Control of light-matter interaction in 2D Van der Waals materials

Vinod M. Menon

Laboratory for Nano and Micro Photonics
City College of The City University of New York (CUNY)
Graduate Center of CUNY

http://www.lanmp.org
E-mail: vmenon@ccny.cuny.edu

Center for Functional Nanomaterials
Brookhaven National Laboratory

EFRI 2DARE
ECCS 1509551
DMR 1120923
MRSEC: PAS^3

ICTS – OQS, 2017

Team

Zheng Sun
Grad Student – CUNY

Jie Gu
Grad Student – CUNY

Dr. Biswanath Chakraborty
Postdoc– CCNY

Ryan Considine
Grad Student– CCNY

Michael Dollar
Undergraduate – CCNY

Dr. Areg Ghazryan
Postdoc-CCNY

Prof. Pouyan Ghaemi
CUNY

Prof. Stéphane Kéna-Cohen
École Polytechnique de Montréal

Prof. Yi-Hsien Lee
NTHU

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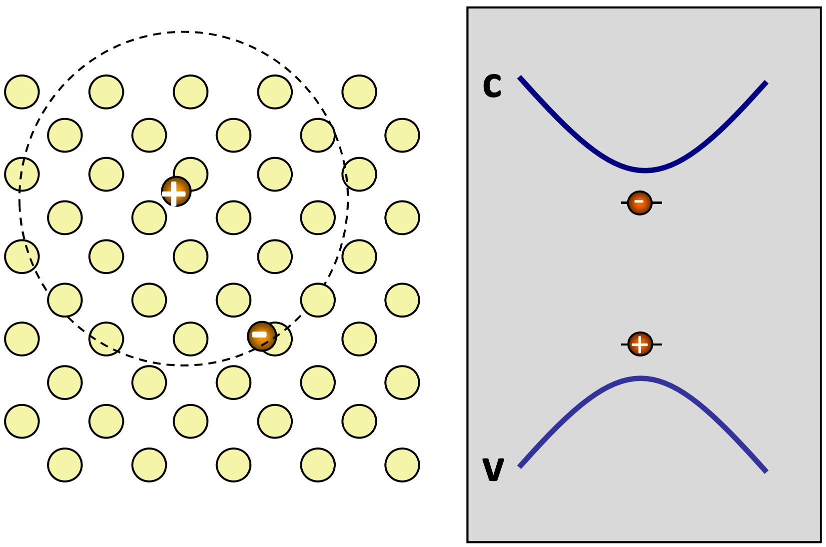
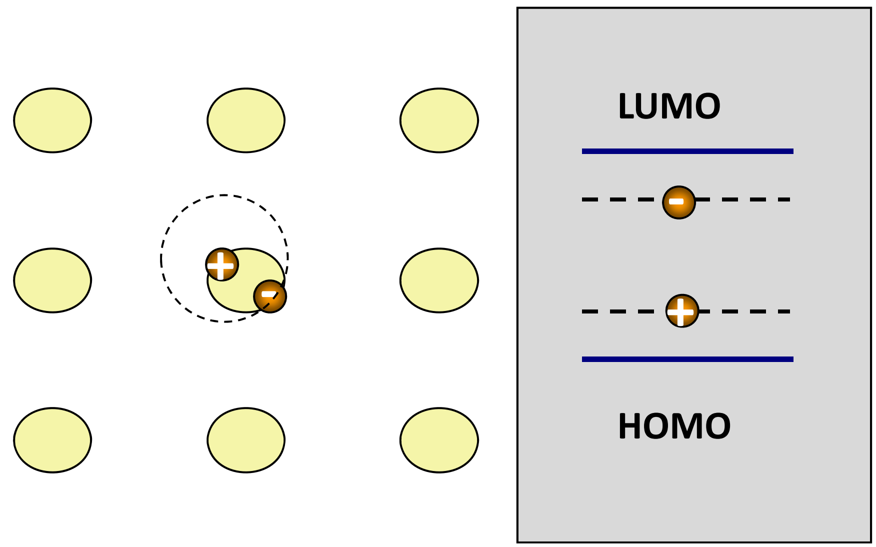
Excitons

Wannier-Mott excitons



Inorganic Materials

Frenkel excitons



Organic Materials

Excitons

Wannier-Mott excitons

Inorganic Materials

- Large exciton radius ~ 100Å
- Small binding energy (10-60meV)
- Long range ballistic transport
- Condensation (Low T)
- Polariton Lasing (~Room T)
- Small saturation density

Frenkel excitons

Organic Materials

- Localized at molecular site
- Large binding energy (0.5 – 1 eV)
- Hopping transport
- Forster / Dexter energy transfer
- Polariton lasing (Room T)
- Large saturation density

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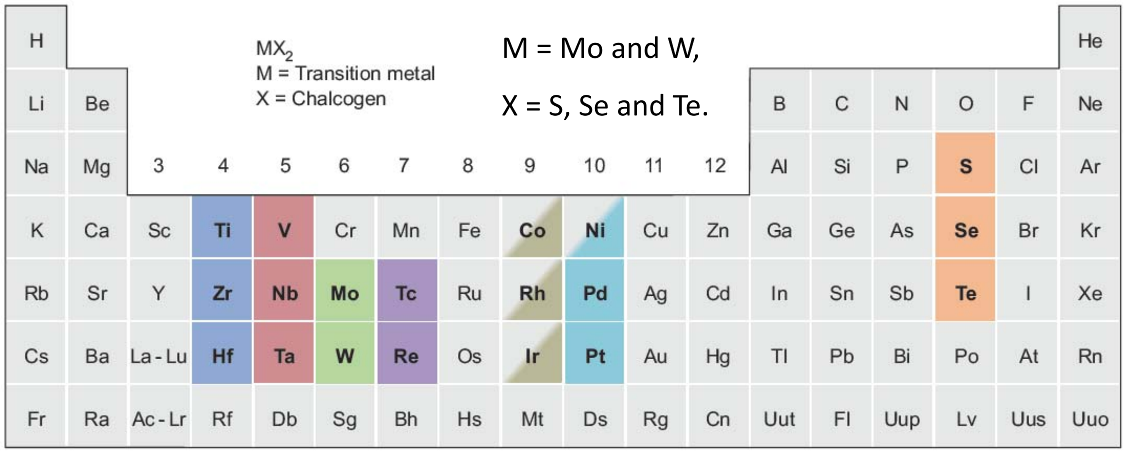
Transition Metal Di-Chalcogenides

2D materials with optical bandgap



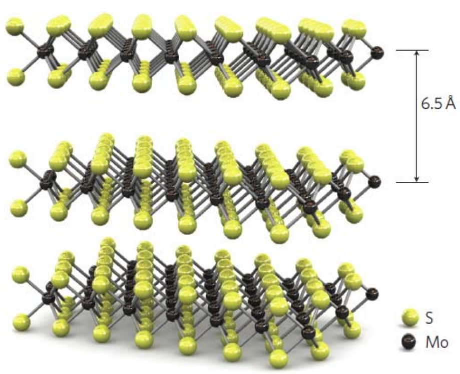
M = Mo and W,

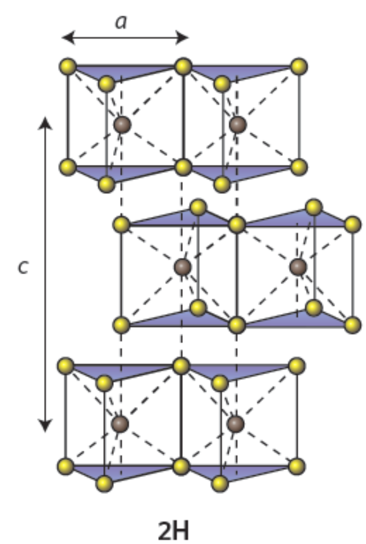
X = S, Se and Te.

Chhowalla, M. et al (2013), *Nat. Chem.*, *5*, 263–275.

MoS_2
1L :1.8eV, Bulk: 1.2 eV

WS_2
1L: 2.1eV, Bulk: 1.4 eV





Radisavljevic, B. et al (2011), *Nat. Nanotechnol.*, 6, 147–150.

Wang, Q. H. et al (2012), *Nat. Nanotechnol.*, *7*, 699–712.

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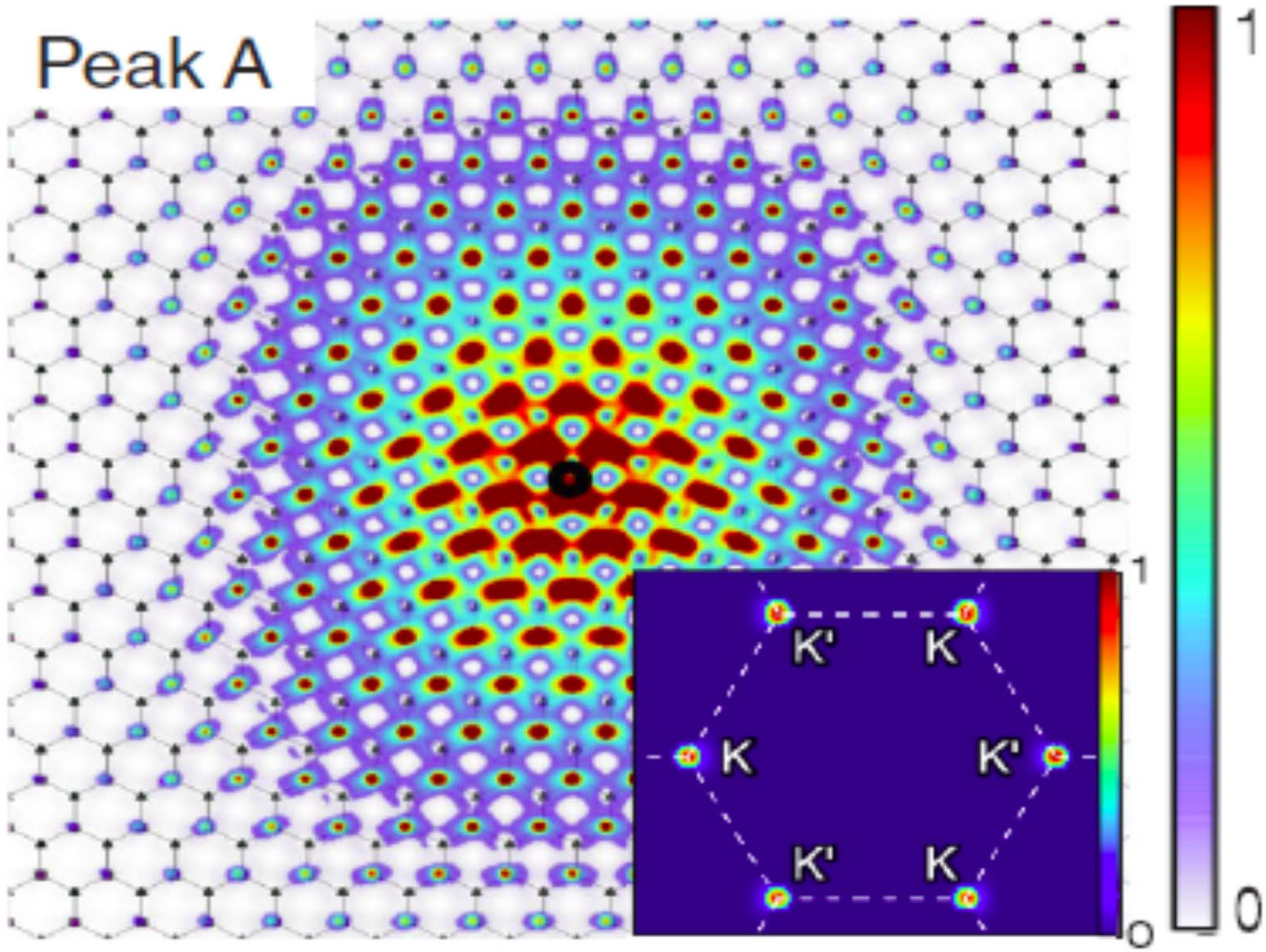
Excitons in 2D TMDs: Best of both worlds?

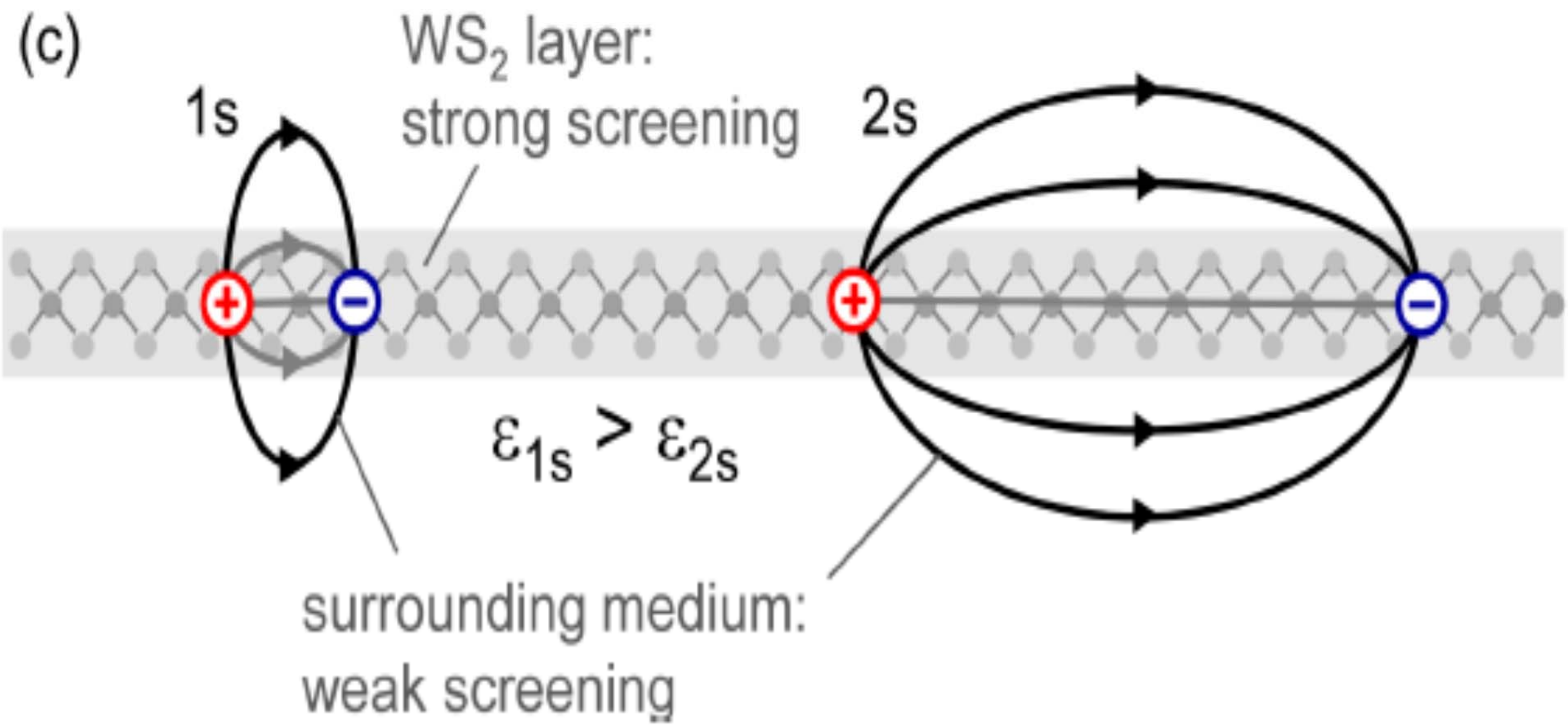
Bohr Radius ~ 1 nm (MoS_2)



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

Excitons in 2D TMDs: Best of both worlds?

Binding Energy (0.3-0.5 eV)



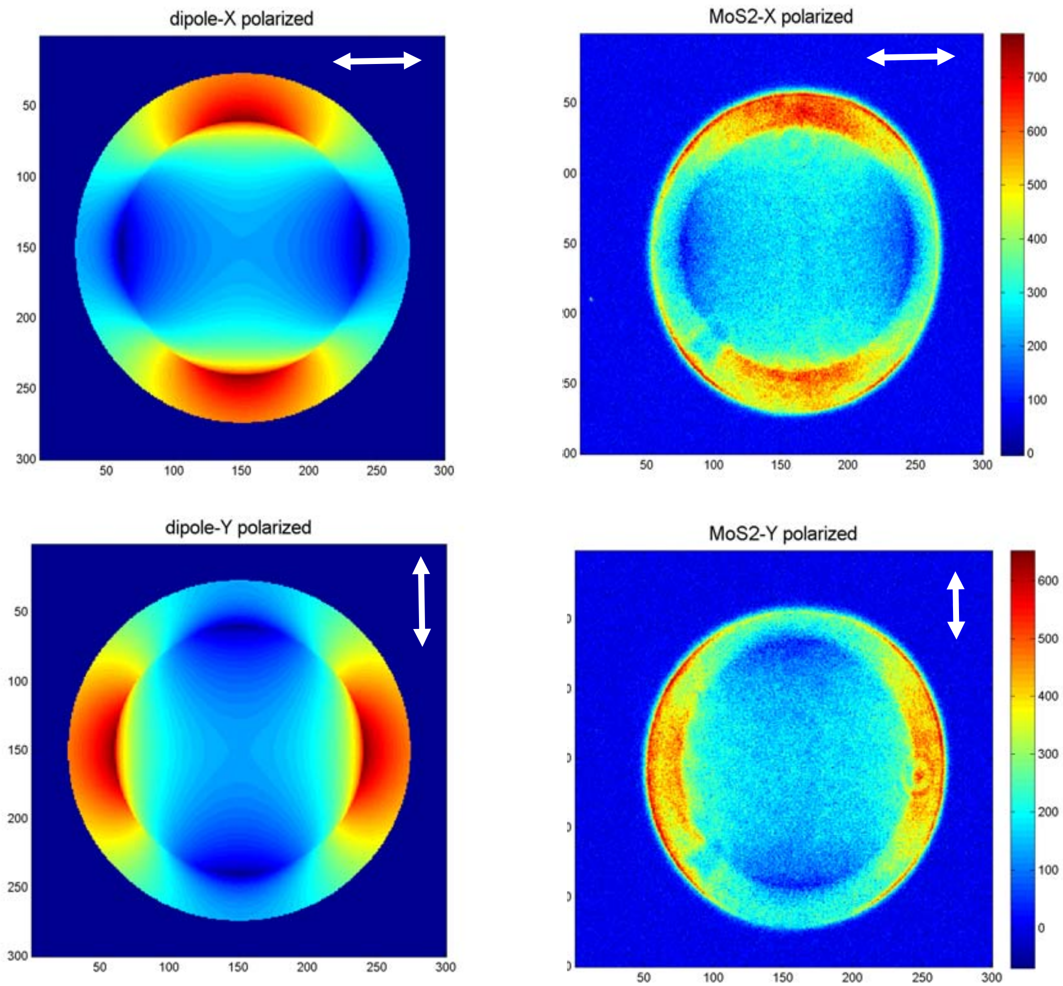
Chernikov et al. PRL 113, 076802 (2014)

In-plane Dipoles

2D dipole orientation.

Simulation

K-space image



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

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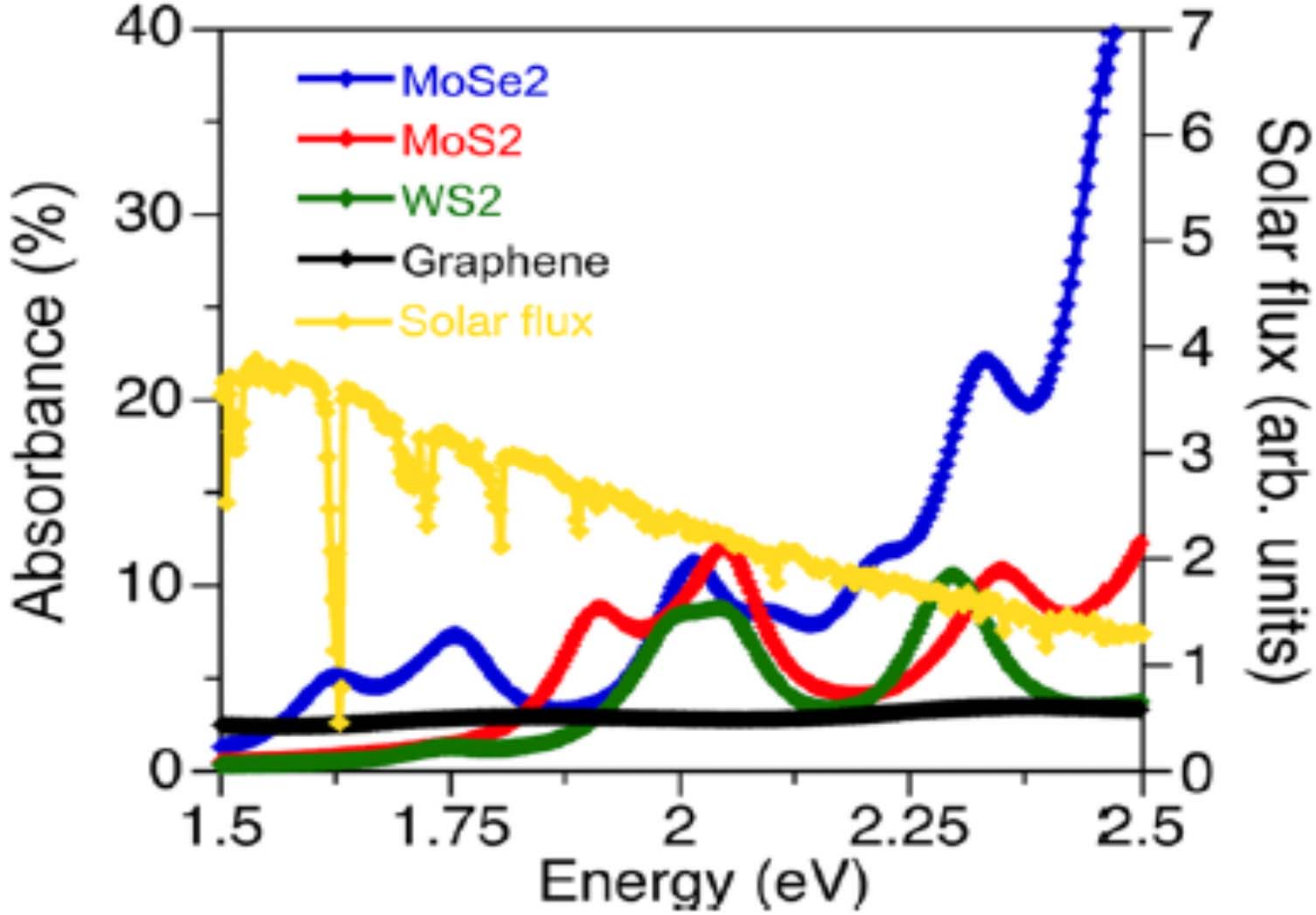
Large oscillator strength

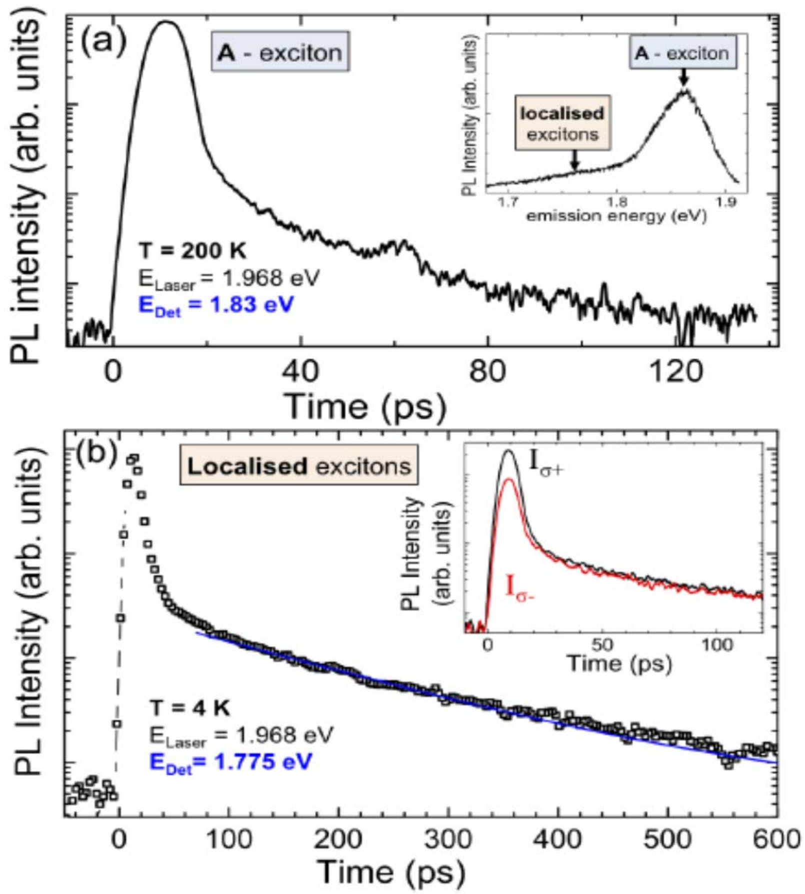


1 ML absorbs 5-10% light !

Bernardi, Palummo and Grossman, *Nano Lett.*, ***13***, 3664 (2013)

Exciton Lifetime

CVD grown 2D MoS_2 : < 4 ps [*Sie et al. arxiv 1312.2918*]
Exfoliated 2D MoS_2: 5-6 ps, 125 ps (localized excitons) [*Lagarde et al. 1308.0696 (2013)*]



Lagarde et al. Physical Review Letters 112, 047401 (2014)

Mai et al. Nano Lett. 14, 202 (2013)

Wang, G. et al. arXiv:1402.6009 (2014)

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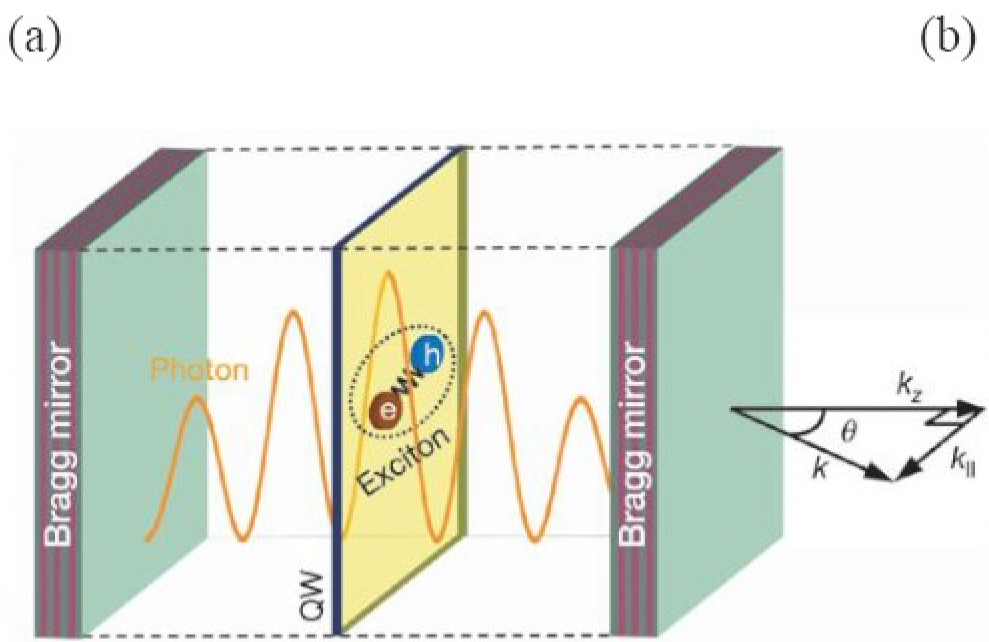
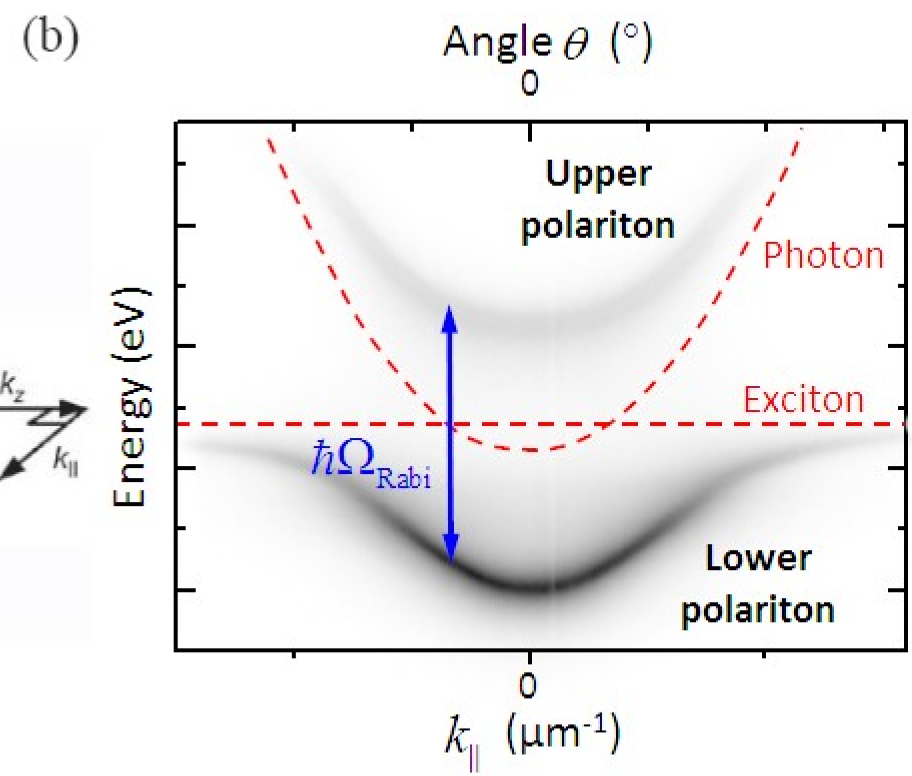
Microcavity Polaritons



J. Kasprzak. et al(2006), *Nature, 443(7110), 409–414.*



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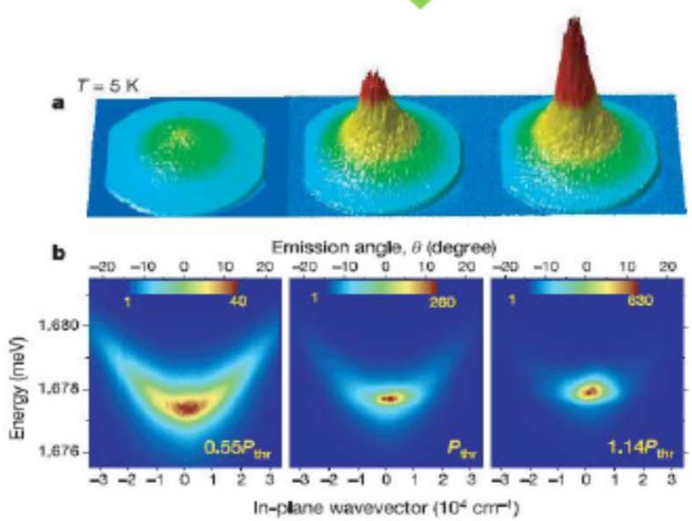
Microcavity Polaritons

Composite bosons: half-exciton half-photon

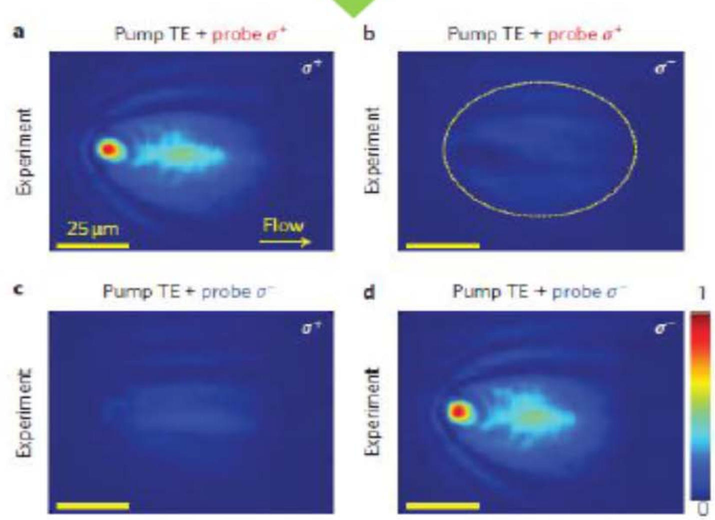
Excitonic component – Electronic response, scattering and nonlinearity
Photonic component – Small mass, spatial coherence and long propagation

Polariton condensation



Kasprzak. J. et al. *Nature* **443**, 409 (2006)
Balili, R., et al. *Science* **316**, 1007 (2007).

Polariton spin switch

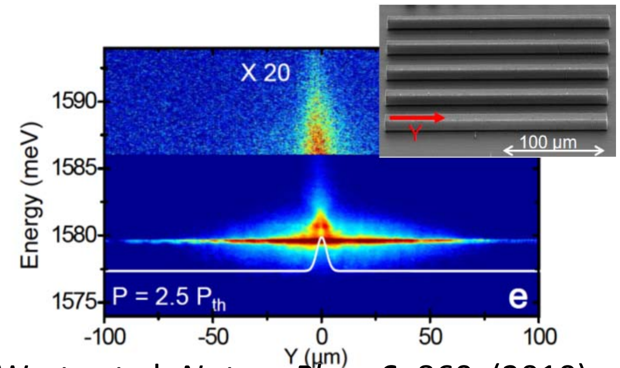


Amo et al. *Nature Photonics* **4**, 361 (2010)

Microcavity Polaritons

Cryogenic Temperatures

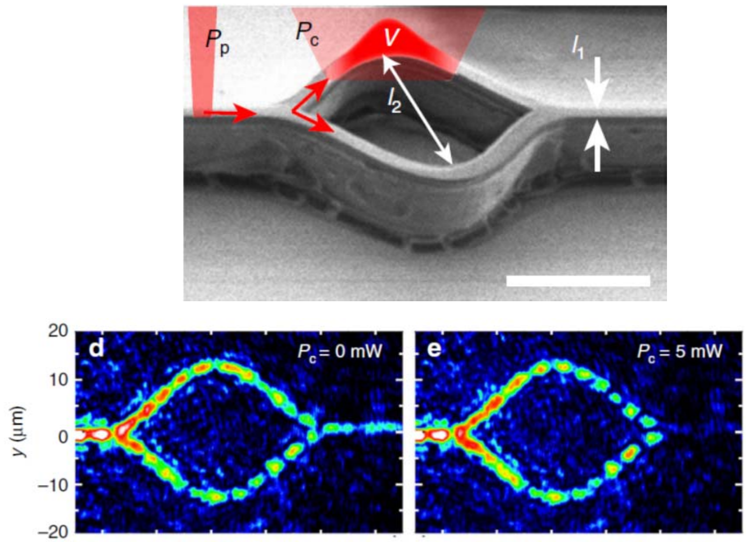
- Condensation – Kasperzak, Balili
- Superfluidity – Amo, Lagoudakis,
- Thermalization of polaritons – Snoke, Pfeiffer, West
- 2DEG polaritons – Imamoglu, Faist
- Polaritons in Intersubband systems – Sirtori, Tredicucci,
- Polariton lattices – Amo, Bloch, Tureci
- Confined polaritons – Wertz, Bloch, Deveaud
- Mach Zehnder/Sagnac interferometer – Amo, Bloch



Wertz et al. *Nature Phys*. **6**, 860 (2010)

Room Temperature

- Organic (Holmes, Kena-Cohen, Forrest, Lidzey…)
- Hybrid (Holmes, VMM, Forrest, Lidzey…)
- Zno (Deng, van Vugt, Trichet, Malpuech, VMM…)
- GaN (Baumberg, Bhattacharya…)
- 2D materials (VMM, Imamoglu, Tartakovskii…)



Sturm et al. *Nature Comm.* **5** 3278 (2014)

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Strong coupling in 2D materials

	Monolayer TMDs	GaAs Quantum wells
Thickness	< 1 nm	> 3 nm
Excitons	Wannier-Mott-like	Wannier-Mott
Binding energy	~ 0.3 – 0.5 eV	~ 10 meV
Bohr radius	~ 2 nm	~ 10 nm
Oscillator strength	High	Low
Mobility	~ 400 $cm^2/V \cdot s$	~10^3 $cm^2/V \cdot s$

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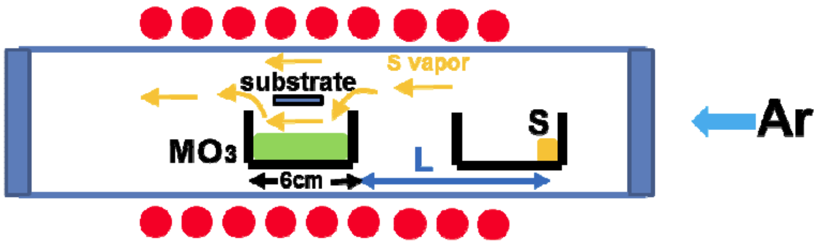
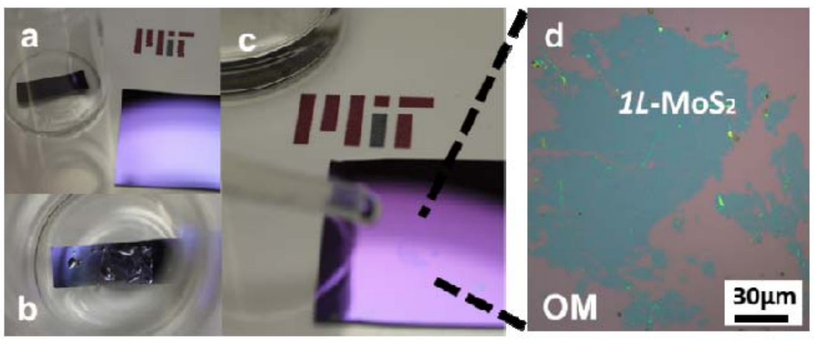
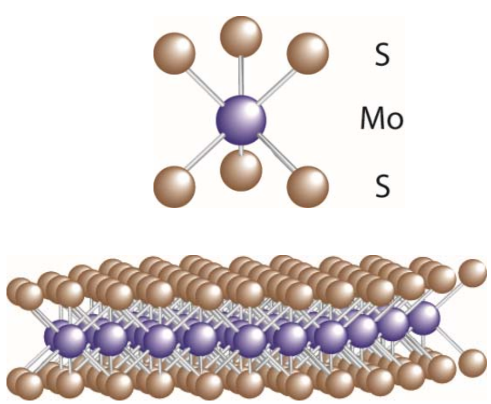
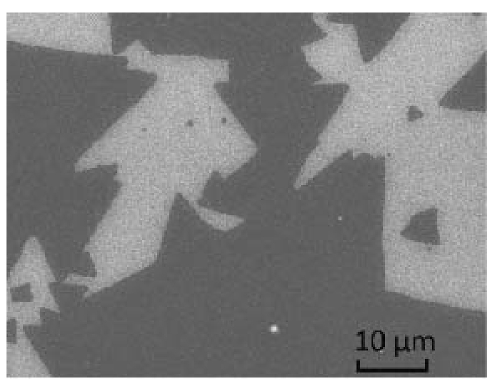
CVD grown MoS_2 Monolayer

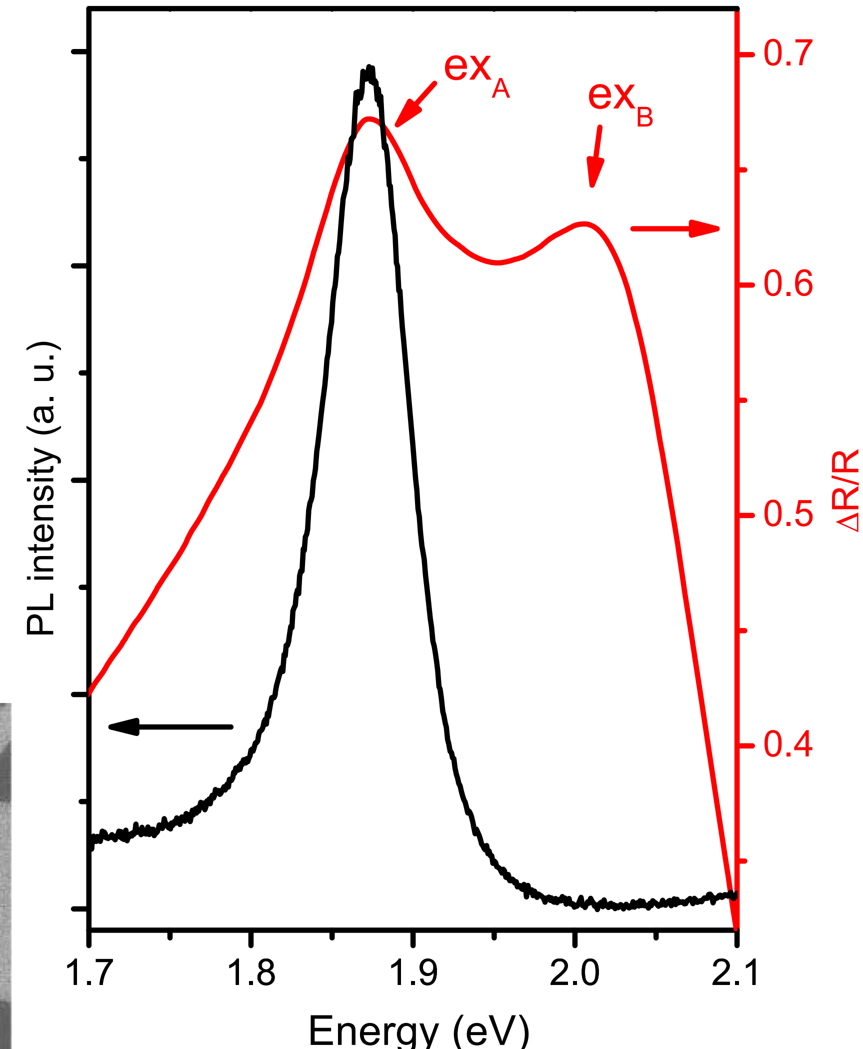




Lee, Y.-H. *et al* (2013), *Nano Lett.* **13,** 1852–1857.







Growth of 2D Materials by Y. H. Lee's group – NTHU, Taiwan

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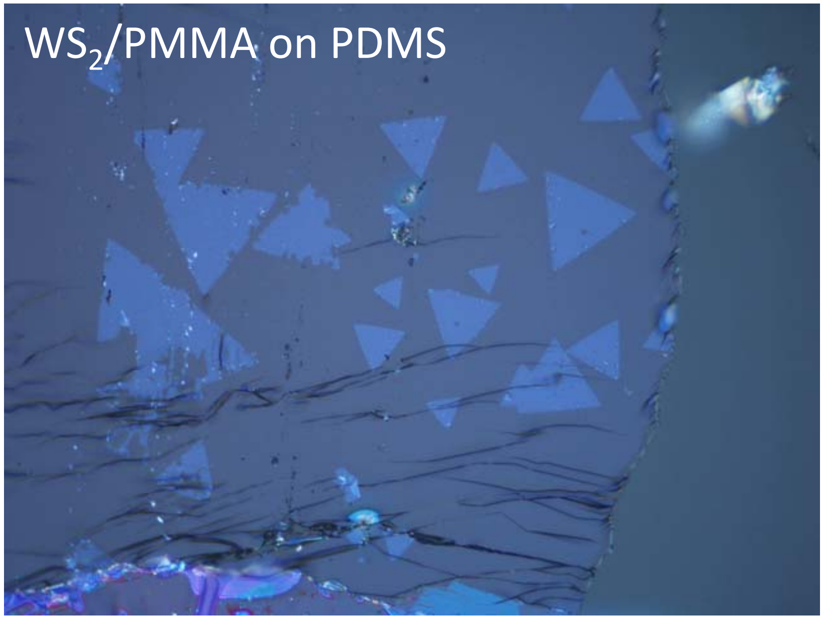
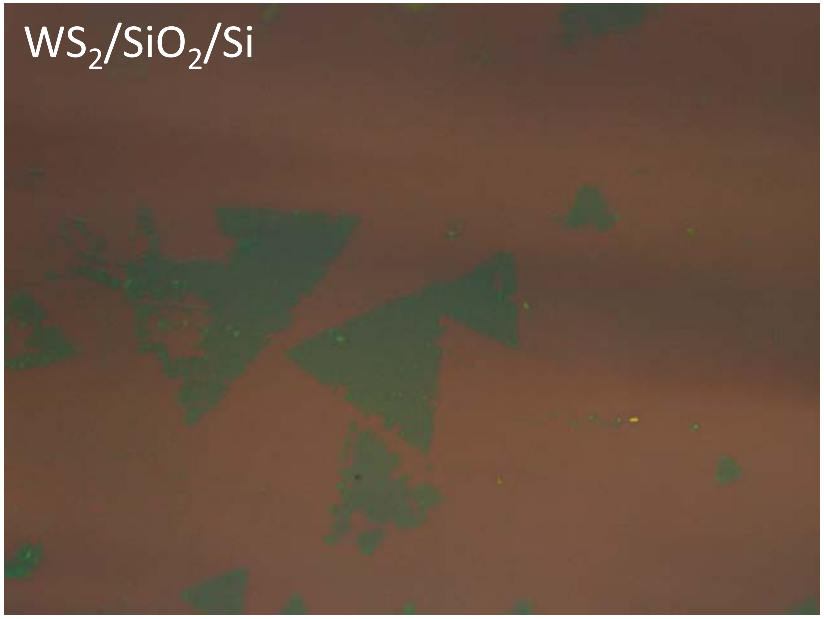
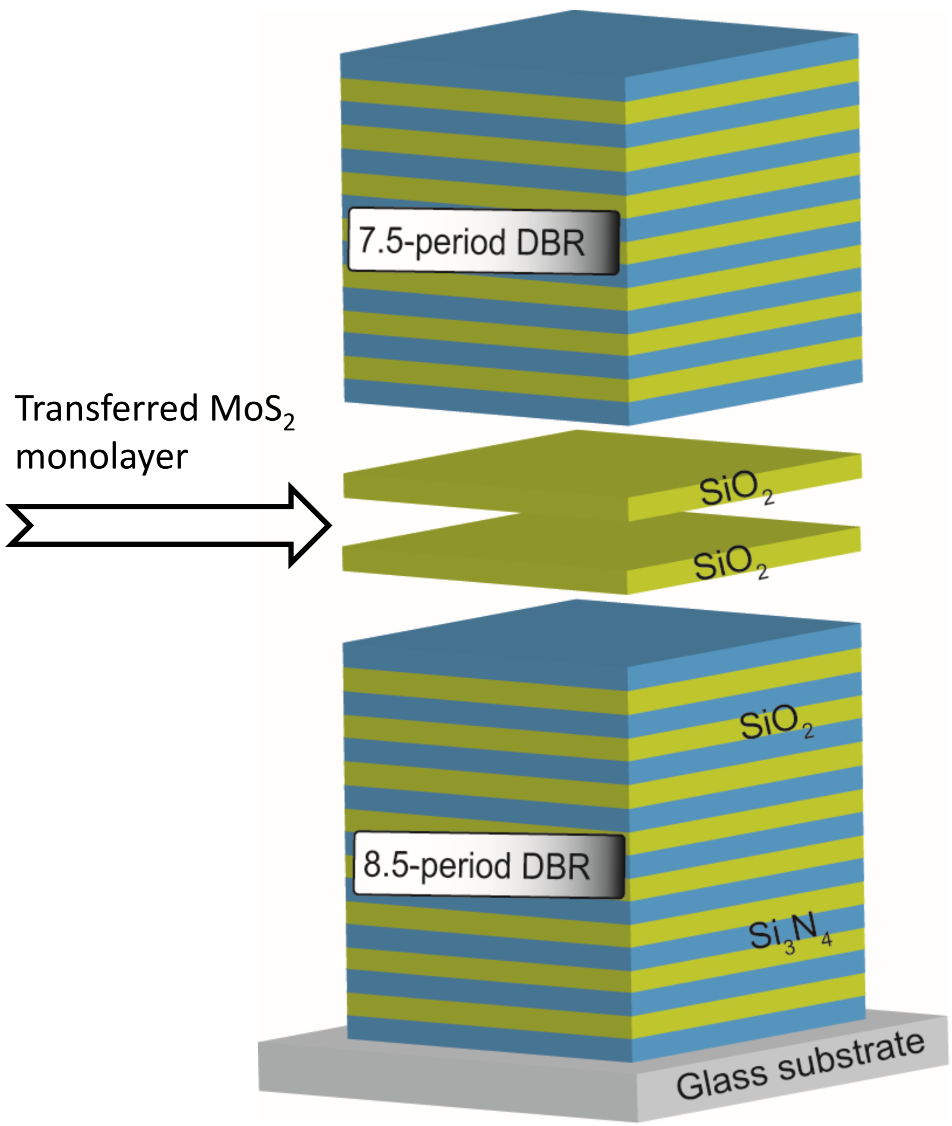
Transfer of CVD grown 2D layers

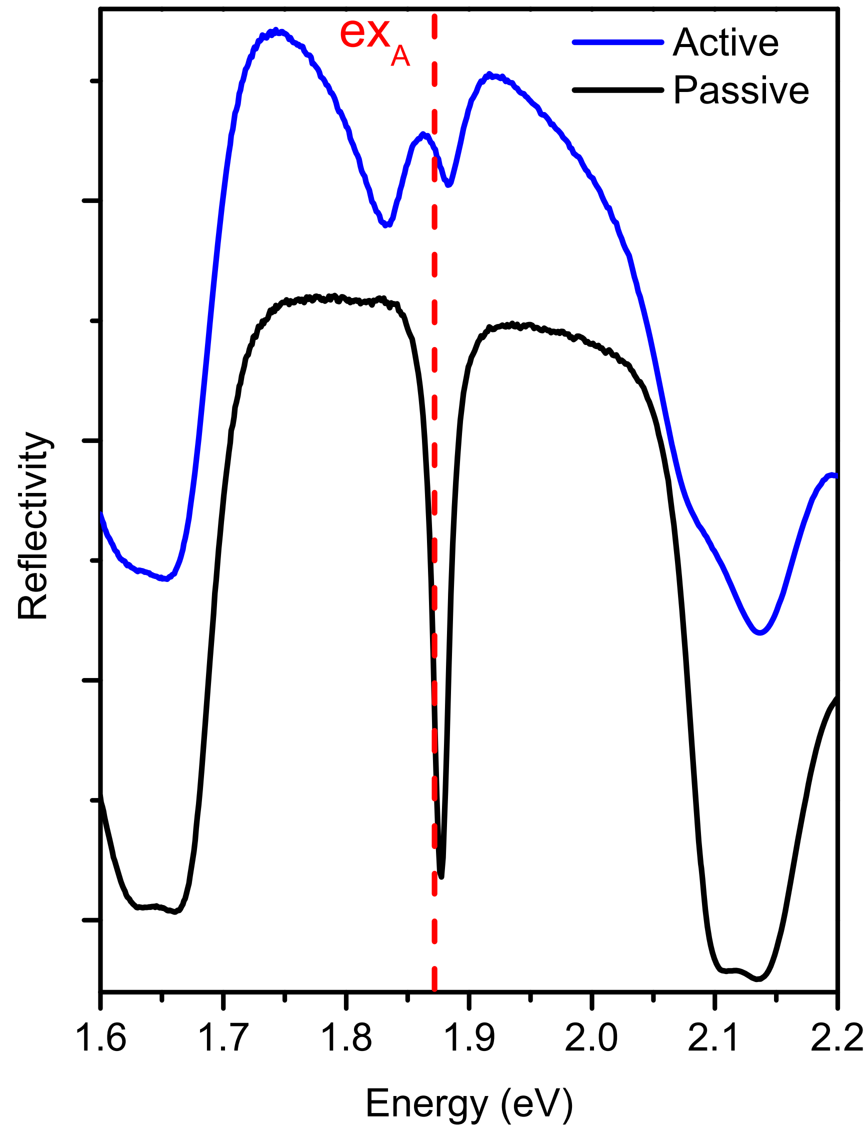




PDMS based transfer
KOH etch

MoS_2 Microcavity





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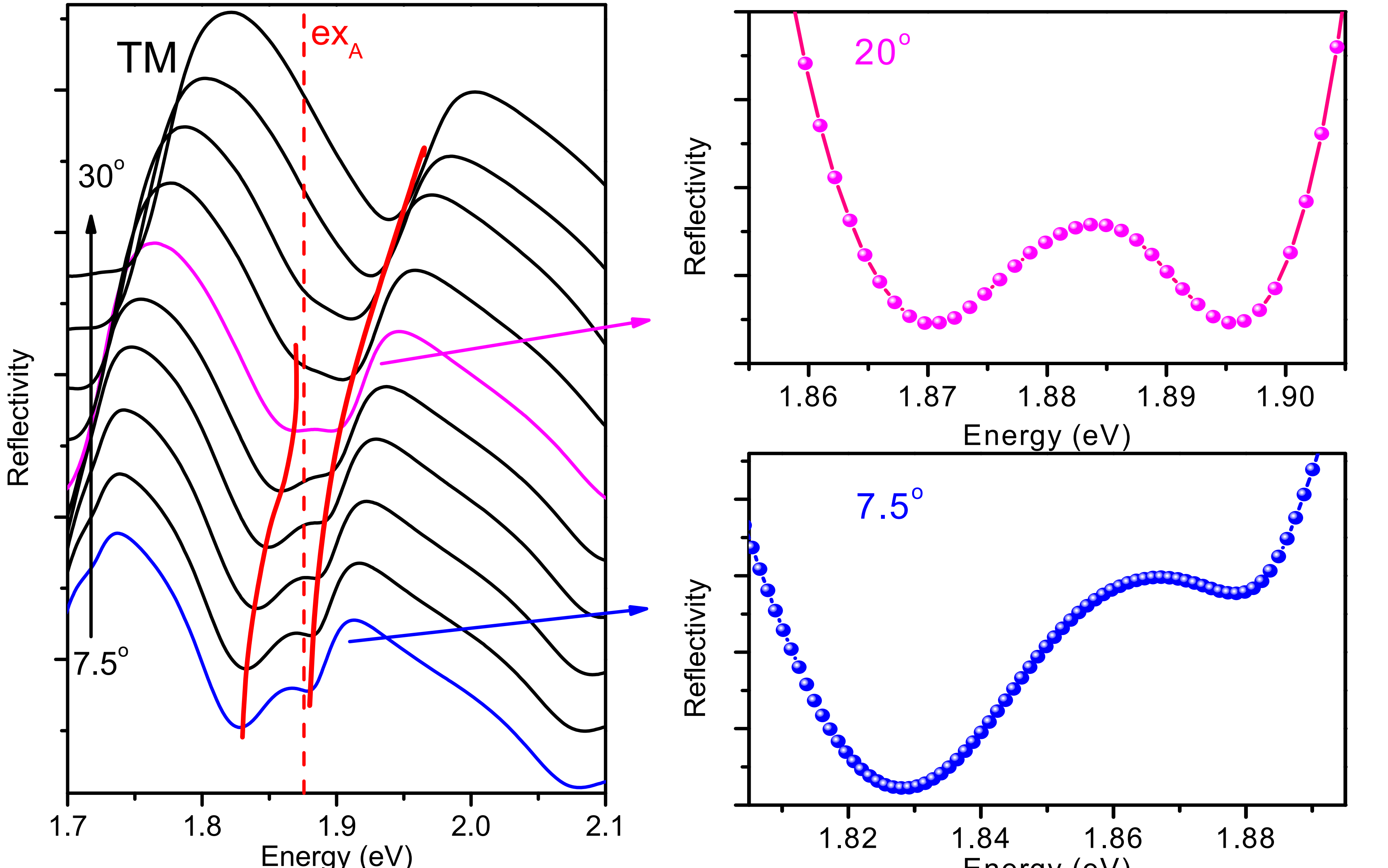
Angle-resolved reflectivity



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

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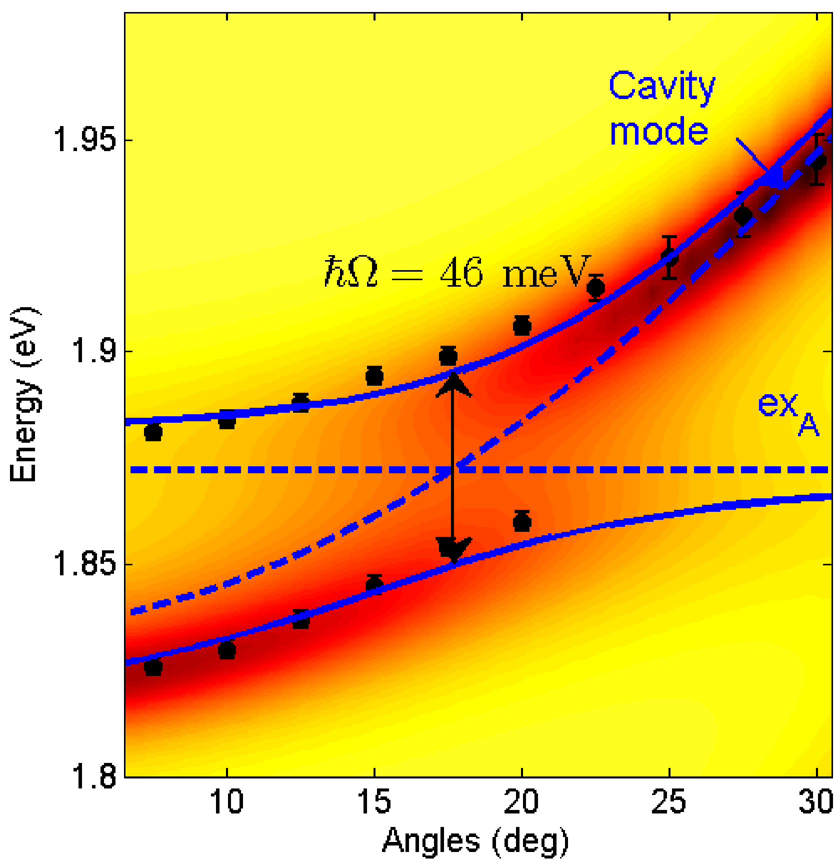
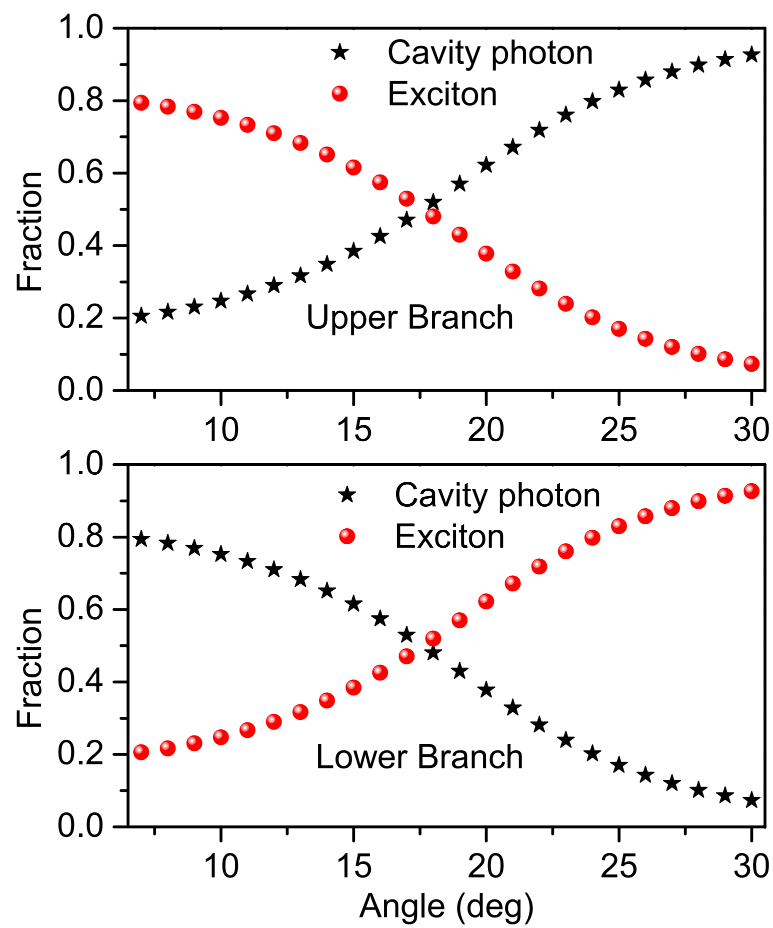
Reflectivity Dispersions



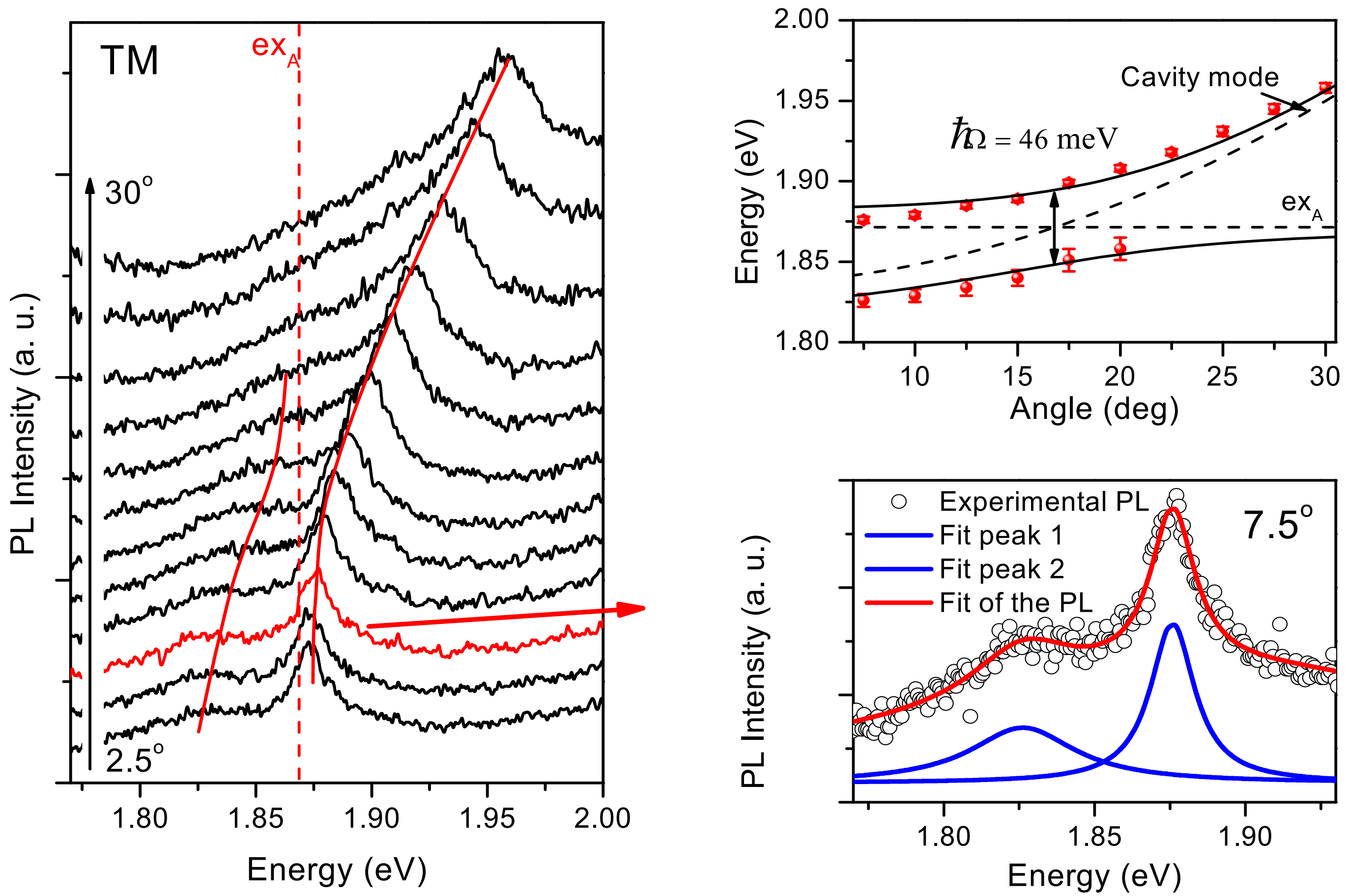


Determining the strong coupling regime:

$$\hbar\Gamma_{ex} = 60\text{ meV},\quad \hbar\Gamma_{cavity} = 17\text{ meV},\quad \hbar\Omega_{Rabi} = 46\text{ meV}$$

$$\Rightarrow \quad V = 31.5\text{ meV} \quad \Rightarrow \quad V^2 > \left(\frac{\hbar\Gamma_{ex} - \hbar\Gamma_{cav}}{2}\right)^2$$

Angle-resolved PL



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).

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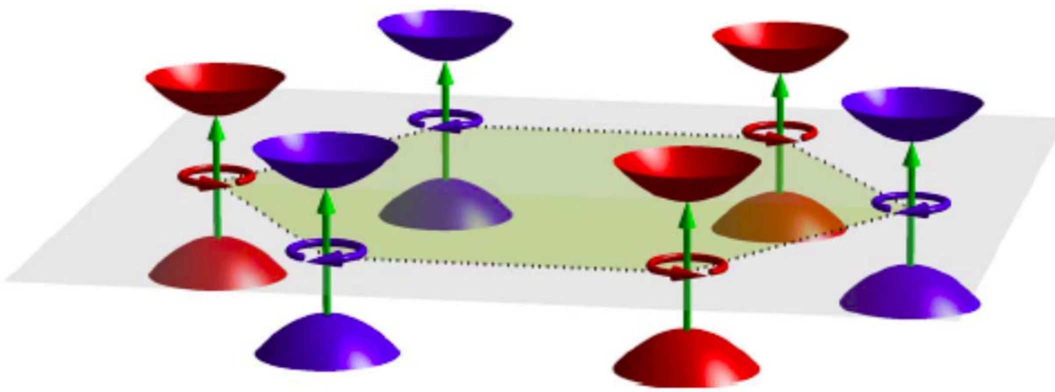
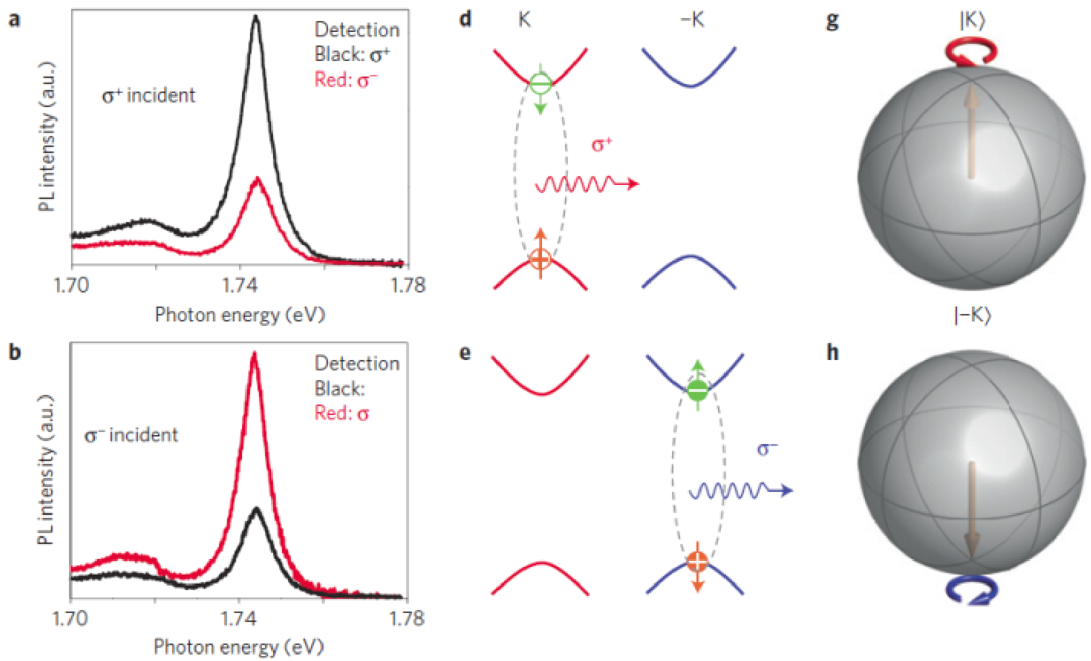
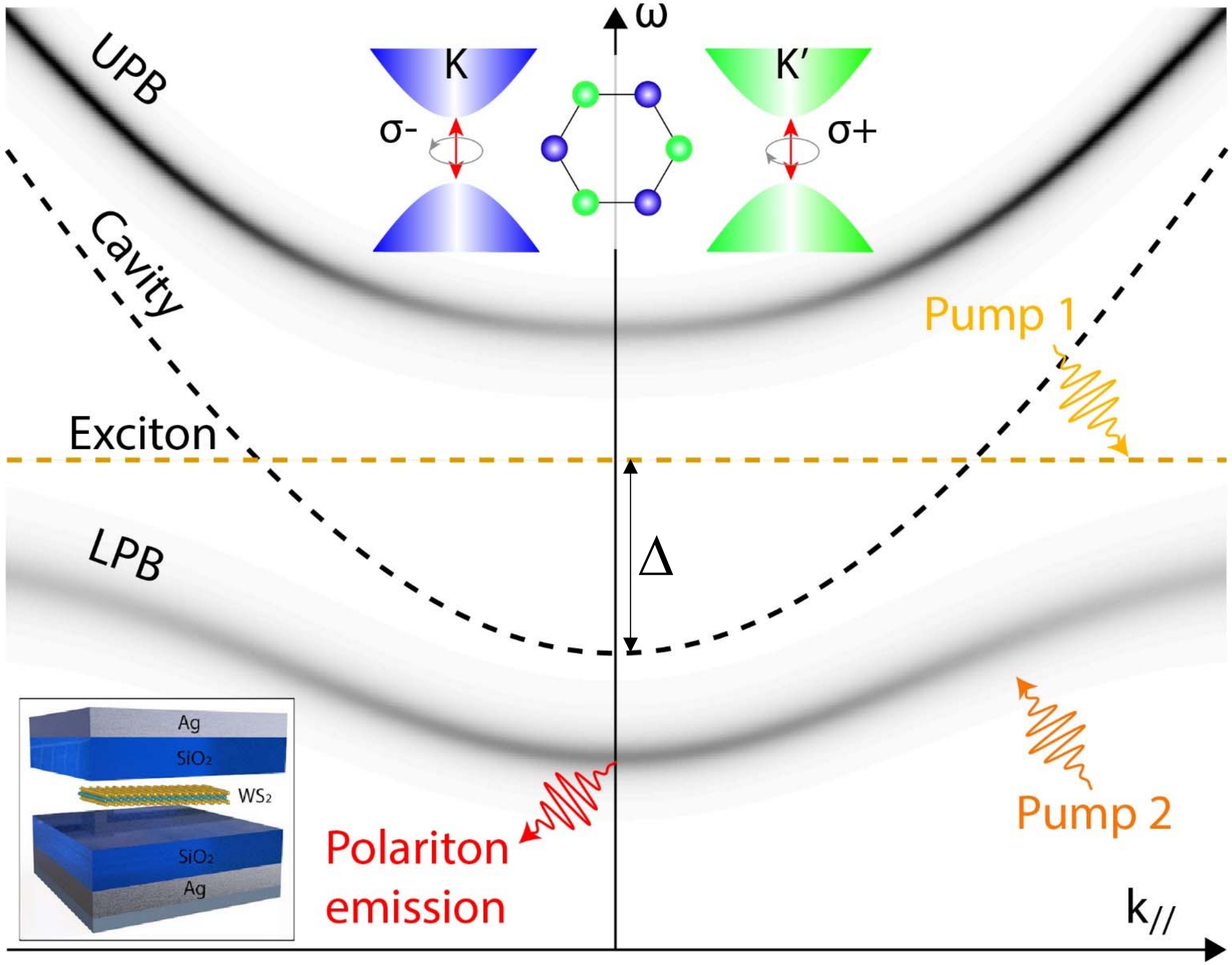
Valley Polarization





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

Valley Polaritons



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

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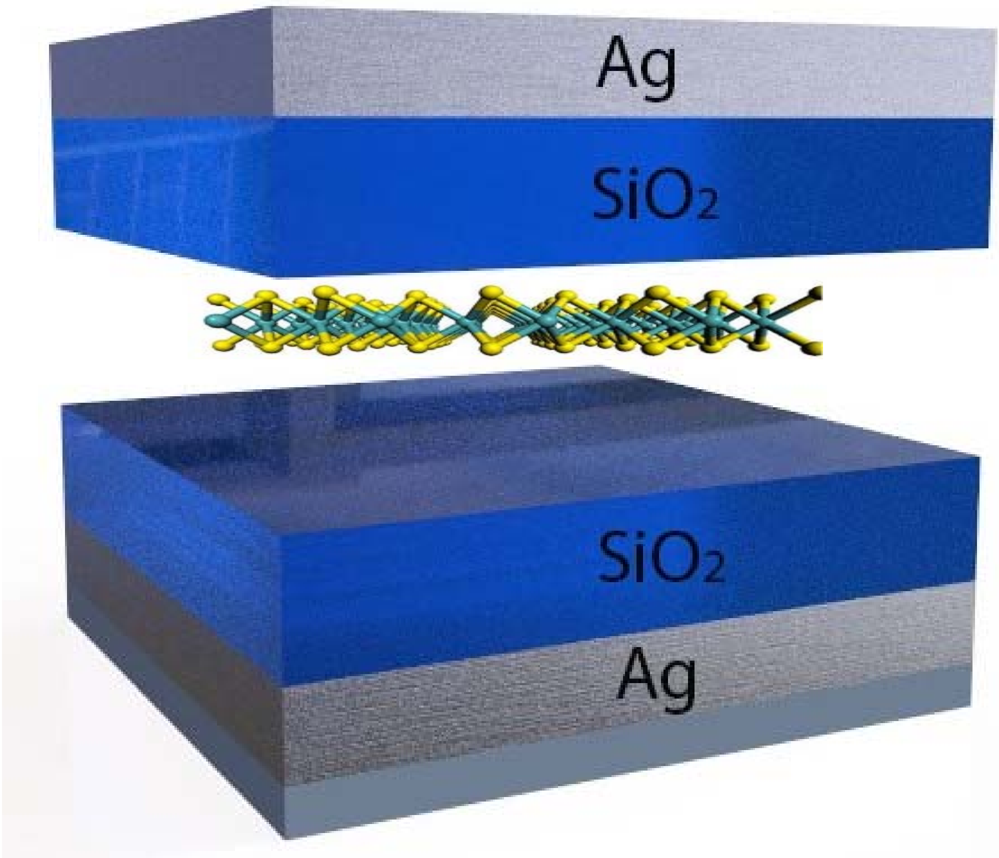
Metal mirror cavity



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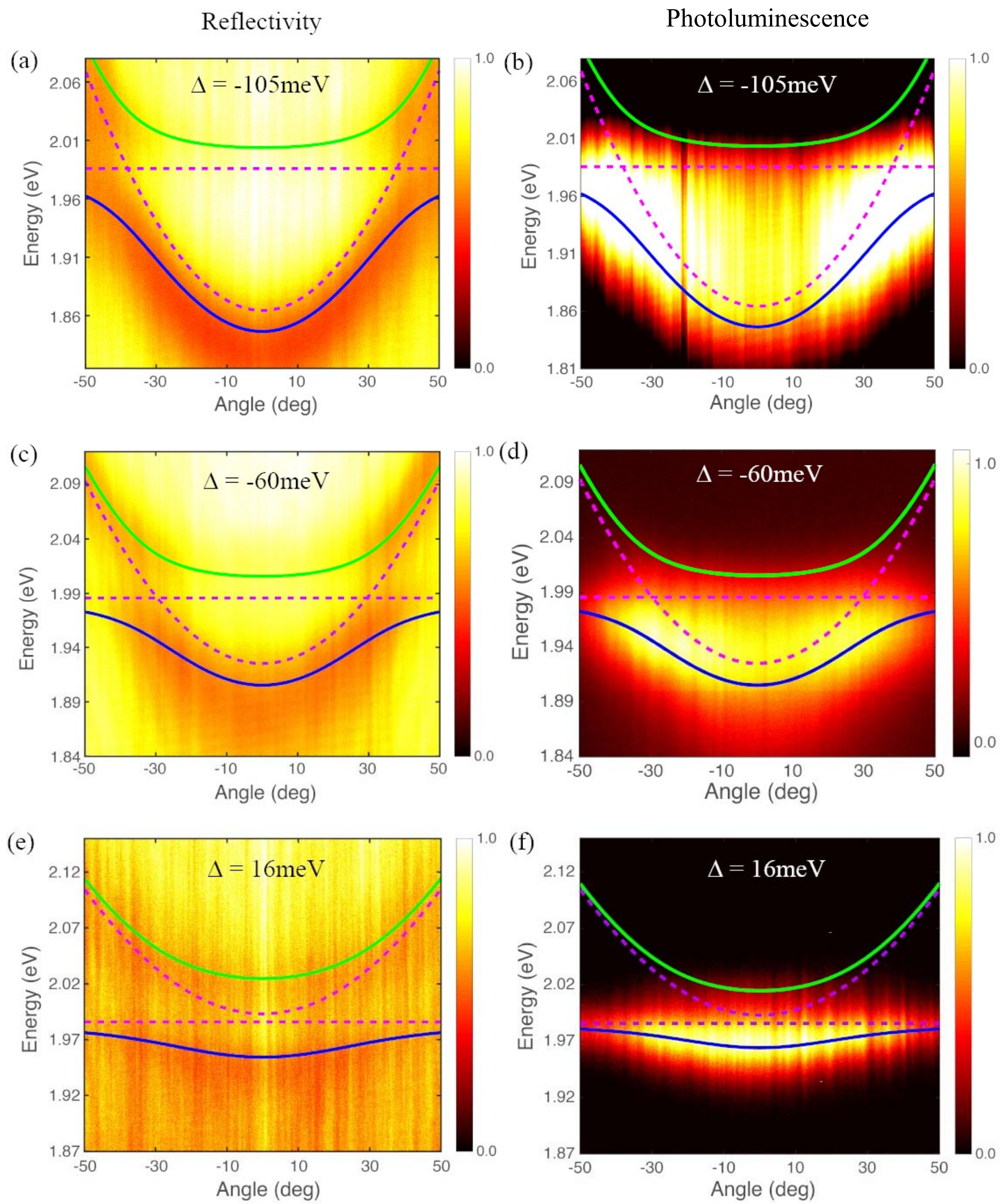
Dispersion



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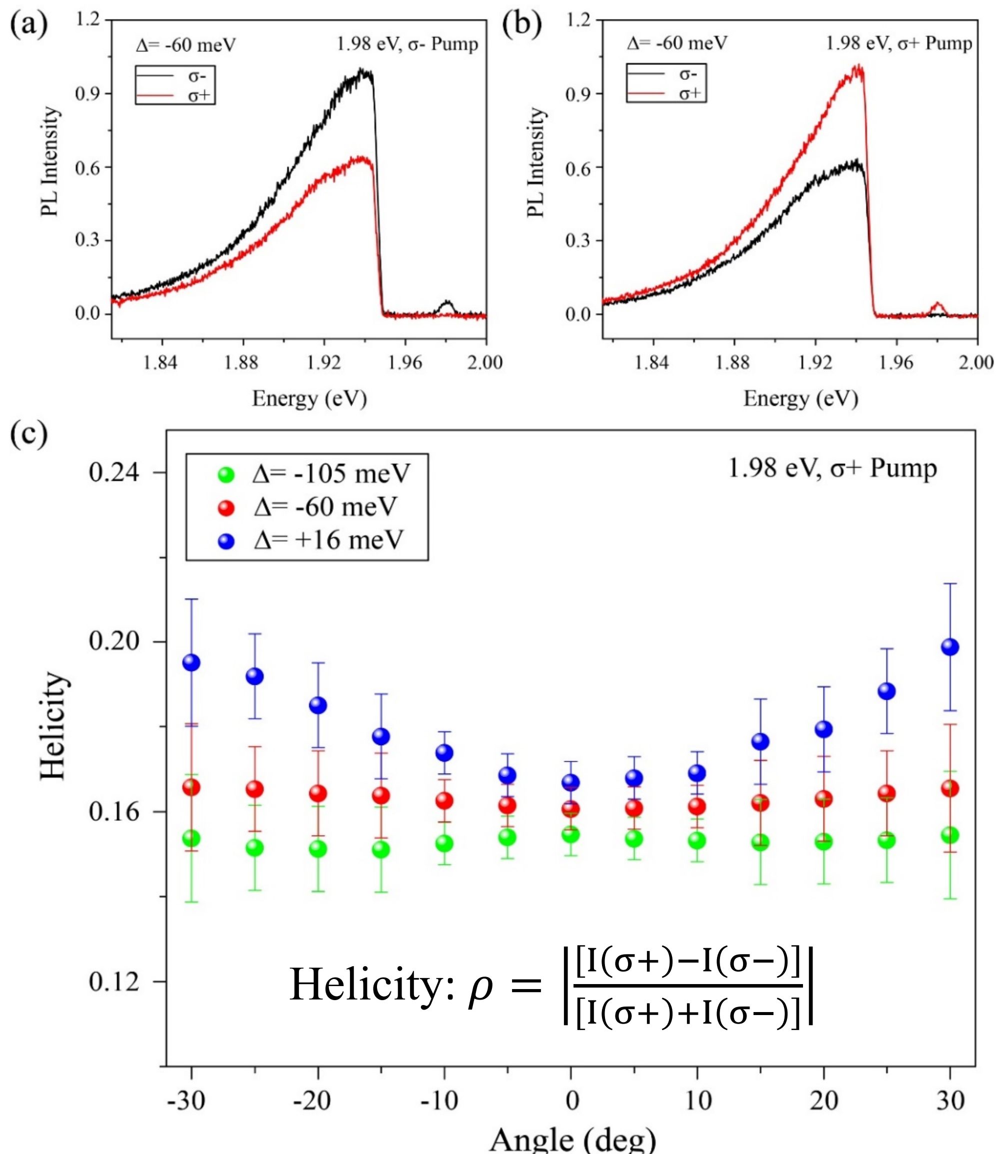
Helicity of polariton emission – Pump 1

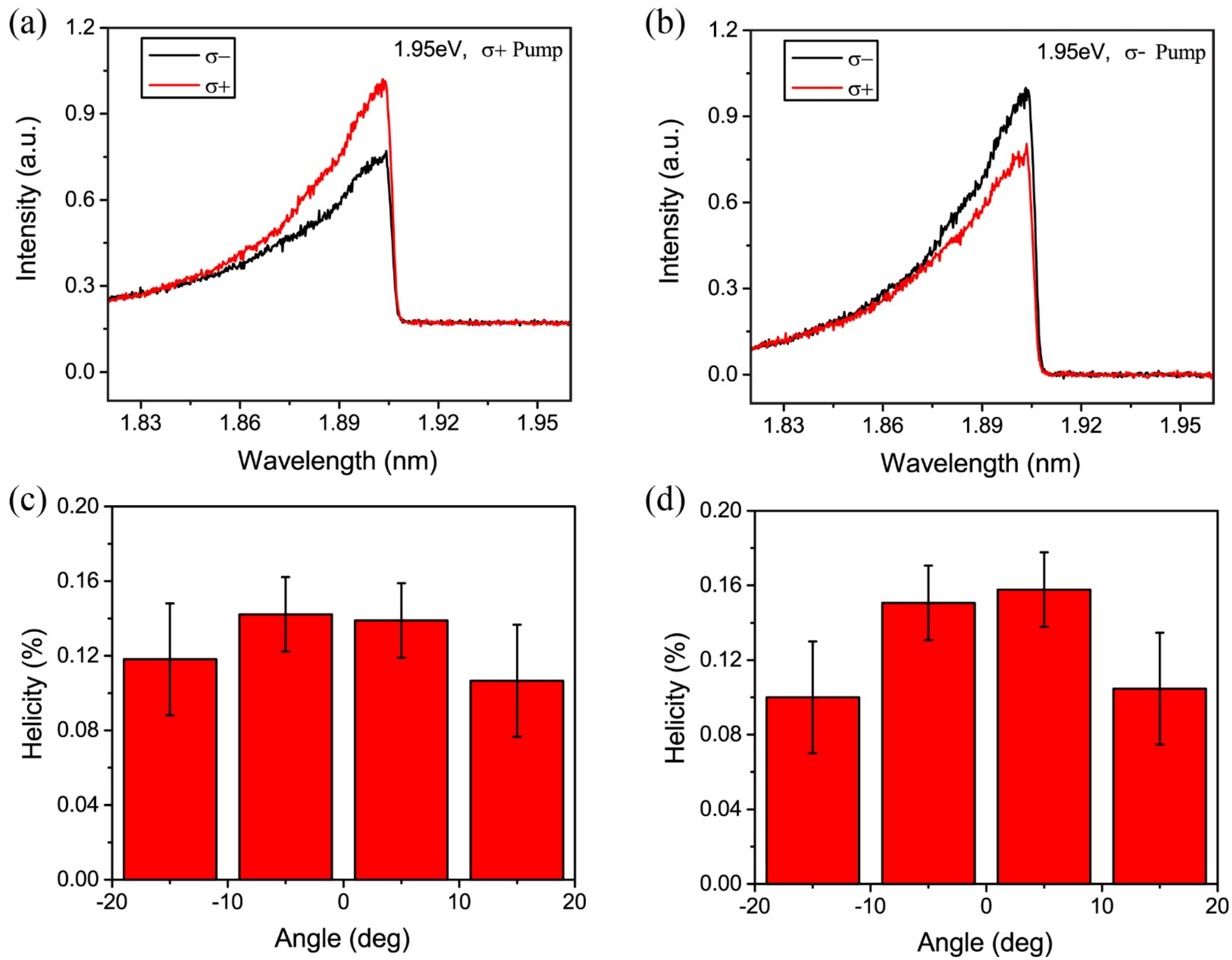
Pump 1: Resonant with exciton energy



Z. Sun…VMM, *Nature Photonics* 2017

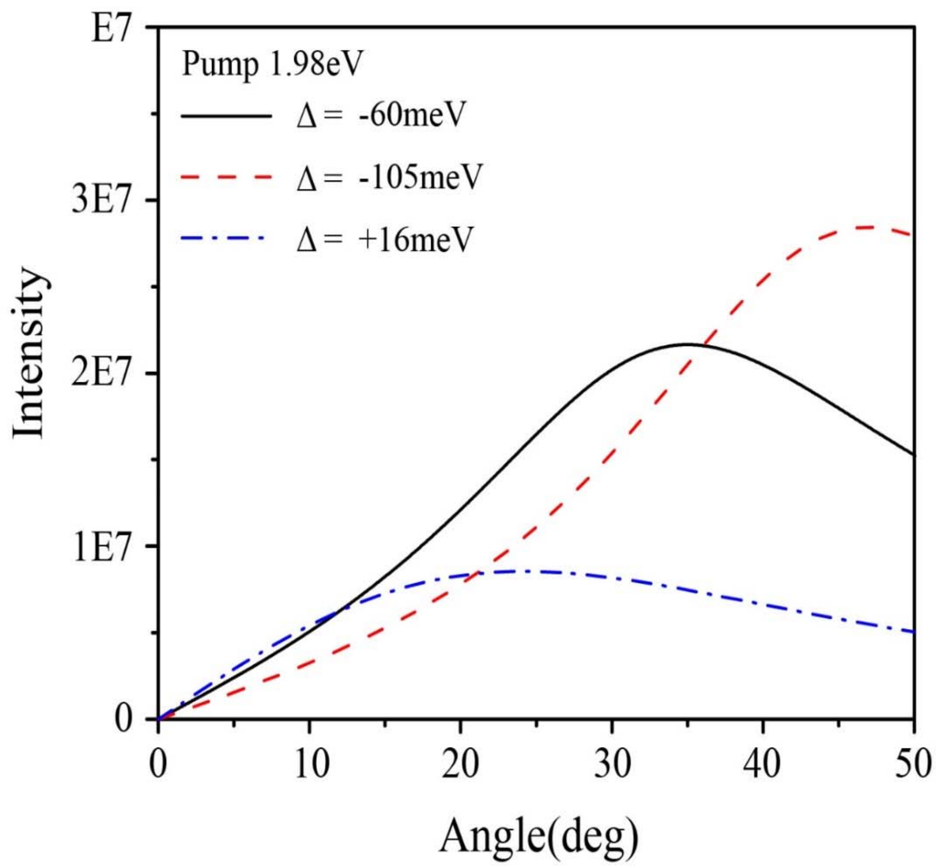
Helicity of polariton emission – Pump 2

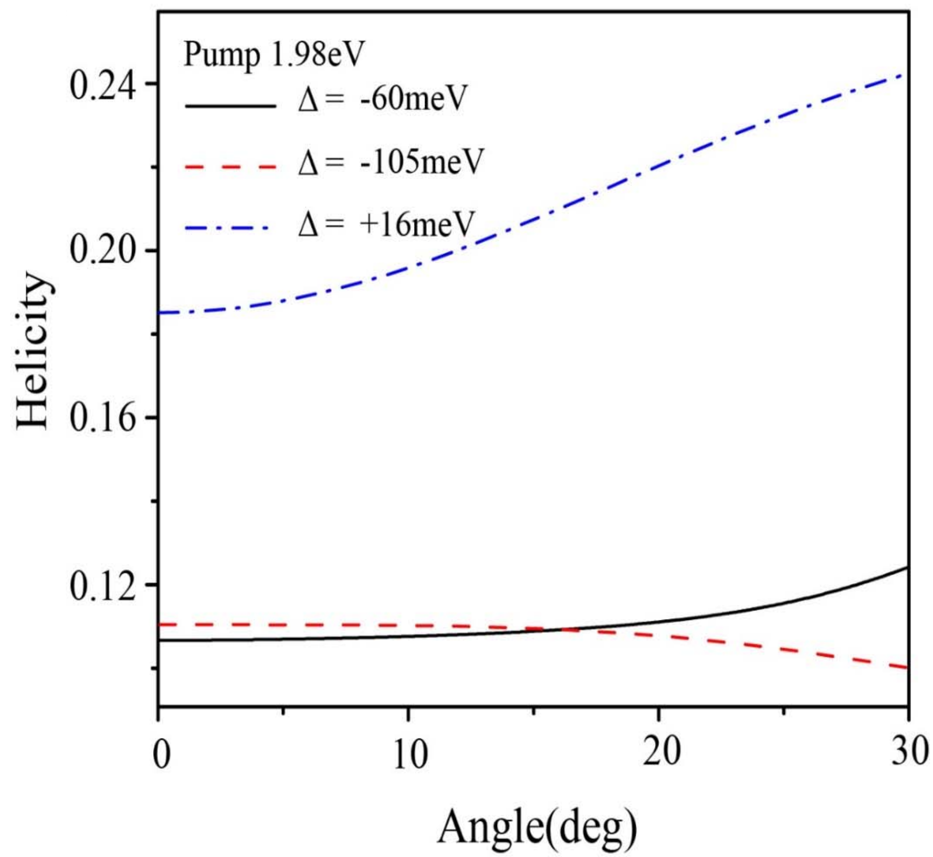
Pump 2: Resonant with lower polariton branch



Z. Sun…VMM, *Nature Photonics* 2017

Theory simulations





Z. Sun…VMM, *Nature Photonics* 2017

nature photonics

ARTICLES

PUBLISHED ONLINE: 5 JUNE 2017 | DOI: 10.1038/NPHOTON.2017.86

Valley-polarized exciton–polaritons in a monolayer semiconductor

Yen-Jung Chen[1], Jeffrey D. Cain[2,3], Teodor K. Stanev[1], Vinayak P. Dravid[2,3] and Nathaniel P. Stern[1]*

nature photonics

LETTERS

PUBLISHED ONLINE: 24 JULY 2017 | DOI: 10.1038/NPHOTON.2017.125

Valley-addressable polaritons in atomically thin semiconductors

S. Dufferwiel[1]*, T. P. Lyons[1], D. D. Solnyshkov[2], A. A. P. Trichet[3], F. Withers[4,5], S. Schwarz[1], G. Malpuech[2], J. M. Smith[3], K. S. Novoselov[4], M. S. Skolnick[1], D. N. Krizhanovskii[1] and A. I. Tartakovskii[1]*

nature photonics

LETTERS

PUBLISHED ONLINE: 24 JULY 2017 | DOI: 10.1038/NPHOTON.2017.121

Optical control of room-temperature valley polaritons

Zheng Sun[1,2], Jie Gu[1,2], Areg Ghazaryan[1], Zav Shotan[1], Christopher R. Considine[1], Michael Dollar[1], Biswanath Chakraborty[1], Xiaoze Liu[1,2†], Pouyan Ghaemi[1,2], Stéphane Kéna-Cohen[3] and Vinod M. Menon[1,2]*

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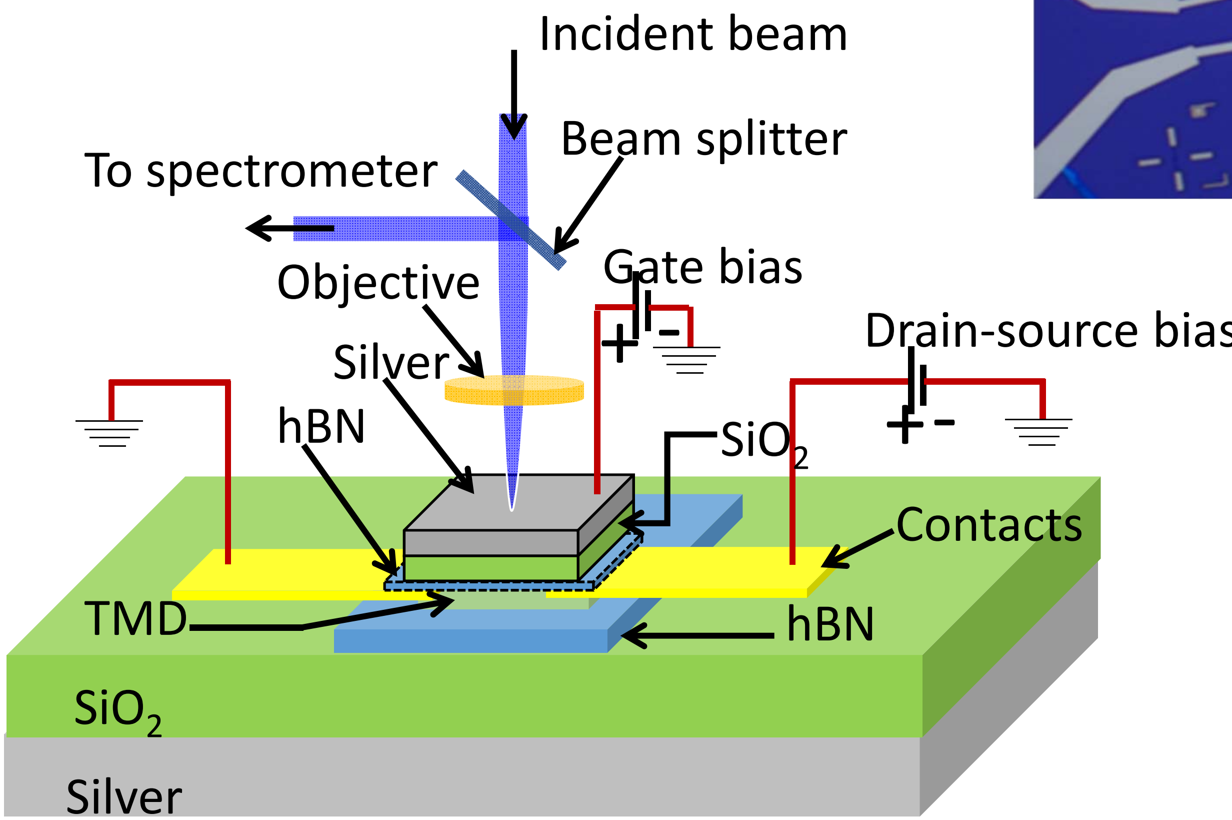
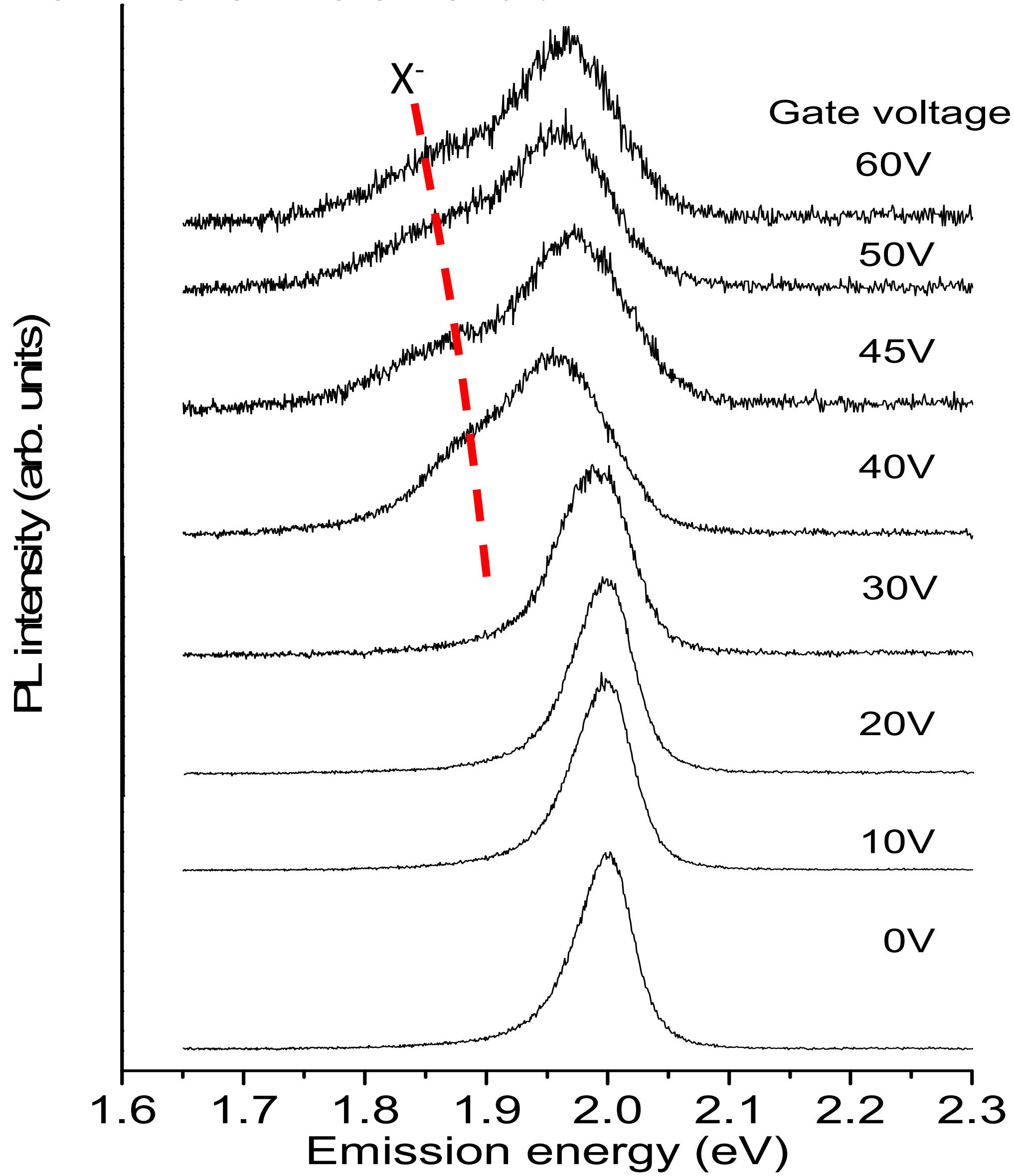
Outlook

Electrical control – Trion Exciton Polaritons ?



Outlook

Electrical control – Trion Exciton Polaritons ?



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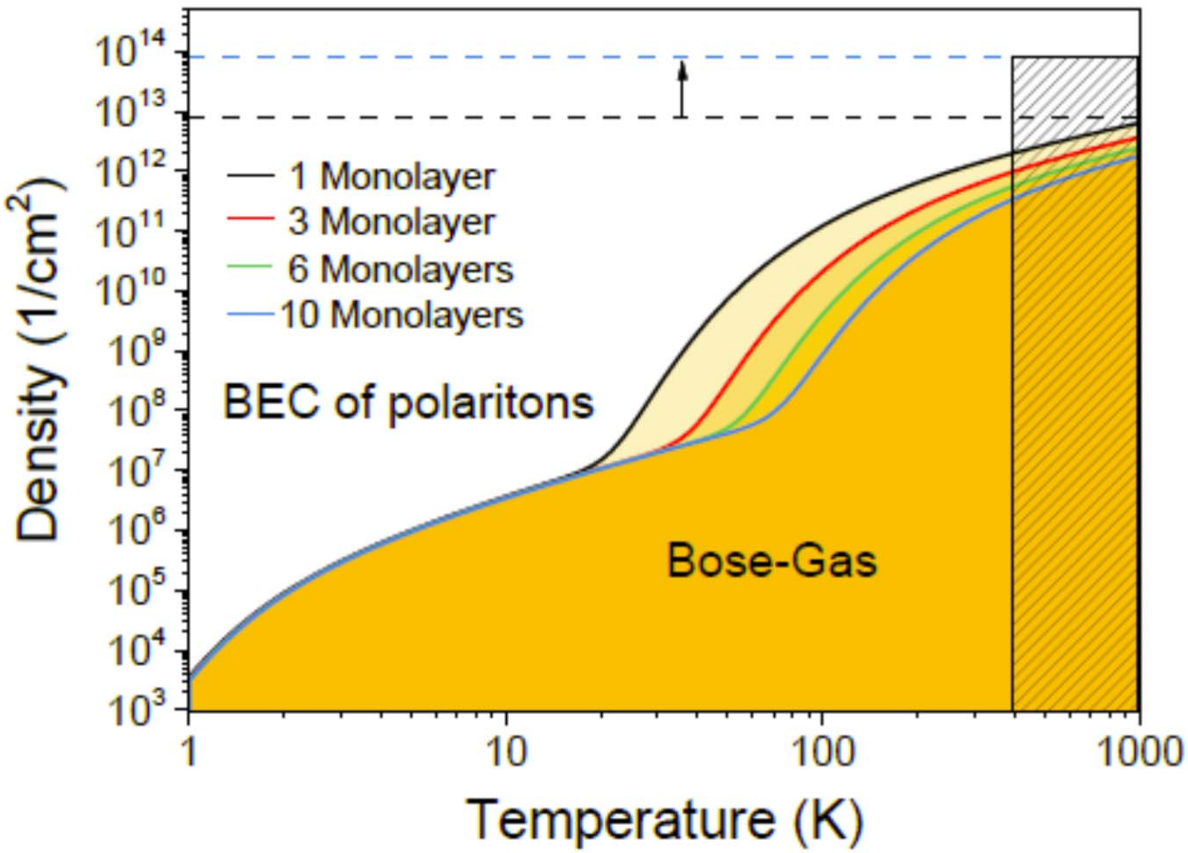
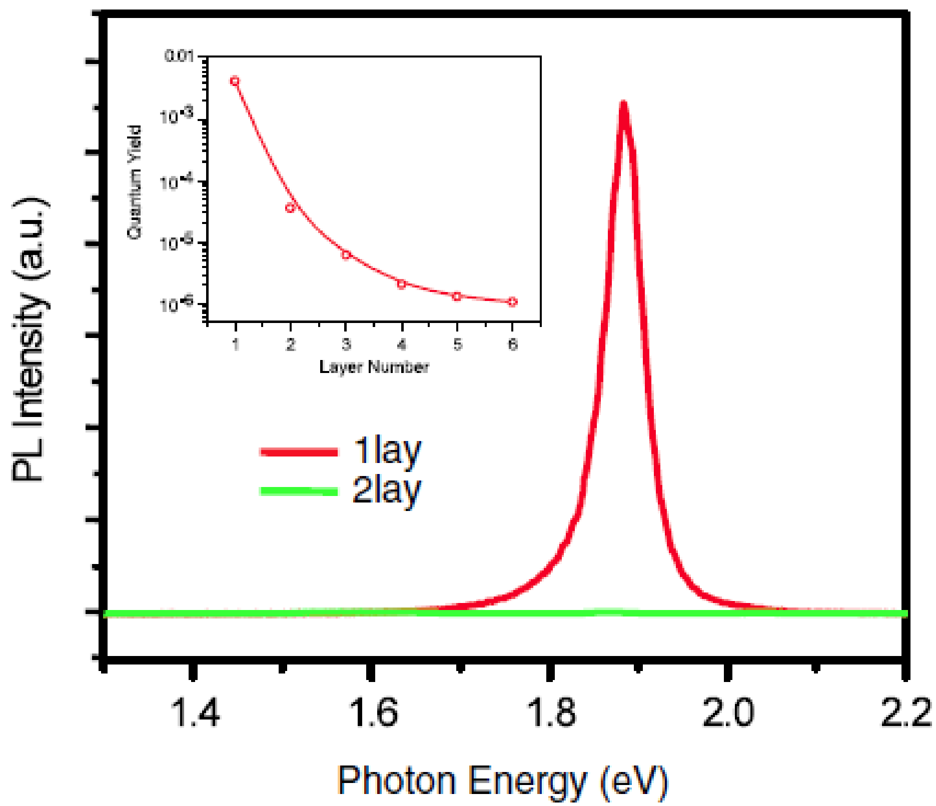
Outlook

Condensation?



Lundt et al. 2D Materials, **4**, 015006 (2016)

Quantum Yield?



~10^{-3}

Mak, K. F. et al *Phys. Rev. Lett.*, ***105***, 136805 (2010)

Chemical approaches to increasing quantum yield

Amani et al. Science 350, 1065 (2015)

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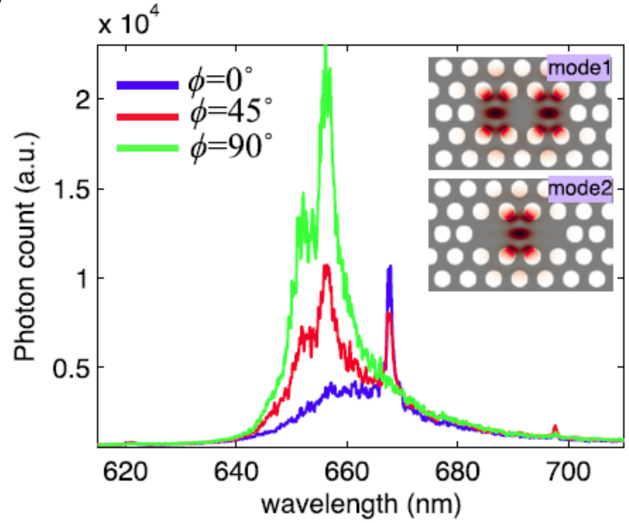
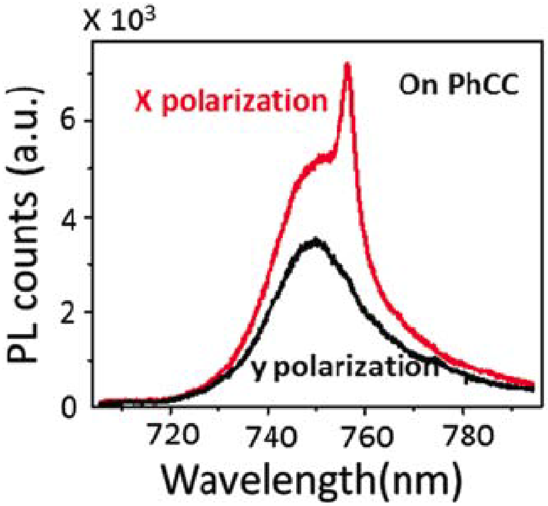
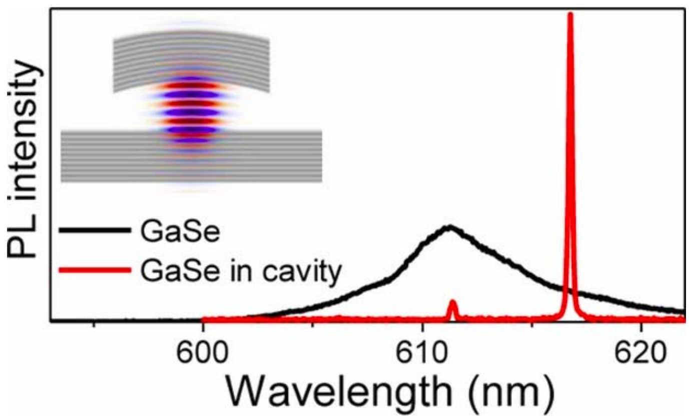
Control of Spontaneous Emission in 2D Materials

Cavity Systems

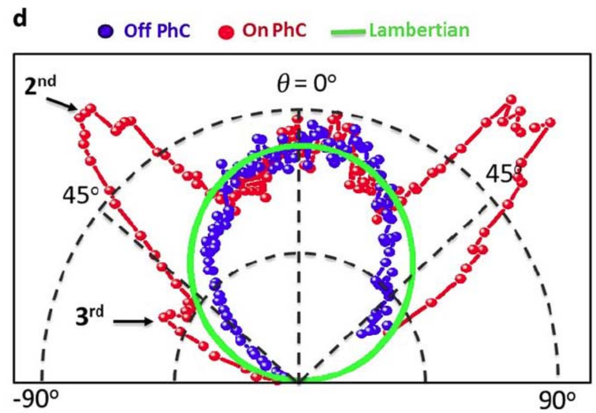


Gan, X. et al (2013). *Appl. Phys. Lett. 103*, 181119.





Schwarz. S. et al (2014). *Nano Lett. 14*, 7003



Wu, S. et al (2014). *2D Materials*, *1*, 011001.

Demonstration of enhanced spontaneous emission and directionality

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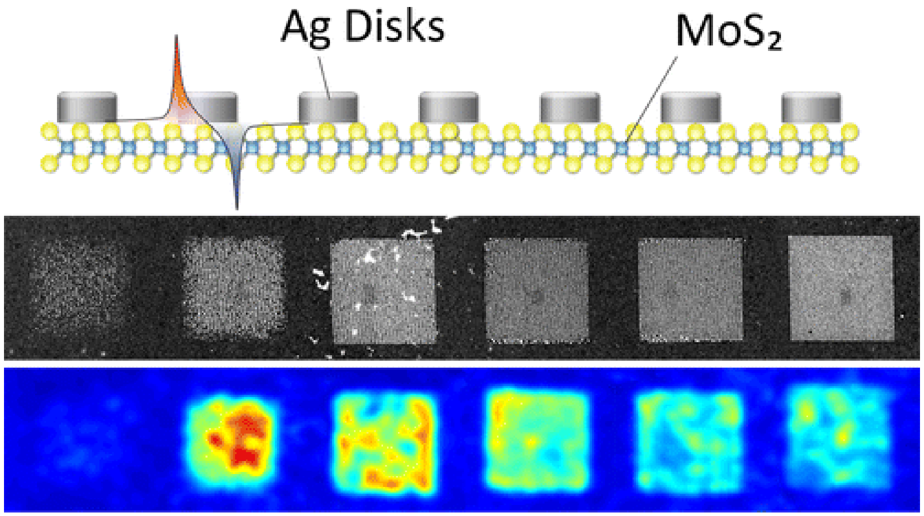
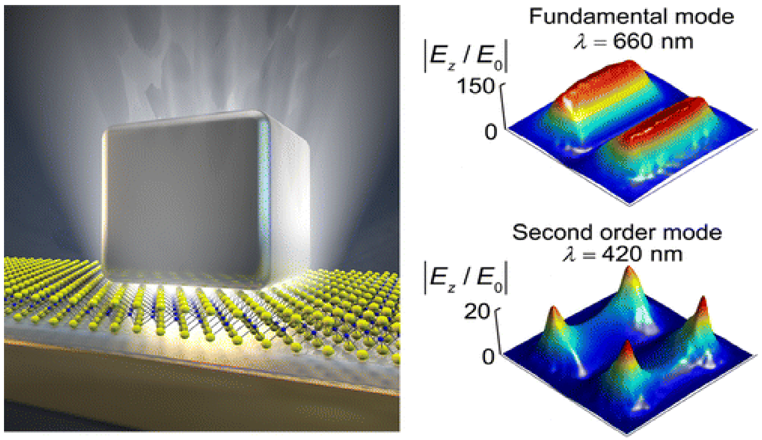
Control of Spontaneous Emission in 2D Materials

Plasmonic Systems



S. Butun. et al (2015). *Nano Lett. 15*, 2700



Akselrod et al. (2015). *Nano Lett. 15*, 3578

and several other groups

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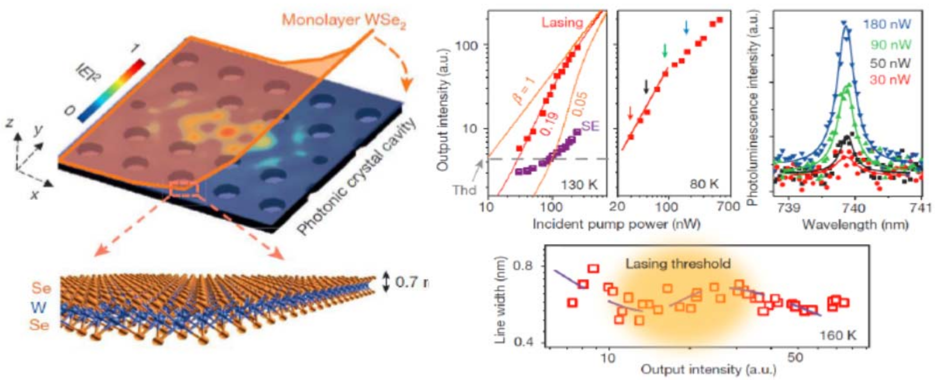
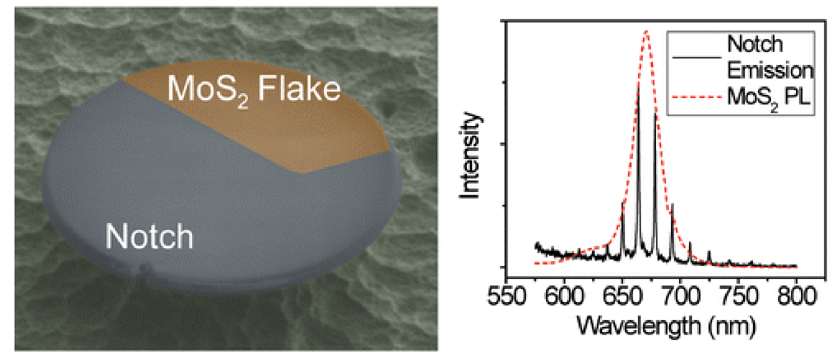
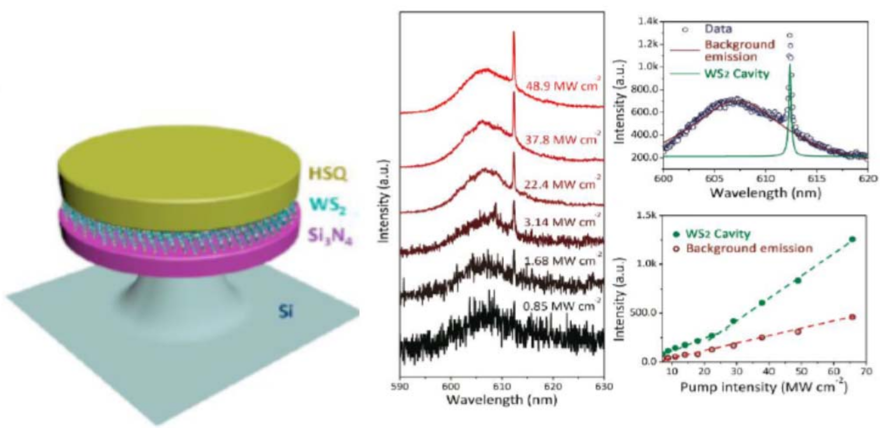
2D Materials Integrated with Microcavities



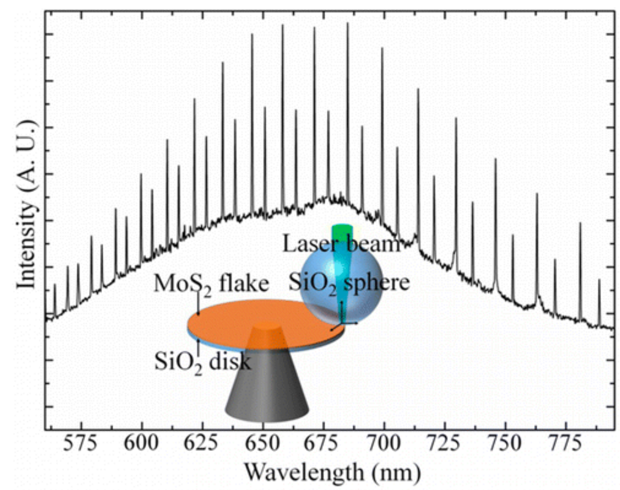
Wu, S., et al. *Nature*, 520, 69-72 (2015)



Reed, J., et al. *Nano Lett. 15, 1967* (2015)



Ye, Y., et al. *Nature Photonics* 2015.



Salehzadeh, O., et al. *Nano Lett. 15, 5302* (2015)

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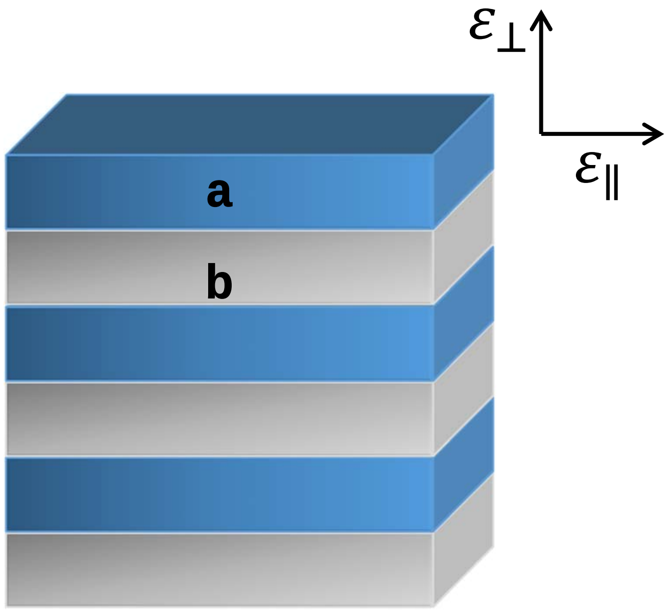
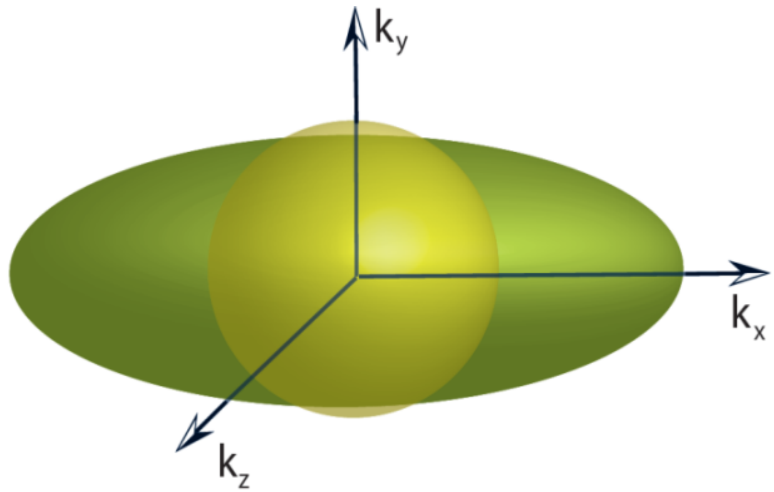
Broadband Enhancement of Spontaneous Emission?

Anisotropic Materials and Dispersion



$$\frac{1}{\varepsilon_{eff}^{\perp}} = \frac{f_a}{\varepsilon_a} + \frac{f_b}{\varepsilon_b}$$

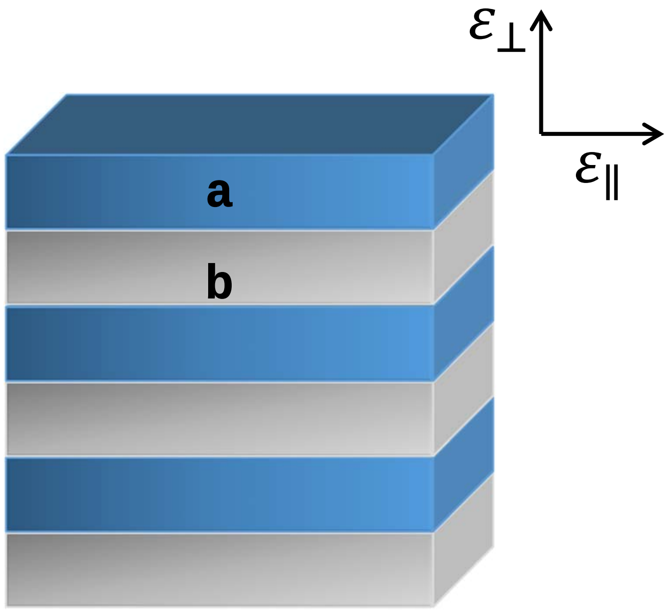
$$\varepsilon_{eff}^{\parallel} = f_a \varepsilon_a + f_b \varepsilon_b$$



$$\varepsilon_\parallel, \varepsilon_\perp > 0; \ \varepsilon_\parallel << \varepsilon_\perp$$

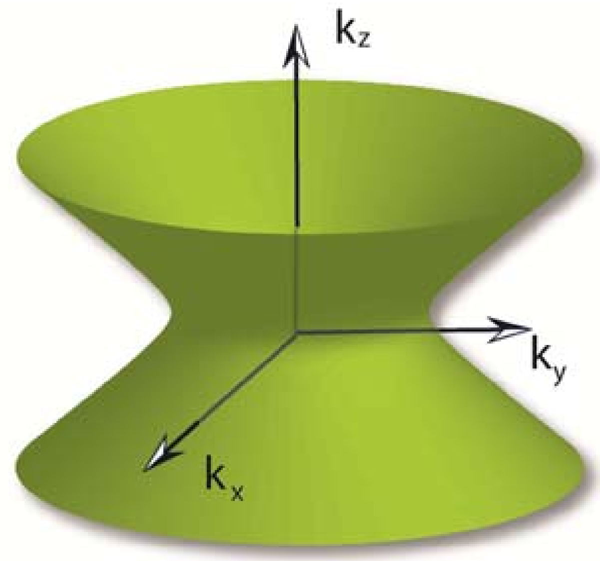
$$\frac{k_z^2}{\varepsilon_\parallel} + \frac{k_x^2 + k_y^2}{\varepsilon_\perp} = \frac{\omega^2}{c^2}$$

Anisotropic Materials and Dispersion



$$\frac{1}{\varepsilon_{eff}^{\perp}} = \frac{f_a}{\varepsilon_a} + \frac{f_b}{\varepsilon_b}$$

$$\varepsilon_{eff}^{\parallel} = f_a \varepsilon_a \boxed{-} f_b \varepsilon_b$$



$$\varepsilon_\parallel < 0; \ \varepsilon_\perp > 0;$$

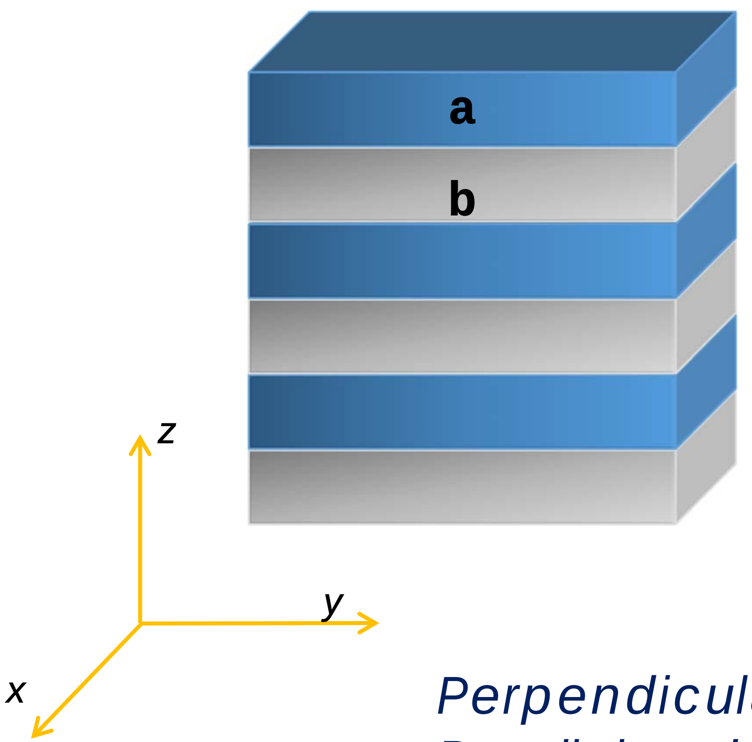
$$\frac{k_x^2 + k_y^2}{\varepsilon_\perp} - \frac{k_z^2}{\varepsilon_\parallel} = \frac{\omega^2}{c^2}$$

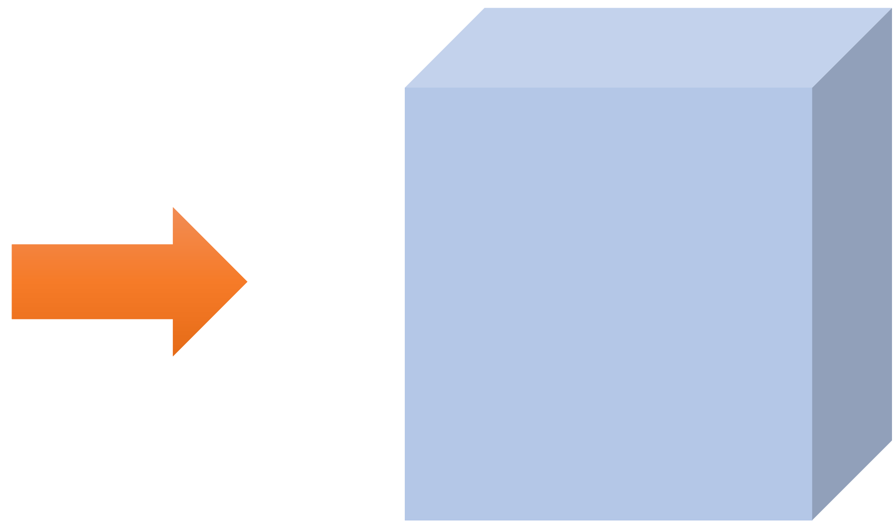
Metals: $\varepsilon < 0$ below plasma frequency
and $f_b > f_a$

Indefinite Media (Hyperbolic Media)

$$\varepsilon_{xy(\parallel)} < 0, \varepsilon_{z(\perp)} > 0$$

Subwavelength metal-dielectric structure ***Effective Anisotropic Medium***





Perpendicular to the layers: Dielectric-like
Parallel to the layers: Metal-like

Felsen L. *IEEE Trans. Antennas Propag.* ***12*** (1964)
V. Podolskiy and E. Narimanov Physical Review B 71 201101 (2005)

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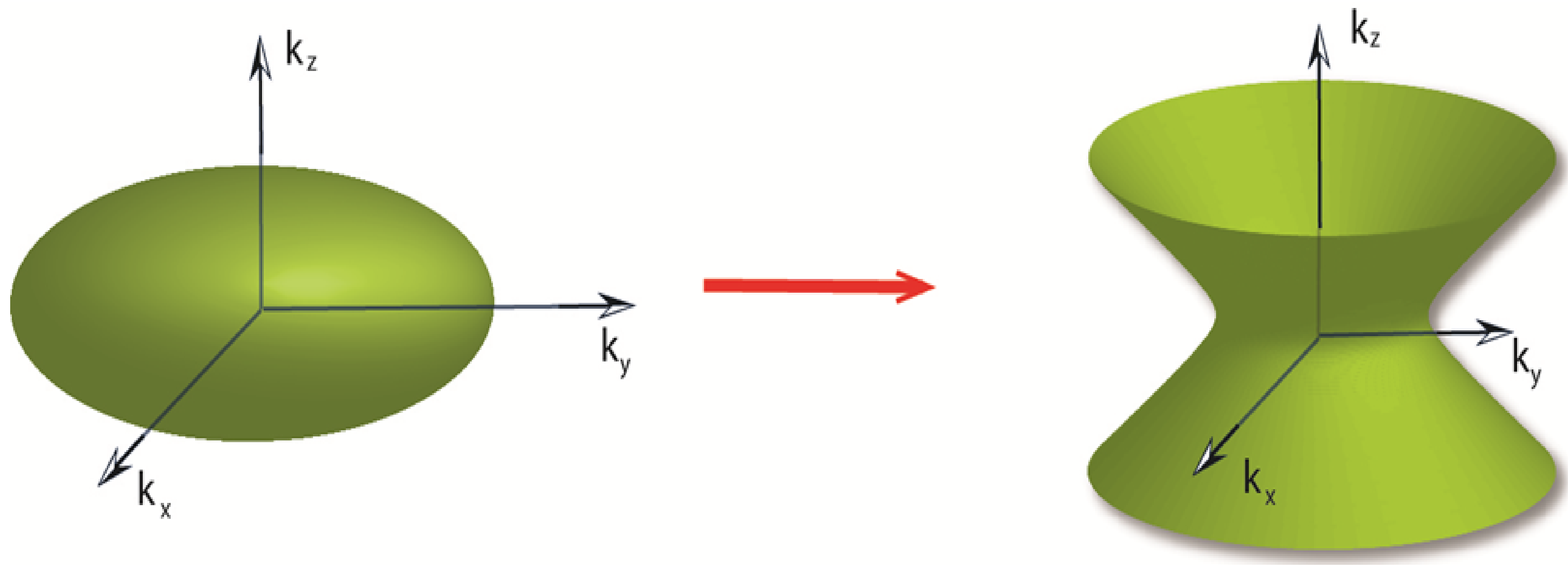
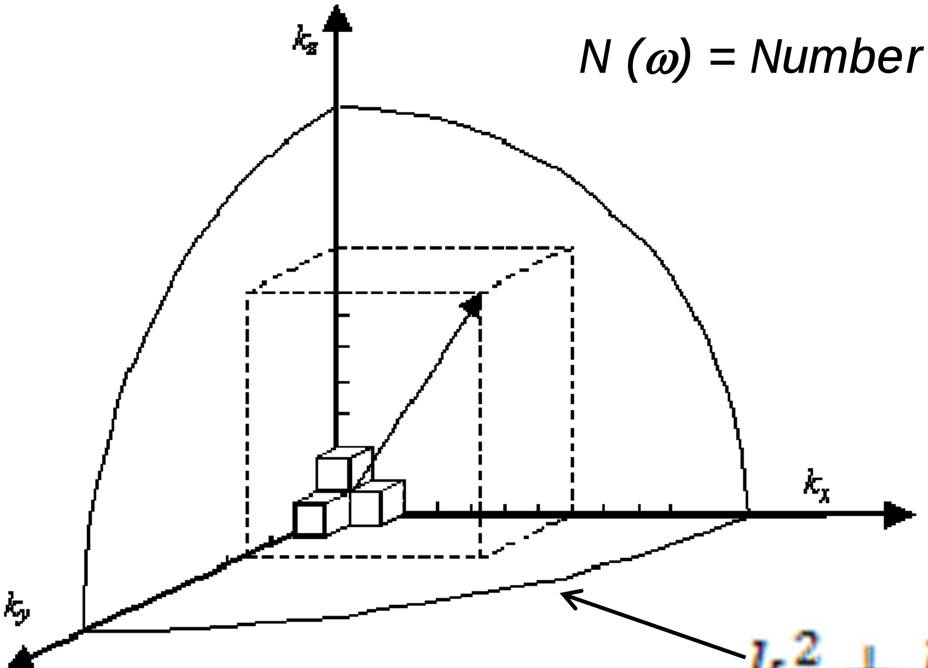
Topology of Iso-frequency Surface



What is the physical manifestation of this transition in Optics?

M. Lifshitz, Sov. Phys. JETP. **11**, 1130 (1960).
Krishnamoorthy, Jacob, Narimanov, Kretzschmar, VMM, *Science* **336**, 205 (2012)

Photon Density of States



N (ω) = Number of states with frequency below ω

$$\rho(\omega) = \frac{dN}{d\omega}$$

$$k_x^2 + k_y^2 + k_z^2 = c\frac{\omega^2}{c^2}$$

Purcell Effect

Fermi Golden Rule

$$\Gamma = \frac{2\pi}{\hbar}\rho(\omega)\times(Dipole\,Matrix\,Element)^2$$

Purcell Factor = Rate in cavity / Rate in free space

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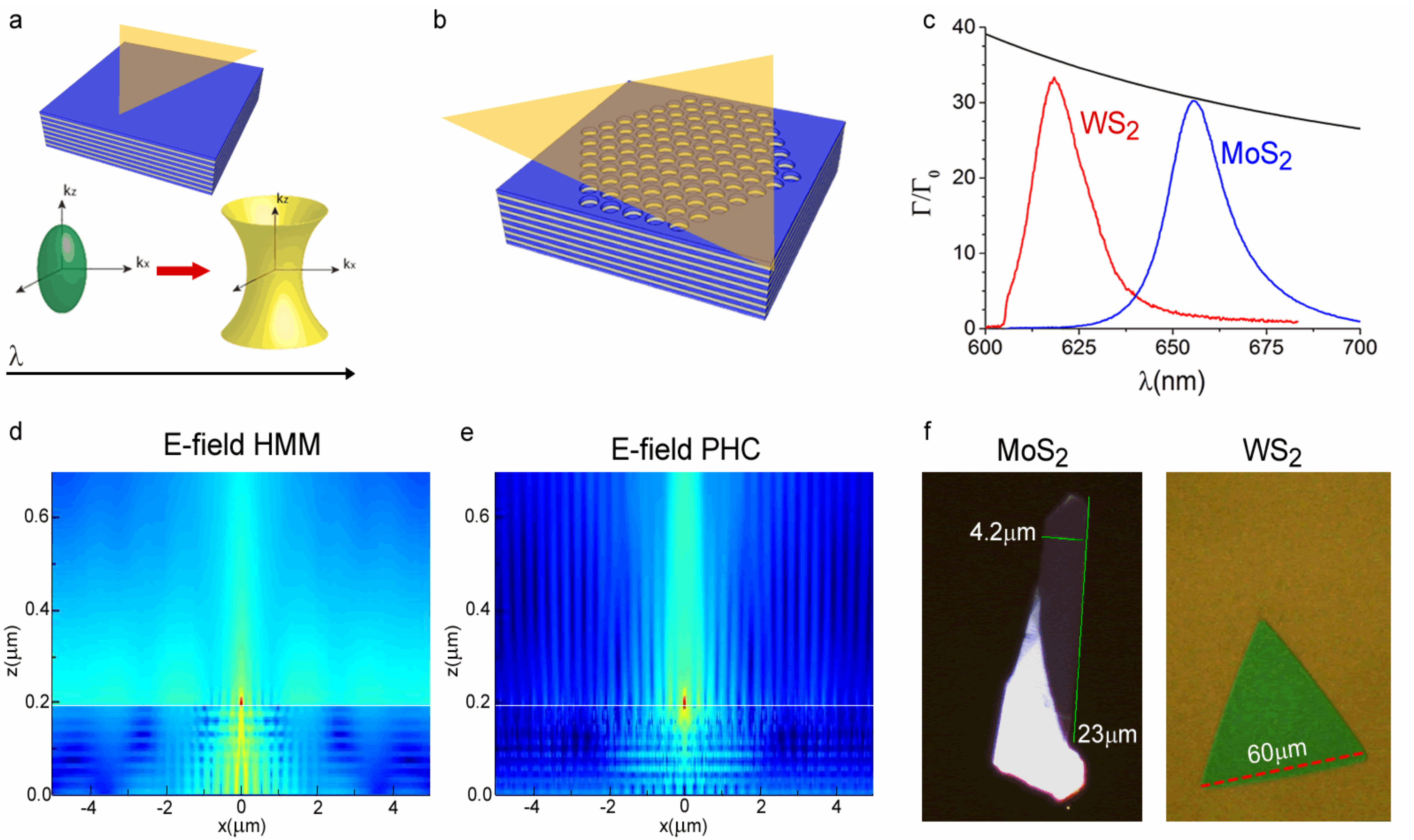
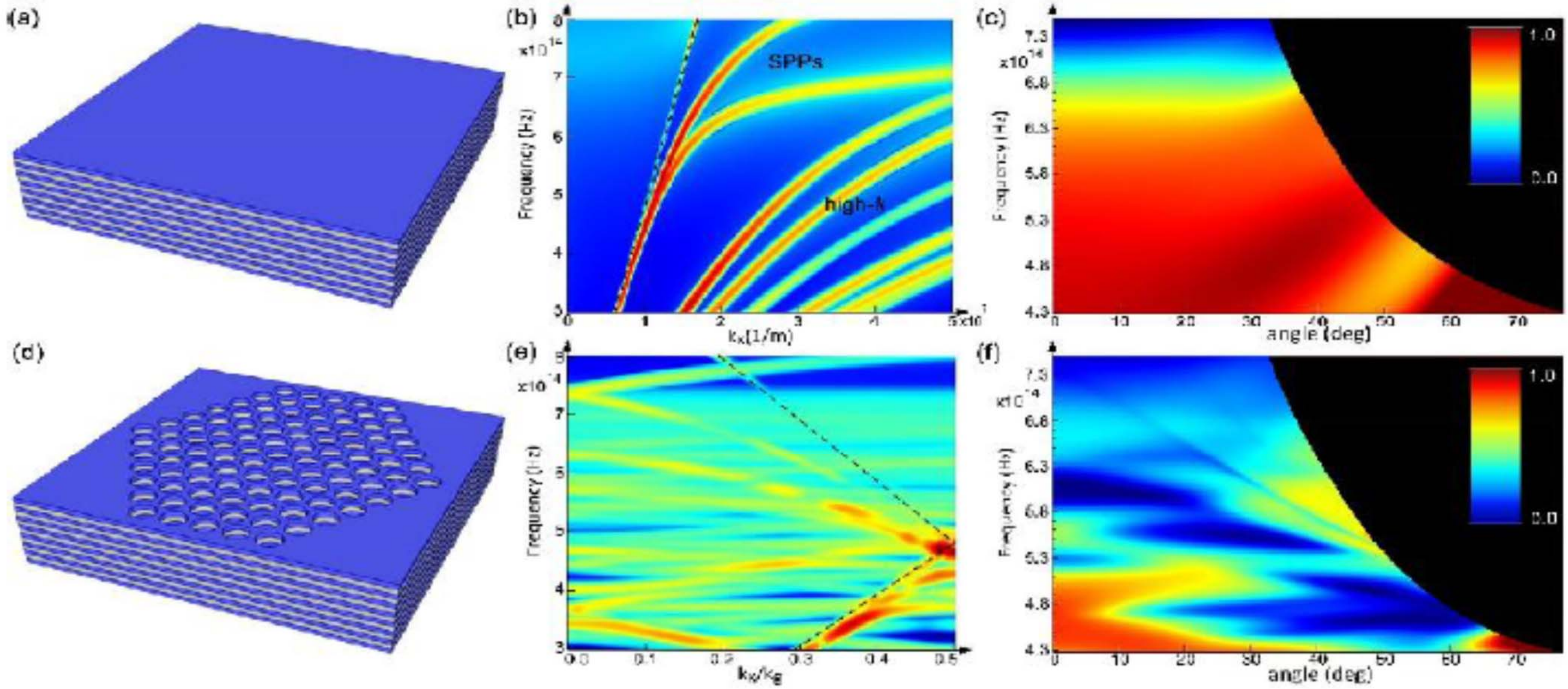
Hyperbolic Metamaterials for Enhanced Spontaneous Emission from 2D TMD



T. Galfsky…VMM, *Nano Lett.* DOI: 10.1021/acs.nanolett.6b01558, (2016)

Photonic Hypercrystal



E. Narimanov, *"Photonic Hypercrystals,"* *Phys Rev X.* **4** (2014)
T.Galfsky, J. Gu, E. Narimanov and VMM, *PNAS* **114**, 5125 (2017)

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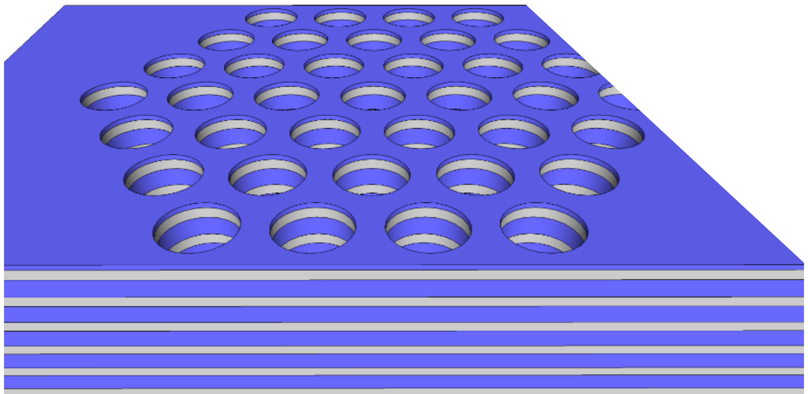
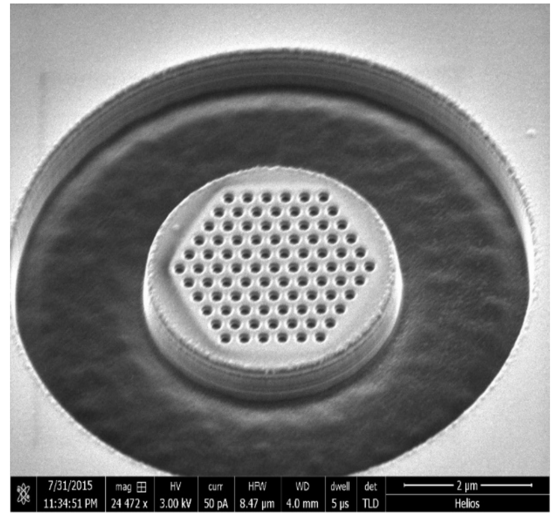
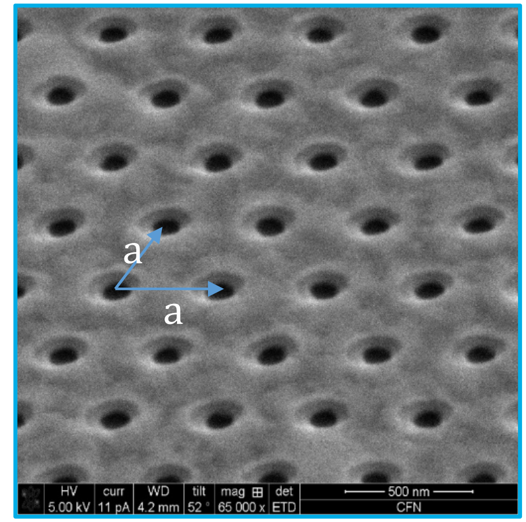
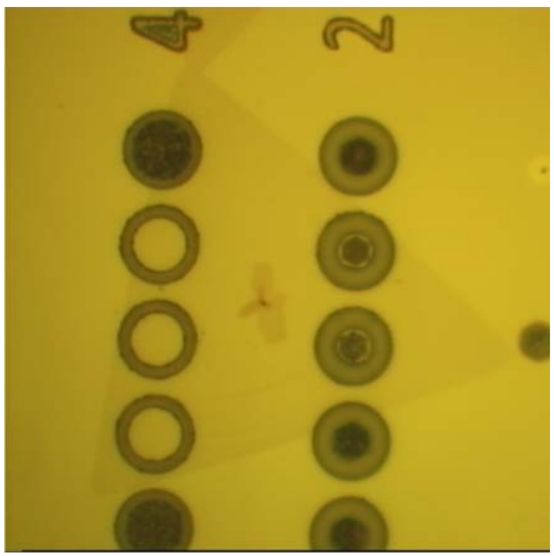
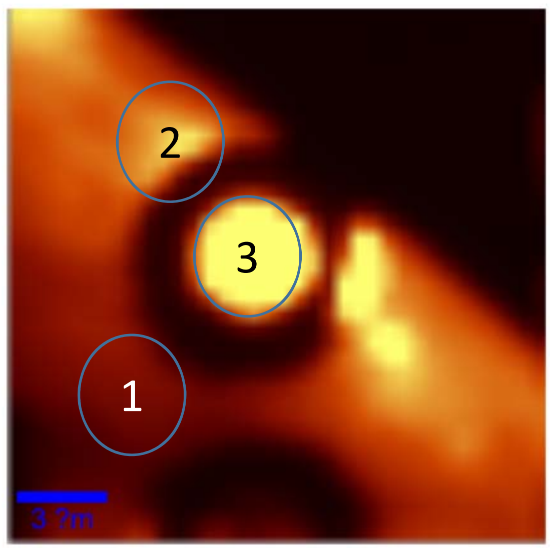
Photonic Hypercrystal

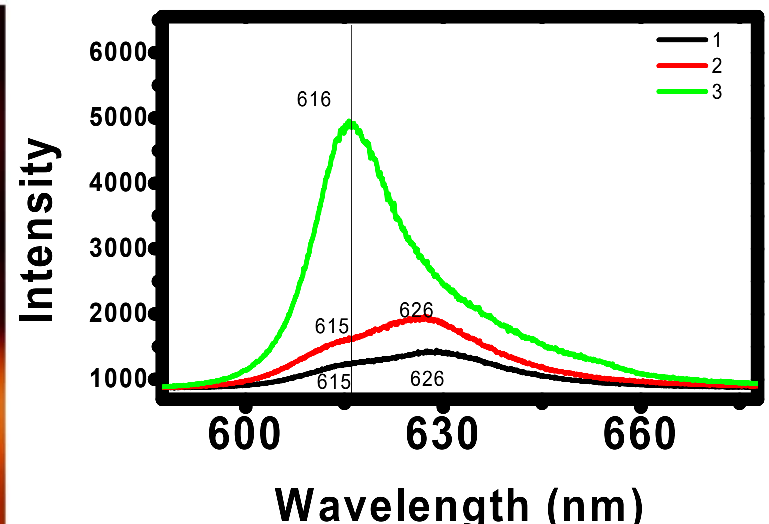












E. Narimanov, *Phys Rev X.* ***4*** (2014)
T. Galfsky…VMM, *PNAS* **114**, 5125 (2017)

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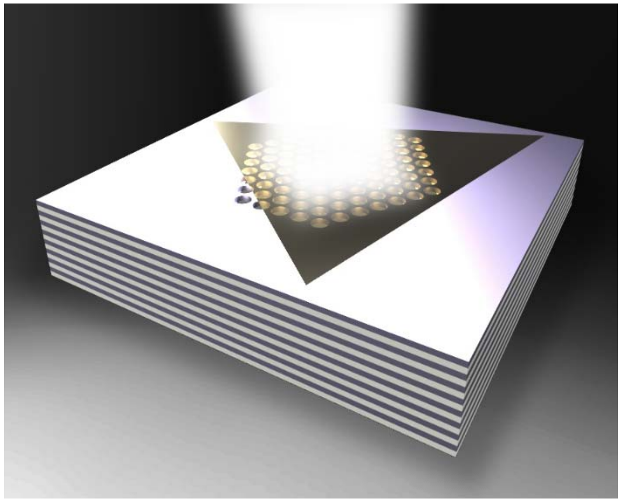
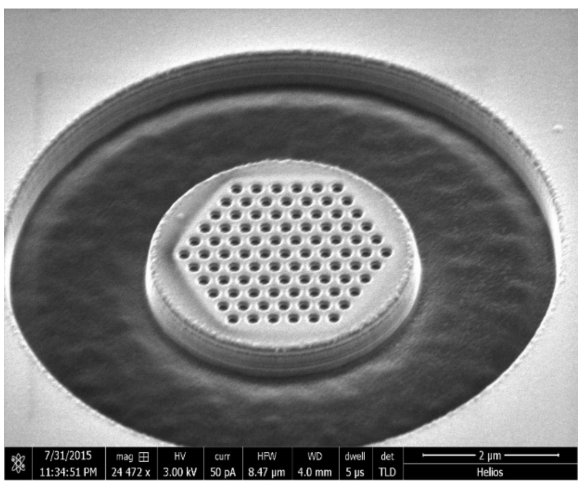
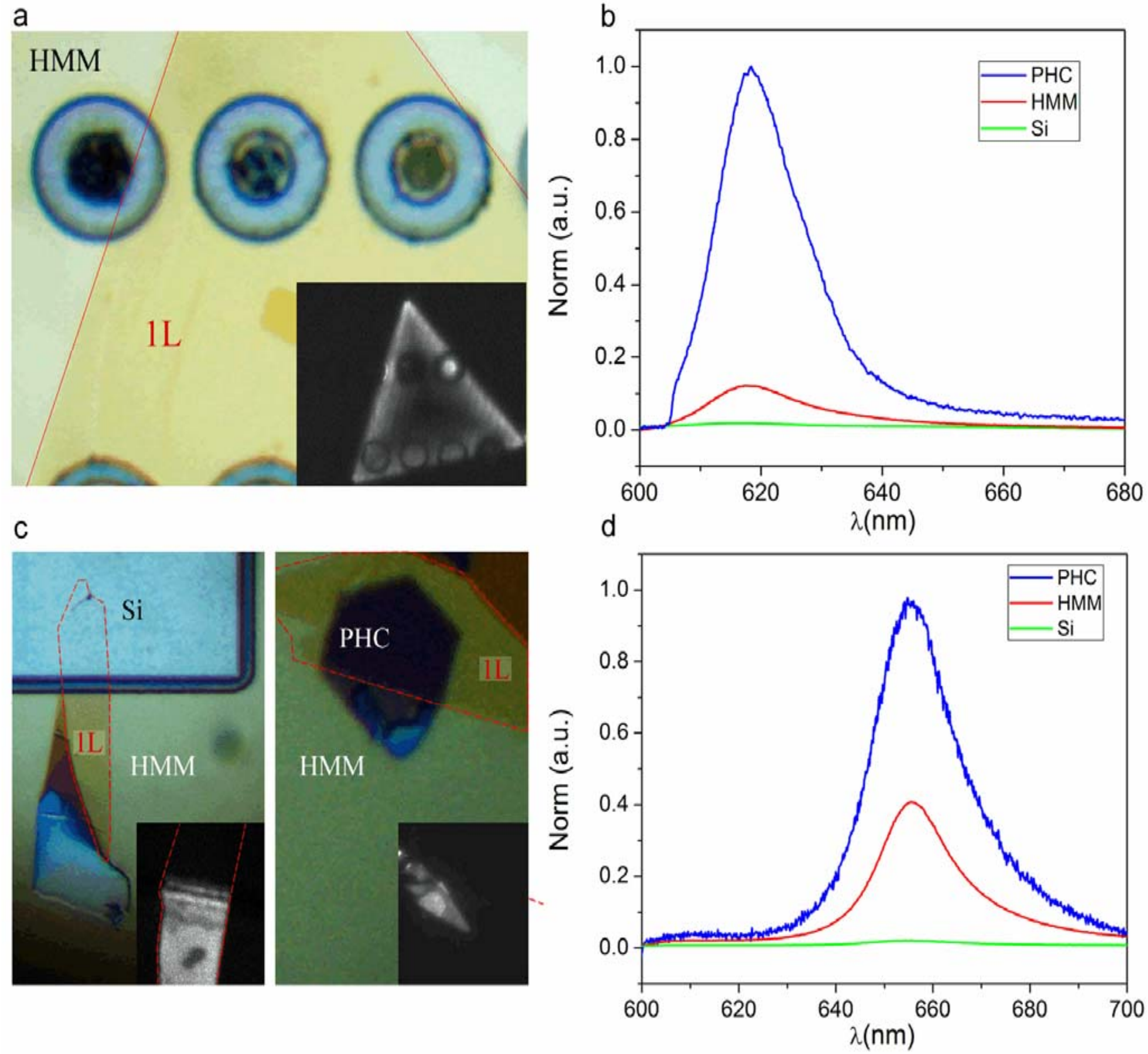
Spontaneous Emission







T. Galfsky…VMM, *Nano Lett.* **16**, 4940 (2016)

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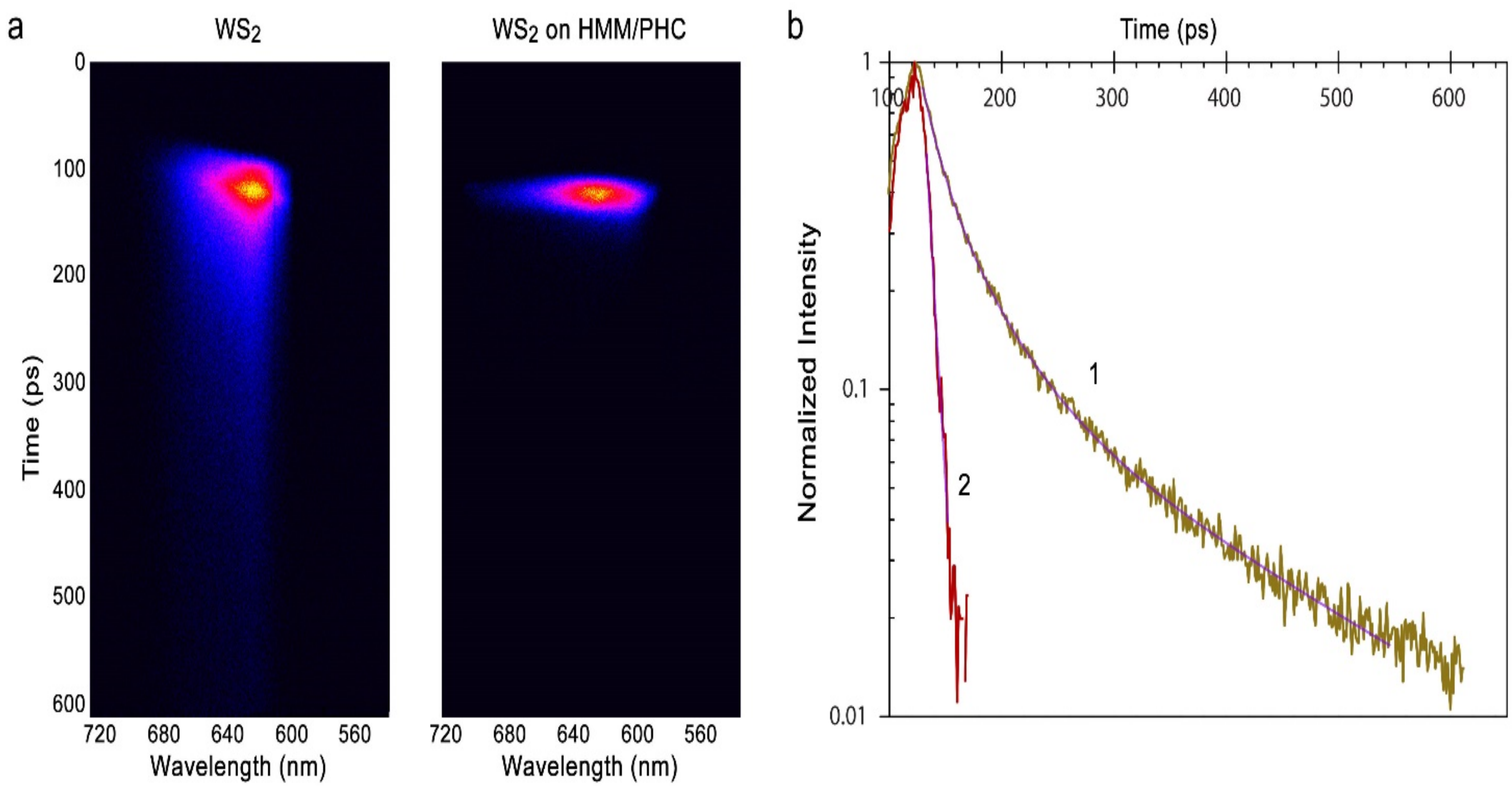
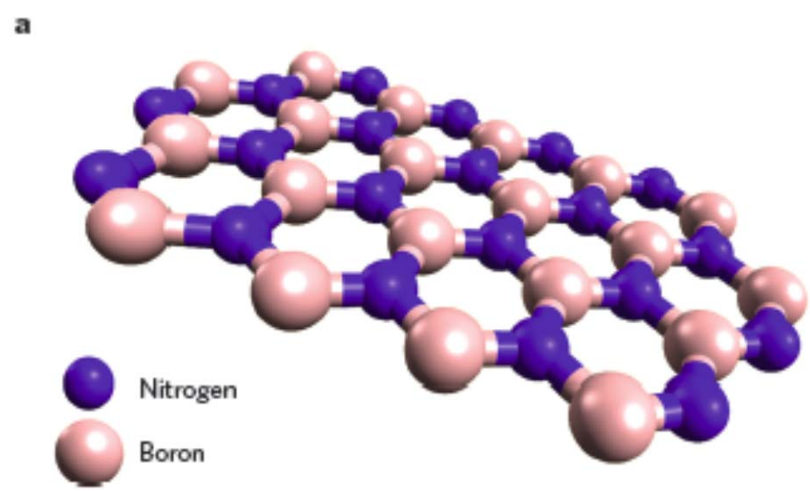
Spontaneous Emission Rate



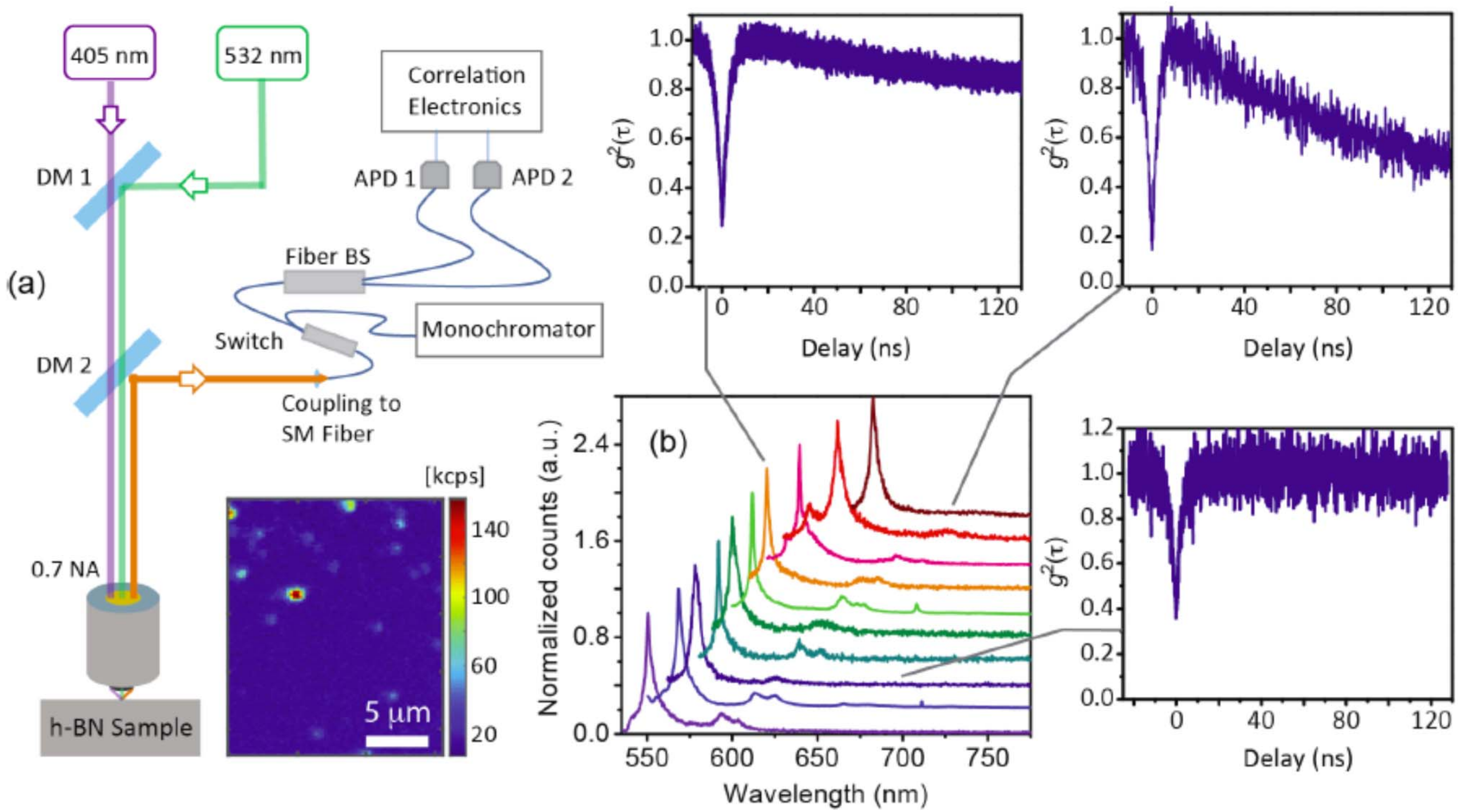
T. Galfsky…VMM, *Nano Lett.* **16**, 4940 (2016)

Quantum Emitters in hBN



Tran et al. *Nat. Nanotechnol.* **11,** 37–41 (2015).

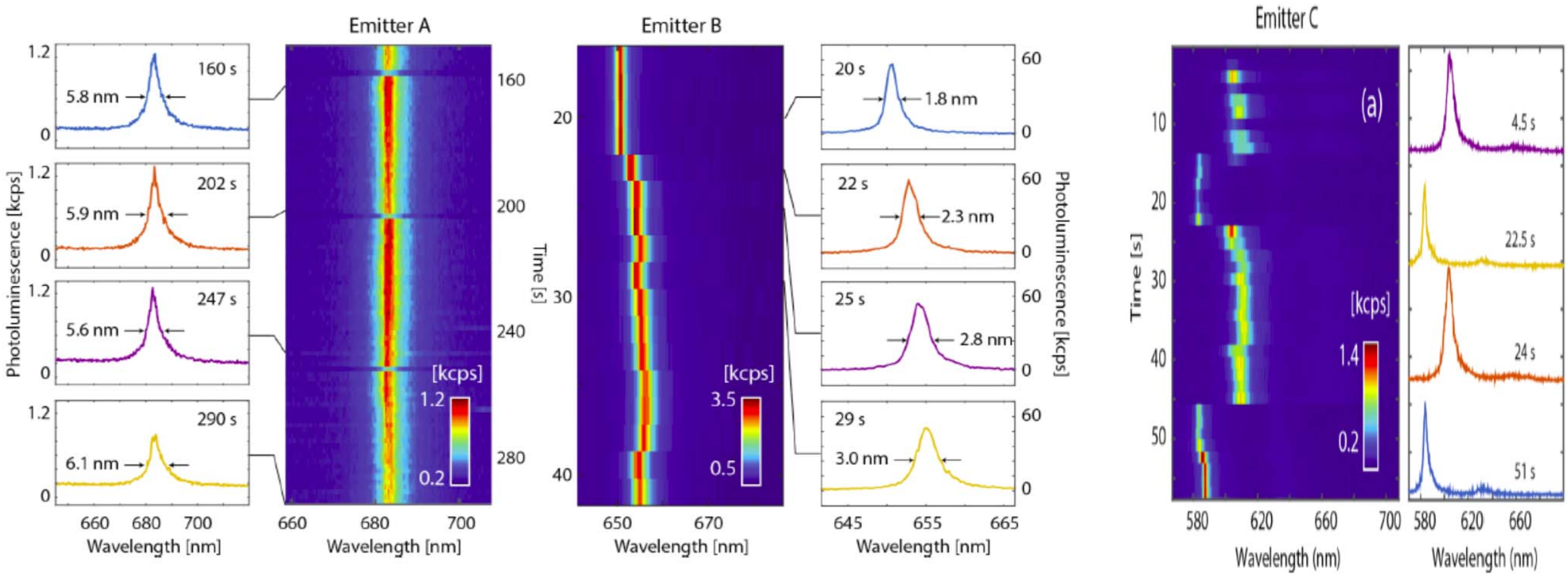
Single Photon Emission from hBN



Z. Shotan, H. Jayakumar….VMM, C. Meriles : *ACS Photonics* 3, 2490 (2016)

Single Photon Emission from hBN

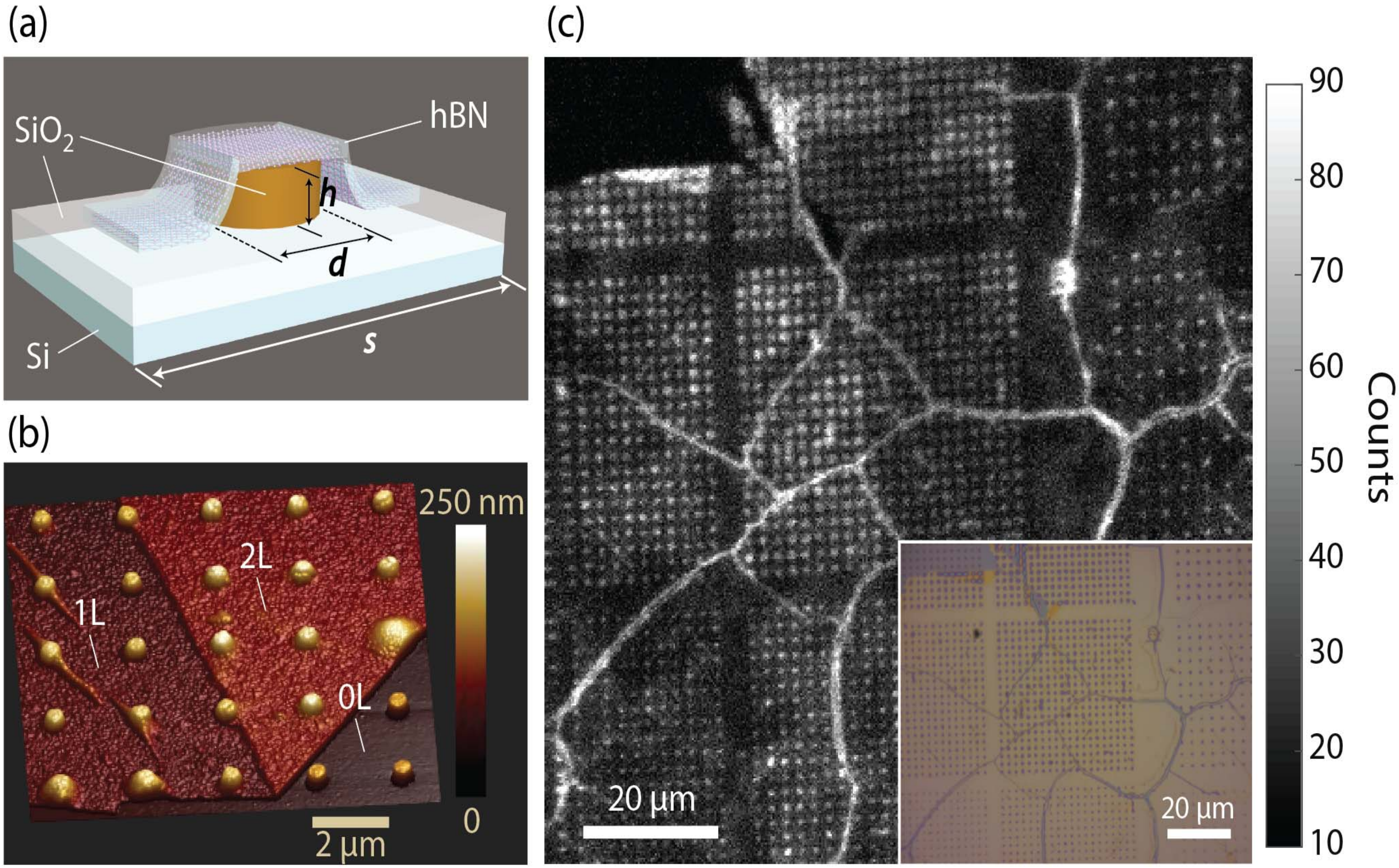
Stability Issues: Spectral diffusion, jumps



Emission wavelength and spatial location are not controlled

Z. Shotan, H. Jayakumar….VMM, C. Meriles : *ACS Photonics* 3, 2490 (2016)

Towards Deterministic Single Photon Emission from hBN



N. Proscia, Z. Shotan, H. Jayakumar…C. Meriles and VMM – Under Review

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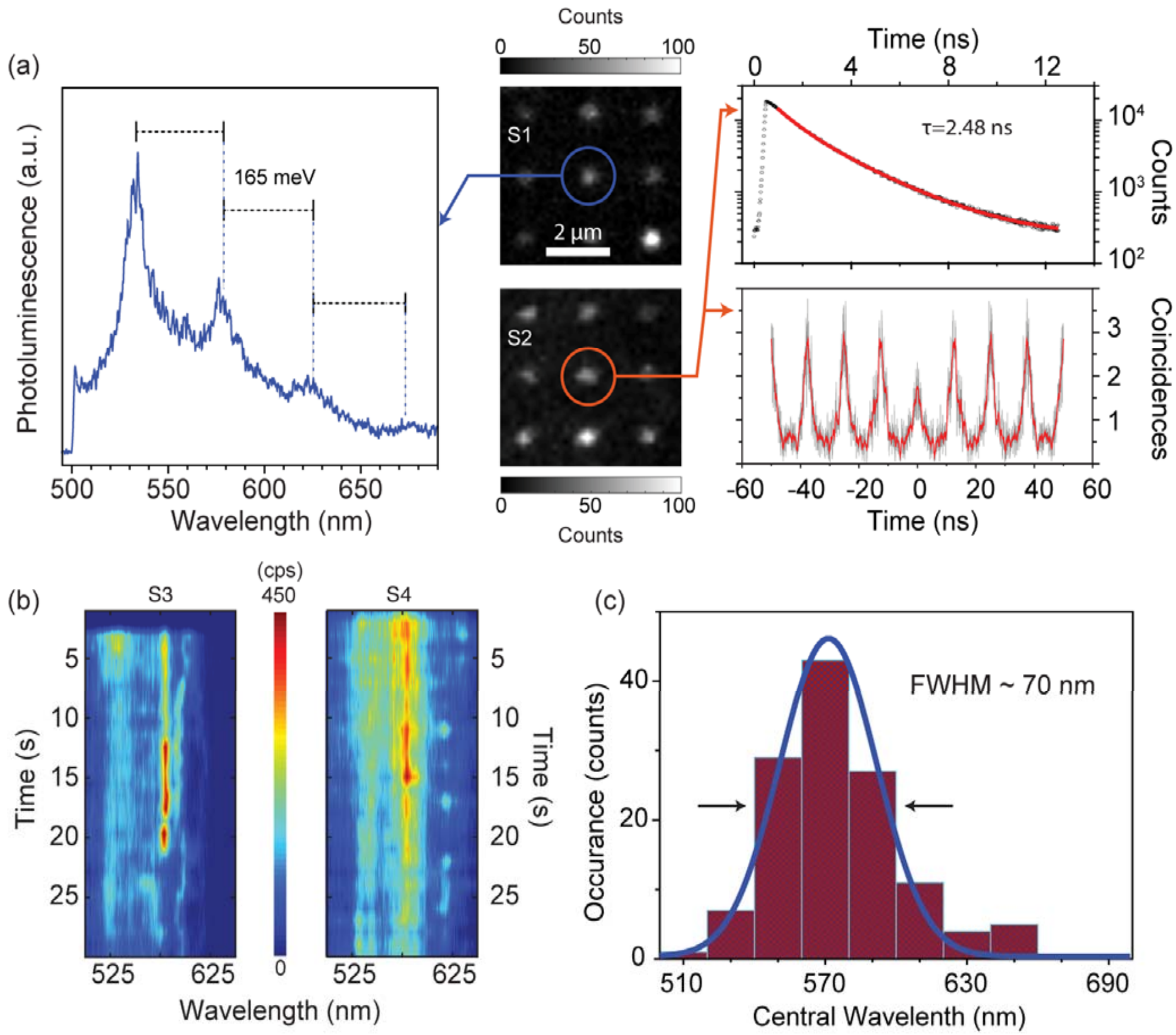
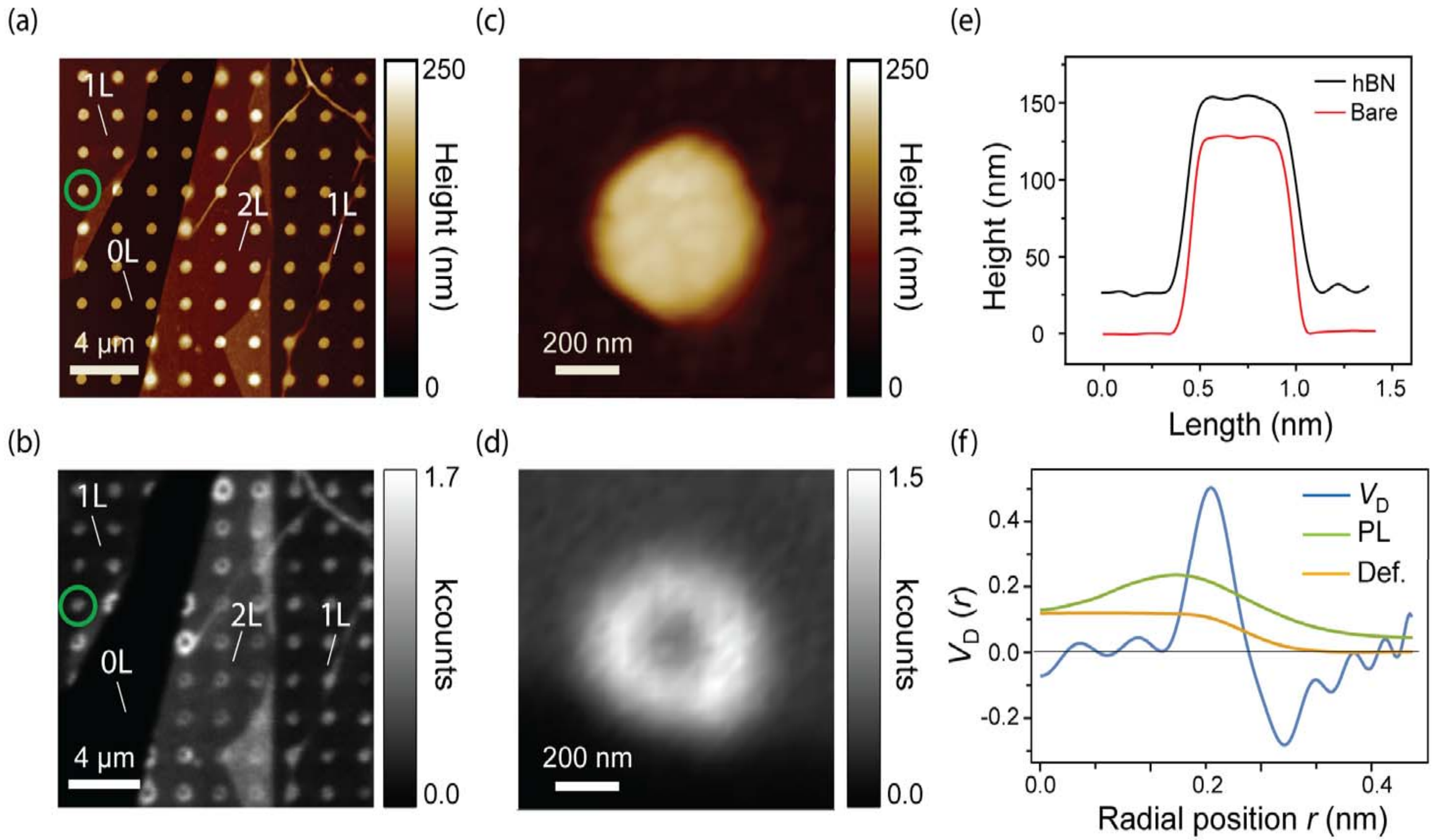
Towards Deterministic Single Photon Emission from hBN



N. Proscia, Z. Shotan, H. Jayakumar…C. Meriles and VMM – Under Review

Towards Deterministic Single Photon Emission from hBN



N. Proscia, Z. Shotan, H. Jayakumar…C. Meriles and VMM – Under Review

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Summary

- Formation of microcavity polaritons in a metal cavity with mononlayer WS_2.
- Demonstration of the angle dependent valley polarized polaritons at room temperature with peak helicity around 27% .
- Observation of valley polarization of polariton emission when excited in resonance with the lower polariton branch.
- Enhanced spontaneous emission from 2D TMDs using photonic hypercrystal
- Room temperature single photon emission from defects in hBN

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Collaborators

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Students

Zheng Sun (PhD)
Nick Proscia (PhD)
Rahul Deshmukh (PhD)
Jie Gu (PhD)
David Cuffari (PhD)
Deanna Lombardo (MA)
Rezlind Bushati (MA)
Paulo Marques (UG)
Michael Dollar (UG)
Charlie Cohen (UG)
Zav Shotan (Post Doc)
Jared Day (Post Doc)
Biswanath Chatterjee (Post Doc)

Alumni

Tal Galfsky, PhD 2016 (Coriant)
Xiaoze Liu, PhD 2015 (UC Berkeley)
Harish Krishnamoorthy, PhD 2014 (NTU)
Nicky Okoye, PhD 2013 (Mt Siniai)
David Goldberg, PhD 2012 (Faculty @ QC)
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Vasilios Passias (UIUC)

http://www.lanmp.org vmenon@ccny.cuny.edu

Relevant Publications

"Room Temperature valley polaritons", Z. Sun, J. Gu. A. Ghazaryan, Z. Shotan, M. Dollar, B. Chatterjee, P Ghaemi, S-K. Cohen and V. M. Menon, *Nature Photonics*, DOI: 10.1038/NPHOTON.2017.121

"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, Z. Sun, C. R. Considine, C-T Chou, W-C Ko, Y-H Lee, E. Narimanov and V. M. Menon, *Nano Lett.* **16**, 4940 (2016).

"Microcavity enhanced second harmonic generation in 2D MoS2," J. K. Day, M. Chung, Y-H. Lee, and V. M. Menon, *Opt. Materials Express* **6**, 2360 (2016).

"Strong light-matter coupling in two-dimensional atomic crystals," X. Liu, T. Galfsky, Z. Sun, F. Xia, E-C. Lin, Y-H. Lee, S. Kena-Cohen, and V. M. Menon, *Nature Photonics* **9**, 30 (2015).

"Topological transitions in metamaterials," H. N. S. Krishnamoorthy, Z. Jacob, E. Narimanov, I. Kretzschmar, and V. M. Menon, *Science* **336**, 205 (2012).

Thank you!

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