Observation of the fractional quantum Hall effect in graphene

Bolotin, K. *et al.*, Nature Letters (2009)

Team One

Nijaid Arredondo, Ahmed Alenezi, Cole Brookhouse, Praveen Balaji

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Overview

Goal: observe the fractional quantum Hall effect in graphene

Contribution: fabricate highly pure graphene sample

Outline:

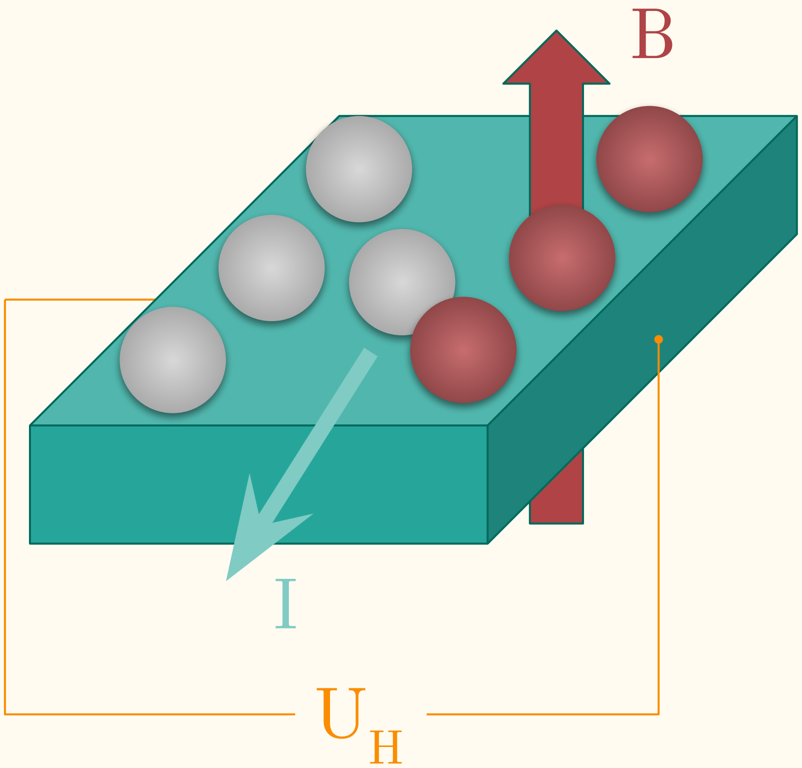
- Quantum Hall Effect
- Optimization of Graphene Sample
- Results
- Criticism
- Impact

What is the Quantum Hall Effect?

The Classical Hall Effect

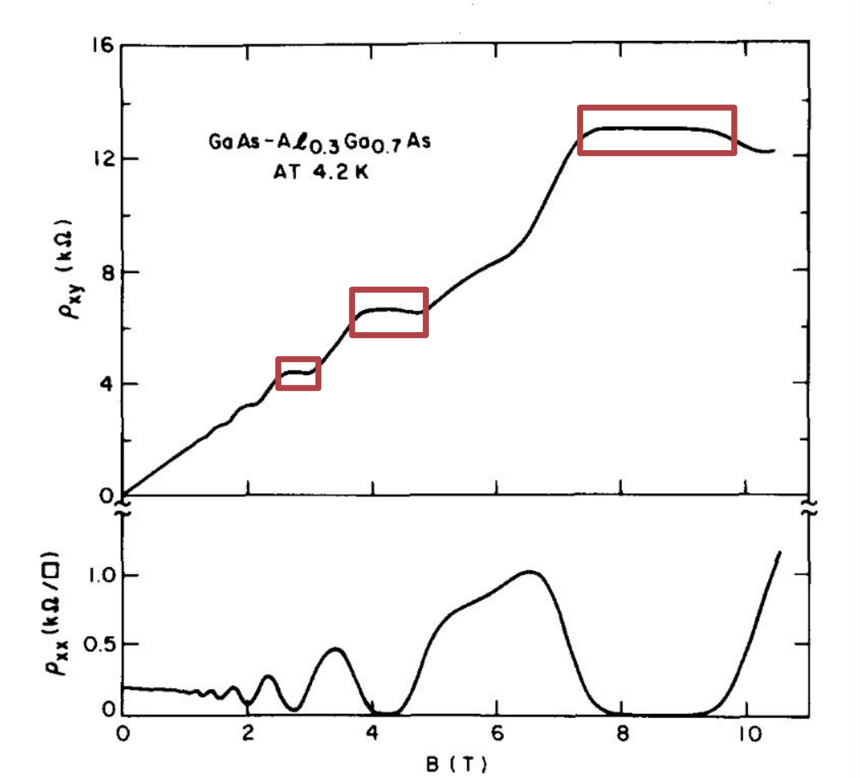
- A magnetic field B will deviate the path of charges towards the sides of a conducting material, creating a potential U_H transverse to the initial current I

- Measurements of U_H probe properties of the material, e.g. charge density, resistivity, conductivity



The Quantum Hall Effect

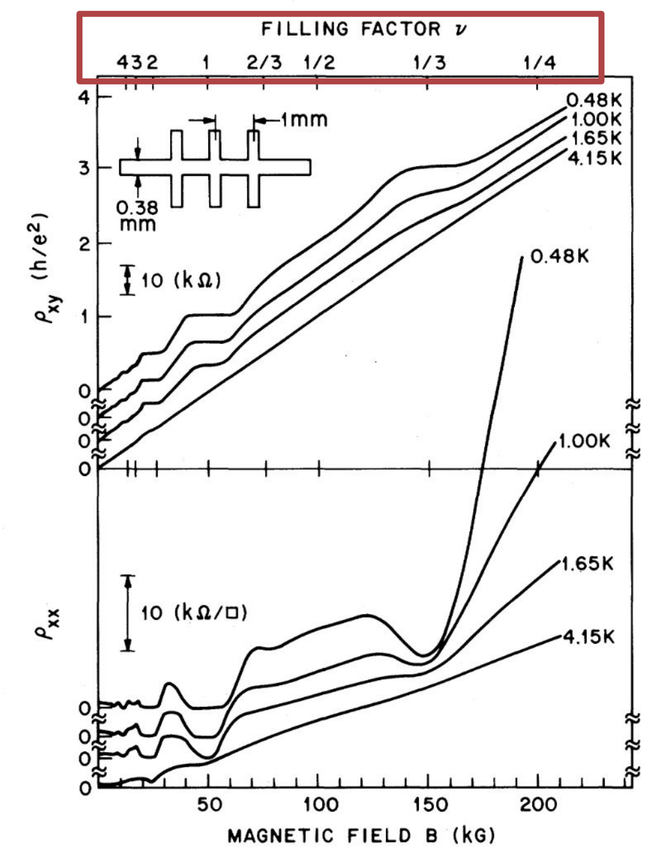
- QHE regime: low temperatures and large magnetic fields
- Plateaus of conductivity identified in a 2D semiconductor[1]:
  $\sigma_{xy} = \nu\, e^2/h$, ν an integer
- The **integer QHE**: electrons are localized at the edge of the surface and only conduct when their Landau level is filled[2]



Transverse (xy) and longitudinal (xx) resistivities of a sample as a function of magnetic field.[3]

1 Von Klitzing, Dorda and Pepper, PRL (1980)
2 Laughlin, PRB (1981)
3 Tsui and Gossard, AIP (1981)

The Fractional Quantum Hall Effect



- Plateaus began to be identified at fractional ν soon afterward[1] (see left)
- IQHE can be explained by non-interacting electrons; the fractional effect implies interactions!
- The **fractional QHE**: electrons form composite quasi-particles of fractional charge[2,3]

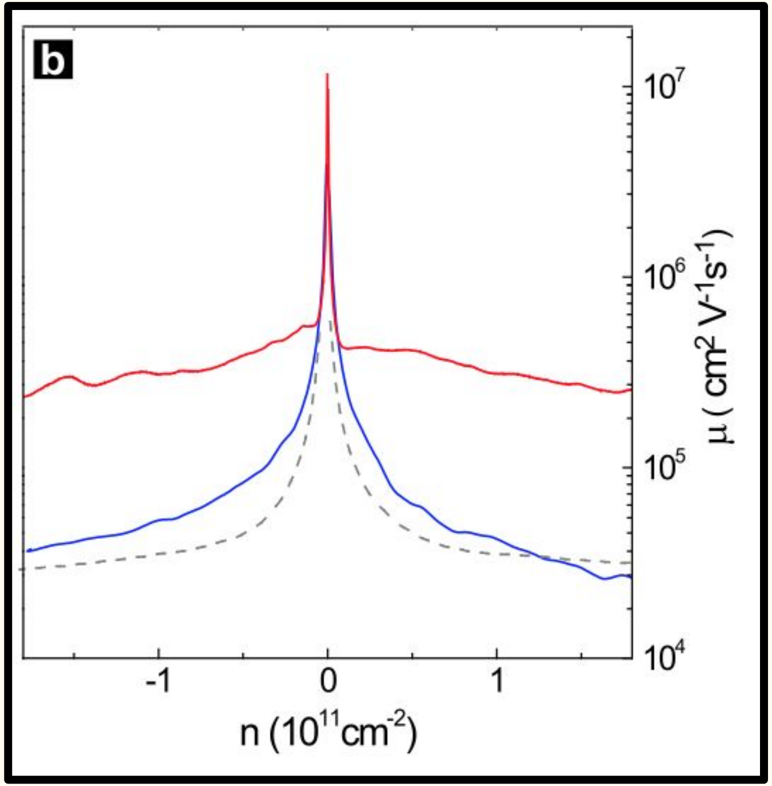
1 Tsui, Stormer and Gossard, PRL (1982)
2 Laughlin, PRL (1983)
3 Jain, PRL (1989)

Fractional quantum hall effect: fractional charges!

A host of quasi-particle physics awaits, some Nobel Prizes

- 2D surfaces allow for **anyons** (rather than just bosons and fermions)
    - These probe physics due to topology, geometric phases
- **Graphene** is expected to contain such quasi-particles

Graphene: A Motivated Material for FQHE

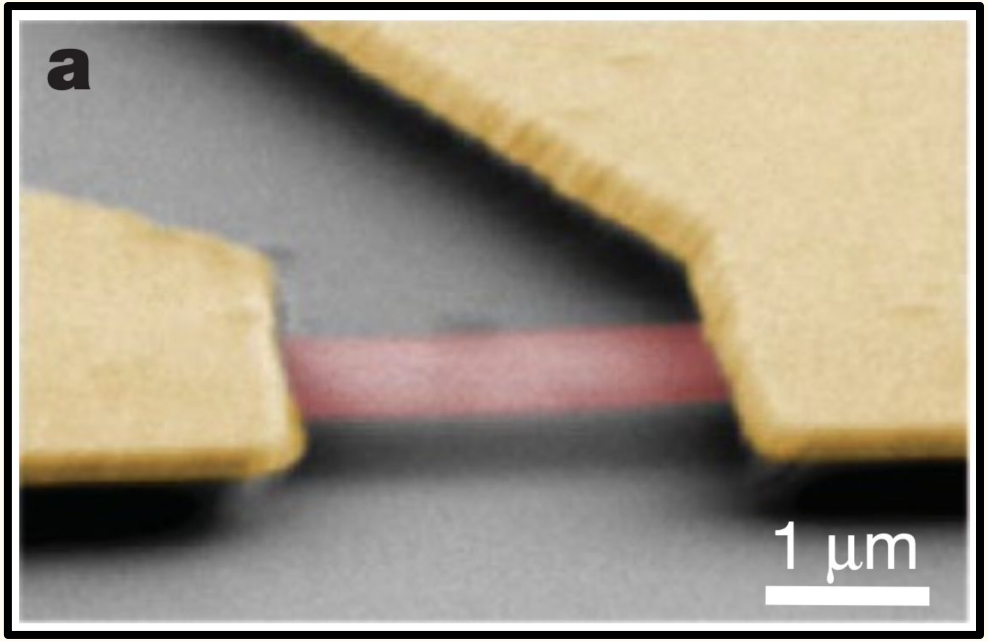


Mobility of graphene sample before (blue) and after (red) suspension

- Observation of FQHE in graphene would advance study of e-e interactions
  - Graphene has nearly perfect lattice
- Complicated by electron scattering from residual impurities
  - Caused by interactions of graphene with underlying substrate
- Suspending graphene above its substrate reduces scattering[1]

[1] Bolotin, et al. Solid State Commun. (2008)

Fabricating Clean Graphene for FQHE Experiment

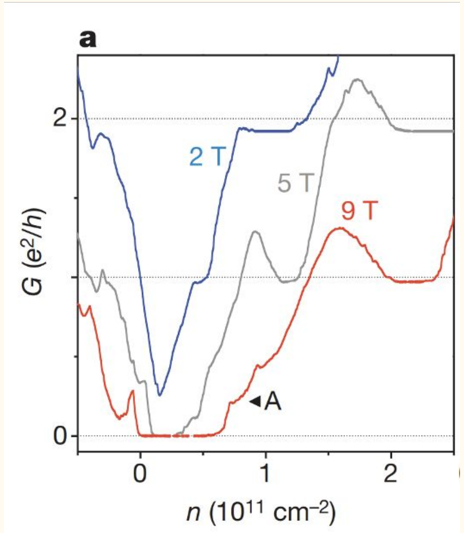


Example of experimental apparatus

- Applied graphene on top of SiO_2/Si substrate
- Conductive layers deposited to make contacts
- Adjacent substrate layer removed with hydrofluoric acid
- Sample placed in alcohol to remove impurities
- These steps optimize graphene purity

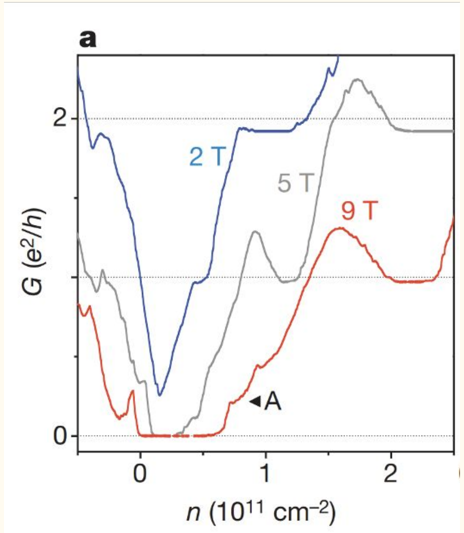
Results

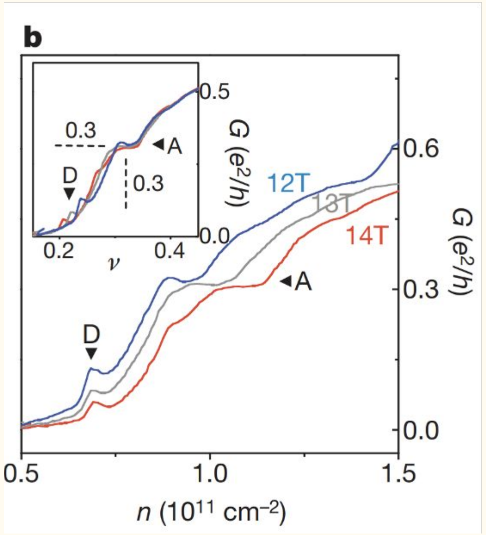
Observing the v=⅓ State



- Only v=1 state for B = 2,5 T
- At B = 9 T , state v= 1/3 starts to appear (A)

Observing the v=⅓ State





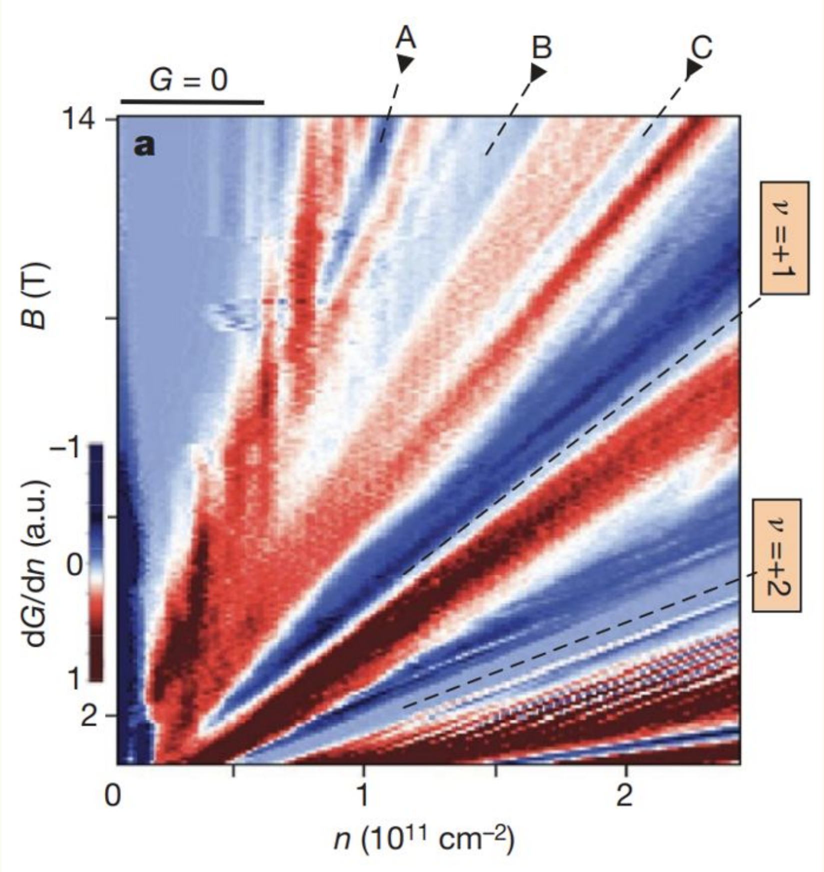
- Only v=1 state for B = 2,5 T
- At B = 9 T , state v= 1/3 starts to appear (A)

- At B = 12,13,14 T the state v=1/3 is clear.

Observing Two More FQH States

- Blue: G is decreasing with n
- Red: G is increasing with n
- FQH states are found in light blue regions

dn/dB = ν/φ

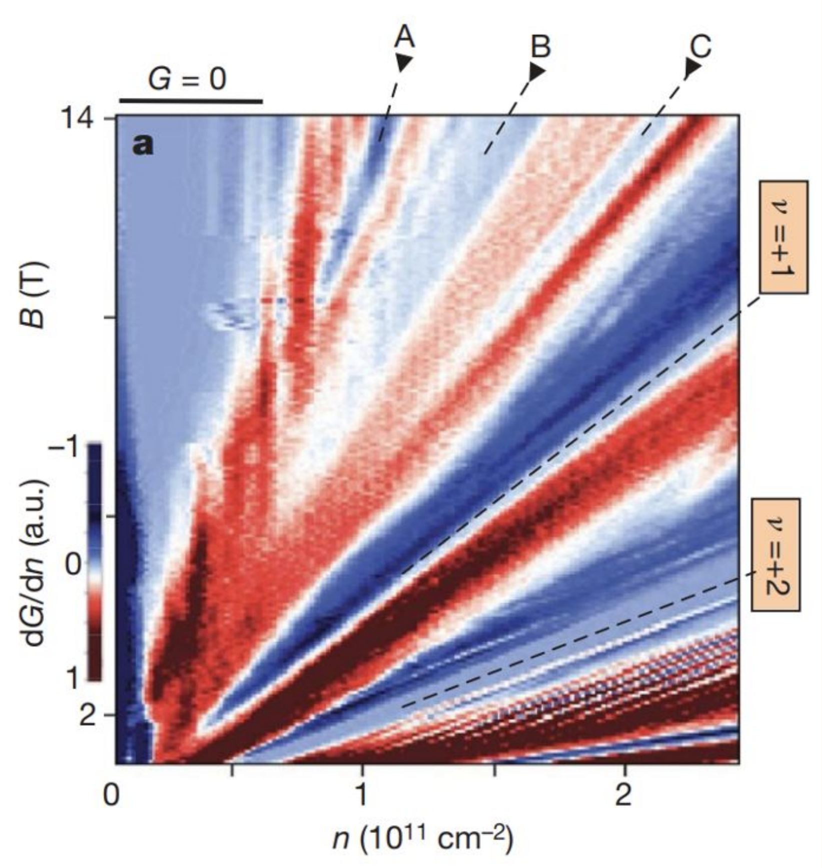


Observing Two More FQH States

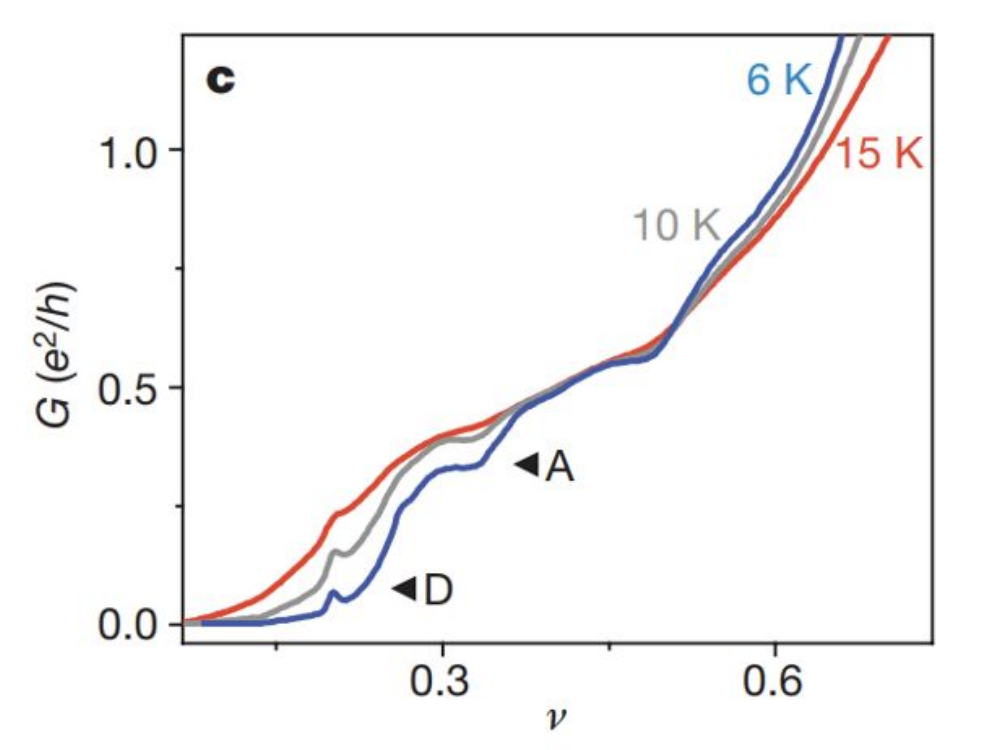
- Blue: G is decreasing with n
- Red: G is increasing with n
- FQH states are found in light blue regions

- Below is a table for the found fractional states

	ν	G (e^2/h)
A	0.30 ± 0.02	0.32 ± 0.02
B	0.46 ± 0.02	0.54 ± 0.02
C	0.68 ± 0.05	0.94 ± 0.02



T-dependence of the Conductance



Higher temperatures wash out FQH states.

Paper Summary

- Observation of FQHE in graphene was of great interest since it would provide a probe into its interesting e-e phenomena. However, previous attempts had failed due to impure samples

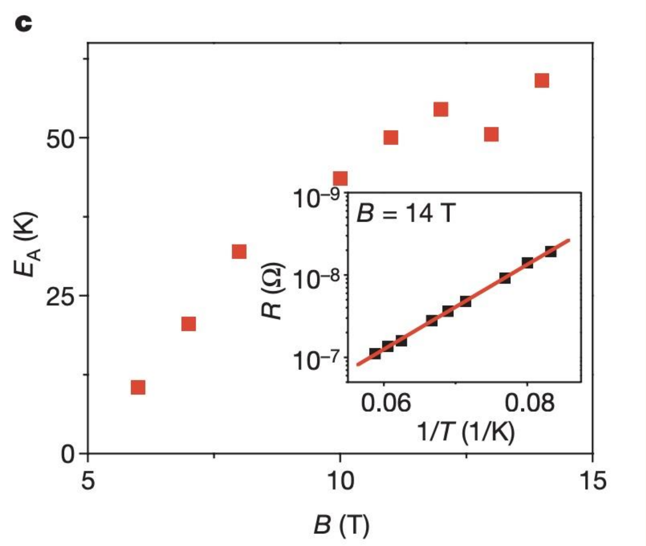
- Authors constructed ultraclean suspended graphene samples and were able to observe FQH factors at $\nu = 1/3$ and $\nu = 2/3$

- Authors were also able to get a resistivity profile (as a function of T) of graphene's insulating state

Criticism

Criticism

- Unclear plots (odd axes, poorly balanced dG/dn gradient)
- Discussion about insulating state of graphene left vague
- Some statements left unexplained (e.g. QAHE not mentioned later)
- No true conclusion (ends with results, no future approaches)



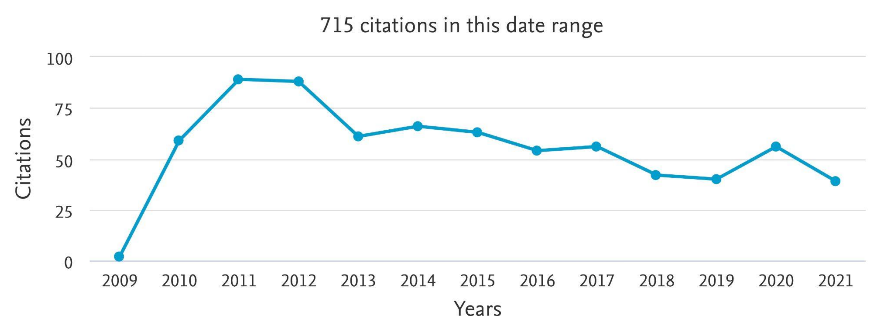
Impact

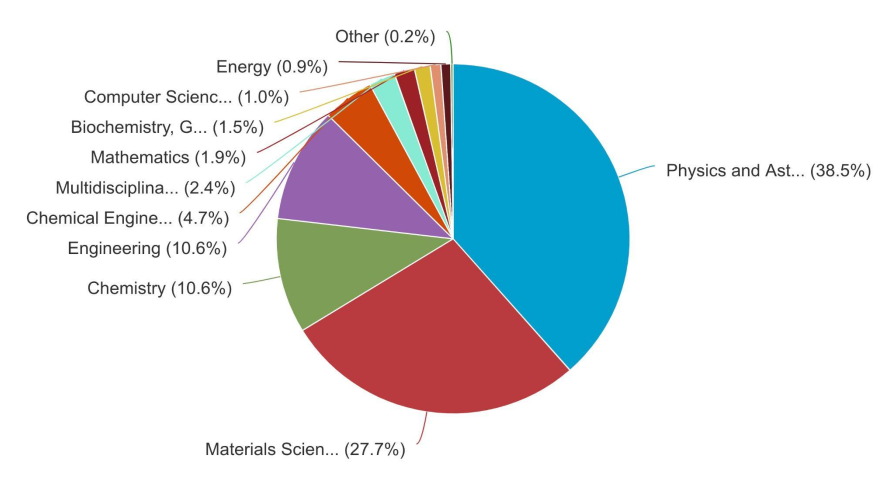
Impact of Paper: Citation Evaluation

- Paper was highly cited, with over 700 citations since 2009

- It received a Field-Weighted Citation Impact of 10.79

- Most citations were in physics, with the expected fields following





Impact of Paper: Review Paper

- Review articles cited this paper the most within its most cited year (2010-2012)

Electronic transport in two-dimensional graphene

S. Das Sarma

Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA

Impact of Paper: Continuation of Research

- Paper on rigorous measurement for ν = 1/3 released by the same group later

Measurement of the $\nu = 1/3$ fractional quantum Hall energy gap in suspended graphene

Fereshte Ghahari, Yue Zhao, Paul Cadden-Zimansky, Kirill Bolotin* and Philip Kim
Department of Physics, Columbia University, New York, New York 10027

We report on magnetotransport measurements of multi-terminal suspended graphene devices. Fully developed integer quantum Hall states appear in magnetic fields as low as 2 T. At higher fields the formation of longitudinal resistance minima and transverse resistance plateaus are seen corresponding to fractional quantum Hall states, most strongly for $\nu = 1/3$. By measuring the temperature dependence of these resistance minima, the energy gap for the 1/3 fractional state in graphene is determined to be at ~20 K at 14 T.

PACS numbers: 73.63.-b, 73.22.-f, 73.43.-f

Impact of Paper: Recent Paper of Interest

- Paper on observation of of anyon braiding statistics

Direct observation of anyonic braiding statistics

J. Nakamura[1,2], S. Liang[1,2], G. C. Gardner[2,3] and M. J. Manfra[1,2,3,4,5]

Anyons are quasiparticles that, unlike fermions and bosons, show fractional statistics when two of them are exchanged. Here, we report the experimental observation of anyonic braiding statistics for the $\nu = 1/3$ fractional quantum Hall state by using an electronic Fabry–Perot interferometer. Strong Aharonov–Bohm interference of the edge mode is punctuated by discrete phase