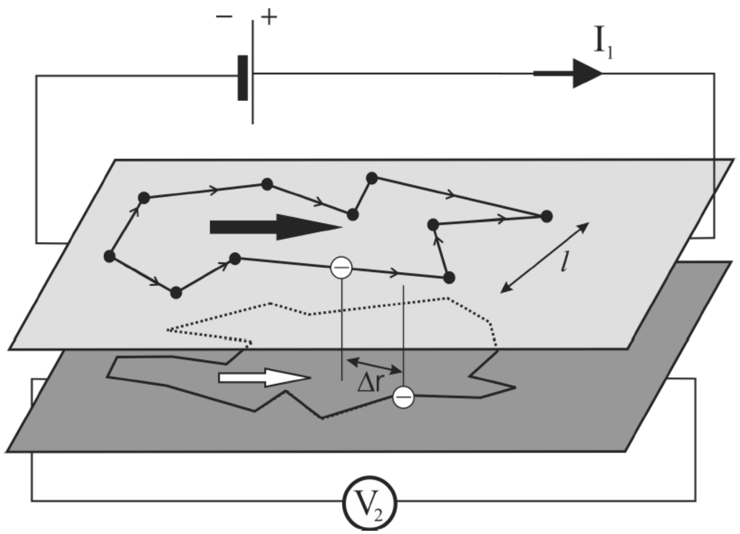
Coulomb Drag in Graphene

-Toward Exciton Condensation

Philip Kim

Department of Physics, Harvard University

Coulomb Drag



Price *et al.*, Science (2012)

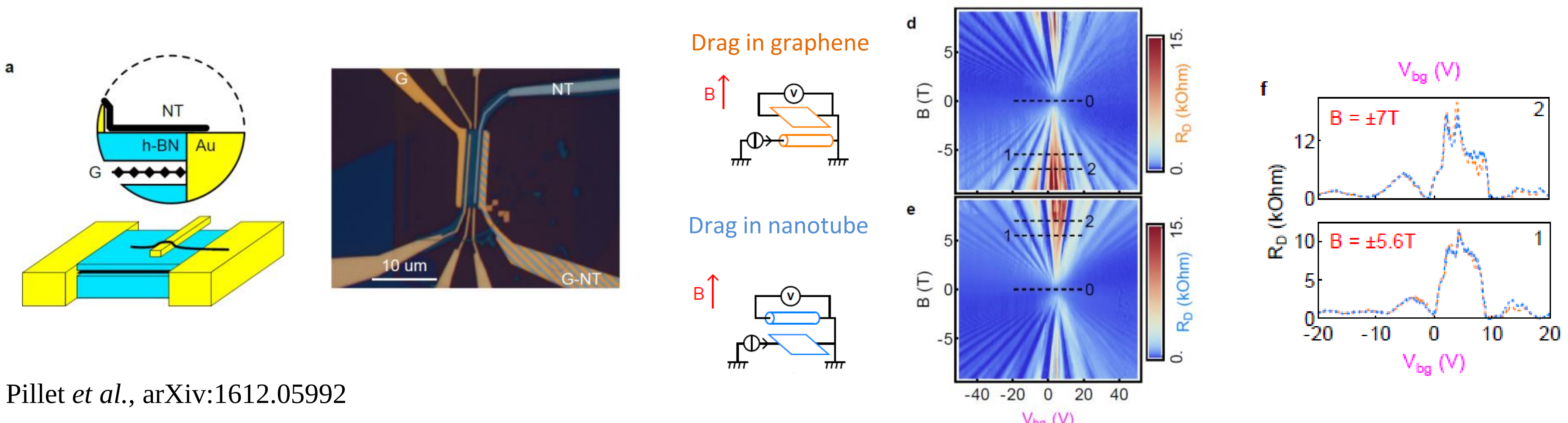
Drag Resistance:

$$R_D = V_2 / I_1$$

Onsager Reciprocity

$$V_2(B)/ I_1 = V_1(-B)/ I_2$$

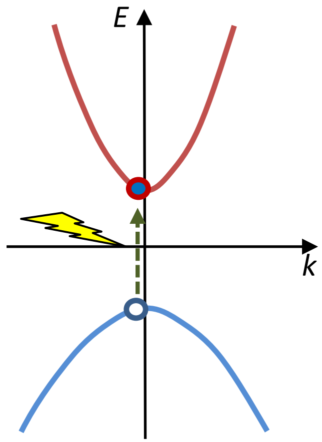
Coulomb drag between graphene/nanotube

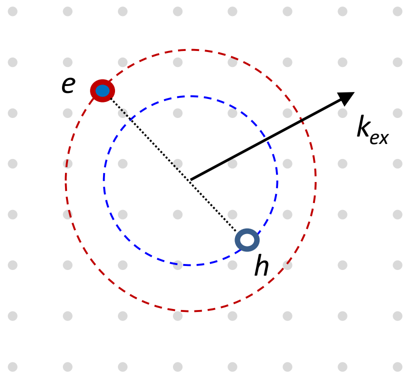


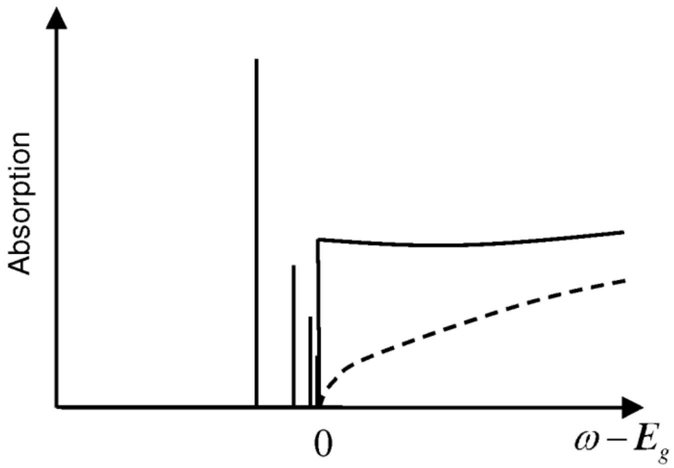
Pillet *et al.*, arXiv:1612.05992

Excitons

Excitons in Semiconductors

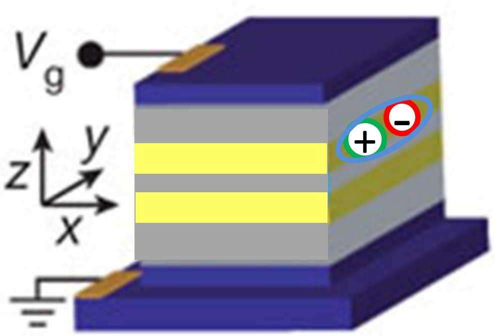


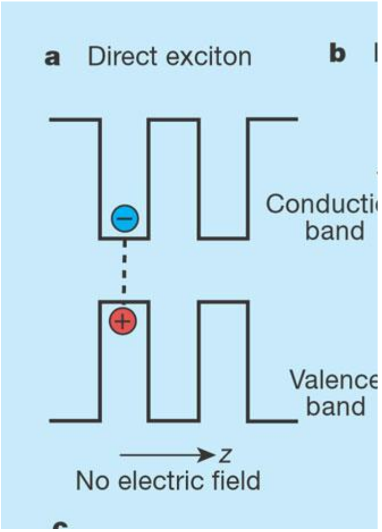




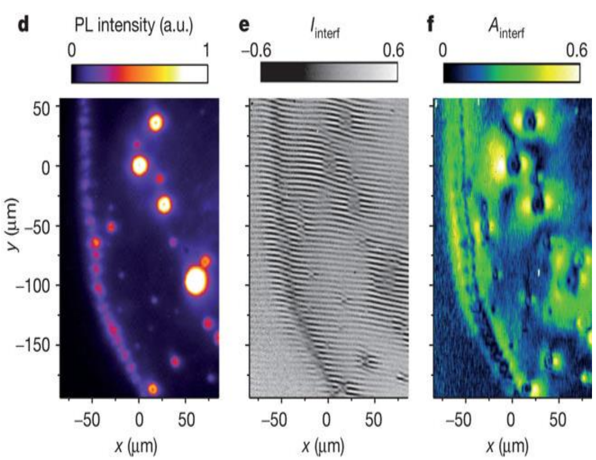
Direct and indirect excitons in semiconducting quantum wells

Semiconductor heterostructure



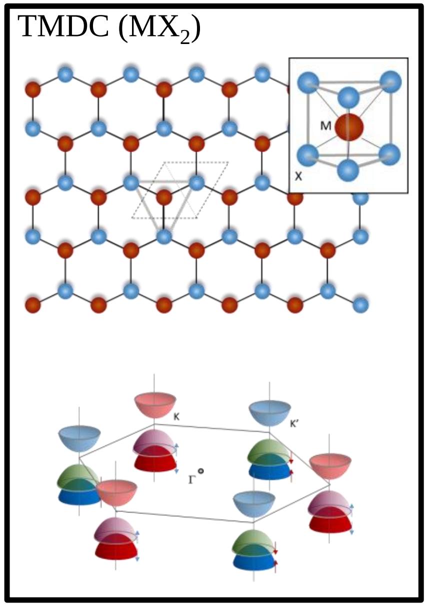


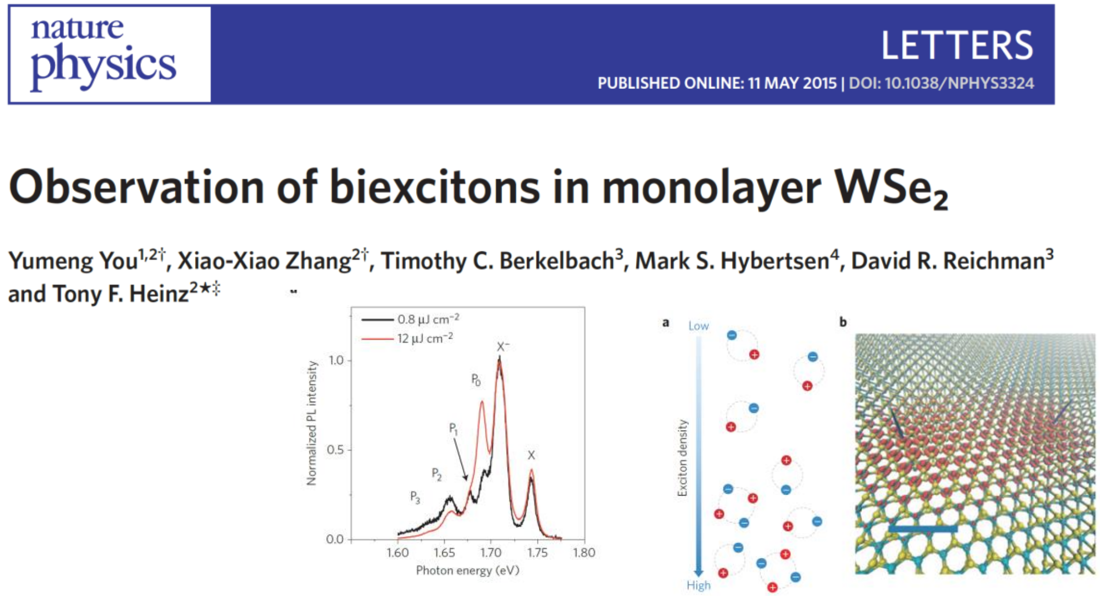
Spontaneous coherence



A. High, Nature 2012

Excitons in 2D Materials



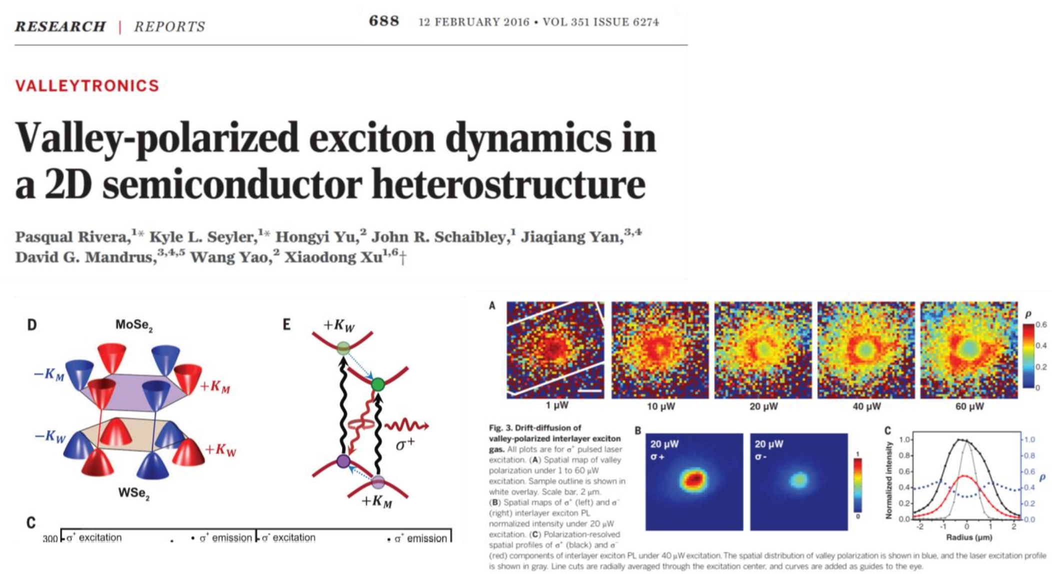

nature physics

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

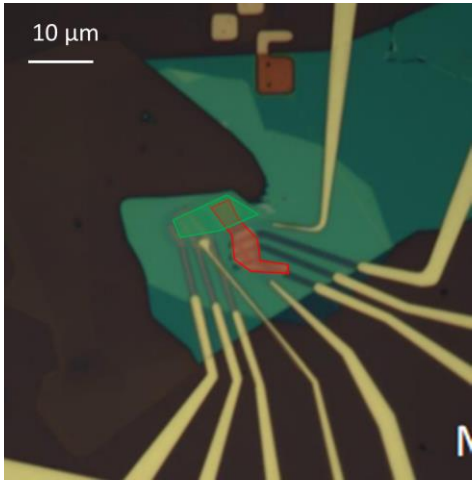
Valley-polarized exciton dynamics in a 2D semiconductor heterostructure

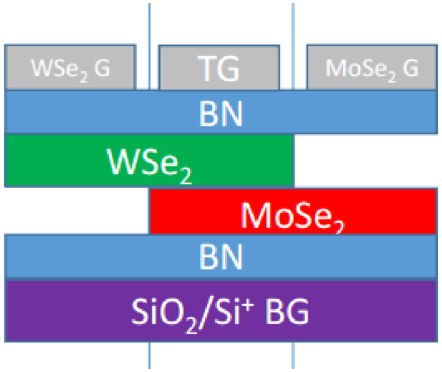
Pasqual Rivera,[1*] Kyle L. Seyler,[1*] Hongyi Yu,[2] John R. Schaibley,[1] Jiaqiang Yan,[3,4] David G. Mandrus,[3,4,5] Wang Yao,[2] Xiaodong Xu[1,6]†

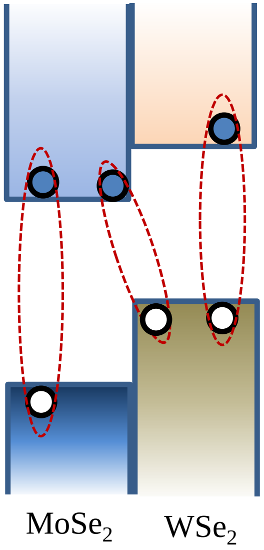
- Strong confinement
- Lack of strong screening effect
- Spin polarized band
- Spin-valley locking

Interlayer Excitons in TMDCs

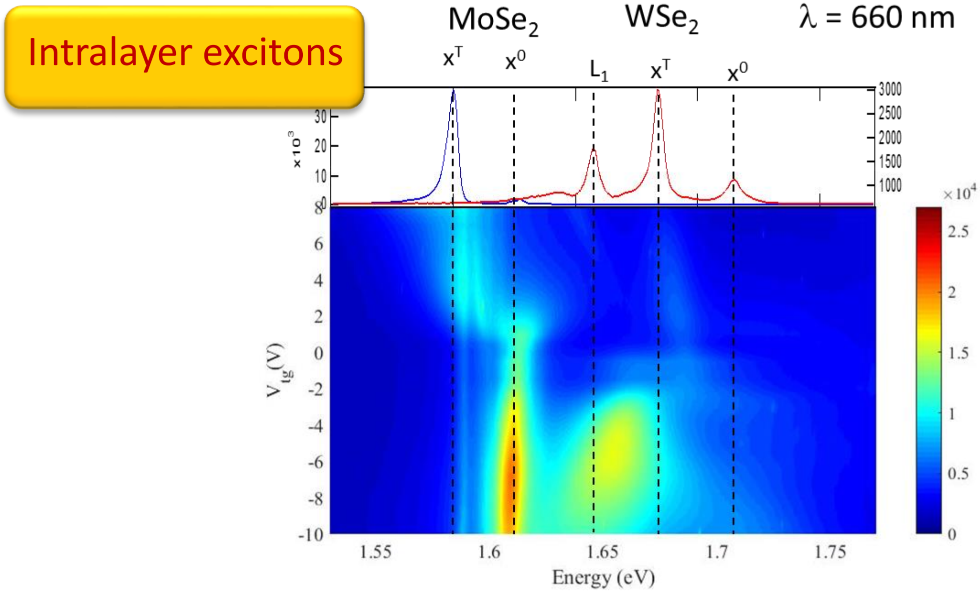
$MoSe_2/WSe_2$ heterostructures

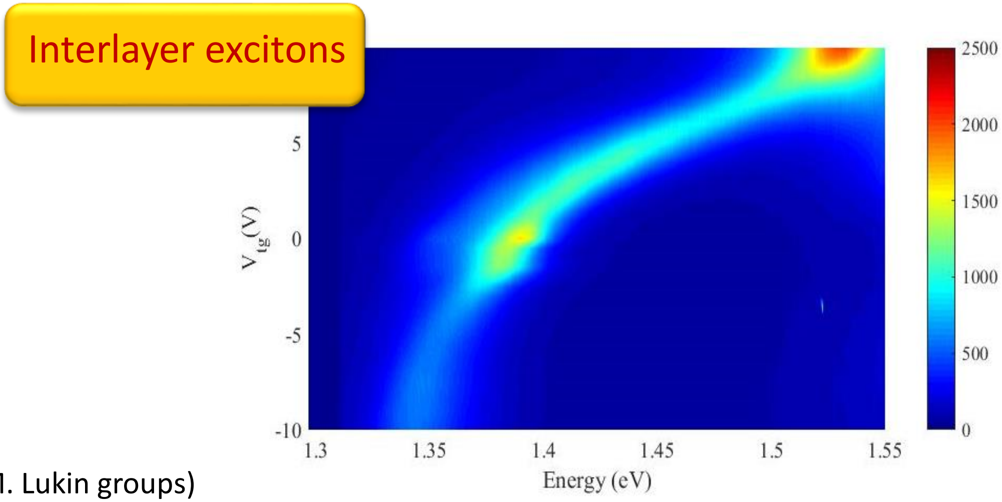






Gate dependent photo luminescent



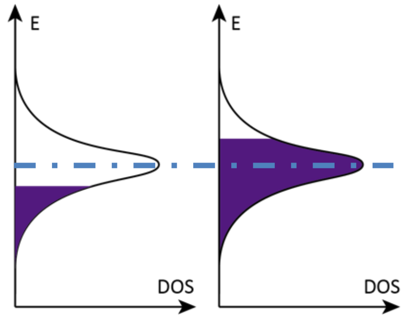


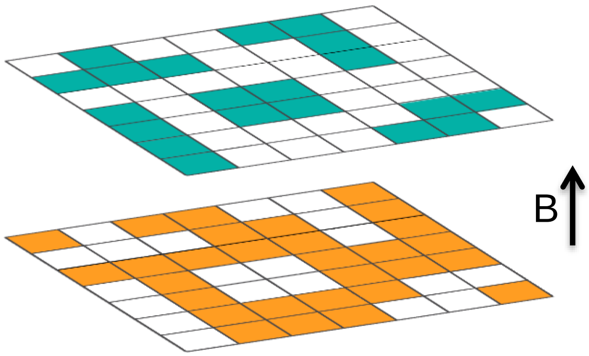
L. Jauregui et. al, unpublished (Collaboration with H. Park and M. Lukin groups)

Exciton condensation between Landau levels

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

Two partially filled
Landau levels

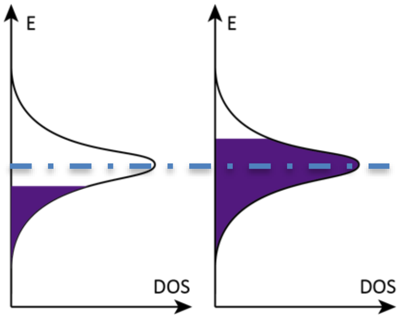


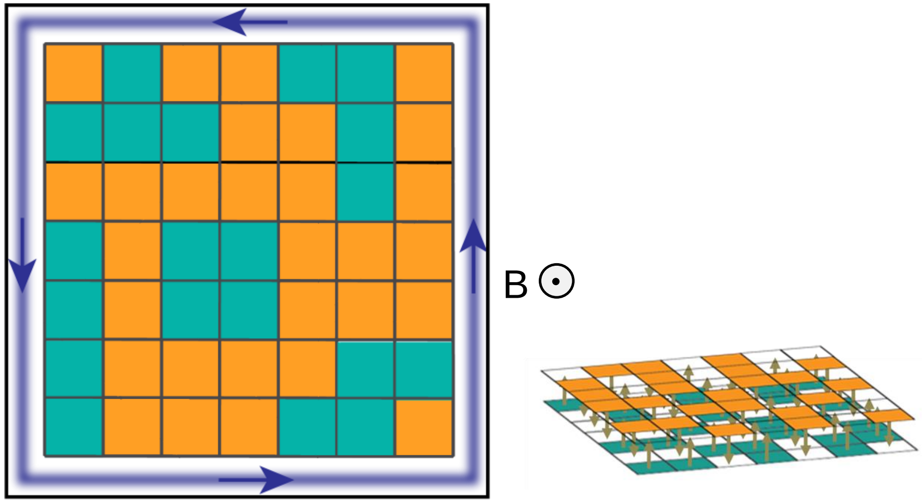


Exciton condensation between Landau levels

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

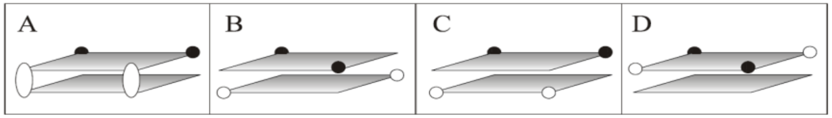
Two partially filled
Landau levels



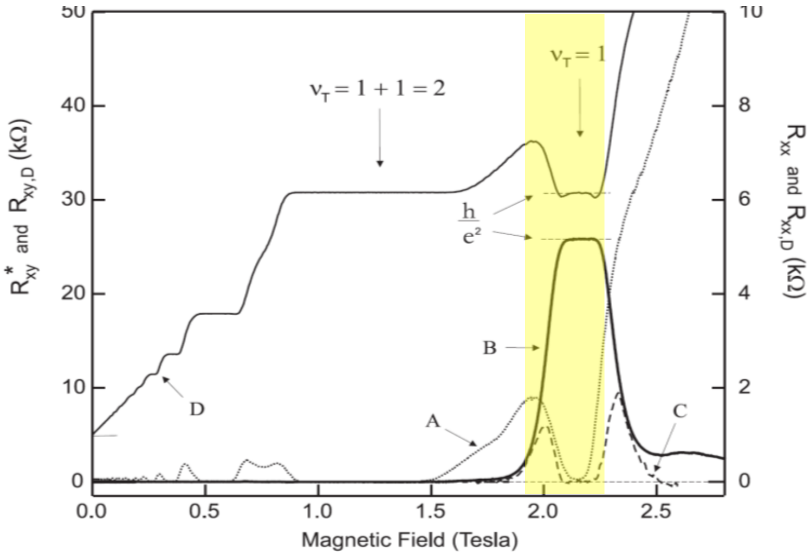


Total Landau level quantum Hall effect

GaAs Double Quantum Well



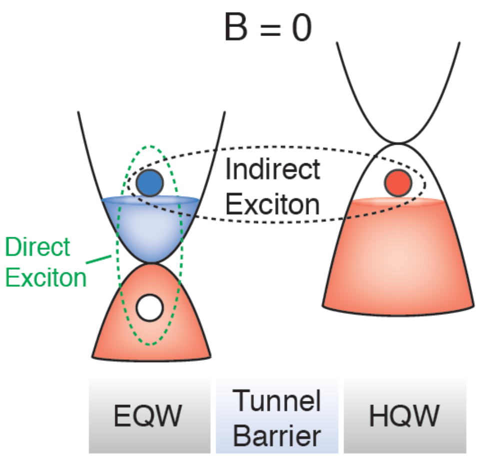
- Quantum Hall effect for two partially filled complementary LLs
- Quantized drag Hall

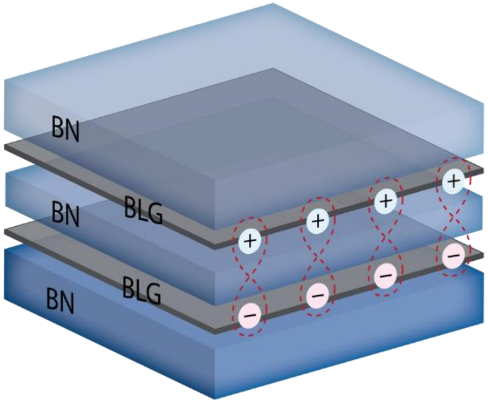


M. Kellogg, et. al, PRL (2002)

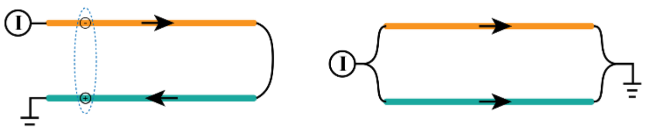
Exciton Condensation: Currents

Exciton condensation (exciton insulator)



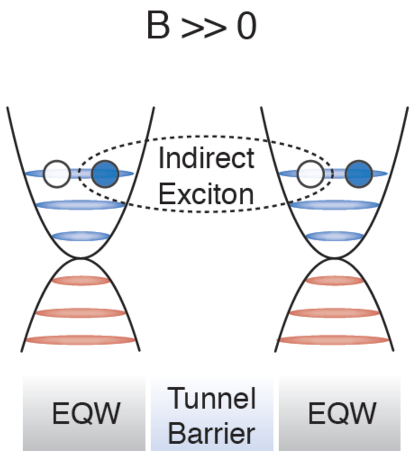


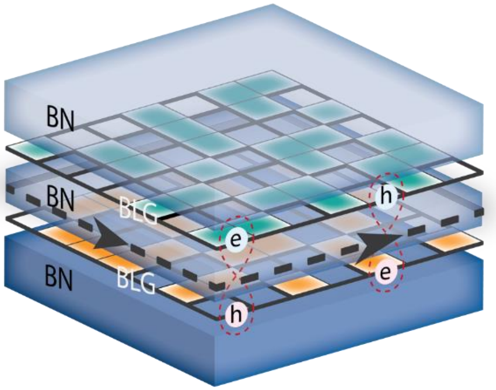
Counter Flow   Symmetric Flow



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

Exciton condensation between LL (topological exciton insulator)

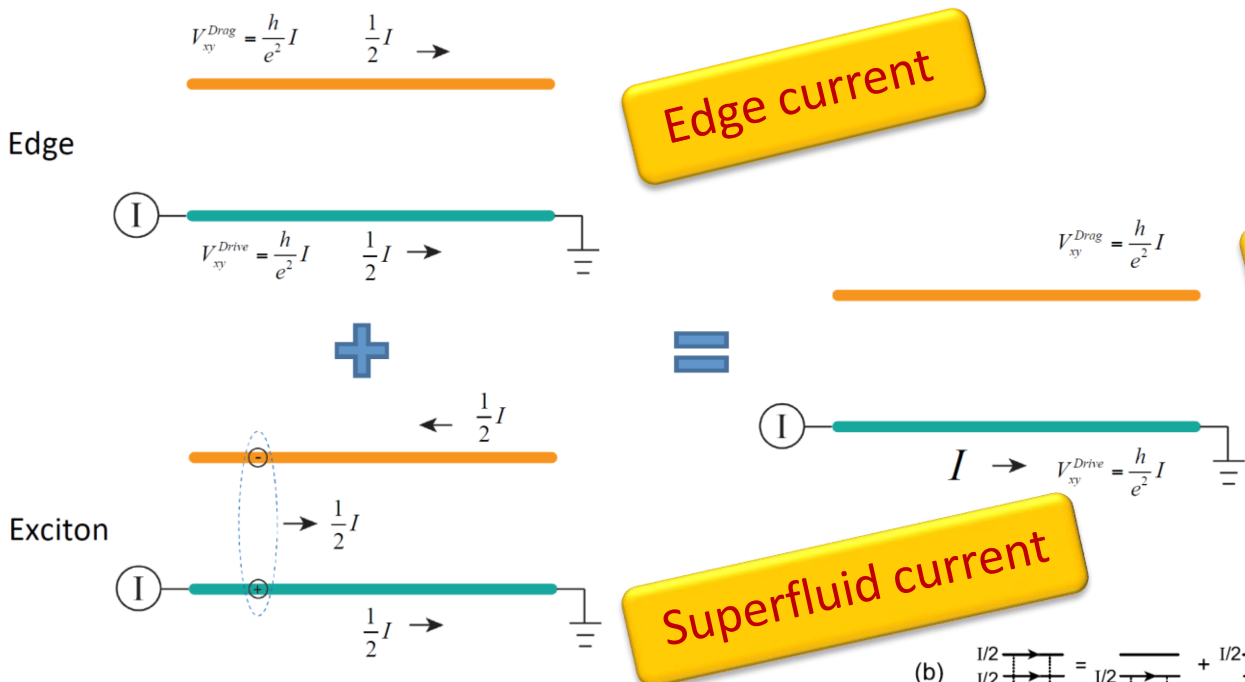




$$R_{xx}^{CF} = 0 \qquad R_{xx}^{sym} = 0$$

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

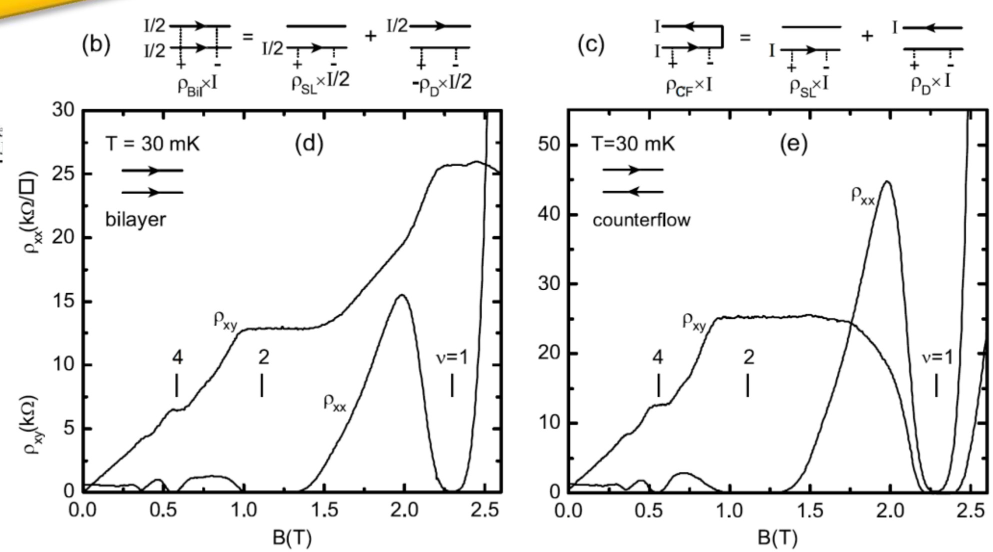
Exciton Current and Quantized Drag



NUMBER 3 PHYSICAL REVIEW LETTERS

Counterflow Measurements in Strongly Correlated GaAs Hole Bilayers: Evidence for Electron-Hole Pairing

E. Tutuc and M. Shayegan
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA
D. A. Huse



Outlines

Frictional magneto-Coulomb drag in graphene hexa boron nitride heterostructure

Xiaomeng Liu,[1] Lei Wang,[2] Kin Chung Fong,[3] Yuanda Gao,[2] Patrick Maher,[4] Kenji Watanabe,[5] Takashi Taniguchi,[5] James Hone,[2] Cory Dean,[4] and Philip Kim[1]

arXiv:1612.08308

Frictional magneto drag effect in semiclassical regime

Quantum Hall Drag of Exciton Superfluid in Graphene

Xiaomeng Liu[1], Kenji Watanabe[2], Takashi Taniguchi[2], Bertrand I. Halperin[1], Philip Kim[1]

Quantized drag in excitonic regime

arXiv:1608.03726

Coulomb Drag Experiment in Graphene

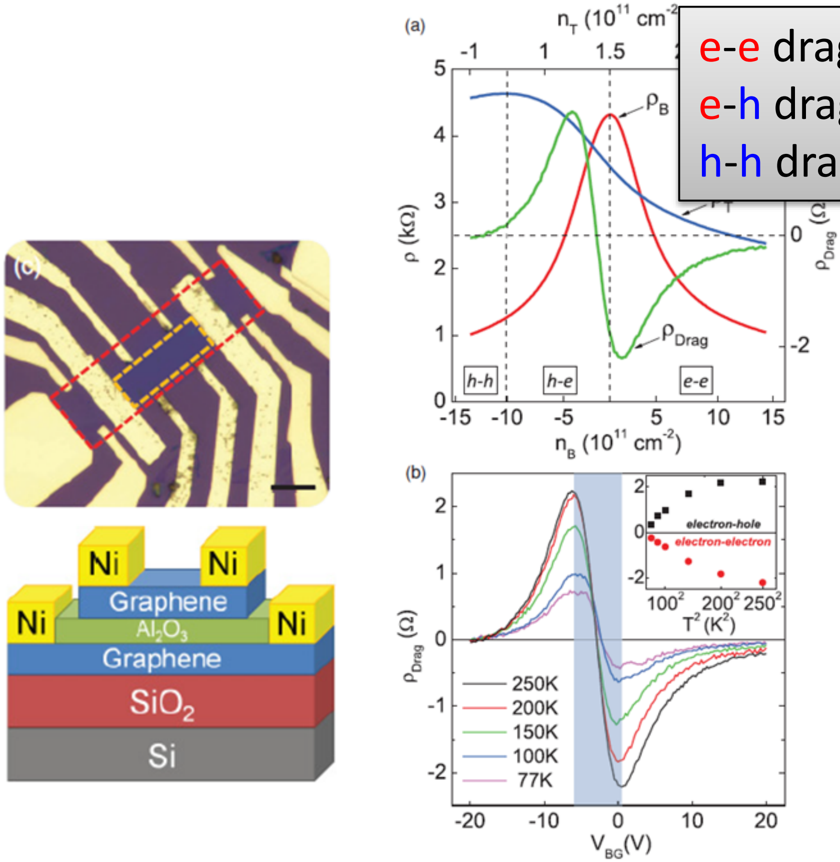
[redacted]

PHYSICAL REVIEW B 83, 161401(R) (2011)

Coulomb drag of massless fermions in graphene

Seyoung Kim,[1] Insun Jo,[2] Junghyo Nah,[1] Z. Yao,[2] S. K. Banerjee,[1] and E. Tutuc[1,*]
[1]*Microelectronics Research Center, The University of Texas at Austin, Austin, Texas 78758, USA*
[2]*Department of Physics, The University of Texas at Austin, Austin, Texas 78712, USA*

(Received 9 October 2010; revised manuscript received 17 March 2011; published 8 April 2011)

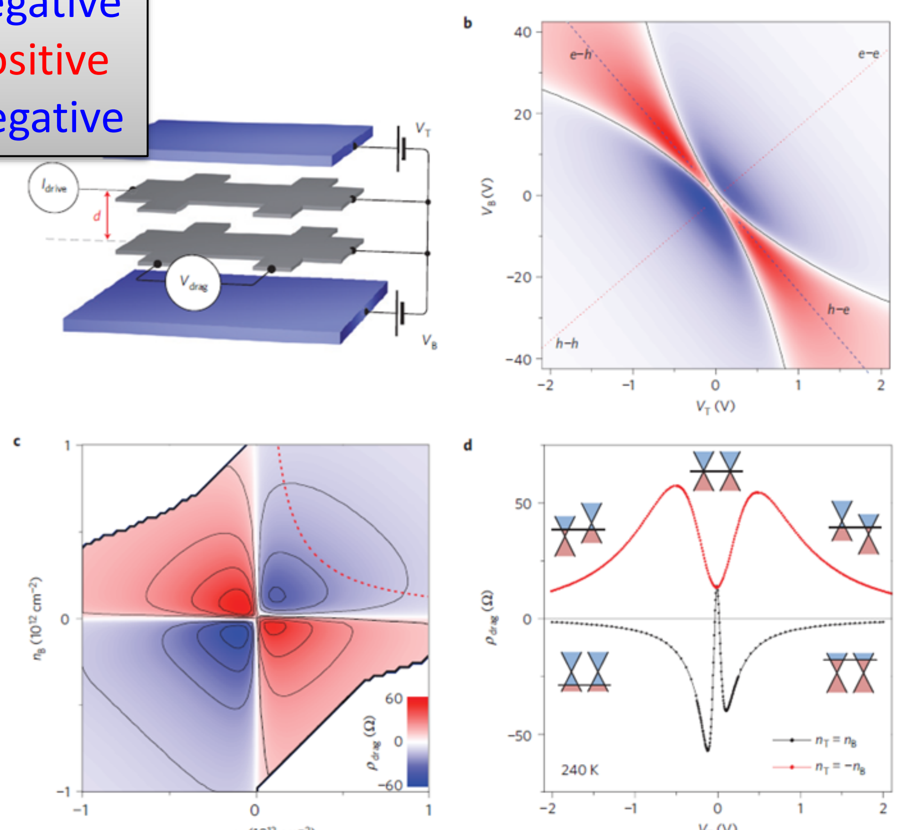


e-e drag: negative
e-h drag: positive
h-h drag: negative

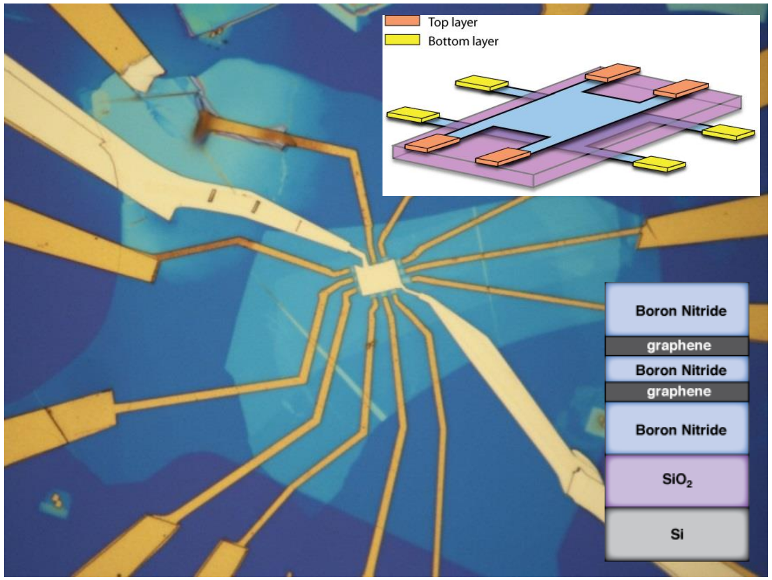
ARTICLES
PUBLISHED ONLINE: 14 OCTOBER 2012 | DOI: 10.1038/NPHYS2441
nature physics

Strong Coulomb drag and broken symmetry in double-layer graphene

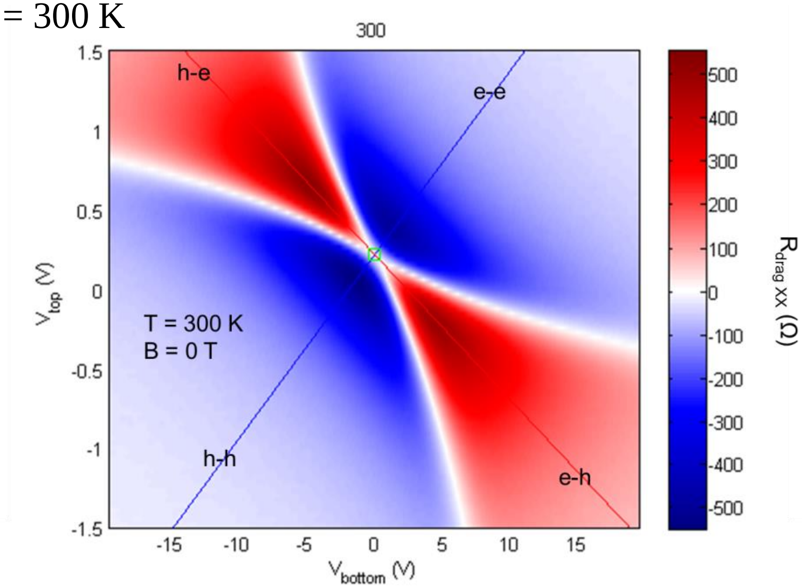
R. V. Gorbachev[1], A. K. Geim[1,2]*, M. I. Katsnelson[3], K. S. Novoselov[2], T. Tudorovskiy[3], I. V. Grigorieva[1,2], A. H. MacDonald[4], S. V. Morozov[2,5], K. Watanabe[6], T. Taniguchi[6] ...marenko[1,2]*



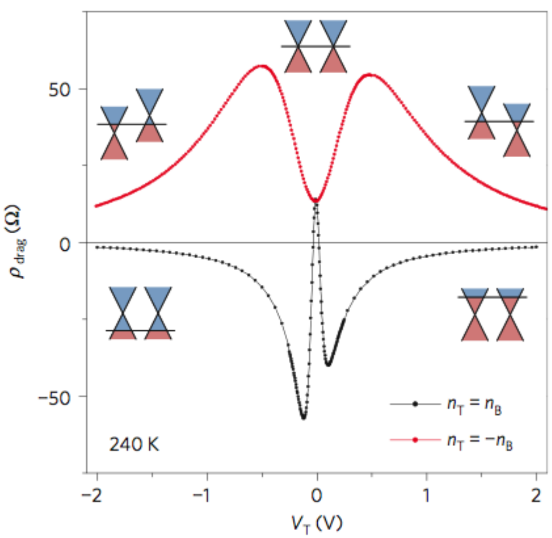
Coulomb Drag in Double Layer Graphene

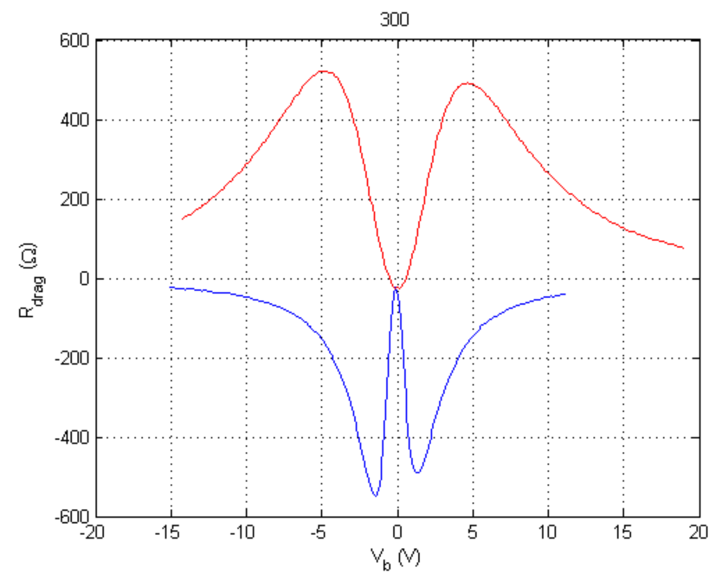


T = 300 K



Drag resistance sign reversal at the double neutrality point

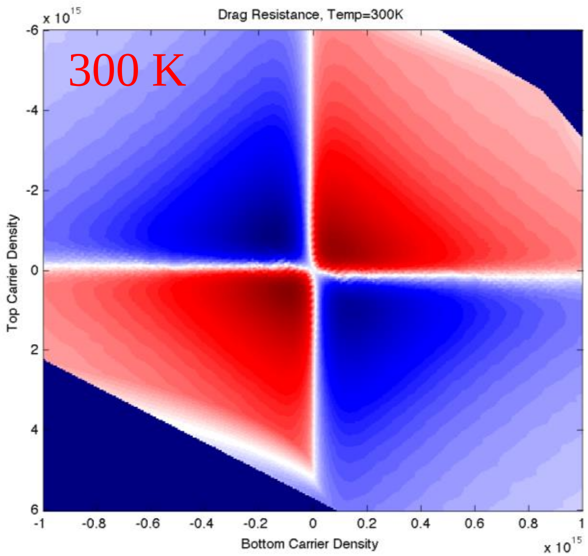


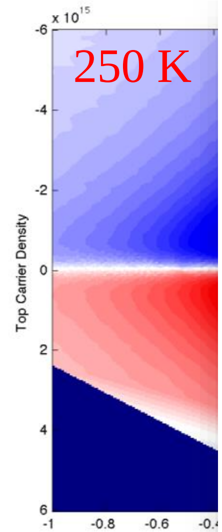


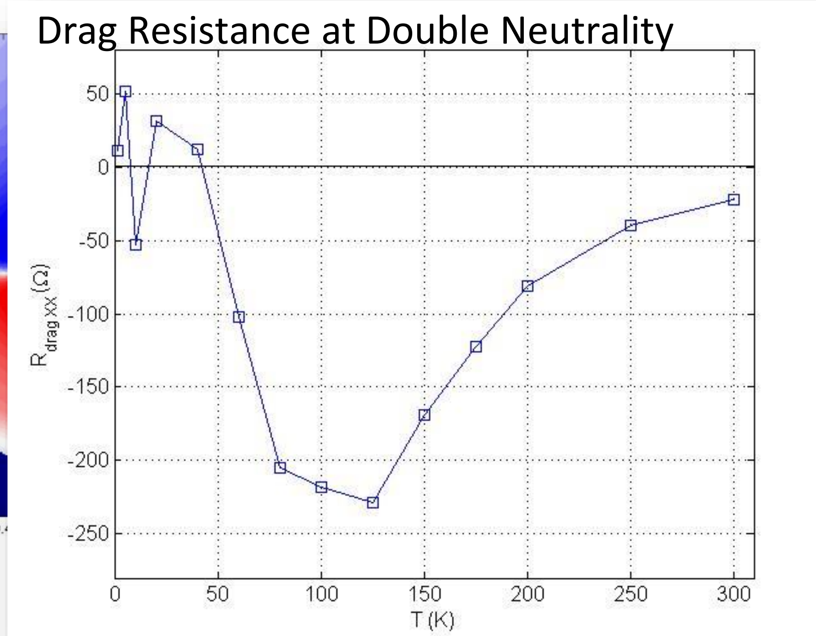
Manchester group, Nature Phys. 8, 896 (2013)

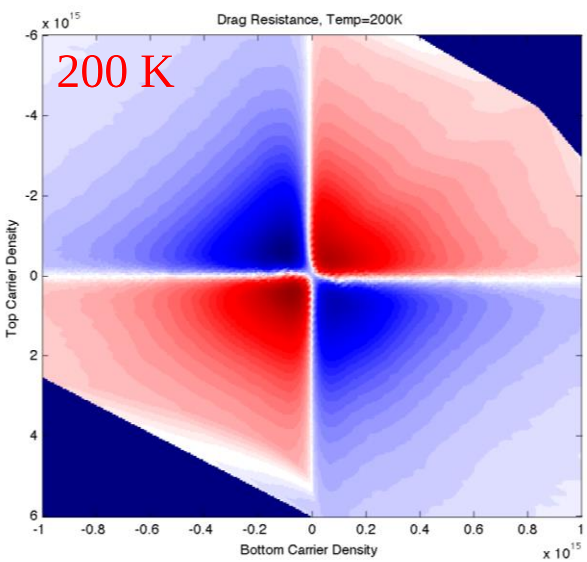
Xiaomeng Liu *et al*, arXiv:1612.08308

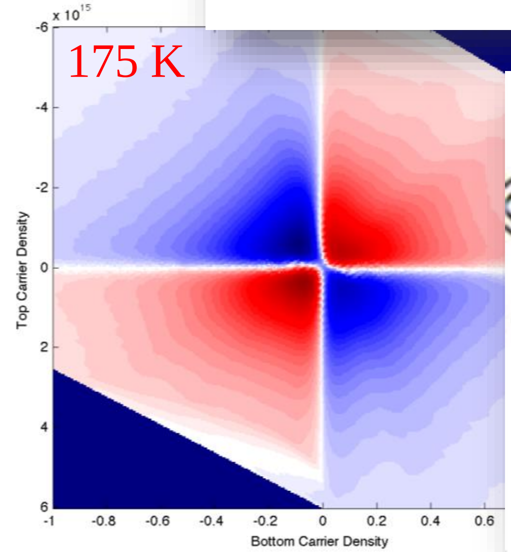
Temperature Dependent Coulomb Drag

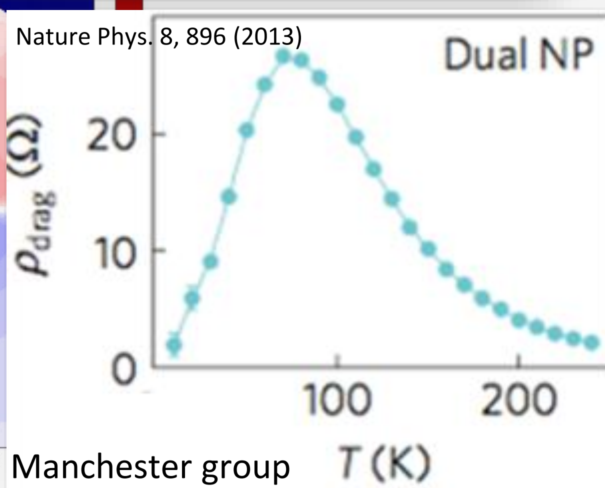












Xiaomeng Liu *et al*, arXiv:1612.08308

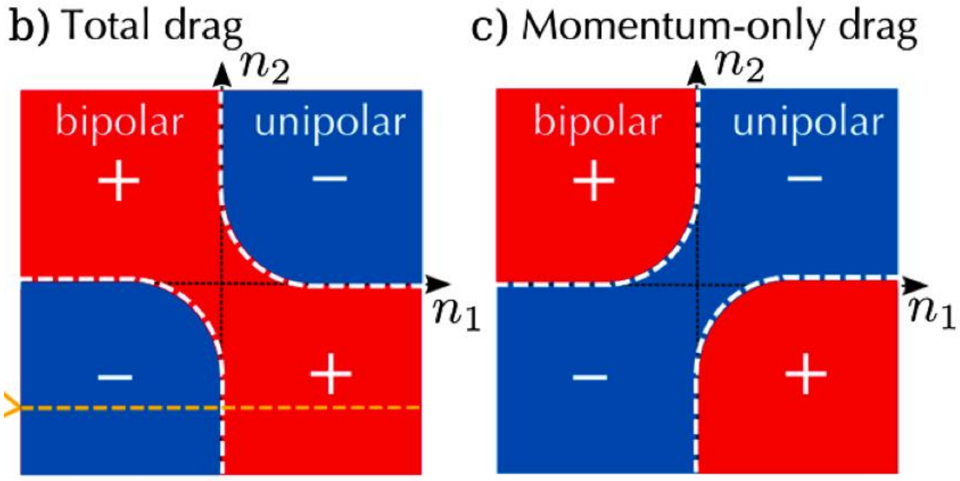
Possible Scenarios

- Interaction dominates at DNP
  (Schutt et al, PRL 110, 026601 (2012))

- Energy vs. momentum drag
  (Song and Levitov, PRL 109, 236602 (2012))

  -correlated disorder

  -anti-correlated disorders



PRL 109, 236602 (2012)

- *Strain induced*
  (Gibertini et al., Phys. Rev. B 85, 201405 (2012))

Sign of Drag Near the Neutrality

Selected for a Viewpoint in *Physics*
PRL **117,** 046802 (2016) PHYSICAL REVIEW LETTERS week ending 22 JULY 2016

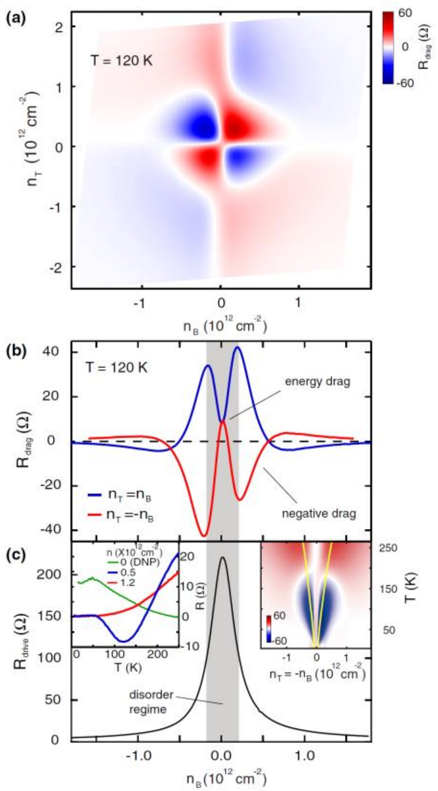
Negative Coulomb Drag in Double Bilayer Graphene

J. I. A. Li,[1] T. Taniguchi,[2] K. Watanabe,[2] J. Hone,[3] A. Levchenko,[4] and C. R. Dean[1]

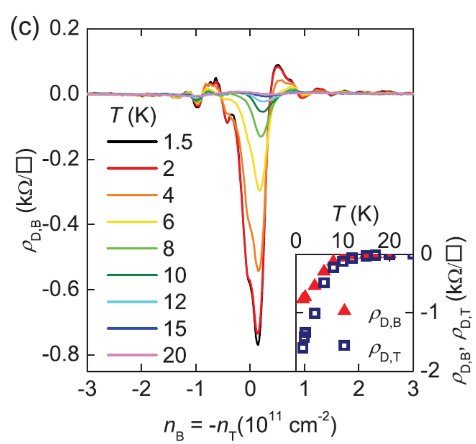
PRL **117,** 046803 (2016) PHYSICAL REVIEW LETTERS week ending 22 JULY 2016

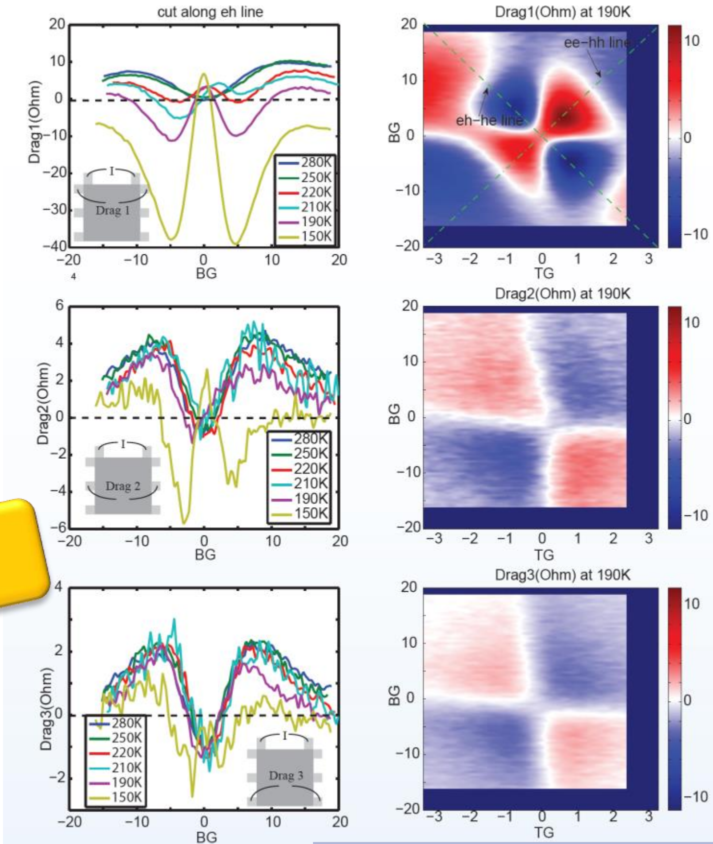
Giant Frictional Drag in Double Bilayer Graphene Heterostructures

Kayoung Lee,[1] Jiamin Xue,[1] David C. Dillen,[1] Kenji Watanabe,[2] Takashi Taniguchi,[2] and Emanuel Tutuc[1]

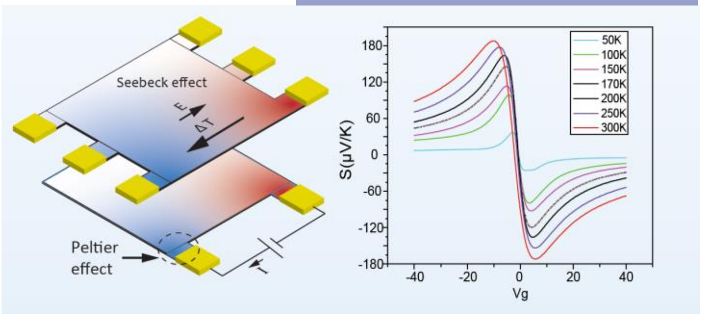


Thermolectric origin?



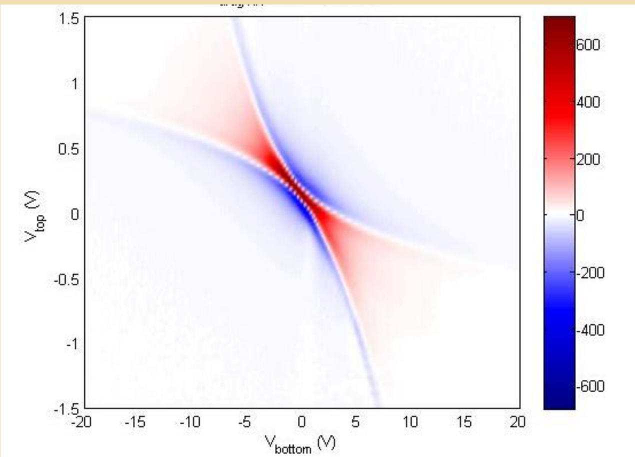


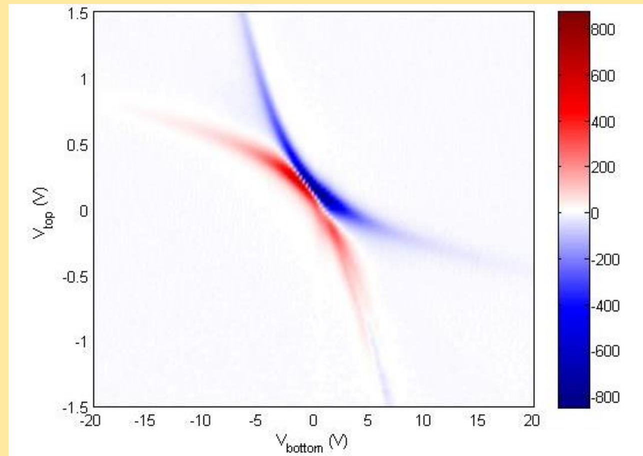
$$R_{drag} = \frac{\Pi^a S^p}{\kappa^a + \kappa^p} = \frac{S^a S^p}{L(\sigma^a + \sigma^b)}$$



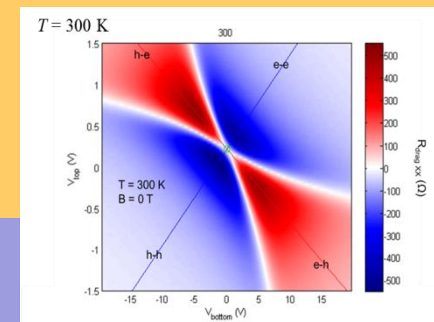
Magneto Drag in Graphene

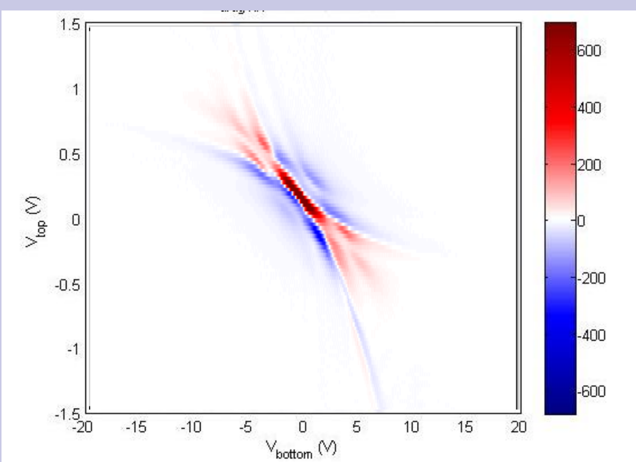
$R_{\text{drag}}{}^{xx}$ (Ω)	$R_{\text{drag}}{}^{xy}$ (Ω)	$B = 1$ T

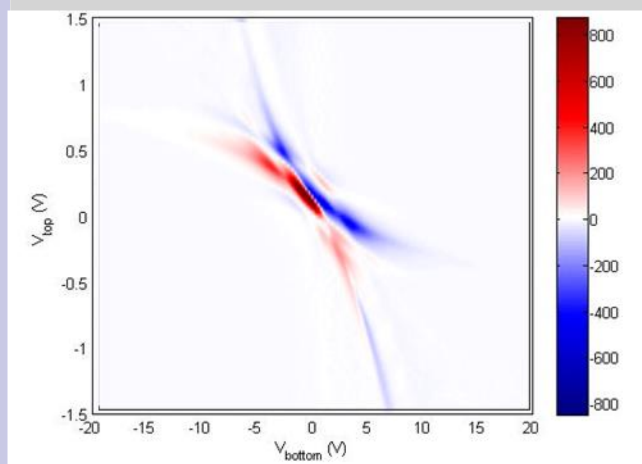




$T = 150$ K







$T = 70$ K

Xiaomeng Liu *et al*, arXiv:1612.08308

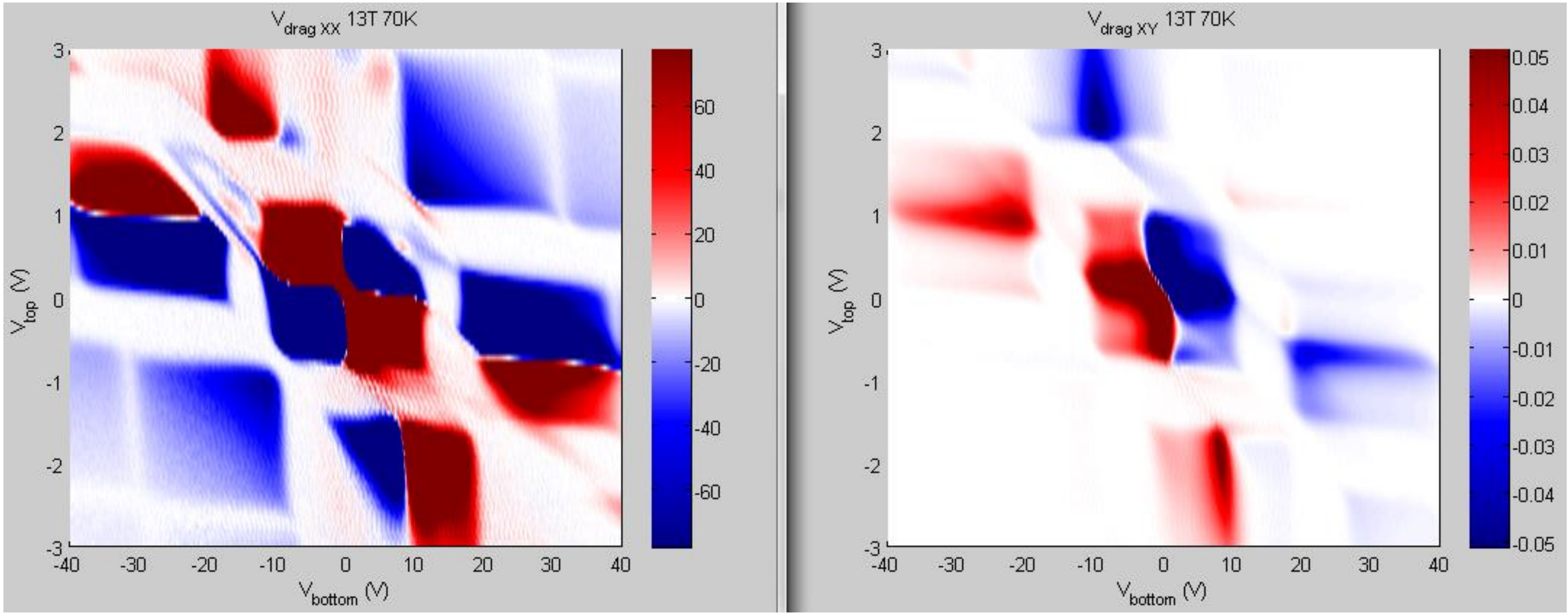
Magneto Drag in Graphene at High Magnetic Field

$B = 13$ T

$T = 70$ K

R_{drag}^{xx} (Ω)

R_{drag}^{xy} (h/e^2)

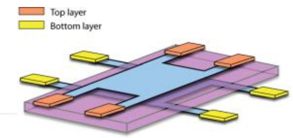


Finite drag signal only when the LLs are partially filled.
No drag if either layer becomes incompressible

Xiaomeng Liu *et al*, arXiv:1612.08308

Correlation Between Drag and Transport

VOLUME 87, NUMBER 10 PHYSICAL REVIEW LETTERS 3 SEPTEMBER 2001



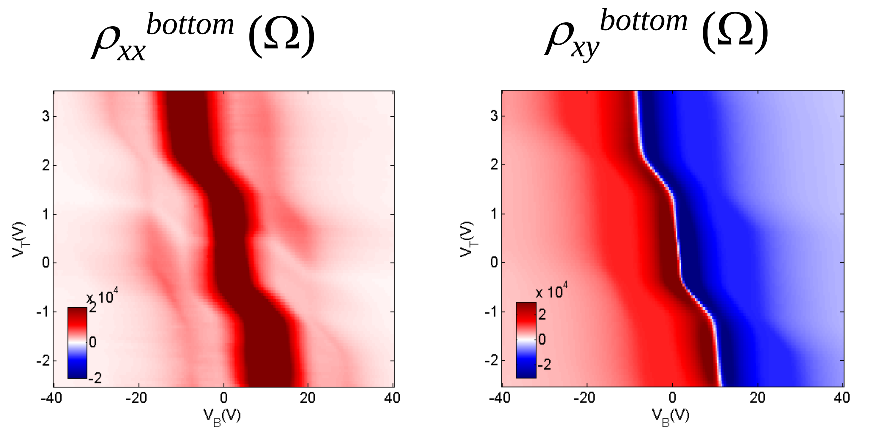
Oscillating Sign of Drag in High Landau Lev

Felix von Oppen,[1] Steven H. Simon,[2] Ady Stern[3]
[1]Institut für Theoretische Physik, Freie Universität Berlin, Arnimallee 14, 14
[2]Lucent Technologies, Bell Labs, Murray Hill, New Jersey, (
[3]Department of Condensed Matter Physics, The Weizmann Institute of Science
(Received 30 April 2001; published 20 August 2001)

$$\rho^D_{xx} \sim \rho^p_{xy}\left\{\frac{d\sigma^p_{yy}}{d(en)}\frac{d\sigma^a_{yy}}{d(en)} + \frac{d\sigma^p_{yx}}{d(en)}\frac{d\sigma^a_{xy}}{d(en)}\right\}\rho^a_{yx}.$$

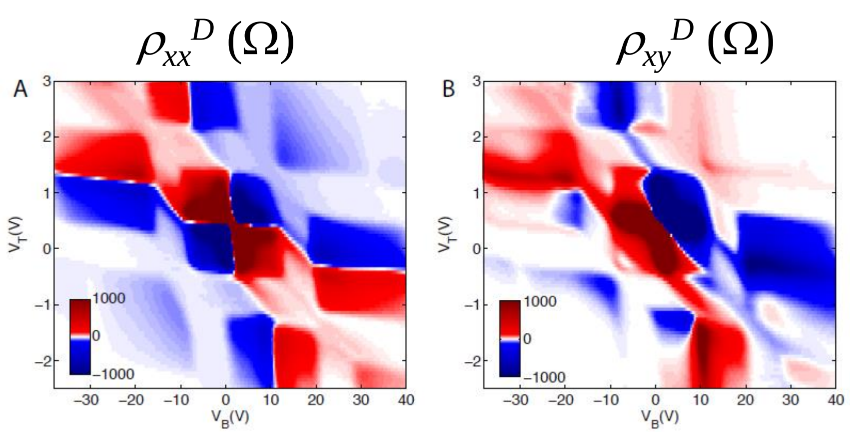
$$\rho^D_{xy} \sim \rho^p_{xy}\left\{\frac{d\sigma^p_{yy}}{d(en)}\frac{d\sigma^a_{yx}}{d(en)} + \frac{d\sigma^p_{yx}}{d(en)}\frac{d\sigma^a_{xx}}{d(en)}\right\}\rho^a_{xy}.$$

Measured Magneto and Hall Resistance

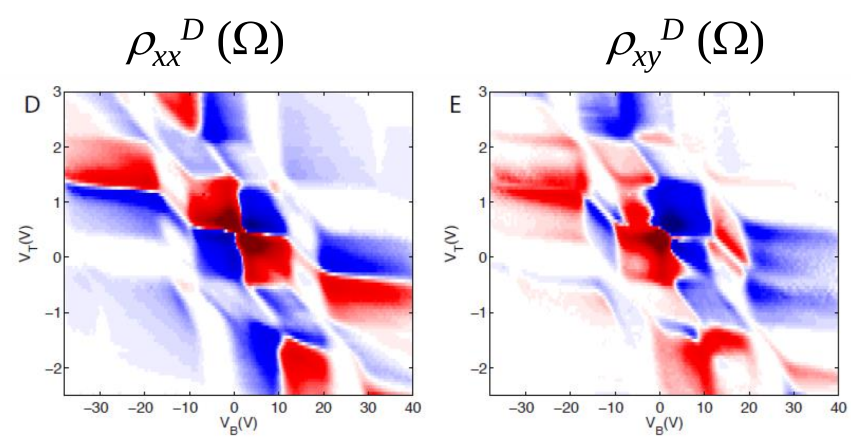


Feng et al., PRL (1998)

Measured magneto and Hall drag



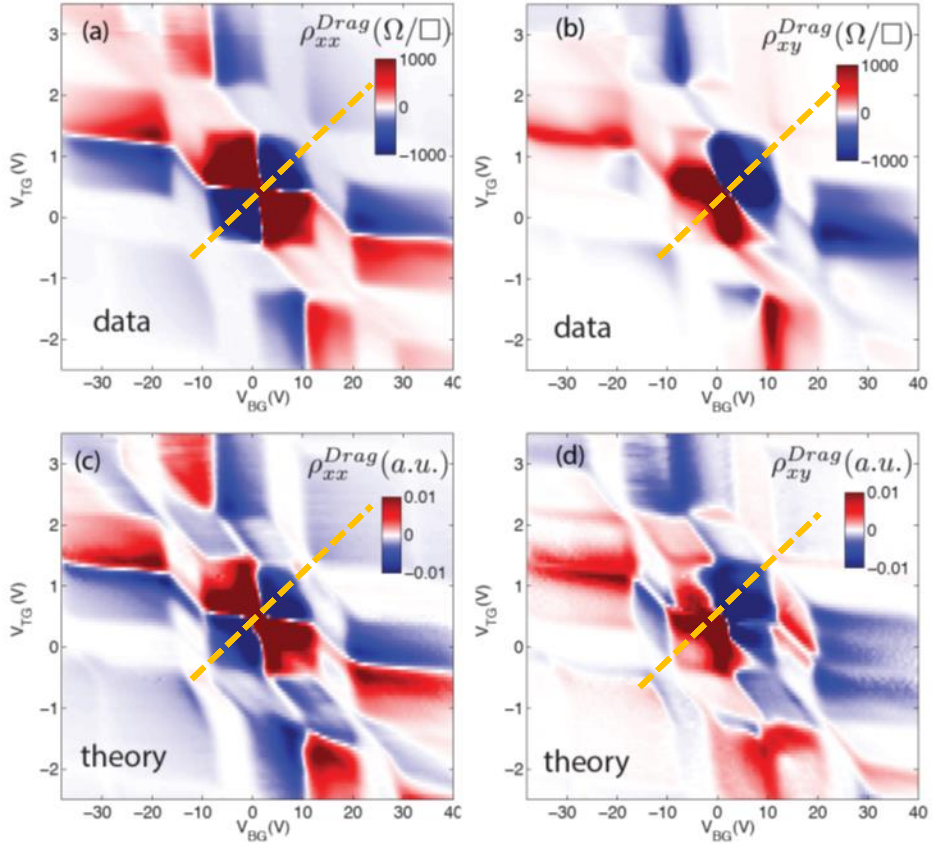
Calculated magneto and Hall drag



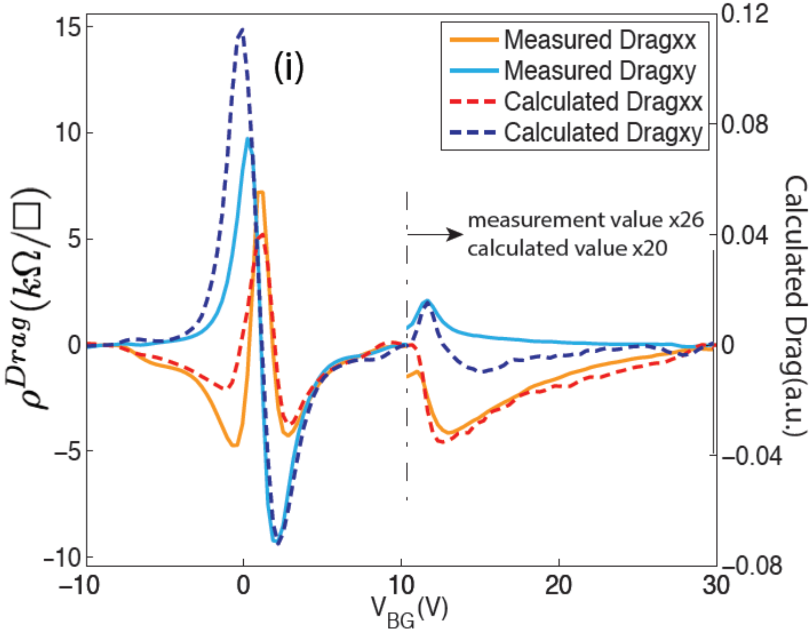
Xiaomeng Liu *et al*, arXiv:1612.08308

Quantitative Comparison

OSS PRL (2001)



$$\hat{\rho}^{Drag} \sim -\hat{\rho}^{p}\frac{d\hat{\sigma}^{p}}{d(en^{p})}\frac{d\hat{\sigma}^{a}}{d(en^{a})}\hat{\rho}^{a}$$

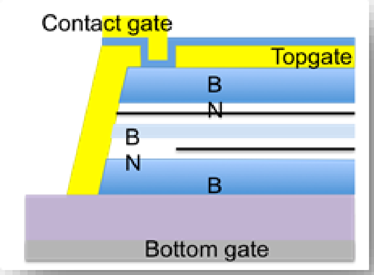


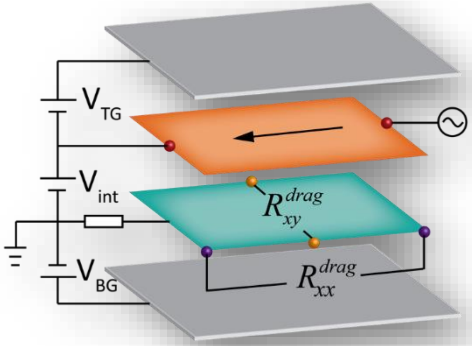
Components of drag tensor follows a similar scaling prefactor.

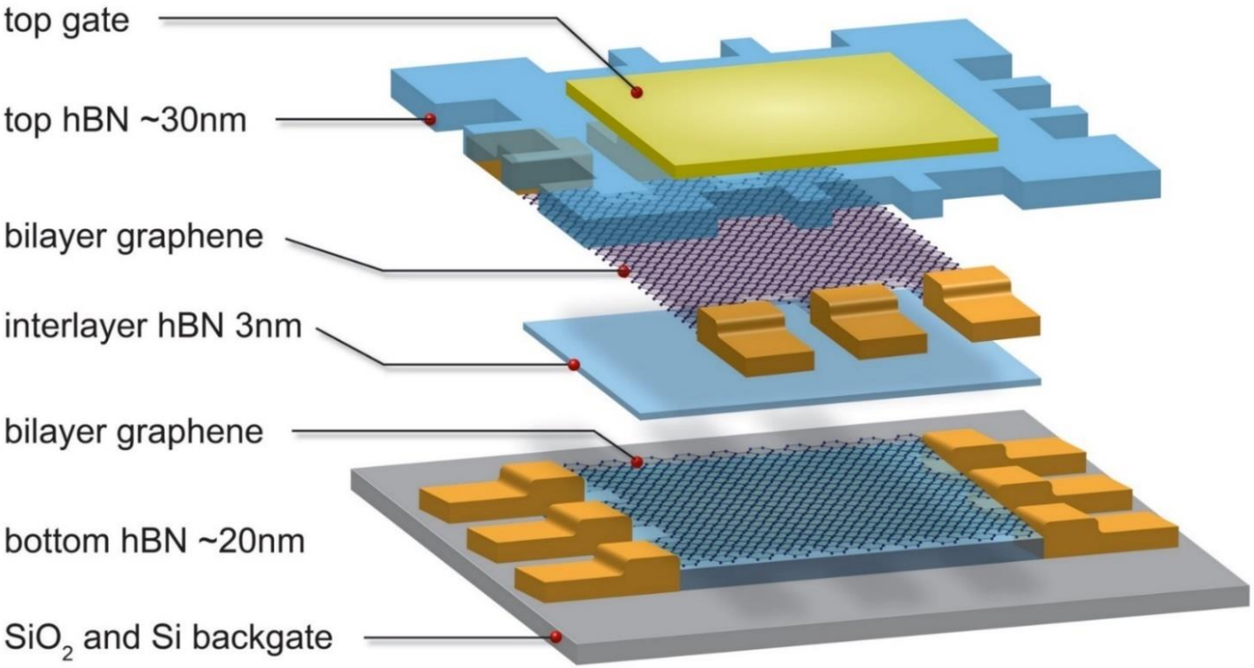
Xiaomeng Liu *et al*, arXiv:1612.08308

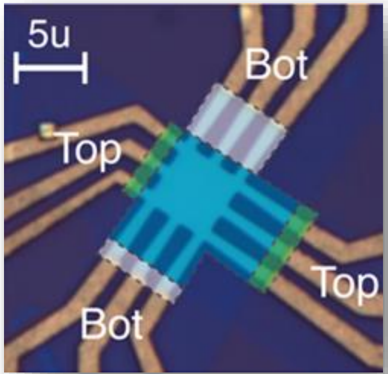
Double Bilayer Graphene Drag Device

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







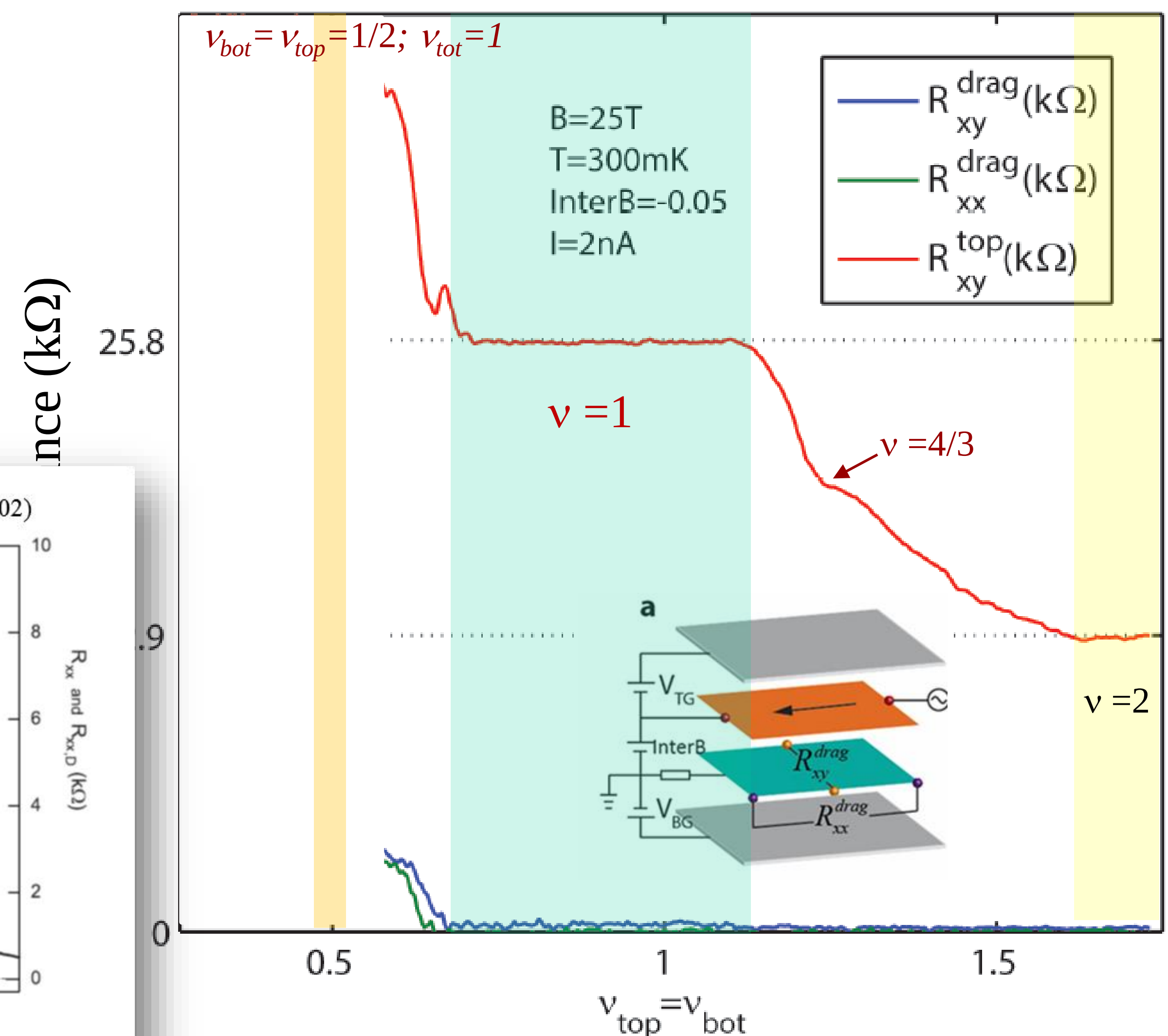


Xiaomeng Liu *et al*, arXiv:1608.03726

Bilayer Graphene/hBN/Bilayer Graphene: Quantized Hall Drag

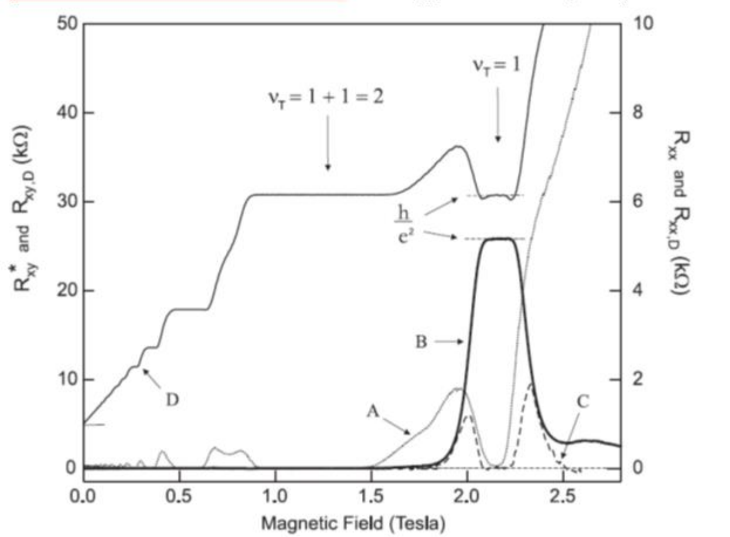
- Mobility ~ 10^6 $cm^2/Vsec$
- hBN thickness d =3 nm
- top and bottom gate
- contact gate
- interlayer bias

Hall Resistance, Magneto Drag, and Hall Drag

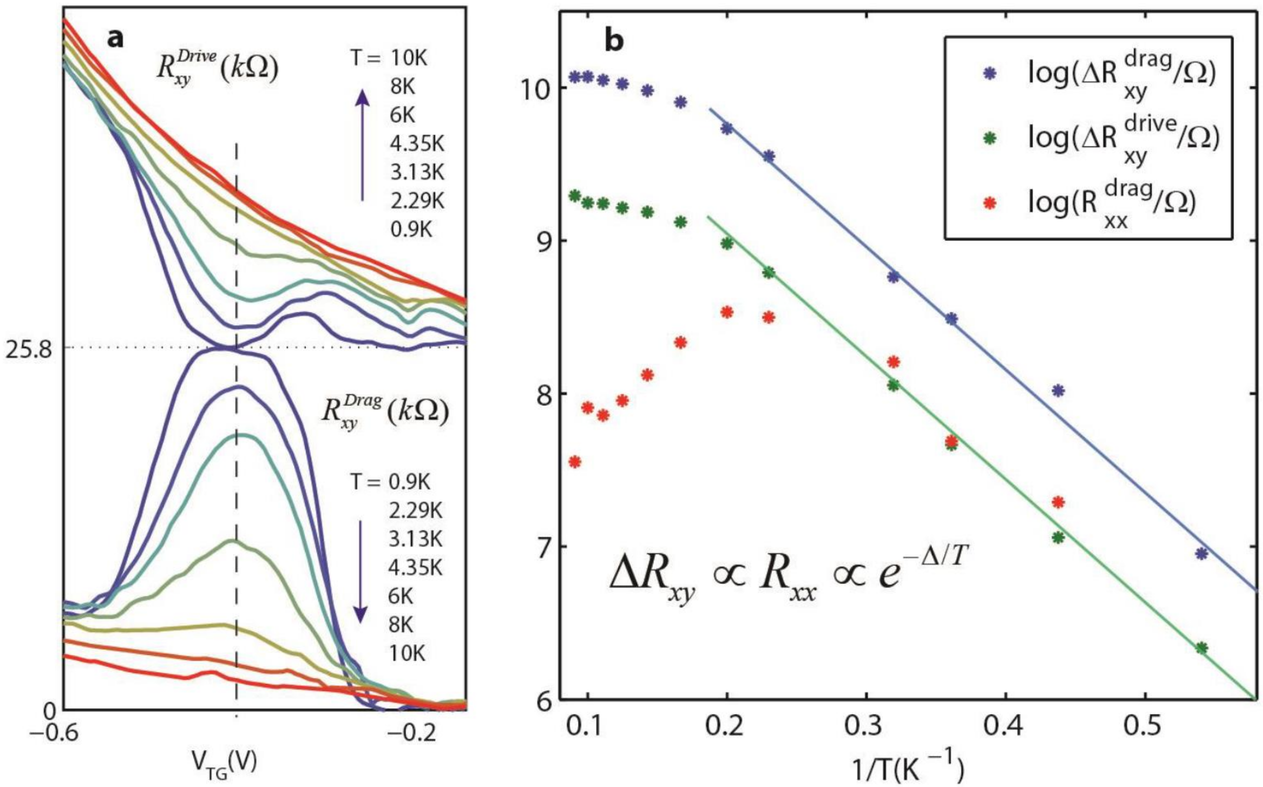


Xiaomeng Liu *et al*, arXiv:1608.03726

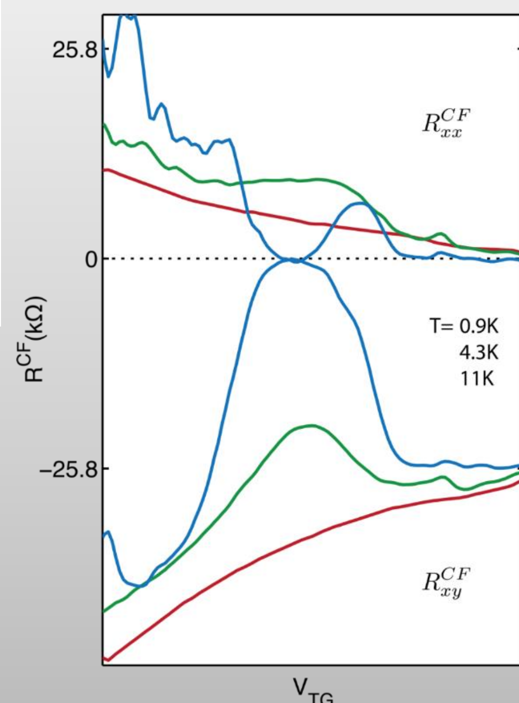
GaAs Double Quantum Well: Kellogg et al. PRL (2002)



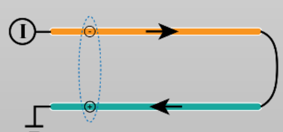
Exciton BEC Energy Scale and Counter Flow



$\Delta \sim 8$ K.



Superfluidic Counter flow

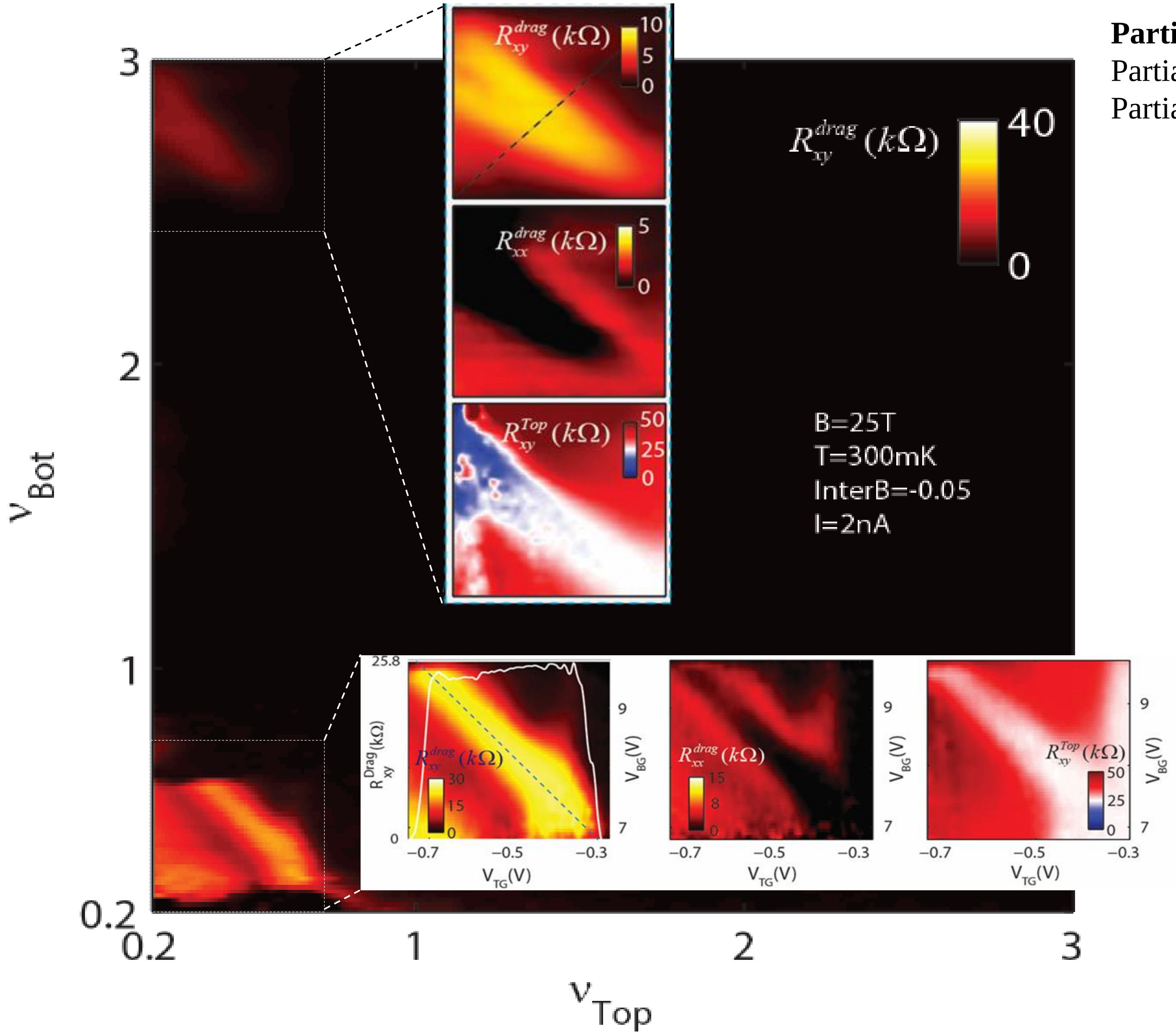


$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \end{bmatrix}$$

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

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

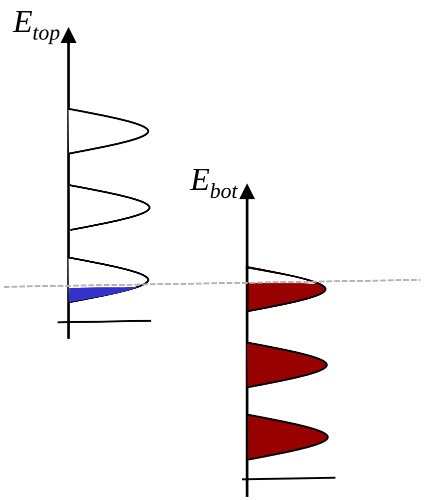
Quantized Hall Drag for ν_{tot} = 1 and 3



Partial coherent exciton current:

Partially filled N_{top} =1

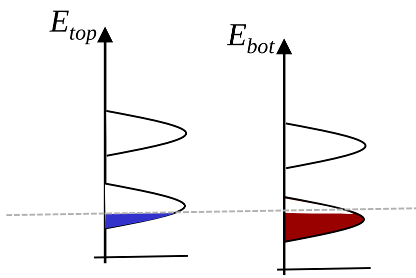
Partially filled N_{bot} =3



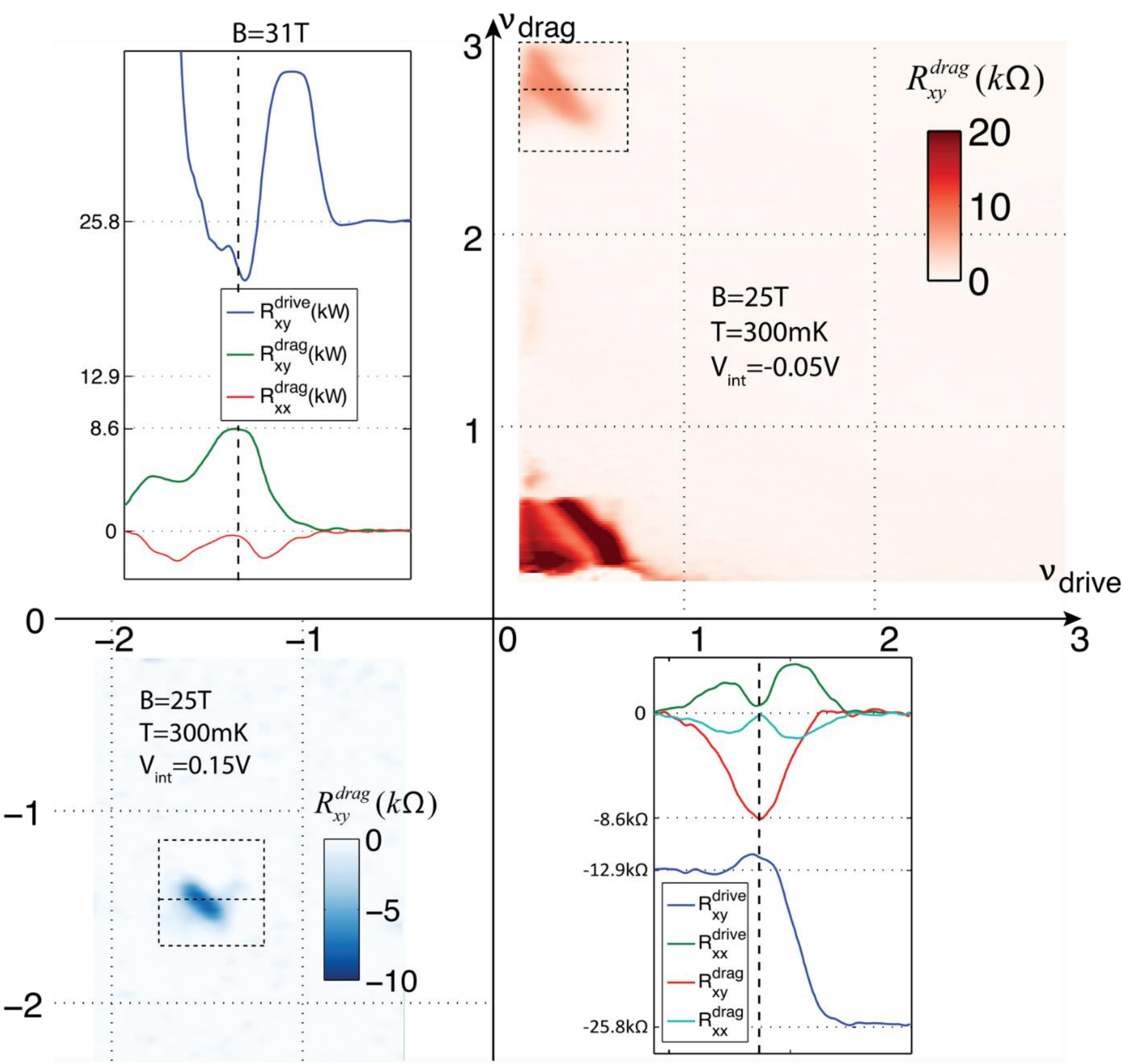
Coherent exciton current:

Partially filled N_{top} =1

Partially filled N_{bot} =1



Magneto Exciton Condensation in Different LLs



Observed Exciton condensations

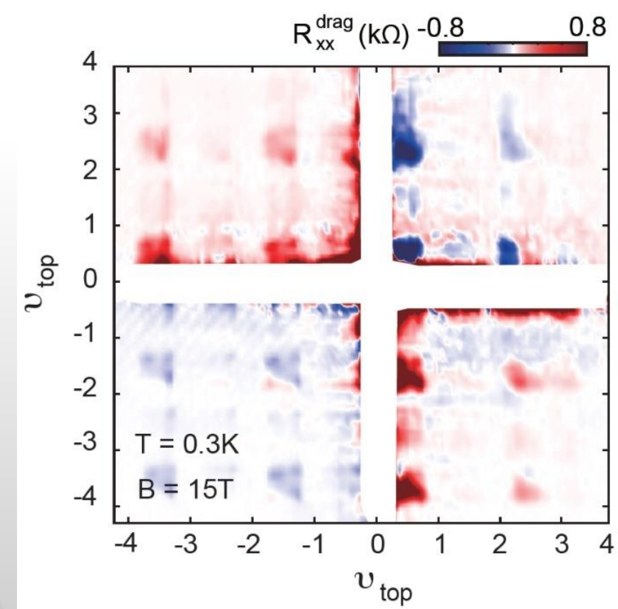
(0.5, 0.5)

(0.5, 2.5); (2.5, 0.5)

(-0.5, -0.5)

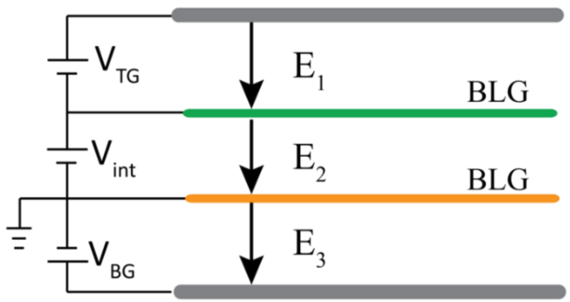
Possible ν -> ν +2 symmetry
in bilayer graphene double layer

Other possible Exciton Condensation



Li et. al., arXiv:1608.05846

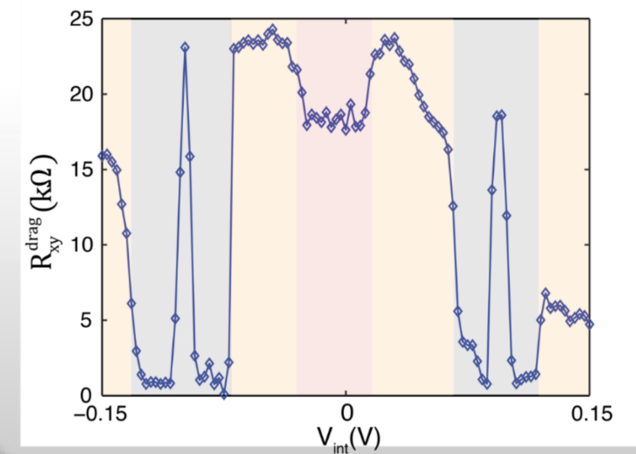
Effect of Interlayer Bias Voltage



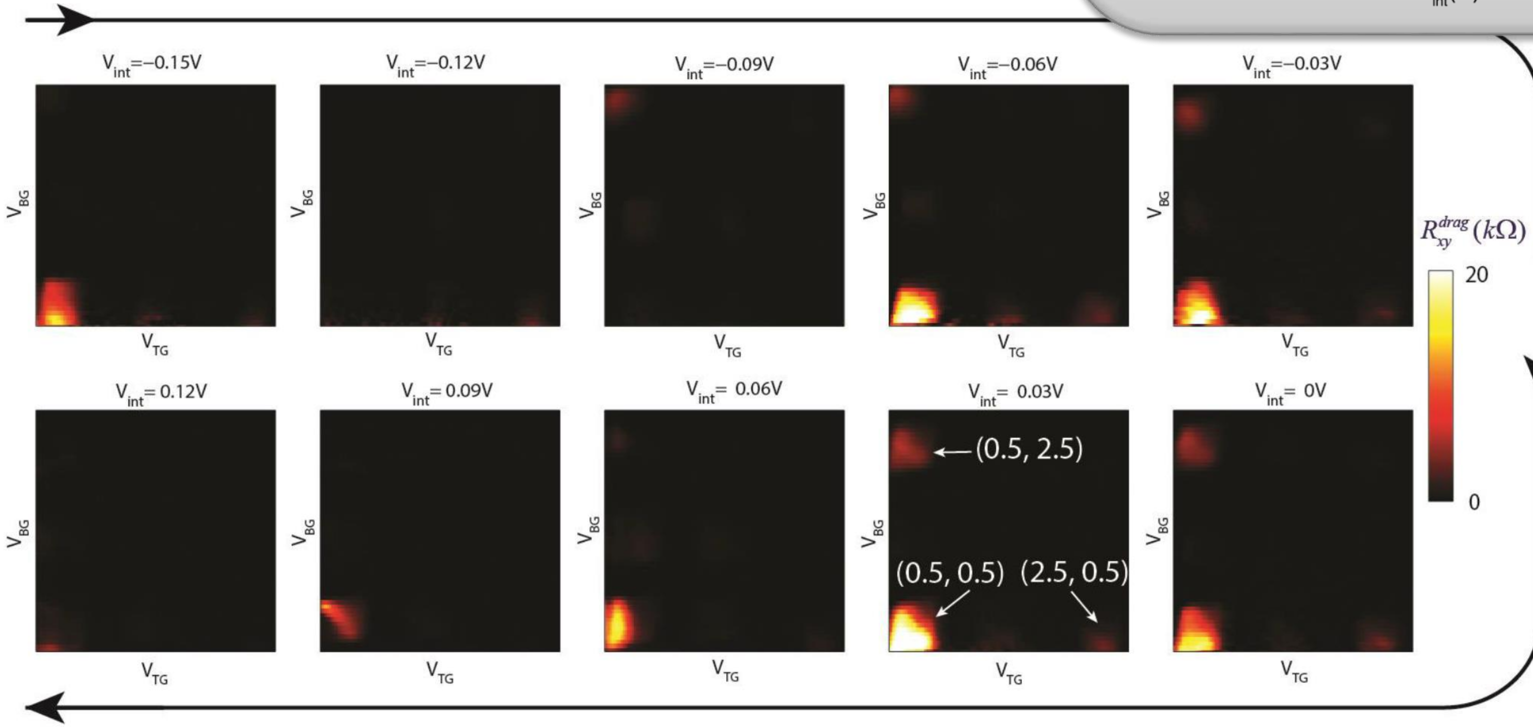
$$n_{top} = C_{TG}V_{TG} - C_{int}V_{int}$$
$$n_{top} = C_{BG}V_{BG} + C_{int}V_{int}$$

$$D_{top} = (C_{int}V_{int} + n_{top})/2$$
$$D_{bot} = (C_{int}V_{int} - n_{bot})/2$$

Interlayer Bias voltage dependence (0.5, 0.5)

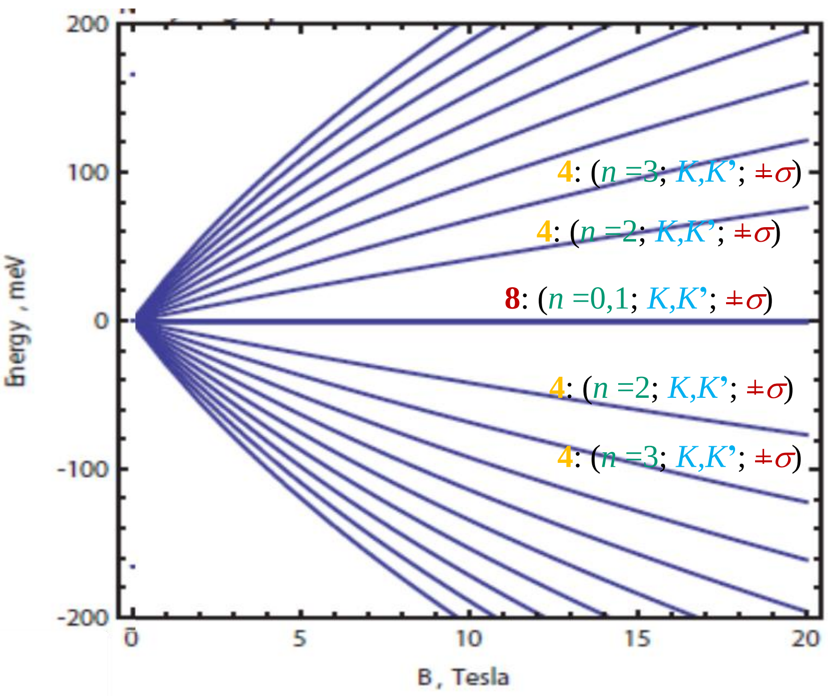


Interlayer Bias voltage dependence E

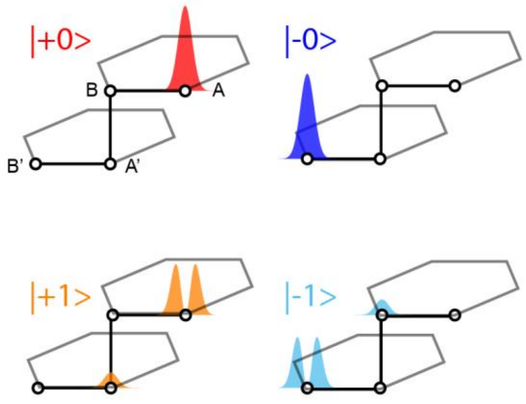


Quantum Hall Ferromagnetic Phase Transition in Bilayer Graphene

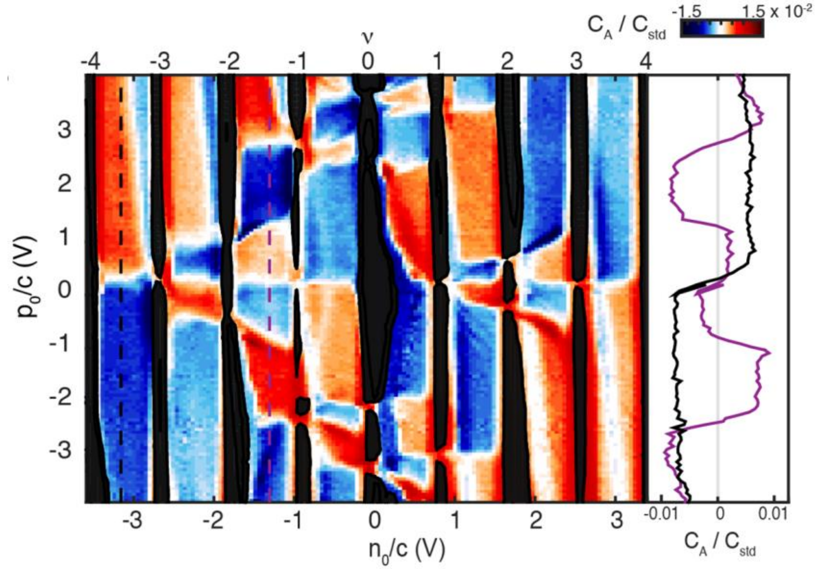
Bilayer Landau level spectrum: SU(4) and SU(8)



Each Landau level is degenerate for spin and valley except zero energy LL where there is an additional 'accidental' degeneracy n =0,1.

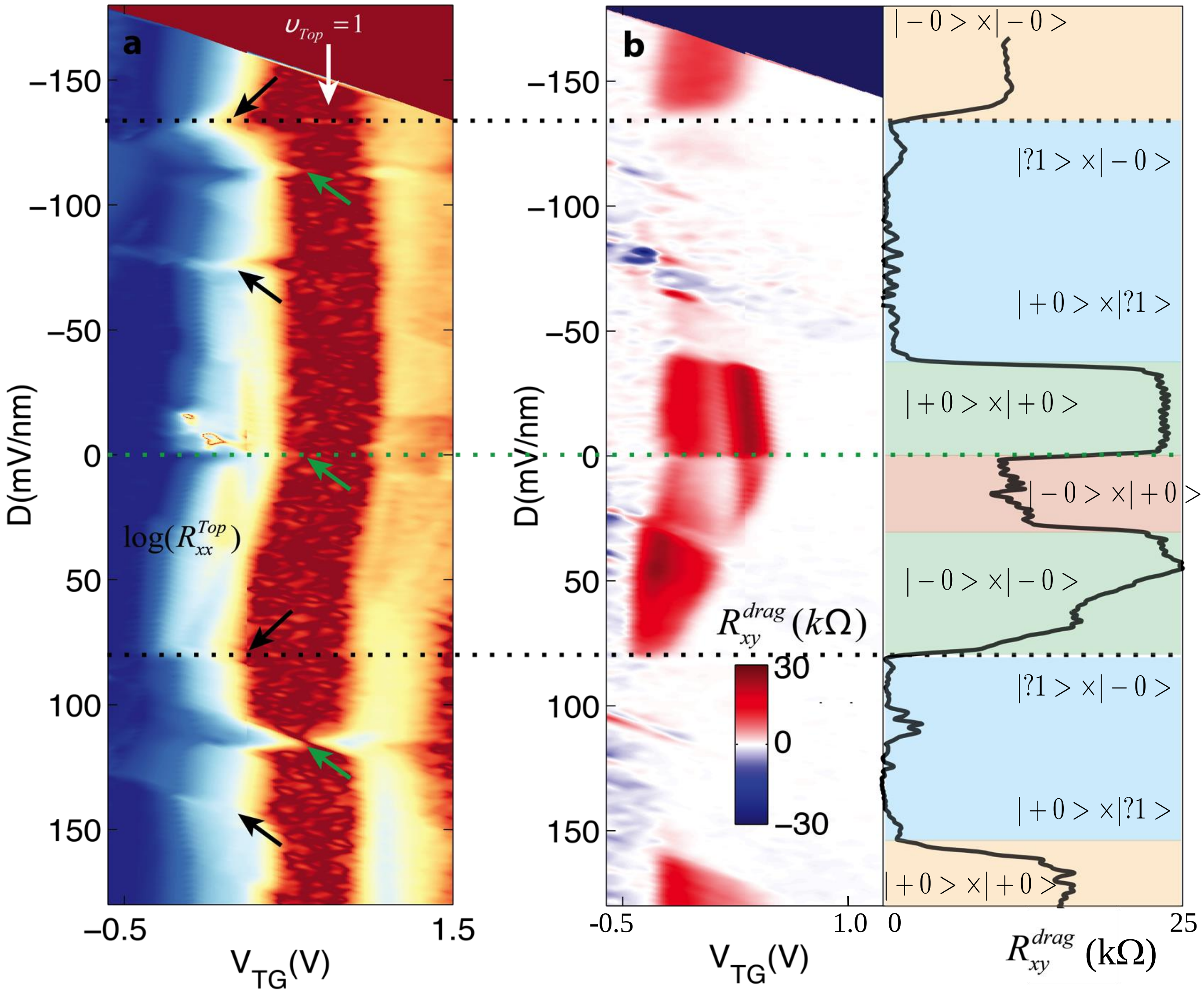


Broken Symmetry Gap in Bilayer due to Interaction:
Tuned by displacement field (pseudo magnetic field)



B. M. Hunt etc. (2016).

Exciton BEC Phase Transition: Internal Degree of Freedom of Exciton



Appearance of BEC closely related to wave function of BLG

Strength of BEC controlled by layer/valley polarization

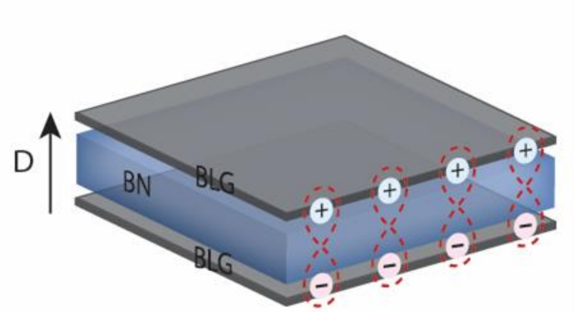
Internal degree of freedom of excitons can be controlled and incur phase transitions in the BEC.

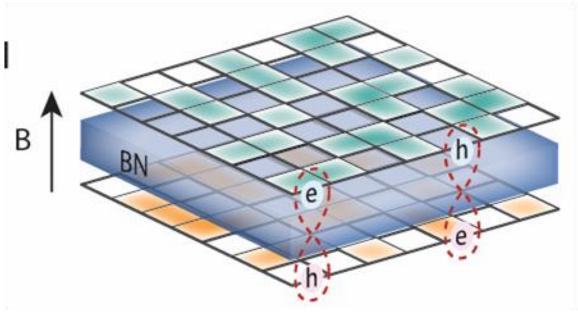
Summary and Outlook

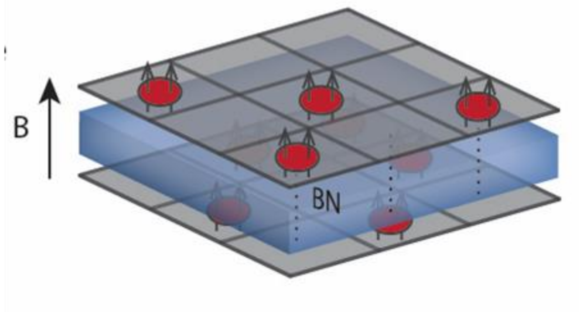
- Semiclassical Coulomb drag in the presence of thermal fluctuations
- Quantum drag Hall effect and robust magneto exciton condensation
- Exciton condensation between different Landau levels
- Phase transition between different exciton condensations

Moving forward:

Double monolayer, resonance tunneling, phase transition in BEC, exciton insulator (B=0), fractional excitons, ...







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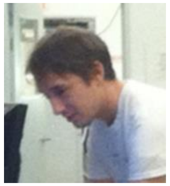

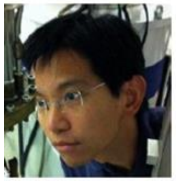


Cory Dean, Patrick Maher, Lei Wang, K.C. Fong, Jim Hone

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