Fractional quantum Hall physics in bilayer graphene probed by transconductance fluctuations

POSTECH POHANG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Youngwook Kim, Jun Sung Kim

KIST Korea Institute of Science and Technology

Dong Su Lee

KRISS Korea Institute of Standards and Science

Suyoung Jung

NIMS

T. Taniquchi, K. Watanabe

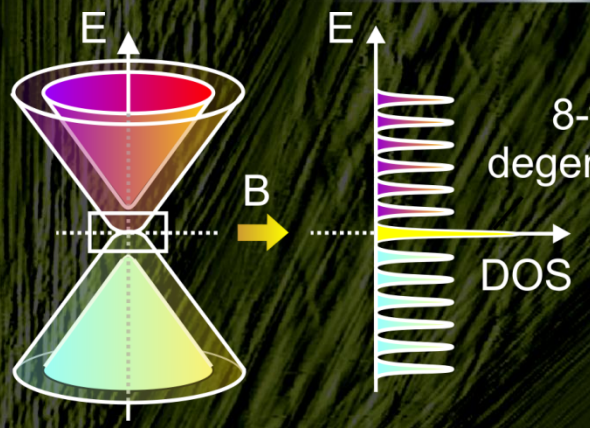
MAX PLANCK INSTITUTE for Solid State Research

Youngwook Kim, V. Skákalová,

J.H. Smet

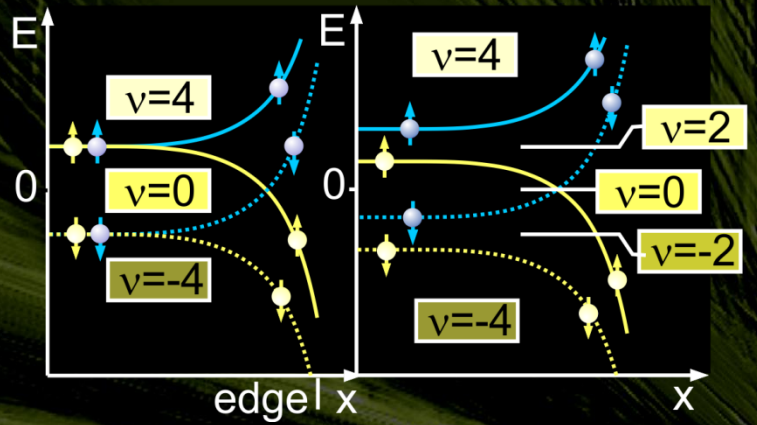
A multitude of inherent symmetries

- spin degeneracy: ↑↓
- valley degeneracy: K, K′
- orbital degeneracy: $E_n = \pm\hbar\omega_c \cdot \sqrt{n \cdot (n-1)}$, $E_0 = E_1 = 0$

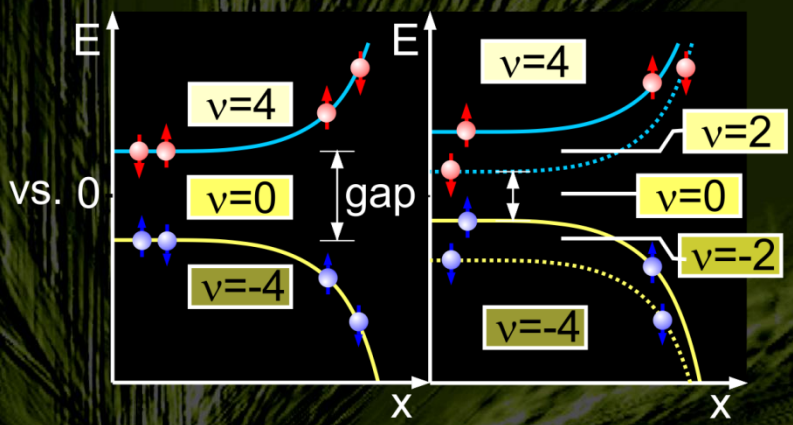


symmetry breaking physics

spin polarization



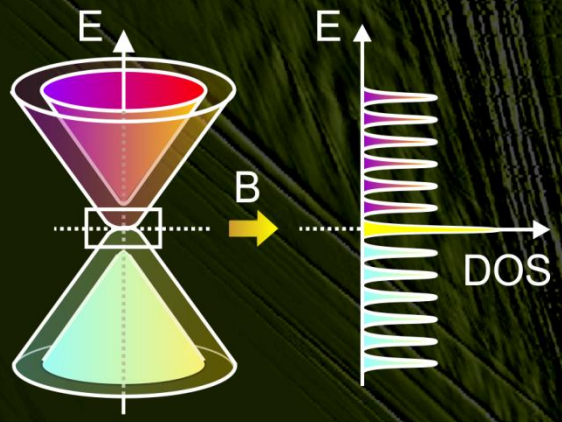
valley polarization



Weitz et al., Science **330**, 812 (2010)
Velasco et al., Nat. Nanotech **7**, 156 (2012)
Lee et al., Science **345**, 58 (2014)

Kim et al., PRL **107**, 016803 (2011)
Maher et al., Nat. Phys. **9**, 154 (2013)

The importance of the orbital index



- spin degeneracy

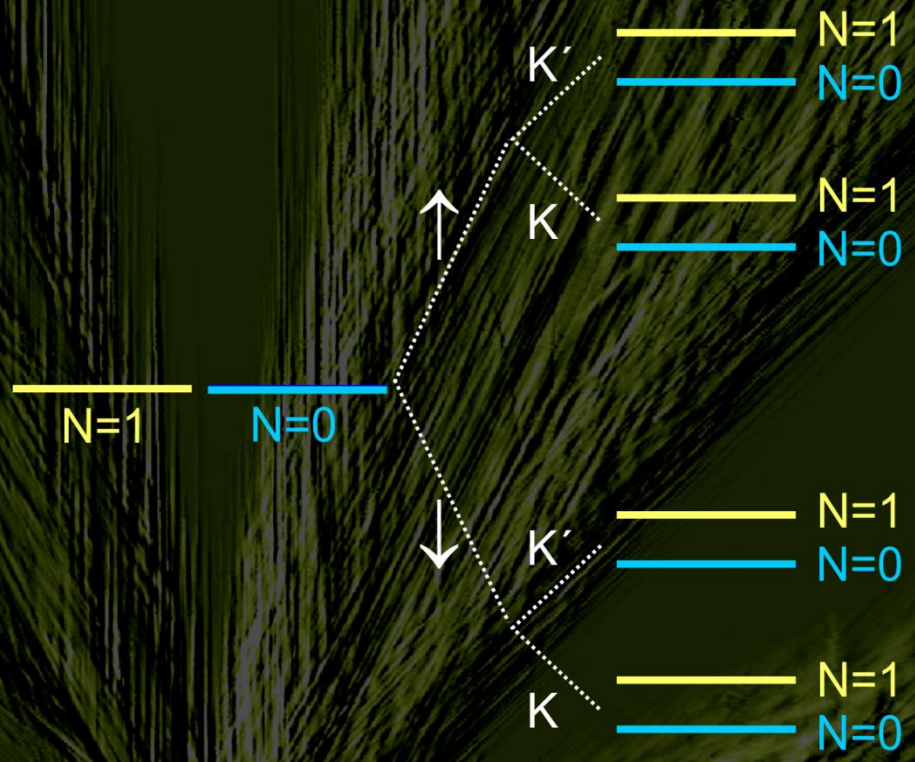
↑↓

- valley degeneracy:

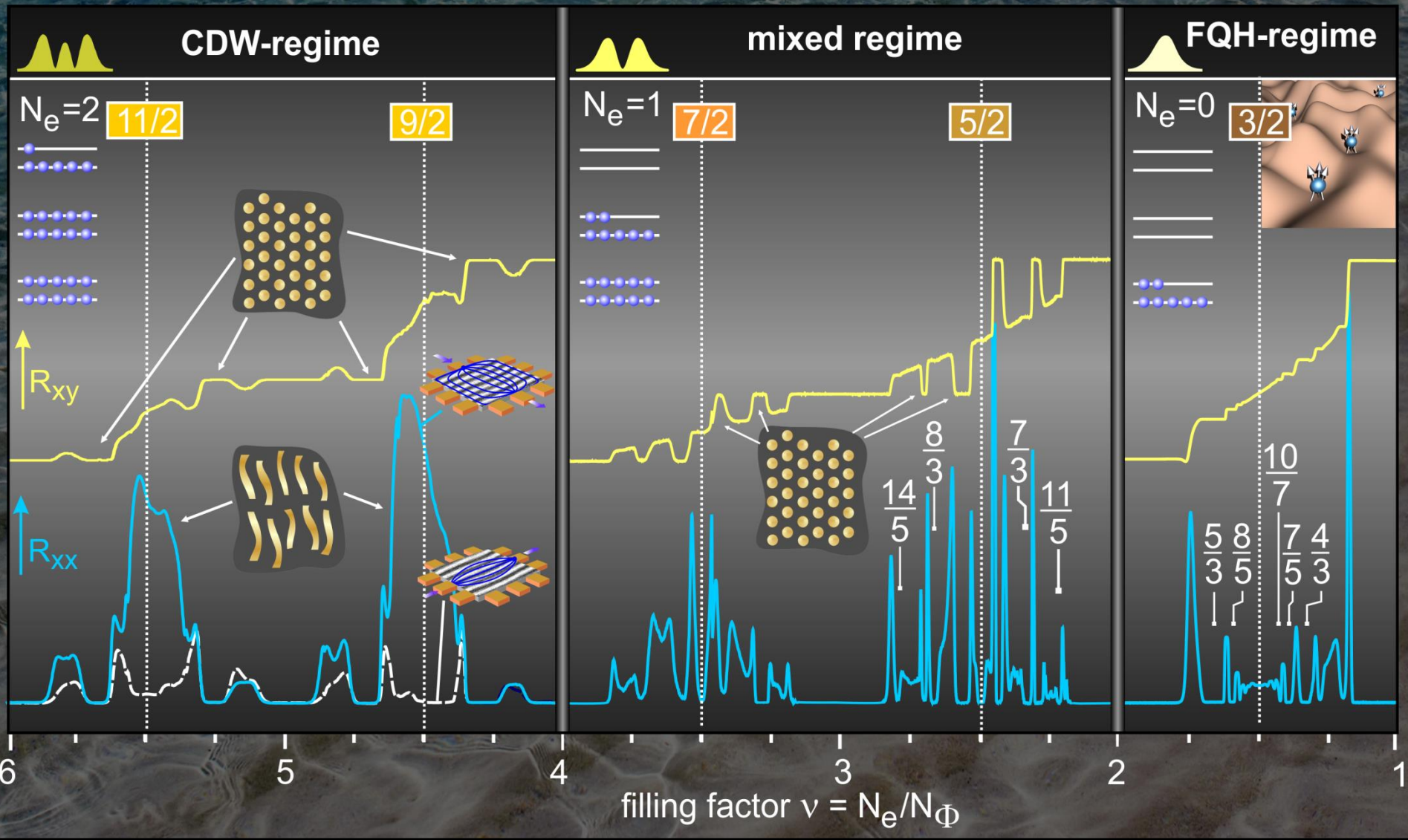
- orbital degeneracy

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

$$E_0 = E_1 = 0$$



The orbital index: the GaAs case



It's all about Pauli exclusion

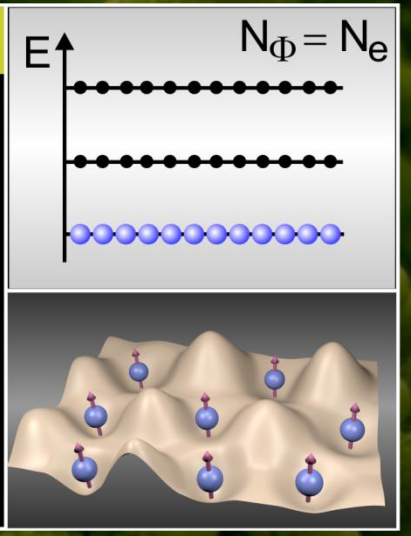
Integer filling 1 many-particle wavefunction

single particle basis function: $\Phi_m(z) = z^m \cdot \exp[-|z|^2/4l_B^2]$

anti-symmetric wave function ➡ Slater determinant

$$\Psi(z_1,\ldots,z_{N_e}) = \begin{vmatrix} 1 & 1 & \cdots & 1 \\ z_1 & z_2 & \cdots & z_{N_e} \\ & & & \\ z_1^{N_e} & z_2^{N_e} & \cdots & z_{N_e}^{N_e} \end{vmatrix} \cdot \prod_j^{N_e} \exp\left(\frac{-|z_j|^2}{4l_B^2}\right) = \prod_{j<k}^{N_e}(z_j - z_k) \cdot \prod_j^{N_e} \exp\left(\frac{-|z_j|^2}{4l_B^2}\right)$$

Pauli exclusion



Fractional quantum Hall state 1/3

$2 \cdot N_e$ extra vortices or zeroes in the wave function

$$\Psi(z_1,\ldots,z_{N_e}) = \prod_{j<k}^{N_e}(z_j - z_k) \cdot \prod_k (z_1 - a_k) \cdots \prod_k (z_{N_e} - a_k) \cdot \prod_j^{N_e} \exp\left(\frac{-|z_j|^2}{4l_B^2}\right)$$

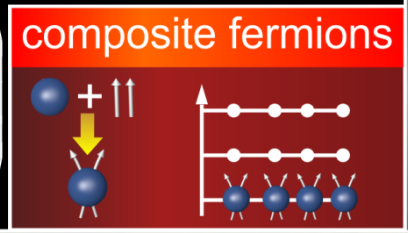
where ???

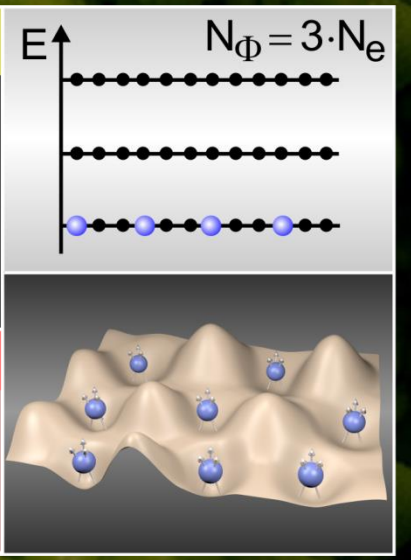
Pauli exclusion

$$= \prod_{<k}^{N_e}(z_j - z_k) \cdot \prod_{j<k}^{N_e}(z_j - z_k)^2 \cdot \prod_j^{N_e} \exp\left(\frac{-|z_j|^2}{4l_B^2}\right)$$

vortex-particle correlation

composite fermions

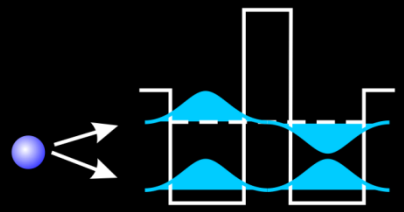


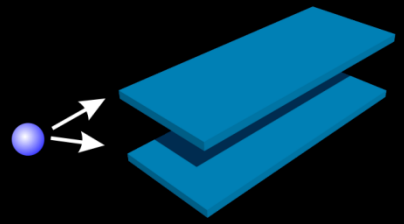


Outwitting Pauli exclusion

Two-component systems: filling 1/2 & 3/2

- subband degree of freedom
- layer degree of freedom

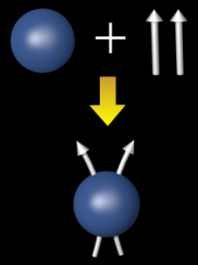




$$\Psi_{331} = \prod_{i<j}(z_{i,t} - z_{j,t})^3 \cdot \prod_{i<j}(z_{i,b} - z_{j,b})^3 \cdot \prod_{i,j}(z_{i,t} - z_{j,b}) \cdot \prod_{j} \exp\left(\left(-|z_{j,b}|^2 - |z_{j,t}|^2\right)/4l_B^2\right)$$

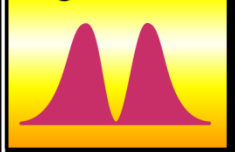
Even-denominator FQH states: conversion to Bosons

$N_e=0$



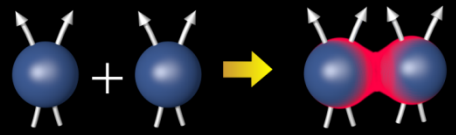
weak residual interaction

$N_e=1$

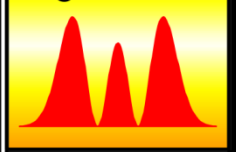


overscreening

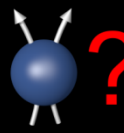
attractive residual interaction



$N_e=2$



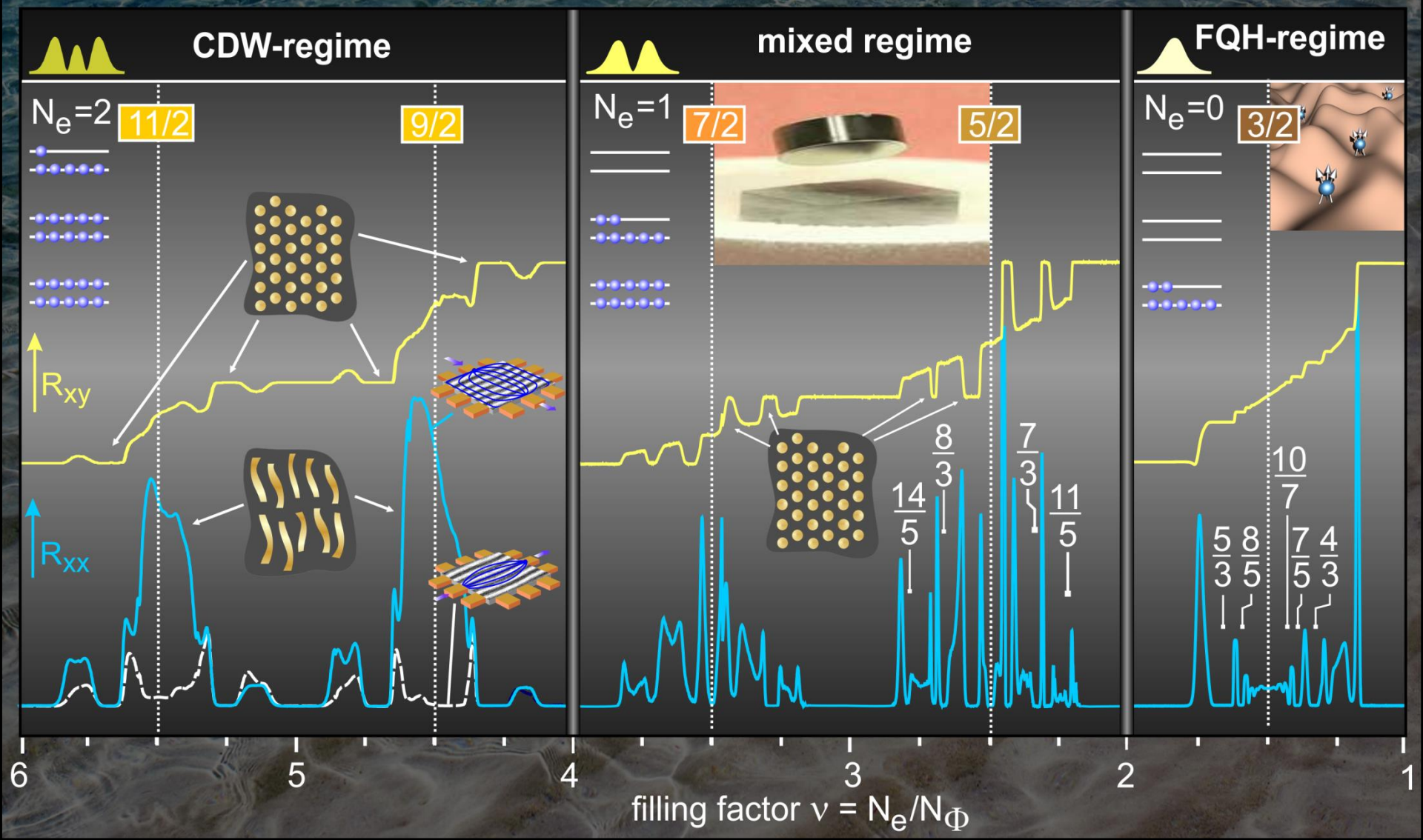
large overscreening



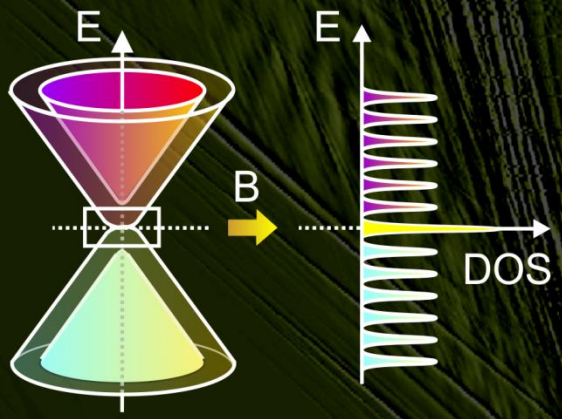
validity CF model?

V.W. Scarola, K. Park, J.K. Jain, *Nature* **406**, 863 (2000)

Even-denominator FQHE



Cool playground



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↑↓

- valley degeneracy:

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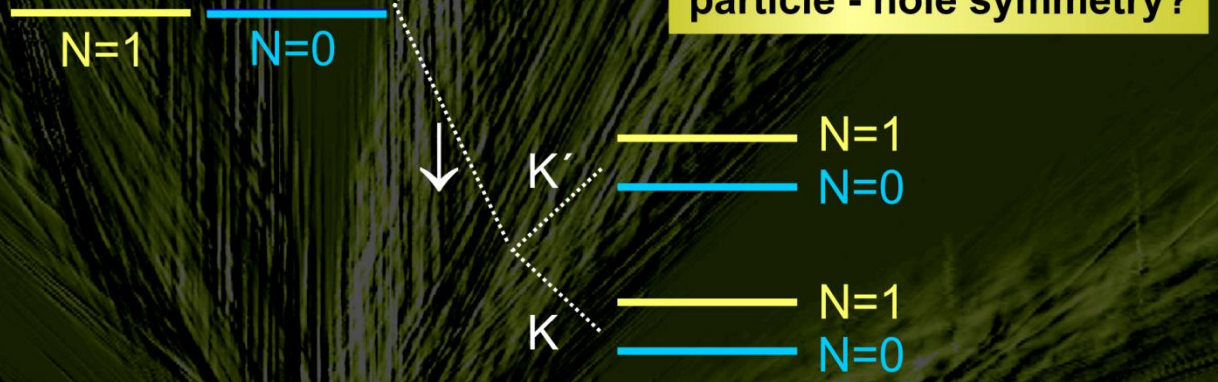
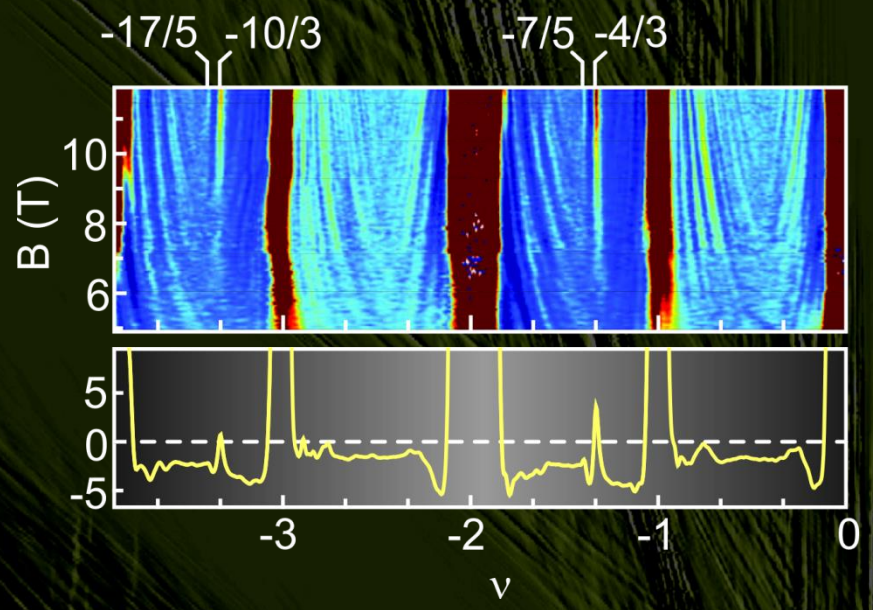
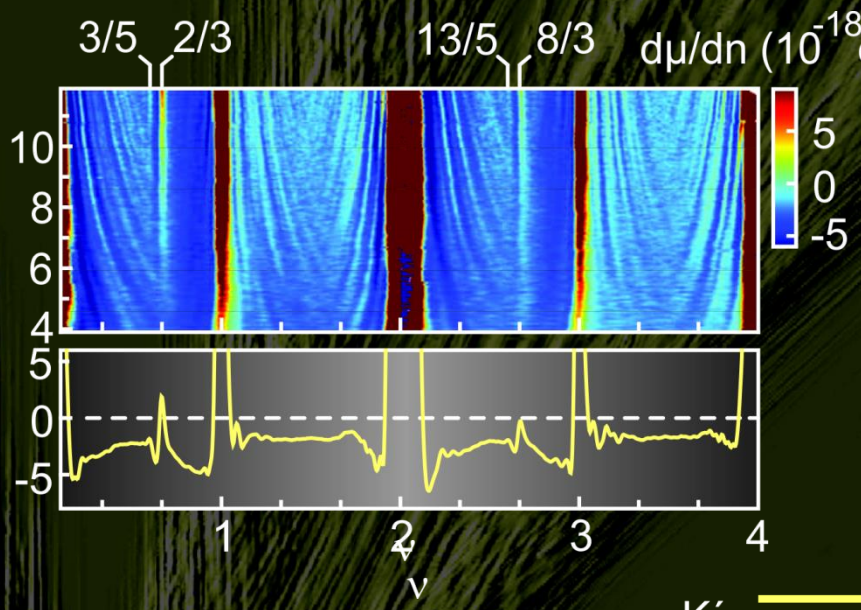


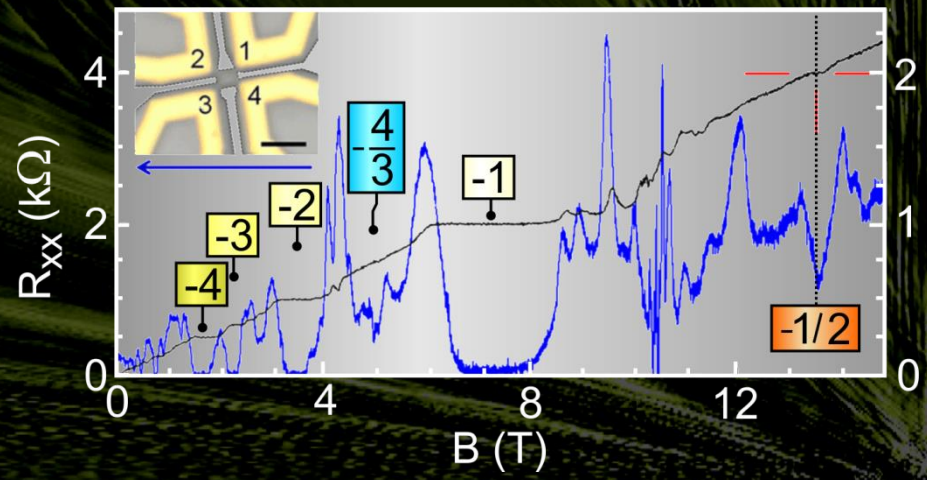
particle - hole symmetry?

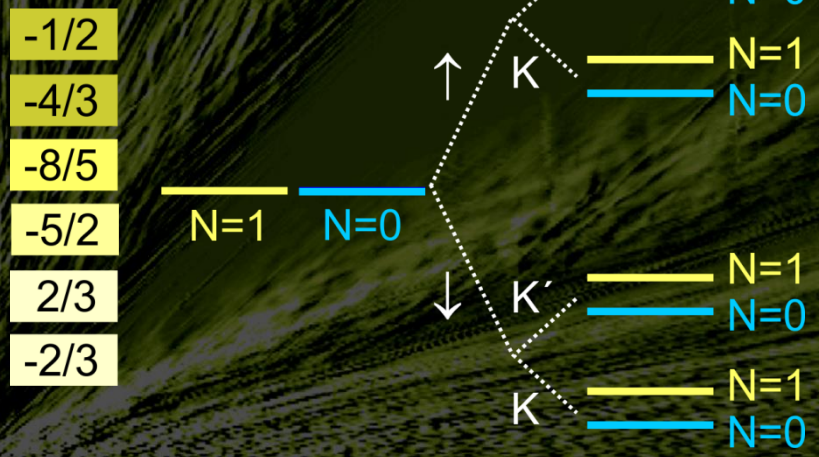
Reported results

- Kou et al., Science **345**, 55 (2014)
- Ki et al., Nano Lett. **14**, 2135 (2014)
- Maher et al., Science **345**, 6192 (2014)

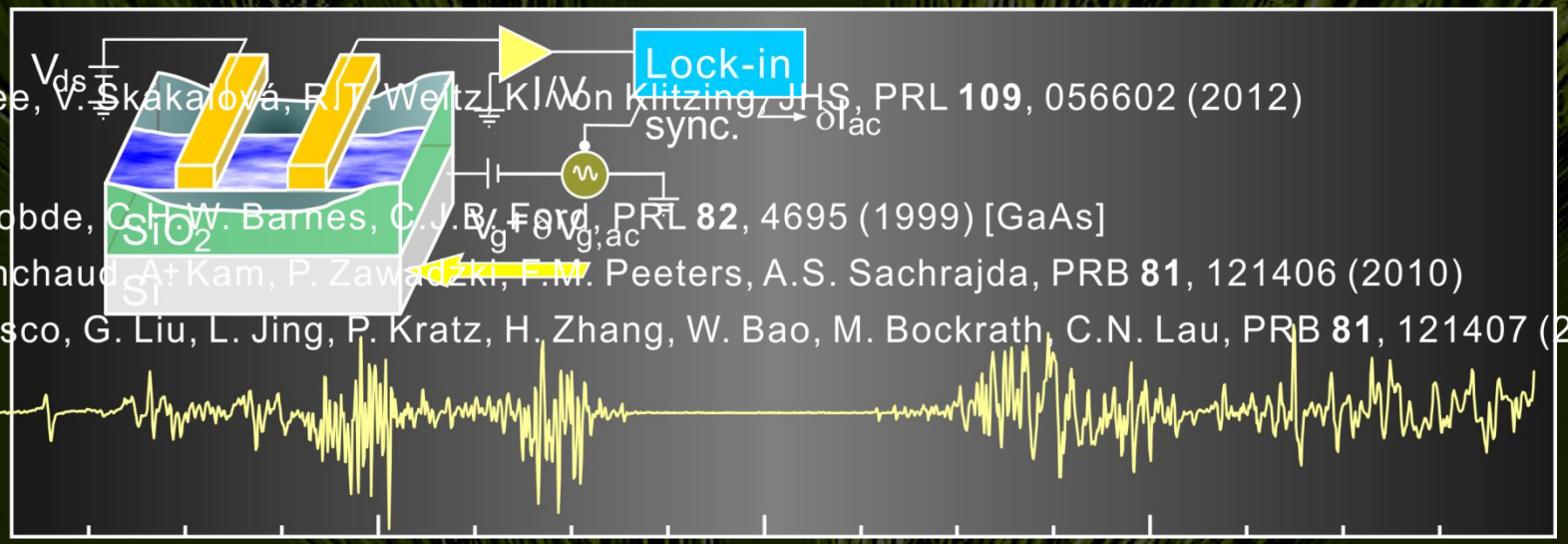


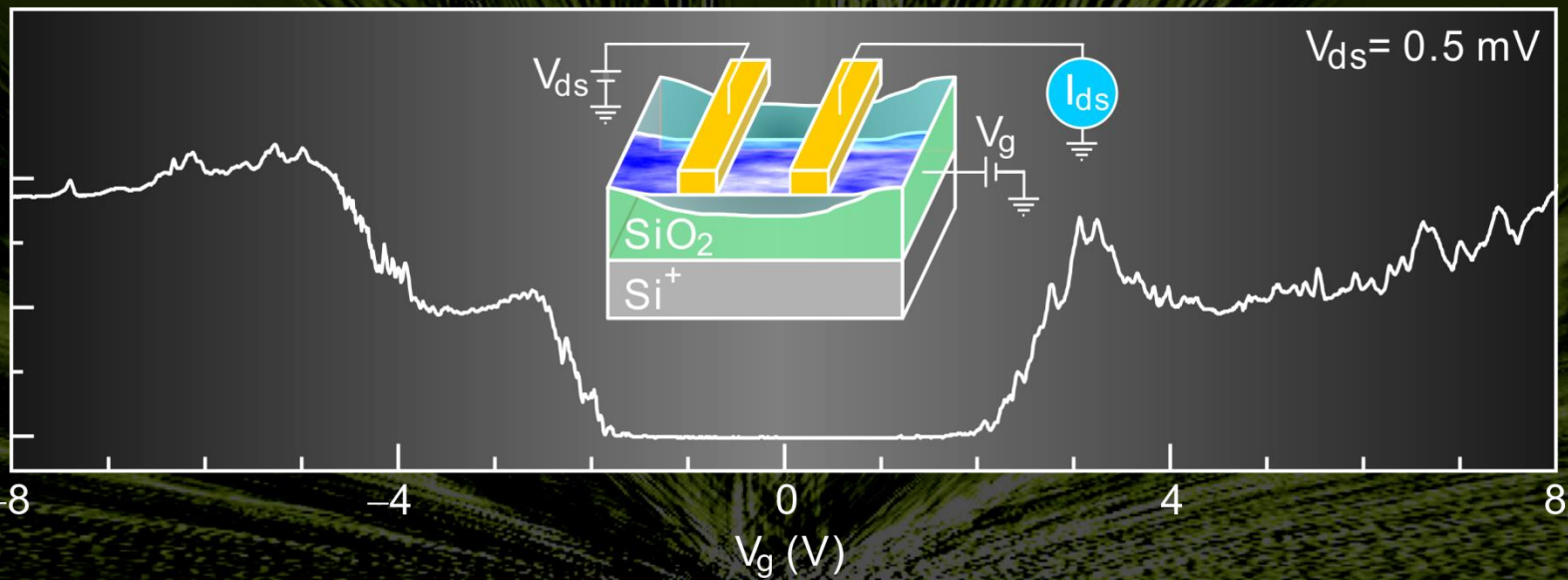




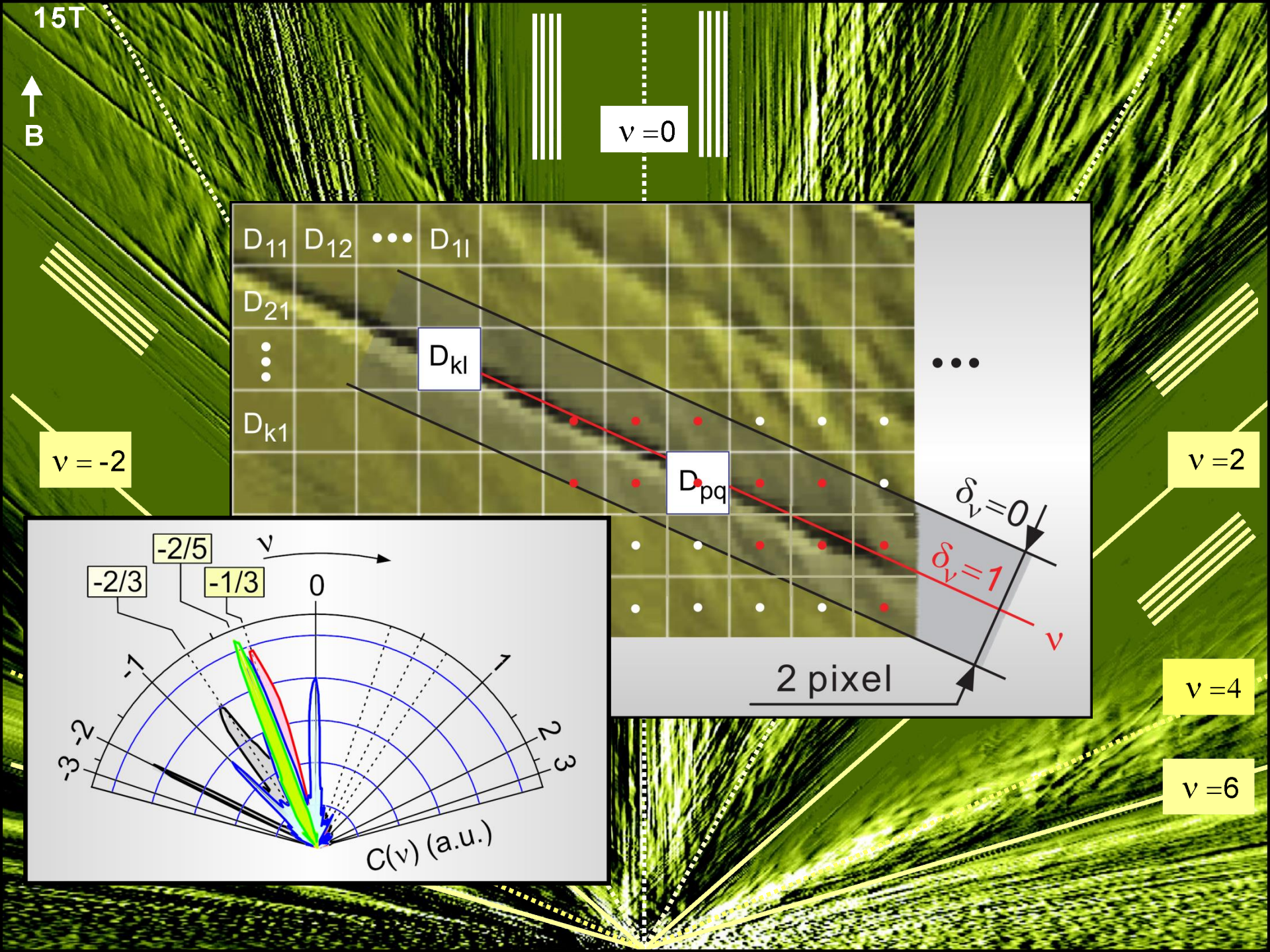


Transconductance fluctuations





- D.S. Lee, V. Skákalová, R.T. Weitz, K. von Klitzing, J.H. Smet, PRL **109**, 056602 (2012)
- D.H. Cobde, C.H.W. Barnes, C.J.B. Ford, PRL **82**, 4695 (1999) [GaAs]
- S. Branchaud, A. Kam, P. Zawadzki, F.M. Peeters, A.S. Sachrajda, PRB **81**, 121406 (2010)
- J. Velasco, G. Liu, L. Jing, P. Kratz, H. Zhang, W. Bao, M. Bockrath, C.N. Lau, PRB **81**, 121407 (2010).


15T
B
ν =0
ν = -2
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Dk1
Dpq
δν=0
δν=1
ν
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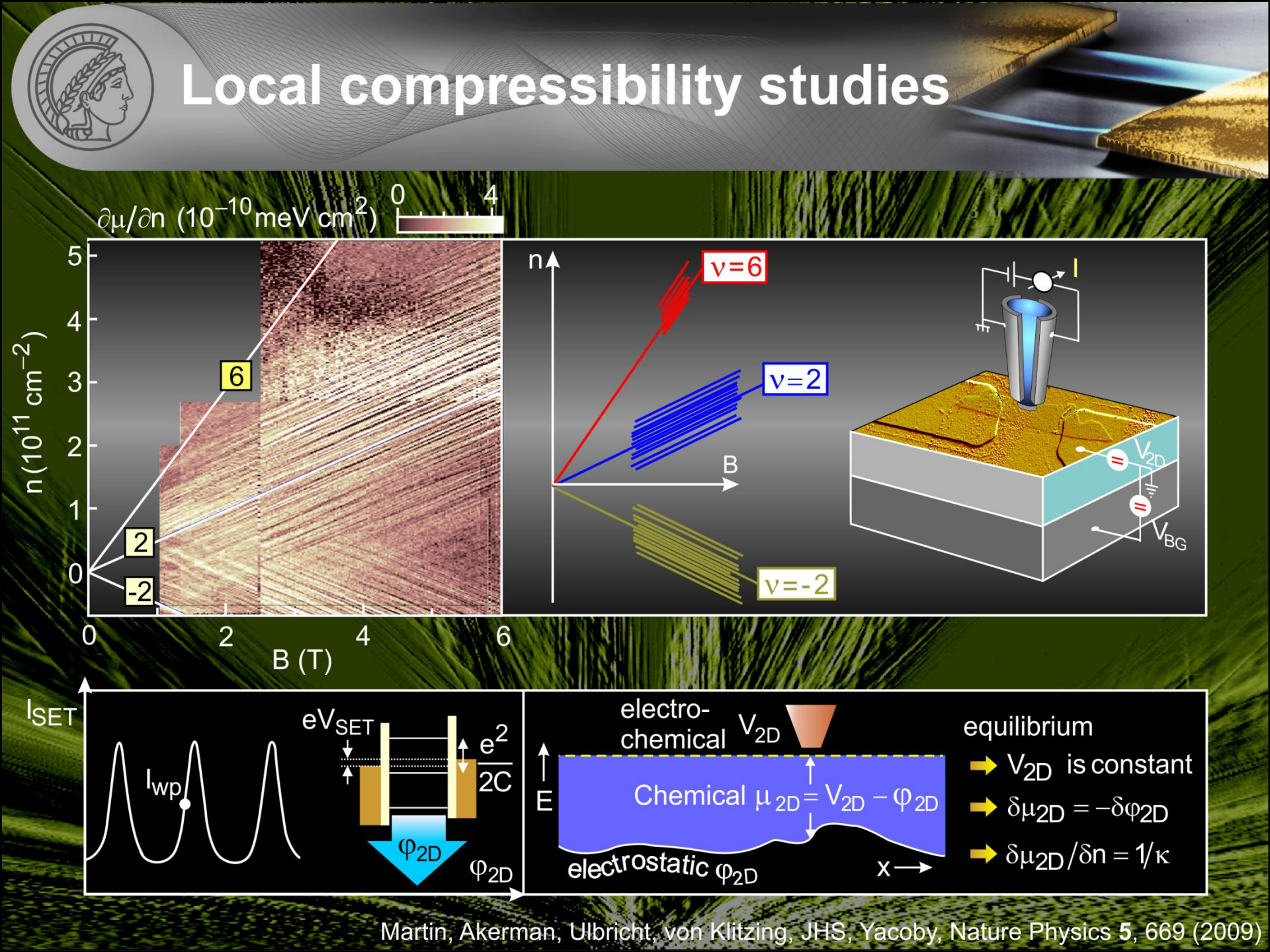
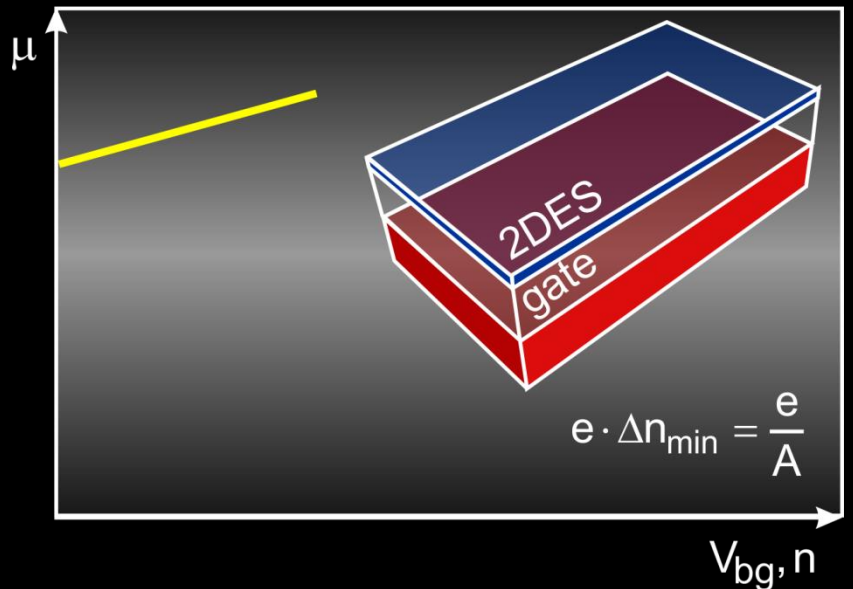
-1
-2
-3
1
2
3
C(ν) (a.u.)

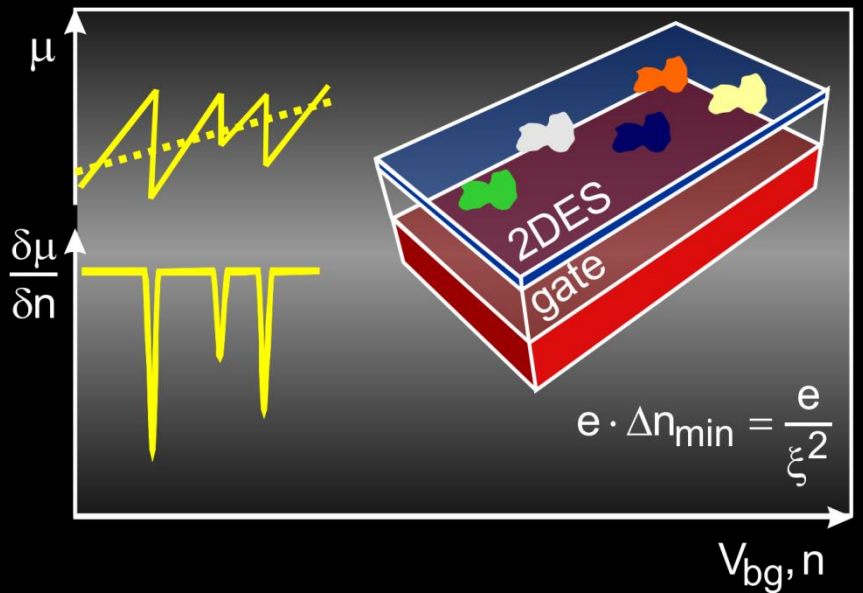
Local compressibility studies

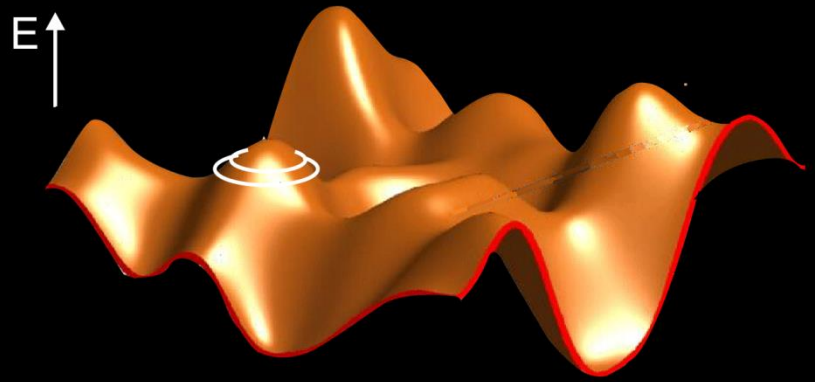


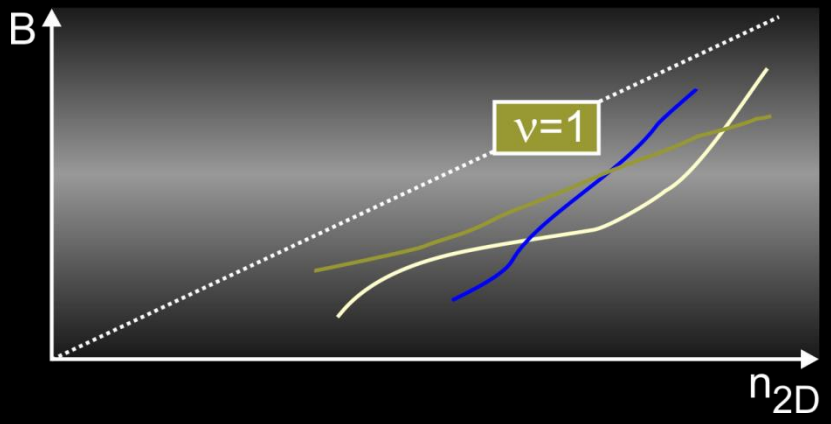
Martin, Akerman, Ulbricht, von Klitzing, JHS, Yacoby, Nature Physics **5**, 669 (2009)

Localization physics

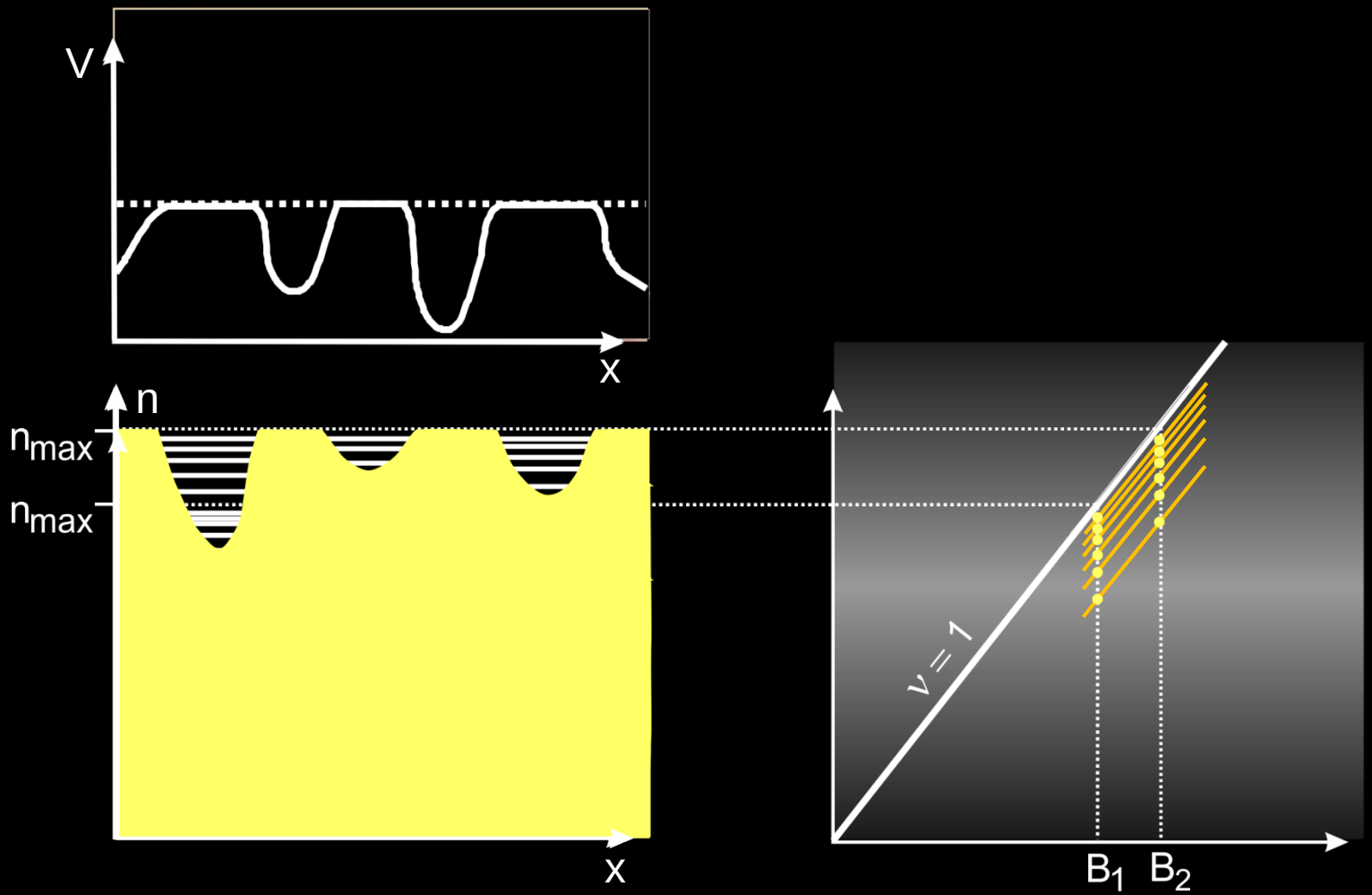




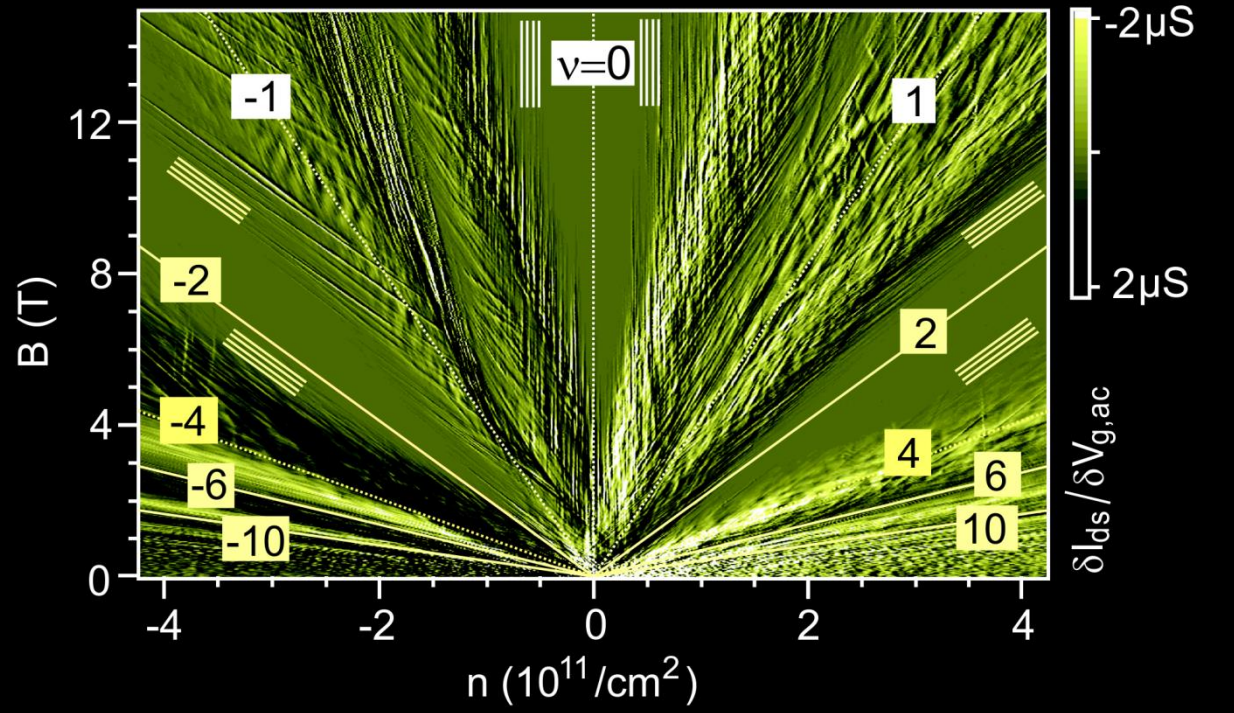


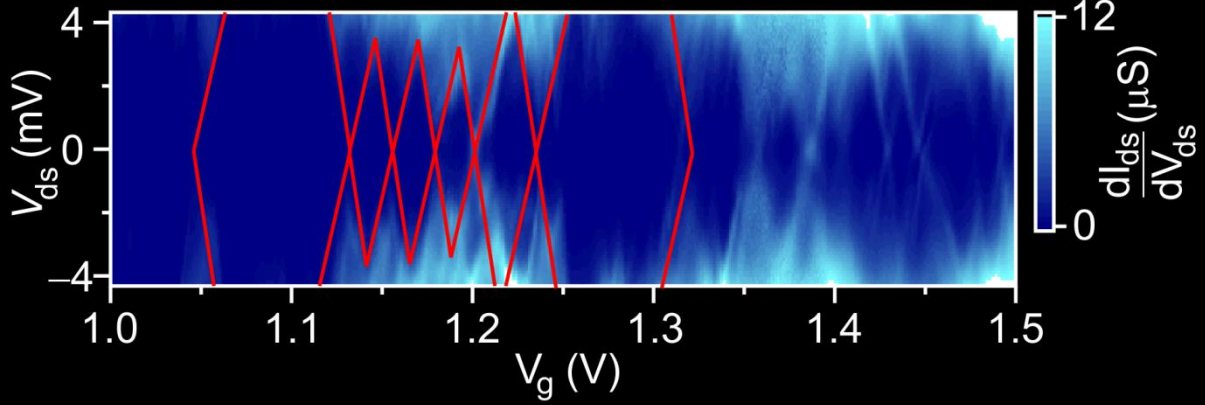


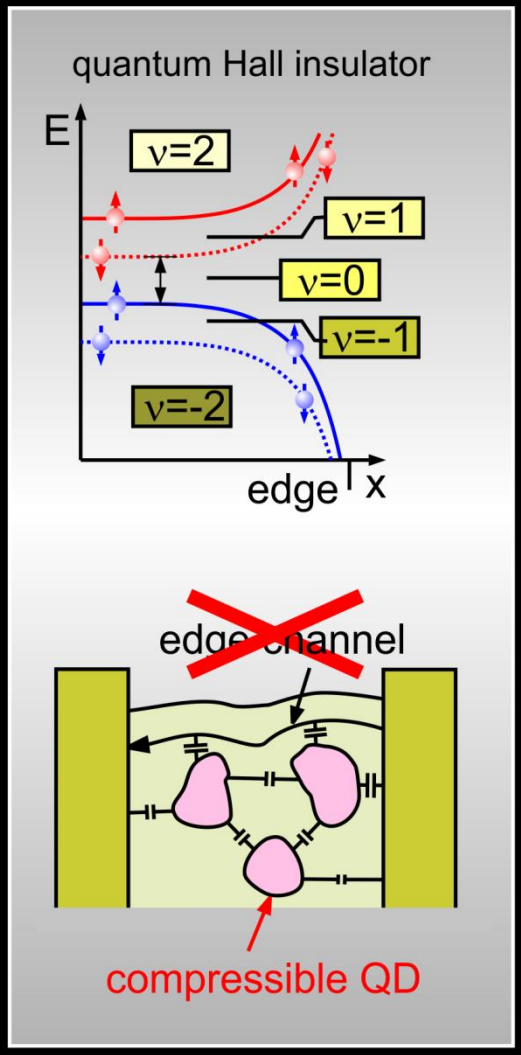
Localization and non-linear screening

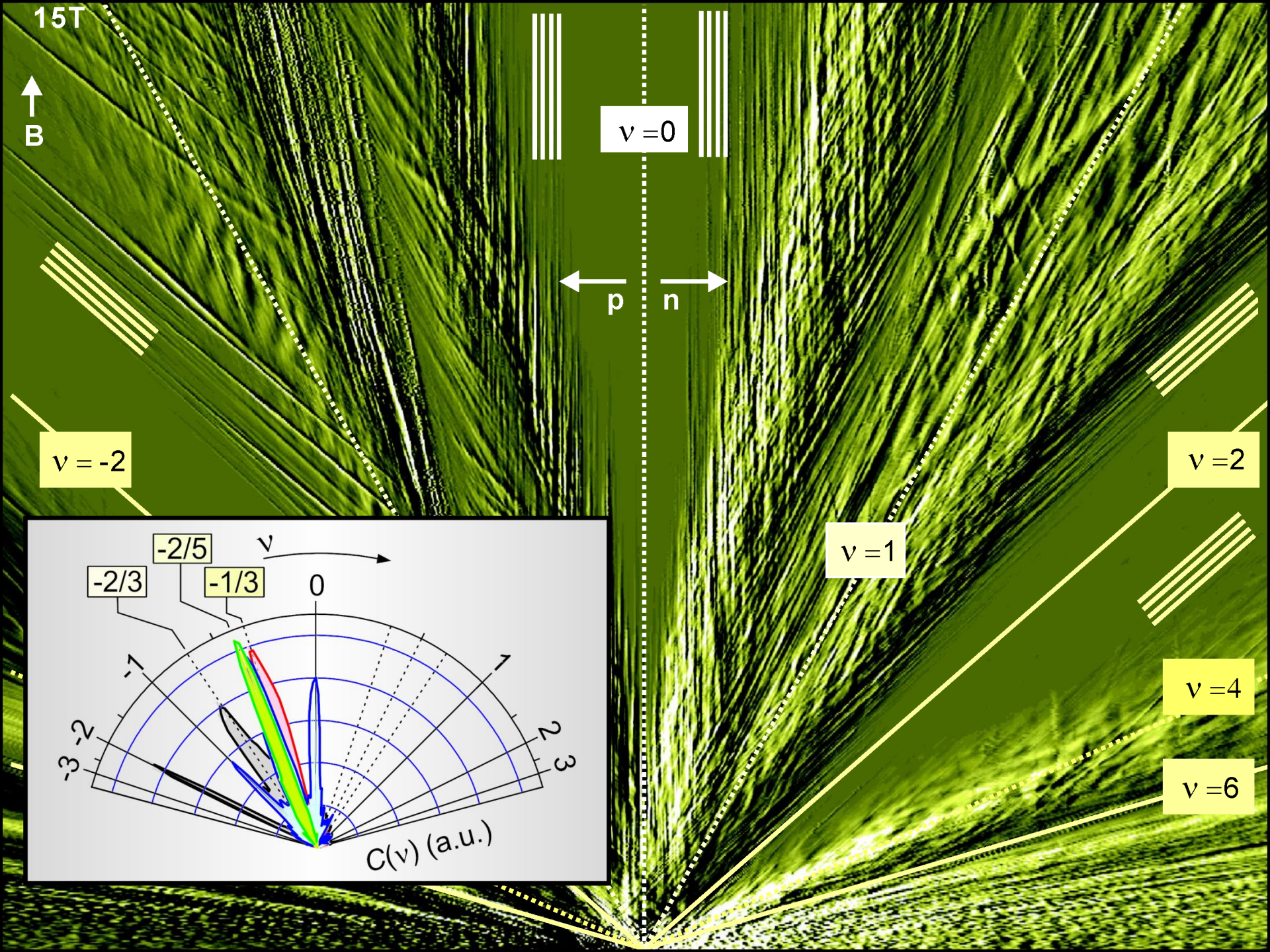


Transport through a dot network








15T
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ν = -2
ν =2
ν =1
ν =4
ν =6
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-2/3
-1/3
ν
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-1
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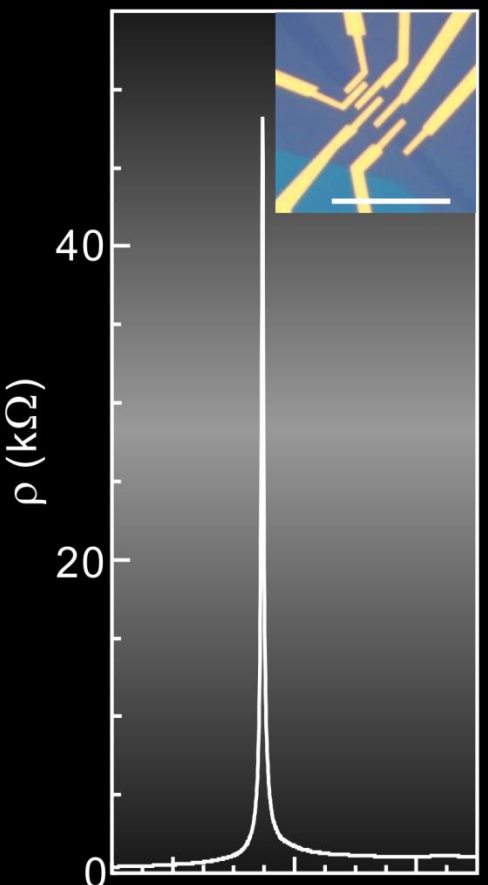
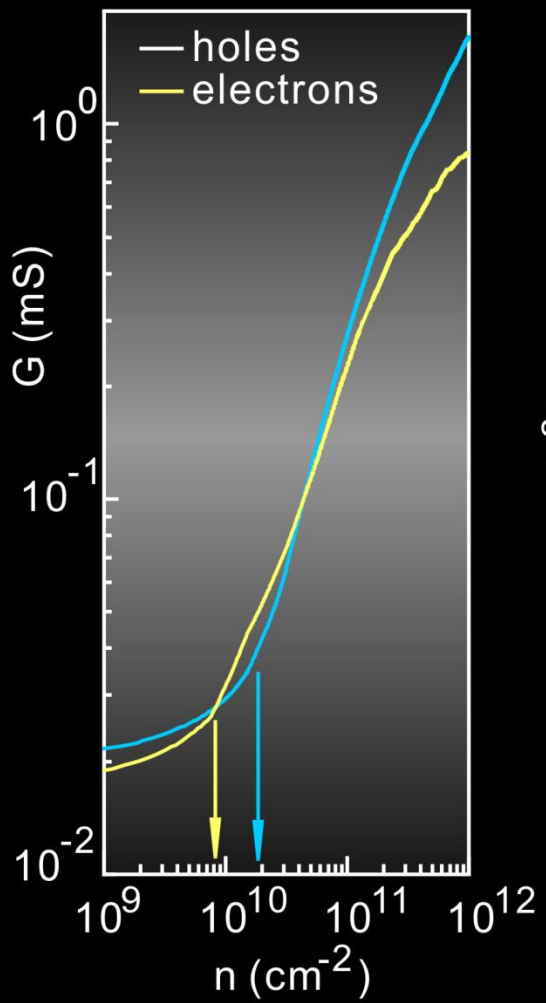
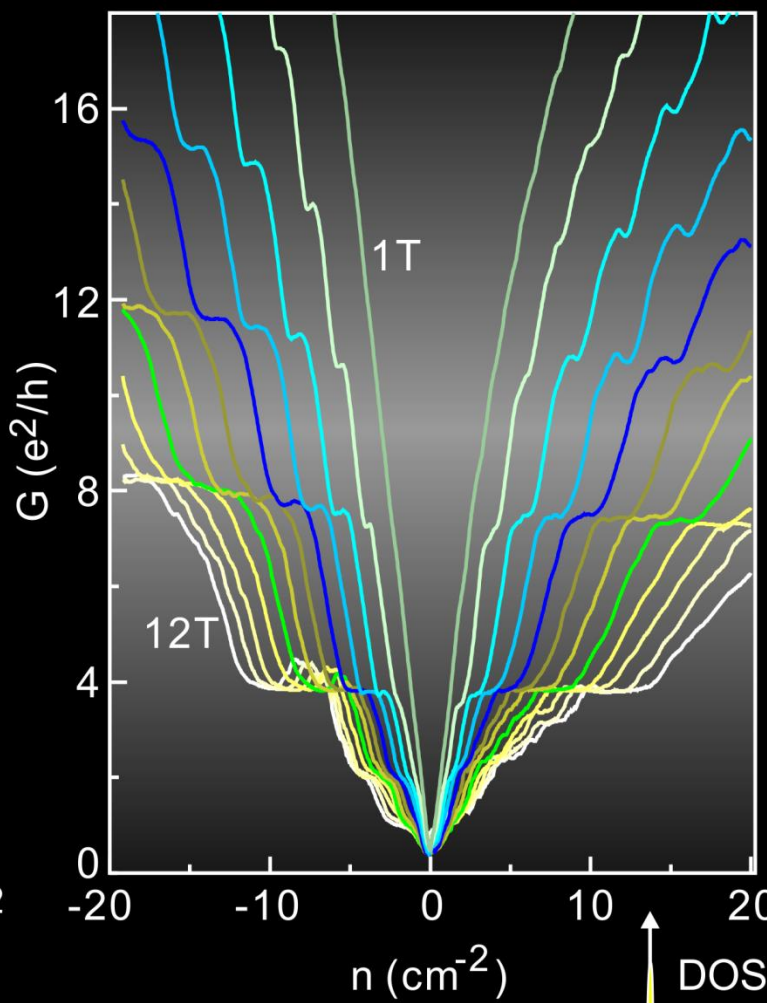
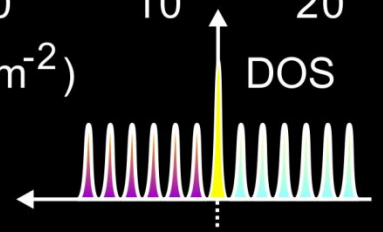
-3
-2
2
3
C(ν) (a.u.)

hBN/bilayer graphene/hBN device

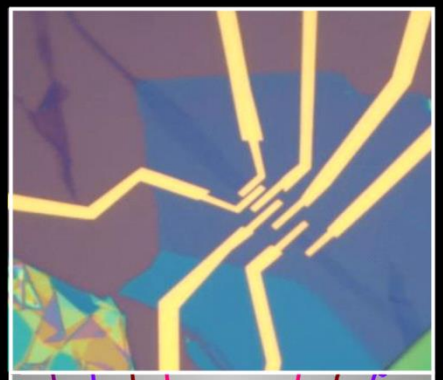


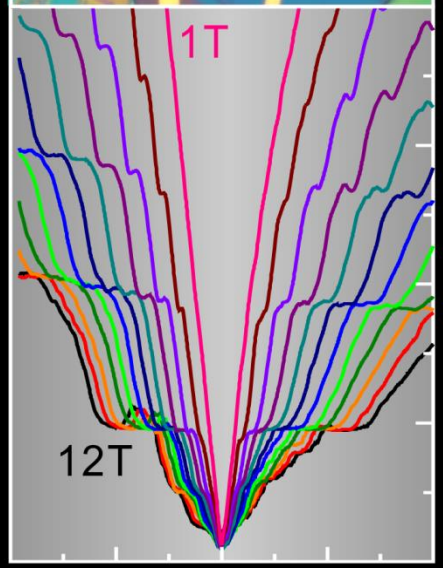


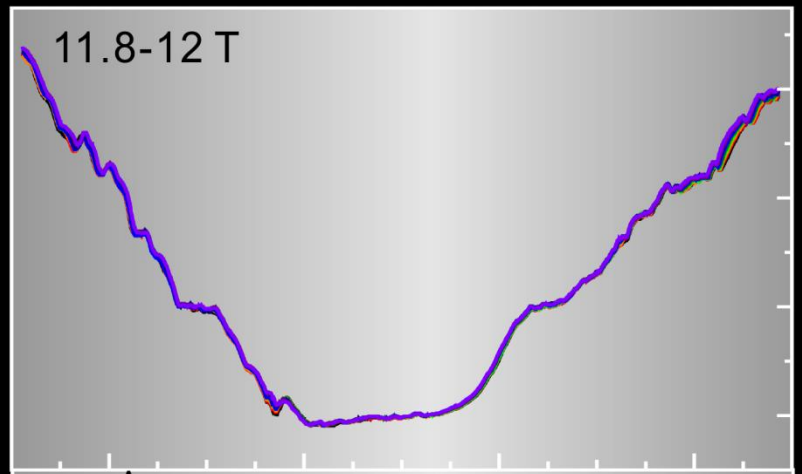


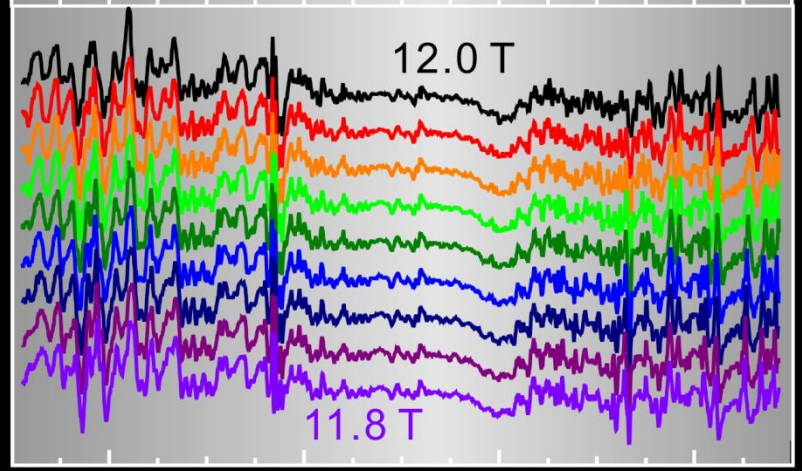


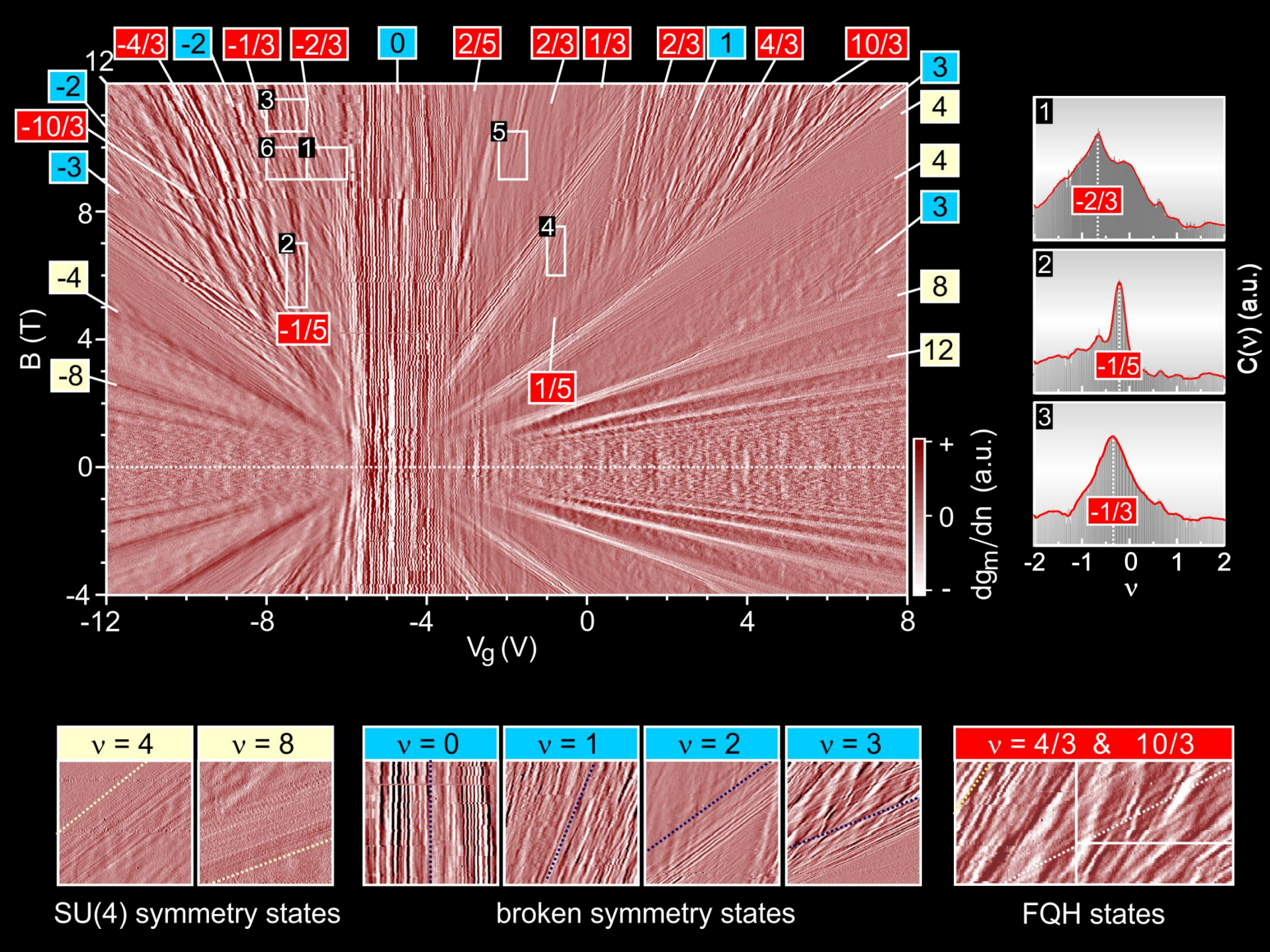
Transconductance fluctuations in bilayer graphene







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B (T)
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-8
-4
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Vg (V)
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6
1
5
4
2
-1/5
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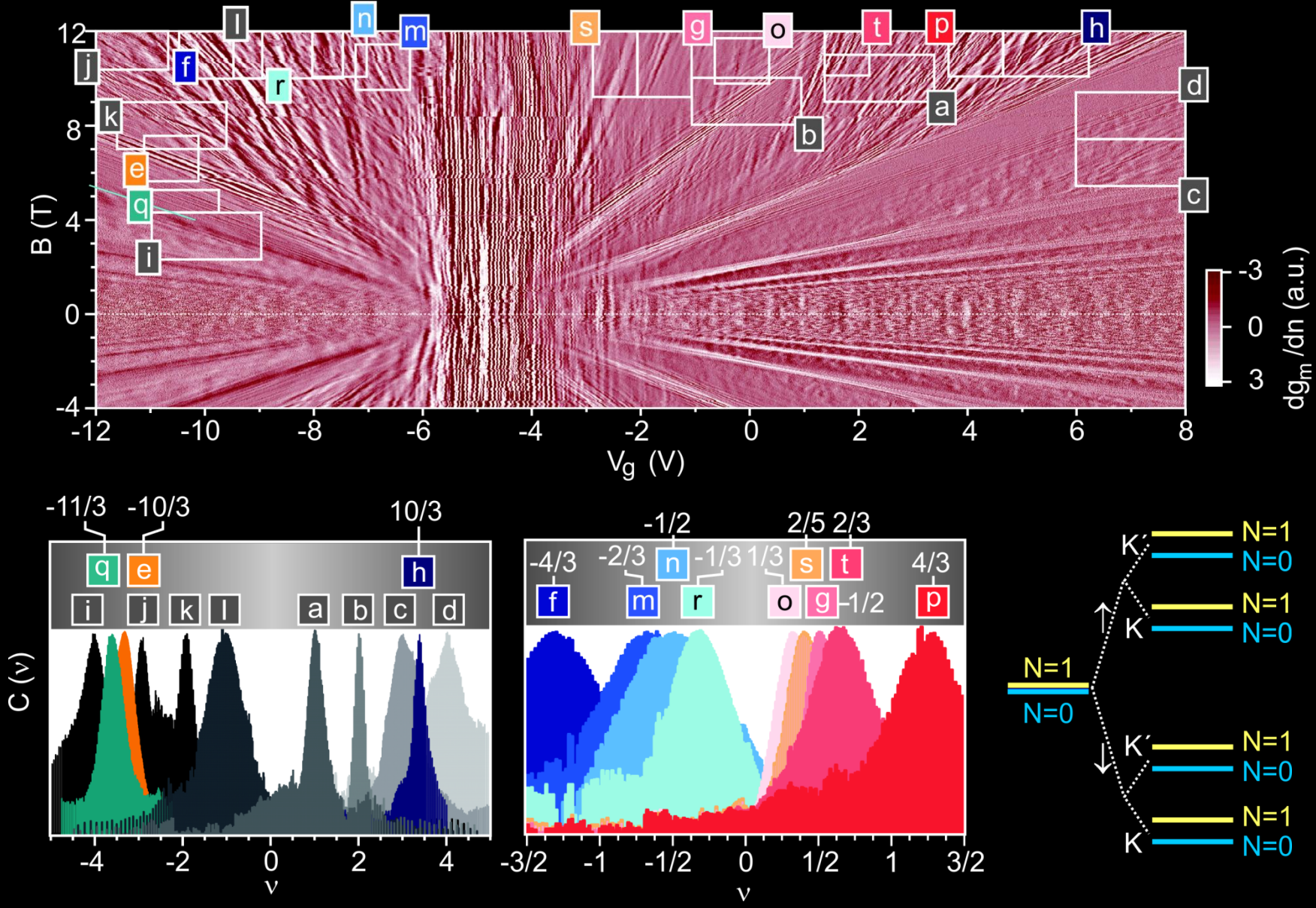
+
0
-
dgm/dn (a.u.)
1
-2/3
2
-1/5
3
-1/3
-2
-1
0
1
2
ν
C(ν) (a.u.)
ν = 4
ν = 8
SU(4) symmetry states
ν = 0
ν = 1
ν = 2
ν = 3
broken symmetry states
ν = 4/3 & 10/3
FQH states



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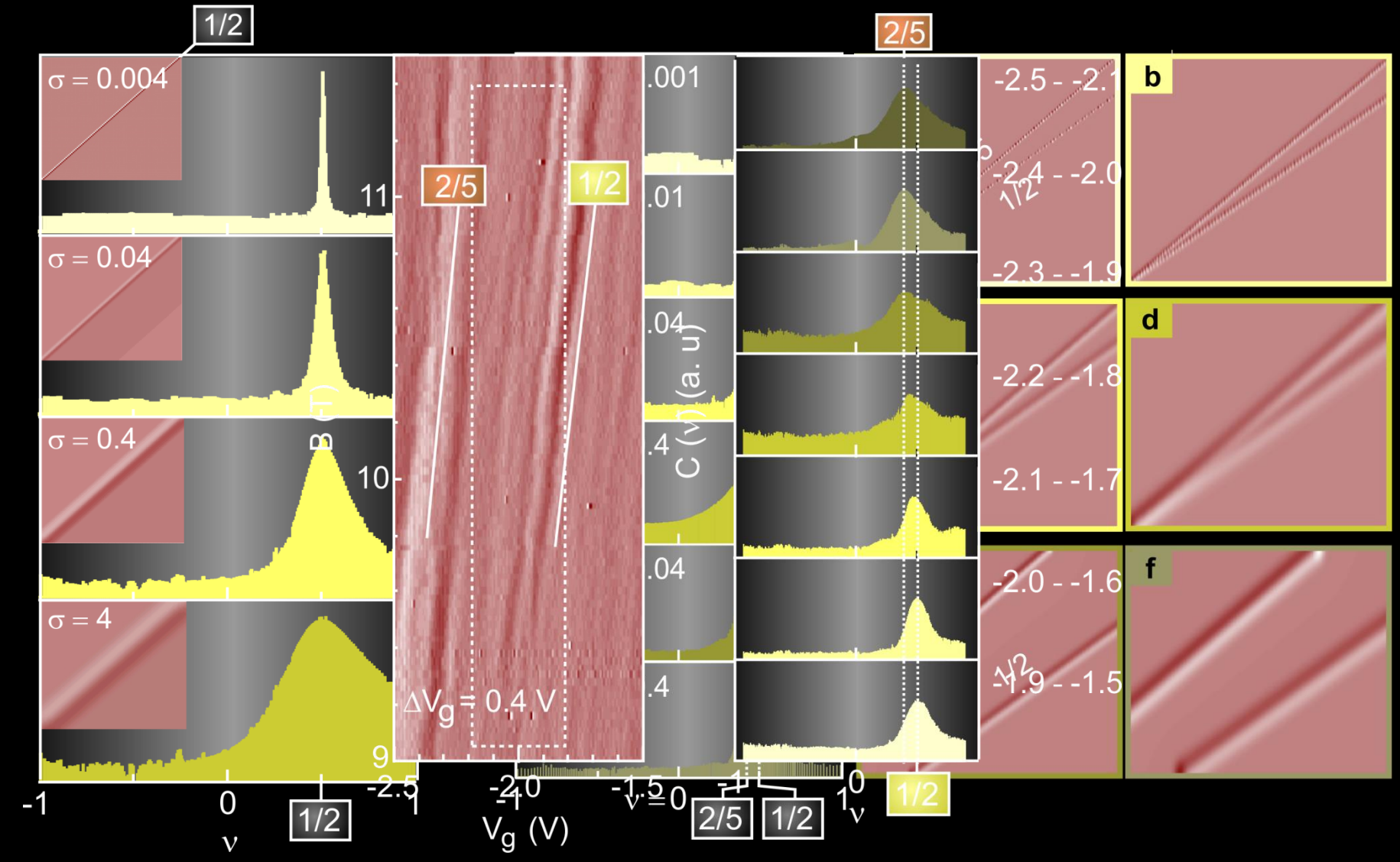
Z. Papic, D.A. Abanin, PRL **112**, 046602 (2014)

Y.H. Wu, T. Shi, J.K. Jain, arXiv:1603.02153v1, March 2016.

Solid State Nanophysics Group

Resolution issues



The fractional quantum Hall effect