半导体光学微腔中的激子极化激元研究进展

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Tsinghua U.: Prof. Qihua Xiong

ECNU: Profs. Jian Wu, Hui Li et al

Westlake U.: Prof. A. Kavokin

Outline

Introduction

Whispering gallery resonators of ZnO

- RT polariton lasing
- RT parametric nonlinearity
- Fano resonance of polaritons

Formation of 1D polaritonic crystal ZnO

- Band folding and engergy gap formation
- Weak lasing of polariton condensates
- 1D Ising chain

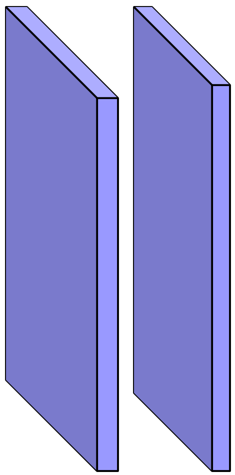
Polariton condensate in a 3D confined structure

- Evaporative cooling of polariton gas

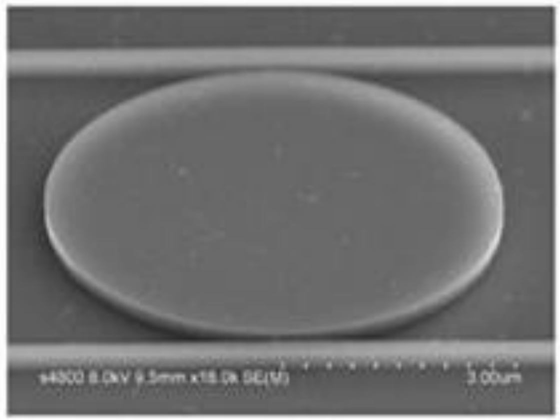
Ultrafast dynamics of polariton condensate

Introduction

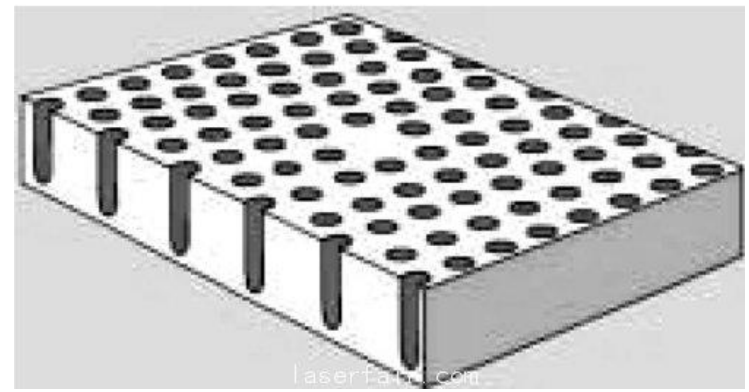
Optical cavities:



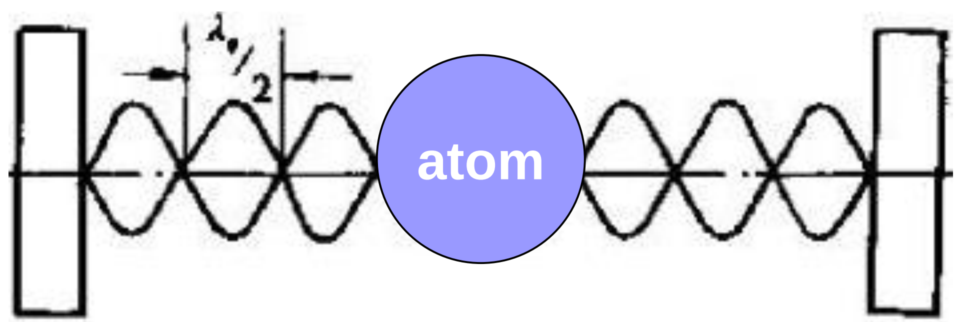
FP cavity



WG cavity



PC cavity

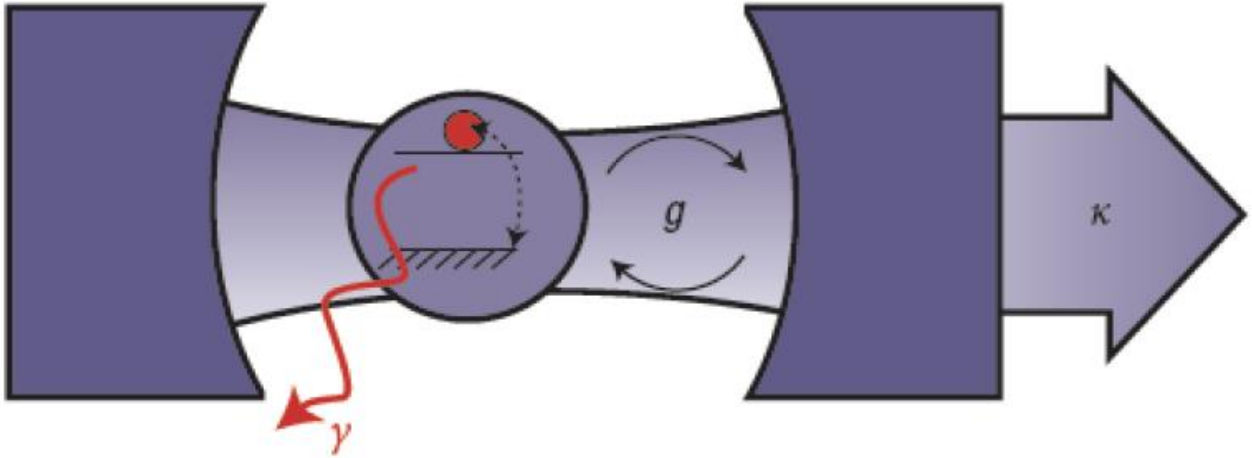


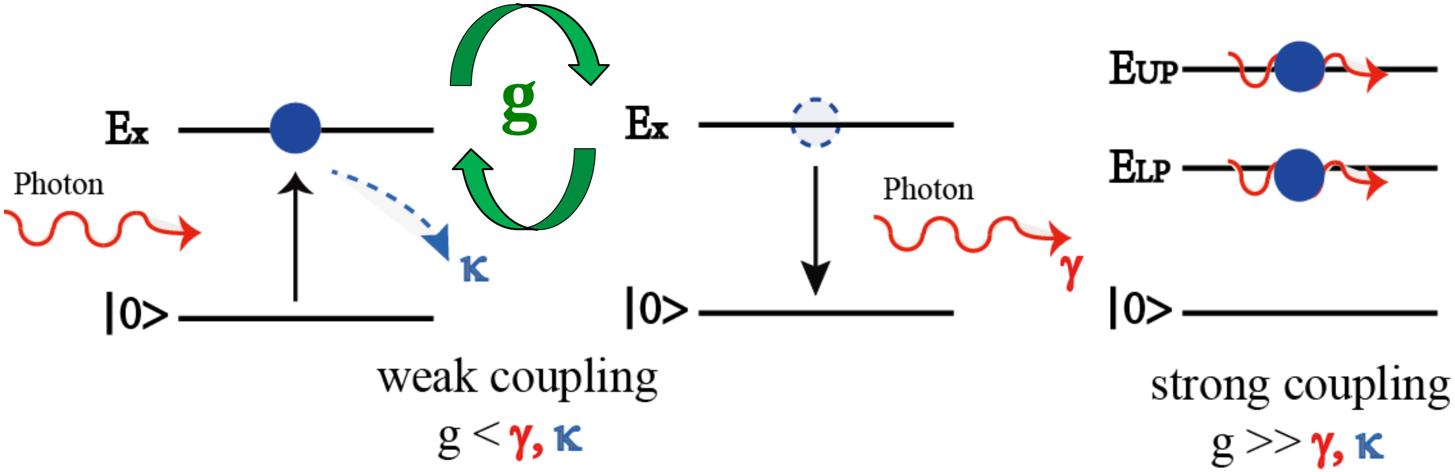
Optical standing waves ---- optical modes

Introduction

C-QED: the atom-photon interaction in an optical cavity

→ highly efficient and controllable light-matter coupling



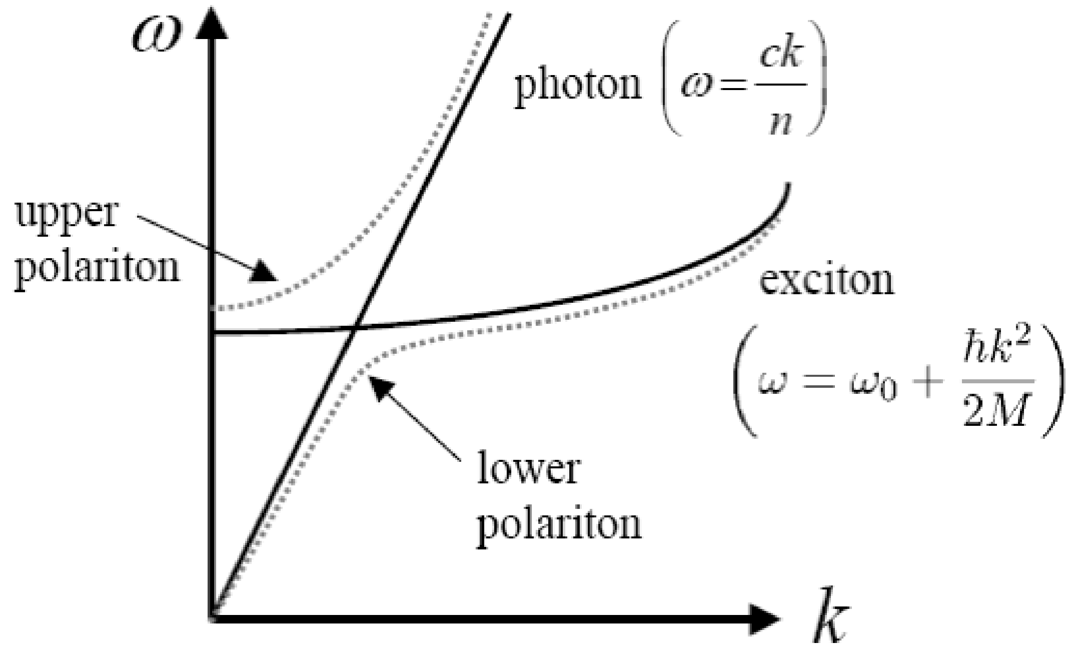


Excitons

---atom-like quasi-particles in semiconductors

Semiconductor optical cavities: controllable photon-exciton coupling

→ C-QED in solid states



strong coupling of excitons and photons

↓

new quasi-particle (polariton)

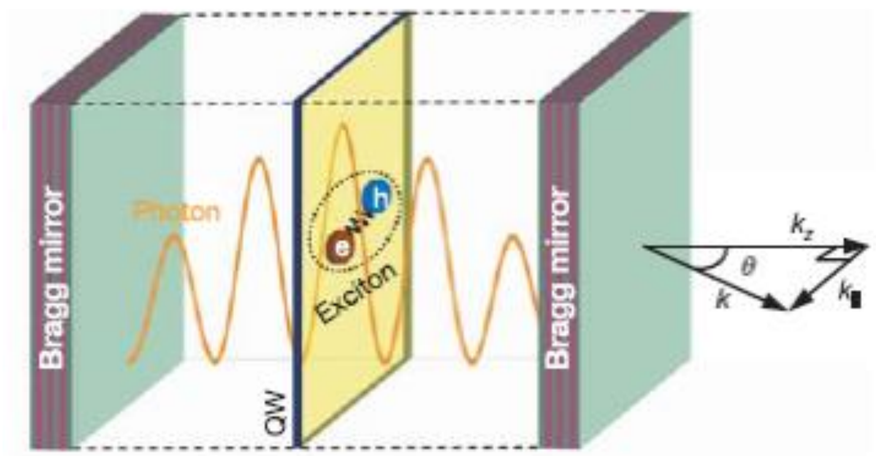
Boson

Fundamental problem：***Polariton BEC → polariton laser etc.***

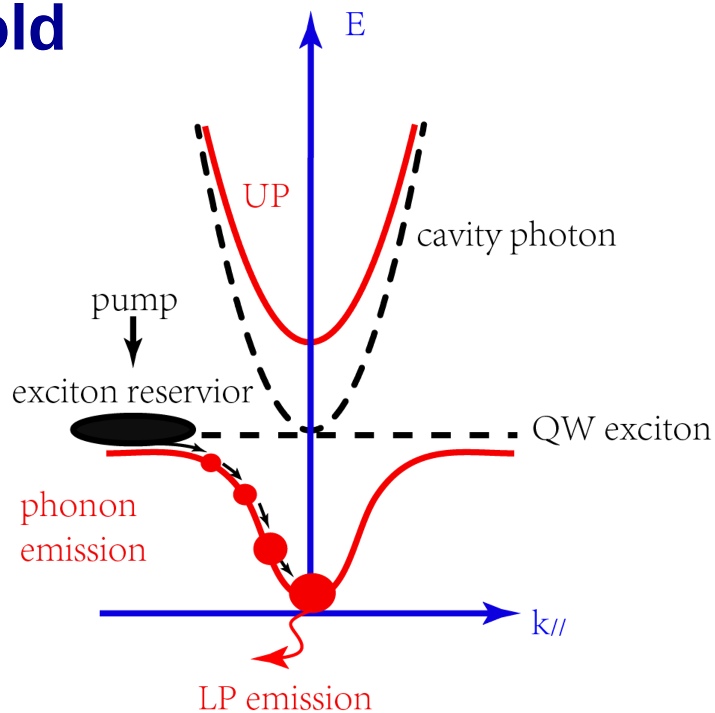
Polariton Laser: （1）coherent condensate of polariton

→ Tc、Nc

（2）low threshold



J. Kasprzak et al. Nature (2006)

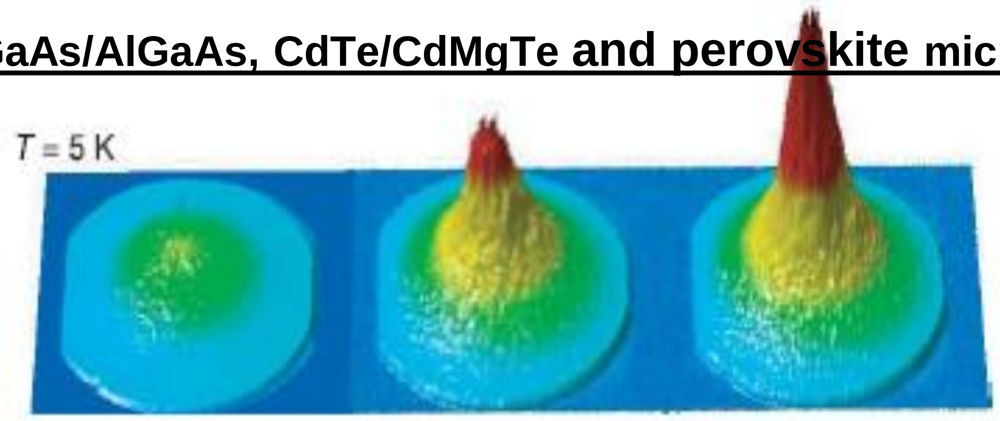


Nc、Tc～de Broglie Wavelength～m*

coherent condensate at RT → laser device

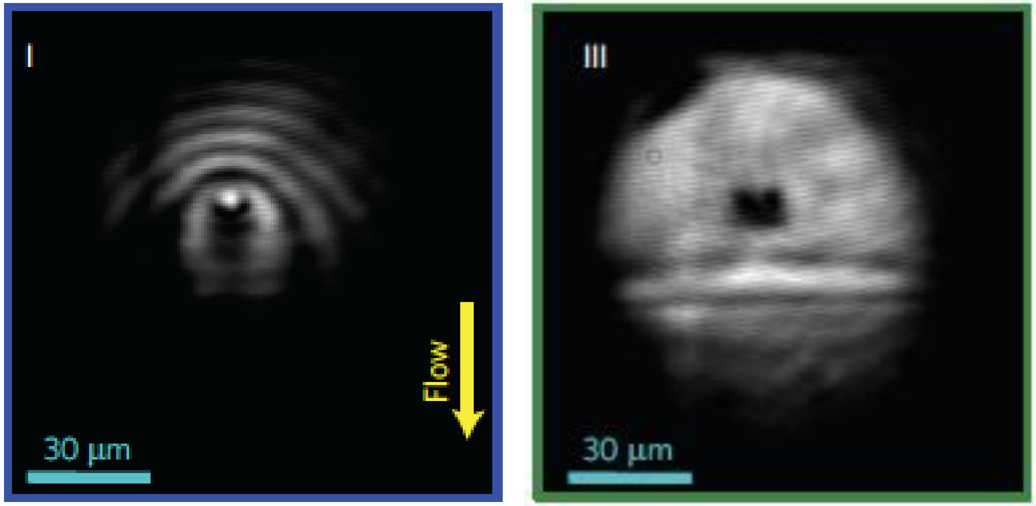
Polariton condensation in 2D cavities

GaAs/AlGaAs, CdTe/CdMgTe and perovskite microcavities



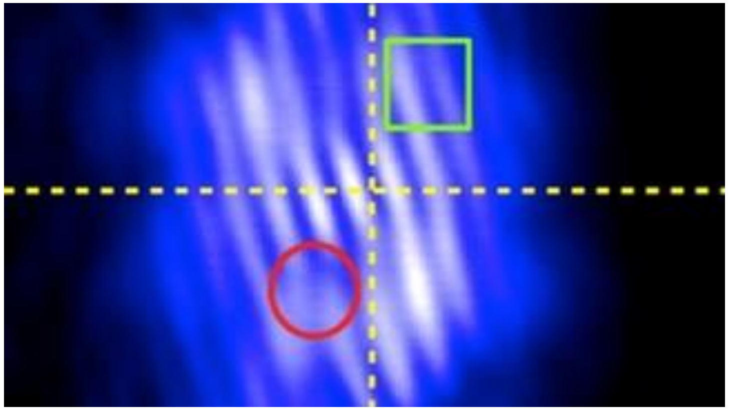
D. Snoke et al, Science (2002)
J. Kasprzak et al. Nature (2006)
R. Su, et al, Nature Physics (2020)

Superfluidity



A. Amo et al., Nature Phys. (2009),
A. Amo et al., Science (2011)

Quantized vortices



F. Manni et al., Nature Comms (2012)
K. G. Lagoudakis et al., Nature Phys. (2008)
D. Sanvitto et al., Nature Photonics (2019)

Polariton condensation in 2D cavities

Room-Temperature Polariton Lasing in All-Inorganic Perovskite Nanoplatelets

Rui Su,[†] Carole Diederichs,[‡,§] Jun Wang,[‖] Timothy C. H. Liew,[†] Jiaxin Zhao,[†] Sheng Liu,[†] Weigao Xu,[†] Zhanghai Chen,[‖] and Qihua Xiong*,[†,‡,⊥]

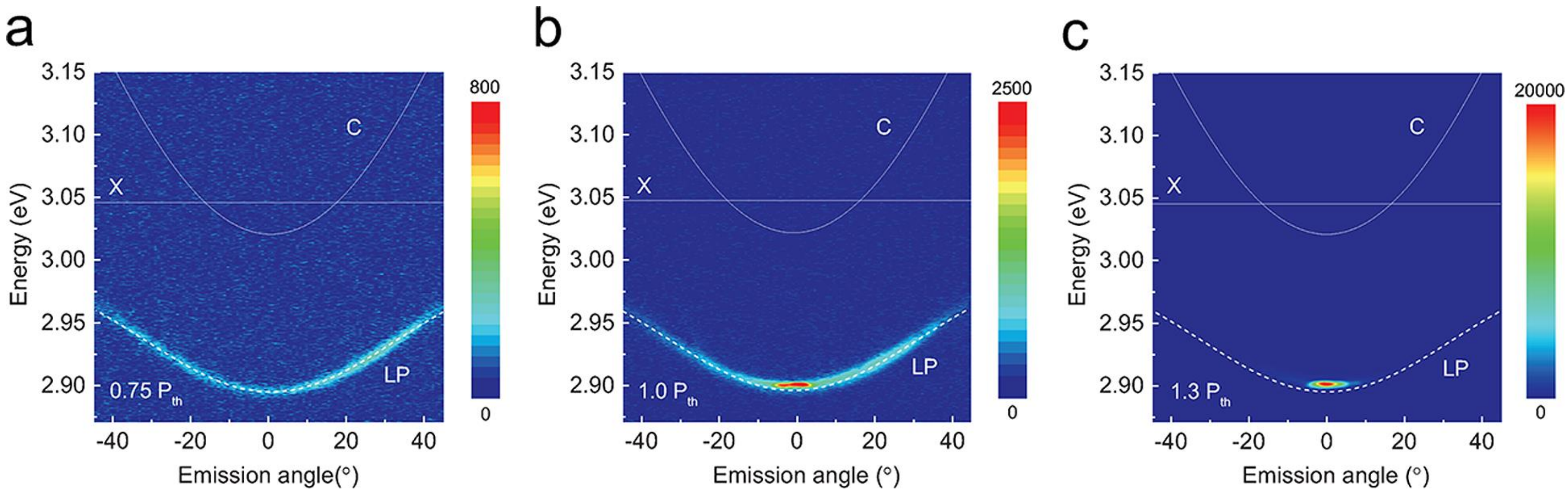
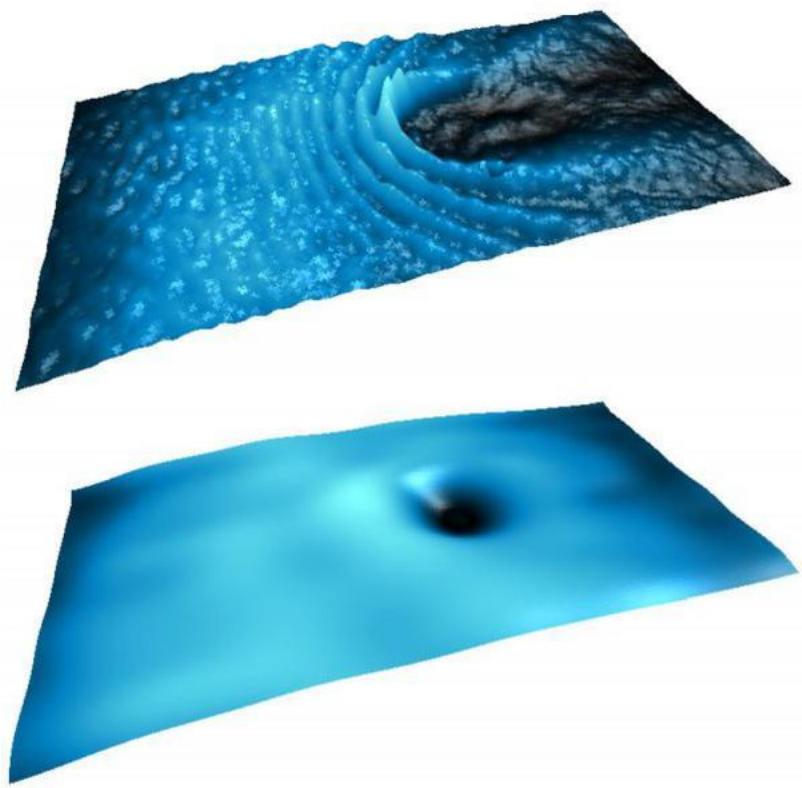
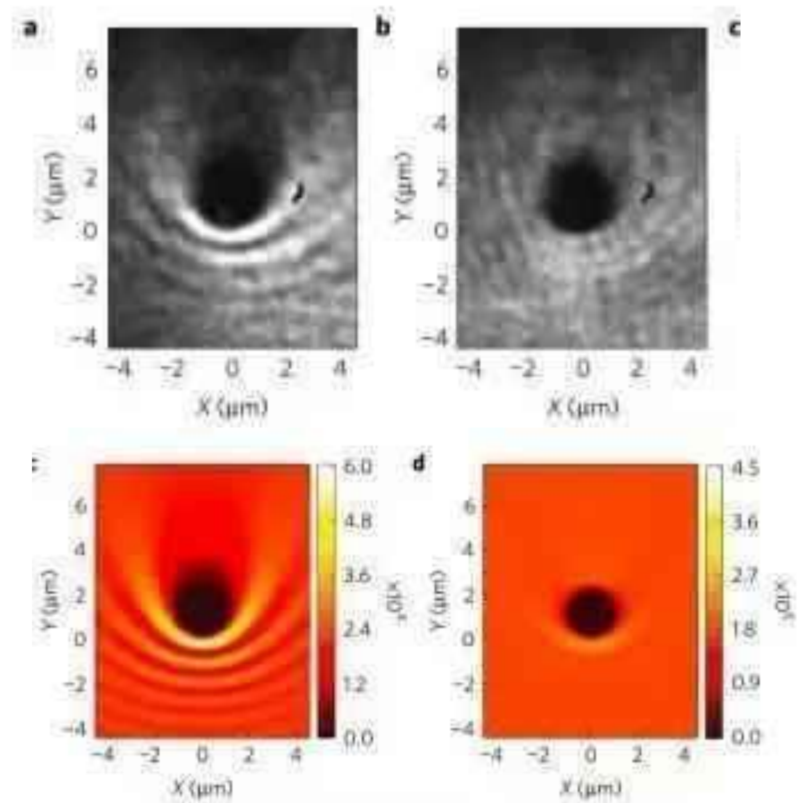


Figure 3. Power-dependent angle-resolved photoluminescence spectra. (a) Angle-resolved photoluminescence spectrum measured at 0.75 P_{th}. Polaritons show a broad emission distribution at all angles. (b) Angle-resolved photoluminescence spectrum measured at 1.0 P_{th}. The ground state near $k_{\|} = 0$ exhibits a much stronger emission than other angles, indicating the onset of polariton lasing. (c) Angle-resolved photoluminescence spectrum measured at 1.3 P_{th}. The ground state near $k_{\|} = 0$ is massively occupied, experiencing a sharp increase of intensity along with a blueshift of peak energy.

“Liquid light”

Superfluidity of polaritons at RT



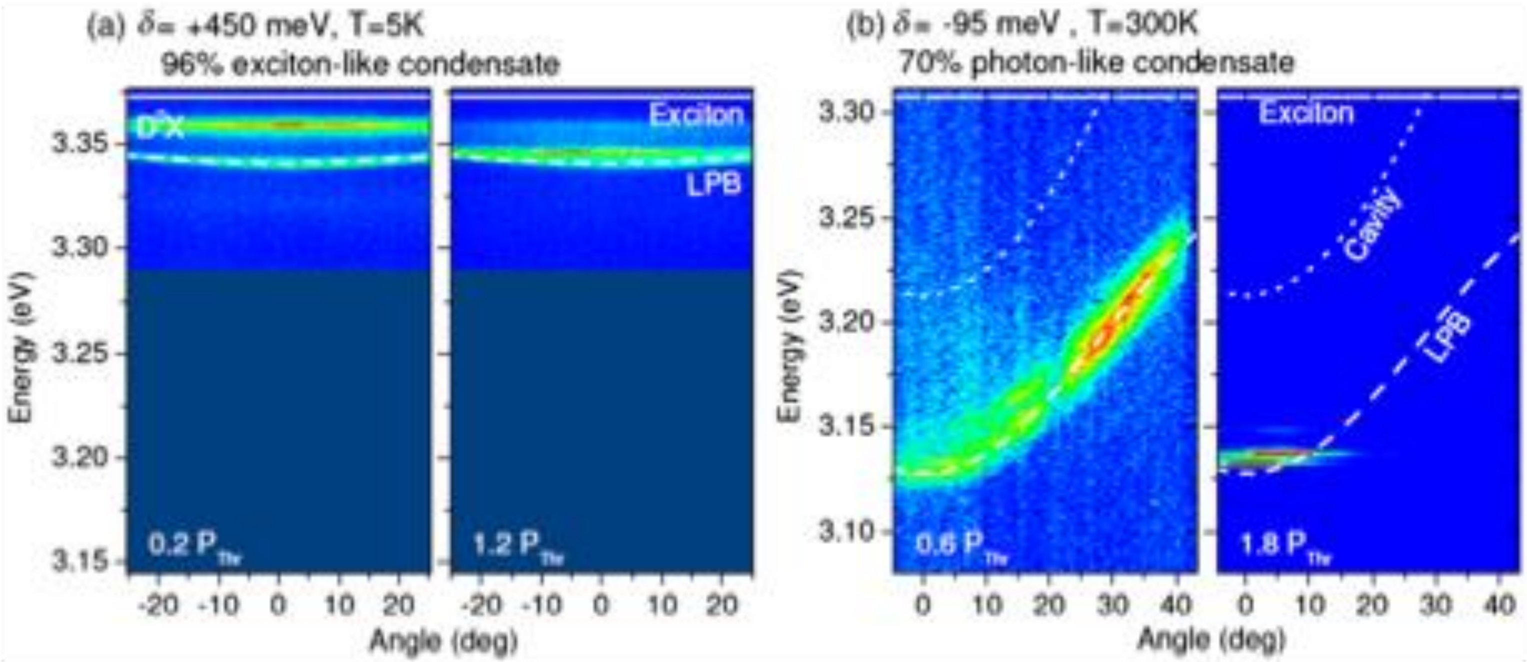


Sanvitto, Cohen et al, **Nature Physics, 2017**

ZnO

Wide band gap semiconductor (~3.3 eV)

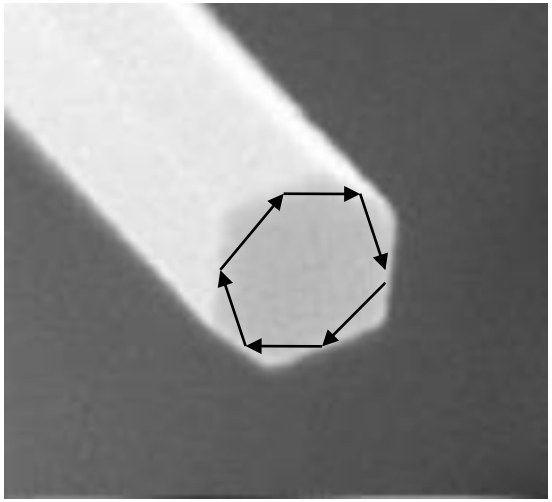
Large exciton binding energy (~60 meV)



Feng Li et al, *Phys. Rev. Lett.* 110, 196406 (2013)

ZnO: Wurtzite crystalline structure → micro-rod

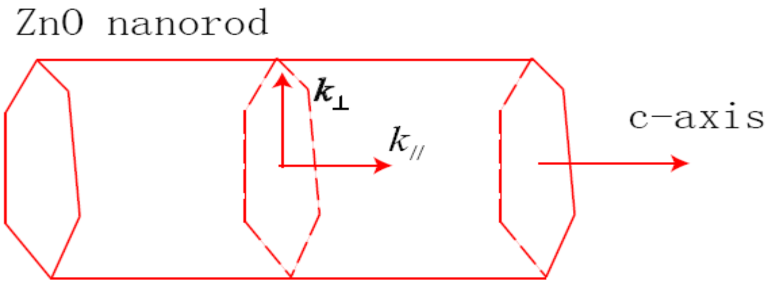
→ Naturally formed WG resonator



Cavity itself is active medium

Large overlapping of cavity mode-exciton

strong photon-exciton coupling



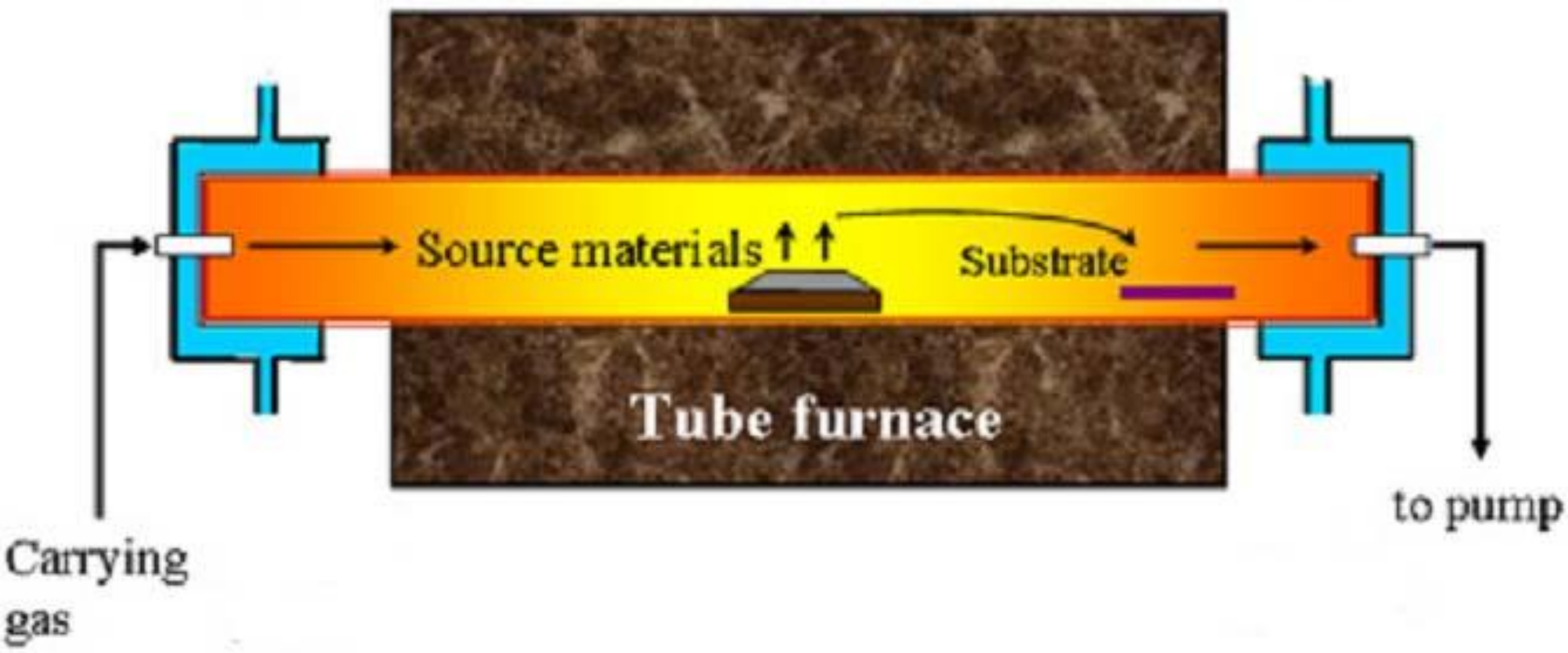
Polariton device at RT

an ideal 1D system

Sample growth:

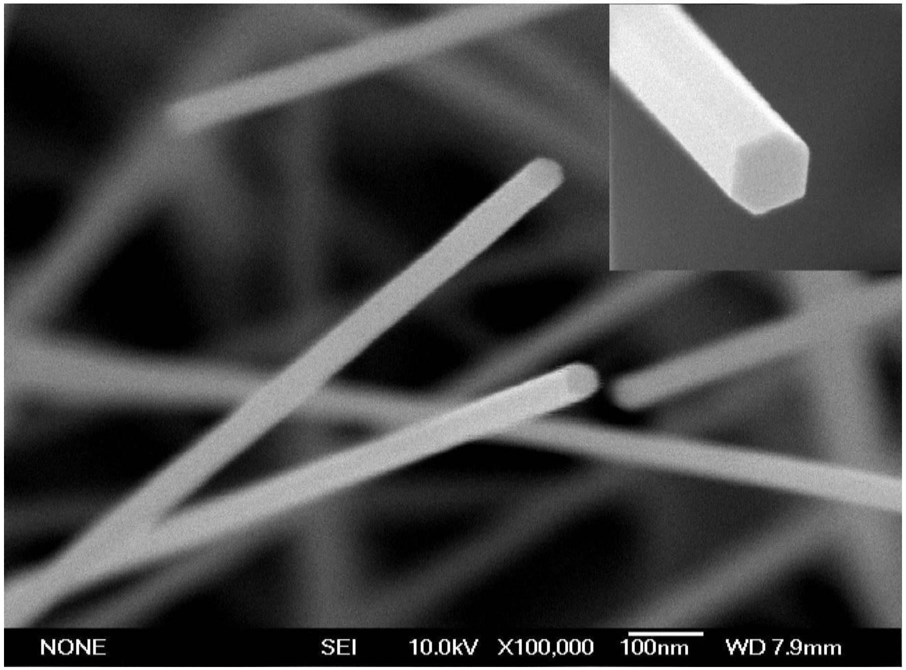
Preparation of the microcavities of ZnO

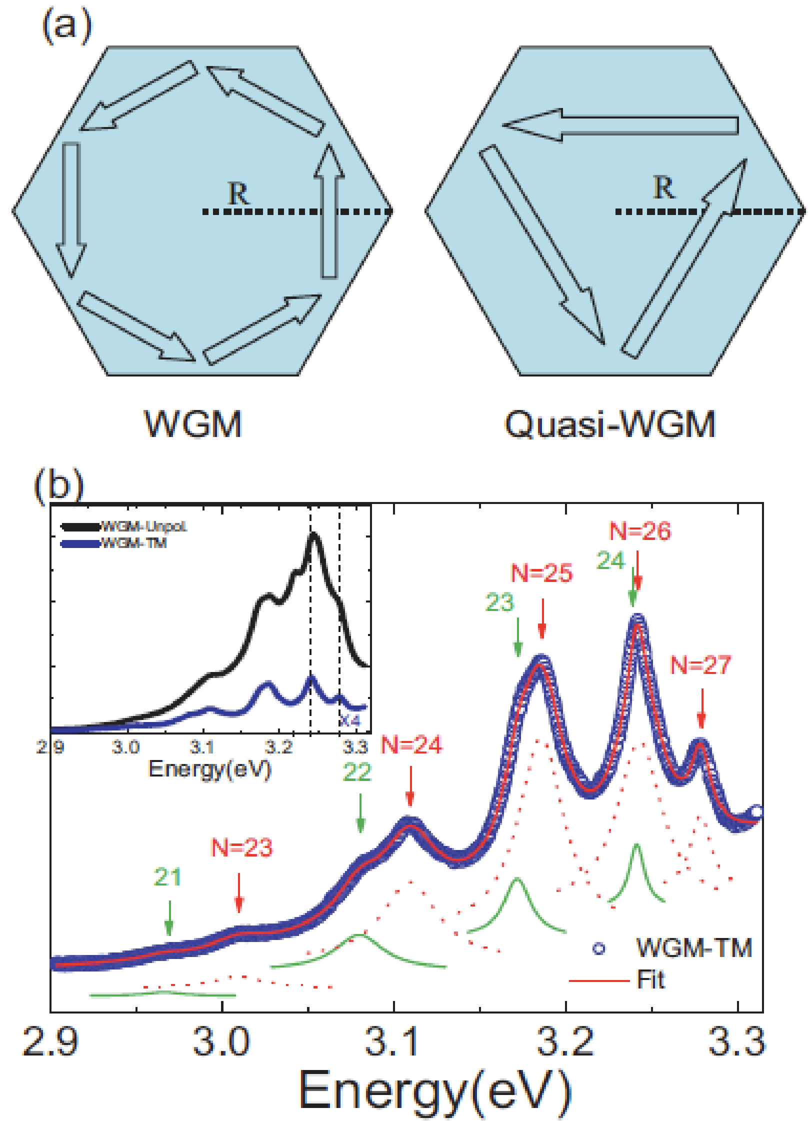
Method: Vapour Phase transport



HX Dong, ZH Chen et al, *Appl. Phys. Lett*. 94, 173115 (2009)
HX Dong, ZH Chen et al, *Appl. Phys. Lett*. 97, 223114 (2010)
HX Dong, ZH Chen et al, *J. Mat. Chem.* 20, 5510 (2010)

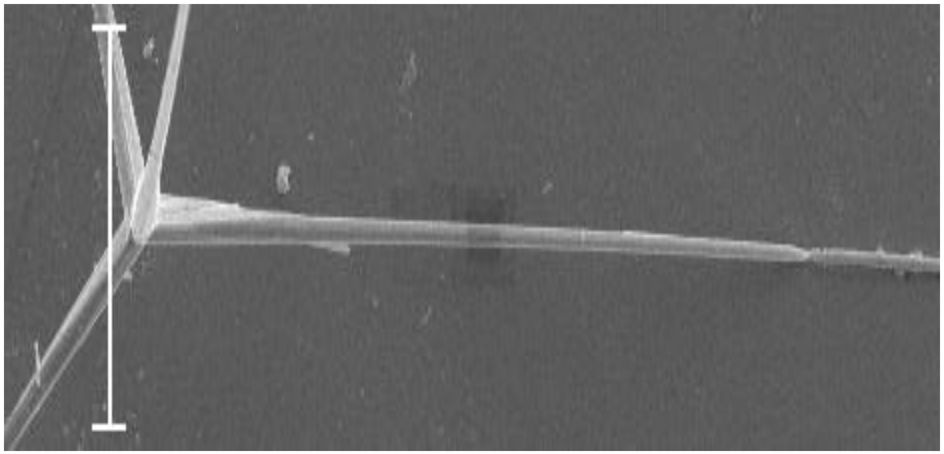
WGM in ZnO microwire

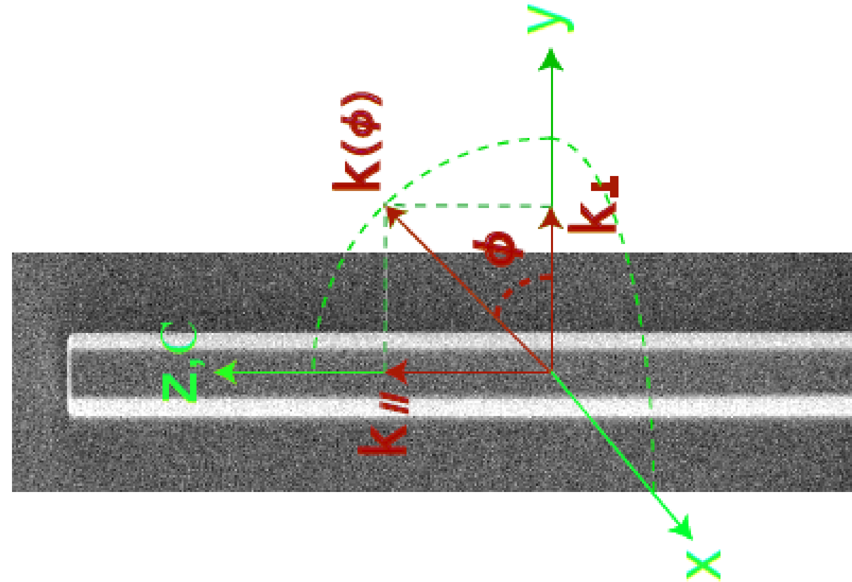




LX Sun, ZH Chen et al,
Optics Express **18, 15372 (2010)**

Polariton effect in ZnO WG cavity:

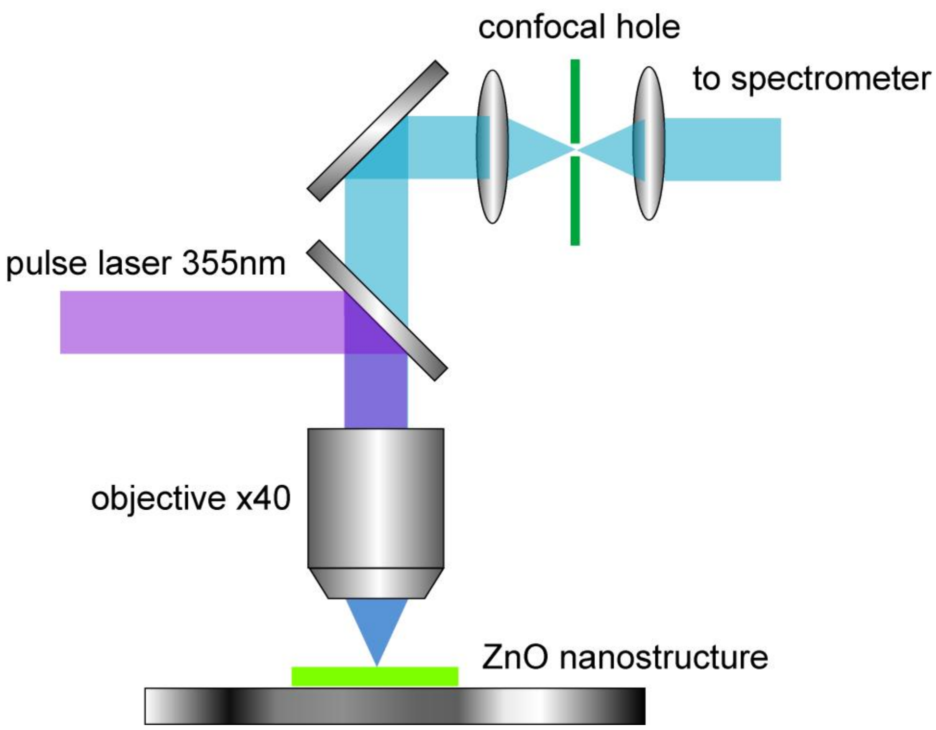




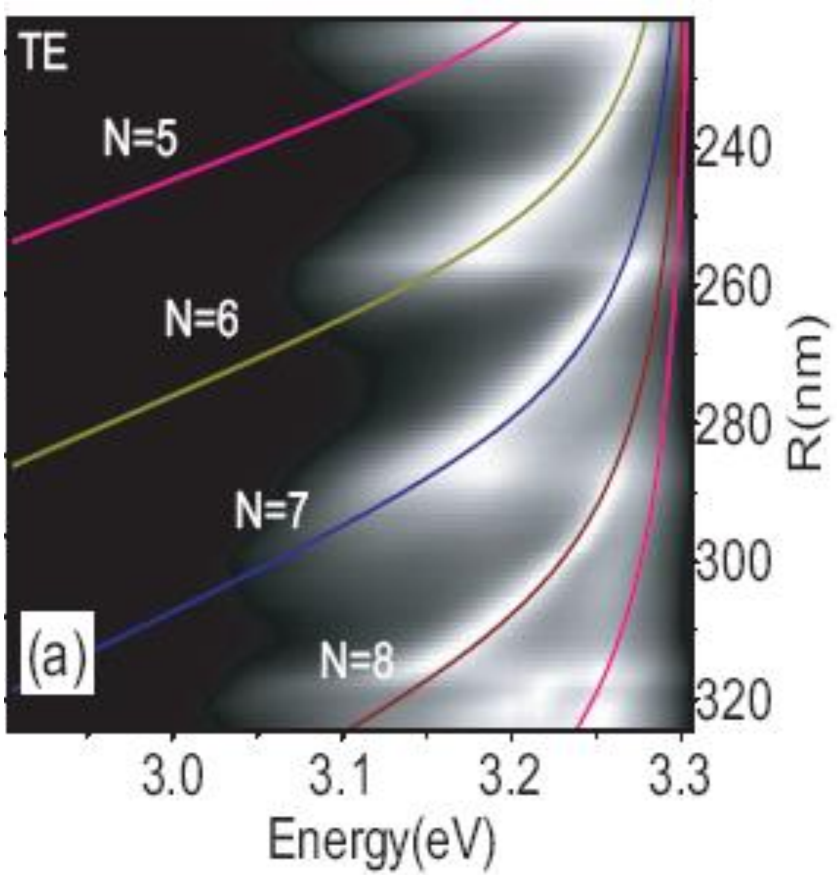
Tetrapods	Uniform rods
R ~ in-plane *k*	Free axis (c-axis)
PL mapping	Angular resolved
dispersion of *k*^ *c-axis*	**dispersion of *k // c-axis***

Spectroscopy setups

The confocal micro-PL system



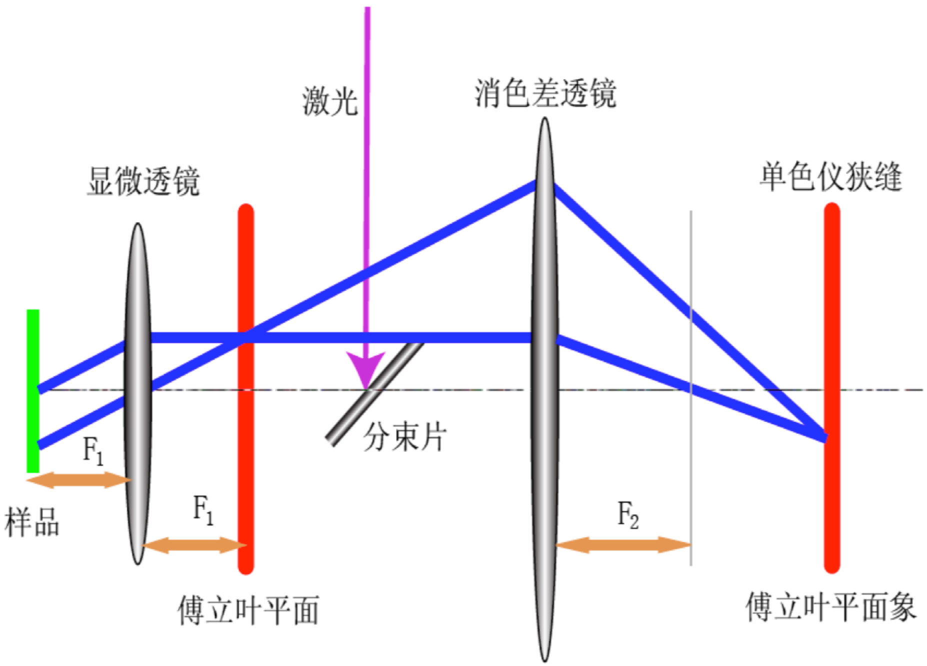
dispersion of k^ *c-axis*



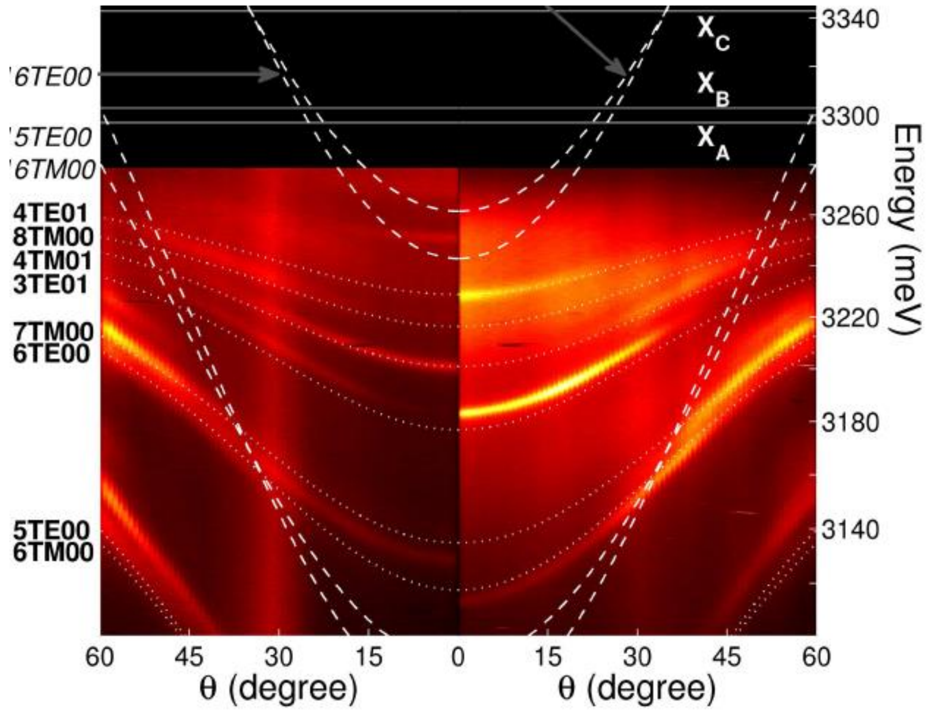
LX Sun, ZH Chen et al, *Phys. Rev. Lett.* 100, 156403 (2008)

Spectroscopy setups

Angular resolved micro-PL system



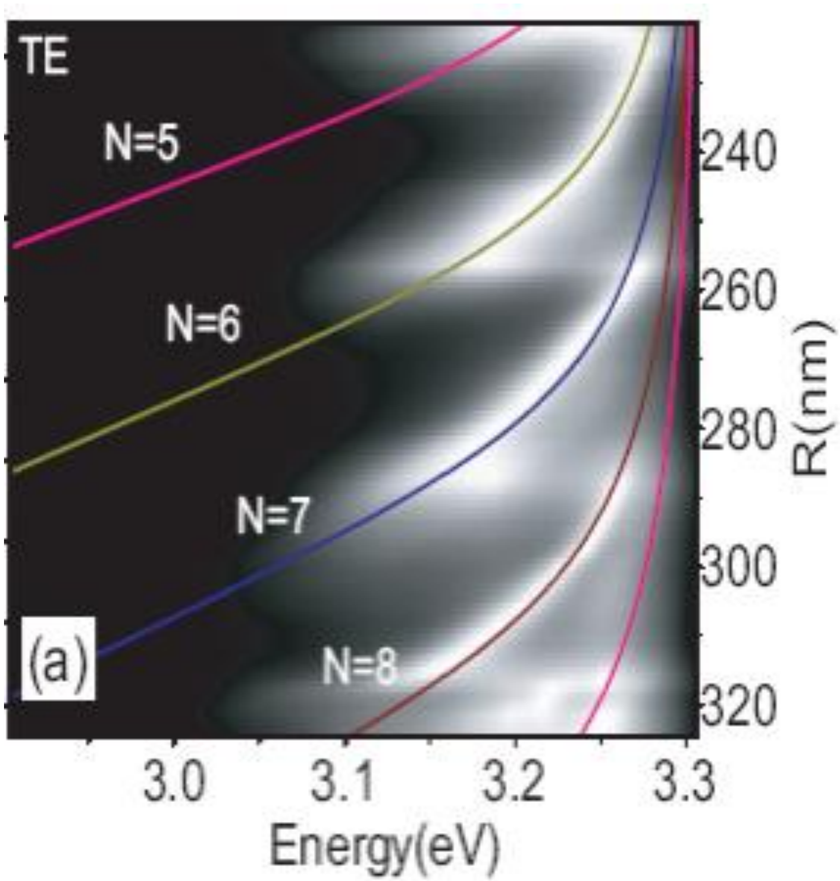
dispersion of *k // c-axis*



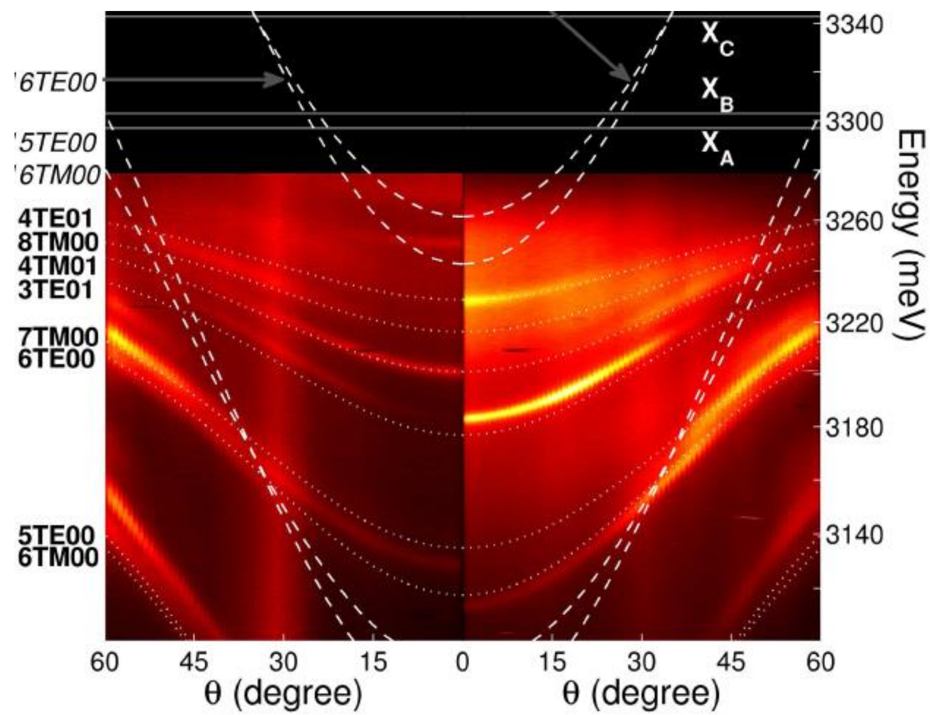
LX Sun, ZH Chen et al, *Phys. Rev.* B83, 041302 (2011) (Rapid Comm.)

Dispersion

dispersion of *k* ⊥ *c-axis*



dispersion of *k* // *c-axis*



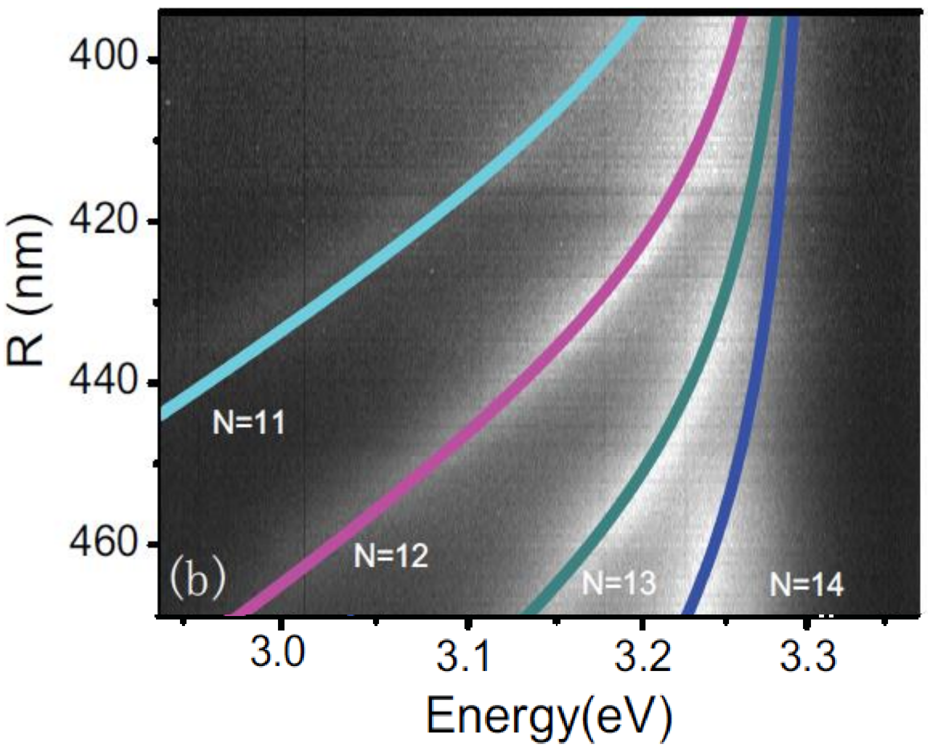
LX Sun, ZH Chen et al, *Phys. Rev. Lett.* 100, 156403 (2008)

A. Trichet, LX Sun et al, *Phys. Rev.* B83, 041302 (2011) (Rapid Comm.)

Polariton Lasing

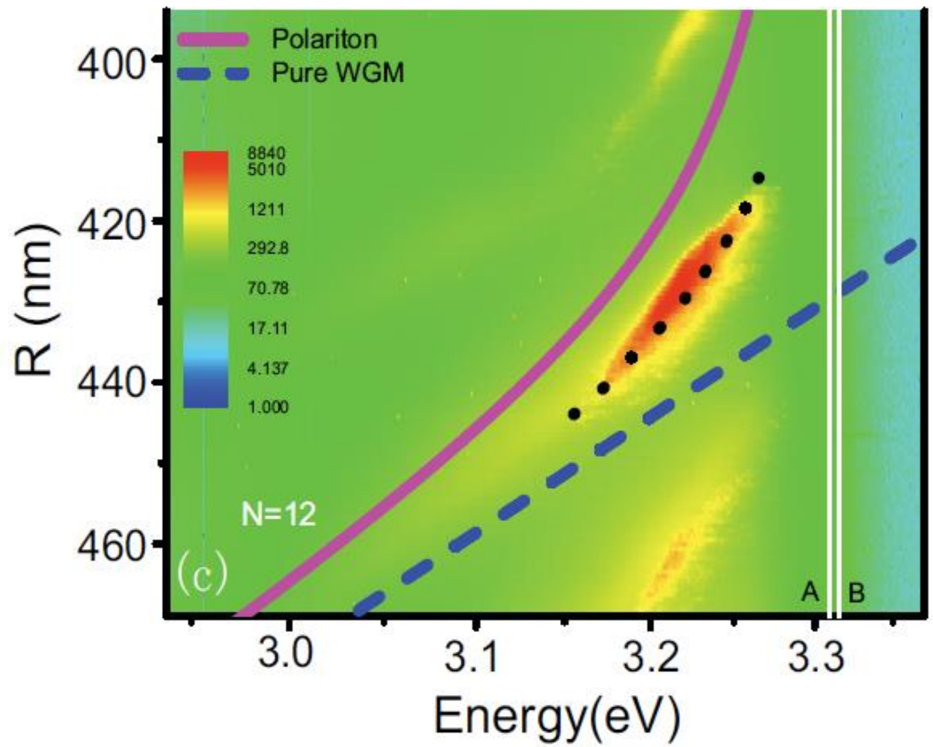
RT lasing mechanism of ZnO:

photon lasing or polariton lasing?



Pump power P=6.2 nW

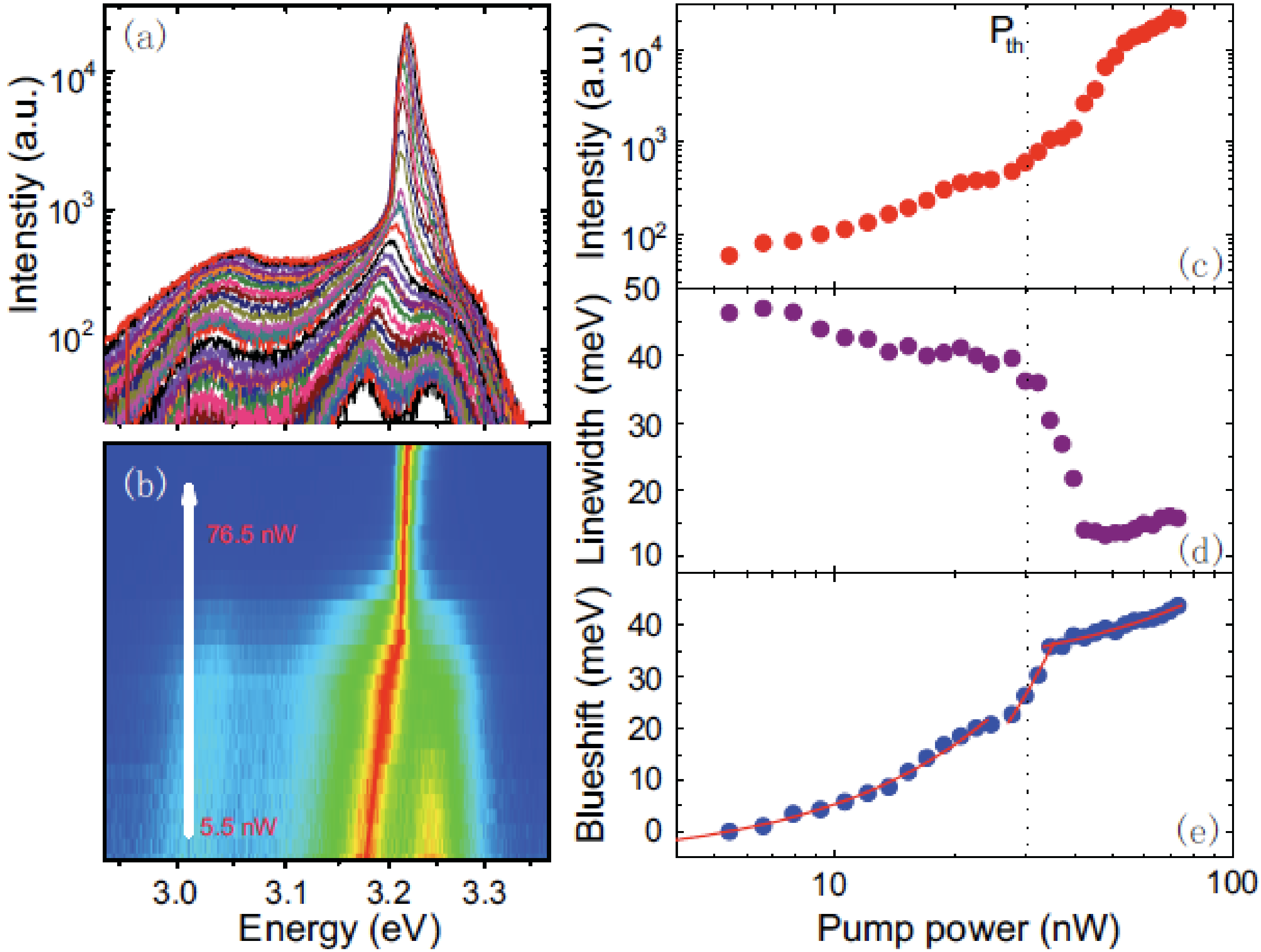
Detuning: $(\delta = E_C - E_X)$



Pump power P=58 nW

The laser effect occurred along the WGM lower polariton branch.

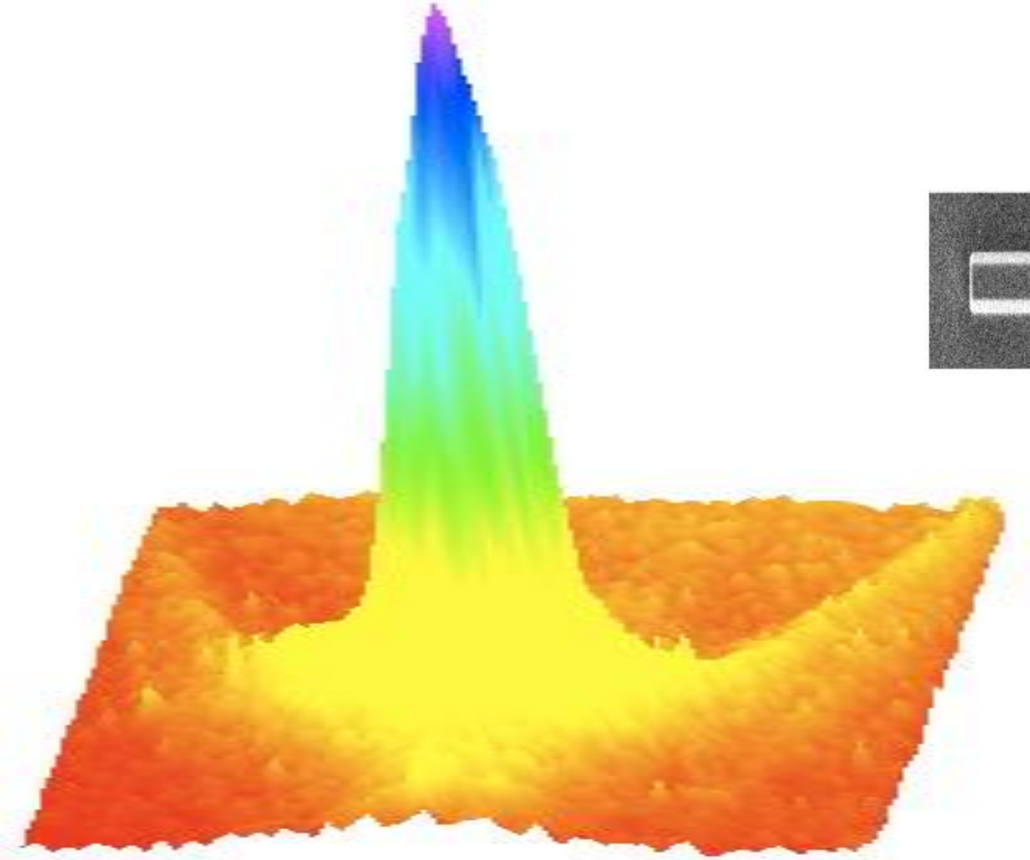
Pump power dependence

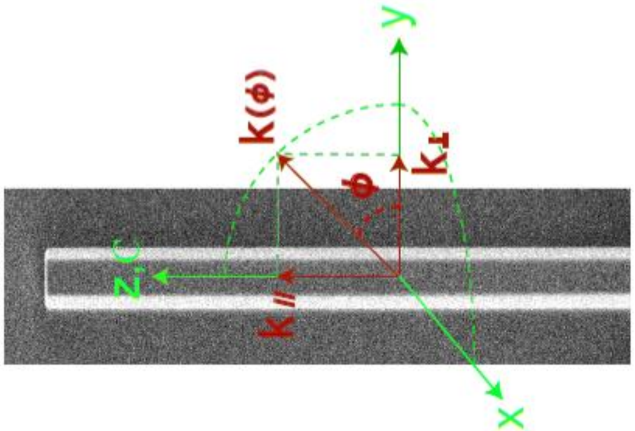


At P_{th}, N_{3D}~4×10^{18} cm^{-3} << Mott Density : 5.5×10^{19} cm^{-3}

Polariton condensate in $k_{//}$ space

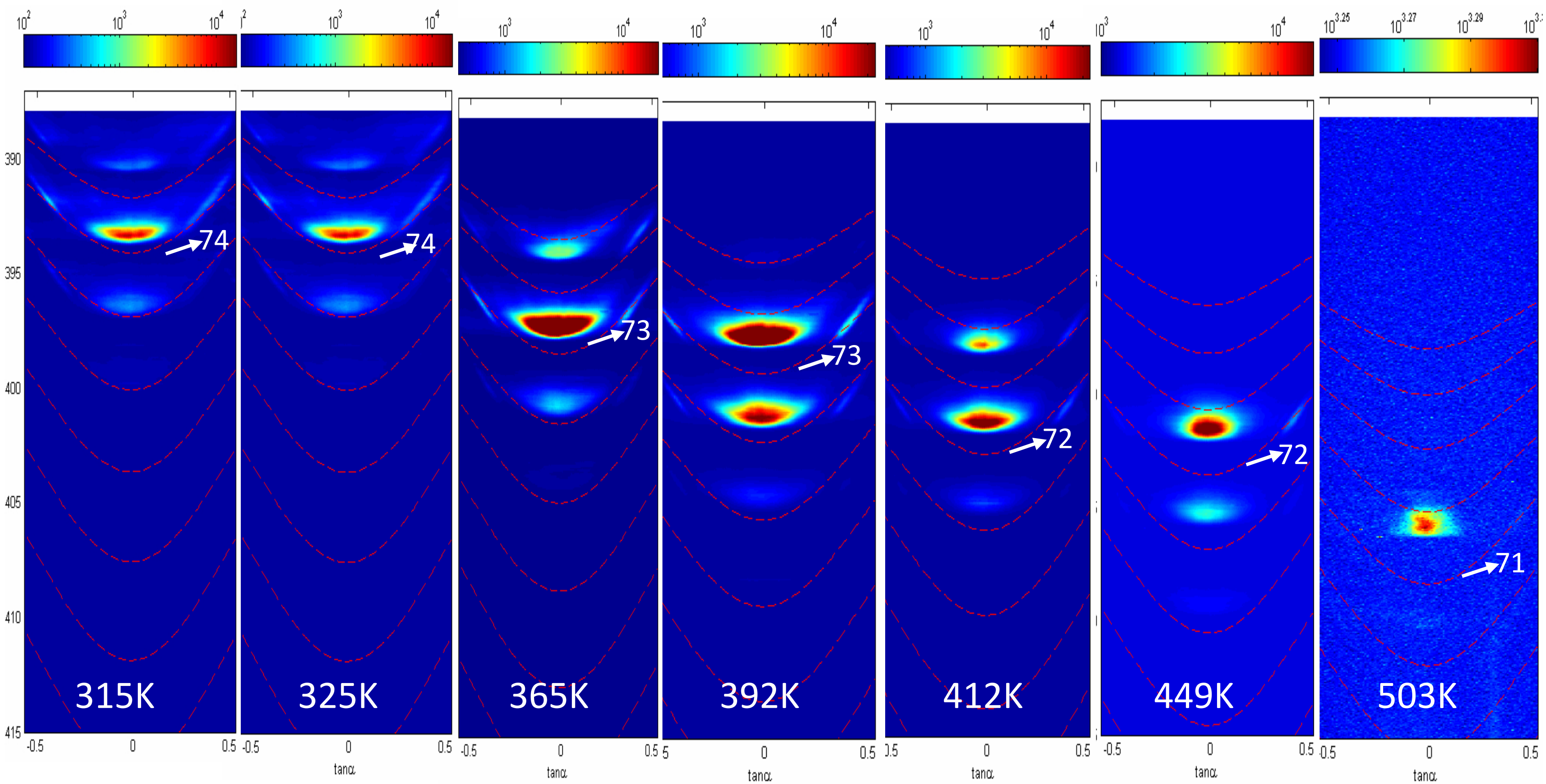
with clear polariton dispersion





W Xie, ZH Chen et al, *Phys. Rev. Lett.* 108, 166401 (2012)

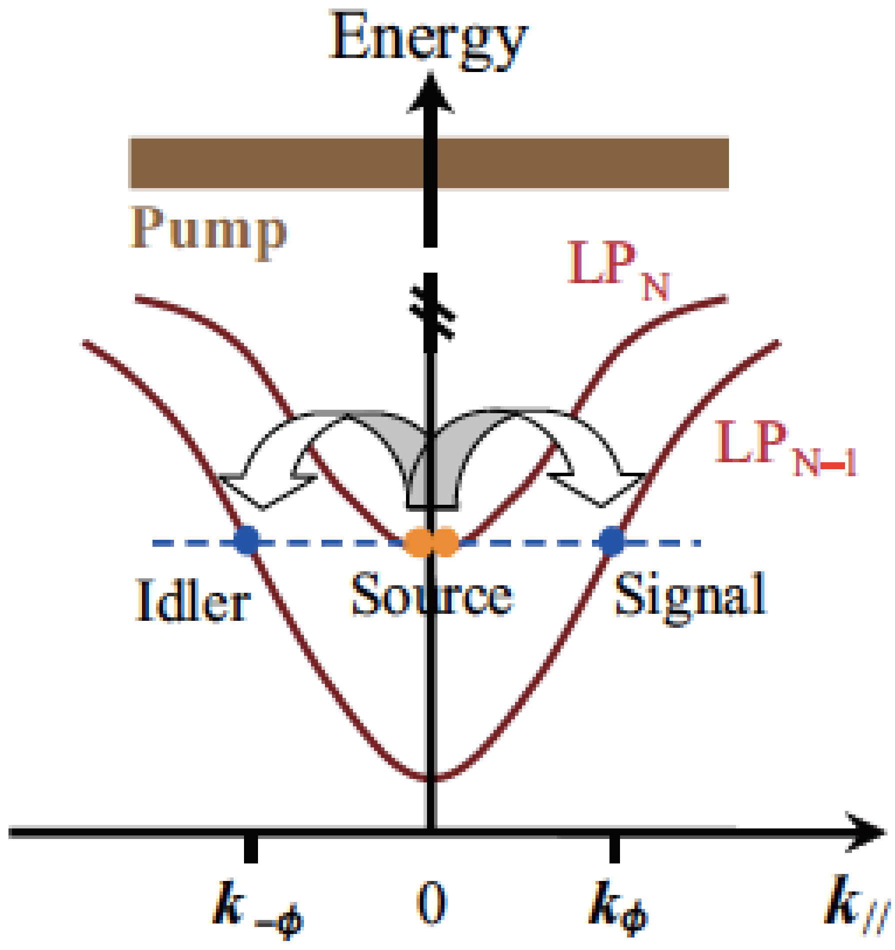
Polariton condensate at 500 K



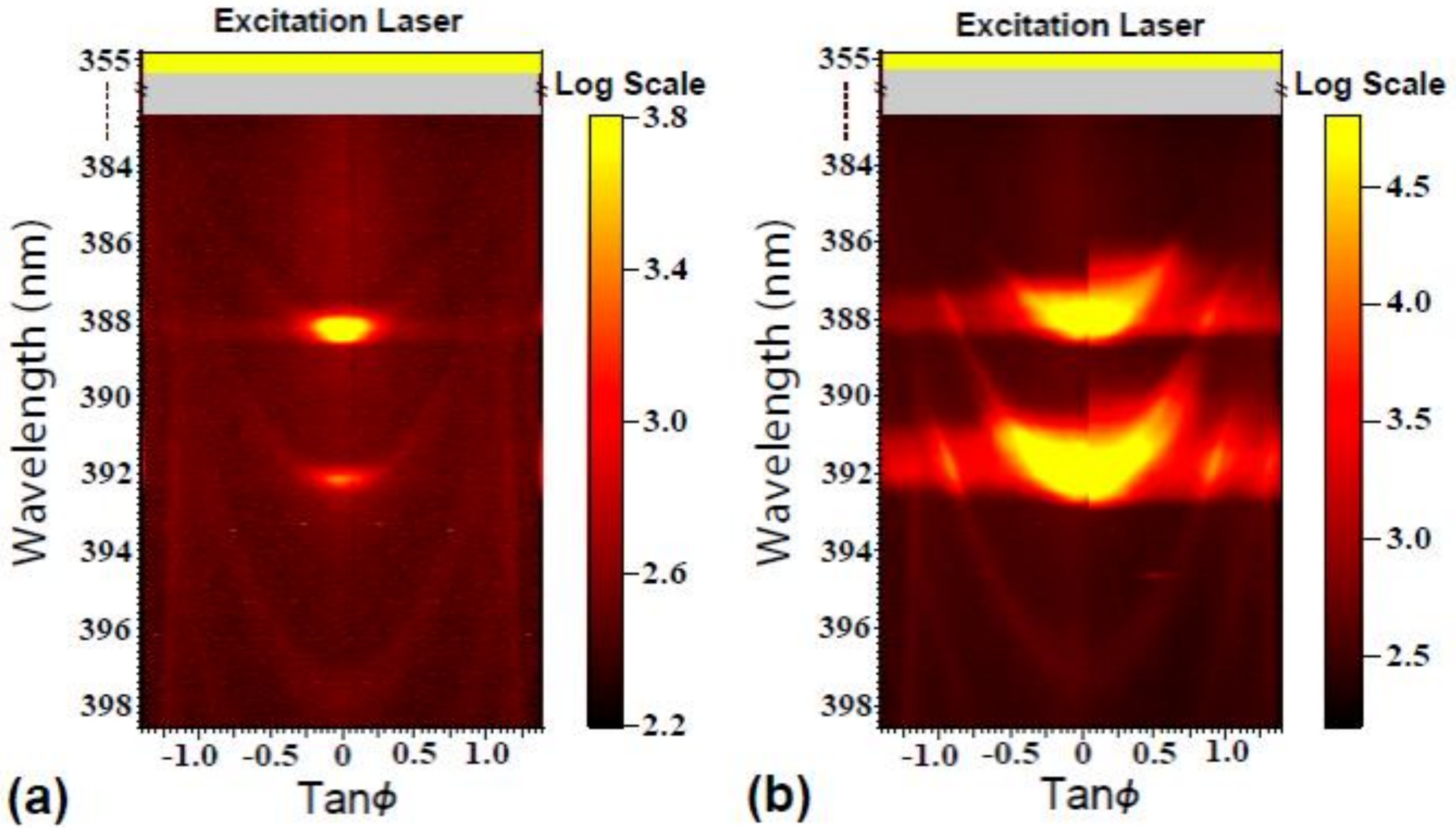
D Xu, ZH Chen et al, *Appl. Phys. Lett.* 104, 082101 (2014)

Degenerative parametric scattering

→ Entangled polariton



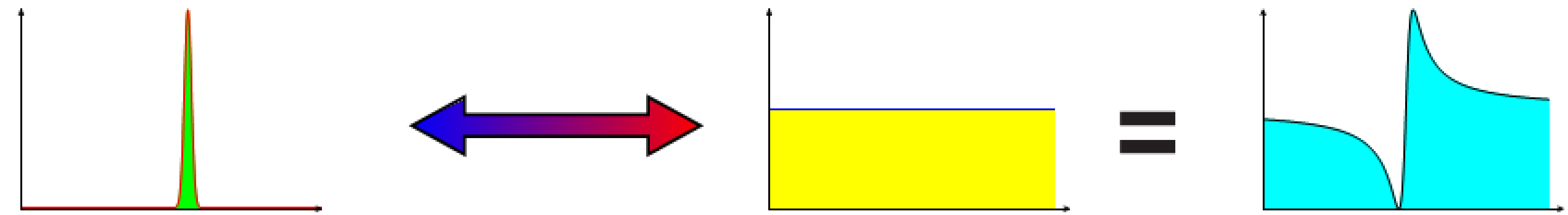
Polariton parametric scattering

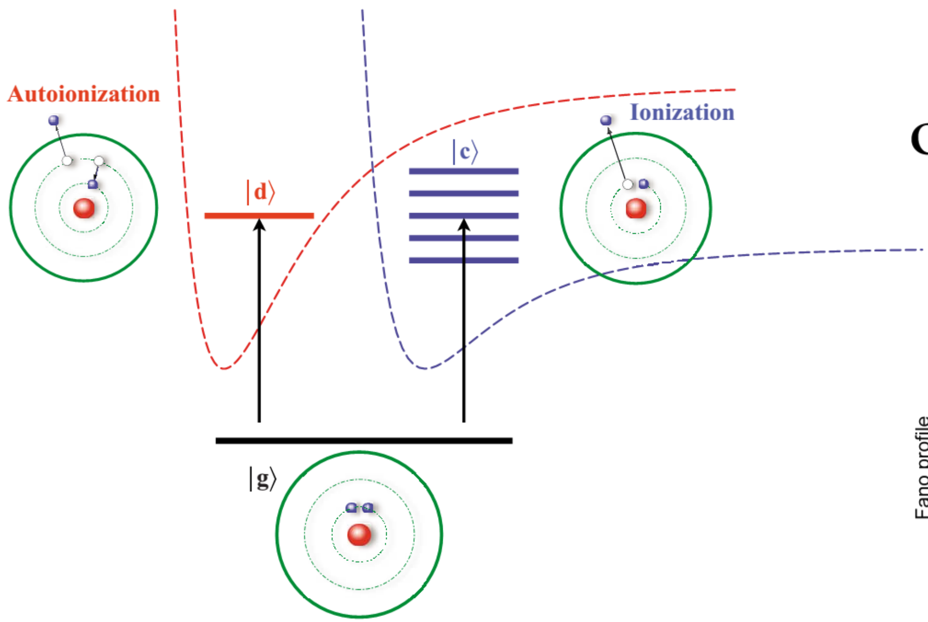


W Xie, ZH Chen et al, *Phys. Rev. Lett.* 108, 166401 (2012)

Fano resonance

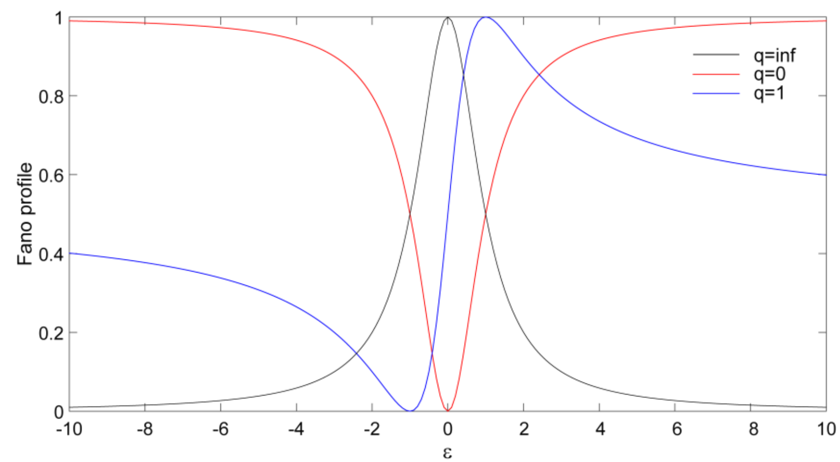
Discrete state **Mixing** **Continuum** **Fano resonance**





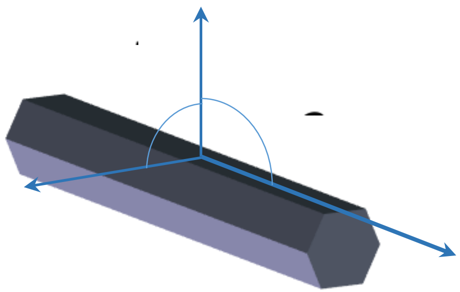
$$\sigma = \frac{(\varepsilon + q)^2}{\varepsilon^2 + 1}$$

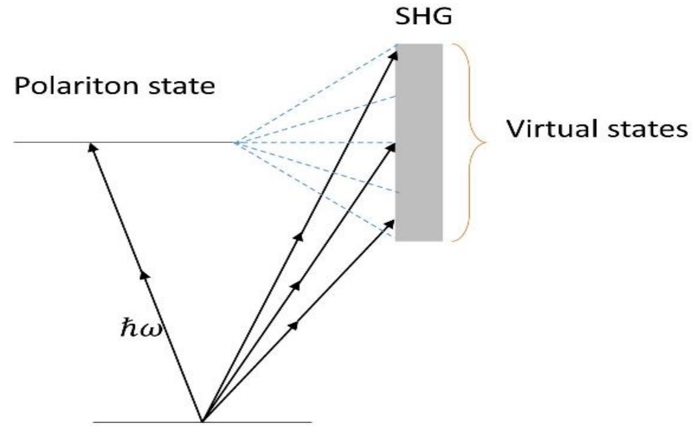
q is the ratio of |g>-|d> and |g>-|c> transition

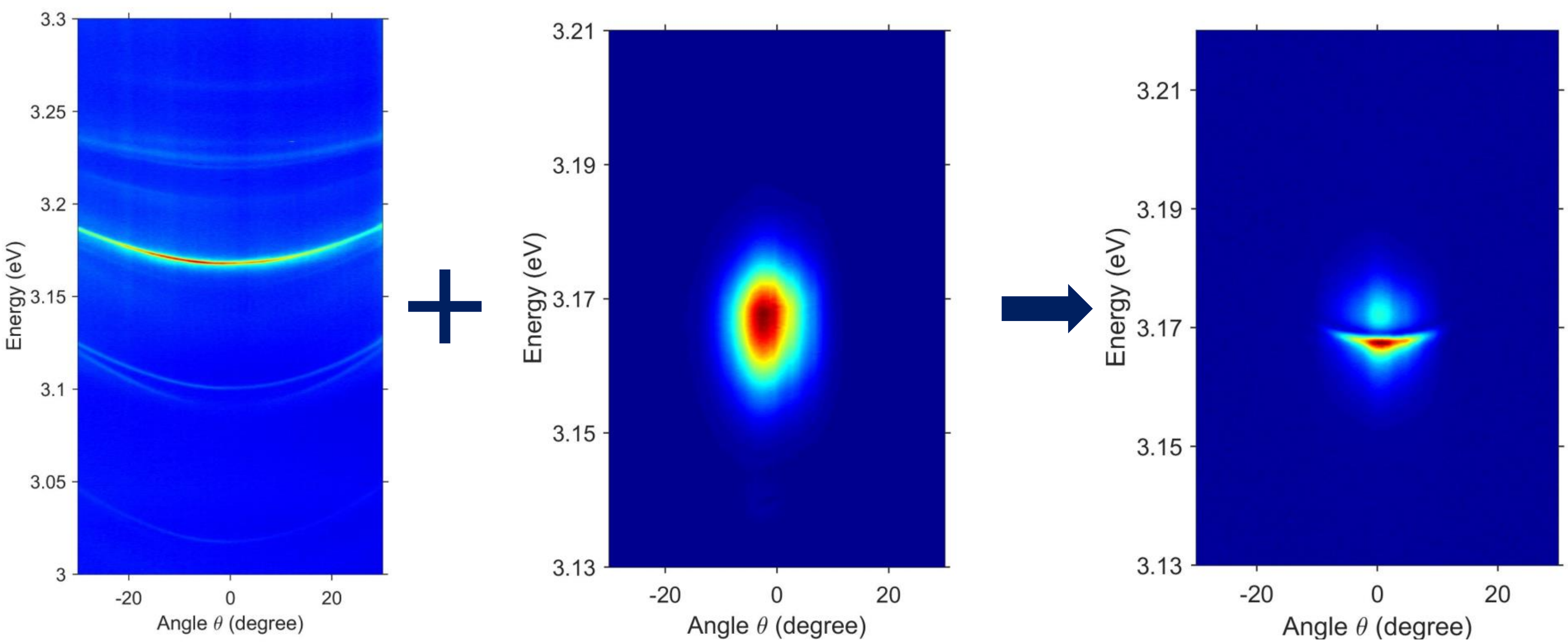


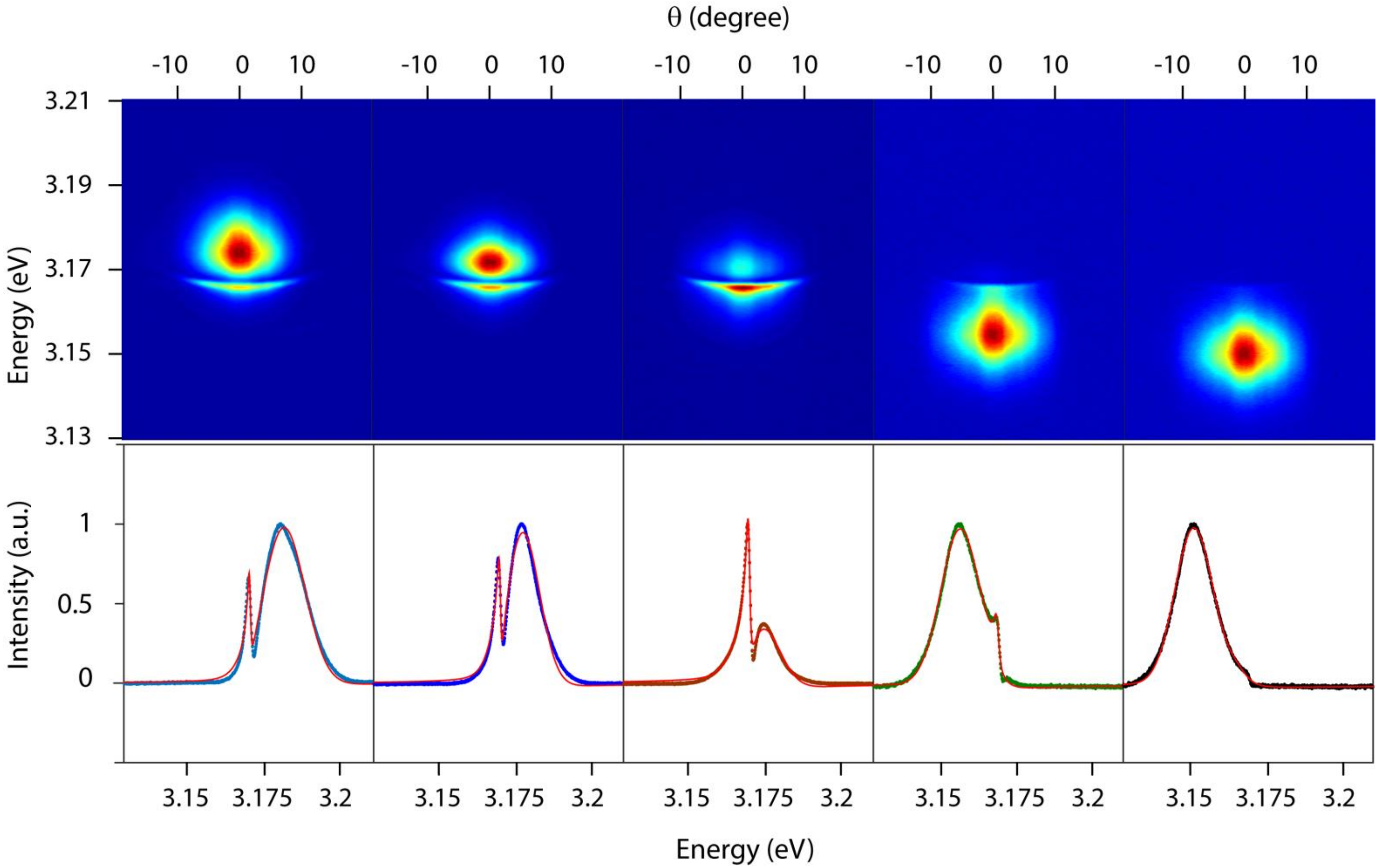
Fano, Ugo. *Physical Review* 124.6 (1961): 1866.

Polariton Fano resonance



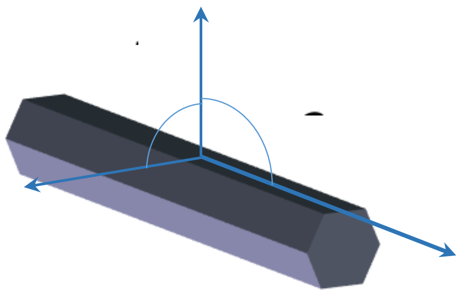


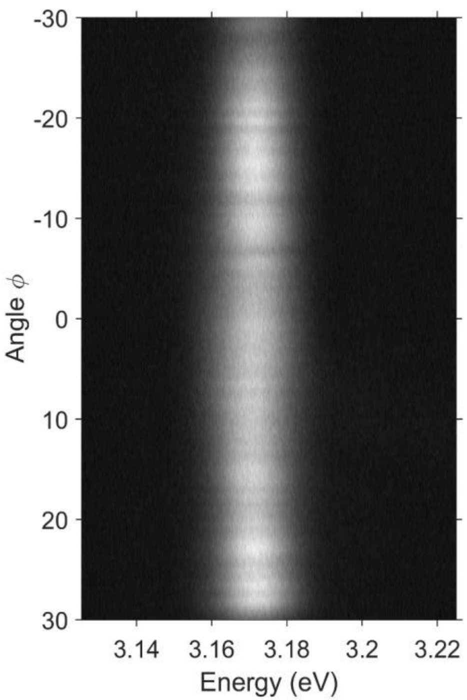




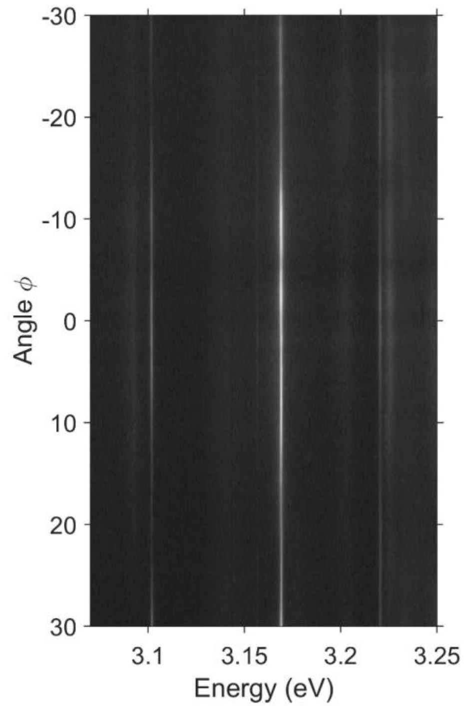
$$I = A_F\left(\frac{(\varepsilon + q)^2}{\varepsilon^2 + 1} - 1\right) + I_b$$

$$I_b = A_b \frac{2}{\pi} \frac{w}{4(\omega - \omega_r)^2 + w^2}$$

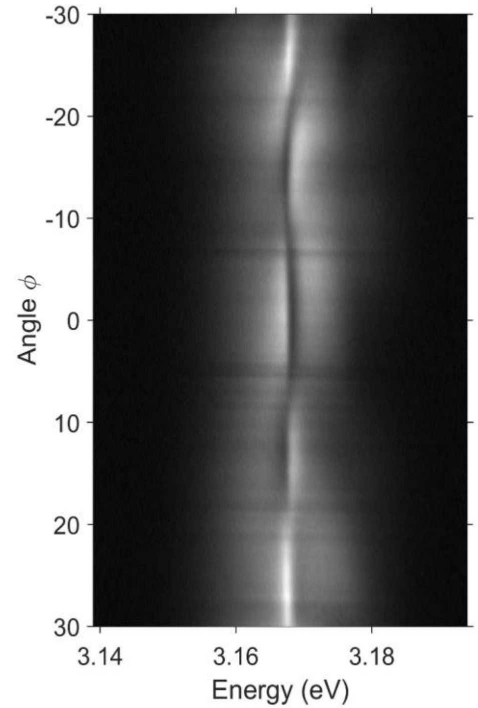




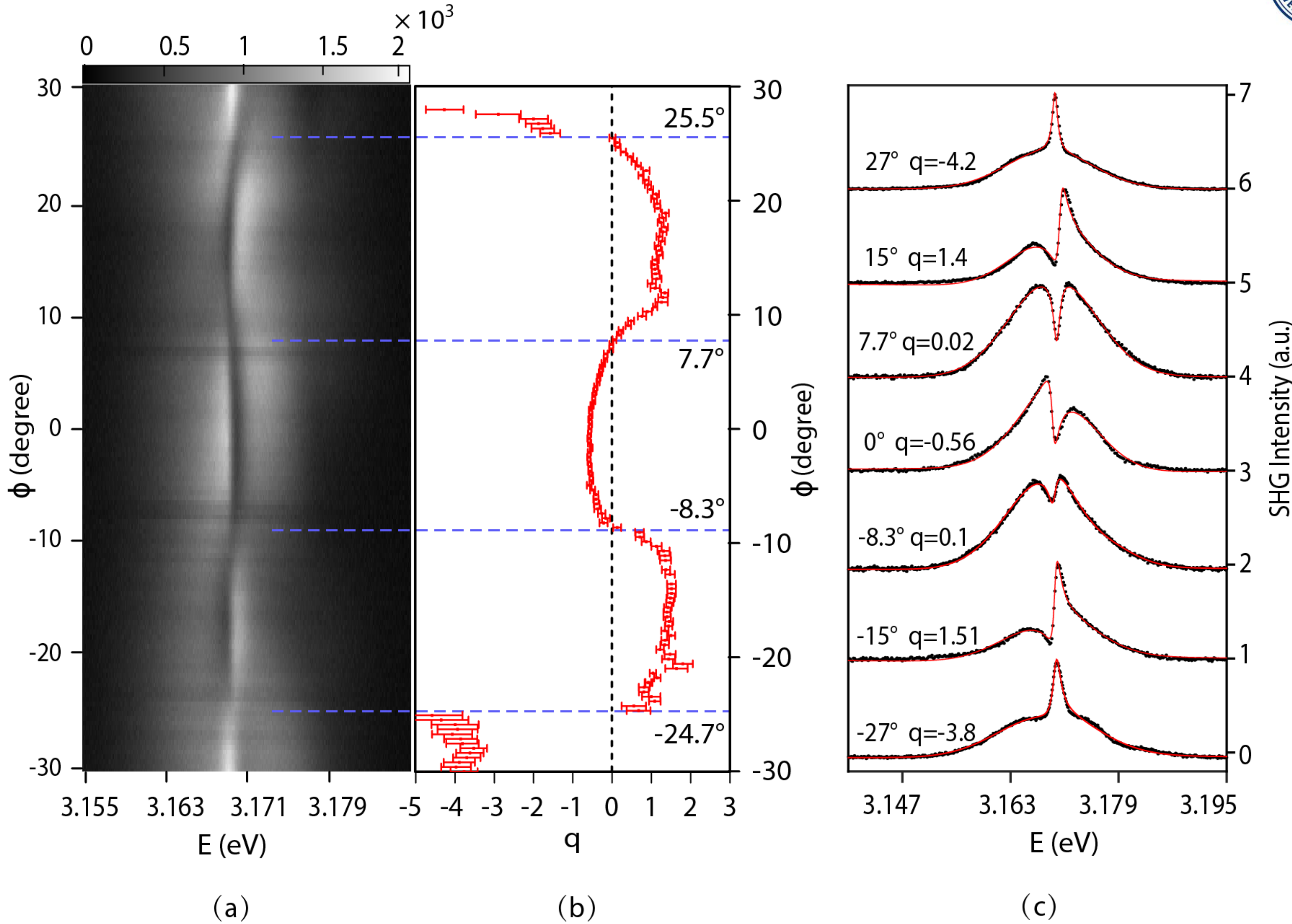
SHG



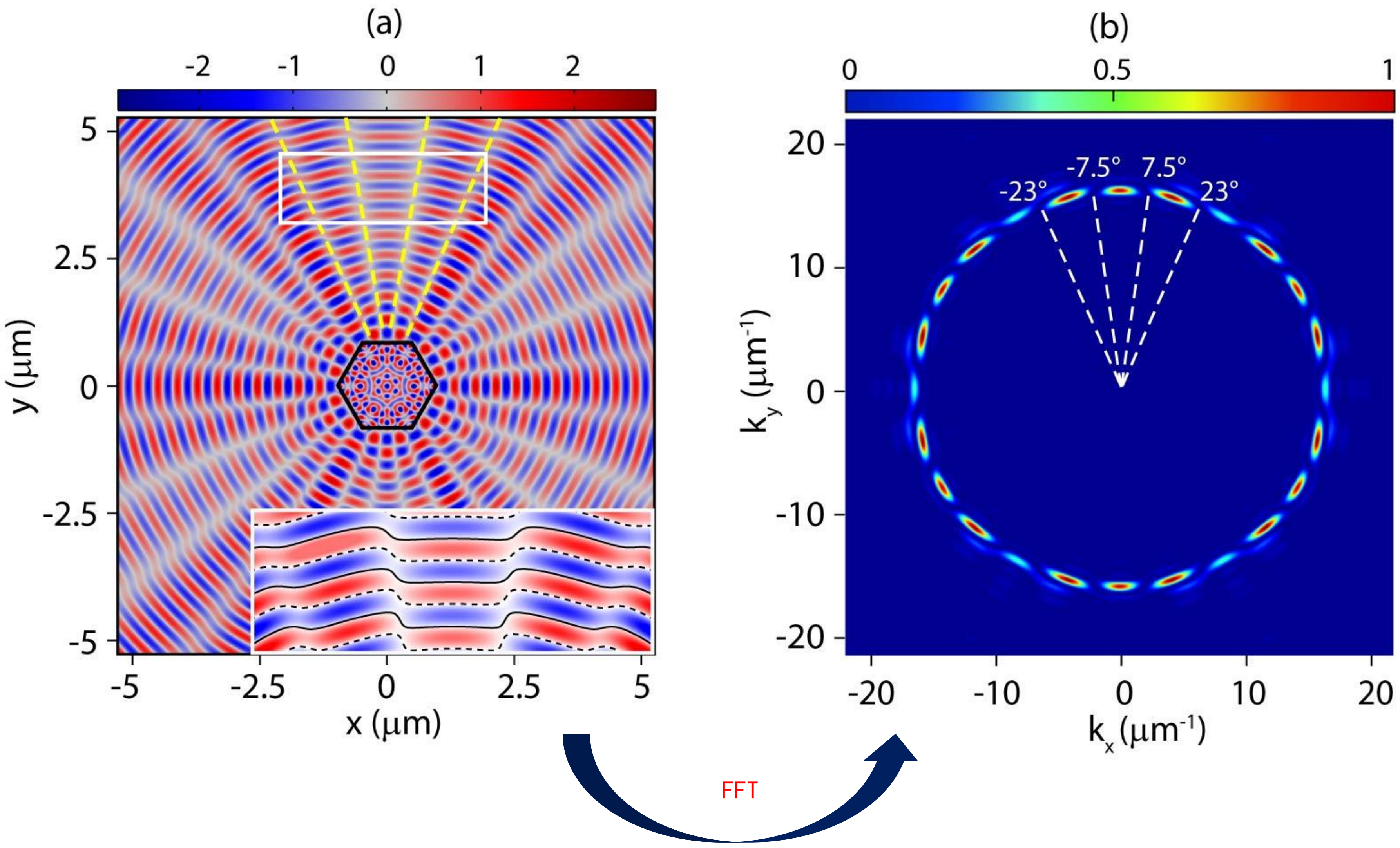
Polariton

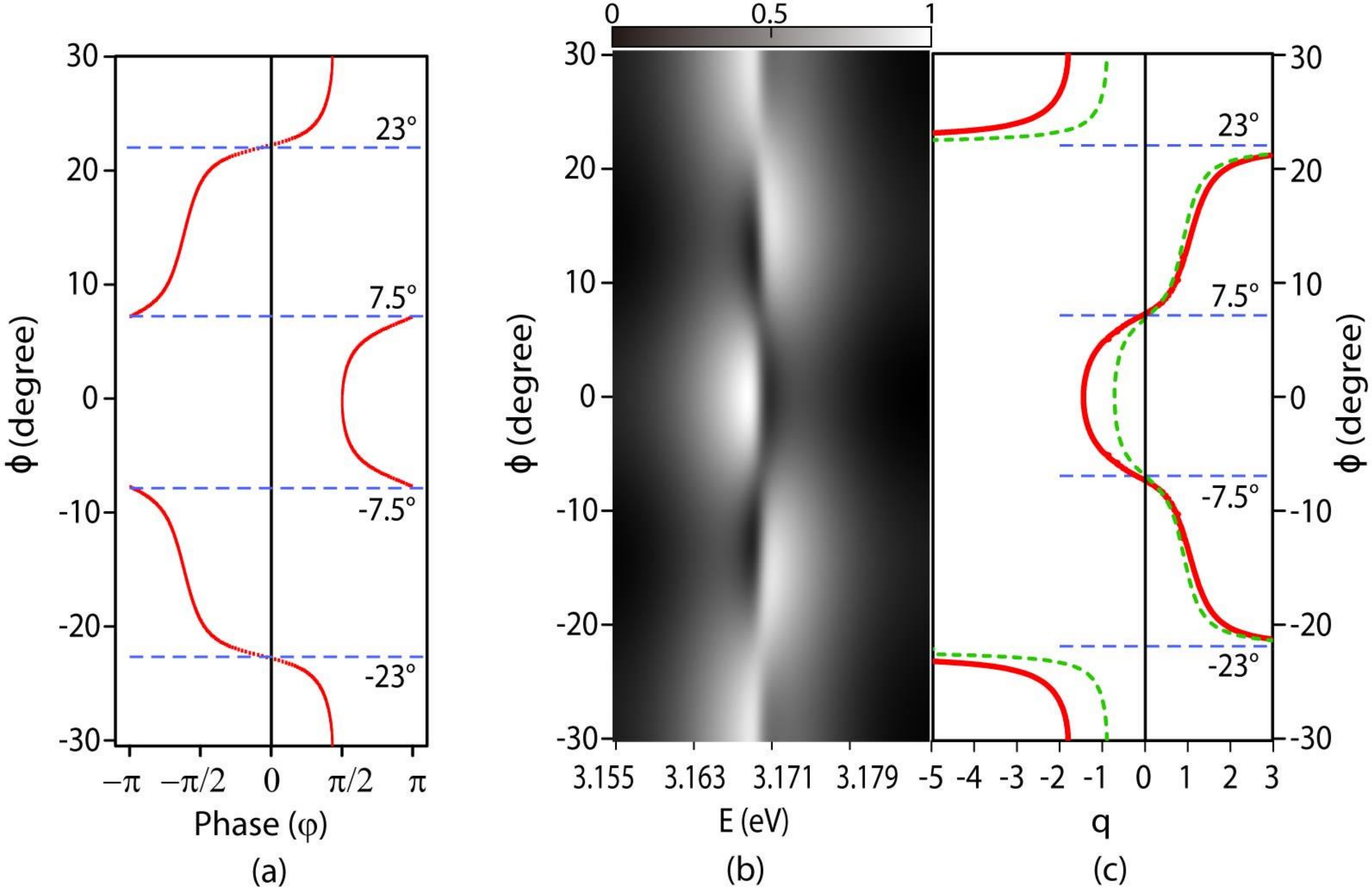


Fano



× 10³
0
0.5
1
1.5
2
30
20
10
0
-10
-20
-30
φ (degree)
3.155
3.163
3.171
3.179
E (eV)
(a)
25.5°
7.7°
-8.3°
-24.7°
-5
-4
-3
-2
-1
0
1
2
3
q
(b)
27° q=-4.2
15° q=1.4
7.7° q=0.02
0° q=-0.56
-8.3° q=0.1
-15° q=1.51
-27° q=-3.8
SHG Intensity (a.u.)
3.147
3.163
3.179
3.195
E (eV)
(c)


(a)
-2
-1
0
1
2
5
2.5
0
-2.5
-5
y (μm)
-5
-2.5
0
2.5
5
x (μm)
(b)
0
0.5
1
20
10
0
-10
-20
k_y (μm^{-1})
-20
-10
0
10
20
k_x (μm^{-1})
-23°
-7.5°
7.5°
23°
FFT

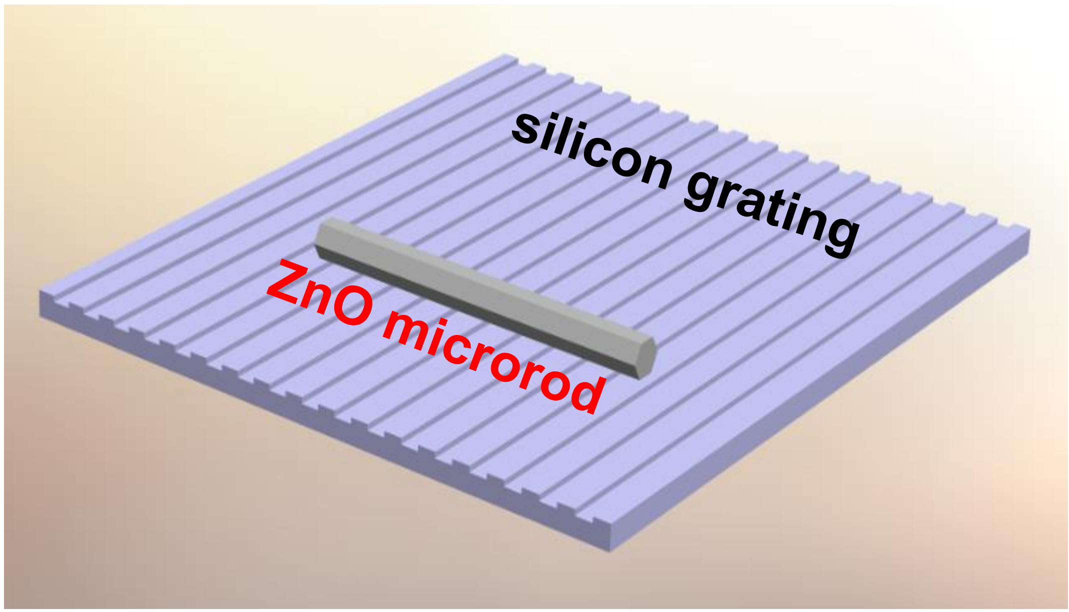


$$I_\omega = |E(\omega)|^2 \propto \left[\frac{A_P{}^2}{\Gamma_P{}^2(1+\varepsilon_P{}^2)} + \frac{A_S{}^2}{\Gamma_S{}^2(1+\varepsilon_S{}^2)} + 2\frac{A_P A_S}{\Gamma_P \Gamma_S} \frac{(1+\varepsilon_P\varepsilon_S)\cos\varphi + (\varepsilon_P - \varepsilon_S)\sin\varphi}{(1+\varepsilon_P{}^2)(1+\varepsilon_S{}^2)} \right]$$

YF Wang, ZH Chen et al, *Phys. Rev. Lett.* 118, 063602 (2017)

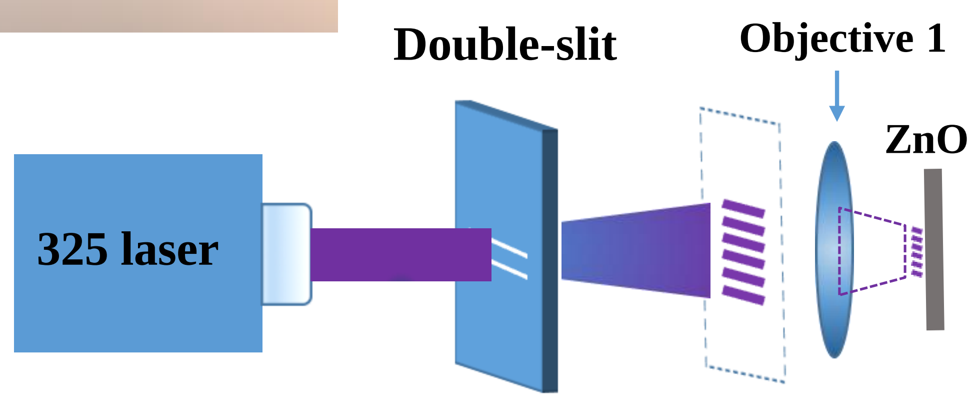
- **Band engineering on polaritonic systems?**
- **Condensate in a modulated structure**

Introducing a periodic potential in the 1D ZnO polariton system

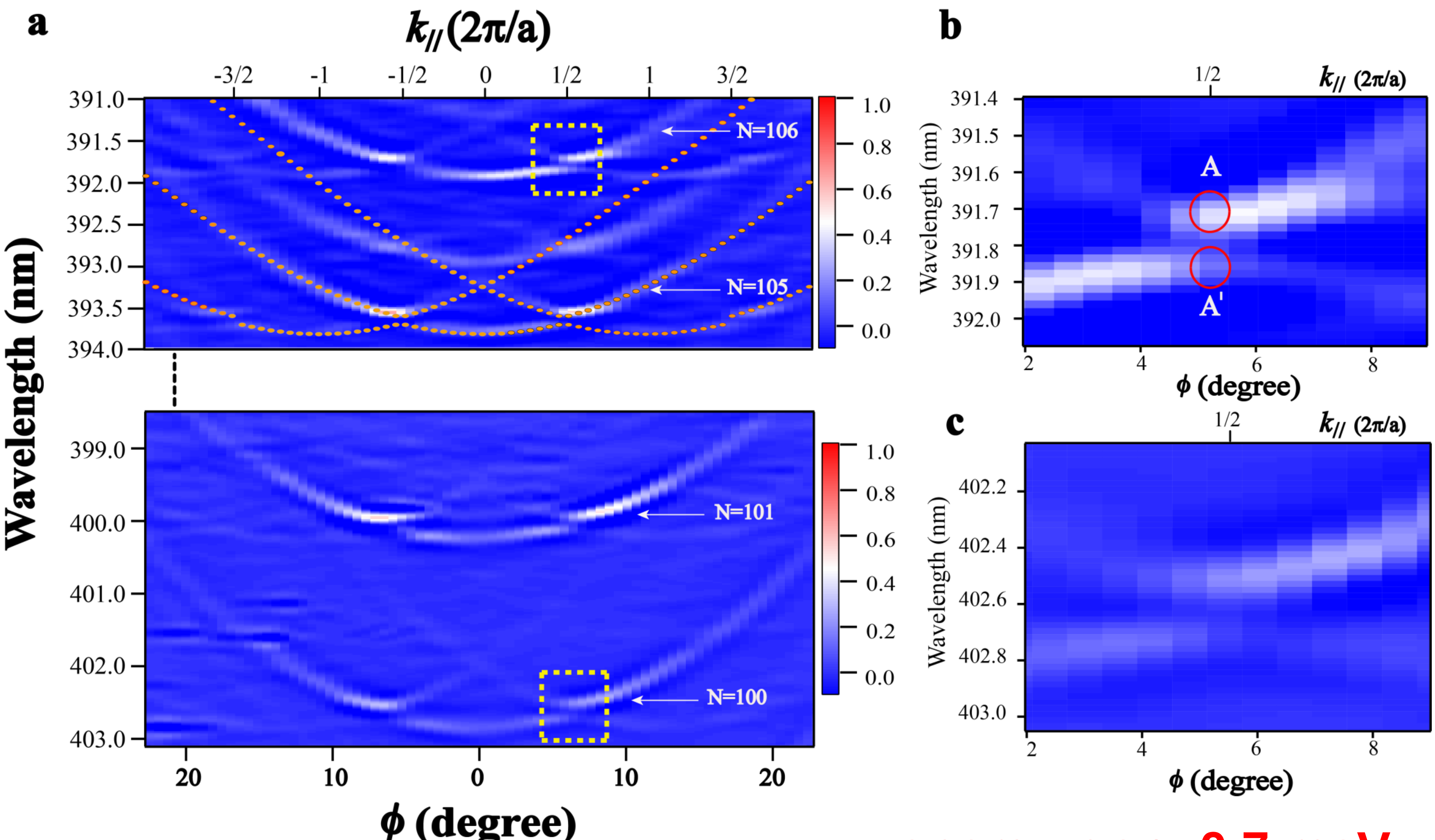


micro assembling

Optical lattice

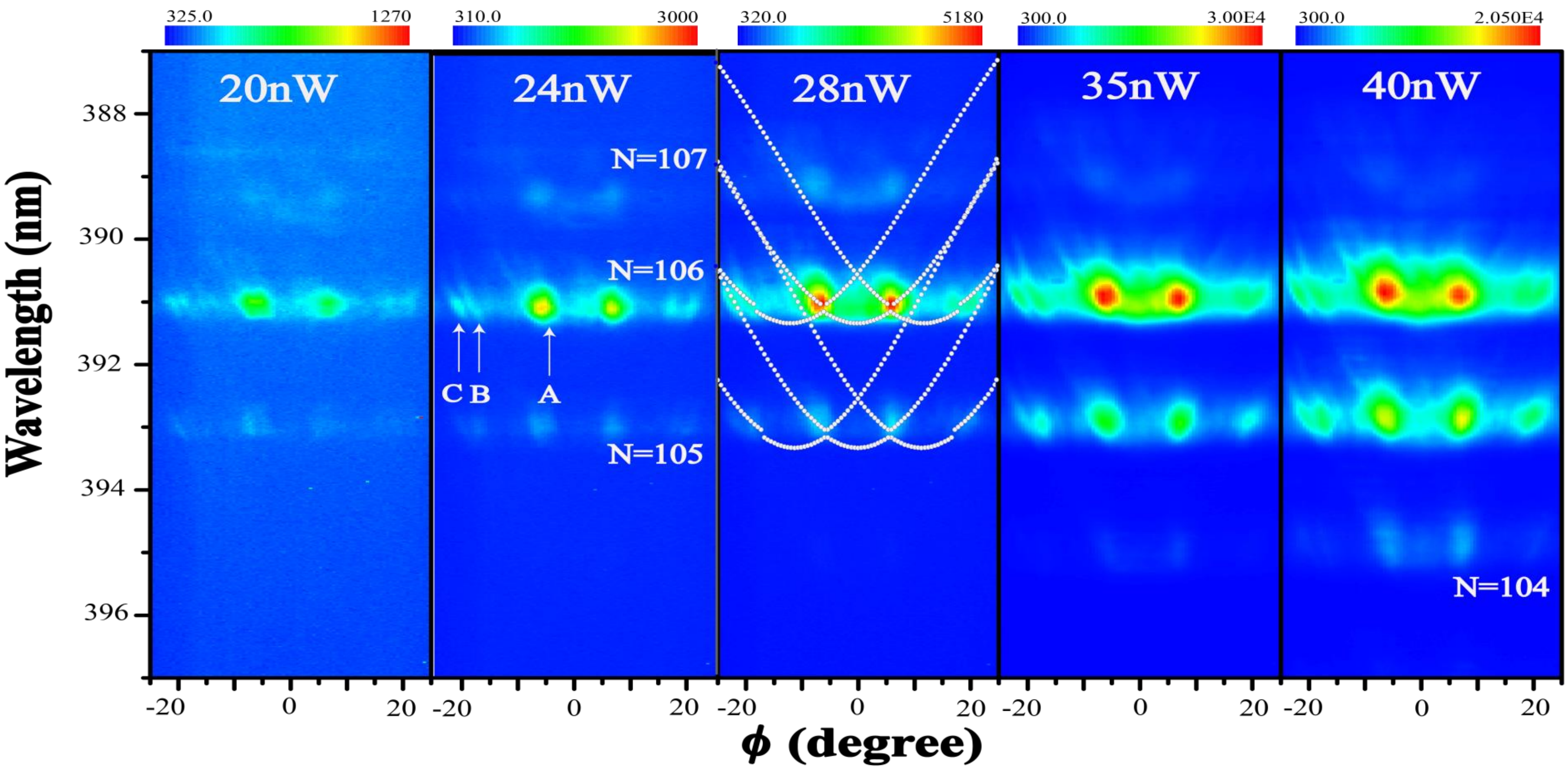


Band structure of the polaritonic crystal:



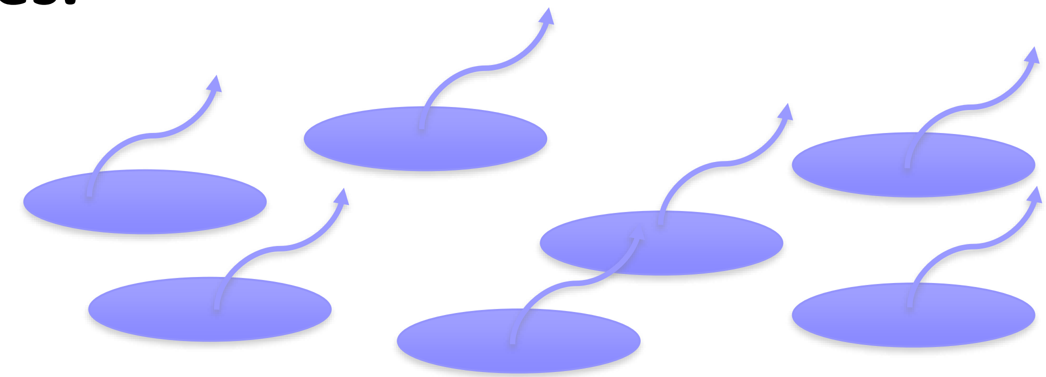
energy gap: 0.7 meV

Polariton condensates at π states

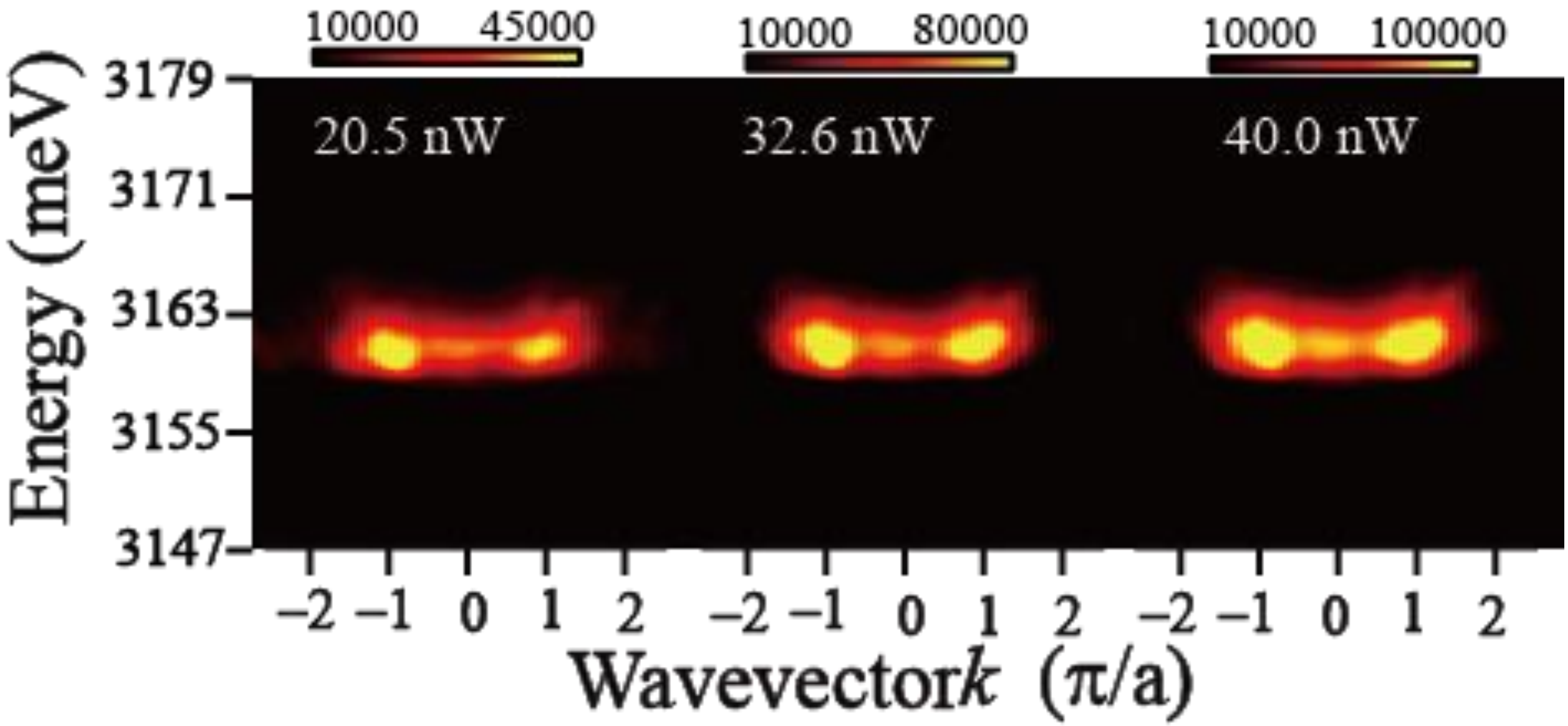


"Weak lasing" of polariton

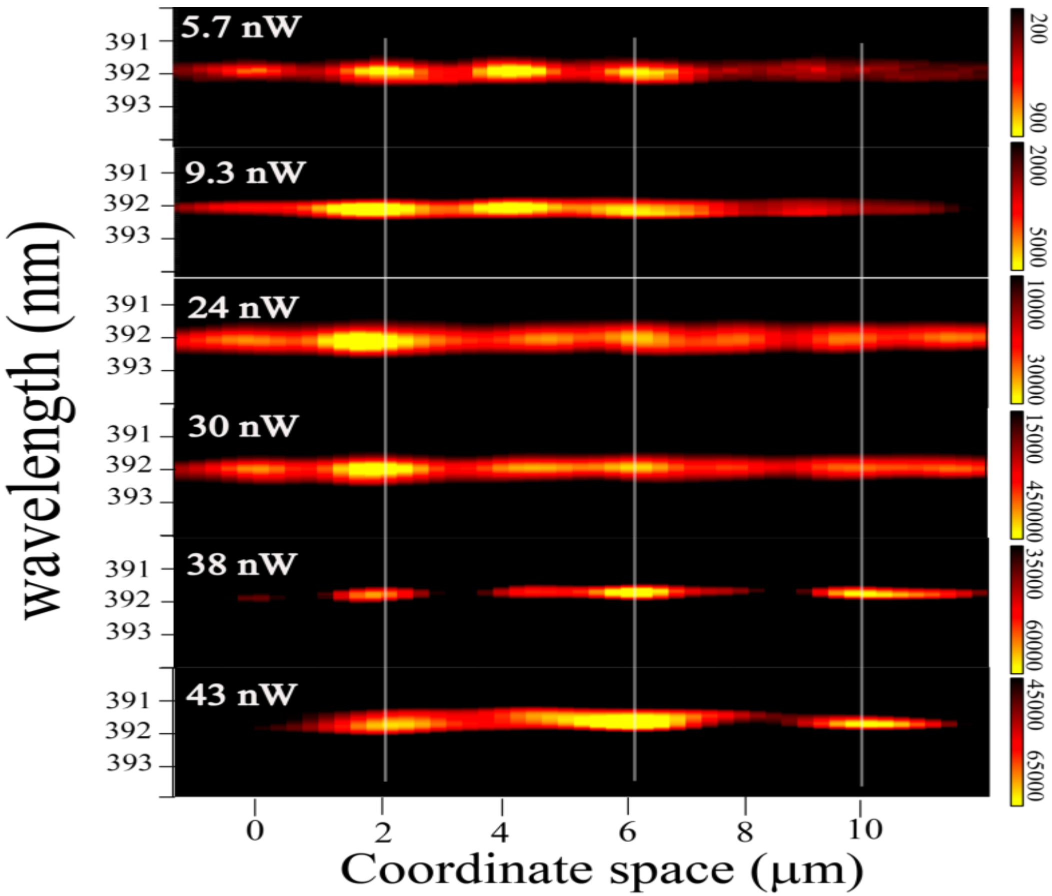
"Weak lasing" represents a particular phase in a dissipative bosonic system. It is characterized by a spontaneous phase-locking and self-organisation of localized bosonic condensates which minimizes the dissipation losses and favors the build-up of the condensates.



Polariton condensates in k-space



Polariton condensates distribution in real space



L Zhang, A. Kavokin, Y. Rubo, ZH Chen, et al, *PNAS* 1502666112 (2015)

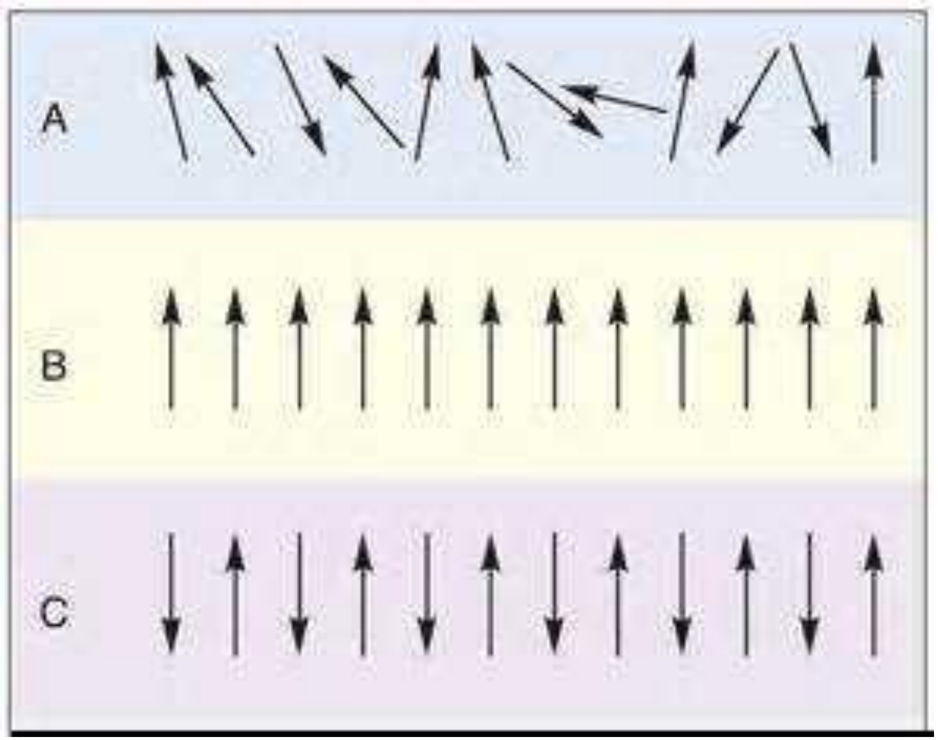
EXCITONICS

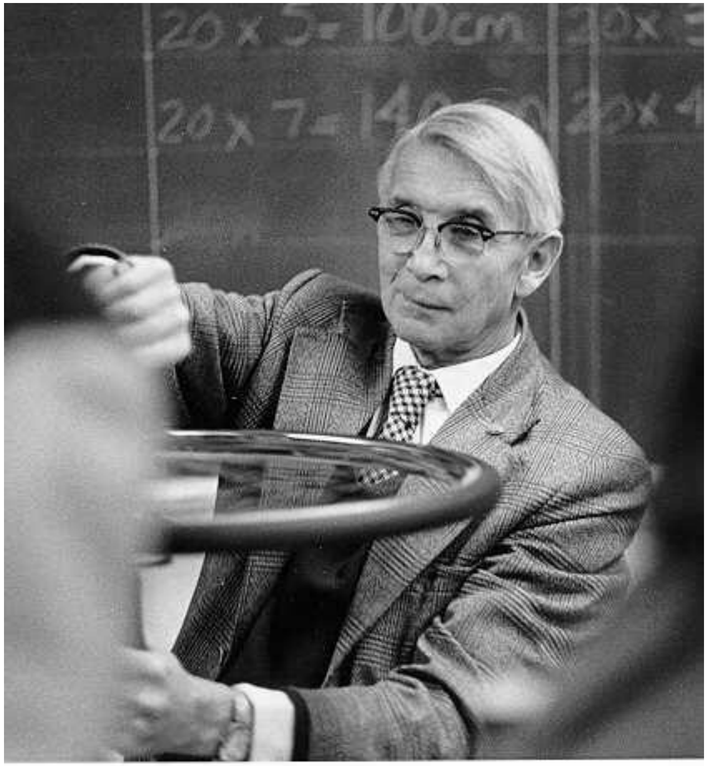
Weak lasing

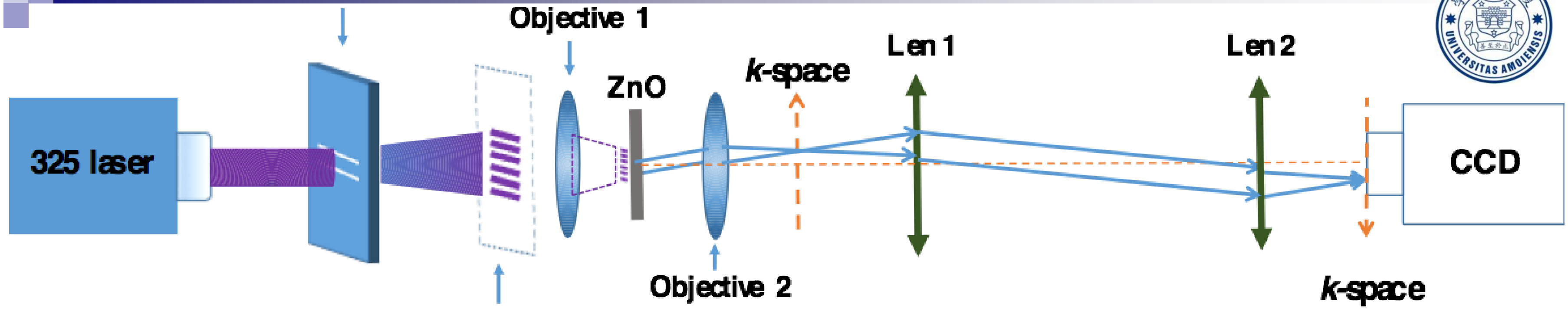
Proc. Natl Acad. Sci USA 112, E1516–E1519 (2015)

Polaritons in periodic potentials are useful for understanding the physics of many-body systems and exploring applications in optoelectronics. Recent experiments by Long Zhang, Wei Xie and an international collaboration from China, Russia, Mexico, the USA and the UK suggest that an effect known as weak lasing in one-dimensional polaritons in superlattices has now been observed at room-temperature. A structure with one-dimensional periodicity was made by laying a ZnO microrod of hexagonal cross-section onto silicon corrugated with 1-μm-wide channels, with a period of 2 μm. The ZnO rod forms a whispering-gallery mode resonator for the exciton-polaritons, subject to a periodic potential along the length of the wire due to the adjacent structured silicon. Photoluminescence was used to investigate the structure when optically pumped at room temperature. Long-range phase coherence was observed and for strong pumping the spatial period of the condensate is twice that of the superlattice period. The authors state that previous work using GaAs did not confirm the period-doubling feature of weak lasing and they suggest that ZnO may yield more robust weak lasing. *DP*

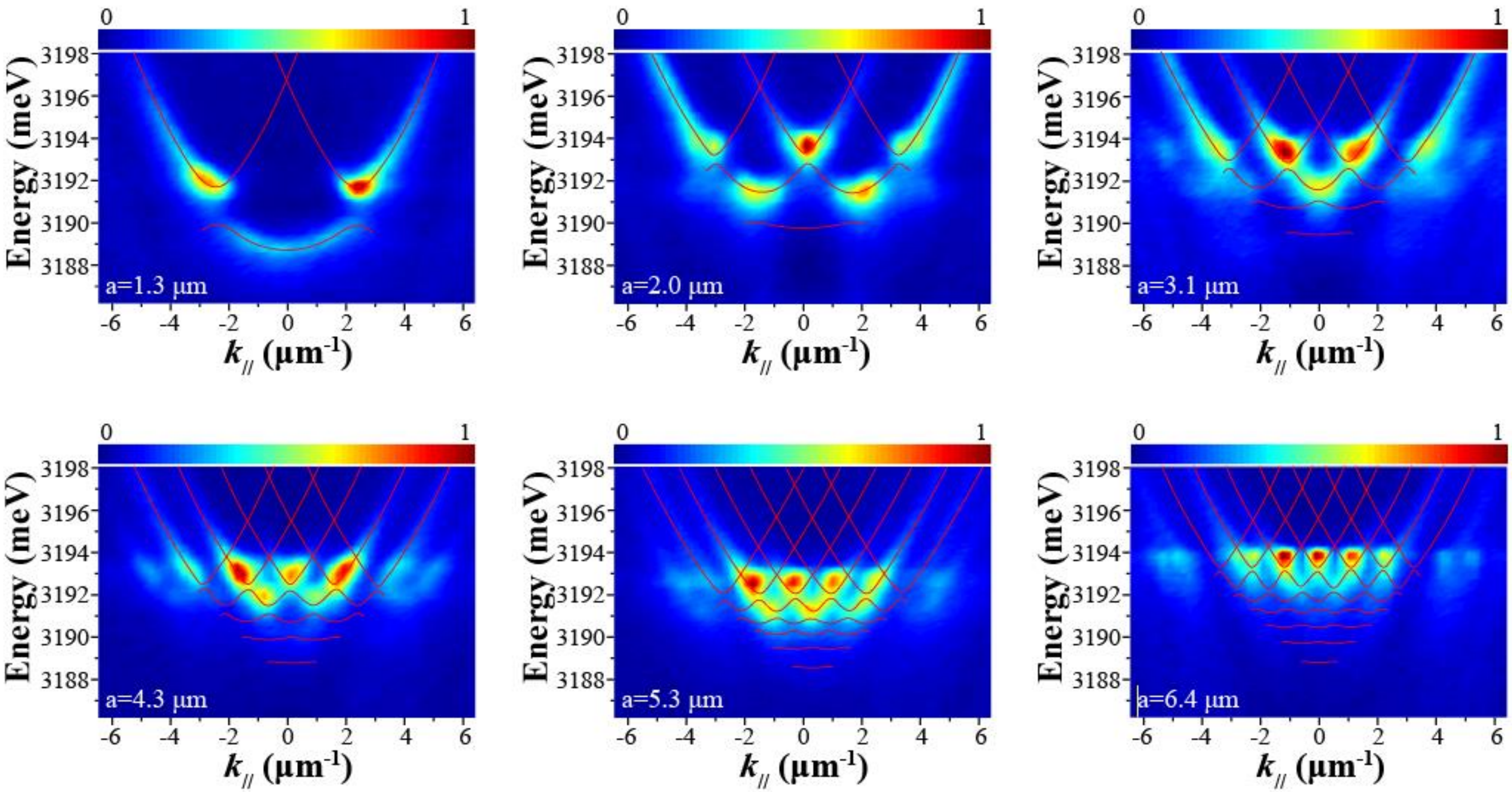
1D Ising model---quantum simulation







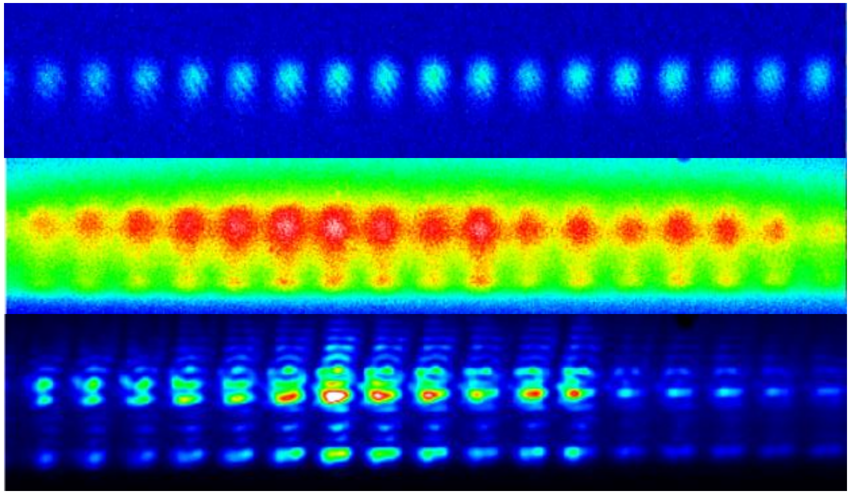
Objective 1
ZnO
k-space
Len1
Len2
325 laser
CCD
Objective 2
k-space

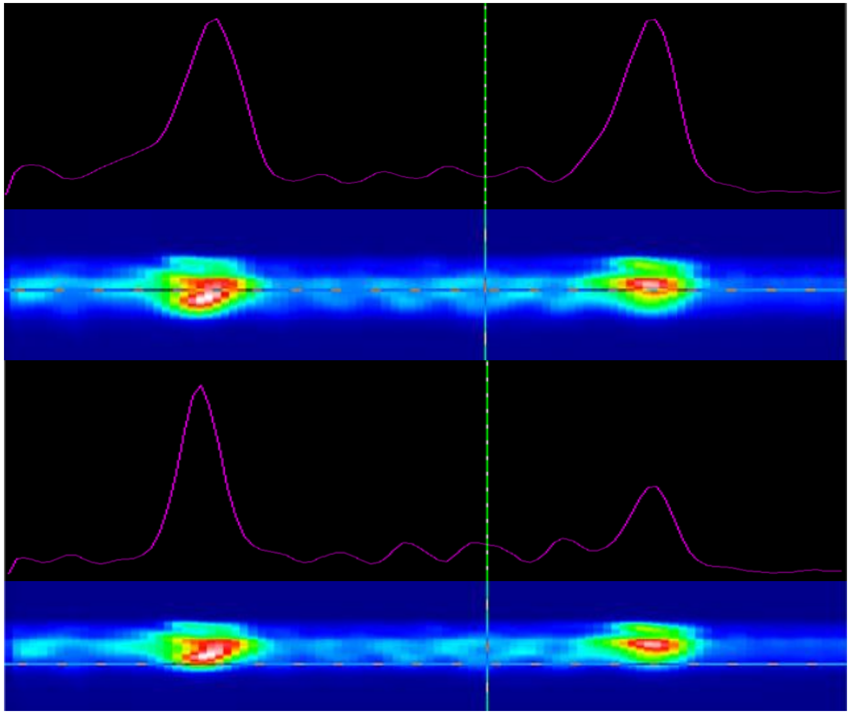


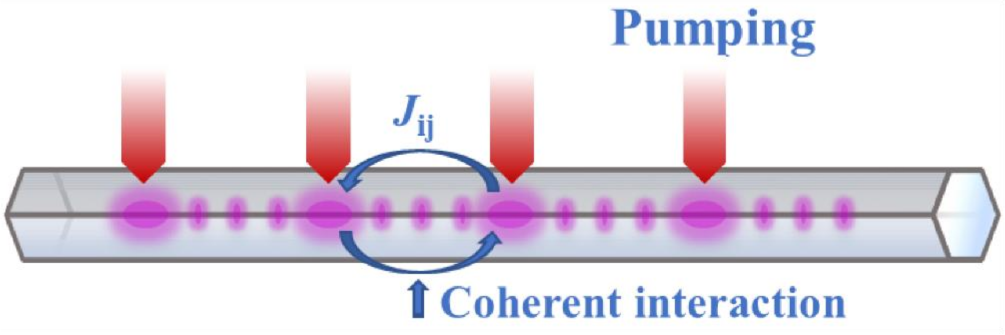
Energy (meV)
$k_{//}$ (μm^{-1})
a=1.3 μm
a=2.0 μm
a=3.1 μm
a=4.3 μm
a=5.3 μm
a=6.4 μm

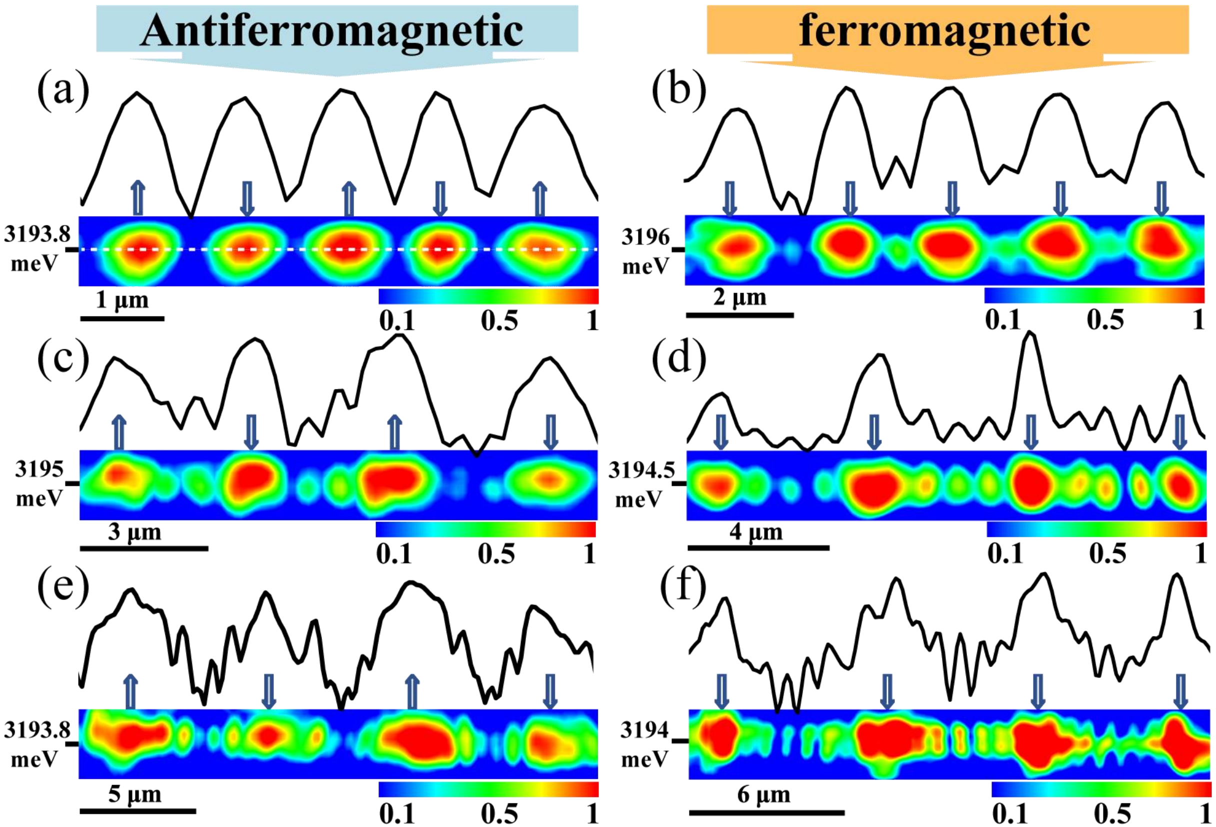
Ising chain of polariton condensates

Real space









Spin

Phase

Spin-Spin interaction

Phase coupling

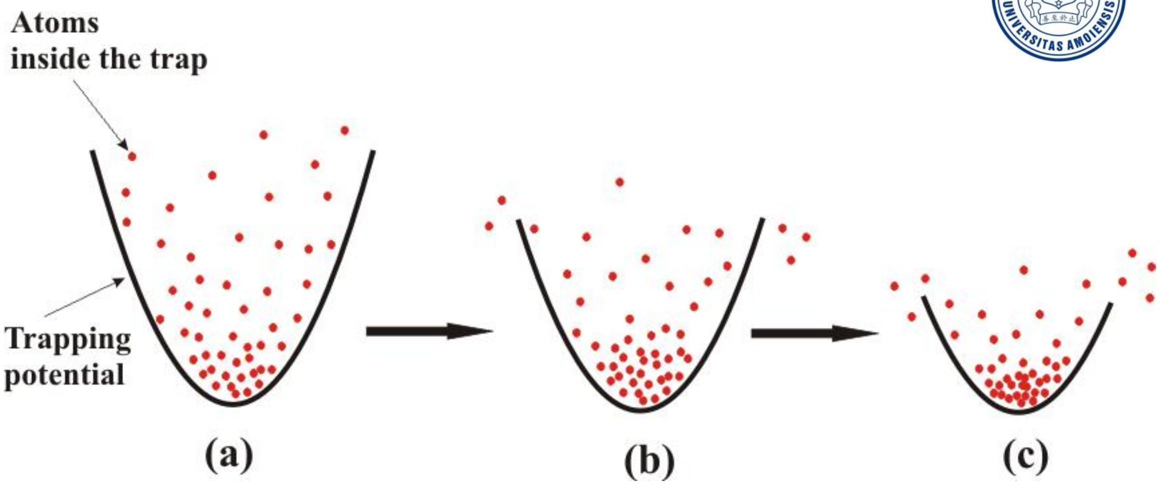
$$J_{ij} = \int_0^\infty |\psi_x|^2 J_0(kd_{ij})\, k\mathrm{d}k$$

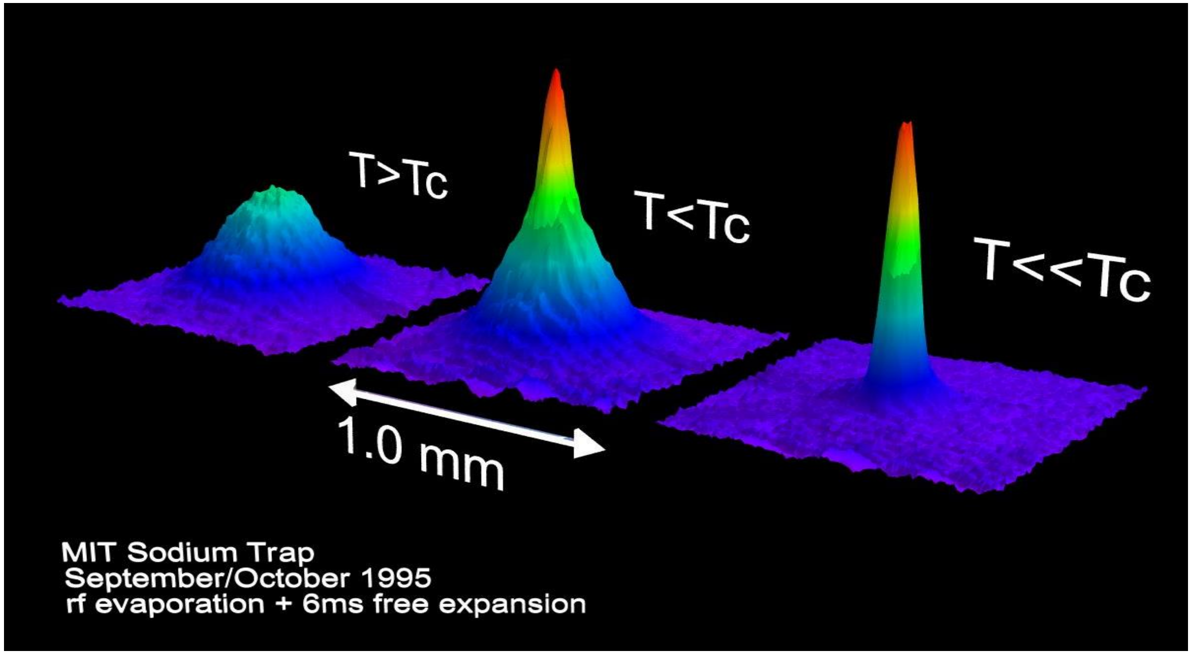
Polaritons condense into the minimum of Ising Hamiltonian:

$$H = -\sum_{ij} J_{ij} s_i s_j = -\sum_{ij} J_{ij} \cos(\theta_i - \theta_j)$$

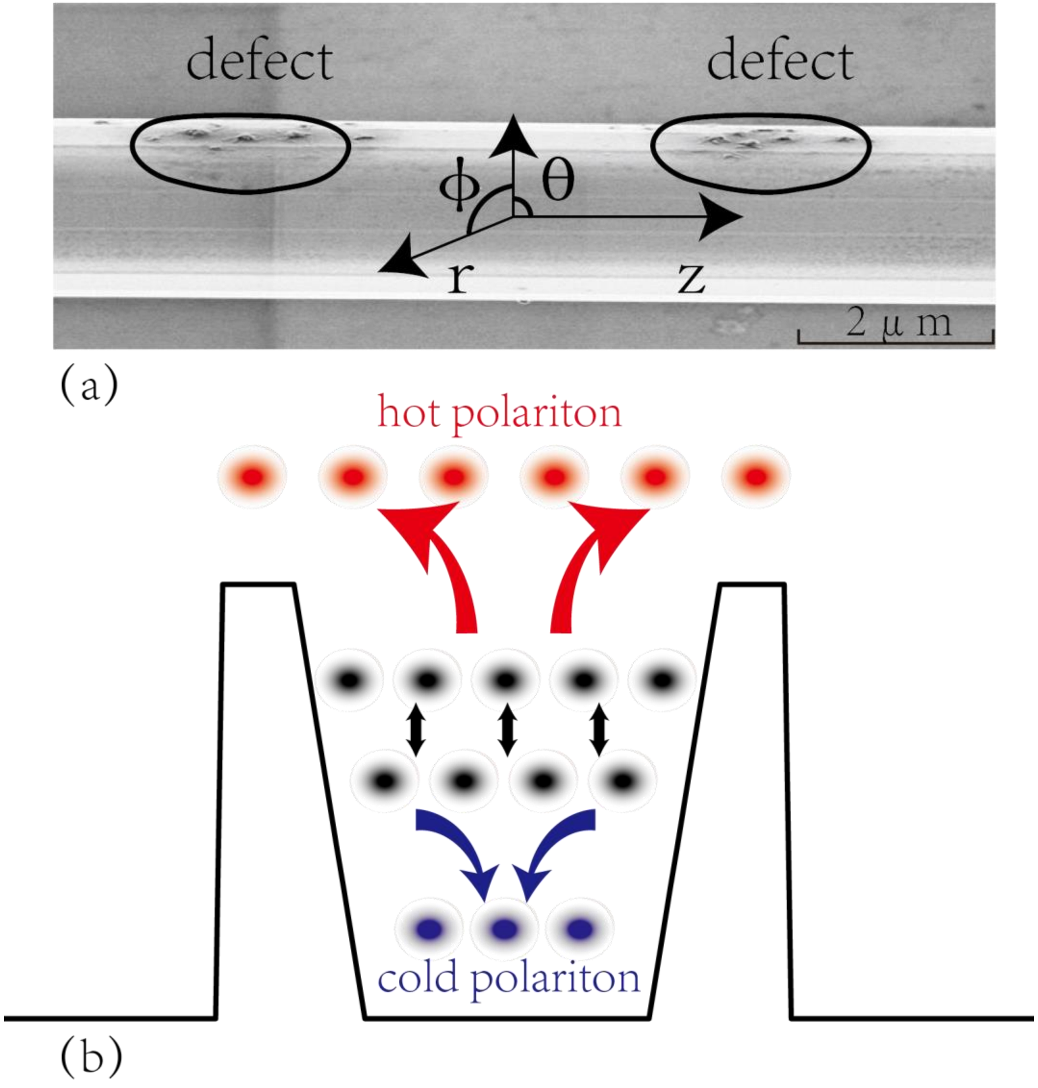
Song Luo, ZH Chen et al, *Phys. Rev. Applied* **13**, 044052 (2020)

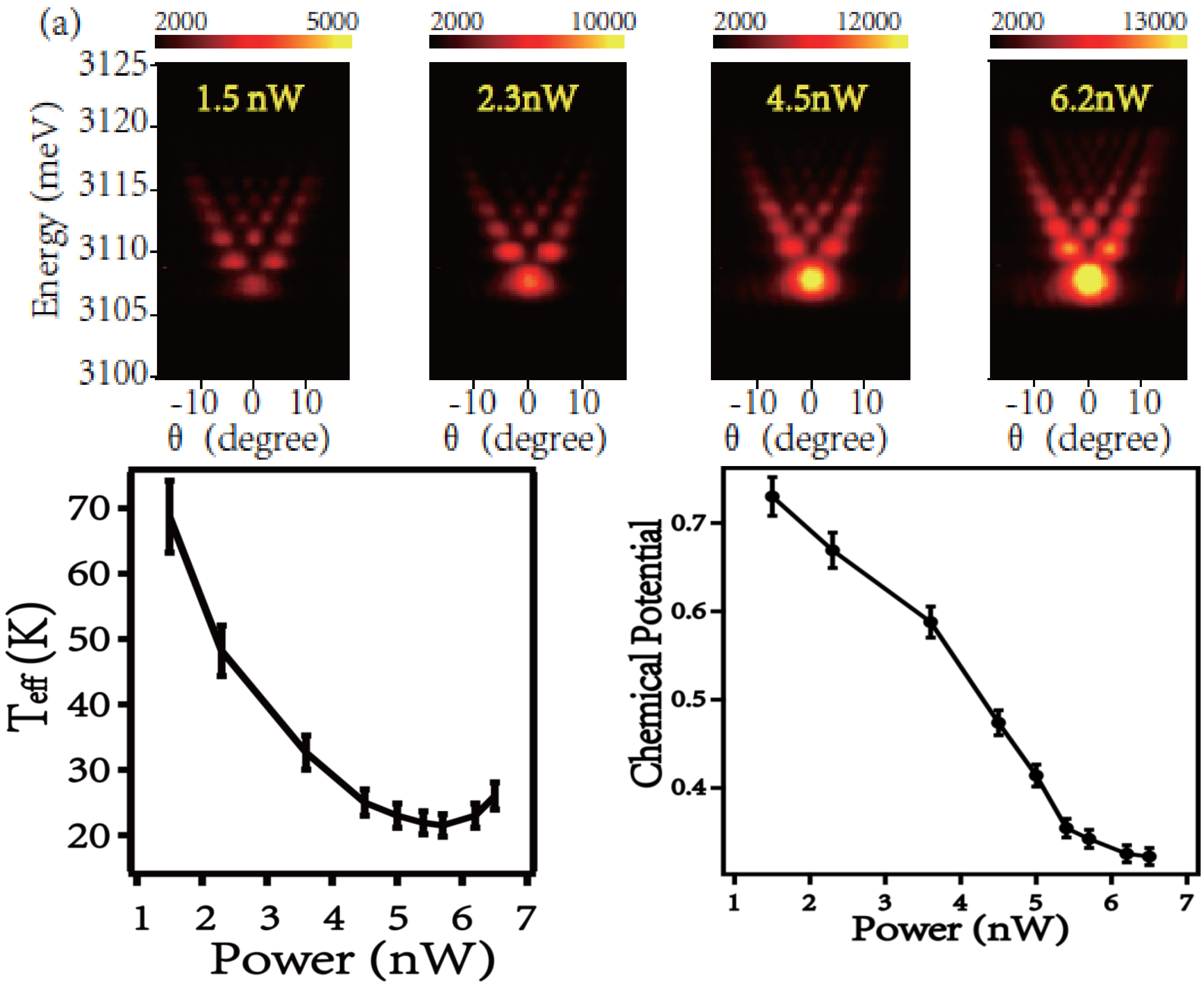
Evaporative cooling of cold atoms

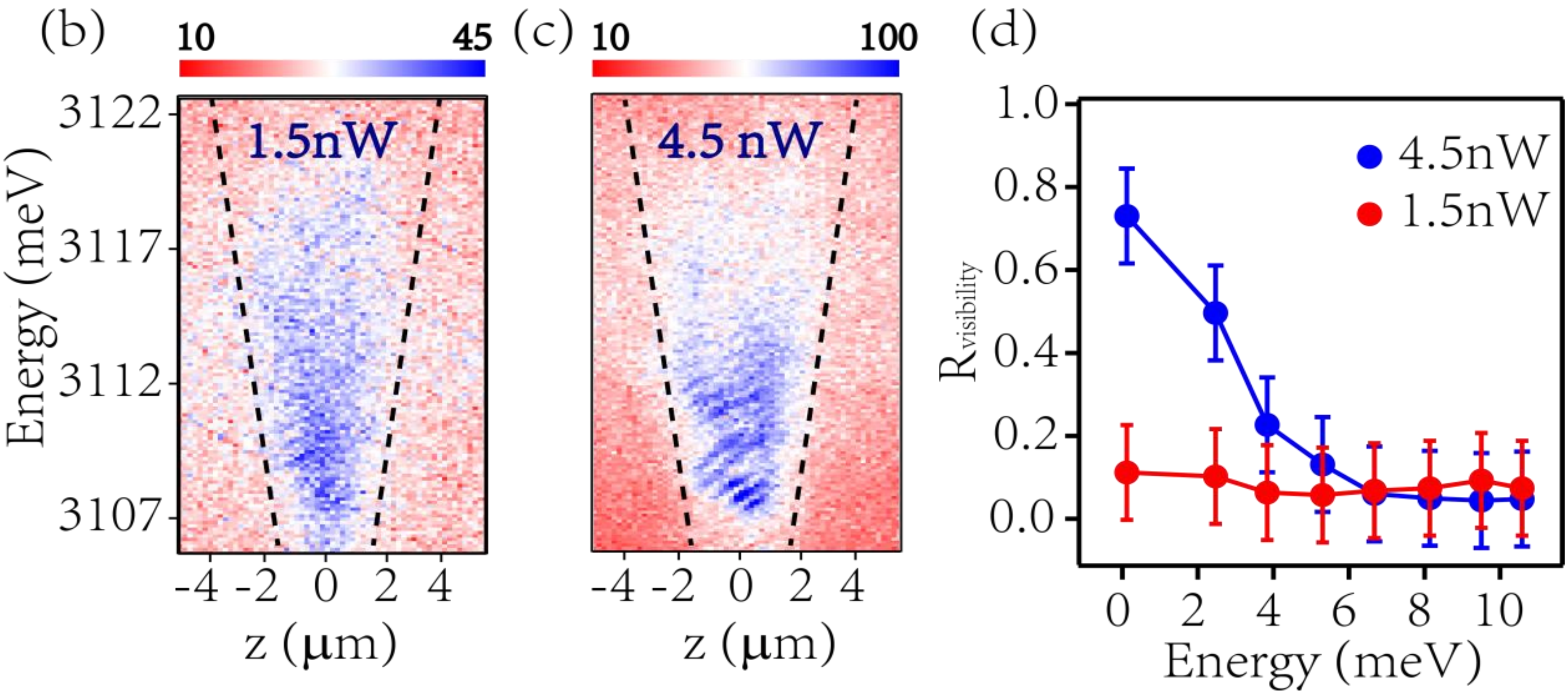




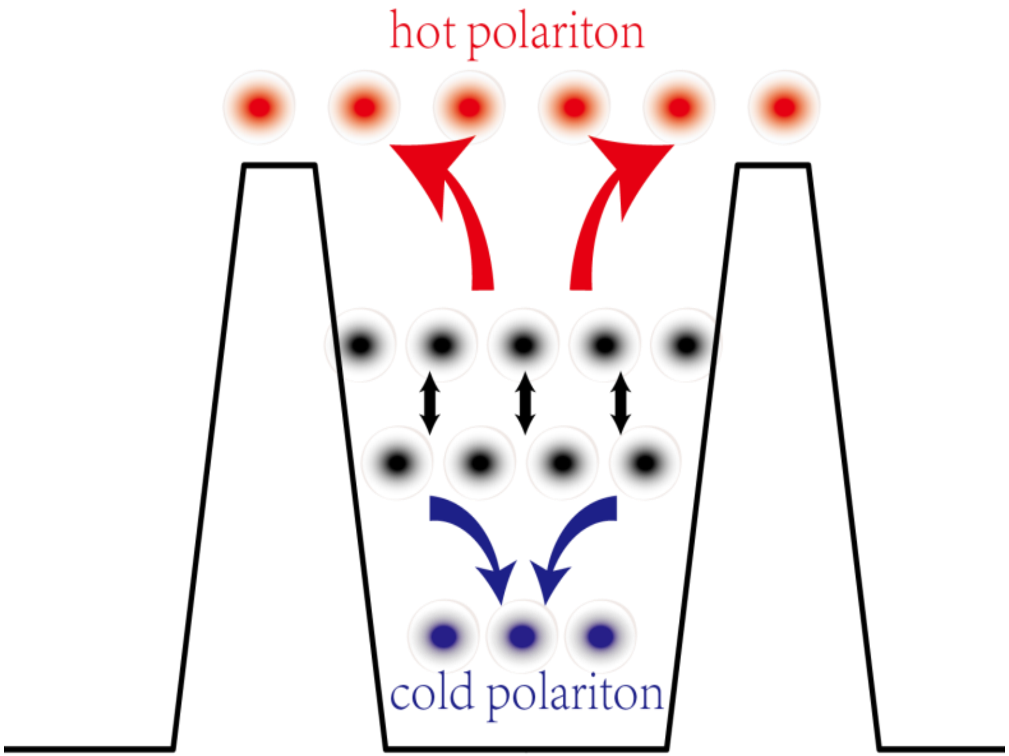
3D confined trap for polaritons

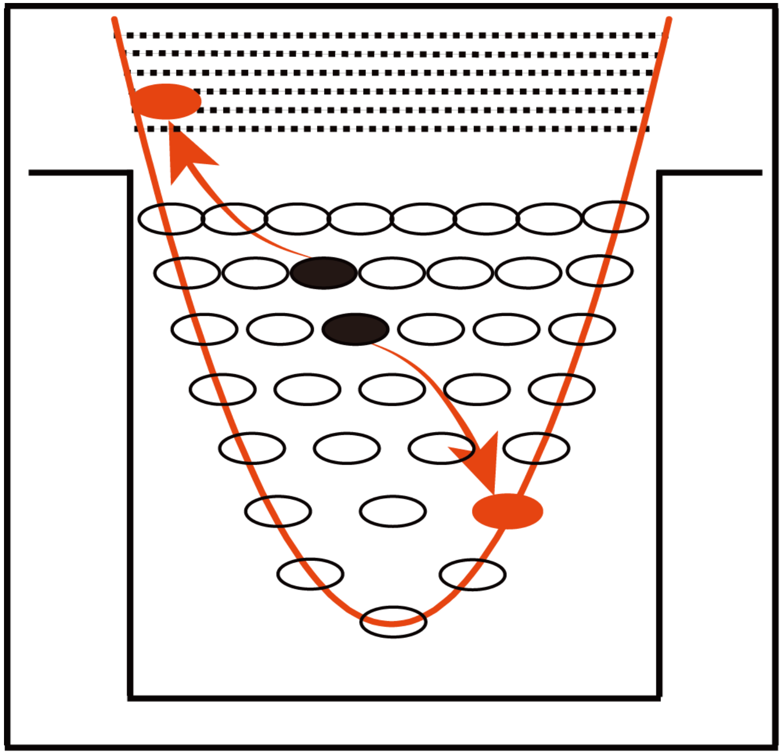



(a)
2000
5000
10000
12000
13000
1.5 nW
2.3nW
4.5nW
6.2nW
Energy (meV)
3125
3120
3115
3110
3105
3100
-10 0 10
θ (degree)
T_{eff} (K)
70
60
50
40
30
20
1 2 3 4 5 6 7
Power (nW)
Chemical Potential
0.7
0.6
0.5
0.4


(b)
10
45
1.5nW
3122
3117
3112
3107
Energy (meV)
-4 -2 0 2 4
z (μm)
(c)
10
100
4.5 nW
-4 -2 0 2 4
z (μm)
(d)
4.5nW
1.5nW
1.0
0.8
0.6
0.4
0.2
0.0
R_visibility
0 2 4 6 8 10
Energy (meV)

Cooling mechanism?





Semiclassical Boltzmann rate equation

$$\frac{\partial n_{\mathrm{R}}}{\partial t} = P - \Gamma_{\mathrm{R}} n_{\mathrm{R}} - \sum_{\mathrm{N,k}} x \;\; A n_{\mathrm{R}}{}^{2} + B_{\mathrm{N}} n_{\mathrm{R}} \;\; n_{\mathrm{N,k}} +$$

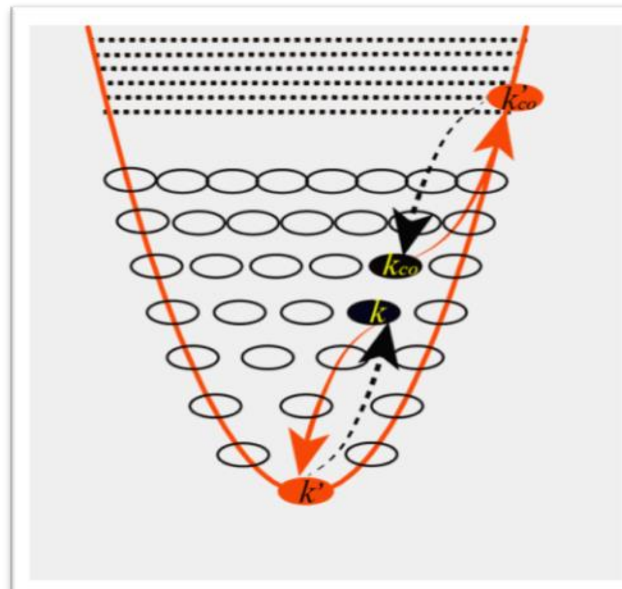
$$\frac{\partial n_{\mathrm{N,k}}}{\partial t} = x\left(A n_{\mathrm{R}}{}^{2} + B_{\mathrm{N}} n_{\mathrm{R}}\right)\left(n_{N,k} + 1\right) - \Gamma_{\mathrm{N,k}} n_{\mathrm{N,k}}$$

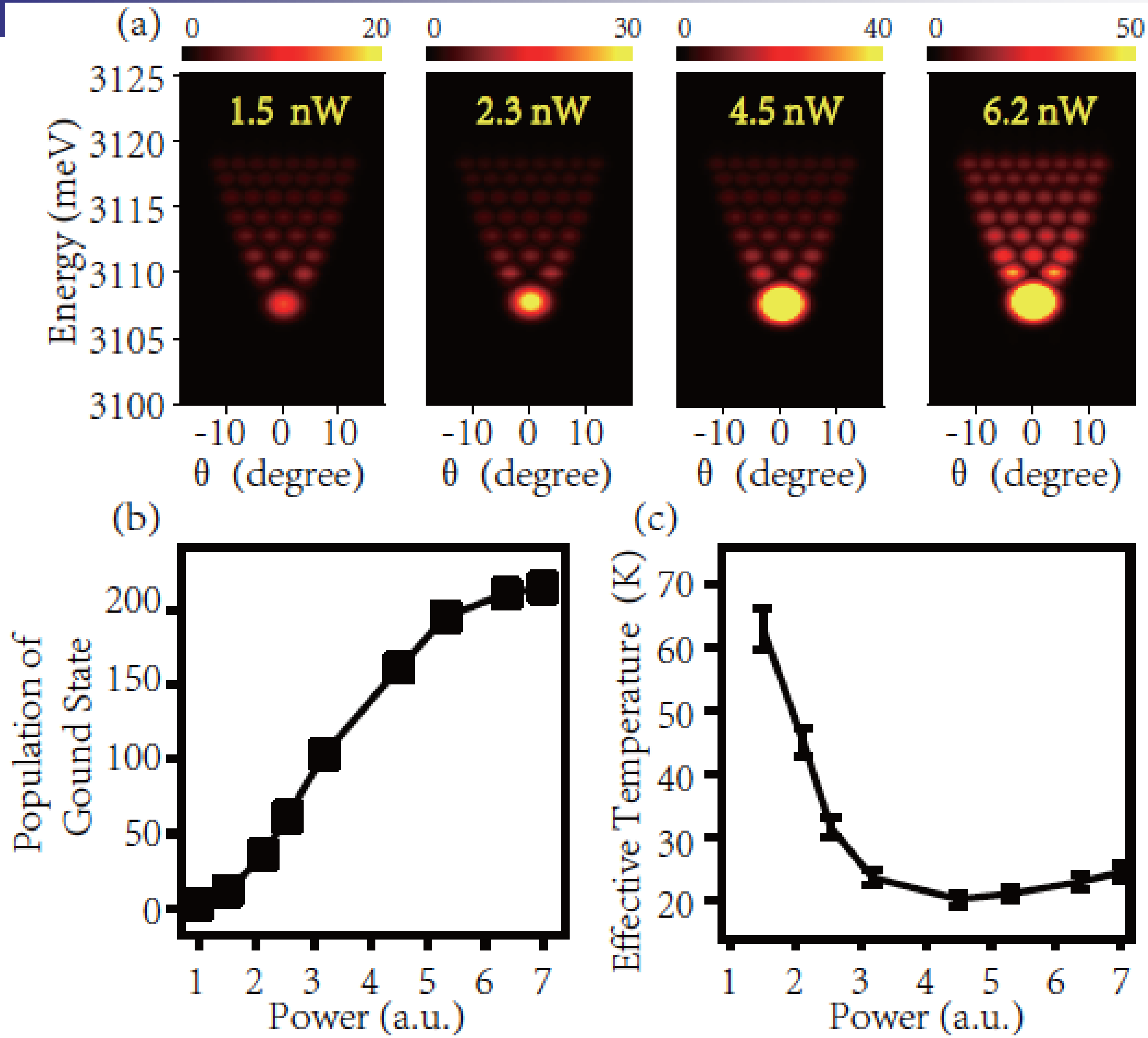
$$-n_{\mathrm{N,k}} \sum_{\mathrm{N}',\mathrm{k}'} W_{\substack{N \to \mathrm{N}' \\ k \to \mathrm{k}'}} \left(n_{\mathrm{N}',\mathrm{k}'} + 1\right) + \left(n_{\mathrm{N,k}} + 1\right) \sum_{N'\mathrm{k}'} W_{\substack{\mathrm{N}' \to N \\ \mathrm{k}' \to k}} n_{\mathrm{N}',\mathrm{k}'}$$

$$n_{\mathrm{N,k}} \sum_{\mathrm{N}',\mathrm{k}'} W_{\substack{N \to \mathrm{N}' \\ k \to \mathrm{k}'}} \left(\mathrm{n}_{\mathrm{N}',\mathrm{k}'} + 1\right)$$

$$= \sum_{\mathrm{N}',\mathrm{N_{co}},\mathrm{k}',\mathrm{k}'_{\mathrm{co}}} A x^{4} n_{\mathrm{N,k}} n_{\mathrm{N_{co}},\mathrm{k}'+\mathrm{k}'_{\mathrm{co}}-\mathrm{k}} \;\; n_{\mathrm{N}',\mathrm{k}'} + \;\; n_{\mathrm{N}'_{\mathrm{co}},\mathrm{k}'_{\mathrm{co}}} +$$

$$\times\delta\left(E_{\mathrm{N}} + E_{\mathrm{N_{co}}} \;\; E_{\mathrm{N}'} + E_{\mathrm{N}'_{\mathrm{co}}}\right)$$

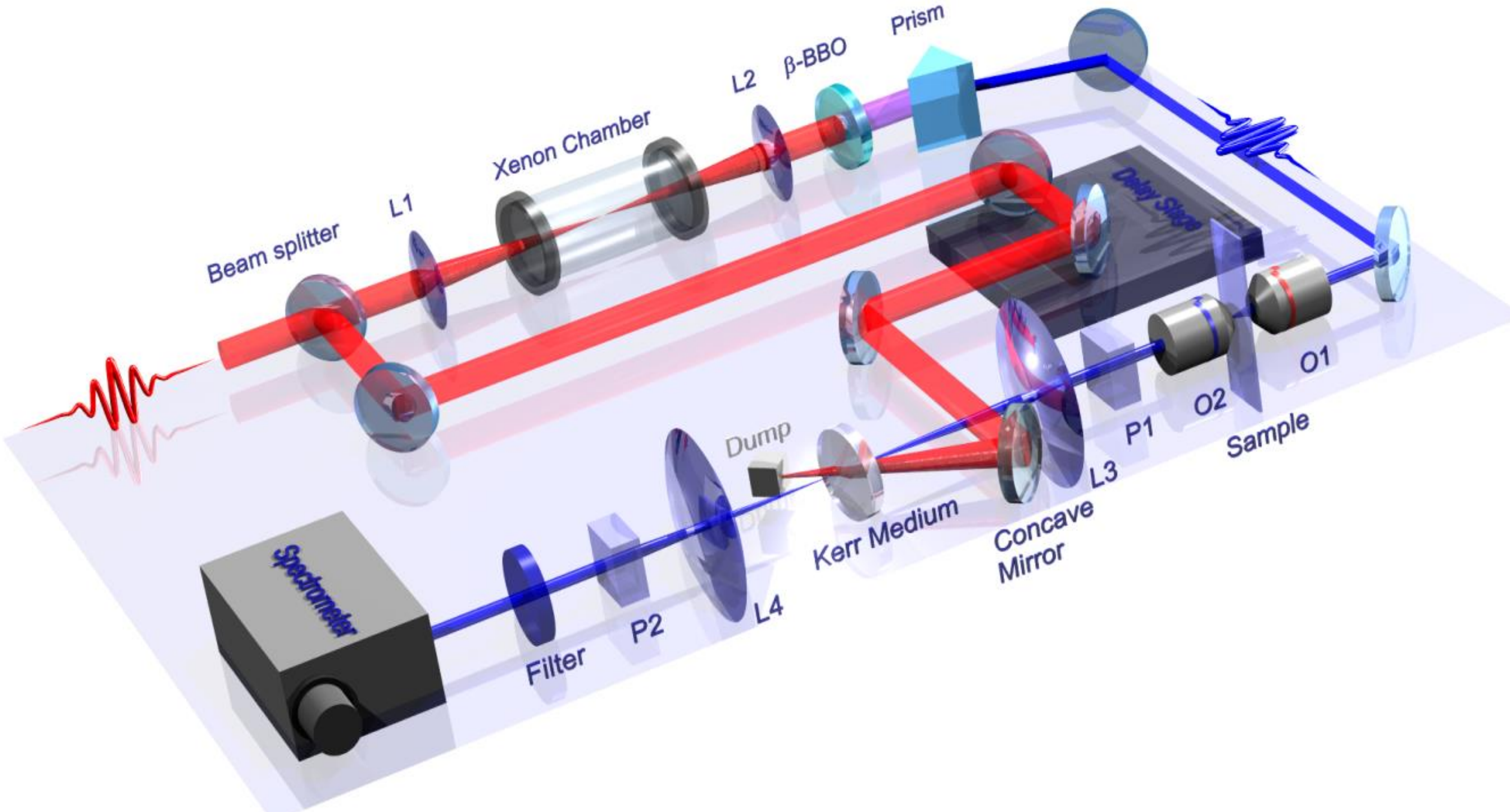




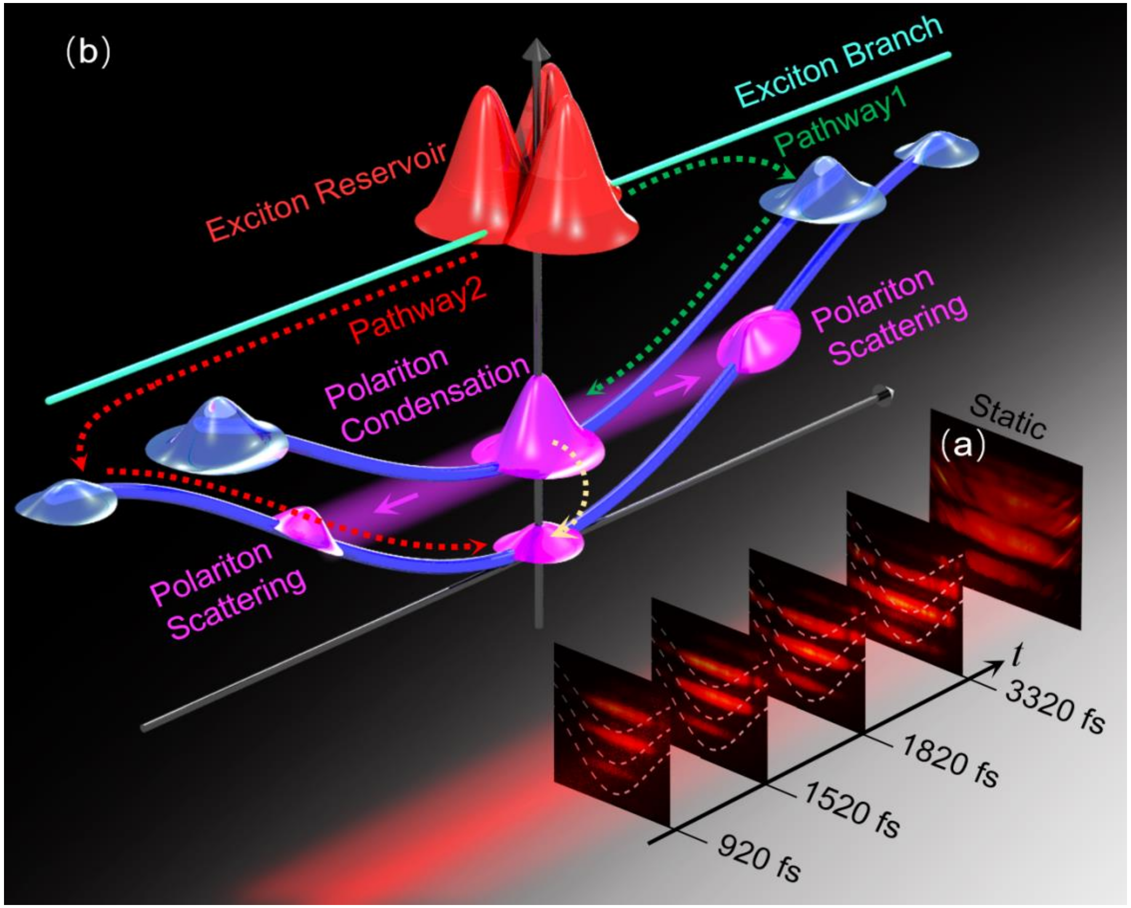
J Wang, ZH Chen et al, Phys. Rev. B 91, 165423 (2015)

Untrafast dynamics of exciton polaritons

Ultrafast dynamics of exciton polariton condensate has never been revealed before

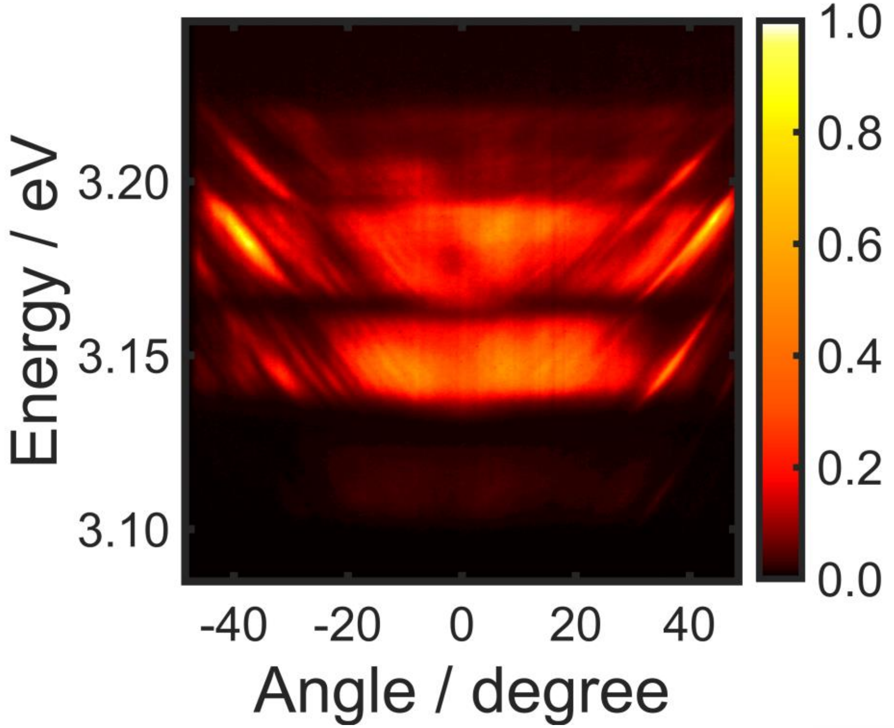


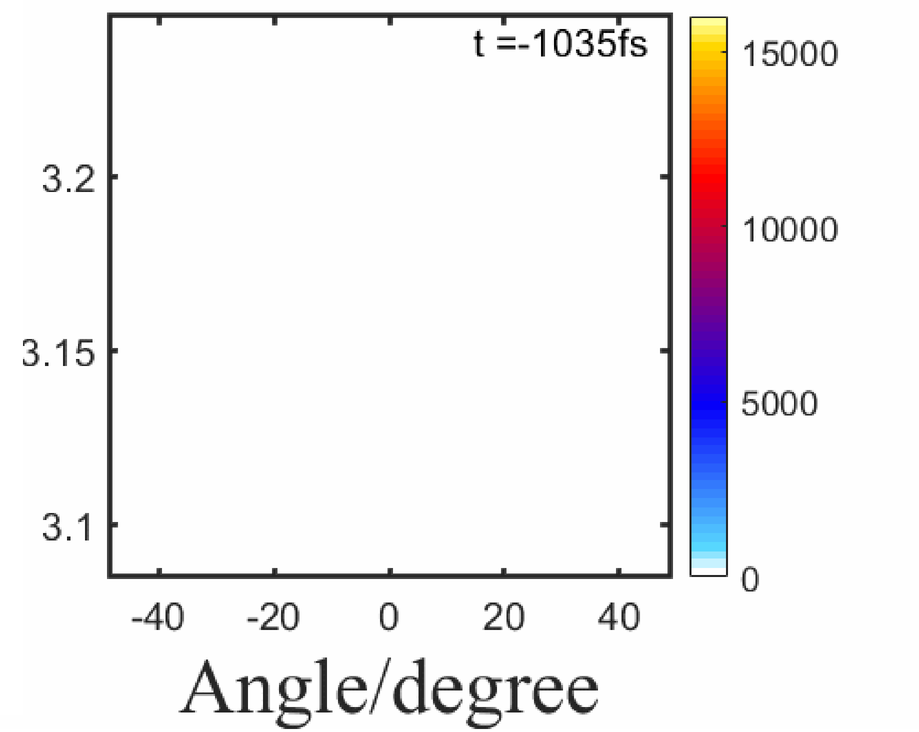
Bosonic cascade lasing of polarition in ZnO



Schematic illustration of polariton dynamics in a Bosonic cascade.

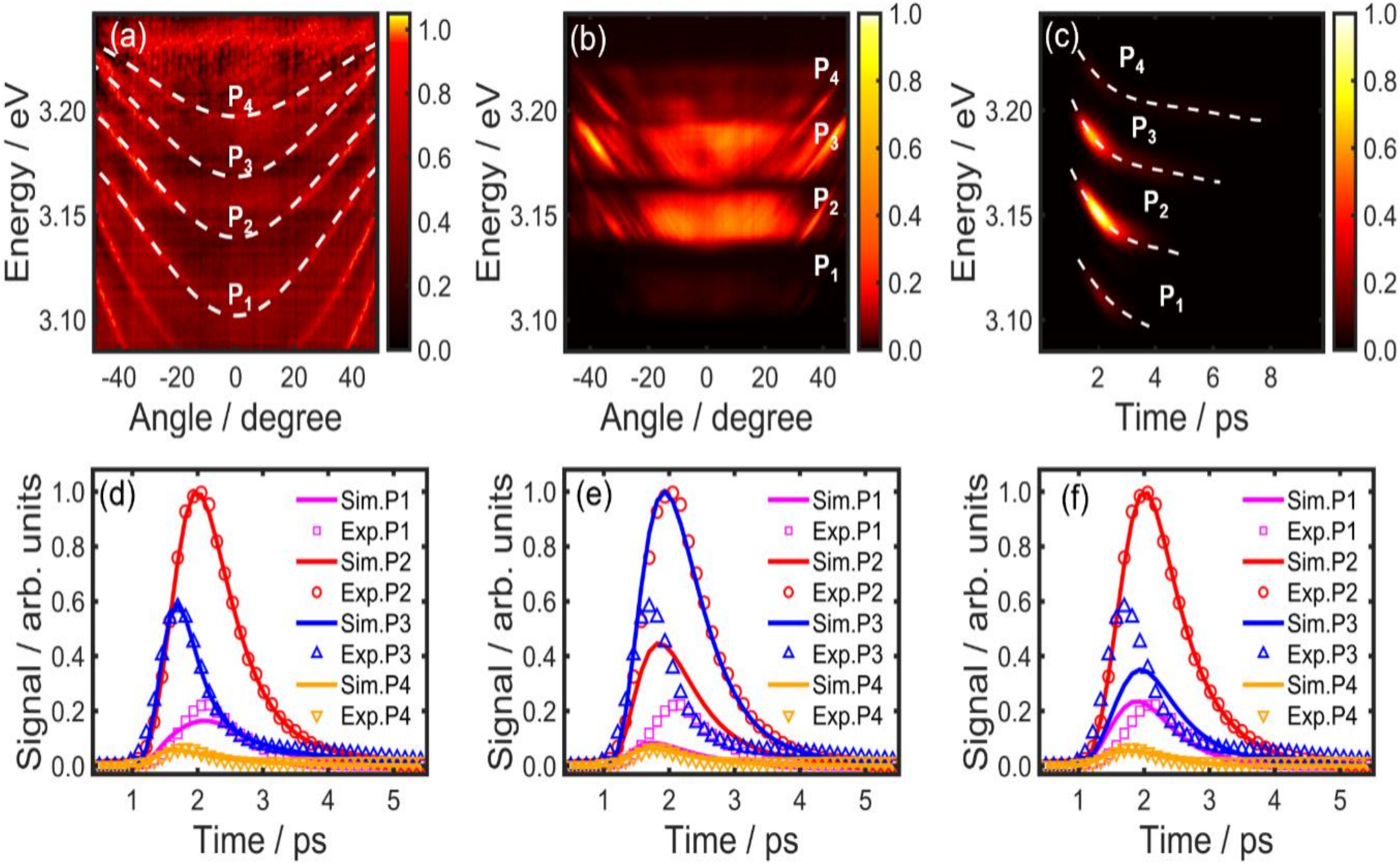
Time lapes of exciton polariton dynamics at room temperature





Time integrated **Time lapse in femtosec scale**

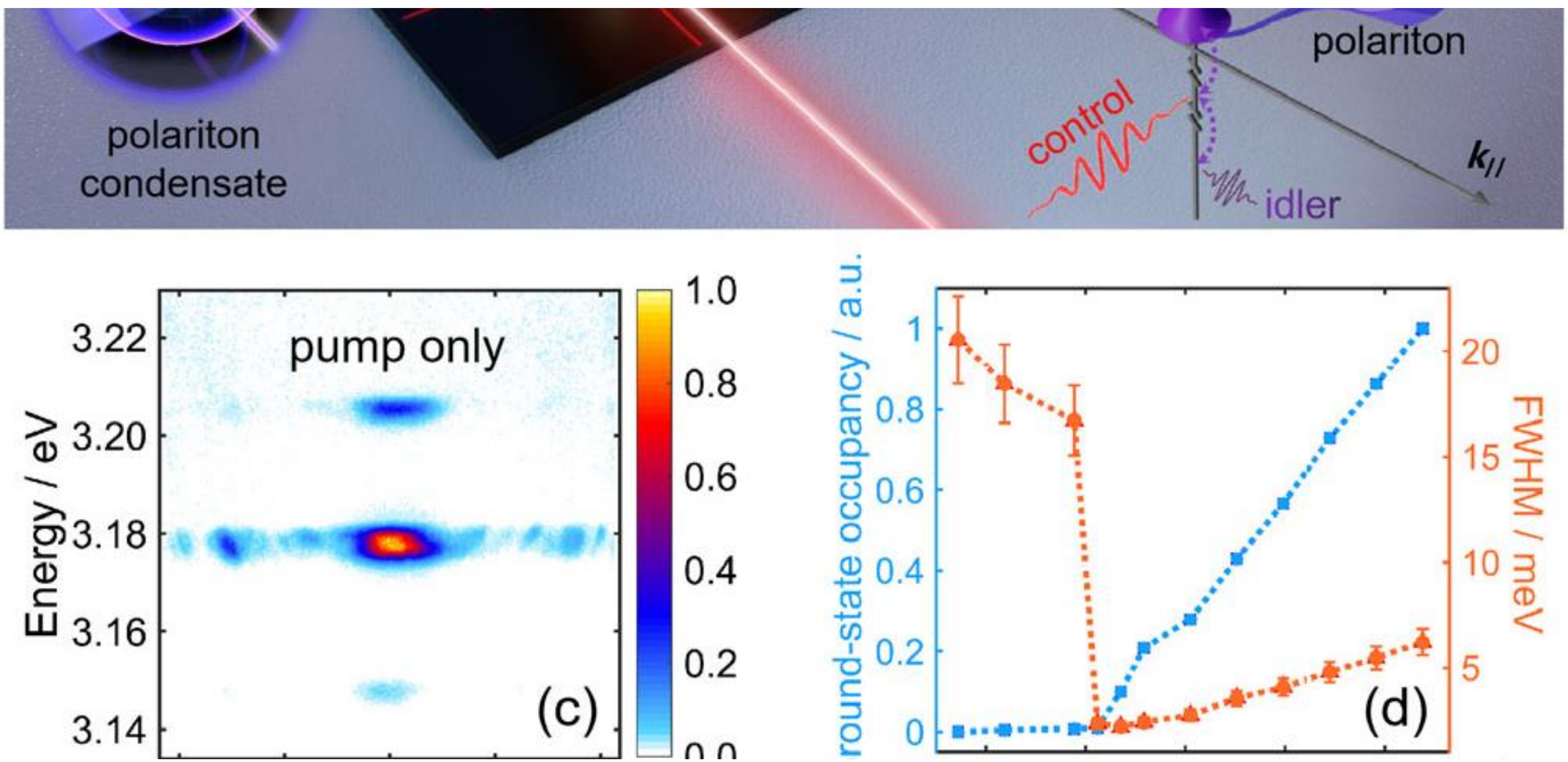
Fei Chen et al, *Nano Lett*. 22, 2023-2029 (2022).



Dominant bosonic cascade process

Fei Chen, Hui Li, Jian Wu, ZH Chen et al, ***Nano Lett*****. 22, 2023-2029 (2022).**

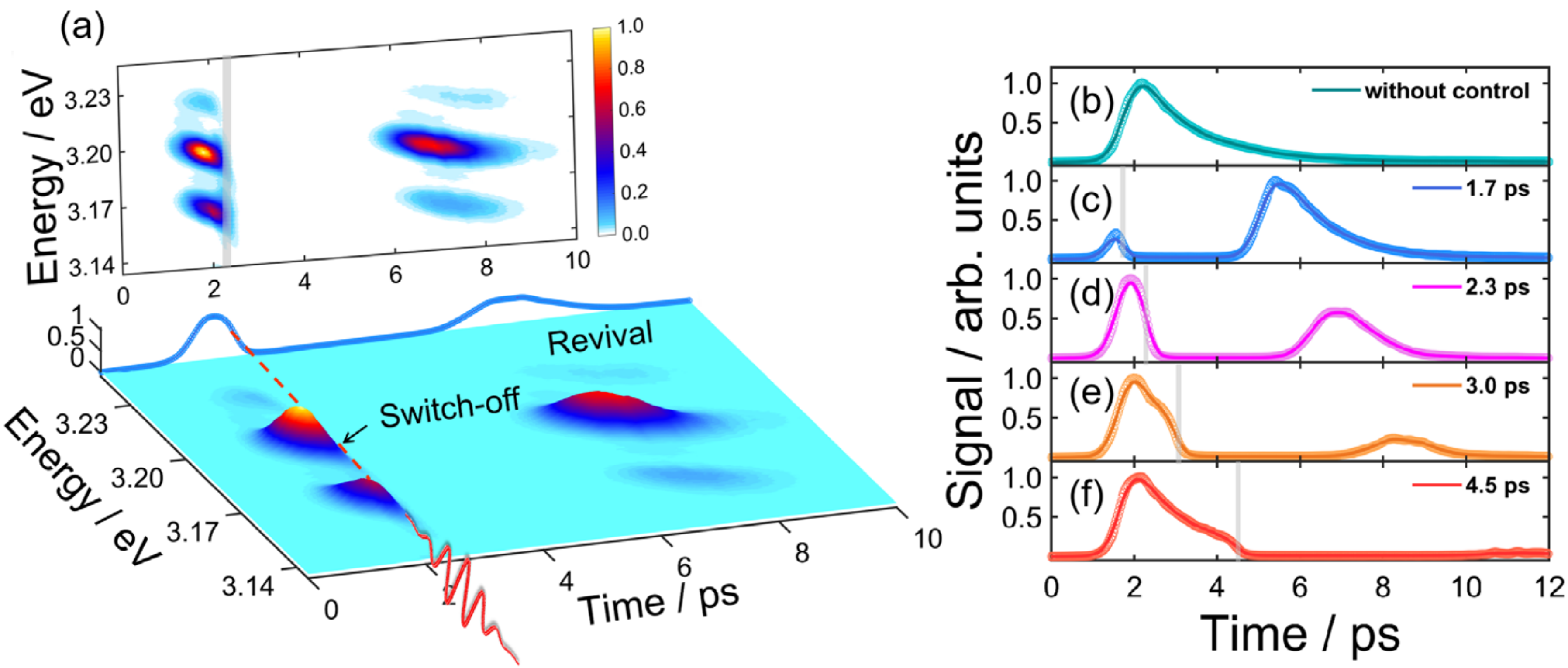
Femtosecond Polariton Switch at Room Temperature



Editors' Suggestion **Featured in Physics**

Fei Chen, Hui Li, Jian Wu and ZH Chen et al, PRL 129, 057402 (2022)

Optically Controlled! 2 orders faster switching time!

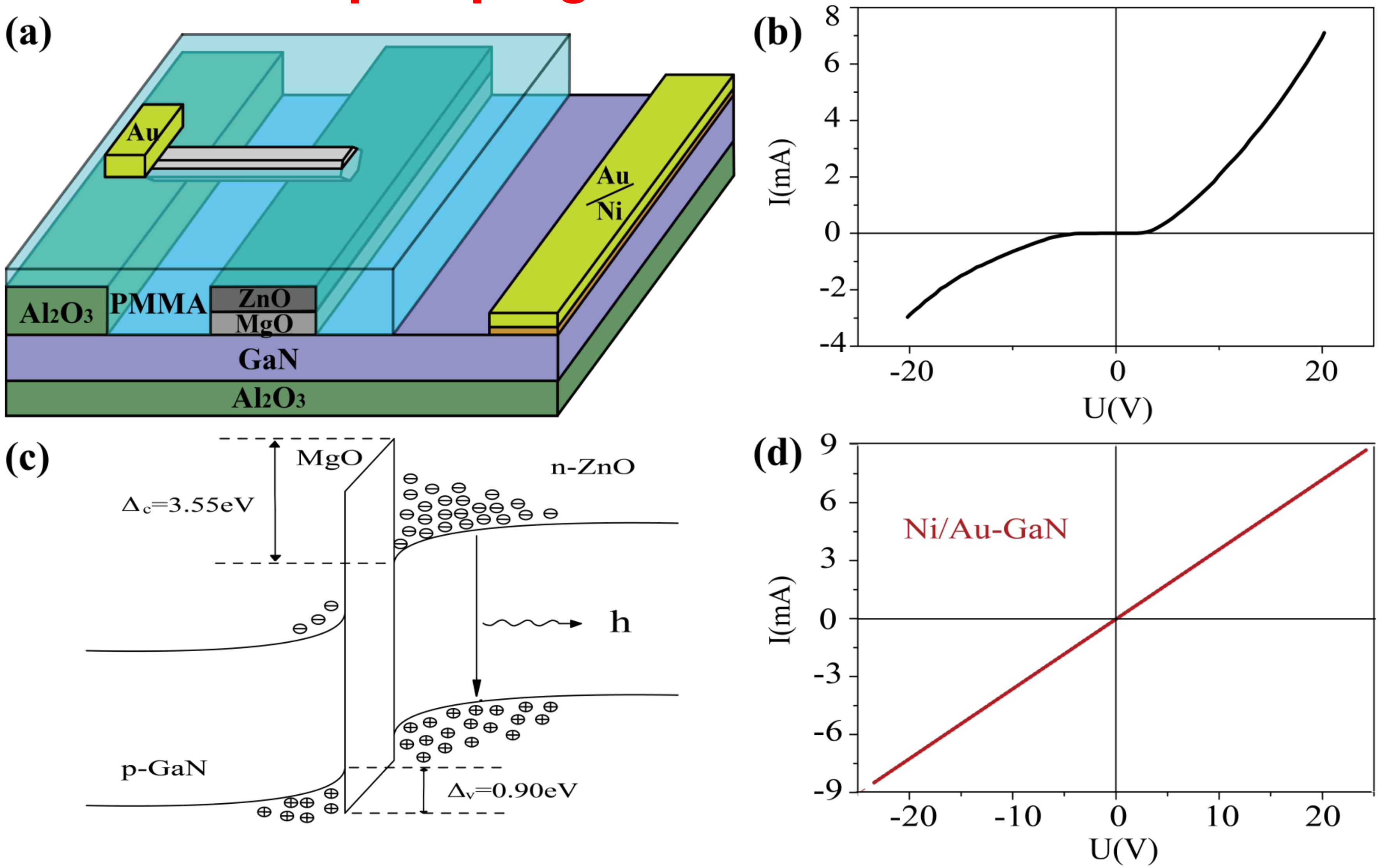


Editors' Suggestion

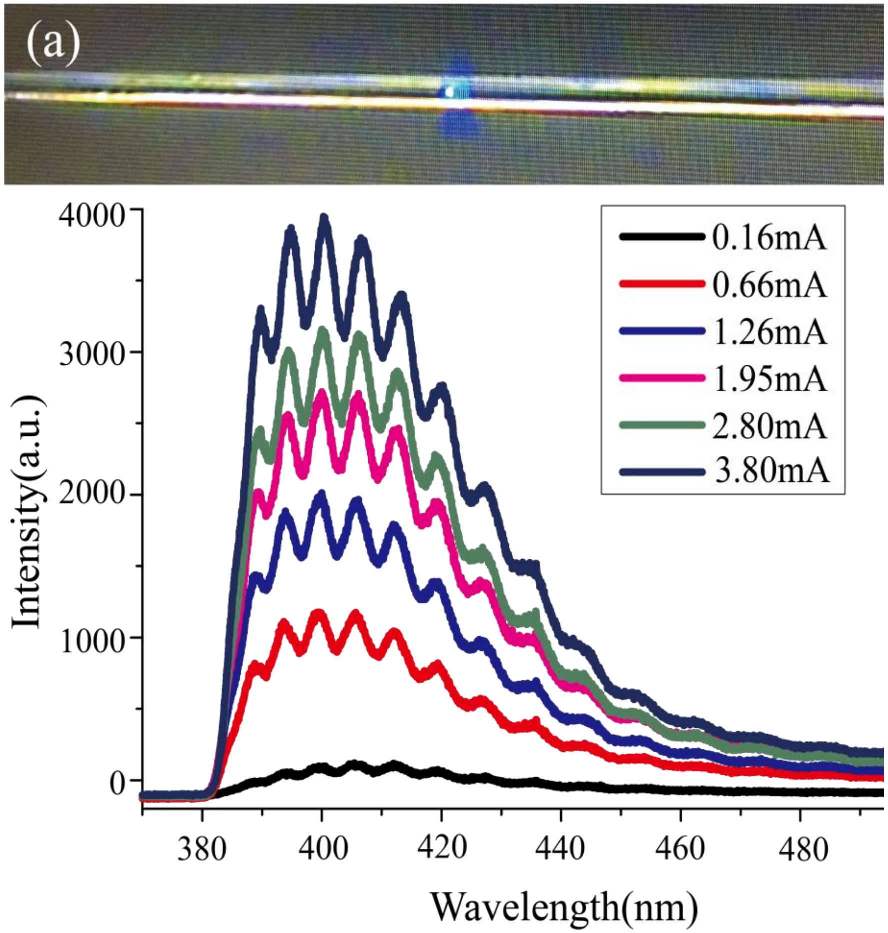
Featured in Physics

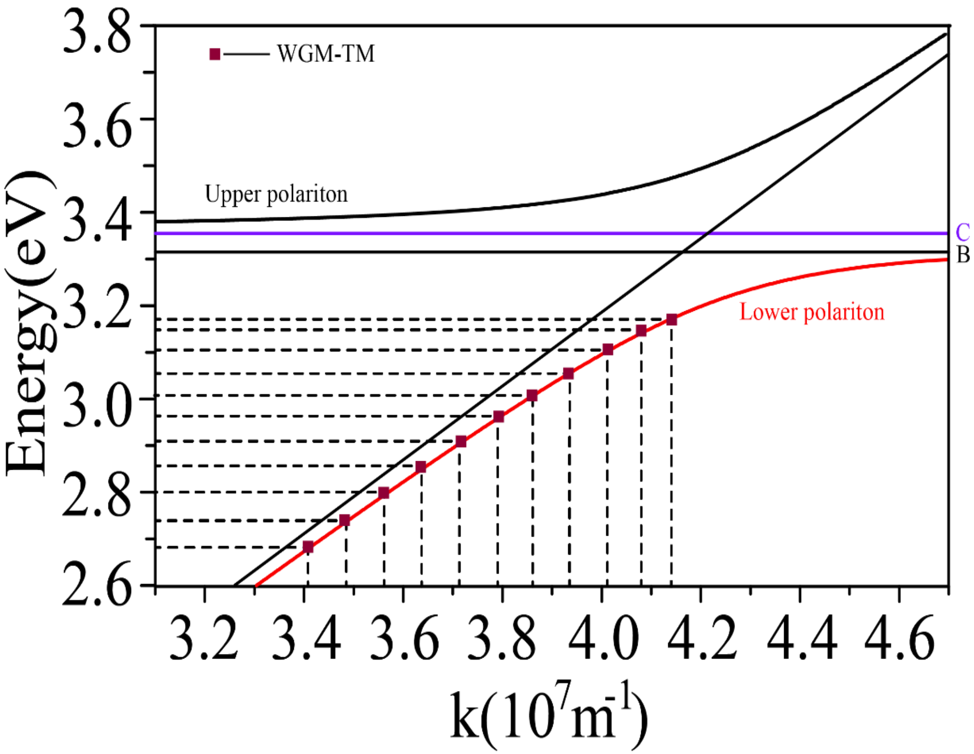
Fei Chen, Hui Li, Jian Wu and ZH Chen et al, PRL 129, 057402 (2022)

Towards device application: electrical pumping



Room temperature Polariton LED





Z Zhang, ZH Chen et al, *Optics Express, 2017*

Summary I

- 1D polariton system
- Very strong coupling
- Polariton lasing at RT
- Parametric scattering of polariton
- Fano resonance of polaritons
- Weak lasing
- Evaporative cooling
- Ultrafast dynamics

Thank you very much!