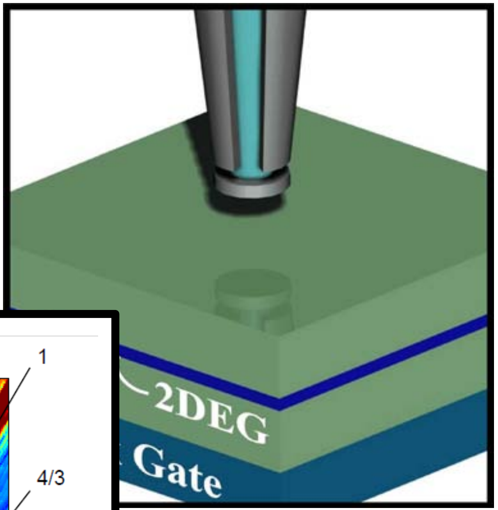
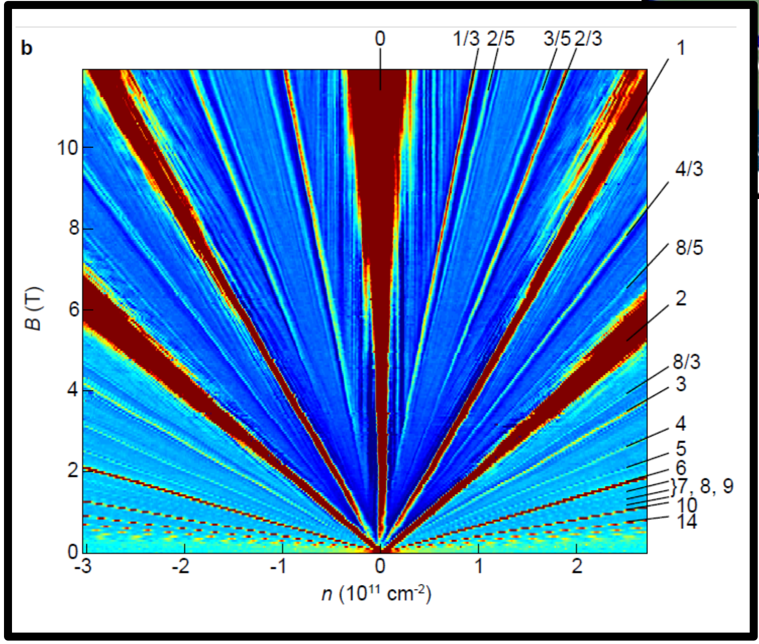
Effects of Interactions in Suspended Graphene

Ben Feldman, Andrei Levin, Amir Yacoby, Harvard University

- Broken and unbroken symmetries in the lowest LL:
  – spin and valley symmetries.
- FQHE



Discussions with Bert Halperin and Dima Abanin



In collaboration with

Benjamin Krauss, Jurgen Smet, MPI Stuttgart

Degeneracy and Interactions

- Kinetic energy (Pauli exclusion) vs Interaction energy

$$E_{e-e} = \frac{e^2}{\varepsilon r} = \frac{e^2}{\varepsilon}\sqrt{n}$$

$$r_s = \frac{E_{e-e}}{E_K} = \frac{e^2/\varepsilon r}{E_F}$$

$$E_F = \frac{\hbar^2 k_F^\alpha}{2m^*} \qquad n \propto g \cdot (k_F)^d$$

α -Disperssion – 1-graphene
2 - bilayer

g - Degeneracy: spin, layer, valley

d - Dimensionality (1d,2d,3d)

$$r_s \propto g^{\frac{1}{d}} \cdot n^{\frac{1}{2}-\frac{\alpha}{d}} \cdot \frac{m^*}{\varepsilon}$$

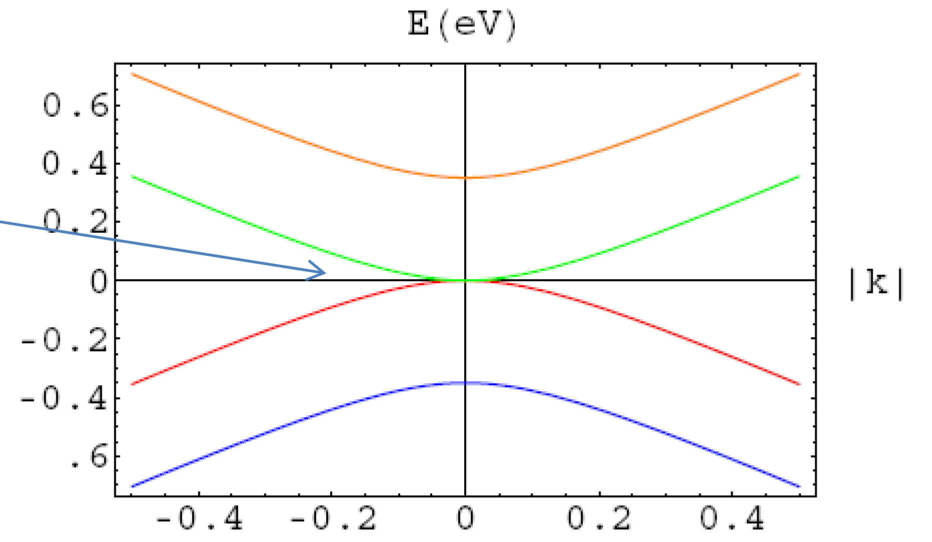
We want:
Large degeneracy, large mass, low density, low dielectric.

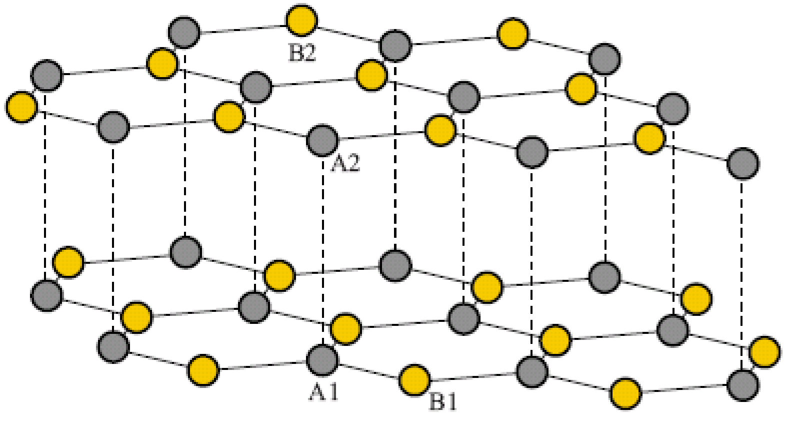
Bilayers - Band Structure

- B=0

- Quadratic dispersion: α=2

  m~0.03m_e
- Near E=0; g =8 - Spin, valley and sub-lattice
- Low density
- Suspended – ε~1





$$r_s \propto g^{\frac{1}{d}} \cdot n^{\frac{1}{2}-\frac{\alpha}{d}} \cdot \frac{m^*}{\varepsilon}$$

Degenerate bands correspond to B1 and B2 sub-lattices

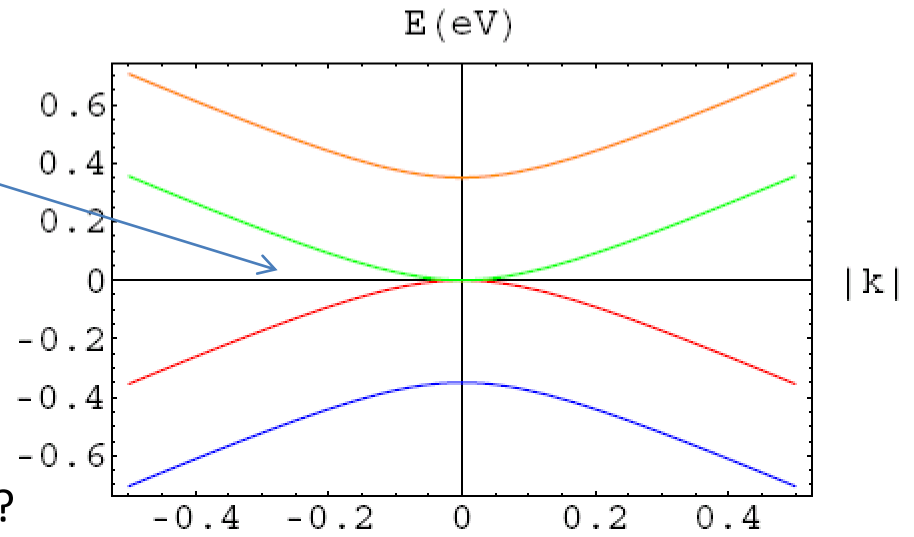
Generalization to Multi-layers

- B=0
- For N layers: ABCABC… stacking

  - Dispersion $\propto k^N \Rightarrow \alpha = N$
  - g - Spin, valley and sub-lattice
  - Low density

$$r_s \propto g^{\frac{1}{d}} n^{\frac{1}{2}-\frac{N}{d}} \frac{m^*}{\varepsilon}$$

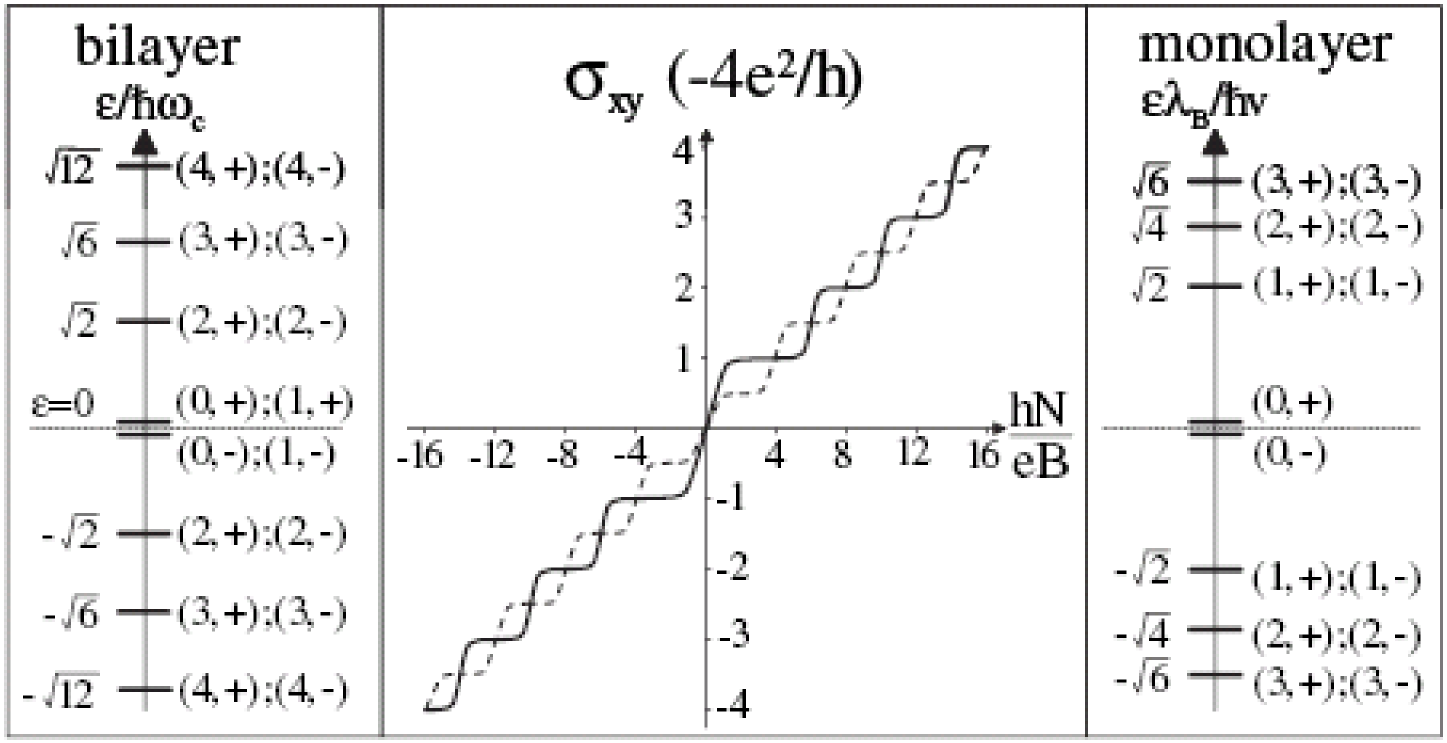
Screening?



Experiments: Lau, Tarucha, Jarillo-Herrero, Kim, Zaliznyak, Geim, Novoselov, Andrei, Heintz, Crommie, Schoenenberger, Ong…

Theory: Falko, McCann, Levitov, Katsnelson, Castro-Neto, Macdonald, Fogler, Fertig, Shimshoni Das Sarma, Polini, Guinea, Aleiner, Altshuler, Abanin, Sondhi, Kharitonov…

QHE - Degeneracy's



$$E_n = \hbar\omega_c\sqrt{n(n-1)}$$

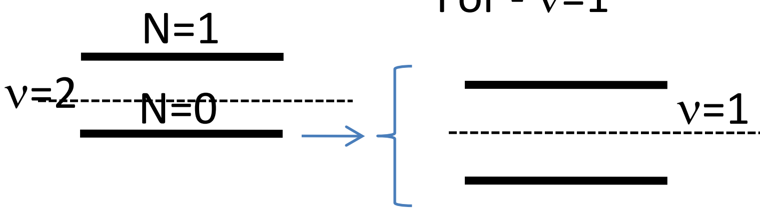
$$E_n = \sqrt{n}\sqrt{2e\hbar v_F^2 B}$$

Diverging mass

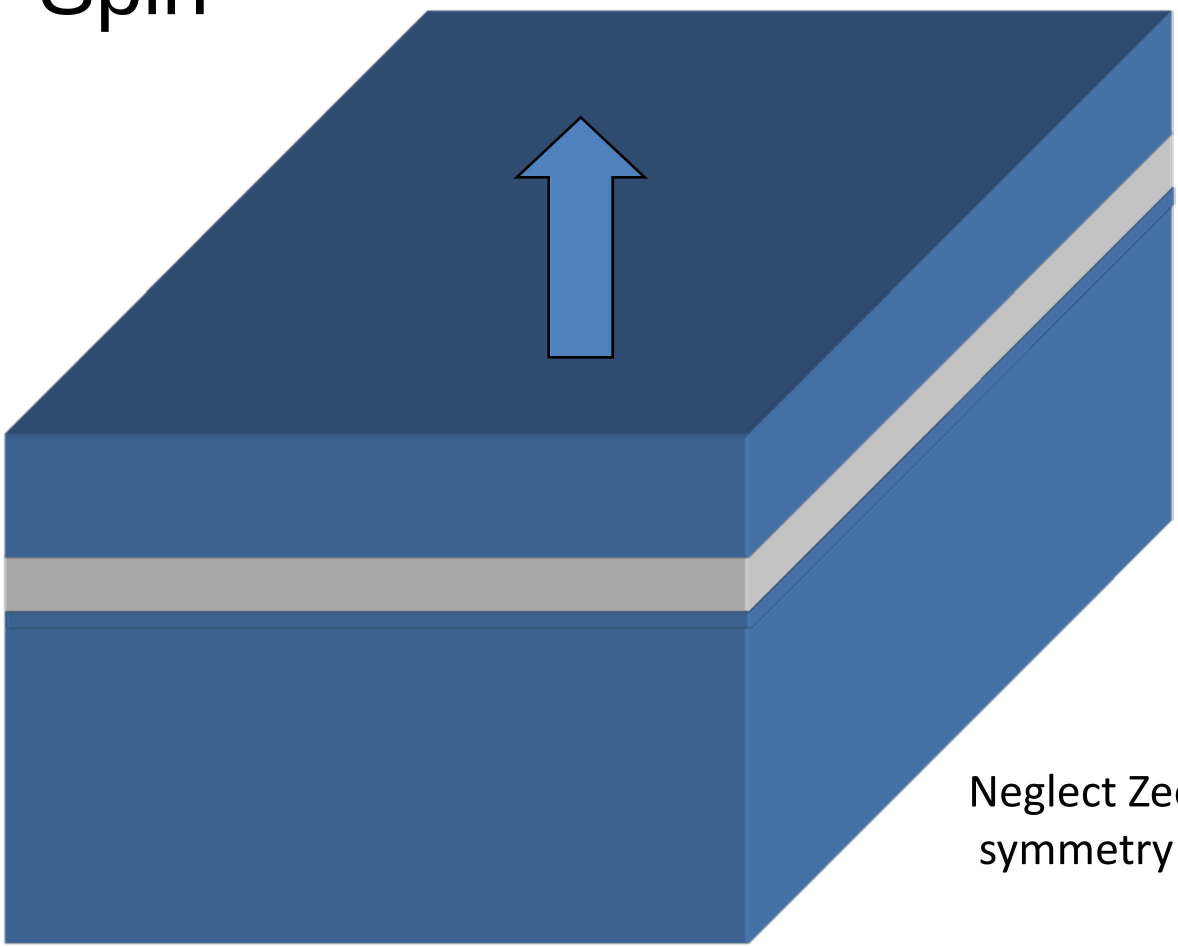
McCann, Falko, '06

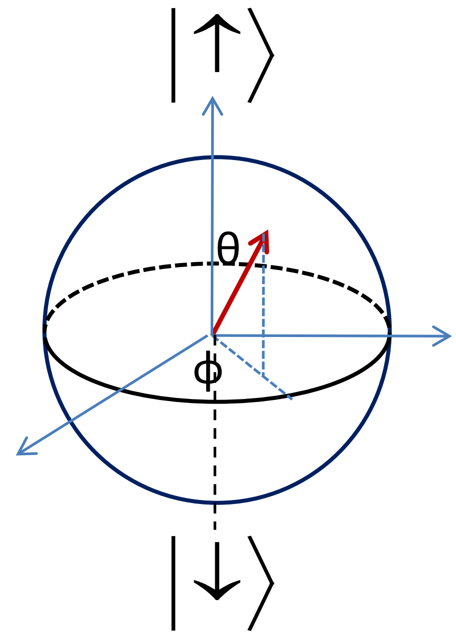
Quantum Hall Ferromagnetism

For - $\nu=1$



- Spin

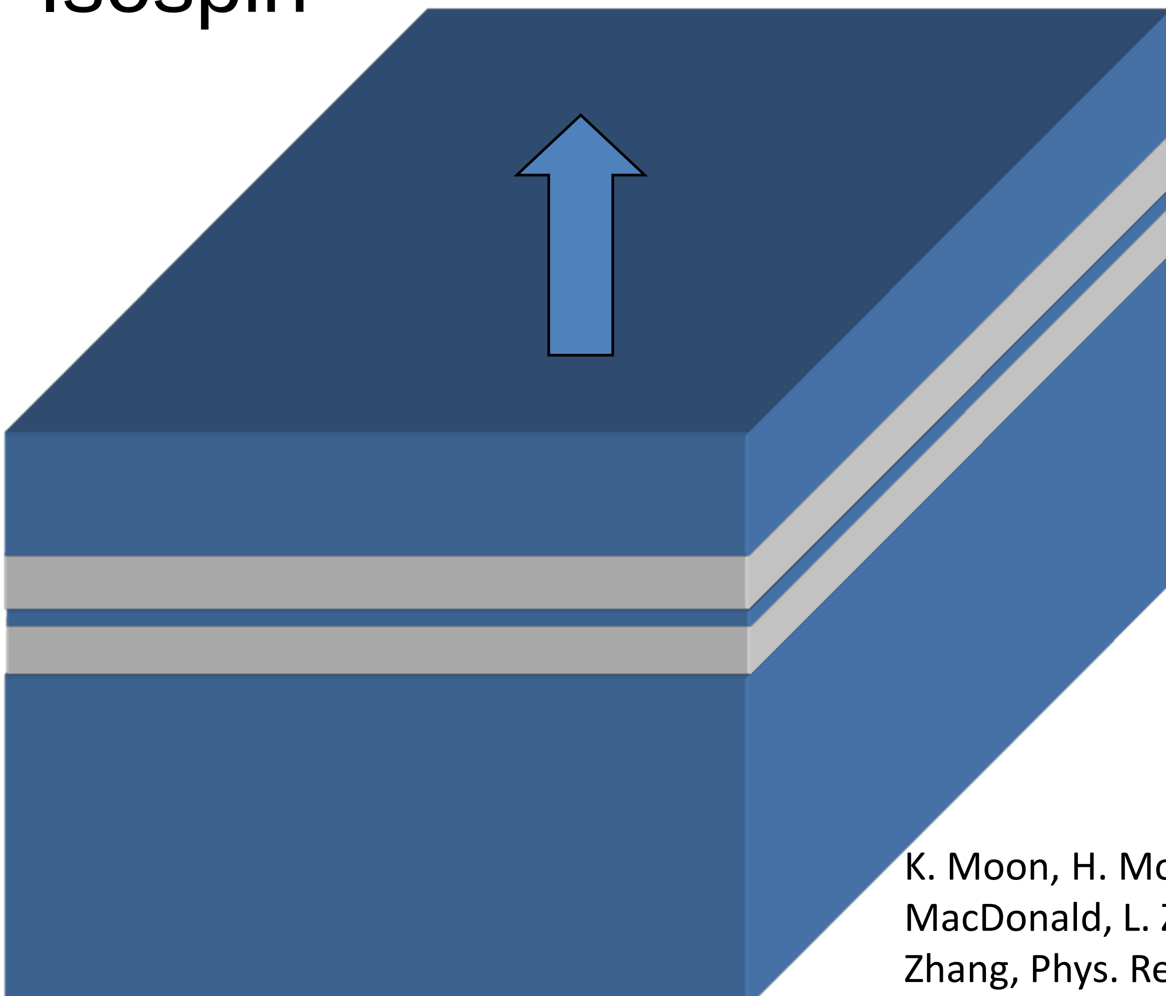


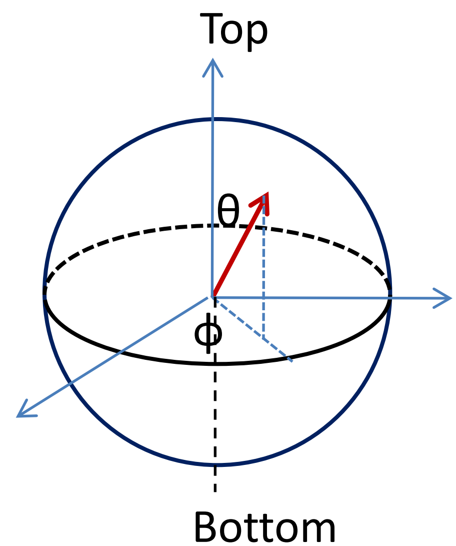


Neglect Zeeman: SU(2) spontaneous symmetry breaking

Quantum Hall Ferromagnetism

- Isospin





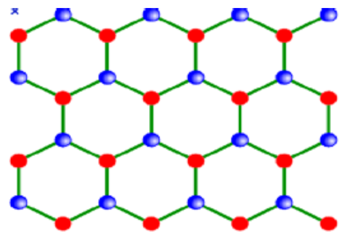
K. Moon, H. Mori, Kun Yang, S. M. Girvin, A. H. MacDonald, L. Zheng, D. Yoshioka, and Shou-Cheng Zhang, Phys. Rev. B **51**, 5138 1995.
S. L. Sondhi, '95

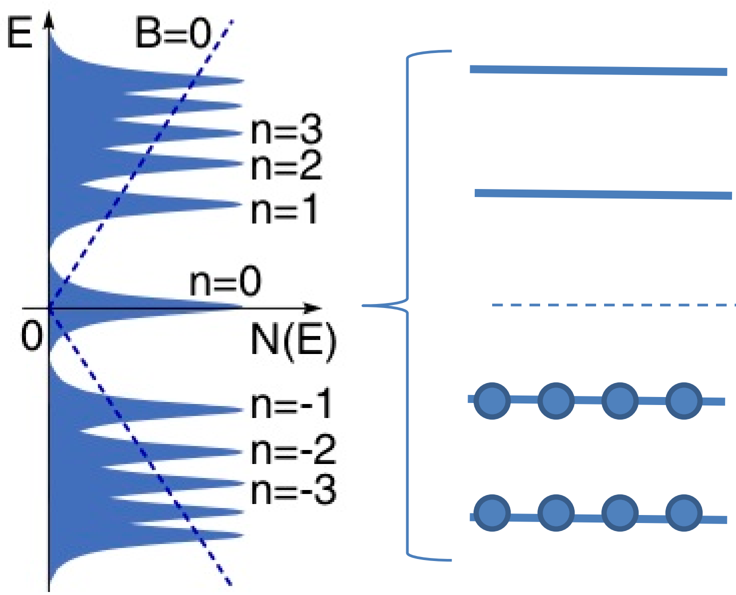
Simple example - ν=1

Monolayer and Bilayers

Interplay between valley and spin:

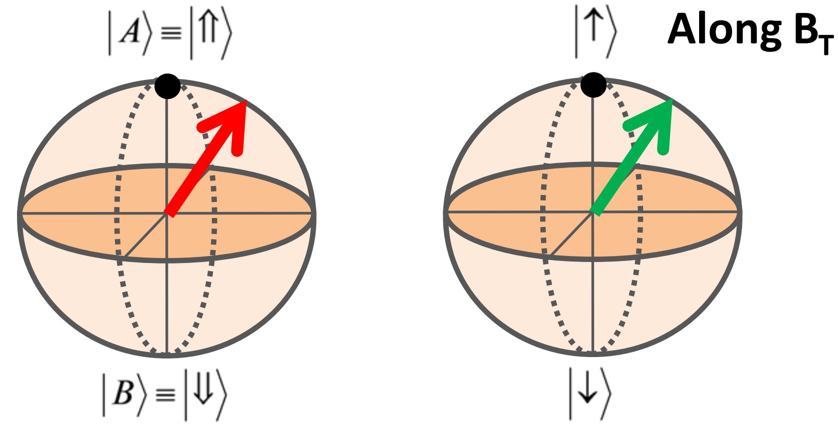
- **Lowest LL occupied by electrons and holes**
- **4 fold degenerate: Valley and spin**





Valley/ sub-lattice (pseudospin)

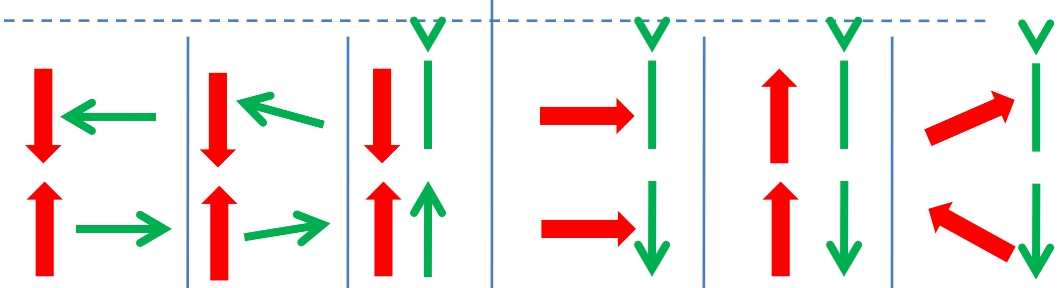
spin



Space of symmetries SU(4)

$\nu=0$

Partial spin ordering | **Partial valley ordering**



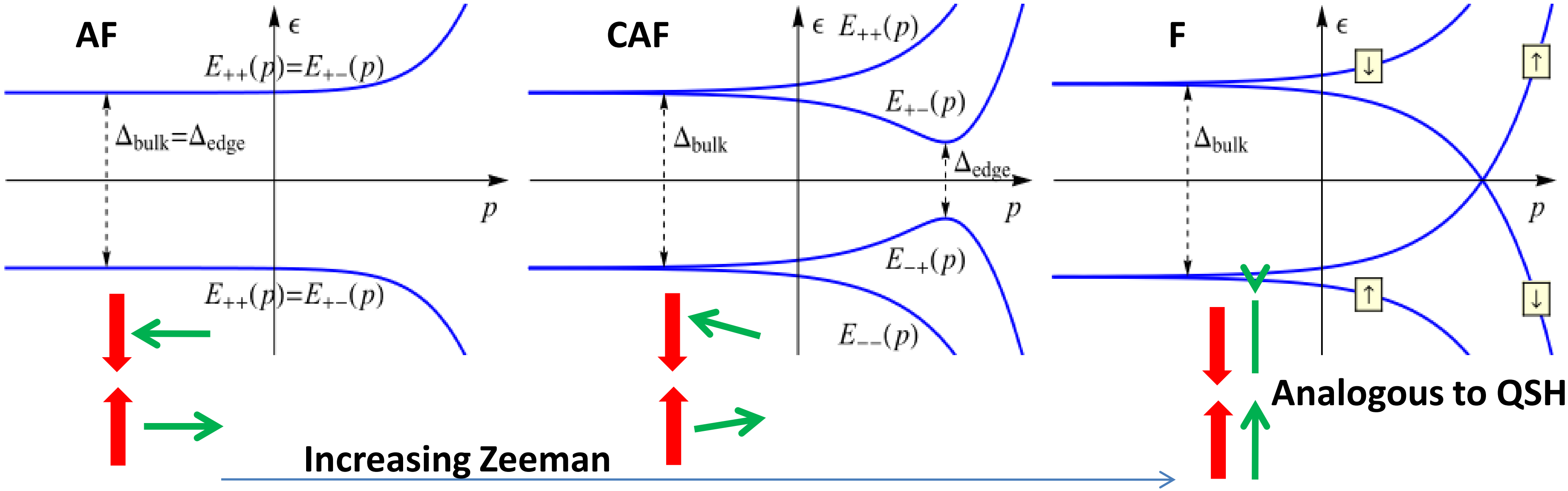
Increasing Zeeman

Determined by lattice scale anisotropy

Abanin et al ’07, Macdonald et al, M. Kharitonov ’11, ‘12…

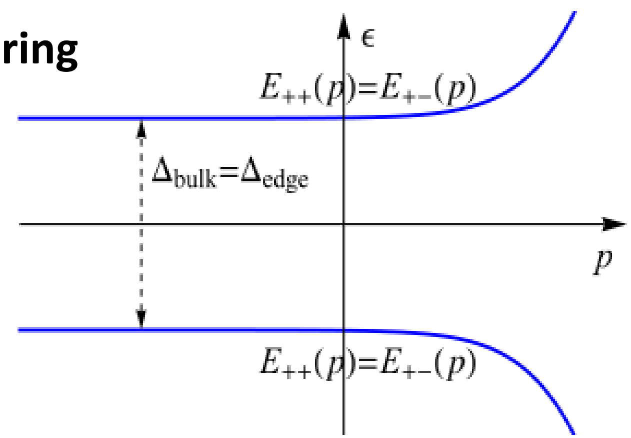
Monolayers at the Edge

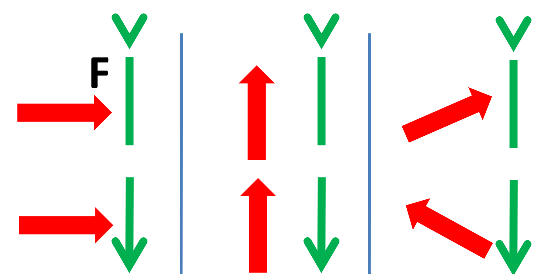
Partial spin ordering



Kharitonov ‘12

Partial valley ordering

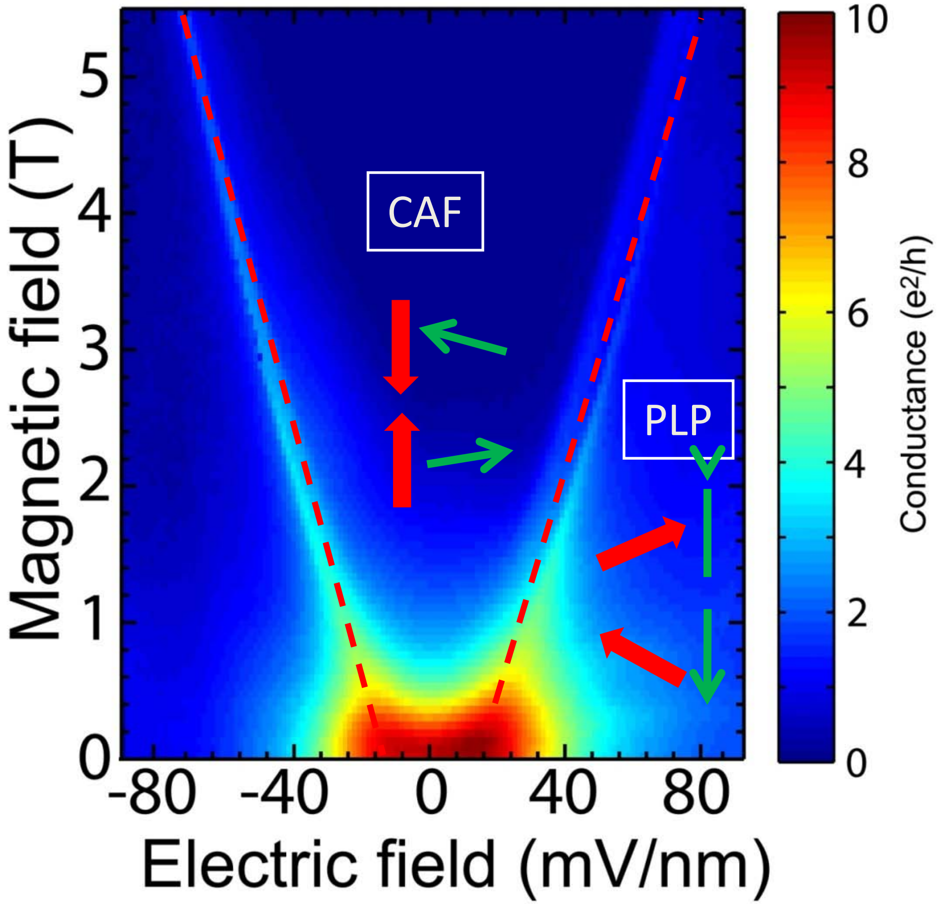


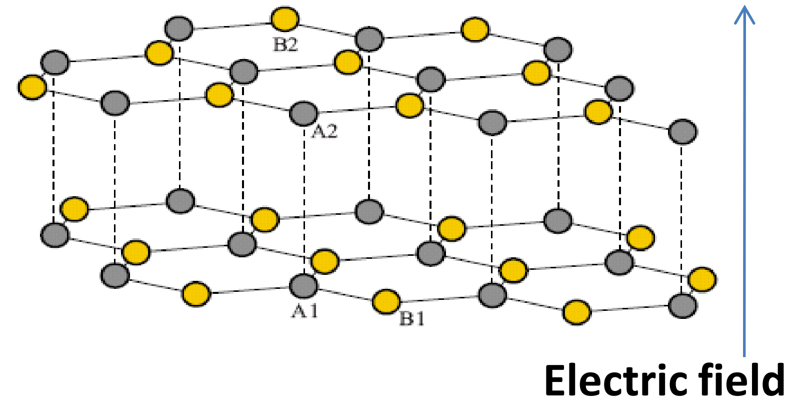


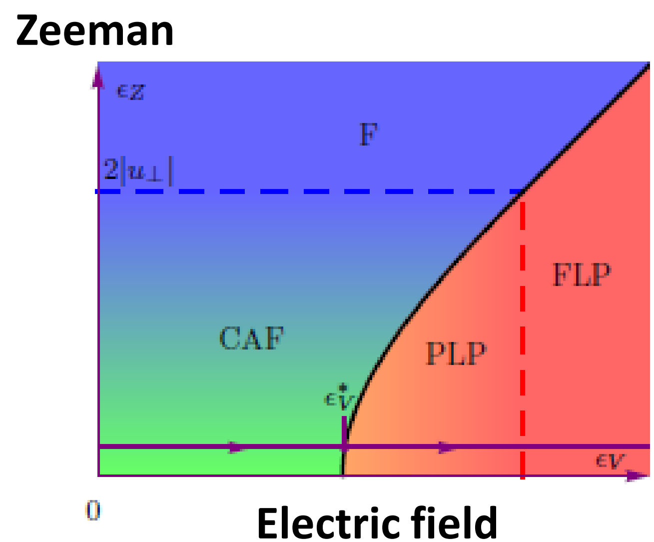
Kekule **CDW** **PLP-Bilayers**

Experimentally (Kim group): Increasing Zeeman reduces transport gap; suggests absence of strong spin polarization – ?? CAF ??

Phase diagram for ν=0 in Bilayers



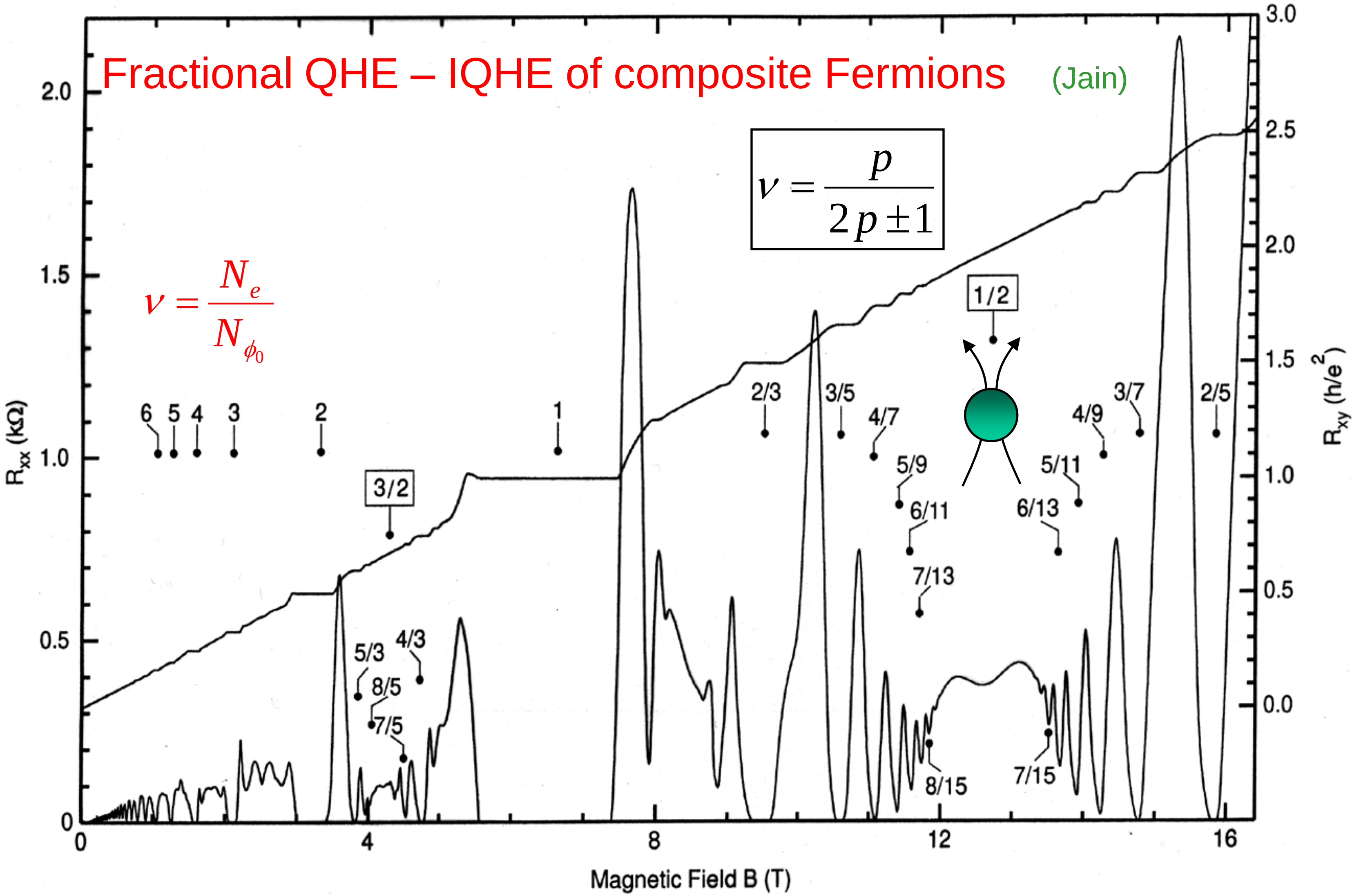




From: Kharitonov, 2011
See also: Macdonald, Levitov

R. T. Weitz, AY, et al, Science 2010.

Fractional Quantum Hall Effect - GaAs



- Non Abelian phases at 5/2 and 12/5 ?? (Moore and Read)
- Edge reconstruction (Barak, AY et al)
- Neutral edge excitation modes (Heiblum et al, Venkatachalam, AY et al)

Fractional topological phases and broken time reversal symmetry in strained graphene

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[2] *Department of Physics, University of California, Berkeley, California 94720, USA*
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[4] *Univ. Bordeaux and CNRS, LOMA, UMR 5798, F-33400 Talence, France*
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[6] *Department of Physics and Astronomy, California State University, Northridge, California 91330, USA*

We show that strained or deformed honeycomb lattices are promising platforms to realize fractional topological quantum states in the absence of any magnetic field. The strained induced pseudo magnetic fields are oppositely oriented in the two valleys [1–3] and can be as large as 60-300 Tesla as reported in recent experiments [4, 5]. For strained graphene at neutrality, a spin or a valley polarized state is predicted depending on the value of the onsite Coulomb interaction. At fractional filling, the unscreened Coulomb interaction leads to a valley polarized Fractional Quantum Hall liquid which spontaneously breaks time reversal symmetry. Motivated by artificial graphene systems [5–8], we consider tuning the short range part of interactions, and demonstrate that exotic valley symmetric states, including a valley Fractional Topological Insulator and a spin triplet superconductor, can be stabilized by such interaction engineering.

arXiv:1111.3640v2 19 May 2012

Fractionalizing Majorana fermions: non-abelian statistics on the edges of abelian quantum Hall states

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Ady Stern
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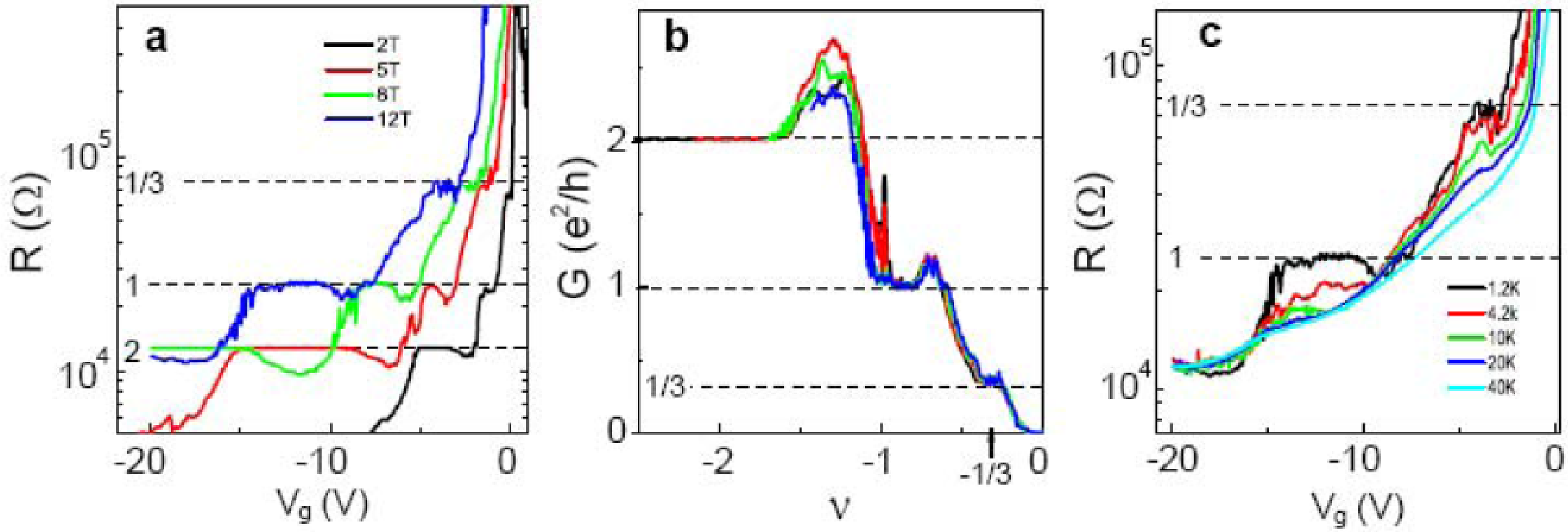
(Dated: July 9, 2012)

lator phase (as of today), one could get by starting from "ordinary" Laughlin fractional quantum Hall state whose edges are coupled to a superconductor. The fractional quantum Hall state in graphene might be a promising candidate for realizing such systems, since the magnetic fields needed for observing it are much lower than the fields needed in semiconductor heterostructure devices.

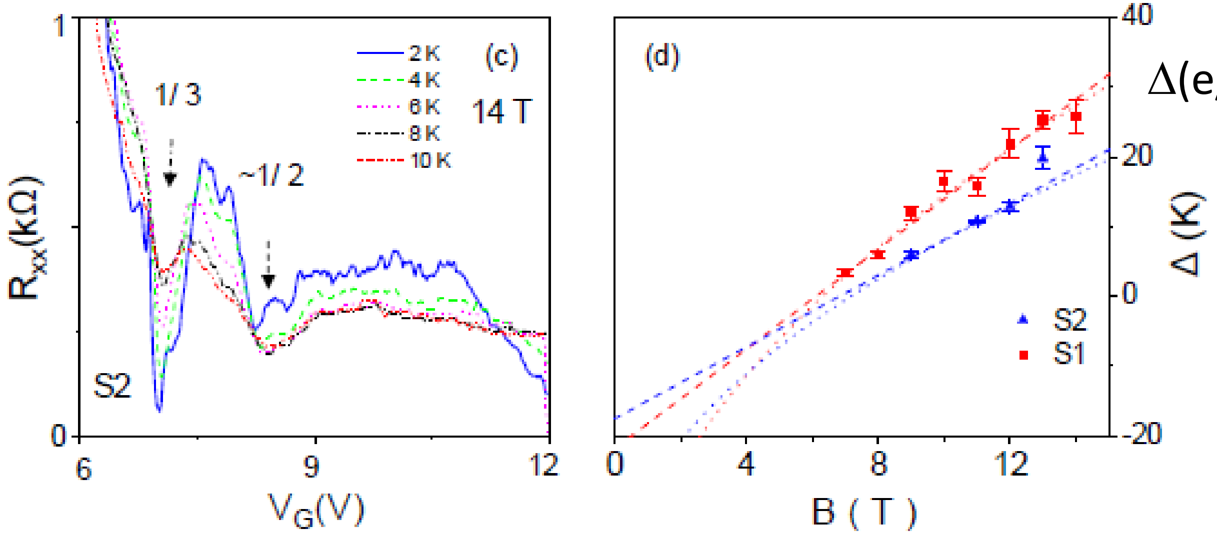
An experimentally accessible signature of the fractionalized Majorana modes is a fractional Josephson effect,

arXiv:1204.5733v2 - 5 Jul 2012

Background on FQHE - Suspended



Andrei group: Nature 462, 192, (2009)



$\Delta(e/3)$= 2meV @12T

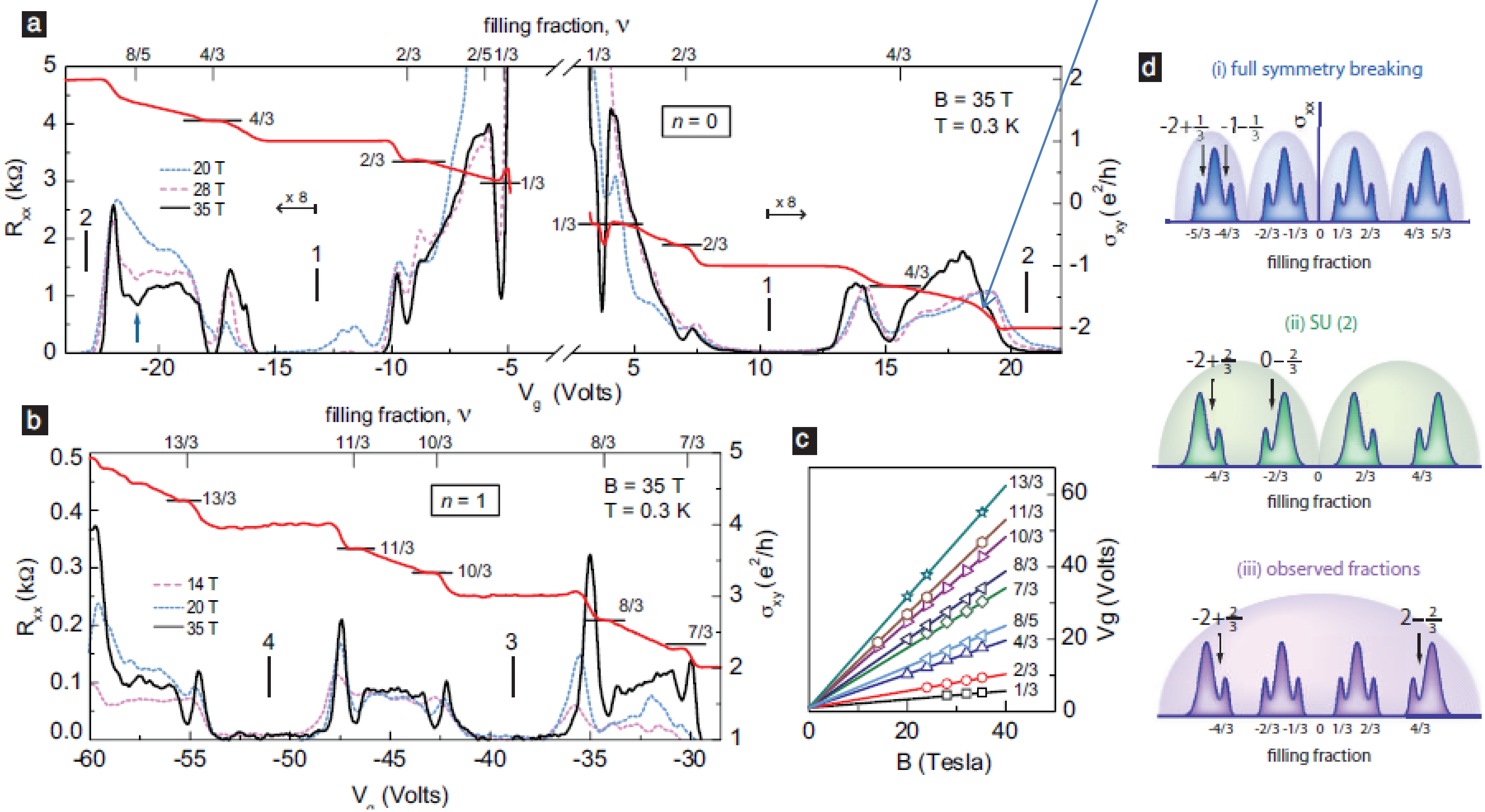
1/3 most developed

Kim group Phys. Rev. Lett. 106, 046801 (2011)

Background on FQHE - hBN

4/3 most developed

5/3 absent

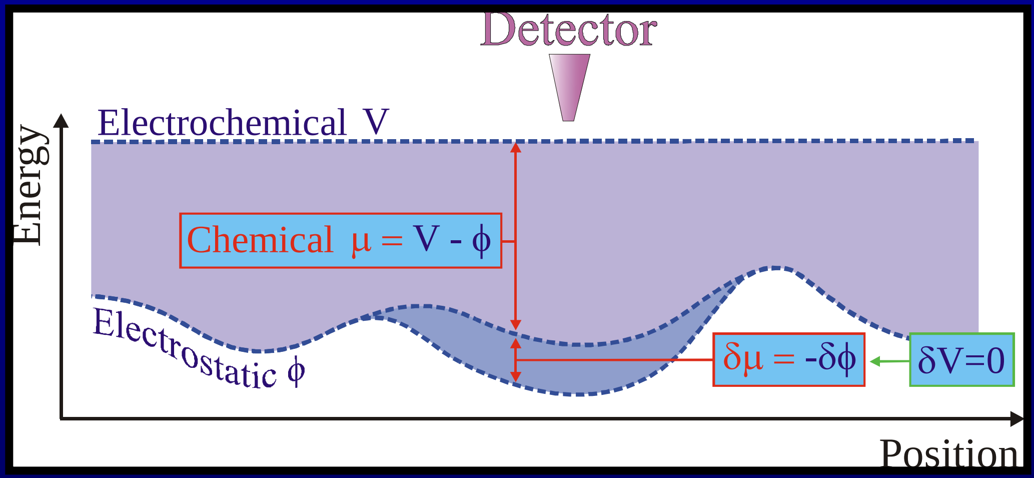


Kim group, Nature Physics 7, 693 (2011)

How to Measure Local Density of States ?

$\left[\frac{\partial n}{\partial \mu}\right]$ = Density of states

$\left[\frac{\partial \mu}{\partial n}\right]$: Inverse (DOS ; Compressibility)



Need to measure

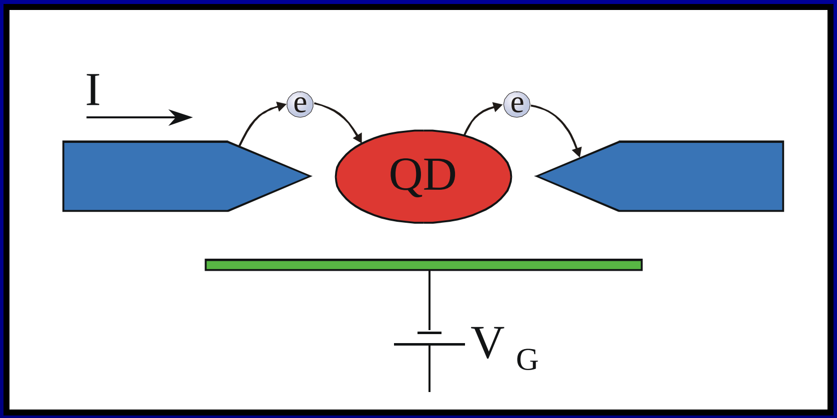
$\delta\mu$

Thermodynamic equilibrium ➡ V is constant in space ➡ $\delta\mu = -\delta\phi$

If we can measure the local $\delta\phi$

we will immediately get the local $\delta\mu$

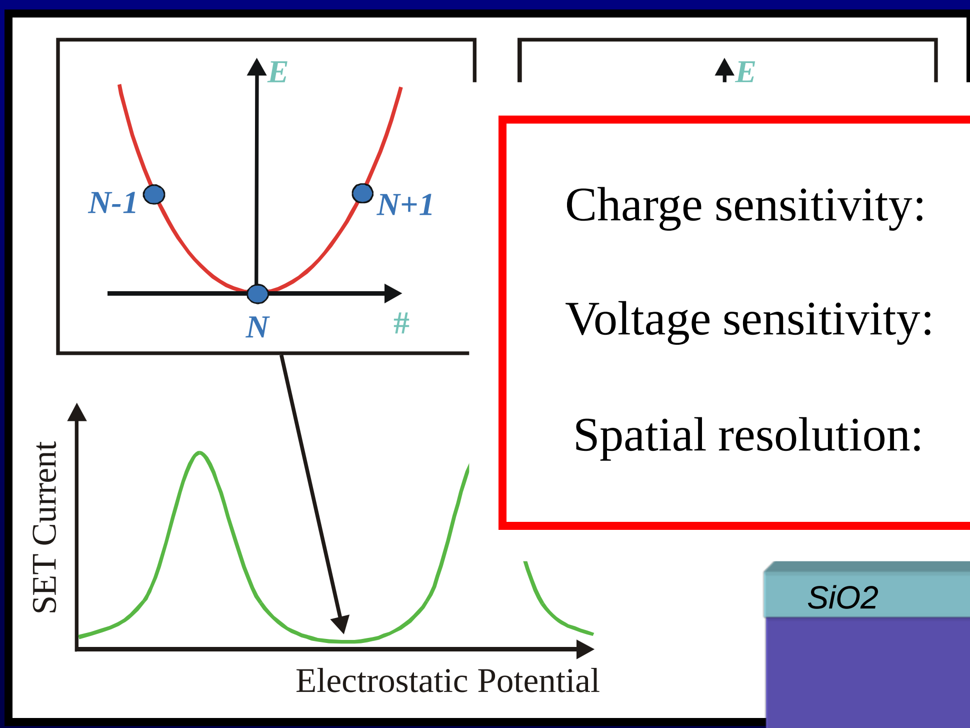
Using a SET as a Local Electrostatic Probe



Current flow $N \rightarrow N+1 \rightarrow N$

Coulomb Blockade $U = \frac{e^2}{c} > kT$

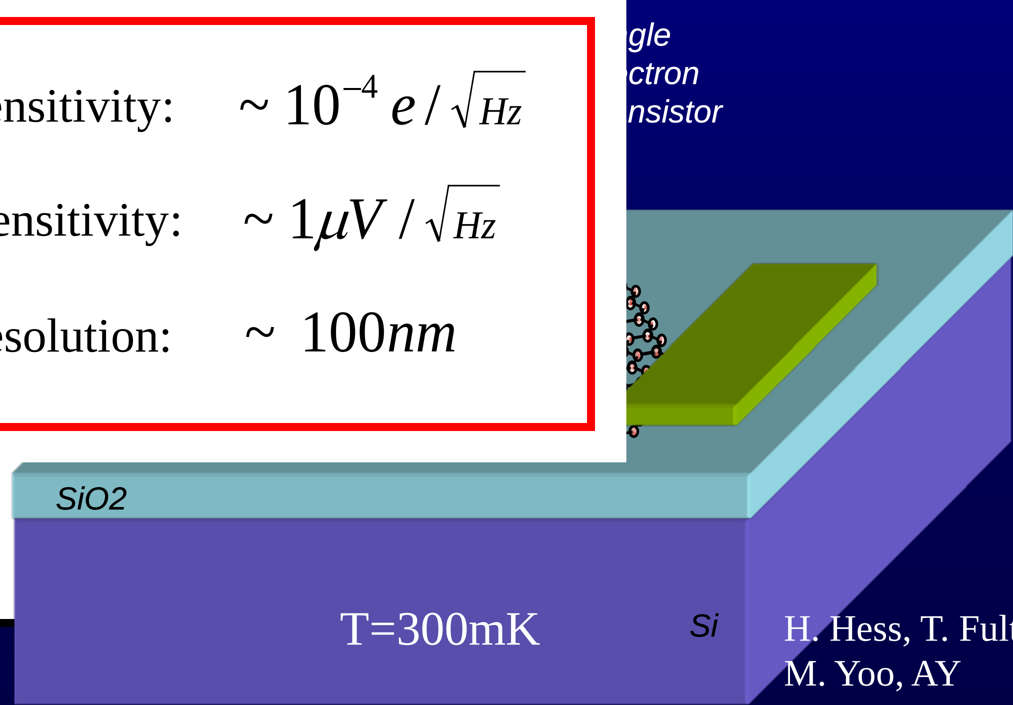
Use graphene as the gate.
By monitoring the current we can extract the local electrostatic potential.



Charge sensitivity: $\sim 10^{-4}\, e/\sqrt{Hz}$

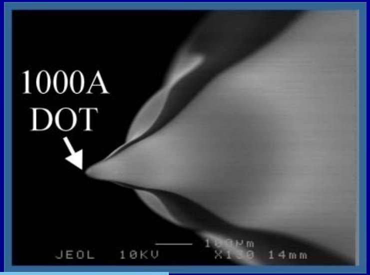
Voltage sensitivity: $\sim 1\mu V/\sqrt{Hz}$

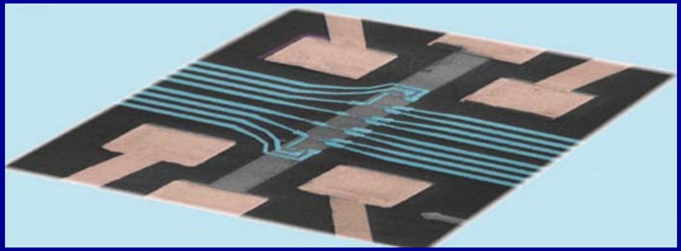
Spatial resolution: $\sim 100nm$



H. Hess, T. Fulton, M. Yoo, AY

Local Measurement of DOS



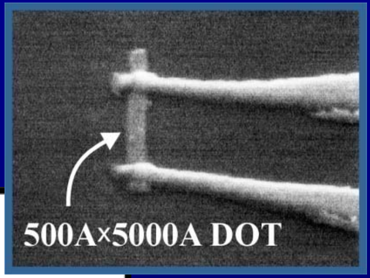


Scanning

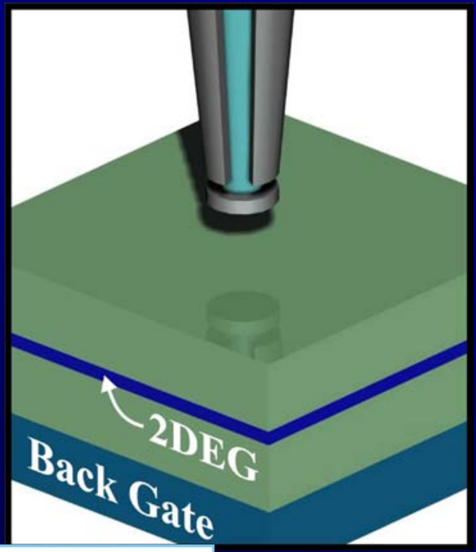
T=300mK

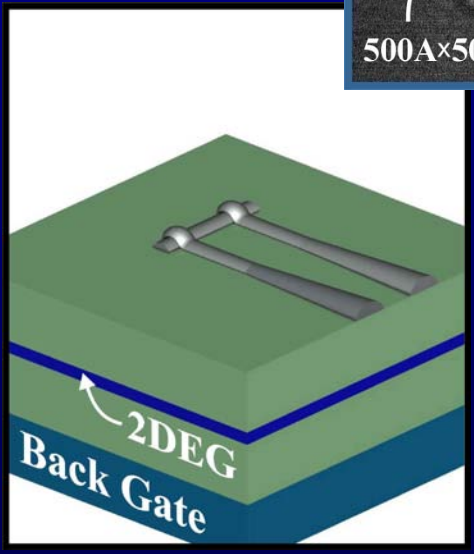
Fixed

T=50mK



Scanning microscope





Metal-Insulator Transition in 2D

S. Ilani, et. al.,

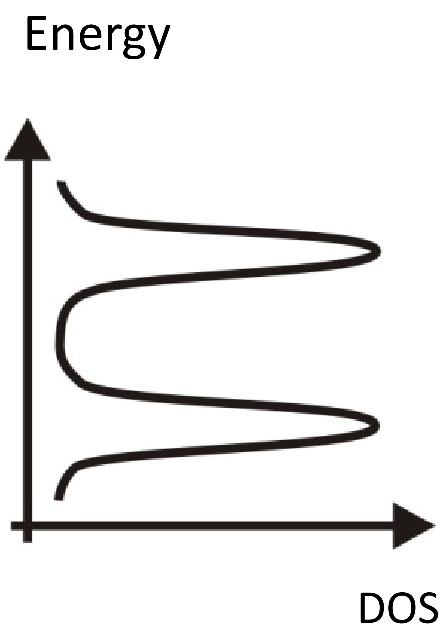
PRL 84 (2000)
Science 292 (2001)

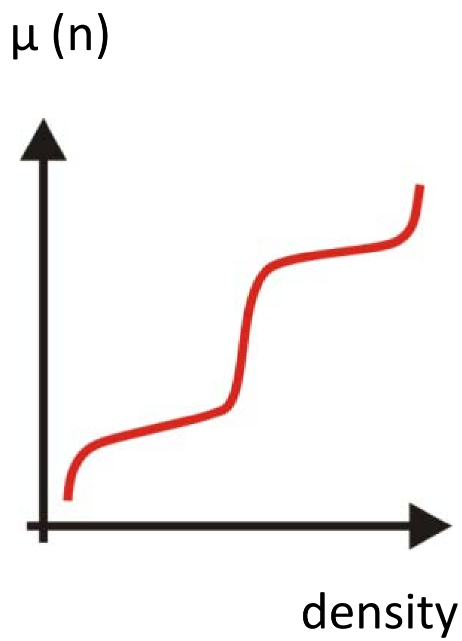
S. Ilani et al,
Nature 328 (2004)
Martin et al,
Science (2004)

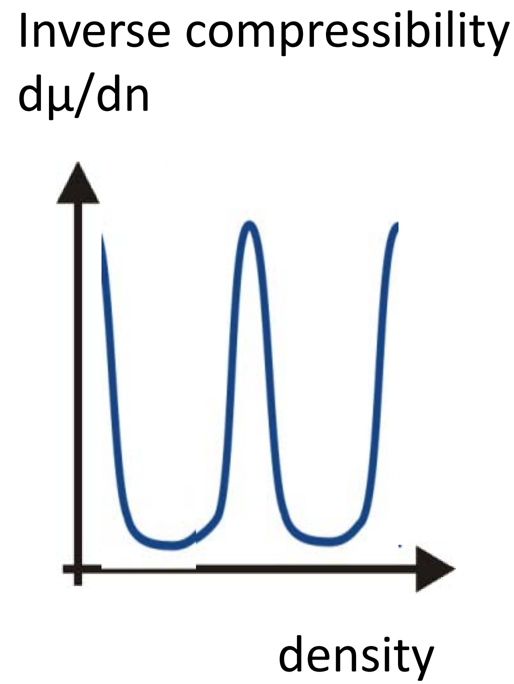
SET Tip

Simultaneous Transport & Local Potential

Inverse compressibility







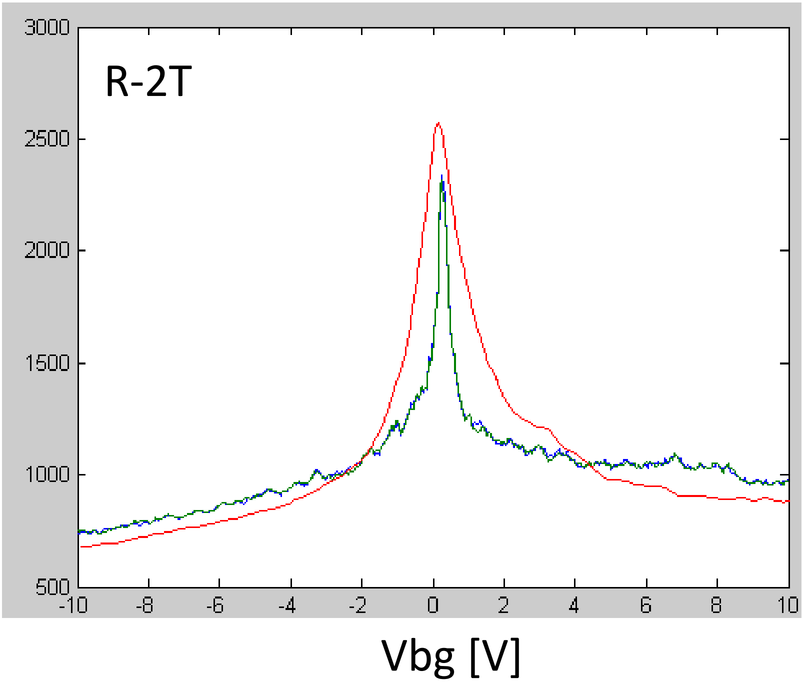
dn: AC voltage on backgate

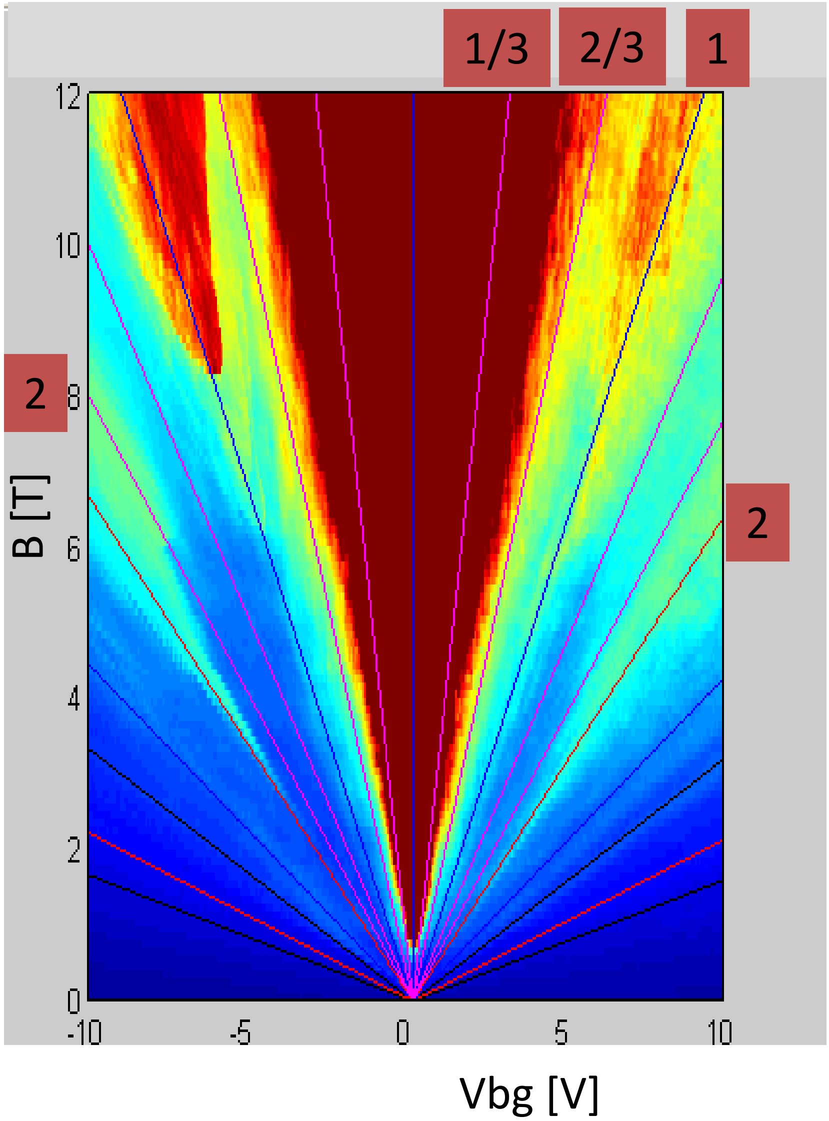
dμ: Single Electron Transistor

1μV, 100nm, B =[0 – 12 T], UHV, 300mK

Sample Geometry

Transport

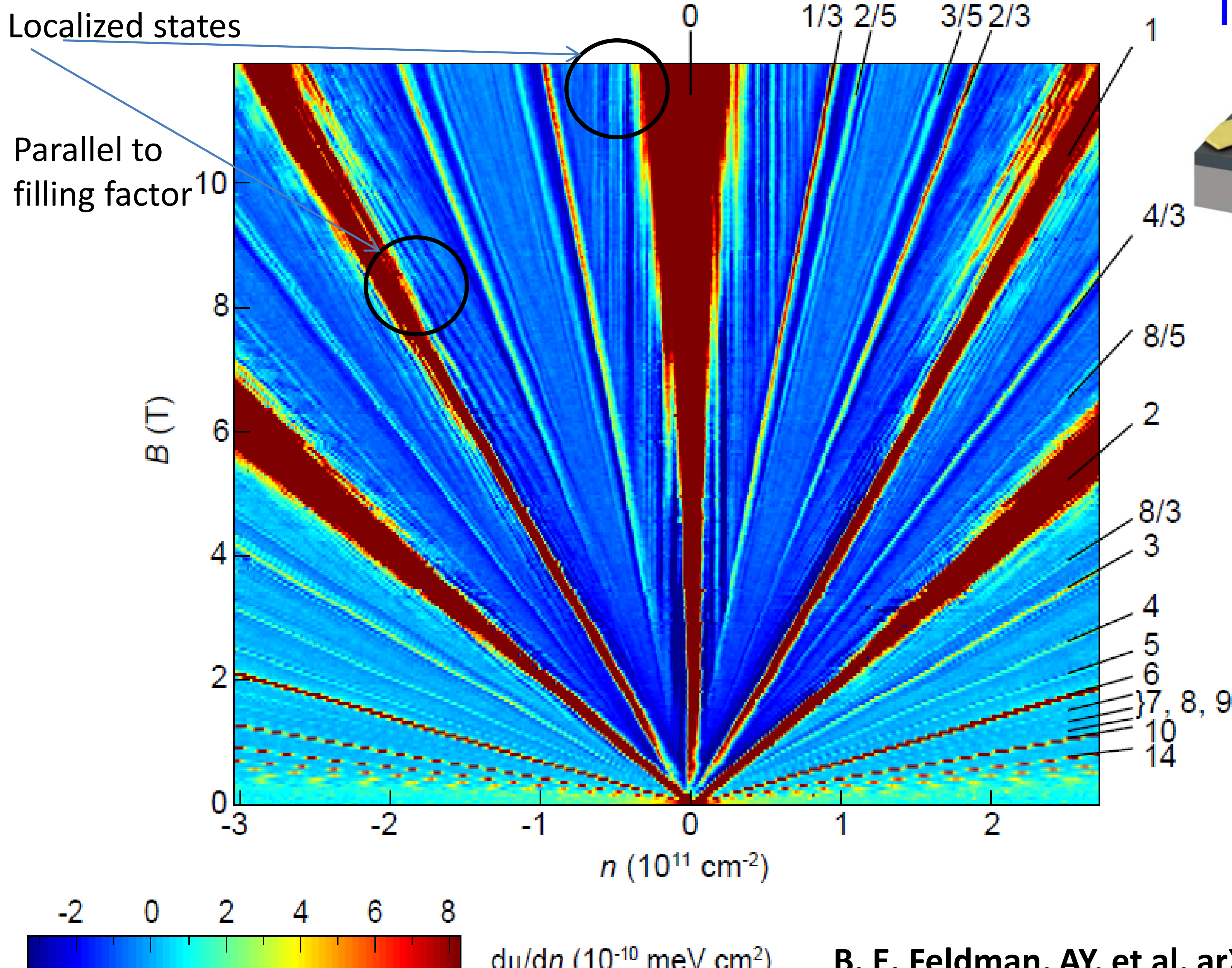


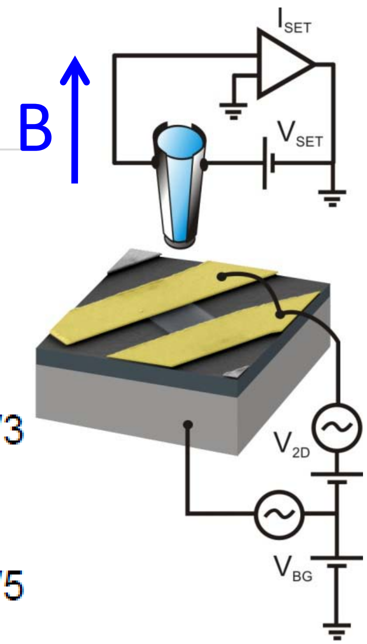


Red: After first round of current annealing

Blue, Green: New

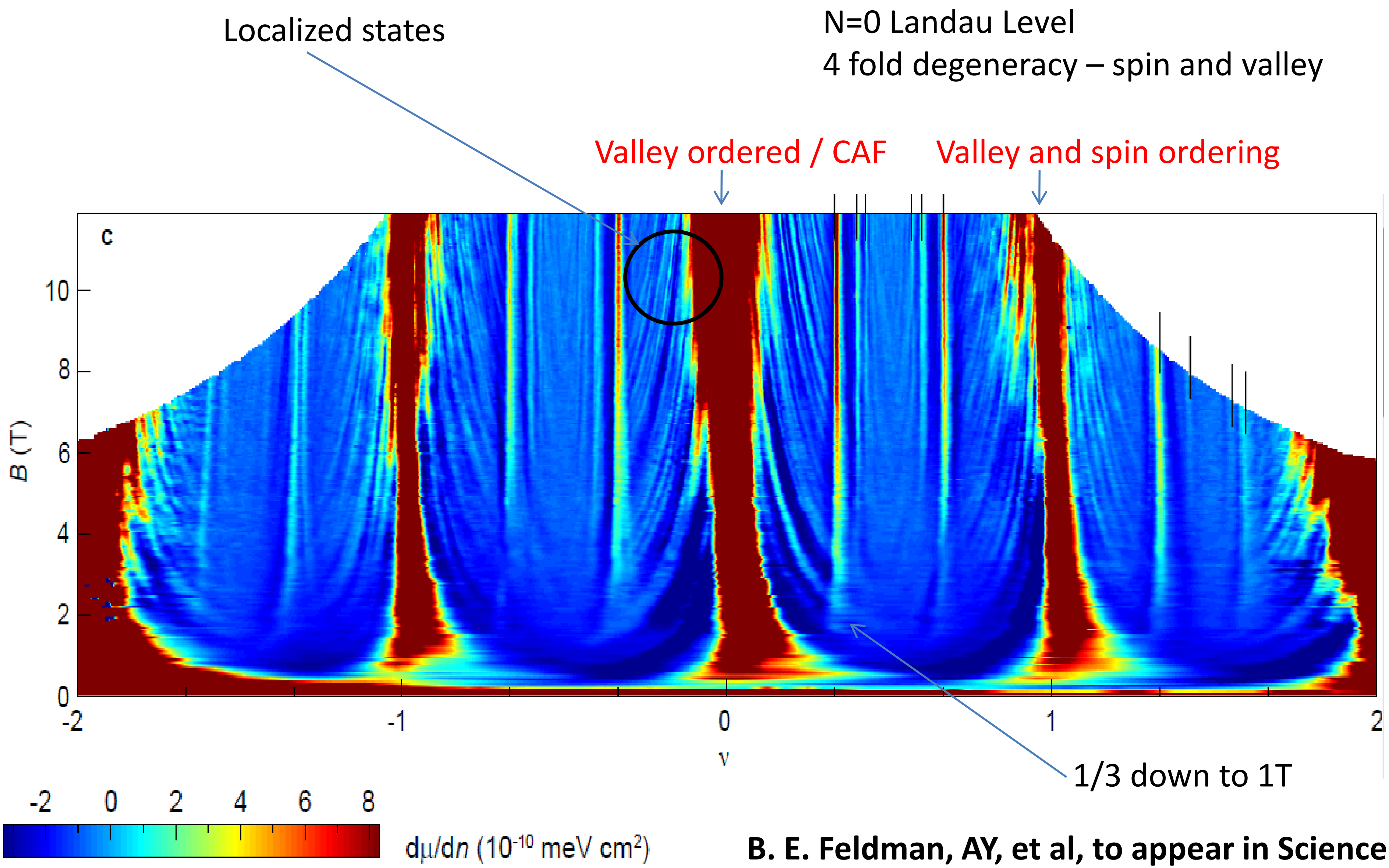
Inverse Compressibility





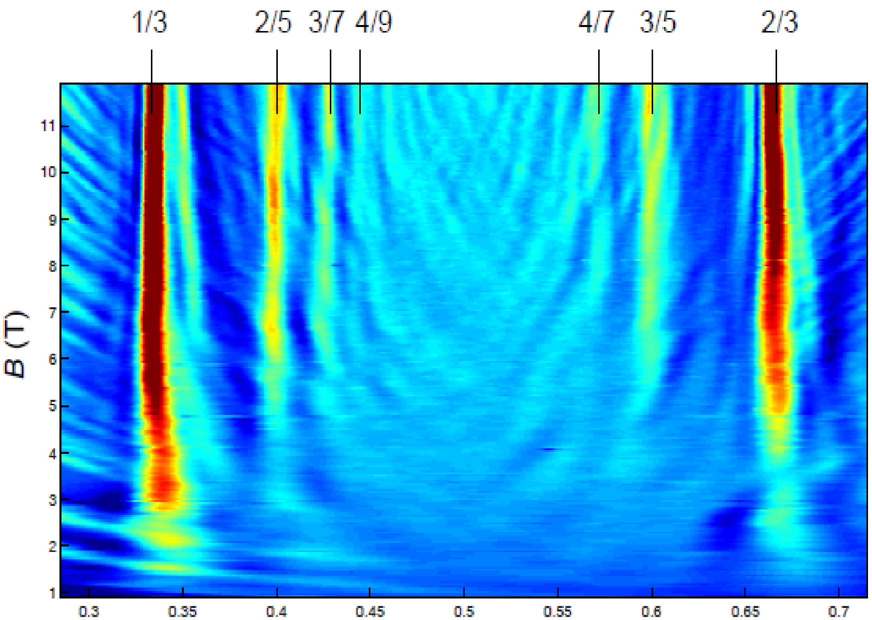
B. E. Feldman, AY, et al, arXiv: 1201.5128

Lowest Landau Level



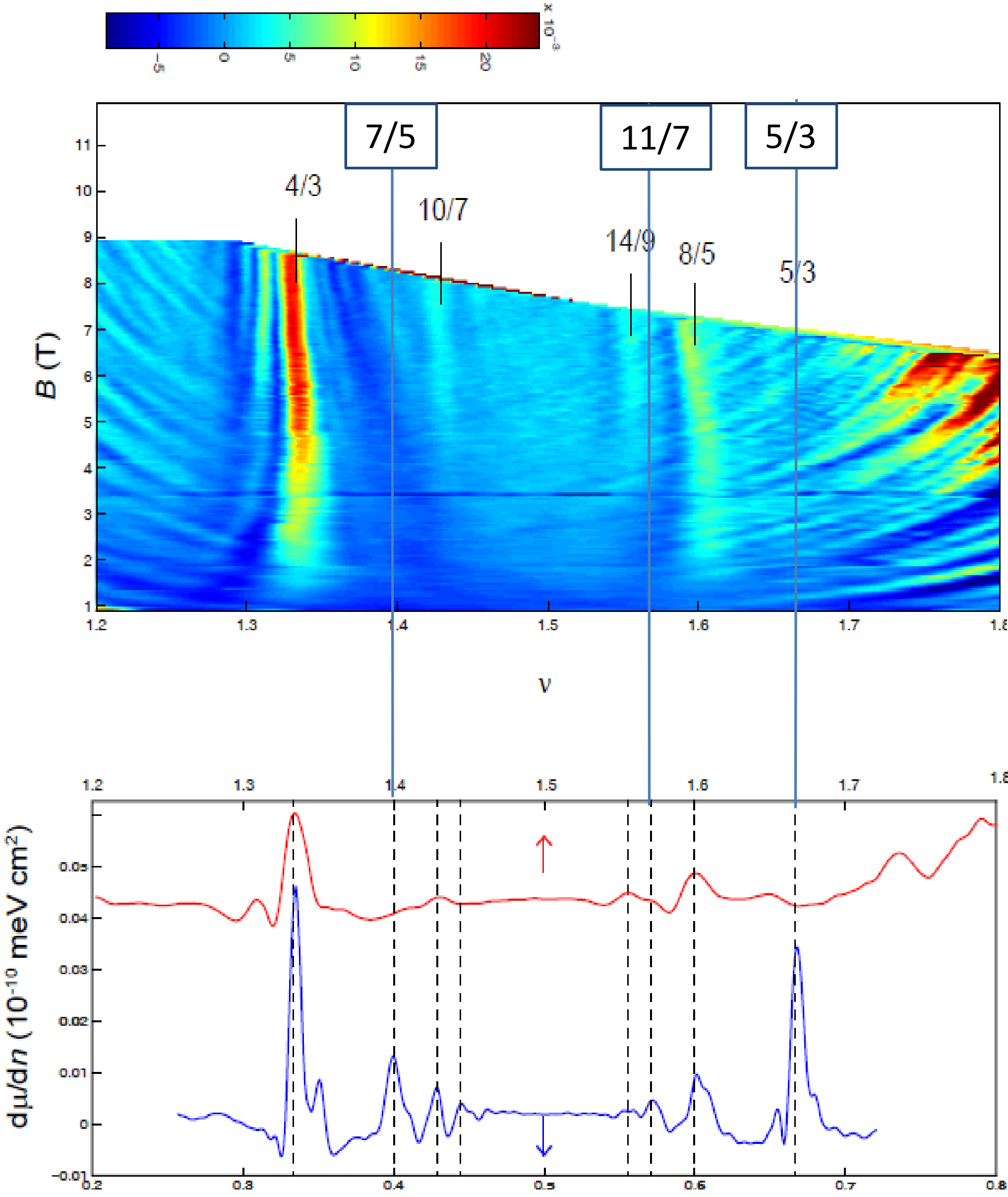
B. E. Feldman, AY, et al, to appear in Science

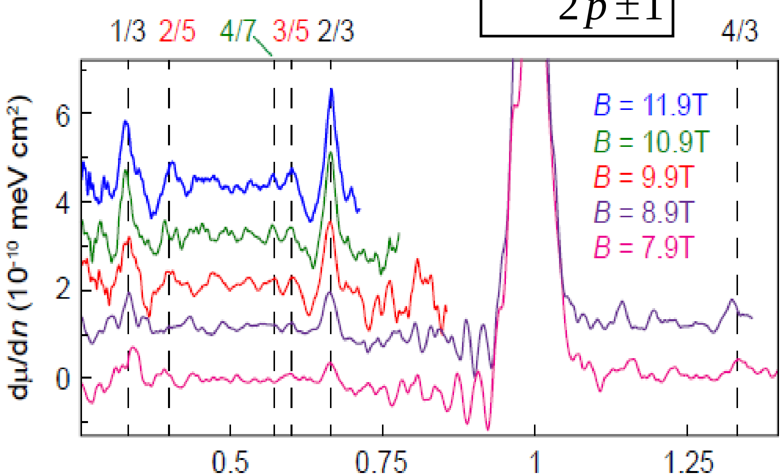
Fractions in the Lowest Landau Level



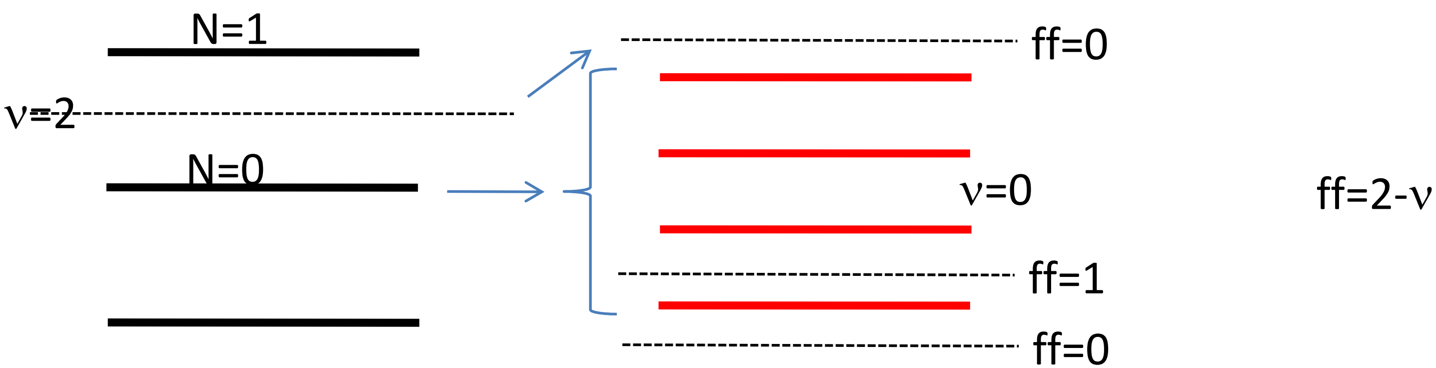
No CF degeneracy's ν

$$\nu = \frac{p}{2p \pm 1}$$



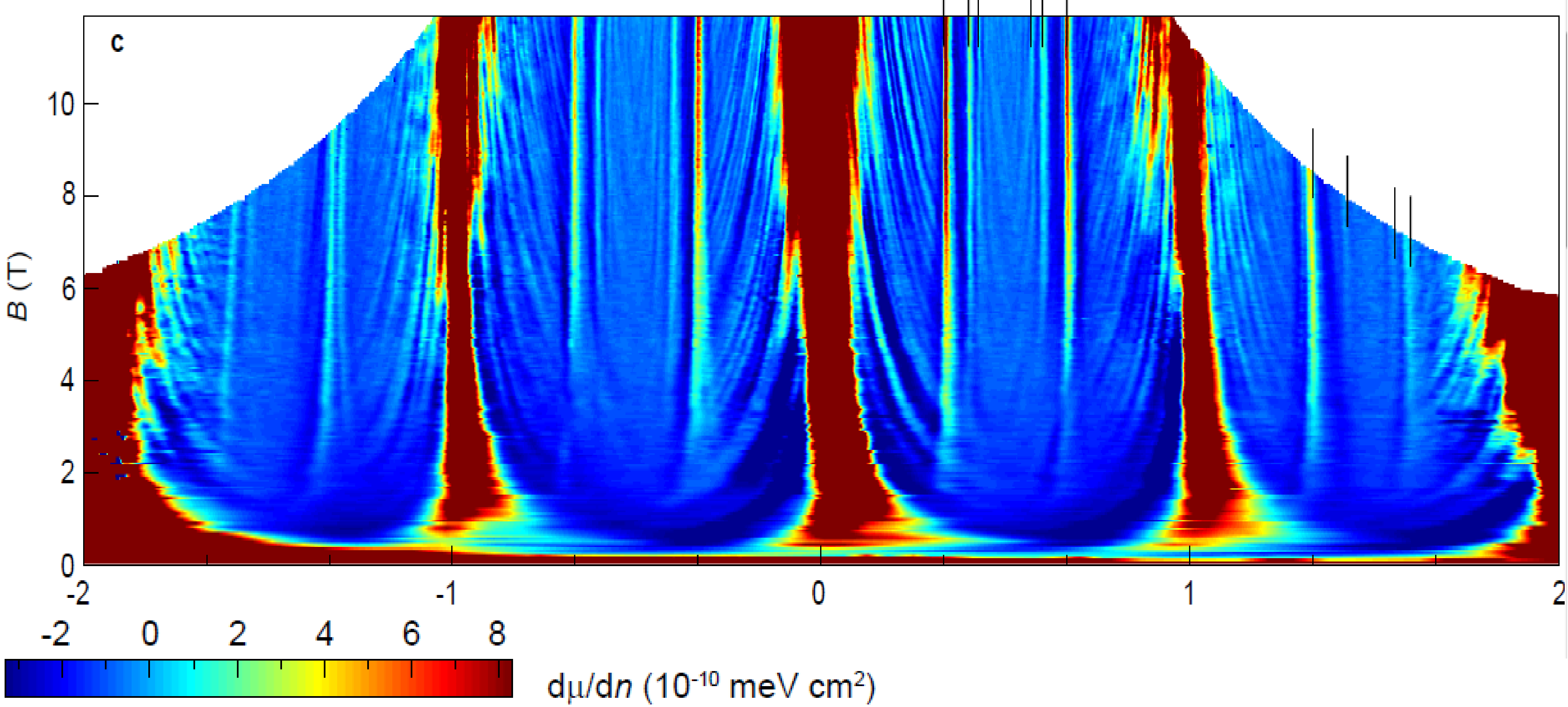


Filling Fraction vs Filling Factor



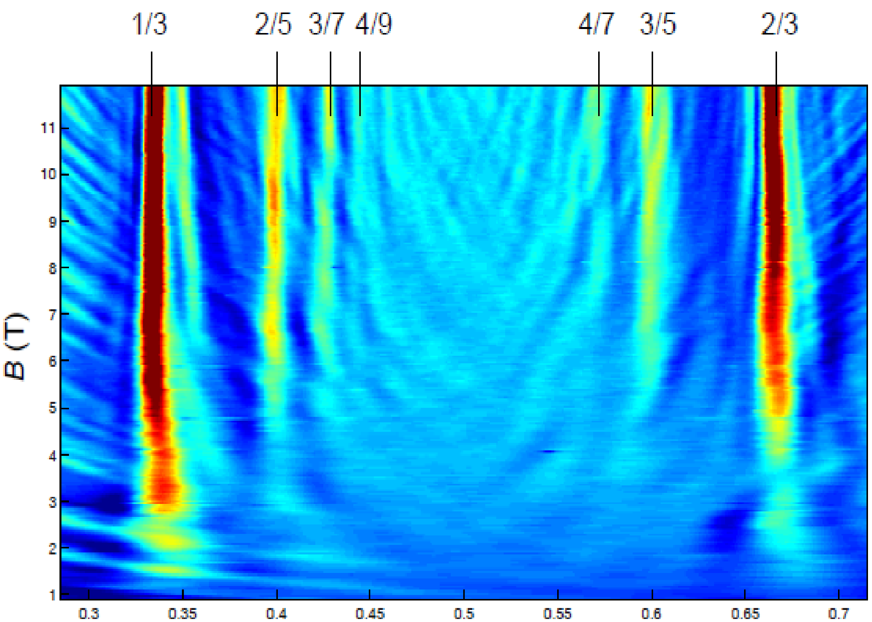
4-fold degeneracy

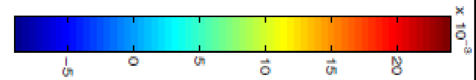
Filling fraction (ff) is analogous to the filling factor in GaAs

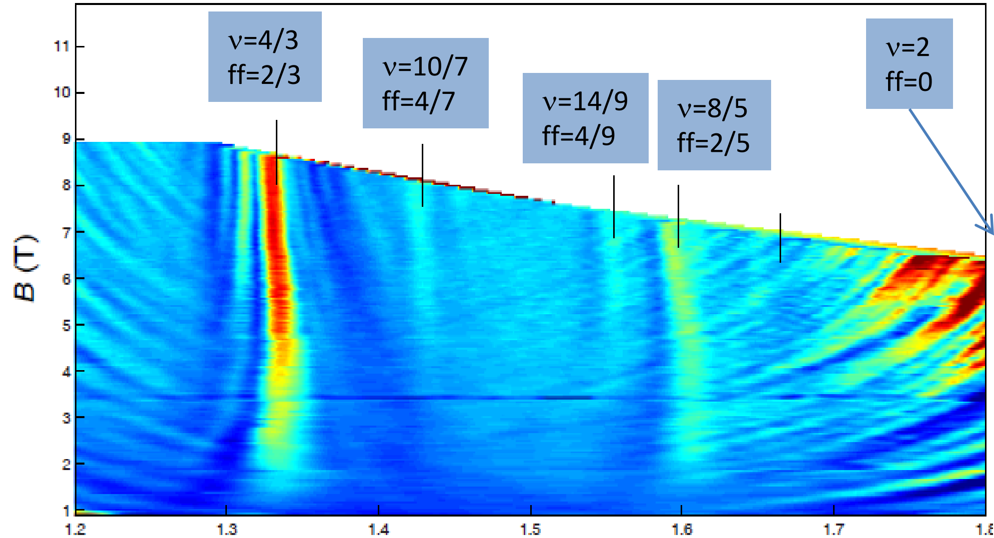


Missing Filling Fractions

$$ff = \frac{p}{2p \pm 1} = \frac{2m}{4m \pm 1}$$





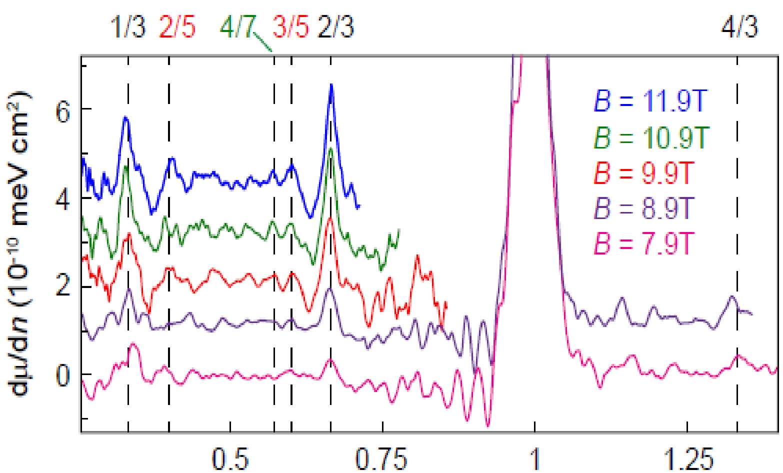


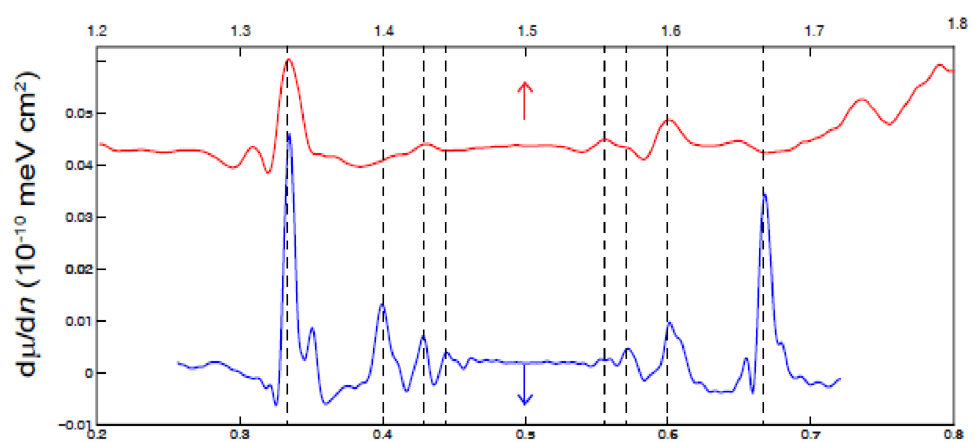
All fractions present ν

Only even numerators ν – Have CF degeneracy's

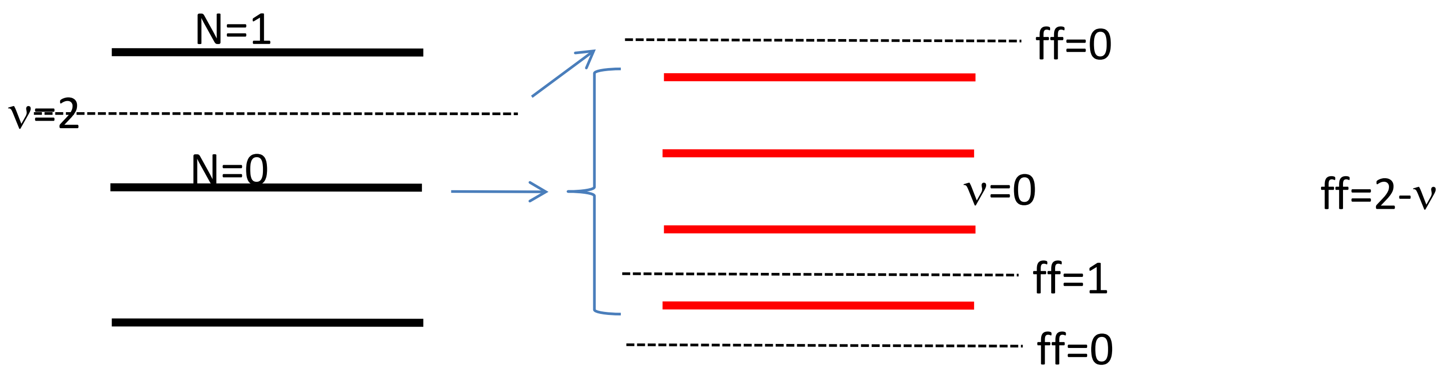
ff=1+(2/3 , 3/5 , 4/7 , 5/9 , … , 4/9, 3/7 , 2/5 , 1/3)

ff= 2/3 , 4/7 , … , 4/9 , 2/5



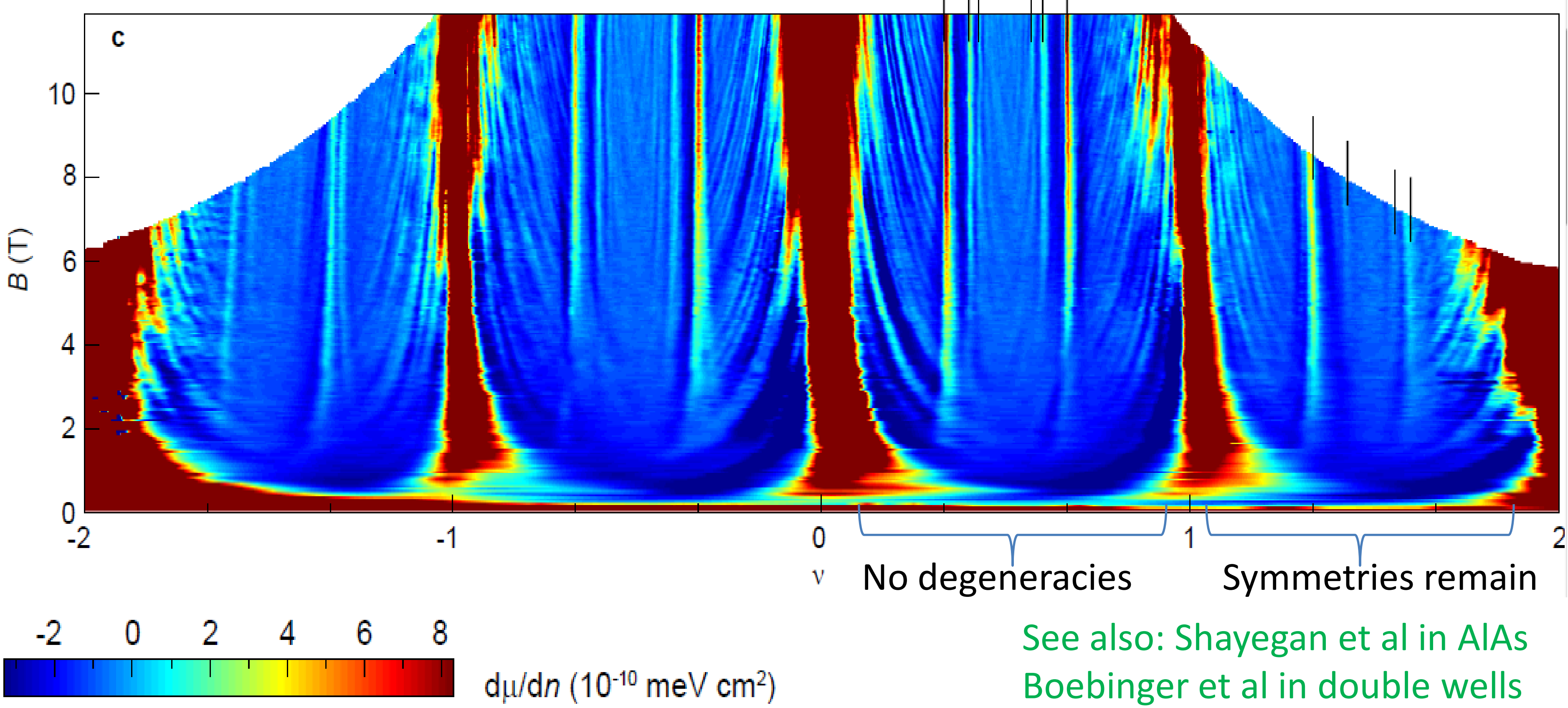


Filling Fraction vs Filling Factor



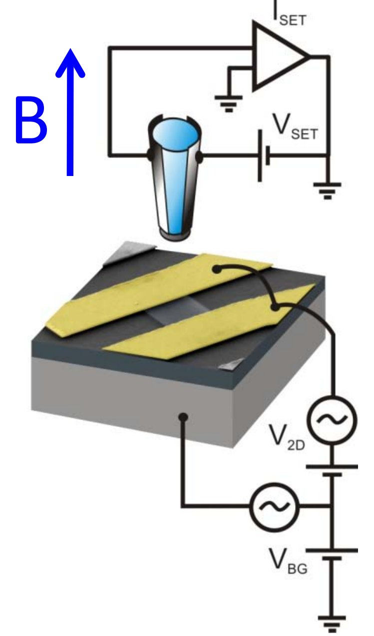
4-fold degeneracy

Filling fraction (ff) is analogous to the filling factor in GaAs



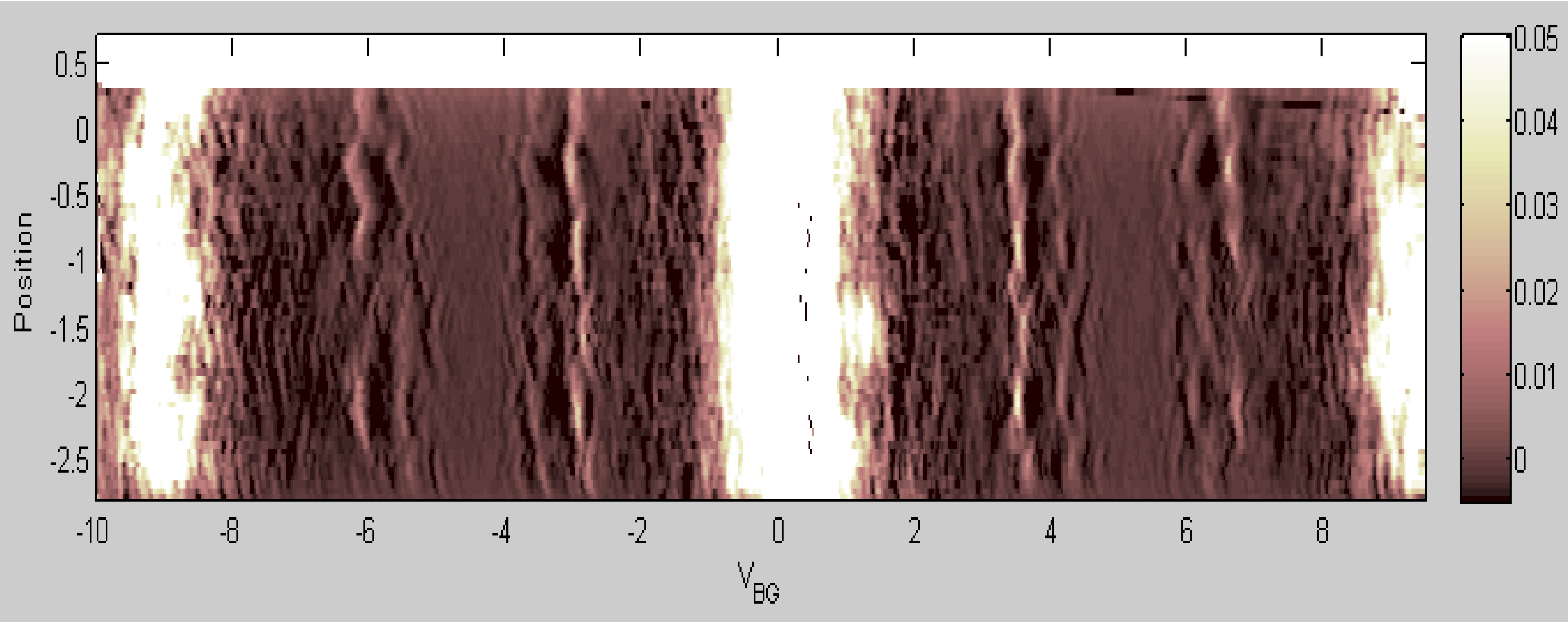
See also: Shayegan et al in AlAs
Boebinger et al in double wells

Spatial Dependence

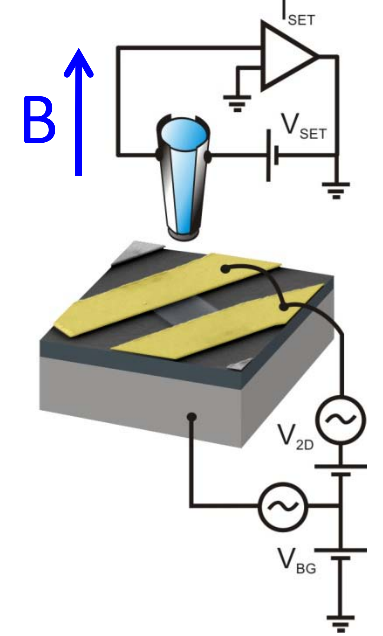


Fractions shift with position

B = 12 T

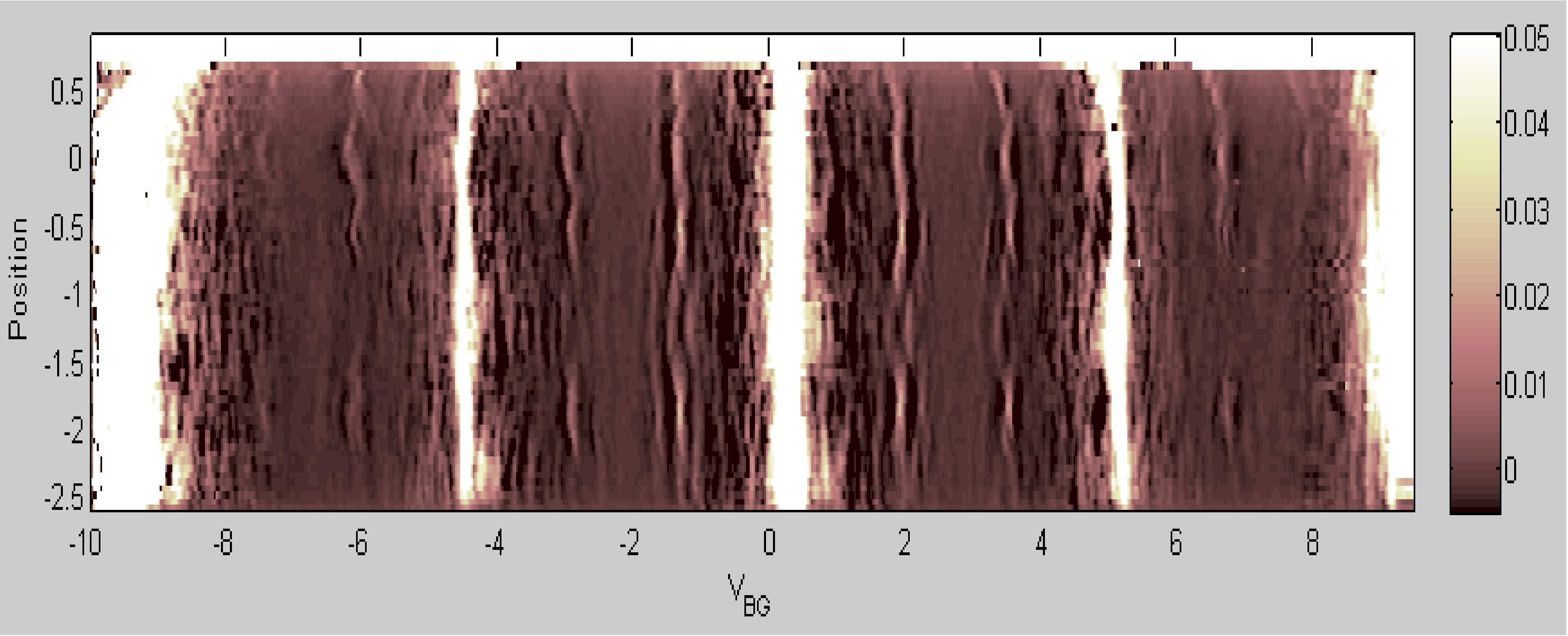


Spatial Dependence



Fractions shift with position

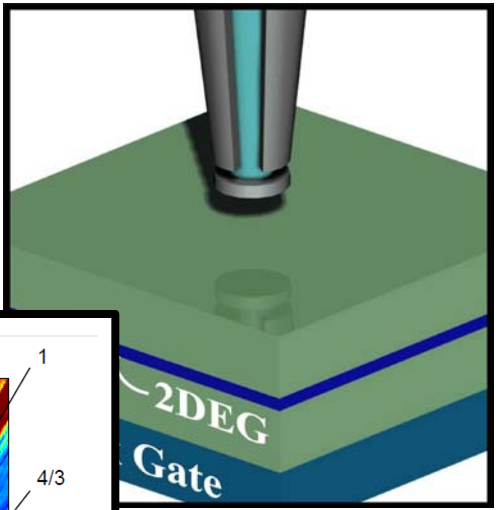
B = 6 T



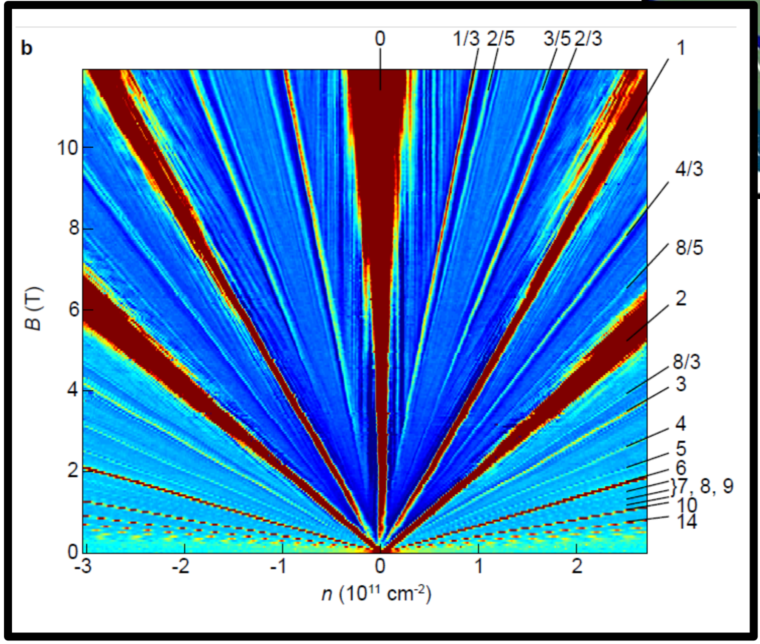
Effects of Interactions in Suspended Graphene

Ben Feldman, Andrei Levin, Amir Yacoby, Harvard University

- Broken and unbroken symmetries in the lowest LL:
  – spin and valley symmetries.
- FQHE



Discussions with Bert Halperin and Dima Abanin



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