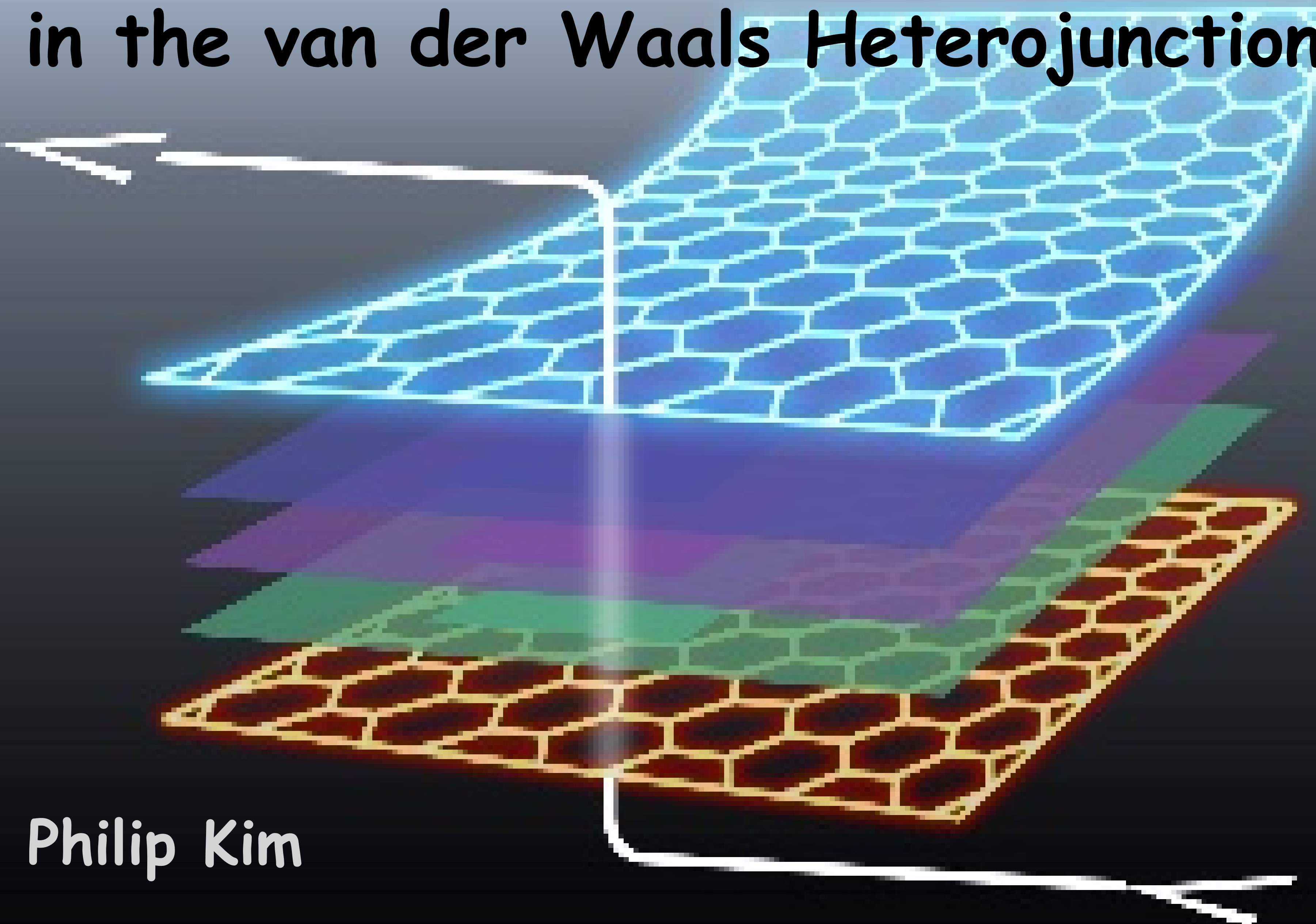
Electronic and Optoelectronic Physics in the van der Waals Heterojunctions



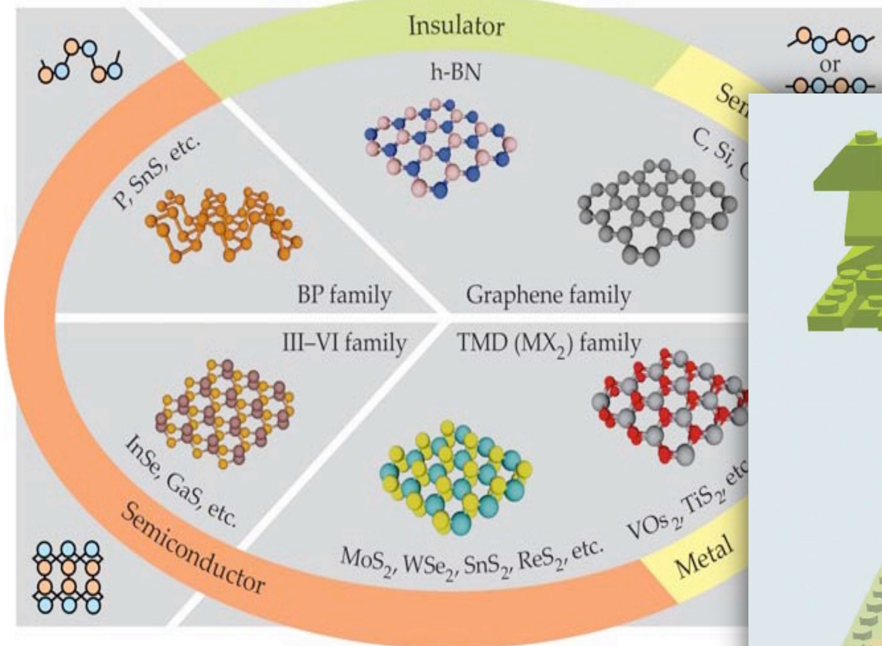
Philip Kim

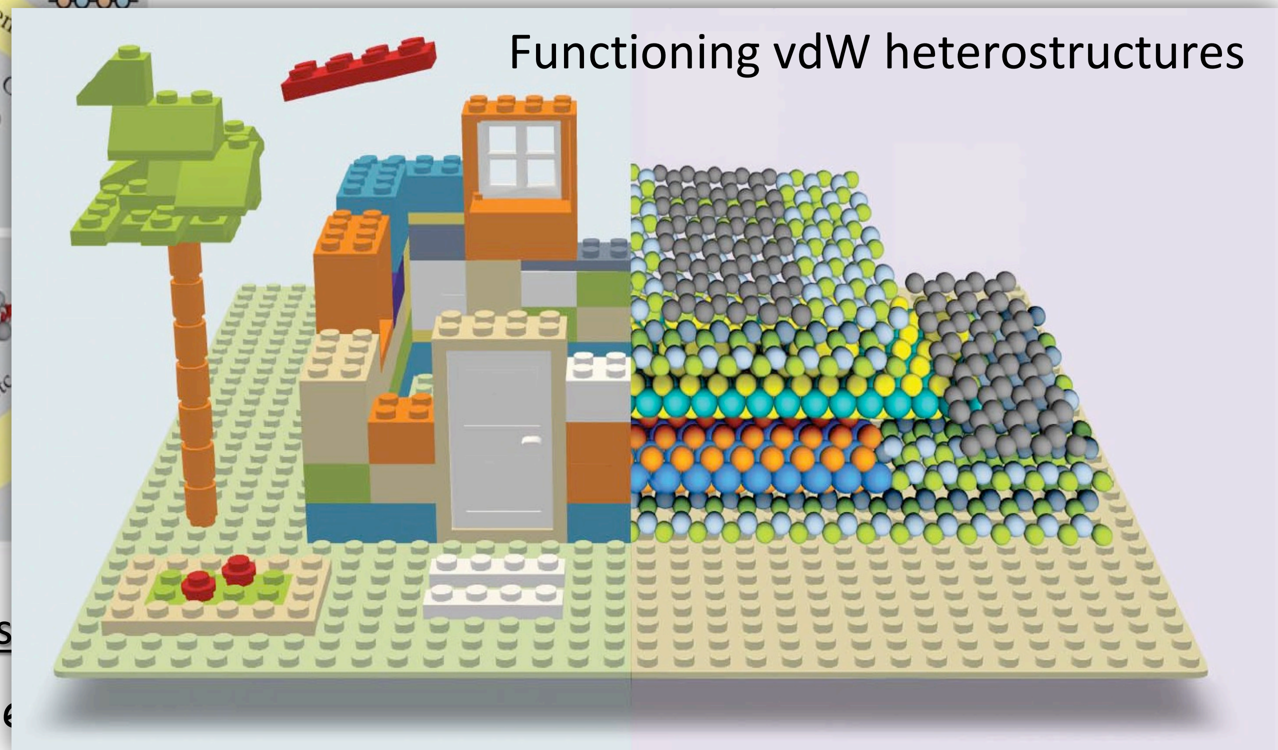
Physics & Applied Physics, Harvard University

Assembling van der Waals Materials

2D van der Waals Materials Family

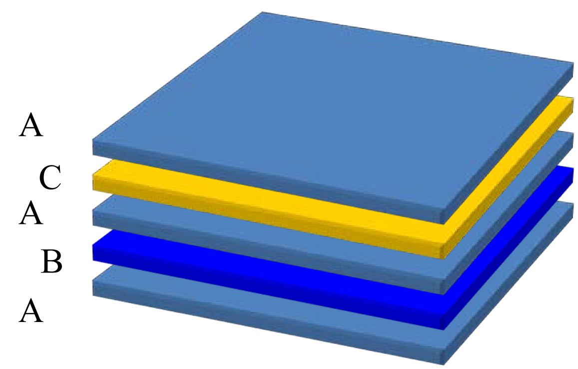
Ajayan, Kim and Banerjee, Physics Today (2016)



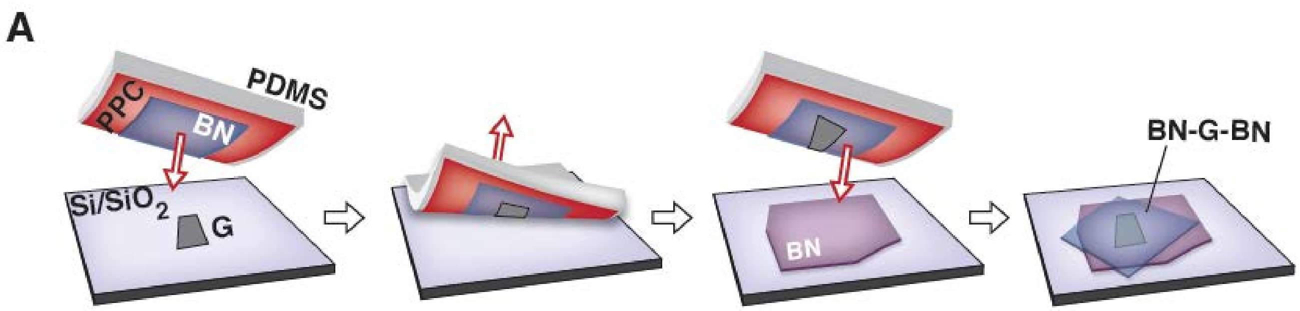


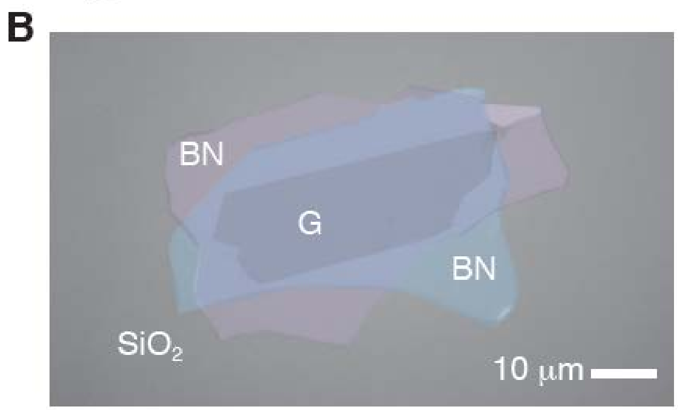
Experimentally popular vdW Materials

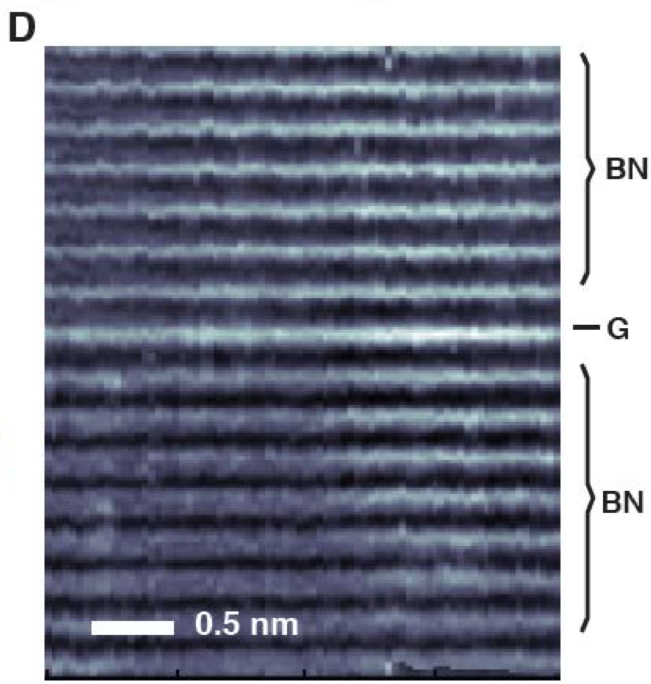
- Semiconducting materials: WSe
- Complex-metallic compounds : $TaSe_2$, TaS_2, …
- Magnetic materials: Fe-TaS_2, $CrSiTe_3$, CrI_3…
- Superconducting: $NbSe_2$, $Bi_2Sr_2CaCu_2O_{8-x}$,…
- Topological Insulator/Wyle SM: Bi_2Se_3, $MoTe_2$

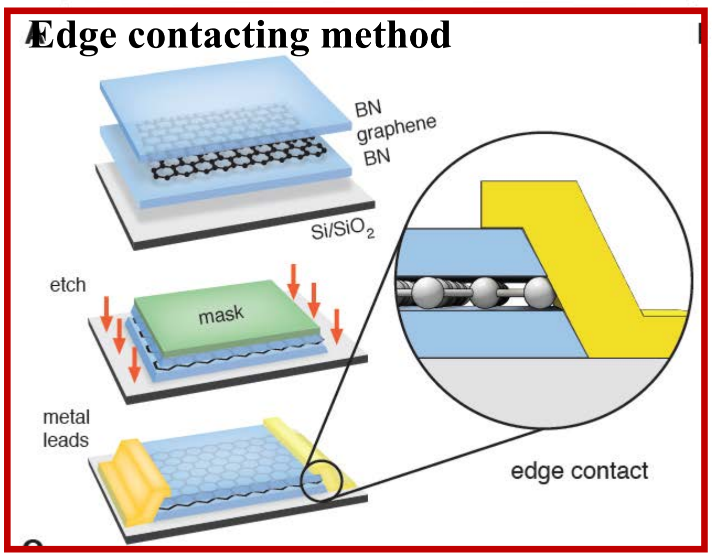


Pick-up Technique and Edge Contacts for Multilayer vdW Stacking



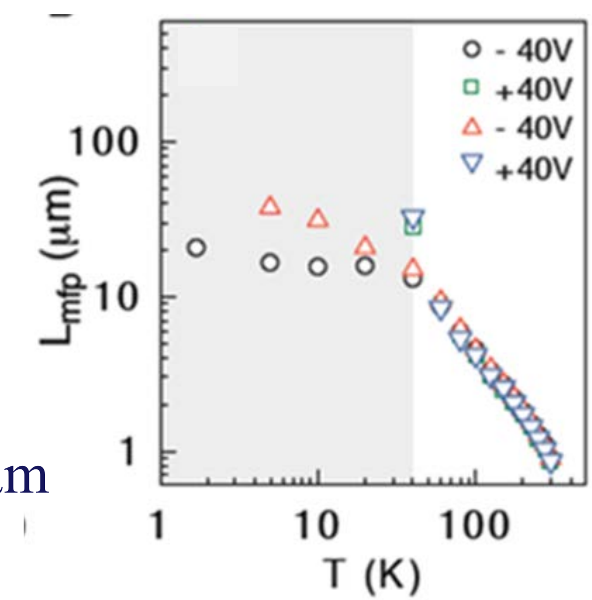






- Creation of multilayer systems with co-lamination techniques
- Encapsulated graphene in hBN
- Completely ballistic at low temperature

Contac Resistance: 100 Ω μm
Mobility ~ 10^6 cm^2/Vsec
Mean free path > 10 μm

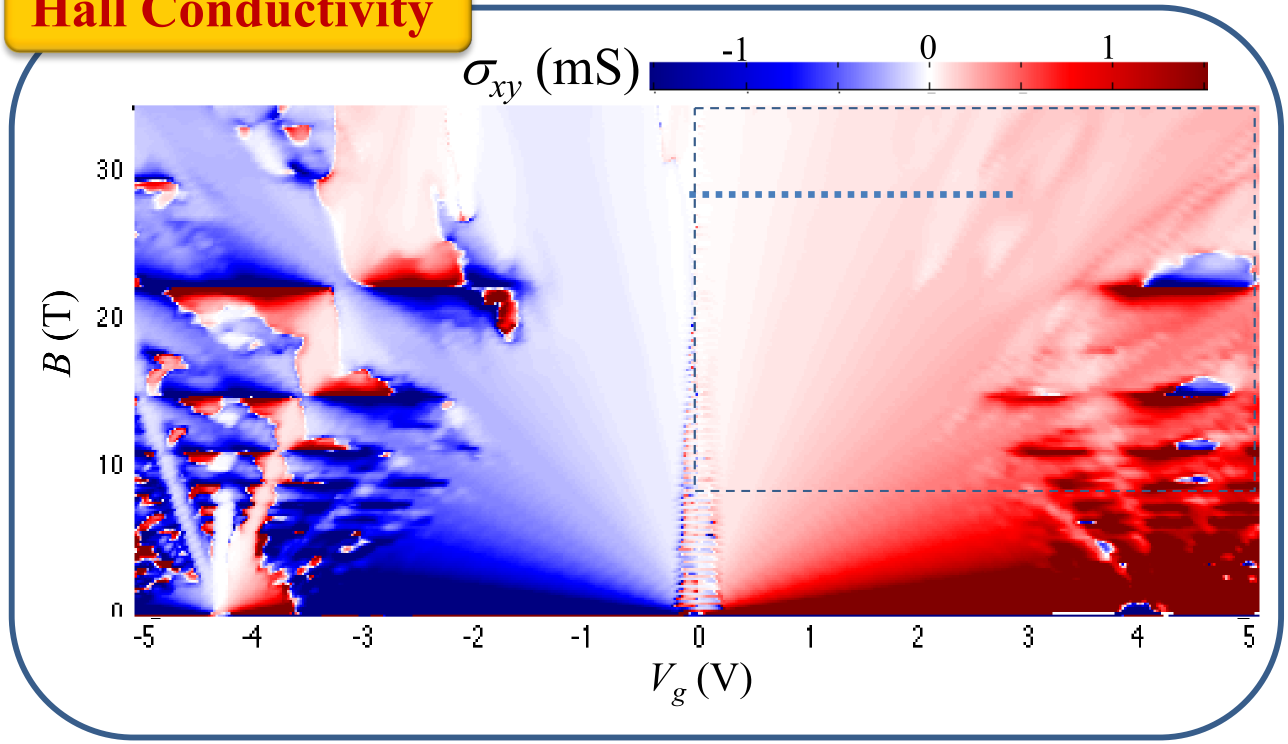


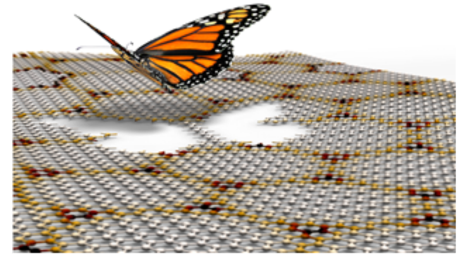
L. Wang *et al*, Science (2013)

Fractional and Fractal Quantum Hall Effect

Single layer graphene on hBN @ 20 mK up to 35 T

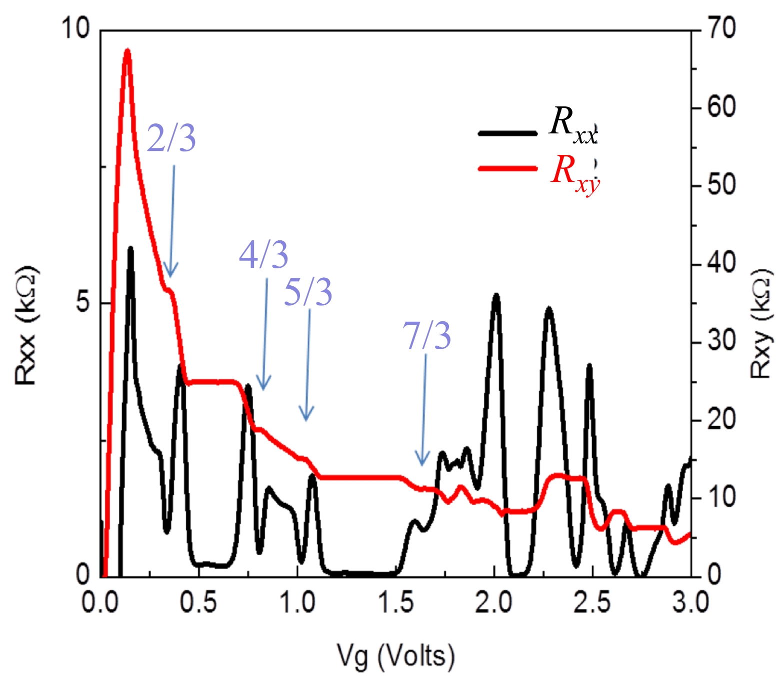
Hall Conductivity

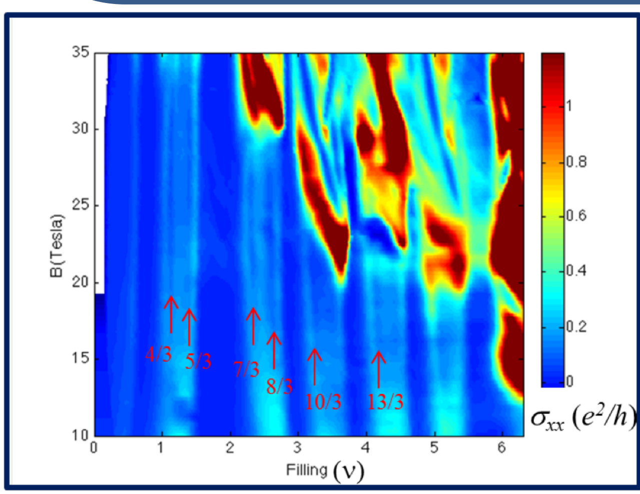




Hofstadter's butterfly in moire superlattice

Fractional Quantum Hall Effect

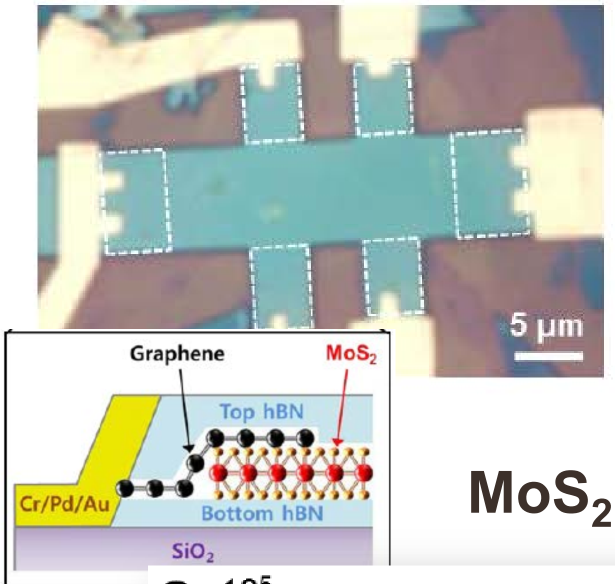


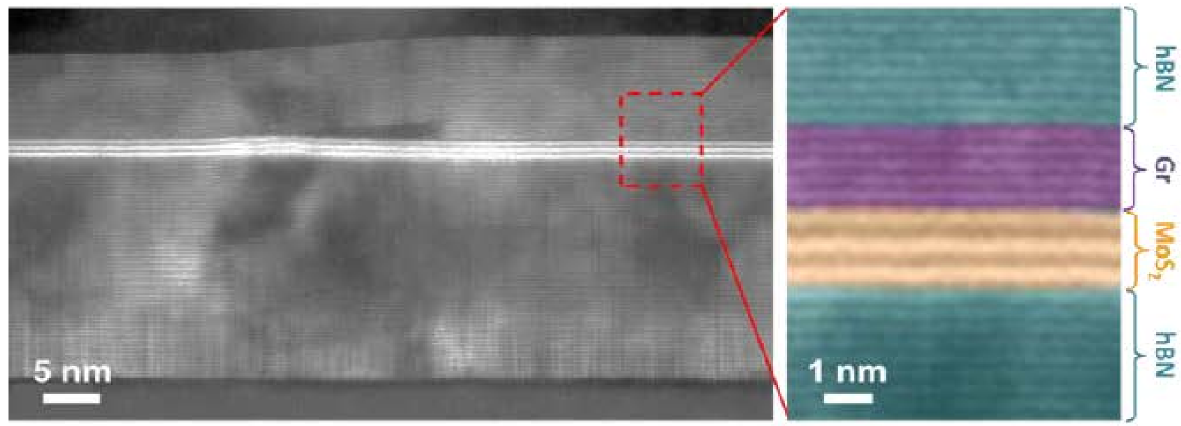


- Coexistence of Fractional Quantum Hall effect and Fractal Quantum Hall Effect.
- Can we observe Fractional Fractal Quantum Hall Effect?

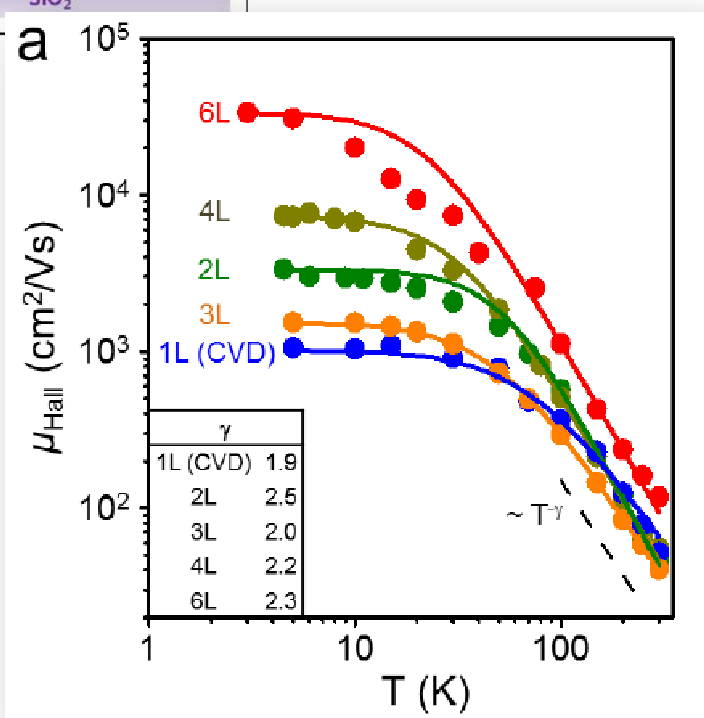
Encapsulation of vdW semiconductors in between hBN

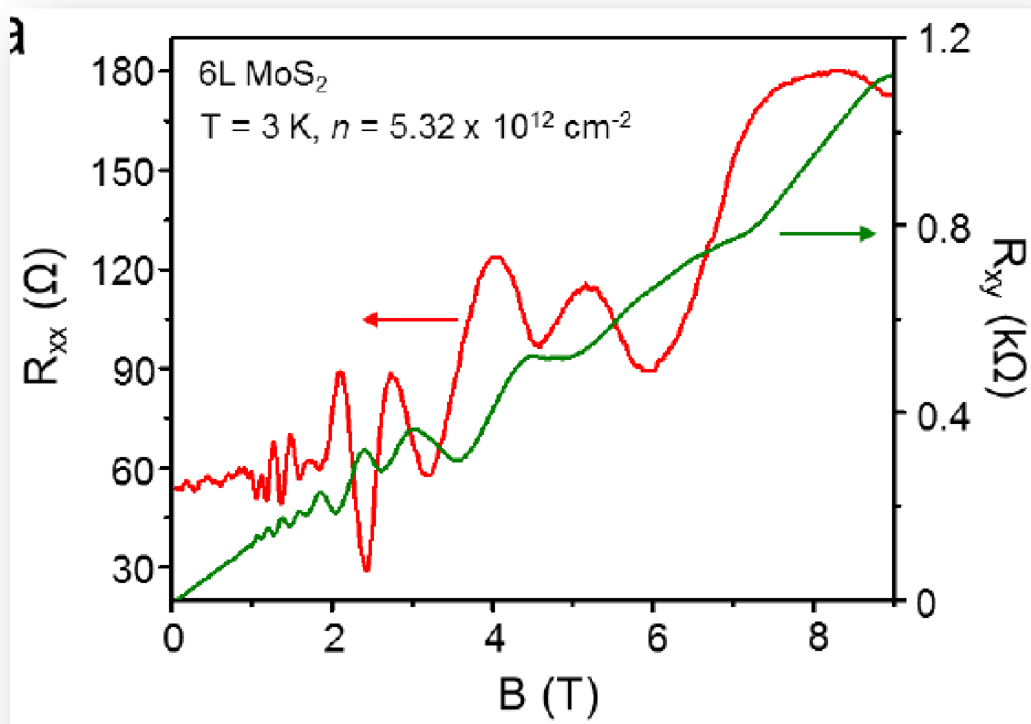
Xu *et.al.*, Nature Nano (2015) (Hone group collaboration)





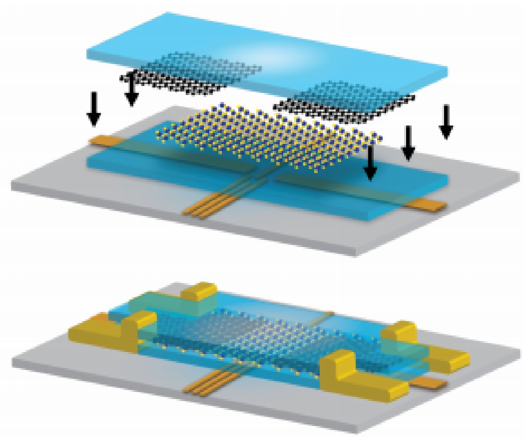
MoS_2 encapsulated in hBN with graphene electrodes

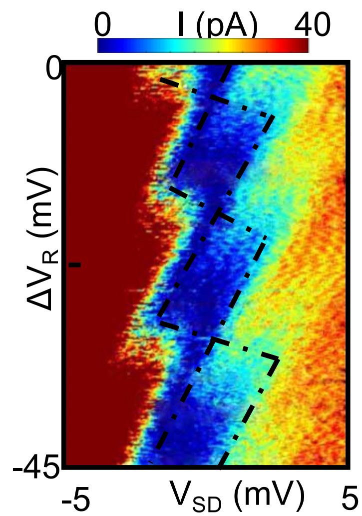




TMDC Quantum Electronic Devices

Single Electron Transistor





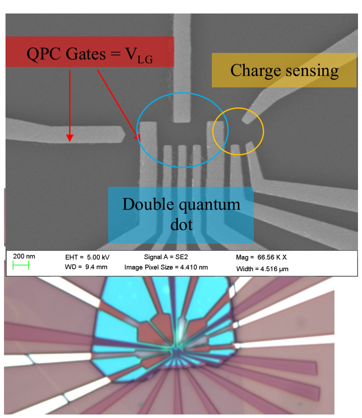
K. Wang *et al.*, Nature Nano (2018);

Graphene contacts

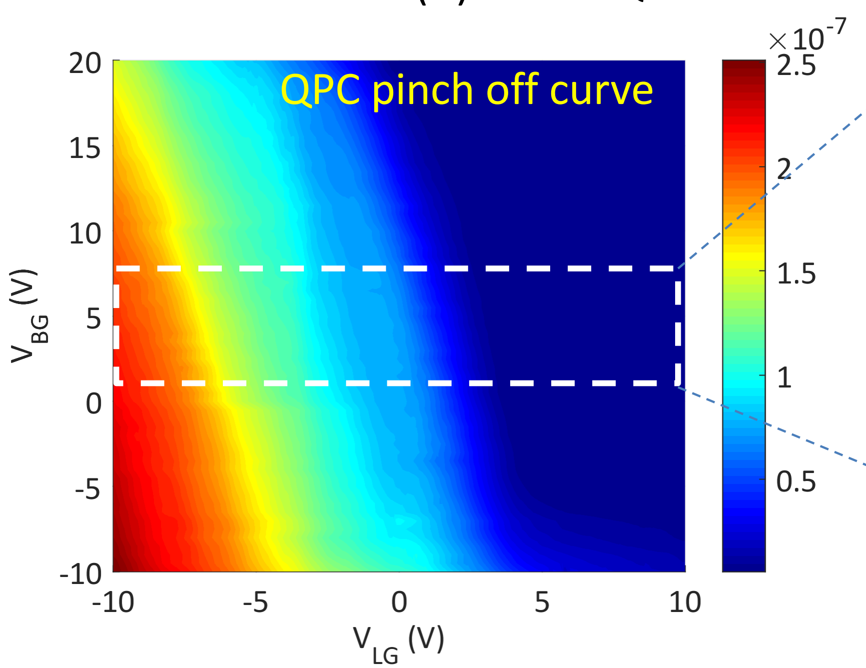
3 layer hBN/ MoS_2 /hBN

Quantum Point Contact

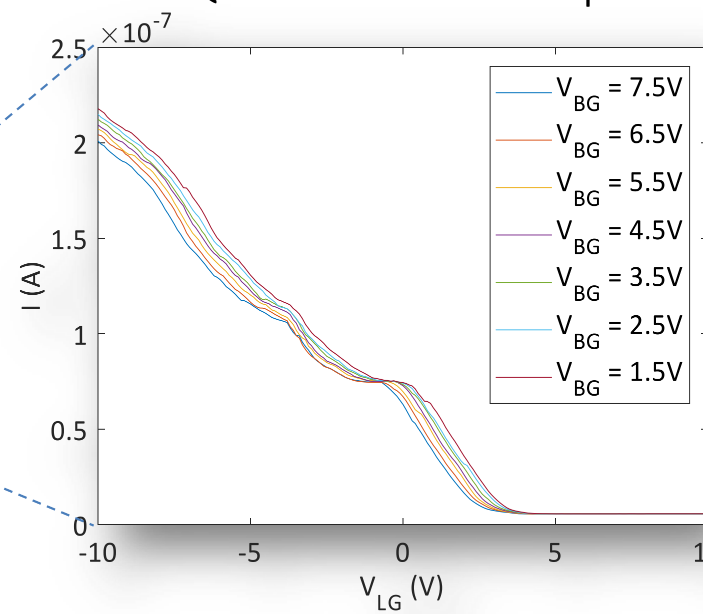
Double quantum dot and QPC charge sensor in hBN-WSe_2-hBN heterostructures.



Current (A) across QPC



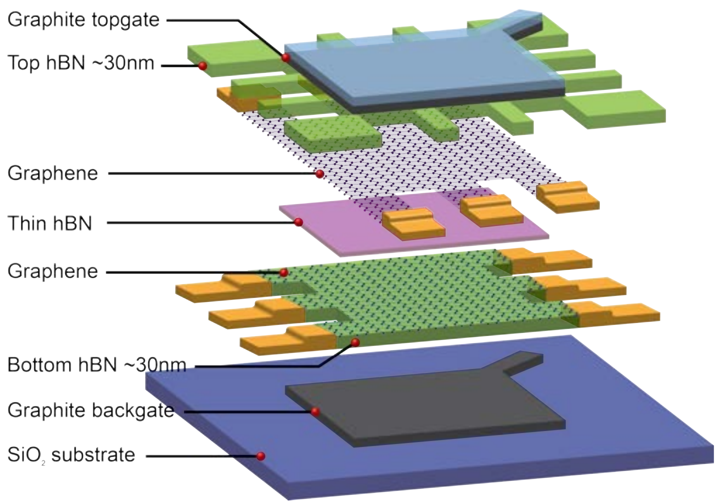
Quantum Conductance plateau

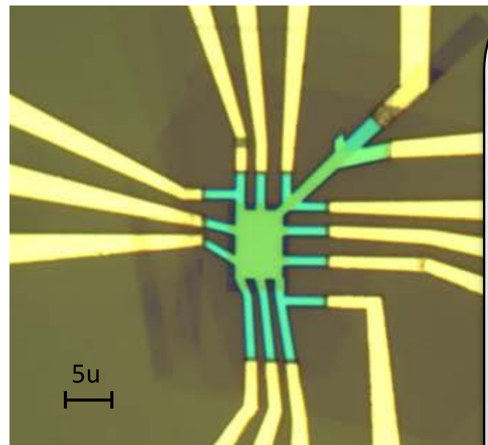


A. Joe *et al.*, unpublished (2018);

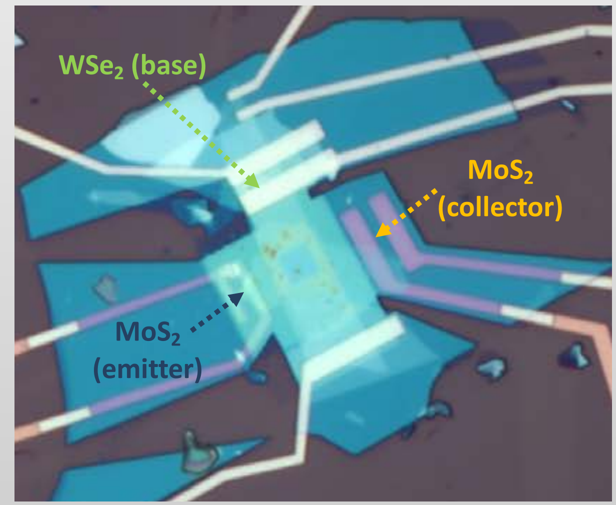
vdW Heterostructure Devices

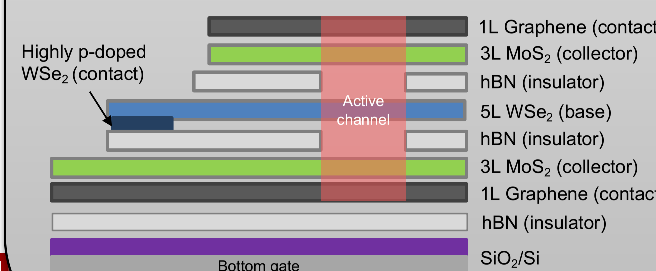
Coulomb Drag in Graphene



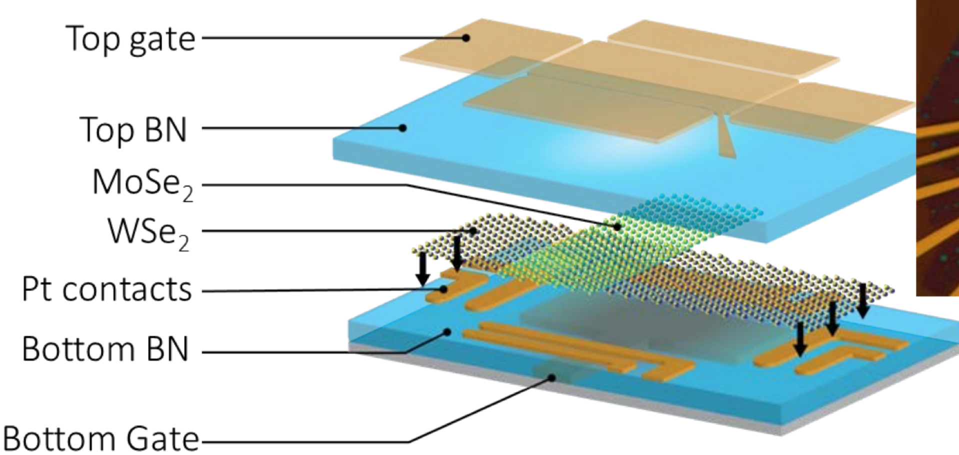


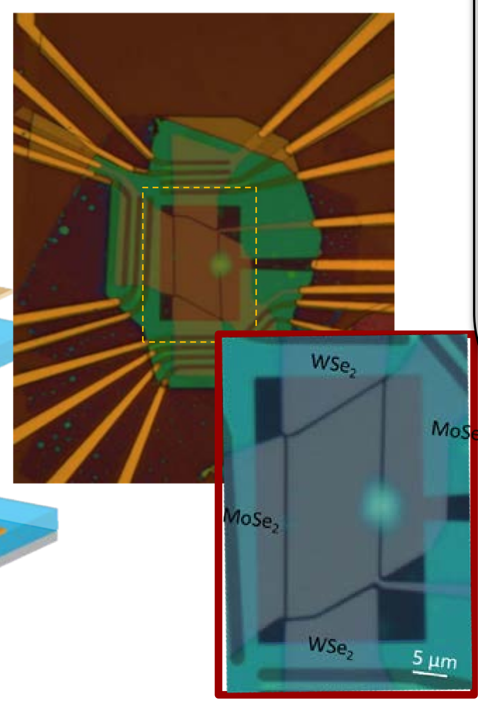
vdW Bipolar Transistor





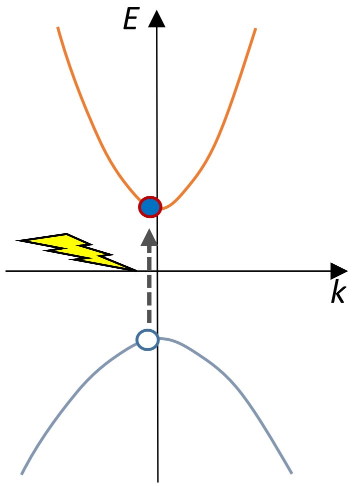
WSe2/MoSe2 Optoelectric Device

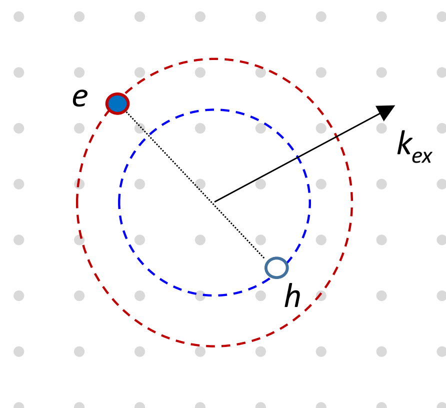


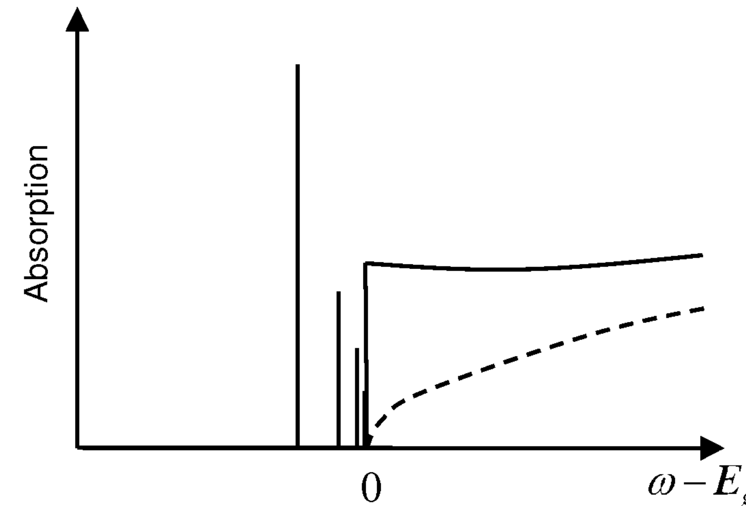


Excitons

Excitons in Semiconductors

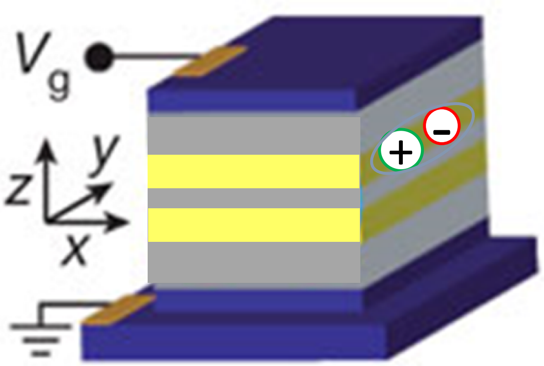


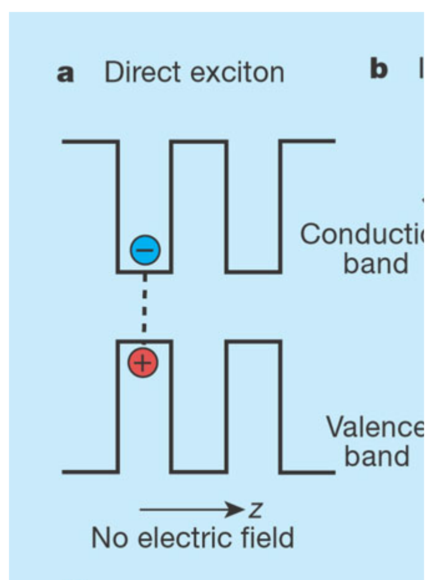




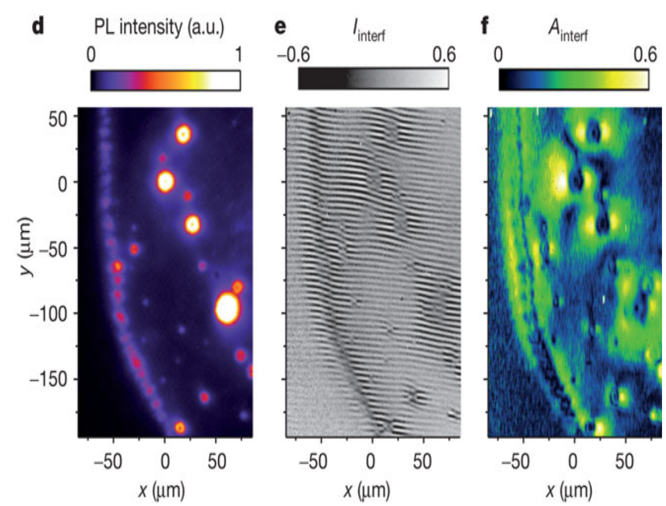
Direct and indirect excitons in semiconducting quantum wells

Semiconductor heterostructure



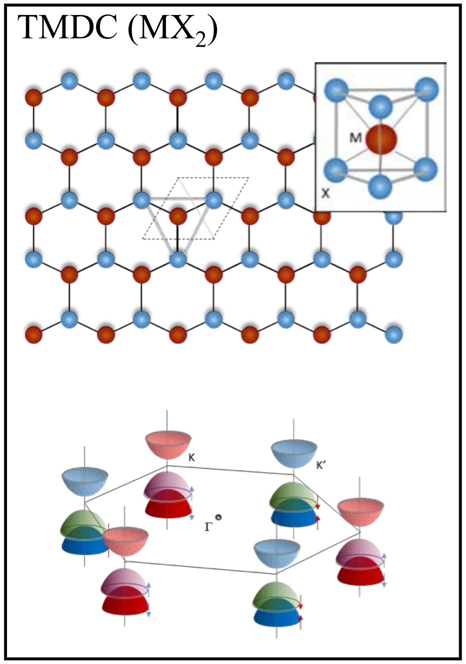


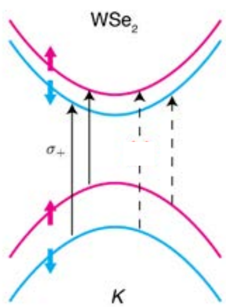
Spontaneous coherence



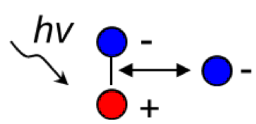
A. High, Nature 2012

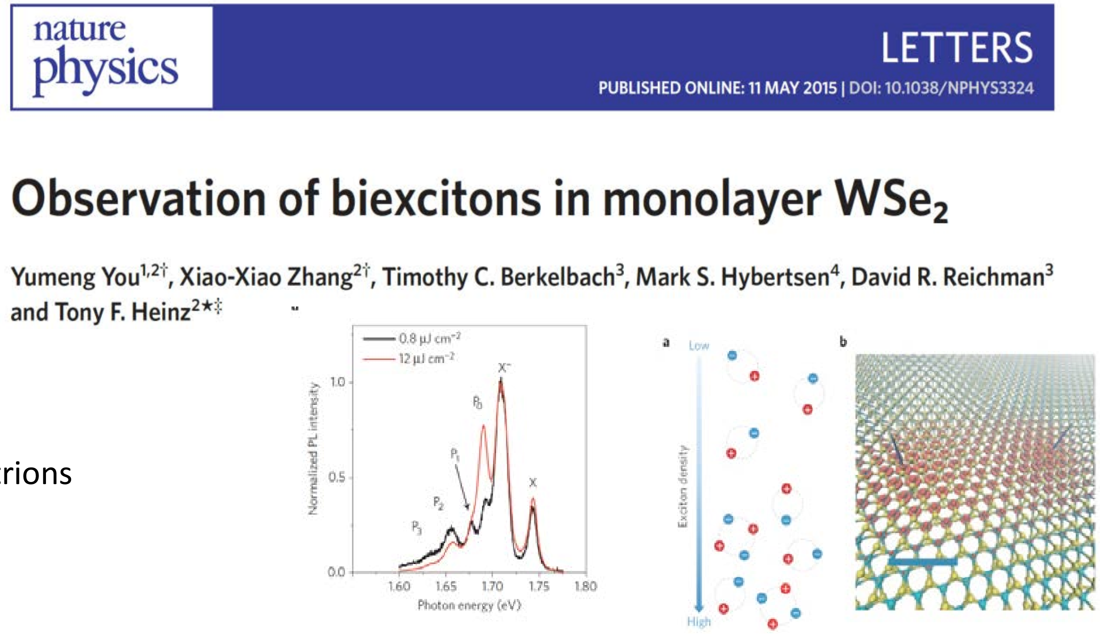
Excitons in 2D Materials





Spin-valley locking
Strongly bound exciton & trions



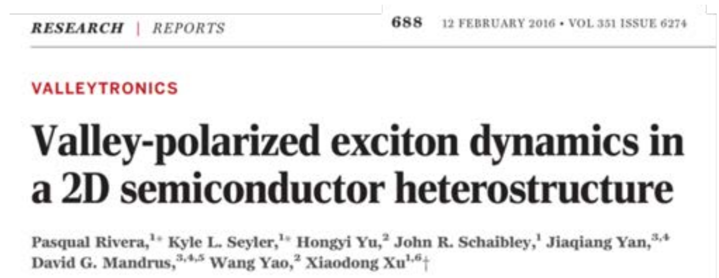

nature physics

LETTERS

PUBLISHED ONLINE: 11 MAY 2015 | DOI: 10.1038/NPHYS3324

Observation of biexcitons in monolayer WSe_2

Yumeng You[1,2†], Xiao-Xiao Zhang[2†], Timothy C. Berkelbach[3], Mark S. Hybertsen[4], David R. Reichman[3] and Tony F. Heinz[2*‡]

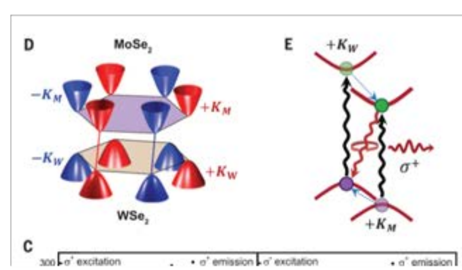

RESEARCH | REPORTS

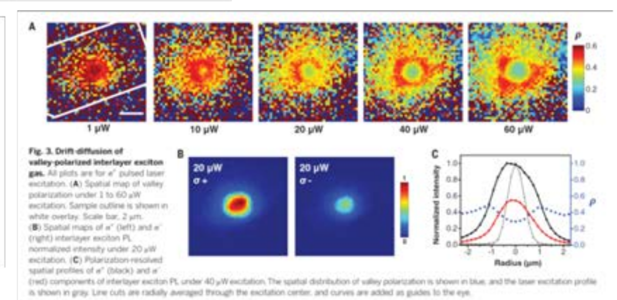
688 12 FEBRUARY 2016 • VOL 351 ISSUE 6274

VALLEYTRONICS

Valley-polarized exciton dynamics in a 2D semiconductor heterostructure

Pasqual Rivera,[1*] Kyle L. Seyler,[1*] Hongyi Yu,[2] John R. Schaibley,[1] Jiaqiang Yan,[3,4] David G. Mandrus,[3,4,5] Wang Yao,[2] Xiaodong Xu[1,6†]



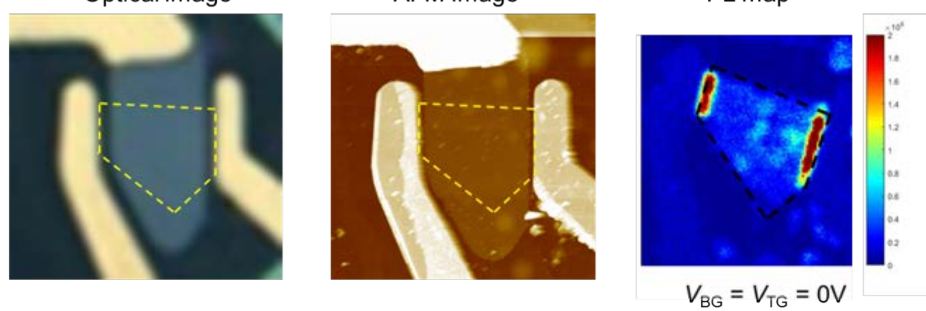


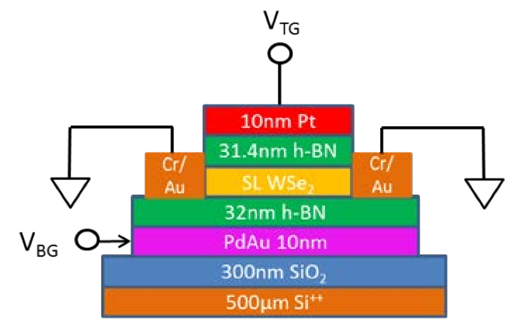
- Strong confinement
- Lack of strong screening effect
- Spin polarized band
- Spin-valley locking

Gate Tunable Optical Properties of WSe_2

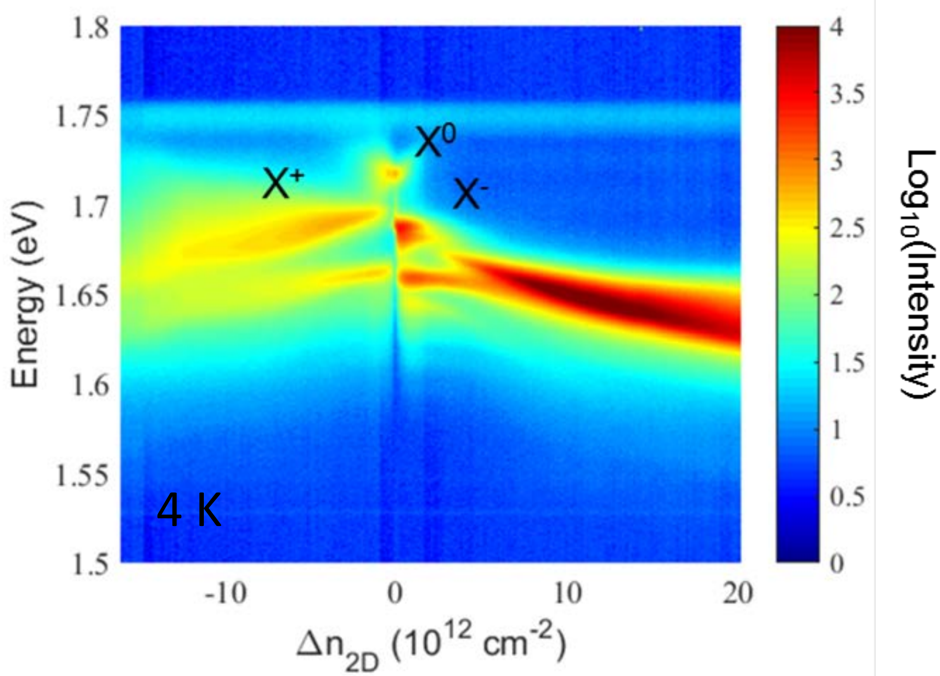
- Top and bottom gate to control electric fields and density at T = 4K
- Monolayer WSe_2 is grounded
- $V_{BG} = V_{TG}$, zero E-field ➔ change of carrier density only
- Thick. of bottom and top h-BN: 32nm and 31.4nm, respectively

Earlier work:
Jones *et al* (Xue), Nat. Nano (2013)

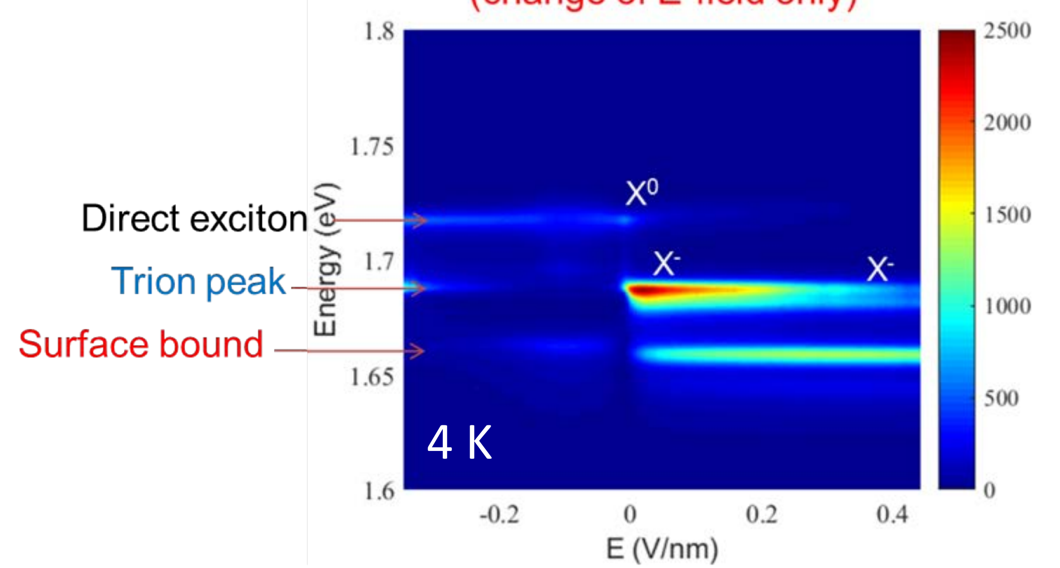




Photoluminescence



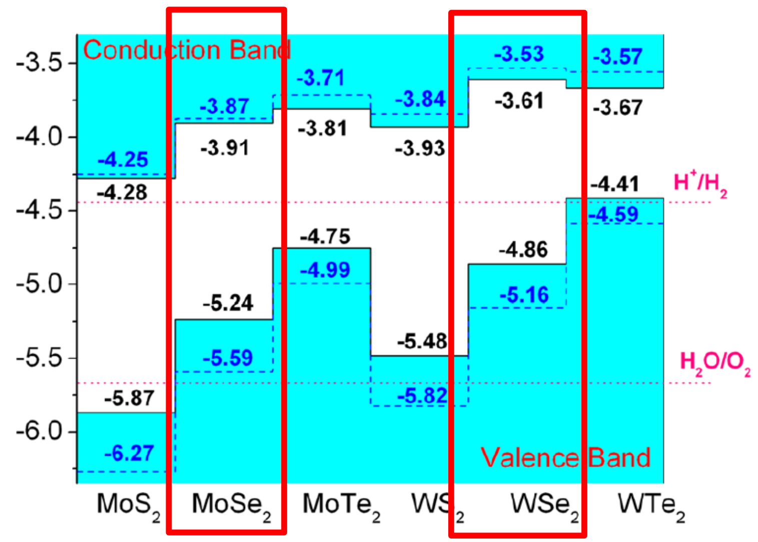
$V_{BG} = - V_{TG}$, zero carrier density (change of E-field only)

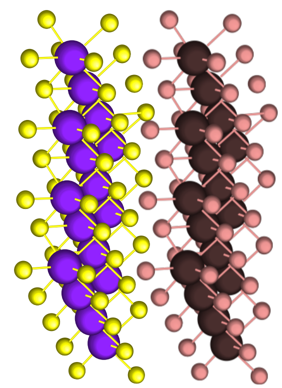


L. Jauregui *et al unpublished* (Kim, Park and Lukin collaboration)

Atomically Thin vdW p-n junction

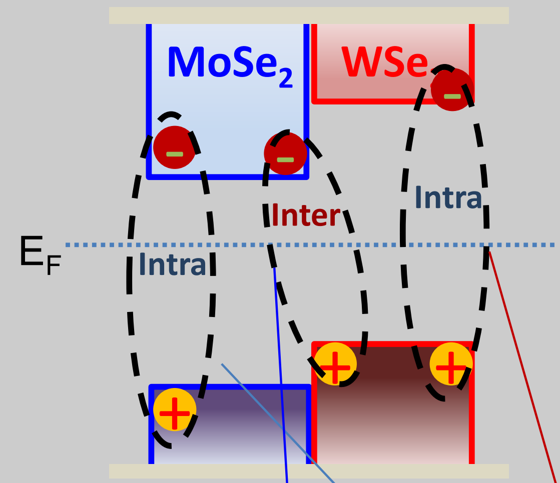
Band gaps and alignment of vdW semiconductors



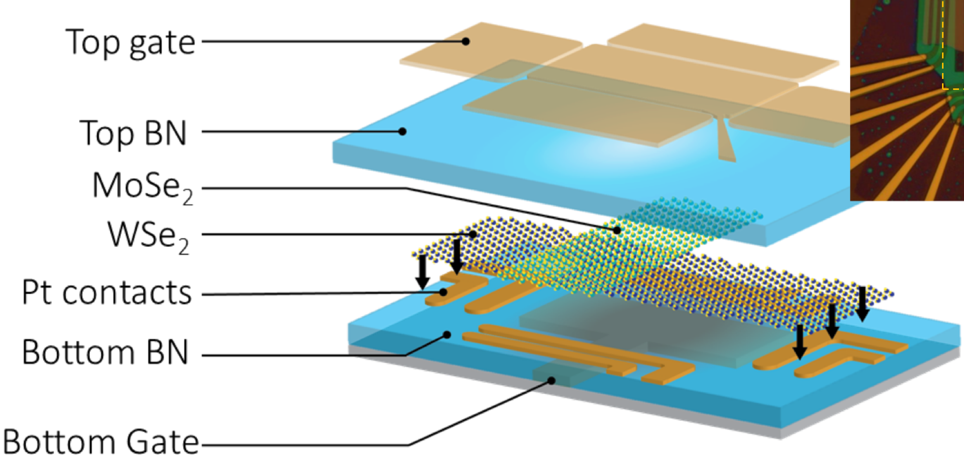


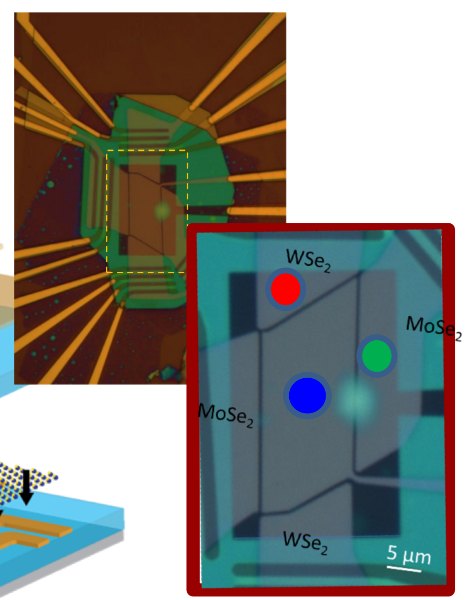
Appl. Phys. Lett. **102**, 012111 (2013)

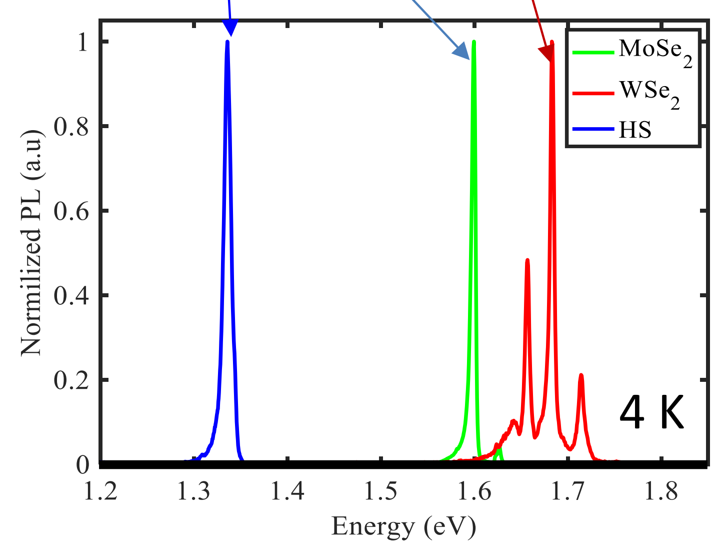
- **Type II semiconductor heterostructures**



Heterostructure Device and PL



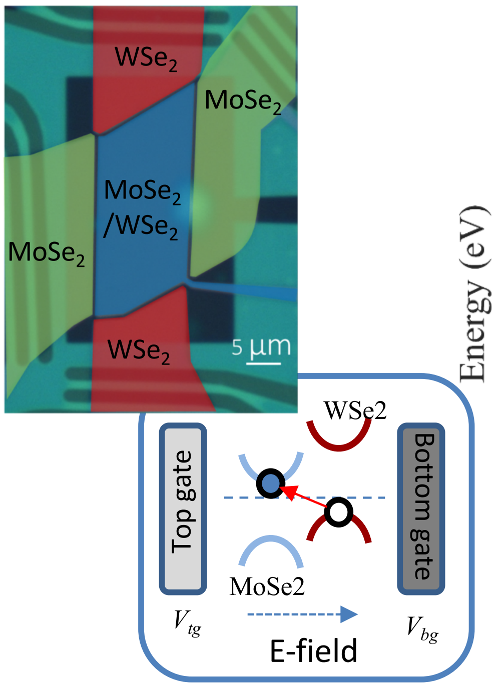




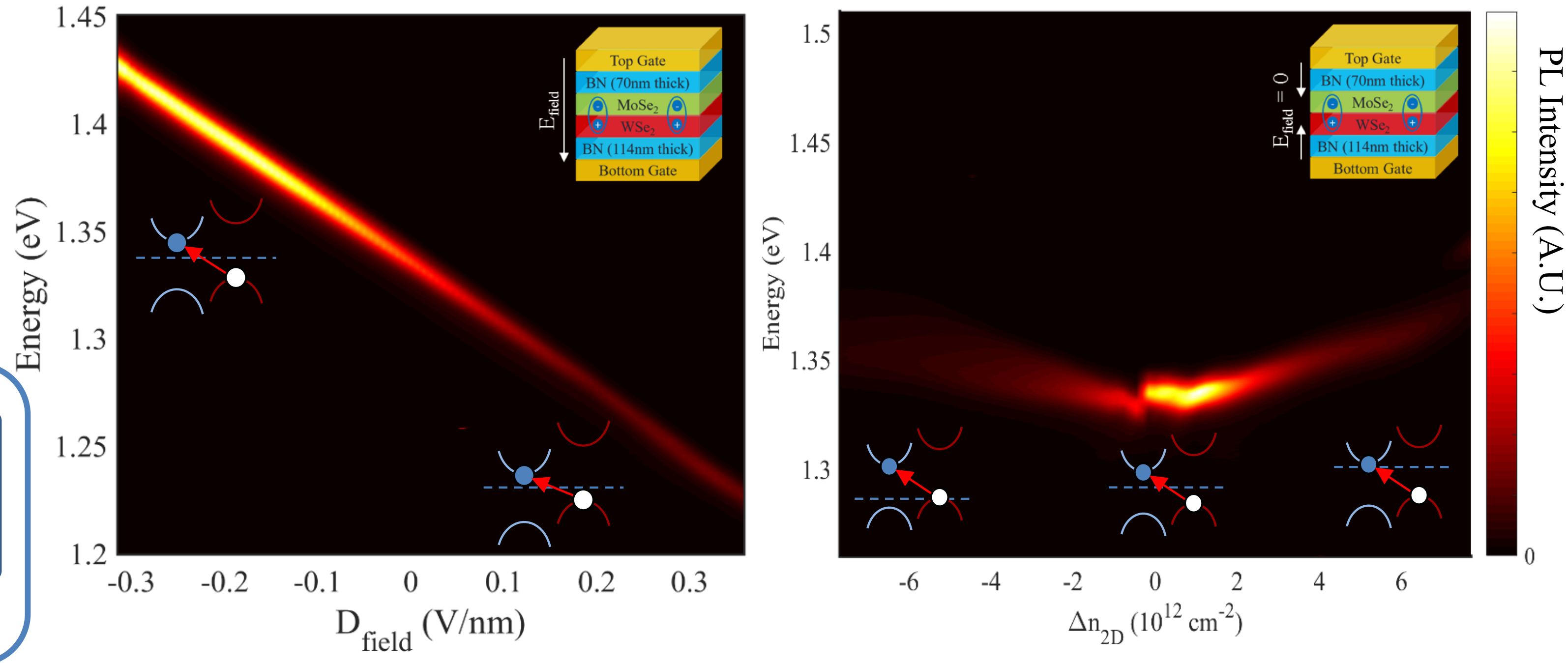
L. Jauregui et. al, unpublished (Collaboration with H. Park and M. Lukin groups)

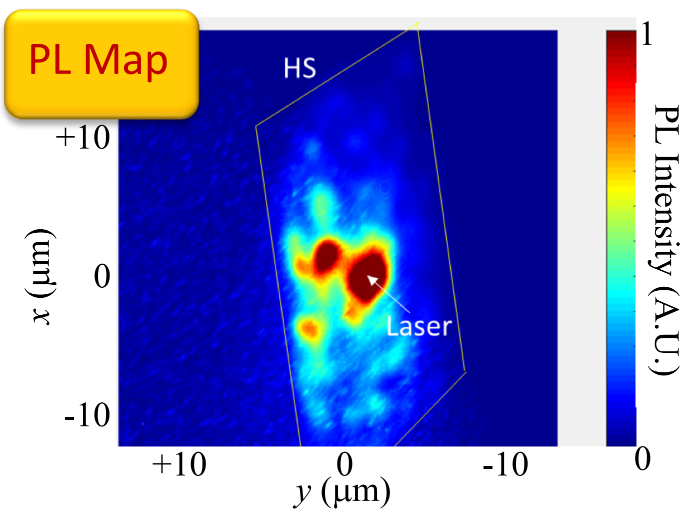
Tunable Interlayer Excitons in TMDCs

$MoSe_2/WSe_2$ heterostructure

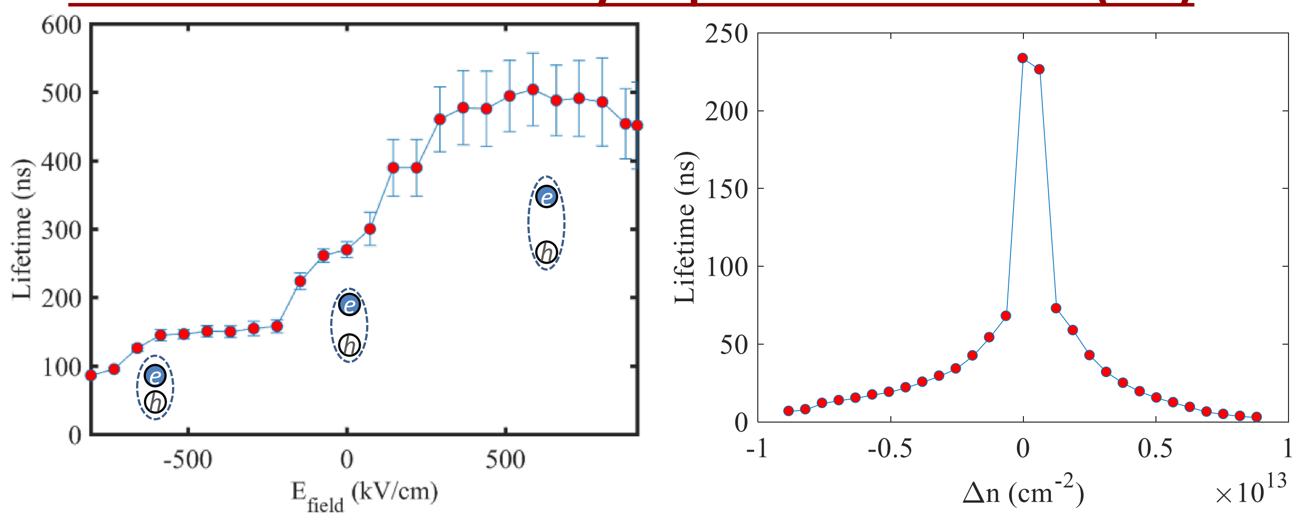


Electric Field and Density Dependent Photo luminescent (4 K)





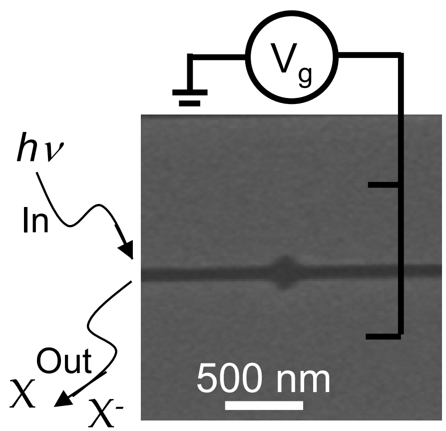
Electric Field and Density Dependent Life Time (4 K)

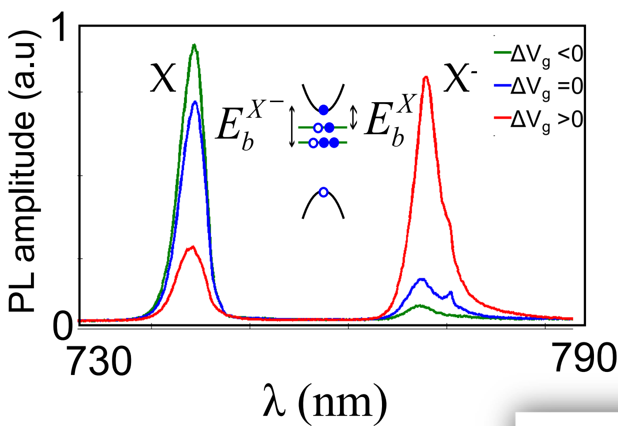


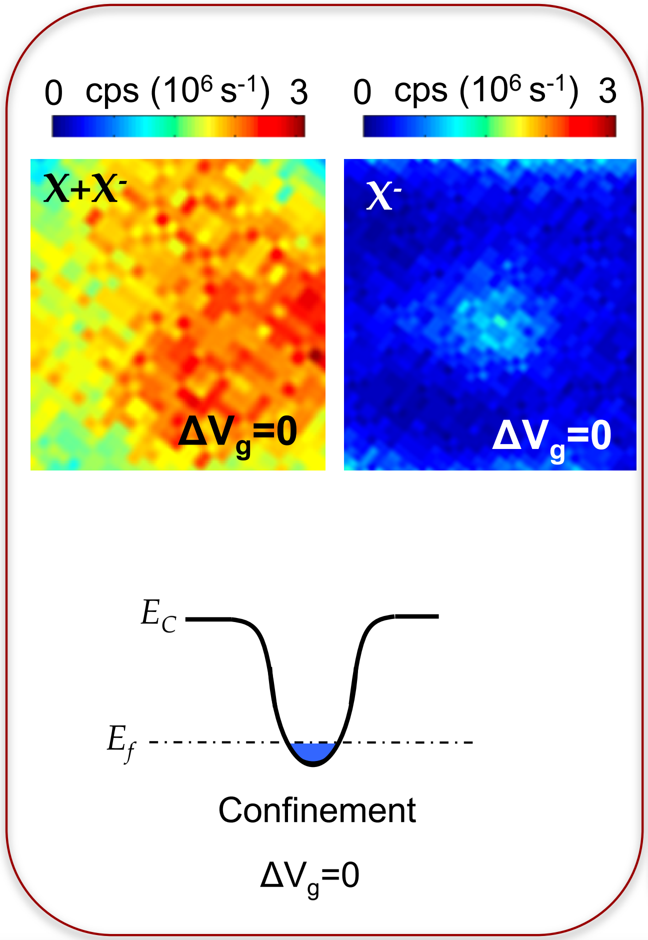
L. Jauregui et. al, unpublished (Collaboration with H. Park and M. Lukin groups)

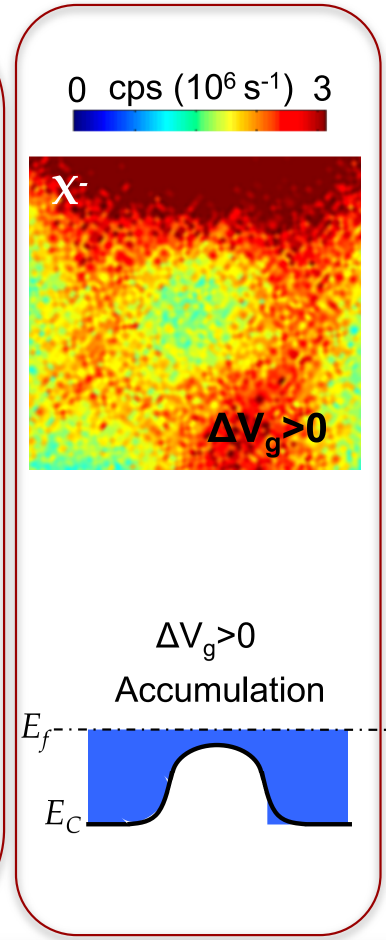
Gate Controlled Quantum Confined Trions

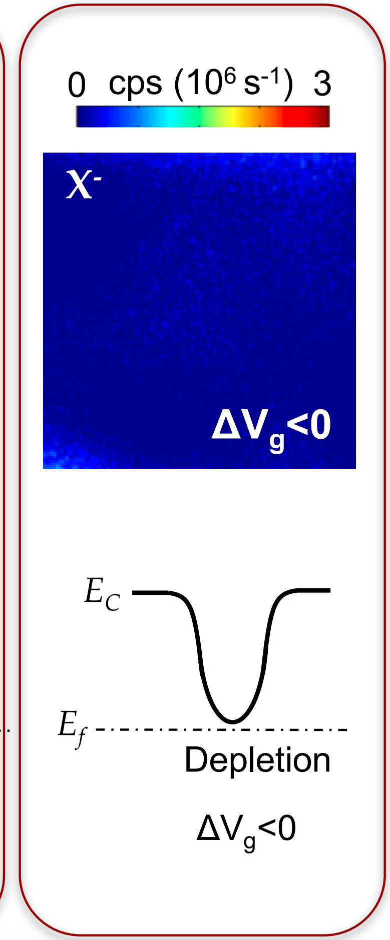
Local gate with monolayer $MoSe_2$



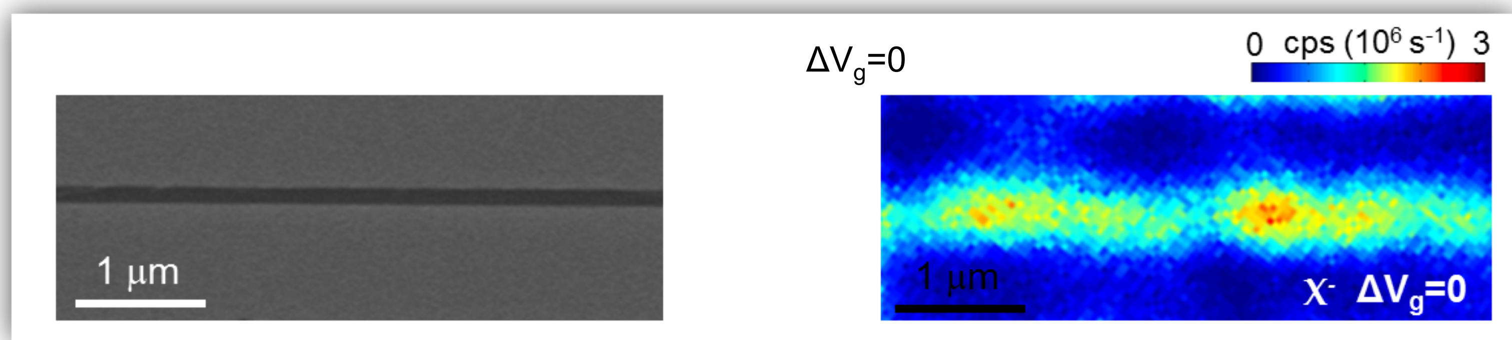








1D confinement of trions by local gate

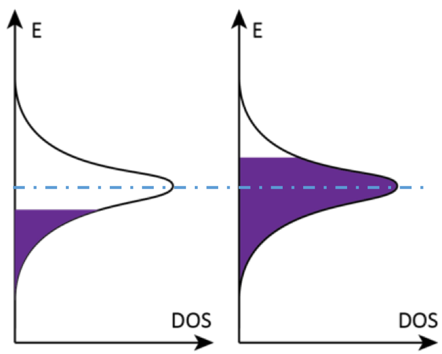


Ke Wang *et al, Nature Nano* (2018) (Kim, Park and Lukin collaboration)

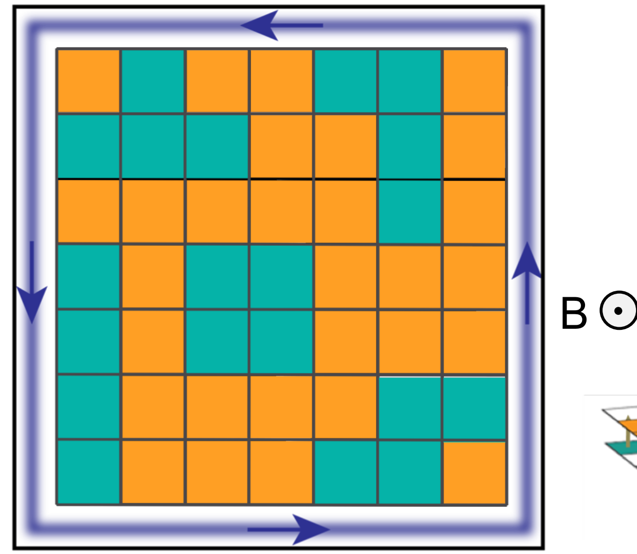
Exciton condensation between Landau levels

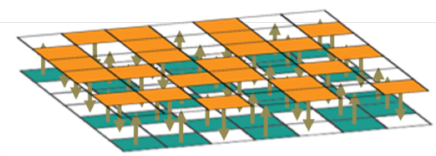
J. P. Eisenstein, Annu. Rev. Condens. Matter Phys. **5**, 159 (2014).

Two partially filled Landau levels



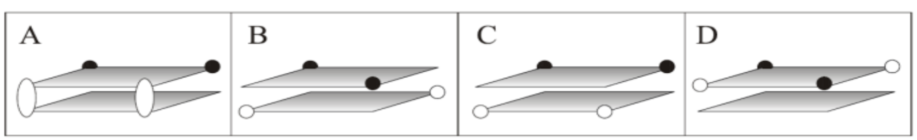
$$|\Psi\rangle = \prod_k \frac{1}{\sqrt{2}}(c^\dagger_{k,T} + e^{i\phi} c^\dagger_{k,B})|0\rangle$$



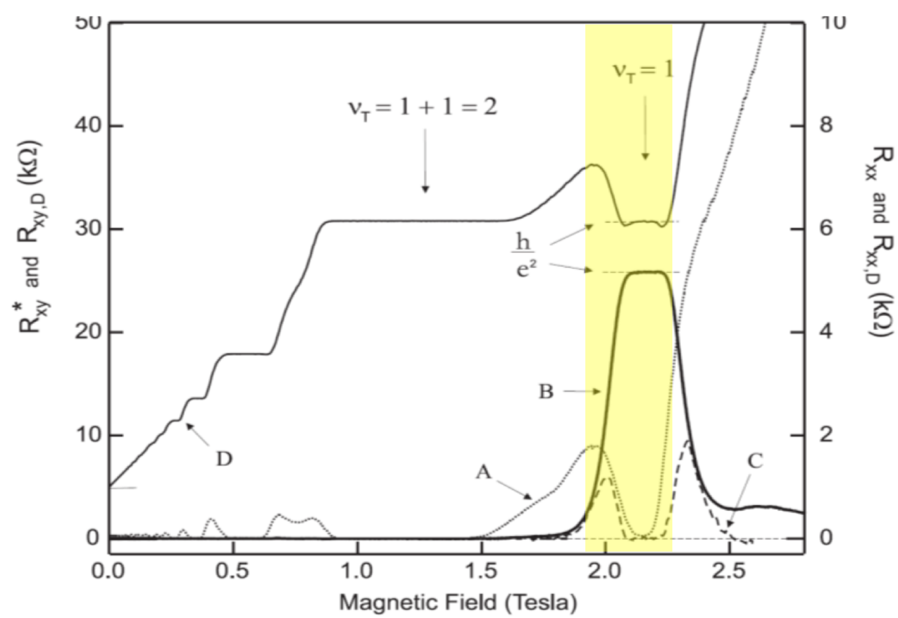


Total Landau level quantum Hall effect

GaAs Double Quantum Well



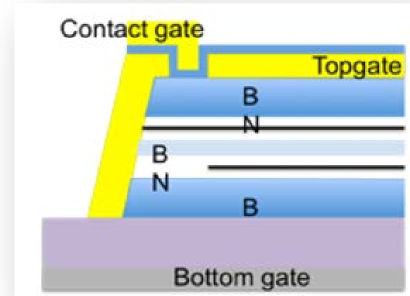
- Quantum Hall effect for two partially filled complementary LLs
- Quantized drag Hall

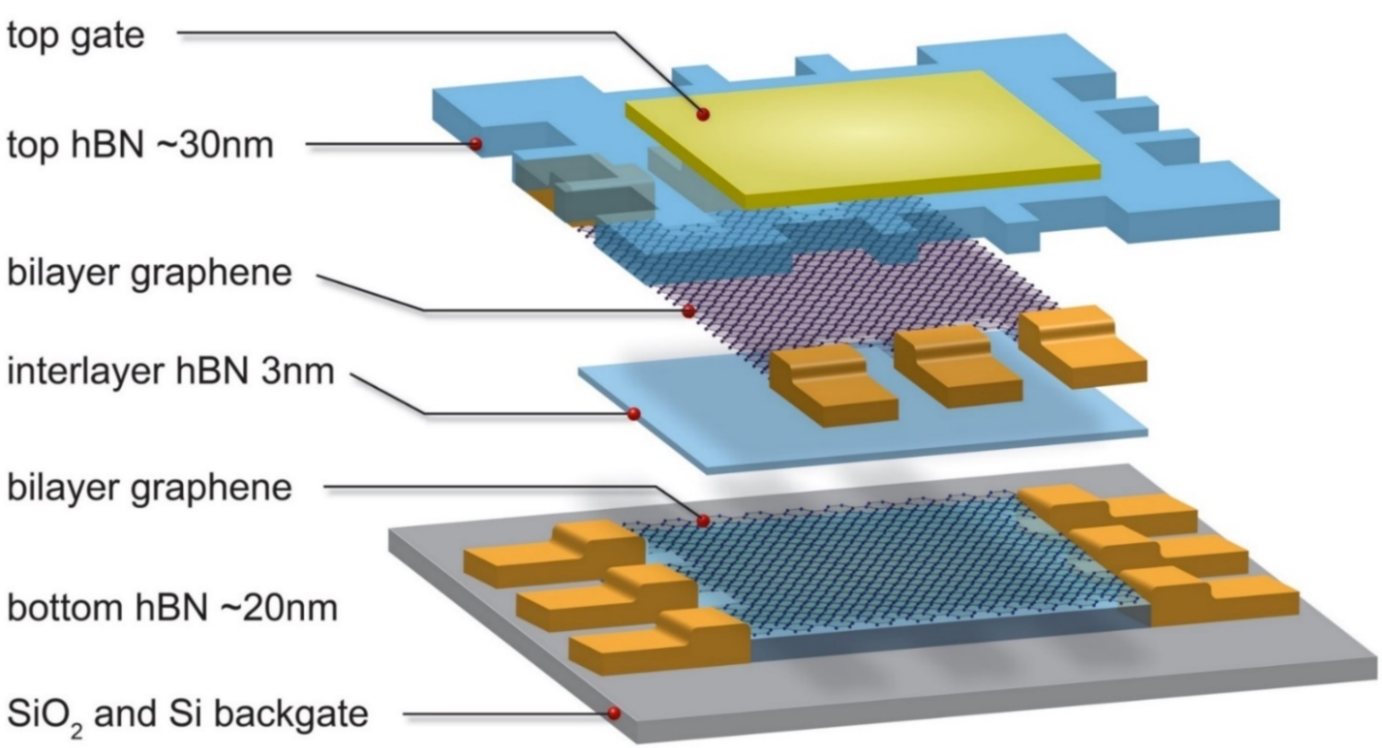


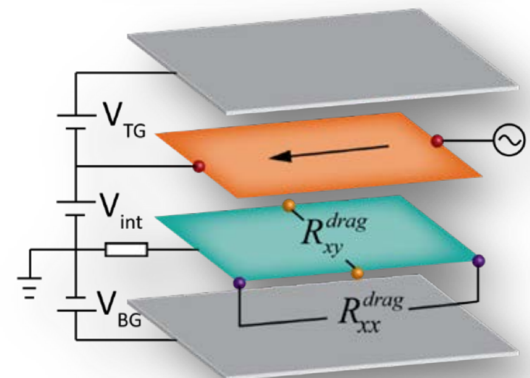
M. Kellogg, et. al, PRL (2002)

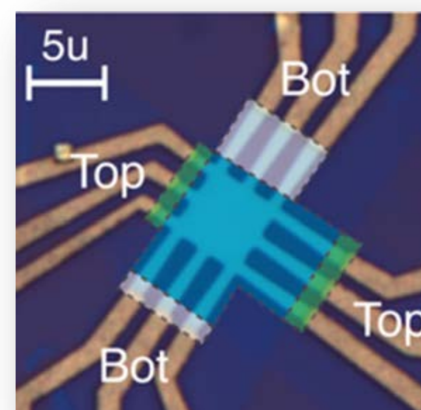
Double Bilayer Graphene Drag Device

- Mobility ~ 10^6 cm^2/Vsec
- hBN thickness d =3 nm
- top and bottom gate
- contact gate
- interlayer bias







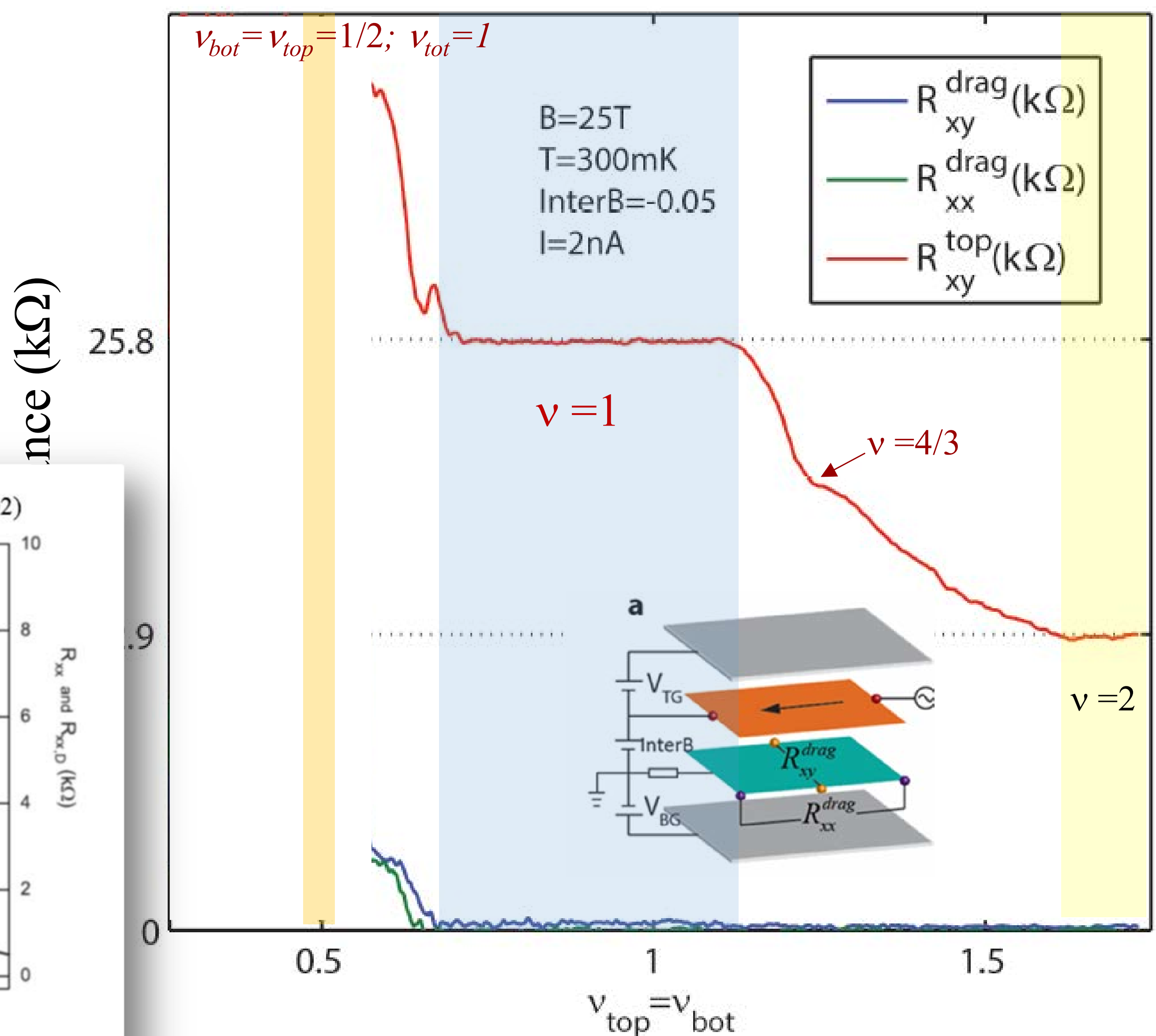


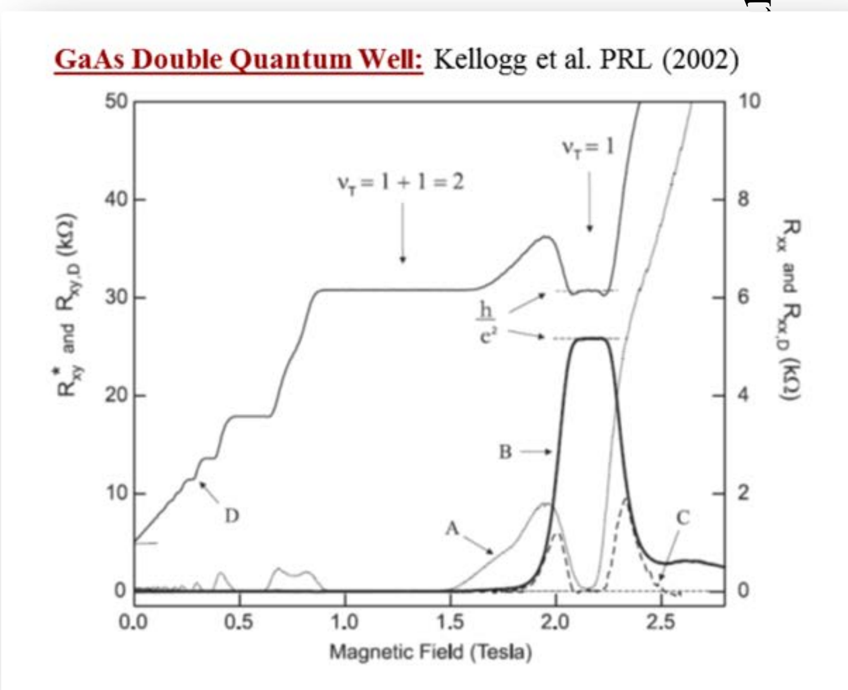
Xiaomeng Liu *et al*, Nature Physics (2017)

Bilayer Graphene/hBN/Bilayer Graphene: Quantized Hall Drag

- Mobility ~ 10^6 cm^2/Vsec
- hBN thickness d =3 nm
- top and bottom gate
- contact gate
- interlayer bias

Hall Resistance, Magneto Drag, and Hall Drag

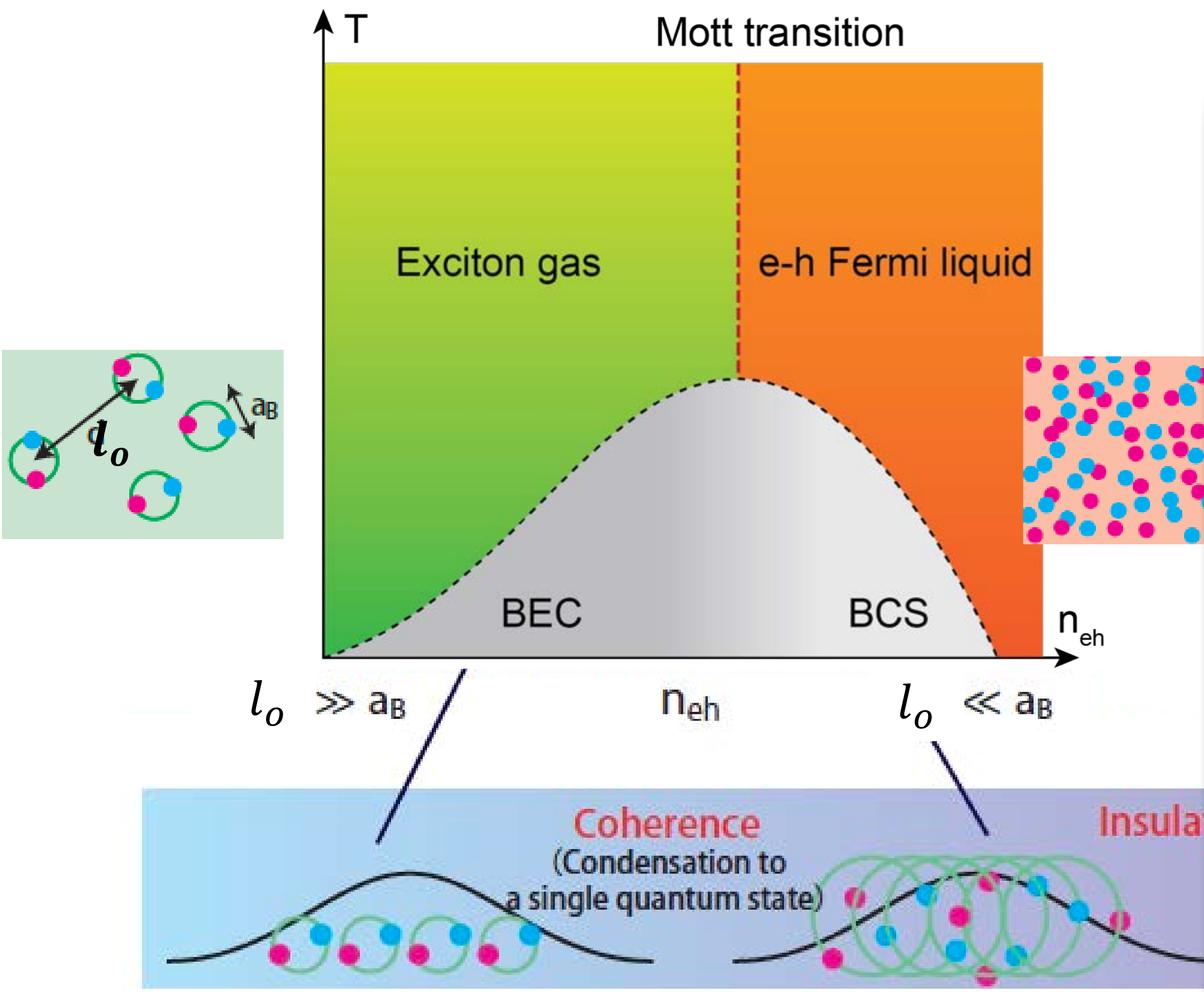




Xiaomeng Liu *et al*, Nature Physics (2017)

Exciton/e-h Phase Diagram

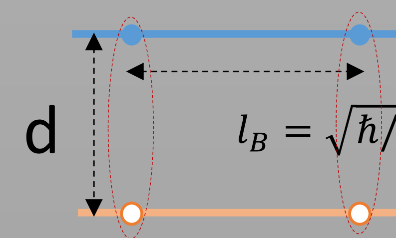
Schematic Meta Stable Phase Diagram of electron-hole in 3D



T. Ogawa and K. Asano (2008)

Quantum Hall Bilayer:

Competition between inner-layer and interlayer interaction



- $d \ll l_B$: Halperin (111) state

$$|\Psi\rangle = \prod (z_i - z_j)(w_i - w_j)(z_i - w_j) \times e^{-\frac{1}{4}(\sum |z_i|^2 + \sum |w_i|^2)}$$

- $d \gg l_B$

: weakly coupled composite fermions

$$|\Psi\rangle = P_{LLL} \prod (z_i - z_j)^2 (w_i - w_j)^2 \Psi(k_{F,T}, k_{F,B})$$

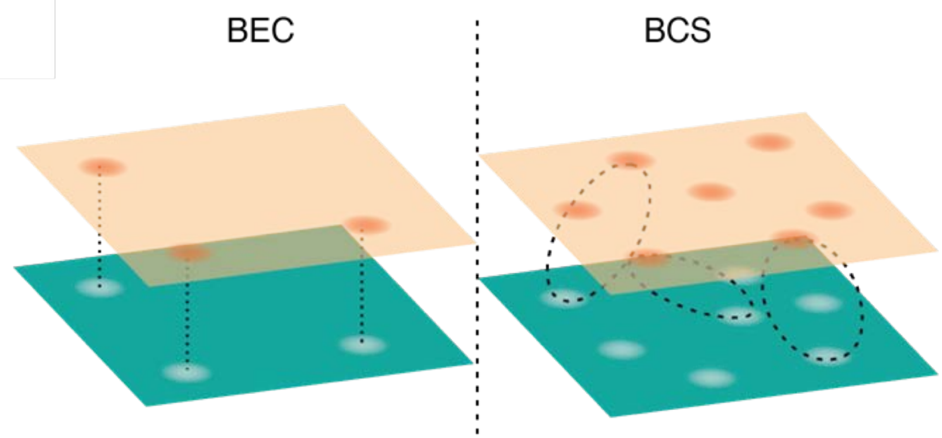
- $d \sim l_B$: many proposals

N. E. Bonesteel, et al., PRL 77, 3009 (1996)
J. Alicea, et al., PRL 103, 256403 (2009).
G. Moller, et al., PRB 79, 125106 (2009)

Potential BCS-BEC Crossover in Magnetoexciton Condensate

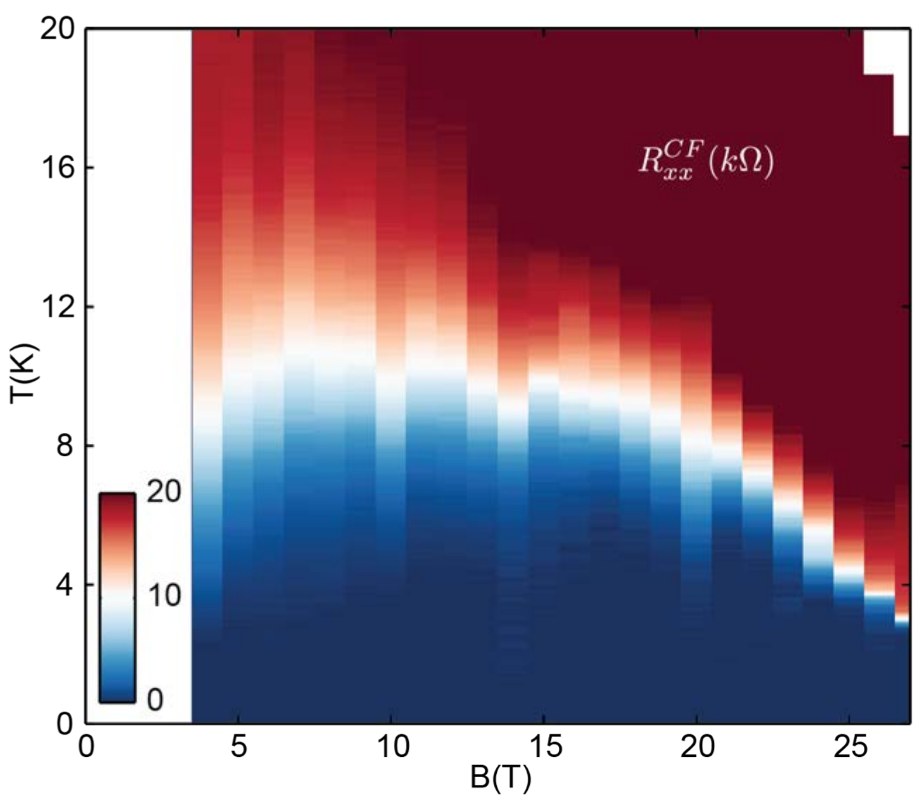
Xiaomeng Liu *et al*, unpublished (collaboration with Dean group)

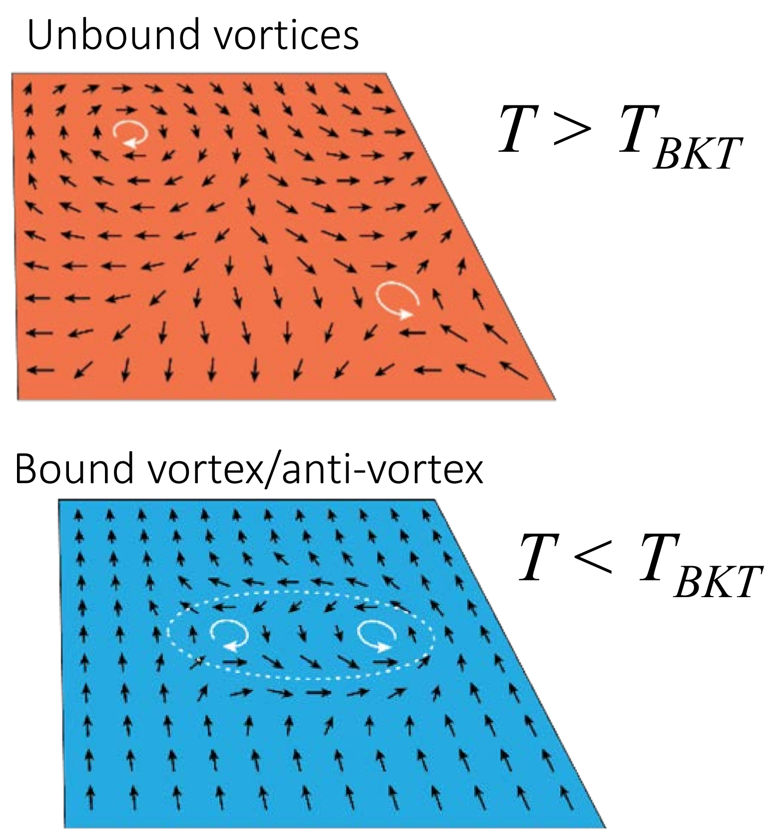
$d << l_B$ $d >> l_B$



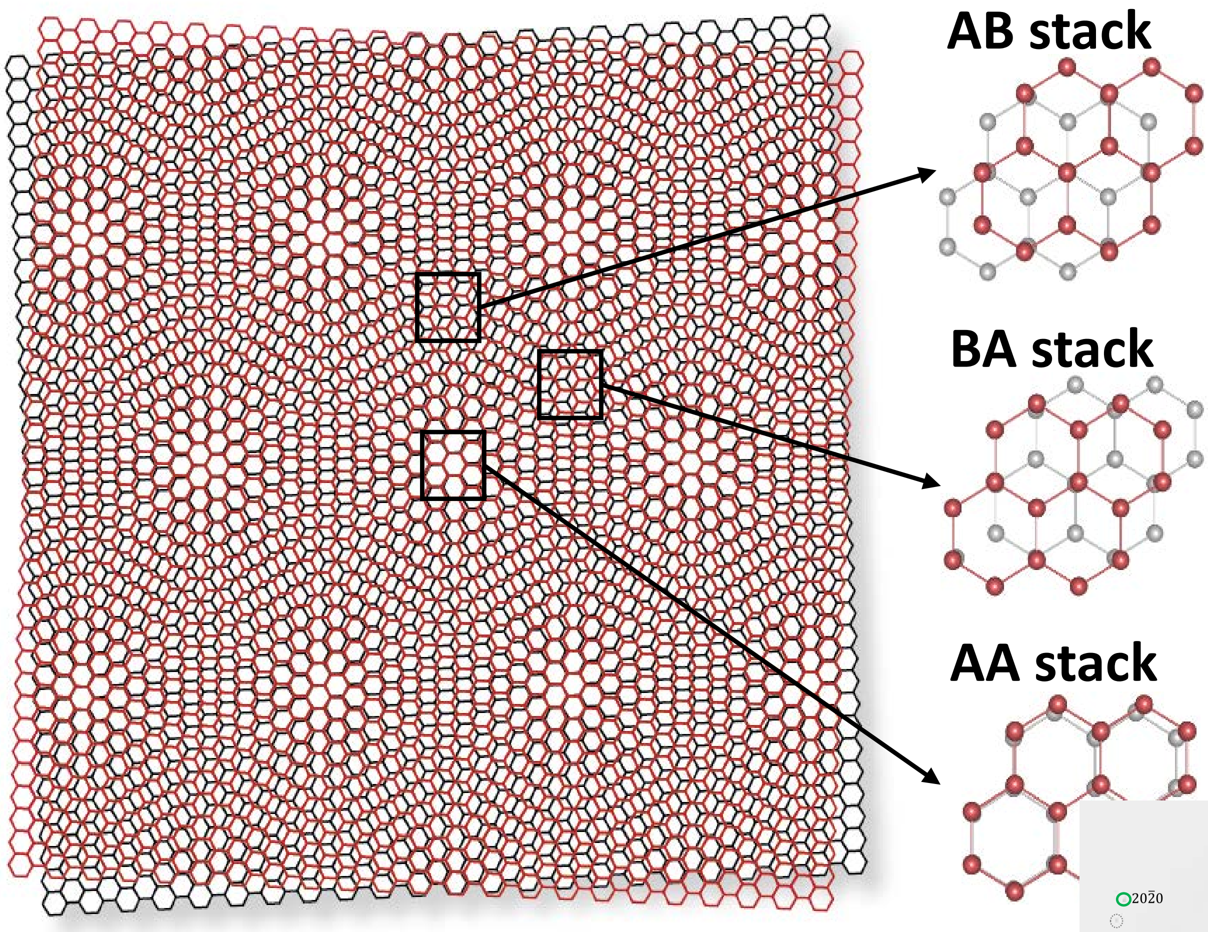
- What is the origin of activating behaviors?
  : merons/anti-meron activation (??)
- What is the nature of the "BCS" ground state?

N. E. Bonesteel, et al., PRL 77, 3009 (1996)
J. Alicea, et al., PRL 103, 256403 (2009).
G. Moller, et al., PRB 79, 125106 (2009)
…



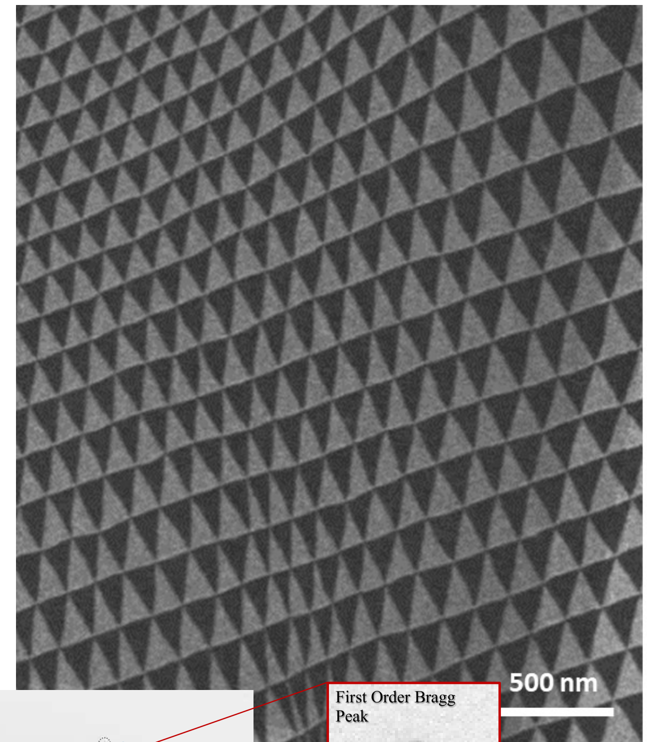


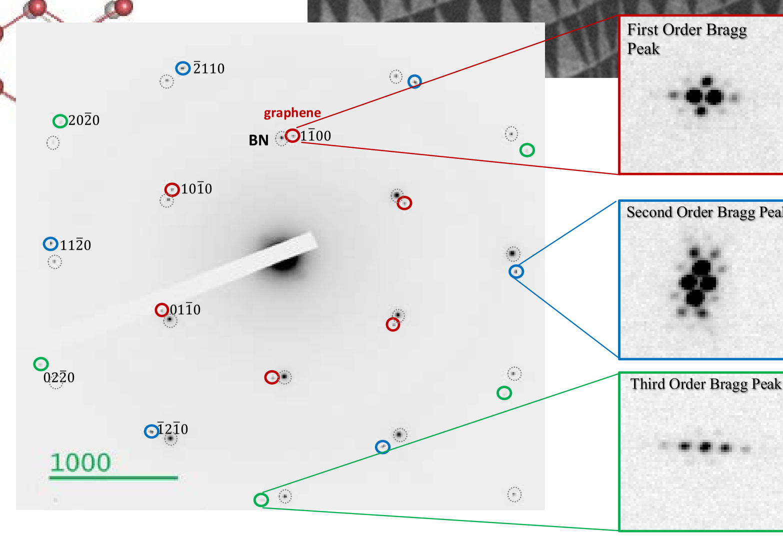
Twisted van der Waals Layer Stack



Moire Structure in Twisted Graphene on Graphene

Structural Reconstruction in Twisted Graphene on Graphene





H. Yoo, *et al.* arXiv:1804.03806

Correlated Quantum State in Twisted Graphene Bilayer

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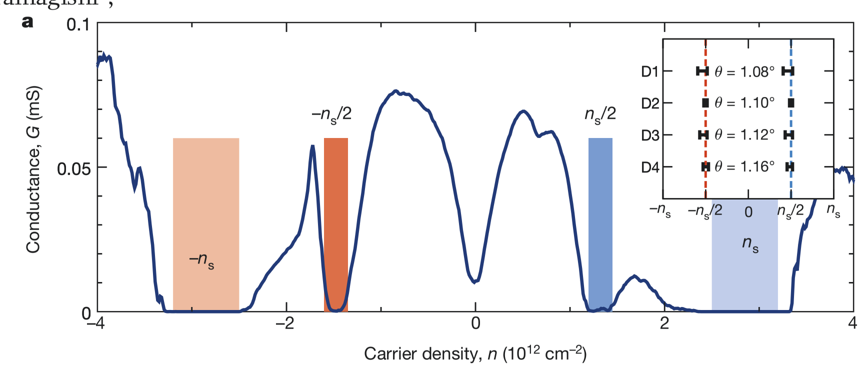
LETTER

doi:10.1038/nature26154

Correlated insulator behaviour at half-filling in magic-angle graphene superlattices

Yuan Cao[1], Valla Fatemi[1], Ahmet Demir[1], Shiang Fang[2], Spencer L. Tomarken[1], Jason Y. Luo[1], Javier D. Sanchez-Yamagishi[2], Kenji Watanabe[3], Takashi Taniguchi[3], Efthimios Kaxiras[2,4], Ray C. Ashoori[1] & Pablo Jarillo-Herrero[1]



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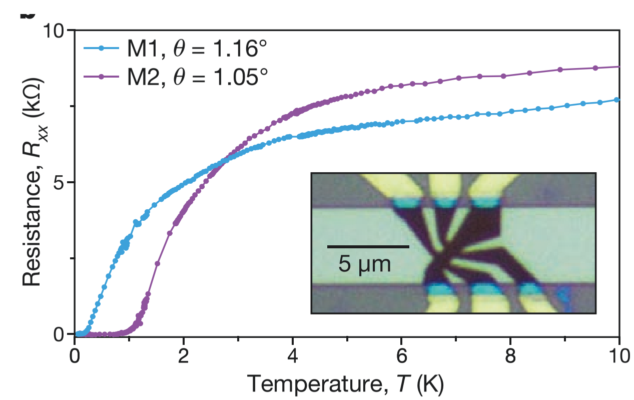
ARTICLE

doi:10.1038/nature26160

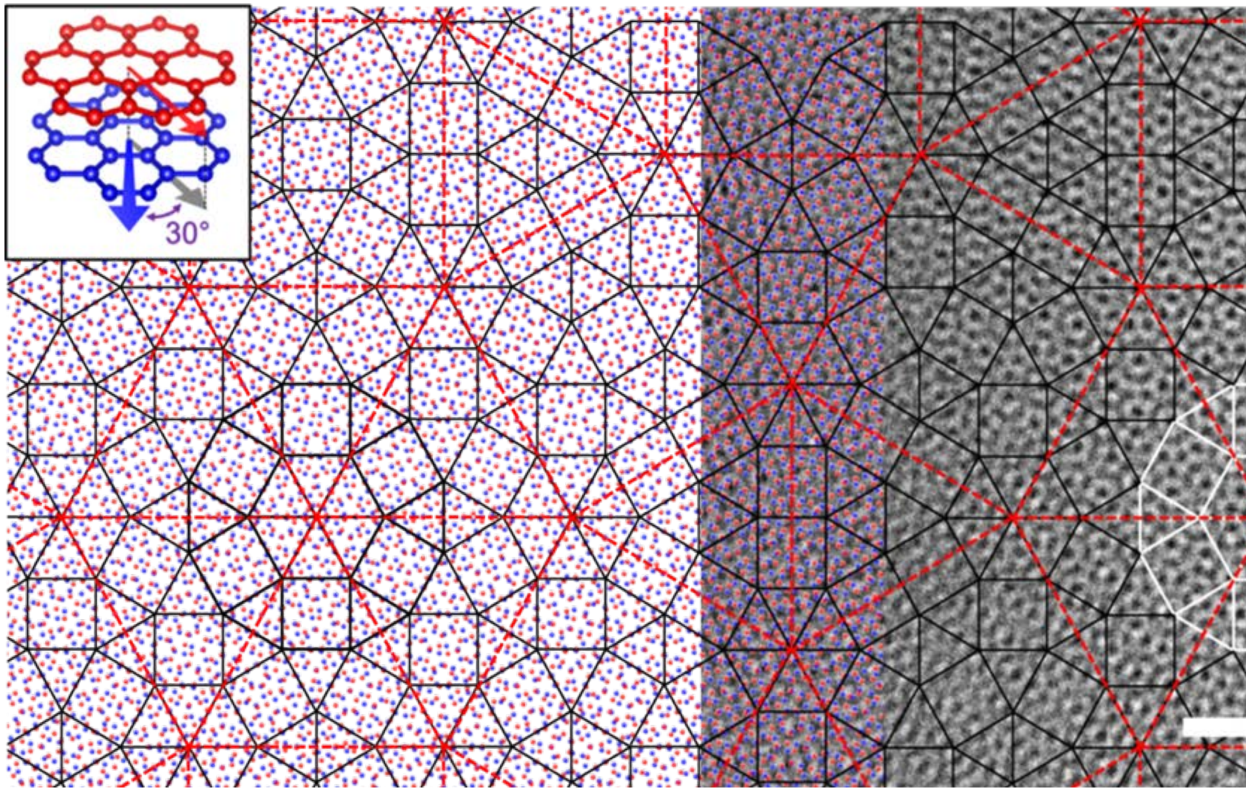
Unconventional superconductivity in magic-angle graphene superlattices

Yuan Cao[1], Valla Fatemi[1], Shiang Fang[2], Kenji Watanabe[3], Takashi Taniguchi[3], Efthimios Kaxiras[2,4] & Pablo Jarillo-Herrero[1]



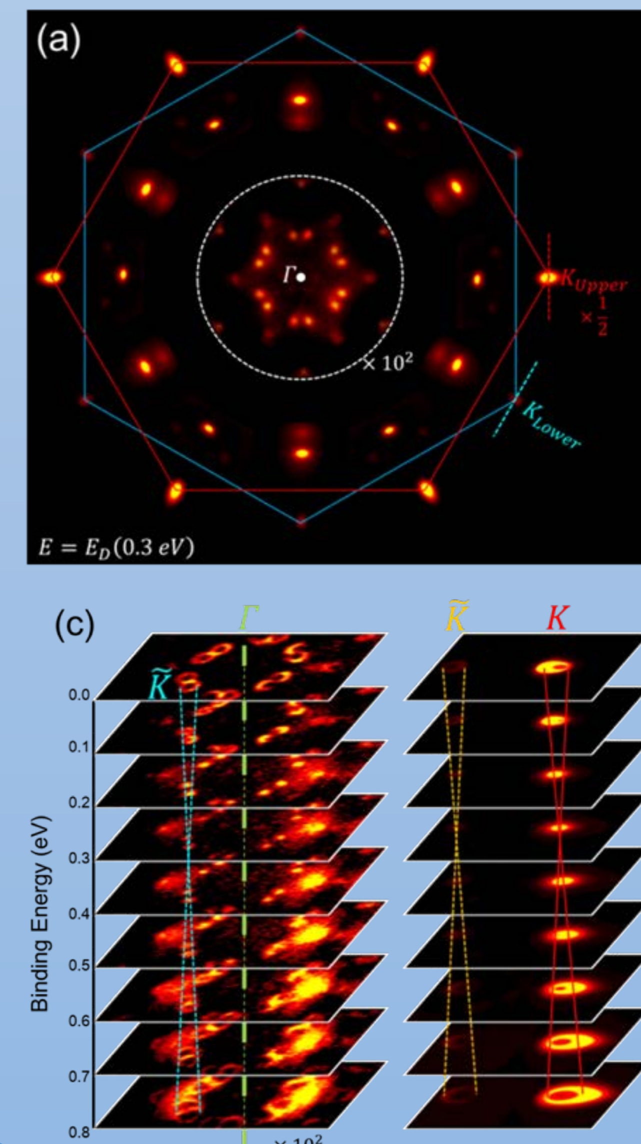
Quasi-Crystals in Twisted Graphene

30 degree misaligned bilayer graphene: 12 fold symmetry quasi crystal



S.J. Ahn *et al.*, Science in press (2018)

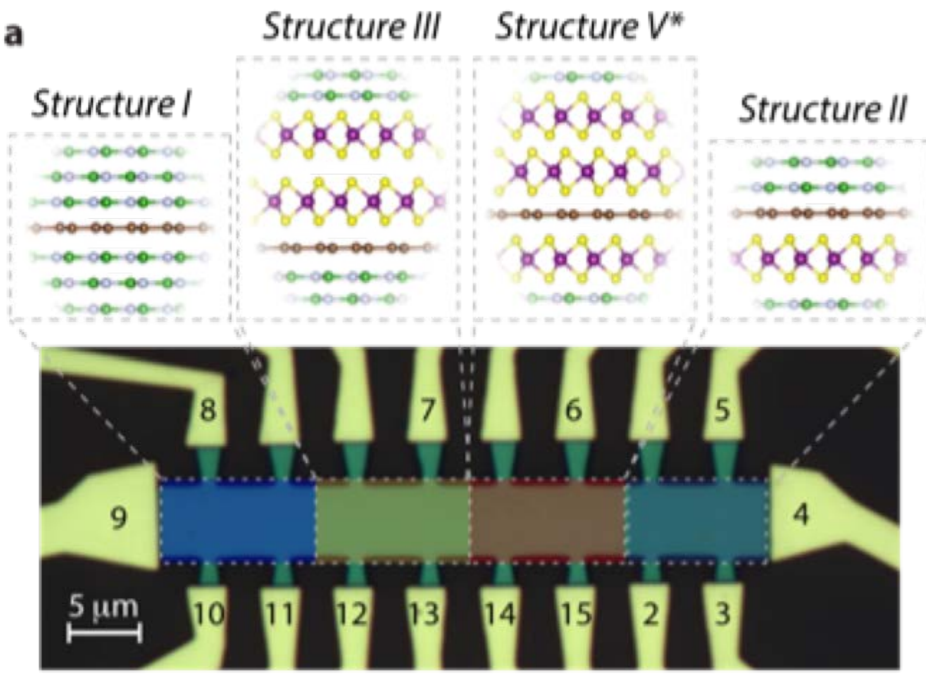
ARPES data on quasicrystals



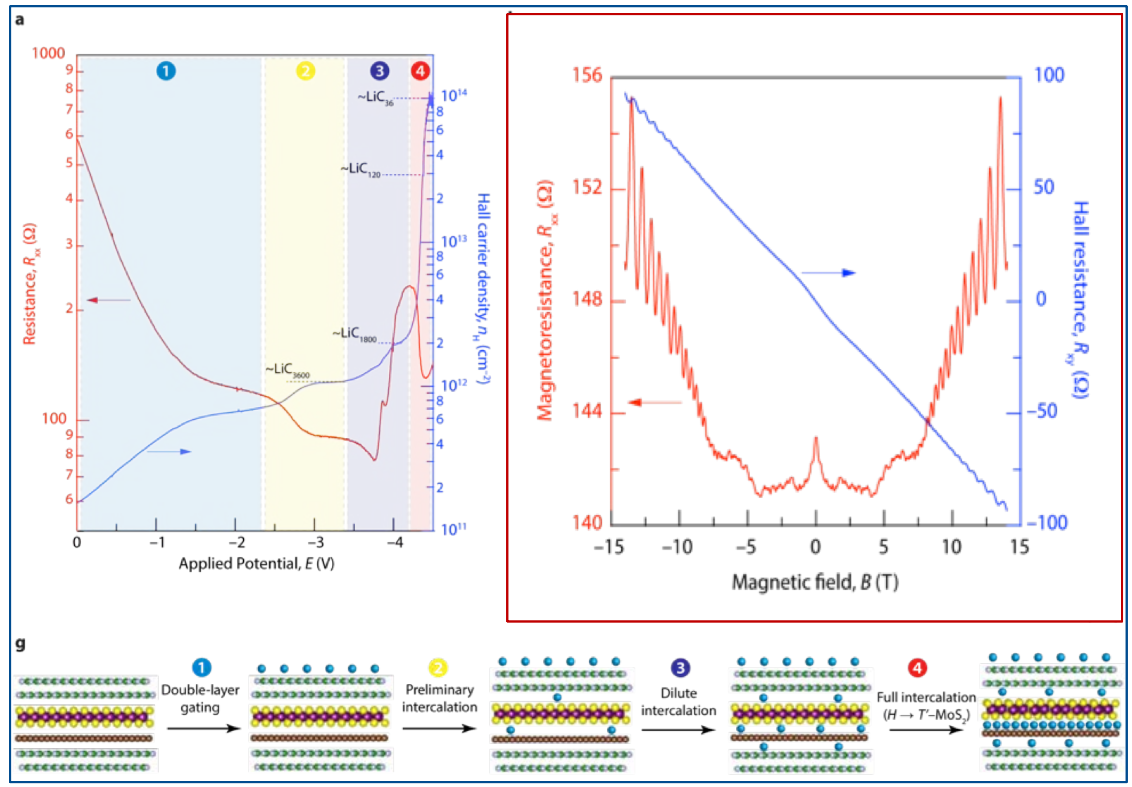
- **W2 Wed 5:30; Joung Real Ahn (experiment)**
- **W3 Wed 18:15; Pilkyung Moon (theory)**

Intercalation of Graphene/MoS_2 Heterolayer

D. K. Bediako *et al.*, Nature in press (2018)



Electrochemical devices deterministically stacked hBN/graphene/MoS2



Magnetotransport measurement:

- Intermediate intercalation of discrete heterointerfaces
- Charge transfer to individual layers

- **Next Keynote Speech by J. Smet**

Acknowledgement: Kim Group 2018

TMD Heterostructure : <u>Ke Wang</u>, K. De Greve, L. Jauregui, A. Joe, K. Pitsunova, D. , M. Lukin and H. Park

Magneto Excitons: <u>Xiaomeng Liu</u>, <u>Jia Li</u>, Cory Dean, Bertrand Halperin

Interlayer Excitons: <u>L. Jauregui</u>, A. Joe, K. Pitsunova, D. Wild, Y. Zhou, G. Scuri, A. High, M. Lukin and H. Park

vdW Intercalation: <u>K. Bediako</u>, <u>M. Rezaee</u>, <u>F. Zhao</u>, H. Yoo, D. Larson, T. Brower, E. Kaxiras

Funding

NSF · Office of Basic Energy Sciences · Army Research Office · Air Force Office of Scientific Research · Office of Naval Research · Gordon and Betty Moore Foundation · NRF National Research Foundation of Korea · Samsung