

Strong light-matter interaction in 2D Materials

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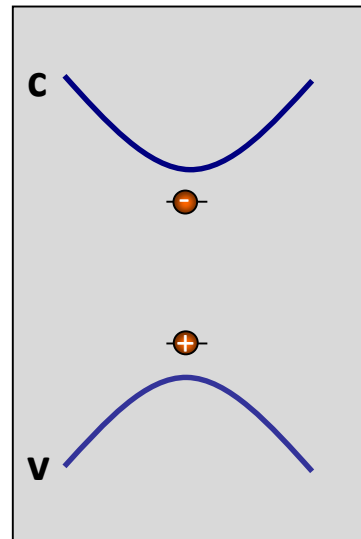
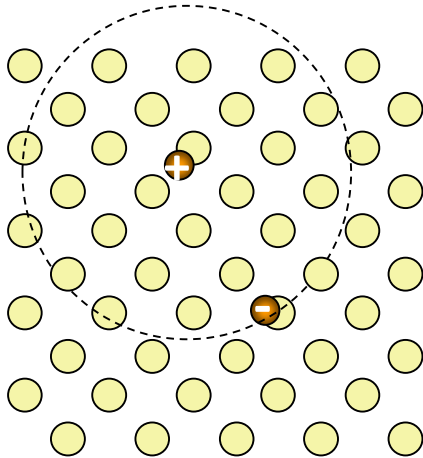
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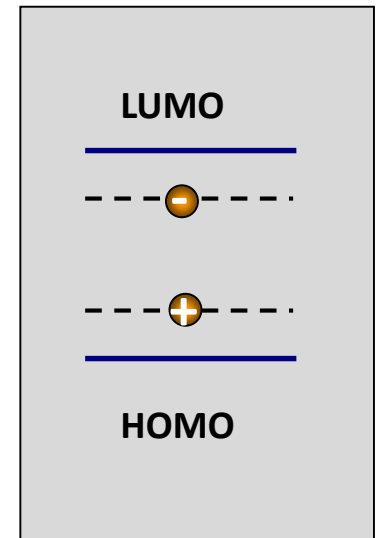
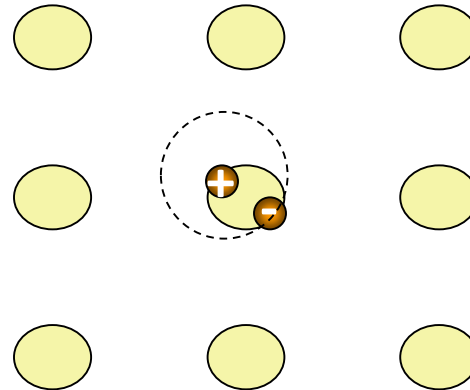
Excitons

Wannier-Mott excitons



Inorganic Materials

Frenkel excitons



Organic Materials

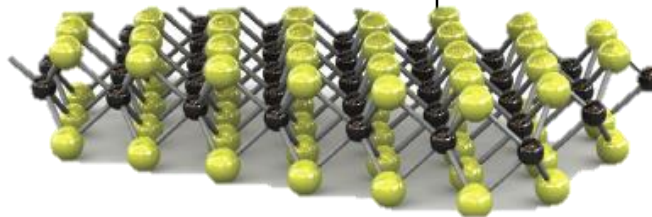
Excitons

Wannier-Mott excitons Inorganic Materials

- Large exciton radius $\sim 100\text{\AA}$
- Small binding energy (10-60meV)
- Long range ballistic transport
- Small saturation density

Frenkel excitons Organic Materials

- Localized at molecular site
- Large binding energy (0.5 - 1 eV)
- Hopping transport
- Large saturation density



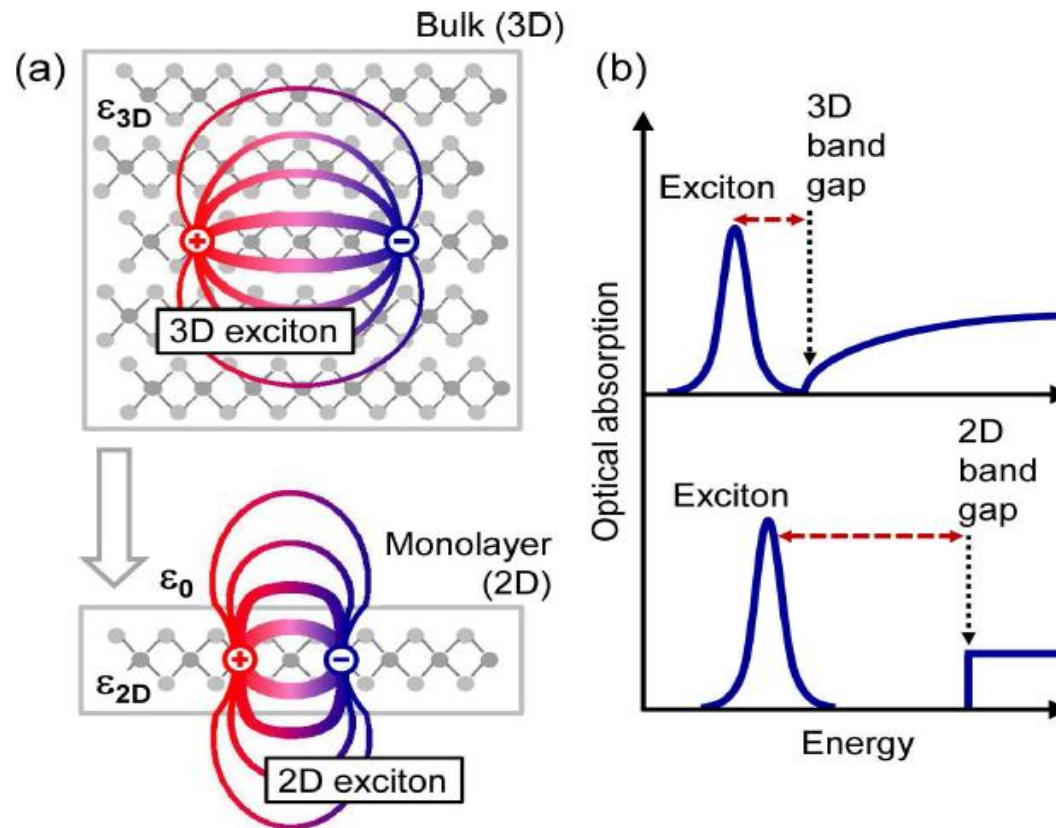
2D Materials

graphene family	graphene	hBN 'white graphene'	BCN	fluorographene	graphene oxide
2D chalcogenides	MoS ₂ , WS ₂ , MoSe ₂ , WSe ₂		semiconducting dichalcogenides: MoTe ₂ , WTe ₂ , ZrS ₂ , ZrSe ₂ , etc.	metallic dichalcogenides: NbSe ₂ , NbS ₂ , TaS ₂ , TiS ₂ , NiSe ₂ , etc.	
				layered semiconductors: GaSe, GaTe, InSe, Bi ₂ Se ₃ , etc.	
2D oxides	micas, BSCCO	MoO ₃ , WO ₃	perovskite-type: LaNb ₂ O ₇ , (Ca,Sr) ₂ Nb ₃ O ₁₀ , Bi ₄ Ti ₃ O ₁₂ , Ca ₂ Ta ₂ TiO ₁₀ , etc.		hydroxides: Ni(OH) ₂ , Eu(OH) ₂ , etc.
	layered Cu oxides	TiO ₂ , MnO ₂ , V ₂ O ₅ , TaO ₃ , RuO ₂ , etc.			OTHERS

Geim & Grigorieva, Nature **499**, 419 (2013)

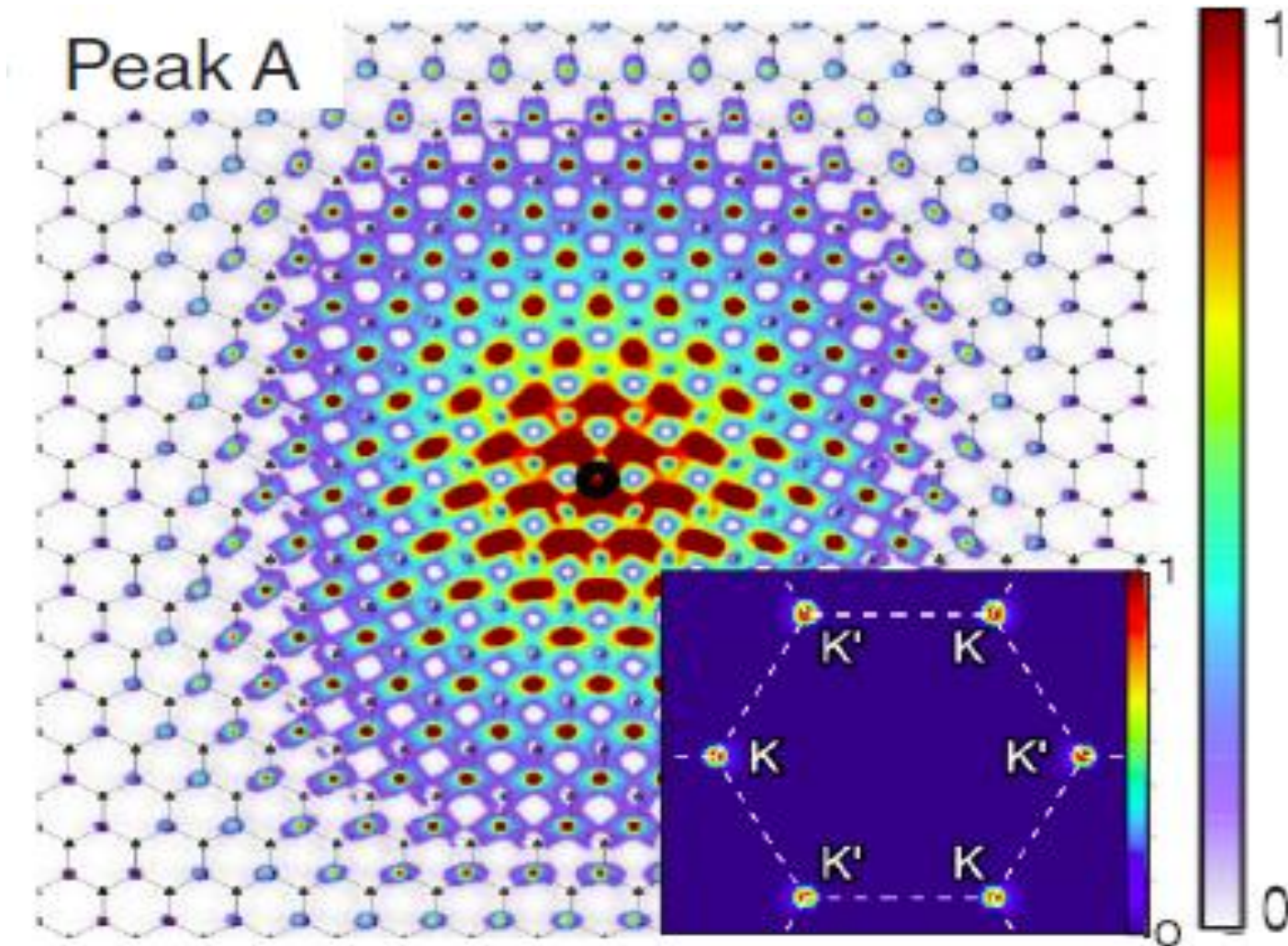
Excitons in 2D TMDs: Binding Energy

Binding Energy (0.1-0.5 eV)

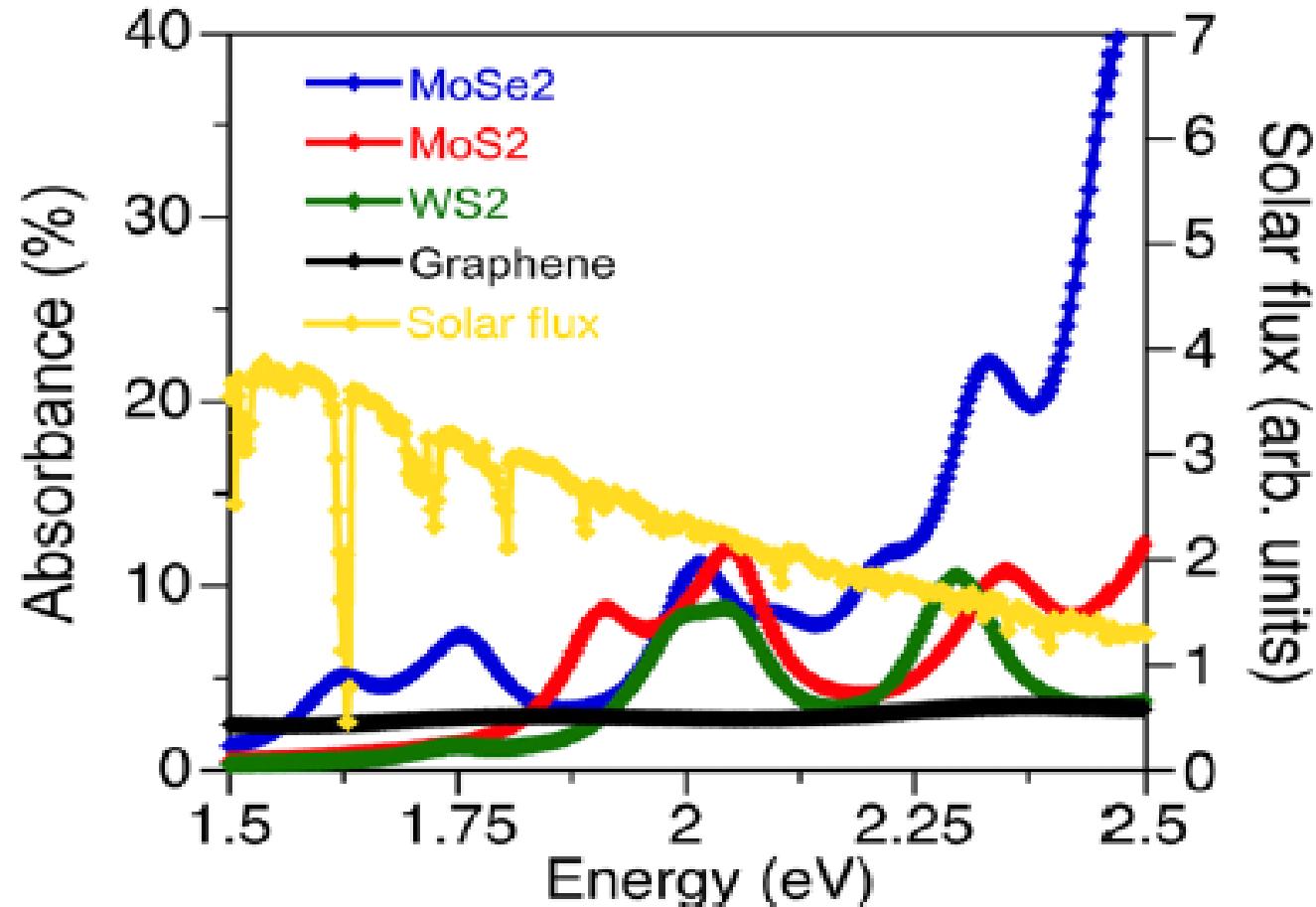


Excitons in 2D TMDs: Bohr Radius

Bohr Radius ~ 1 nm (MoS_2)



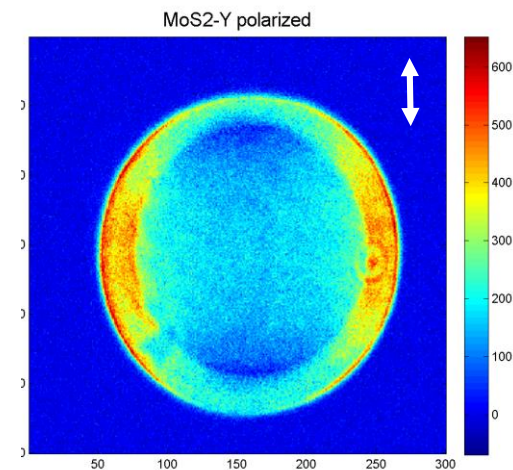
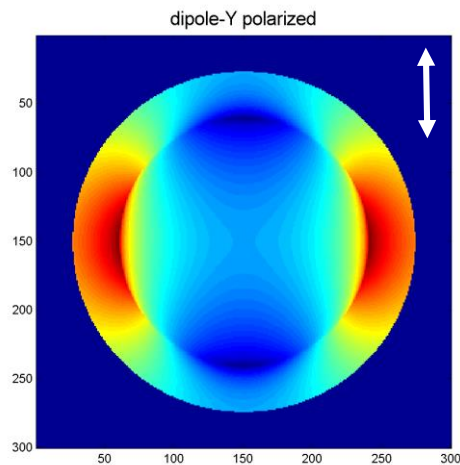
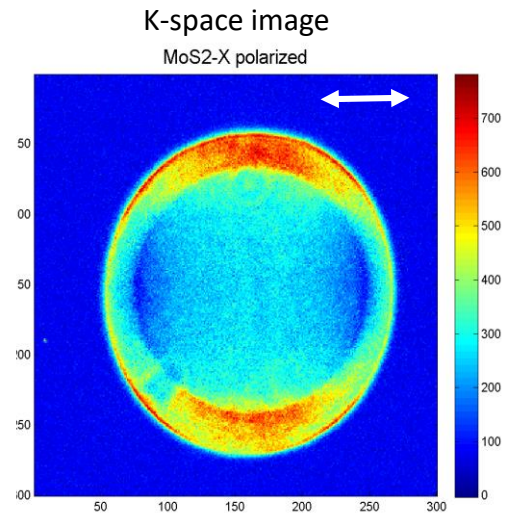
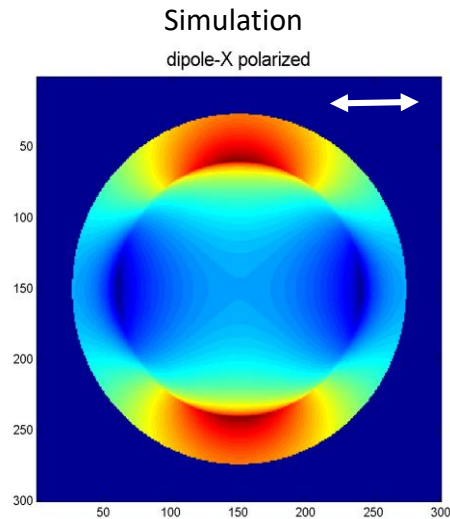
Excitons in TMDs: Oscillator strength



1 ML absorbs 5-10% light !

In-plane Dipoles

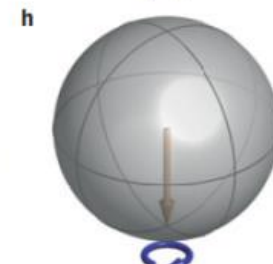
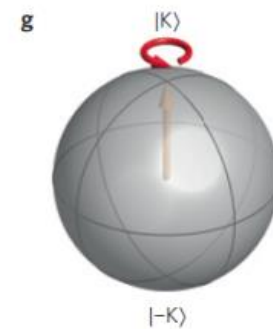
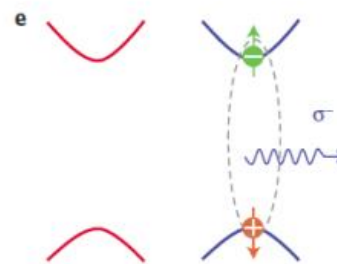
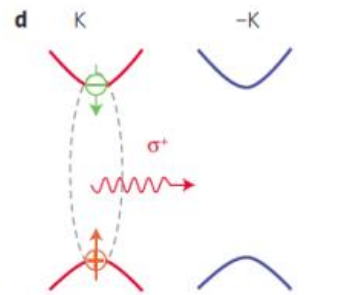
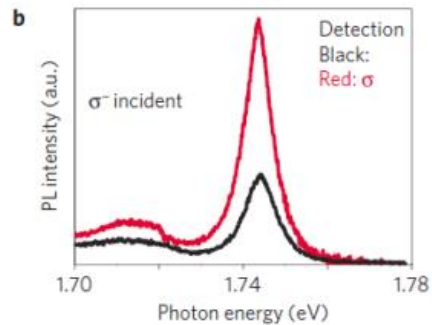
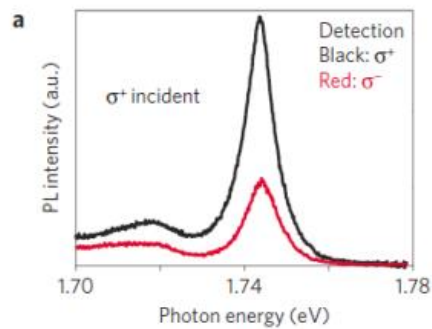
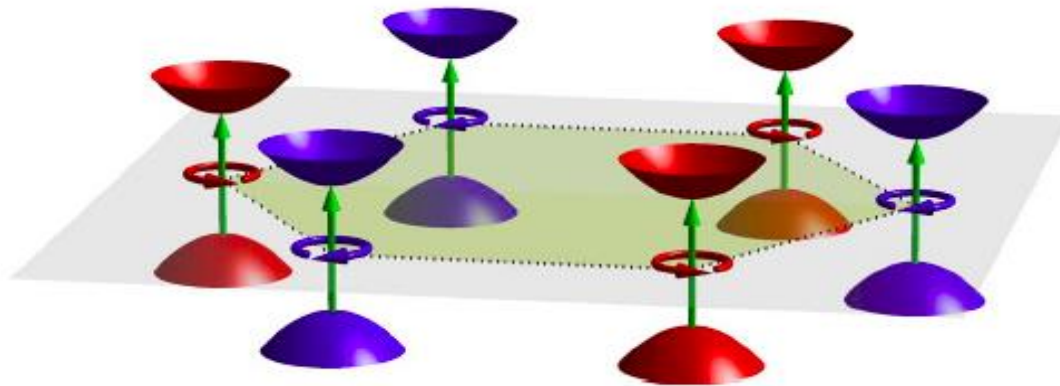
2D dipole orientation.



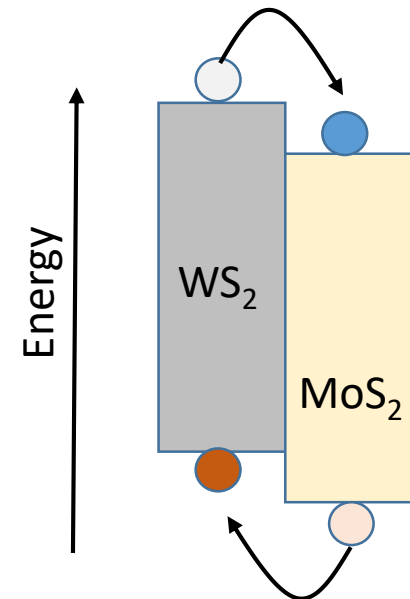
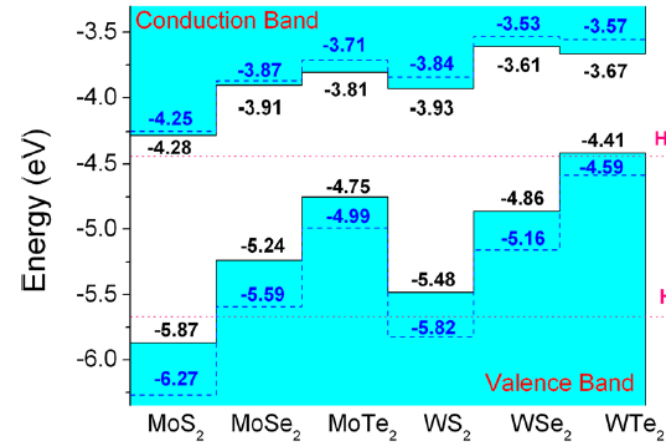
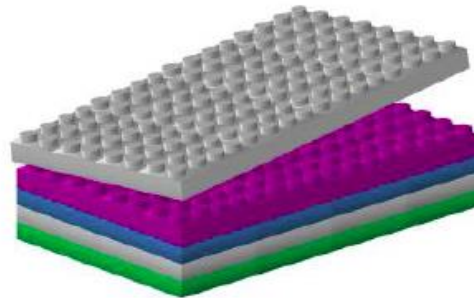
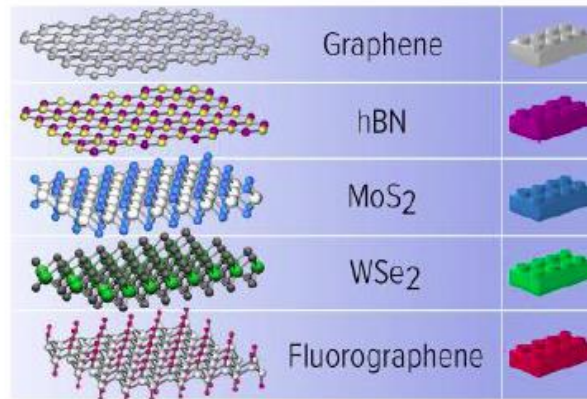
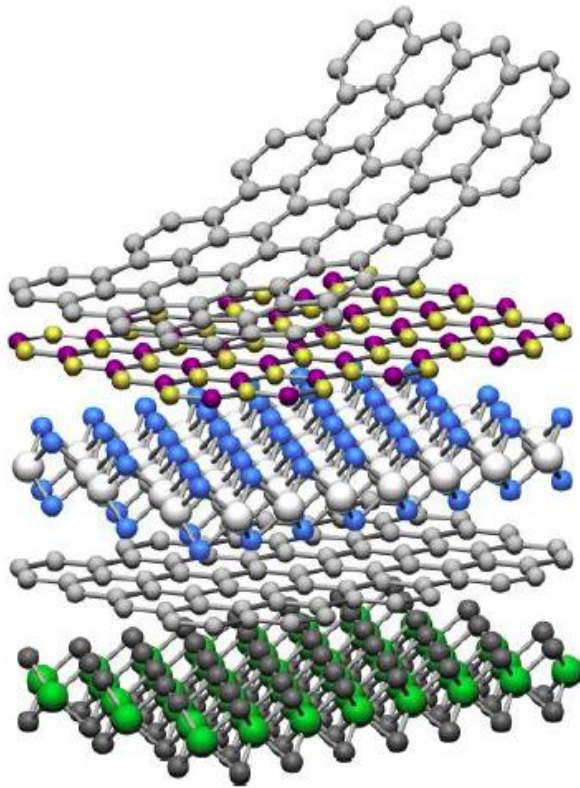
J. Gu...VMM (unpublished)

Also: J. Schuller et al., Nat. Nanotech **8** 271 (2013)

Valley Polarization

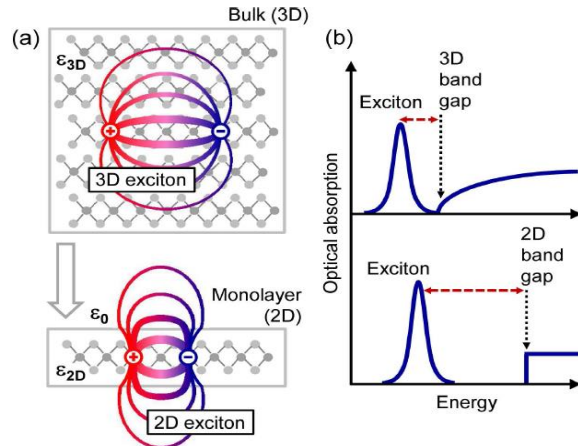


van der Waals heterostructures



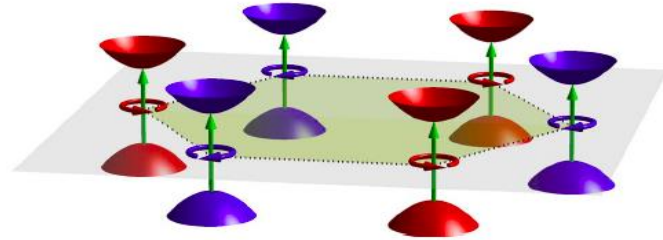
Why do microcavity polaritons with 2D TMDs?

Binding energy: 0.1 – 0.3 eV



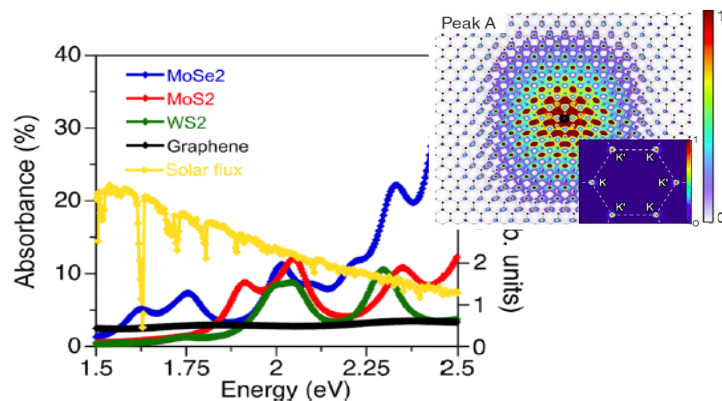
Chernikov et al. PRL 113, 076802 (2014)

Valley properties



Xu, X. et al. (2014). *Nat. Phys.*, 10, 343–350.

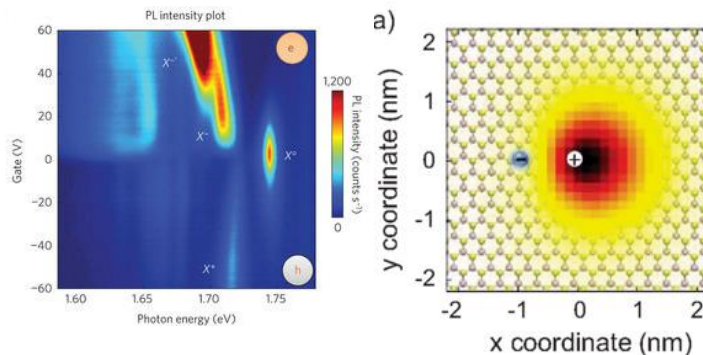
Large oscillator strength



D. Y. Qiu et al. PRL 111, 216805 (2013)

Bernardi, et al. *Nano Lett.*, **13**, 3664 (2013)

Trions

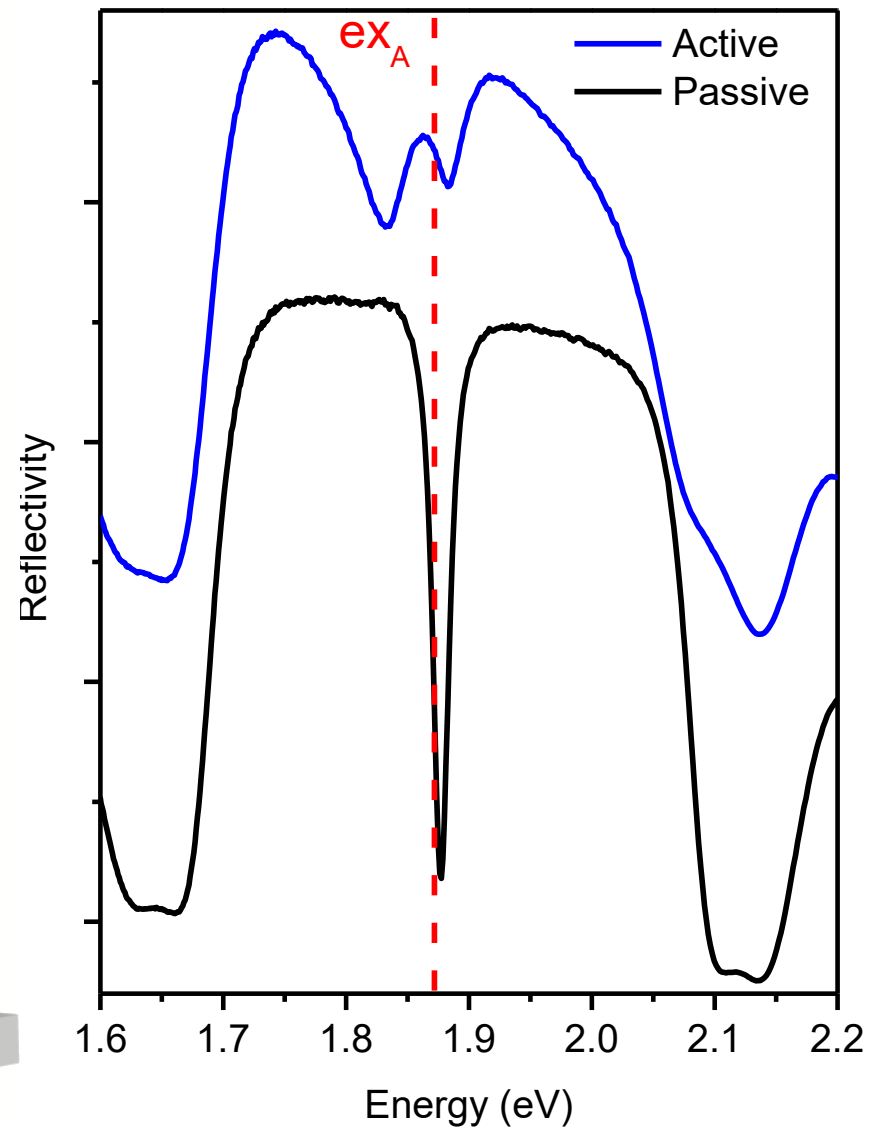
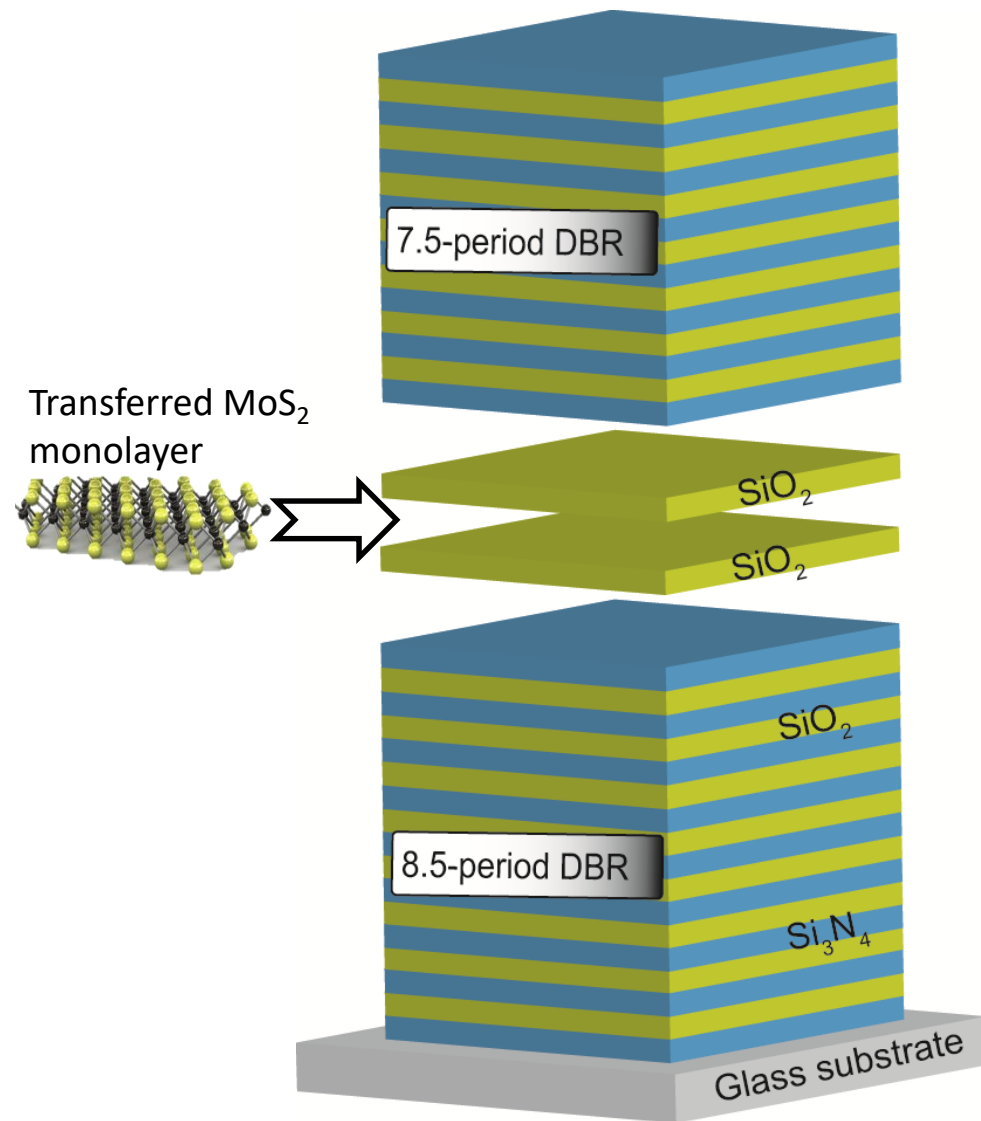


Ross, J. S. et al.. *Nature Commun.* **4**, 1474 (2013).

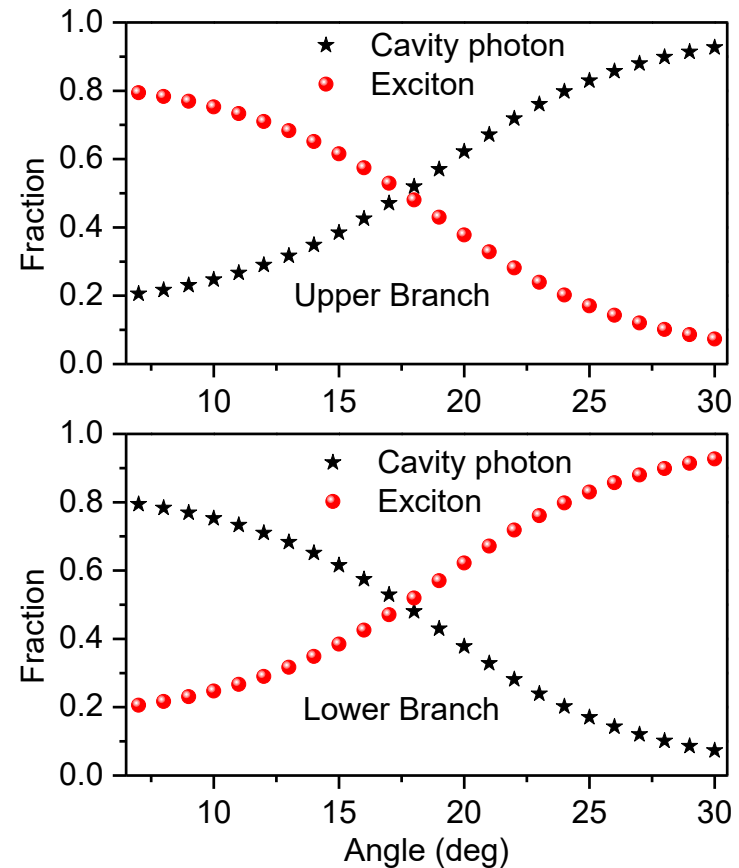
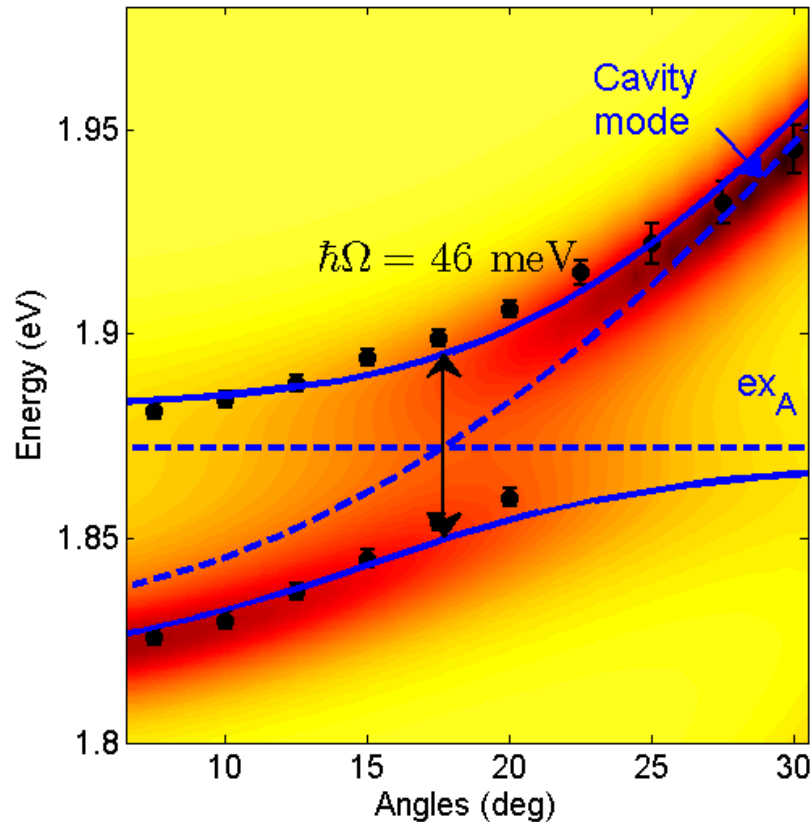
Mak, K. F. et al.. *Nature Mater.* **12**, 207211 (2013)

Singh A. et al. *Phys rev. B* 93 041401 (2016)

MoS₂ Microcavity



Reflectivity Dispersions



X. Liu,...VMM, *Nature Photonics* **9**, 30 (2015)

Other reports:

Dufferwiel, S. *et al. Nat. Commun.* **6**, 8579 (2015).

Sidler, M. *et al. Nat. Phys.* (2016). doi:10.1038/nphys3949

Liu, W. *et al. Nano Lett.* **16**, 1262–1269 (2016).

Wang, S. *et al. Nano Lett.* **16**, 4368–4374 (2016).

Lundt, N. *et al. Nat. Commun.* **7**, 13328 (2016).

Zhang, L. *et al. Nat. Commun.* **9**, 713 (2018)



Xiaozhe Liu

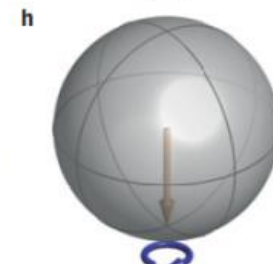
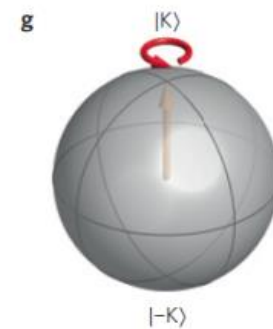
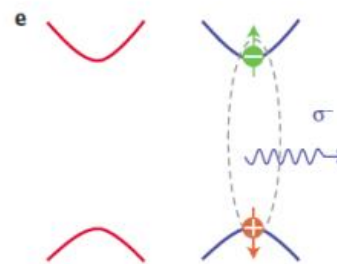
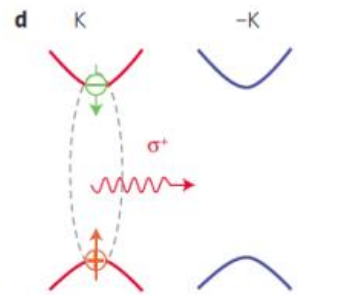
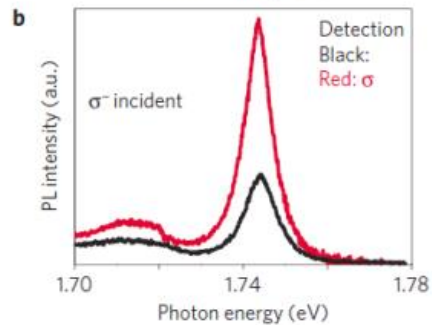
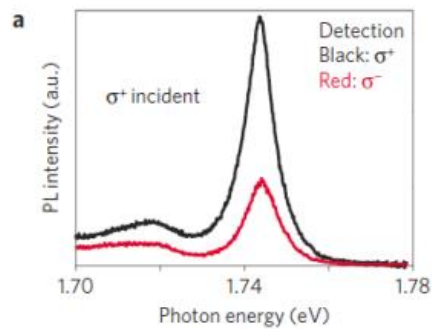
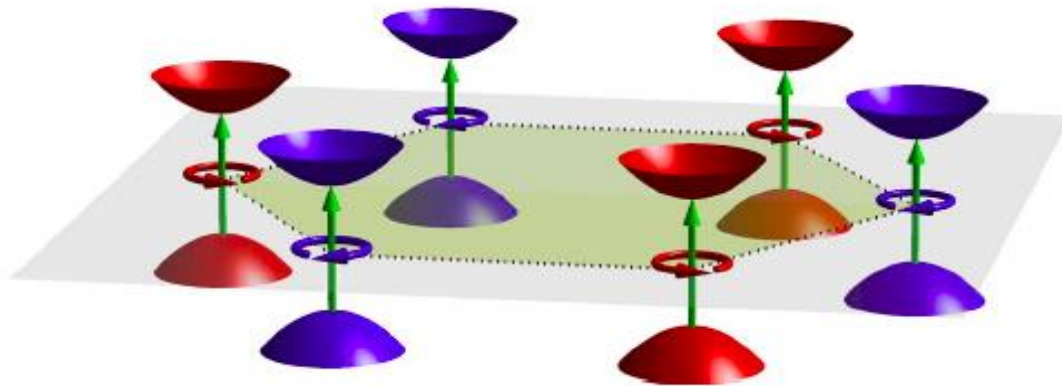
Grad Student – CCNY
(Currently @ UC Berkeley)



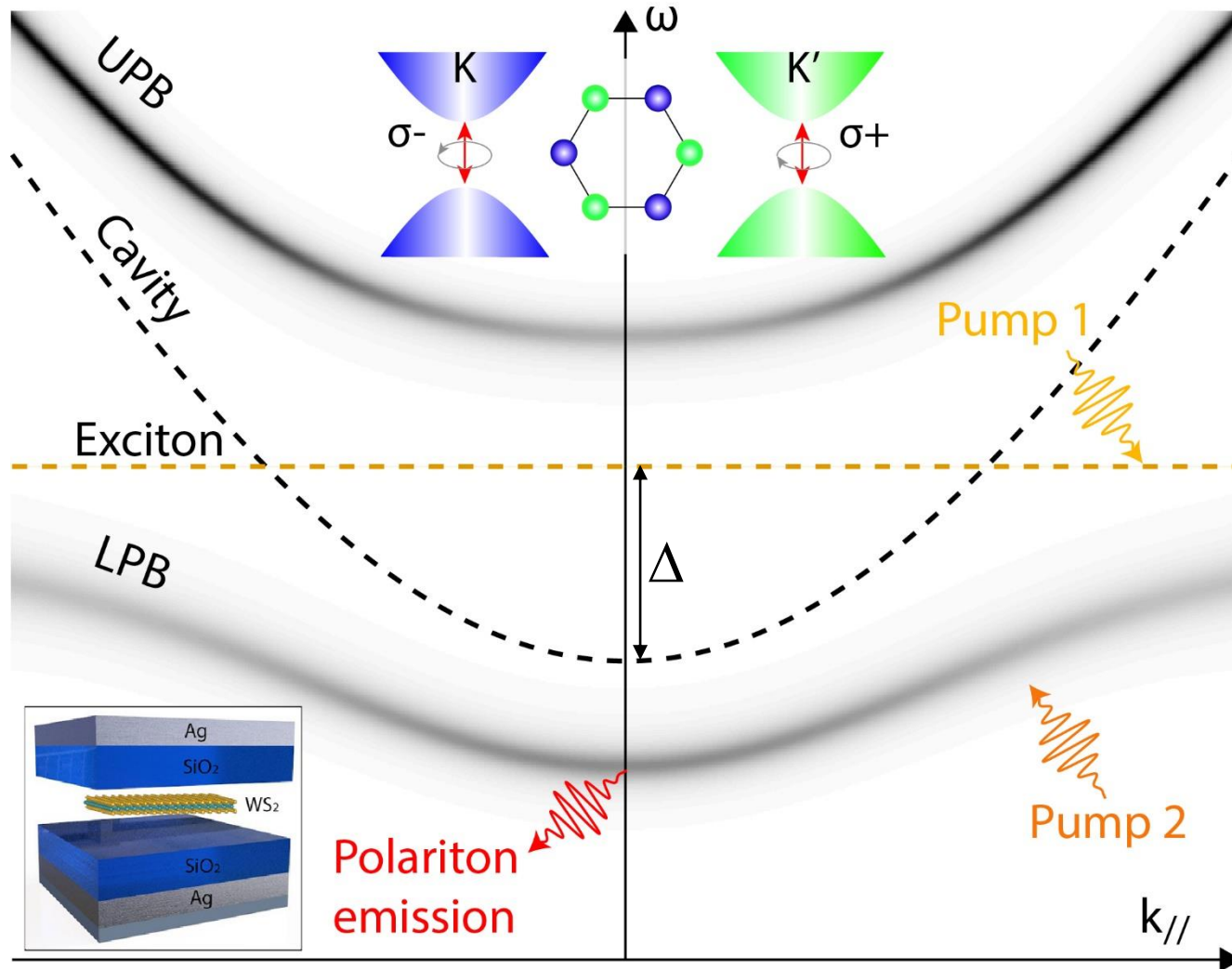
Zheng Sun

Grad Student – CUNY
(Currently @ Pittsburg)

Valley Polarization

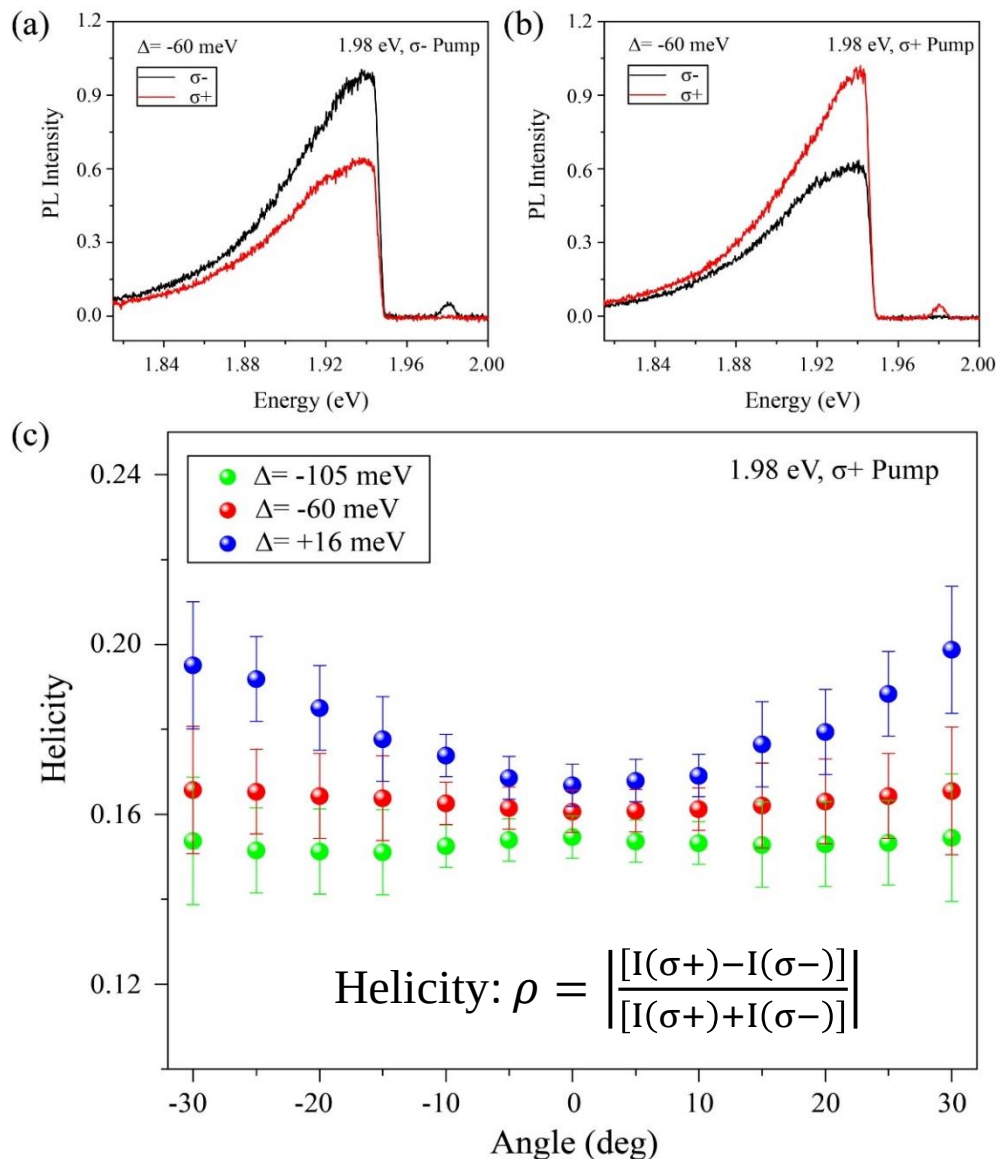


Valley Polaritons



$$\text{Helicity: } \rho = \left| \frac{[I(\sigma^+) - I(\sigma^-)]}{[I(\sigma^+) + I(\sigma^-)]} \right|$$

Valley polarized polaritons

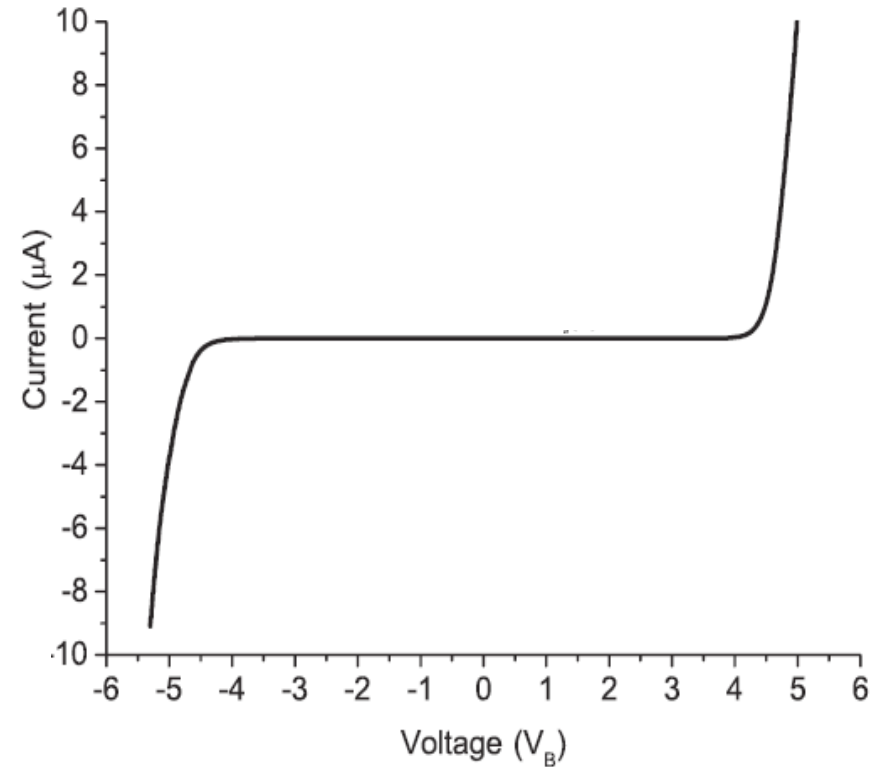
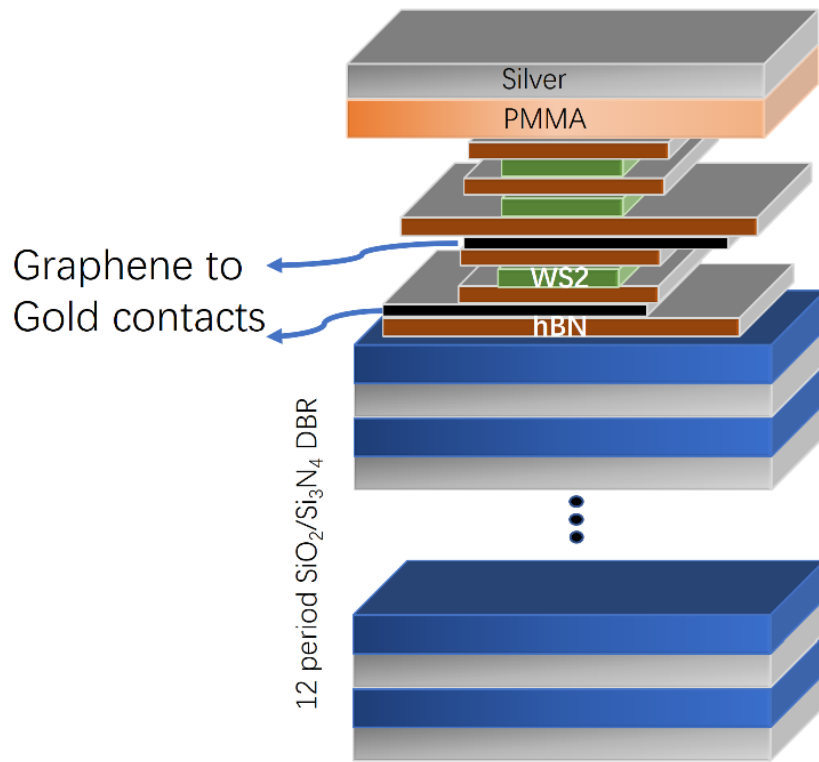


Zheng Sun
Grad Student – CUNY
(Currently @ Pittsburg)

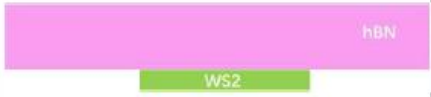
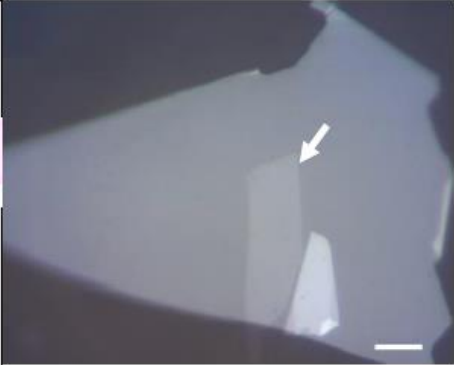
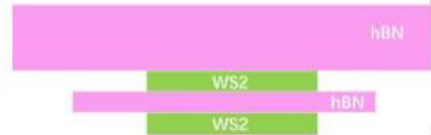
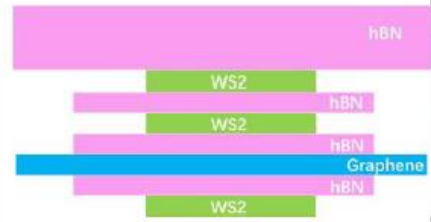
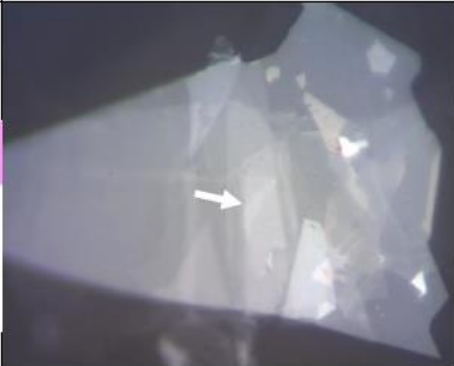
Z. Sun...VMM, *Nature Photonics* **11**, 491 (2017)

Similar results from Sheffield, Wurzburg, Northwestern groups

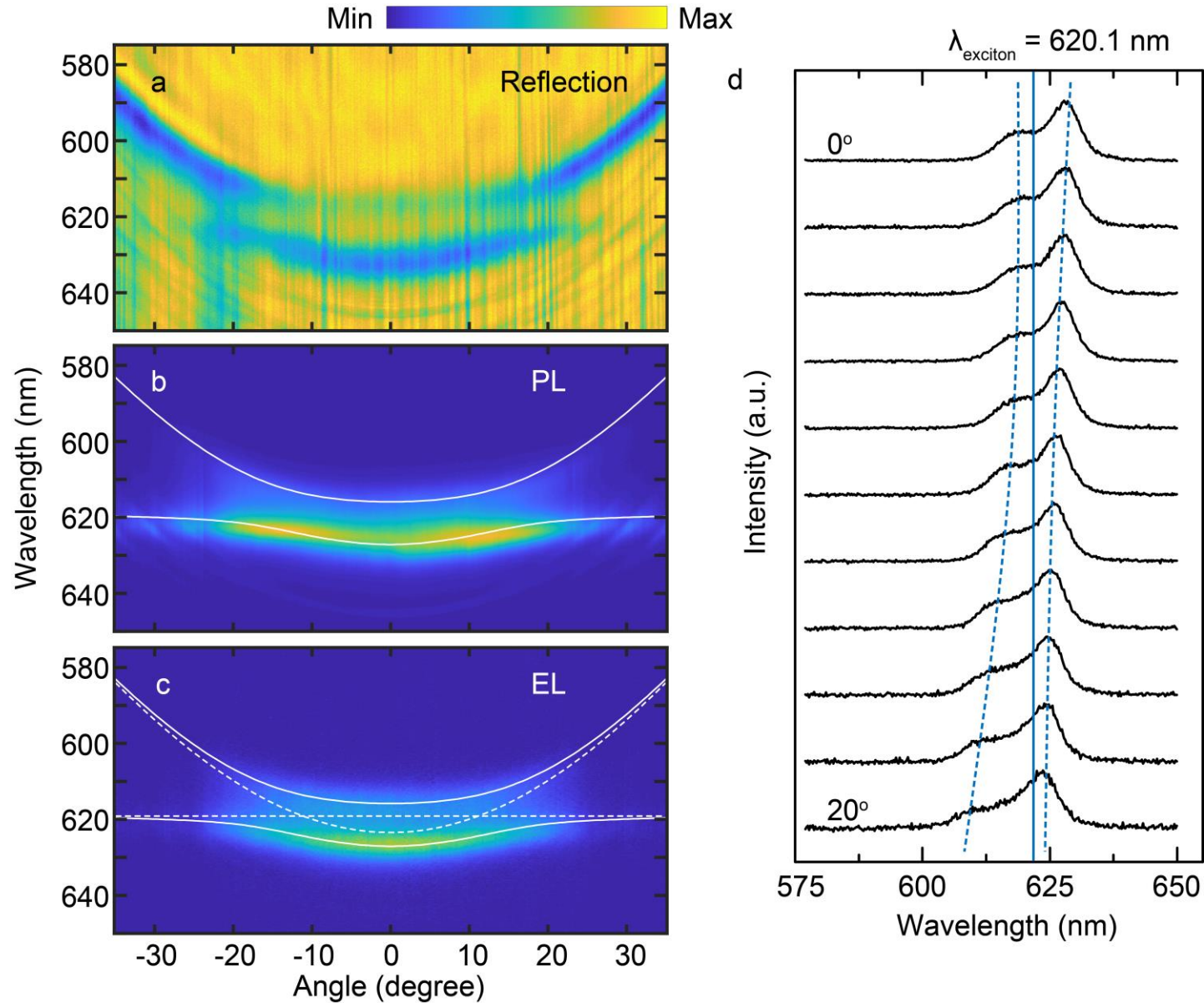
Polariton LED @ Room Temperature



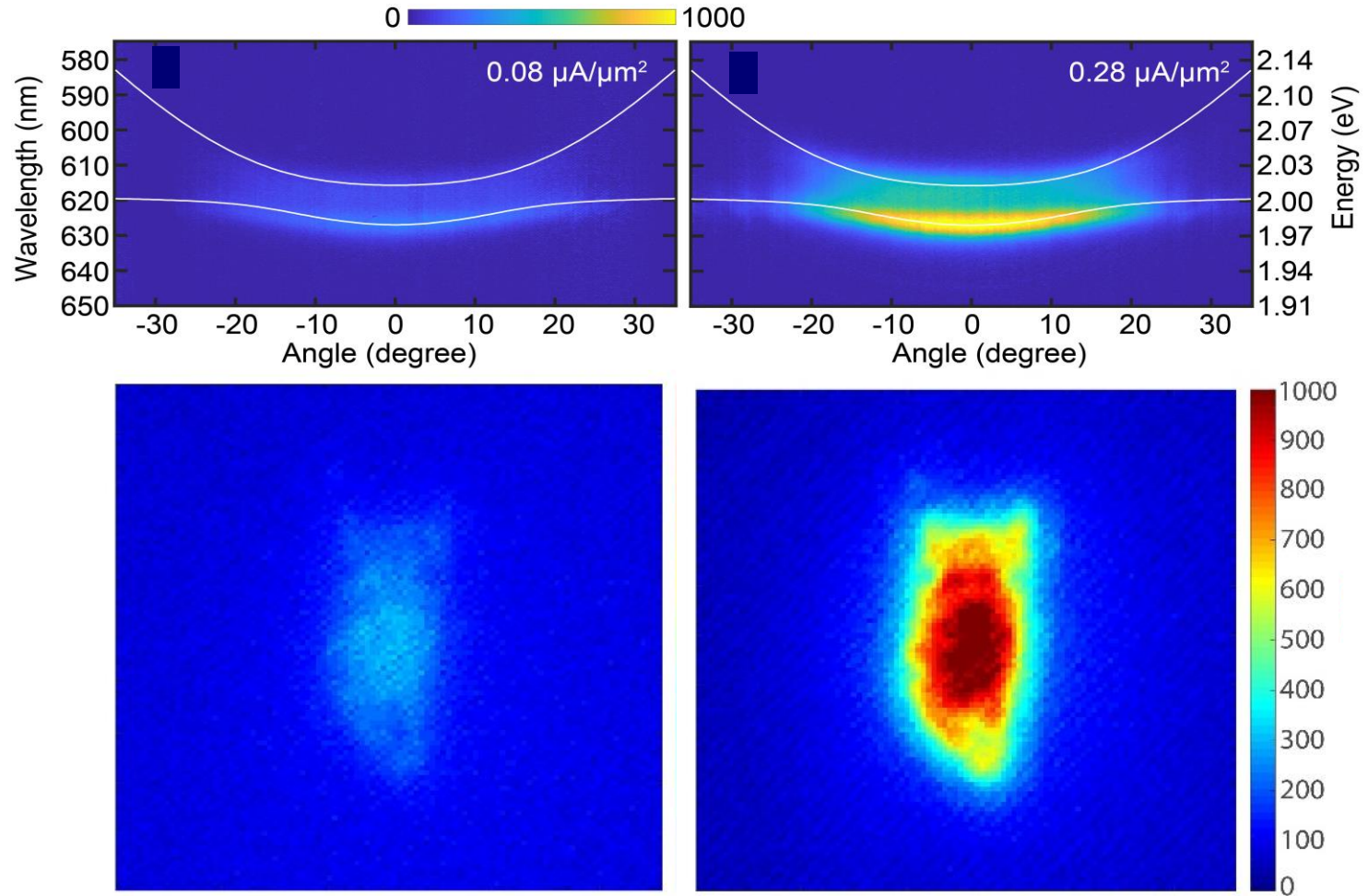
Polariton LED: Fabrication

Stacking order	Image on PPC film	WS ₂ image
1. First WS₂ 		
2. Second WS₂ 		
3. Third WS₂ 		

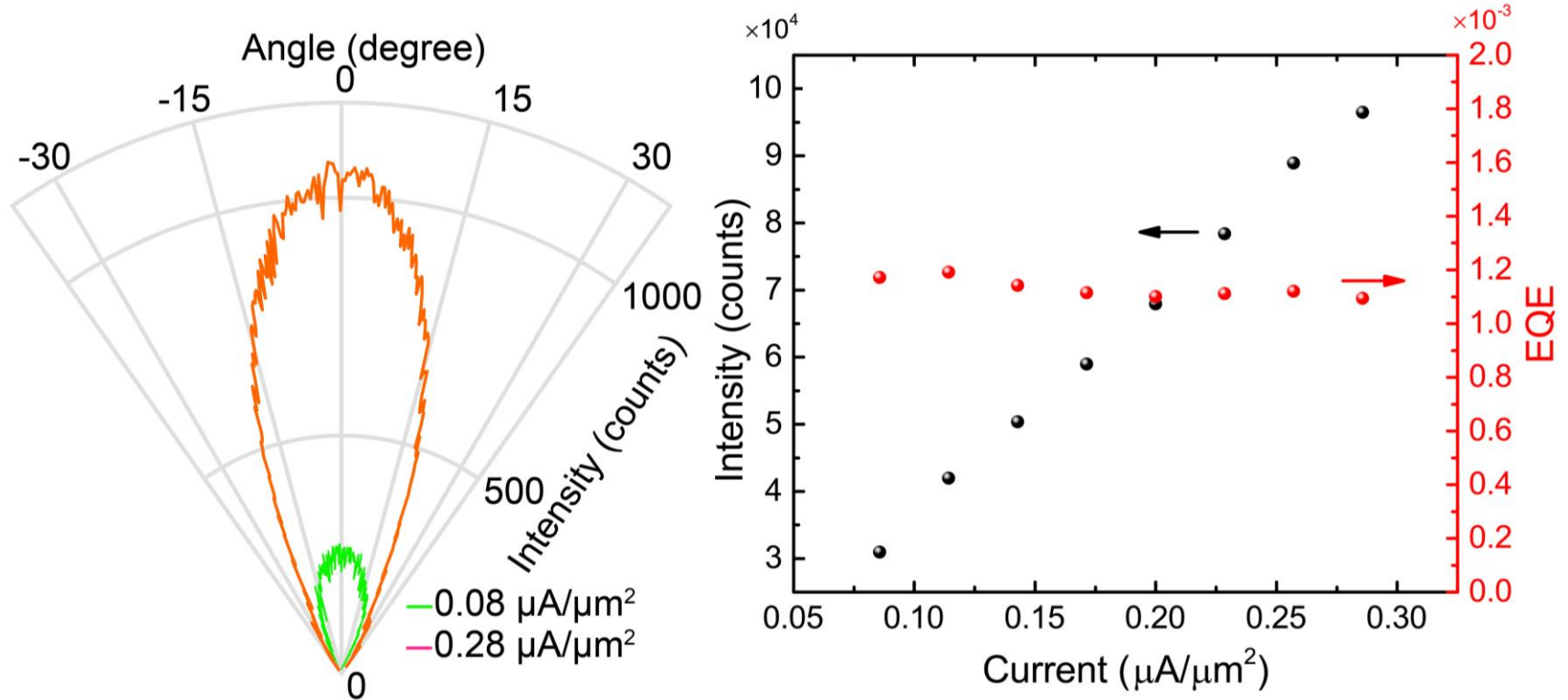
Polariton LED @ Room Temperature



Polariton LED @ Room Temperature



Polariton LED @ Room Temperature

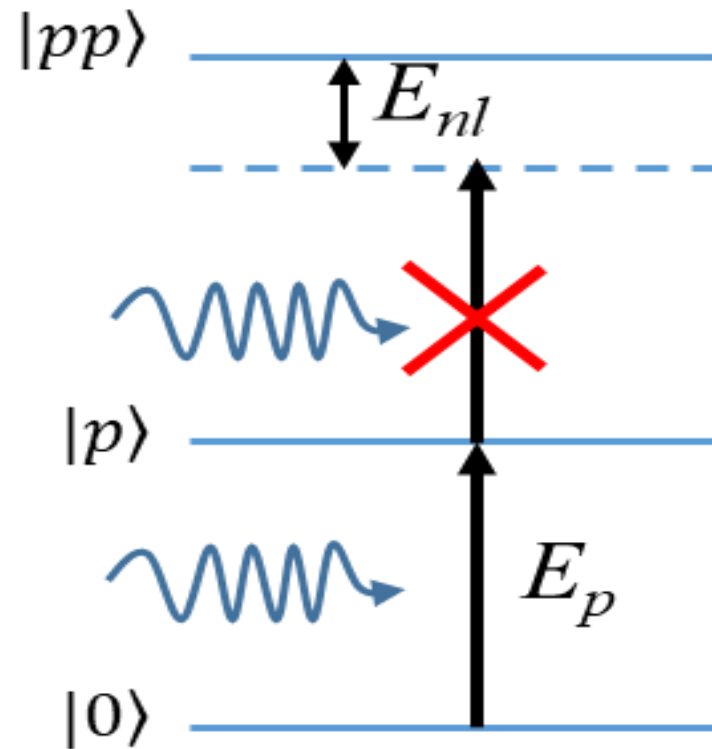


Dr. Biswanath
Chakraborty
Postdoc- CCNY



Jie Gu
Grad Student - CUNY

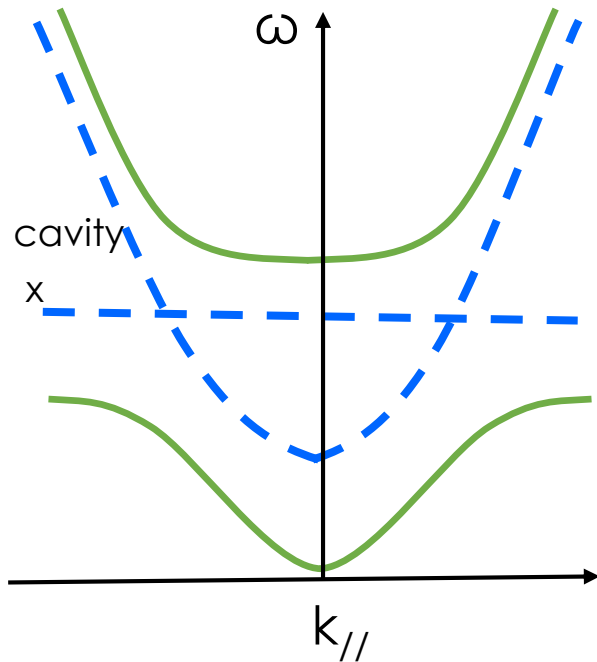
Polariton blockade



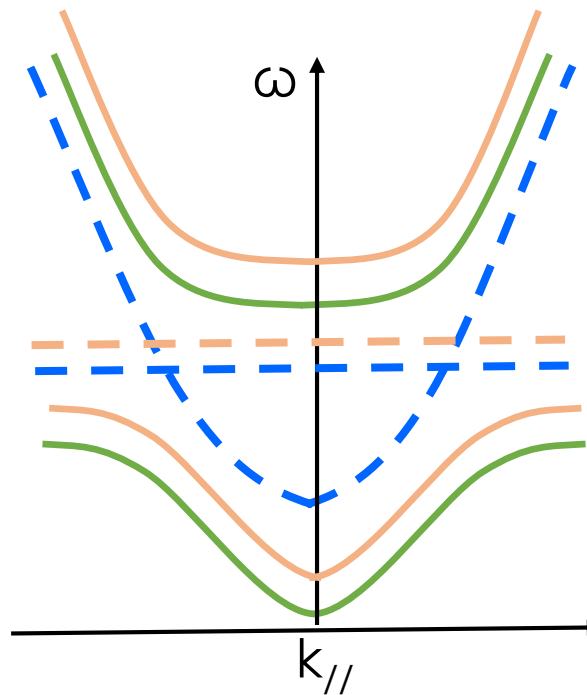
Nonlinear polariton-polariton interaction

$$\chi(E) \propto \frac{f_{\text{osc},X}}{E - E_X + i\gamma_X}$$

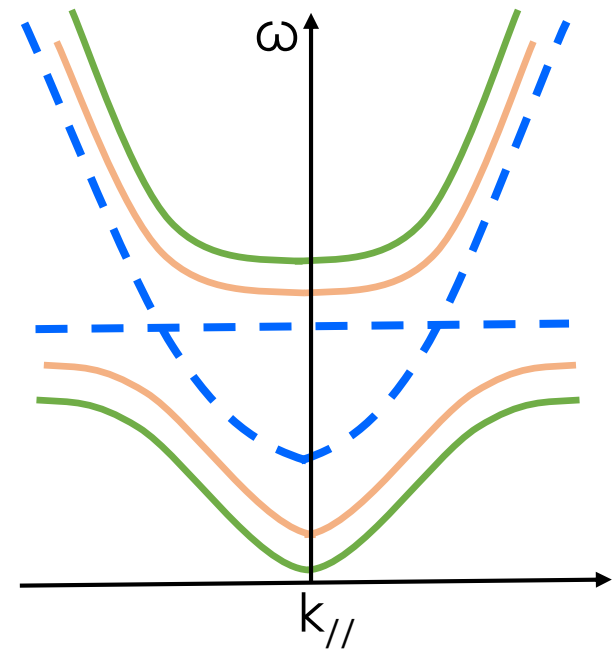
Cavity Polariton dispersion



Exciton – exciton interaction



Phase Space Filling

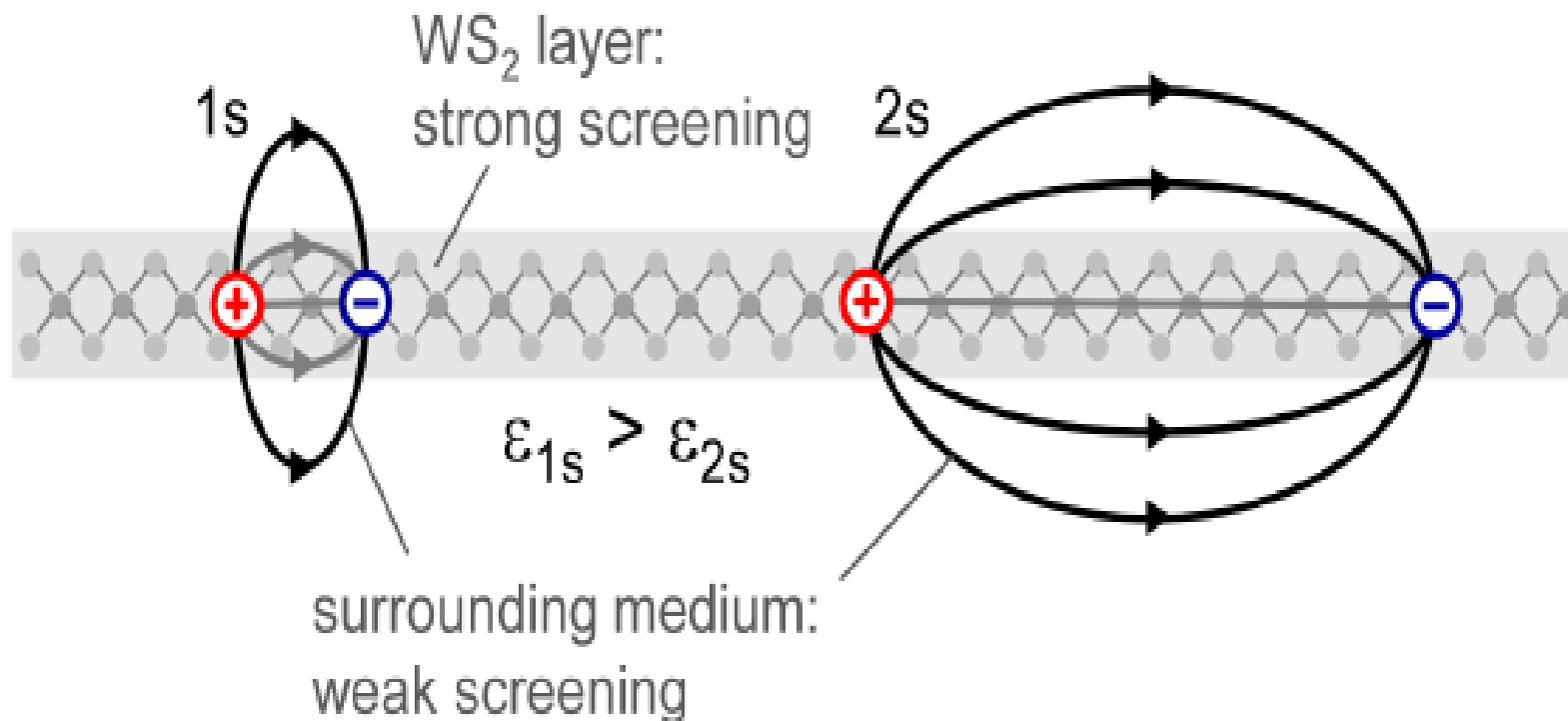


$$\delta E_X = E_X^b \frac{n_X}{n_X^{\text{sat},1}}$$

$$f_{\text{osc},X}(n_X) = \frac{f_{\text{osc},X}(0)}{1 + n_X/n_X^{\text{sat},2}}$$

Excited States of Excitons in 2D TMDs

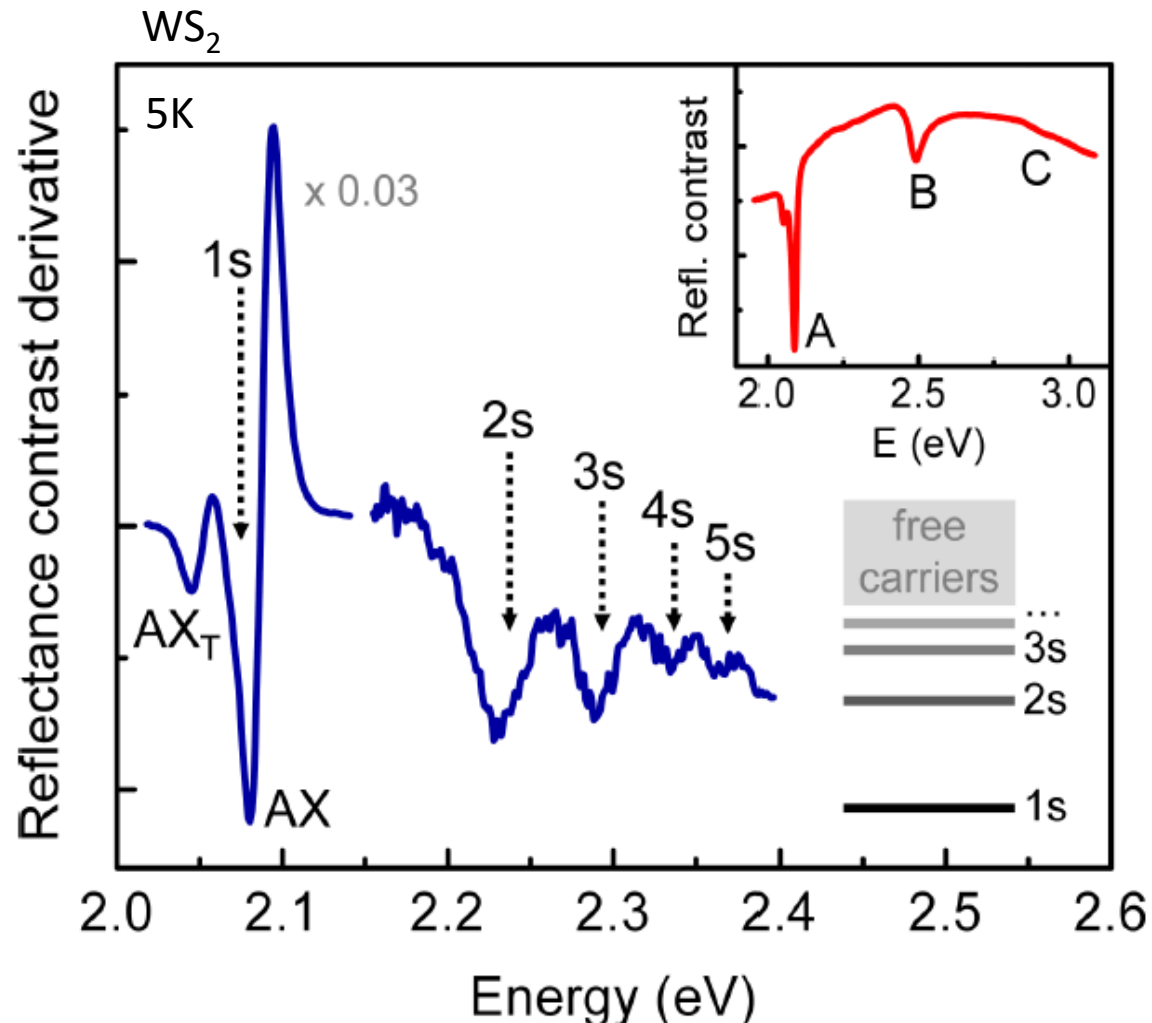
Rydberg States



$$\text{Interactions: } g \propto \hbar \Omega_0 a_B^2.$$

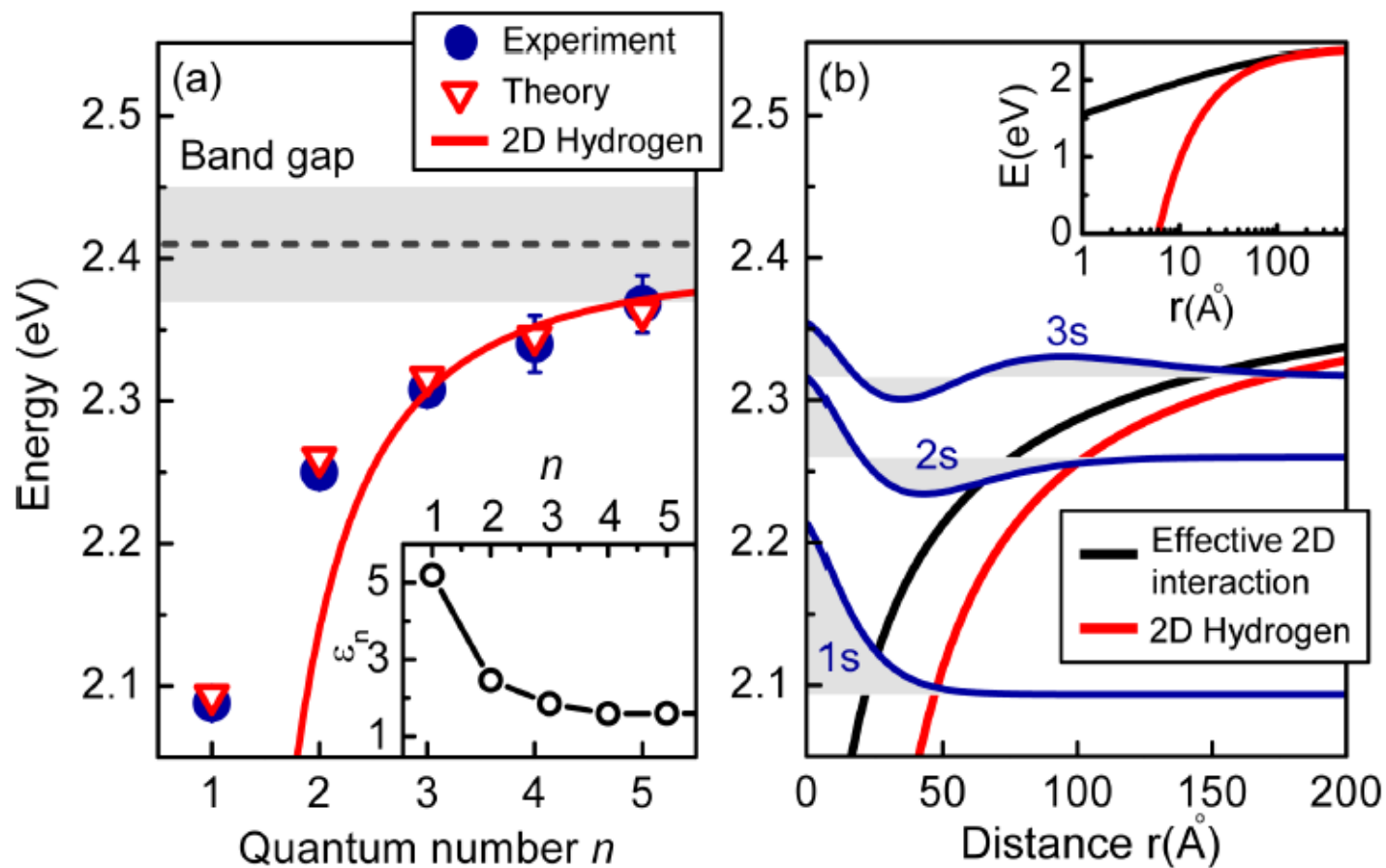
Excited States of Excitons in 2D TMDs

Rydberg States

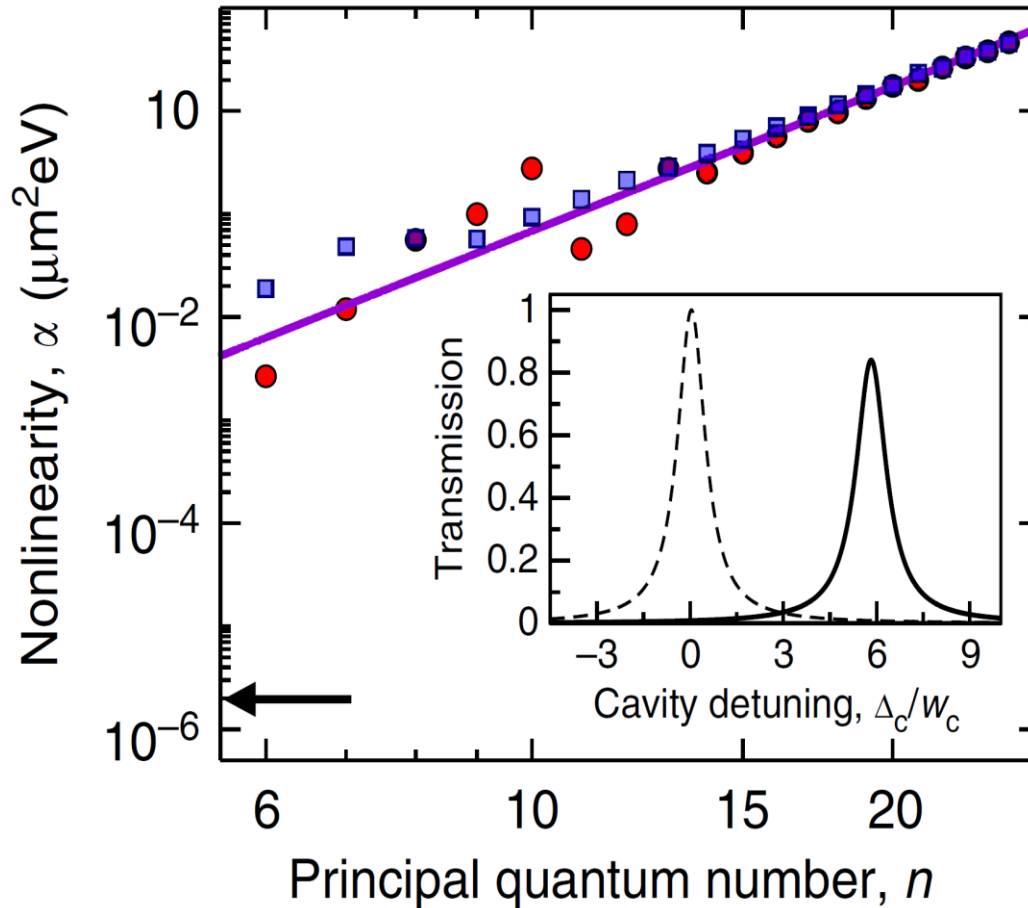


Excited States of Excitons in 2D TMDs

Rydberg States



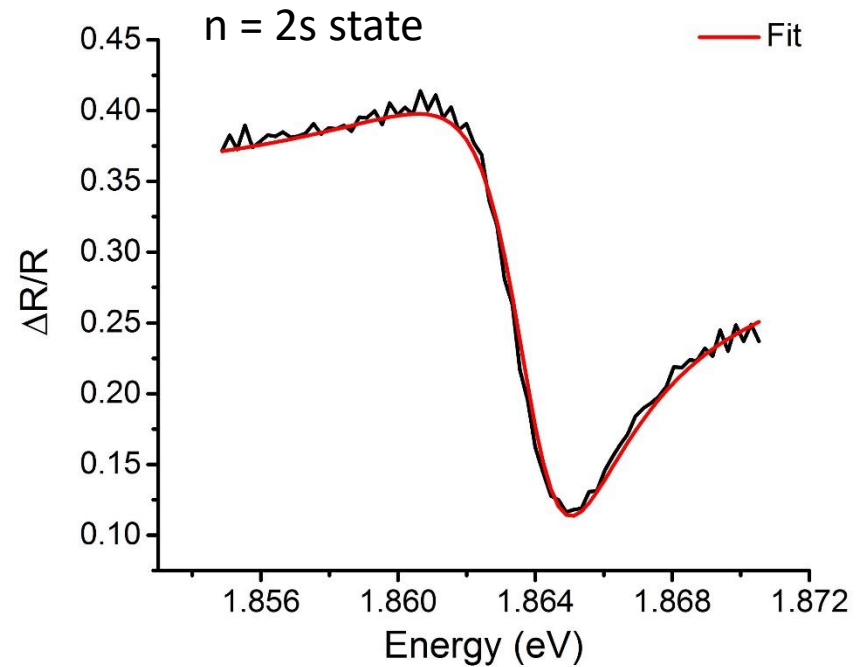
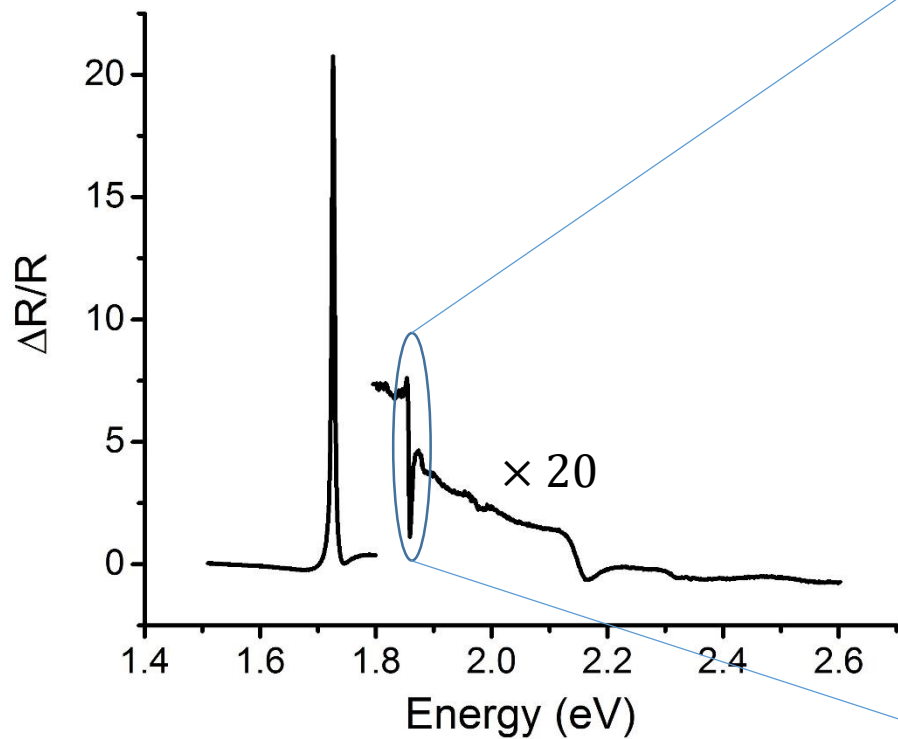
Enhanced interactions via Rydberg States



Valentin Walther, ..., Thomas Pohl. NATURE COMMUNICATIONS **9**, 1309 (2018)

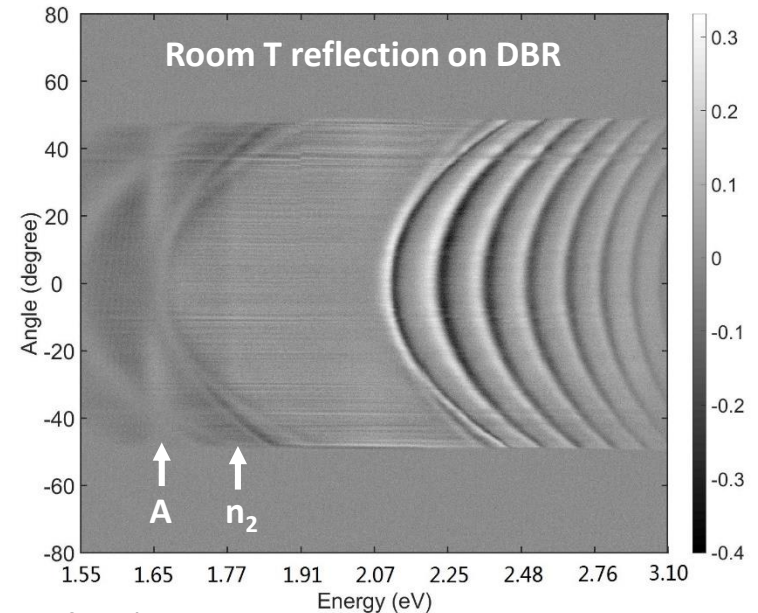
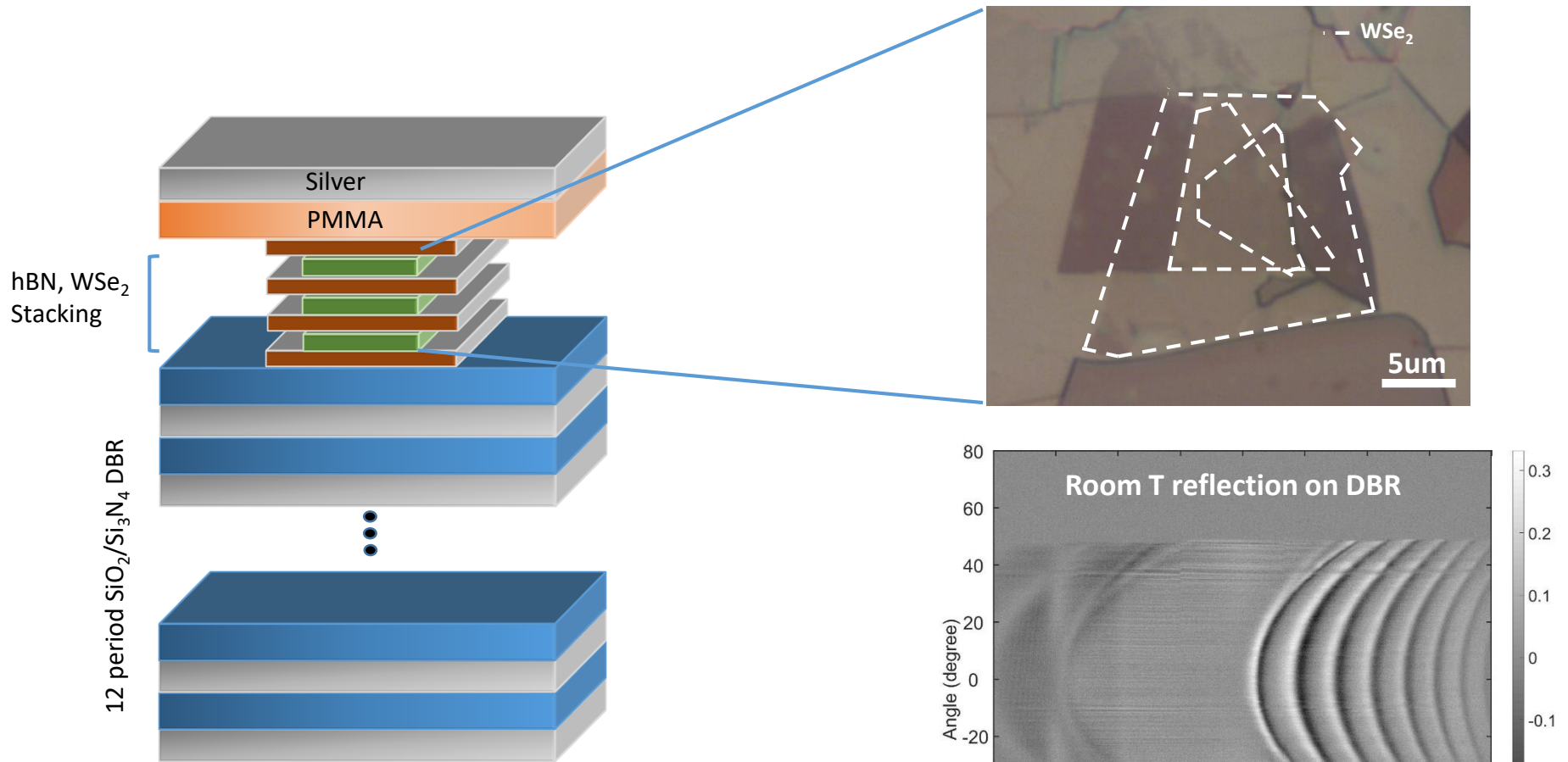
Excitons in 2D TMDs: Excited States

WSe₂ 4K



Linewidth = 4meV

Excited State Exciton Polaritons



Collaborators:

Archana Raja, Lutz Waldecker Tony Heinz (Stanford)

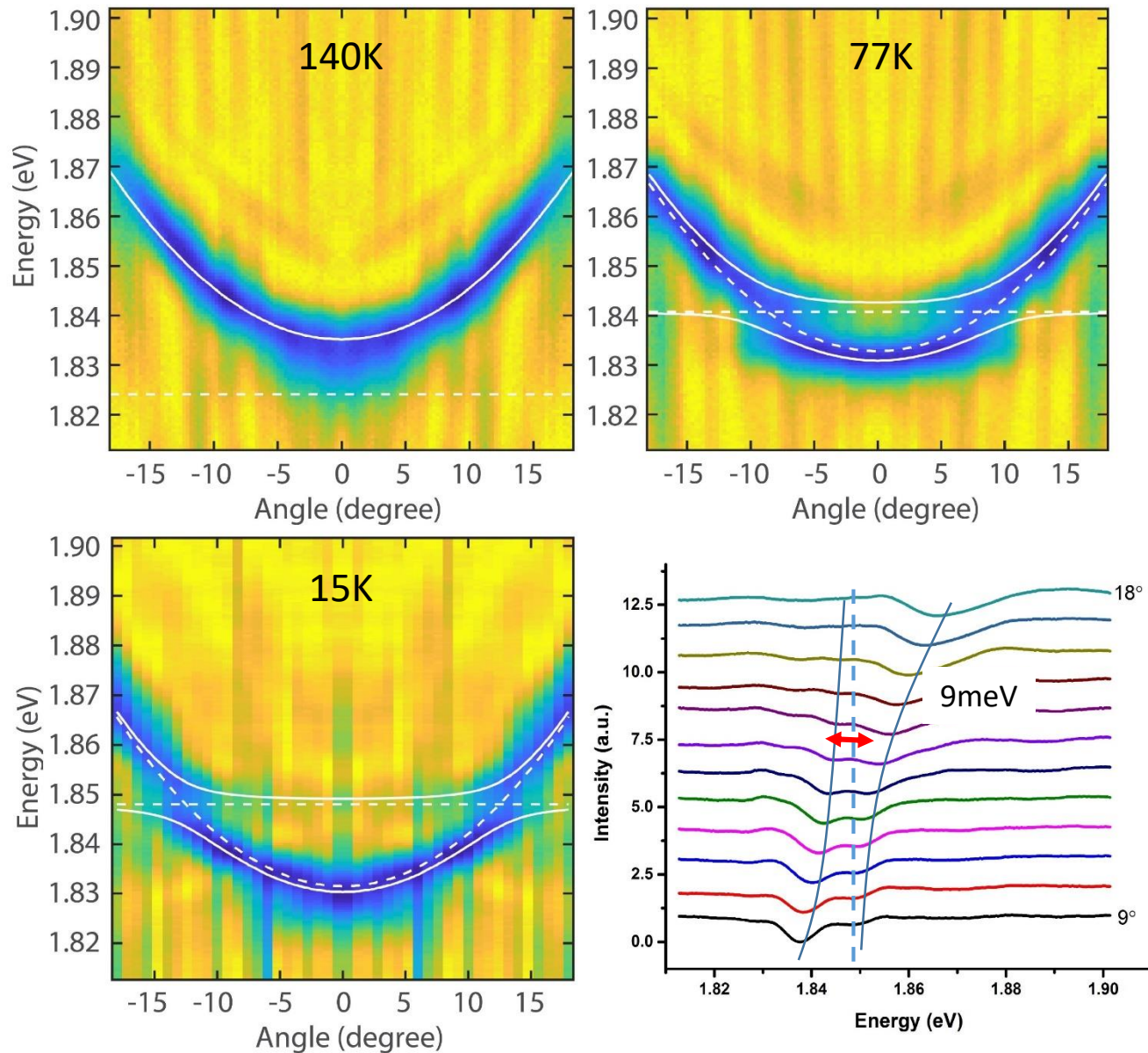
Daniel Rhodes, Jim Hone (Columbia)

Stephane Kena-Cohen (Montreal Polytechnic)

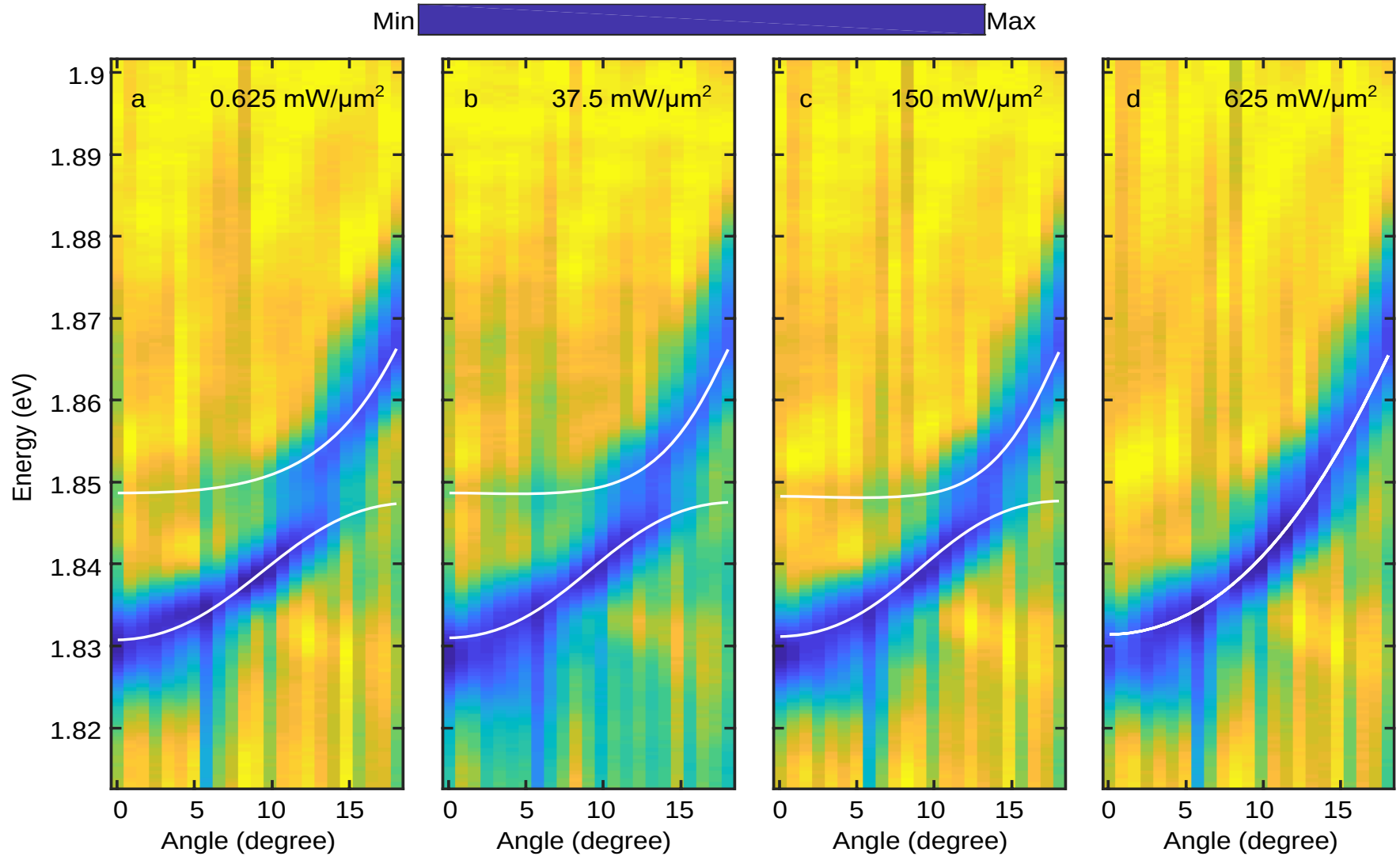
Jie Gu

Grad Student – CUNY

Excited State Exciton Polaritons ($n = 2S$)

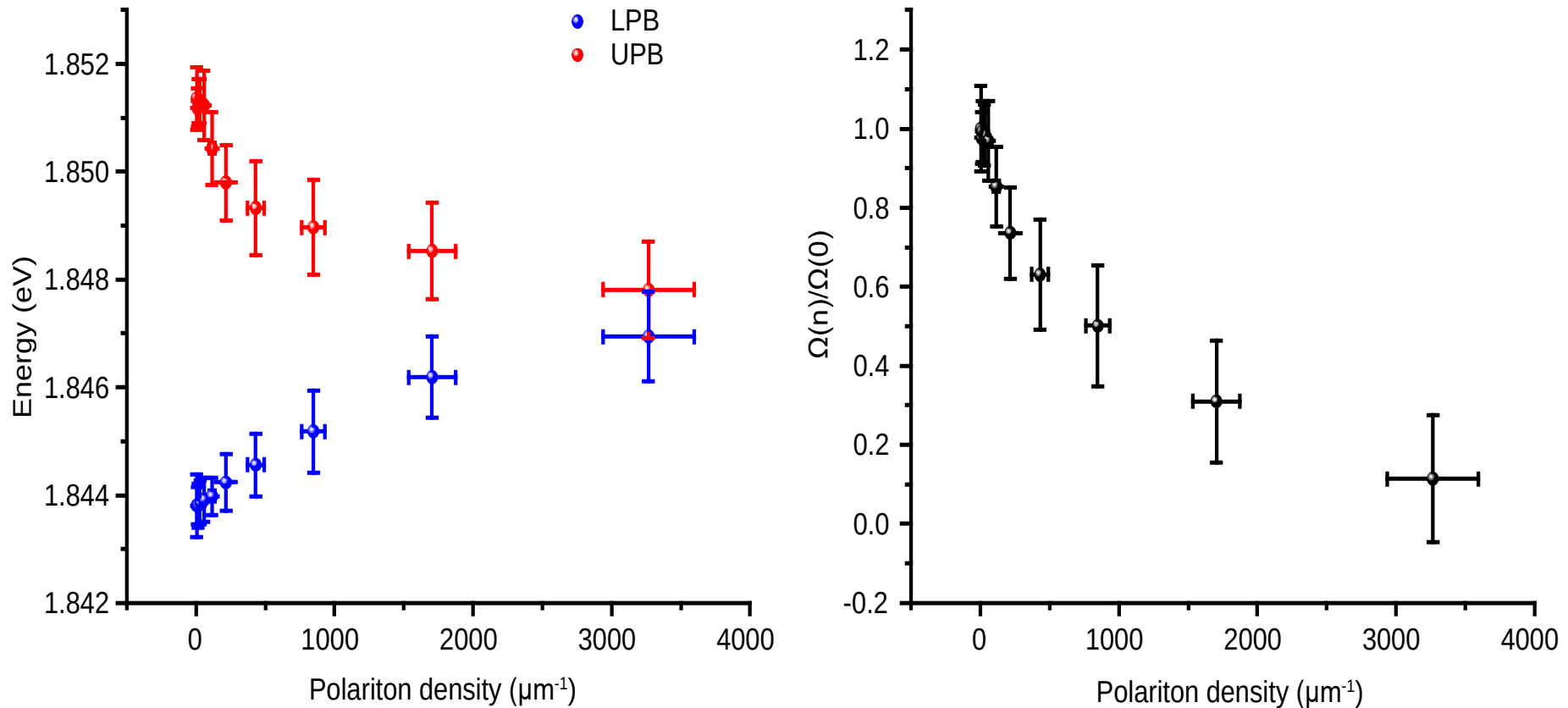


Pump dependence of “2S” Exciton Polaritons



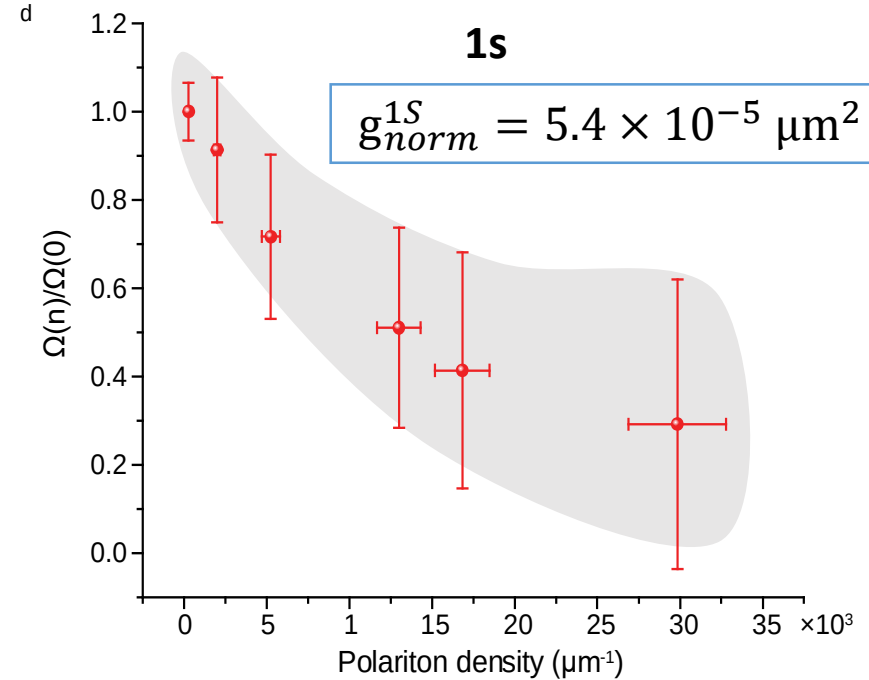
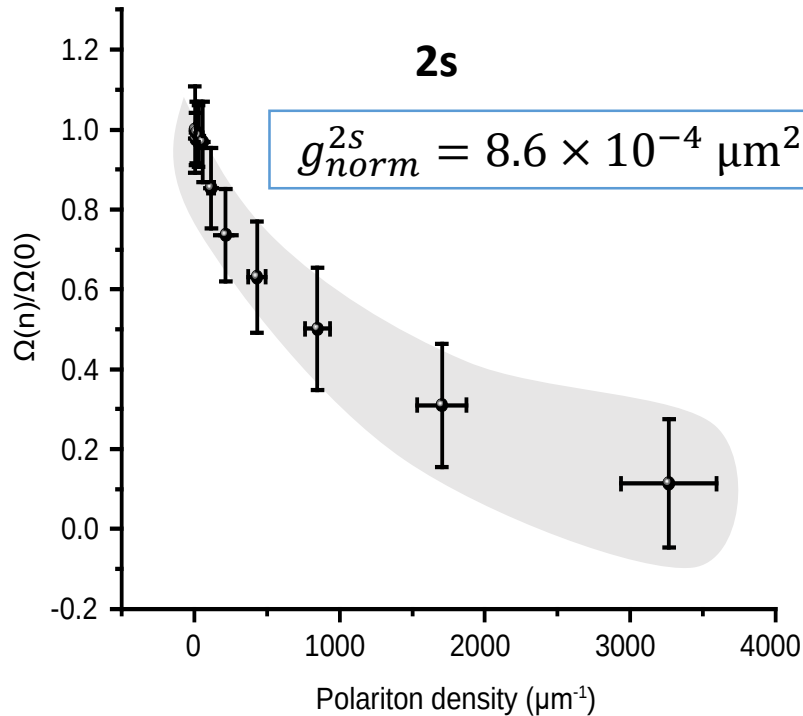
Interaction of excited state polaritons

$$g \propto \hbar \Omega_0 a_B^2.$$



$$g_{norm} = (2\hbar\Omega_0 - 2\hbar\Omega_n) / (2\hbar\Omega_0) / n = (\Omega_0 - \Omega_n) / \Omega_0 / n$$

Interaction of excited state polaritons



$$g_{\text{norm}}^{2s}/g_{\text{norm}}^{1s} = 8.6 \times 10^{-4} \mu\text{m}^2 / (5.4 \times 10^{-5} \mu\text{m}^2) = 15.9$$

$$\text{Theoretically: } g_{\text{norm}}^{2s}/g_{\text{norm}}^{1s} = (6.6 \text{ nm})^2 / (1.7 \text{ nm})^2 = 15.1$$



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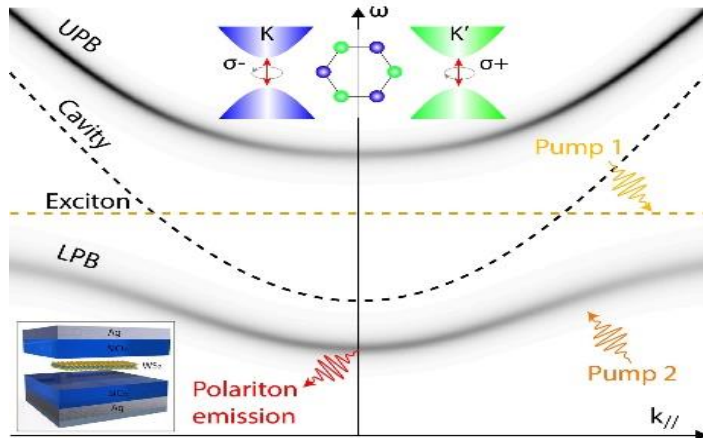
$$g_{\text{sat}}^{(2s)} \sim 15 g_{\text{sat}}^{(1s)}$$

$$g^{2s} \sim 0.2 \mu\text{eV} \mu\text{m}^2$$

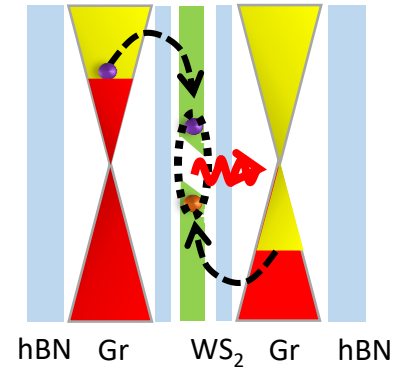
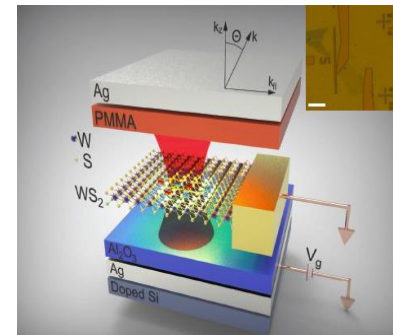
Manuscript under preparation

Summary

Valley exciton polaritons



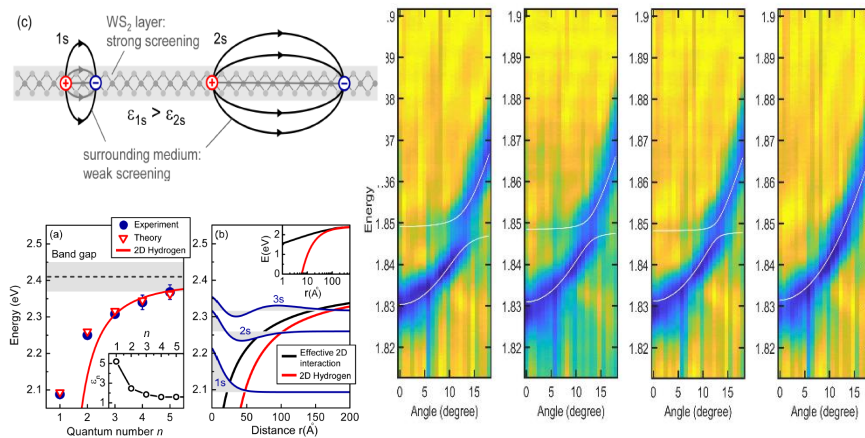
Electrical control and polariton LED



Weak to strong coupling

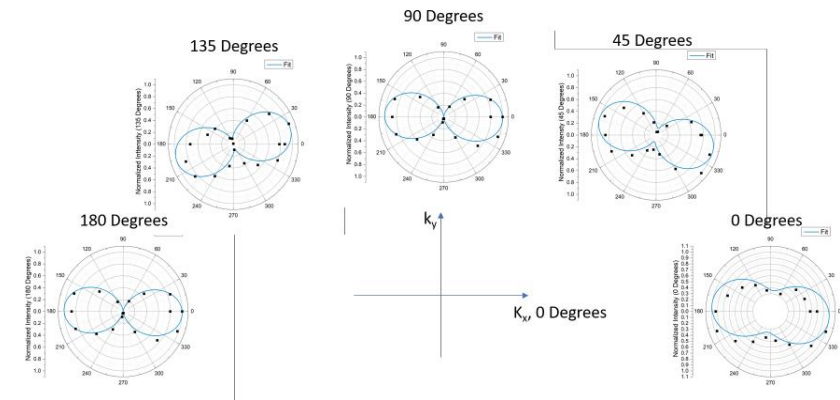
Electroluminescence

Rydberg exciton-polaritons



$$g(2s) \sim 15 g(1s)$$

Control of valley pseudospin



The Team

Graduate Students



Jie Gu



Mandeep Khatoniyar



Rezlind Bushati



Gabriel Lopez
(w/ Carlos Meriles)



Rong Wu

Post Docs



Sriram Guddala

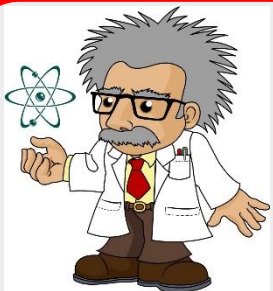


Biswanath Chakraborty



Bin Liu

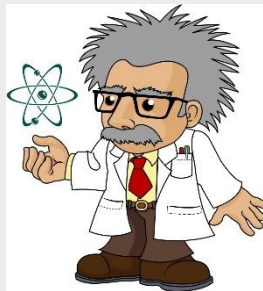
UG Students



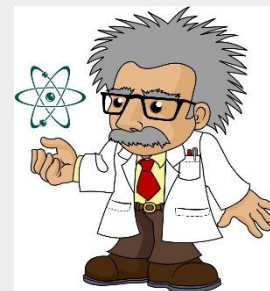
Nicholas Yama



Rian Koots



Michael Miranda



Mohammad Hassan



Francesca Suddu

Relevant Publications

“Control of strong light-matter interaction in monolayer WS₂ through electric field gating,” B. Chakraborty, et. al., *Nano. Lett.* **18**, 6455 (2018).

“Interacting polariton fluids in a monolayer of tungsten disulfide,” F. Brachati, et. al., *Nature Nanotech.* **13**, 906(2018)

“Near deterministic activation of room temperature quantum emitters in hexagonal boron nitride,” N. V. Proscia, et. al., *Optica* **5**, 1128 (2018).

“Optical control of room temperature valley polaritons”, Z. Sun, et al., *Nature Photonics*, **11** 491 (2017)

“Photonic hypercrystals for control of light-matter interaction,” T. Galfsky, J. Gu, E. Narimanov and V. M. Menon, *PNAS* **114**, 5119 (2017).

“Broadband enhancement of spontaneous emission in 2D semiconductors using photonic hypercrystals,” T. Galfsky, et. al., *Nano Lett.* **16**, 4940 (2016).

“Photoinduced modification of single photon emitters in hBN,” Z. Shotan, et. al., *ACS Photonics* **3**, 2490 (2016).

“Strong light-matter coupling in two-dimensional atomic crystals,” X. Liu, et. al., *Nature Photonics* **9**, 30 (2015).

Thank you!

