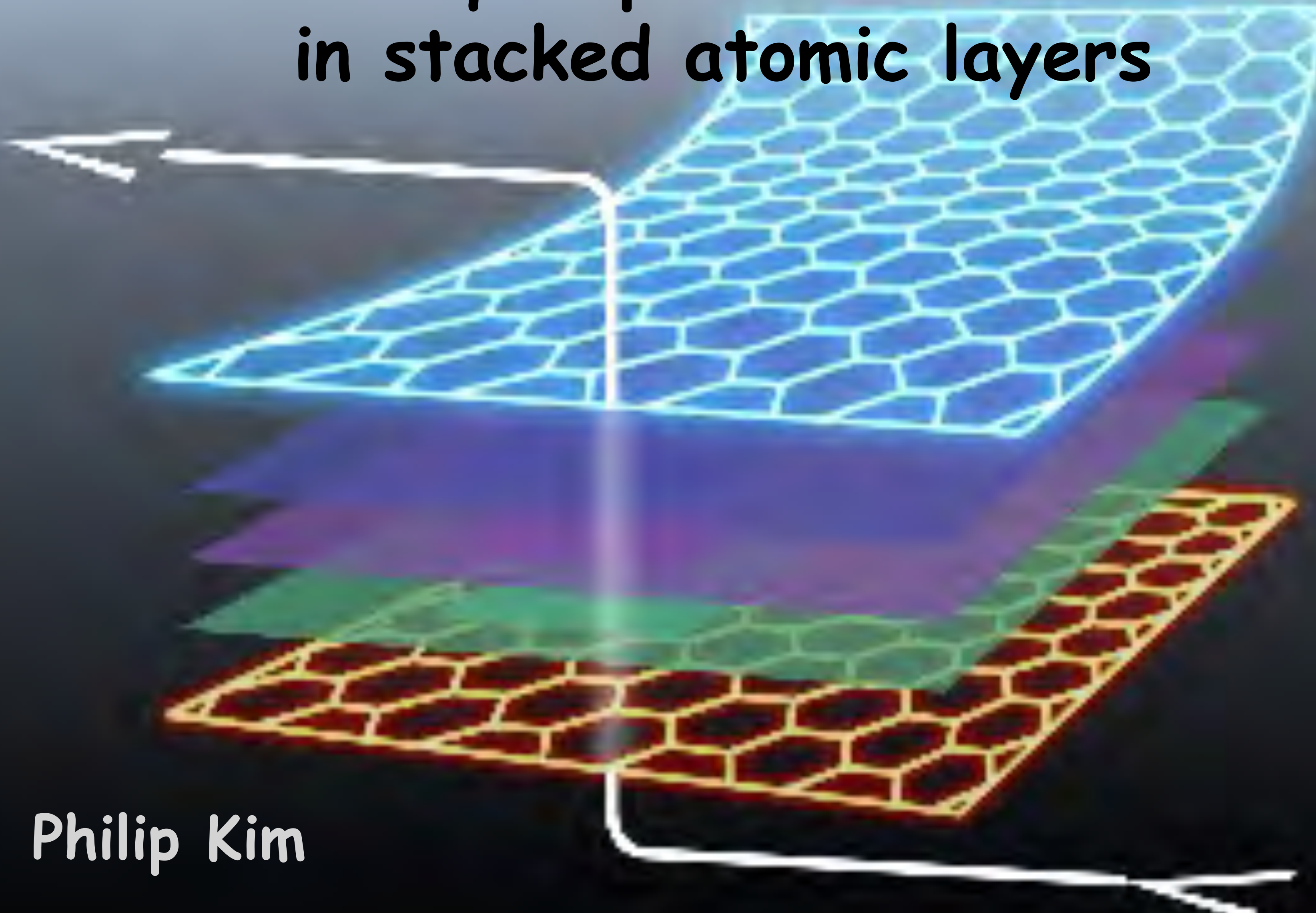
Unusual quasiparticle correlation in stacked atomic layers

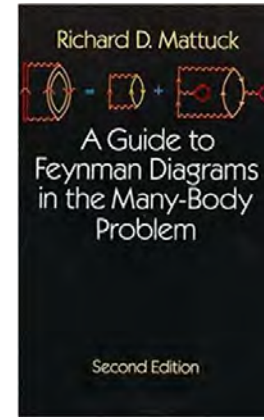


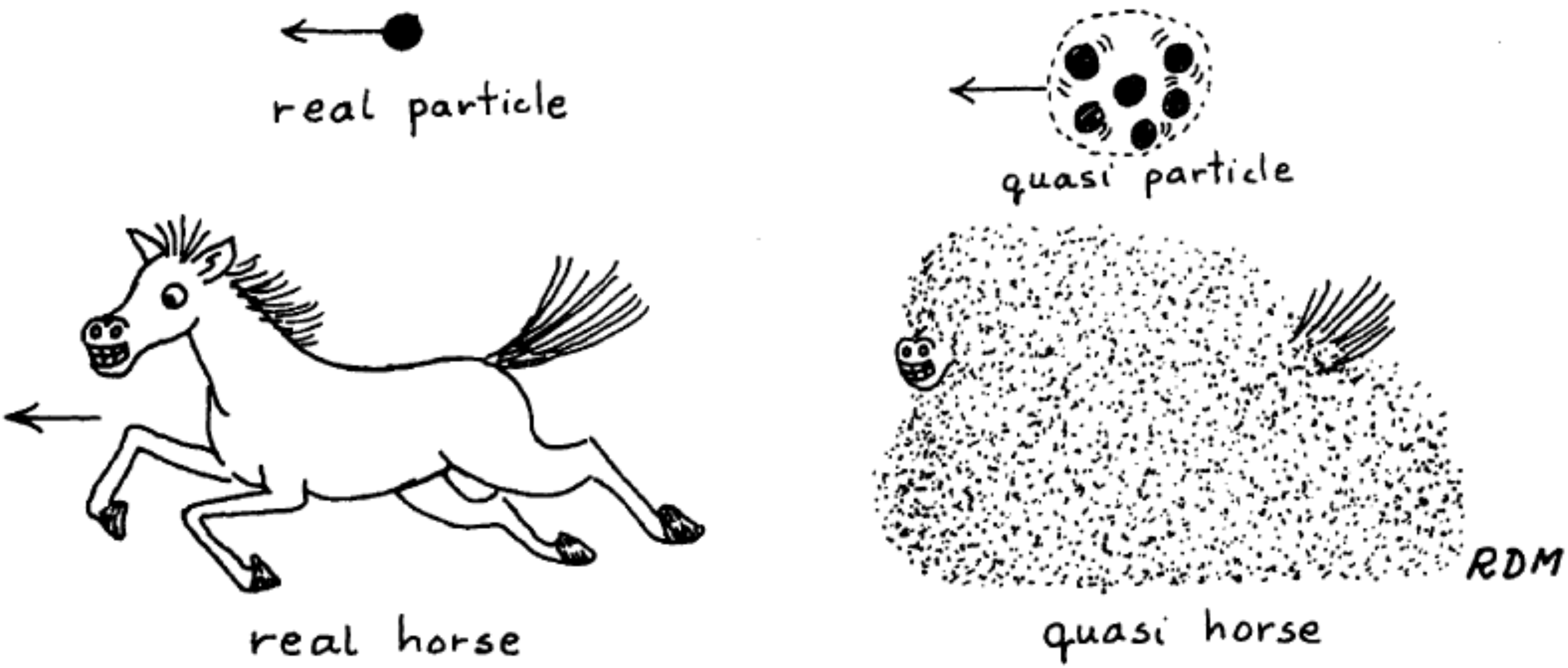
Philip Kim

Physics & Applied Physics, Harvard University

‘Real’ Particles and ‘Quasi’ Particles

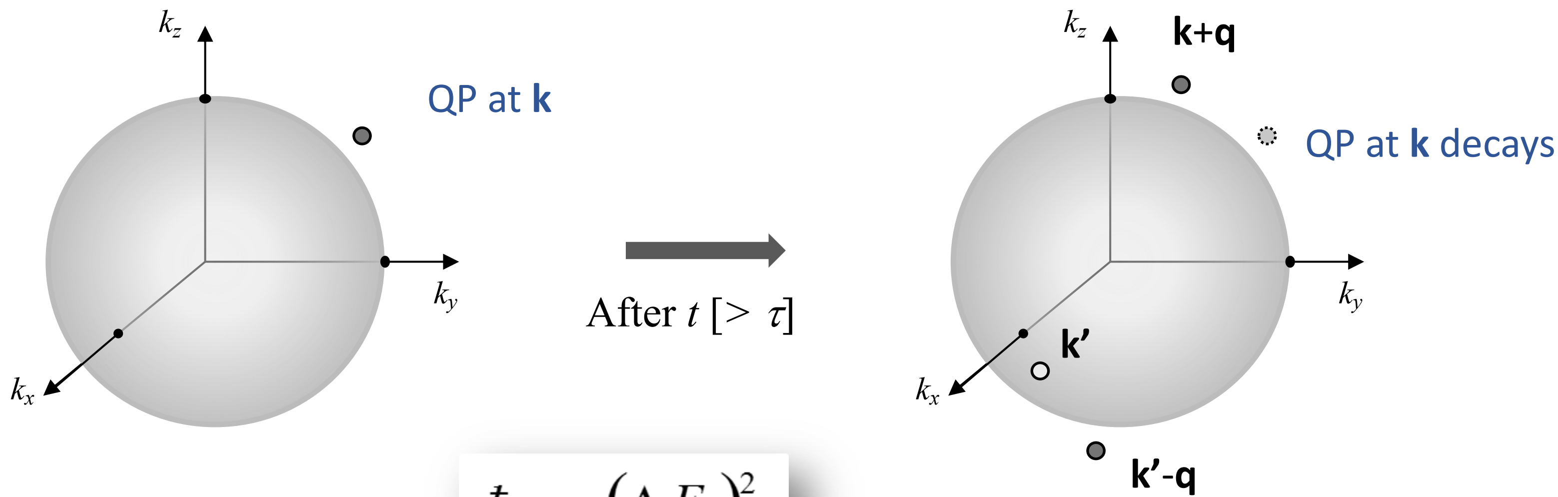
R. Mattuck, "A guide to Feynman diagrams in the many-body problem"





Landau Theory of Fermi Liquid

L. D. Landau (1957).



$$\frac{\hbar}{\tau} \sim \frac{(\Delta E)^2}{E_F}$$

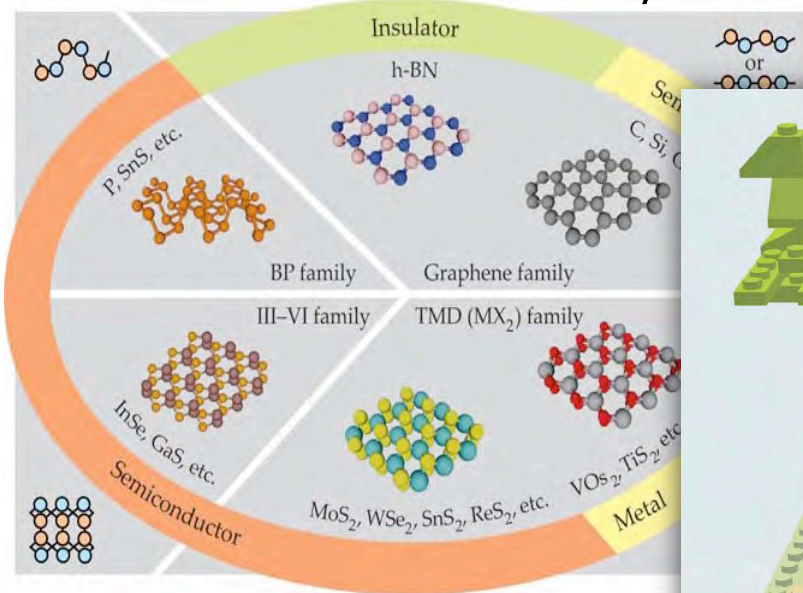
Fermi liquid: Weakly interacting quasiparticles

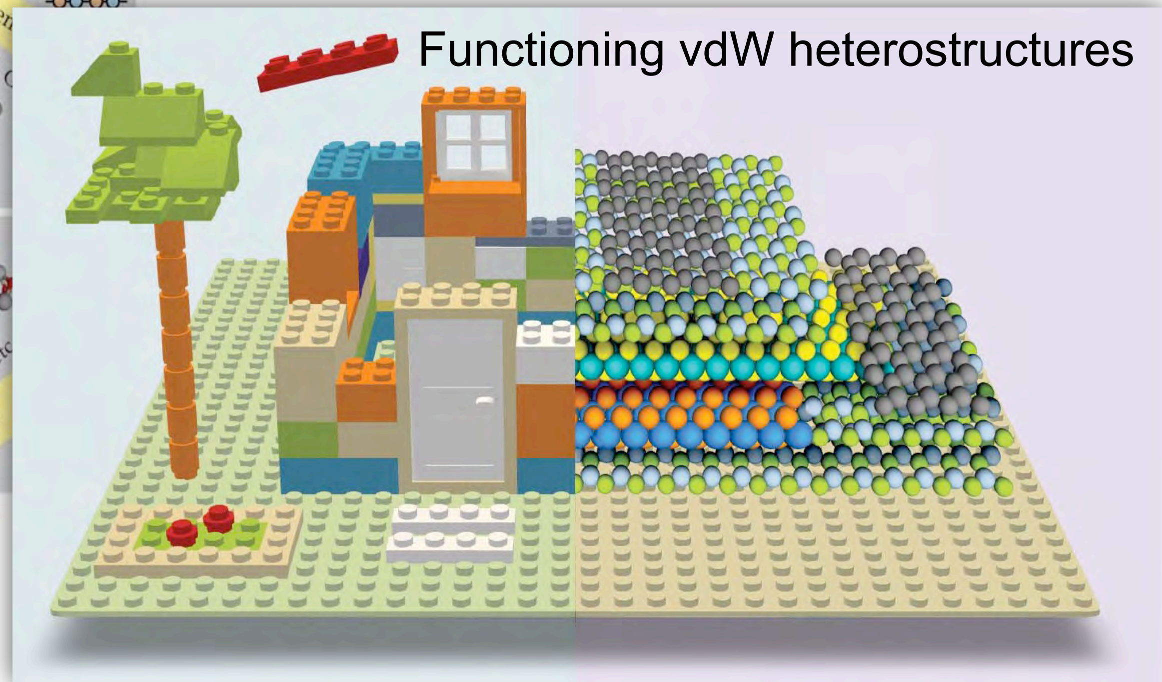
Non-Fermi liquid: Luttinger liquid (1D),
Strongly correlated system near the quantum criticality,
. . .

Assembling van der Waals Materials

2D van der Waals Materials Family

Ajayan, Kim and Banerjee, Physics Today (2016)

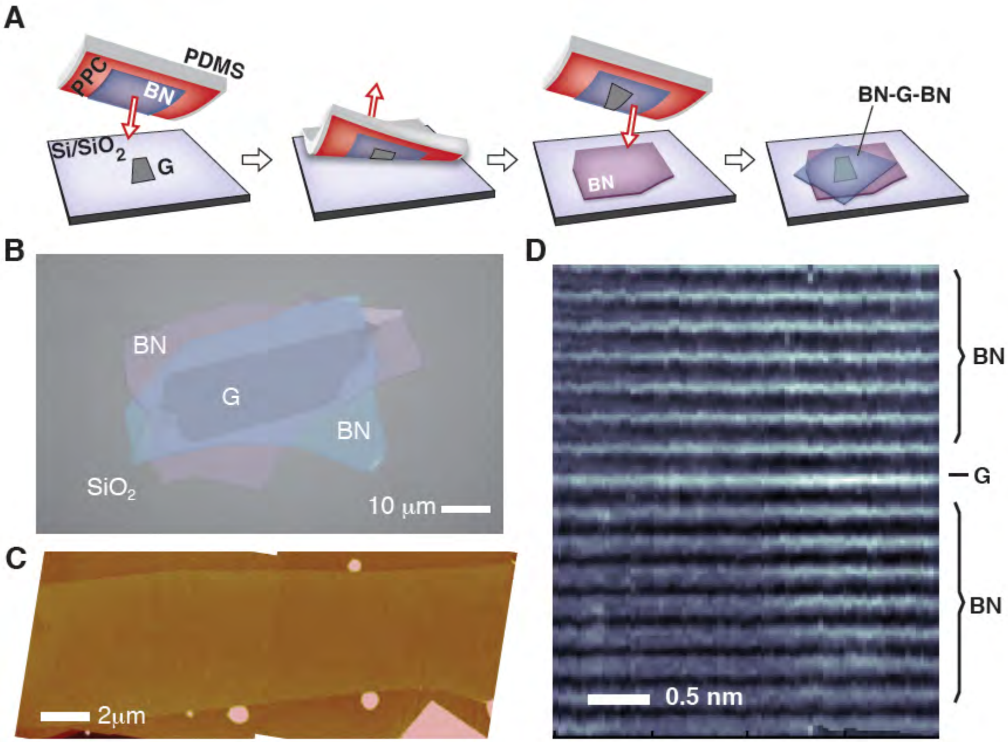




vdW Materials (partial list)

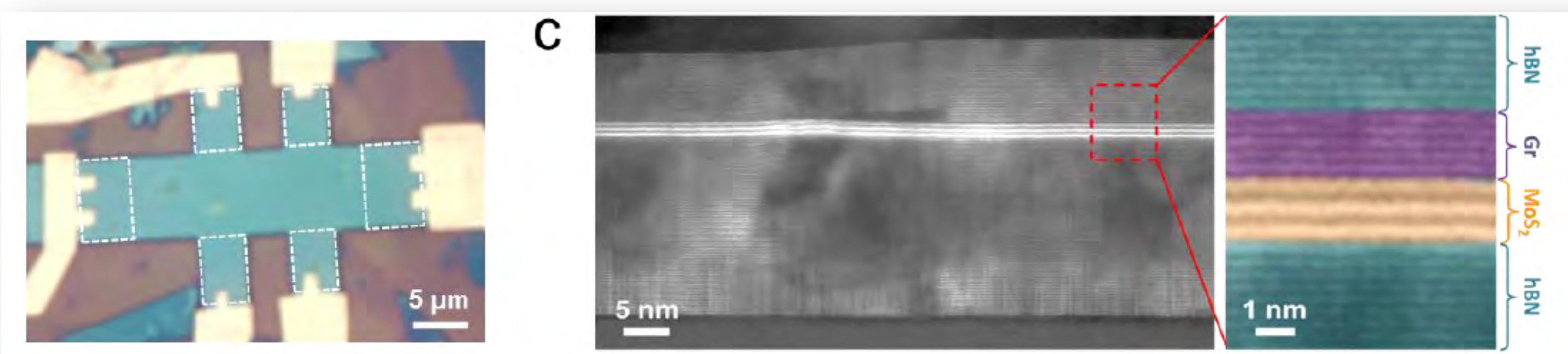
- Semiconducting materials: WSe_2, $MoSe_2$, MoS_2, WS_2, BP…
- Complex-metallic compounds : $TaSe_2$, TaS_2, …
- Magnetic materials: Fe-TaS_2, $CrSiTe_3$, CrI_3…
- Superconducting: $NbSe_2$, $Bi_2Sr_2CaCu_2O_{8-x}$,…
- Topological Insulator/Wyle SM: Bi_2Se_3, $MoTe_2$

Atomic Layer-by-Layer Stacking Up of VdW Materials



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

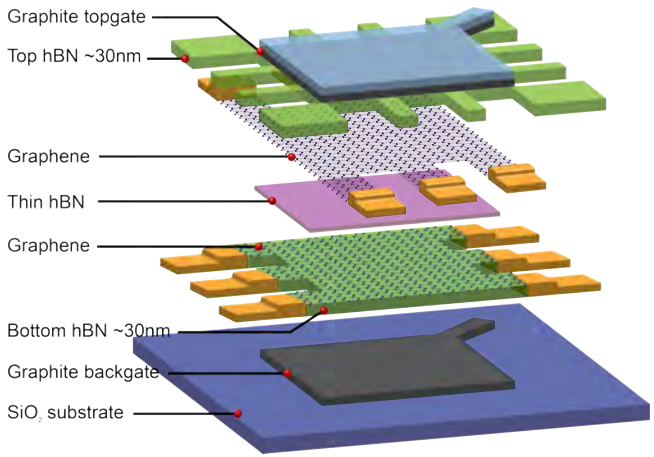
- Creation of multilayer systems with co-lamination techniques
- Encapsulated graphene in hBN
- Completely ballistic at low temperature

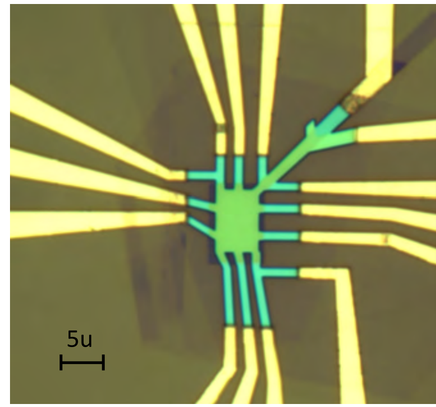


Xu *et.al.*, Nature Nano (2015) (Hone group collaboration)

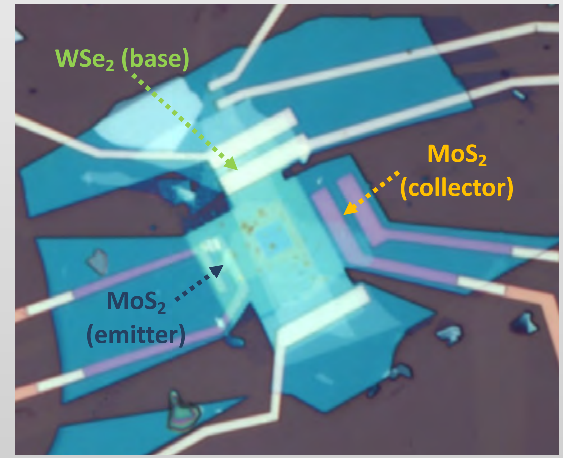
vdW Heterostructure Devices

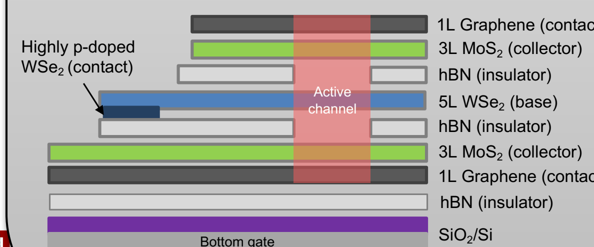
Coulomb Drag in Graphene



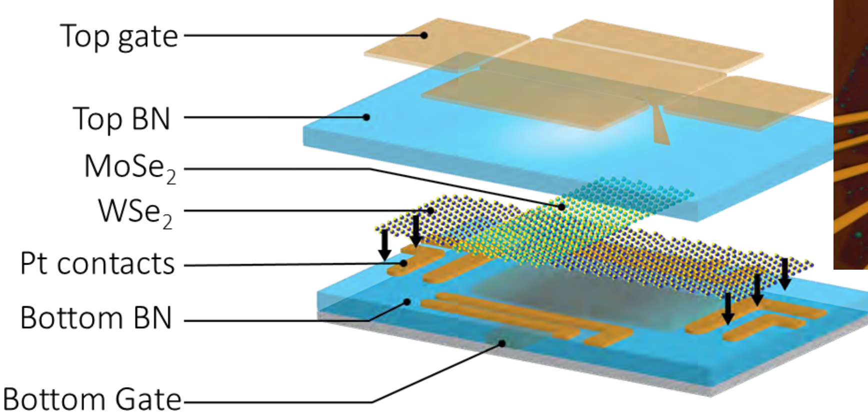


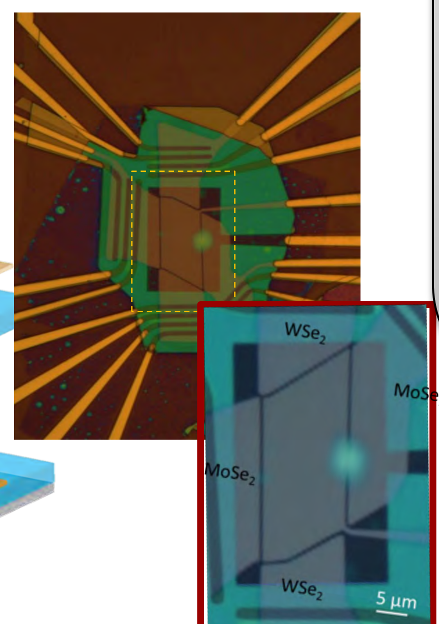
vdW Bipolar Transistor





WSe2/MoSe2 Optoelectric Device





Van der Waal Heterostructures

	Graphene	hBN	MoS_2	WSe_2	$NbSe_2$	TaS_2	$Cr_2Ge_2Te_6$	Bi_2Se_3
Graphene (semimetal)	Twisted stacking ○	Hofstadter Butterfly; tunneling	Schottky diode	Schottky diode	Andreev reflection	Super lattice potential	Magnetic insulating	Contacting surface states
hBN (insulator)	○	Twisted stacking ○	Encapsulation	Encapsulation	Encapsulation, tunneling	Encapsulating, tunneling	Control exchange interaction	Encapsulating, tunneling
MoS_2 (n-semicond)	○	○	Twisted stacking ○	Atomic pn junction	Supercond /Semicond juntion	Super lattice modulation	Magnetic semiconductor	Valley tronics
WSe_2 (p-semicond)	○	△	○	Twisted stacking △	Supercond /Semicond juntion	Super lattice modulation	Magnetic semiconductor	Valley tronics
$NbSe_2$ (supercond.)	○	○	□	□	Josephson coupling □	Competing order parameters	Triplet superconductor	Majorana
TaS_2 (CDW)	△	○	□	□	□	C-axis CDW orders □	Competing order parameters	Super lattice modulation
$Cr_2Ge_2Te_6$ (magnetic)	○	□	□	□	□	□	C-axis magnetic orders □	Creating gap in TI surface
Bi_2Se_3 (T. I.)	△	○	□	□	□	□	□	Annihilation of TI surface states □

○ performed △ in-progress □ Planned

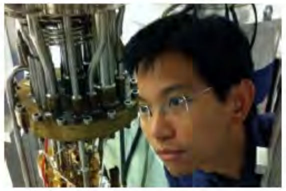
~ 5 years ago

Outline

- Electron and hole interaction near the Dirac point:
  Dirac Fluid in graphene
- Electron and hole correlation across the vdW interface:
  Long lived interlayer excitons
- Electron and hole correlation across the Landau levels:
  Magnetoexciton condensation in Quantum Hall bilayer
- Feromagnetic Superconductors in Flat bands:
  Twisted Double Bilayers
- Electron and hole correlation by superconducting proximitized quantum Hall edge: Crossed Andreev reflection

Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene

Jess Crossno



Kin Chung Fong

J. Crossno, J. K. Shi, K. Wang, X. Liu, A. Harzheim, A. Lucas, S. Sachdev, P. Kim, T. Taniguchi, K. Watanabe, T. A. Ohki, K. C. Fong *Science* ***351****, 1058-1061 (2016).*

Jing K. Shi

Ke Wang

Achim Harzheim

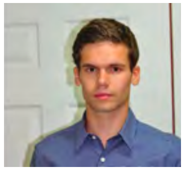
Thomas Ohki

Andrew Lucas

Subir Sachdev

T. Taniguchi, K. Watanabe

Jonah Waissman



Artem Talanov

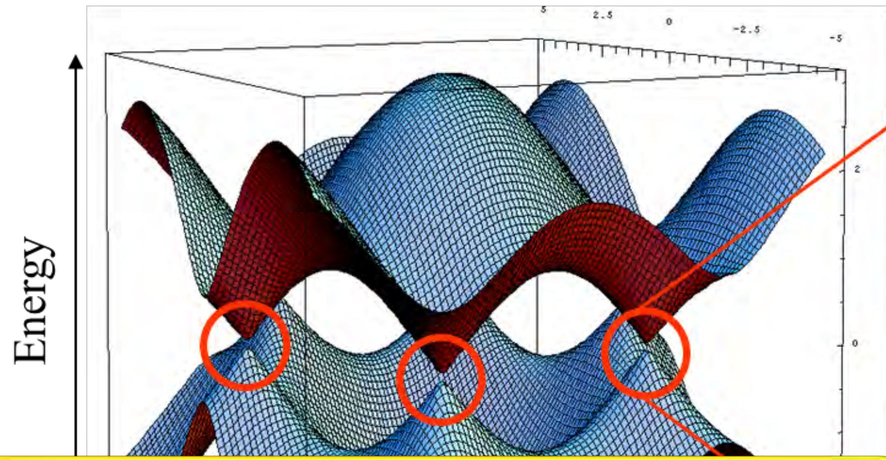
Zhonging Yan

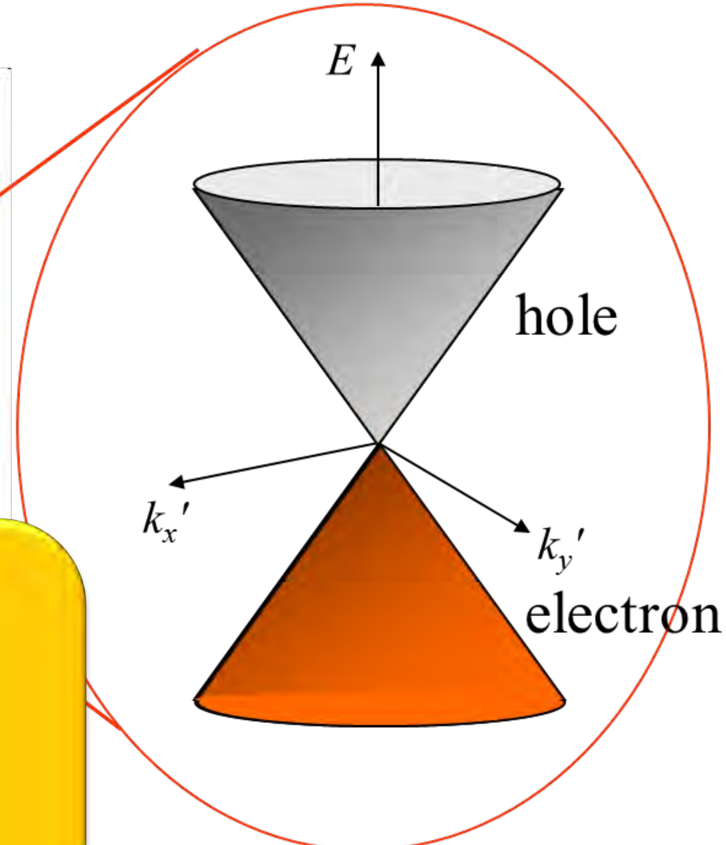
Sang-Jin Sin

Matt Forster

Dirac Point in Graphene

Band structure of graphene (Wallace 1947)





$$E \approx \hbar v_F \left| \vec{k}'_\perp \right|$$

Physics at Dirac Point

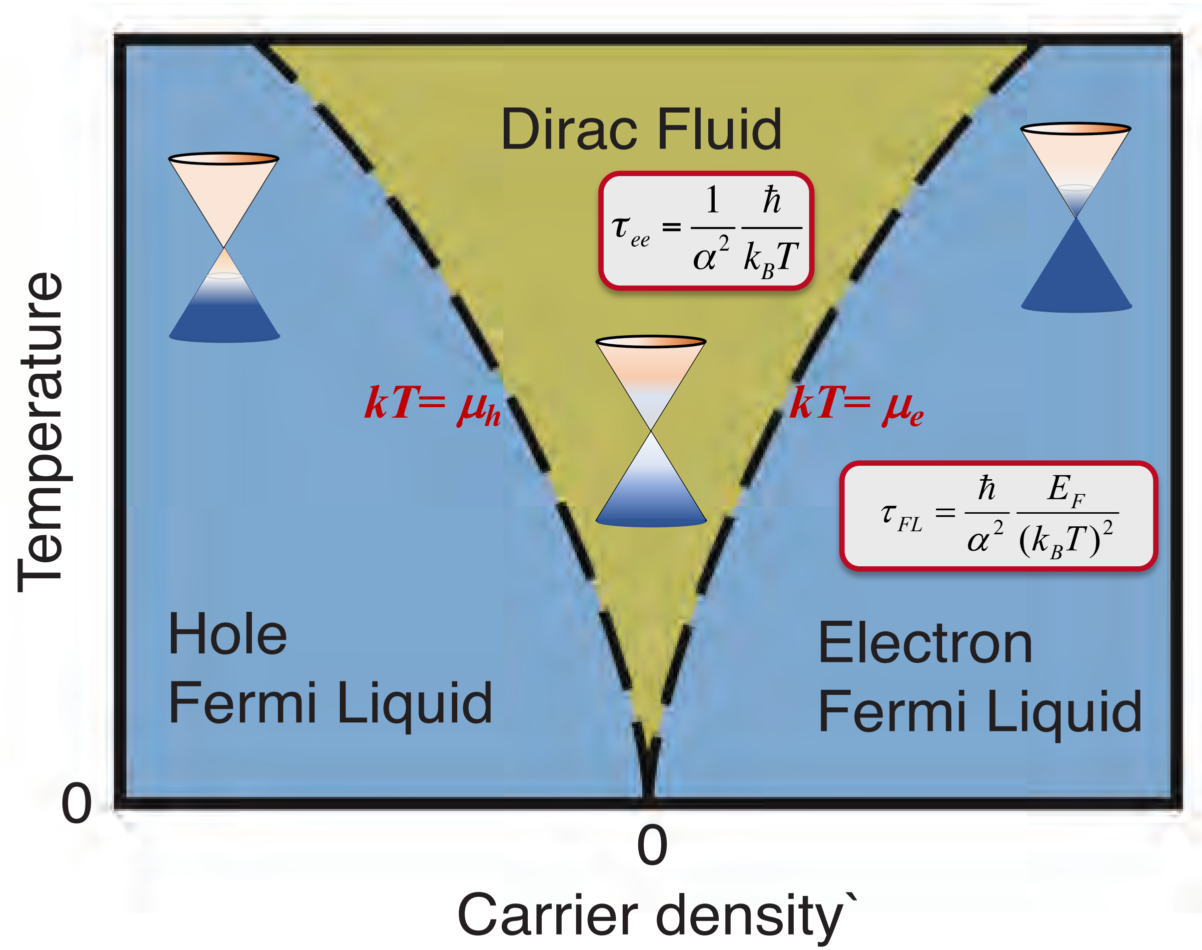
- Symmetry protected degeneracy
- Charge Neutral
- Strong electro-electron interaction
- Quantum Criticality

Ze… speed v_F

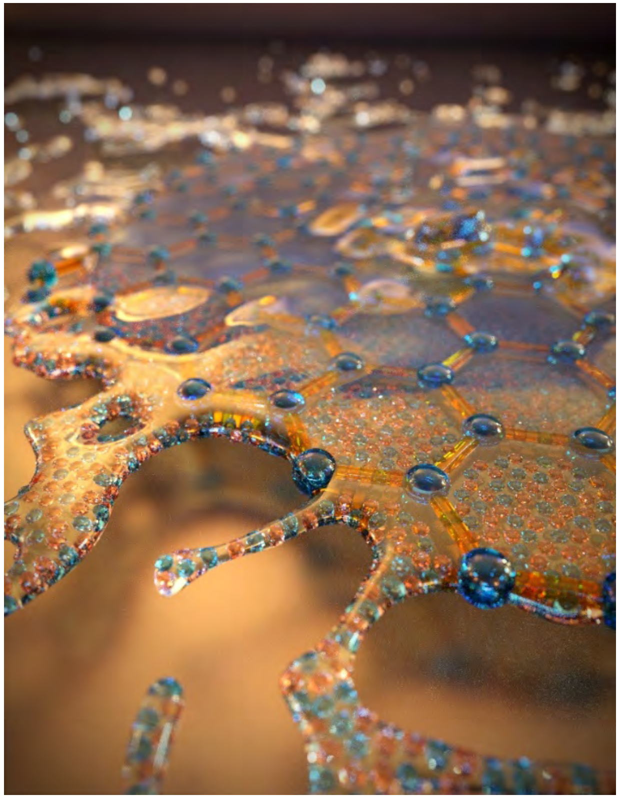
Effective Fine Structure Constant $\alpha = \dfrac{e^2}{\varepsilon_r \hbar v_F} \sim 1$

Effective Dirac Hamiltonian: $H_{eff} = \pm \hbar v_F \vec{\sigma} \cdot \vec{k}_\perp$

Hydrodynamic Transport in Dirac Point in Graphene



Sheehy and Schmalian, PRL 99, 226803 (2007)
Fritz, Schmalian, Muller, and Sachdev, PRB (2008).
Mueller, Fritz, and Sachdev, PRB (2008).
Foster and Aleiner, PRL (2009).
Mueller, Schmalian, Fritz, PRL (2009)

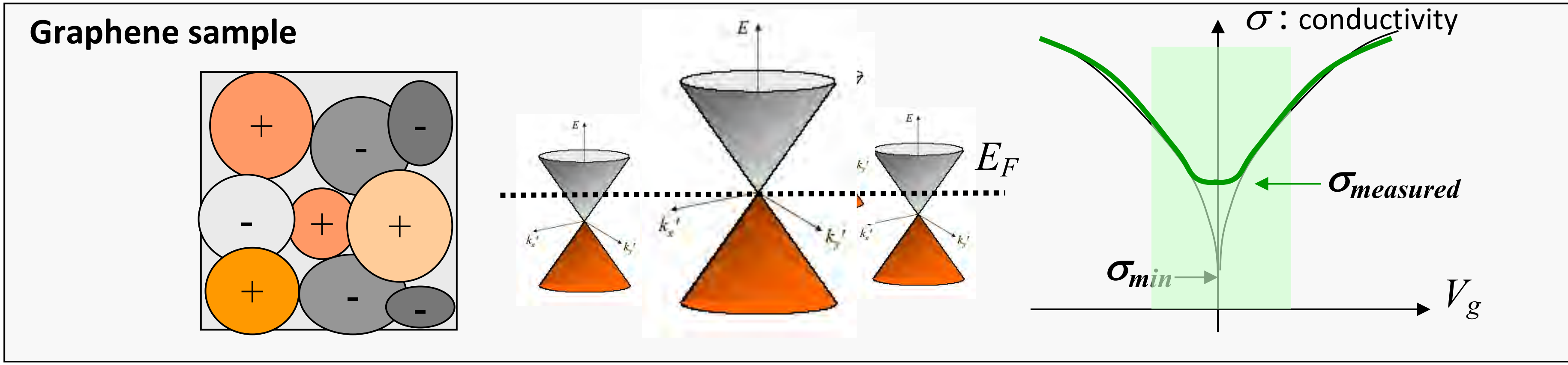


Condition of hydrodynamic description:

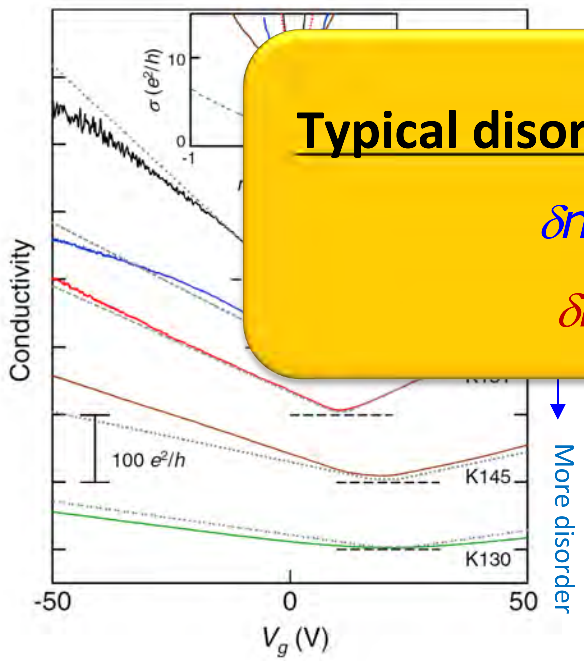
$$\tau_{ee} << \tau_{imp}$$

Dirac Fluid at the CNP of graphene

Disorder and Charge Puddles Near the Neutrality

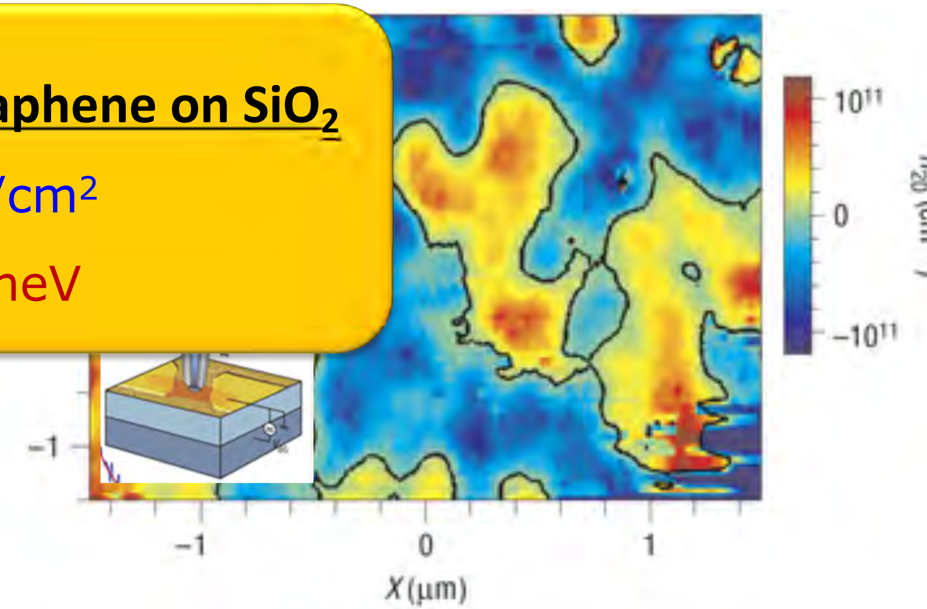


Conductivity of Graphene on SiO_2 Substrate



Tan et al., PRL (2008)

Potential Mapping by Scanning Single Electron Transistor



Martin *et al.*, Nature Physics 4, 144 (2008)

Typical disorder in graphene on SiO_2

$\delta n \sim 10^{11}$ /cm^2

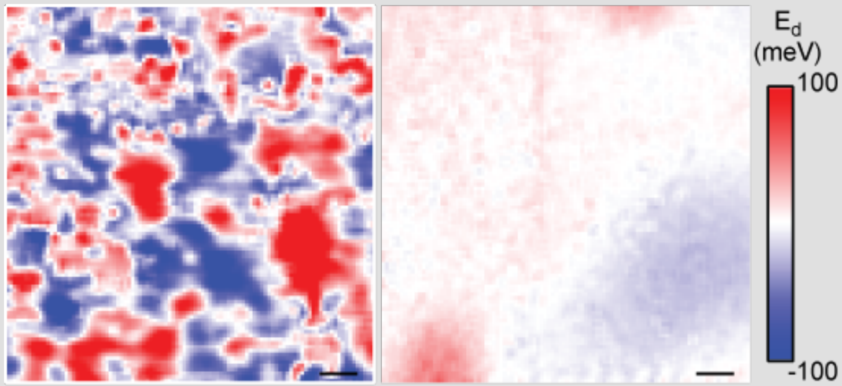
$\delta E_f \sim 40$ meV

Stacking graphene on hBN

Dean et al. Nature Nano (2009)

Hone, Kim and Shepard groups collaboration

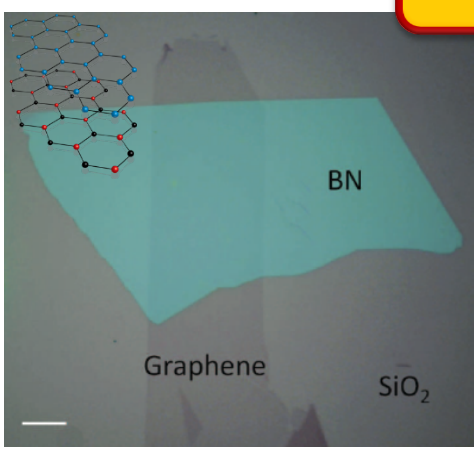
Potential Fluctuation Measured by STM

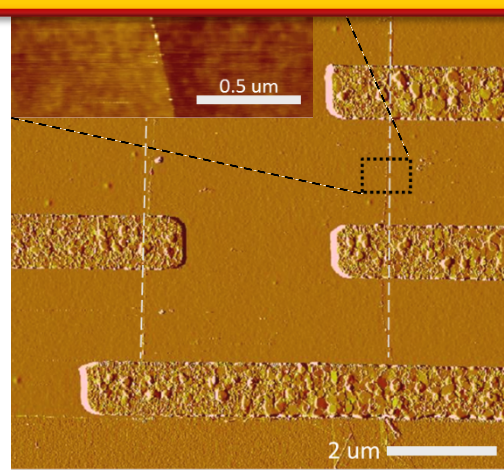


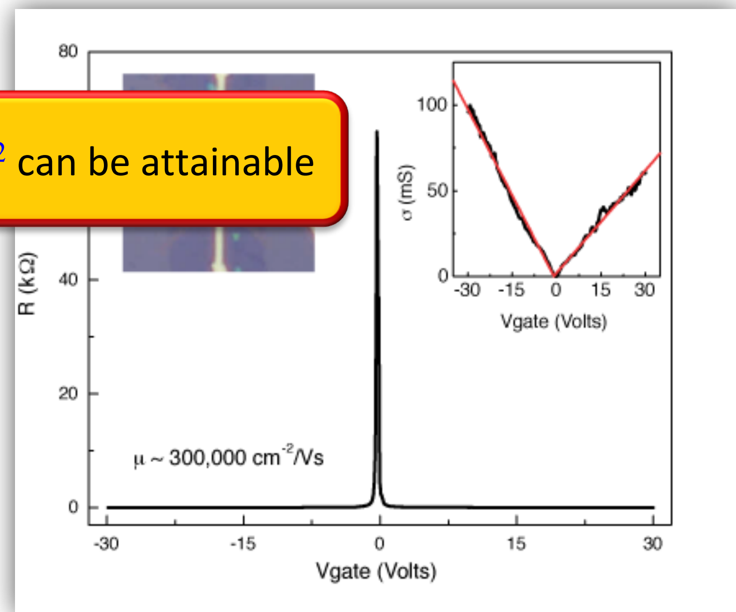
J. Xue *et al*. Nature Materials 10, 282 (2011)

- Co-lamination techniques
- Submicron size precision
- Atomically smooth interface

Density fluctuation: $\delta n < 10^{10}\ /\mathrm{cm}^2$ can be attainable



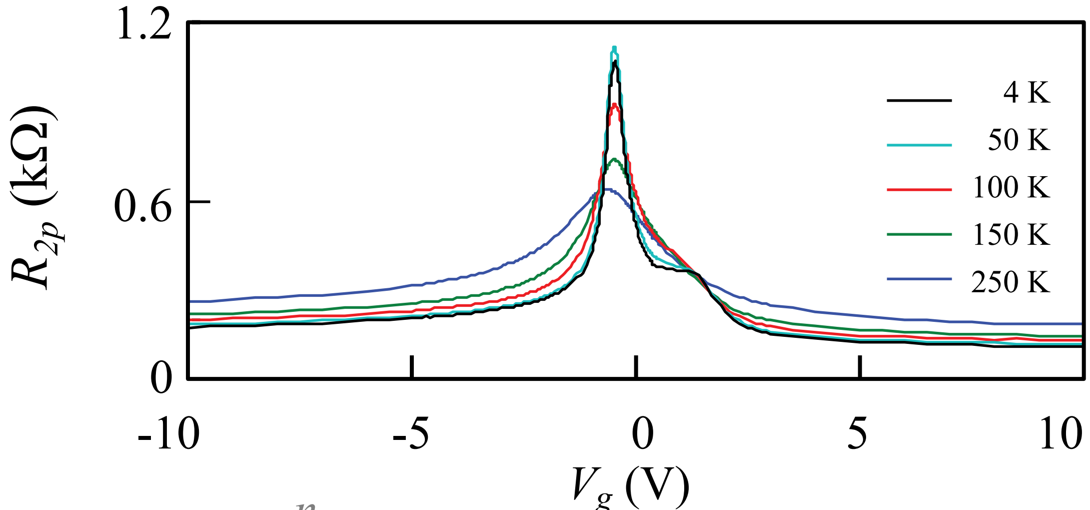




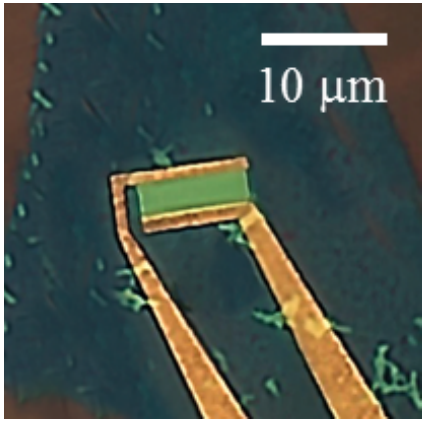
LT Mobility : ~1,000,000 $cm^2V^{-1}s^{-1}$

RT Mobility : ~100,000 $cm^2V^{-1}s^{-1}$

Non-Degenerate Electron Gas at Dirac Point

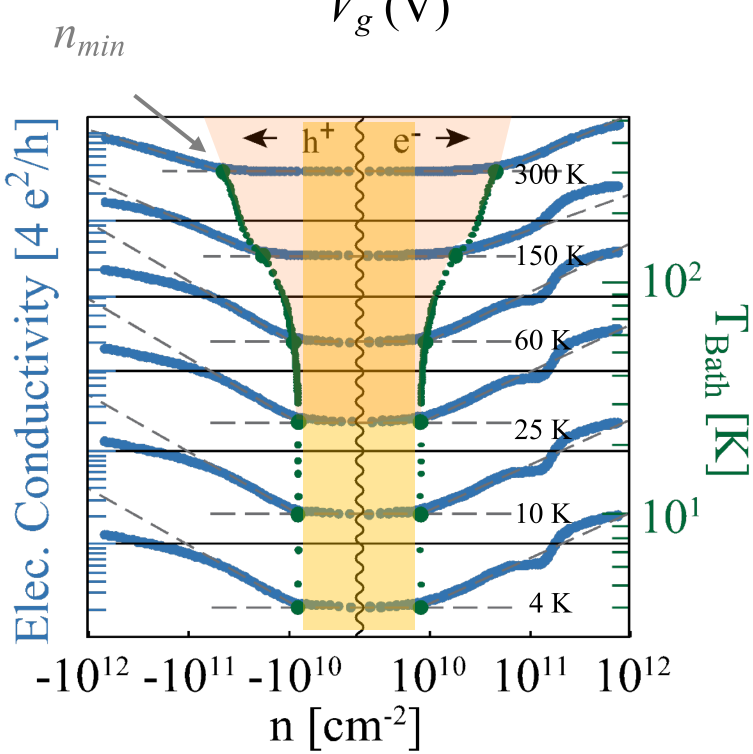


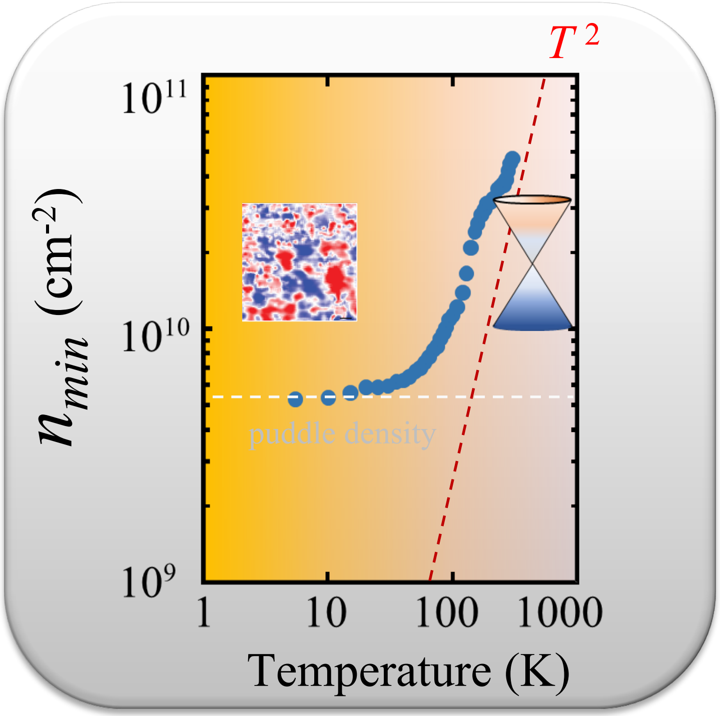
hBN encapsulated single layer graphene



Thermal broadening

Disorder broadening





Wiedemann Franz Law in Fermi Liquid

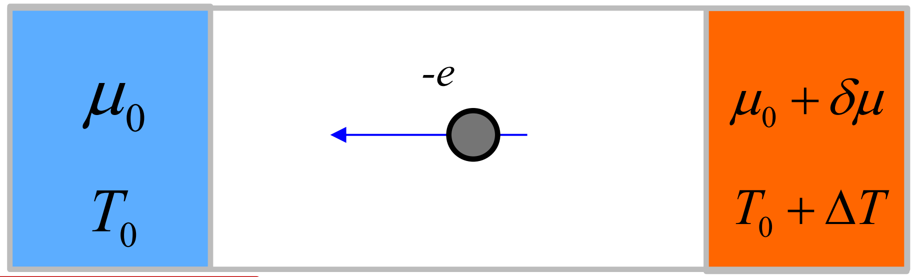
Thermal conductivity
versus electrical conductivity

$$\frac{\kappa}{\sigma T} = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 = L_0$$: Sommerfeld value

Relaxation of charge current and heat current

$$j = -en_e \langle v_e \rangle$$

$$j_Q = u_e n_e \langle v_e \rangle$$

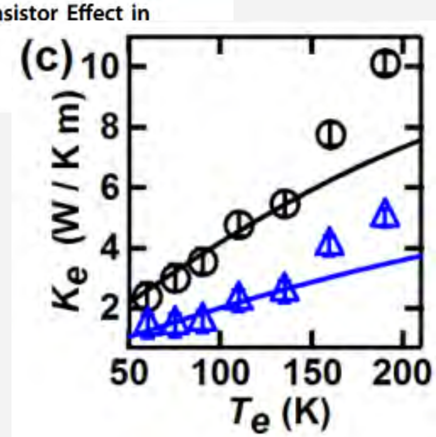


Works well for graphene in the degenerate limit…

NANO LETTERS
Letter
pubs.acs.org/NanoLett

Wiedemann–Franz Relation and Thermal-Transistor Effect in Suspended Graphene

S. Yiğen and A. R. Champagne*
Department of Physics, Concordia University, Montréal, Québec, H4B 1R6 Canada

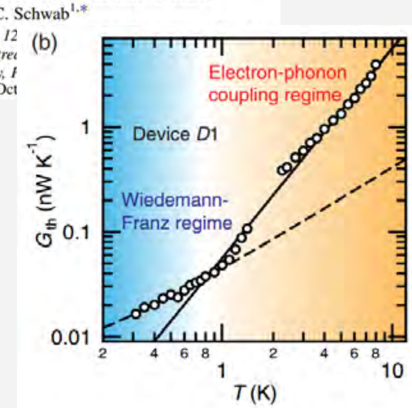


PHYSICAL REVIEW X 3, 041008 (2013)

Measurement of the Electronic Thermal Conductance Channels and Heat Capacity of Graphene at Low Temperature

Kin Chung Fong,[1] Emma E. Wollman,[1] Harish Ravi,[1] Wei Chen,[2] Aashish A. Clerk,[2] M. D. Shaw,[3] H. G. Leduc,[3] and K. C. Schwab[1,*]
[1]Kavli Nanoscience Institute, California Institute of Technology, MC 12
[2]Department of Physics, McGill University, Montre
[3]Jet Propulsion Laboratory, California Institute of Technology, P

(Received 29 June 2013; published 29 Oct



Wiedenmann Franz in Non Fermi Liquid

ARTICLE

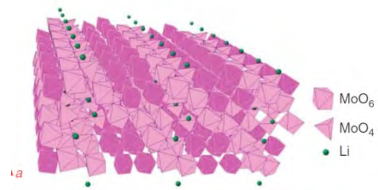
NATURE COMMUNICATIONS | 2:396 | DOI: 10.1038/ncomms1406

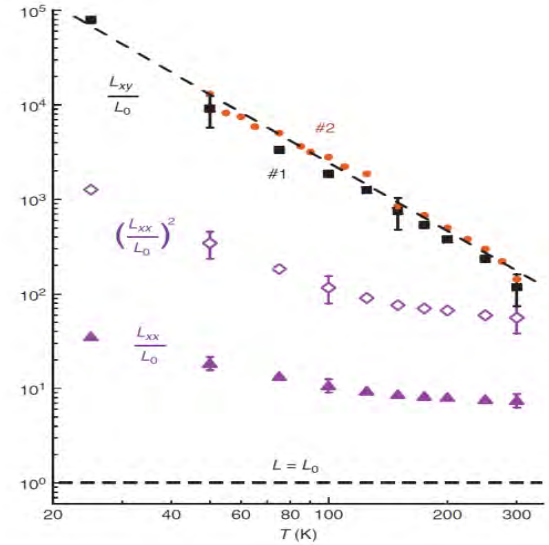
Received 25 Feb 2011 | Accepted 20 Jun 2011 | Published 19 Jul 2011

DOI: 10.1038/ncomms1406

Gross violation of the Wiedemann–Franz law in a quasi-one-dimensional conductor

Nicholas Wakeham[1], Alimamy F. Bangura[1,2], Xiaofeng Xu[1,3], Jean-Francois Mercure[1], Martha Greenblatt[4] & Nigel E. Hussey[1]





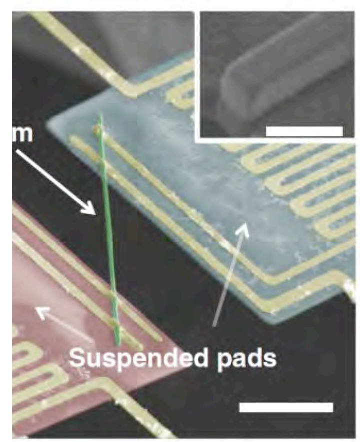
REPORT

Lee *et al.*, *Science* **355**, 371–374 (2017) 27 January 2017

SOLID-STATE PHYSICS

Anomalously low electronic thermal conductivity in metallic vanadium dioxide

Sangwook Lee,[1,2*] Kedar Hippalgaonkar,[3,4*] Fan Yang,[3,5*] Jiawang Hong,[6,7*] Changhyun Ko,[1] Joonki Suh,[1] Kai Liu,[1,8] Kevin Wang,[1] Jeffrey J. Urban,[5] Xiang Zhang,[3,8,9] Chris Dames,[3,8] Sean A. Hartnoll,[10] Olivier Delaire,[7,11]† Junqiao Wu[1,8]†



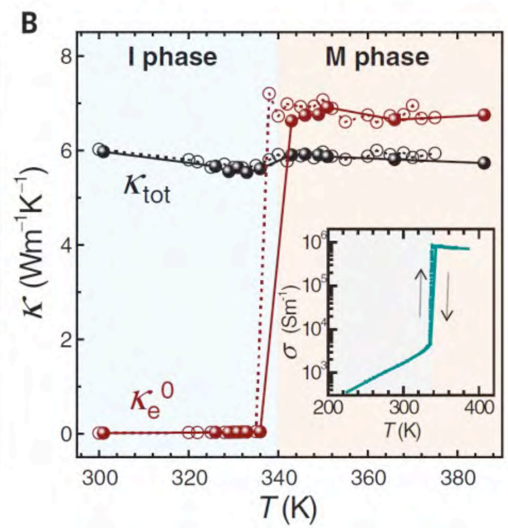
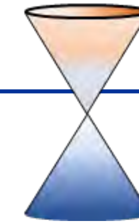


Fig. 1. Thermal conductivity of VO$_2$ across the metal-insulator transition. (**A**) False-color scanning

Charge and Heat Transport at Dirac Point



For a Dirac fluid at chemical potential $\mu = 0$;

Density: $n_e = n_h$

Energy density: $u_e = u_h$

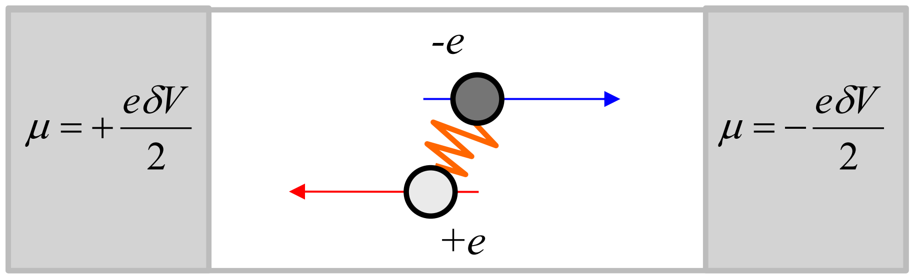
Drift velocity: $|\langle v_e \rangle| = |\langle v_h \rangle|$

Charge current: $j = en_h\langle v_h\rangle + (-e)n_e\langle v_e\rangle$

Heat current: $j_Q = u_h n_h \langle v_h\rangle + u_e n_e \langle v_e\rangle$

Electric Transport

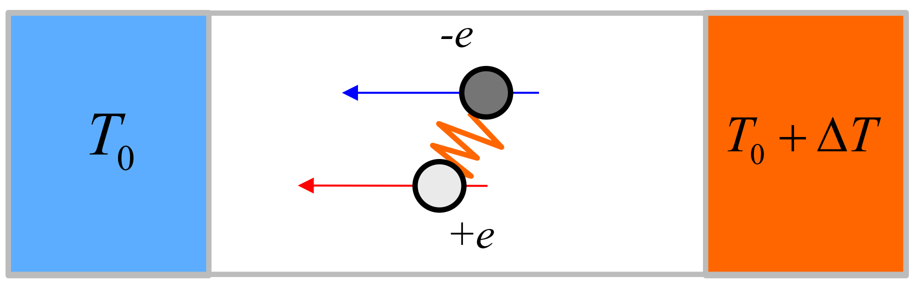
$$j \neq 0$$
$$j_Q = 0$$



e-h **interaction provides a friction to electric current!**

Thermal Transport

$$j = 0$$
$$j_Q \neq 0$$



e-h **interaction provides no friction to heat current!**

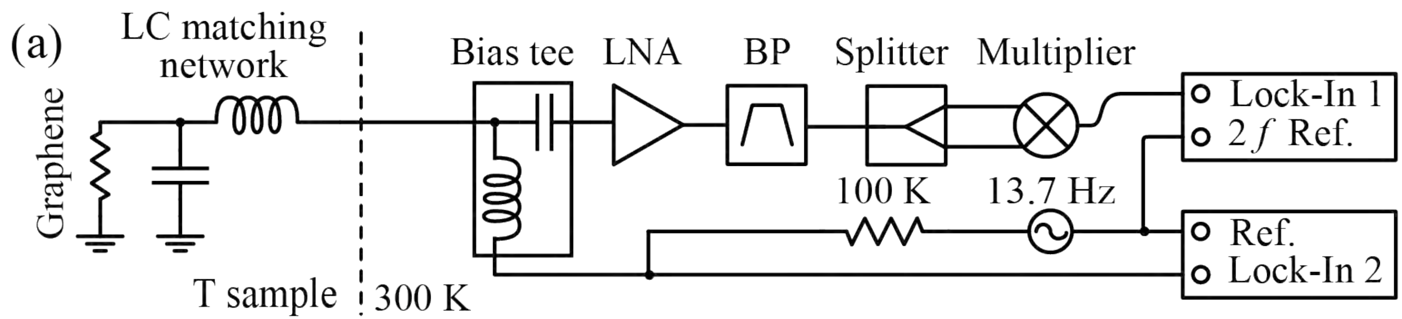
Near the charge neutrality,

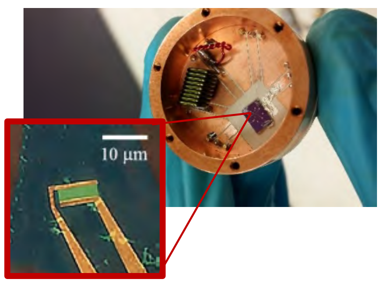
$$\frac{\kappa}{\sigma T} > \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 = L_0$$

- L. Fritz, J. Schmalian, M. Müller, and S. Sachdev, Phys. Rev. B 78, 085416 (2008).
- M. Müller, L. Fritz, and S. Sachdev, Phys. Rev. B 78, 115406 (2008); M. Müller and S. Sachdev, *ibid.* 78, 115419 (2008).
- M. S. Foster and I. L. Aleiner, Phys. Rev. B 77, 195413 (2008).

Johnson Noise Thermometry for Thermal Conductivity Measurement

J. Crossno *et al.*, APL (2015)

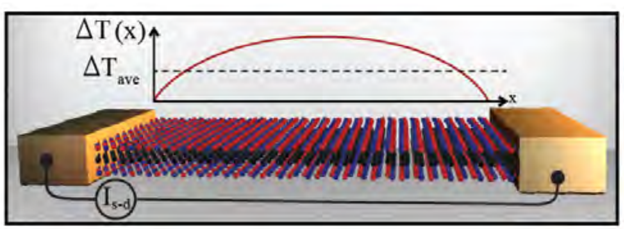




$$\sqrt{4 k_b T \, \Delta f \, R} = V_{RMS}$$

Electron temperature can be measured in the range of 1-300 K @ 100 MHz

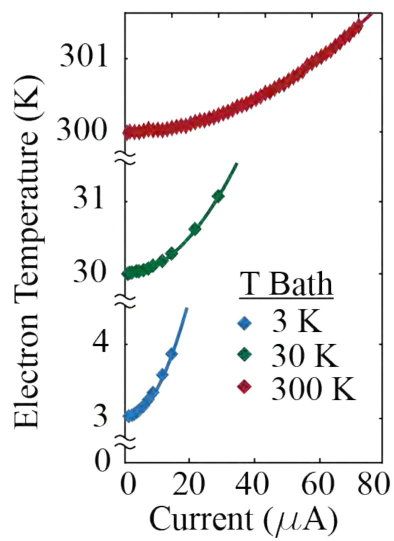
Joule heating by DC bias through bias T

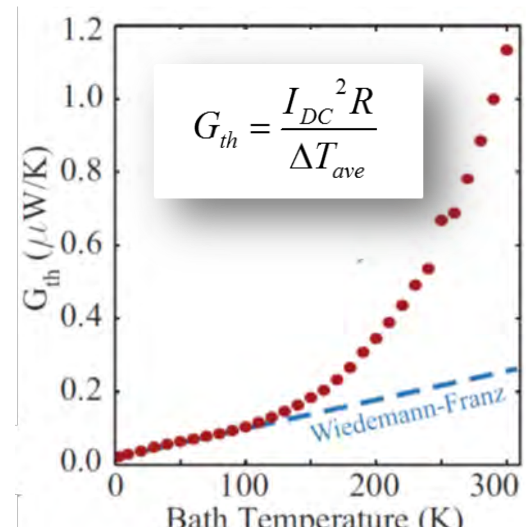


Johnson Noise Temperature

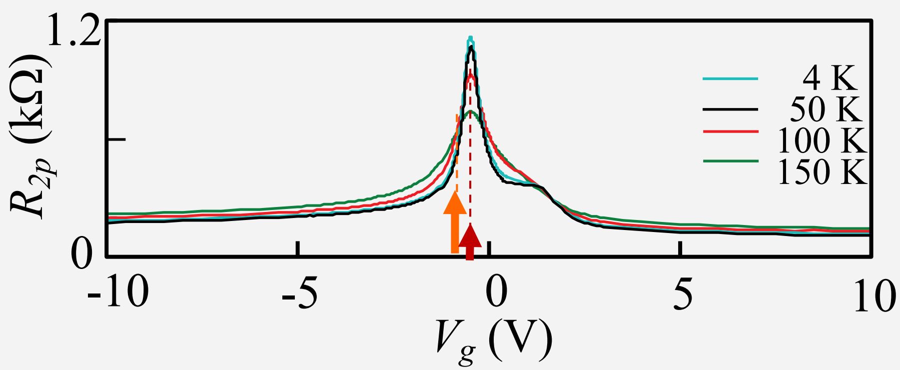
$$T_{JN} = \frac{\int \dot{q}(x,y) * T(x,y) dA}{\int \dot{q}(x,y) dA}$$

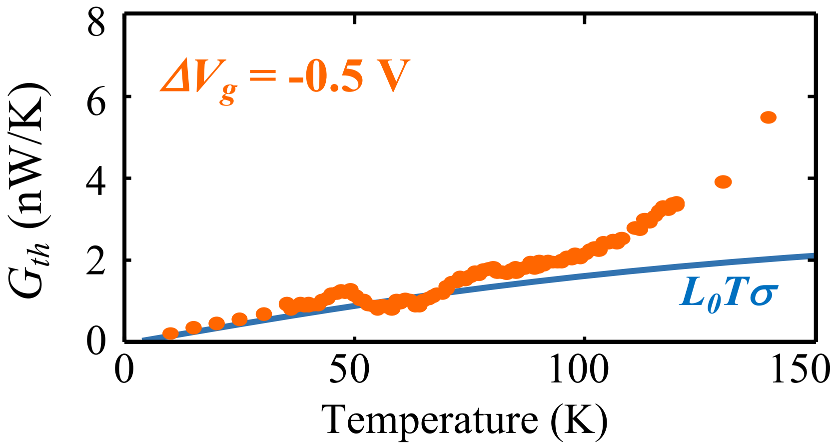
Local heat dissipation

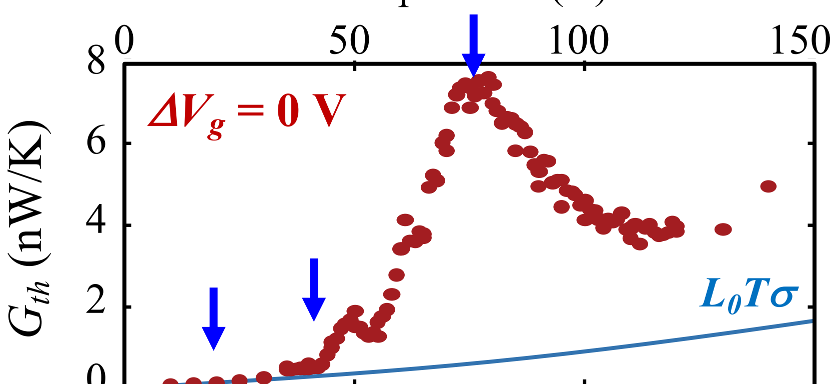




Electronic Thermal Conductance Near the Neutrality



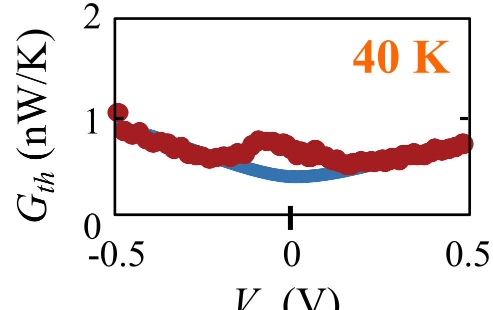


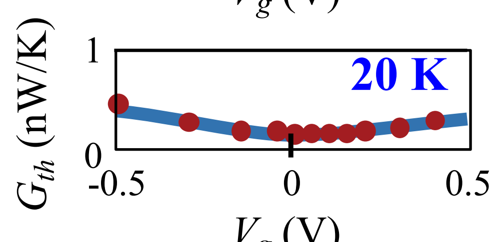


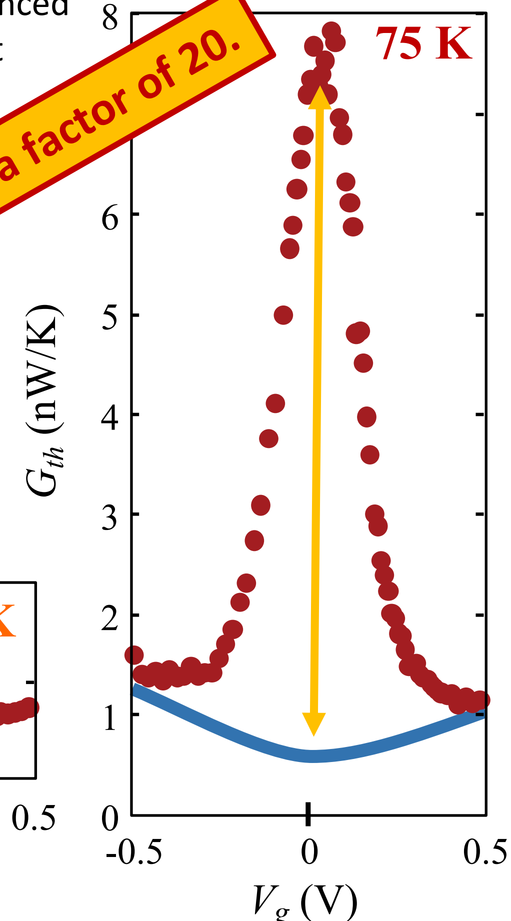
Thermal conductivity enhanced

- close to the Dirac point
- at high temperatures

W-F law violated by a factor of 20.







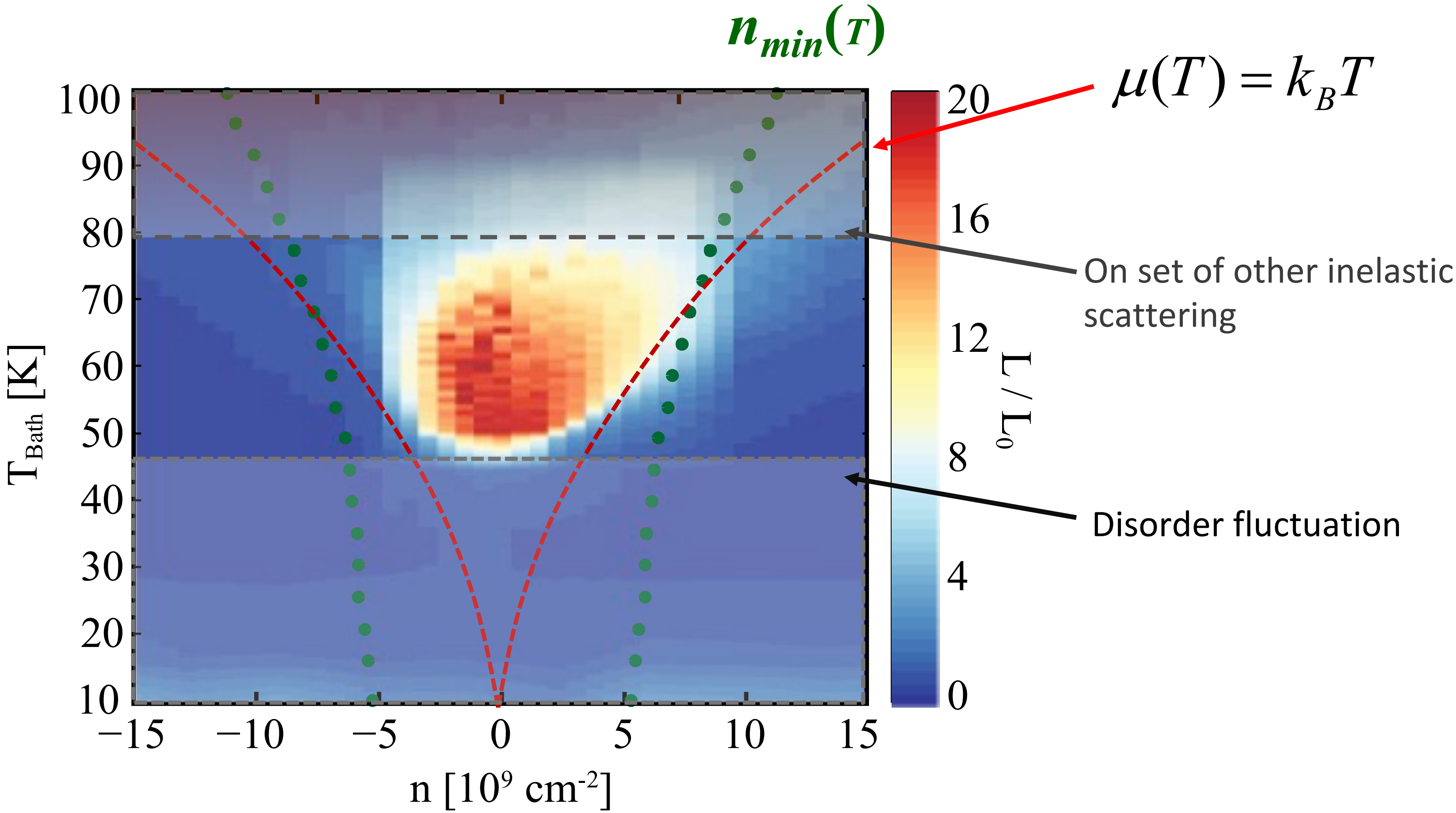
Lorentz Number as Function of Temperature and Density

Experimentally obtained Lorentz value:

$$L = \frac{\kappa}{\sigma T} \approx \frac{G_{th} R}{12 T}$$

Sommerfeld value:

$$L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$$



Relativistic Hydrodynamics Analysis

Muller *et al*, PRB (2008) & Foster *et al.*, PRB (2009)

$\eta / s \sim 10 > 1/4\pi$ (Kovtun-Son-Starinets limit)

See A. Lucas arXiv: 1510.01738 for detail

Lorentz number for Dirac fluid

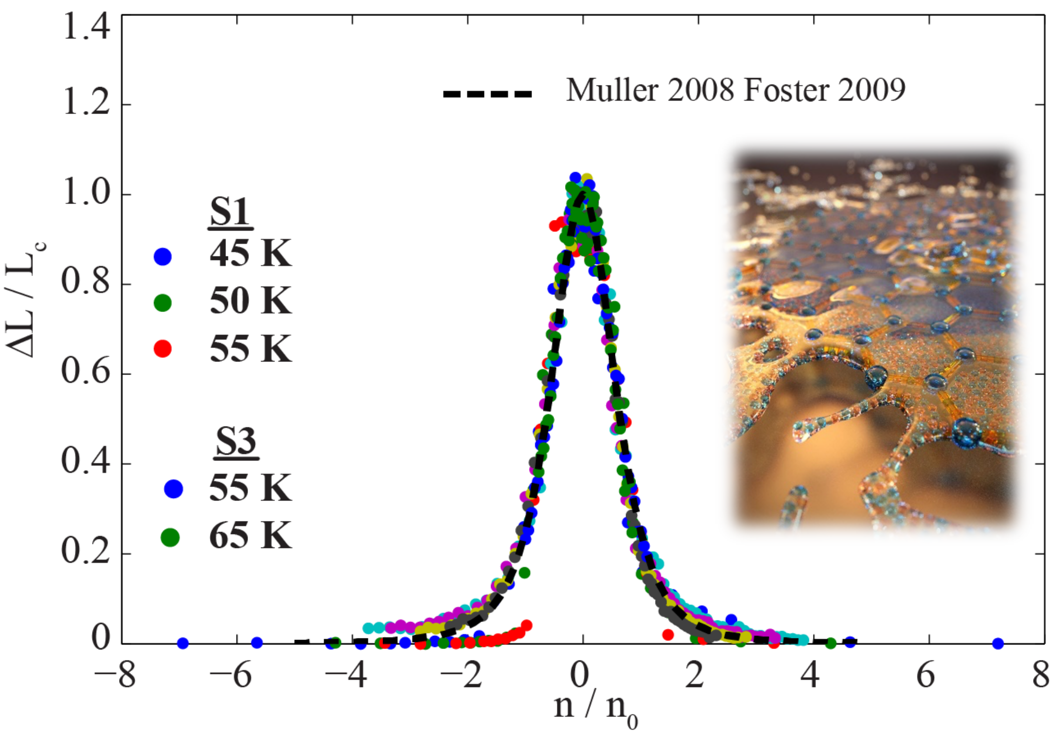
$$L = \frac{1}{((n/n_0)^2+1)} L_c$$

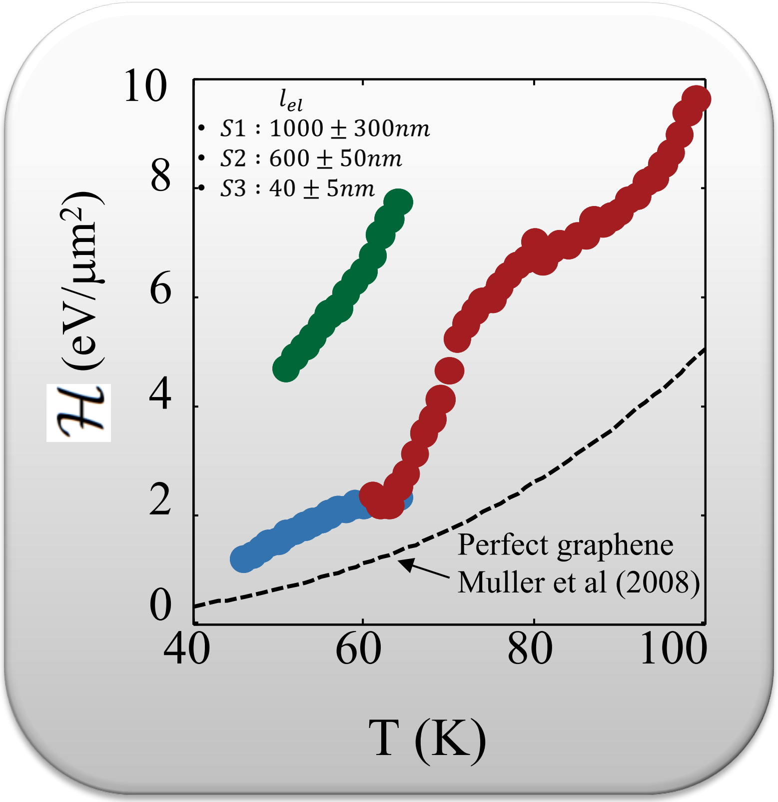
$$L_c = \frac{v_F}{\sigma_{min} T^2} \mathcal{H} \ell_{el}$$

$$n_0^2 = \frac{\sigma_{min}}{e^2 v_F} \frac{\mathcal{H}}{\ell_{el}}$$

$\mathcal{H}$: Fluid enthalpy density

ℓ_{el} : elastic mean free path



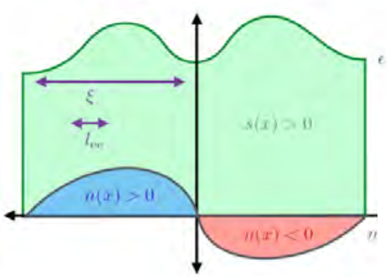


Electrical and Thermal Conductance

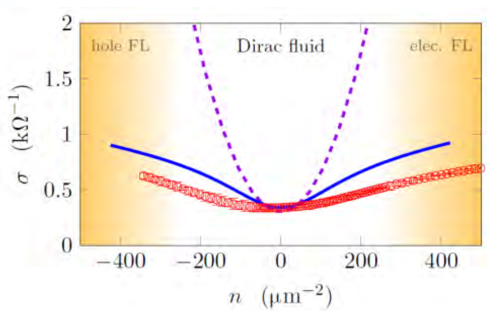
Effect of Disorder

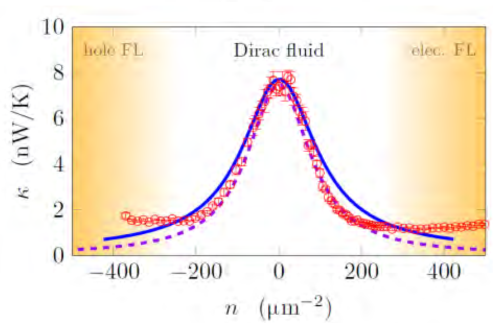
Lucas et al, PRB (2016).

$$\partial_\mu T^{\mu\nu} = e\, F^{\mu\nu} J_\nu \quad \text{and} \quad \partial_\mu J^\mu = 0$$
$$T^{ti} = (\varepsilon + P)\, v^i$$
$$T^{ij} = P\, \delta^{ij} - \eta\, (\partial^i v^j + \partial^j v^i) - (\zeta - \eta)\, \delta^{ij}\, \partial_k v^k$$
$$J^i = n v^i - \sigma_Q[\partial_i(\mu - \mu_0) - (\mu/T)\, \partial_i T]$$



$$F^{ti}_{\text{ext}} = -F^{it}_{\text{ext}} = \partial_i \mu_0$$

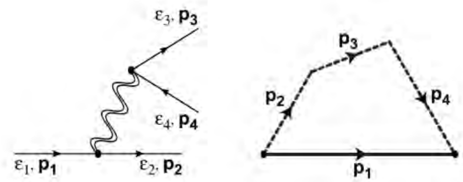




Disorder affect charge current more than energy current

Slow Imbalance

Foster and Aleiner PRB (2012);



$$e^- \leftrightarrow e^- + e^- + h^+,$$
$$h^+ \leftrightarrow h^+ + h^+ + e^-.$$

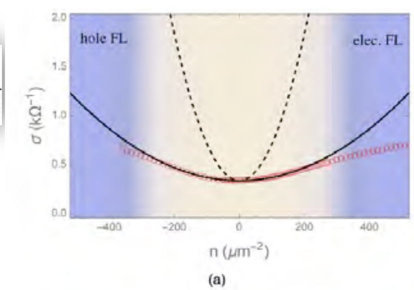
Kinematical constraint of the Dirac cone make the electron and hole current are nearly conserved separately.

Holography of the Dirac Fluid in Graphene with two currents

Yunseok Seo[1], Geunho Song[1], Philip Kim[2,3], Subir Sachdev[2,4] and Sang-Jin Sin[1]

PRL (2017)

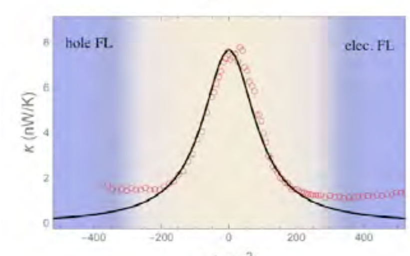
$$\sigma = W_0 + Z_0 + \frac{Q^2}{k^2 r_0^2}, \quad \kappa = \frac{(4\pi r_0^2)^2\, T}{r_0^2 k^2 + (Q^2 + Q_n^2)/2Z_0}$$



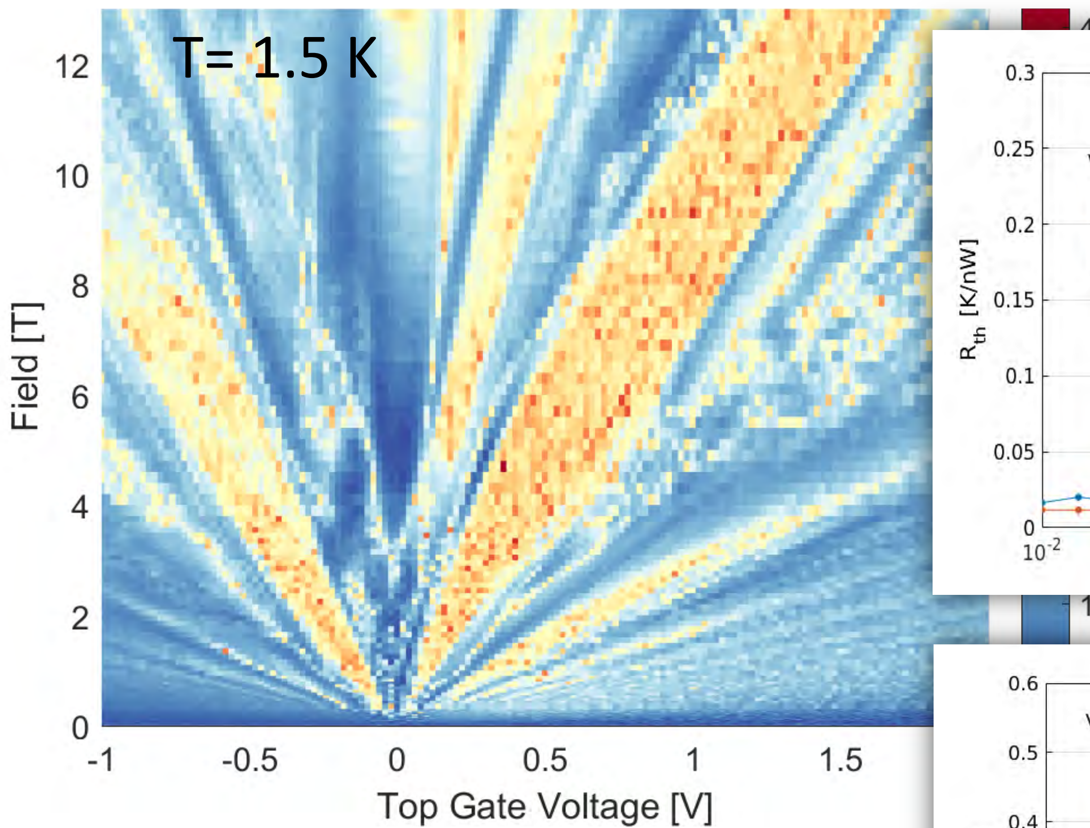
Charged current: $J = J_e + J_h$

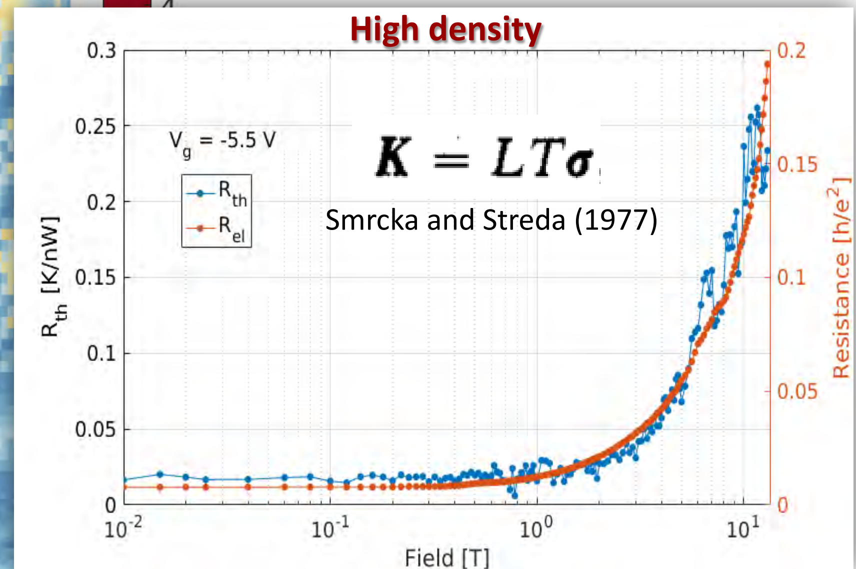
Neutral current: $J_n = J_e - J_h$

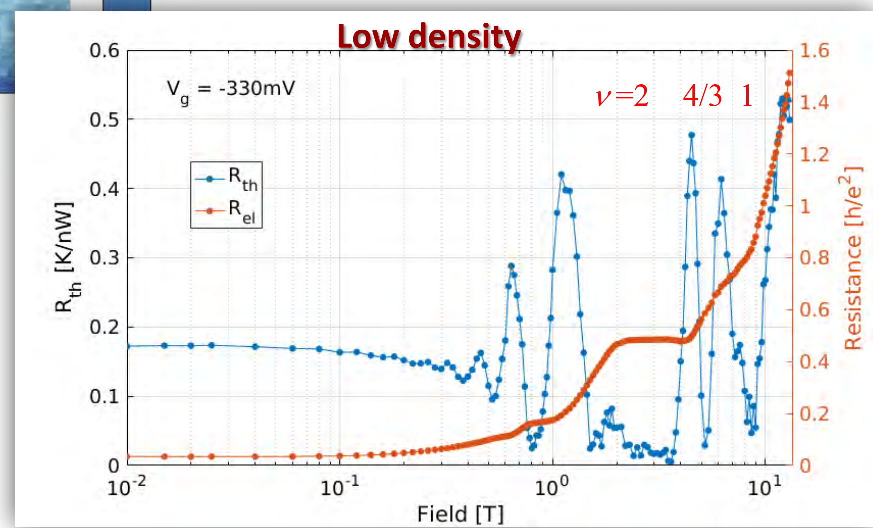
Corresponding conservative quantities by continuity equation: Q, Q_n



Magento-Thermal Transport Measurement







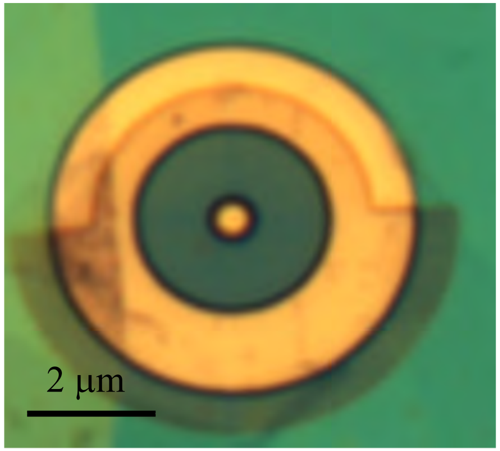
Hot spot formation in quantum Hall edge states

Ikushima et al (2007)

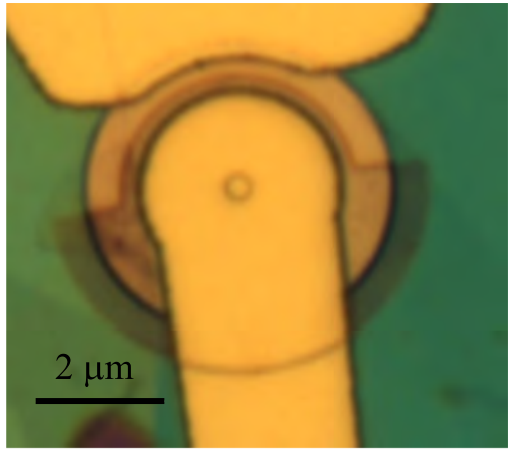
Crossno et al., unpublished

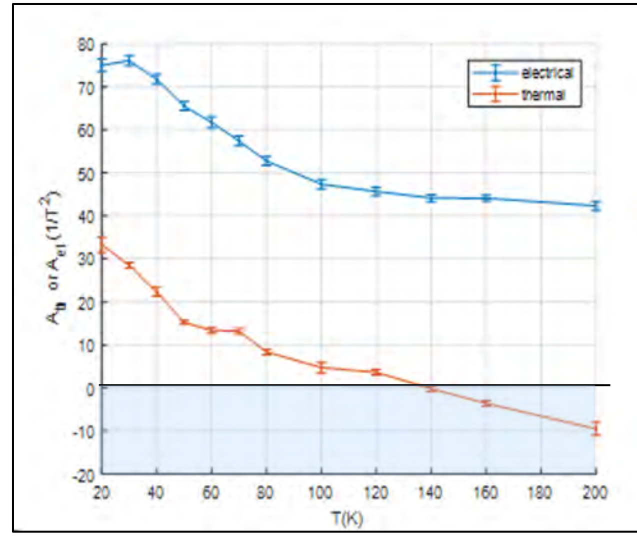
Magneto Thermal Transport in Corbino Device

Corbino without bridge contact

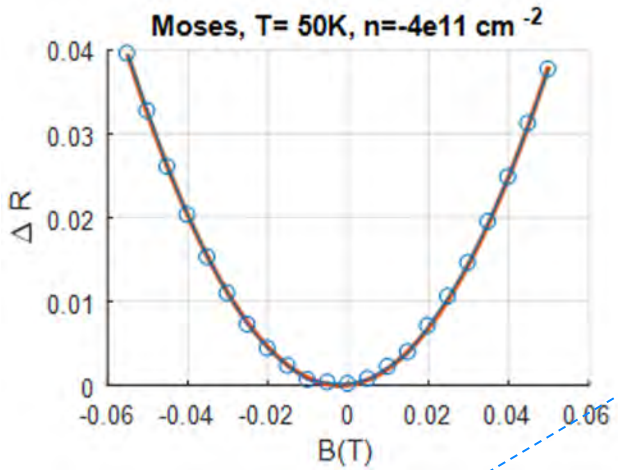


Corbino with bridge contact

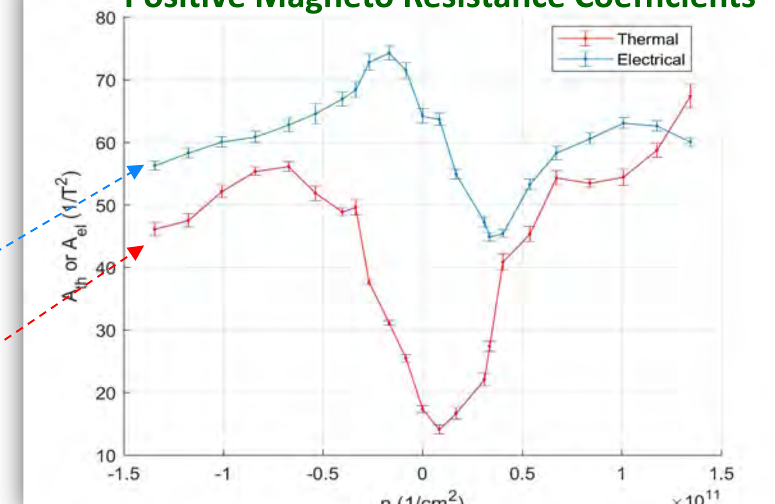




Normalized Magneto-Resistance



Positive Magneto Resistance Coefficients



Electrical

$$\Delta R = \frac{R(B)}{R(0)} - 1 = A_{el} \cdot B^2$$

Thermal

$$\Delta R_{th} = \frac{R_{th}(B)}{R_{th}(0)} - 1 = A_{th} \cdot B^2$$

What can we extract viscosity from A_{el} and A_{th}?

Magneto-Exciton Condensation in quantum Hall Graphene Double Layers

Xiaomeng Liu

Zeyu Hao

Jia Li.

Cory Dean.

Jim Hone

T. Taniguchi, K. Watanabe

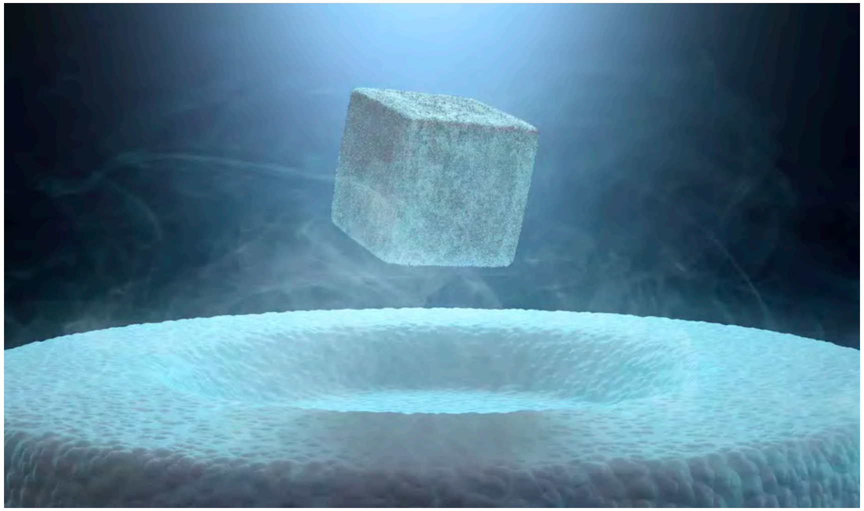
Bert Halperin

Quantum Hall Drag of Exciton Condensate in Graphene
X. Liu, K. Watanabe, T. Taniguchi, B. I. Halperin, P. Kim
Nature Physics **13**, 746–750 (2017)

Interlayer fractional quantum Hall effect in a coupled graphene double-layer
X. Liu, Z. Hao, K. Watanabe, T. Taniguchi, B. Halperin, P. Kim
Nature Physics **15**, 893–897 (2019)

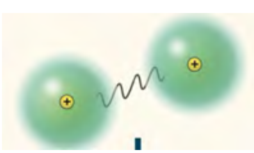
Crossover between Strongly-coupled and Weakly-coupled Exciton Superfluids
X. Liu1, J.I.A Li, K. Watanabe, T. Taniguchi, J. Hone, B. I. Halperin, C.R. Dean, and P. Kim
in preparation

Superconductor and Superfluid

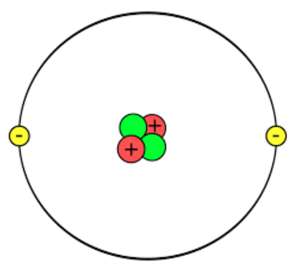


Superconductor: magnetic levitation

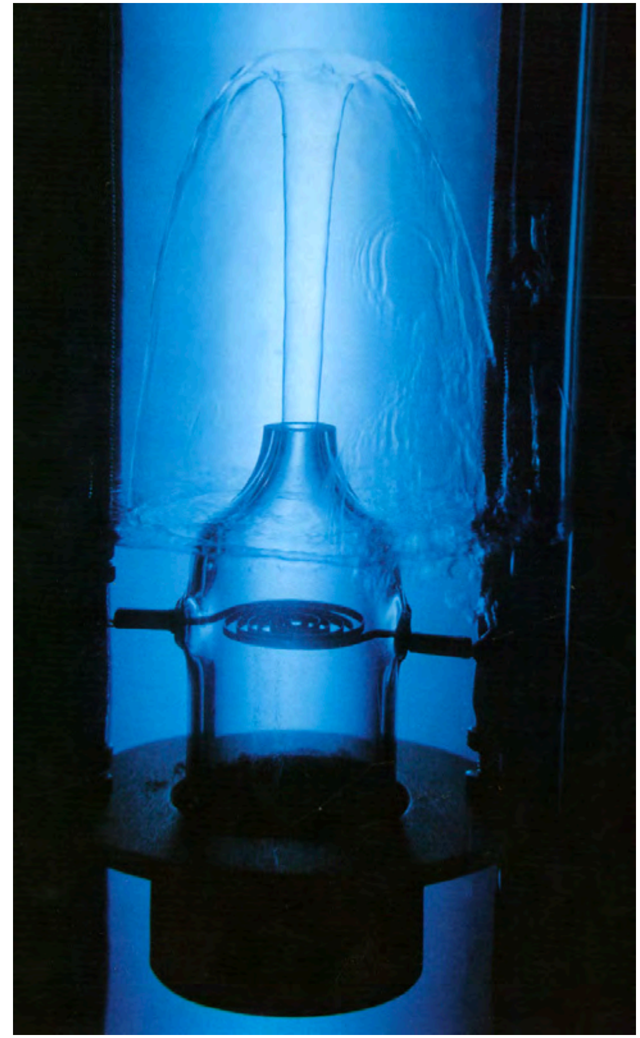
Composite bosons



Cooper pair



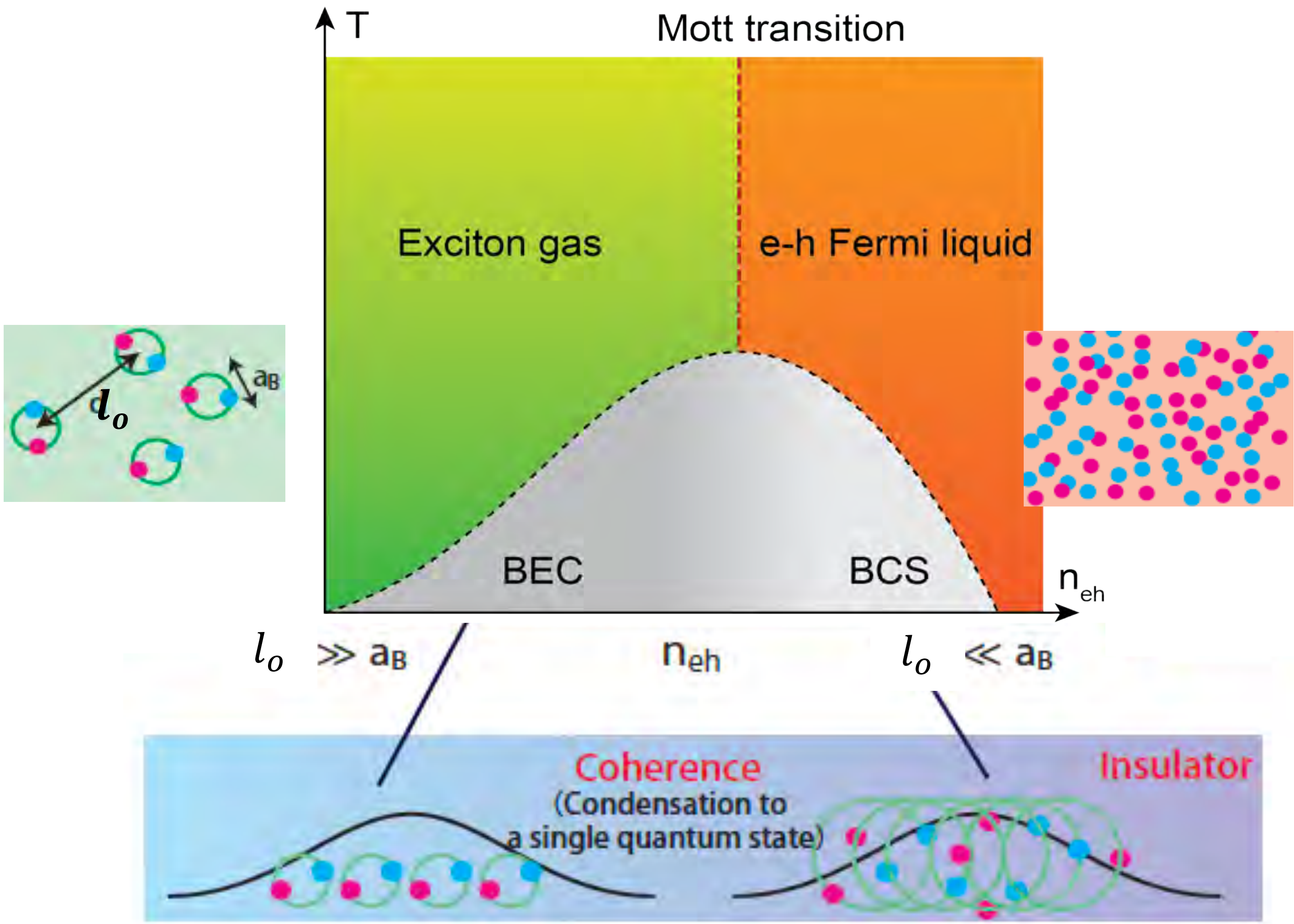
^{4}He



Superfluid ^{4}He: fountain effect

Exciton/e-h Phase Diagram

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

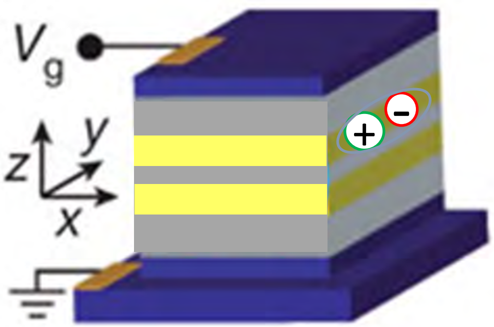


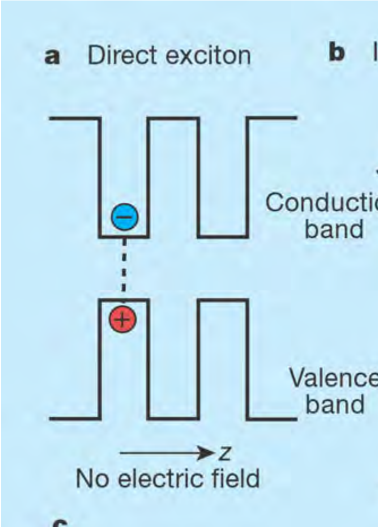
T. Ogawa and K. Asano (2008)

Excitons in semiconducting quantum wells

Direct and indirect excitons in semiconducting quantum wells

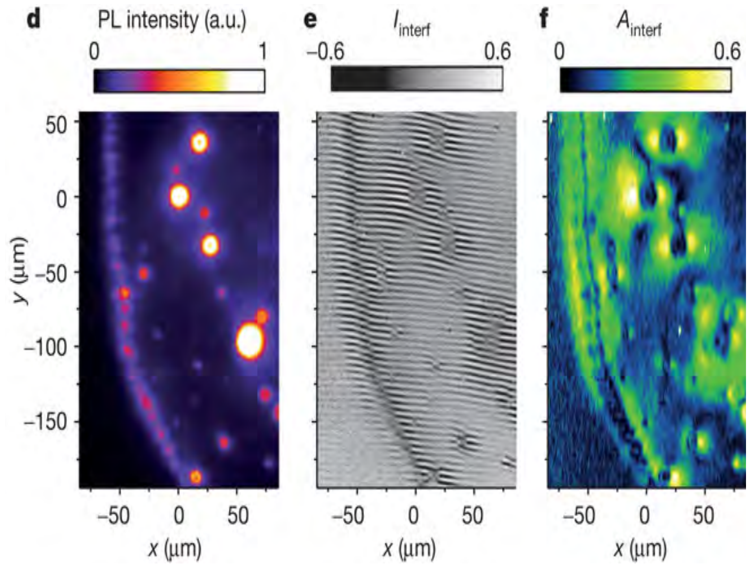
Semiconductor heterostructure





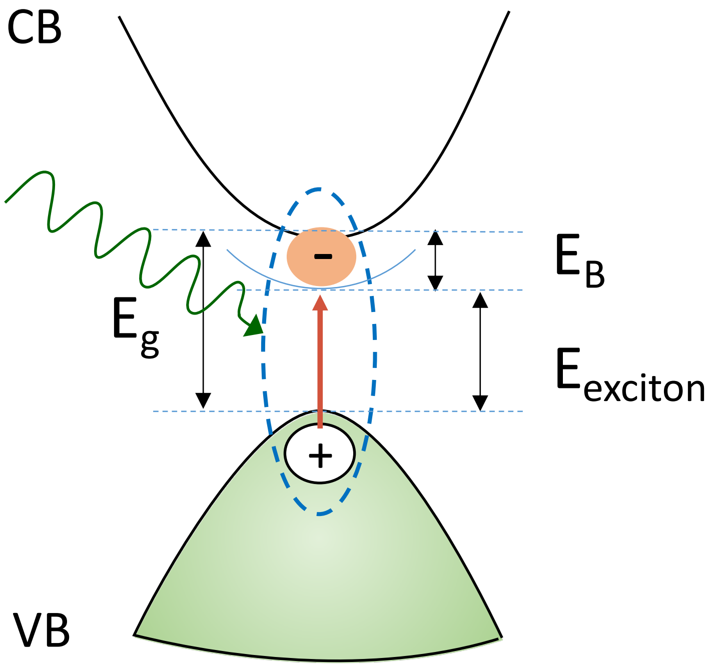
Ilias Perakis Nature (2002)

Spontaneous coherence in cold interlayer exciton gas formed in GaAs quantum wells



A. High, Nature 2012

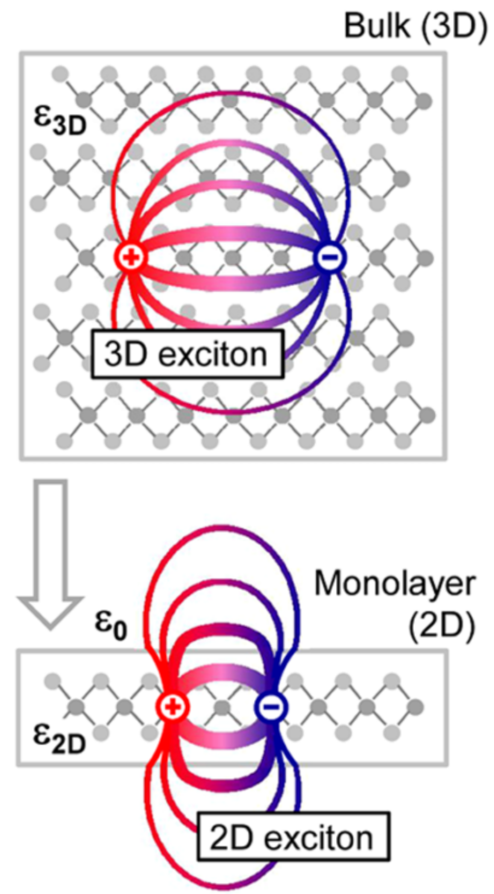
Excitons in 2D Materials



$E_{exciton} = E_g - E_B$

E_B = Exciton binding energy

E_g = Energy gap



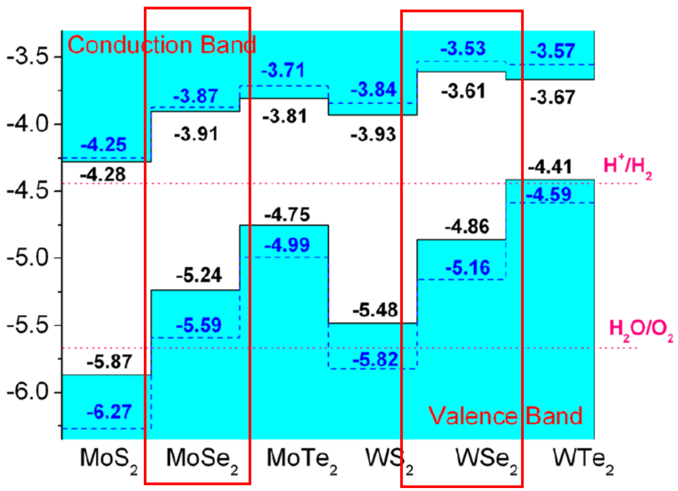
A. Chernikov *et al. Phys. Rev. Lett.* **113**, 076802 (2014).

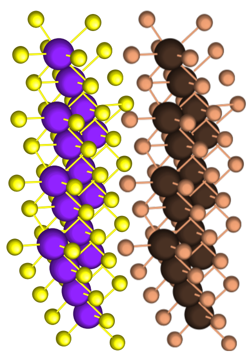
Exciton is a bound electron-hole pair.

Exciton is strongly bound in 2D

Atomically Thin vdW p-n junction

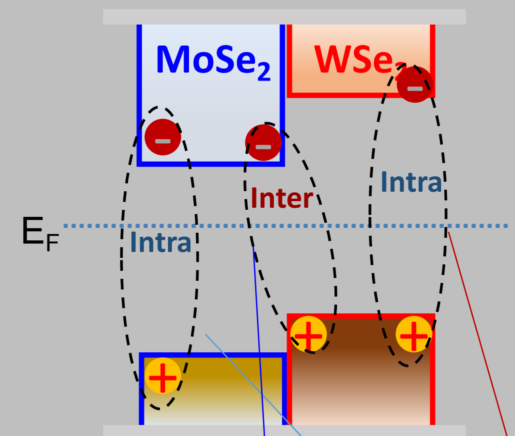
Band gaps and alignment of vdW semiconductors



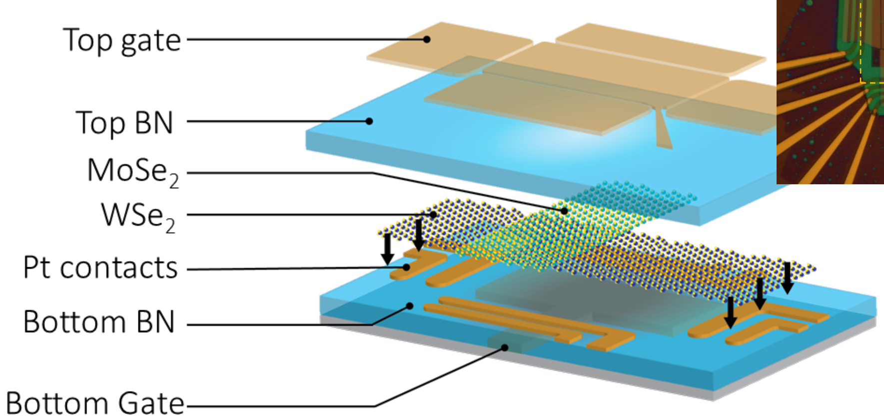


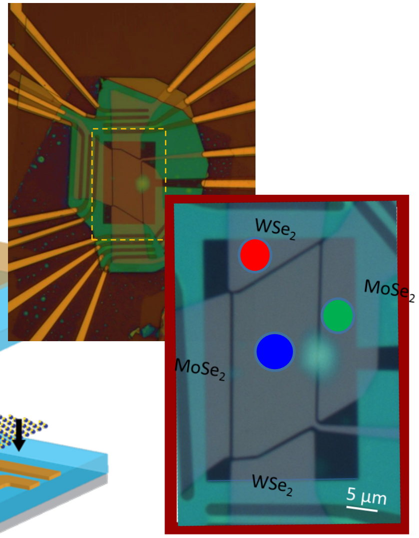
Appl. Phys. Lett. **102**, 012111 (2013)

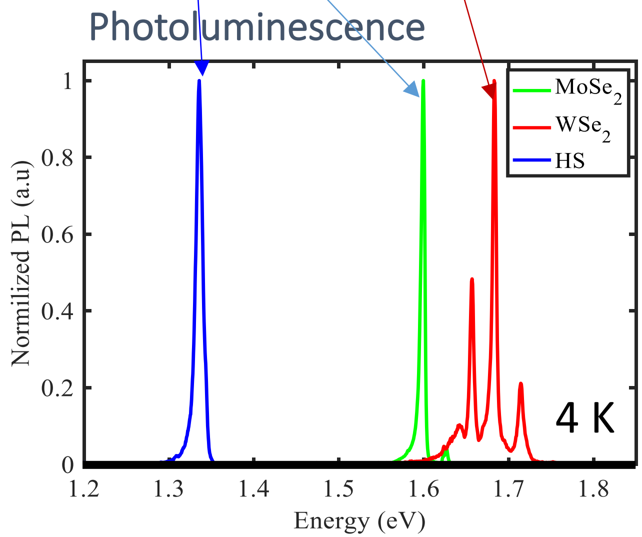
- **Type II semiconductor heterostructures**



Heterostructure Device and PL



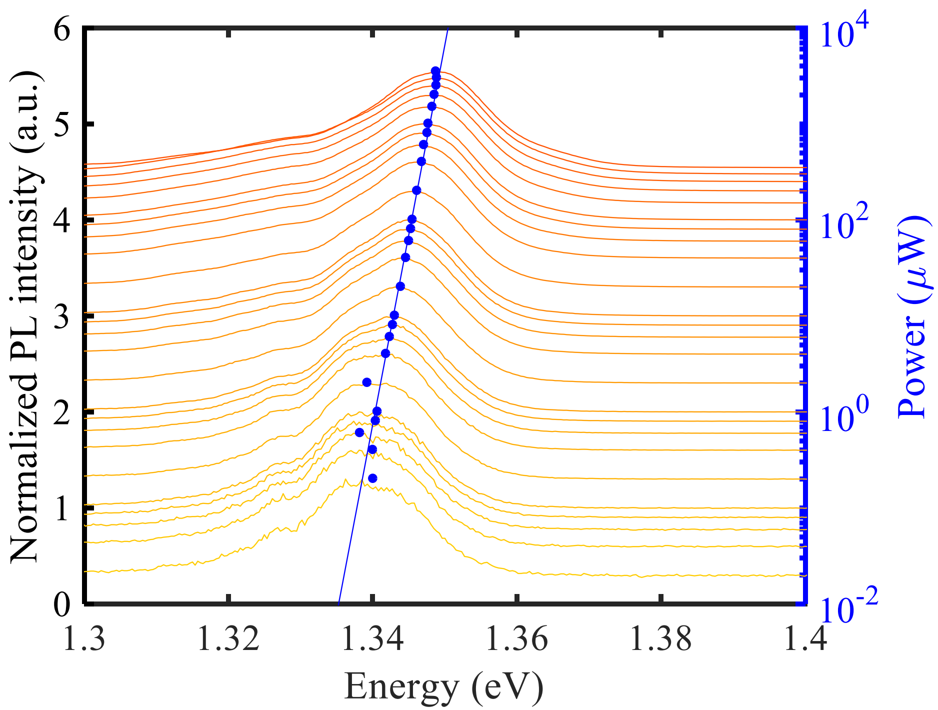


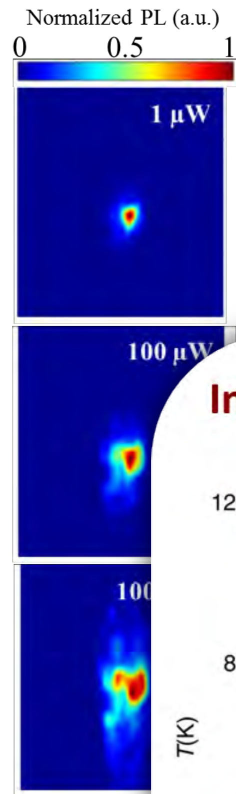


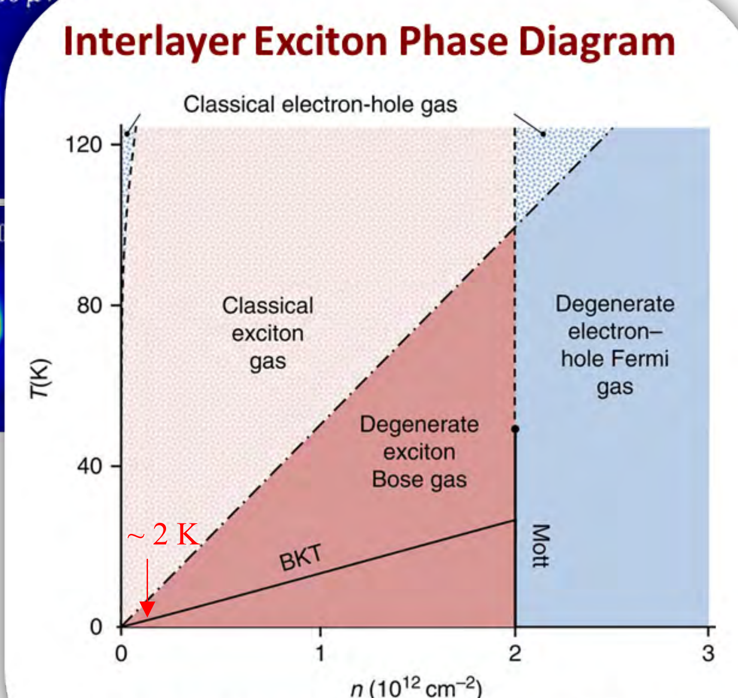
L. Jauregui et. al, unpublished (Collaboration with H. Park and M. Lukin groups)

Toward Interlayer Exciton Condensation

Laser power dependent PL







Fogler, M. M.; et al. Nat. Commun. 5, 4555 (2014).

Blue shift due to the exciton-exciton interaction

$$\delta E = n_{eh} e^2 d / \varepsilon$$

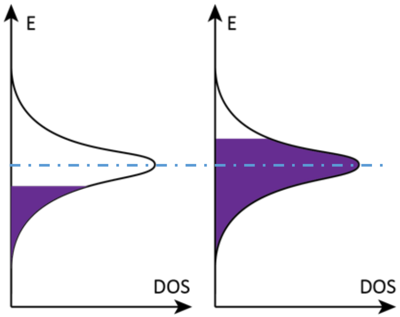
Estimated exciton density: $n_{IE} \sim 10^{11}$ cm^{-2}

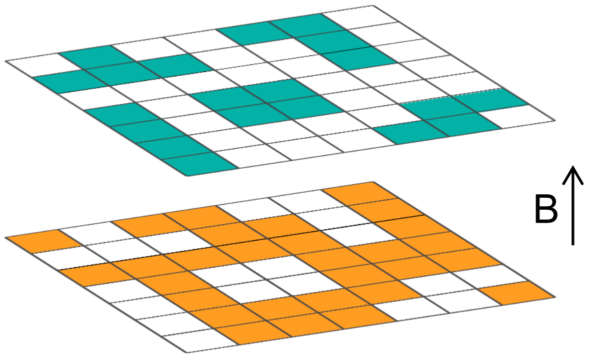
L. Jauregui et. al, unpublished (Collaboration with H. Park and M. Lukin groups)

Exciton condensation between Landau levels

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

Two partially filled
Landau levels

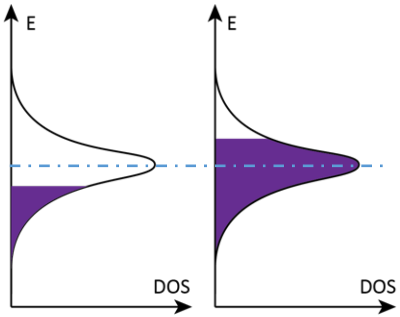


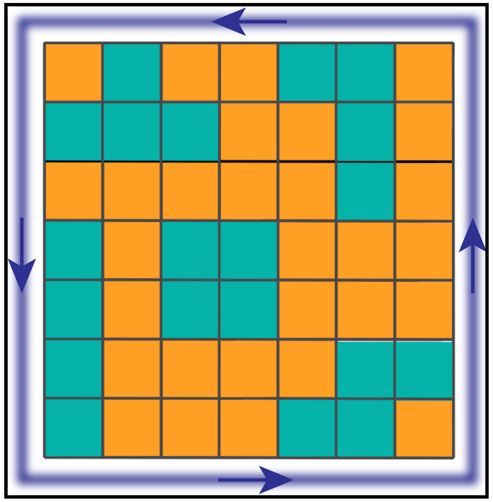


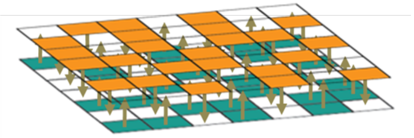
Exciton condensation between Landau levels

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

Two partially filled Landau levels



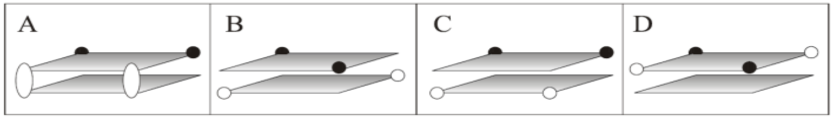




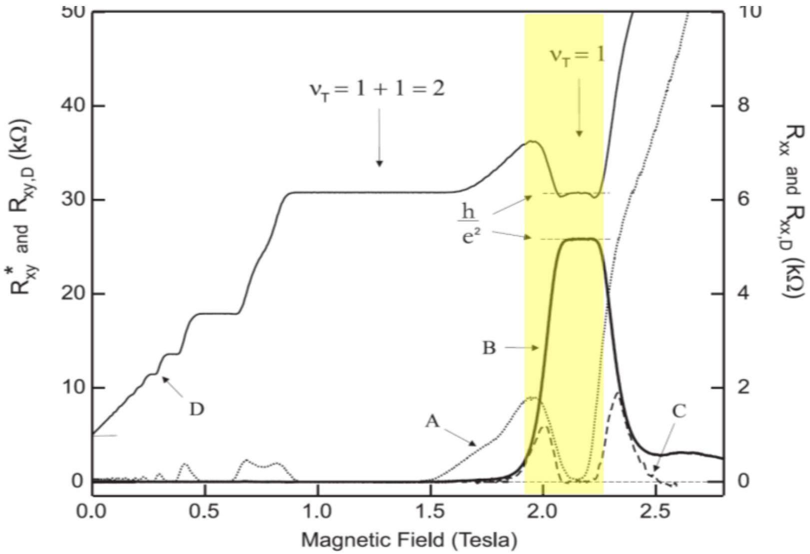
$$|\Psi\rangle = \prod_k \frac{1}{\sqrt{2}}(c^\dagger_{k,T} + e^{i\phi} c^\dagger_{k,B})|0\rangle$$

Total Landau level quantum Hall effect

GaAs Double Quantum Well

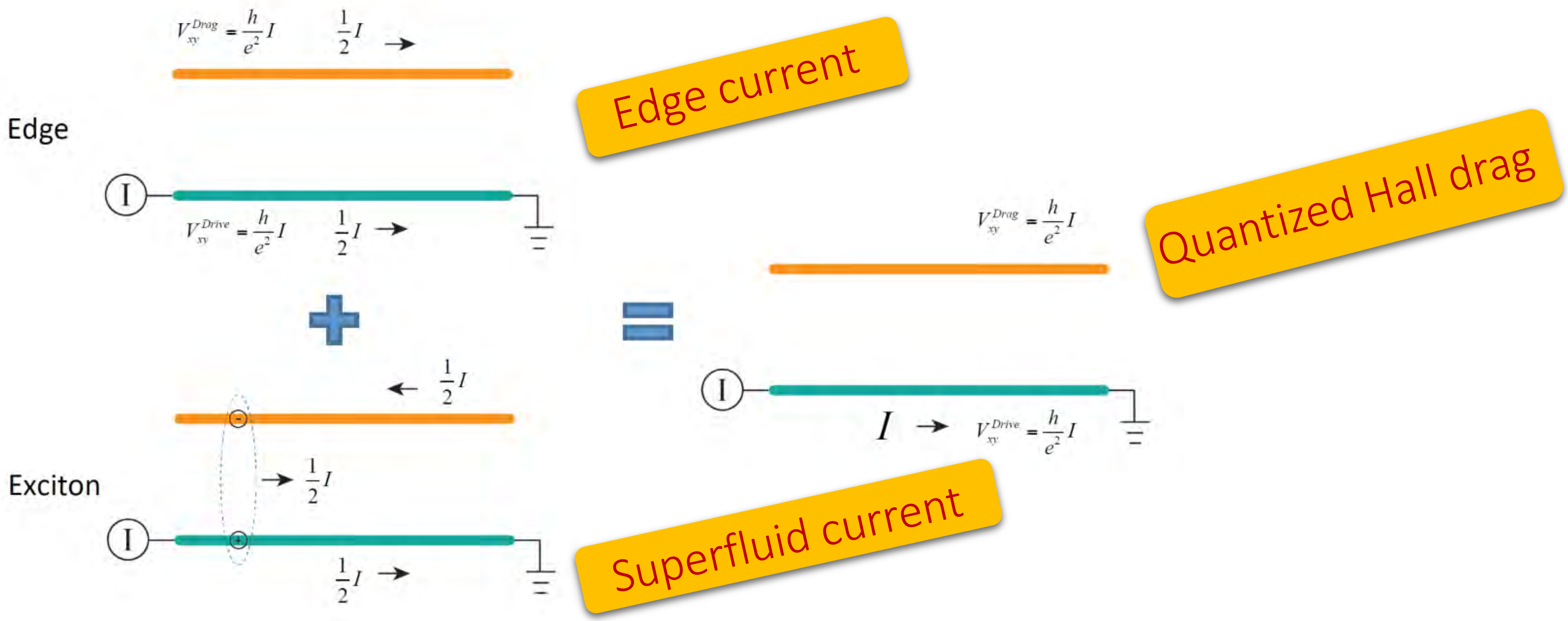


- Quantum Hall effect for two partially filled complementary LLs
- Quantized drag Hall

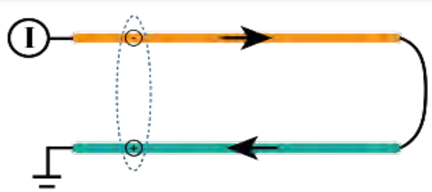


M. Kellogg, et. al, PRL (2002)

Exciton Current and Quantized Drag



Counter Flow Current

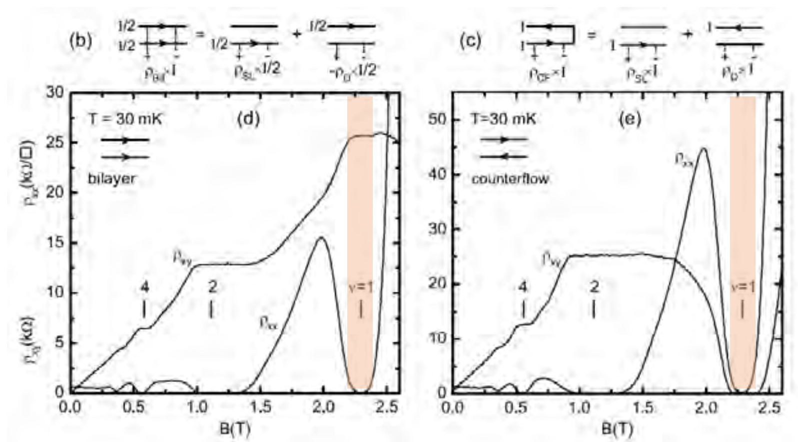


Dissipationless counter flow current flow:

$$R_{xx}^{CF} = \frac{V_{xx}}{I_{CF}} = 0$$

No net force on exciton:

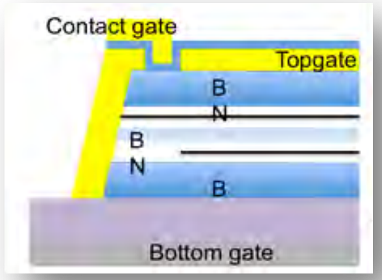
$$R_{xy}^{CF} = \frac{V_{xy}}{I_{CF}} = 0$$

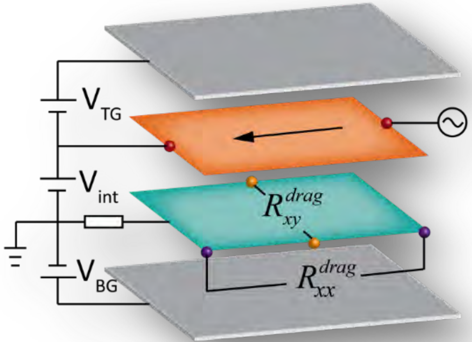


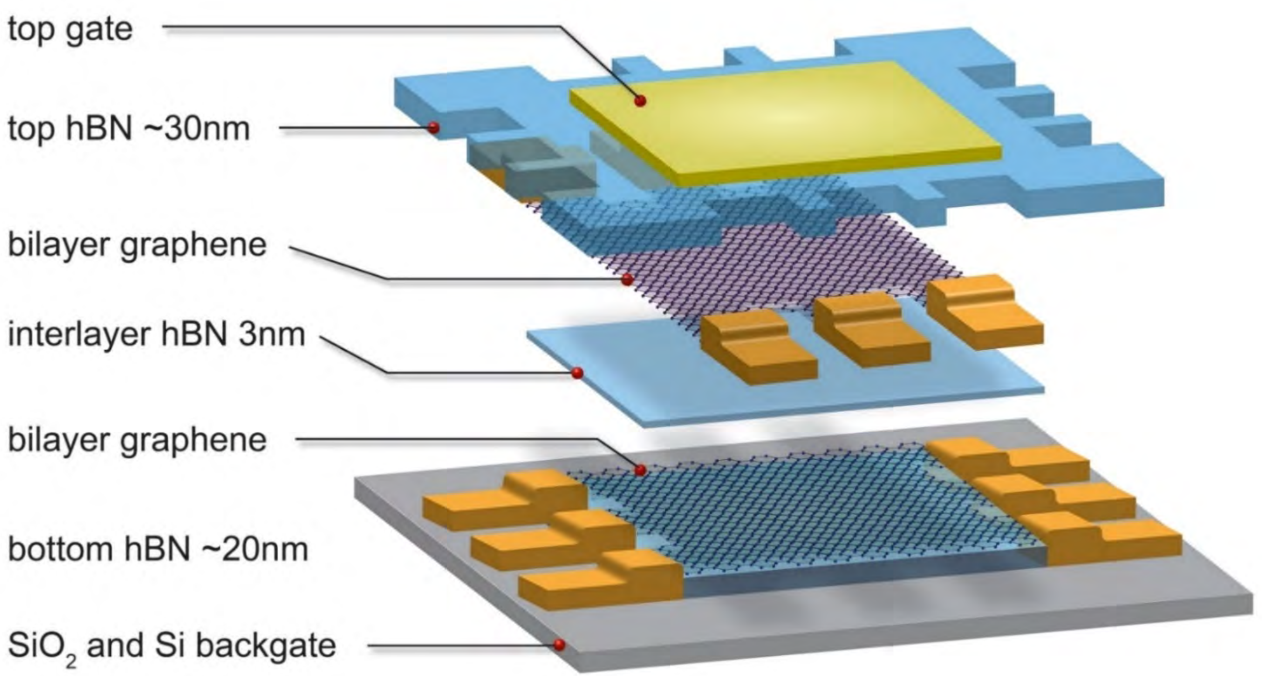
GaAs 2DEG: Princeton & MPI (2004)

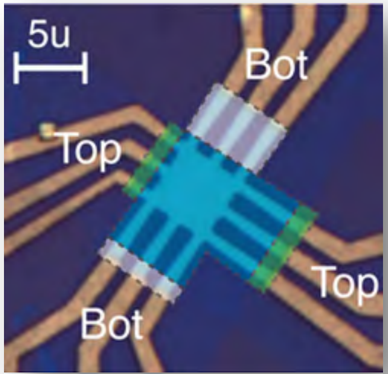
Double Graphene Layer Drag Device

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



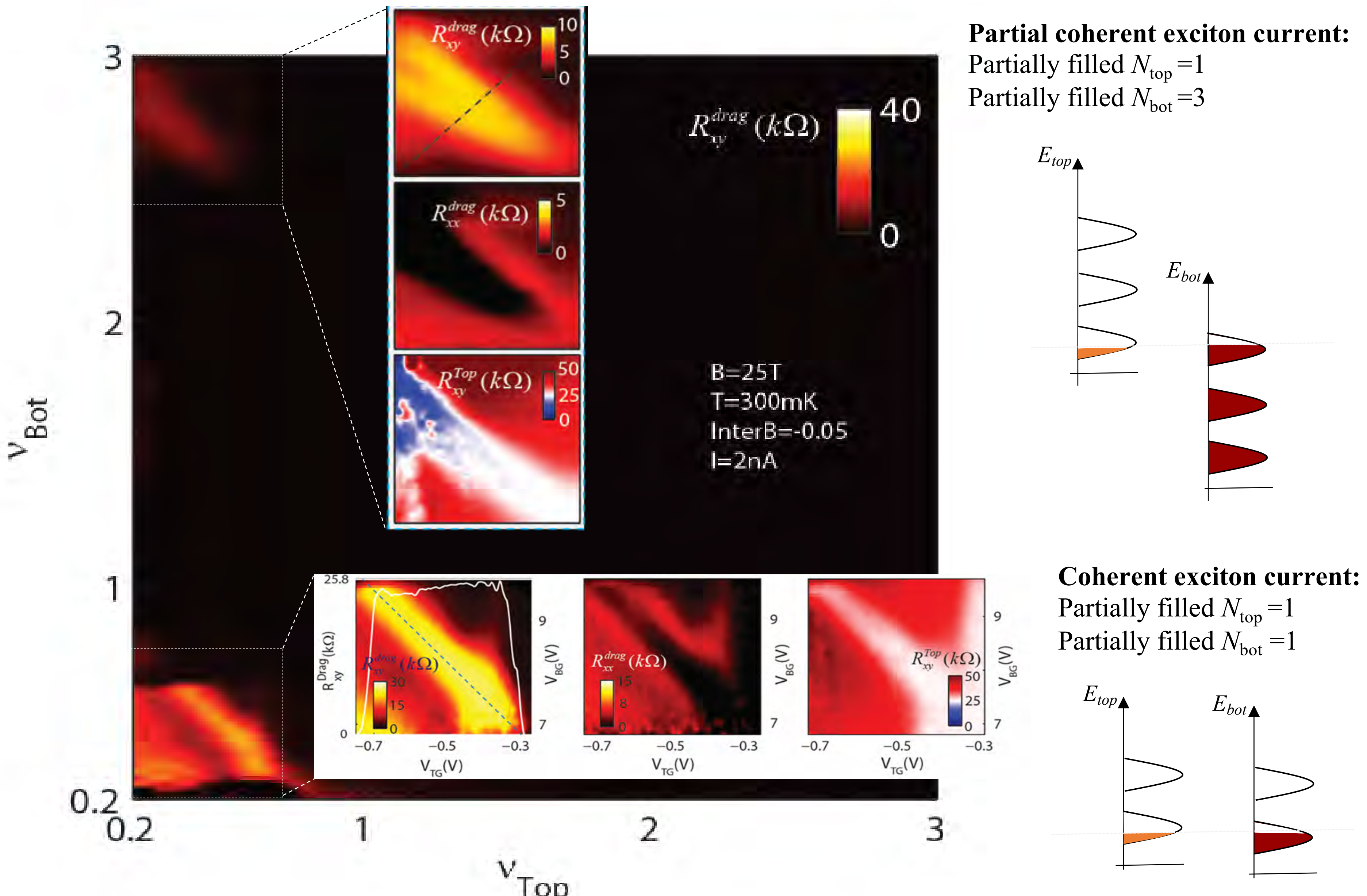






Xiaomeng Liu *et al*, Nature Physics (2017); Similarly J. Li et al. Nature Physics (2017)

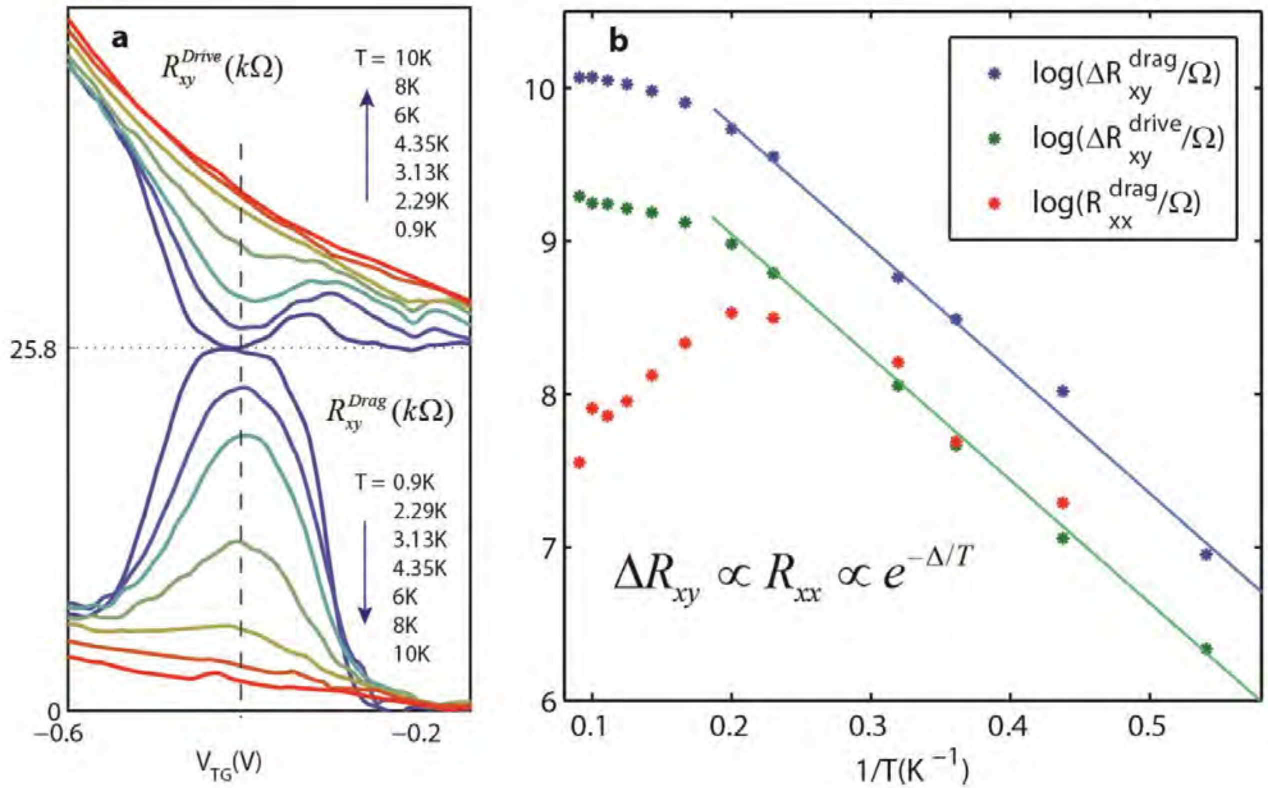
Quantized Hall Drag for ν_{tot} = 1 and 3



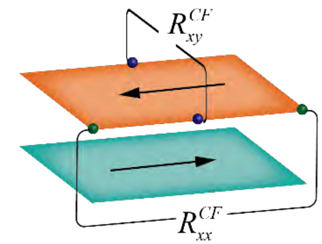
aomeng Liu *et al*, Nature Physics (2017); J. Li *et al*, Nature Physics (2017);

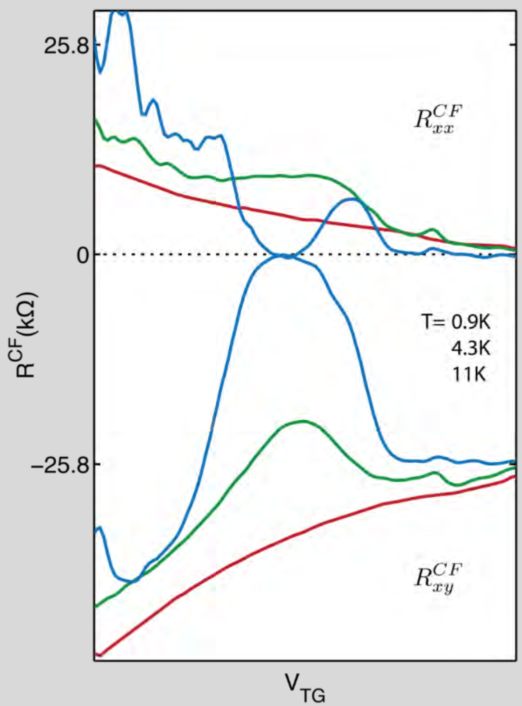
Exciton BEC Energy Scale and Counter Flow

X. Liu *et al*, J. Li *et al*, Nature Physics (2017)

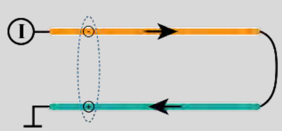


$\Delta \sim 8$ K.





Superfluidic Counter flow



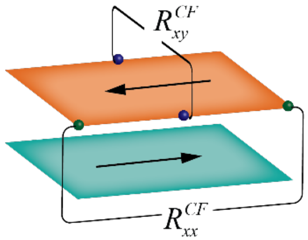
$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

$$V_{top}^{CF} = R_{top} I - R_{drag} I$$

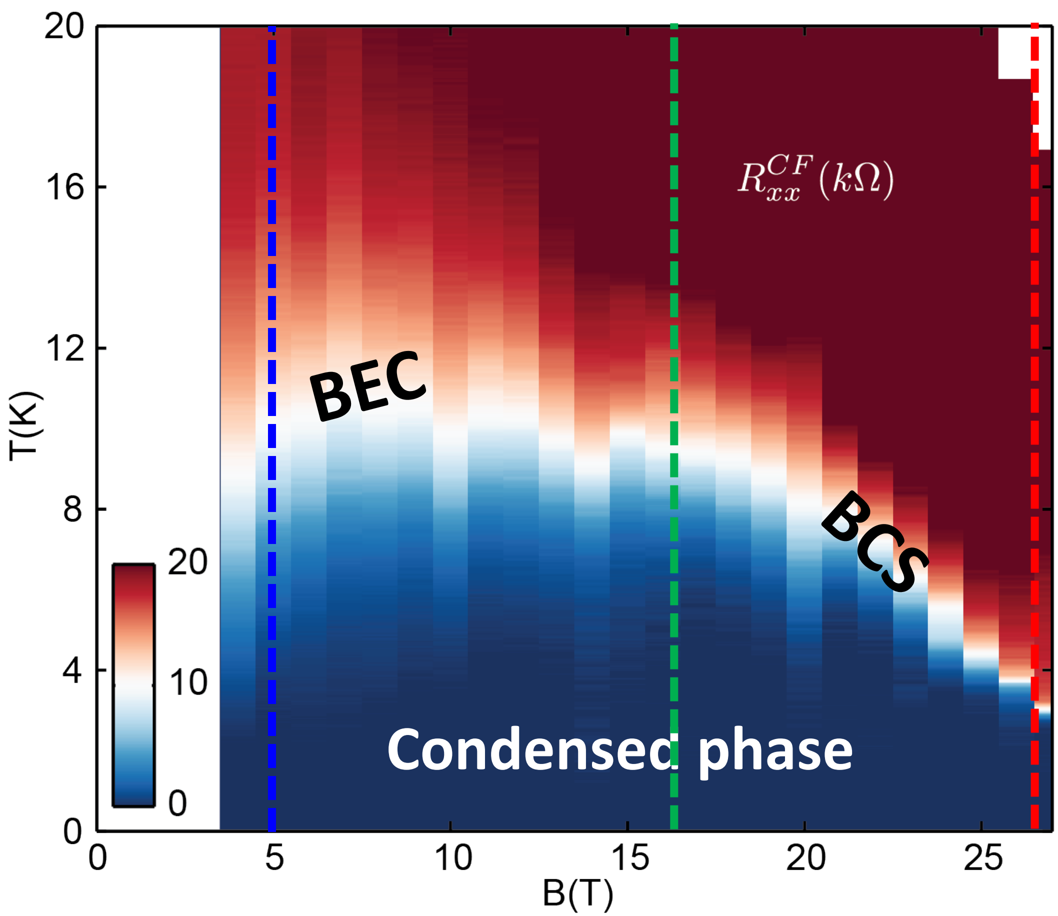
$$V_{bot}^{CF} = R_{drag} I - R_{bot} I$$

Counter-Flow Resistance of $\nu_{tot} = -1$

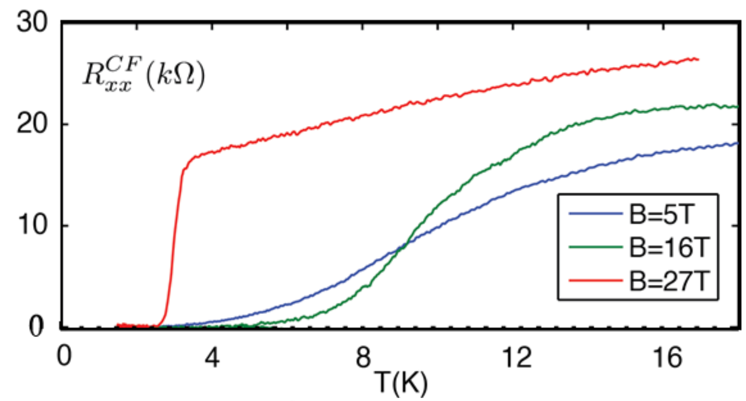
Xiaomeng Liu *et al*, unpublished (collaboration with Dean group)



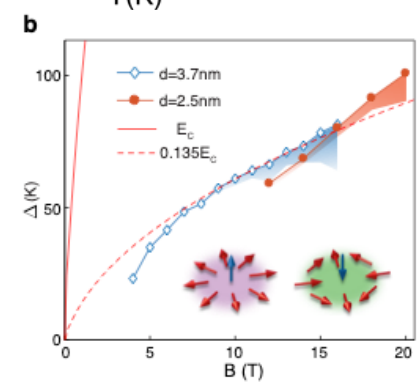
$R_{xx}{}^{CF}$ (keeping $\nu_{tot} = -1$)



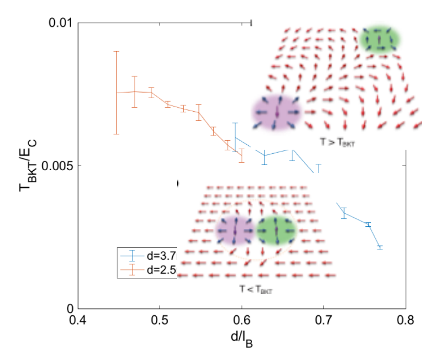
Temperature Dependence



BEC

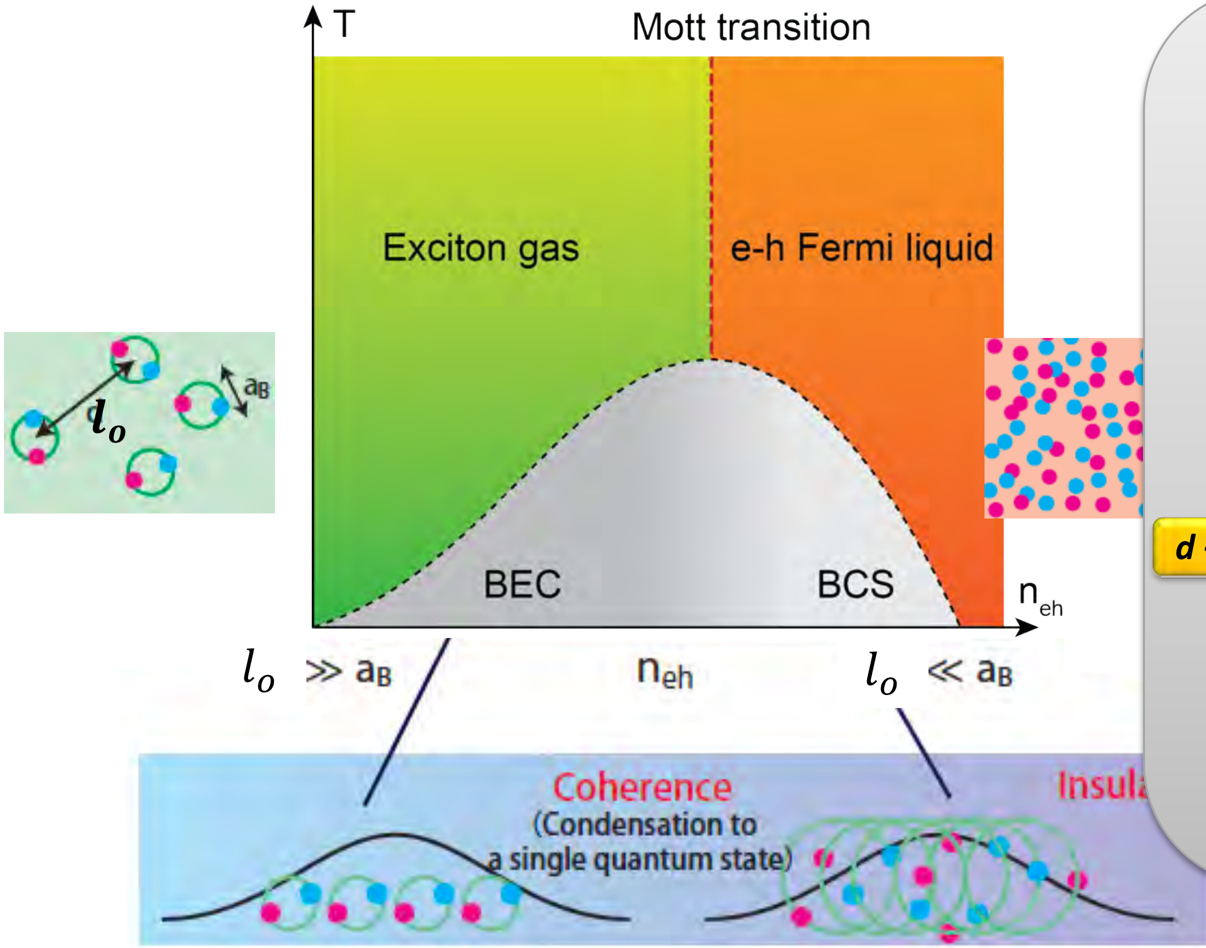


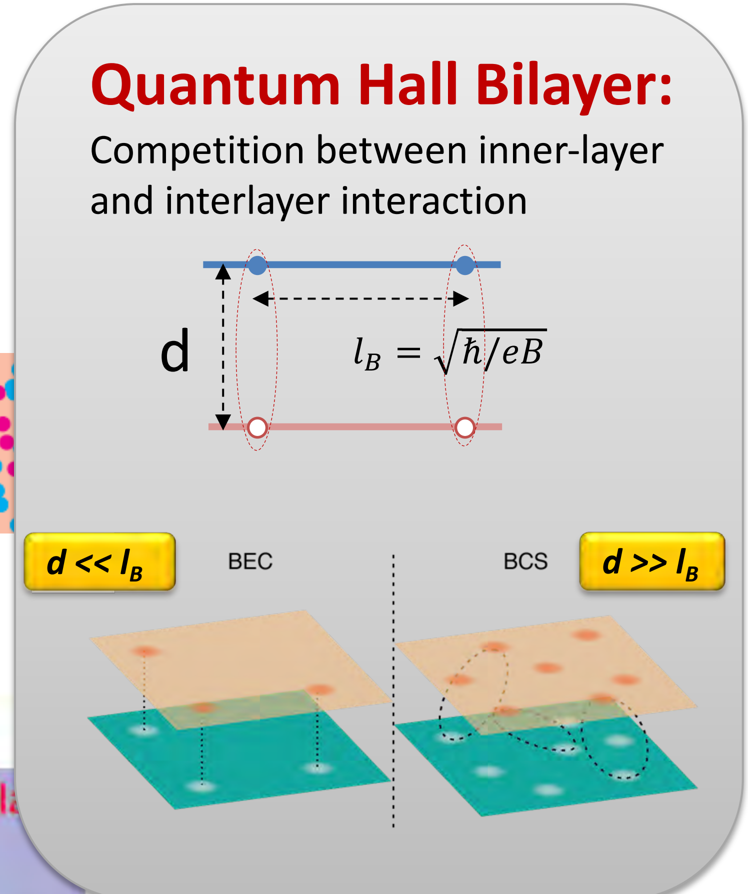
BCS



Exciton/e-h Phase Diagram

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



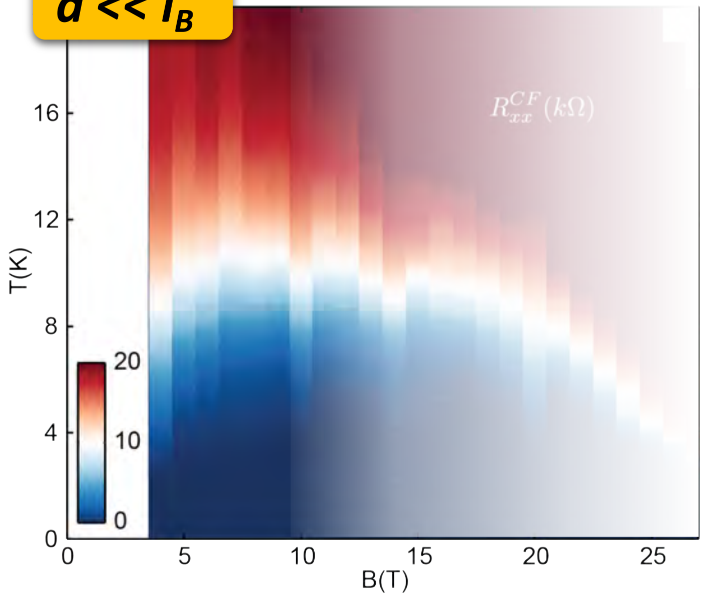


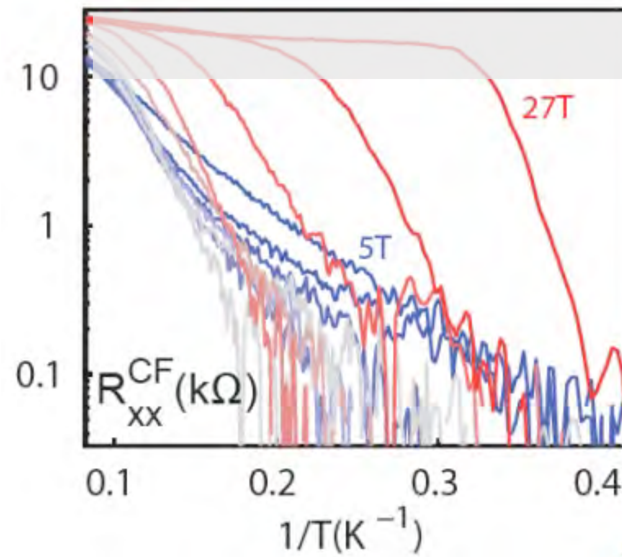
T. Ogawa and K. Asano (2008)

Activation Gap at the BEC Limit

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

$d << l_B$

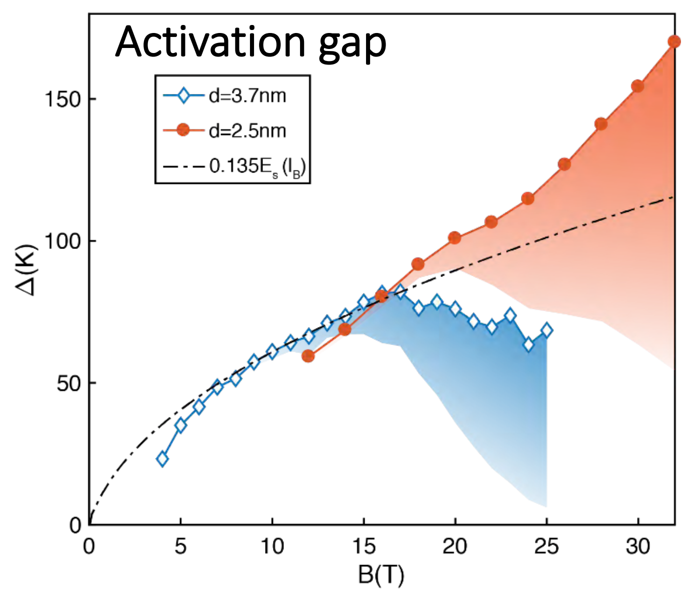




Activating behaviors

2D XY Ground State: → Anisotropic SU(2)

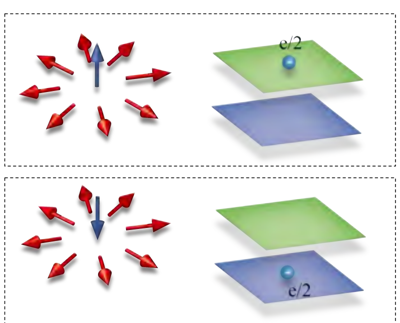
$$|\Psi\rangle = \prod_k \frac{1}{\sqrt{2}}(c^\dagger_{k,T} + e^{i\phi}c^\dagger_{k,B})|0\rangle \qquad |\psi\rangle = \prod_k (\cos\theta \ c^\dagger_{k,T} + e^{i\phi}\sin\theta \ c_{k,B})|0\rangle$$



$$E_S = 0.135\frac{e^2}{\epsilon l_B}$$

Low Energy Excitation

meron-antimeron pair, each carrying e/2 charge on one graphene layer.



meron

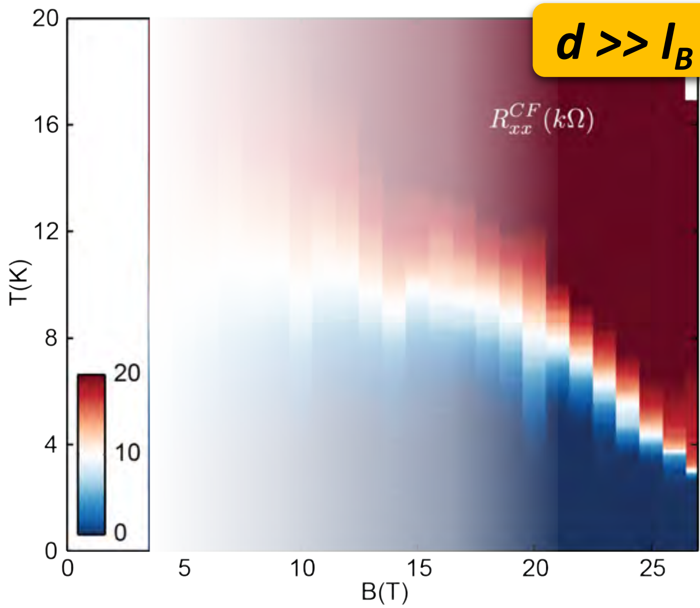
Anti-meron

$$E_{m-am} = \sqrt{\pi/32}\frac{e^2}{\epsilon l_B} \sim 0.31\ \frac{e^2}{\epsilon l_B}$$

Moon *et al.*, PRB **51** 5138 (1995)

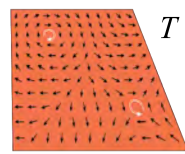
BKT Transition at the BCS Limit

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



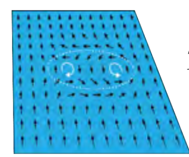
BKT transition

Unbound vortices

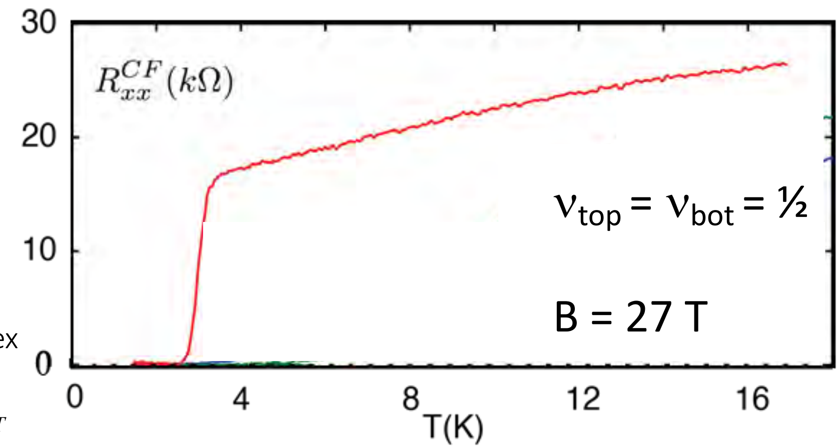


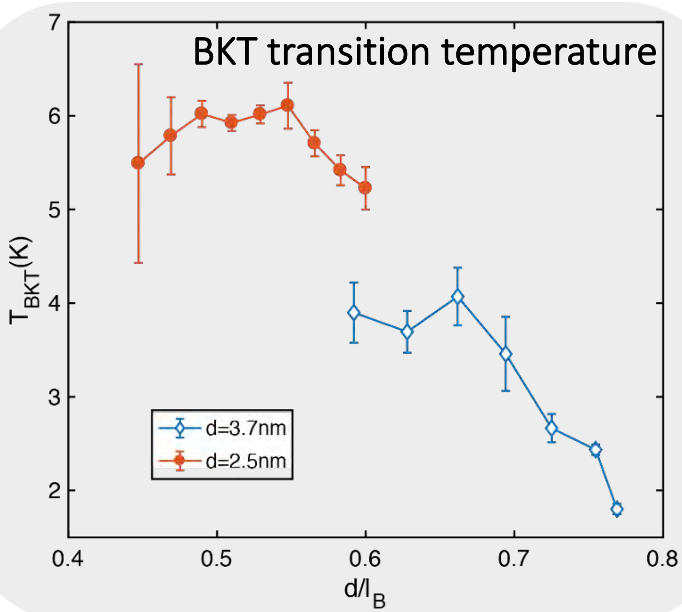
$T > T_{BKT}$

Bound vortex/anti-vortex

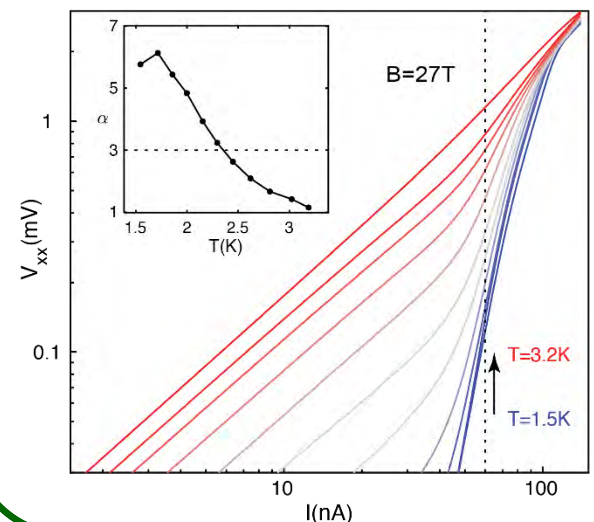


$T < T_{BKT}$





Counter Flow I-V Characteristic



IV curves exhibit power law

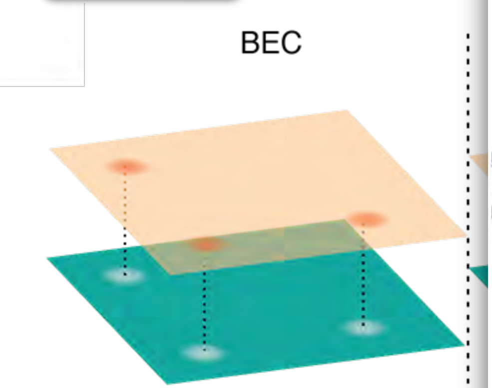
$$T < T_{KT}: V \propto I^{\alpha},$$

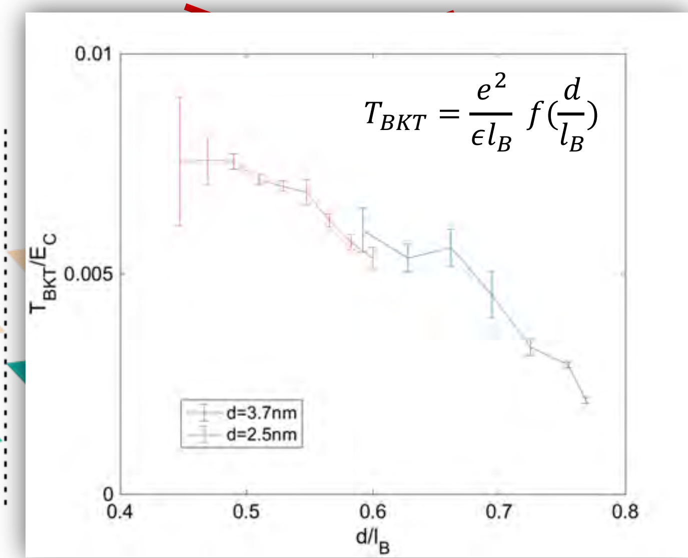
$$\alpha = 1 + 2\frac{T_{KT}}{T}$$

$$T > T_{KT}: V \propto I$$

BCS-BEC Crossover in Magnetoexciton Condensate

$d << l_B$





Ground States

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

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

- $d \gg l_B$

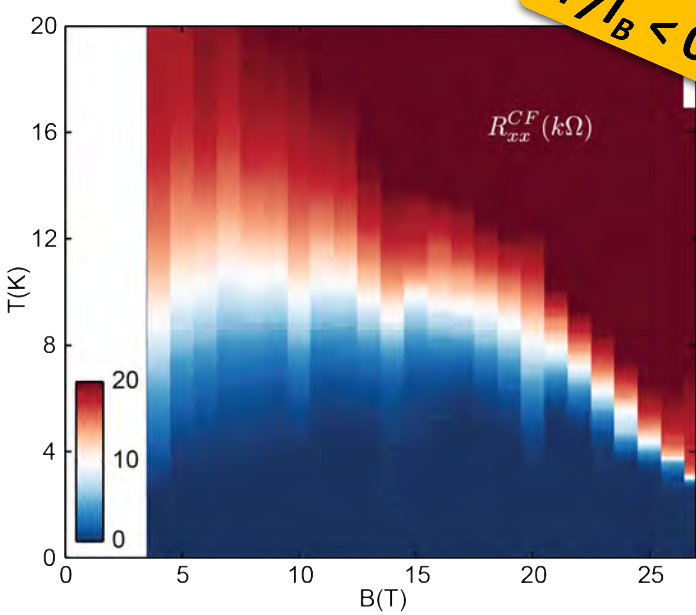
: weakly coupled composite fermions

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

- $d \sim l_B$: many proposals

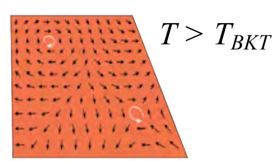
N. E. Bonesteel, et al., PRL 77, 3009 (1996)
J. Alicea, et al., PRL 103, 256403 (2009).
G. Moller, et al., PRB 79, 125106 (2009)
I. Sodemann, et al., PRB 95, 085135 (2017)
…

$d / l_B < 0.8$

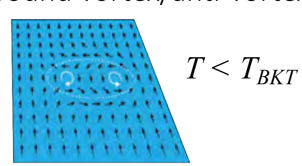


BKT transition

Unbound vortices

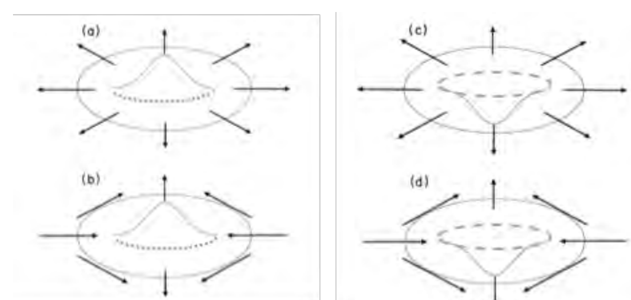


Bound vortex/anti-vortex



Topological defects:

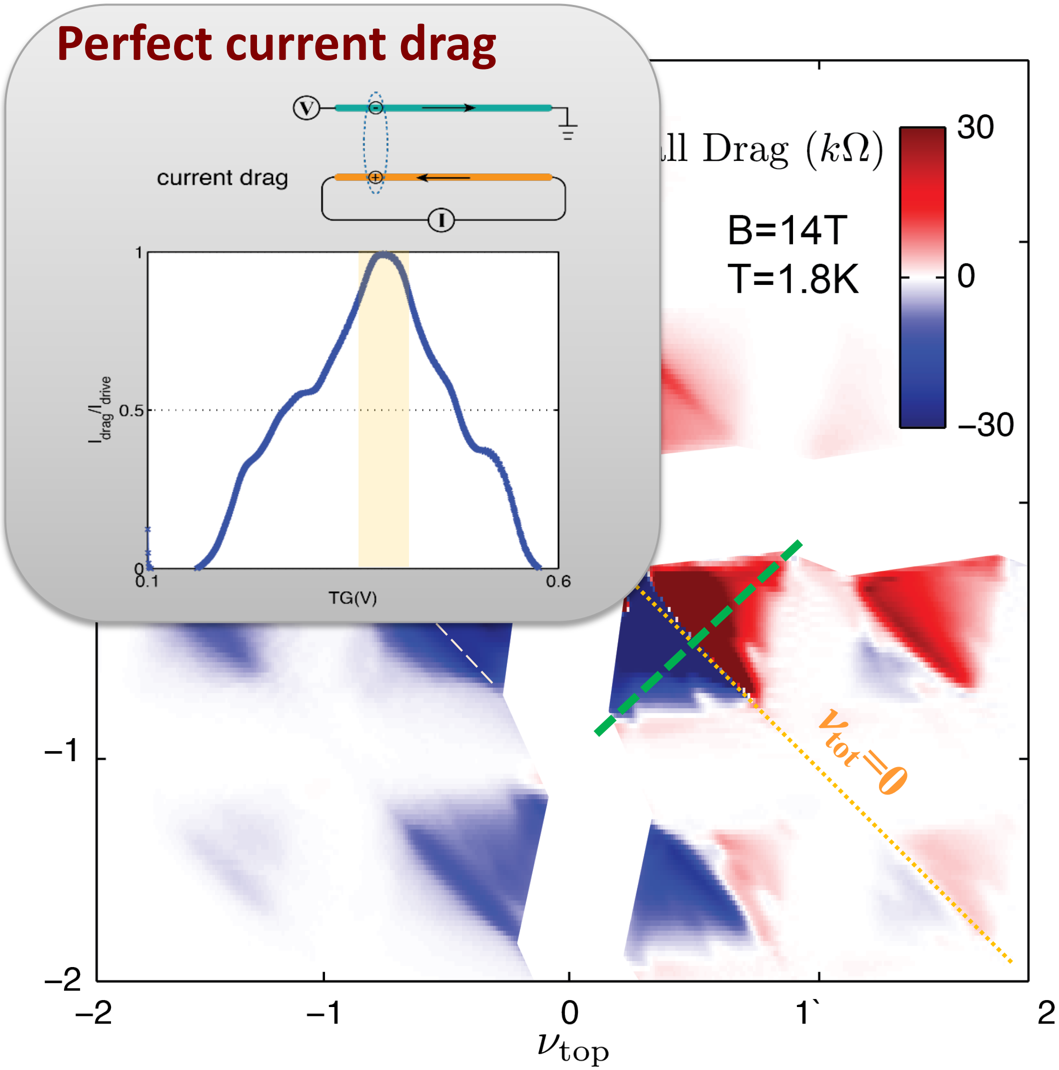
vorticity and fractionalized charges

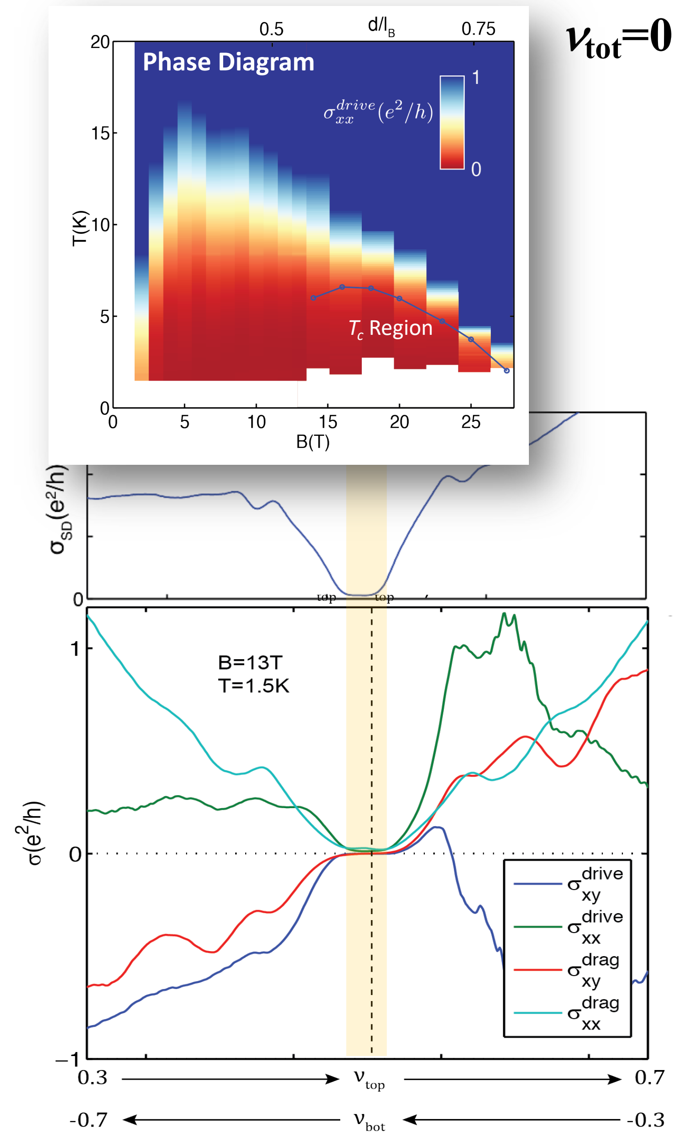


K. Moon, et al., PRB 51, 5183 (1995)

Magneto Exciton Insulator: $\nu_{tot} = 0$

Monlayer/hBN/Monolayer



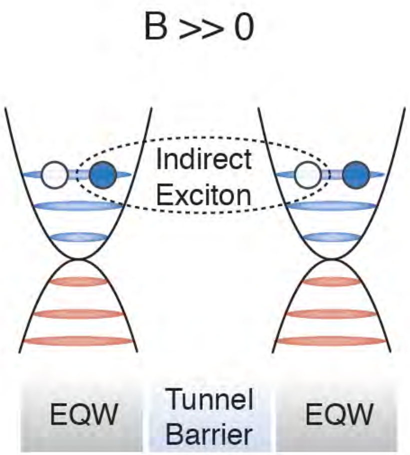


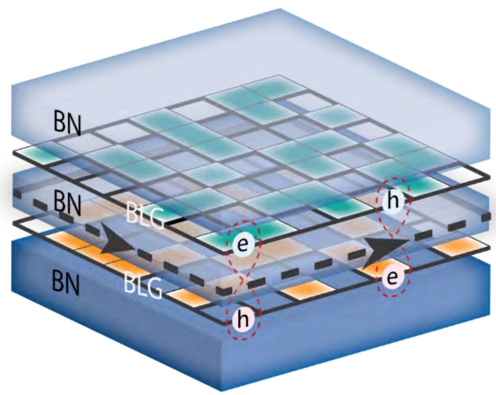
Exciton insulator!

Xiaomeng Liu *et al*, unpublished: collaboration with Dean group

Topological Insulating Exciton Condensation

Exciton condensation between LL (topological exciton insulator)

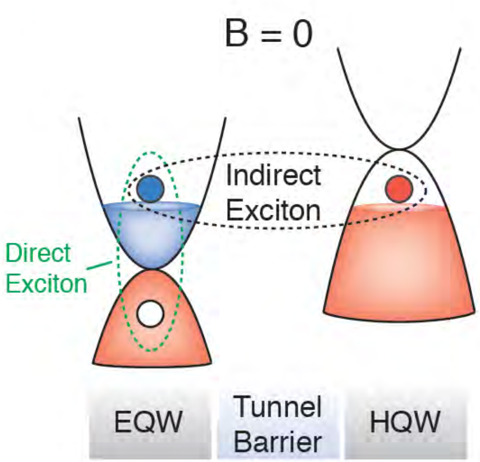


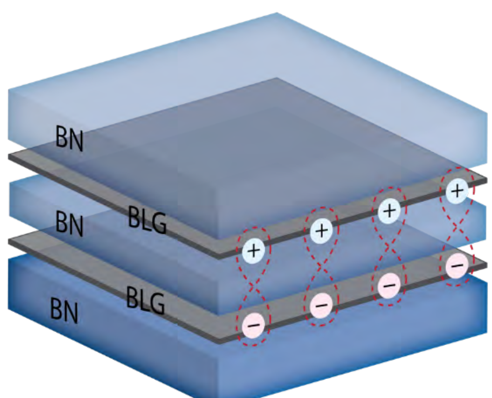


$$R_{xx}^{CF} = 0 \qquad R_{xx}^{sym} = 0$$

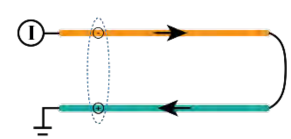
$$R_{xy}^{CF} = 0 \qquad R_{xy}^{sym} = \frac{h}{\nu_{tot} e^2}$$

Exciton condensation (exciton insulator)

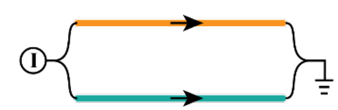




Counter Flow

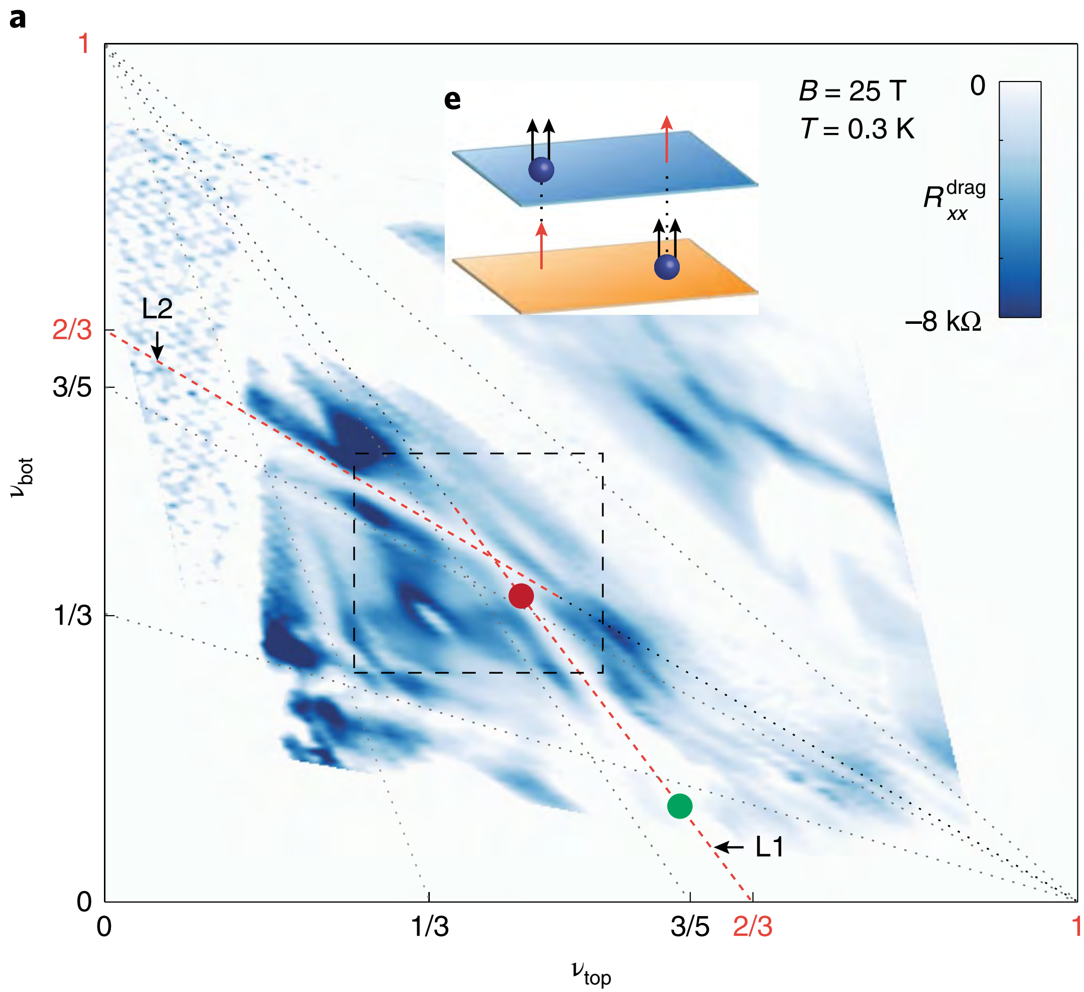


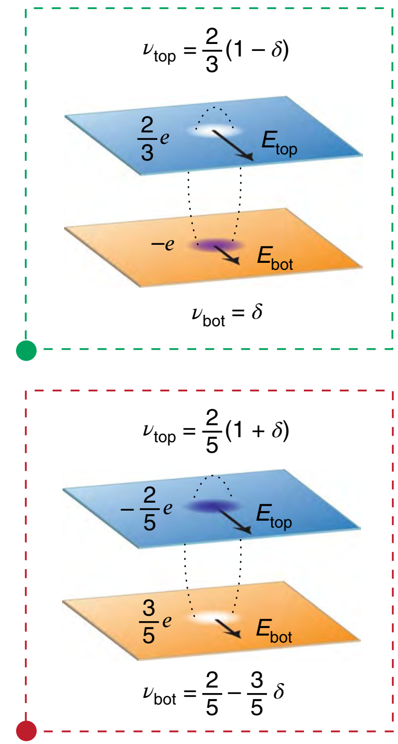
Symmetric Flow



$$R_{CF} = 0 \qquad R_{sym} = \infty$$

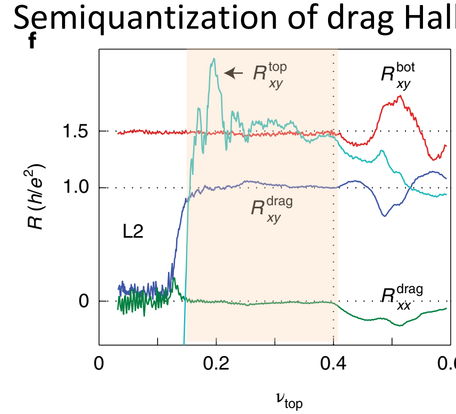
Anyon Pairing Across vdW Gap





Anyonic quasiparticles pairings with fractionalized charges

Semiquantization of drag Hall



Interlayer composite fermion pairing

Xiaomeng Liu *et al*, Nature Physics (2019); Similarly J. Li et al. Nature Physics (2019)

Ferromagnetic Superconductivity in Twisted Double Bilayer Graphene

Xiaomeng Liu

Zeyu Hao

Ashvin Vishwanath

Jong Yeon Lee

Eslam khalaf

T. Taniguchi, K. Watanabe

Spin-polarized Correlated Insulator and Superconductor in Twisted Double Bilayer Graphene
X. Liu, Z. Hao, E. Khalaf, J. Y. Lee, K. Watanabe, T. Taniguchi, A. Vishwanath, P. Kim
arXiv:1903.08130, *submitted*

Graphene

Dirac Fermions

Quantum Hall Effect

Klein Tunneling

Fractional Quantum Effect

Fractal Quantum Hall Effect

Hydrodynamics

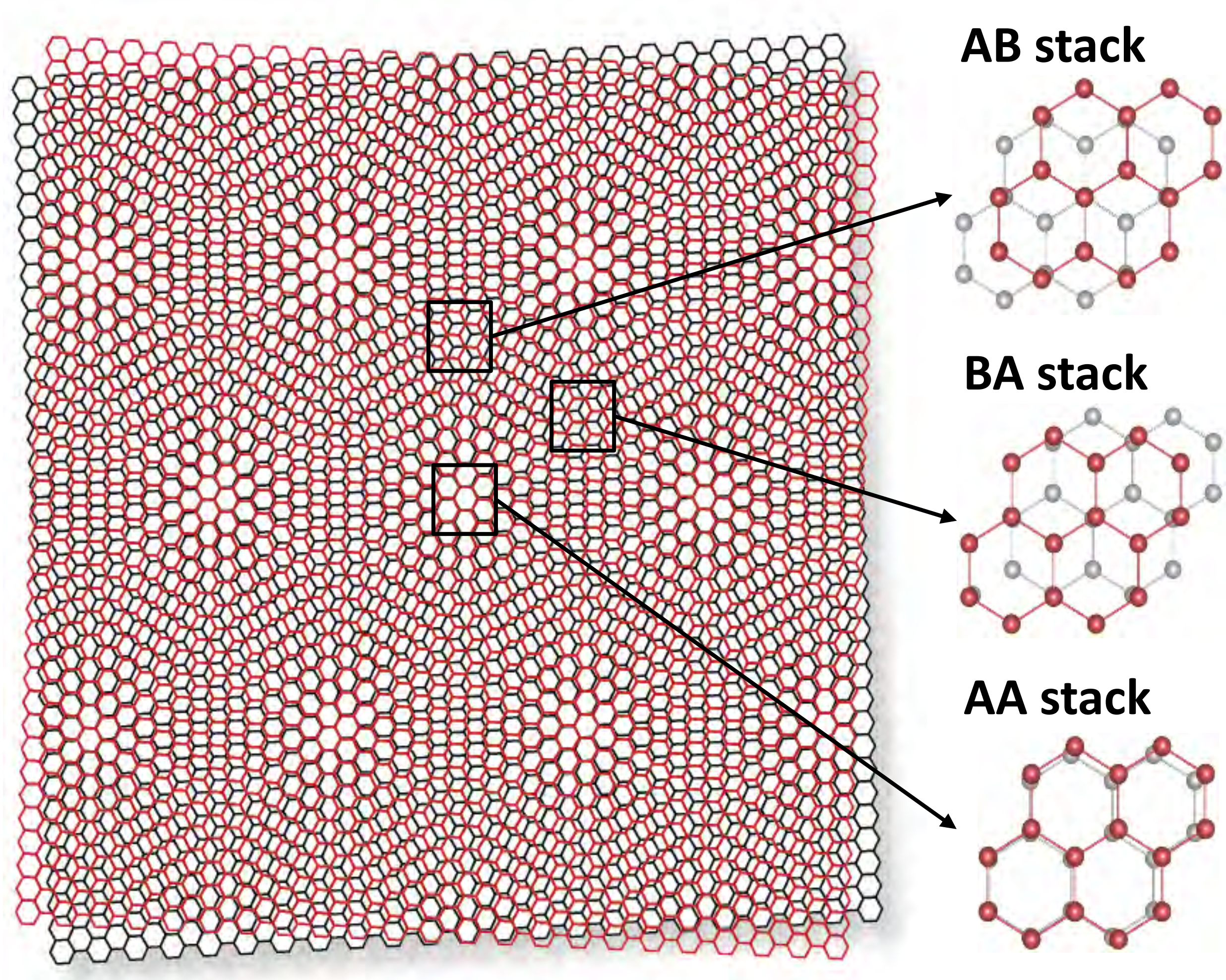
⋮

Superconductivity ?

Magnetism ?

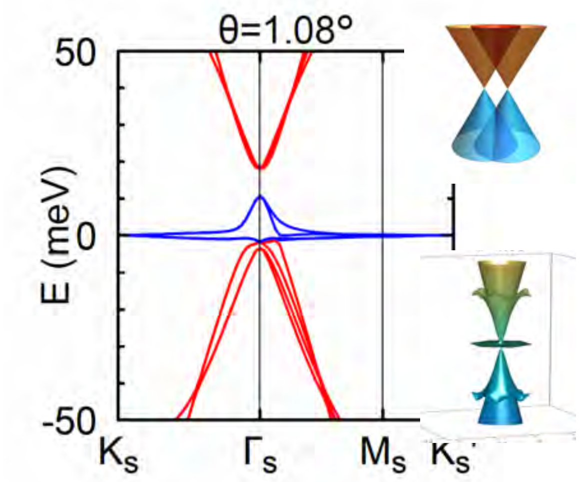
since 2004

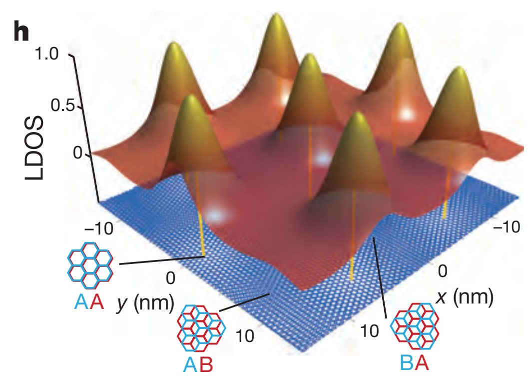
Twisted Graphene Bilayer: Magic Angle



Moire Structure in Twisted Graphene on Graphene

Special 'magic' angle



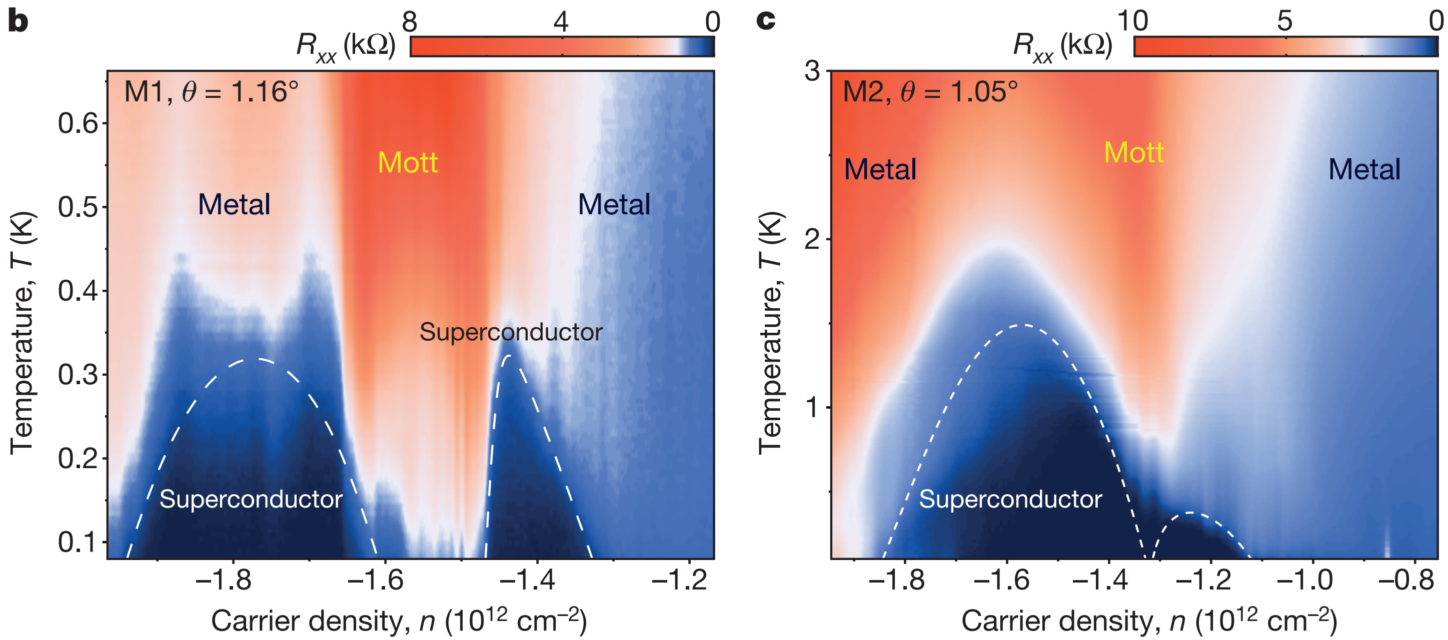


Localized electron wave function at AA sites

Bistritzer & MacDonald, PNAS (2011)

S. Fang, E. Kaxiras. *PRB* 93, 235153 (2016)

Superconductivity of Magic Angle TBG



Mott Insulator
&
Superconductors

Y. Cao et al. Nature (2018) x 2

Followed by:

Yankowitz et. al., *Science* 363 (2018): pressure tunable superconductivity

Chen et. al. *Nature (2019)*: trilayer graphene/hBN

Lu et. al. *Nature (2019)*: superconductivity and orbital magnet in magic angle graphene

• • •

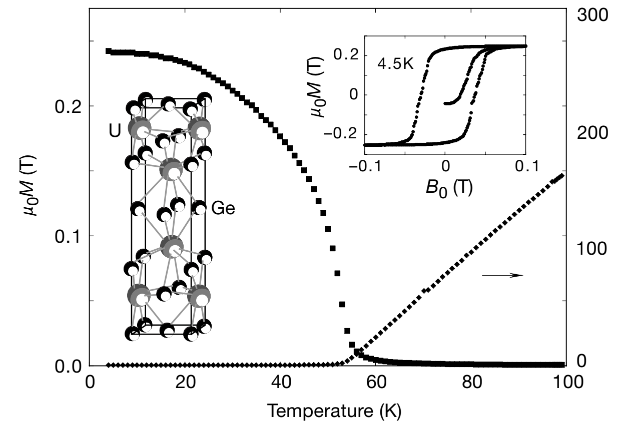
Ferromagnetic Superconductors

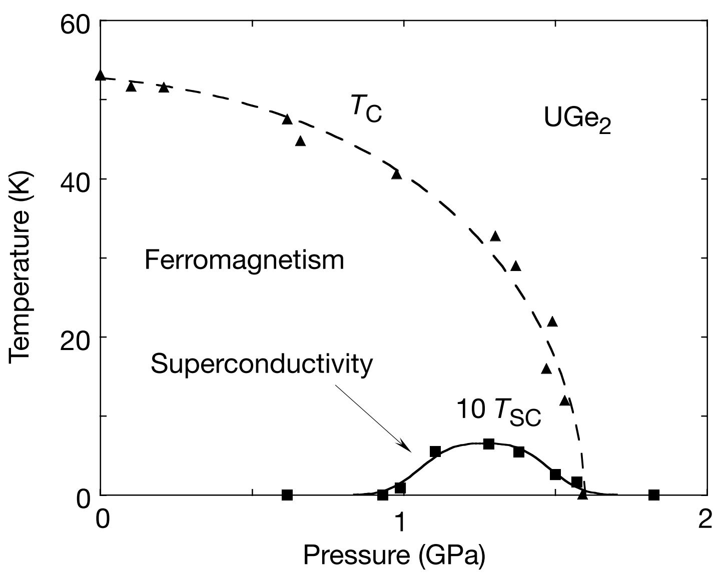
Superconductivity on the border of itinerant-electron ferromagnetism in UGe_2

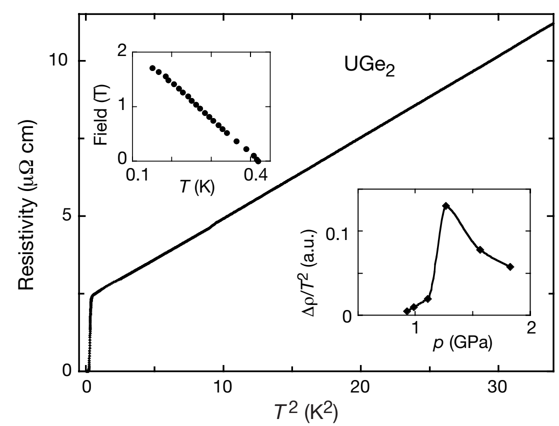
S. S. Saxena*†‡, P. Agarwal*, K. Ahilan*, F. M. Grosche*‡, R. K. W. Haselwimmer*, M. J. Steiner*, E. Pugh*, I. R. Walker*, S. R. Julian*, P. Monthoux*, G. G. Lonzarich*, A. Huxley§, I. Sheikin§, D. Braithwaite§ & J. Flouquet§

** Department of Physics, Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge CB3 0HE, UK*
† Materials Science Centre, University of Groningen, Nigenborgh 4, 9747AG, The Netherlands
§ Département de Recherche Fondamentale sur la Matière condensée - SPSMS, CEA Grenoble, 17 Av. des Martyrs, Grenoble 38054, France

NATURE | VOL 406 | 10 AUGUST 2000 |

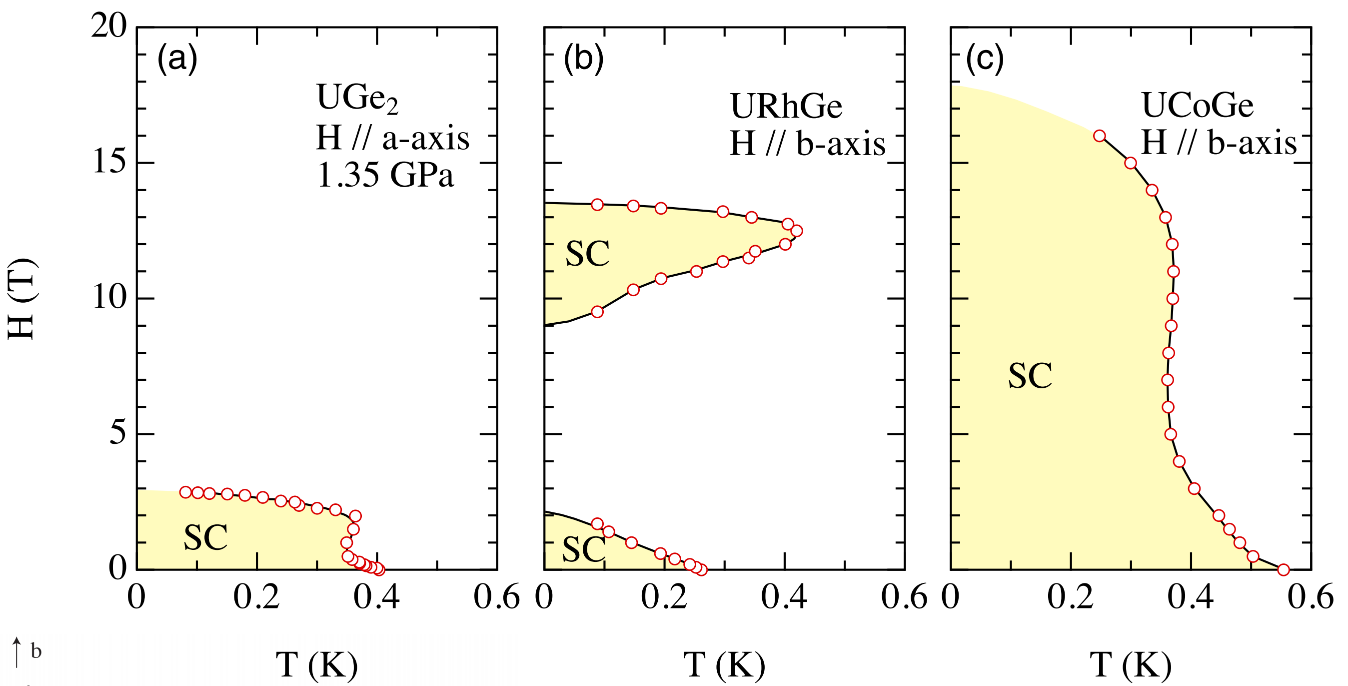


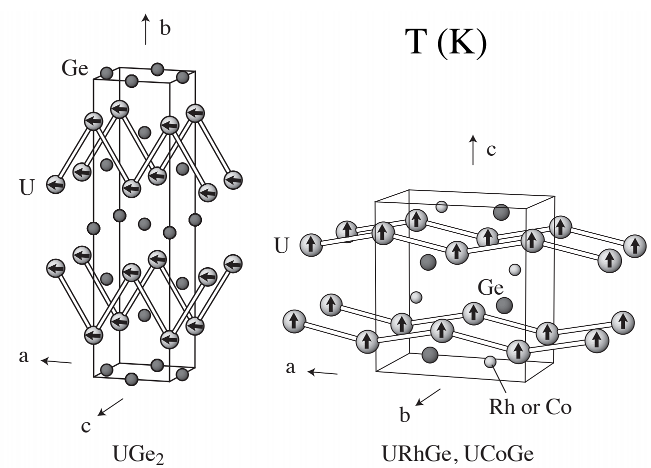




Followed by URhGe (Aoki et al., 2001)
UCoGe (Huy et al., 2007)

Ferromagnetic Superconductors: H_c versus T





Magnetic field along the hard axis of ferromagnet.

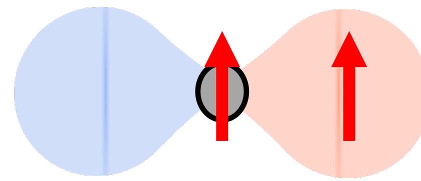
H_c exceeds the Pauli limit (~ 1.85 T_c [T/K])

From review by Aoki and Flouquet, JPSJ 83, 061011 (2014)

Equal-Spin p-wave Pairing: Superfluid ^{3}He A phase

A. J. Leggett (1972)

A-phase Superfluid ^{3}He

$\Psi_{pair}(\mathbf{r}) =$ 

p-wave pairing

VOLUME 53, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 1984

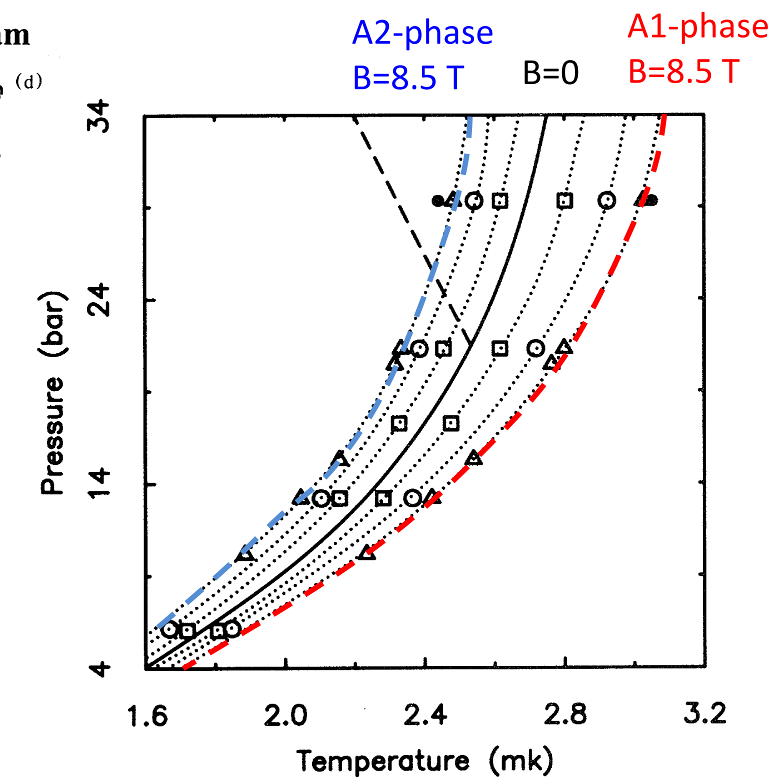
Superfluid ^{3}He in High Magnetic Fields: The Phase Diagram

D. C. Sagan,[a] P. G. N. deVegvar, E. Polturak,[b] L. Friedman,[c] S.-S. Yan [d]
E. L. Ziercher, and D. M. Lee
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14
(Received 30 July 1984)

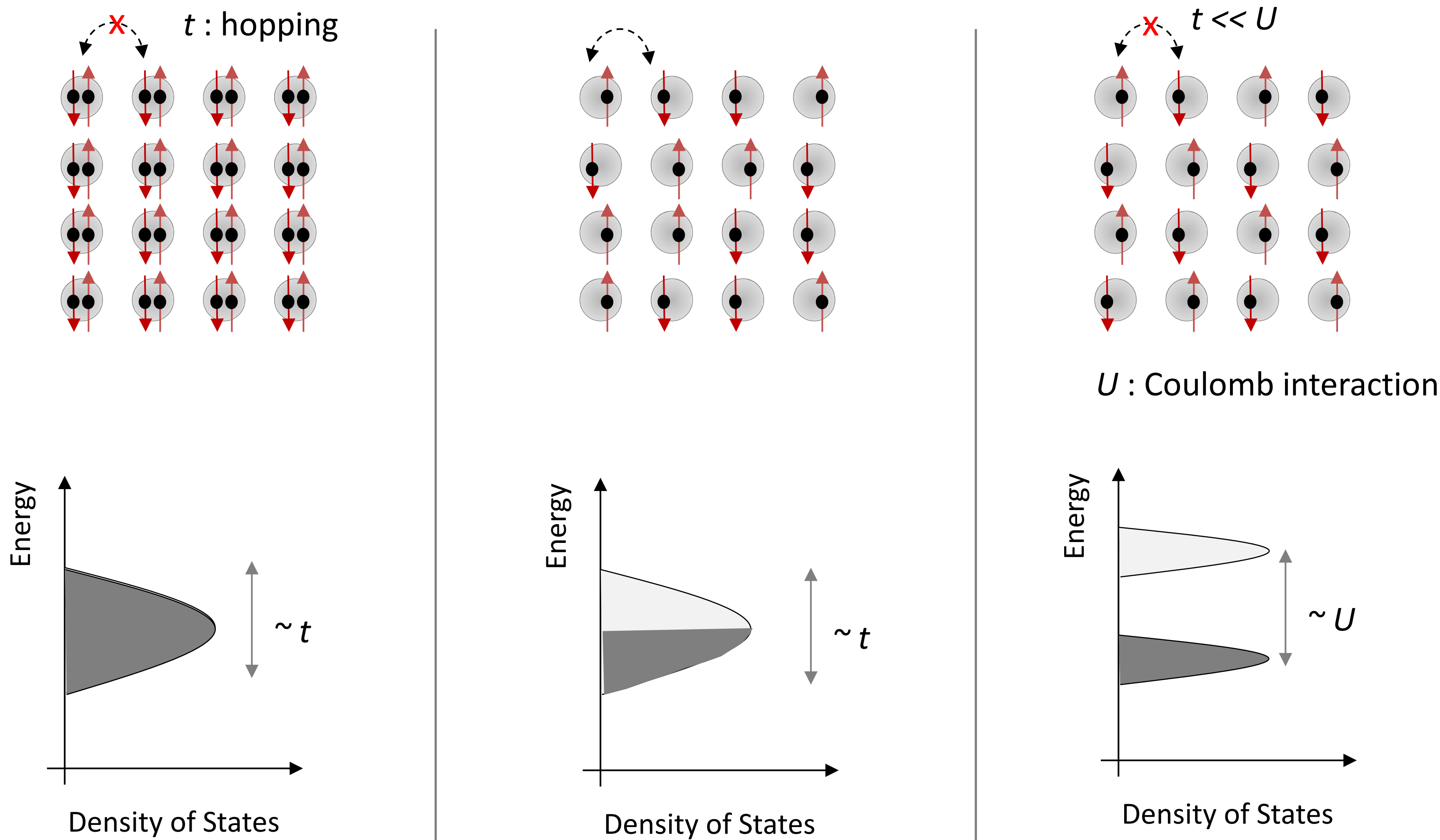
- ↑↑ Cooper pairs condense at $T_c^{A_1} = T_c + \lambda^{A_1} B$
- ↓↓ Cooper pairs condense at $T_c^{A_2} = T_c - \lambda^{A_2} B$

$$\lambda^{A_1} \approx \left|\frac{\gamma\hbar}{2}\right| \left(\frac{k_B T_c}{E_f}\right)$$

Ambegaokar and Mermin (1973)



Mott Insulator



Insulator **Conductor** **Mott Insulator**

N. Mott (1949)

Mott Insulator and Magnetism

The Mott insulators can further be correlated,
considering the exchange interaction of localized electrons.

Anti-Ferromagnetic Mott Insulators are more common, as tightly localized electrons/holes prefer for anti-ferromagnetic spin coupling with neighbors.

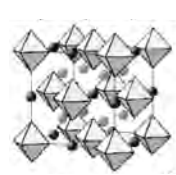
However, ferromagnetic Mott Insulators are also possible for more extended Wannier orbitals.

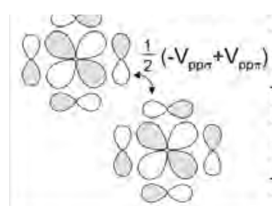
Examples: $YTiO_3$, $Lu_2V_2O_7$, Ba_2NaOsO_6 …

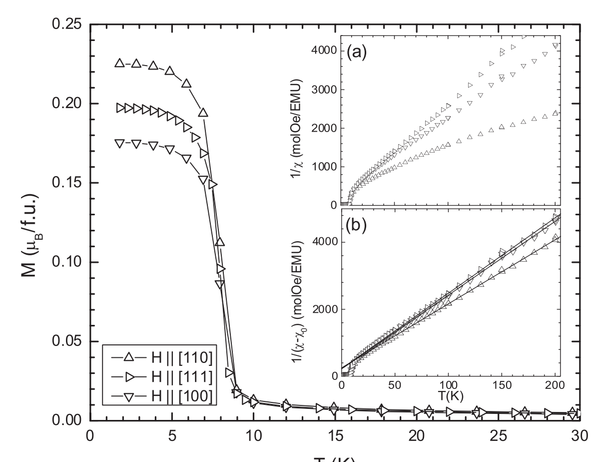
PRL **99,** 016404 (2007) PHYSICAL REVIEW LETTERS week ending 6 JULY 2007

Ferromagnetism in the Mott Insulator Ba_2NaOsO_6

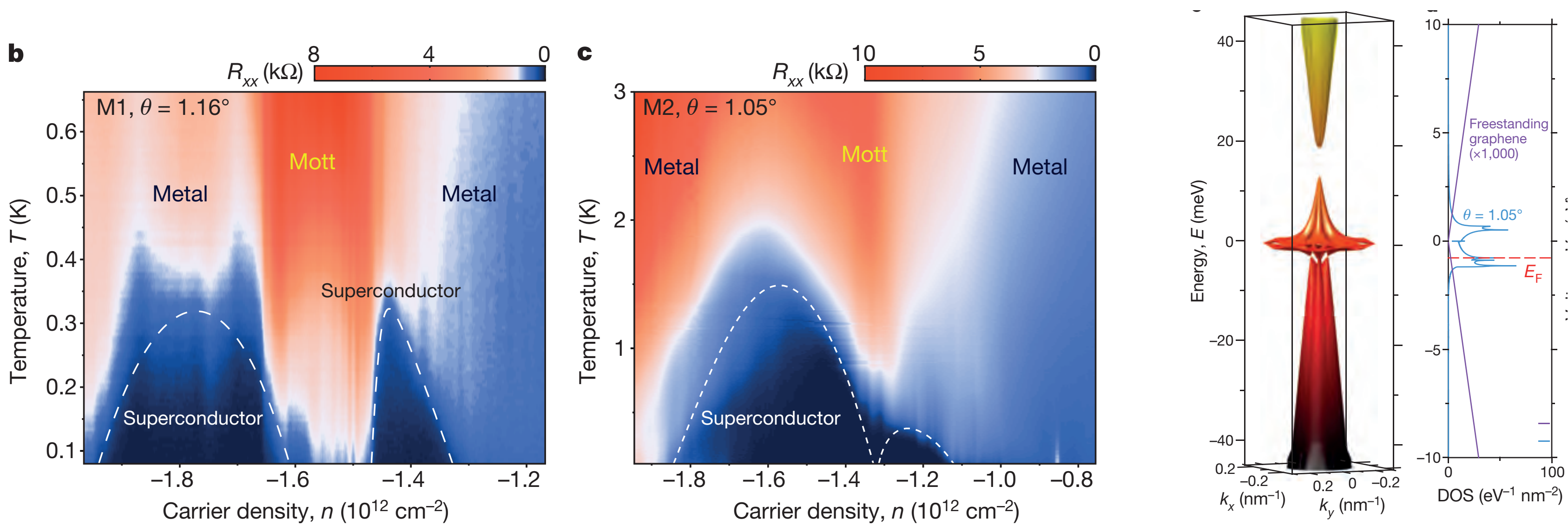
A. S. Erickson,[1] S. Misra,[2] G. J. Miller,[2] R. R. Gupta,[3] Z. Schlesinger,[3] W. A. Harrison,[1] J. M. Kim,[1] and I. R. Fisher[1]
[1]*Department of Applied Physics and Geballe Laboratory for Advanced Materials, Stanford University, California 94305, USA*
[2]*Department of Chemistry and Ames Laboratory, Iowa State University, Ames, Iowa 50011-2300, USA*
[3]*Department of Physics, University of California, Santa Cruz, California 95064, USA*
(Received 29 September 2006; published 6 July 2007)



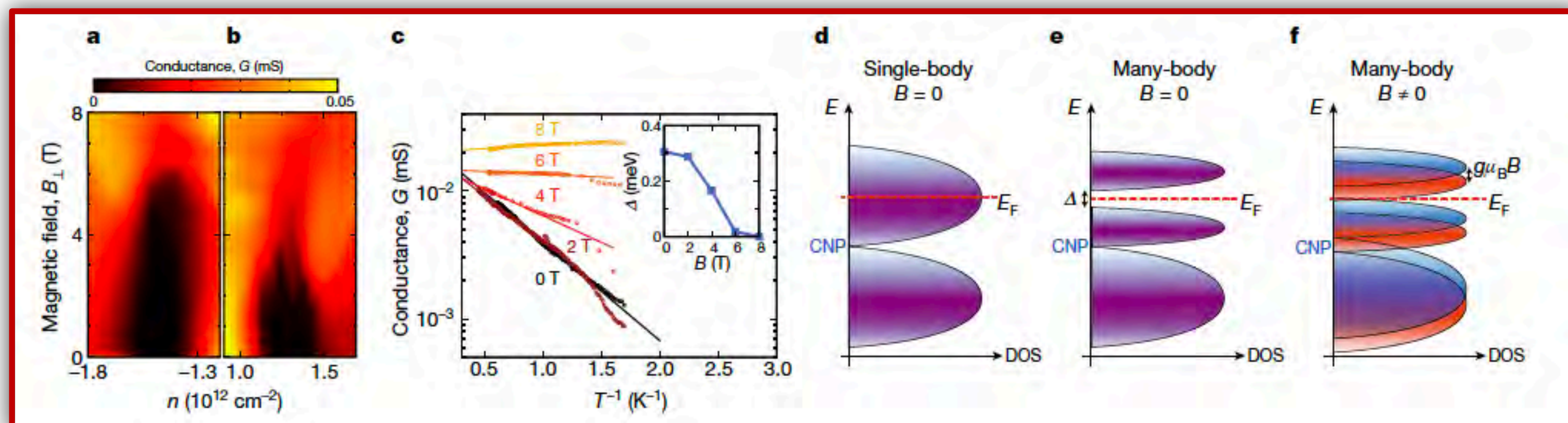




Correlated Quantum State in Twisted Graphene Bilayer

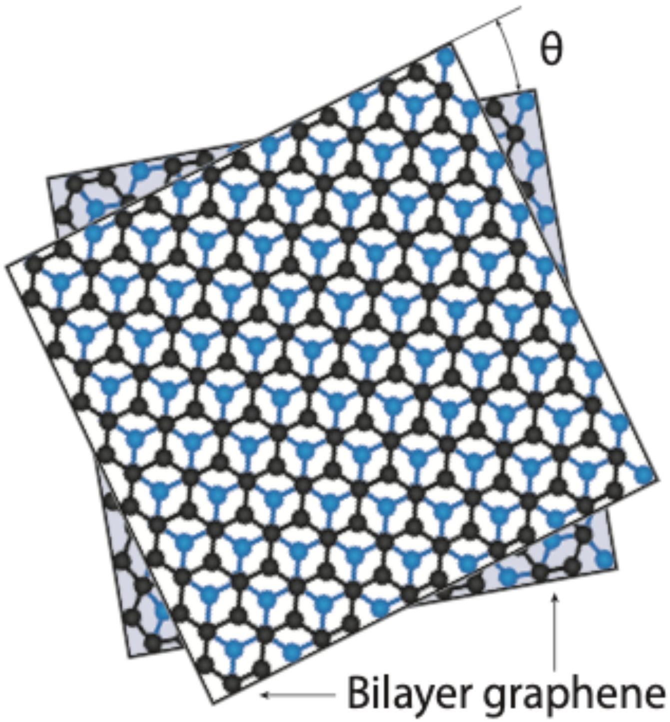


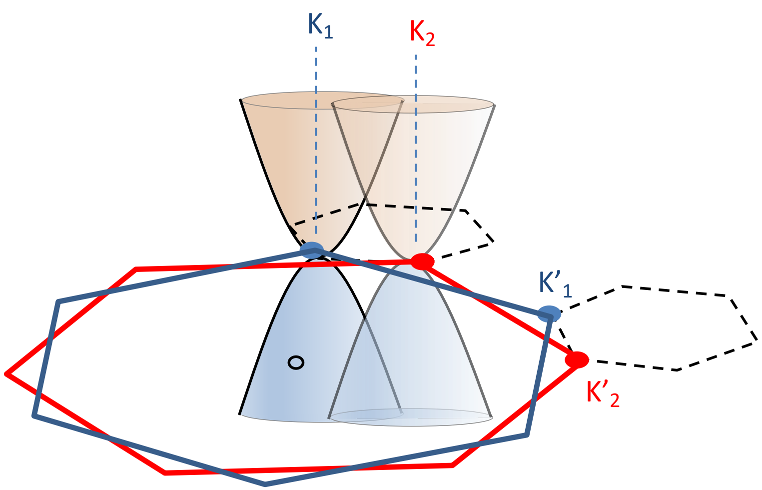
Spin unpolarized Mott Insulators (?)



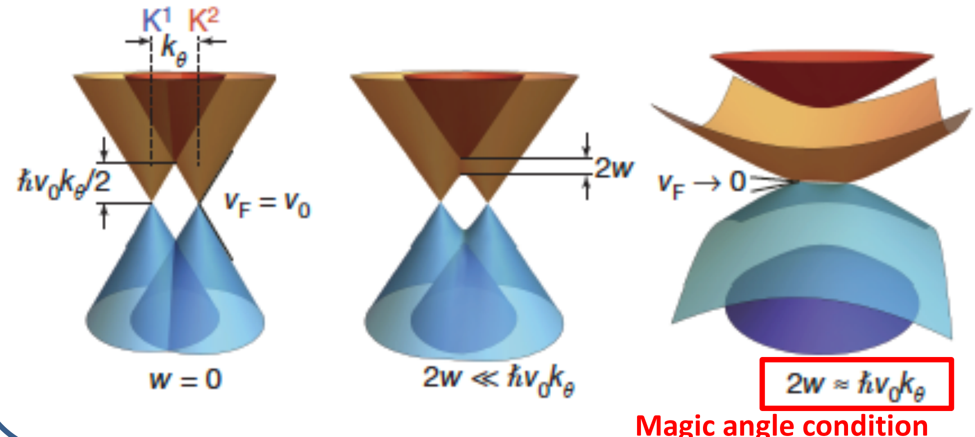
Y. Cao et al. Nature (2018) x 2

Twisted Double Bilayer Graphene

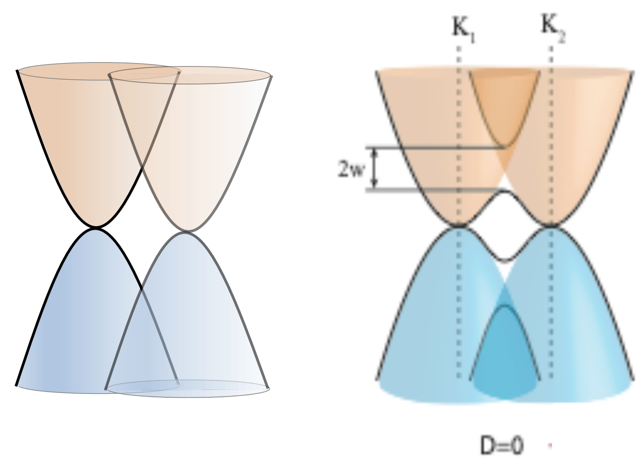




Twisted single layer graphene (tBG)



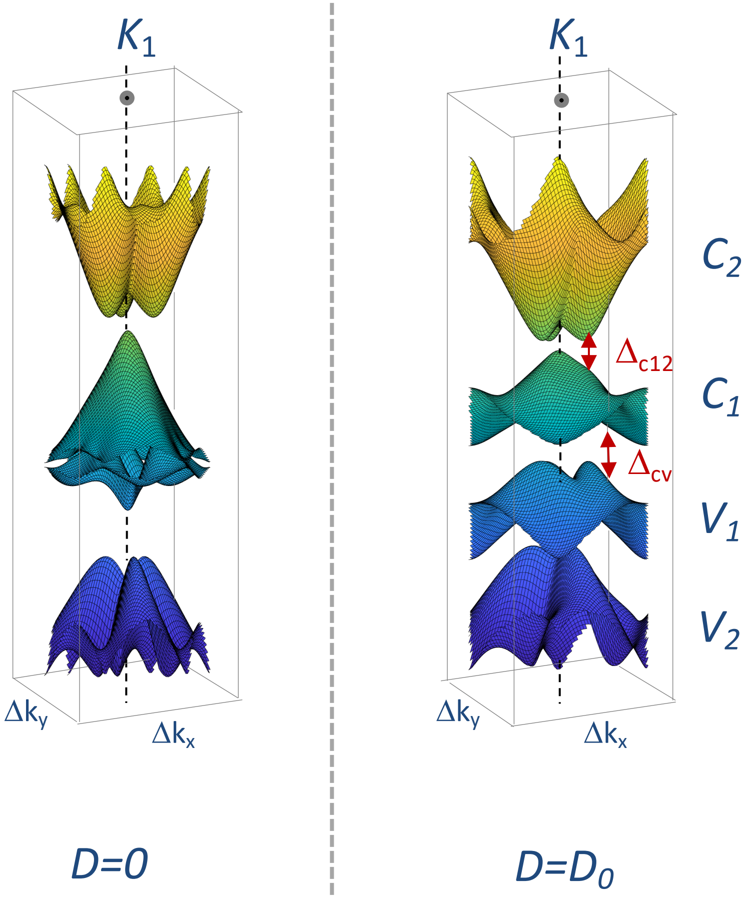
Twisted Double Bilayer Graphene (tDBG)



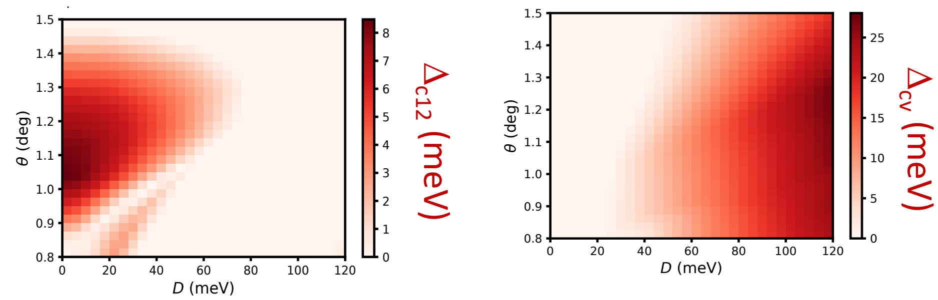
Gate tunable flat bands, no exact angle control needed!

Twisted Double Bilayer Graphene: Tunability

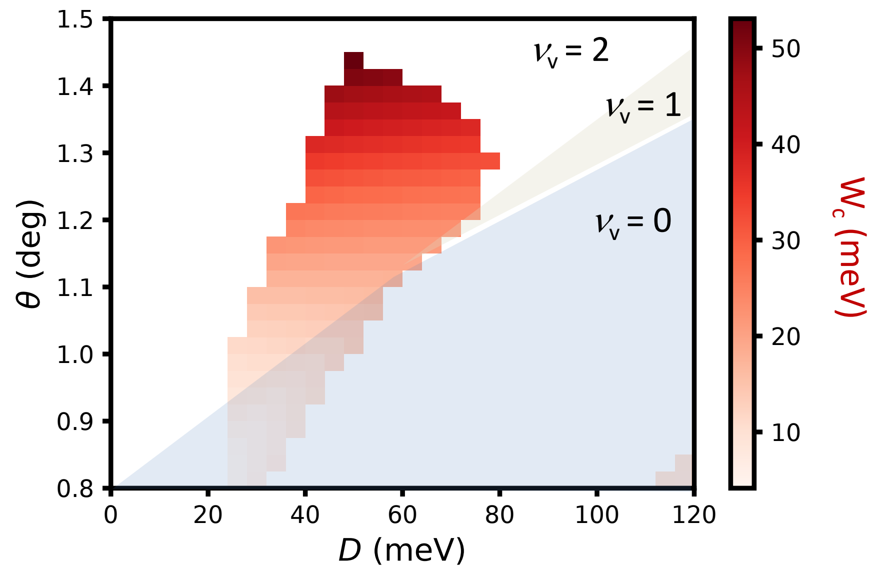
Tight binding with effective Wannier orbits



Band Gaps

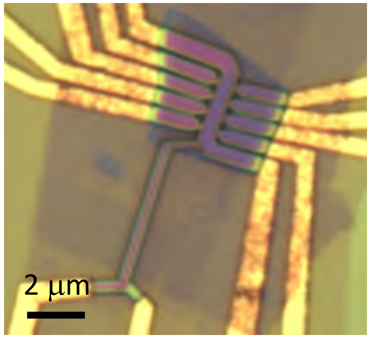


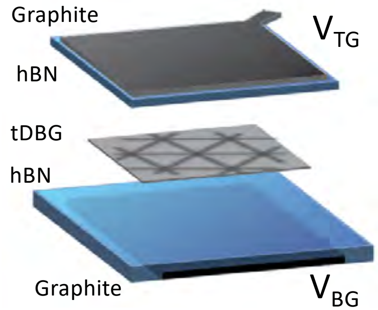
Isolated Conduction band width



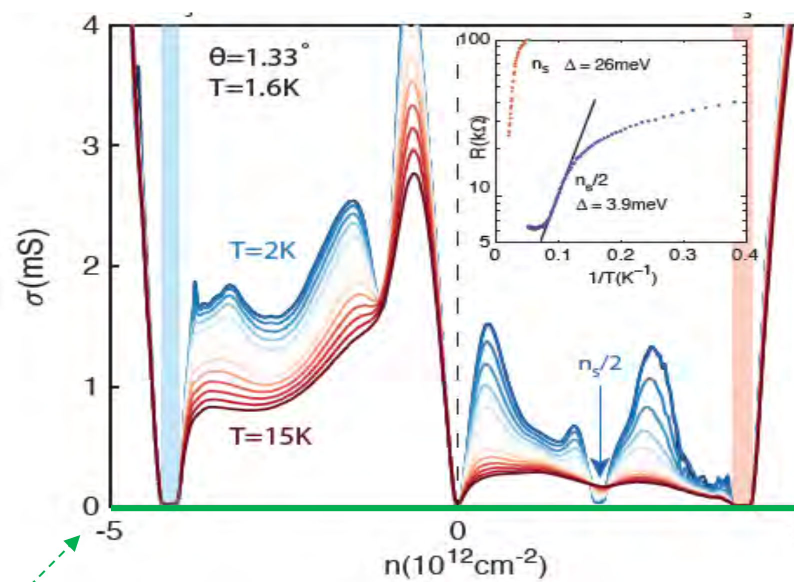
J. Y. Lee, E. Khalaf, S. Liu, X. Liu, Z. Hao, P. Kim, A. Vishwanath, Nature Comm. 10, 5333 (2019).

Mott Insulators in tDBG: $\theta = 1.33^\circ$

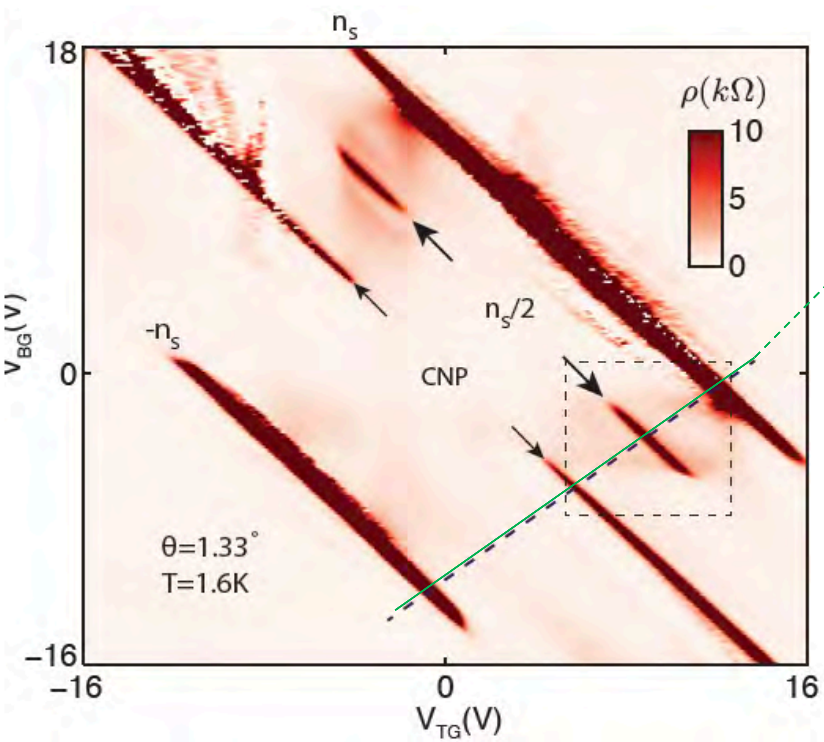


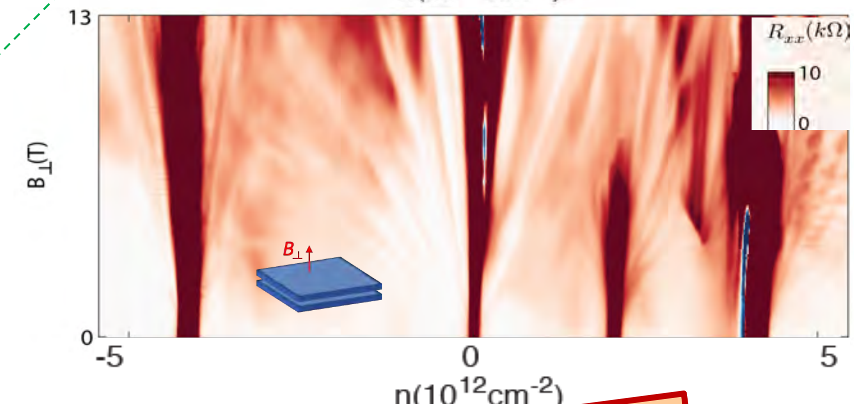


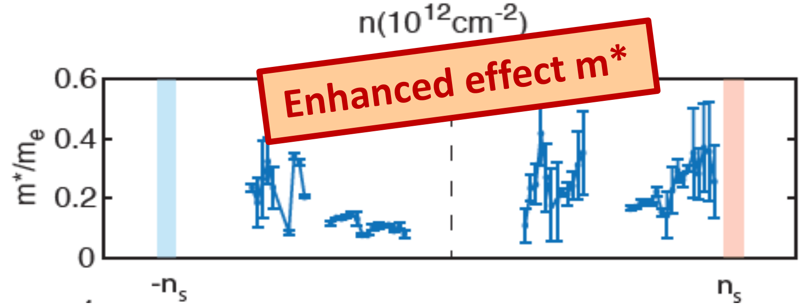
Temperature dependent 2-p conductance



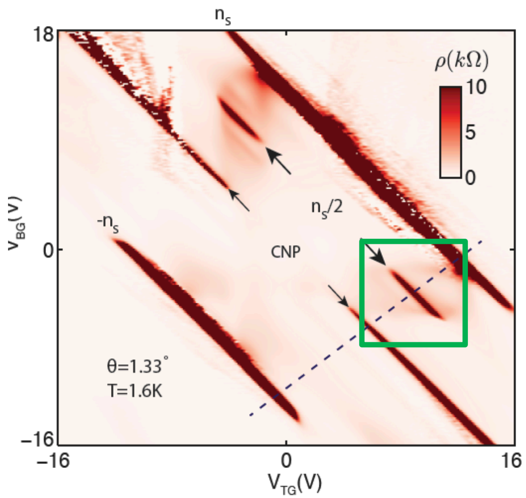
Top and bottom Gate dependent 4-terminal ρ

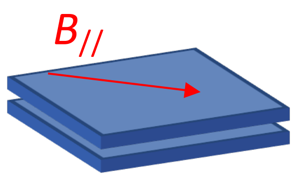


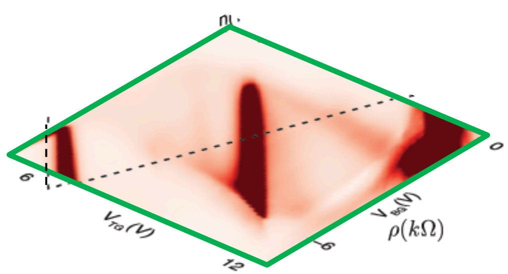




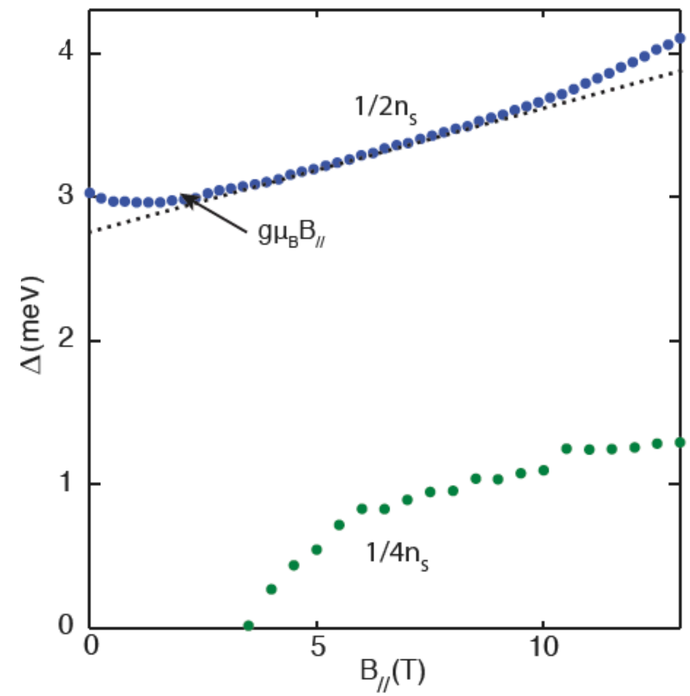
Ferromagnetic Mott Insulators in tDBG $\theta = 1.33^{o}$







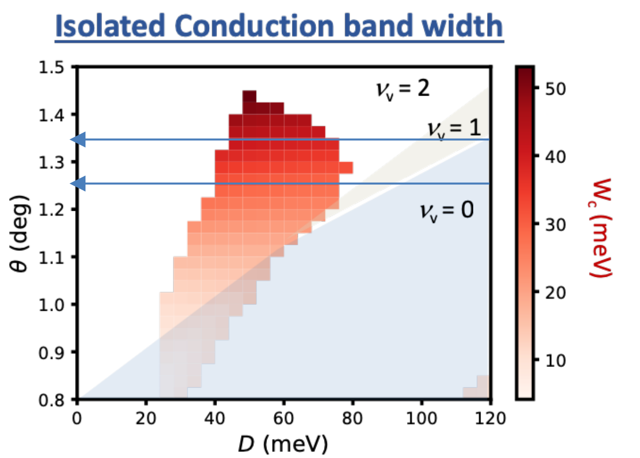
- *$n_s/4$ & $3n_s/4$ gaps appear at finite $B_{//}$*
- *$n_s/2$ states become stronger*

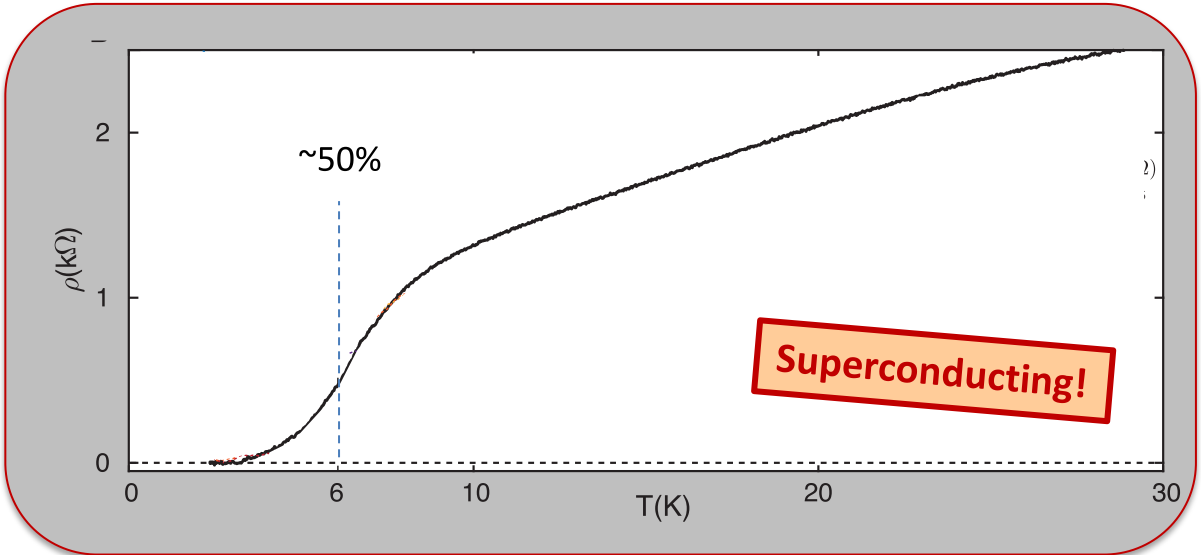


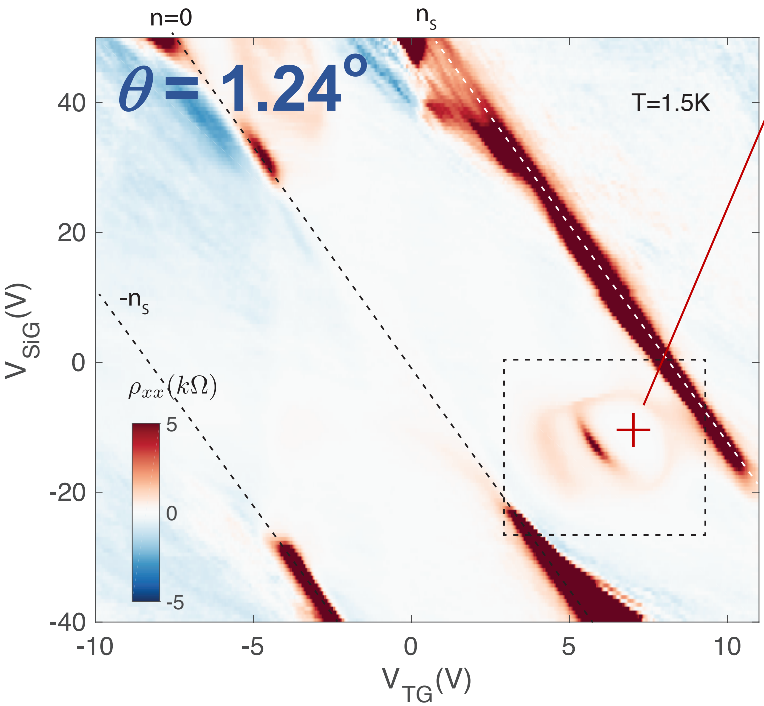
- **Gap increases with $B_{//}$**
- ***$g \approx 2$***

Spin polarized Mott State!

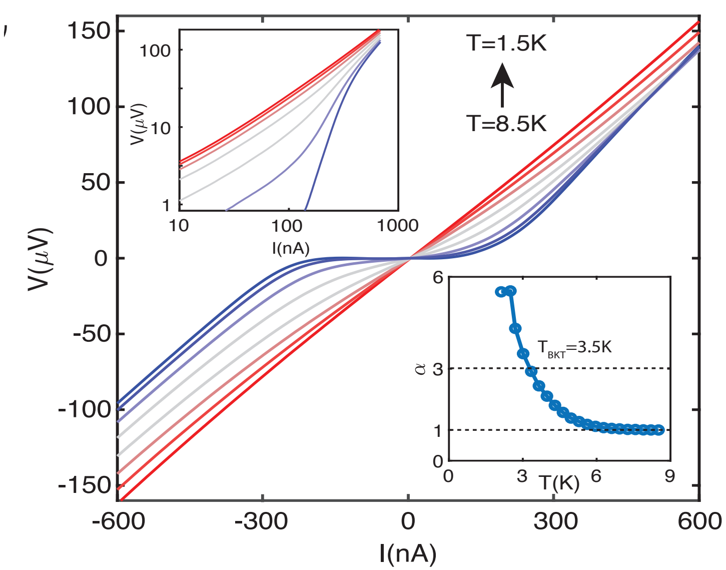
Superconductivity in tDBG





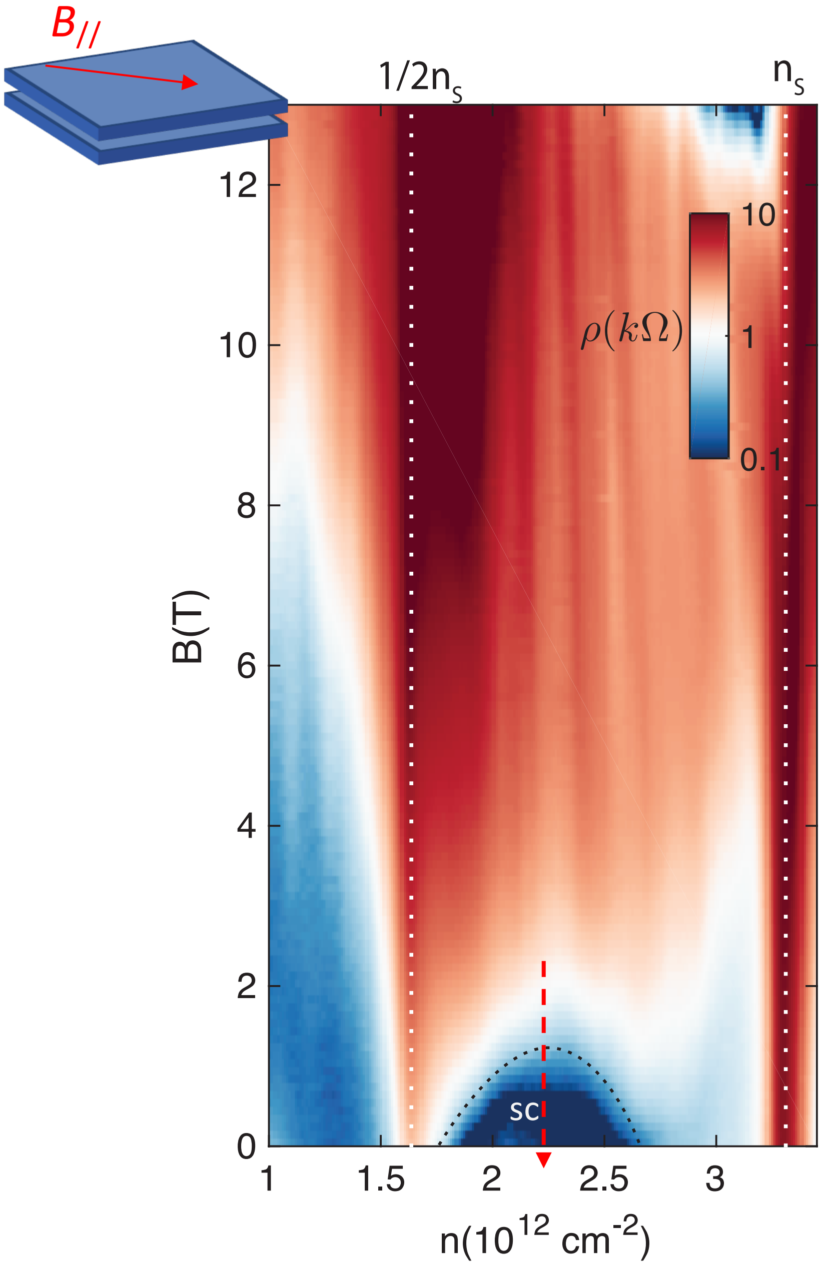


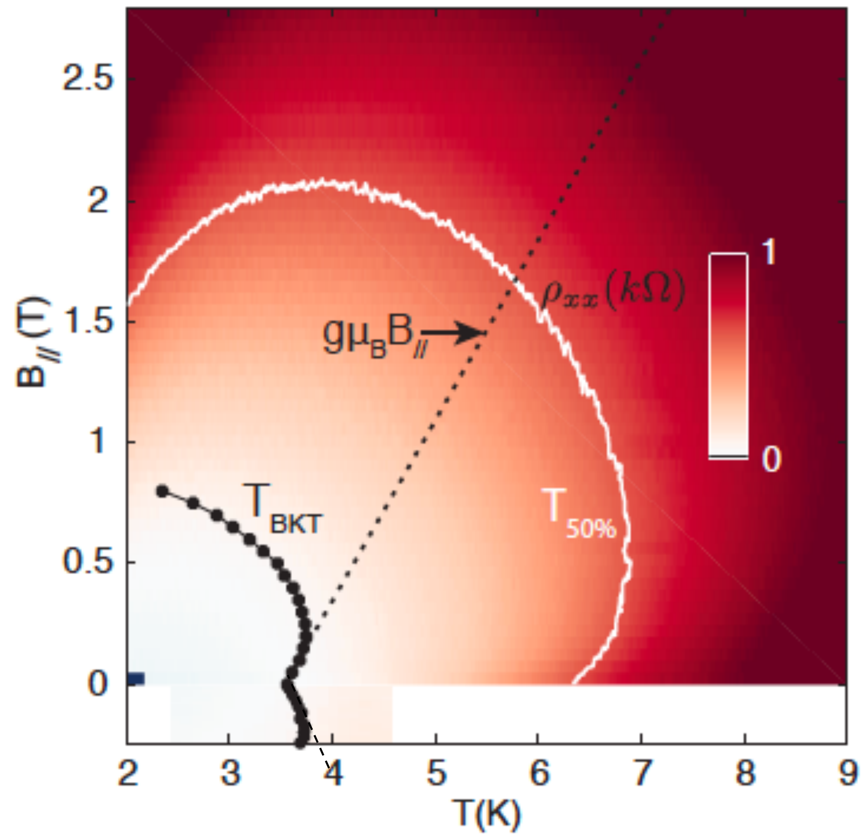
I-V characteristics: BTK Transition



T_{BTK} =3.5 K

Parallel Magnetic Field Dependent SC





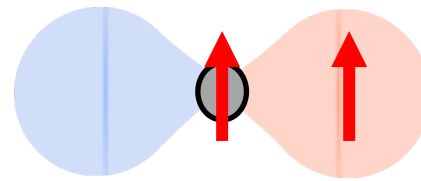
Superconducting state is enhanced by low magnetic field!

Equal-Spin p-wave Pairing: Superfluid ^{3}He A phase

A. J. Leggett (1972)

A-phase Superfluid ^{3}He

$$\Psi_{pair}(\mathbf{r}) =$$



p-wave pairing

VOLUME 53, NUMBER 20 PHYSICAL REVIEW LETTERS 12 NOVEMBER 1984

Superfluid ^{3}He in High Magnetic Fields: The Phase Diagram

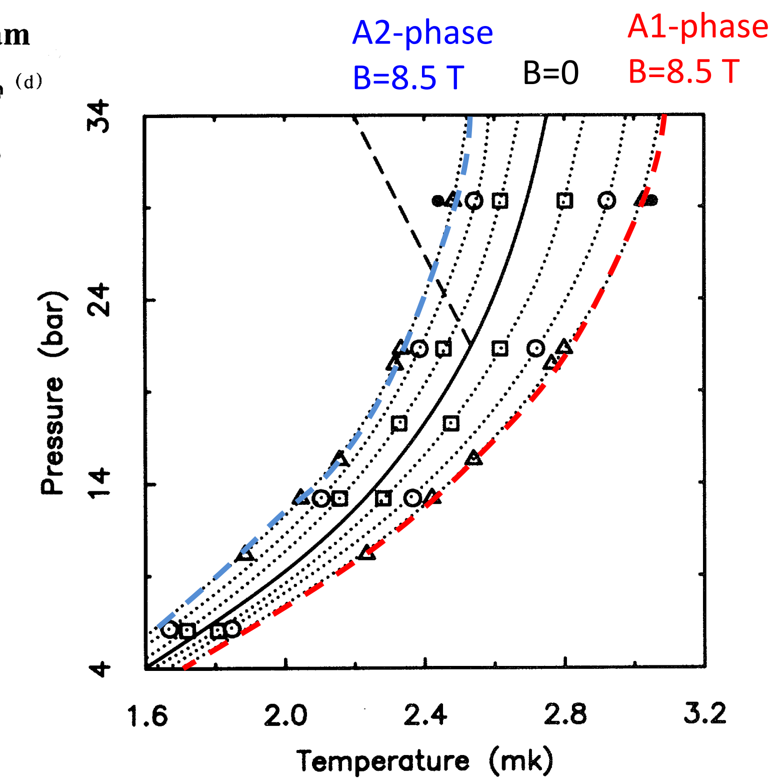
D. C. Sagan,[a] P. G. N. deVegvar, E. Polturak,[b] L. Friedman,[c] S.-S. Yan [d]
E. L. Ziercher, and D. M. Lee
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14

(Received 30 July 1984)

- ↑↑ Cooper pairs condense at $T_c^{A_1} = T_c + \lambda^{A_1} B$
- ↓↓ Cooper pairs condense at $T_c^{A_2} = T_c - \lambda^{A_2} B$

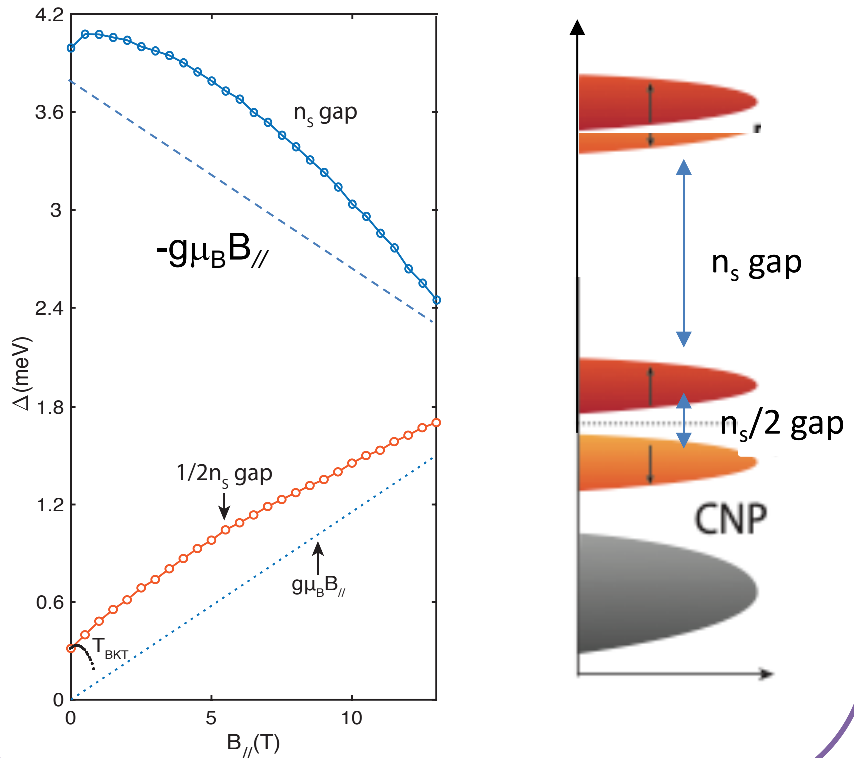
$$\lambda^{A_1} \approx \left|\frac{\gamma\hbar}{2}\right| \left(\frac{k_B T_c}{E_f}\right)$$

Ambegaokar and Mermin (1973)

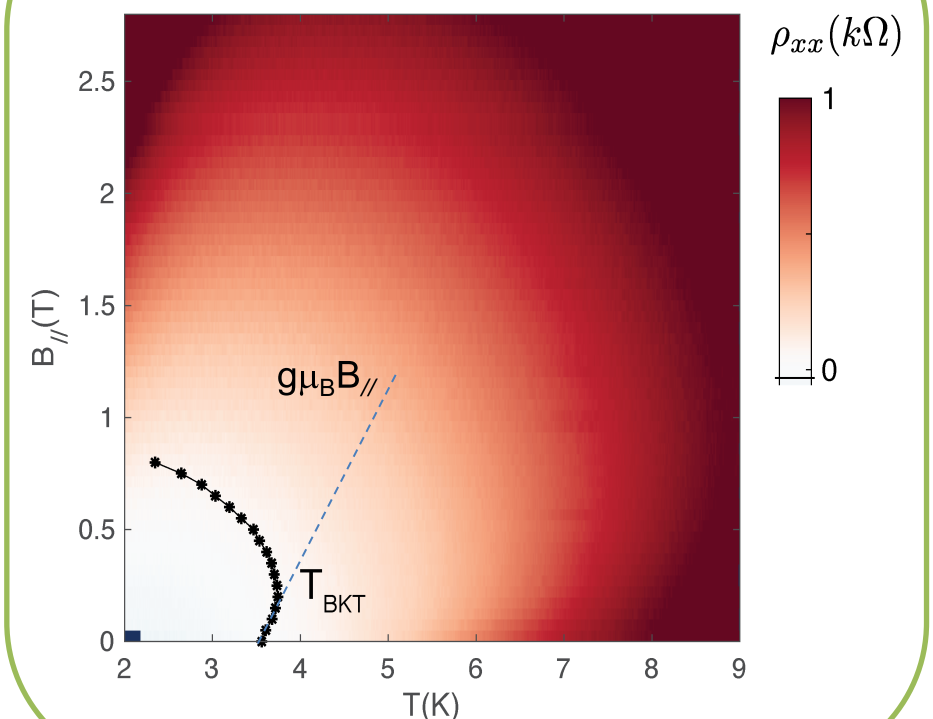


Ferromagnetic Superconductivity in tDBG

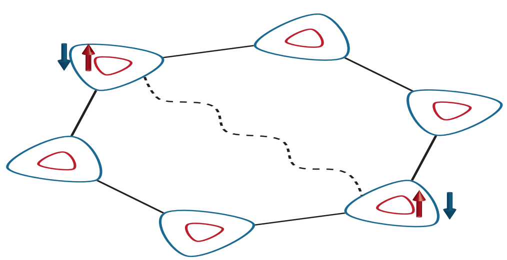
Spin-polarized Mott State



Spin-polarized SC State



Cooper Pair: Spin triplet & Valley singlet

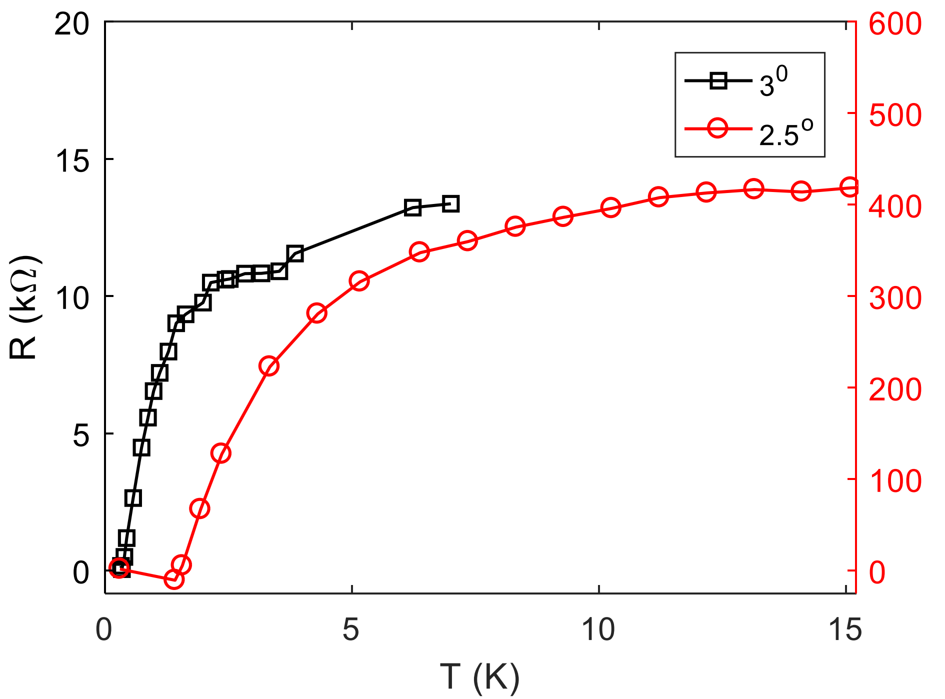


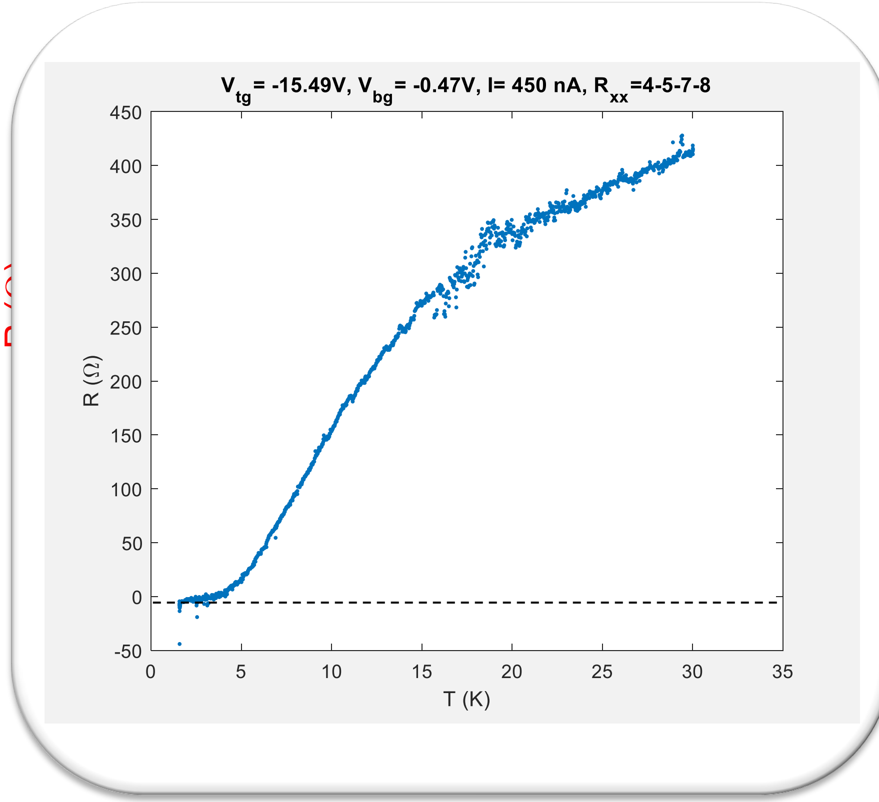
$$T_c(B) = T_c + aB - bB^2$$

$$a = 2\mu_B T_c \chi \frac{N'(\epsilon_F)}{N(\epsilon_F)} \ln\frac{\Lambda}{T_c}, \quad b = \frac{\mu_B^2}{T_c}\int_{\mathrm{FS}} \sum_{\sigma=\pm} \frac{d\boldsymbol{k}}{\kappa} |\phi_{\boldsymbol{k}}|^2 (\hat{\boldsymbol{e}}_{\boldsymbol{B}} \cdot \boldsymbol{g}_{\sigma,\boldsymbol{k}})^2$$

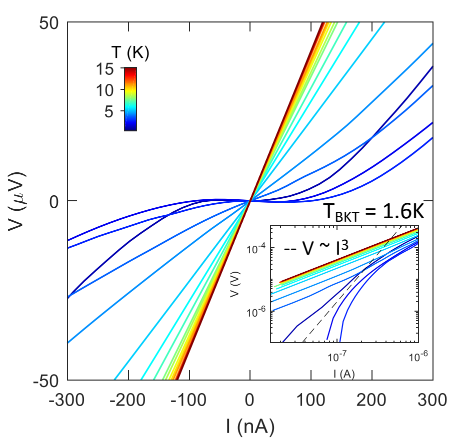
J. Y. Lee, E. Khalaf, S. Liu, X. Liu, Z. Hao, P. Kim, A. Vishwanath, Nature Comm. 10, 5333 (2019).

Superconducting Twisted bilayer WSe_2

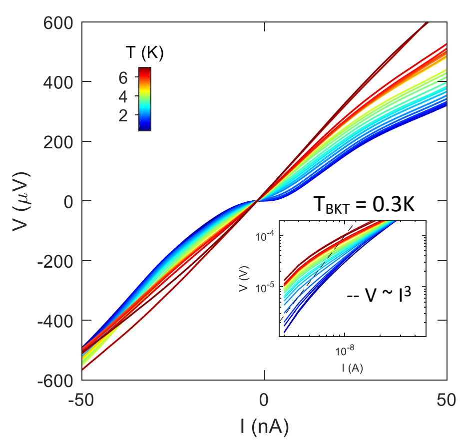




Angle : 2.5°



Angle : 3°

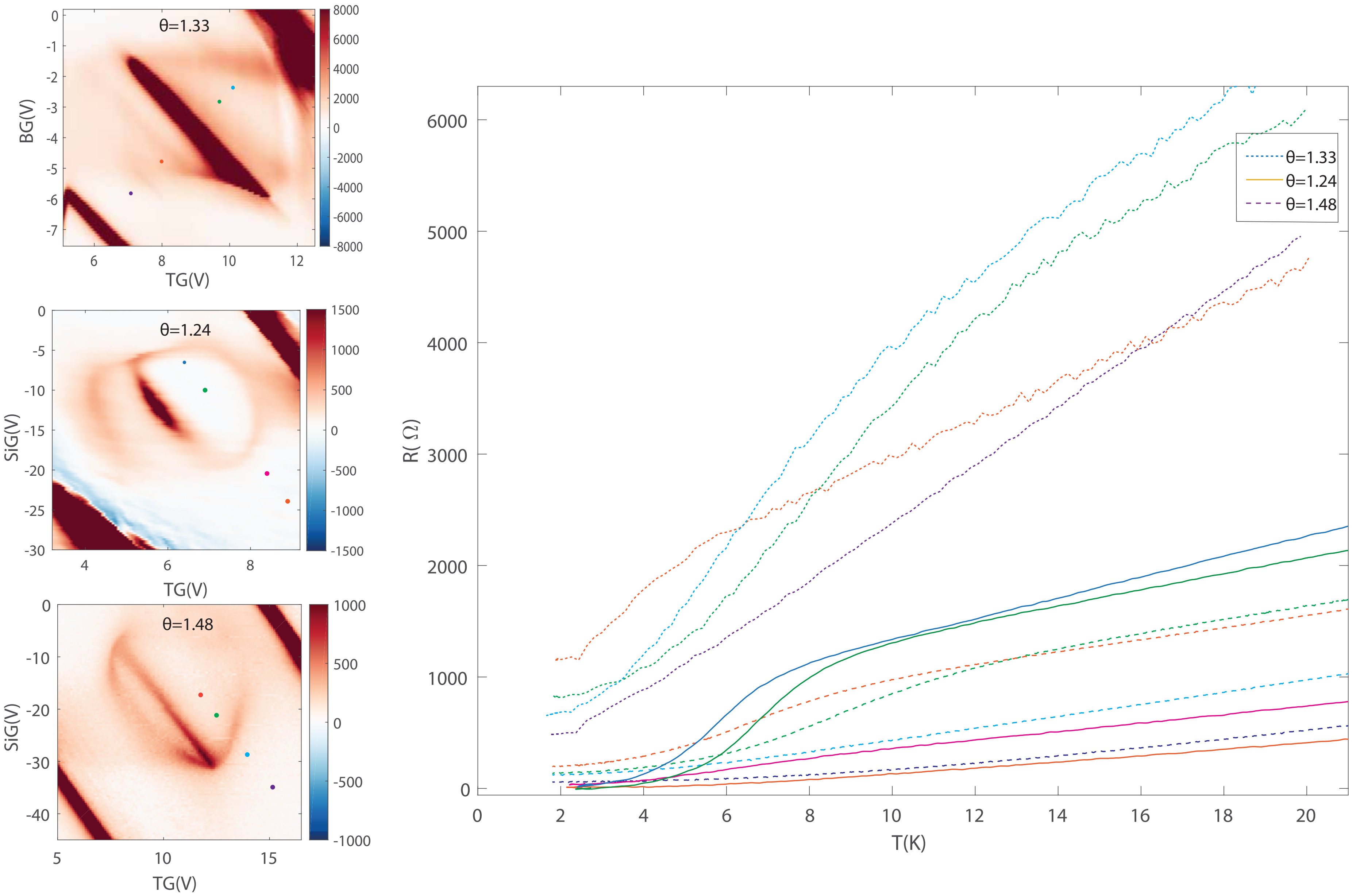


~ 8 K

Superconducting-like state T_c ~ 0.3 ~~- 3 K~~
has been realized in a wide angle range!

See also similar data in An *et al.*, arXiv:1907.03966

Superconducting Or Not Superconducting?

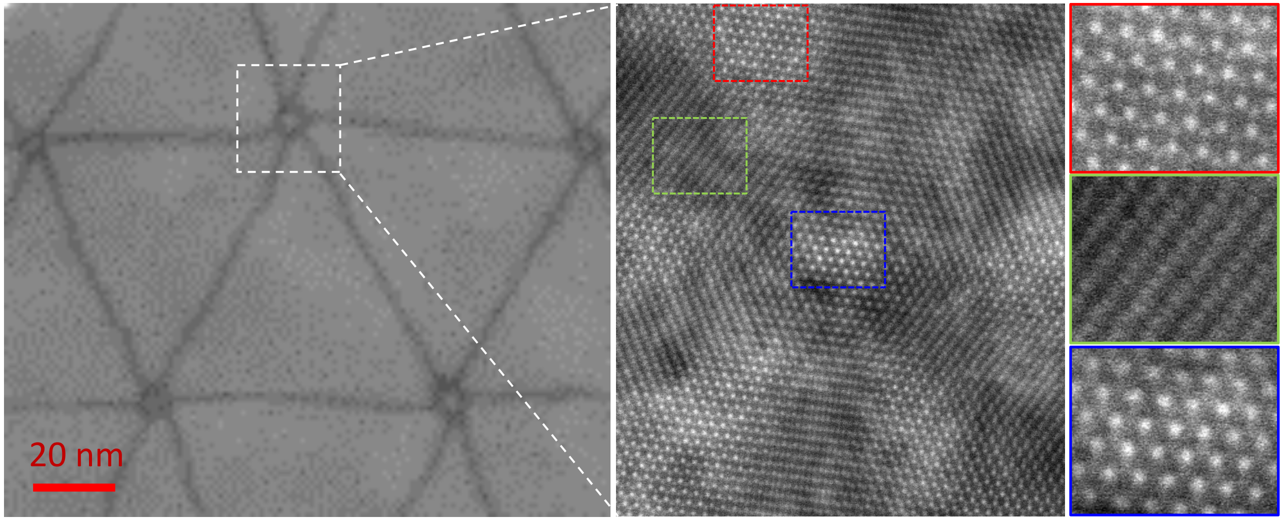


Atomic Registry in Domains and Boundaries

MoS_2/MoS_2

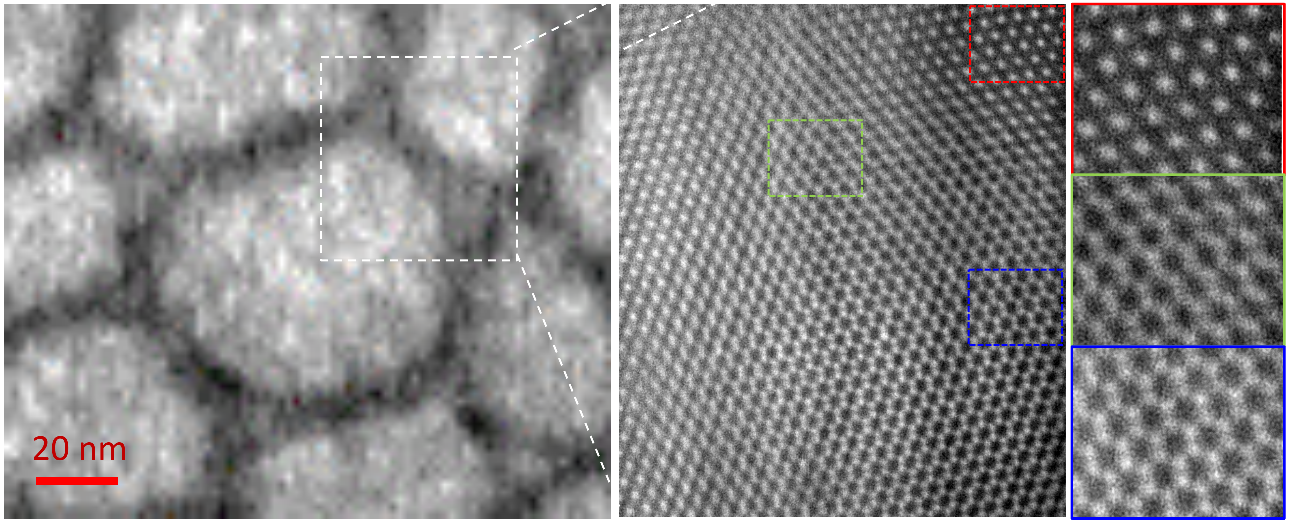
~ 0 degree

Circular AA domains where 6 domains (3 AB domains and 3 BA domains) meet each other



~ 180 degree

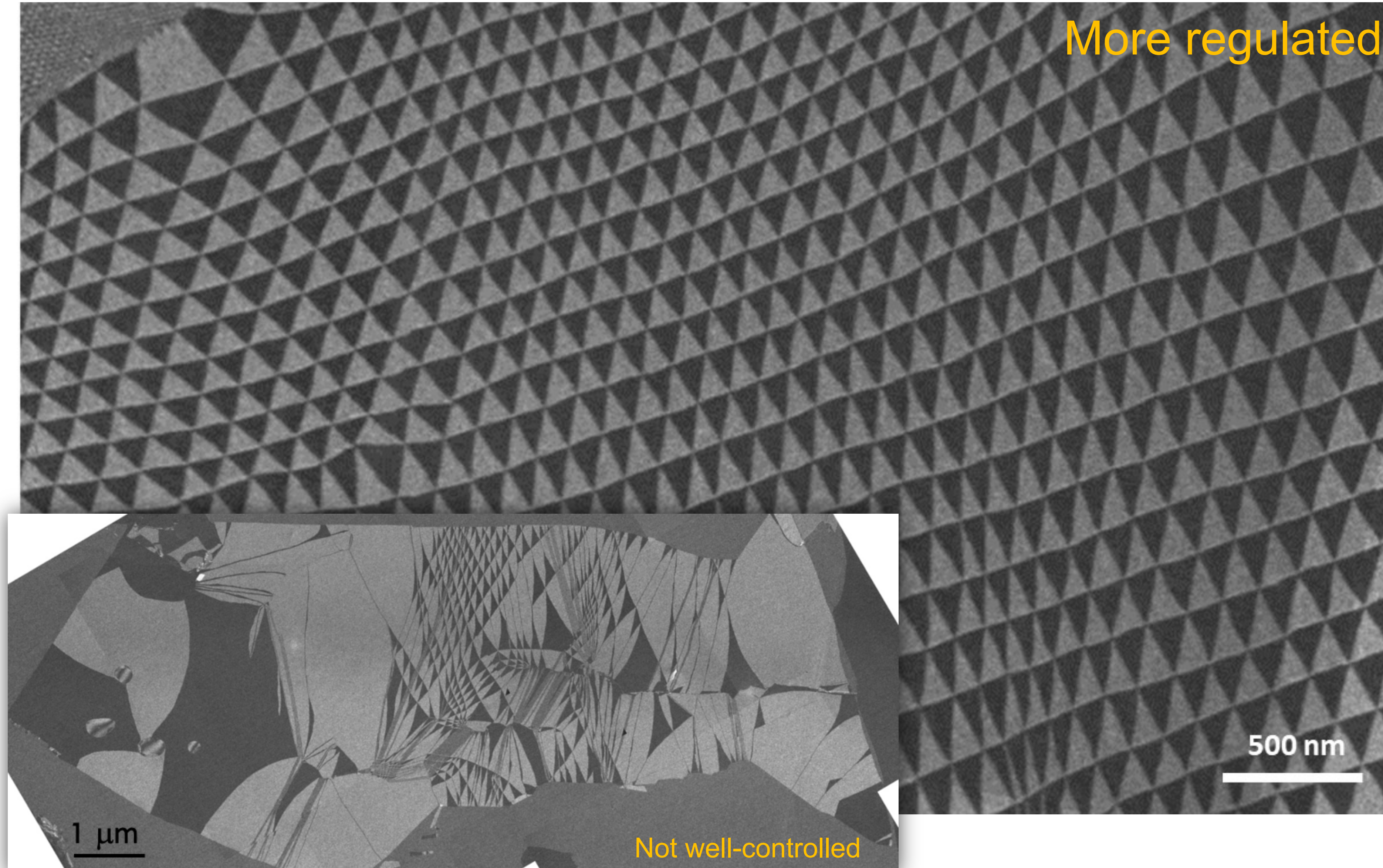
Triangular AB' and BA' domains where 3 domains (AA') meet each other.



Yoo et al., (Collaboration with Muller group at Cornell)

Twisting Engineering of Moire Superlattice

Graphene/graphene 0.1-0.2deg



Summary and Outlook

- Spin polarized Mott gap state is realized in half-filled tDBL bands tuned by *D*.
- Quarter filled tDBT band can develop a spin polarized gap.
- Superconductivity appears near the half field states in 1.26 degree rotated tDBL.
- Superconductivity appeared in tDBL samples can be tuned by *D* and *n*.
- Tc enhanced with small in-plane magnetic fields.

Going Forward:

- What is the optimal Tc in tDBT?
- Will spin-polarized SC in tDBL exhibit topological superconductivity?