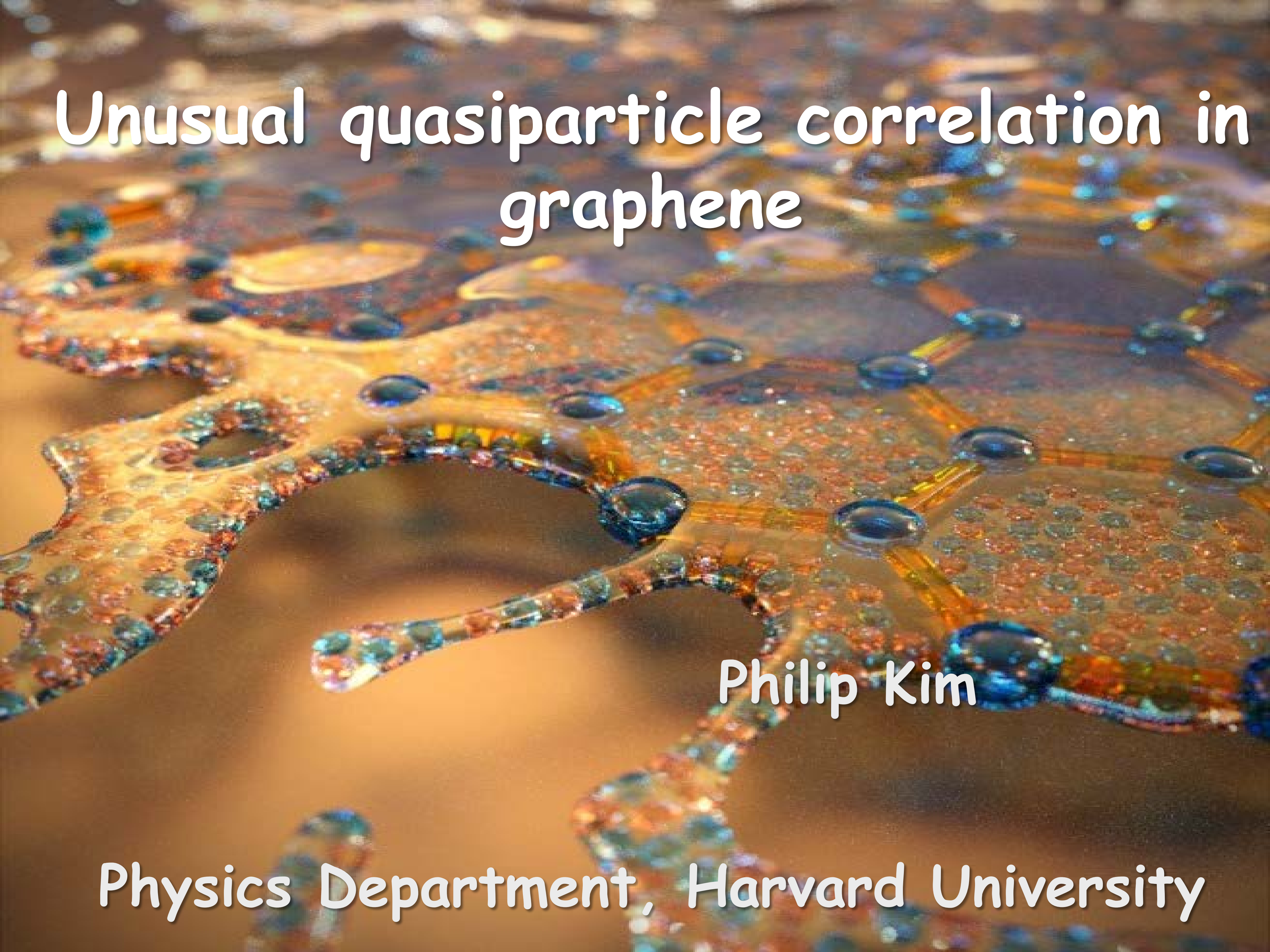
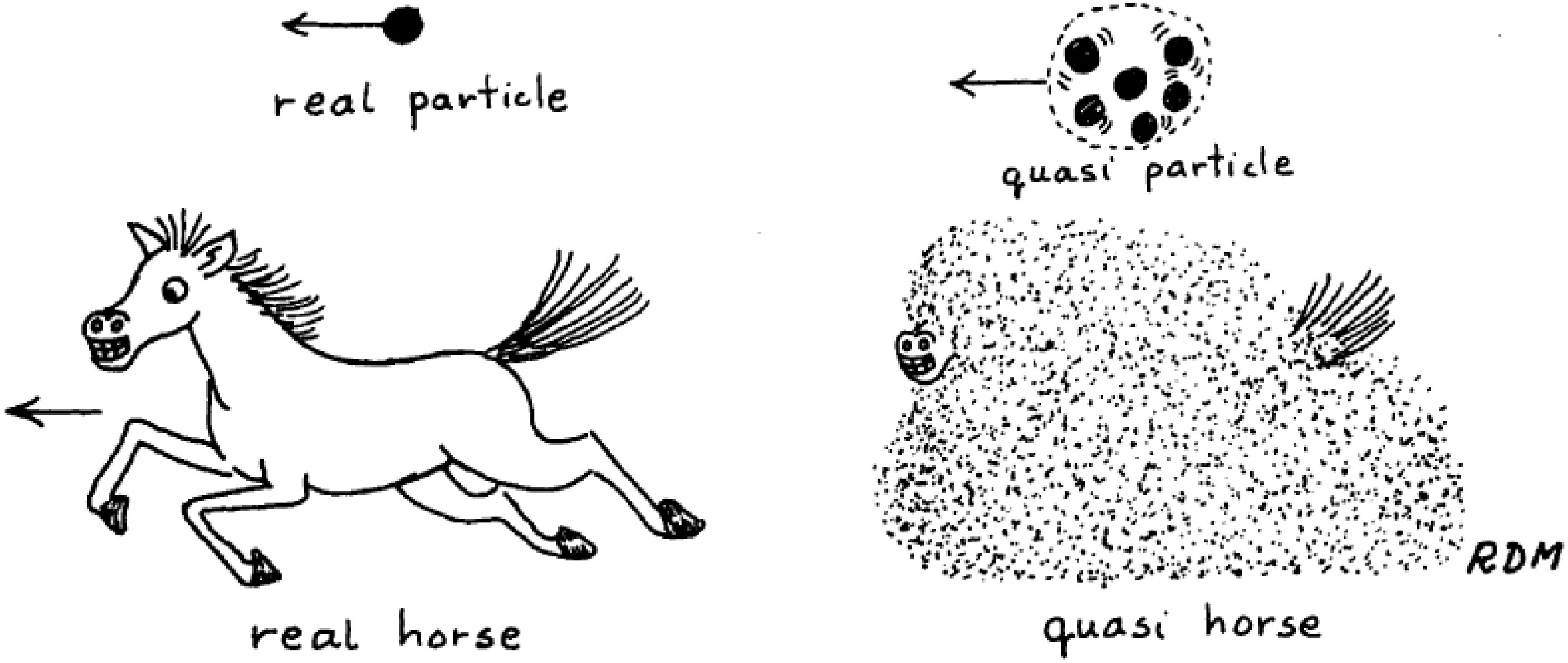


Unusual quasiparticle correlation in graphene

Philip Kim

Physics Department, Harvard University

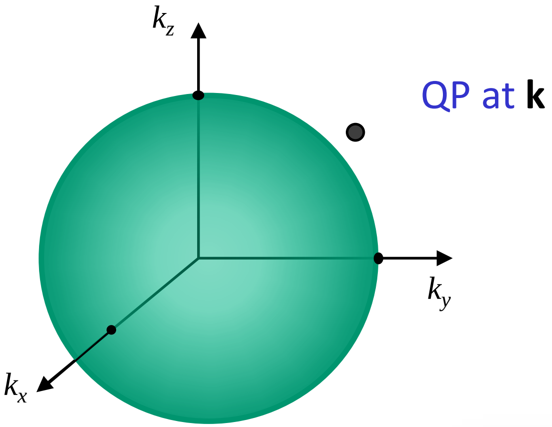
'Real' Particles and 'Quasi' Particles



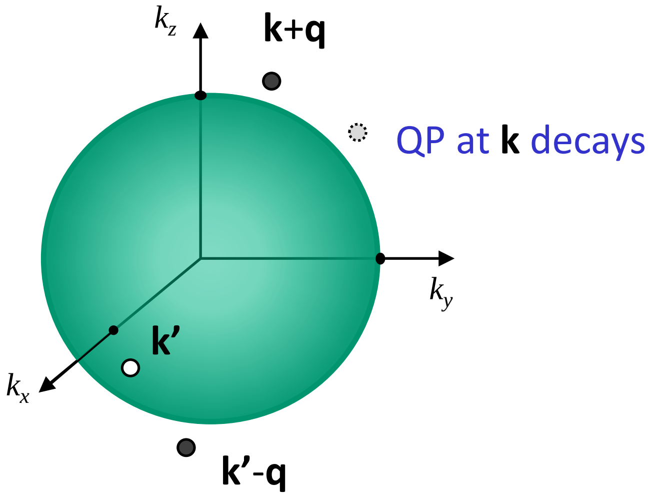
R. Mattuck, "A guide to Feynman diagrams in the many-body problem"

Landau Theory of Fermi Liquid

L. D. Landau (1957).



After t [> τ]



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

Fermi liquid: Weakly interacting quasiparticles

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

Wiedemann Franz Law in Fermi Liquid

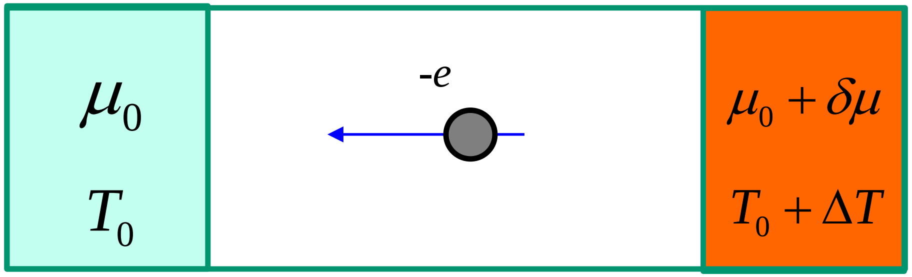
Thermal conductivity
versus electrical conductivity

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

Relaxation of charge current and heat current

$$j = -e n_e \langle v_e \rangle$$

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



μ_0

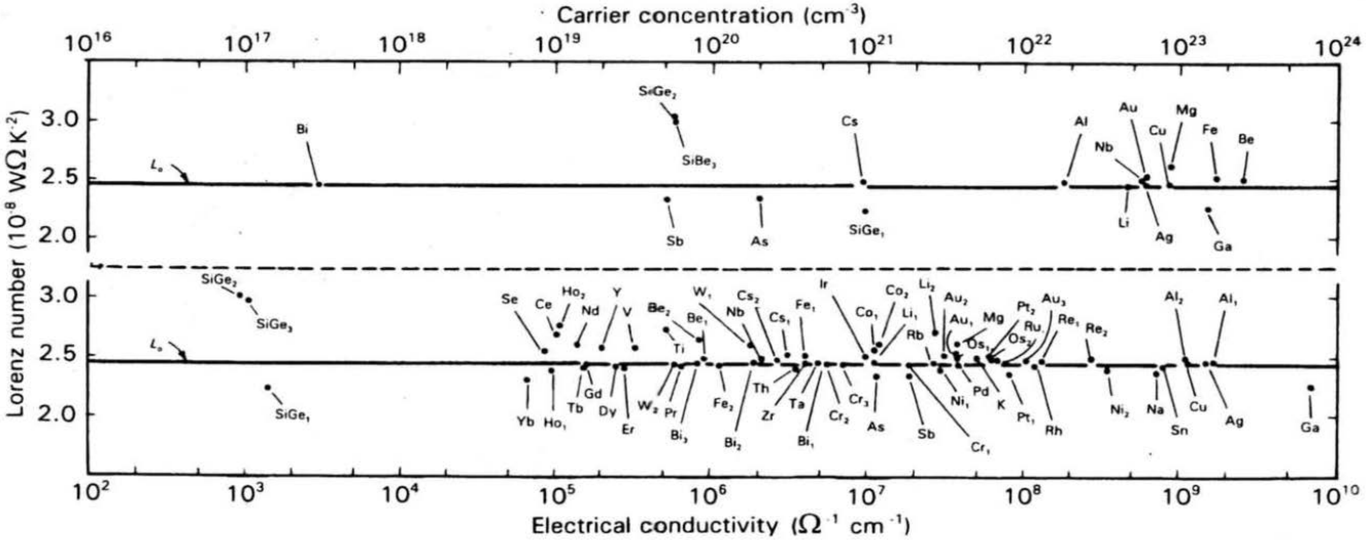
T_0

$-e$

$\mu_0 + \delta\mu$

$T_0 + \Delta T$

Works well with metals…



Kumar, Prasad, Pohl,
J. of Materials Sci. 28, 4261 (1993)

Wiedenmann Franz in Non Fermi Liquid

ARTICLE

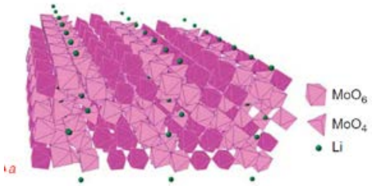
NATURE COMMUNICATIONS | 2:396 | DOI: 10.1038/ncomms1406

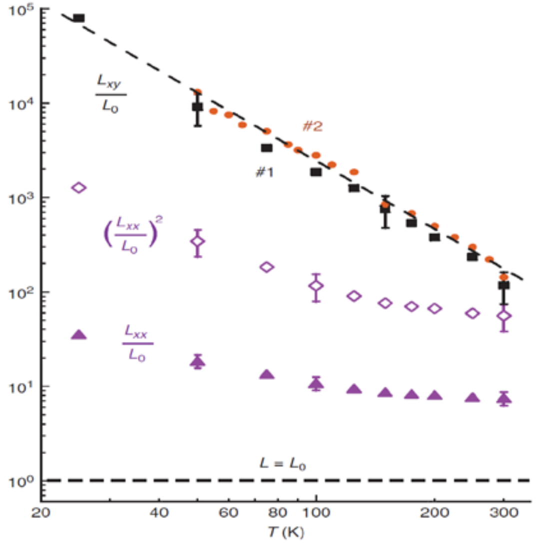
Received 25 Feb 2011 | Accepted 20 Jun 2011 | Published 19 Jul 2011

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]†

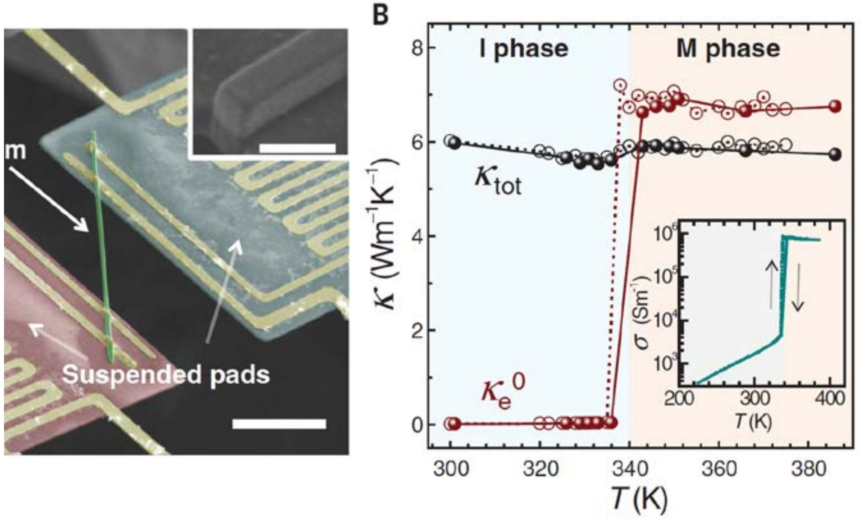


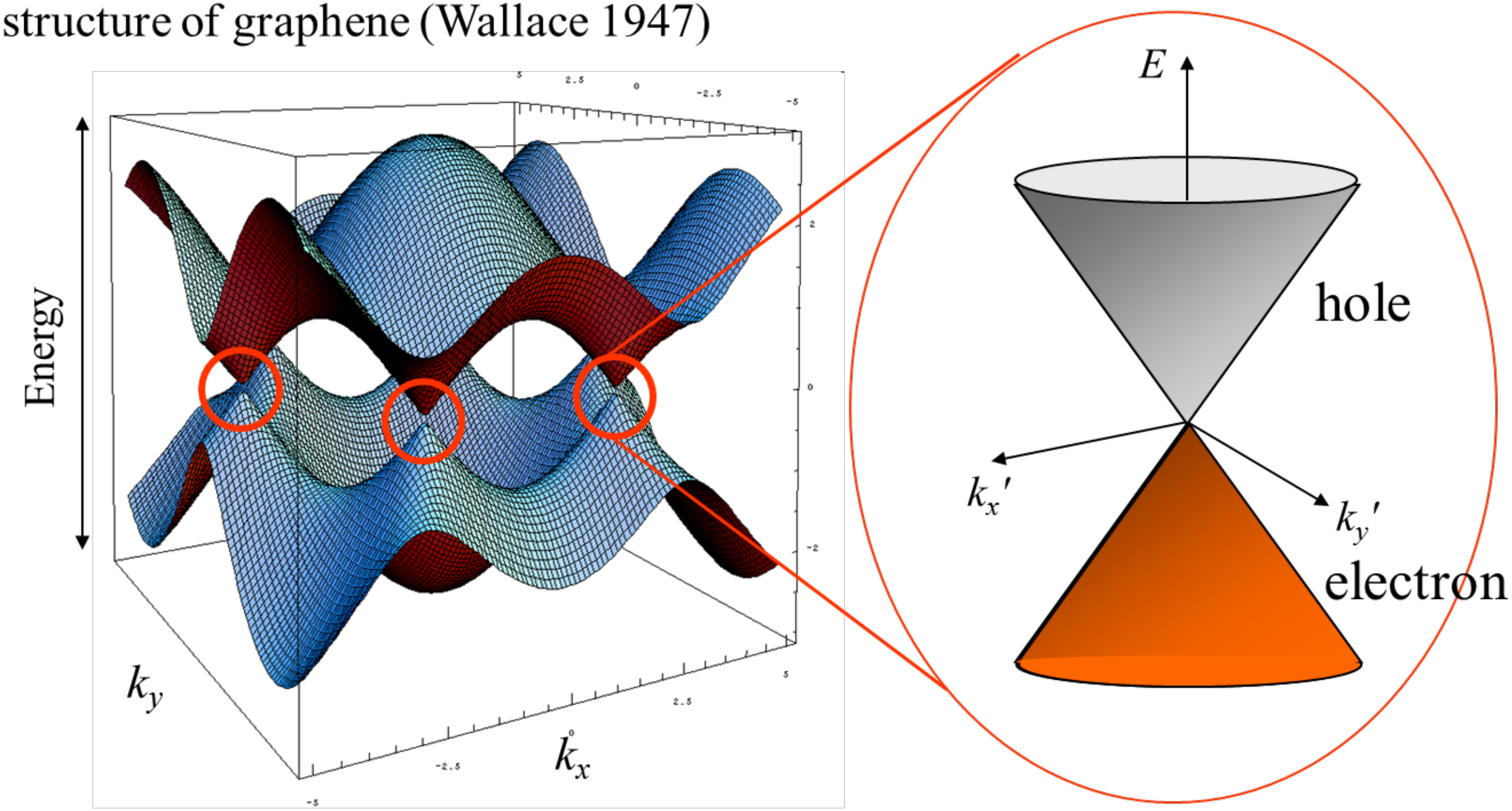
Fig. 1. Thermal conductivity of VO_2 across the metal-insulator transition. (A) False-color scanning

Outline: Quasiparticle Interaction in Graphene and vdW Heterostructures

- **Electron and hole interaction near the Dirac point: Dirac Fluid**
- **Electron and hole correlation by superconducting proximitized quantum Hall edge: Crossed Andreev reflection**
- **Electron and hole correlation across the atomic layers: Excitons and Magnetoexcitons**

Dirac Point in Graphene

Band structure of graphene (Wallace 1947)



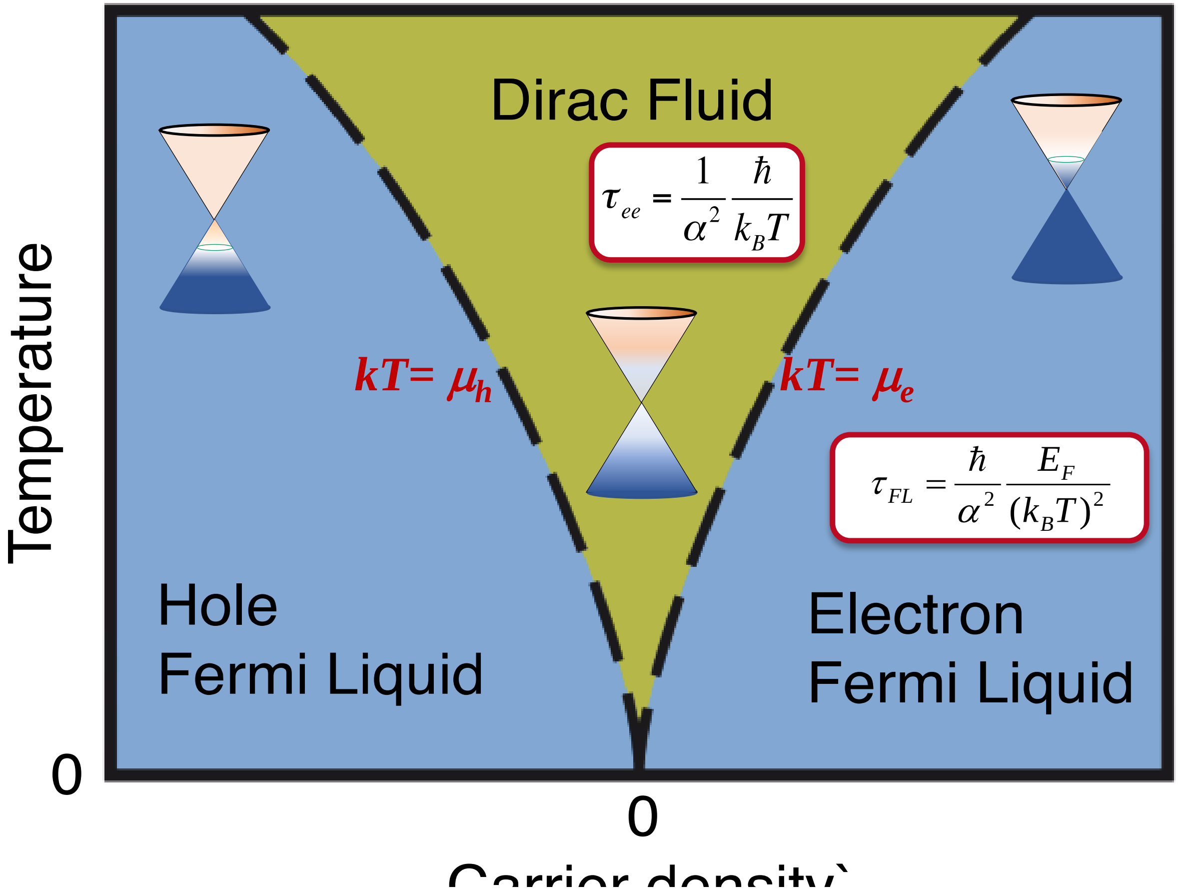
$$E \approx \hbar v_F \left| \vec{k}'_{\perp} \right|$$

Zero effective mass particles moving with a constant speed v_F

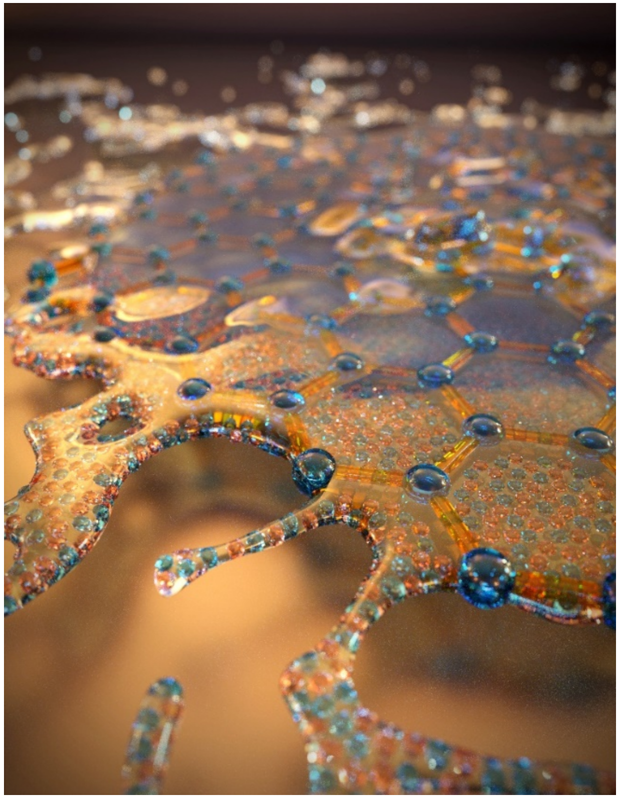
Effective Fine Structure Constant $\alpha = \dfrac{e^2}{\varepsilon_r \hbar v_F} \sim 1$

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

Hydrodynamic Transport in Dirac Point in Graphene



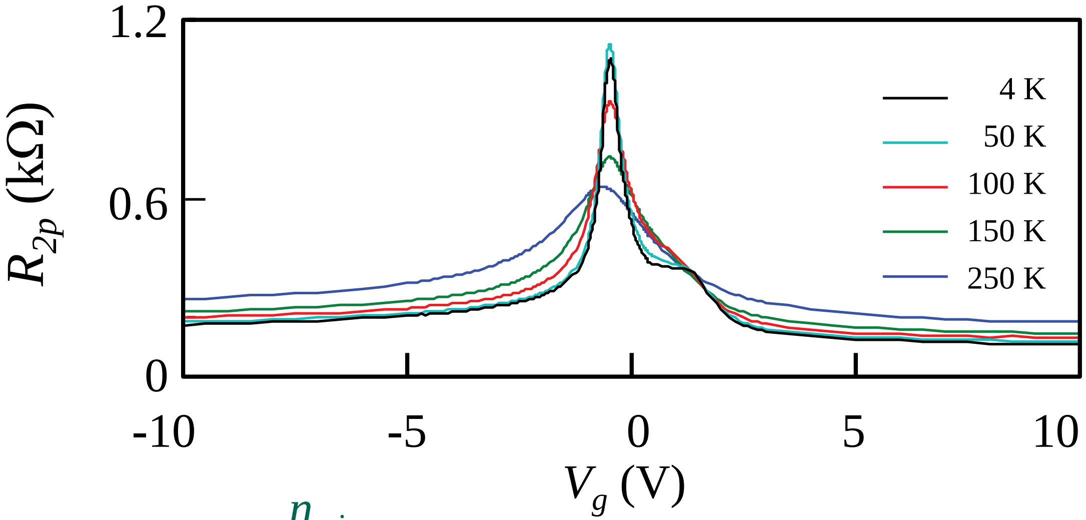
Sheehy and Schmalian, PRL 99, 226803 (2007)
Fritz, Schmalian, Muller, and Sachdev, PRB (2008).
Mueller, Fritz, and Sachdev, PRB (2008).
Foster and Aleiner, PRL (2009).
Mueller, Schmalian, Fritz, PRL (2009)



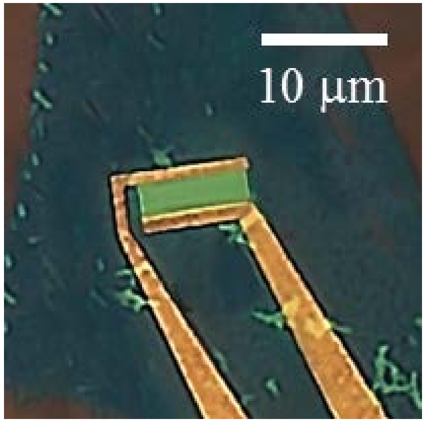
Dirac Fluid at the CNP of graphene

Condition of hydrodynamic description: $\tau_{ee} << \tau_{imp}$

Non-Degenerate Electron Gas at Dirac Point

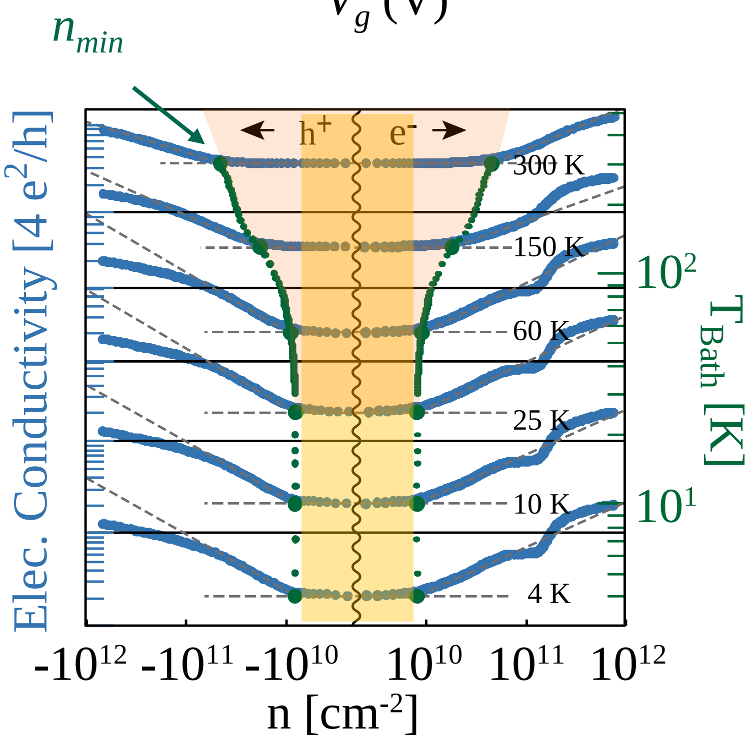


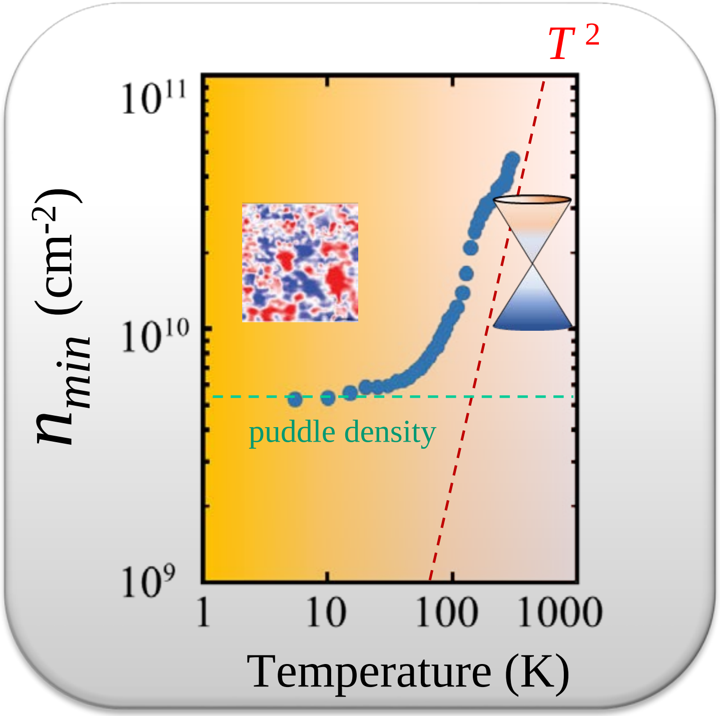
hBN encapsulated single layer graphene



Thermal broadening

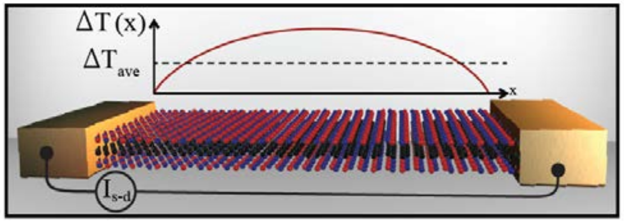
Disorder broadening





Johnson Noise Thermometry for Thermal Conductivity Measurement

Joule heating by DC bias through bias T



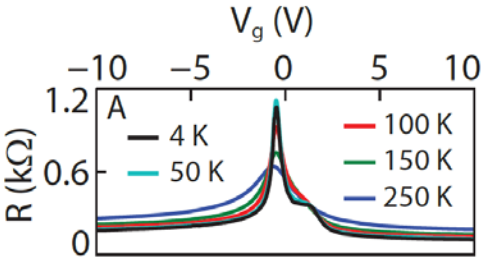
$$\sqrt{4k_bT\,\Delta f\,R} = V_{RMS}$$

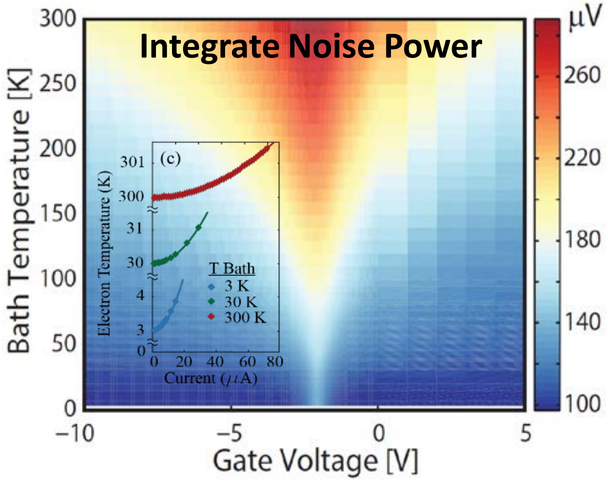
Johnson Noise Temperature

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

Local heat dissipation

$$G_{th} = \frac{I_{DC}^{\,2}R}{\Delta T_{ave}}$$





- **Measurement of electronic contribution of thermal conductivity**
- **Comparison with electrical conductivity to check Wiedemann-Franz law**

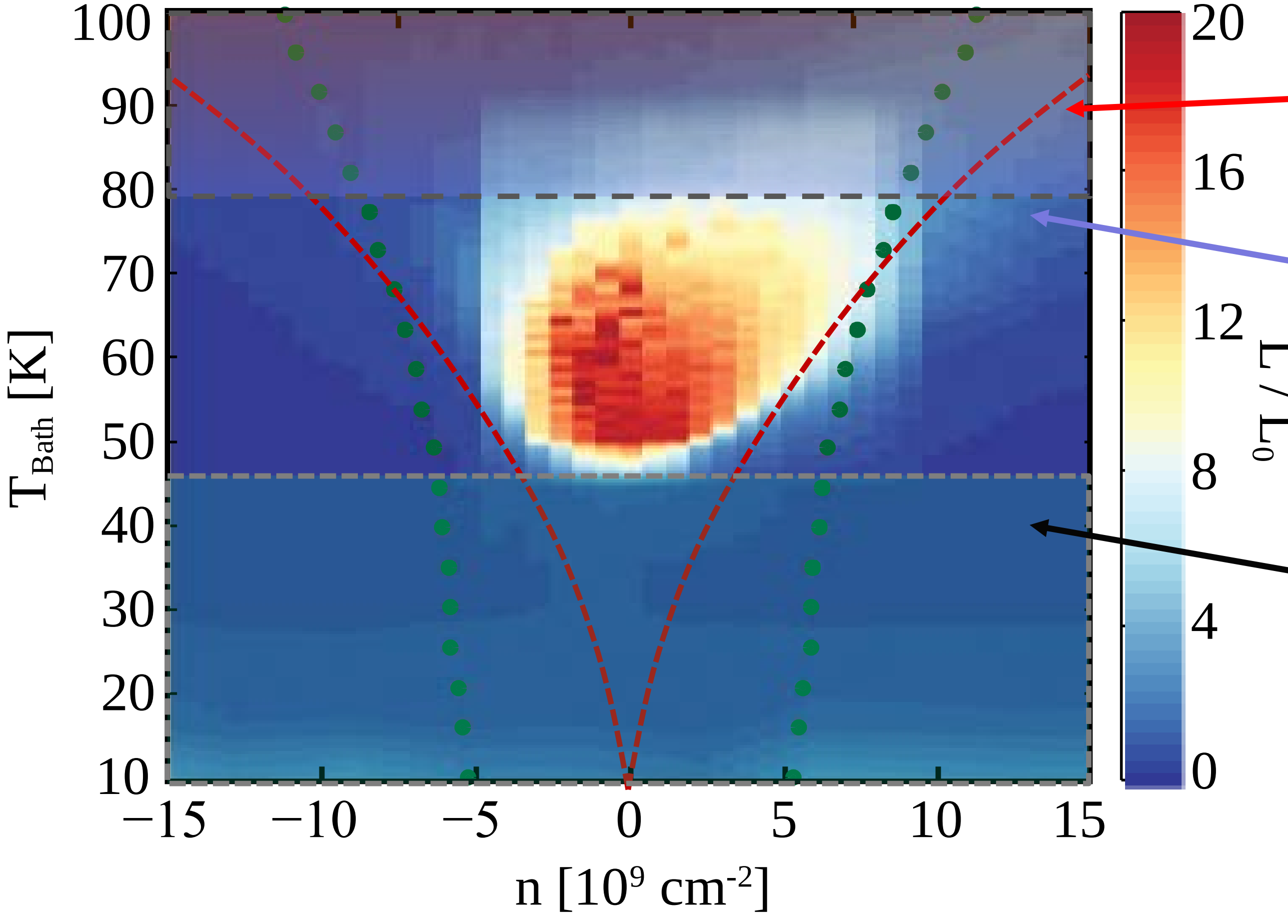
J. Crossno *et al.*, APL (2015)

J. Crossno *et al.*, Science (2016)

Violation of Wiedemann Franz Law in Charge Neutrality of Graphene

Experimentally obtained Lorentz value: $L = \frac{\kappa}{\sigma T} \approx \frac{G_{th} R}{12T}$

Wiedemann-Franz Law Sommerfeld value: $L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$



$\mu(T) = k_B T$

On set of other inelastic scattering

Disorder fluctuation

J. Crossno *et al.*, Science (2016): Collaboration with Subir Sachdev

Relativistic Hydrodynamics Analysis

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

Lorentz number for Dirac fluid

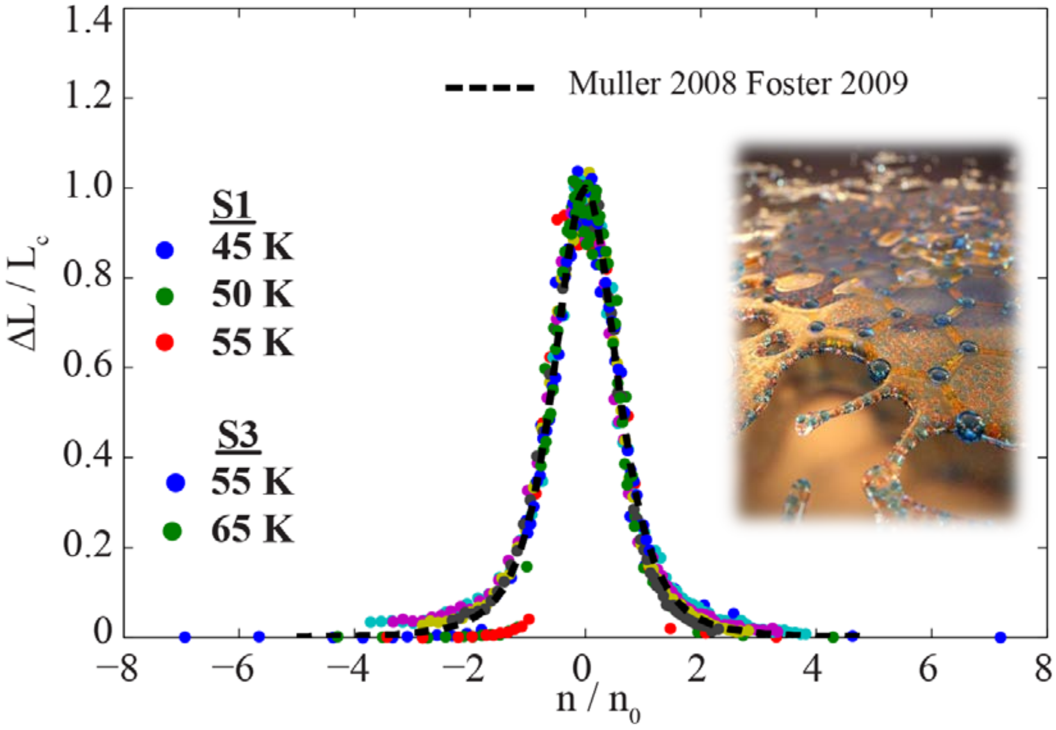
$$L = \frac{1}{((n/n_0)^2+1)} L_c$$

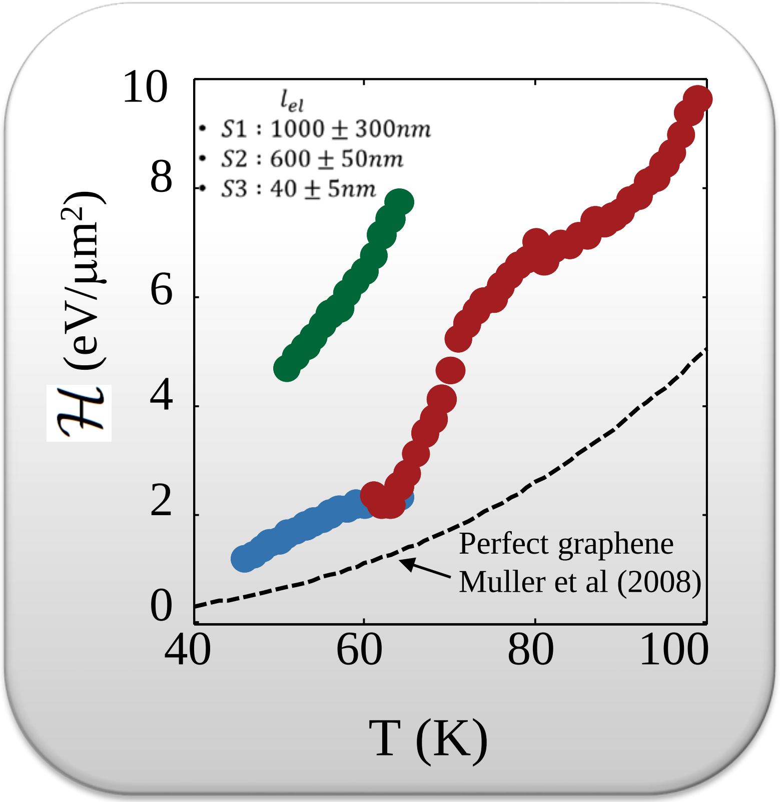
$$L_c = \frac{v_F}{\sigma_{min} T^2} \mathcal{H} \ell_{el}$$

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

$\mathcal{H}$: Fluid enthalpy density

ℓ_{el} : elastic mean free path



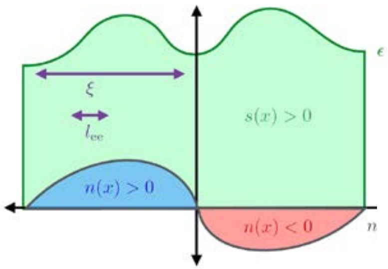


Electrical and Thermal Conductance

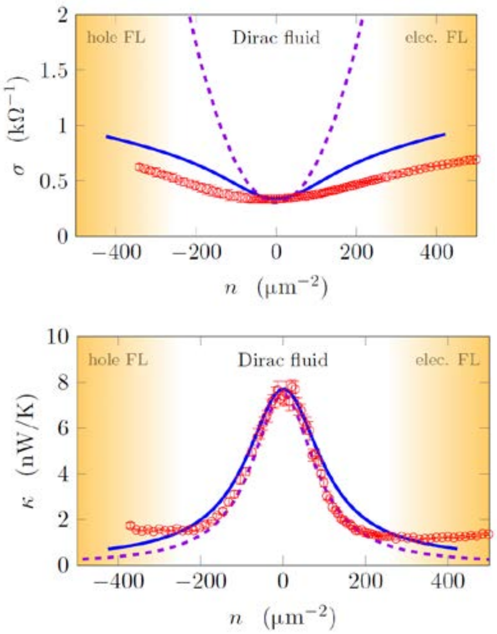
Effect of Disorder

Lucas et al, PRB (2016).

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



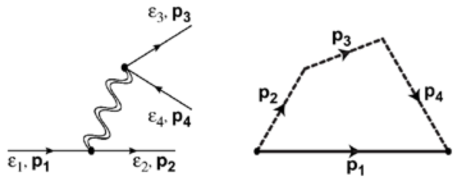
$$F^{ti}_{\text{ext}} = -F^{it}_{\text{ext}} = \partial_i \mu_0$$



Disorder affect charge current more than energy current

Slow Imbalance

Foster and Aleiner PRB (2012);



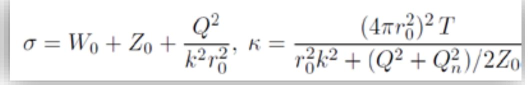
$$e^- \leftrightarrow e^- + e^- + h^+,$$
$$h^+ \leftrightarrow h^+ + h^+ + e^-.$$

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

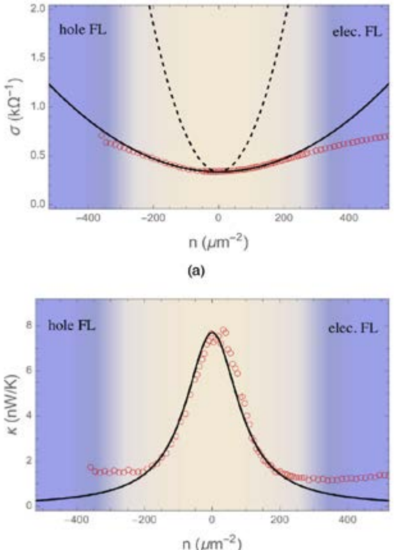
Holography of the Dirac Fluid in Graphene with two currents

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

PRL (2017)



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

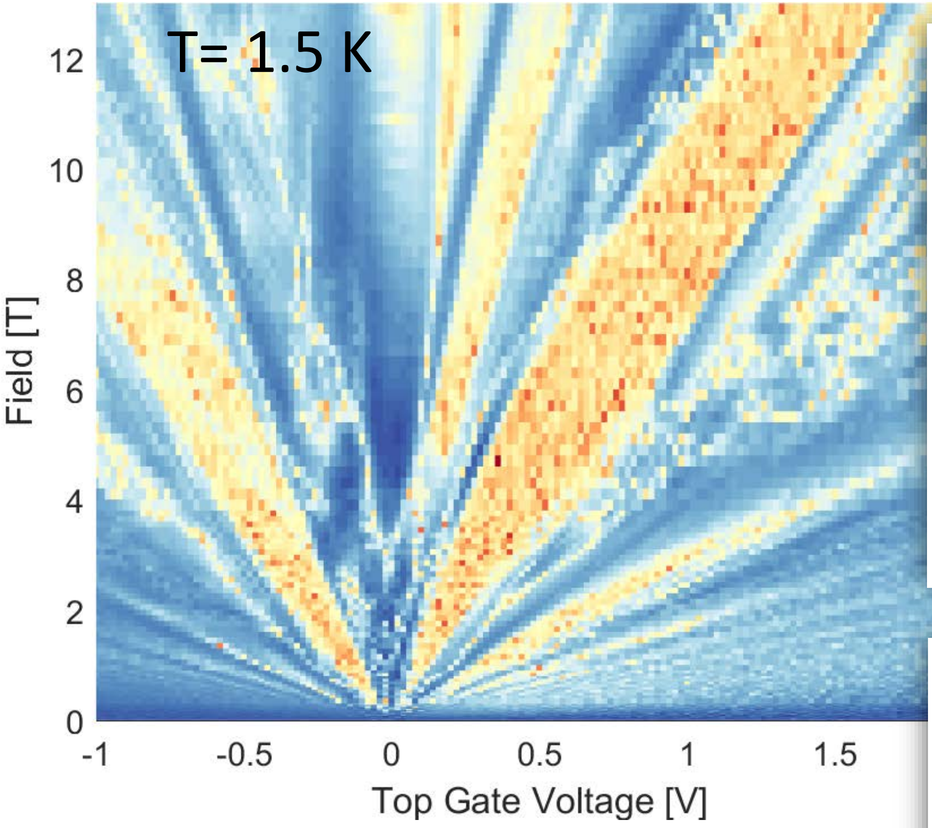


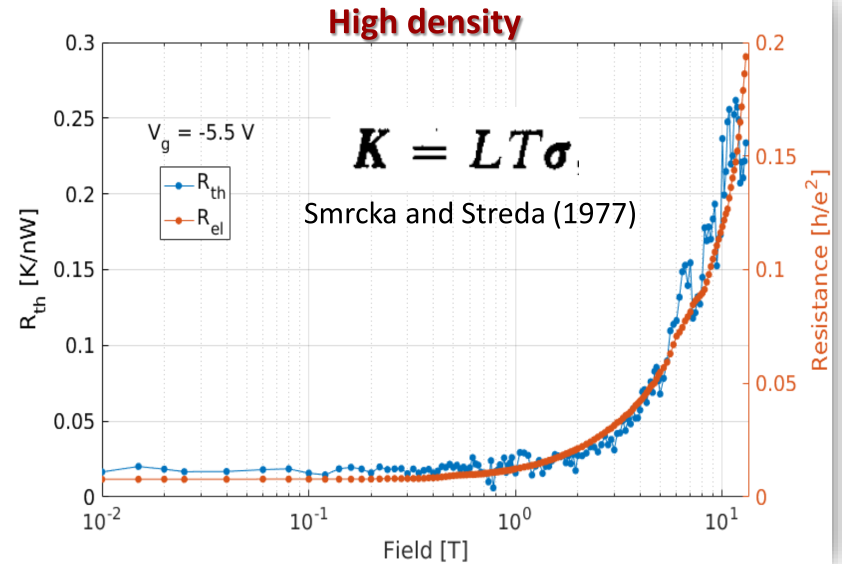
Charged current: $J = J_e + J_h$

Neutral current: $J_n = J_e - J_h$

Corresponding conservative quantities by continuity equation: Q, Q_n

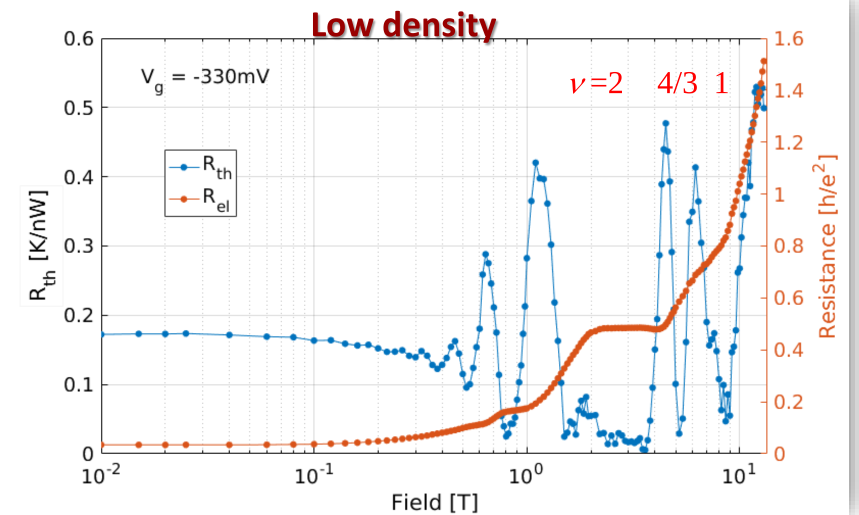
Magento-Thermal Transport Measurement





$$K = LT\sigma$$

Smrcka and Streda (1977)



Hot spot formation in quantum Hall edge states

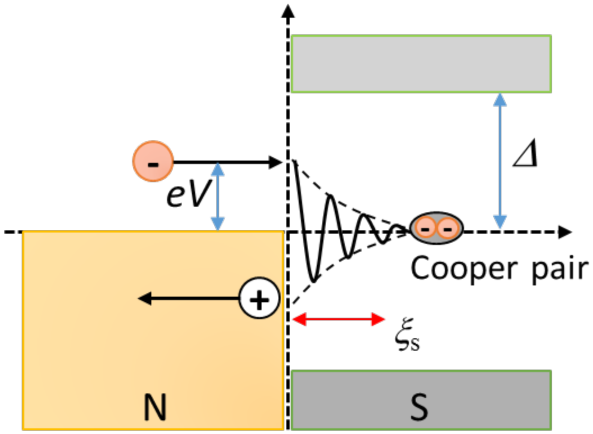
Ikushima et al (2007)

Crossno et al., unpublished

Friday Morning: X30.00001

Andreev Reflection in Magnetic Fields

A. F. Andreev (1964)



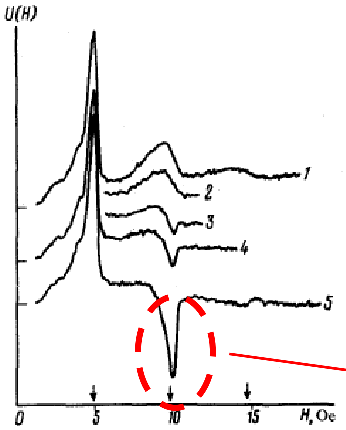
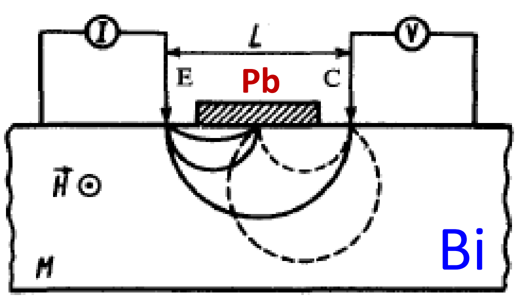


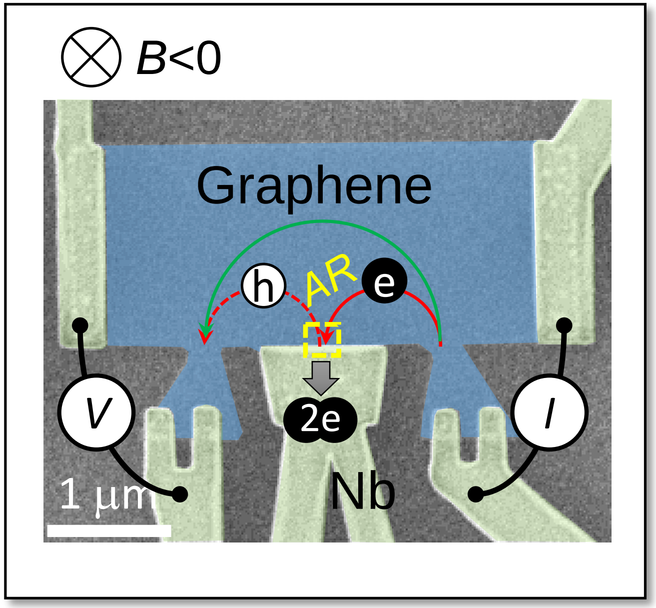
FIG. 2. The curves $U(H)$ at different temperatures. The curves 1–5 are presented for specimen temperatures of 3.80, 3.78, 3.74, 3.70, and 2.78 K, respectively. The arrows of the abscissa axis indicate the quantities H_0, $2H_0$, and $3H_0$. The curves are arbitrarily shifted along the ordinate axis and the values of $U(0)$ are indicated on the axis for $T=3.80$, $T=3.70$, and $T=2.78$ K.

Bozhko, Tsoi, and Yakovlev (1982)



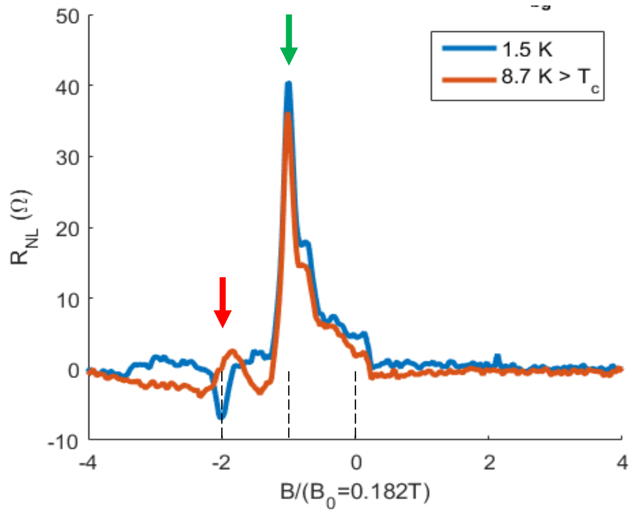
Negative focusing signal!

Magnetic focusing in graphene with Nb electrodes



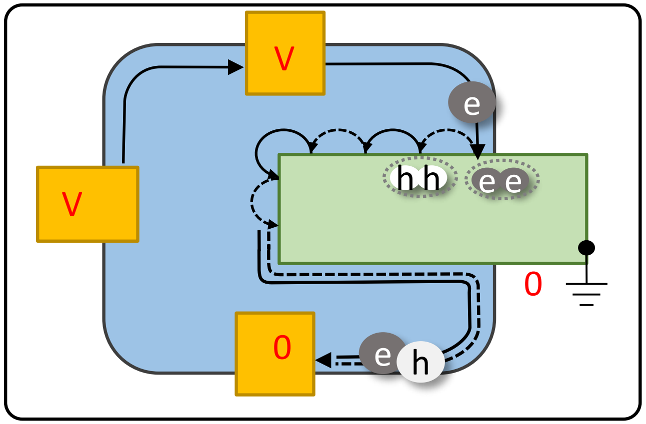
G.-H. Lee, *et al.*
(unpublished)

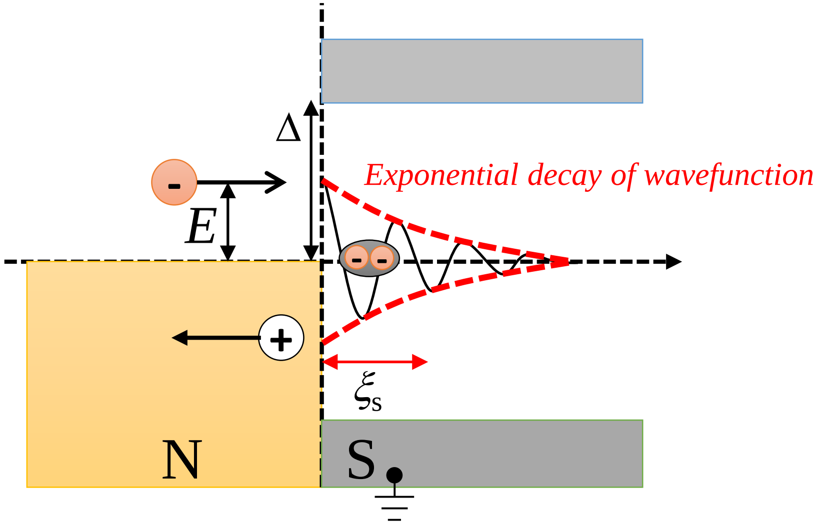
- Detecting positive bending resistance: $T > T_c$
- Detecting negative bending resistance: $T < T_c$



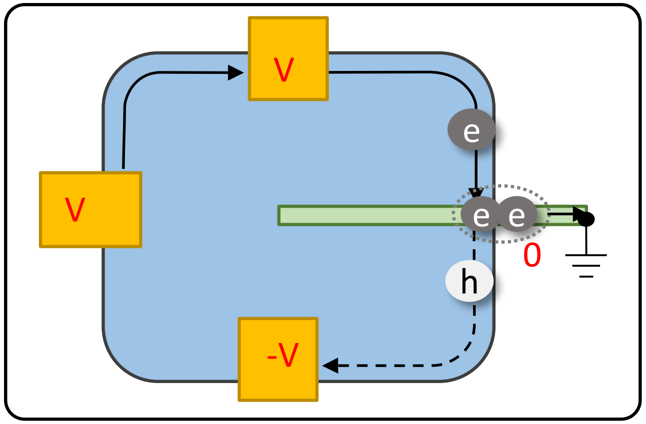
Crossed Andreev Reflection in Quantum Hall Edge

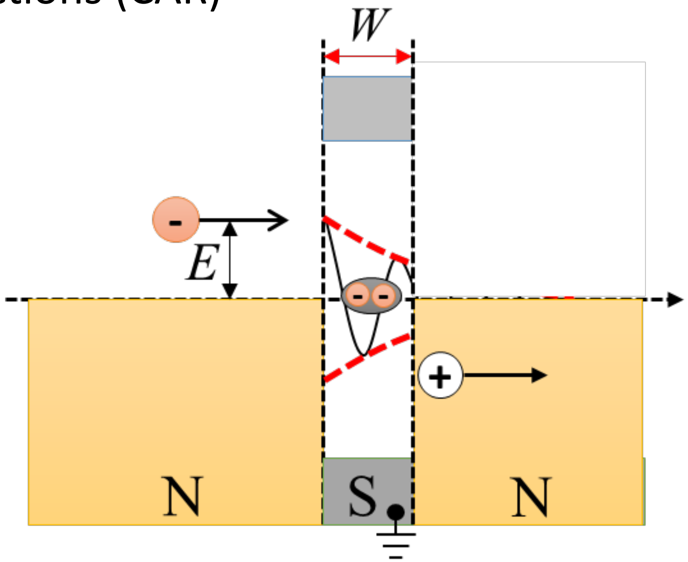
Wide superconductor: Andreev Edge State



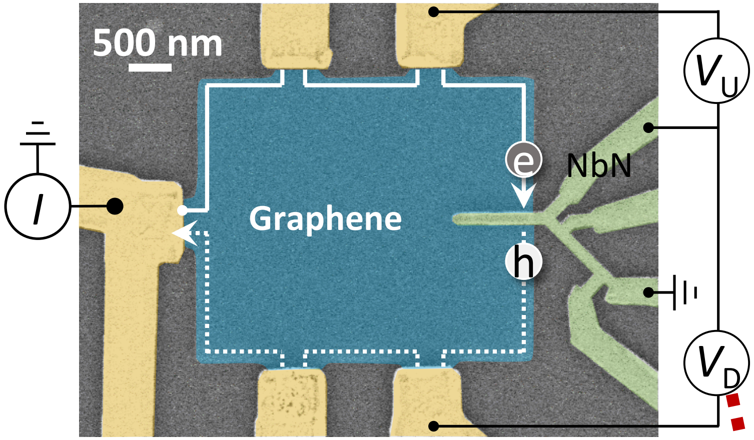


Narrow superconductor: Crossed Andreev reflections (CAR)

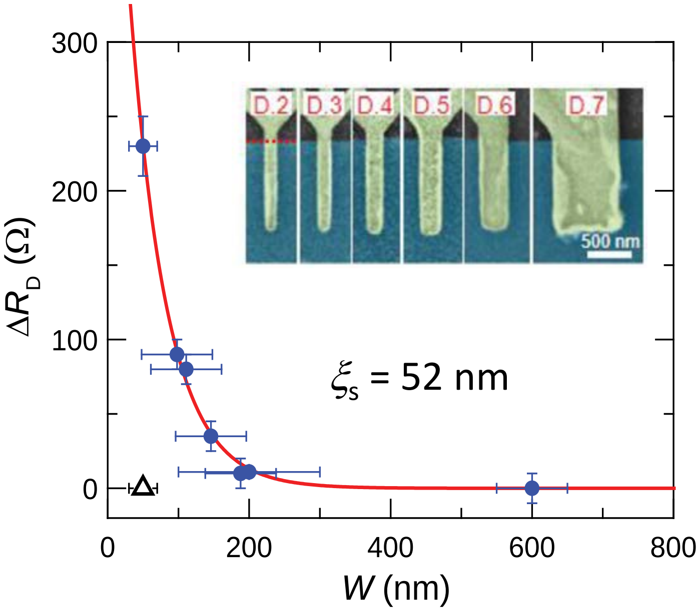


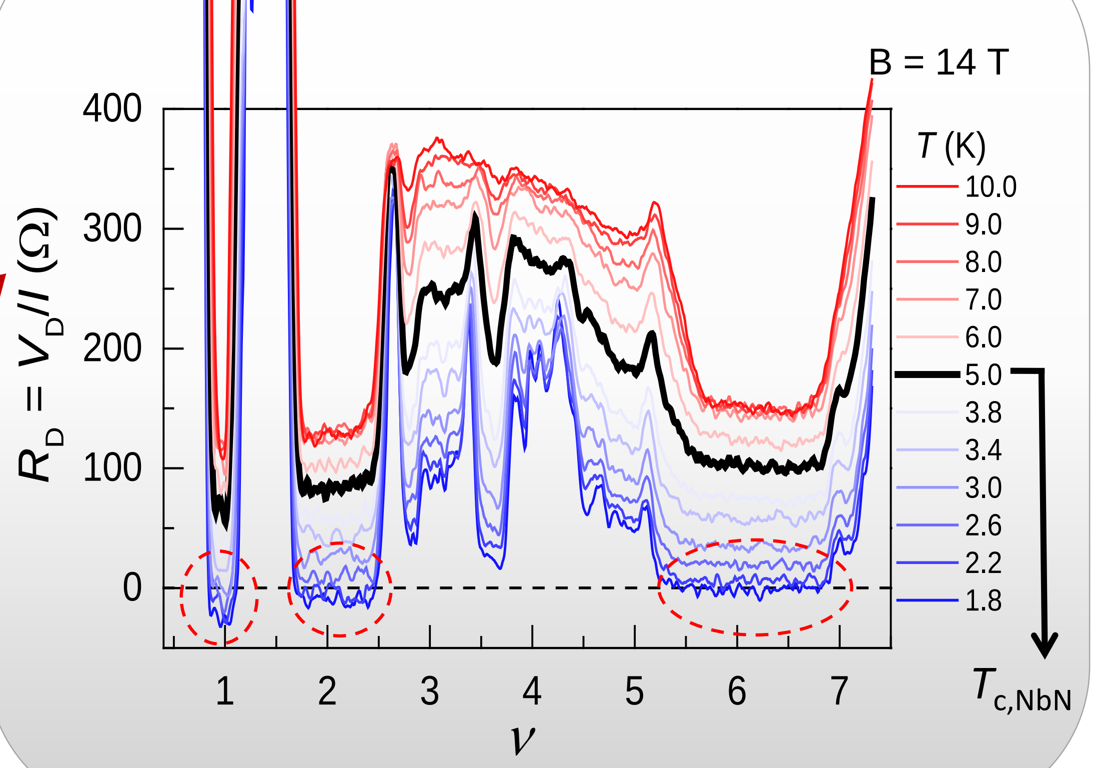


Crossed Andreev Reflection of Proximitized Quantum Hall Edge States



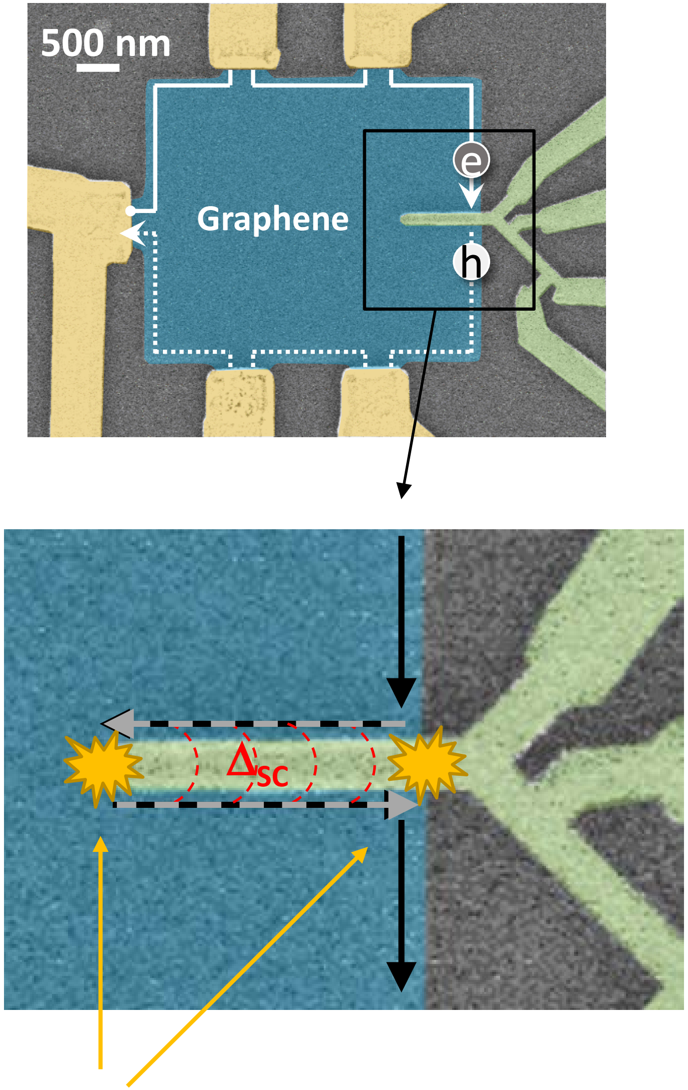
Graphene Hall bar with a superconducting drain contact.
(graphene underneath the contacts are etched away)


Effect of Superconducting Electrode Width

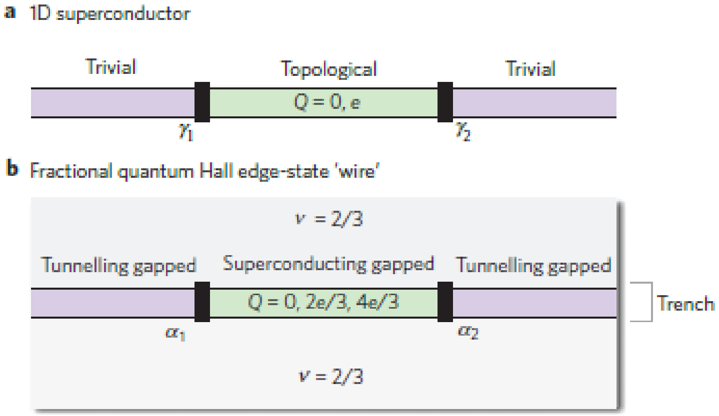

Measurement of Down Stream Chemical Potential

G.-H. Lee *et al*. Nature Physics (2017): collaboration with Amir Yacoby

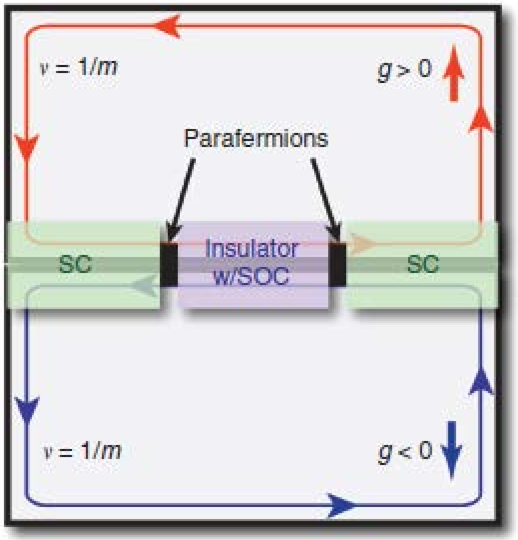
Alternative View: Majorana Fermion Resonance



Localized majorana fermions

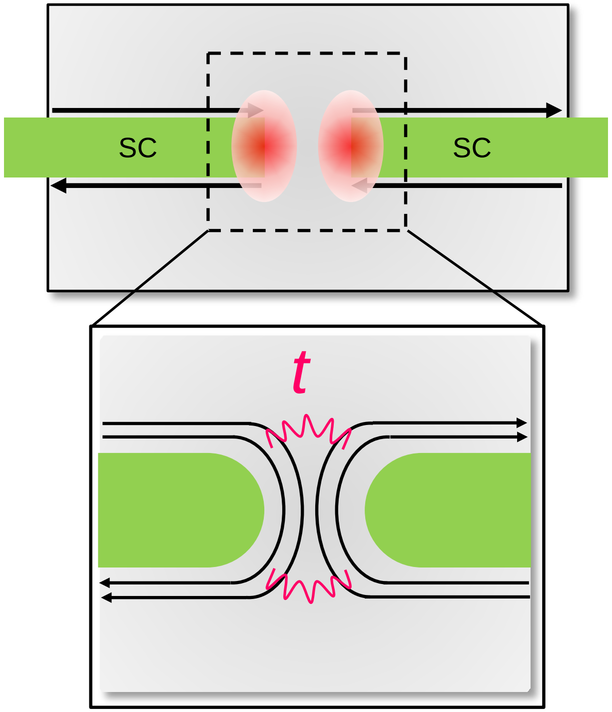


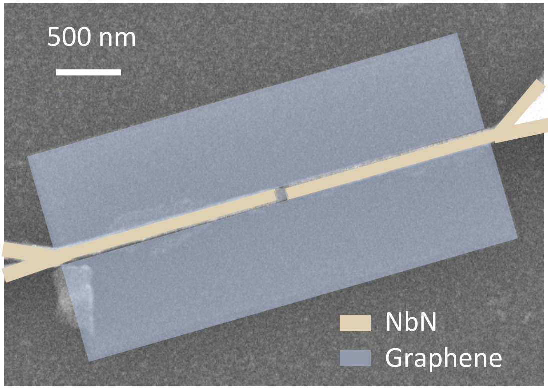
[D. J. Clarke, J. Alicea and K. Shtengel, *Nature Phys.* **11**, 877-882 (2014)]



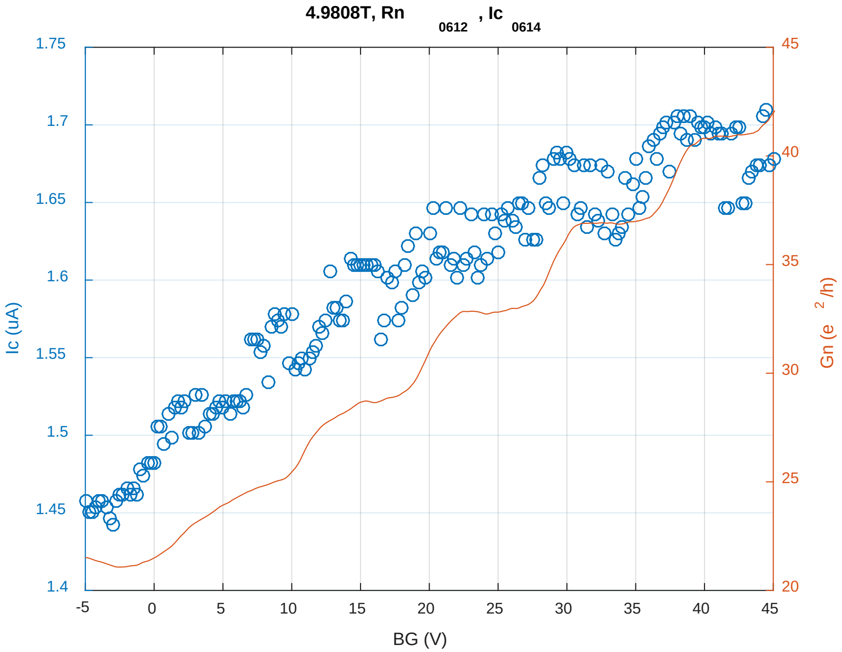
[D. J. Clarke, J. Alicea and K. Shtengel, *Nature Comm.* **4**, 1348 (2013)]

Majorana Josephson Junctions: Preliminary Data





NbN electrode separation < 80 nm

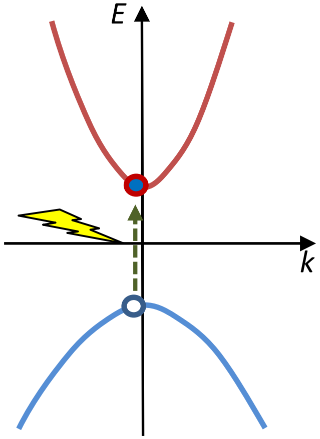


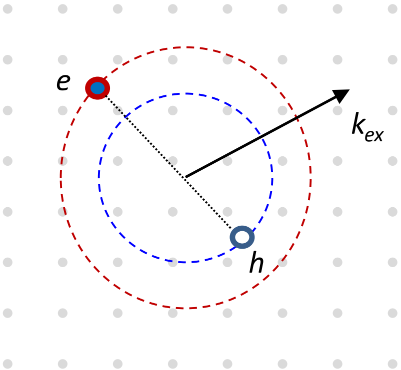
JJ across the quantum Hall edge states

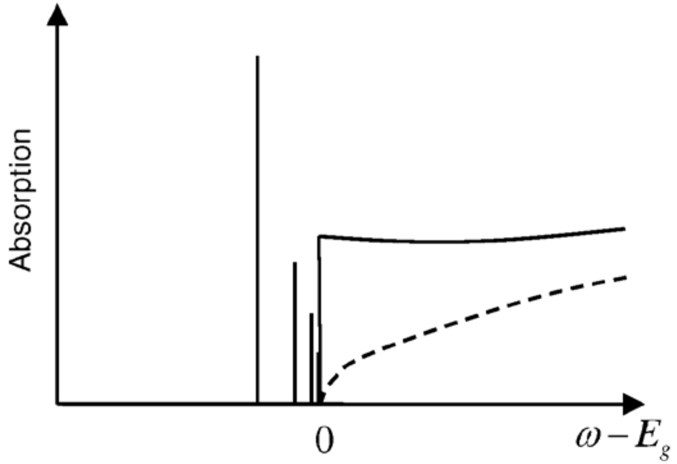
$$\Delta I_c \sim \left(\frac{4e}{h}\right) e\Delta$$

Excitons

Excitons in Semiconductors

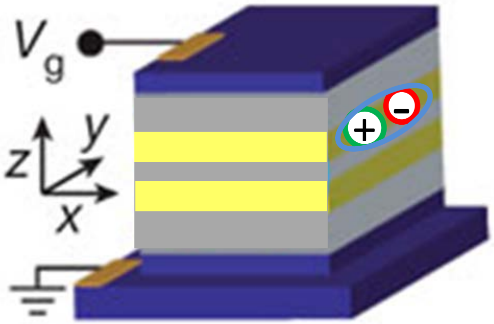


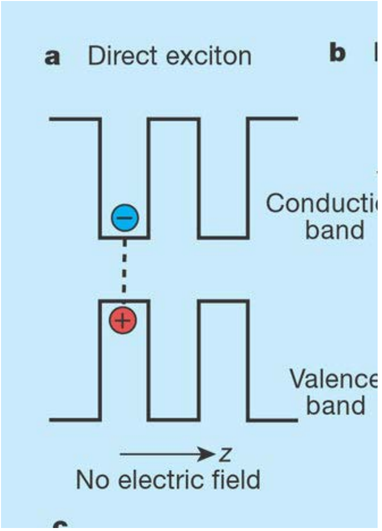




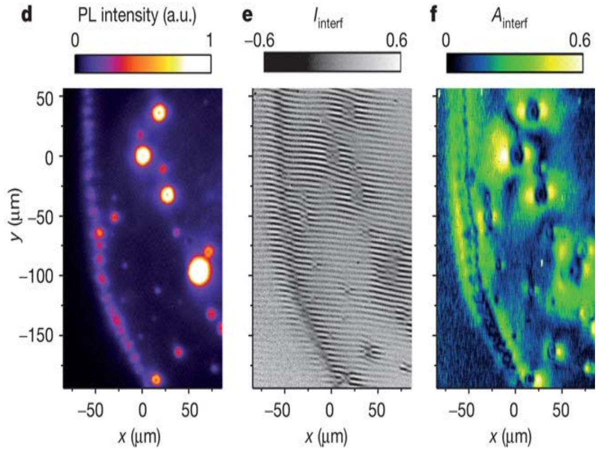
Direct and indirect excitons in semiconducting quantum wells

Semiconductor heterostructure





Spontaneous coherence

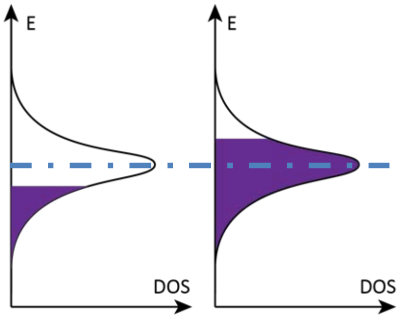


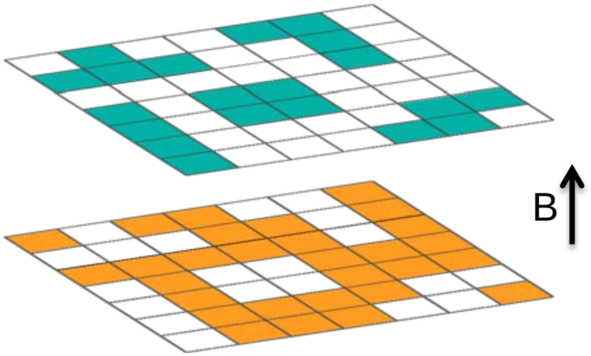
A. High, Nature 2012

Exciton condensation between Landau levels

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

Two partially filled
Landau levels

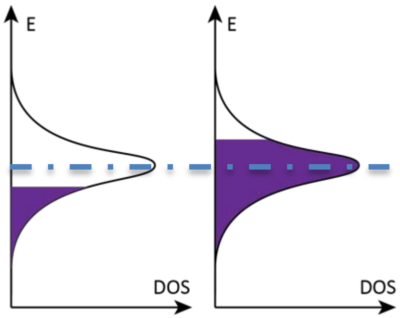


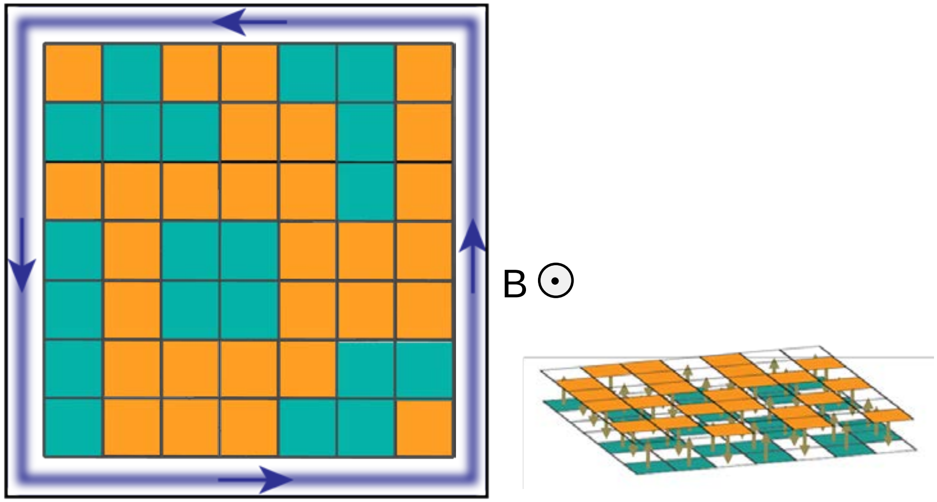


Exciton condensation between Landau levels

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

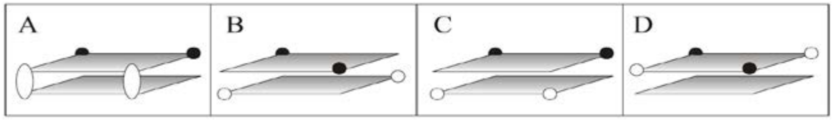
Two partially filled
Landau levels



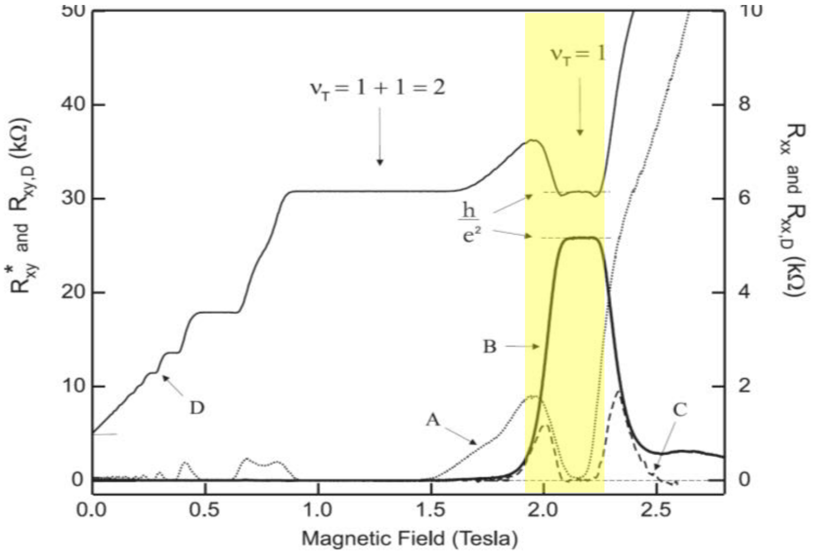


Total Landau level quantum Hall effect

GaAs Double Quantum Well



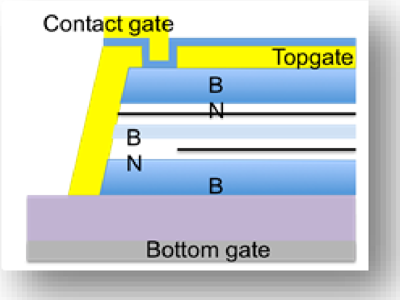
- Quantum Hall effect for two partially filled complementary LLs
- Quantized drag Hall

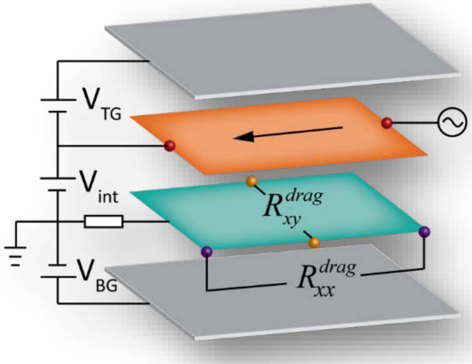


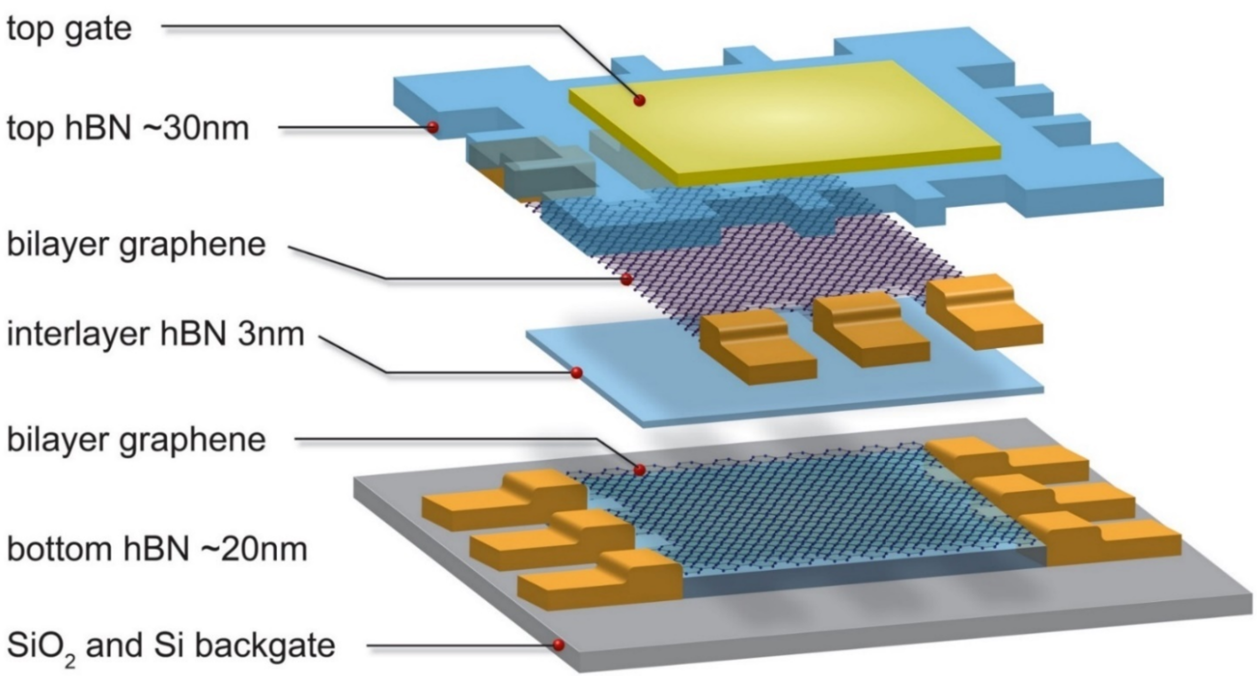
M. Kellogg, et. al, PRL (2002)

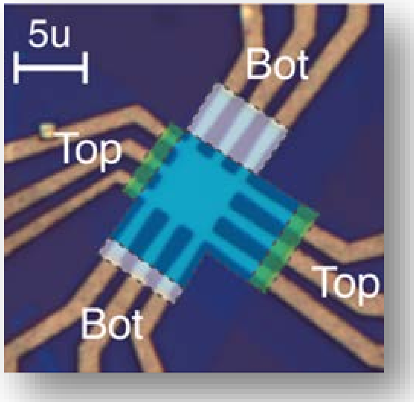
Double Bilayer Graphene Drag Device

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



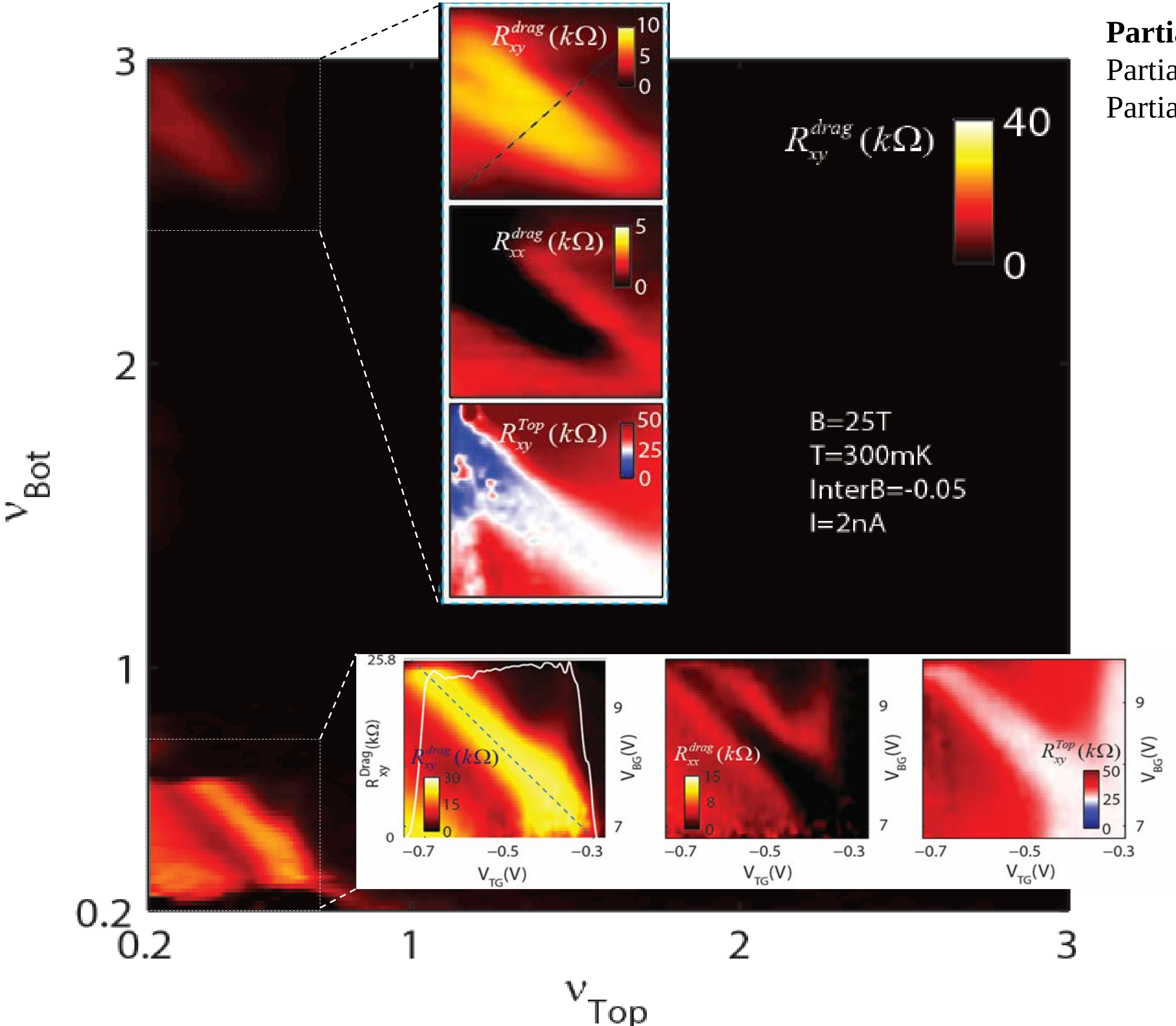






Xiaomeng Liu *et al*, Nature Physics (2017)

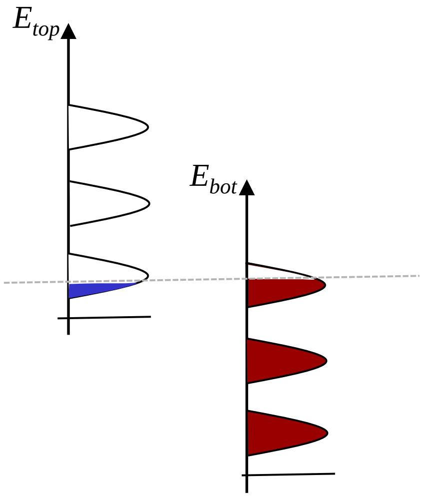
Quantized Hall Drag for ν_{tot} = 1 and 3



Partial coherent exciton current:

Partially filled N_{top} =1

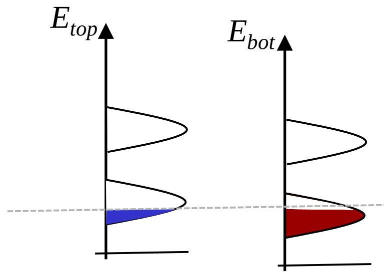
Partially filled N_{bot} =3



Coherent exciton current:

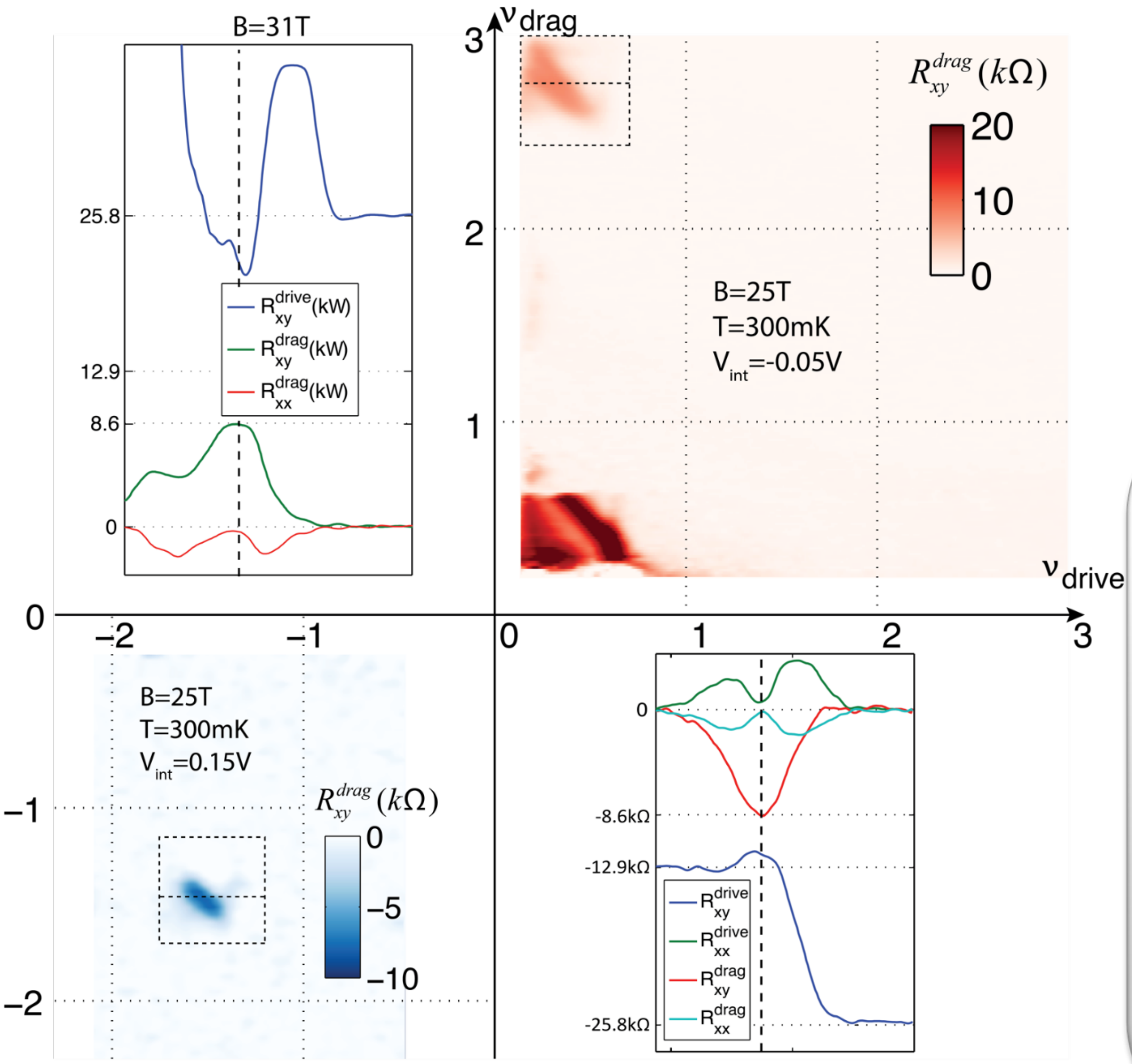
Partially filled N_{top} =1

Partially filled N_{bot} =1



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

Magneto Exciton Condensation in Different LLs



Observed Exciton condensations

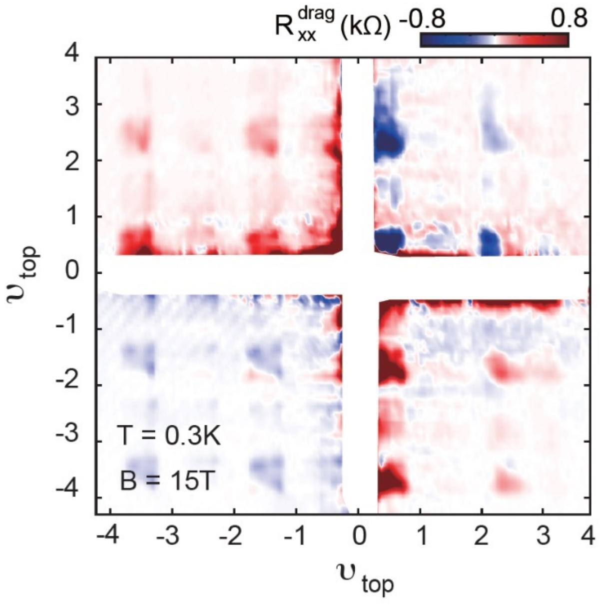
(0.5, 0.5)

(0.5, 2.5); (2.5, 0.5)

(-1.5, -1.5)

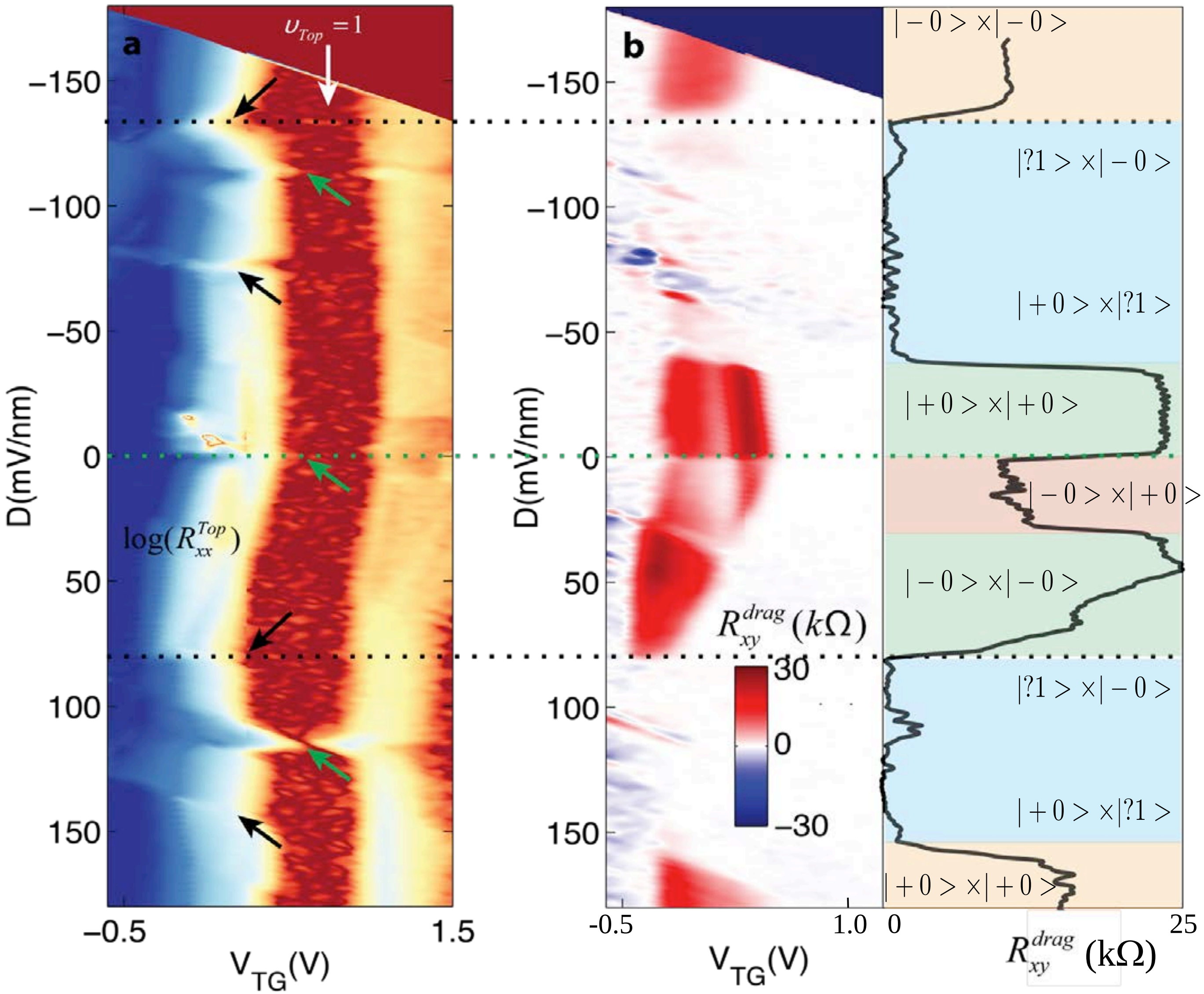
Possible ν -> ν +2 symmetry
in bilayer graphene double layer

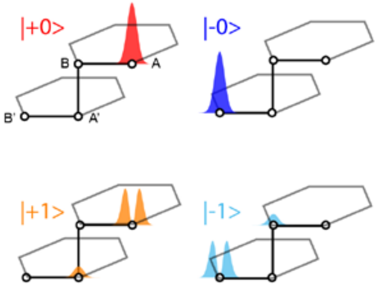
Other possible Exciton Condensation



Li et. al., arXiv:1608.05846

Exciton BEC Phase Transition: Internal Degree of Freedom of Exciton





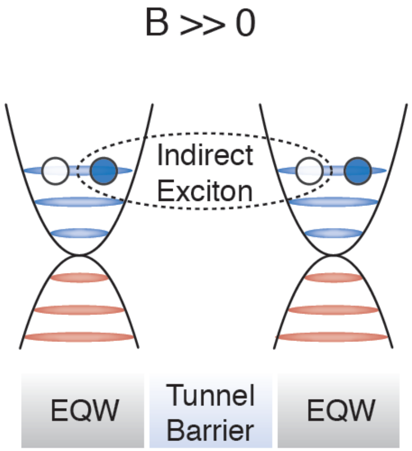
Appearance of BEC closely related to wave function of BLG

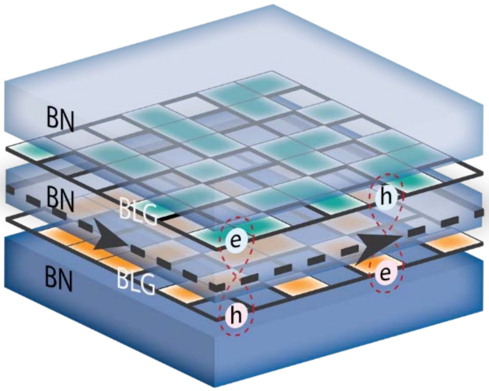
Strength of BEC controlled by layer/valley polarization

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

Exciton Condensation

Exciton condensation between LL (topological exciton insulator)

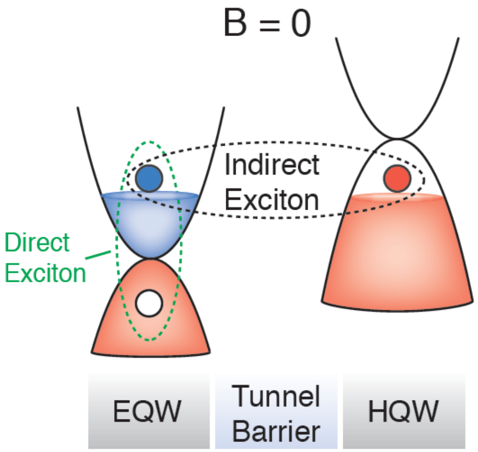


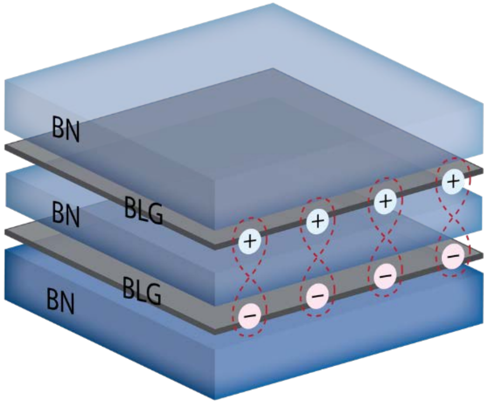


$$R_{xx}^{CF} = 0 \qquad R_{xx}^{sym} = 0$$

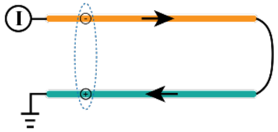
$$R_{xy}^{CF} = 0 \qquad R_{xy}^{sym} = \frac{h}{\nu_{tot} e^2}$$

Exciton condensation (exciton insulator)

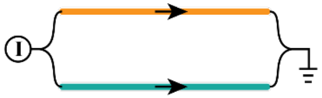




Counter Flow



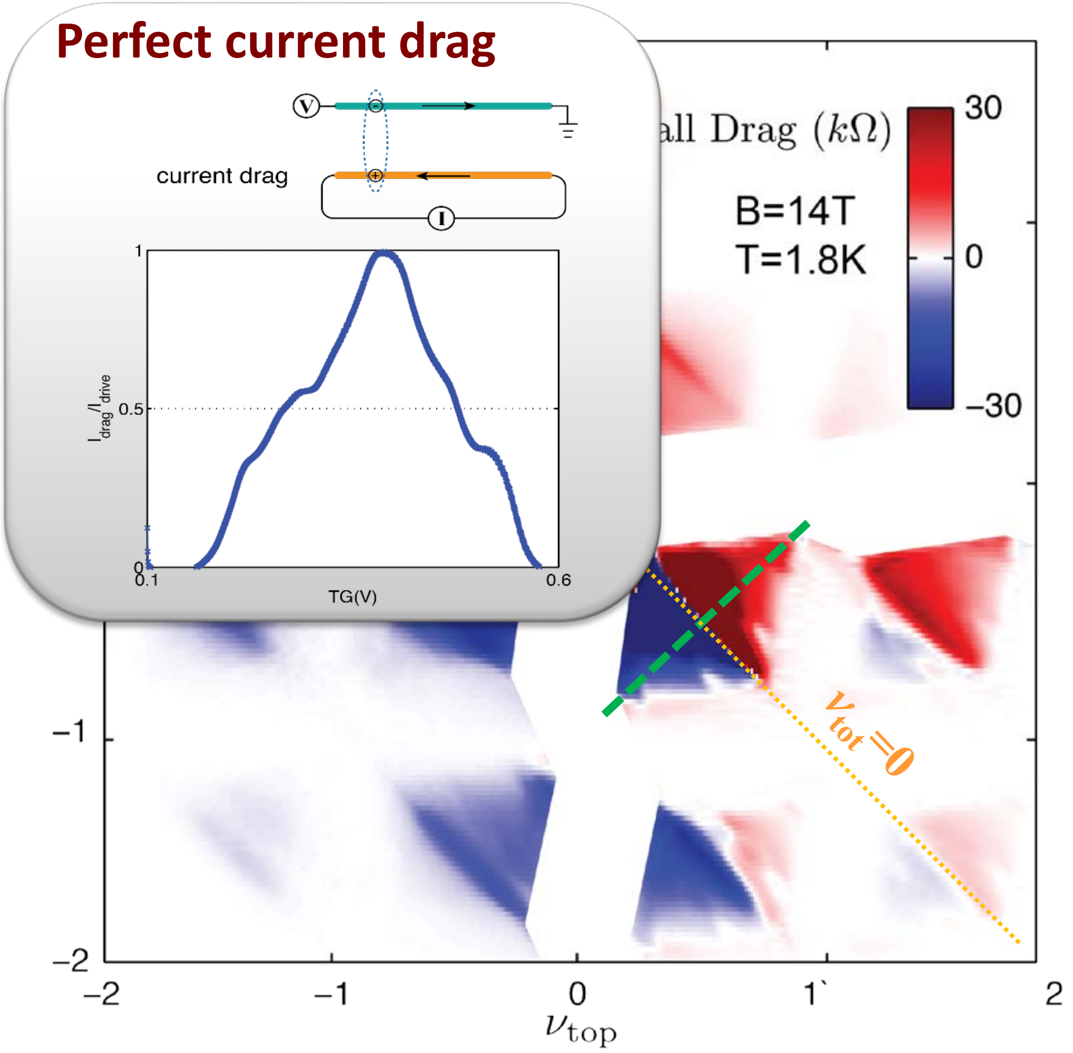
Symmetric Flow



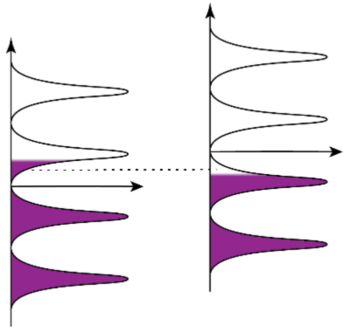
$$R_{CF} = 0 \qquad R_{sym} = \infty$$

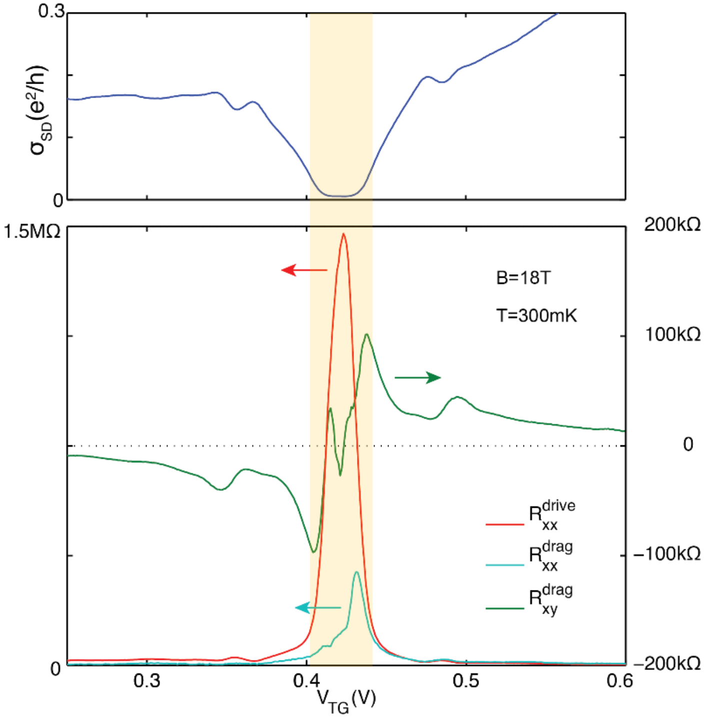
Magneto Exciton Insulator: ν_{tot}= 0

Monlayer/hBN/Monolayer



Perfect current drag

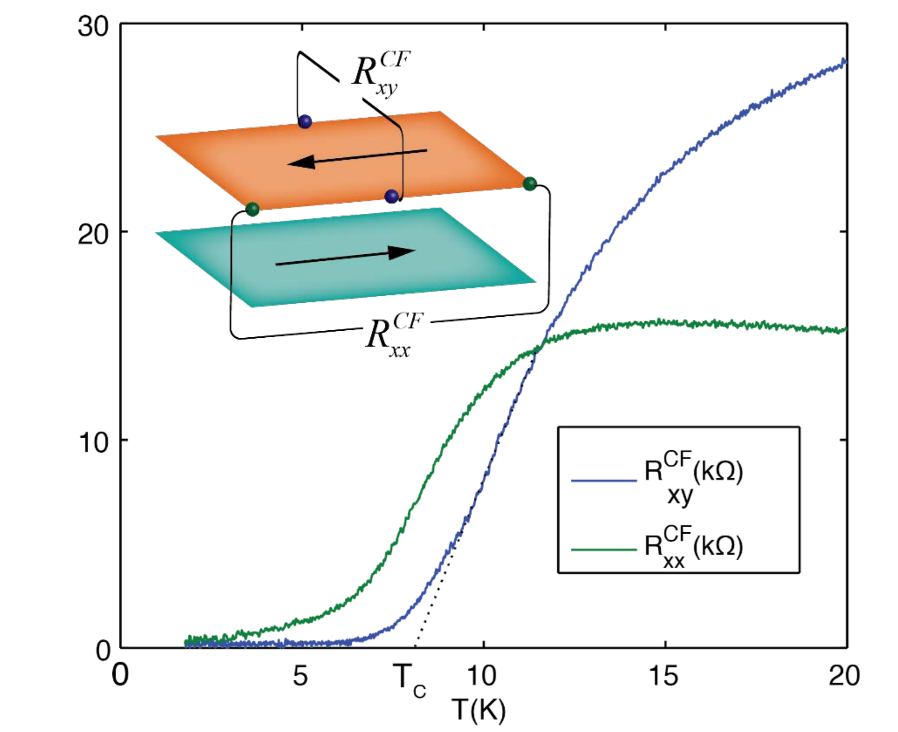




Exciton insulator!

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

Potential BCS-BEC Crossover in Magnetoexciton Condensate



d: distance between the layers

l_B: magnetic length ~ distance between the electrons in LL

- Large (d/l_B) → BCS
- Small (d/l_B) → BEC

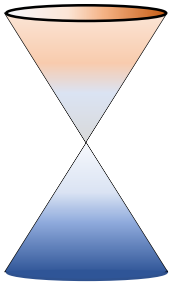
Xiaomeng Liu *et al*, unpublished: collaboration with Dean group

Summary

- Hydrodynamic transport in strongly interacting electron and hole plasma in the Dirac Fluid

  - Johnson noise thermometry and electronic thermal conductivity measurement

  - Strongly violated WF law at the charge neutrality

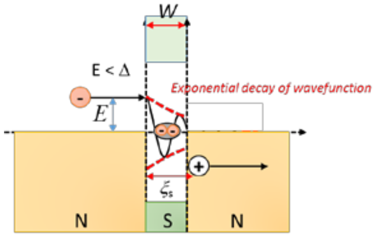


J. Crossno, et al., *Science* ***351***, *1058-1061 (2016).*

- Correlation of Bogolibove quasi particles in chiral edge modes

  - Demonstration of superconducting proximization of quantum Hall edge states

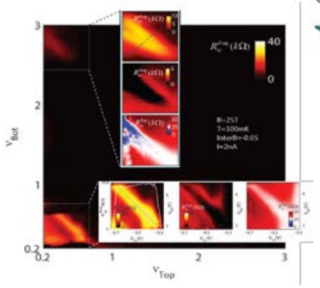
G. Lee, et al., *Nature Physics (2017).*

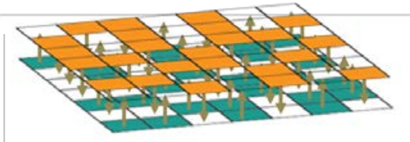


Crossed Andreev reflection (CAR)

- Excitons in vdW heterostructures

  - Observation of quantized Hall drag and zero counter flow resistance





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

Acknowledgement: Kim Group 2017

Collaborations

Superconductors: A. Yacoby, R. Cava
Optics: H. Park and M. Lukin
Theory: S. Sachidev, E. Demler B. Halperin
hBN: T. Taniguchi, K. Watanabe

Funding

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Office of Basic Energy Sciences • Serving the Present, Shaping the Future •
Army Research Office
Air Force Office of Scientific Research
Office of Naval Research
STARnet
NRF National Research Foundation of Korea
GORDON AND BETTY MOORE FOUNDATION

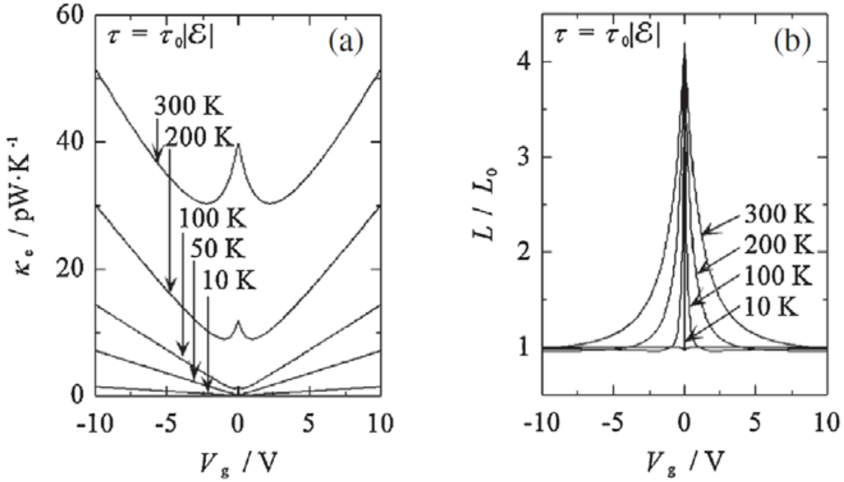
Bipolar Diffusion versus Dirac Fluid

Bipolar diffusion

P. J. Price, Philos. Mag. **46**, 1252 (1955)

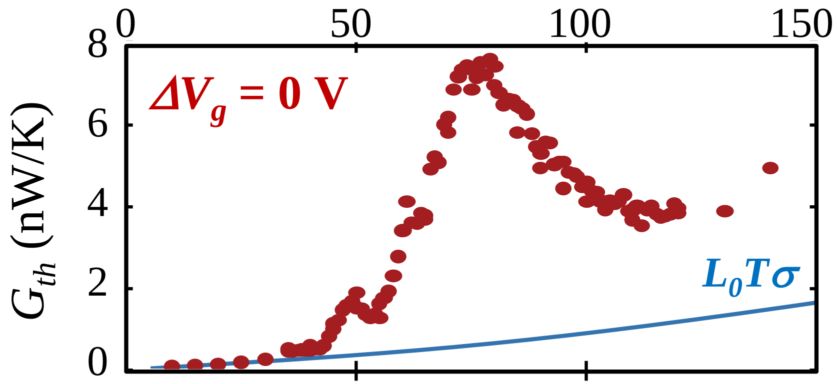
$$\kappa_{\mathrm{e}} = \kappa_{\mathrm{e1}} + \kappa_{\mathrm{e2}} + \kappa_{\mathrm{bd}}$$

$$\kappa_{\mathrm{bd}} = \frac{\sigma_1 \sigma_2}{\sigma_1 + \sigma_2} T (S_2 - S_1)^2$$

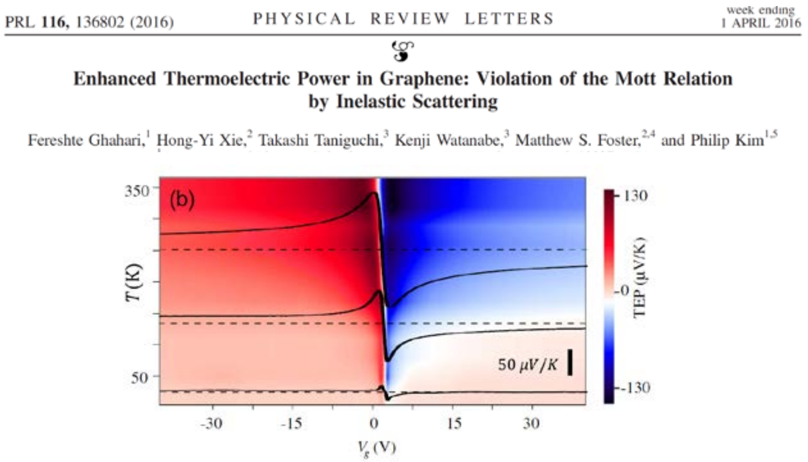


Harukazu Yoshino* and Keizo Murata

Journal of the Physical Society of Japan **84**, 024601 (2015)



- Magnitude is factor of 5 larger
- Temperature dependent is different

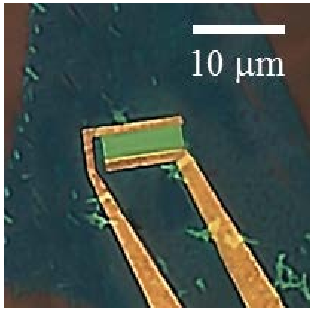


PRL **116**, 136802 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

Enhanced Thermoelectric Power in Graphene: Violation of the Mott Relation by Inelastic Scattering

Fereshte Ghahari,[1] Hong-Yi Xie,[2] Takashi Taniguchi,[3] Kenji Watanabe,[3] Matthew S. Foster,[2,4] and Philip Kim[1,5]

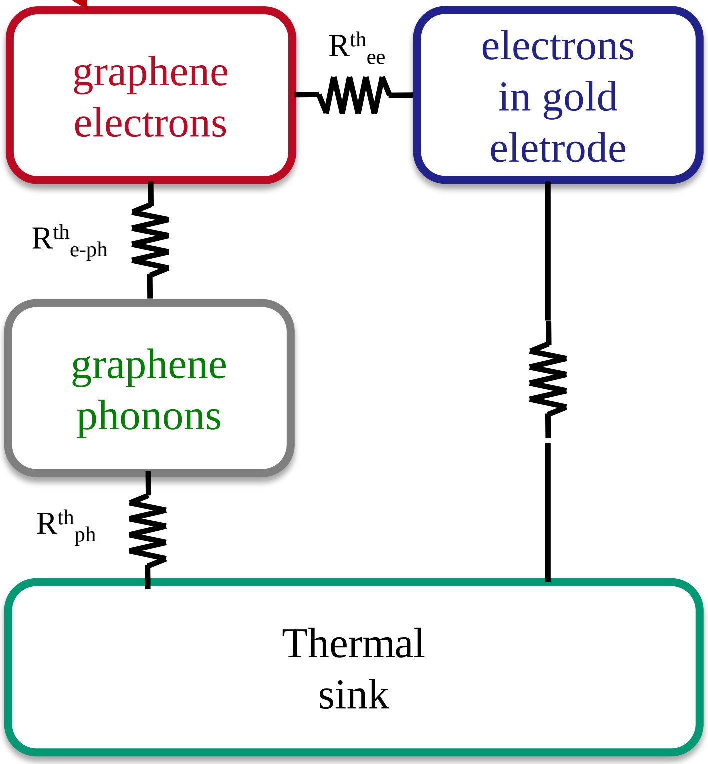
Understanding the thermal pathways



Joule heating

Heat carried by electrons

$$P_{WF} = G_{th}\left(T_{JN} - T_{ph}\right)$$



Heat transferred to phonons

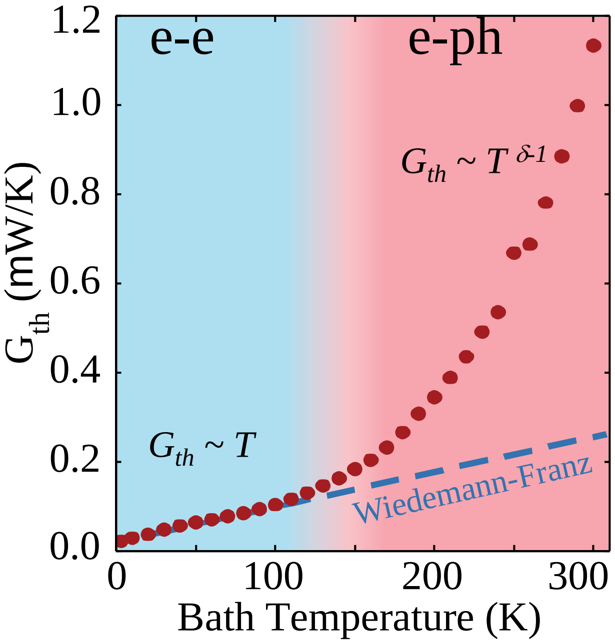
$$P_{e-ph} = A\Sigma_{e-ph}\left(T_e^{\delta} - T_{ph}^{\delta}\right)$$

Experimental Lorentz Ratio

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

IF the WF law works,

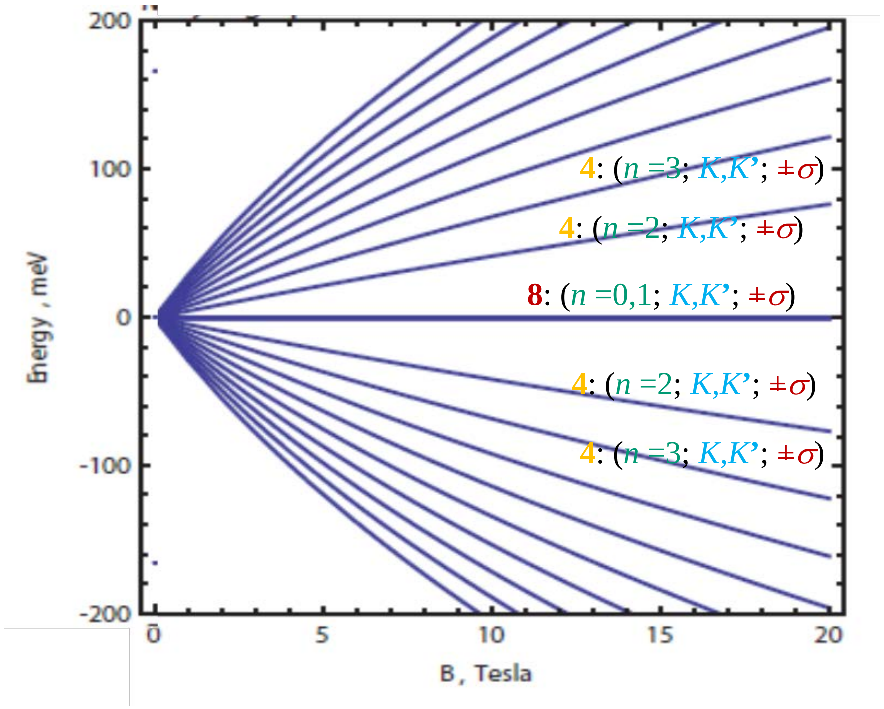
$$G_{th} \approx L_0 \frac{R}{12T} = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2 \frac{R}{12T}$$



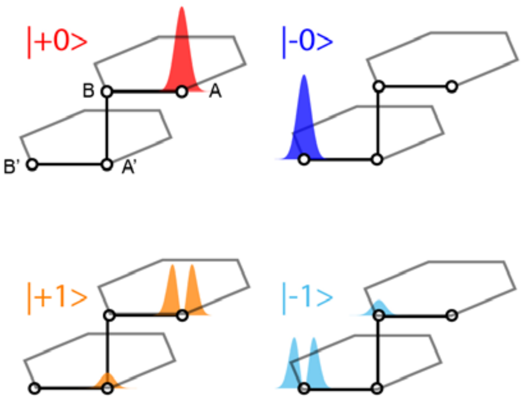
Fong *et al.*, PRX 3, 041008 (2013); Crossno *et al.*, APL (2015)

Quantum Hall Ferromagnetic Phase Transition in Bilayer Graphene

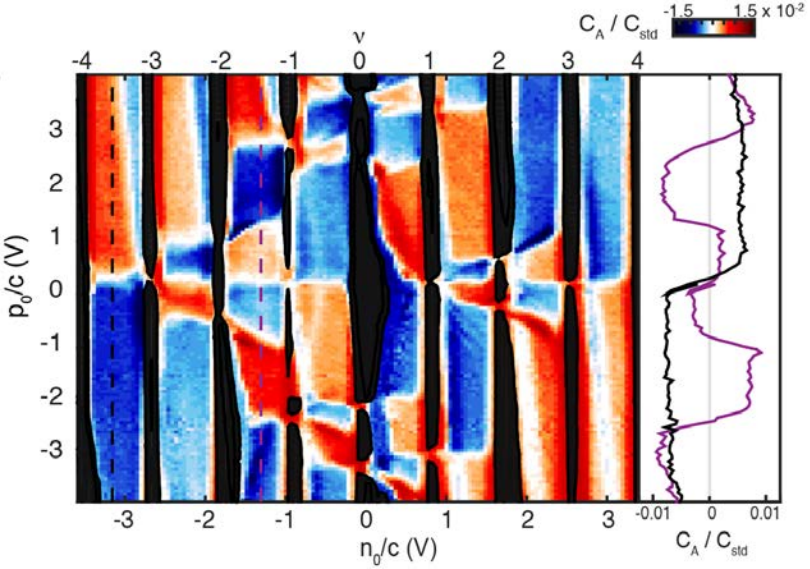
Bilayer Landau level spectrum: SU(4) and SU(8)



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 et al. (2016).