Université de Strasbourg

IPCMS Institut de Physique et Chimie des Matériaux de Strasbourg

CNRS

Exciton dynamics and valley-contrasting properties in heterostructures based on atomically-thin semiconductors

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Workshop on Chiral Optical Modes, Aussois, Nov. 27, 2018

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UNIVERSITÉ DE STRASBOURG

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NIMS

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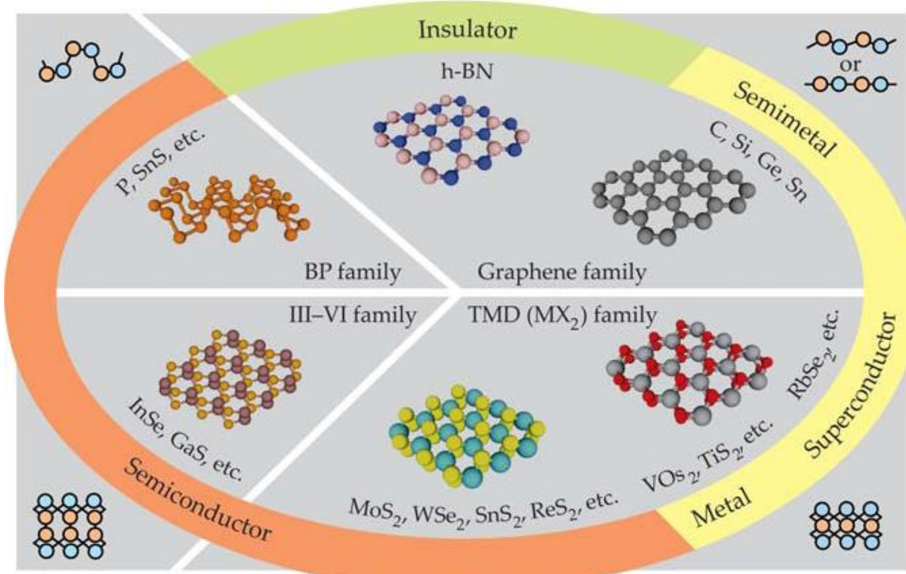
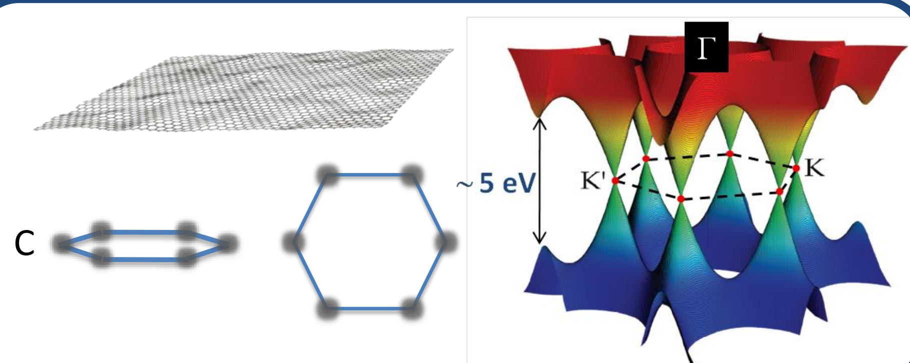
Entering "Flatland"

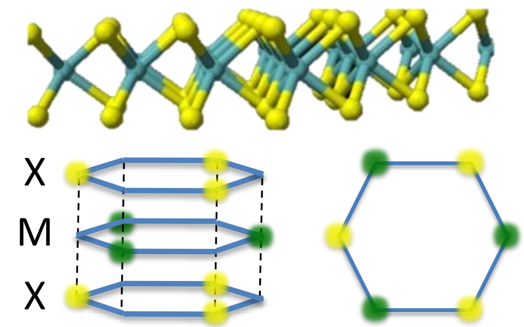


Ajayan, Kim, Banerjee - Physics Today (2016)

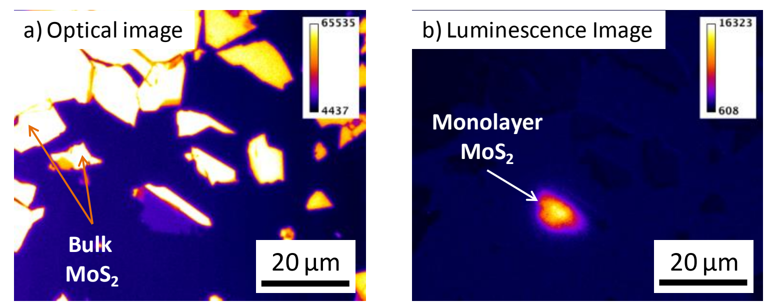
Graphene (semimetal)



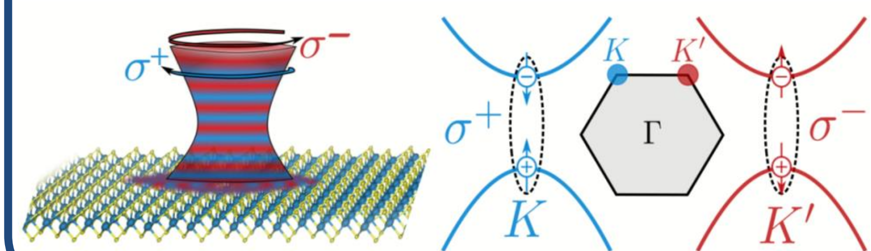
2H-TMD (semiconductors)
M= Mo, W X= S, Se, Te



Direct bandgap emission



Helicity-dependent valley addressability



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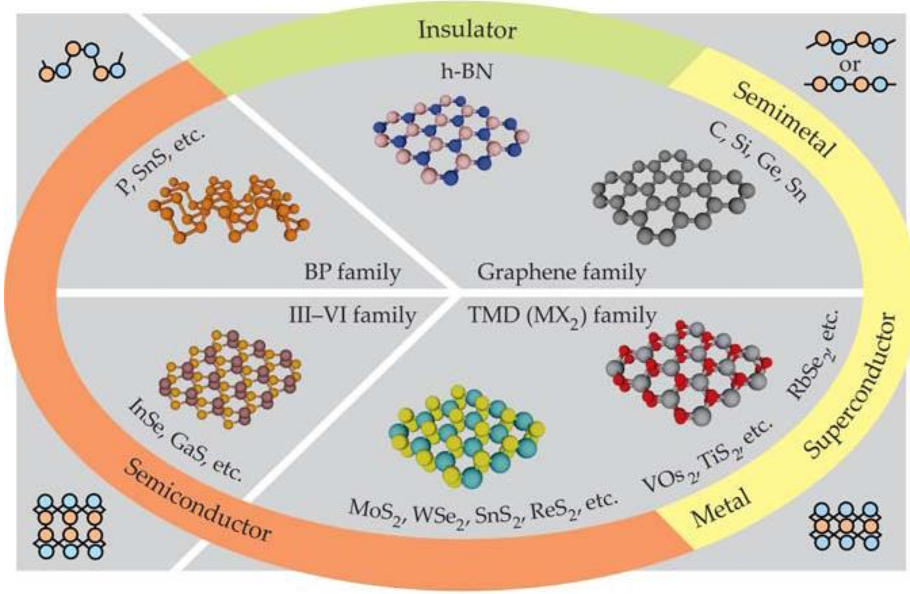

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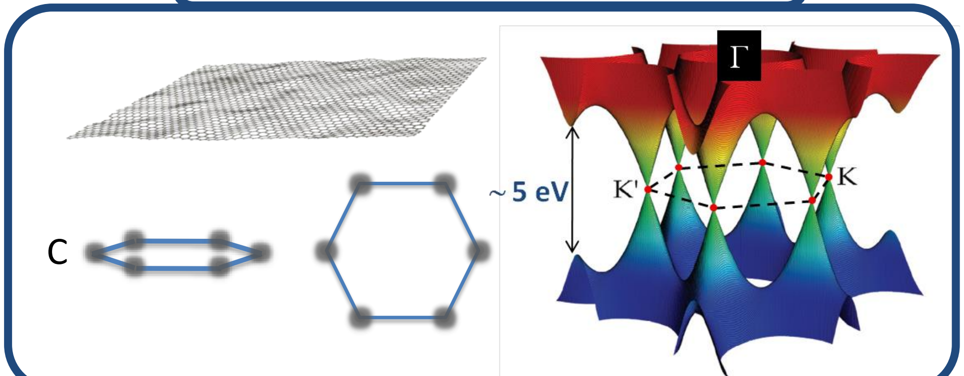

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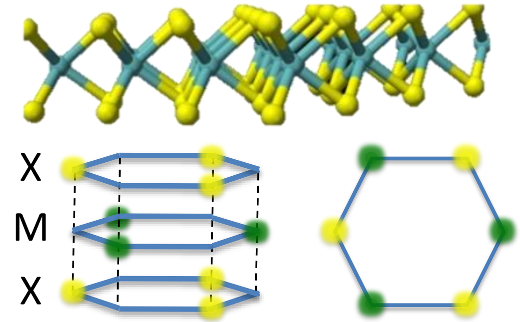

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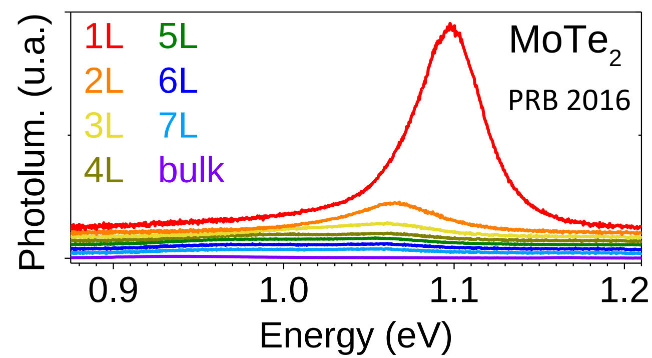

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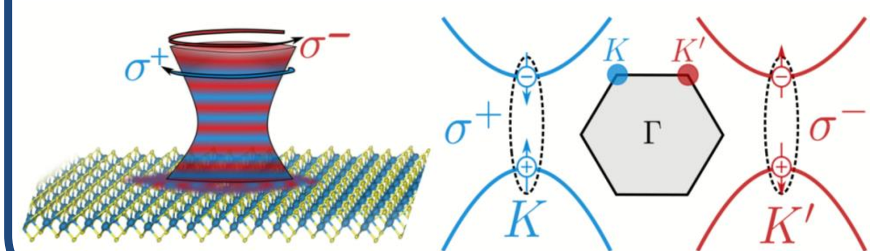
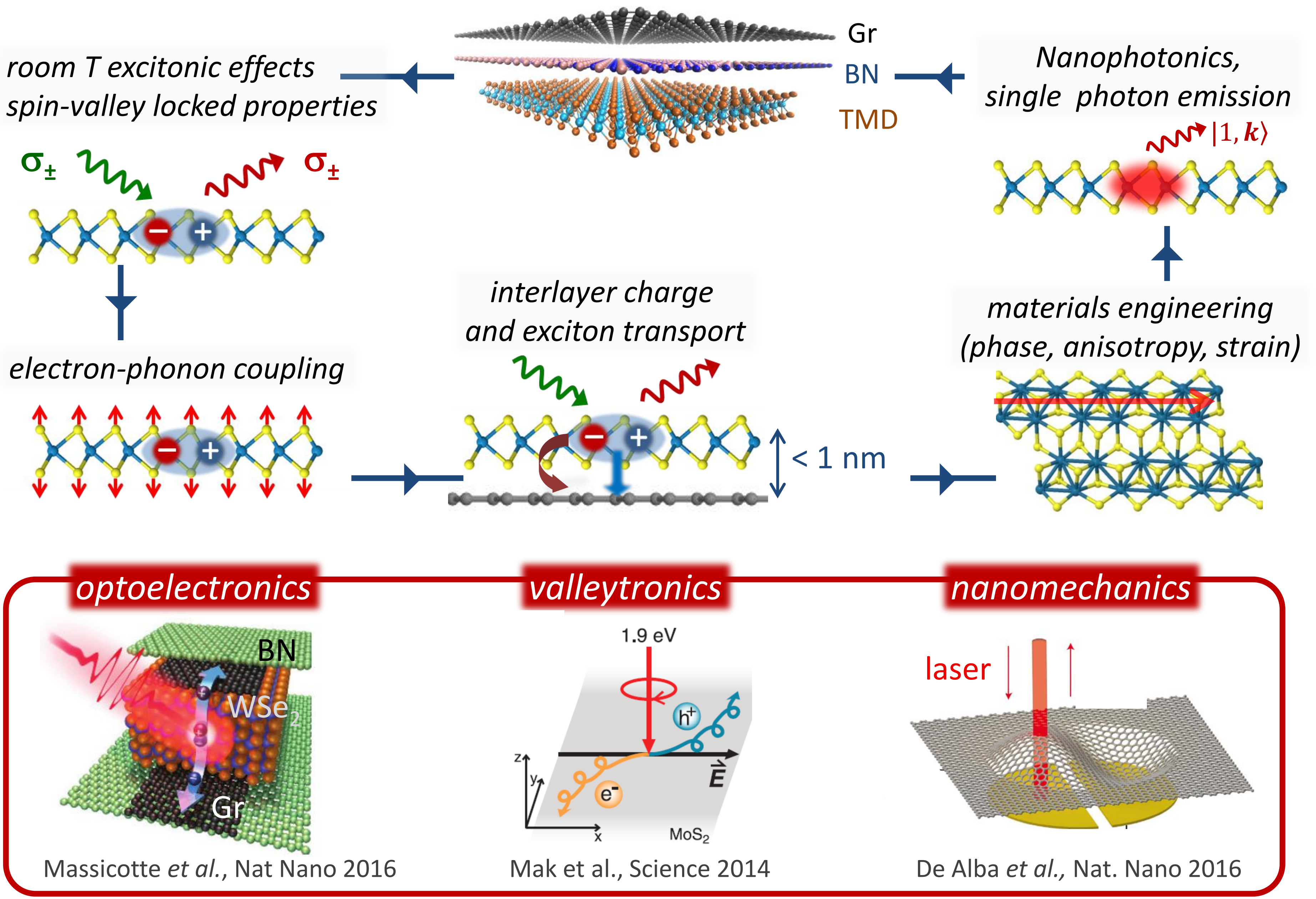
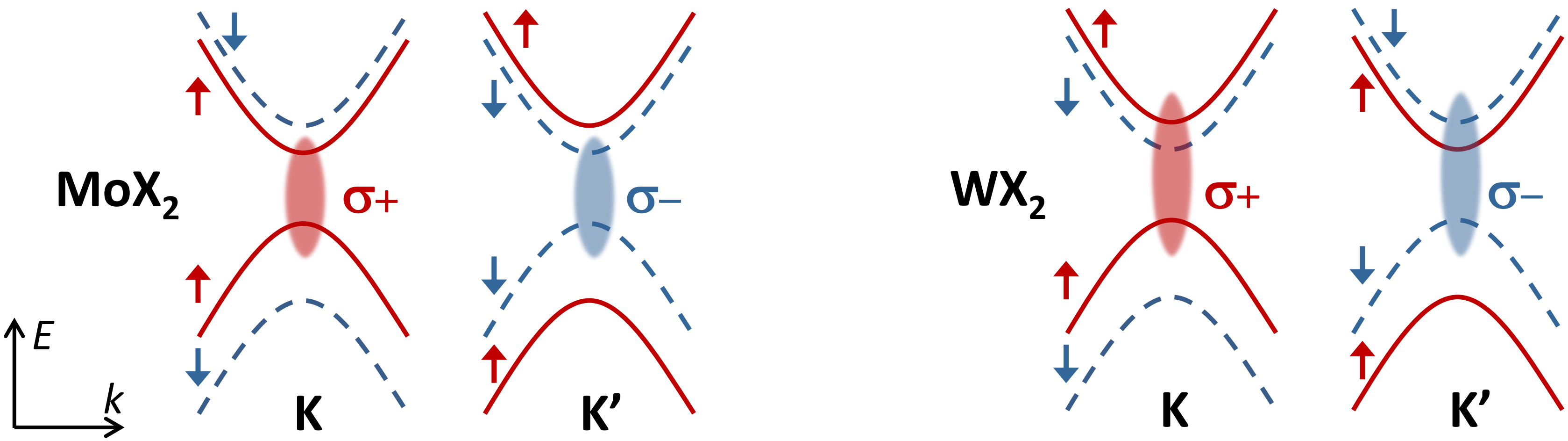


2D Materials: a unique toolkit for fundamental and applied physics

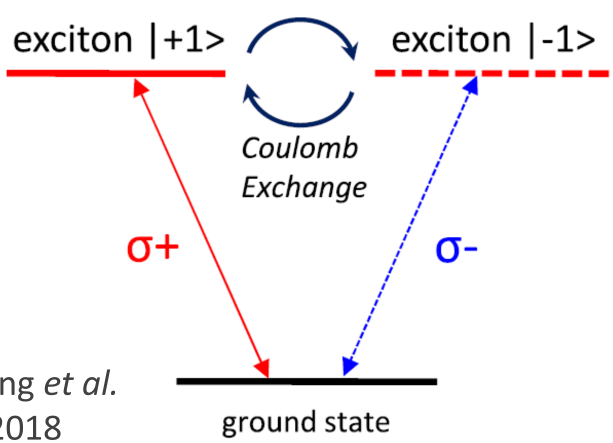


Spin-valley locking in monolayer TMDs

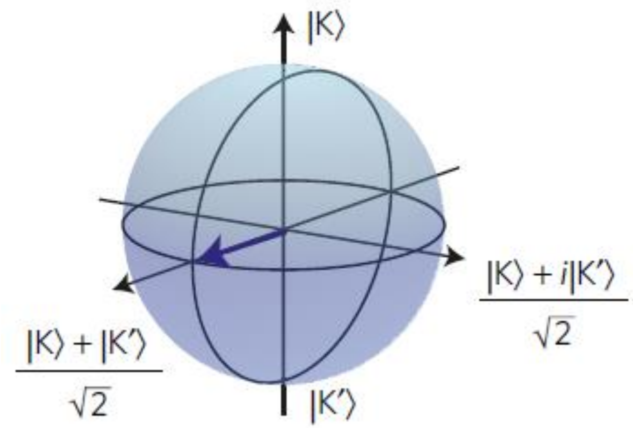
Broken inversion symmetry + strong spin orbit coupling



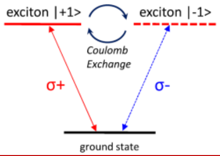
Valley-polarized excitons...and their coherent superpositions



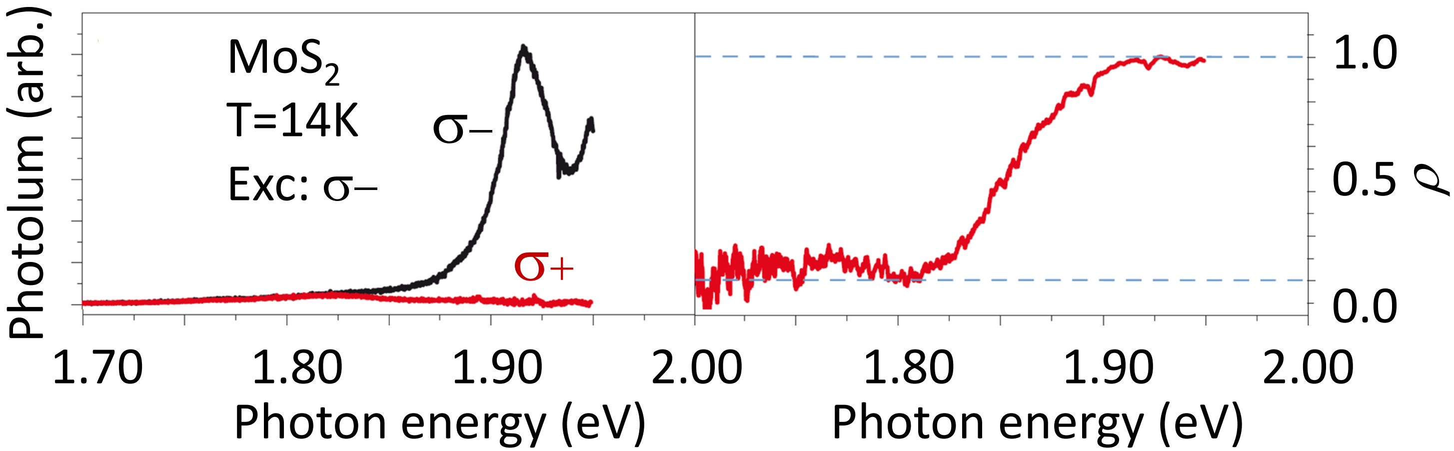
G. Wang *et al.*
RMP 2018



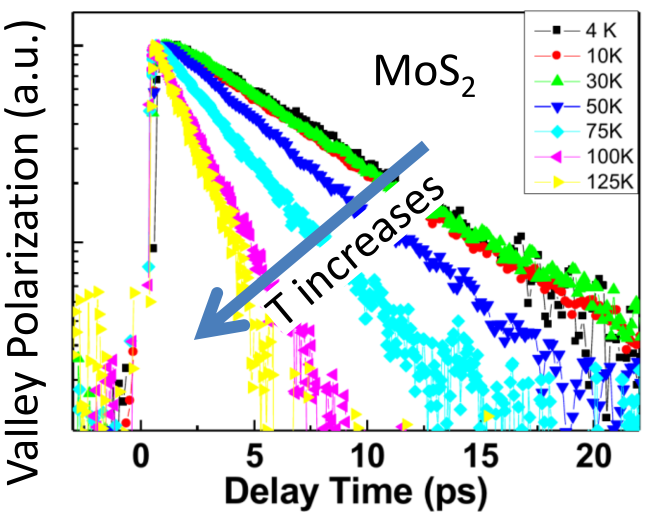
Z. Ye *et al.*, Nat. Phys. 2016



Fragile Valley Contrasts



K.F. Mak *et al.*, Nat. Nano 2012



C. R. Zhu *et al.*, PRB 2014

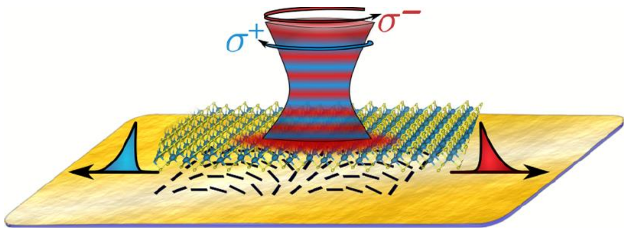
ρ (γ) degrees of circular (linear) polarization

- ρ up to ~100 % at low T (MoS_2)
- γ up to 60 % at low T (MoS_2)

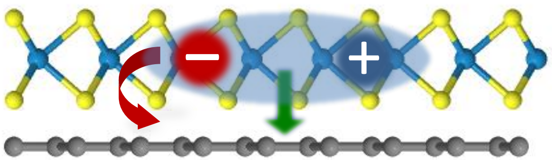
$$\rho = \frac{\rho_0}{1 + 2\tau_X/\tau_S}$$

- Valley contrasts are lost at room T
- ➢ How to protect/tailor valley contrasts?

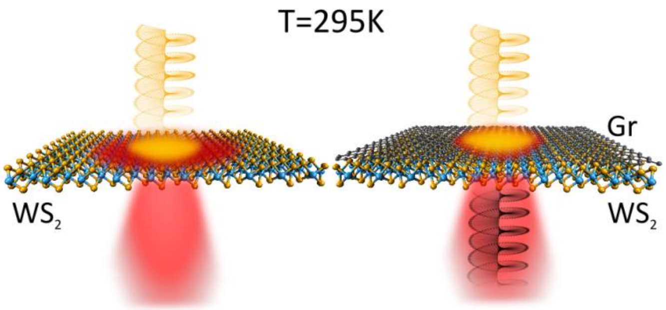
Outline



Room temperature Chiral coupling of valley excitons with spin-momentum locked surface plasmons



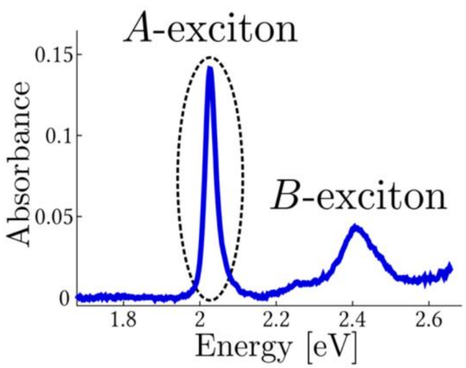
Graphene/TMD heterostructures as a 2D optoelectronic building block

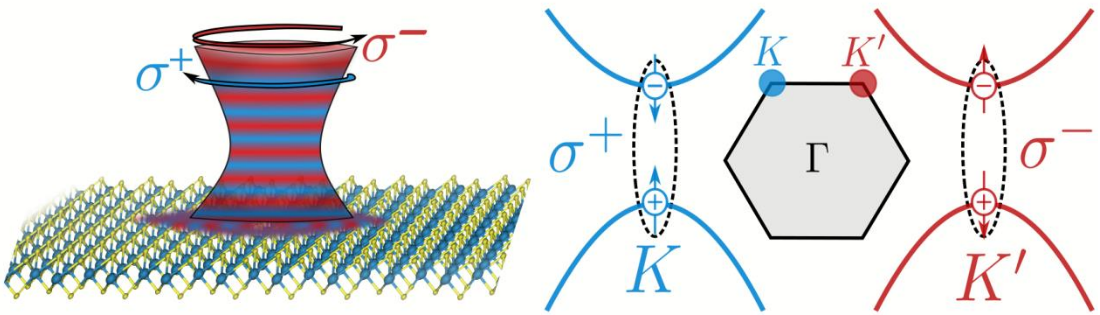


Room temperature valley polarization and coherence in TMD/Graphene heterostructures

2D Matter meets 2D Light

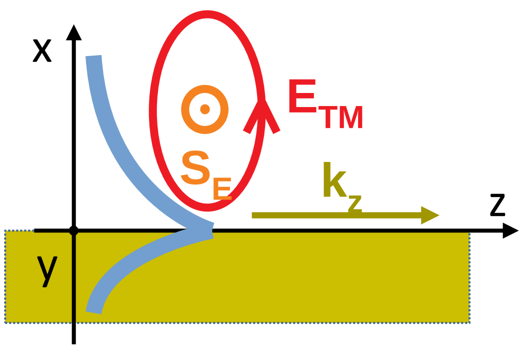
Semiconducting 2H-TMDs

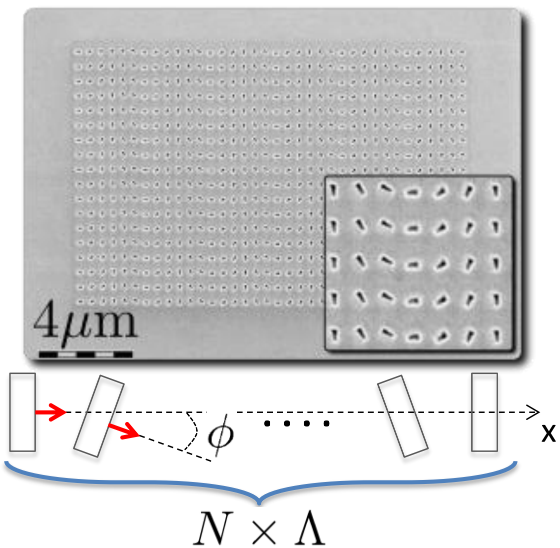




Helicity-dependent valley addressability

Surface plasmons (SPs)

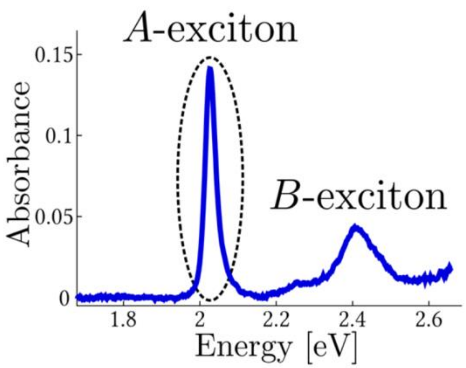


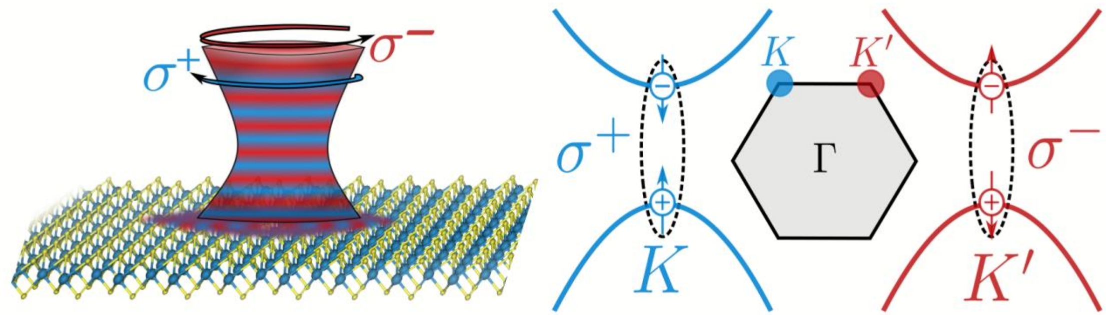


Helicity-dependent directional SP launching

2D Matter meets 2D Light

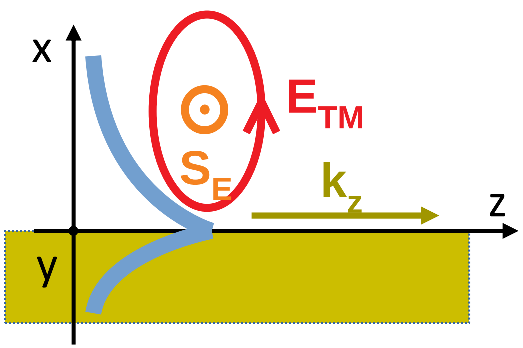
Semiconducting 2H-TMDs

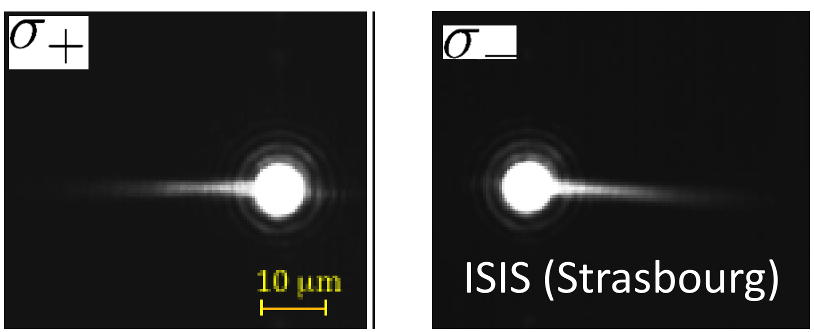




Helicity-dependent valley addressability

Surface plasmons (SPs)

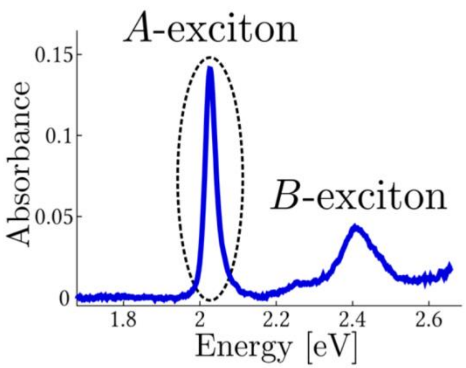


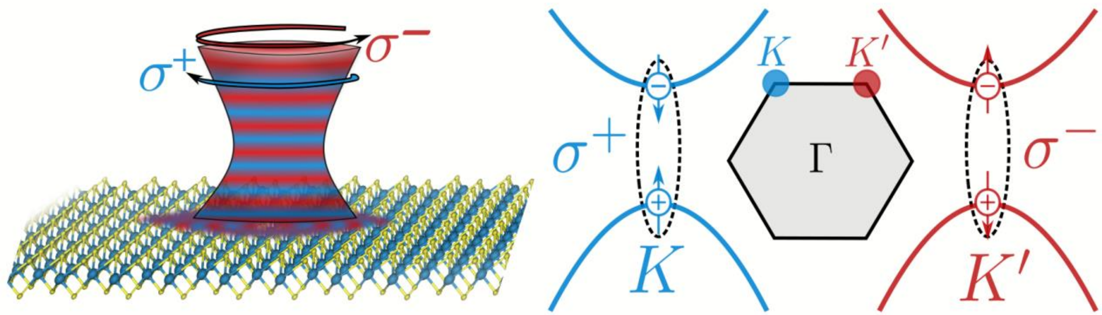


Helicity-dependent directional SP launching

2D Matter meets 2D Light

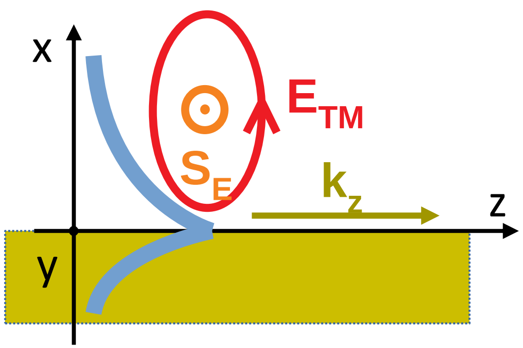
Semiconducting 2H-TMDs

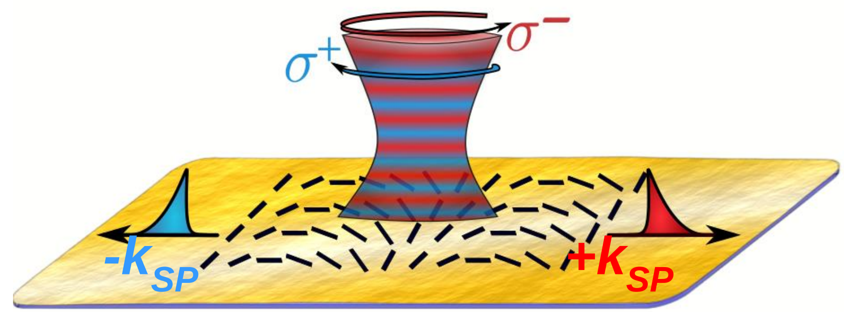




Helicity-dependent valley addressability

Surface plasmons (SPs)



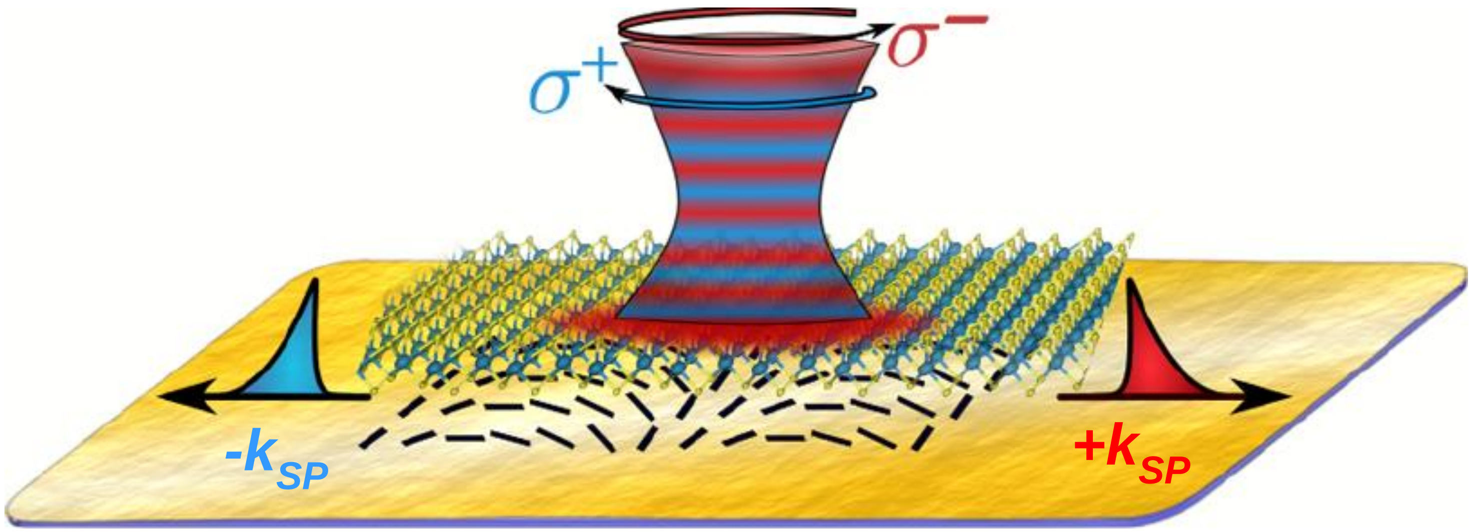


Helicity-dependent directional SP launching

Tailored control of the valley pseudospin using TMD-SP architectures

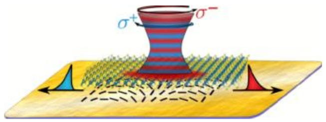
2D Matter meets 2D Light

*Room temperature **chiral coupling** between valley excitons and helicity-momentum locked surface plasmons*



T. Chervy*, S. Azzini*, *et al.,* **ACS Photonics 5, 1281 2018 (**Arxiv 1701.07972)
See also K. Kuipers' "intermezzo"

Coll: **T. Chervy, S. Azzini**, J.A. Hutchinson, T.W. Ebbesen, **C. Genet** (ISIS, Uni. Strasbourg)
Y. Gorodetzki (Ariel, IL), S. Wang (Eindhoven, NL)

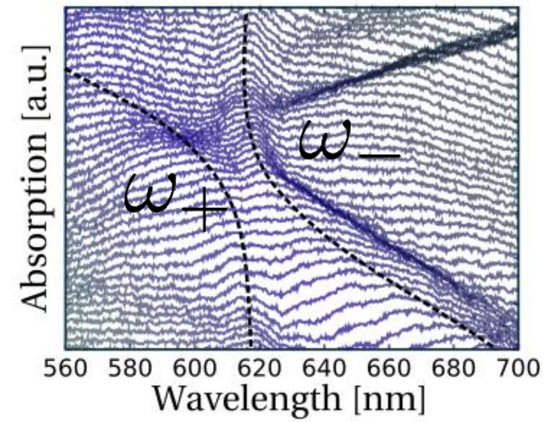


Chiral coupling: 1L-TMD exciton with spin-orbit SP mode

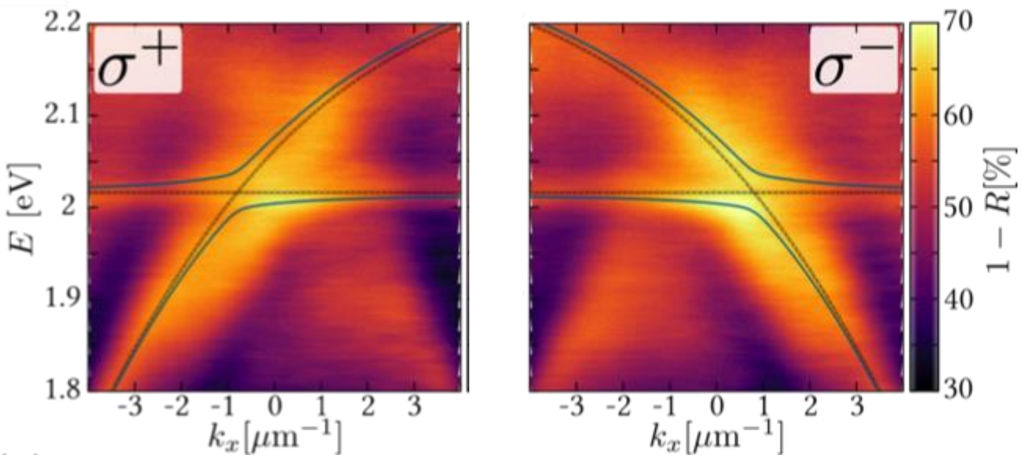
- ✓ Resonant condition TMD excitons / $(n = \pm 1\ ,\ \sigma = \mp 1)$ SP modes

Grating period Λ=480 nm

$$\omega_{SP} \sim \omega_{Aexc} \sim 2.010\text{ eV}$$



- ✓ Angle-resolved WL absorption (*1-R ~ A*) – CPL analysis

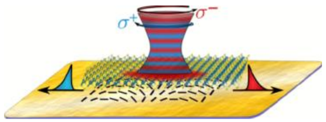


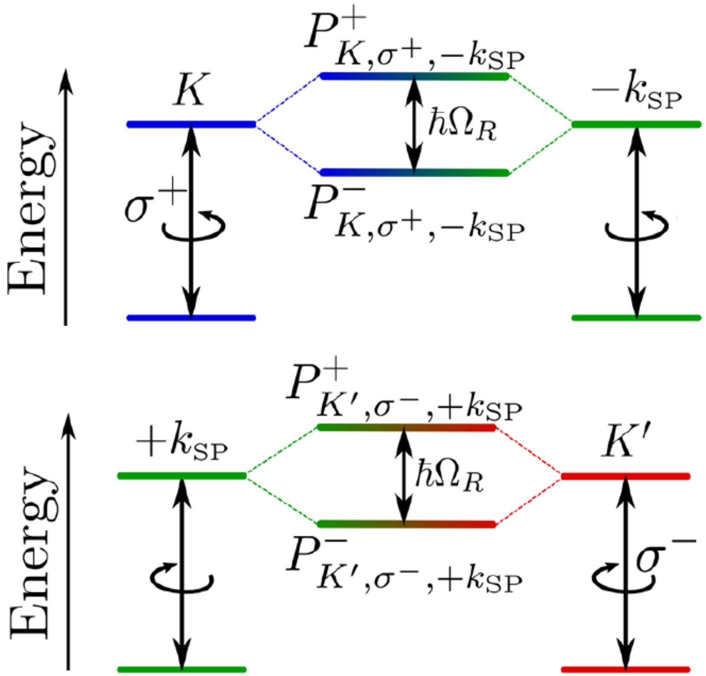
Anticrossing $\hbar\left(\omega_+ - \omega_-\right) = 40\text{meV}$

Strong-coupling FOM

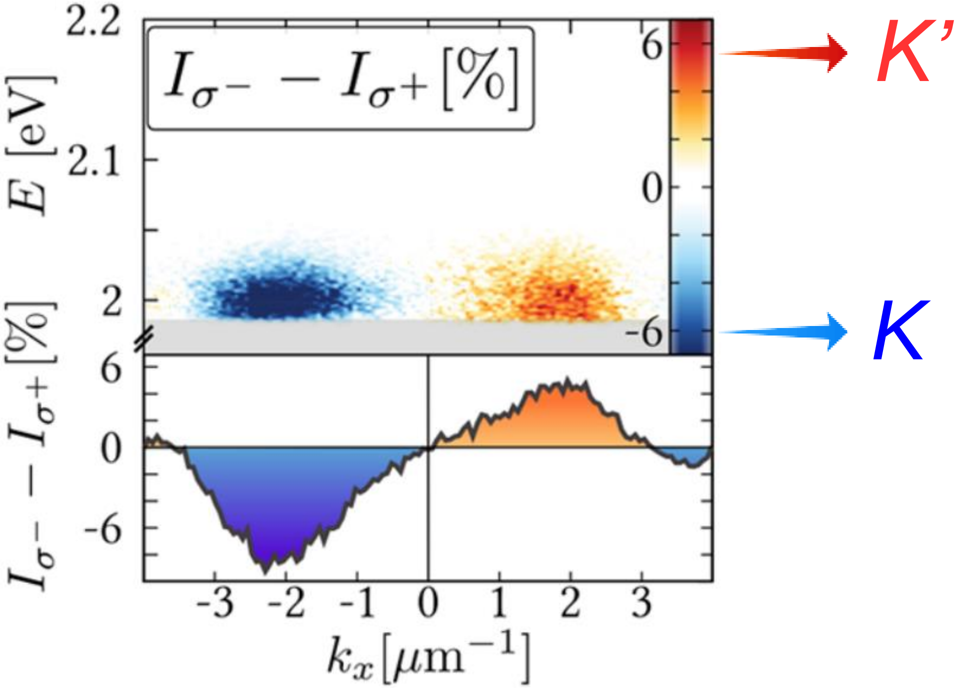
$$\mathcal{C} = \frac{2\Omega_R}{\gamma_{exc} + \Gamma_{OSO}} = 0.9$$

Room temperature chiralitons





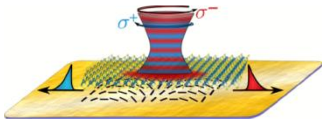
"Chiralitons"



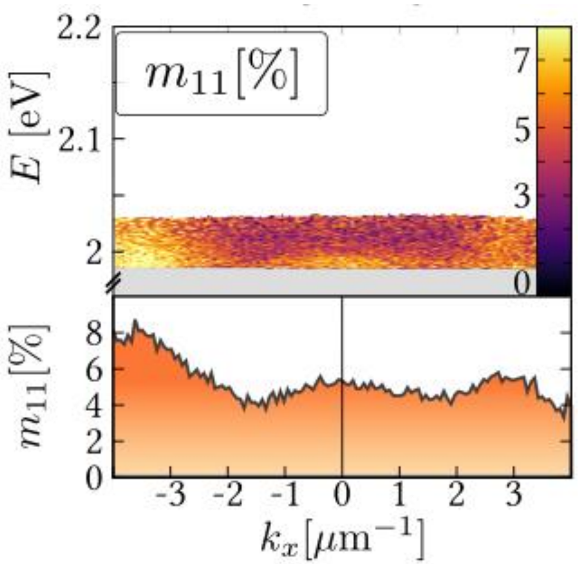
T. Chervy*, S. Azzini* *et al.*, **ACS Photonics 2018**

- *Plasmon sorter efficiency: 15%*
  - ➢ *Net chiraliton flow: 6 % → 40 %*

Recent related results: Spin-momentum locking: TU Delft (Science 2018), UT Austin (arXiv:1801.06543)
Valley polaritons: U. Sheffield, Nat. Photon. 2018, Northwestern U. Nat Photon 2018, Würzburg PRB2017



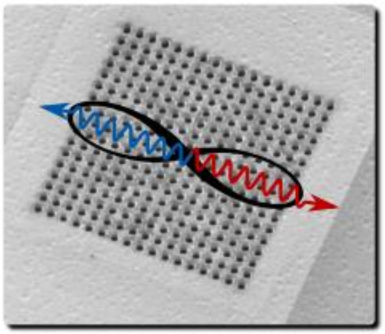
Coherent superposition of counterpropagating chiralitons



- *PL polarization tomography on a linear basis Measured as the m_{11} Mueller matrix element*

- *Chiralitonic valley coherence*

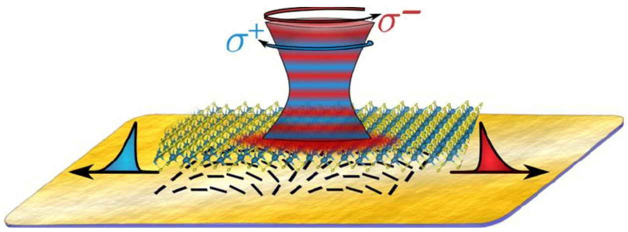
$$(S_1|^{TM} - S_1|^{TE})/2 = m_{11} \sim 5 - 8\ \%$$



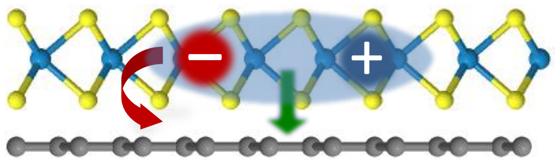
$$|\Psi\rangle = |P^{\pm}_{K,\sigma_+,-k_{\mathrm{SP}}}\rangle + |P^{\pm}_{-K,\sigma_-,+k_{\mathrm{SP}}}\rangle$$

Outlook: No valley contrasts in bare TMD $\rightarrow$ Cavity protection mechanism?
Designing new 2D building blocks for chiral optics.

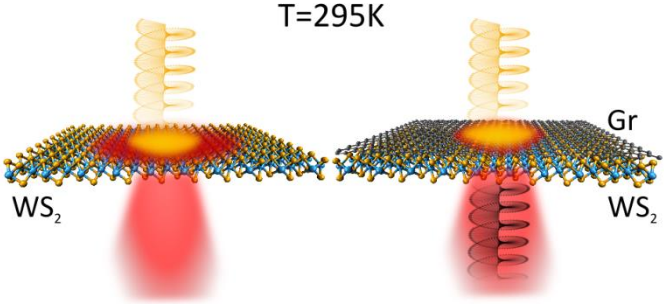
Outline



Room temperature Chiral coupling of valley excitons with spin-momentum locked surface plasmons



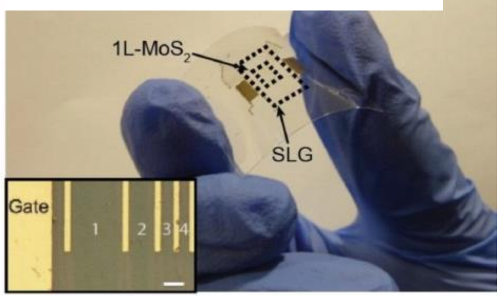
Graphene/TMD heterostructures as a 2D optoelectronic building block



Room temperature valley polarization and coherence in TMD/Graphene heterostructures

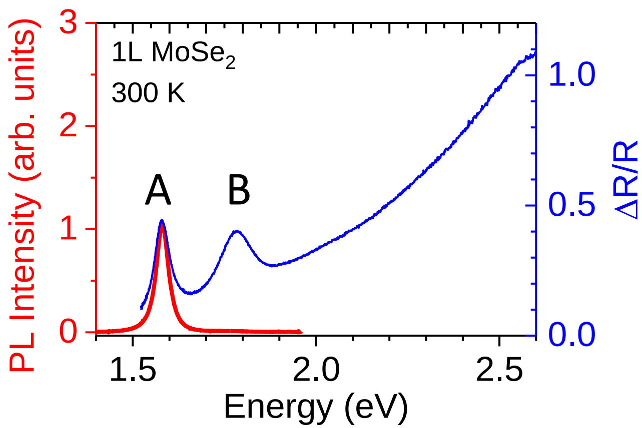
Gr/TMD heterostructures: why the interest?

- *Graphene: 2D semi-metallic channel*
  - ✓ Quasi-transparent (~2% absorption per layer)
  - ✓ High carrier mobility and large carrier density
  - ✓ Gate-tunable properties

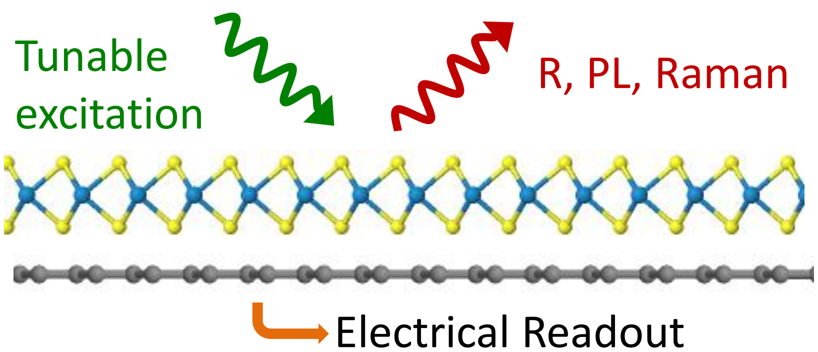


De Fazio *et al.*, ACS Nano 2016

- *TMD: 2D semiconducting channel*
  - ✓ Strong light-matter interaction
  - ✓ Broadband absorption and tunable emission



- *Gr-TMD heterostructures:*
  - ✓ Strong interlayer coupling
    (J. He *et al.*, Nat Comm. 2014)
  - ✓ Photogating/photodetection
    (W. Zhang *et al.*, Sci. Rep. 2014)
  - ✓ ps-range photoresponse
    (M. Massicotte *et al.*, Nat Nano 2016)



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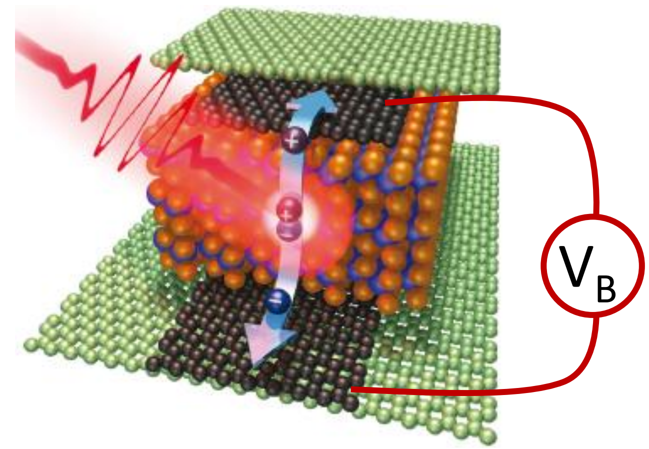
(J. He et al., Nat Comm. 2014)

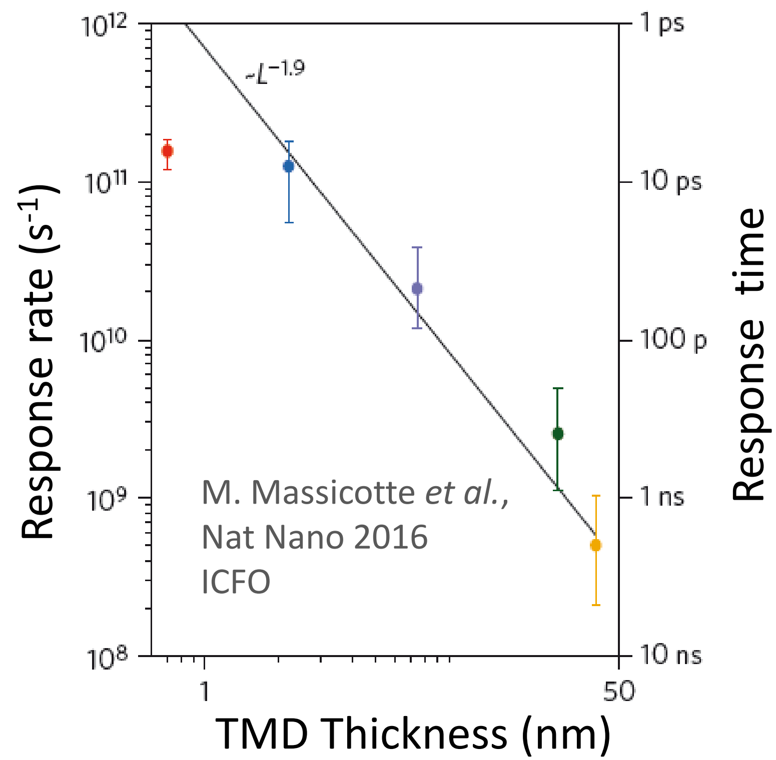
- ✓ Photogating/photodetection
(W. Zhang et al., Sci. Rep. 2014)

- ✓ ps-range photoresponse
(M. Massicotte et al., Nat Nano 2016)

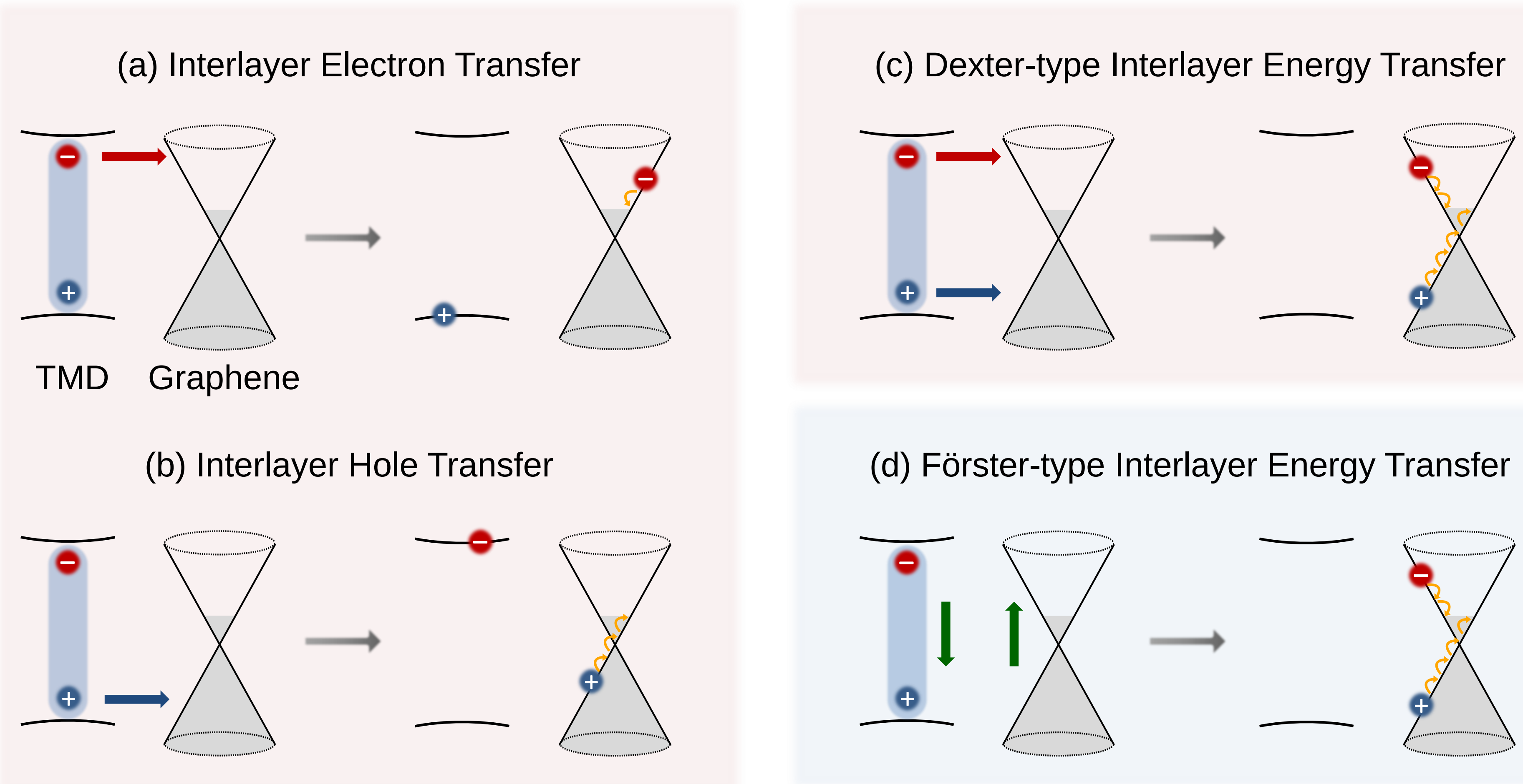
Low efficiency with monolayer TMD

➢ *Energy transfer?*





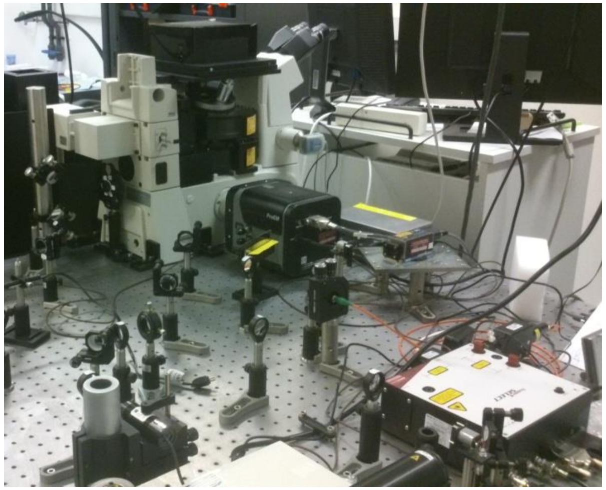
Charge and energy transfer mechanisms

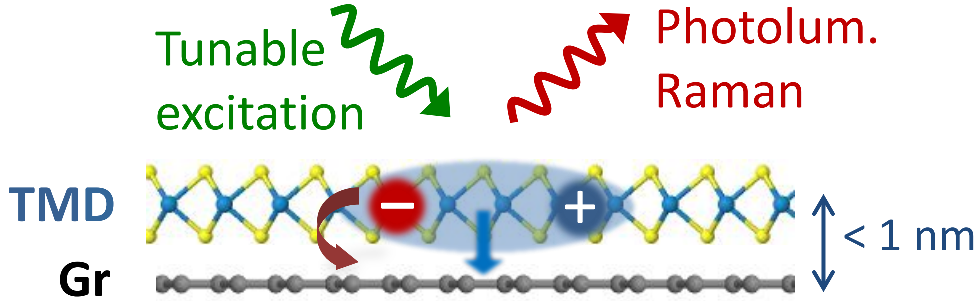


✓ Probed in the steady state (Raman)
✓ Balanced electron and hole transfer

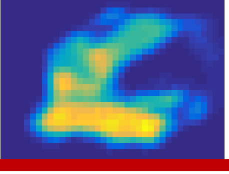
✓ Determine exciton dynamics
→ Relative efficiencies?

Our Experimental Approach

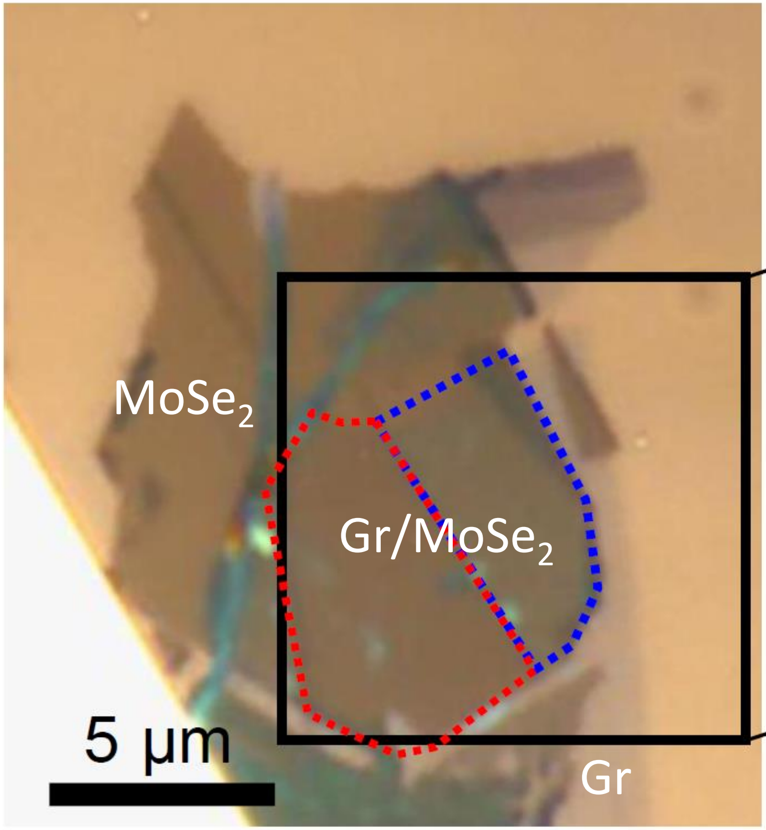


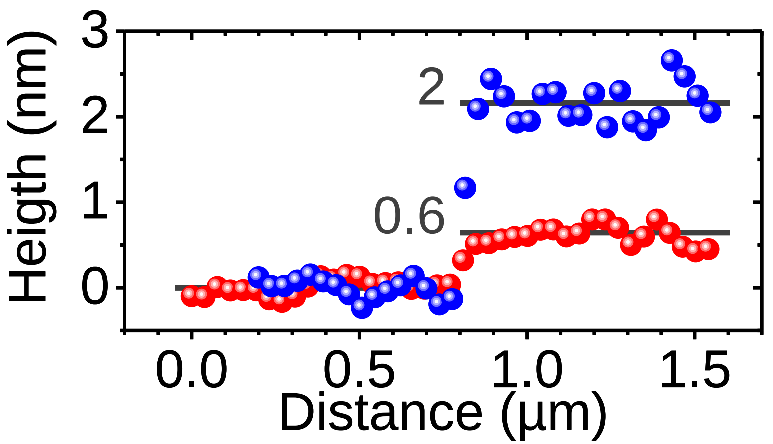


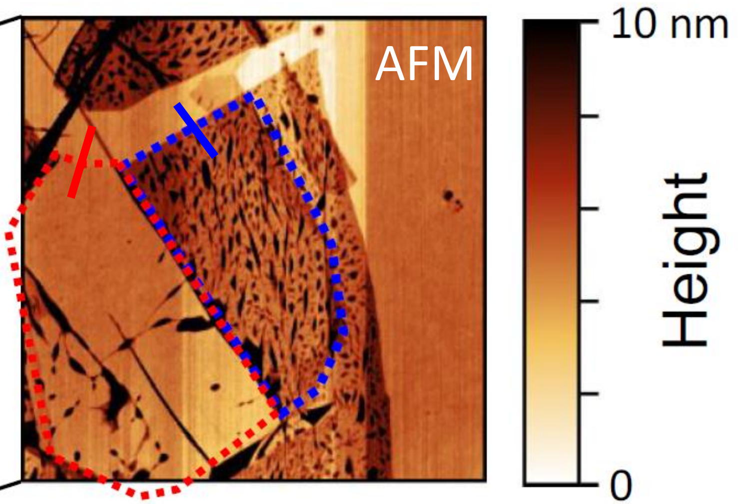
- *Understanding near-field interactions (IET vs ICT)*
- *Implications for optoelectronic devices*



Atomic Force Microscopy

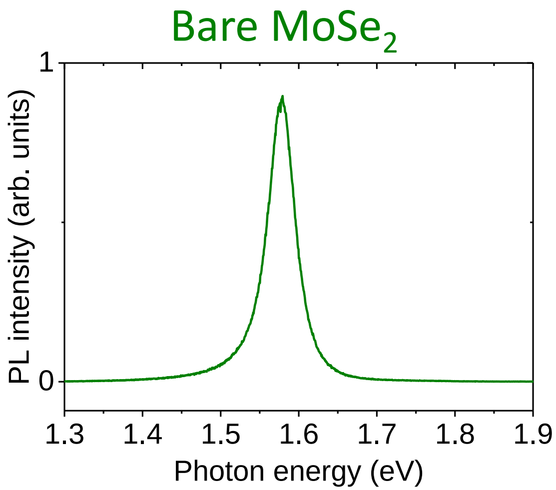


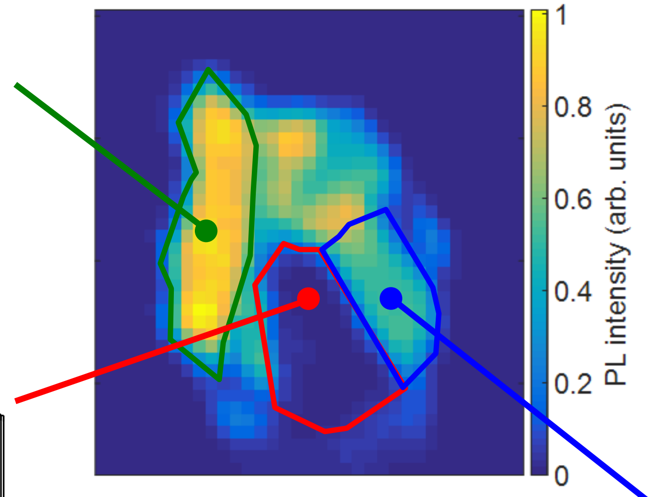


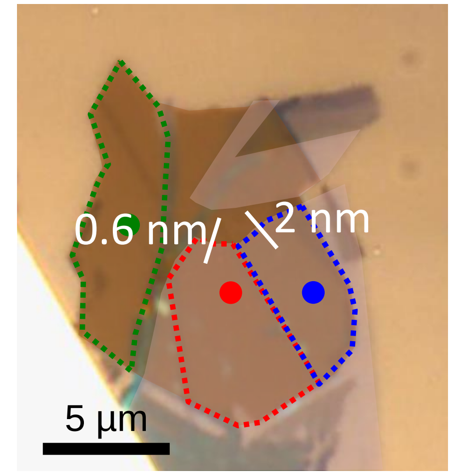


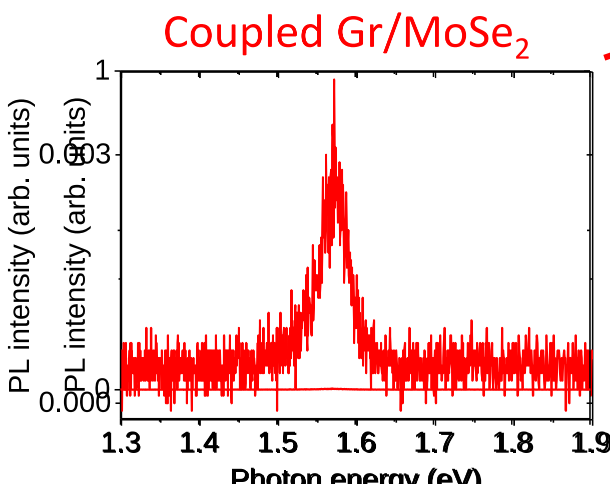
Smooth Gr/MoSe$_2$ domains

Photoluminescence mapping

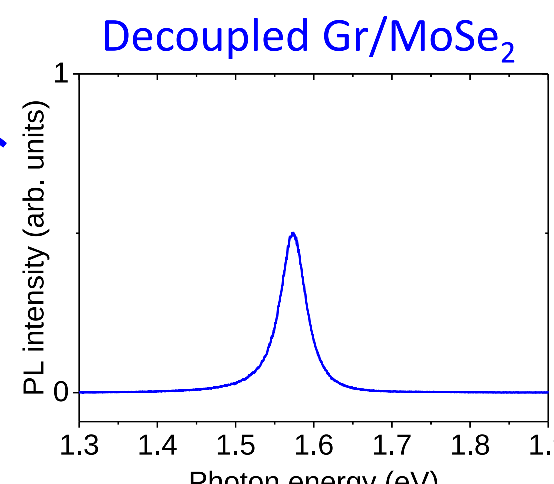


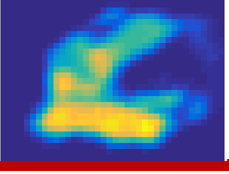




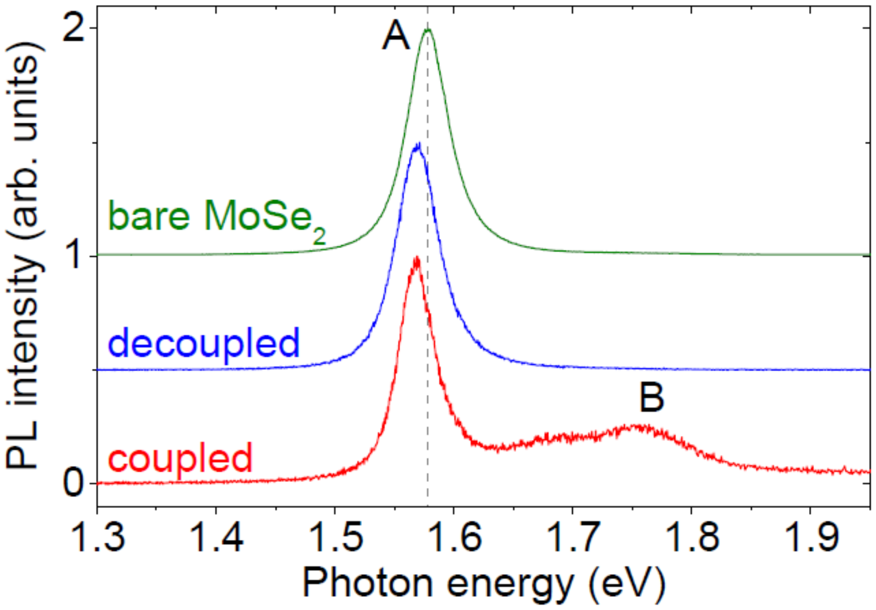


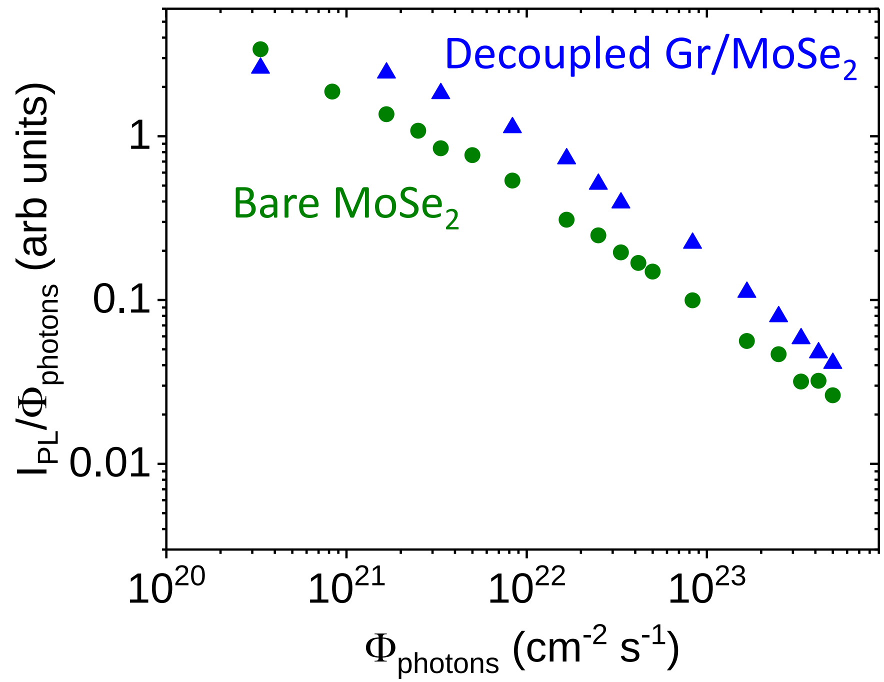
➡ Strong PL Quenching ~ 300



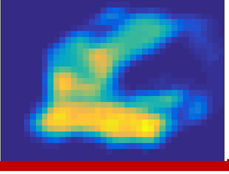


Exciton: dynamics: PL vs $\Phi_{photons}$

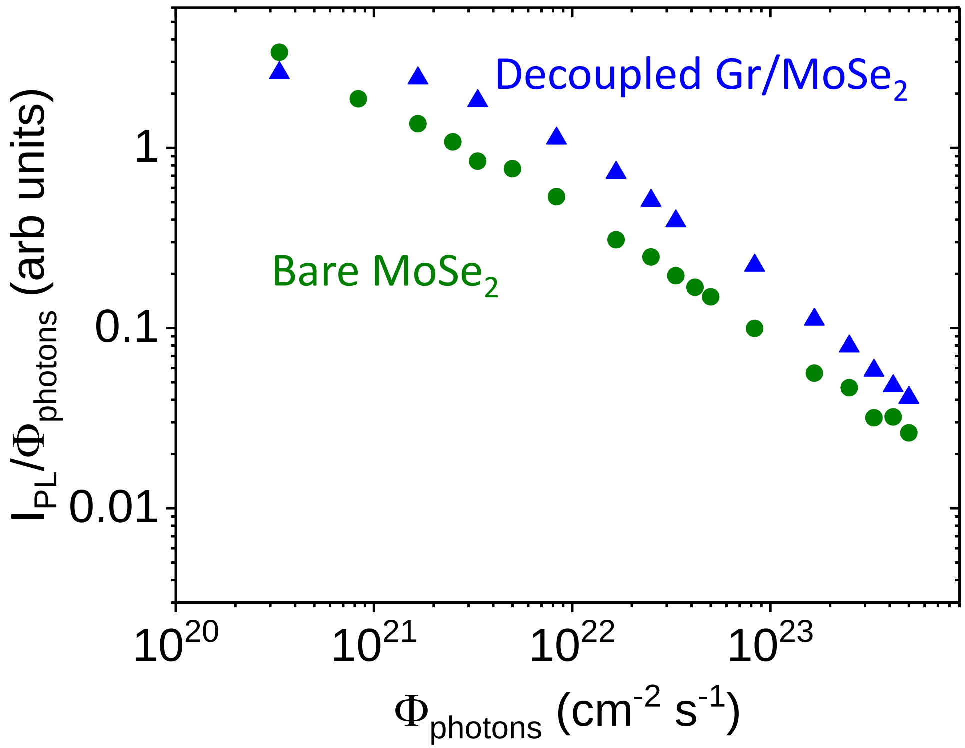


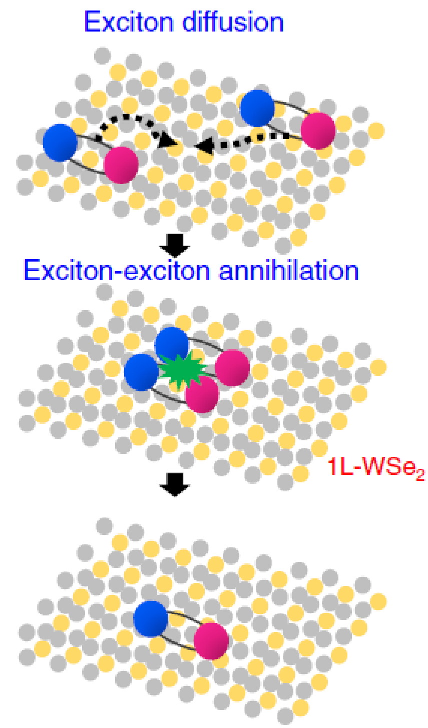


- PL saturation on bare and decoupled $MoSe_2$



Exciton dynamics: PL vs $\Phi_{photons}$

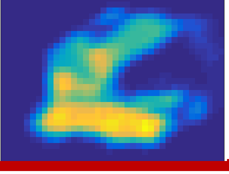




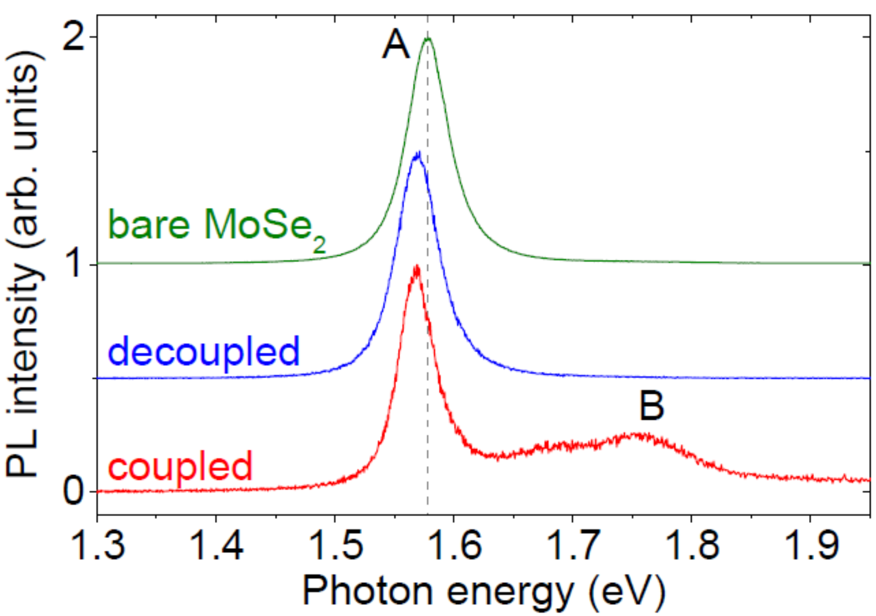
S. Mouri *et al.*, PRB 2014

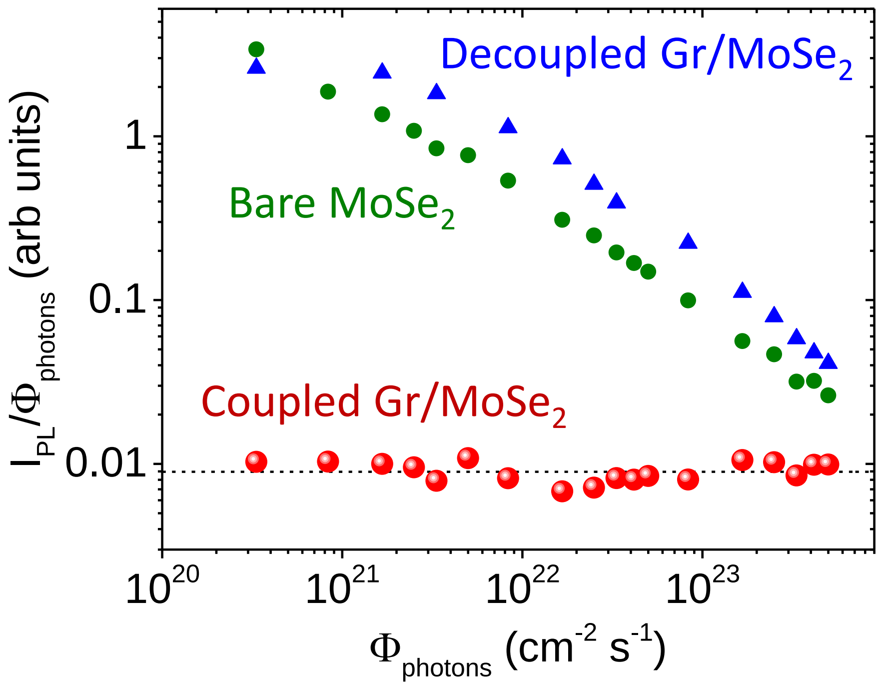
- PL saturation on bare and decoupled MoSe$_2$:
  $\rightarrow$ *Exciton-Exciton Annihilation (EEA)*

EEA: N. Kumar *et al.*, PRB **89**, 125427 (2014), S. Mouri *et al.*, PRB **90**, 155449 (2014), D. Sun *et al.*, Nano Lett. **14**, 5625 (2014)

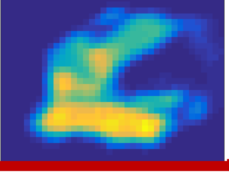


Exciton dynamics: PL vs $\Phi_{photons}$

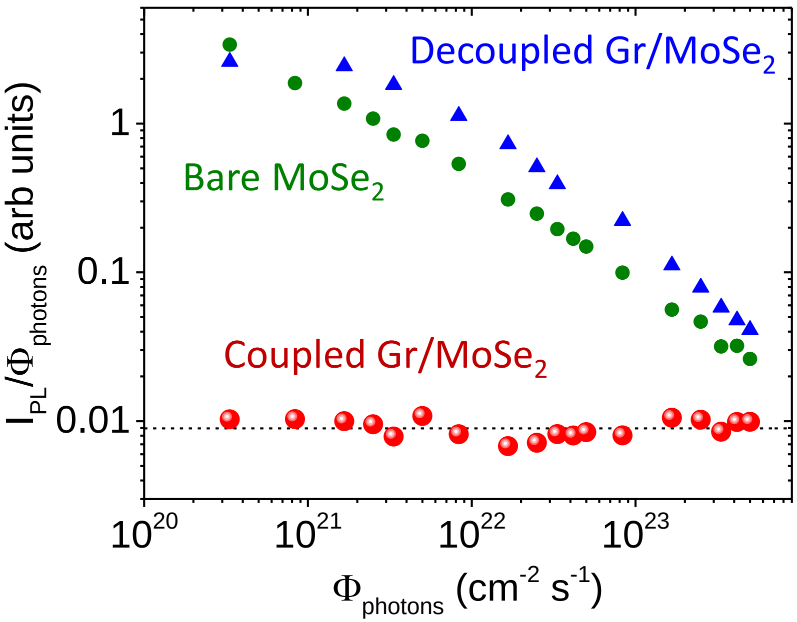


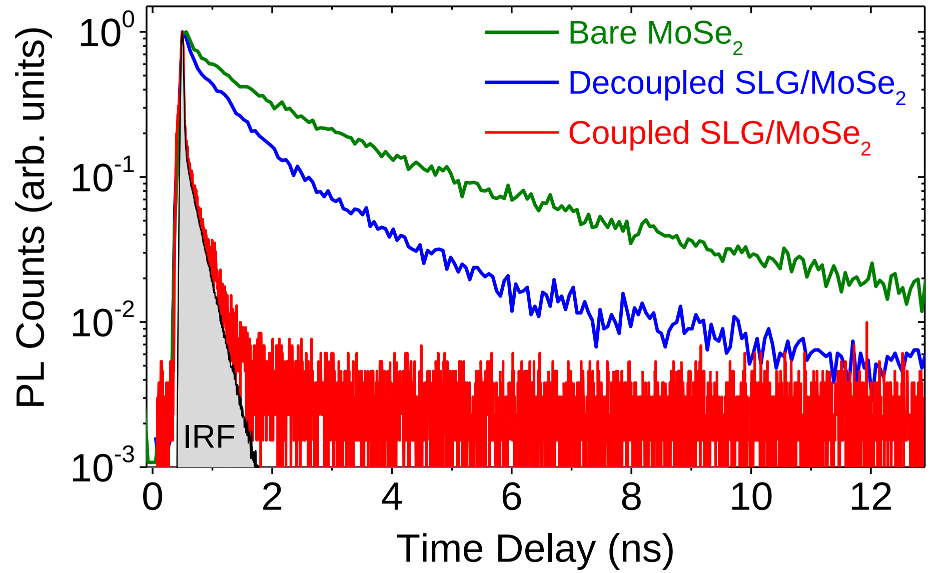


- PL saturation on bare and decoupled $MoSe_2$
  → *Exciton-Exciton Annihilation (EEA)*
- **No PL saturation on Gr/$MoSe_2$ and $I_{PL}(B)$ ~ $I_{PL}(A)$**



Exciton dynamics: PL vs $\Phi_{photons}$





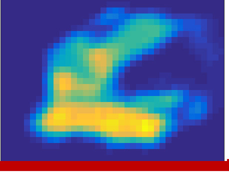
- PL saturation on bare and decoupled $MoSe_2$
- **No PL saturation on Gr/$MoSe_2$ and $I_{PL}(B) \sim I_{PL}(A)$**

→ Drastic reduction of the excitonic lifetime (< 1 ps)

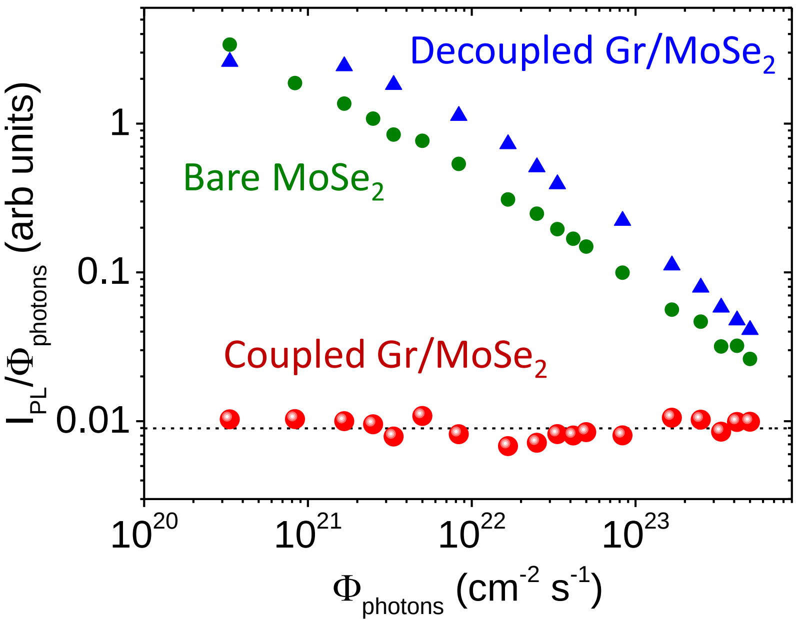
→ **Fast interlayer Energy Transfer?**

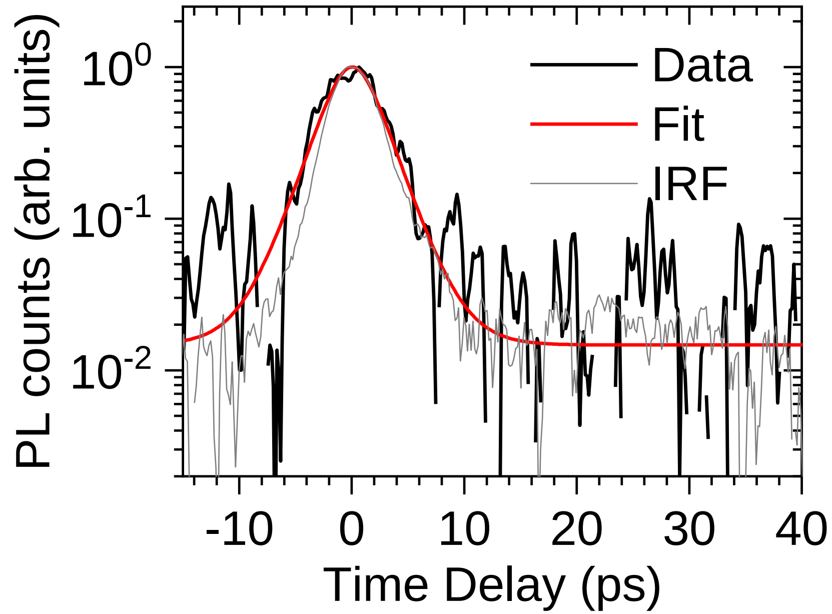
G. Froehlicher, E. Lorchat, S. Berciaud, Phys. Rev. X **8,** 011007 (2018)

Fast TRPL at INSA Toulouse



Exciton dynamics: PL vs $\Phi_{photons}$





- PL saturation on bare and decoupled $MoSe_2$
- **No PL saturation on Gr/$MoSe_2$ and $I_{PL}(B) \sim I_{PL}(A)$**

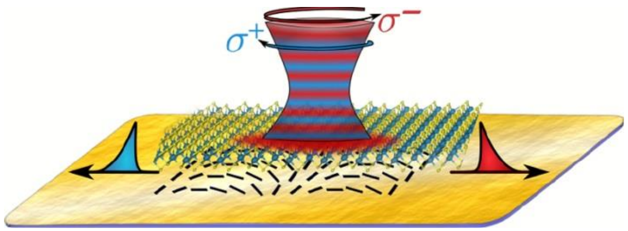
$\rightarrow$ Drastic reduction of the excitonic lifetime (< 1 ps)

$\rightarrow$ **Fast interlayer Energy Transfer?**

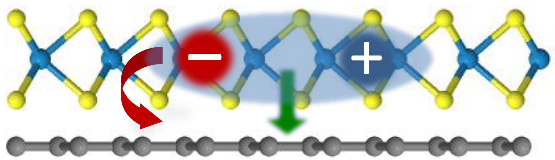
G. Froehlicher, E. Lorchat, S. Berciaud, Phys. Rev. X **8,** 011007 (2018)

Fast TRPL at INSA Toulouse

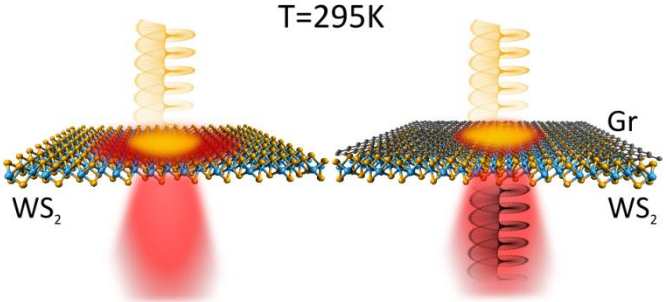
Outline



Room temperature Chiral coupling of valley excitons with spin-momentum locked surface plasmons

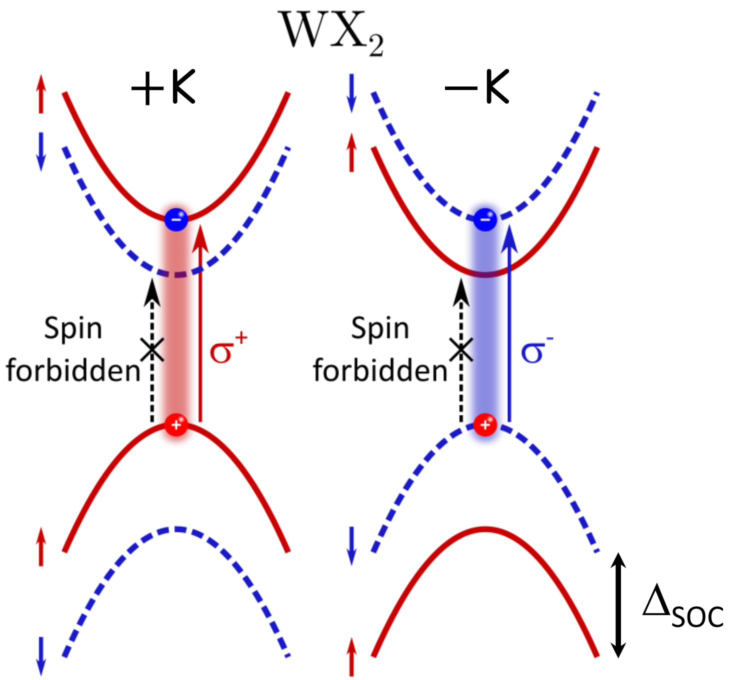


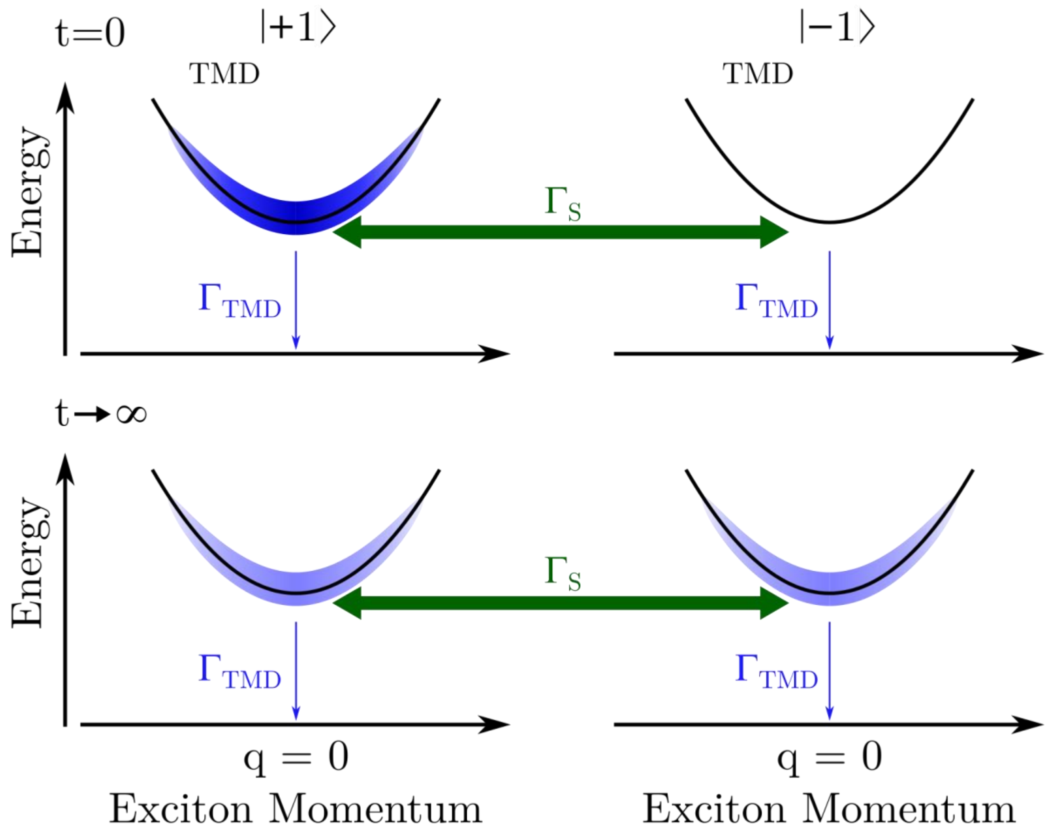
Graphene/TMD heterostructures as a 2D optoelectronic building block



Room temperature valley polarization and coherence in TMD/Graphene heterostructures

Back to valley contrasts

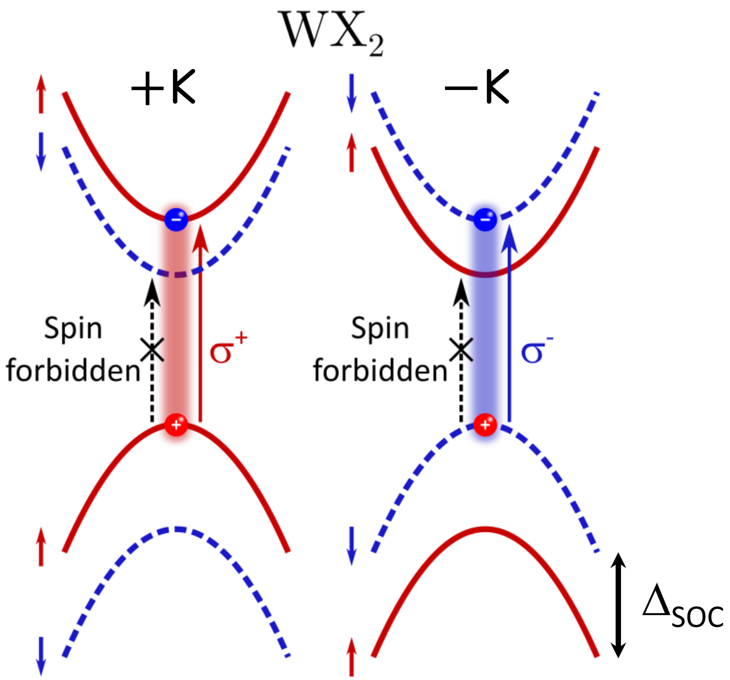


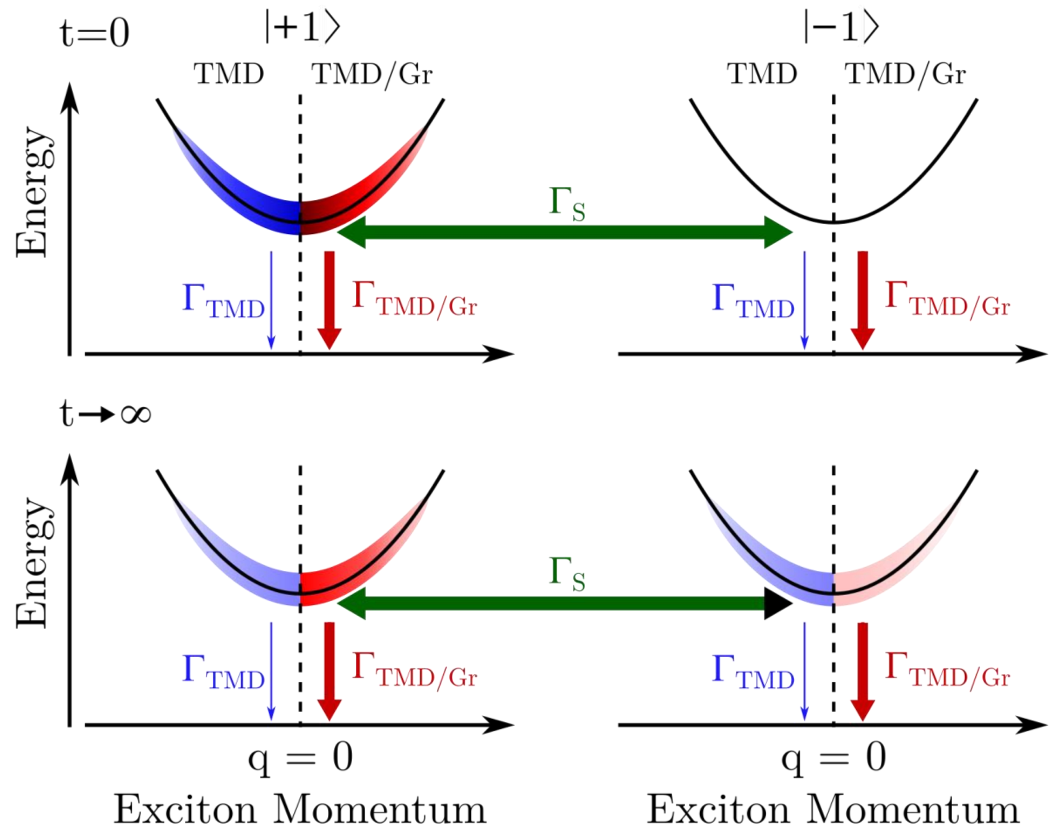


Photonic state	Excitonic state
$\lvert\sigma^{\pm}\rangle$	$\lvert\pm 1\rangle$
$\frac{1}{\sqrt{2}}(\lvert\sigma^{+}\rangle \pm \lvert\sigma^{-}\rangle)$	$\frac{1}{\sqrt{2}}(\lvert+1\rangle \pm \lvert-1\rangle)$

- $\Gamma_{TMD} \ll \Gamma_S \Rightarrow$ 0% valley polarization

Back to valley contrasts



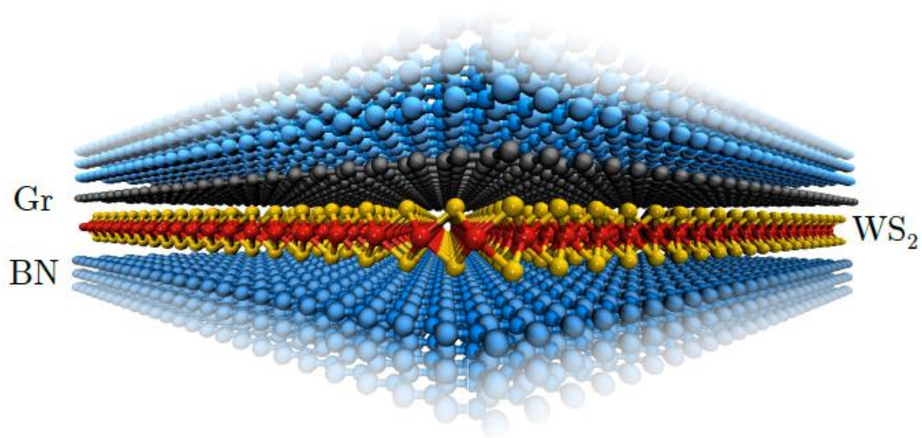


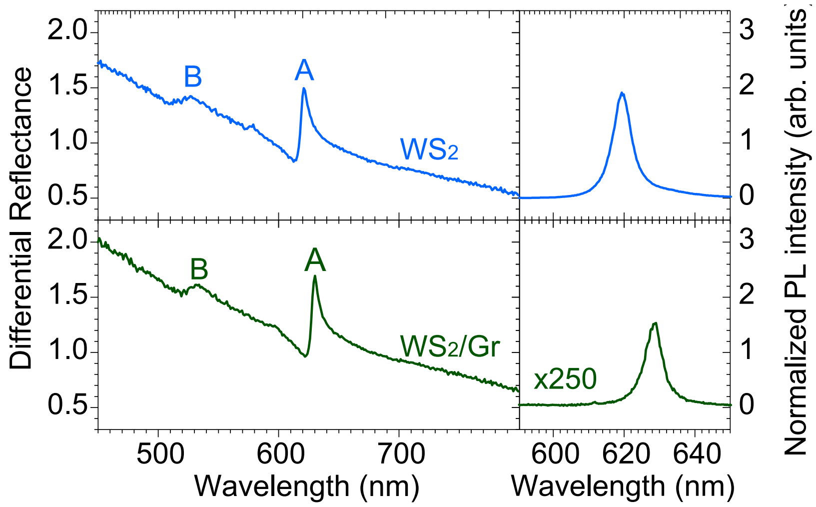
Photonic state	Excitonic state
$\lvert\sigma^{\pm}\rangle$	$\lvert\pm 1\rangle$
$\frac{1}{\sqrt{2}}(\lvert\sigma^{+}\rangle \pm \lvert\sigma^{-}\rangle)$	$\frac{1}{\sqrt{2}}(\lvert+1\rangle \pm \lvert-1\rangle)$

- $\Gamma_{TMD} \ll \Gamma_S \Rightarrow$ 0 % valley polarization
- $\Gamma_{TMD/Gr} \ll \Gamma_S \Rightarrow$ finite valley polarization

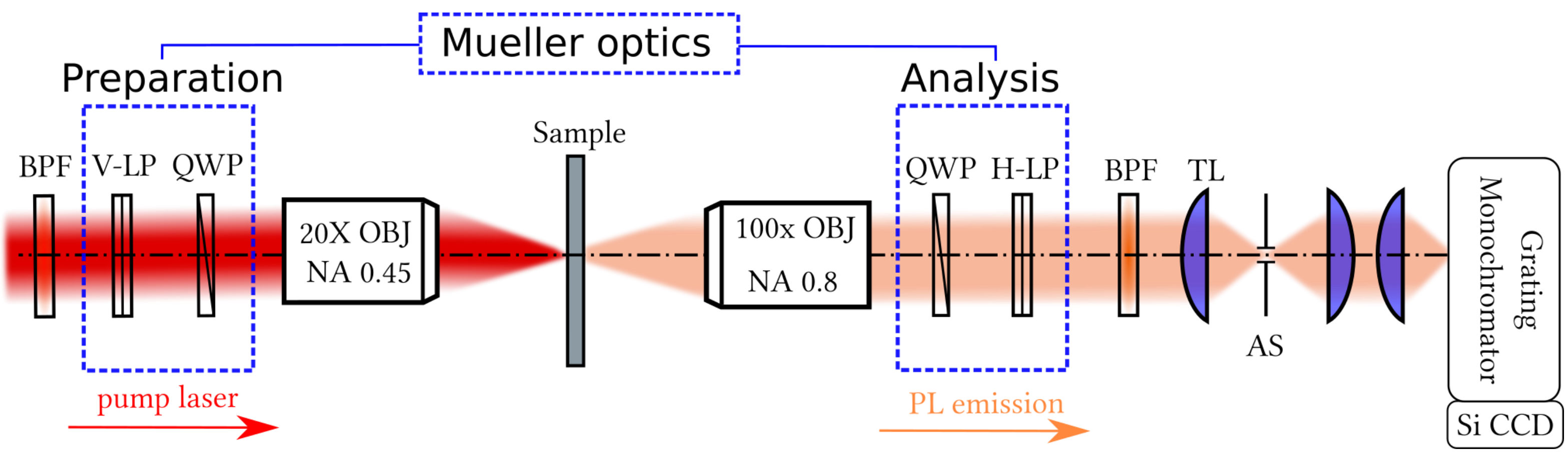
Our experimental approach

BN-encapsulated WS_2-Gr heterostructure





Mueller polarimetry setup



Mueller Polarimetry

$$\mathbf{S}^{\text{out}} = \begin{pmatrix} I \\ I_V - I_H \\ I_{45} - I_{-45} \\ I_{\sigma+} - I_{\sigma-} \end{pmatrix}_{\text{out}} = \mathcal{M} \cdot \mathbf{S}^{\text{in}} = \mathcal{M} \begin{pmatrix} I_0 \\ I_V - I_H \\ I_{45} - I_{-45} \\ I_{\sigma+} - I_{\sigma-} \end{pmatrix}_{\text{in}}$$

$$\mathcal{M} = \begin{pmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{pmatrix}$$

m_{i0}: birefringence

m_{0i}: dichroisim

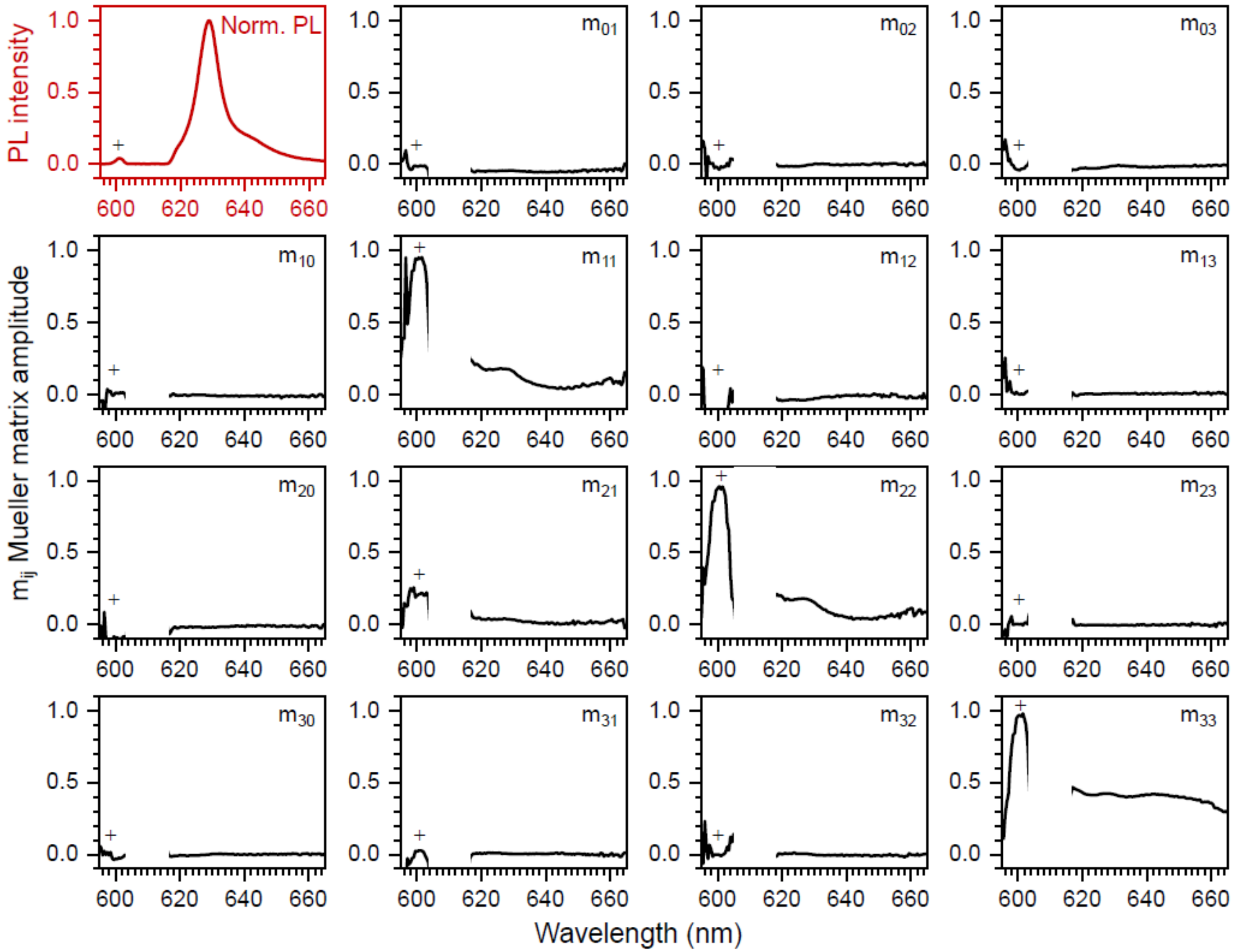
$m_{11,22}$ = valley coherence
m_{33} = valley polarization

Degrees of linear and circular polarization

$$\gamma^{VH} = \frac{m_{10} + m_{11}}{m_{00} + m_{01}}, \gamma^{+45°,-45°} = \frac{m_{20} + m_{22}}{m_{00} + m_{02}}, \rho^{\pm} = \frac{m_{30} \pm m_{33}}{m_{00} \pm m_{03}}$$

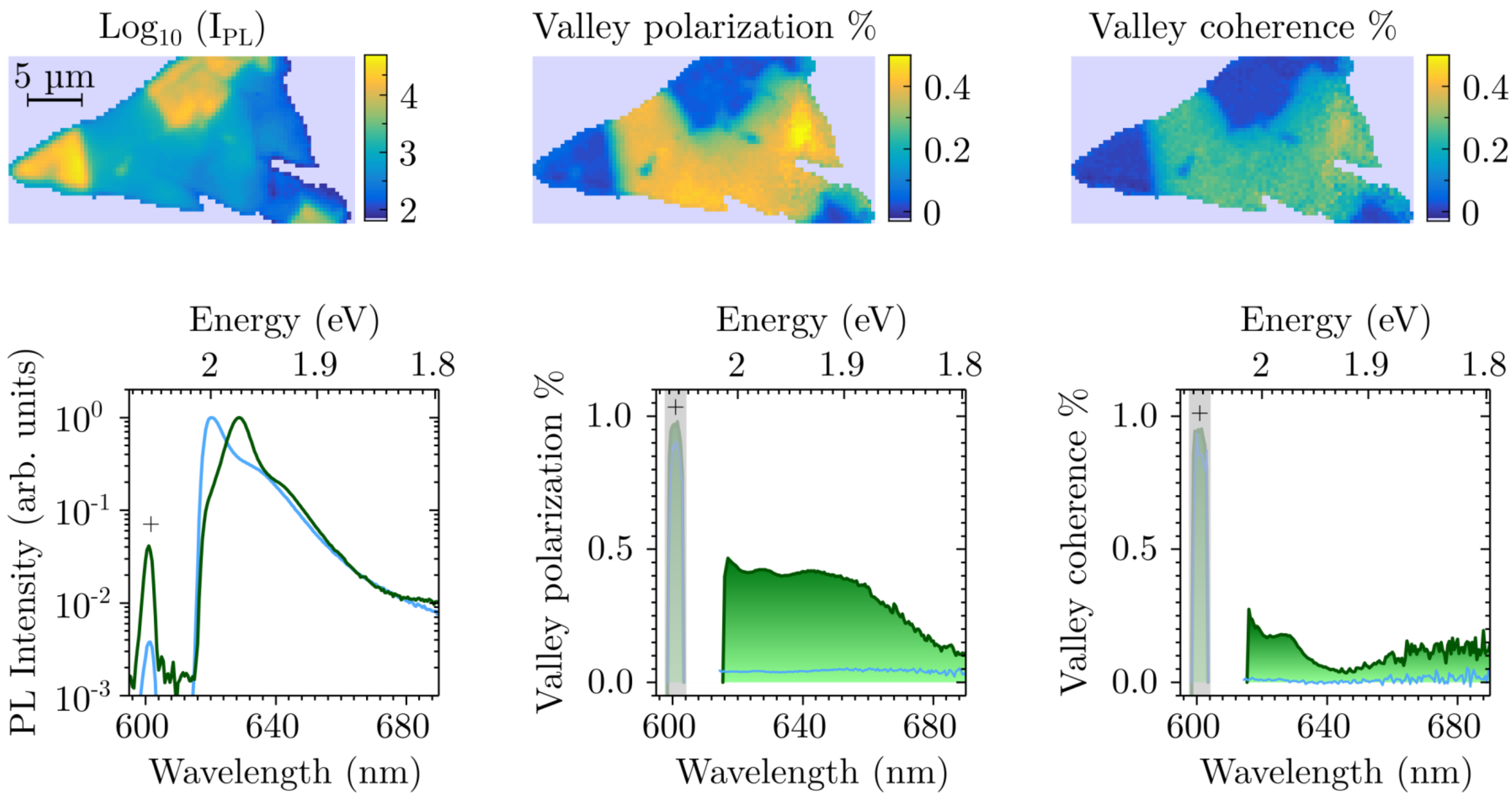
Mueller Polarimetry in WS_2/Gr

Laser
@600 nm



Experimental “sanity check” : $m_{11} = m_{22}$ and $m_{ij,i\neq j} = 0$

Mapping valley contrasts

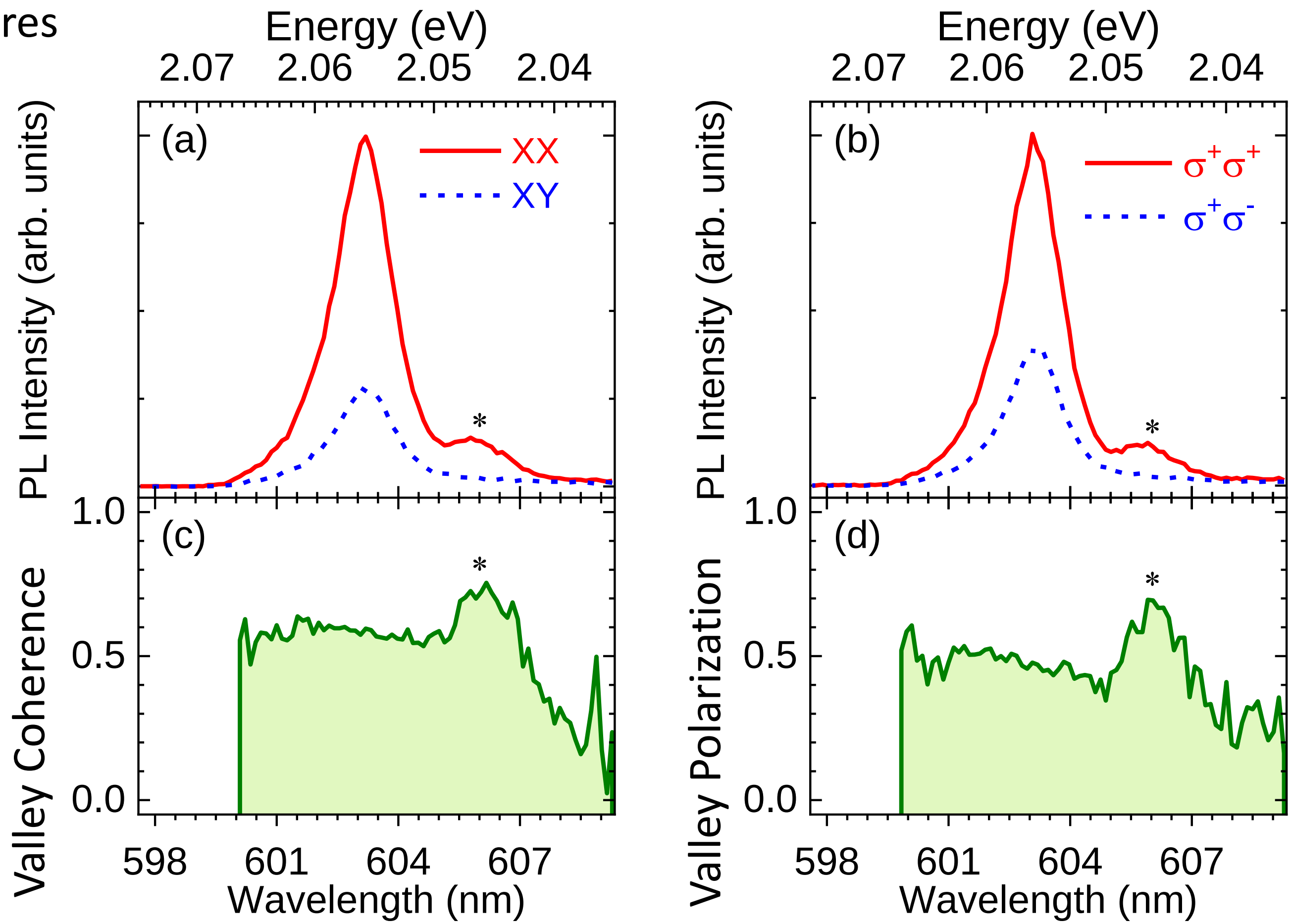


E.Lorchat, S.Azzini, T.Chervy *et al.*, ArXiv:1804.06725 (**doi: 10.1021/acsphotonics.8b01306**)

➢ 45% valley polarization, 30% valley coherence @Room Temperature

Large valley contrasts in WS_2/Gr (20 K)

*Raman features



Record valley coherence up to 60 % (10 %) in BN-capped WS_2/Gr (BN capped WS_2)

E.Lorchat, S.Azzini, T.Chervy *et al.*, ArXiv:1804.06725 (**doi: 10.1021/acsphotonics.8b01306**)

F. Cadiz et al. PRX 2017 (valley coherence of 50% in BN-capped MoS2)

Conclusion and outlook

✓ 2D matter meets 2D light:
many games to play at the interface between (chiral) nanophotonics, condensed matter physics and materials science

- Interfacing 2D materials with chiral plasmonic resonators
- Probing dark excitonic states using surface plasmons
- Electrical and electromechanical control of chiral coupling

- Charge and energy transfer mechanism(s)
- Intervalley scattering mechanisms in TMD/Gr vs bare TMD

Acknowledgements

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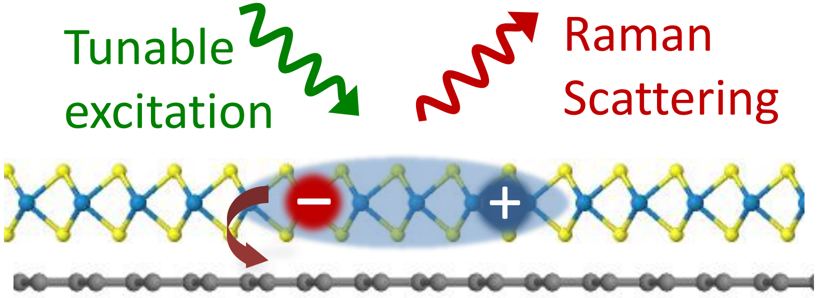
Supplementary Slides

Net charge transfer in TMD-Gr heterostructures

General slides on heterostructures and on energy transfer

How about photoinduced charge transfer?



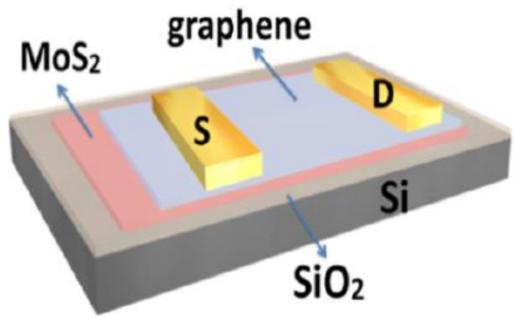
…study of net (and slow) eletron transfer from TMD to Graohene (cf PRX 2018).
This effect is likely extrinsic (not observable if we replace SiO2 by hBN)
but is of interest for photodetection/photogating (see next slide).

Gr/TMD heterostructures: why the interest?

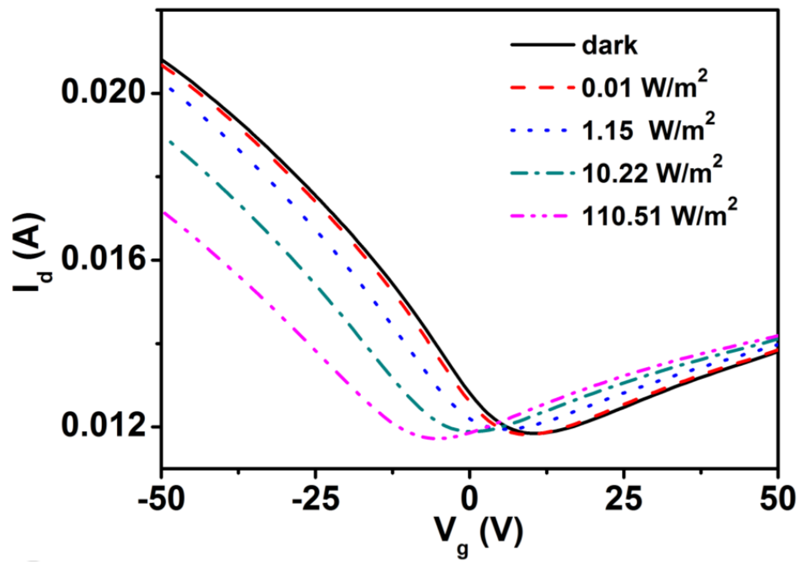
- ✓ Strong interlayer coupling
(J. He et al., Nat Comm. 2014)

- ✓ Photogating/photodetection
(W. Zhang et al., Sci. Rep. 2014)

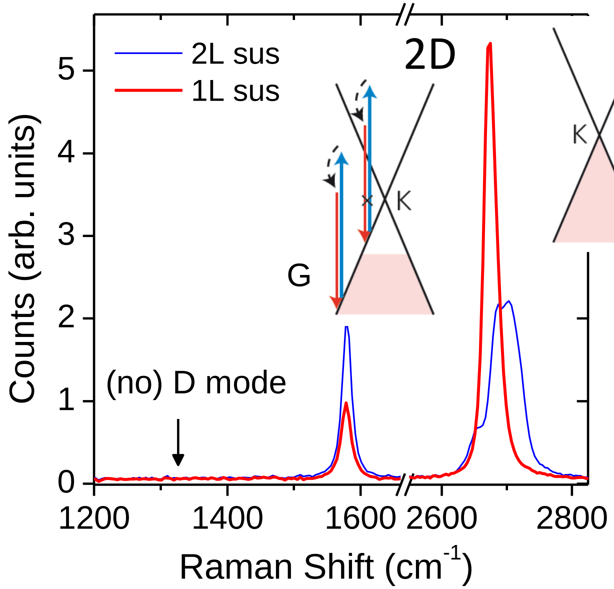
- ✓ ps-range photoresponse
(M. Massicotte et al., Nat Nano 2016)

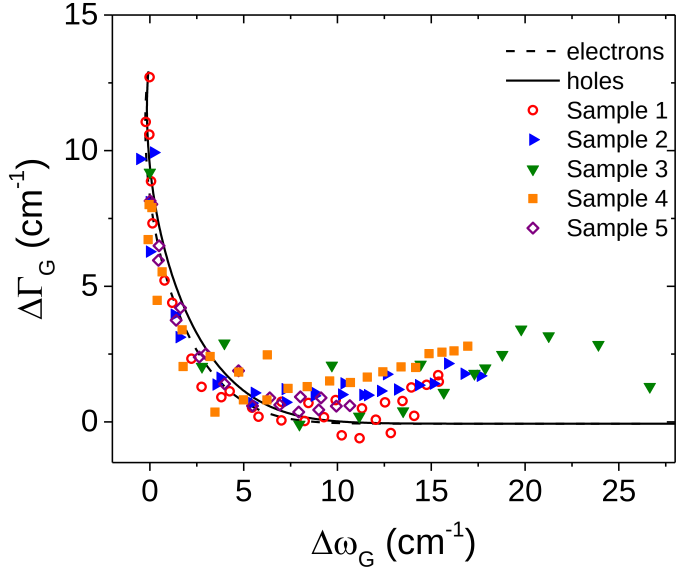


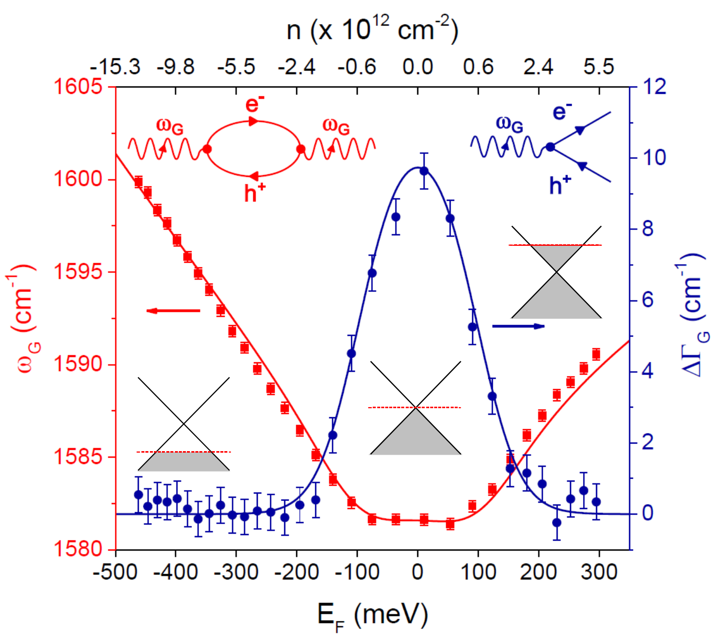
W. Zhang *et al.*, Sci. Rep. 2014 KAUST

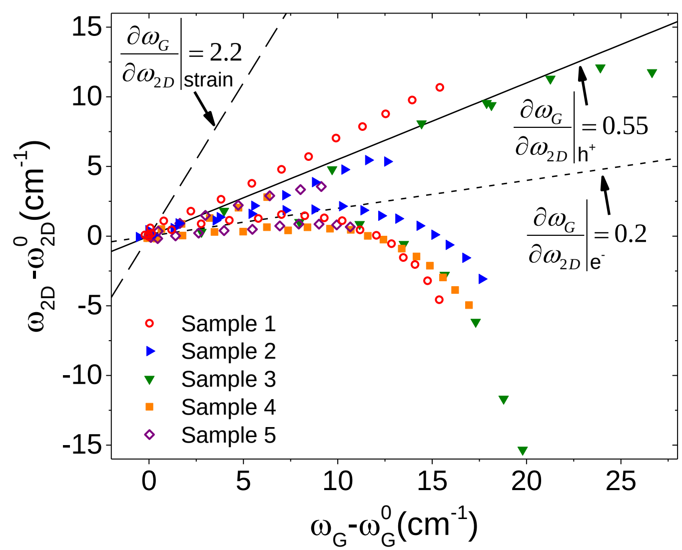


Raman spectroscopy: a quantitative probe of doping



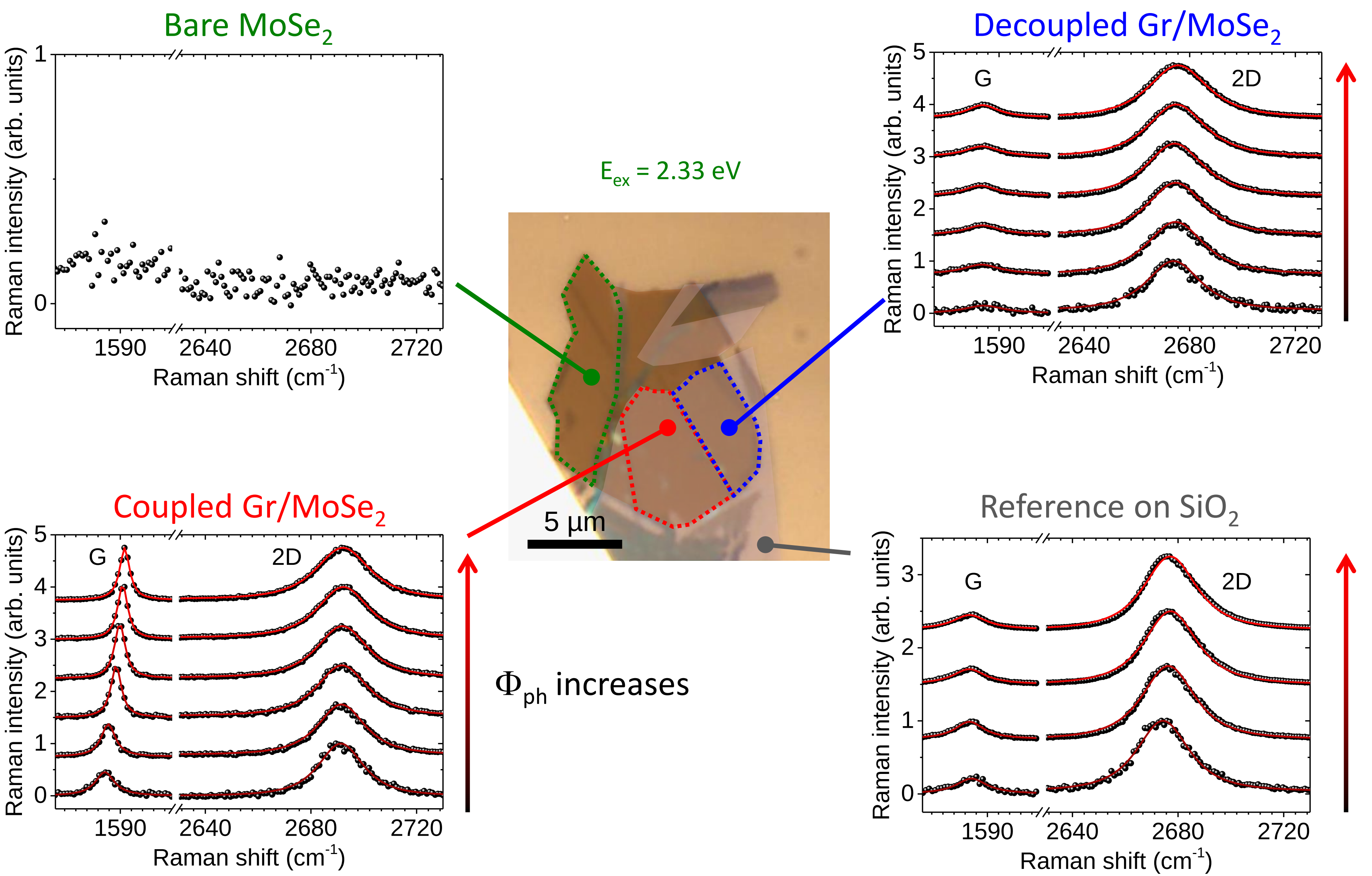


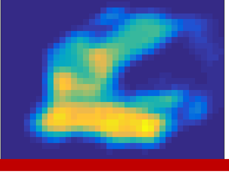




Data: G. Froehicher & SB, PRB 2015. See also: A. Das *et al.*, Nat. Nano 2008
S. Pisana *et al.*, Nat Mater 2007, J. Yan *et al.*, PRL 2007,…

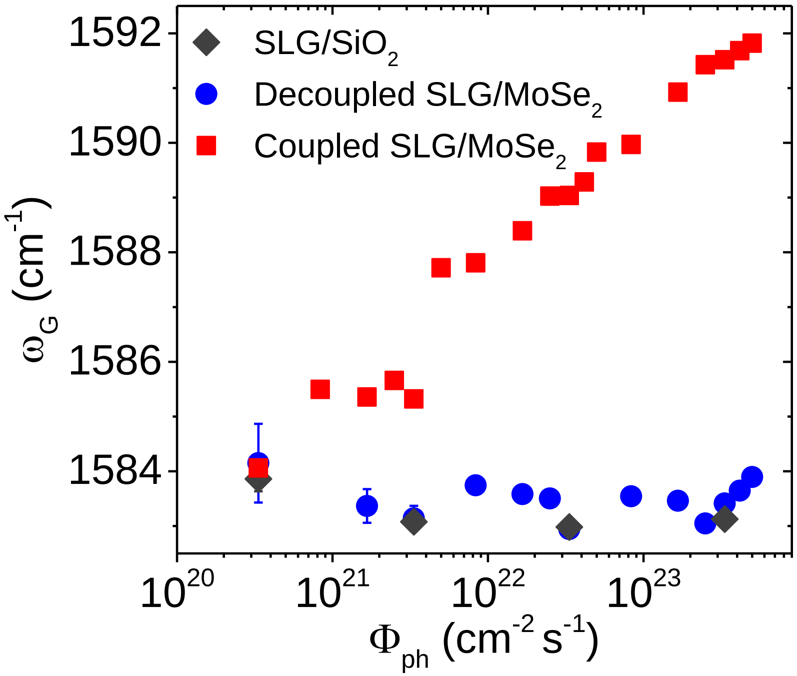
Raman response vs photon flux (1)



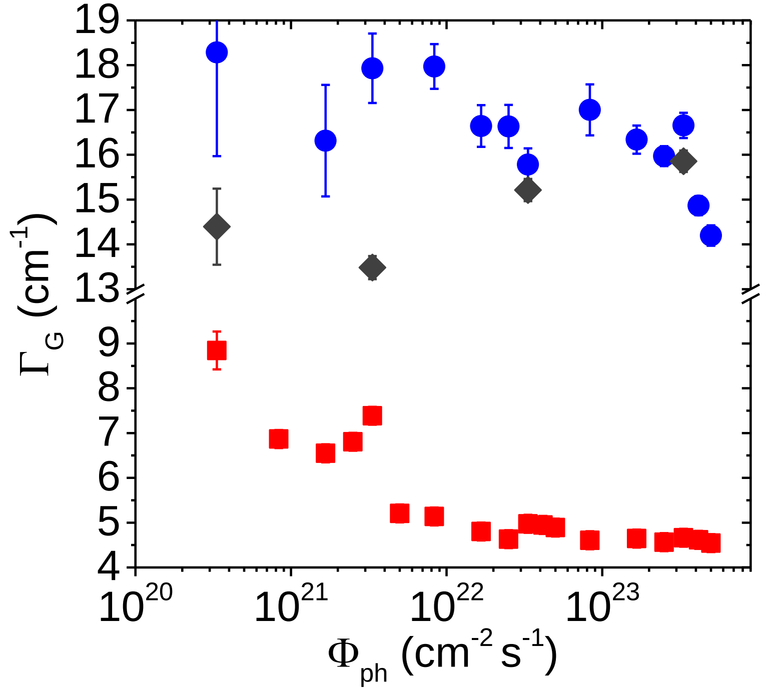


Raman response vs photon flux (2)

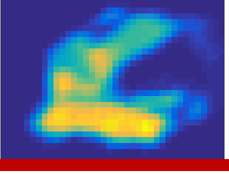
G-mode frequency



G-mode FWHM

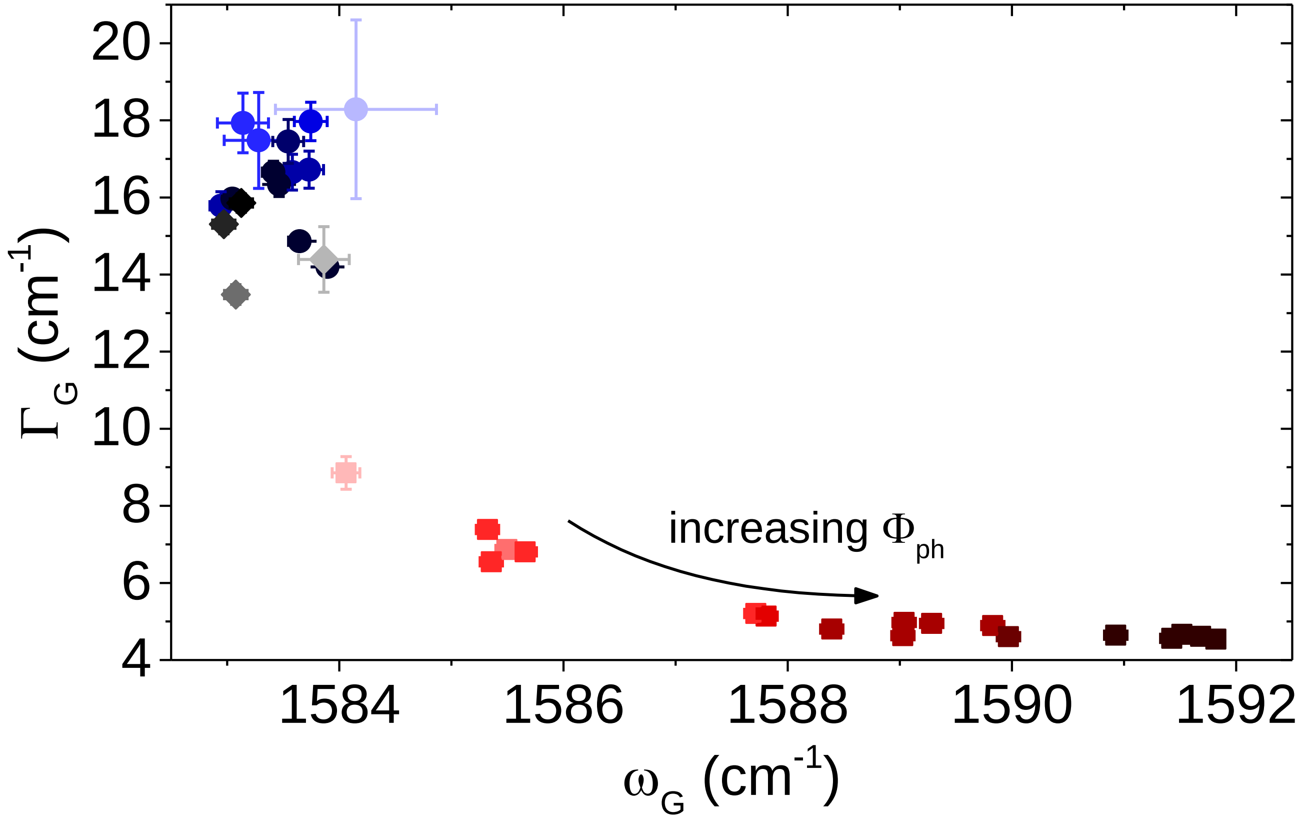


→ Clear signatures of a net photoinduced charge transfer



Raman response vs photon flux (2)

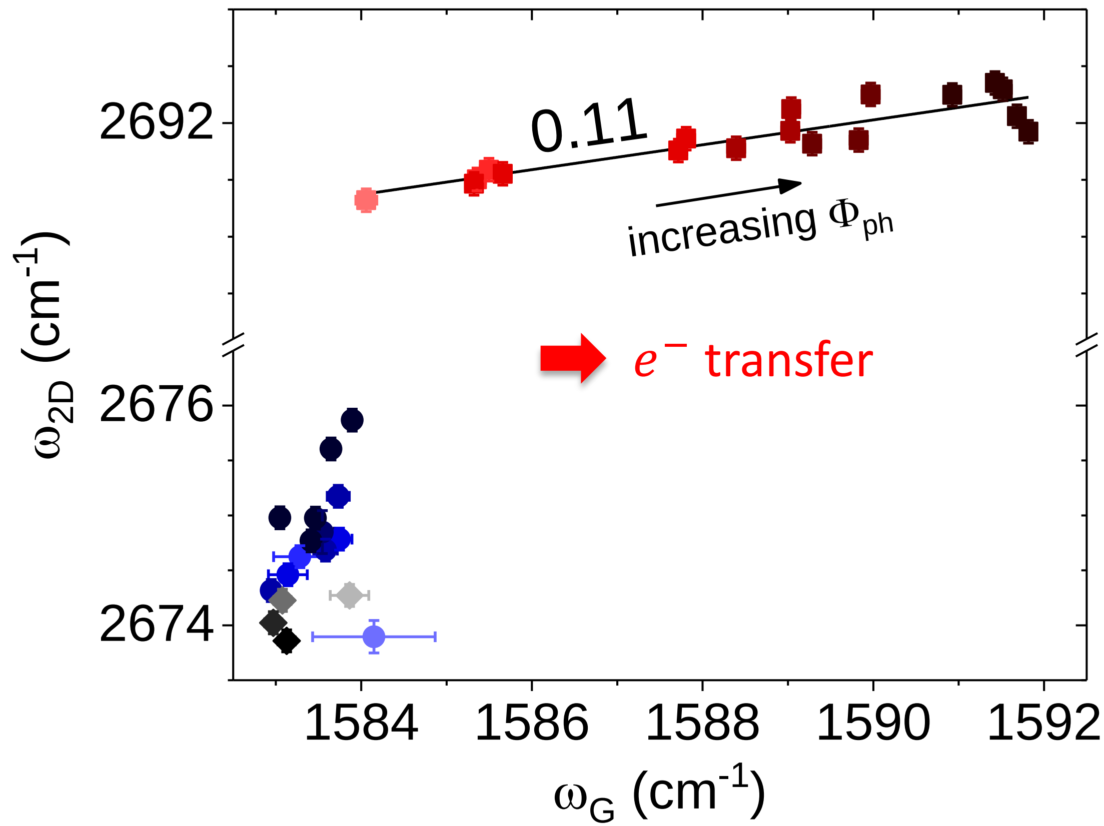
Width-Frequency Correlation

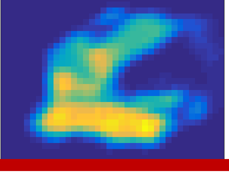


➡ Clear signatures of a net photoinduced charge transfer

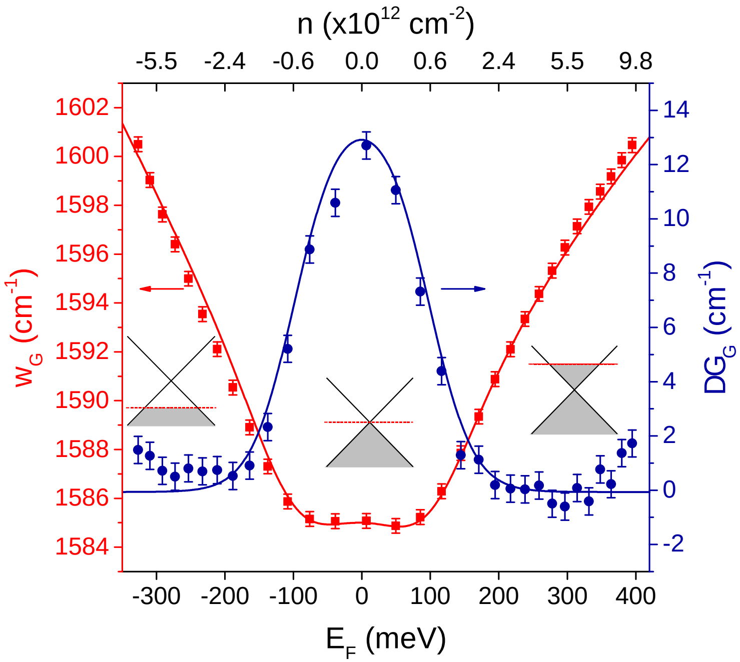
Evidence for TMD→ Gr electron transfer

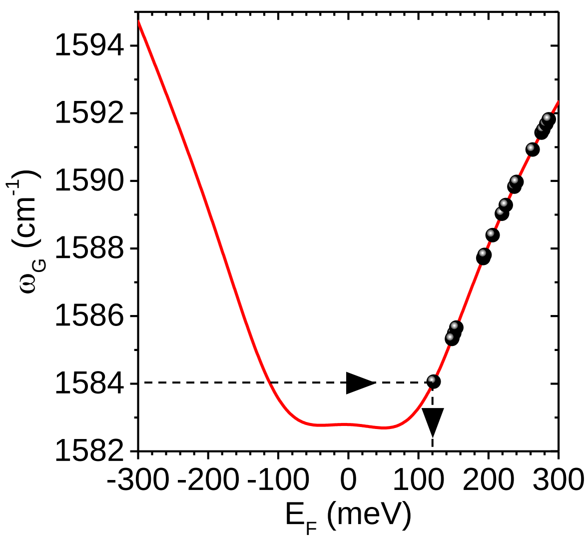
Correlation between the 2D- and G-mode frequencies

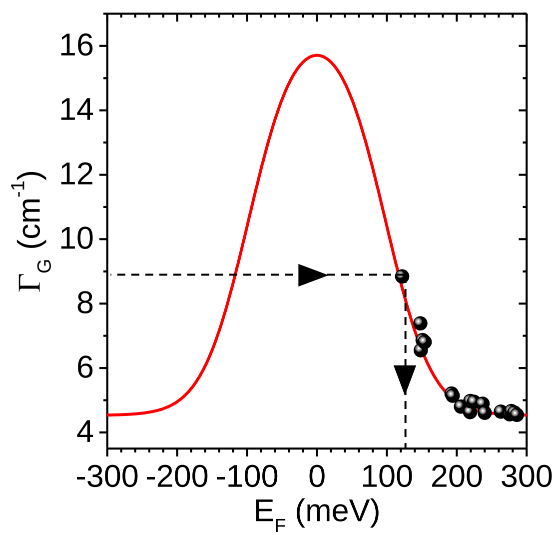




Quantifying photoinduced doping



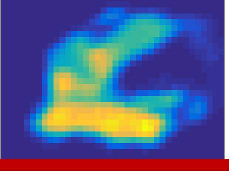




- *Evidence for net photoinduced electrpon transfer*
- *Extrinsic effect – slow dynamics*

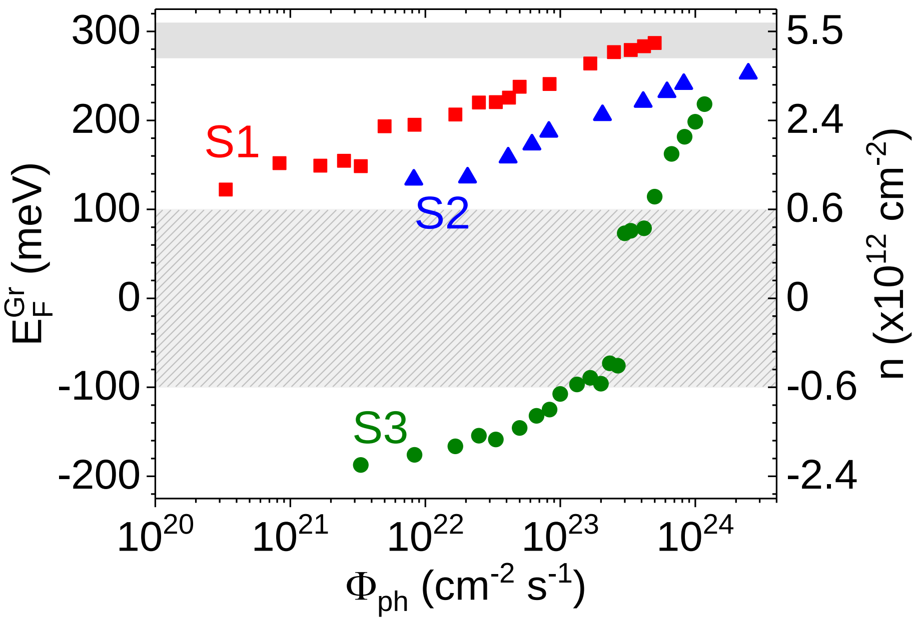
G. Froehlicher and S. Berciaud, PRB **91**, 205413 (2015)

G. Froehlicher, E. Lorchat, S. Berciaud, Phys. Rev. X **8,** 011007 (2018)

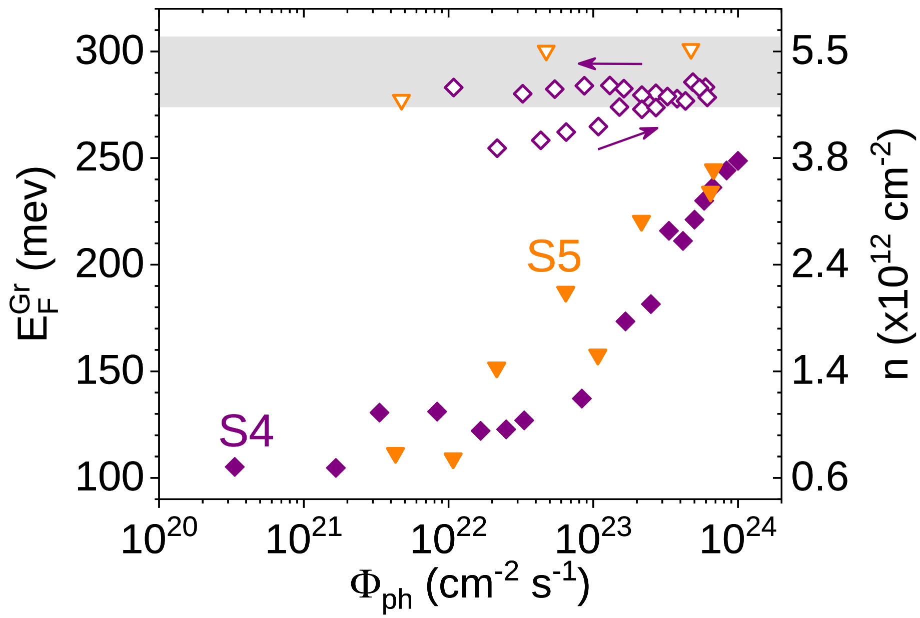


Reproducibility and environmental effects

Several Gr/MoSe$_2$/SiO$_2$ samples
Ambient AIR

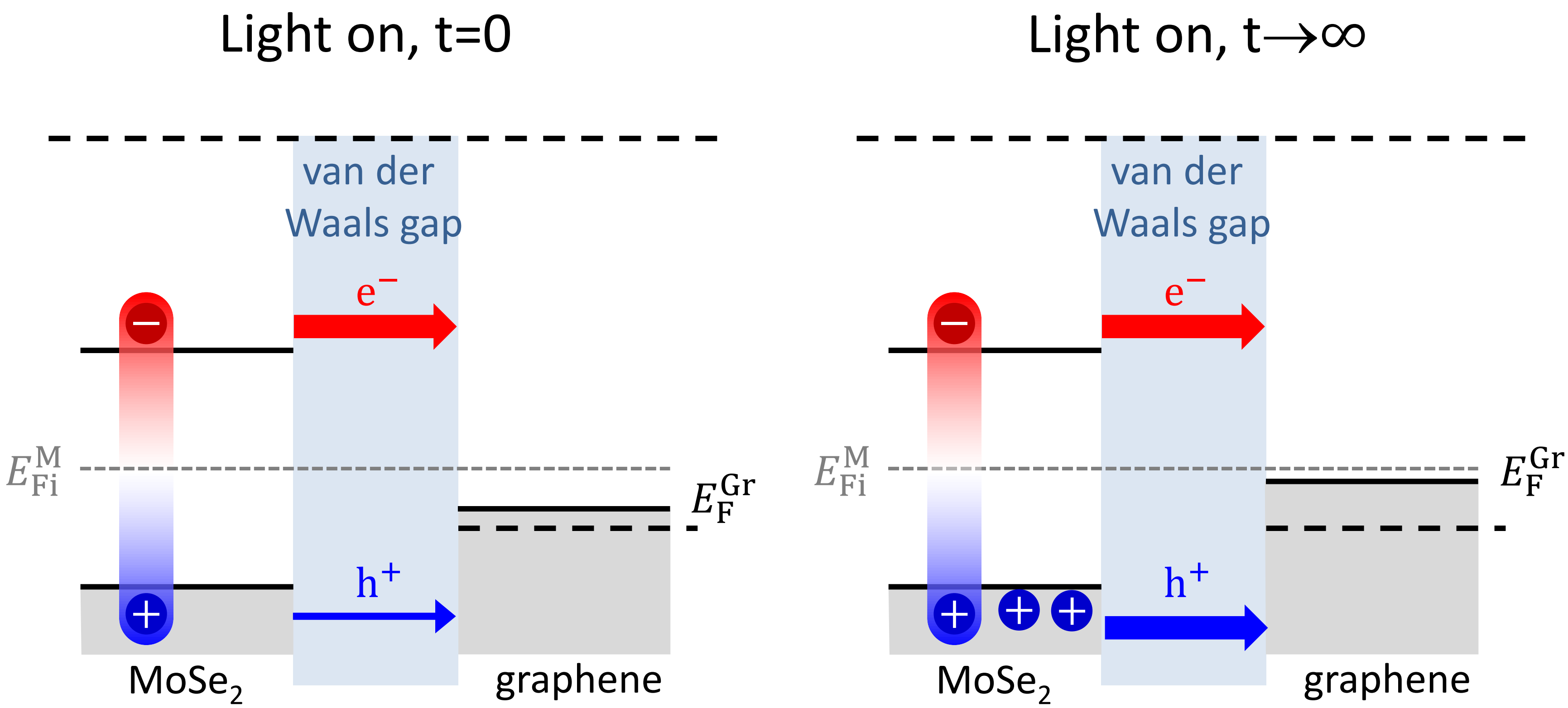


Gr/MoSe$_2$/SiO$_2$ vs MoSe$_2$/Gr/SiO$_2$
Air (full) vs vacuum (open)



- *Electron trapping by molecular adsorbates in air*
- *Direct saturation under vacuum*

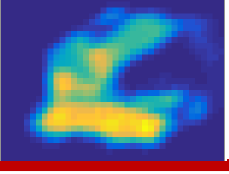
Microscopic mechanism (in vacuum)



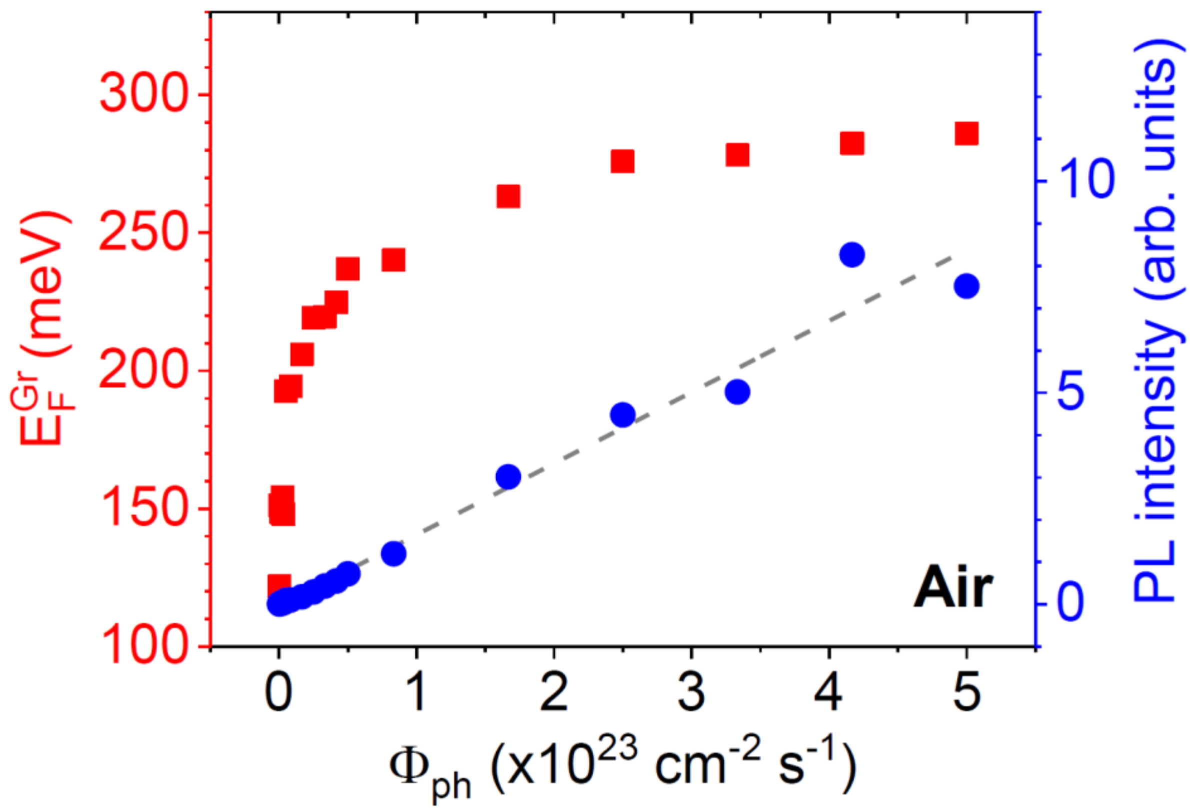
✓ *Balanced electron and hole currents at saturation*

➢ *Intrinsic mechanism?*

➢ *Optical determination of band offsets?*



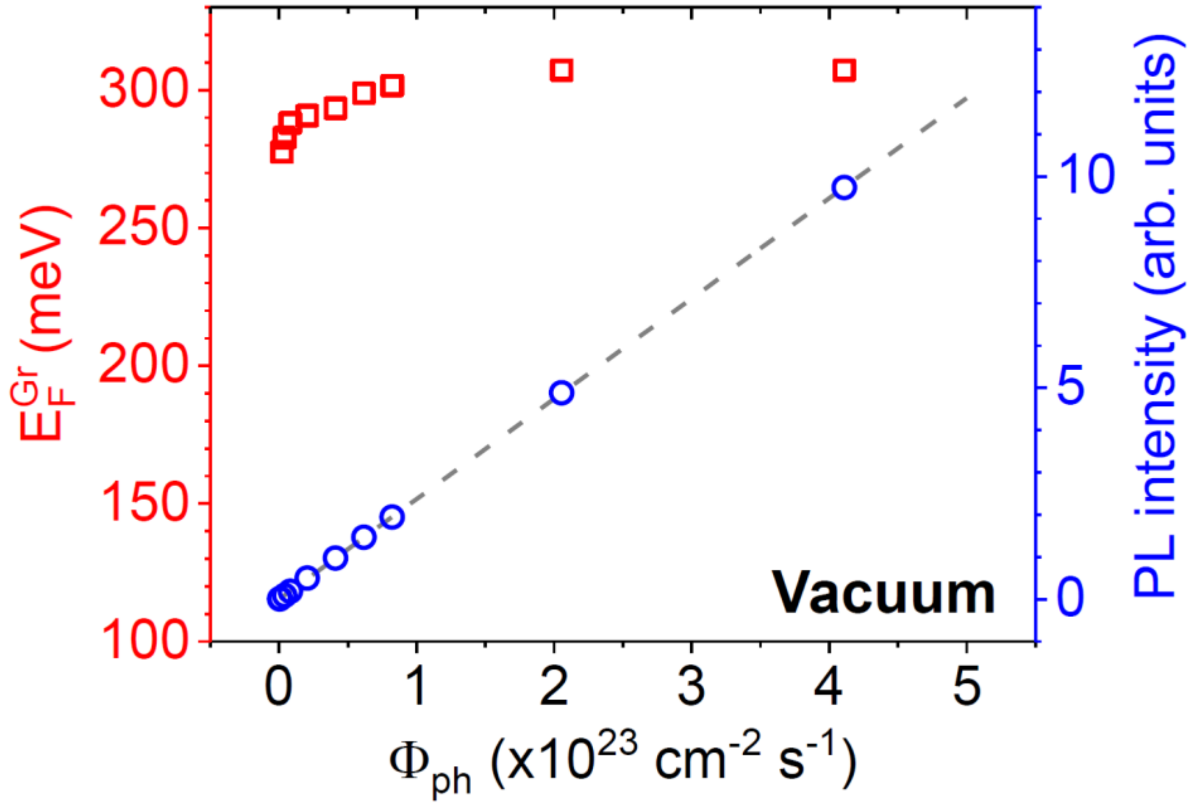
Recap: Fermi level and PL intensity



- Exciton dynamics in $MoSe_2$ is largely independent of the electron and hole transfer efficiencies

  → Strong hint for dominant energy transfer

Recap: Fermi level and PL intensity



➢ Exciton dynamics in $MoSe_2$ is largely independent of the electron and hole transfer efficiencies

→ Strong hint for dominant energy transfer

Partial conclusion

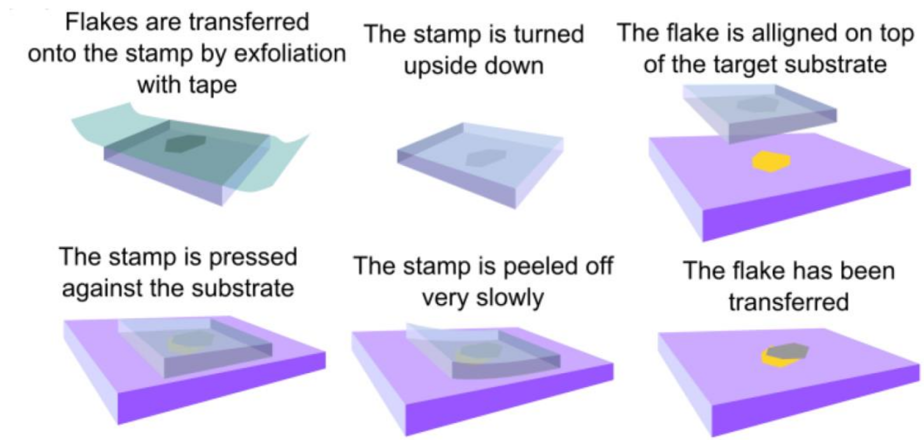
- ✓ ***Strong interlayer coupling in Gr/TMD heterostructures***
- ✓ ***Saturation of the net electron transfer***
- ✓ ***Highly efficient (sub)-picosecond energy transfer***
- ➢ **Förster vs Dexter energy transfer?**
- ➢ **Electrical control of charge and energy transfer**
- ➢ ***Implications for optoelectronics and optospintronics***

More info: G. Froehlicher, E. Lorchat, S. Berciaud, Phys. Rev. X **8,** 011007 (2018)

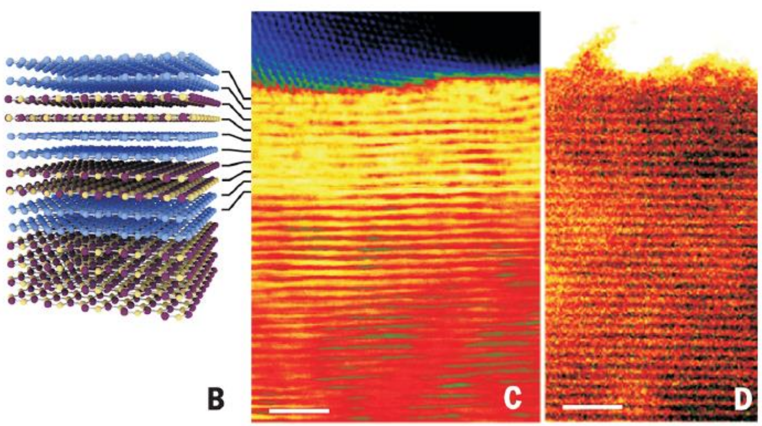
van der Waals Heterostructures

- ✓ No dangling bounds
- ✓ No lattice mismatch issues
- ✓ Rotational degree of freedom

- 2010 : Graphene on hBN
- 2017 : wet or dry transfer, pick up and lift,…
- Numerous possibilities!



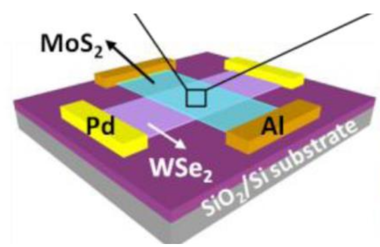
Castellanos-Gomez *et al.* 2D Materials **1** 011002 (2014)

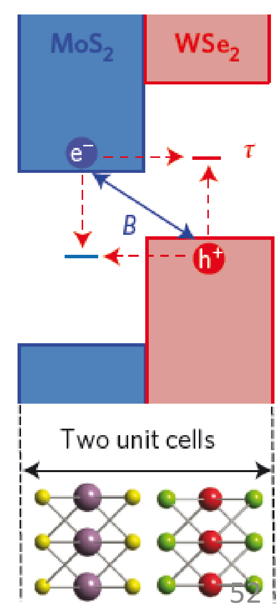


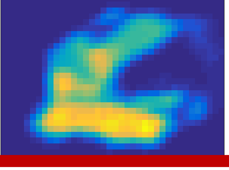
Haigh, Gorbachev *et al.*, Nature Materials 2012
Manchester Group

Atomically thin p-n junctions

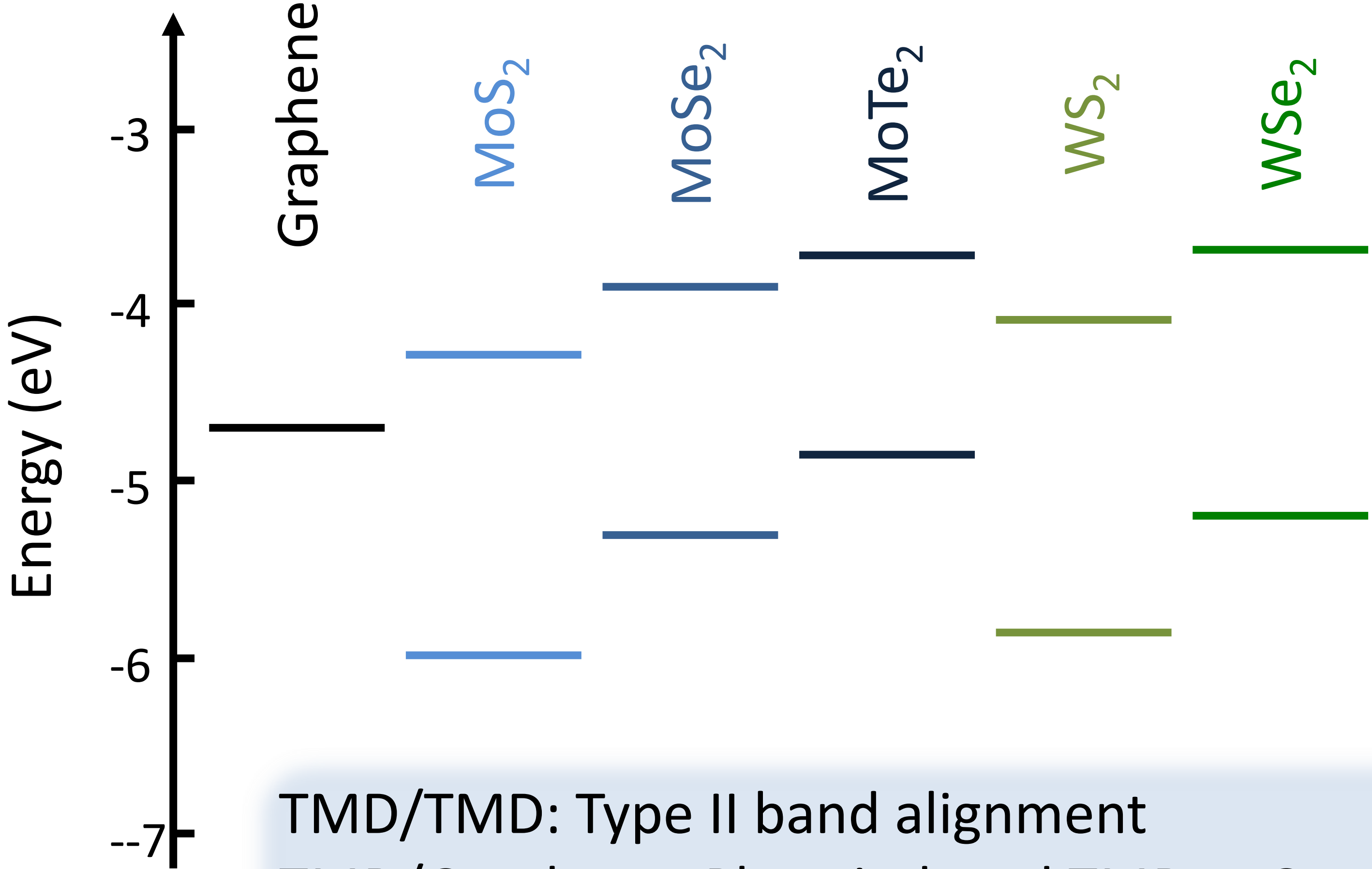
C-H Lee *et al.*
Nat. Nano (2014)
(Columbia)







Band offsets in 2D materials



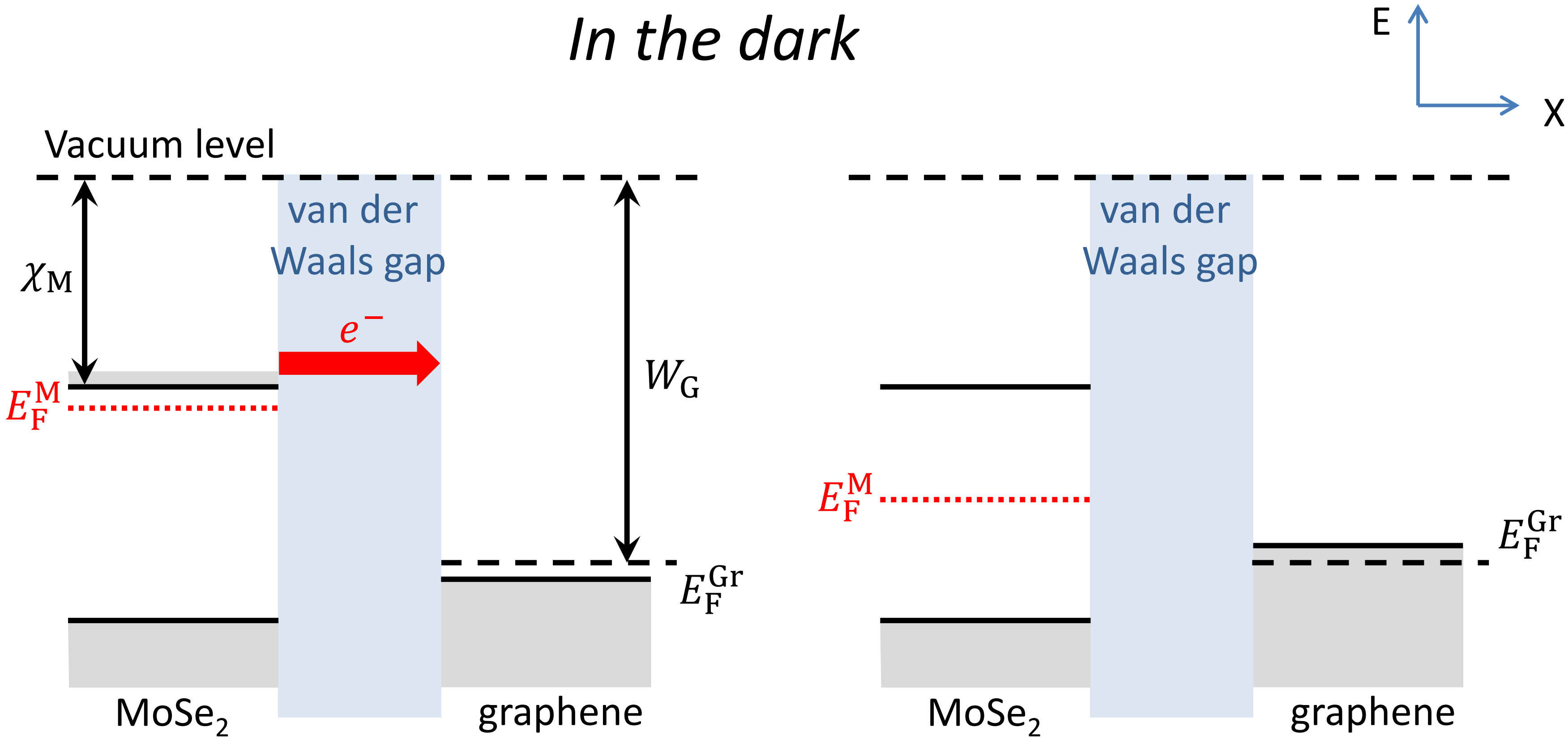
TMD/TMD: Type II band alignment

TMD/Graphene: Photoinduced TMD→ Gr e and h transfer

TMD: Y. Liang et al., APL **103**, 42106 (2013), M. Ugeda *et al.*, Nat. Mater. **5**, 1091 (2014)
Graphene: Y.-J. Yu *et al.*, Nano Lett. **9**, 3430 (2008)

Microscopic Mechanism

In the dark



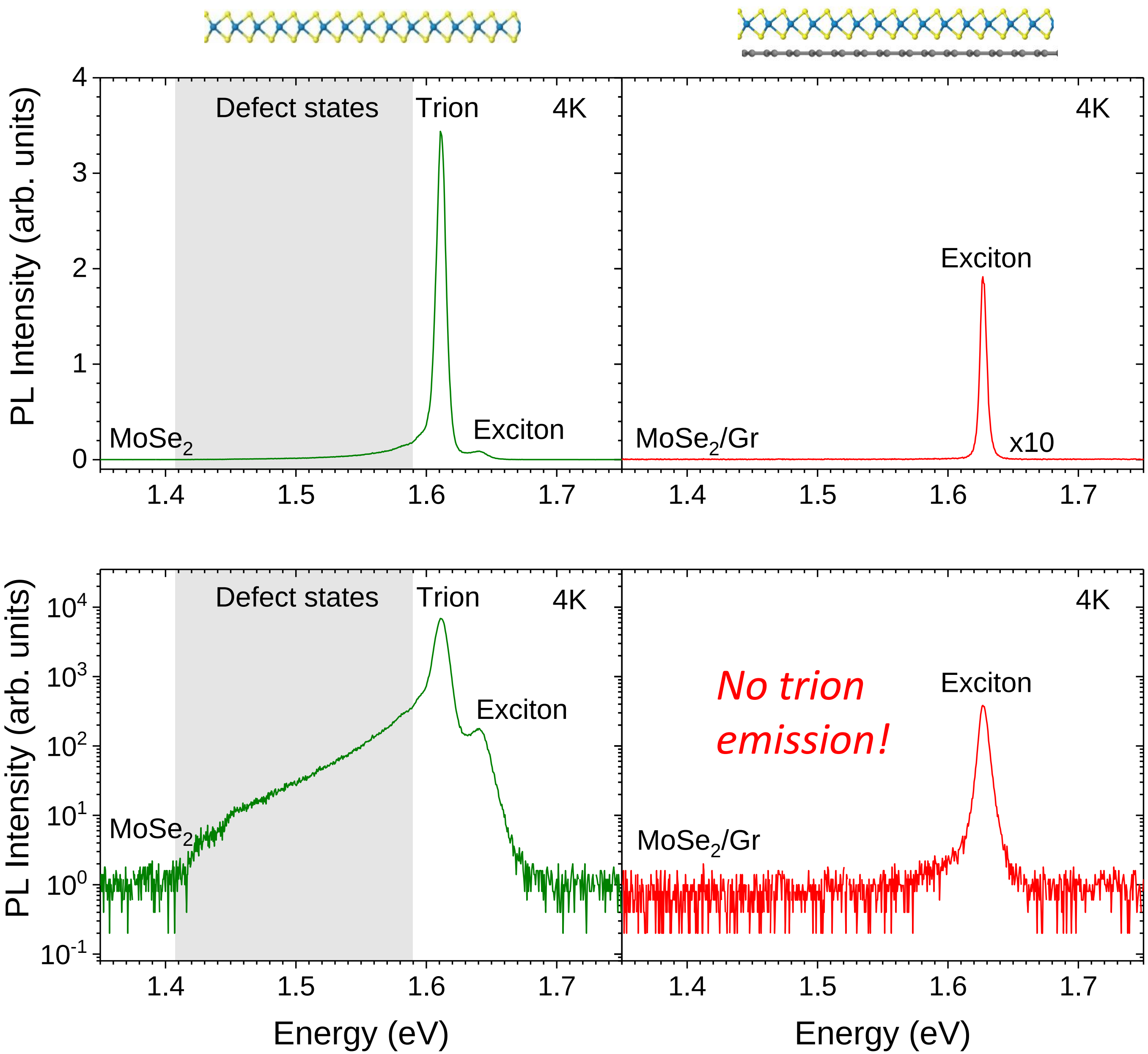
Before contact:

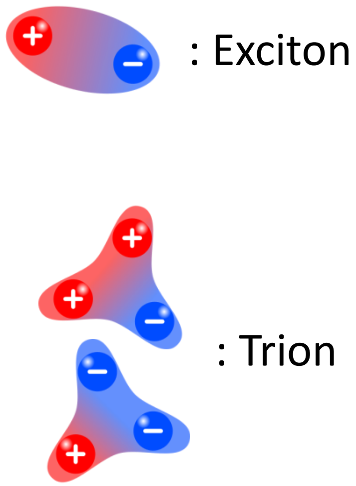
- n-doped $MoSe_2$
- Weakly doped graphene

After contact (in the dark):

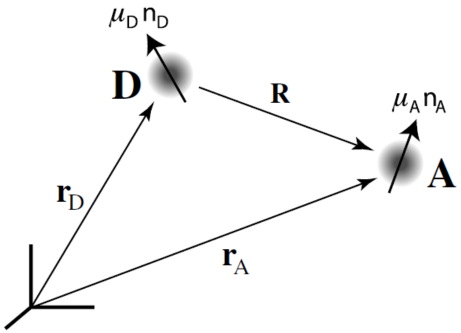
- Neutral $MoSe_2$
- n-doped graphene

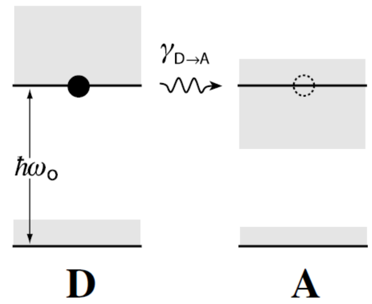
Outlook: low-temperature photoluminescence





Förster energy transfer: near field dipole-diople interaction





$$\frac{\gamma_{\mathrm{D}\to\mathrm{A}}}{\gamma_0} = \frac{P_{\mathrm{D}\to\mathrm{A}}}{P_0}$$

$$\mathbf{E}_D = \frac{1}{4\pi\varepsilon_0}\left[k^2(\mathbf{r}\wedge\boldsymbol{\mu}_D)\wedge\boldsymbol{\mu}_D\frac{e^{ikr}}{r^2} + \left(\frac{3\mathbf{r}(\mathbf{r}.\boldsymbol{\mu}_D)}{r^2} - \boldsymbol{\mu}_D\right)\left(\frac{1}{r^3} - \frac{ik}{r^2}\right)e^{ikr}\right]$$

$$P_{\mathrm{D}\to\mathrm{A}} = -\frac{1}{2}\int_{V_\mathrm{A}} \mathrm{Re}\{\mathbf{j}_\mathrm{A}^* \cdot \mathbf{E}_\mathrm{D}\}\,\mathrm{d}V \approx \frac{\omega_0}{2}\,\mathrm{Im}\{\alpha_\mathrm{A}\}\left|\mathbf{n}_\mathrm{A}\cdot\mathbf{E}_\mathrm{D}(\mathbf{r}_\mathrm{A})\right|^2$$

$$\frac{\gamma_{\mathrm{D}\to\mathrm{A}}}{\gamma_0} = \left[\frac{R_0}{R}\right]^6 \qquad R_0^6 = \frac{9c^4\kappa^2}{8\pi}\int_0^\infty \frac{f_\mathrm{D}(\omega)\,\sigma_\mathrm{A}(\omega)}{n^4(\omega)\,\omega^4}\,\mathrm{d}\omega$$

Th. Förster Annalen der Physik **437**, 55 (1948)
Novotny, Hecht Principles of Nano Optics, Ch 8

R_0 : Förster radius

Förster and Dexter energy transfer

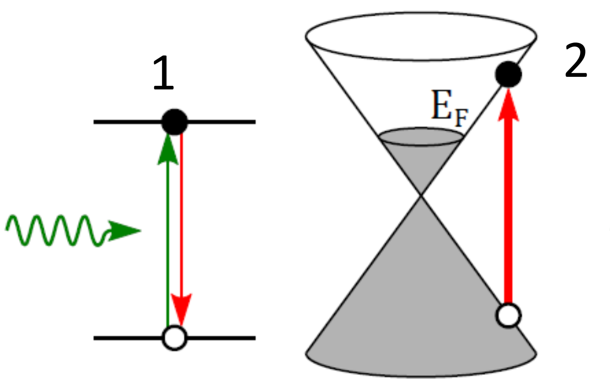
$$(D^*, A) \rightarrow (D, A^*)$$

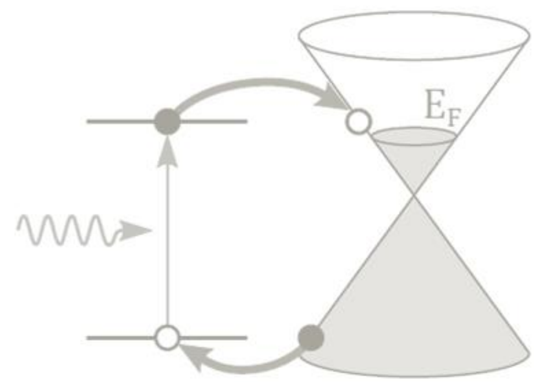
$$U = \langle \Psi_i | \hat{V} | \Psi_f \rangle$$

$$U = \langle \Psi_{D^*}(1)\Psi_A(2)|\hat{V}|\Psi_D(1)\Psi_{A^*}(2)\rangle - \langle \Psi_{D^*}(1)\Psi_A(2)|\hat{V}|\Psi_D(2)\Psi_{A^*}(1)\rangle$$

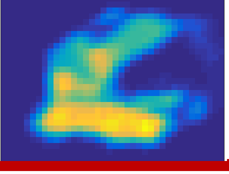
Coulomb (FRET) term
- ✓ 'Long' range (power law)
- ✓ Implies spectral overlap

Exchange (Dexter) term
- ✓ Short range (exponential, idem CT)
- ✓ Implies overlap of molecular orbitals



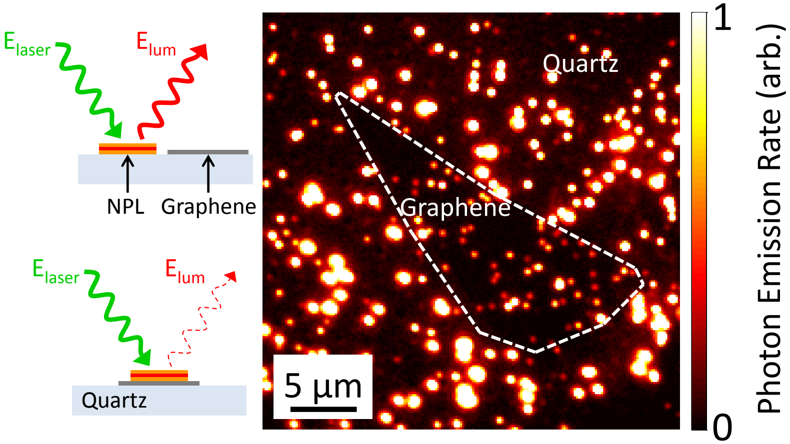


A Govorov, PL Hernandez Martinez, HV Demir
Understanding and Modeling Förster-type Resonance Energy Transfer (FRET), Springer 2016



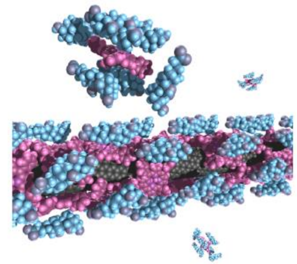
Energy transfer in low-dimensional heterostructures

Nanoscale emitter/graphene



Z. Chen et al., ACS Nano **4,** 2964 (2010) (QD-Gr)
F. Federspiel *et al.*, Nano Lett. **15**, 1252 (2015) (QD-Gr, NPL-Gr)
L. Gaudreau *et al.*, Nano Lett. **13**, 2030 (2013) (Dye-Gr)

Molecules/nanotubes



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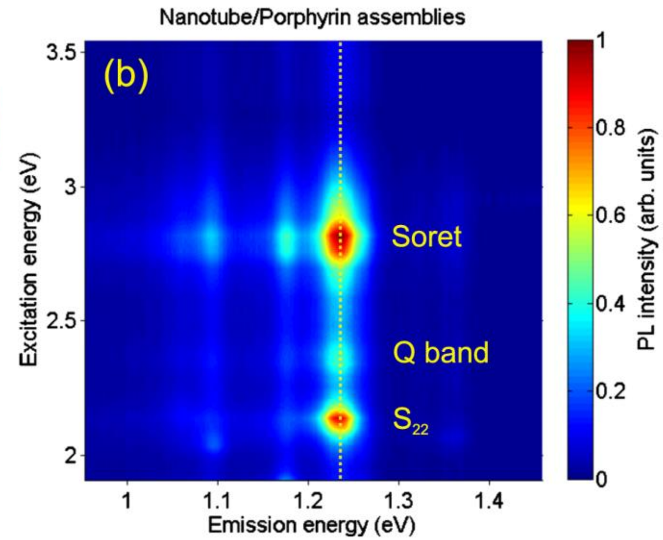
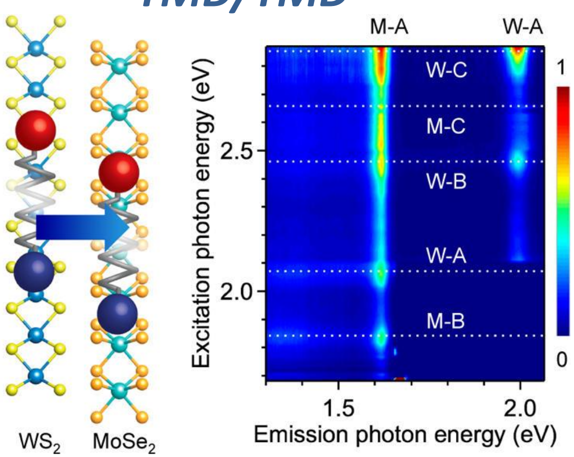


C. Roquelet *et al.*, APL **97**, 141918 (2010)

TMD/TMD

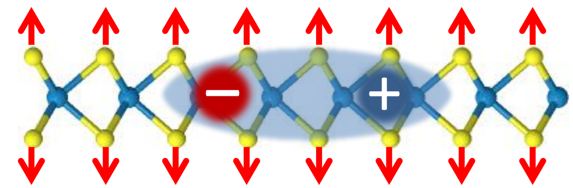


D. Kozawa *et al.*, Nano Lett. **16**, 4087 (2016)

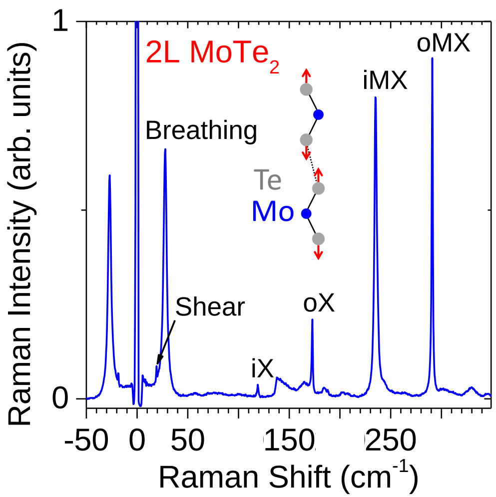
Interlayer energy transfer has been largely overlooked in TMD/Gr

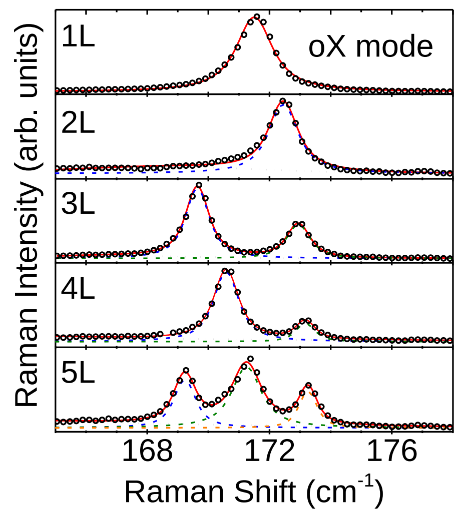
2D Materials at IPCMS

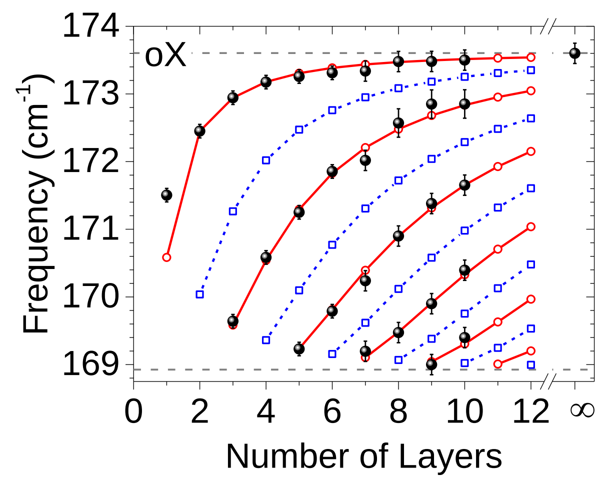
- Optical spectroscopy
- Phonons, excitons and their coupling(s)



✓ Interlayer interactions: Davydov splitting and unified description of the phonon modes







2H TMD - Froehlicher *et al.*, Nano Lett. 2015, Miranda *et al.*, Nano Lett. 2017. Coll: L. Wirtz group, Uni. Luxembourg

1T' TMD - Lorchat *et al.* ACS Nano 2016 (ReS_2 and $ReSe_2$)

See also Froehlicher *et al.*, J. Raman Spec. 2018 (special issue on 2D materials)