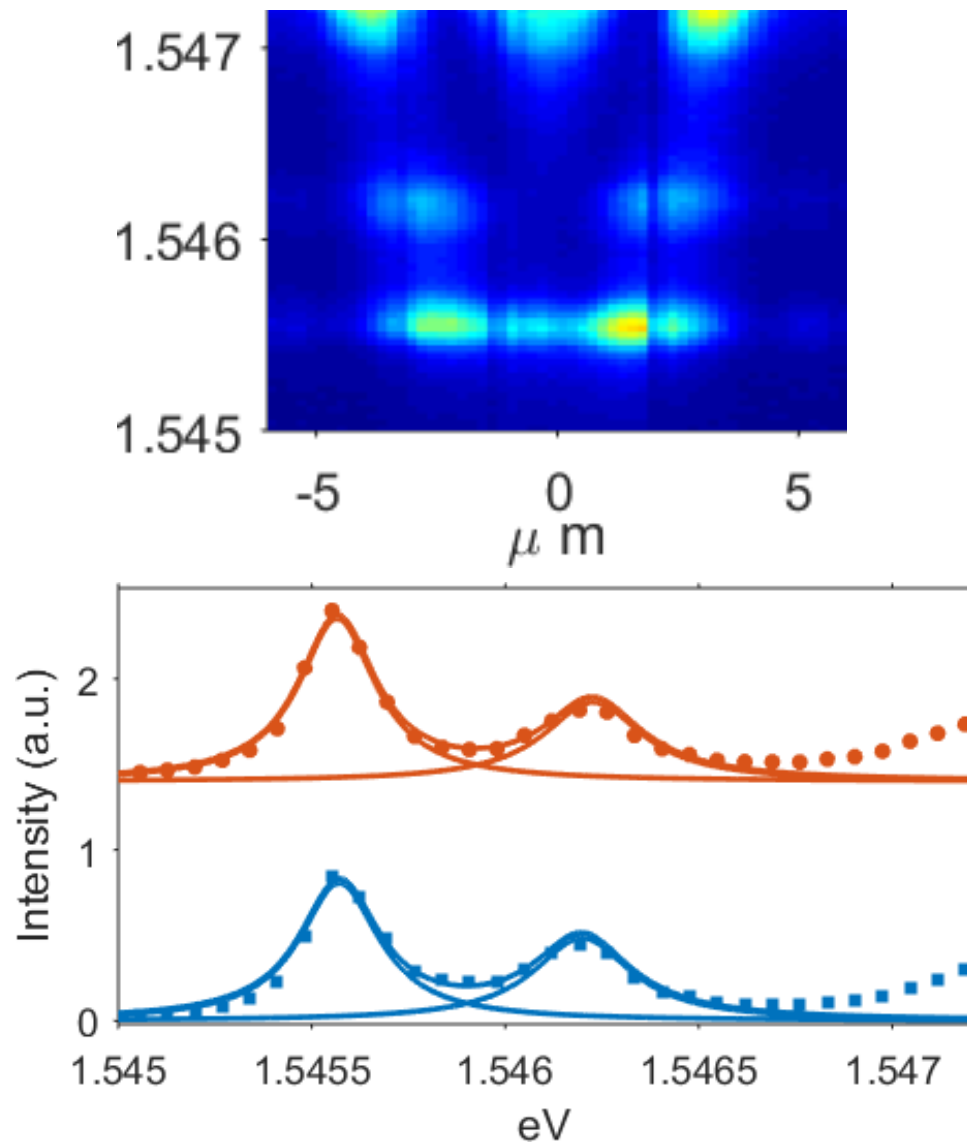
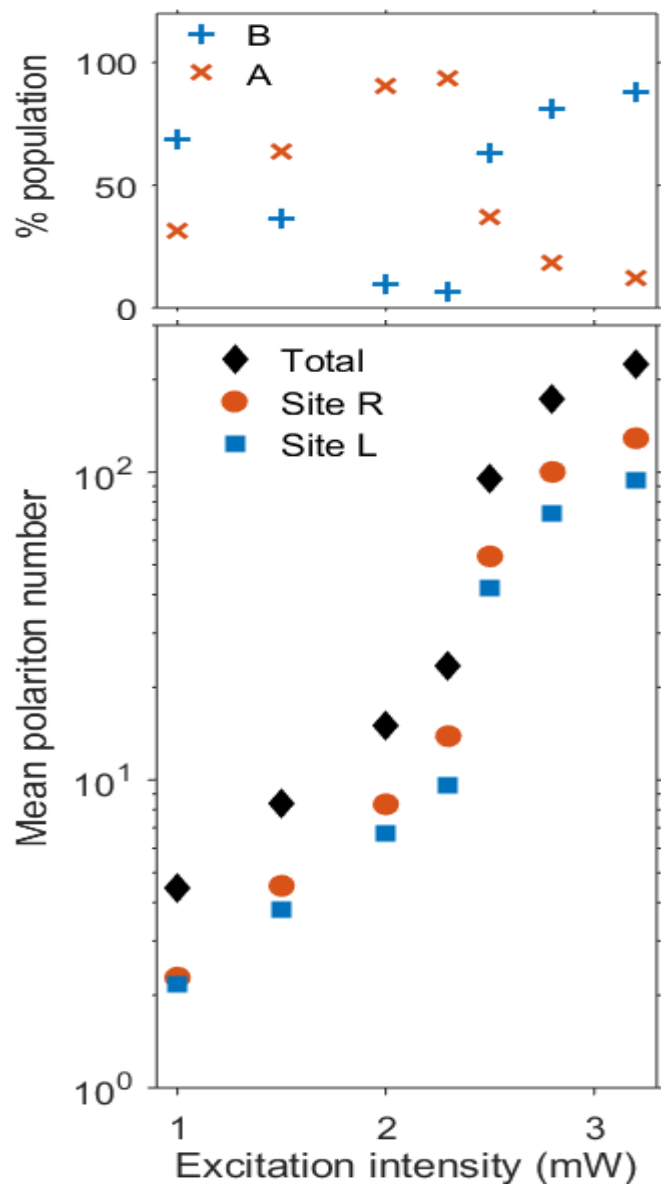
- GaAs : $1\text{-}10 \mu\text{eV}\mu\text{m}^2$
- Small single site dimension $\rightarrow$ large interaction

white dashed line : modelled detuning change

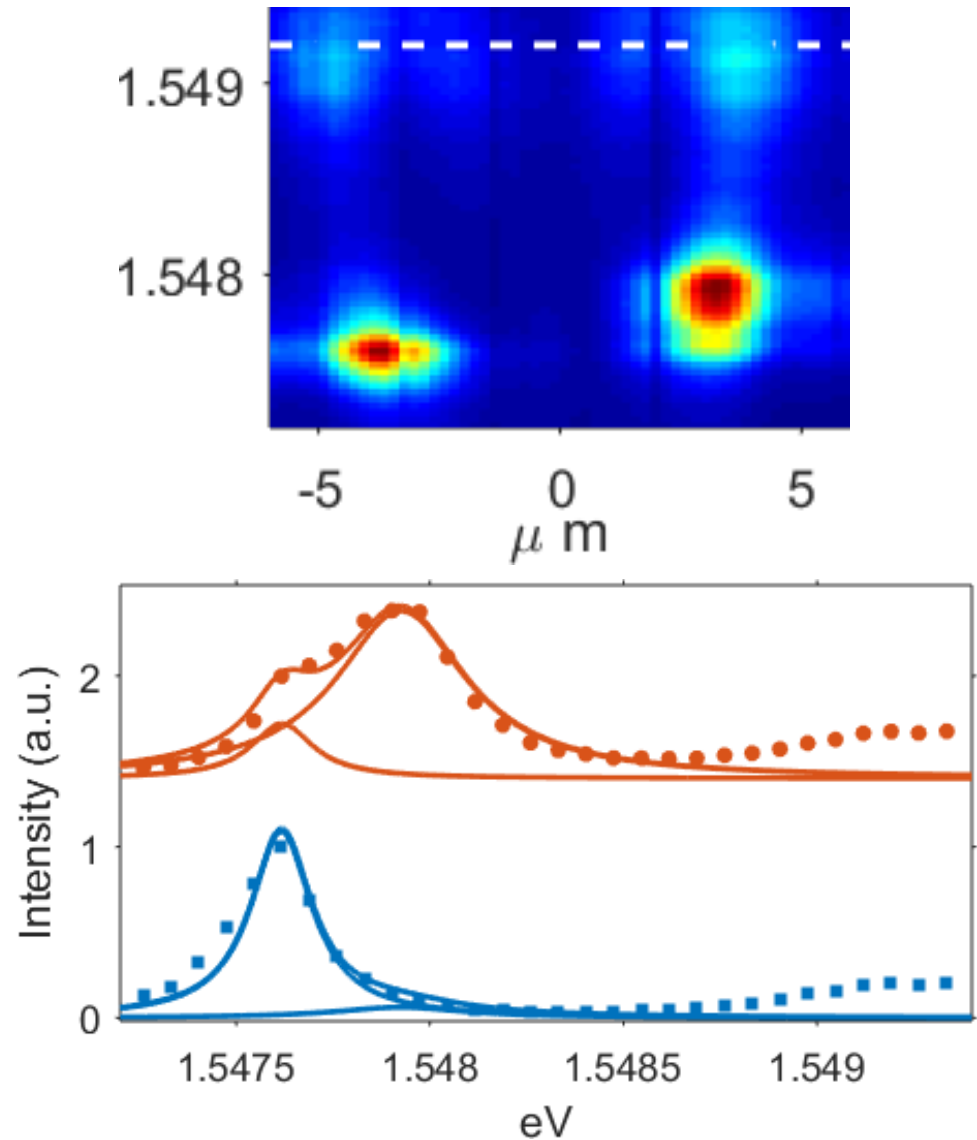
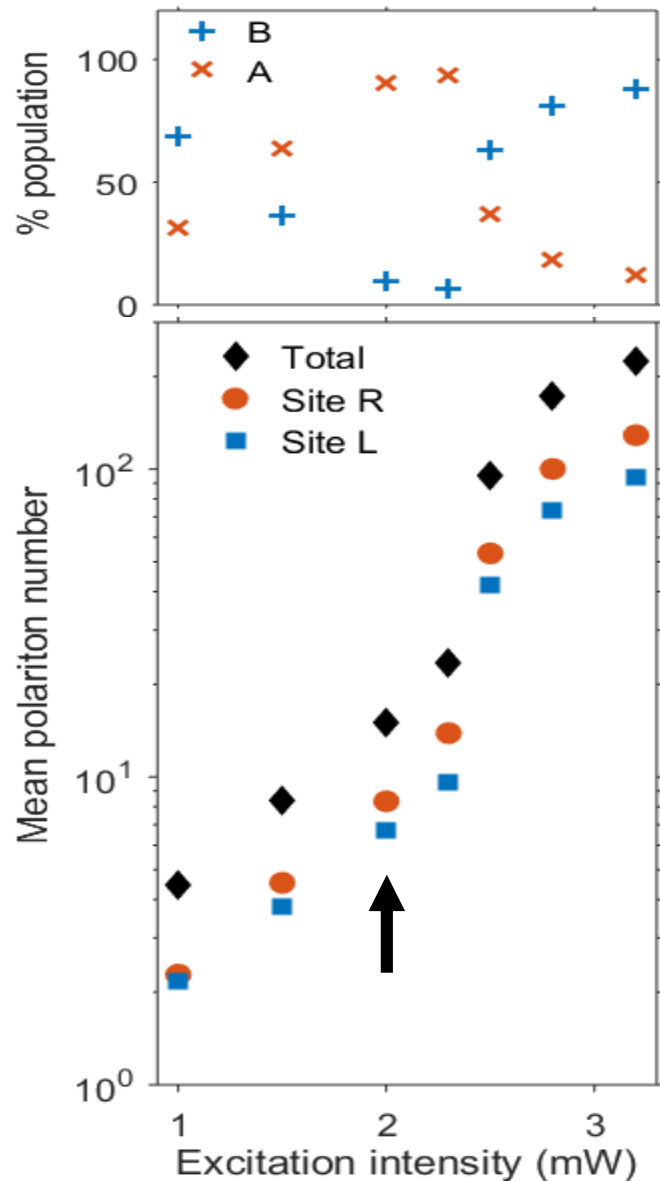


A : Antibonding state, B : Bonding state

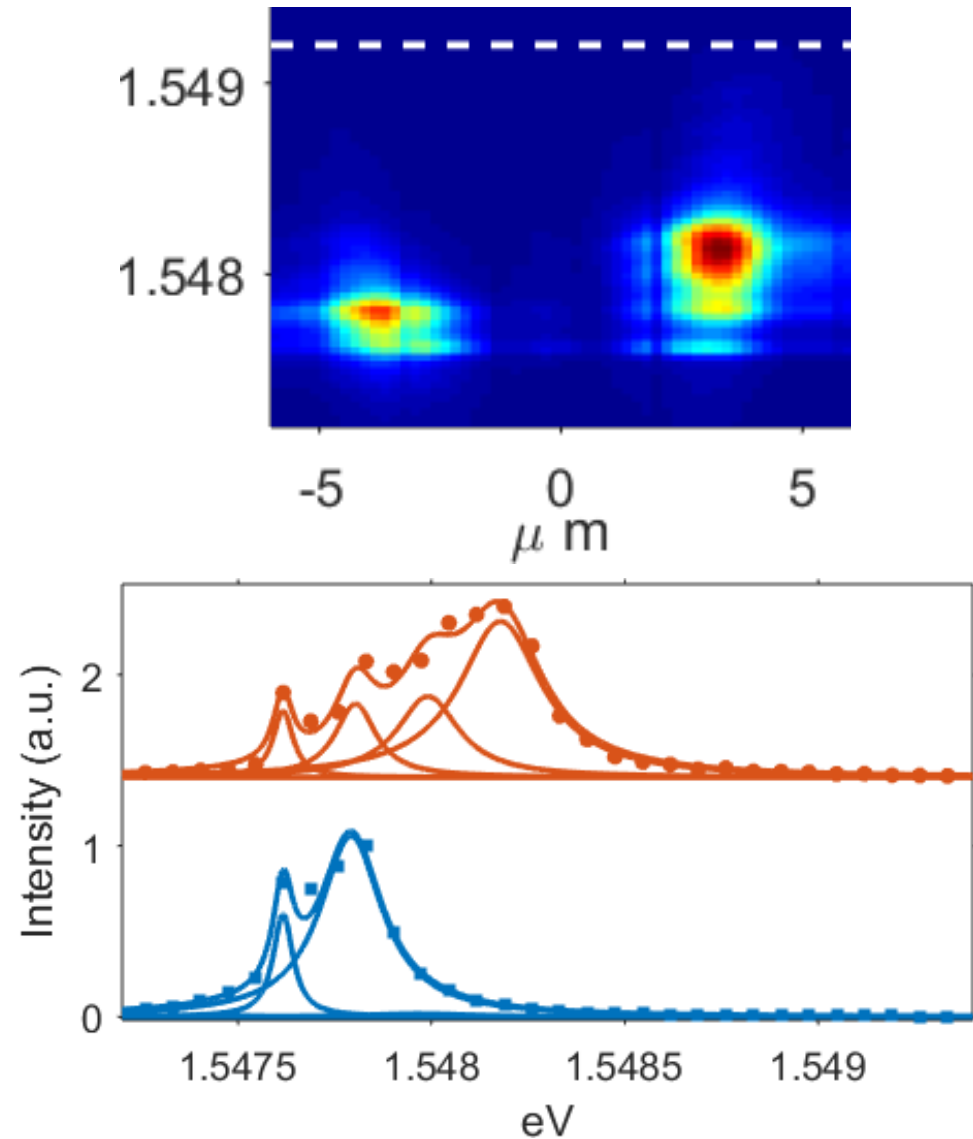
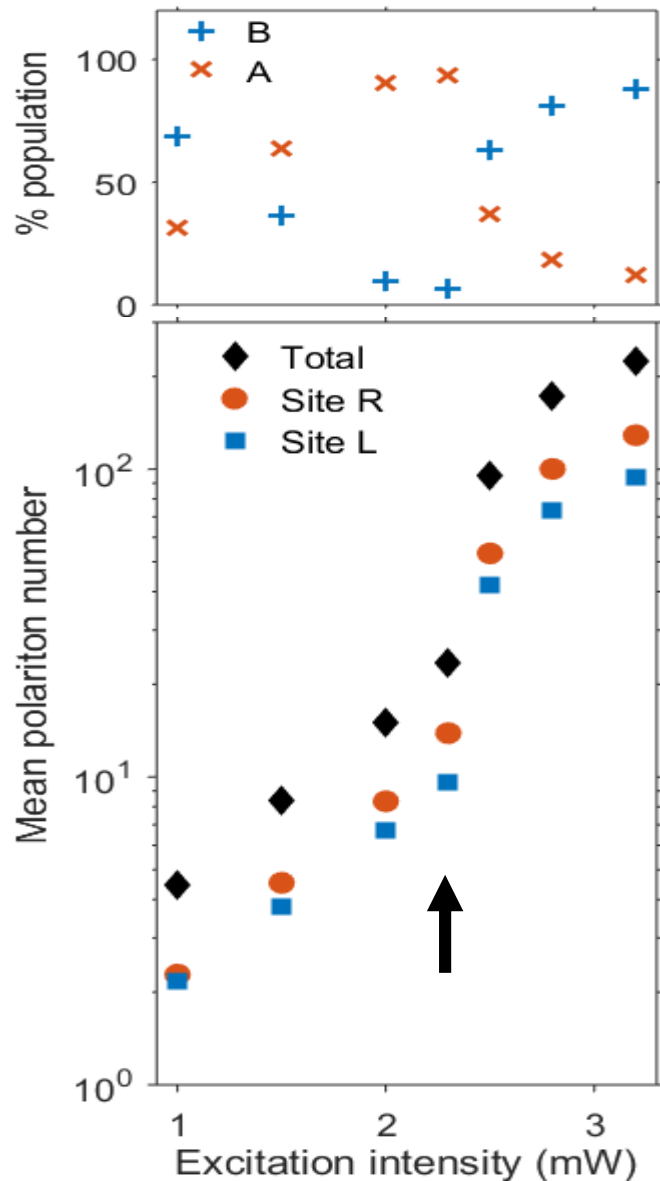
Power dependent PL



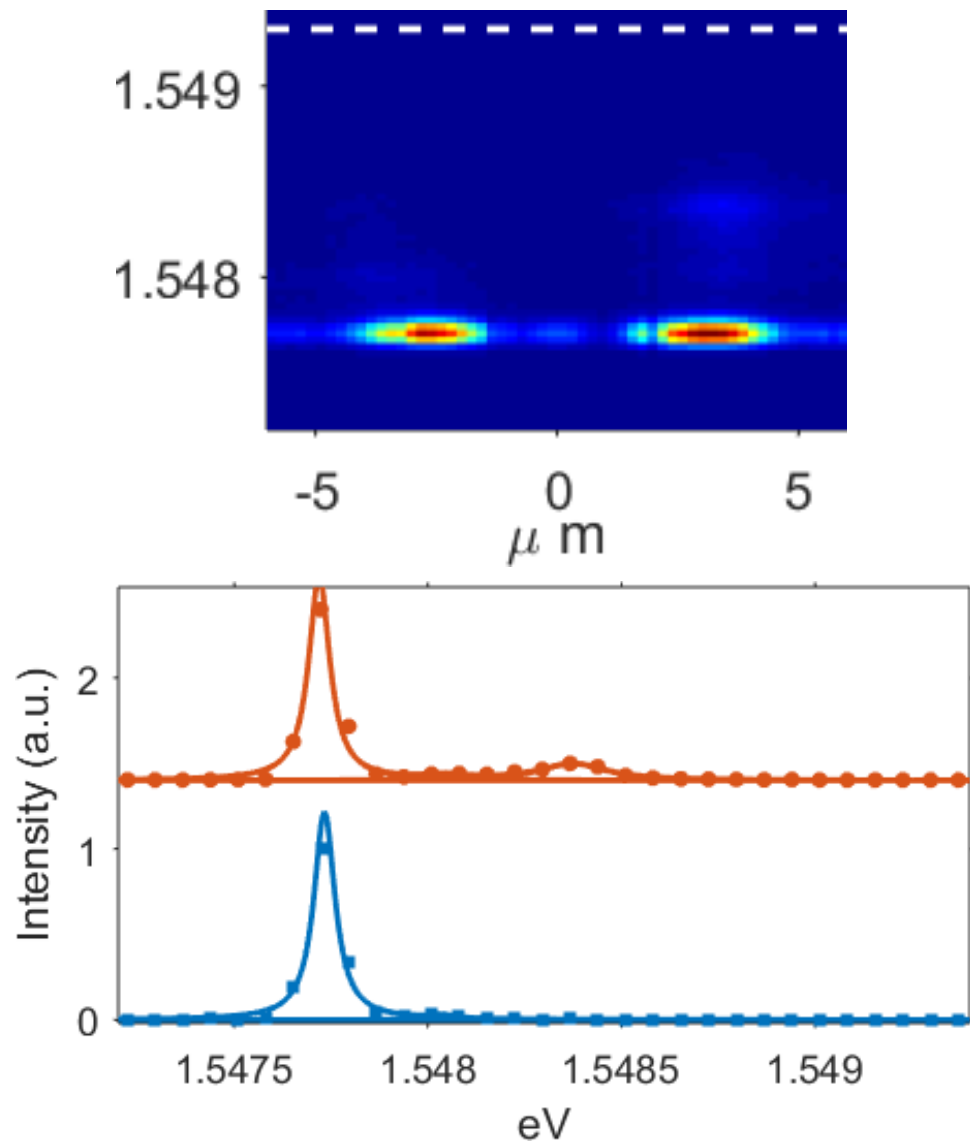
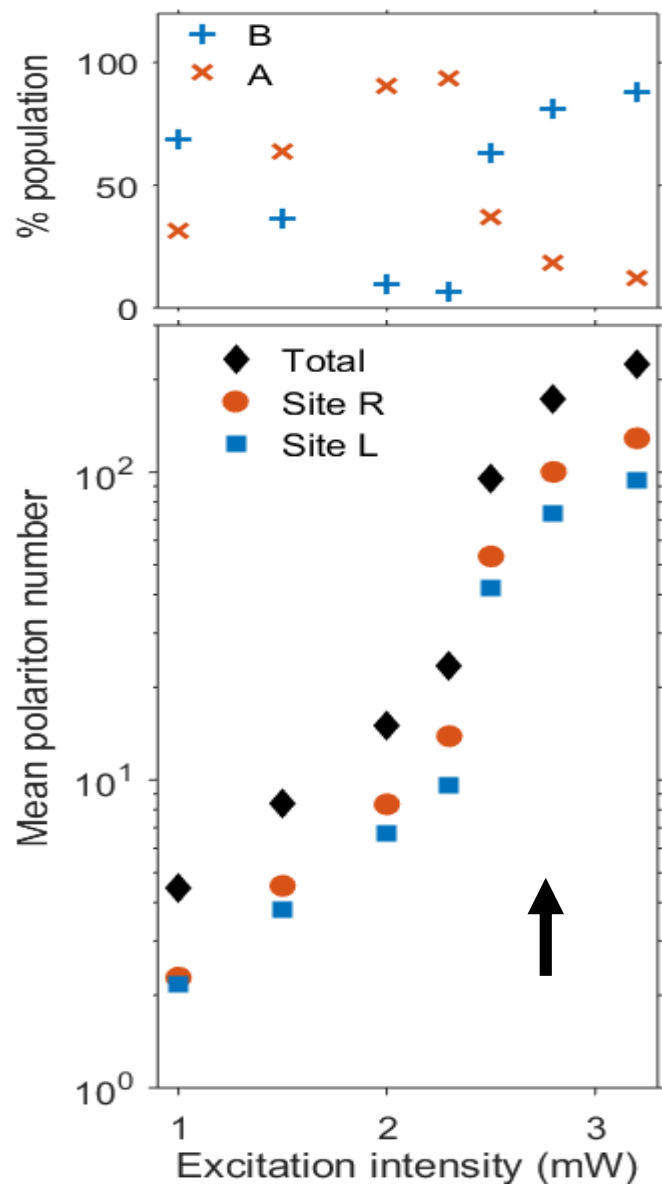
Power dependent PL



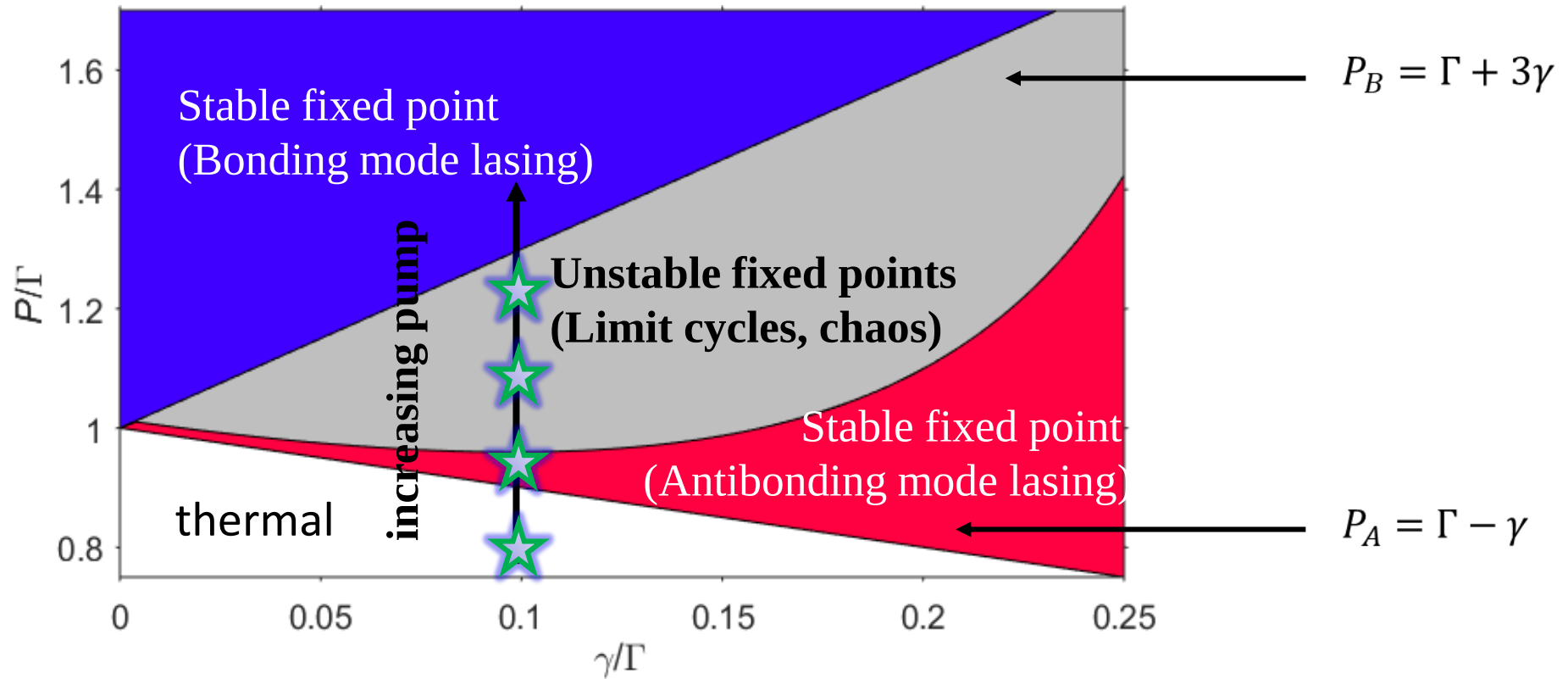
Power dependent PL



Power dependent PL



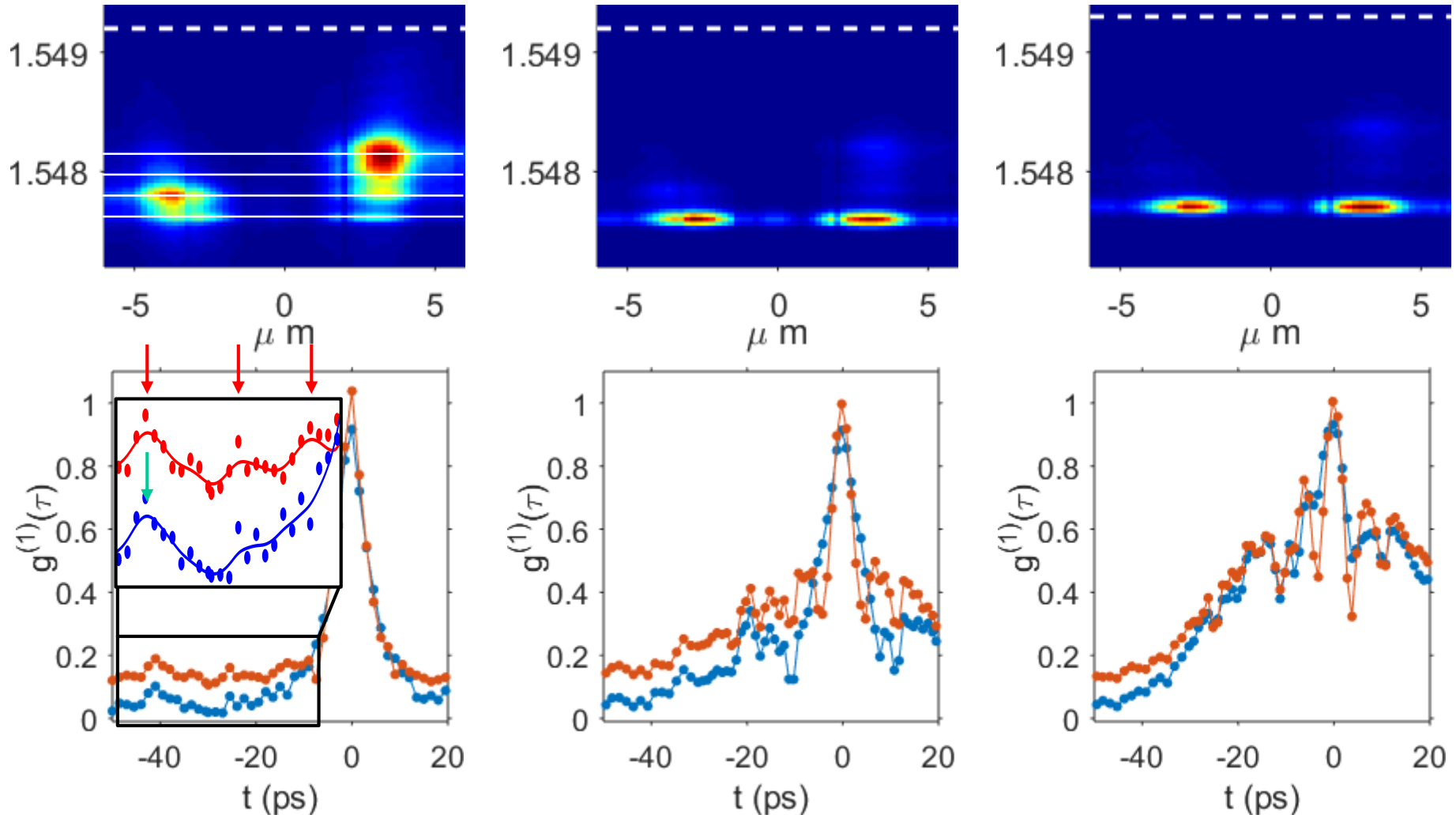
Bifurcation Diagram



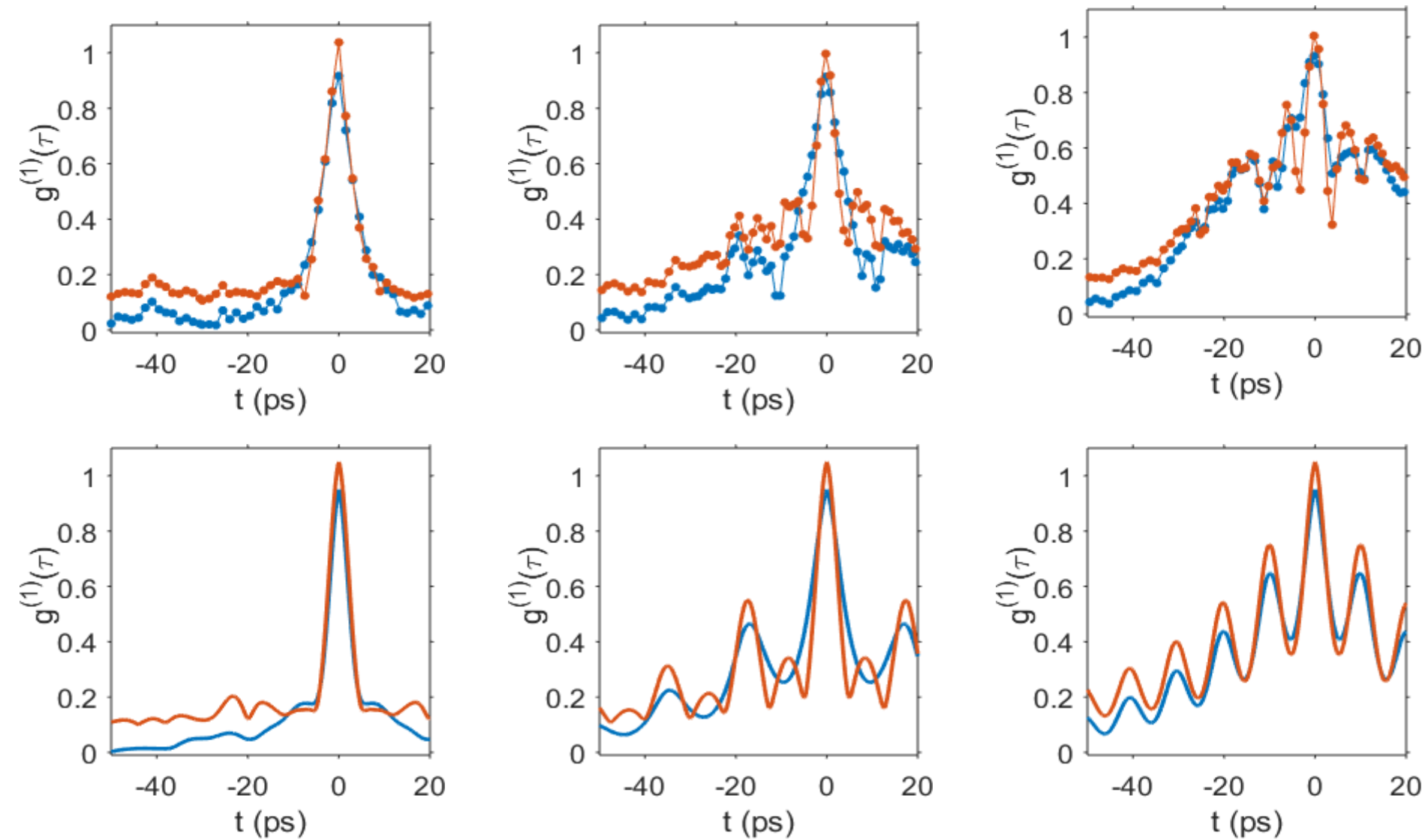
- Assuming P is a linear function of pump power, $\gamma \sim 0.1\Gamma$

Beating signal measured by $g^{(1)}(\tau)$

Number of beating peaks $\propto$ Number of frequency components

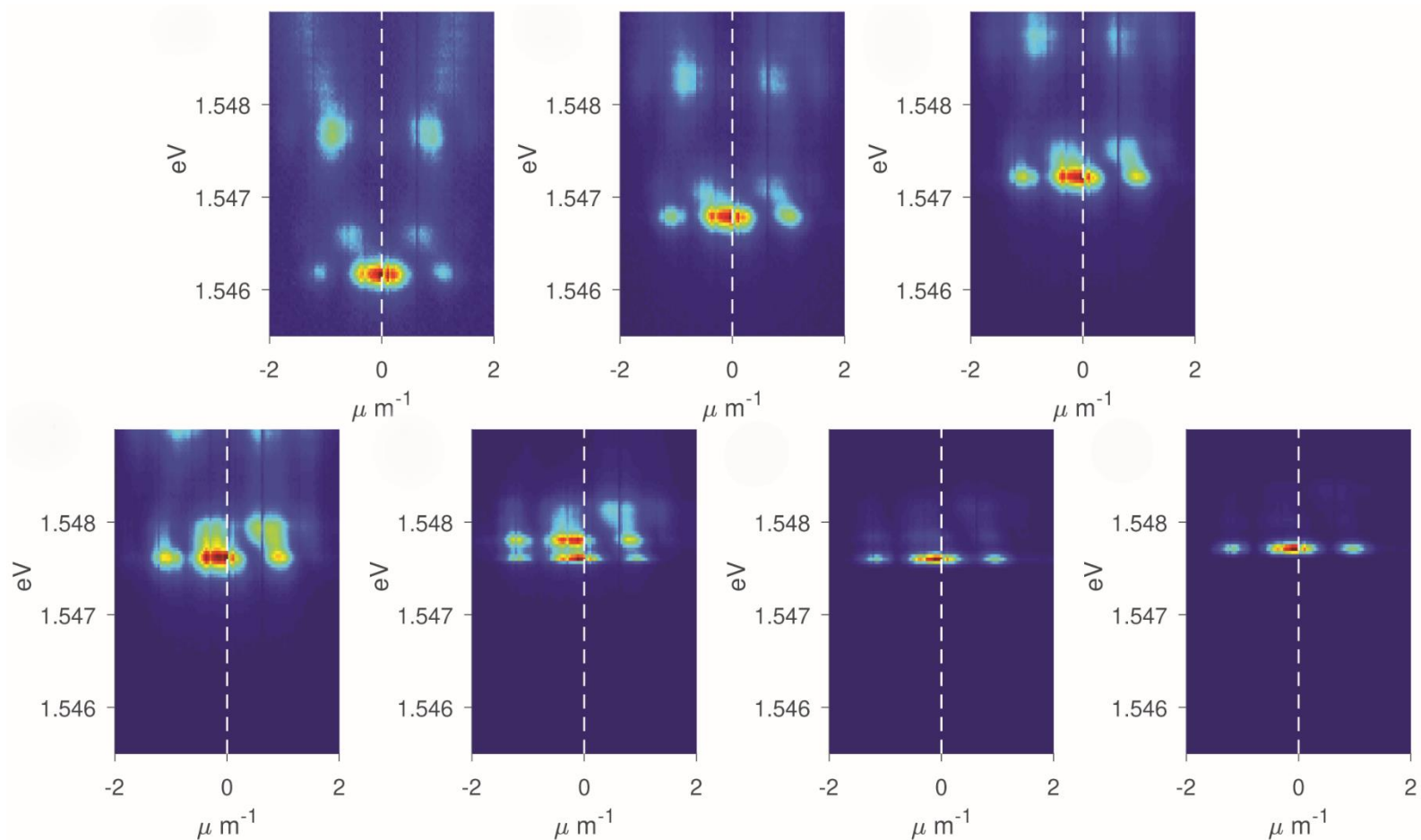


Beating signal measured by $g^{(1)}(\tau)$



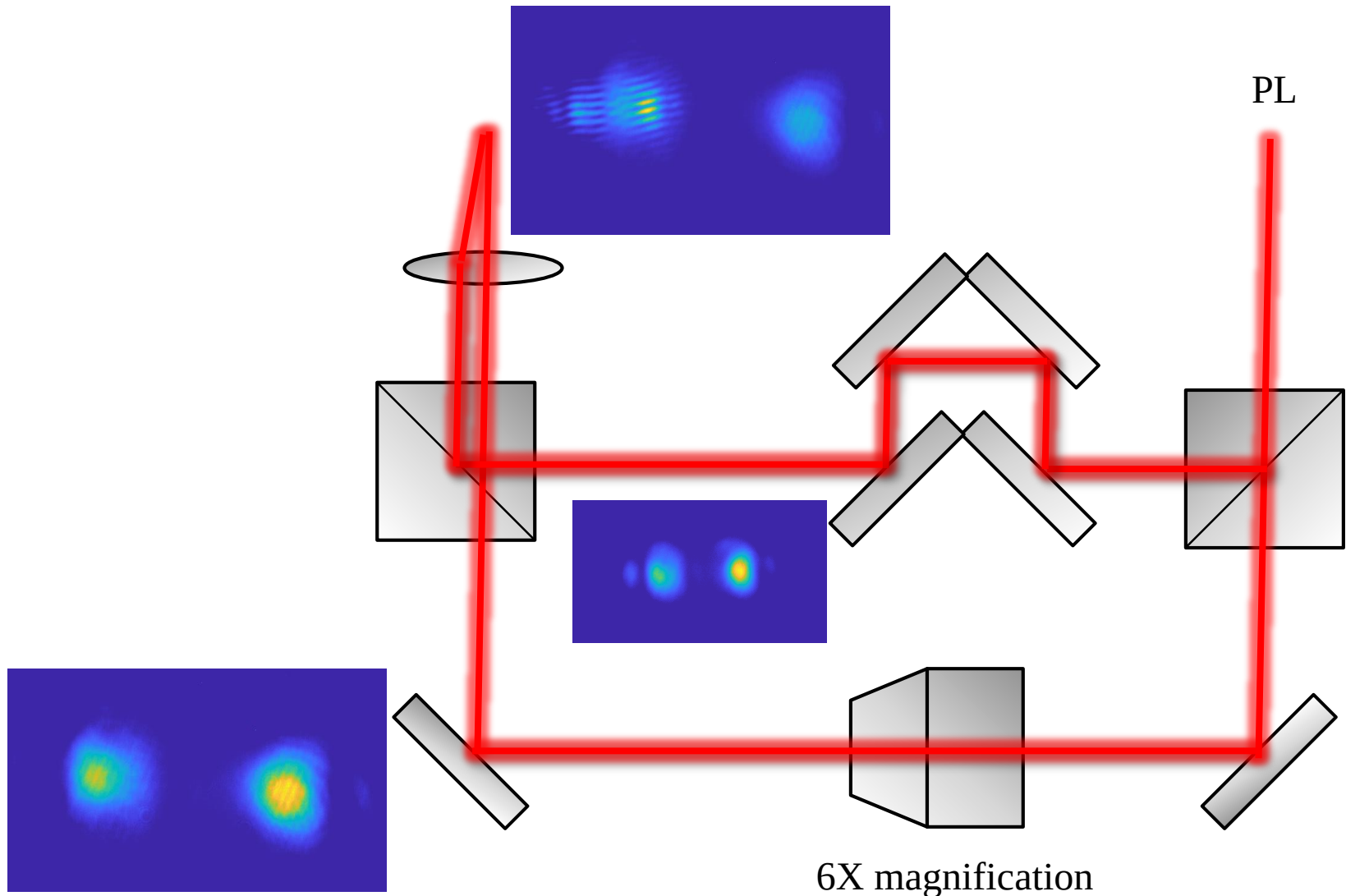
Spontaneous Current – k-space Asymmetry

Momentum-space measurements



Relative phase between two sites

Direct measurement from interference



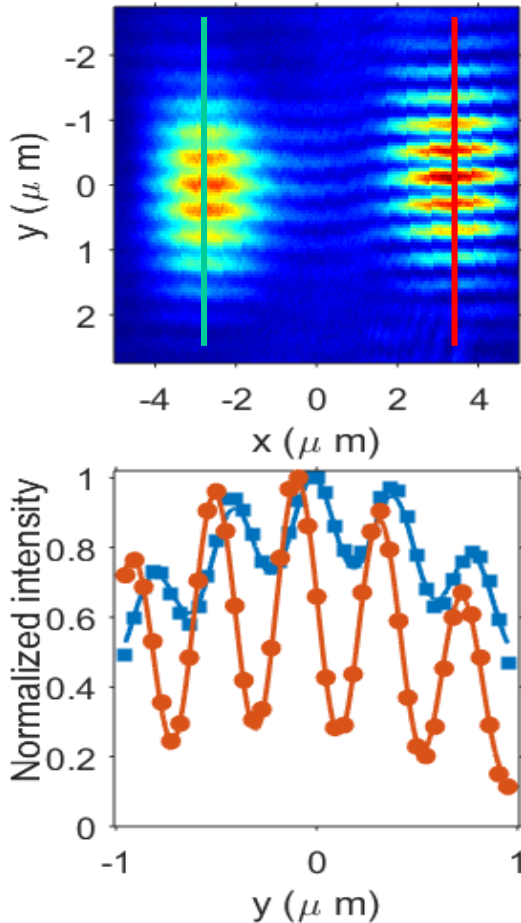
Relative phase between two sites

Limit cycles

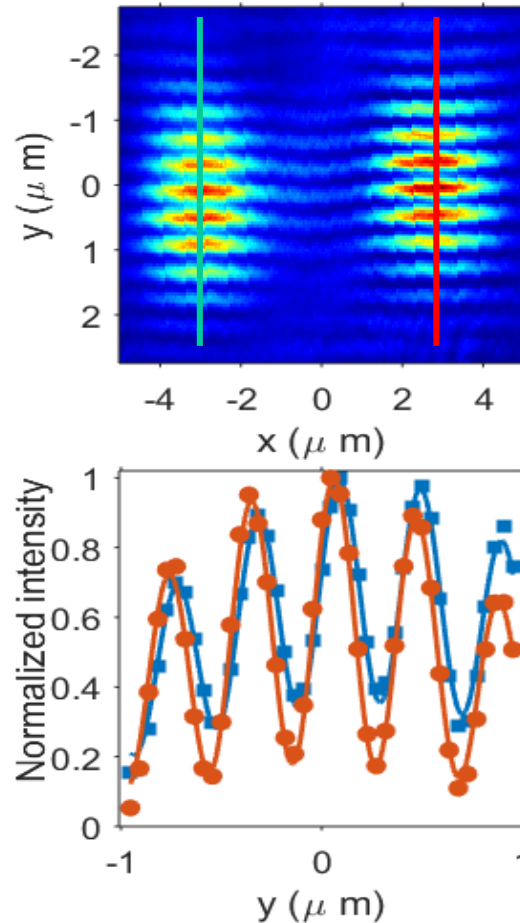


Stable ground state lasing

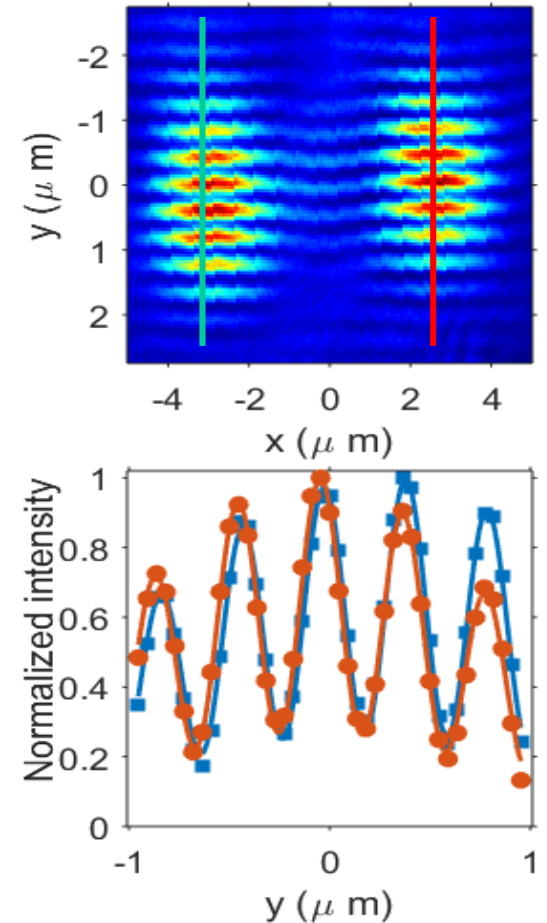
$$\Delta\phi = 0.51 \pm 0.08 \pi$$



$$\Delta\phi = 0.21 \pm 0.06 \pi$$



$$\Delta\phi = 0.15 \pm 0.04 \pi$$



Frequency Comb by Limit Cycle Oscillations

- Limit cycles in a pair of coupled condensates
 - ✓ New frequency lines, equi-distant separation
 - ✓ Beating in $g^{(1)}(\tau)$
 - ✓ Asymmetric k-space distribution & asymmetric (r-space) site occupations
 - ✓ Non trivial phase $\phi \neq 0$ or π between two sites
 - Unique to nonlinear dynamic system of ≥ 2 D phase space
 - Underpin many cyclic phenomena in nature
 - Result from interplay of on-site nonlinearity and dissipative coupling
- Frequency comb generation
 - Allows incoherent pumping (e.g. electrical pumping)
 - Allows very low threshold
 - Line-spacing adjustable by interaction & coupling (not determined by cavity mode, nor driving laser), up to THz

Controlling Strong Light Matter Coupling with Photonic Crystals

Many-body physics with GaAs-microcavity polaritons

- A designer polariton system with a photonic crystal mirror
- The nonlinear polariton laser

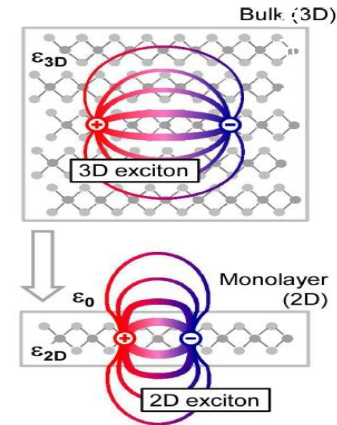
Coherent light-matter coupling in 2D materials

- Polaritons in 1D photonic crystals
- From perfect reflection to perfect absorption

Monolayer van der Waals Crystals

Reduced Coulomb screening

- Large binding Energy (100s meV)
- Strong exciton-photon interaction
- Well bound excited states: trion, polaron, Rydberg exciton...

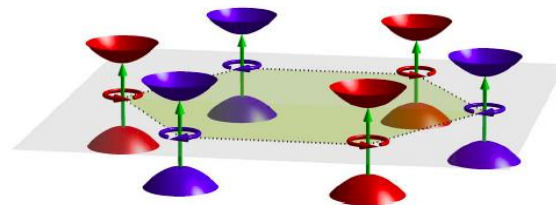


Chernikov
PRL **113**,
076802 (2014)

Large spin-orbit coupling

→ Spin-Valley Locking

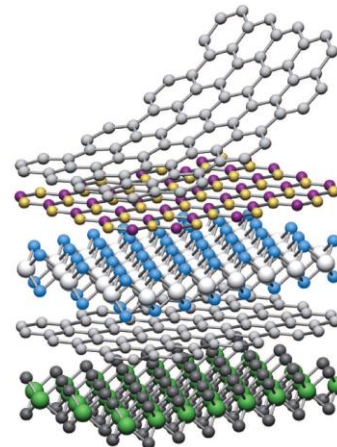
- Valleytronics
- Topological states



Xu *Nat. Phys.*
10, 343 (2014)

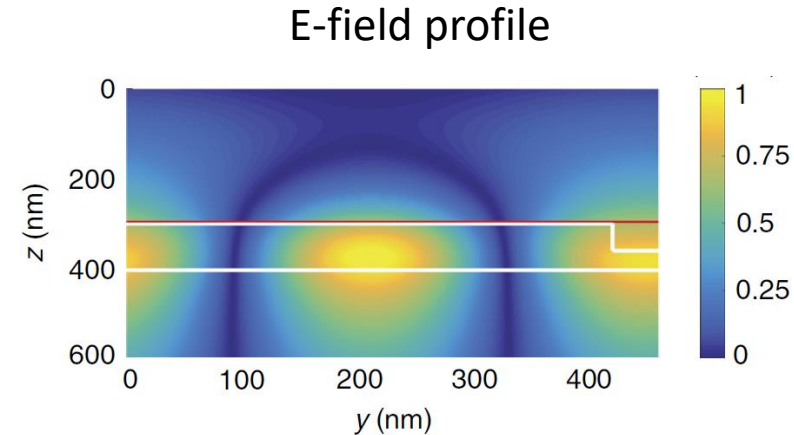
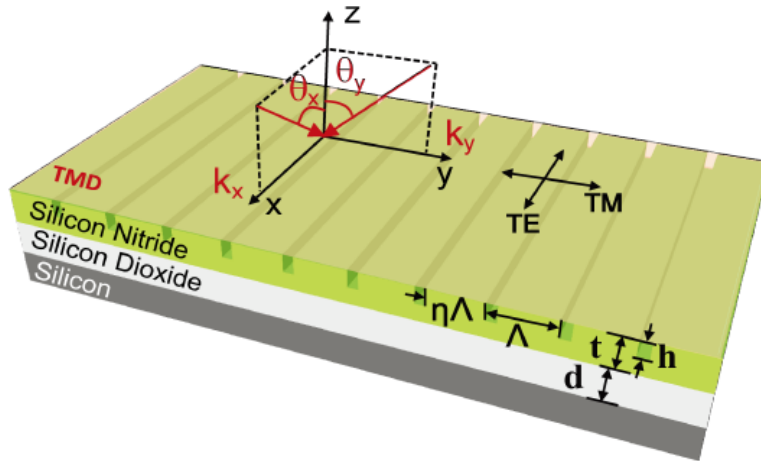
Fabrication flexibility

- Integration (substrate, photonic structures)
- Hetero-structures the lego-way



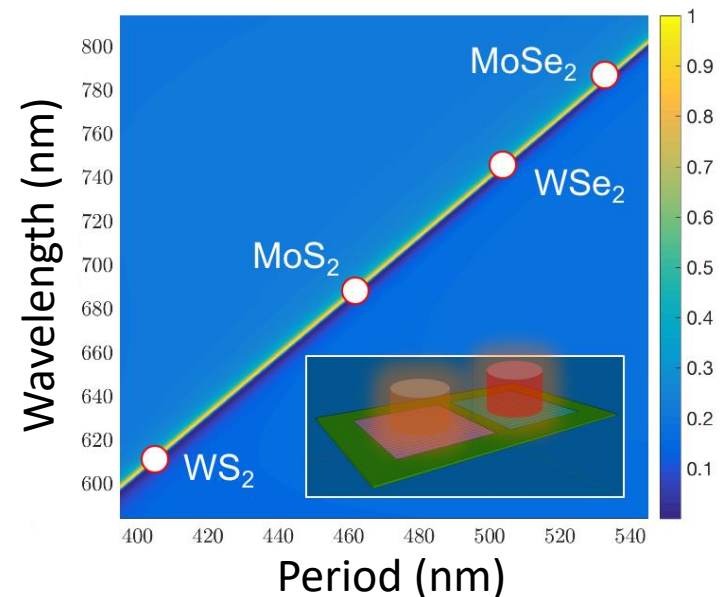
Geim *Nature*,
499, 419 (2013)

Slab Photonic Crystals for TMDs



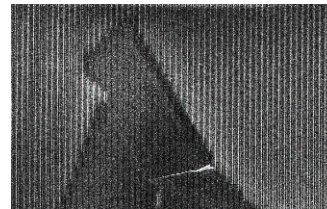
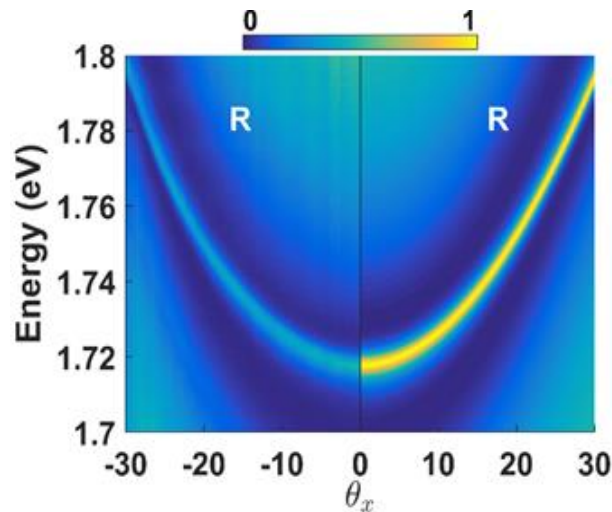
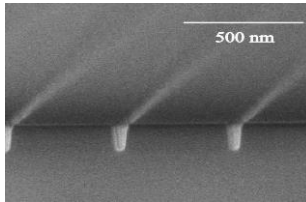
Highly flexible and practical:

- Easy to fabricate
- Easy to integrate with 2D materials and in 2D layout
- Calibrate and select the cavity separately from 2D medium
- Broad mode design possibilities

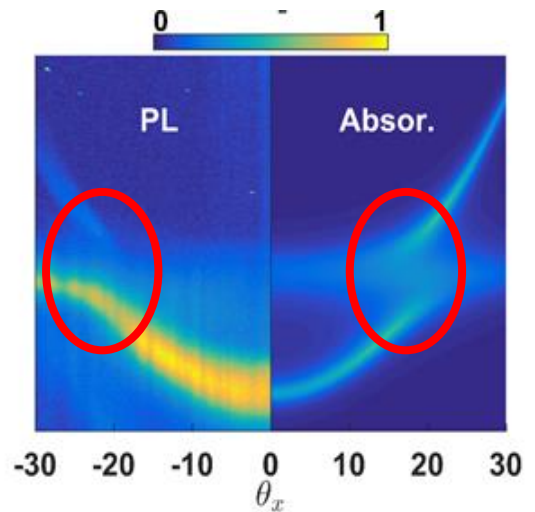
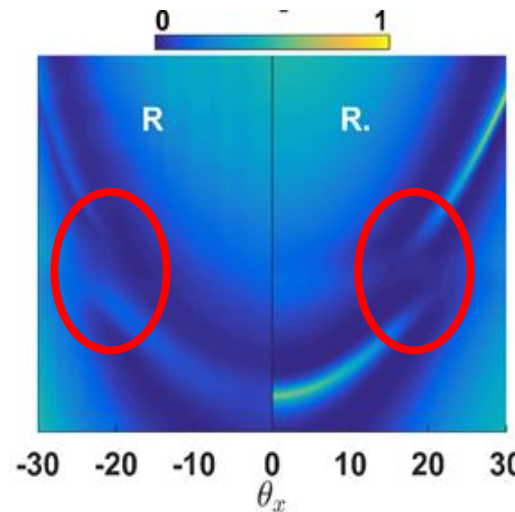


WSe₂-PC Polaritons (10 K –110 K)

PC only

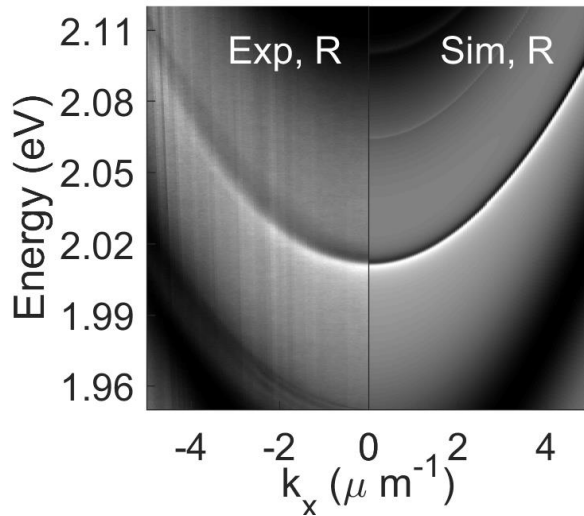


WSe₂-PC



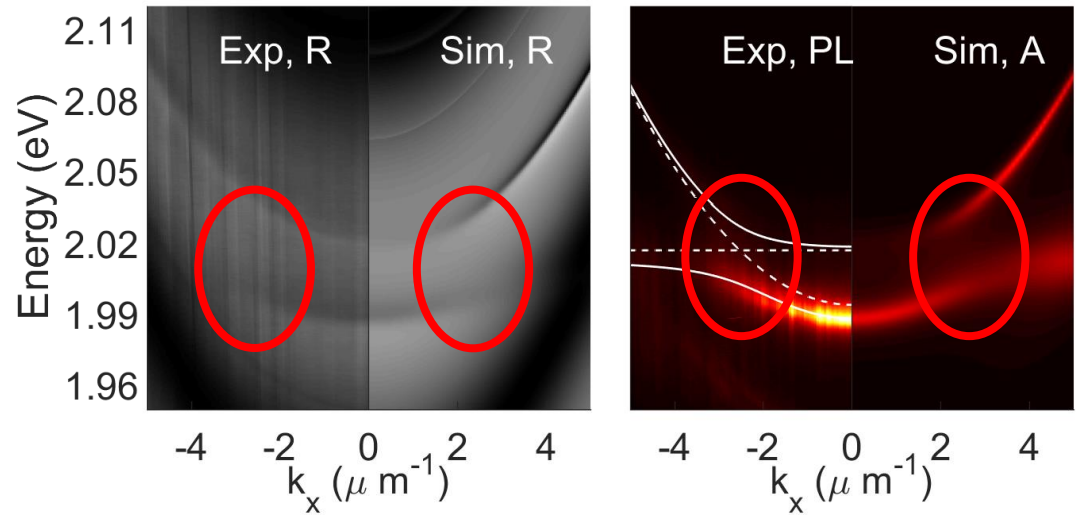
WS₂-PC Polaritons @ 300 K

PC only



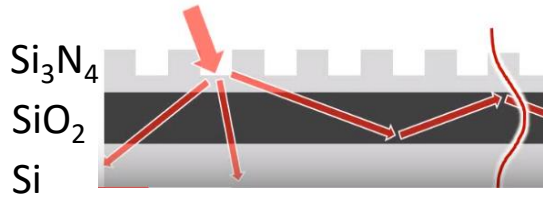
$$\gamma_{ph} \sim 4.5 \text{ meV}$$
$$\gamma_{exc} \sim 11 \text{ meV}$$

WS₂-PC



$$2\Omega = 22 \text{ meV} \gg \gamma_{ph} + \gamma_{exc}$$

Adjustable “Off-Resonant” Reflectance



1. Low/High off-resonant R by SiO₂ buffer layer thickness.

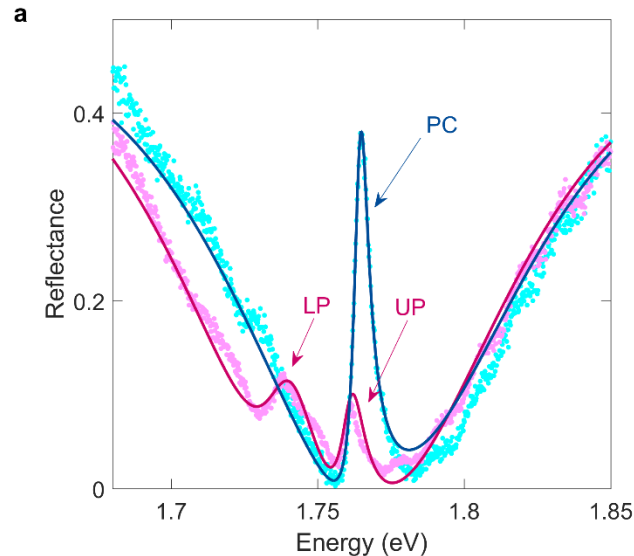
2. Adjustable Fano line-shape

$$R_F = \frac{(\epsilon + q)^2}{\epsilon^2 + 1} - 1$$

$$\epsilon = \hbar(\omega - \omega_0)/\gamma_0$$

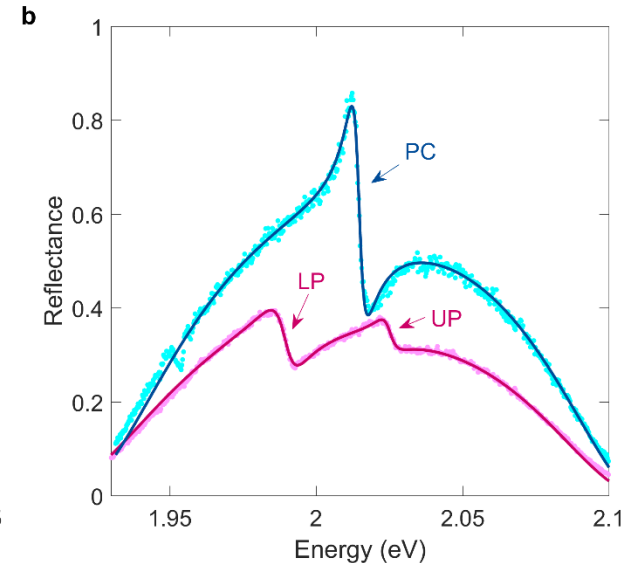
q : asymmetry parameter

WSe₂ Device



- Low off-resonant R
- Lorentzian-like lines
 $q_{PC} \sim 5.0$

WS₂ Device

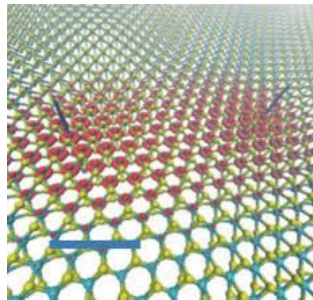
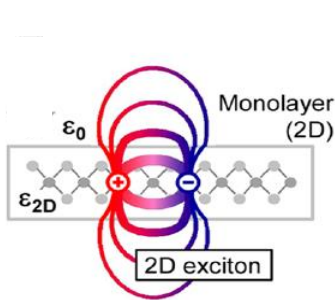


- High off-resonant R
- Asymmetric lines
 $q_{PC} \sim 1.16$

Vacuum Engineering of Exciton-Photon Coupling

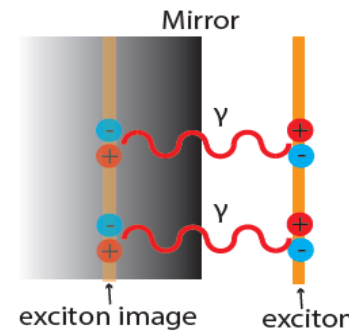
Excitons in Monolayer 2D semiconductors

- Large exciton-photon coupling strength
- Near radiative-limited linewidth
- Two-dimensional translational symmetry

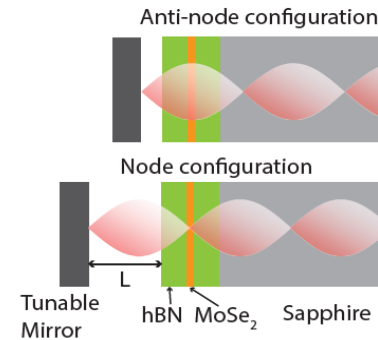


A. Chernikov et. al., PRL **113**, 076802 (2014)

Controlling Exciton-Photon Interactions



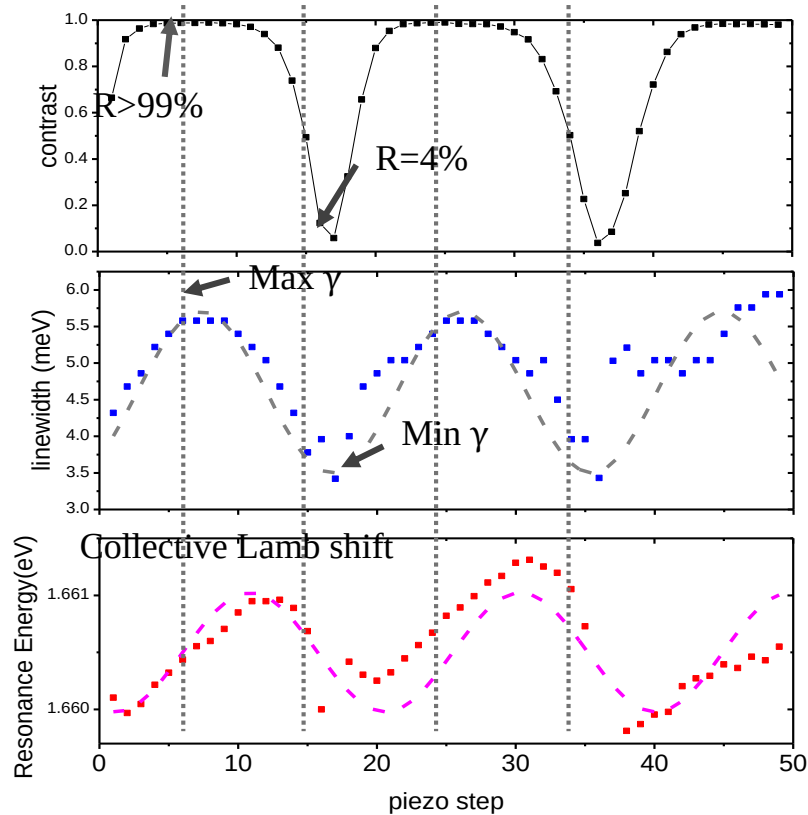
energy conservation + 2D
 $\rightarrow \vec{G}$ does not decay with L



$$\tilde{\gamma} = 2\gamma \cos^2 kL$$

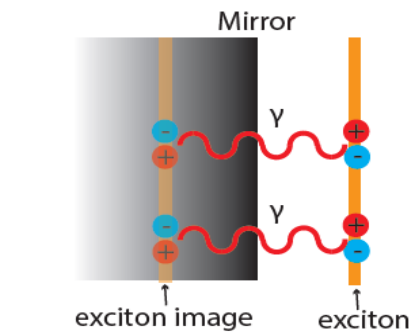
Horng et. al. 2019, *arXiv:1903.06645*,
 “Engineering Effects of Vacuum Fluctuations
 on Two-dimensional Semiconductors.”

Vacuum Engineering of Exciton-Photon Coupling

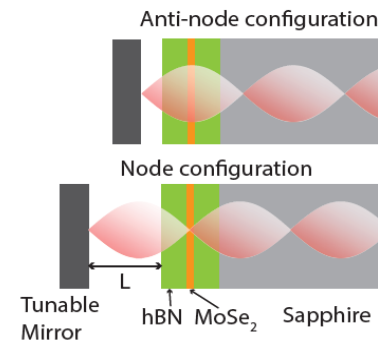


- Collective Lamb shift
- from Perfect Reflection to Perfect Absorption in a single molecular layer

Controlling Exciton-Photon Interactions



energy conservation + 2D
 $\rightarrow \vec{G}$ does not decay with L



$$\tilde{\gamma} = 2\gamma \cos^2 kL$$

Horng et. al. 2019, *arXiv:1903.06645*,
 “Engineering Effects of Vacuum Fluctuations
 on Two-dimensional Semiconductors.”

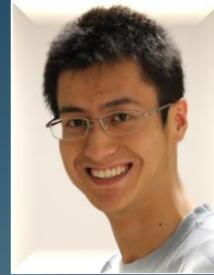
Acknowledgements



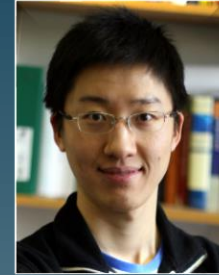
Jiaqi
Hu



Seonghoon
Kim (Ford)



Zhaorong
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(Yahoo)



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