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Fractional quantum Hall effect and Wigner crystallization in suspended graphene

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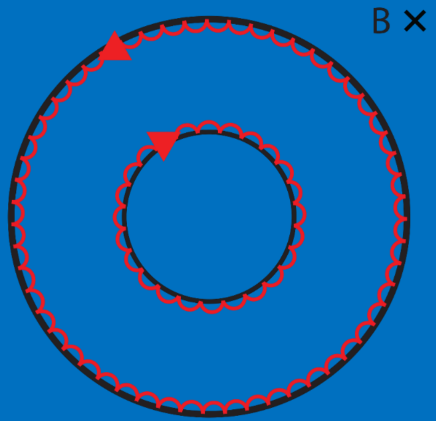

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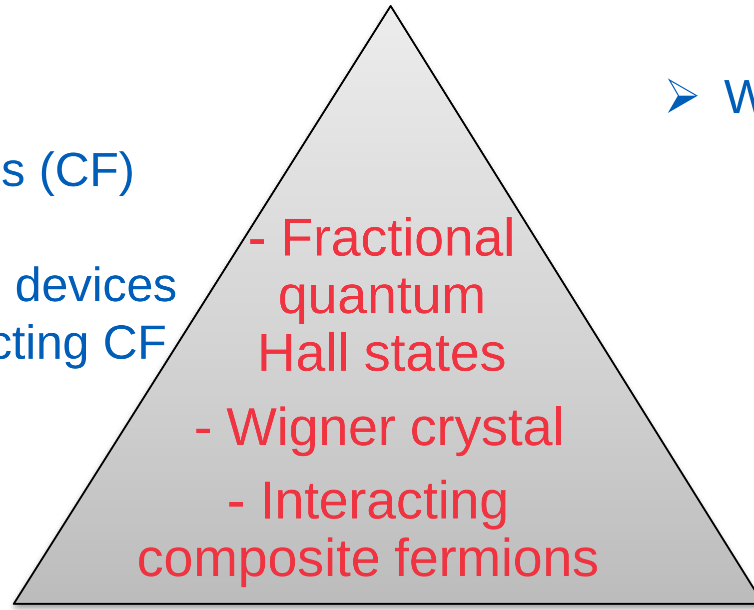
GRAPHENE FLAGSHIP

Overview

- ➢ Introduction
  - Hall effect
  - composite fermions (CF)
  - Wigner crystal
- ➢ FQH states in Corbino devices
  - evidence of interacting CF

Magnetic field



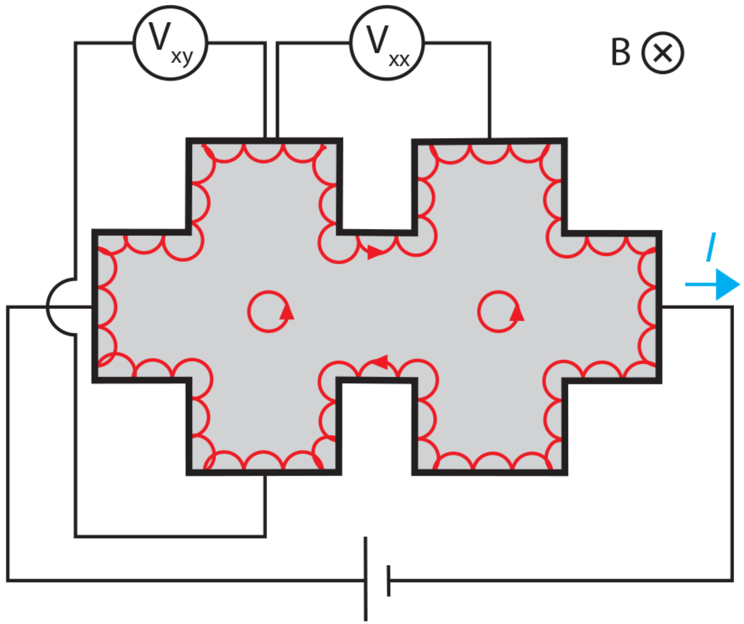
Dirac particles

Suspended graphene

- ➢ Wigner crystallization
  - depinning by bias
  - high melting *T*
  - microwave resonance

- ➢ Mechanical resonances and FQH states

Quantum Hall effect

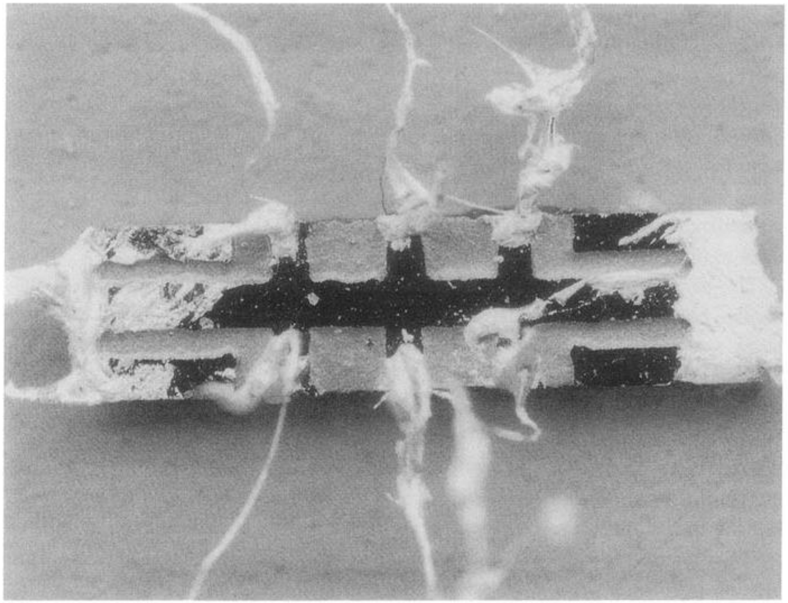


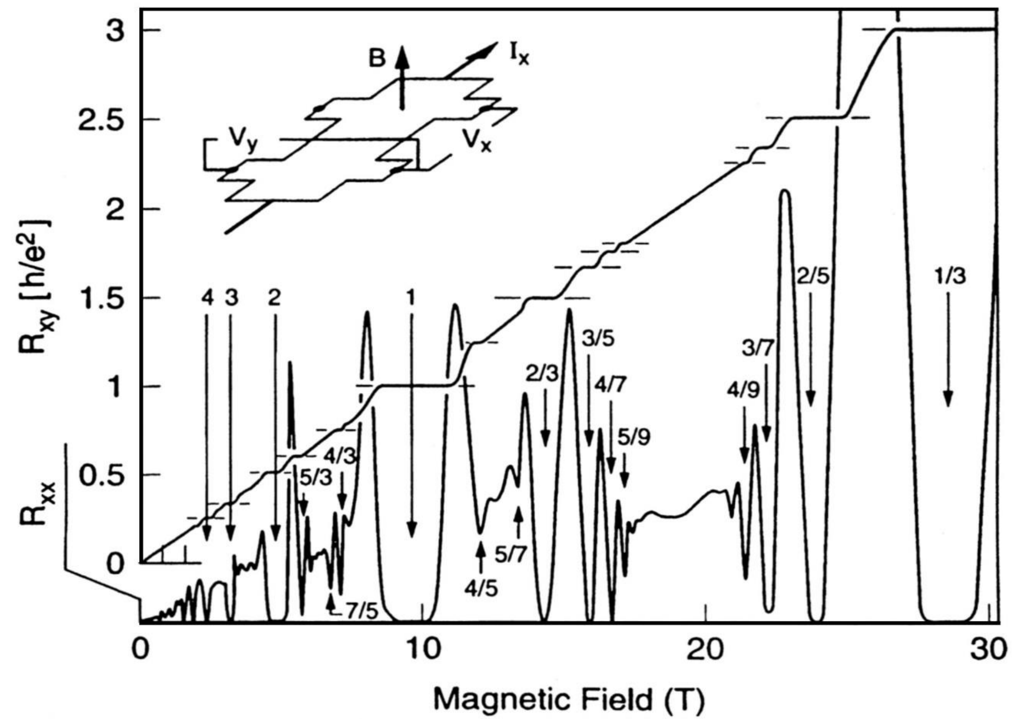
- **Quantized edge conductance**
  - $\sigma_{xy} = \frac{I}{V_{xy}} = \nu \frac{e^2}{h}$
  - Filling factor: $\nu = \frac{nh}{eB}$
- **Dipping diagonal resistivity**
  - $\rho_{xx} = \frac{V_{xx}}{I} \rightarrow 0$
- **Insulating bulk**

- $E_n = \hbar\omega_c(\mathrm{n}+\frac{1}{2}), \quad \omega_c = \frac{eB}{m}$

K. v. Klitzing, G. Dorda, and M. Pepper
Phys. Rev. Lett. ***45****, 494 (1980)*

In the extreme limit: Formation of new particles



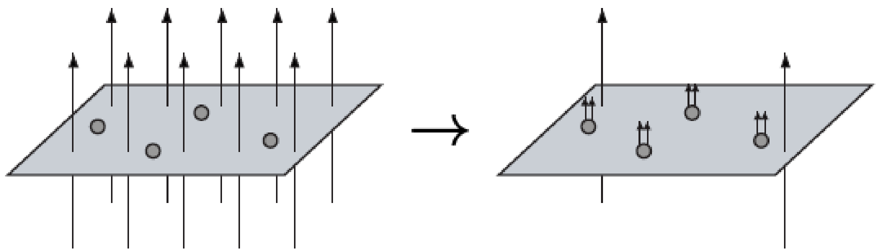


Sample : GaAs/AlGaAs
***T* = 400 mK**
B = 15 T.

D. C. Tsui, H. L. Stormer, and A. C. Gossard
Phys. Rev. Lett. ***48****, 1559 (1982)*

Composite fermions

- Real electron + 2m fluxes ⇒ "composite fermion" (CF)

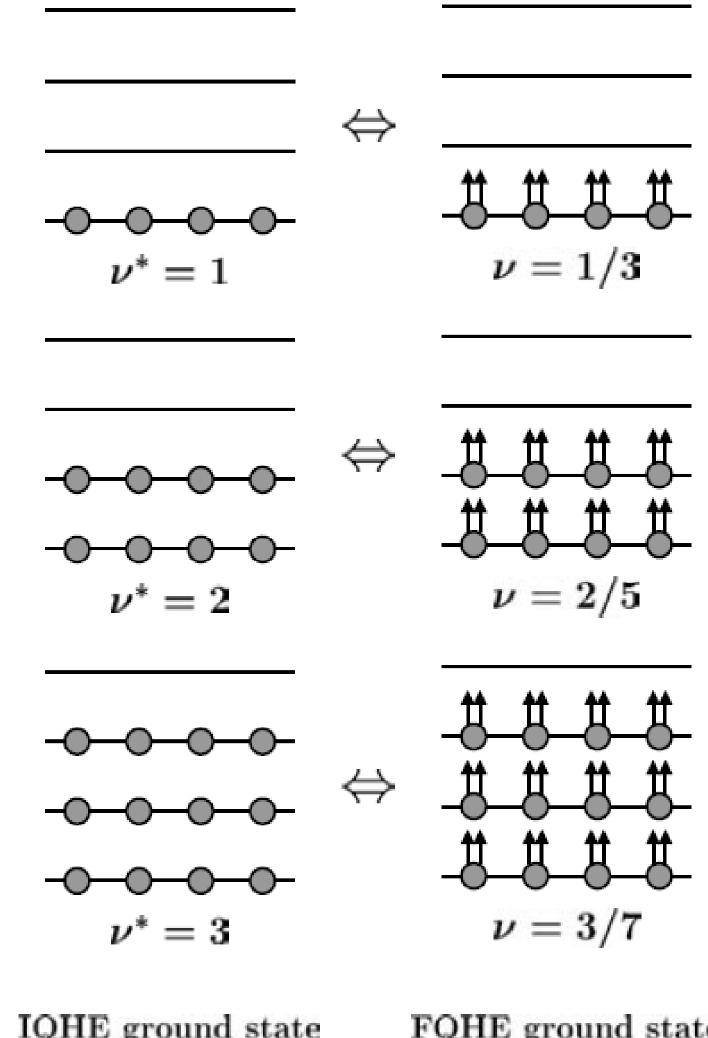


- Real and effective fields

$$B^* = B - 2m\phi_0 n$$

- Real and effective filling factors

$$\nu = \frac{n\phi_0}{B} \qquad \nu^* = \frac{n\phi_0}{B^*} \qquad \nu = \frac{\nu^*}{2m\nu^* \pm 1}$$



J. K. Jain, Phys. Rev. Lett. **63**, 199202 (1989).
Jain, http://www.personal.psu.edu/jkj2/cf-fqhe.pdf

The original idea of Wigner

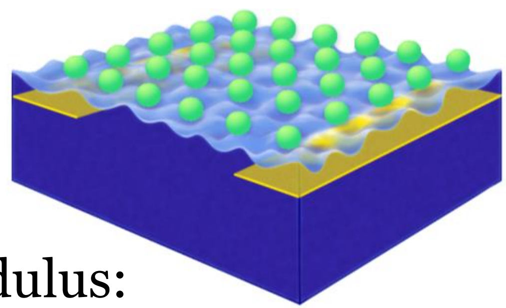
Potential energy per particle due to Coulomb interaction:

$$E_{\mathrm{pot}}/N_{\mathrm{e}} \approx e^2/4\pi\epsilon_0 r_0 \propto n_{\mathrm{e}}^{1/D}$$

$$r_0 = \begin{cases} \left(\dfrac{3}{4\pi}\right)^{1/3} n_e^{-1/3} \\ \dfrac{1}{\sqrt{\pi}} n_e^{-1/2} \end{cases}$$

Kinetic energy per particle:

$$E_{\mathrm{kin}}/N_{\mathrm{e}} \propto \frac{\hbar^2 k_F^2}{2m} \propto r_0^{-2} \propto n_{\mathrm{e}}^{2/D}$$



Dimensionless parameters:

$$\Gamma = \frac{E_{\mathrm{pot}}}{E_{\mathrm{kin}}} \propto n_{\mathrm{e}}^{-1/D}$$

Shear modulus:

$$\mu = \frac{0.245 e^2 n^{3/2}}{4\pi\varepsilon_0\varepsilon_g}$$

$$f_p = \frac{2\pi\mu}{neBL^2}$$

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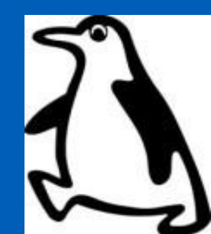
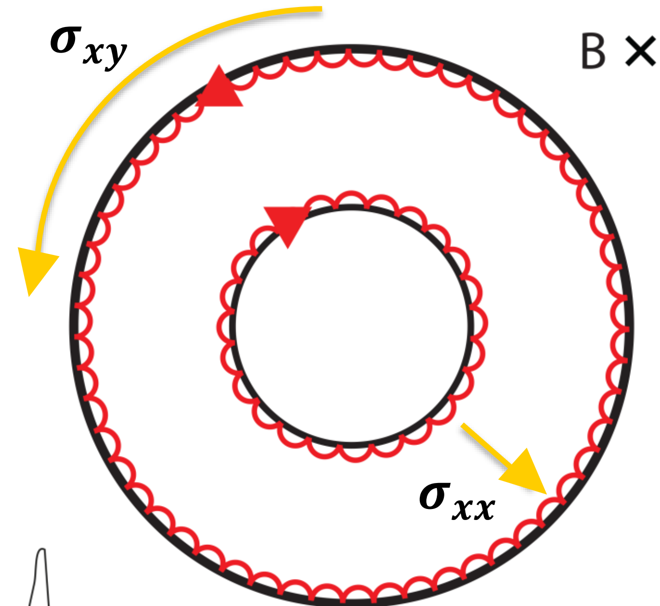
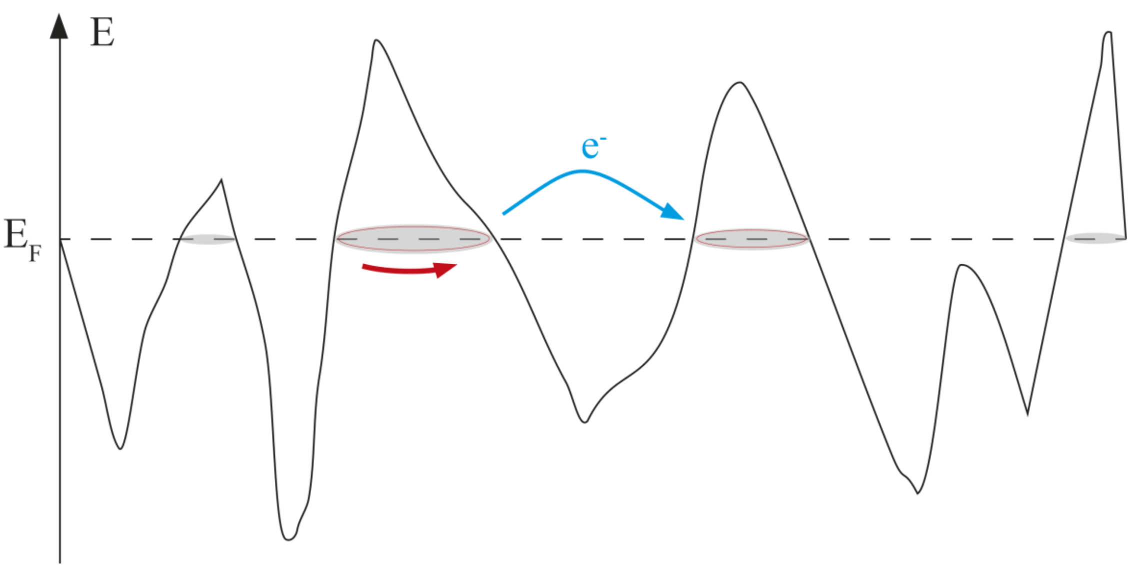
FQH states in a graphene Corbino device

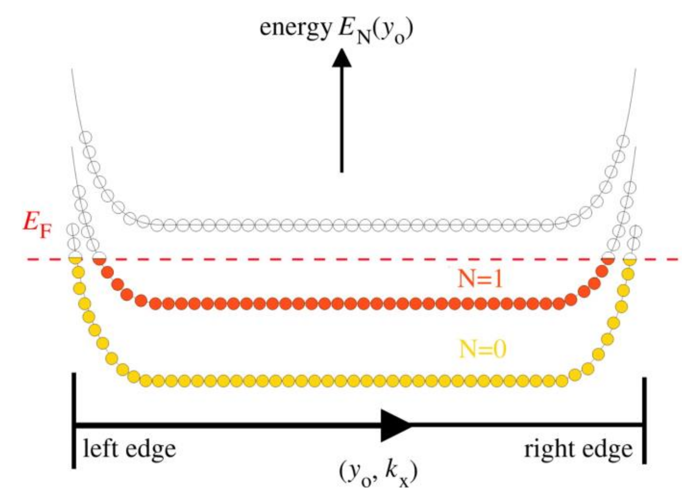


Corbino geometry

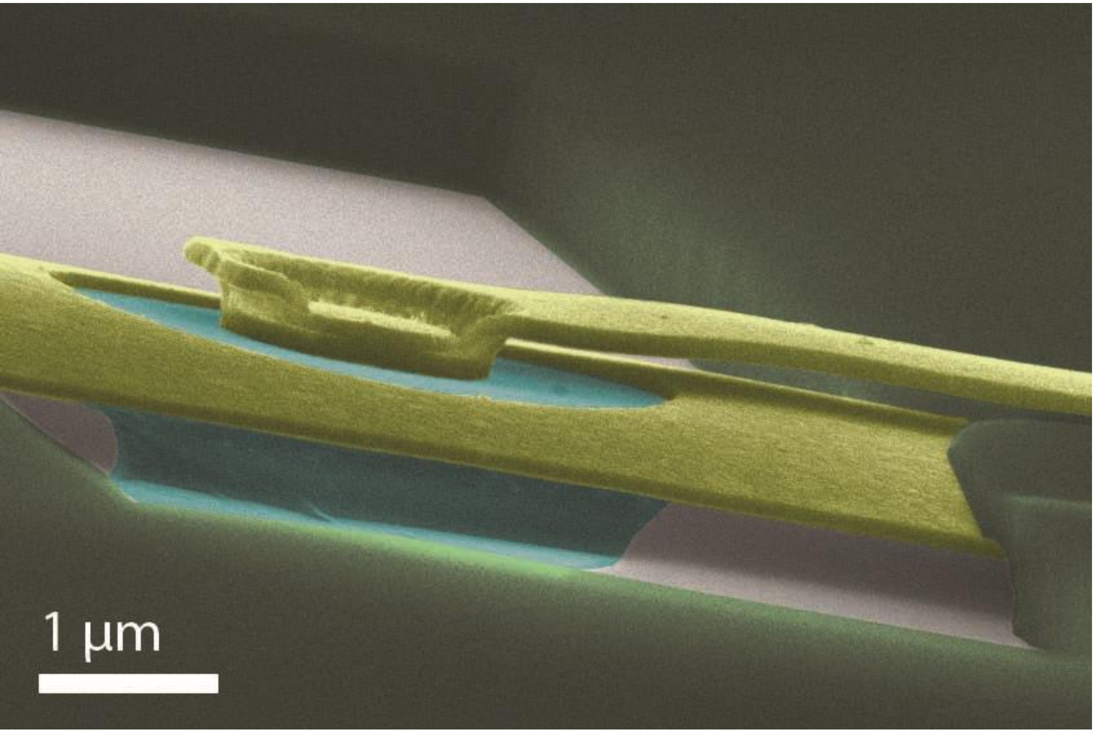
- **Corbino disk in B-field**
  - Counter-rotating edge states
  - No measurement of σ_{xy}
  - σ_{xx} vanishes on a QH-state

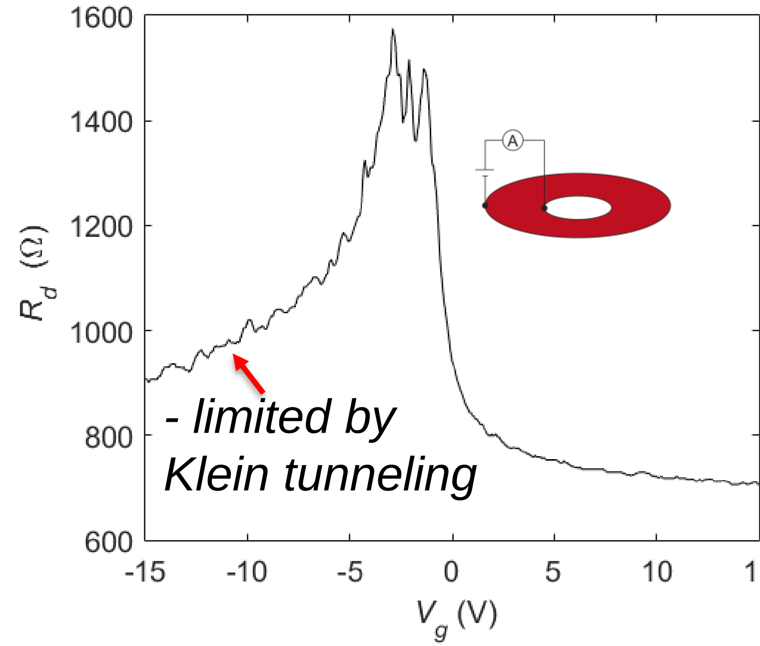






Suspended Corbino samples

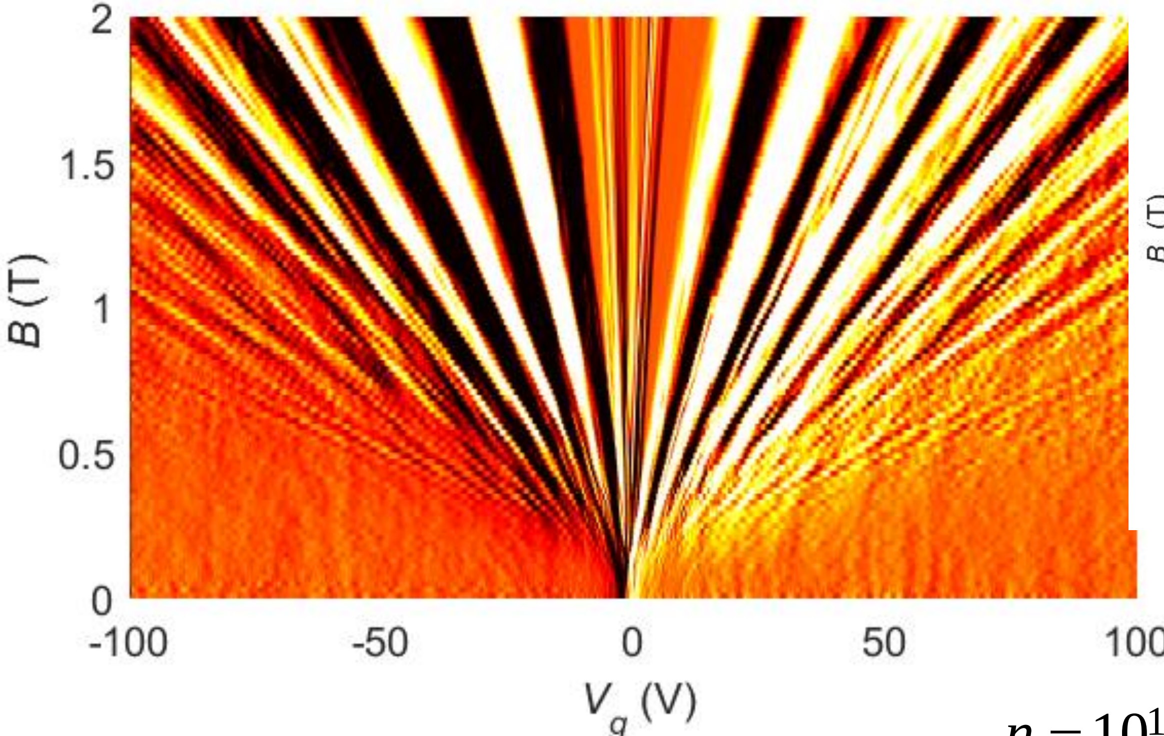


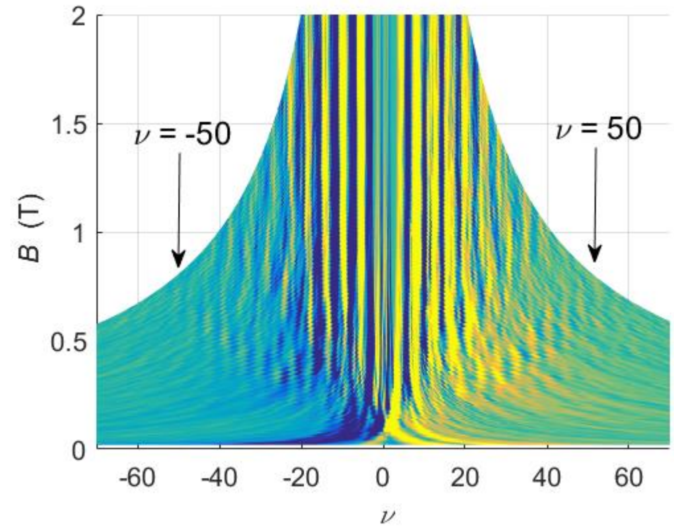


Field effect mobility $\mu_f \gtrsim 10^5 \frac{\mathrm{cm}^2}{\mathrm{Vs}}$

Quantum Hall effect

dG/dV_g

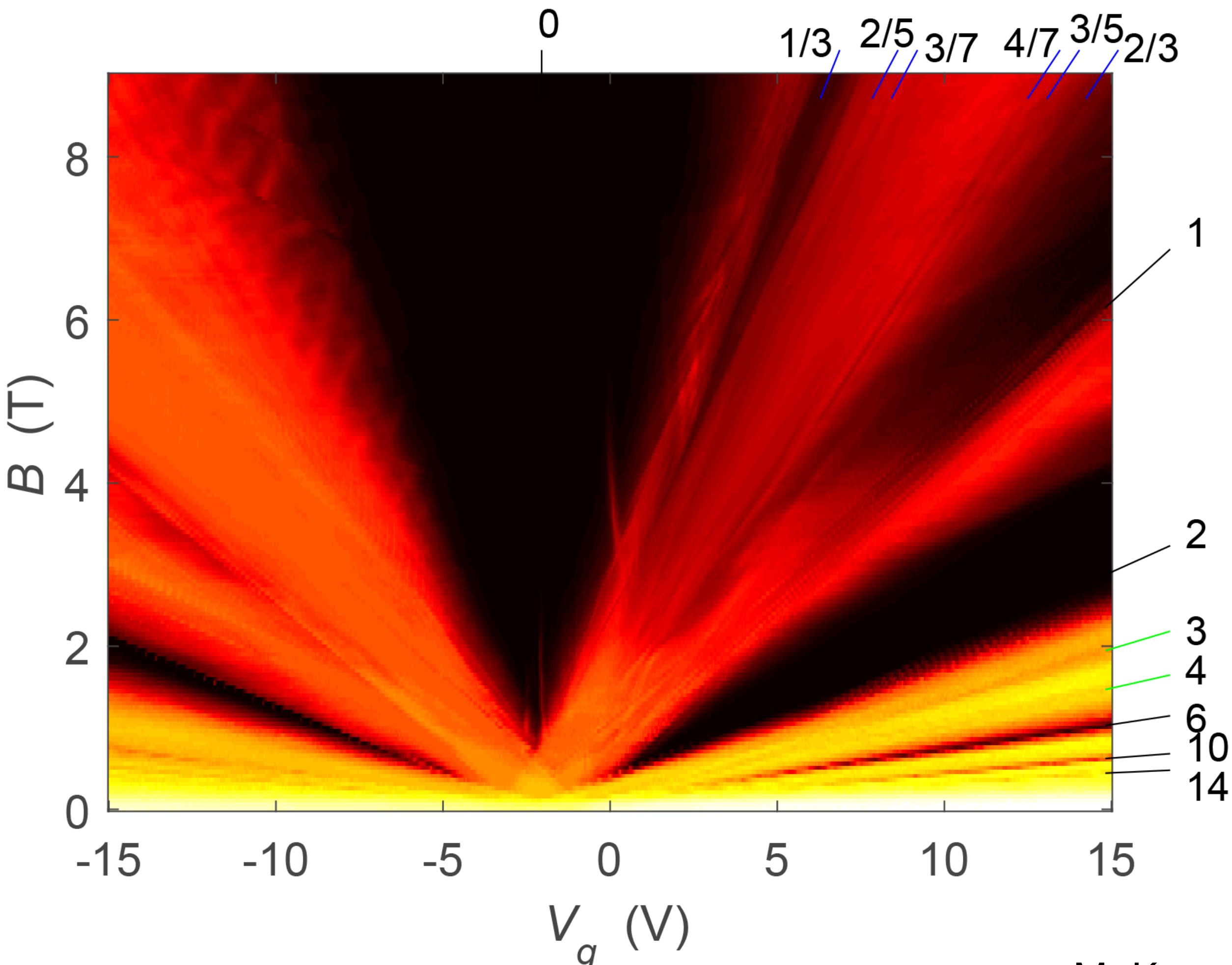




$$\nu = \frac{nh}{eB}$$

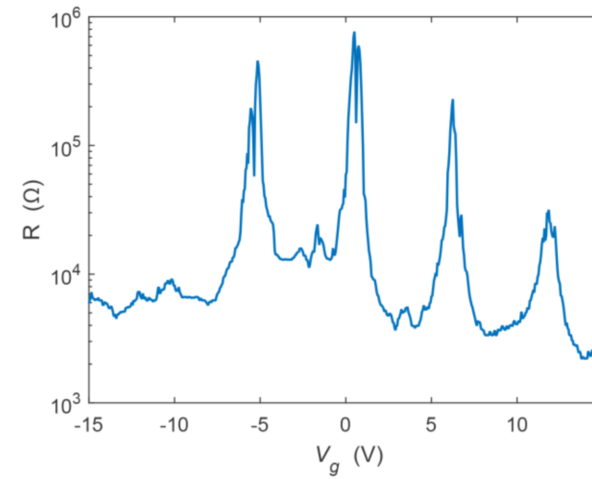
$$n = 10^{12}\ \mathrm{cm}^{-2}$$

Quantum Hall effect



- **Filling factor**

$$\nu = \frac{nh}{eB}$$



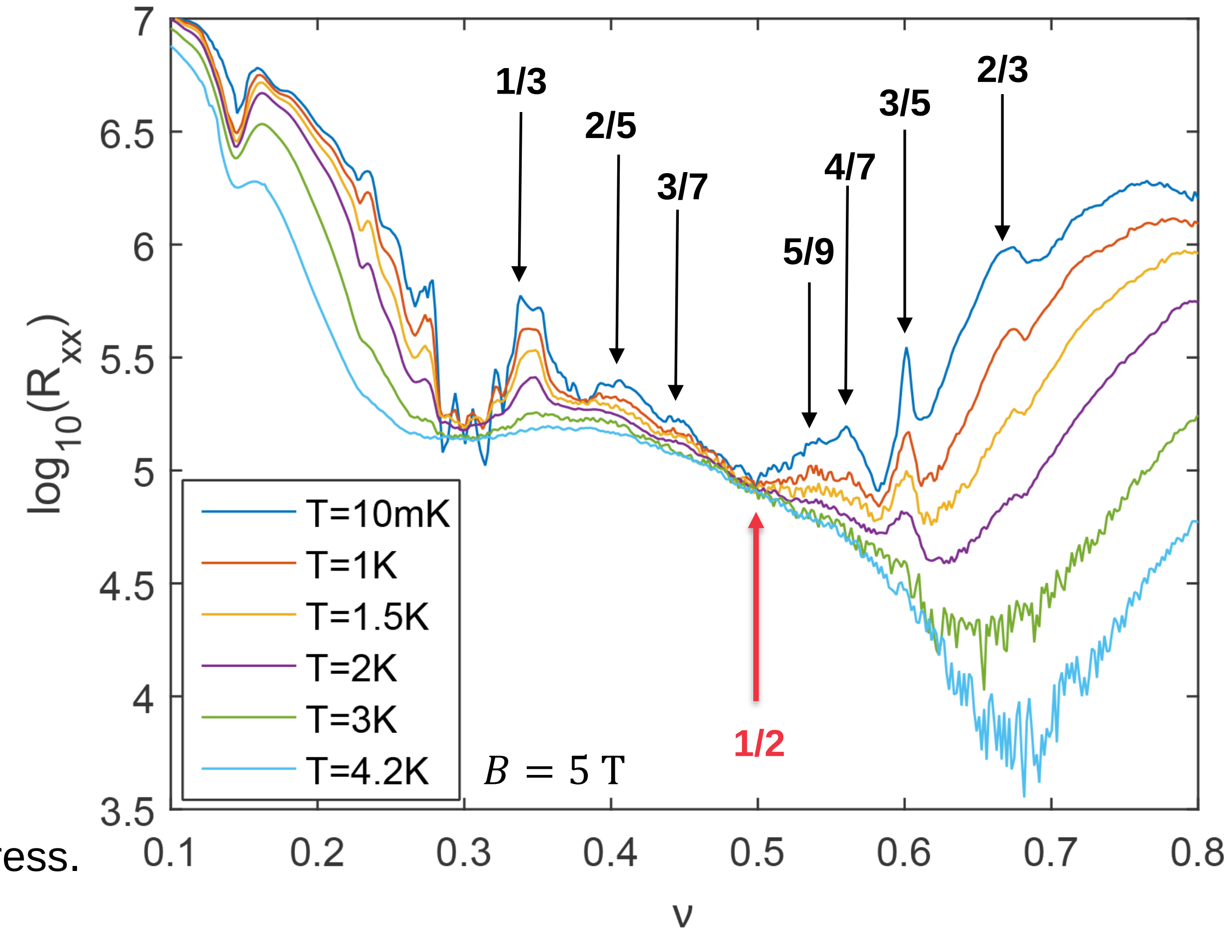
M. Kumar, et al., arXiv:1611.02742 (2016).

FQHE – composite fermions

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

- ***T*-dependence**
  - Fractional states
    - ➢ $\sigma_{xx} = \sigma_0 e^{\frac{-T_0}{2T}}$
    - ➢ Gaps T_0 = 6-1 K
  - $\nu = 1/2$
    - ➢ *Fermi liquid with little T-dependence*
    - ➢ *Dirac particles*

A. Laitinen, et al., PRB in press.



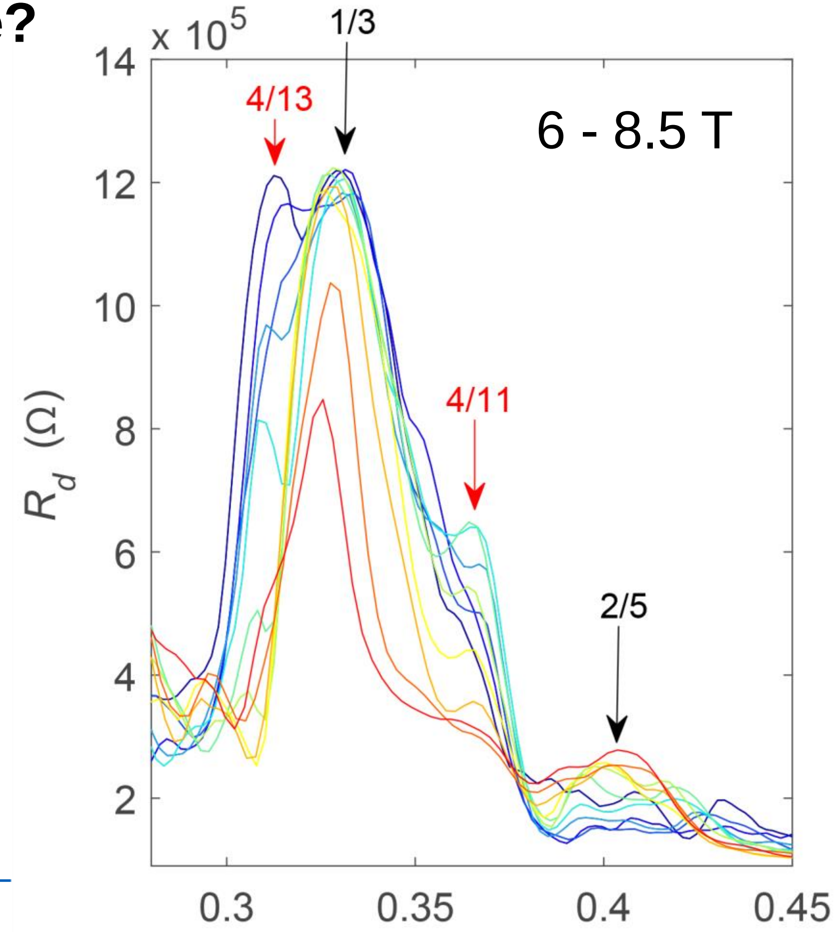
Unconventional fractional quantum Hall effect

- **States in between Jain's sequence?**
  - Interactions between CFs
  - FQHE of composite fermions

$$\nu = \frac{\nu^*_{CF}}{2m\nu^*_{CF} \pm 1}$$

$$\nu^*_{CF} = \frac{4}{3} \rightarrow \nu = \frac{4}{11} \approx 0.36$$

- **Small gaps**
  - Arrhenius fits at low T/high T
  - 2% of the 1/3 state gap



M. Kumar, A. Laitinen, and P. Hakonen, submitted.

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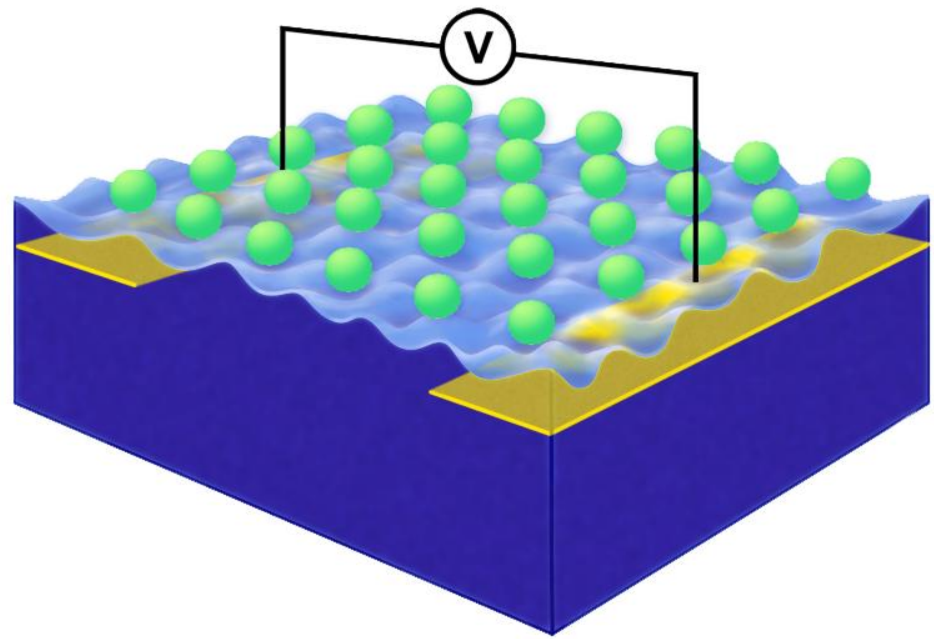
Wigner crystal – electron solid

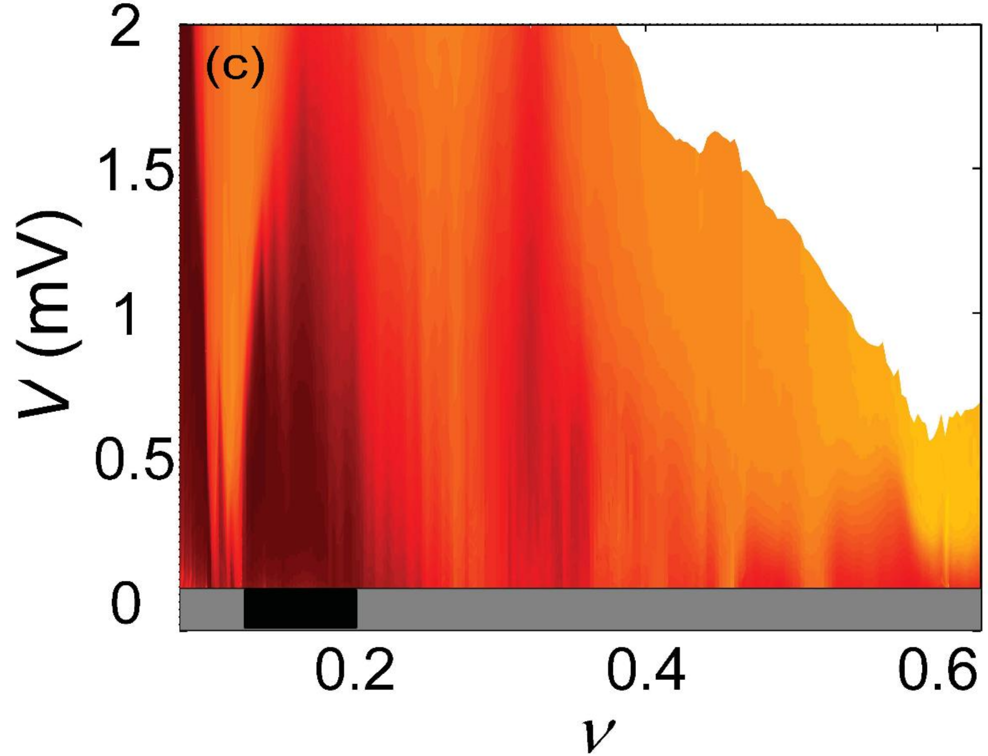
Wigner crystallization in graphene

- **Experimental signatures**
  1. Insulating at DC, below T_c
  2. IVs: thermal depinning
  3. Oscillation modes around the pinning potential



Wigner Crystallization – conductance

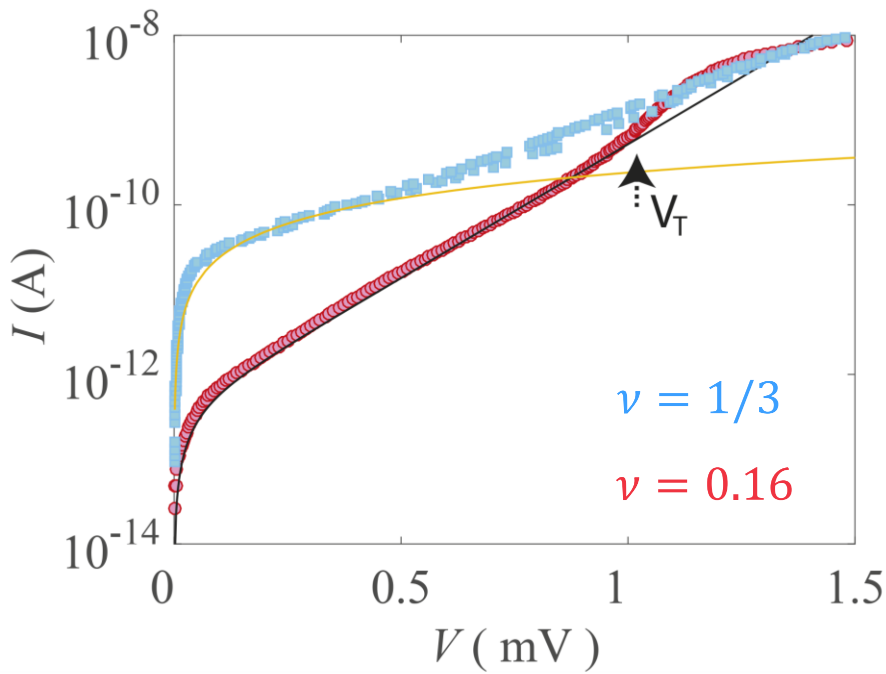
- **Small σ_{xx}**
  - ➢ ν = 0.14 – 0.20
  - ➢ V_g = - 0.3 …1.5 V
- **Re-entrant behavior?**



Wigner current-voltage characteristics

- **Quantum tunneling at $\nu = 1/3$ (blue markers)**
- **Thermally activated depinning (red markers)**

$$I_W = e^* f_p \left\{ exp\left[-\frac{\bar{\Delta} - V/2N}{k_B T}\right] - exp\left[-\frac{\bar{\Delta} + V/2N}{k_B T}\right] \right\}$$



- $\bar{\Delta} = 180\ \mu\text{eV} \approx 1.8\ \text{K}$
- $N = 6$

F. Williams, et al., Phys. Rev. Lett. **66**, 3285 (1991)

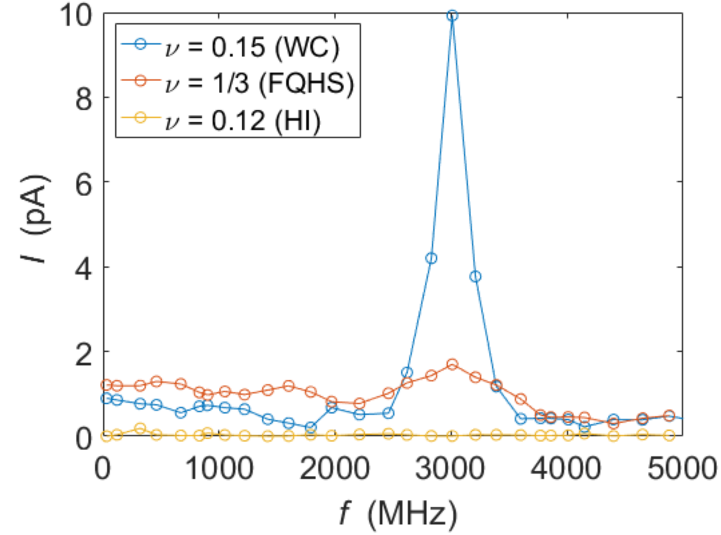
Pinning resonance

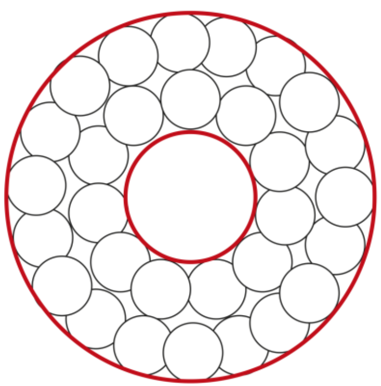
- **Resonance at $f_p = 3$ GHz**
- **Domain size:**

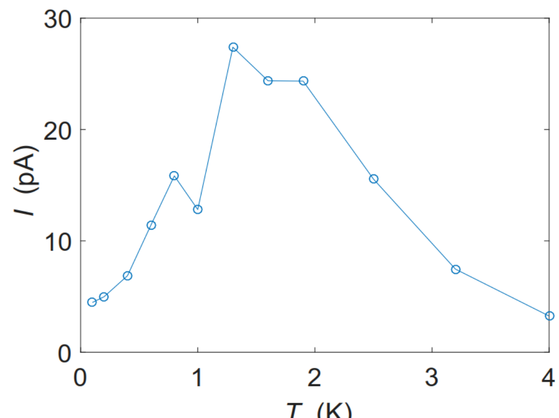
$$L = \sqrt{\frac{2\pi\mu}{neBf_p}} \approx 0.63\ \mu m$$

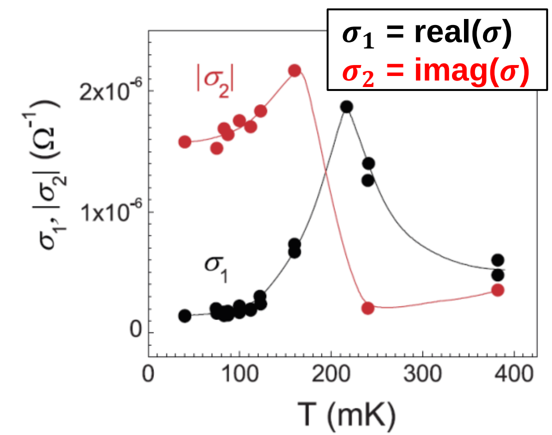
$$\text{Shear modulus } \mu = \frac{0.245 e^2 n^{3/2}}{4\pi\varepsilon_0\varepsilon_g}$$

- **~30 crystallites**





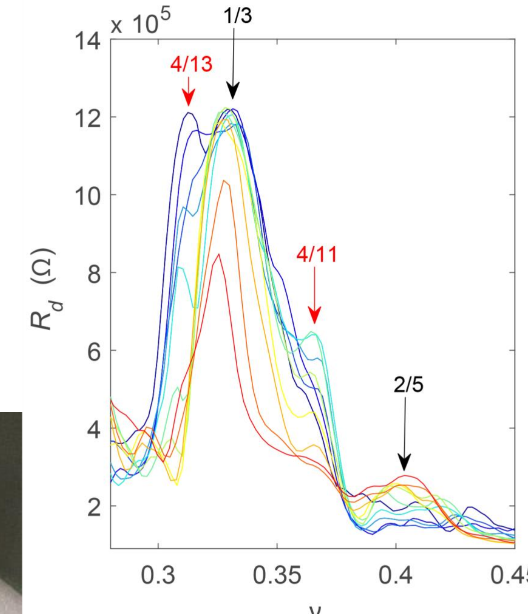




Drichko, et al., *Phys. Rev. B* **94**, 075420 (2016)

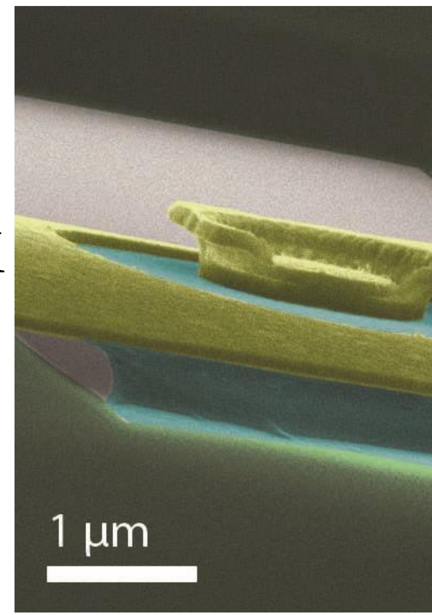
Summary

- **FQH states**
  - Unconventional states: fractional CF states
  - FQH states studied via mechanical resonances



- **Wigner crystal**
  - Solid electron crystal
    100 e/crystallite
  - Pinning resonance
  - Depinning by bias
  - Low conductance

  $T_m \approx 1.5\,\mathrm{K}$



- **Future**
  - Current in edge states
  - Cooper pair splitting
  - Parafermions?