Gapped and gapless phases of the half filled Landau Level in bilayer graphene

Andrea Young

UCSB

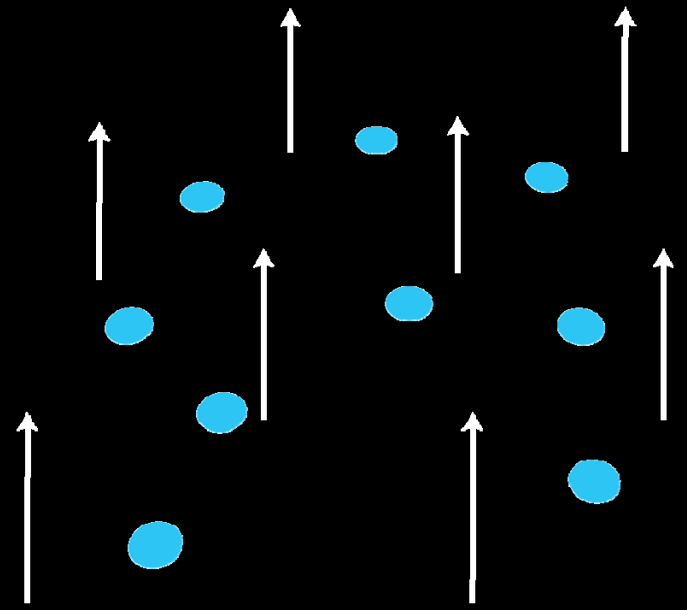
Outline

- Half filled landau levels – experimental perspective
- Bilayer graphene introduction: spin, valley and orbital symmetry breaking from layer resolved capacitance measurements
- Fractional quantum Hall effect in all vdW bilayer graphene heterostructures
- Intertwined phases at half filling

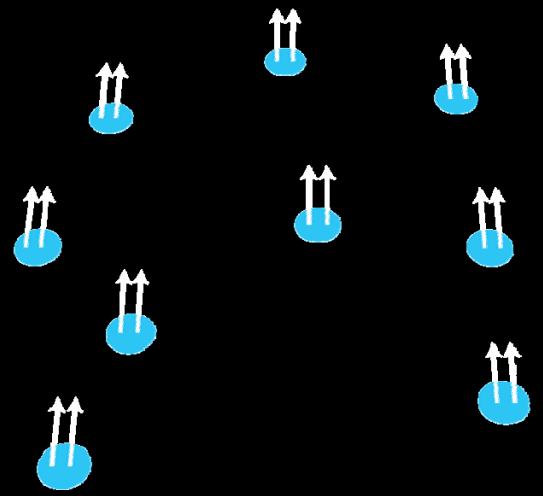
Composite fermion ansatz

Jain 1989

Electrons in magnetic field w/strong interactions



Composite fermions in zero magnetic field with weak interactions



B_{eff} = B(1−2ν)

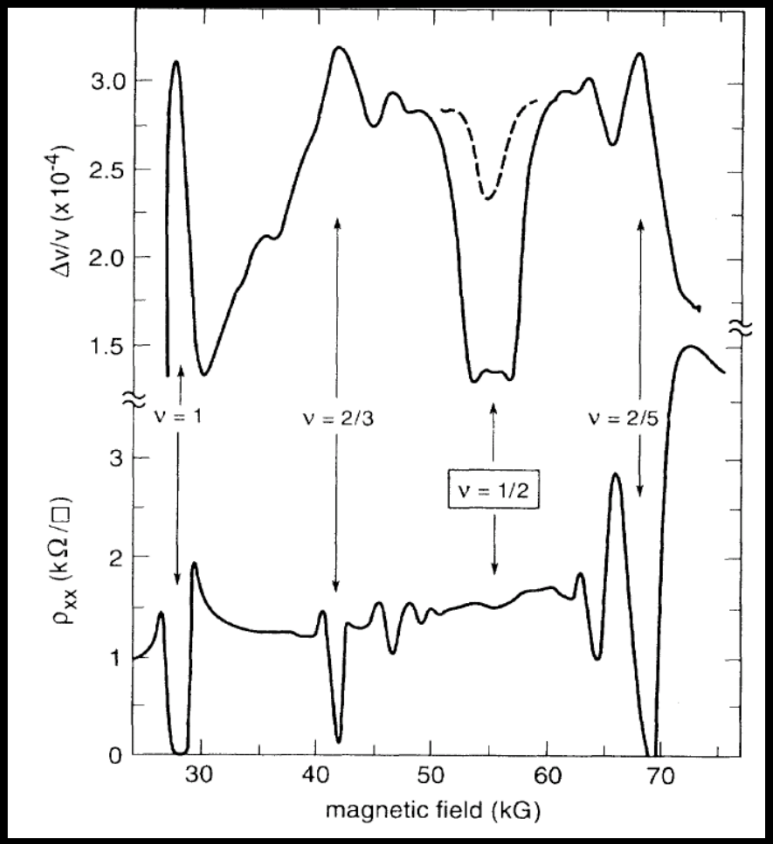
Field vanishes at $\nu = \frac{1}{2}$

What is left over? 'residual' interactions + anisotropies determine fate

- Composite fermion liquid
- 'superconductor'
- CDW

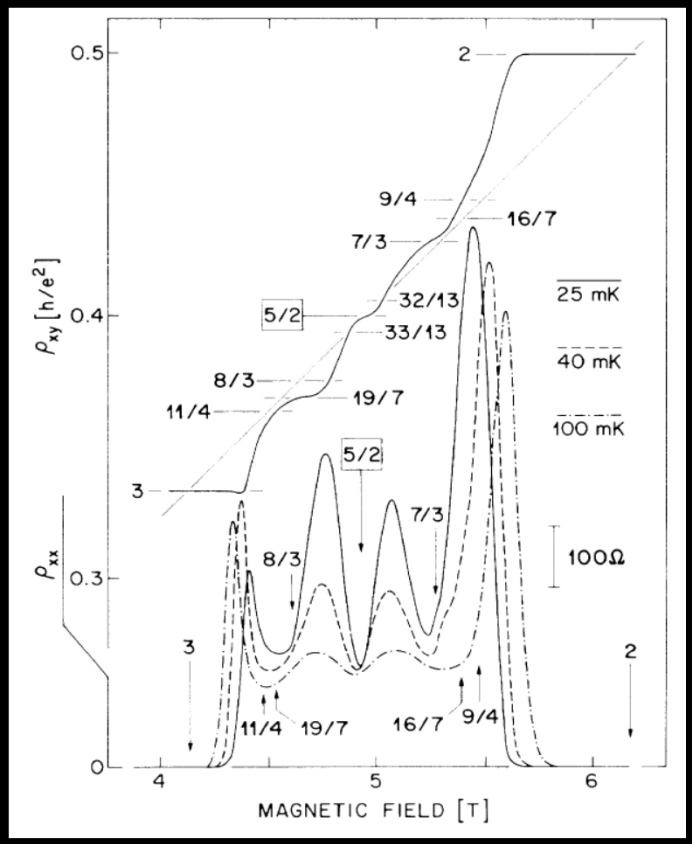
Half filling: phases

N=0: Fermi surface



Willet 1993
Halperin, Lee, Read 1993

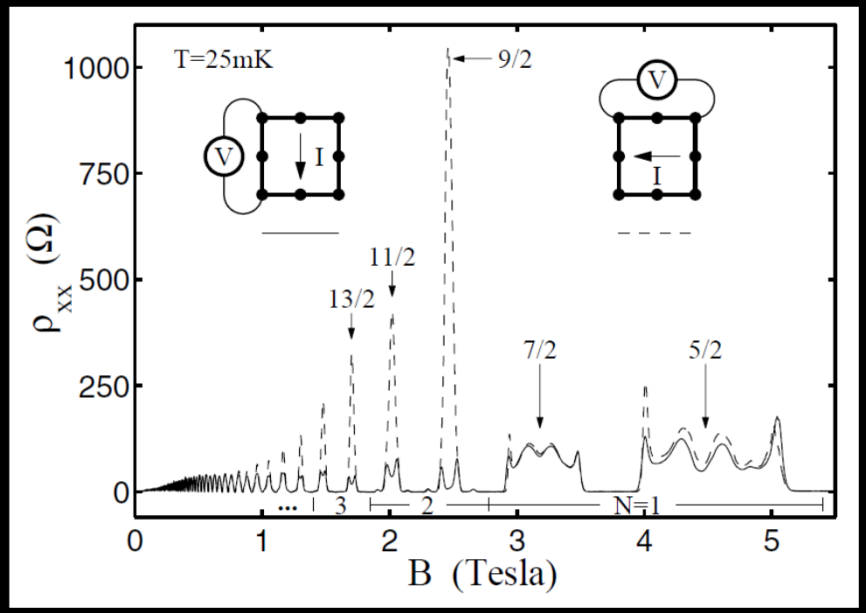
N=1: 'paired' QH state



Willet 1987
Moore, Read 1991

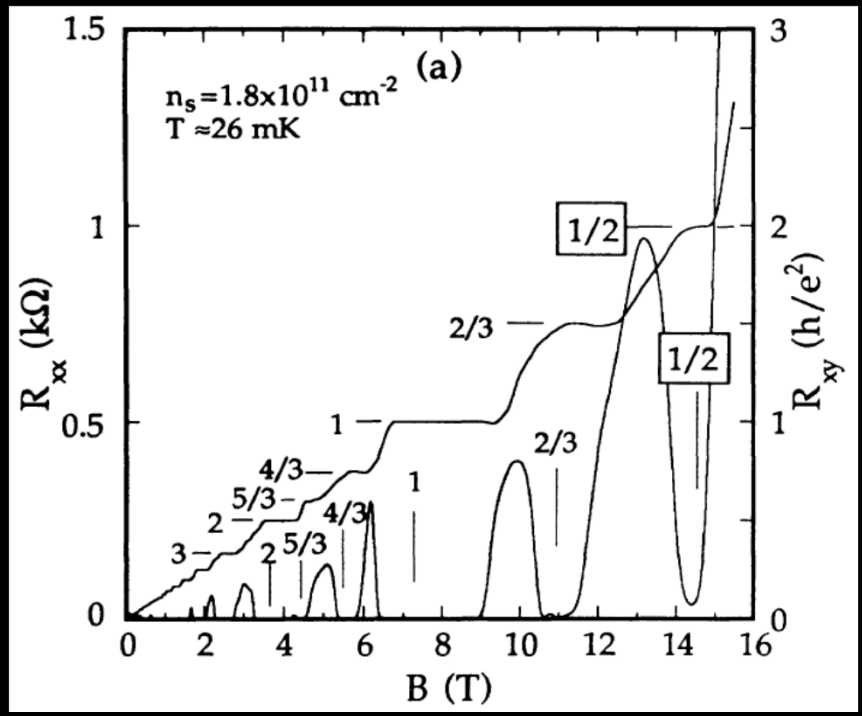
Half filling: phases

Nematics/stripes : N>1



Lilly 1999

Multicomponent – '331' QH



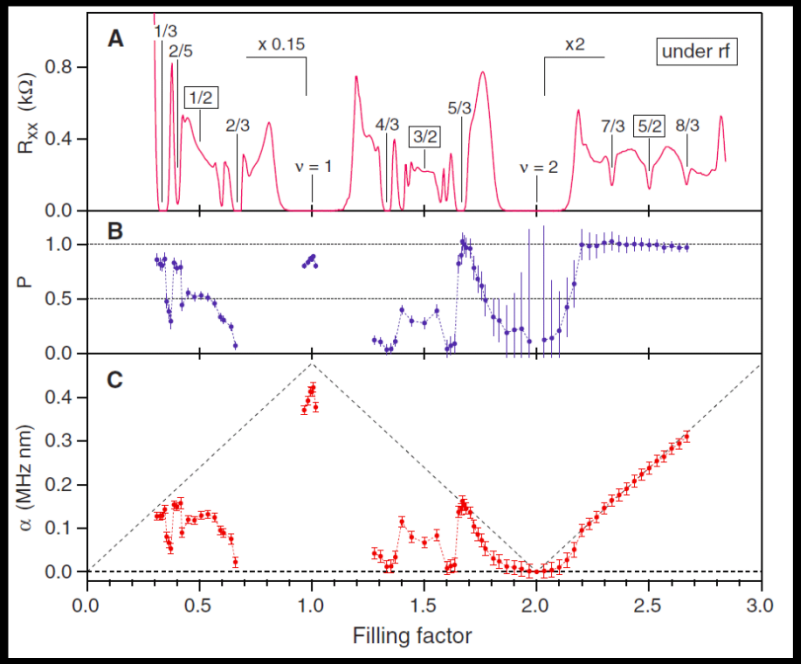
Suen 1992

Eisenstein 1992

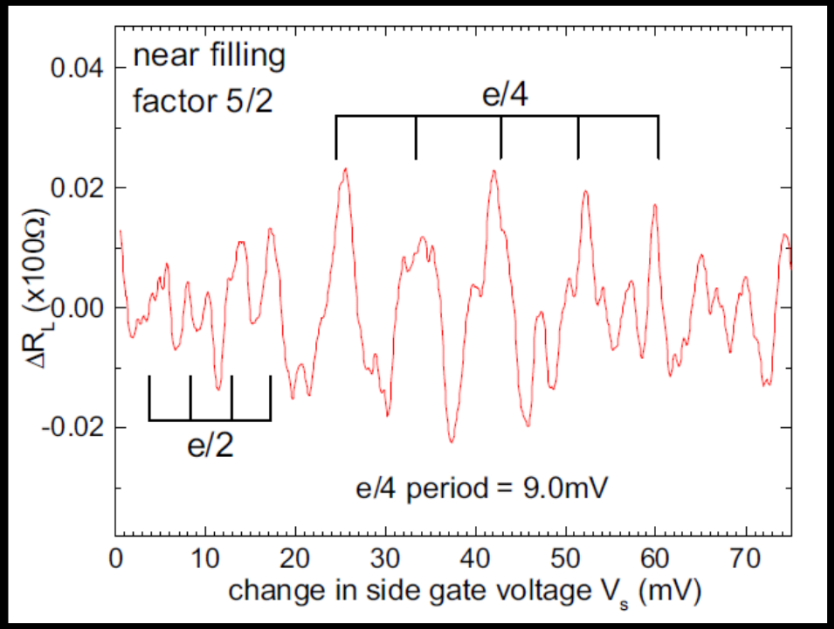
Halperin 1983

Pfaffian phase at $\nu = \frac{5}{2}$

- Numerics (Morf 1998)
  N=1 LL, no spin, no mixing:
  Pfaffian, $\Delta \approx .03\ E_c$
- Experiment: spin polarized (Tiemann 2012)



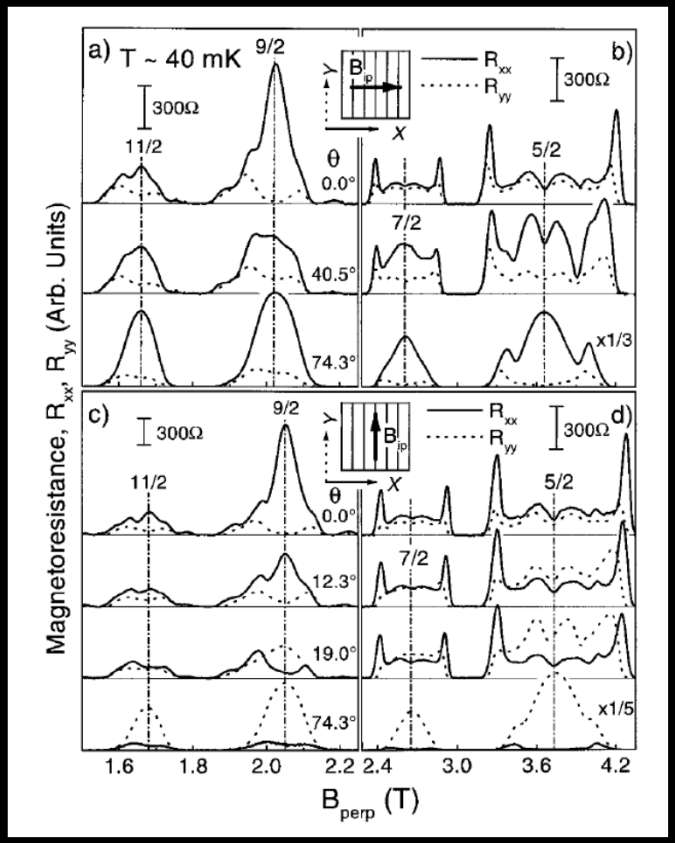
- Charge e/4 consistent
  Heiblum, Yacoby gps
- Quantum dots: no smoking gun…



Willet 2009

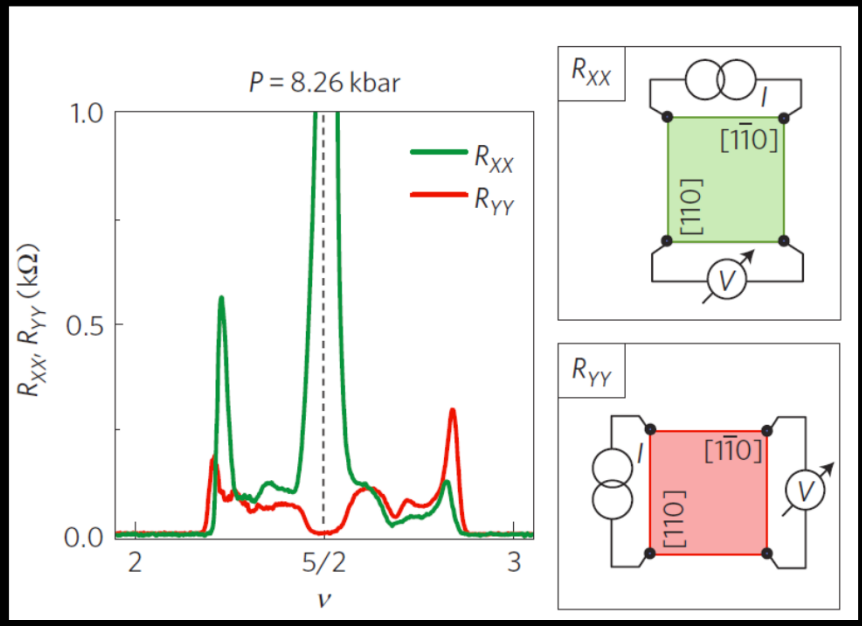
Complex energy landscape

In-plane field



Pan 1999

'Isotropic' pressure



Samkharadze 2016

Bernal bilayer Landau levels

- 2x spin, 2x valley "degeneracy"
- ($\psi_{A,K}$, $\psi_{B,K}$) or ($\psi_{B,K'}$, $\psi_{A,K'}$)

$$H_0 = -\frac{1}{2m}\begin{pmatrix} 0 & \hat{p}^2 \\ (\hat{p}^\dagger)^2 & 0 \end{pmatrix}$$

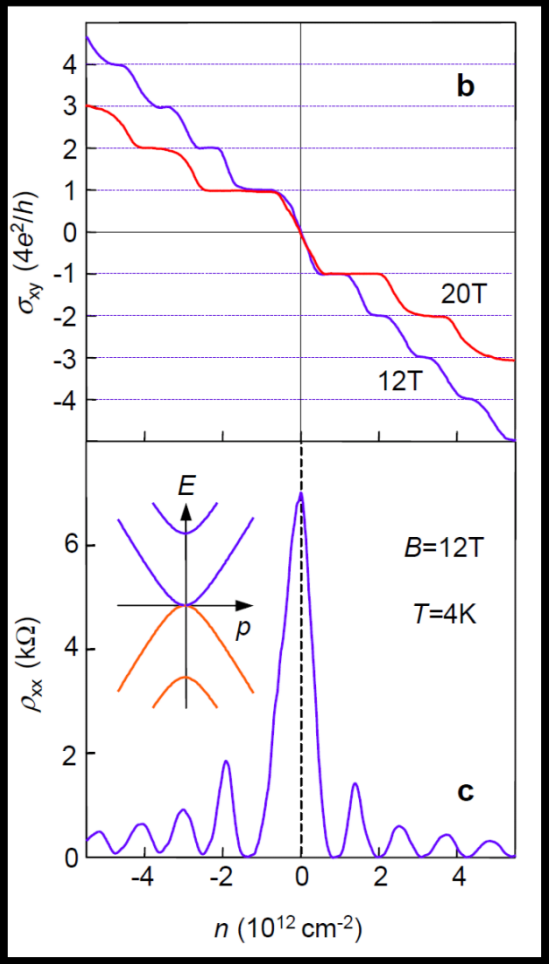
$$H_B = -\hbar\omega_c \begin{pmatrix} 0 & \hat{a}^2 \\ (\hat{a}^\dagger)^2 & 0 \end{pmatrix}$$

$$\Psi_{n>1} = \frac{1}{\sqrt{2}}\begin{pmatrix} |n-2\rangle \\ |n\rangle \end{pmatrix} \qquad \epsilon_{n>1} = \hbar\omega_c\sqrt{n(n-1)}$$

$$\Psi_{n=0,1} = \left\{\begin{pmatrix} 0 \\ |0\rangle \end{pmatrix}, \begin{pmatrix} 0 \\ |1\rangle \end{pmatrix}\right\} \qquad \epsilon_{0,1} = 0$$

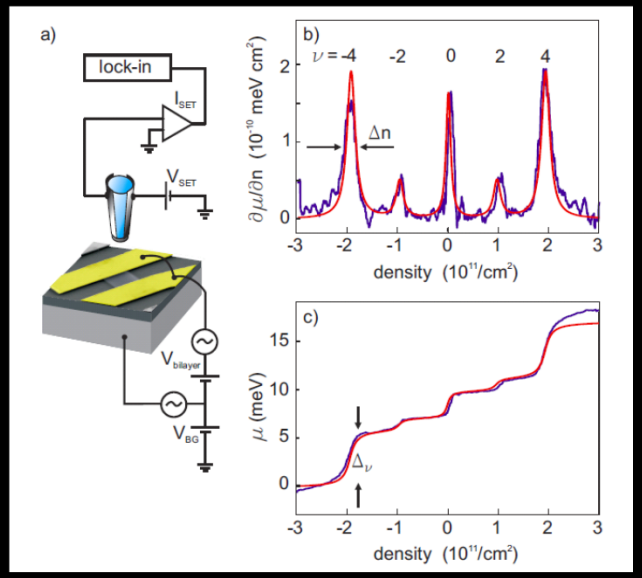
- *Sublattice=valley=layer* in zero energy LL
- 2x *orbital* degeneracy ➔ 8x total degeneracy

Bernal bilayer Landau levels



Novoselov 2006

- 8x degenerate ZLL
- Degeneracies lifted in cleaner samples



Feldman 2010

No *real* degeneracy

Single particle

- Zeeman effect
  - $\Delta_\sigma = g\mu_B B \approx 1.3K\ B_{tot}/T$
- Valley splitting by e field
  - $\Delta_V \sim \frac{p_0}{c}\frac{d_{BLG}}{d_{gate}} \approx 10K\frac{p_0/c}{volt}$
- Electron-hole asymmetry γ_4
  - $\Delta_{10} \approx 3.3K\ B_\perp/T$

Many body

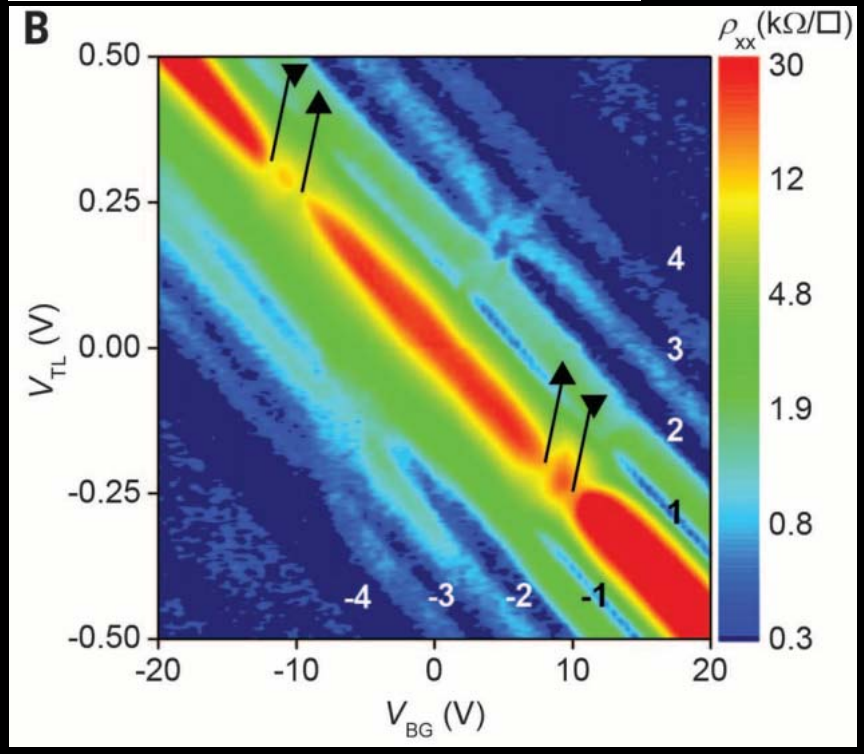
- N=0, N=1: different exchange energies
  - $\zeta_{10} \approx \frac{e^2}{\epsilon \ell_B}$
- SU(4) isospin: short range interactions
  - $u_i \approx \frac{a}{\ell_B}\frac{e^2}{\epsilon \ell_B}$

- Spin-valley: like monolayer, approx SU(4) symmetry
- Orbital: *not a symmetry*

Degeneracies lifted in experiment

Chemical potential and quantum Hall ferromagnetism in bilayer graphene

Kayoung Lee,[1] Babak Fallahazad,[1] Jiamin Xue,[1] David C. Dillen,[1] Kyounghwan Kim,[1] Takashi Taniguchi,[2] Kenji Watanabe,[2] Emanuel Tutuc[1]*

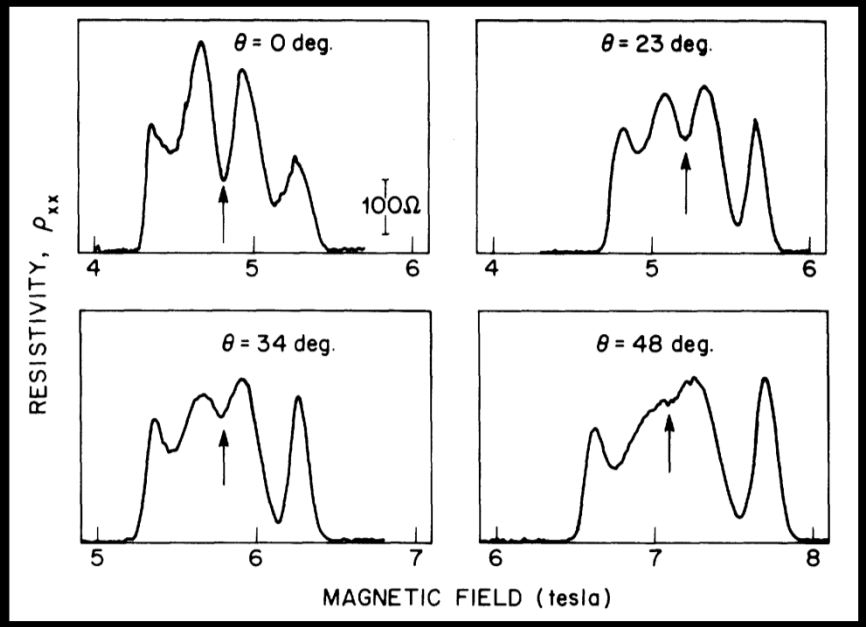


- In what "order?"
- Conventional wisdom: Fill $SU(4)$ polarized $|0\rangle$
- Next fill $|1\rangle$ same isospin
- $\sim SU(4)$ QHFM of orbital doublets

Barlas 2008
Abanin 2009

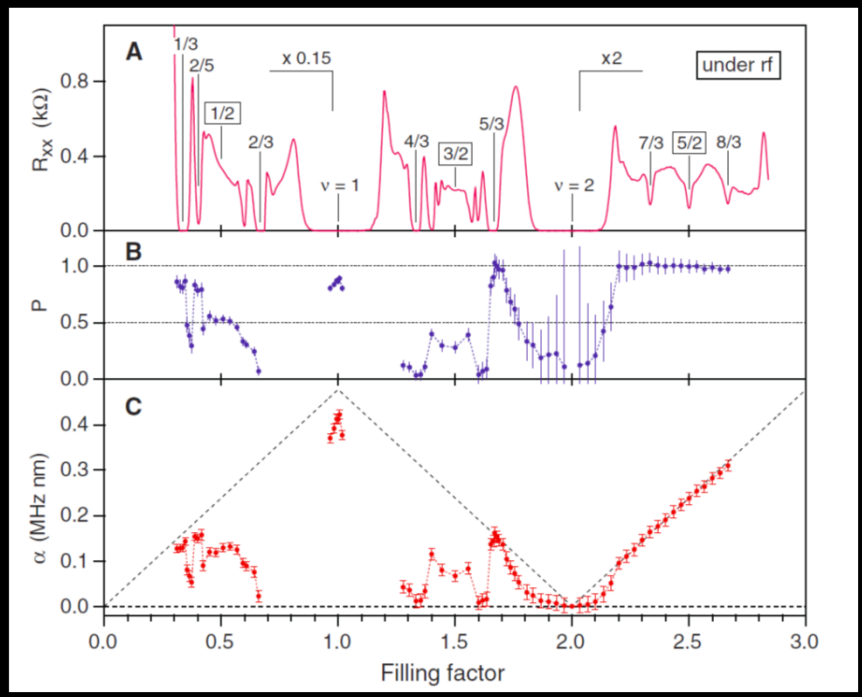
Transport vs. direct probes: 5/2

Transport: unpolarized



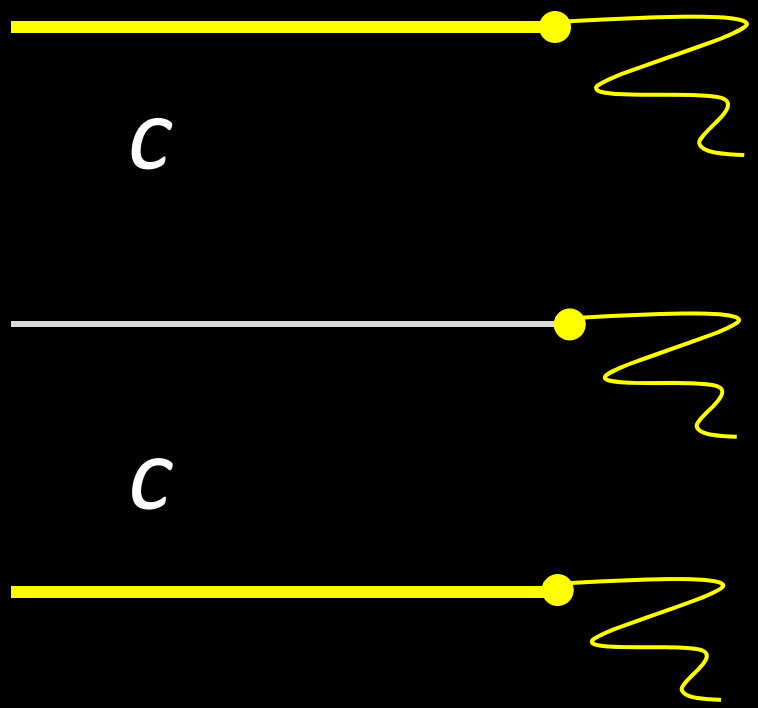
Eisenstein 1988

Direct probe: polarized



Tiemann 2012

Capacitance in a 2DES



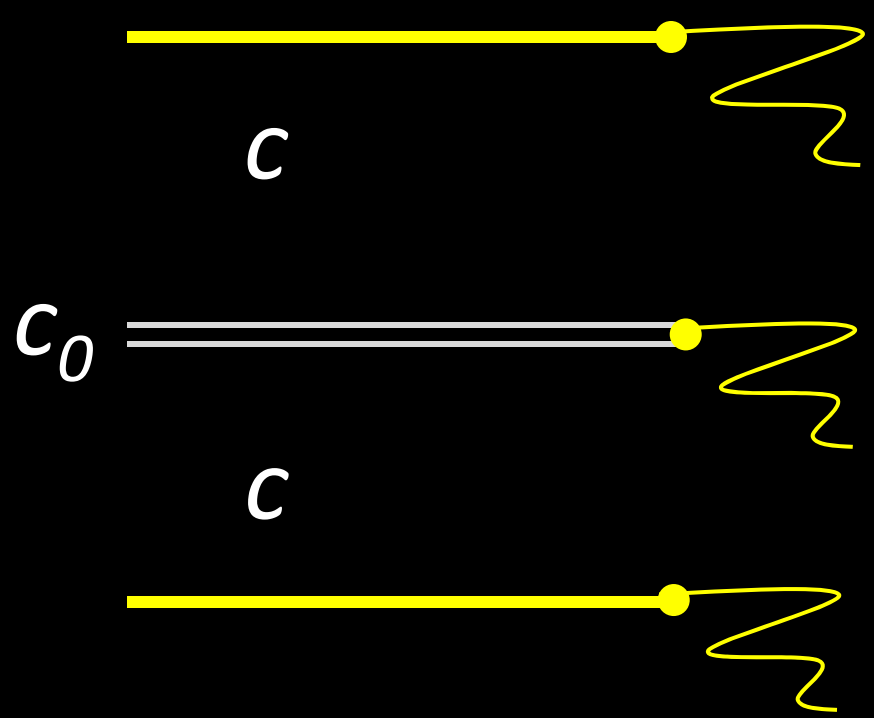
- Geometric capacitance & electronic compressibility

$$C_T \sim \frac{c\nu}{2c+\nu}$$

$$C_B \sim \frac{c\nu}{2c+\nu}$$

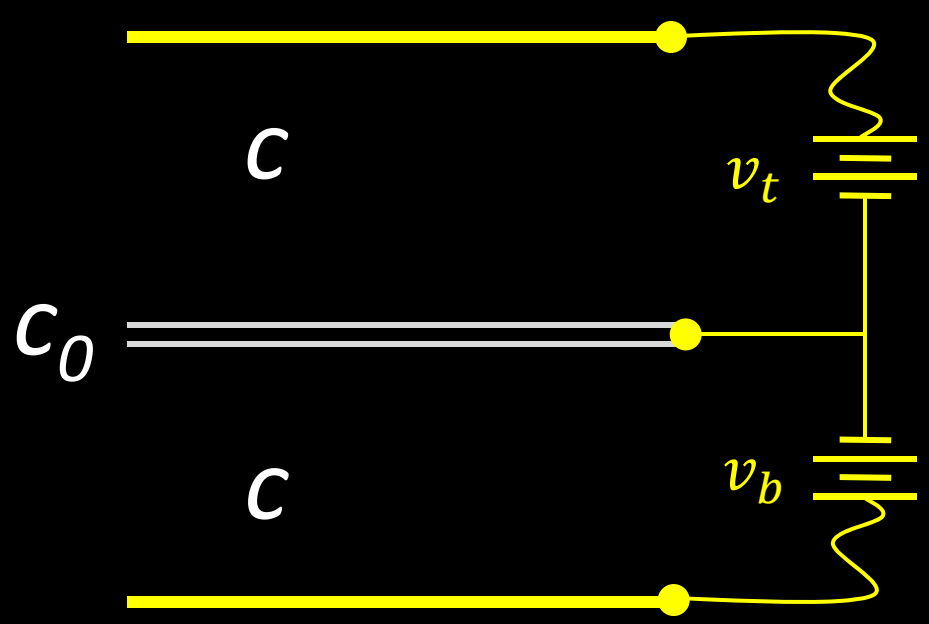
$$C_P \sim \frac{c^2}{2c+\nu}$$

Capacitance in a bilayer



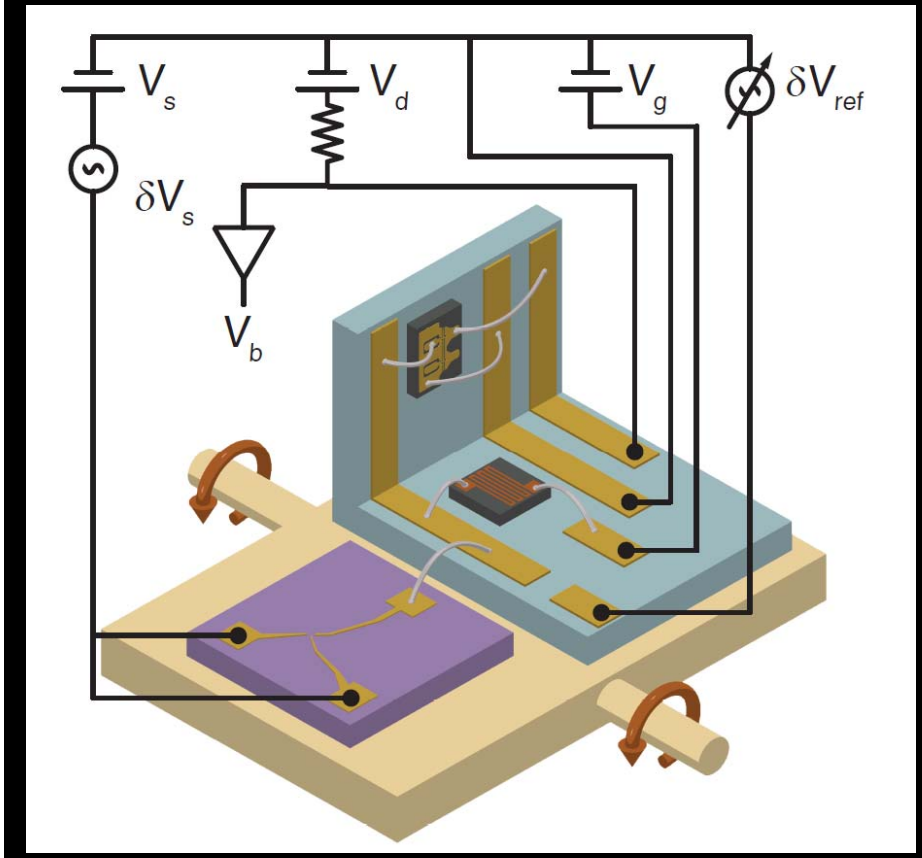
- Geometric capacitance & electronic compressibility
- *Interlayer capacitance:* charge can rearrange
- Layers: $\mu_1 + \varphi_1 = \mu_2 + \varphi_2$
  $\varphi_1 \neq \varphi_2$, $\mu_1 \neq \mu_2$
- C_T, C_B, and C_P probe different physics

Capacitance in a bilayer

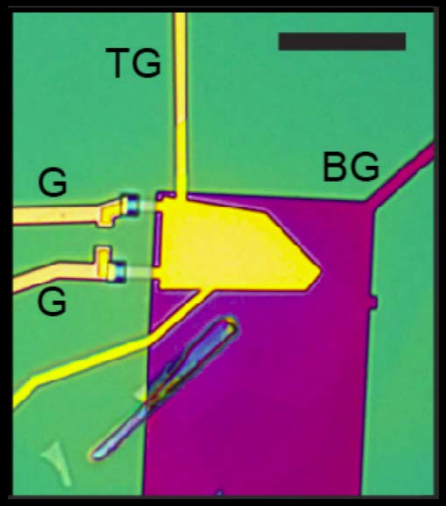


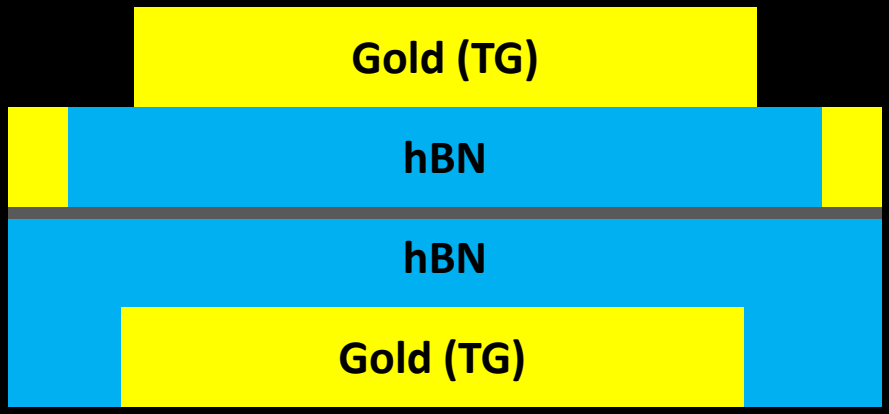
- $\begin{cases} n_0 \equiv c(v_t + v_b) \\ p_0 \equiv c(v_t - v_b) \end{cases}$
- $\frac{\partial n}{\partial n_0} = C_S$
- $\frac{\partial p}{\partial n_0} \propto \frac{\partial n}{\partial p_0} = C_A$
- $\frac{\partial p}{\partial p_0} = C_S + 4C_P$

Device and measurement

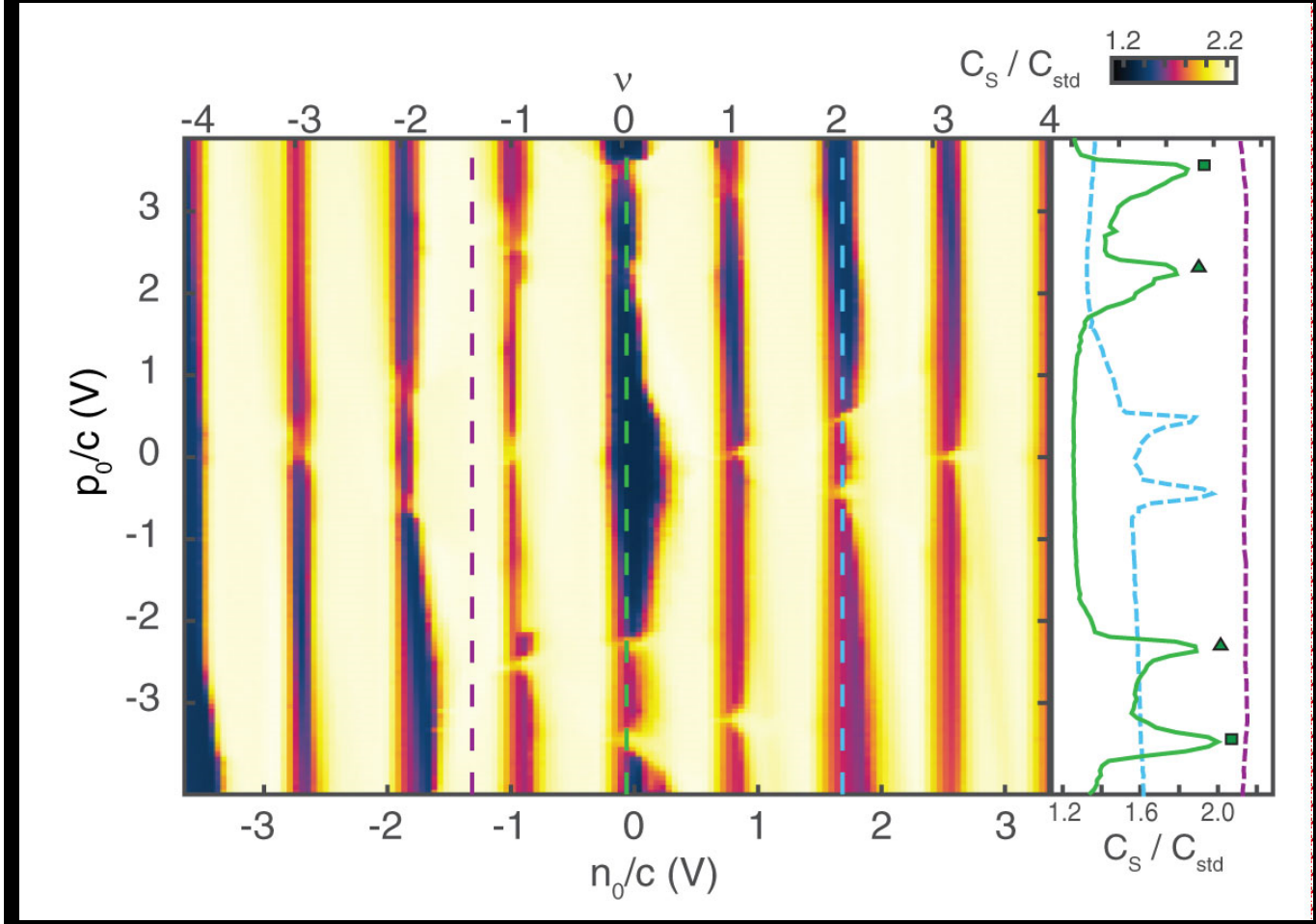


HEMT Cryogenic amplifiers
Ashoori *PRL* (1991)



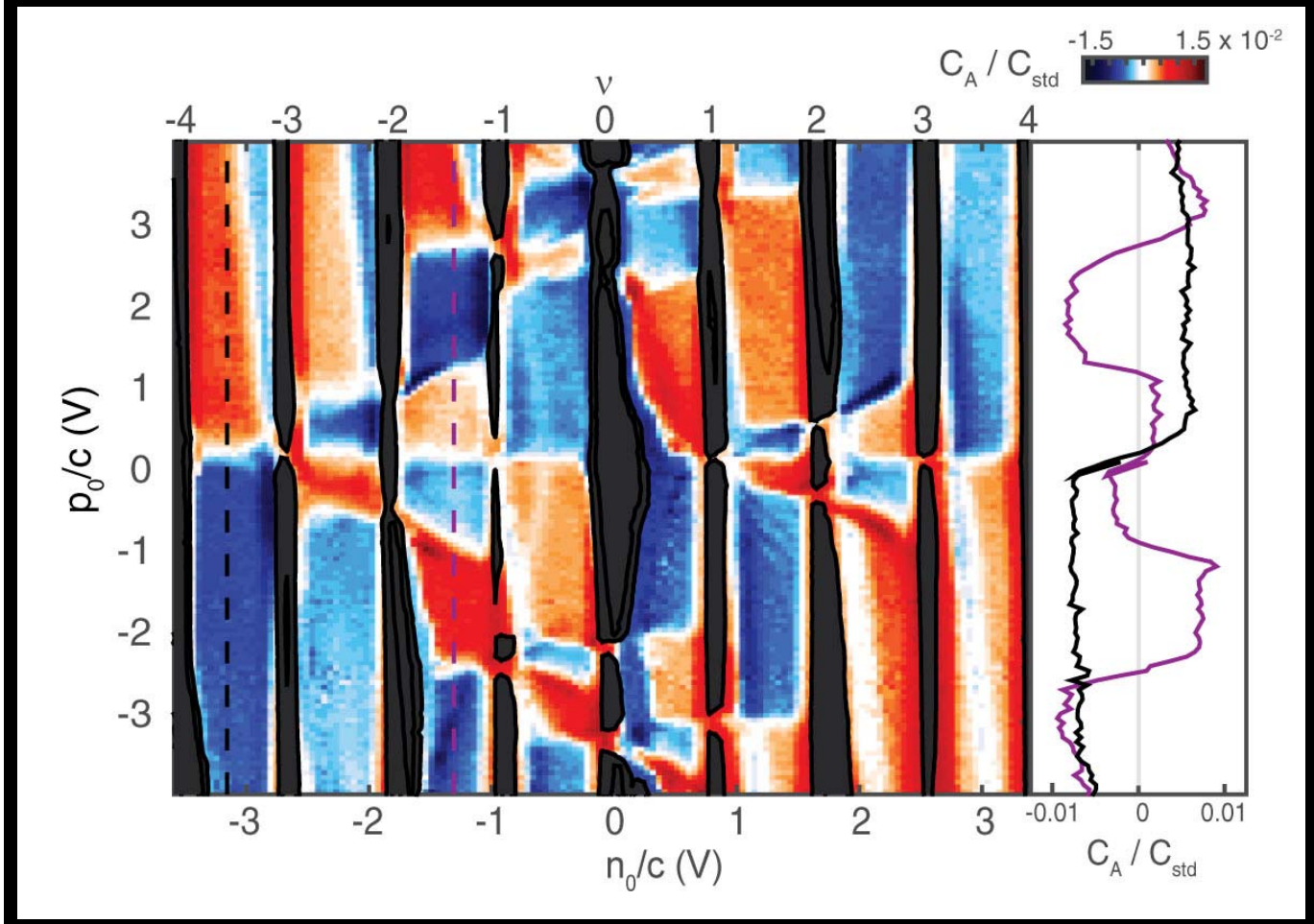


Bilayer graphene: 31T



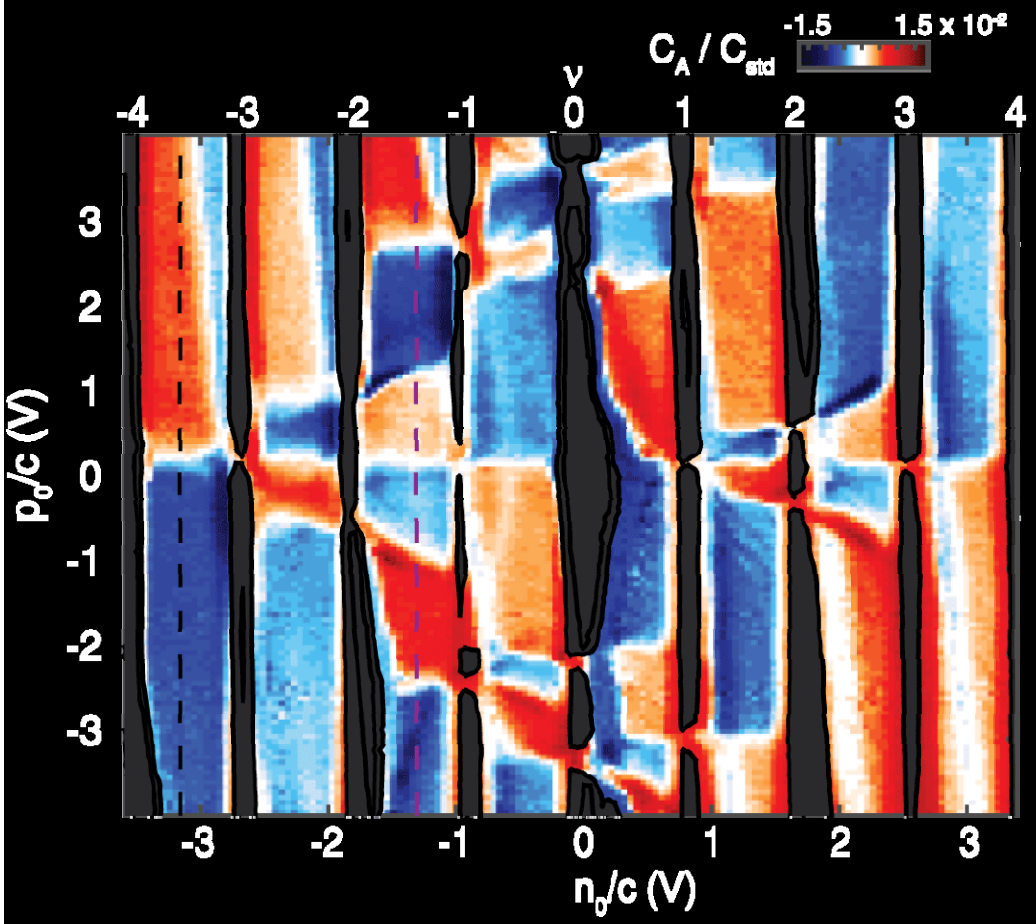
16 compressibility transitions

Bilayer graphene: 31T



- C_A: richer phase diagram
- red/blue ➔top/bottom
- orange/red; blue/cyan ➔???

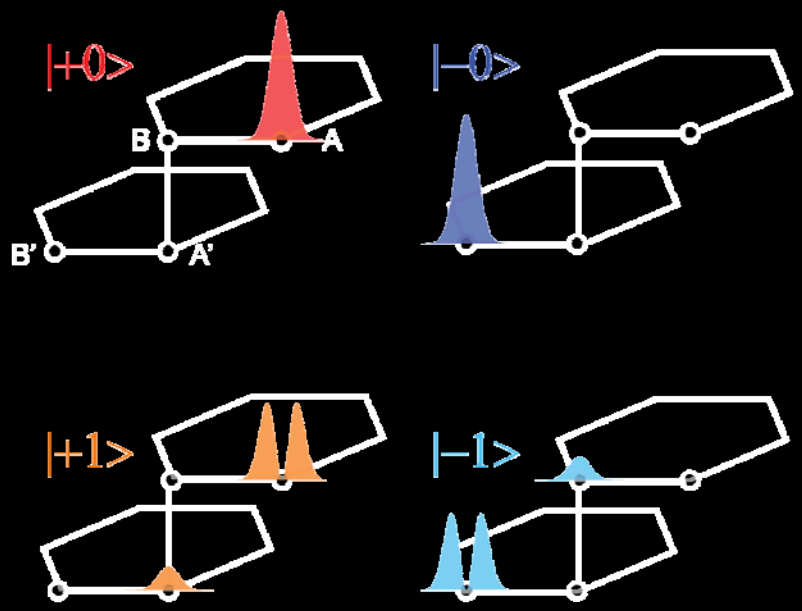
BLG, B=31T (ZLL)



4 Band Orbital Wavefunctions

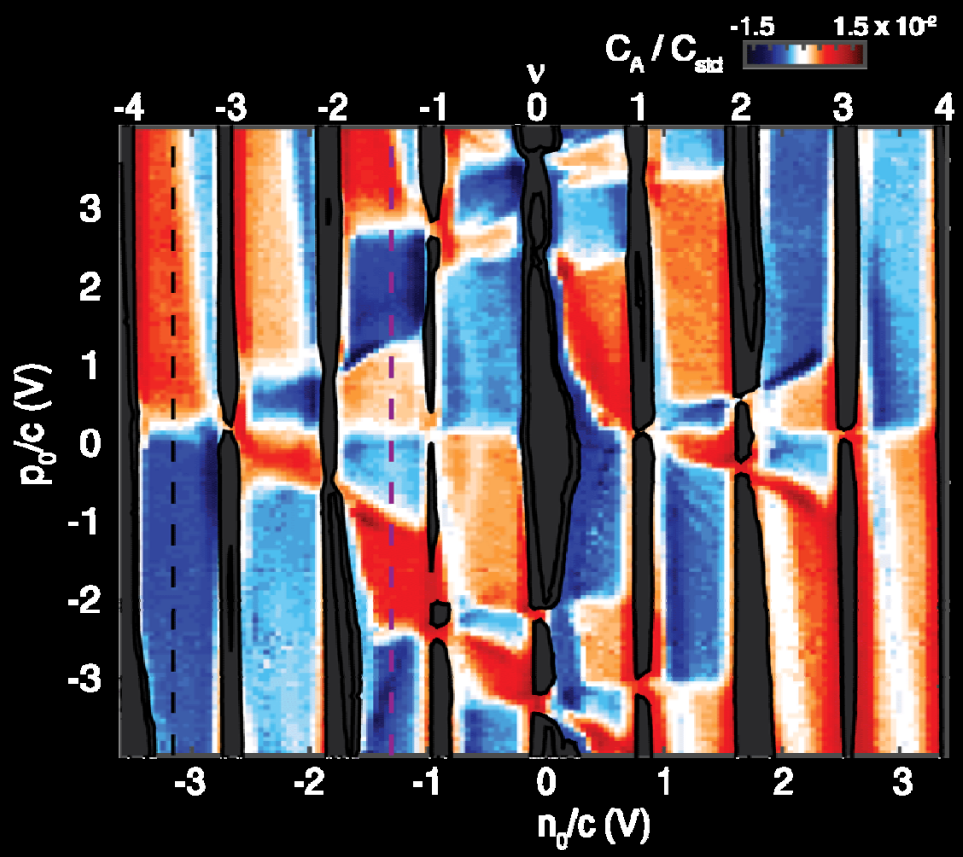
$$\psi_0 = \begin{pmatrix} |0\rangle \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad \psi_1 = \begin{pmatrix} \alpha|1\rangle \\ 0 \\ \beta|0\rangle \\ \gamma|0\rangle \end{pmatrix} \begin{matrix} A \\ B' \\ B \\ A' \end{matrix}$$

$$p = (\alpha^2 + \beta^2) - \gamma^2 \sim 0.6 \; @ \; 31\,T$$



$C_A = \frac{\partial p}{\partial n_0}$: *where did the last electron added go?*

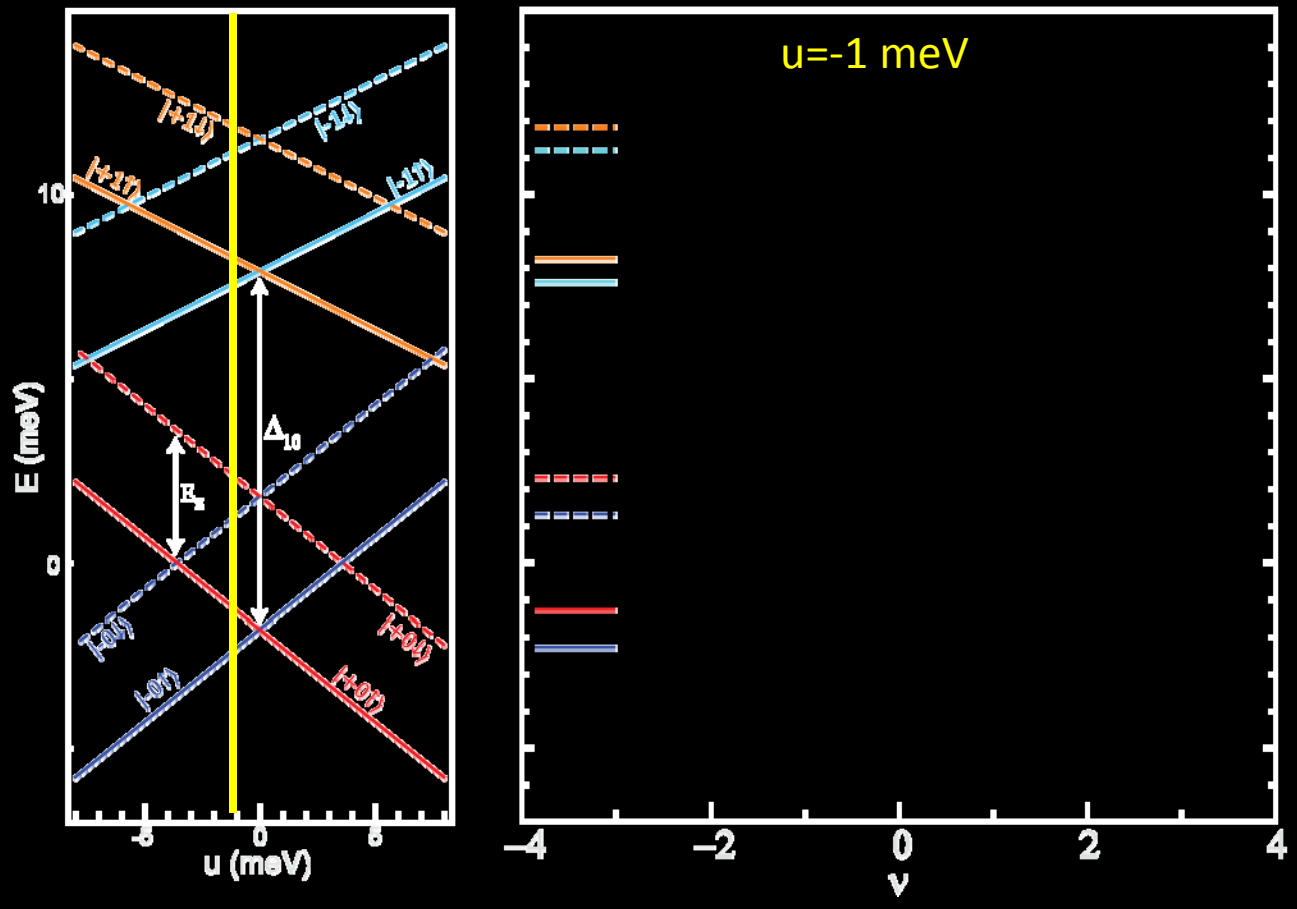
Bilayer graphene: 31T



- High p_0: $|0+\rangle, |1+\rangle$ order respected
- BUT low p_0: $|0+\rangle, |0-\rangle$
- TL;DR: $|NK\sigma\rangle$ levels fill in some order, but *one component at a time*

Constructing a model

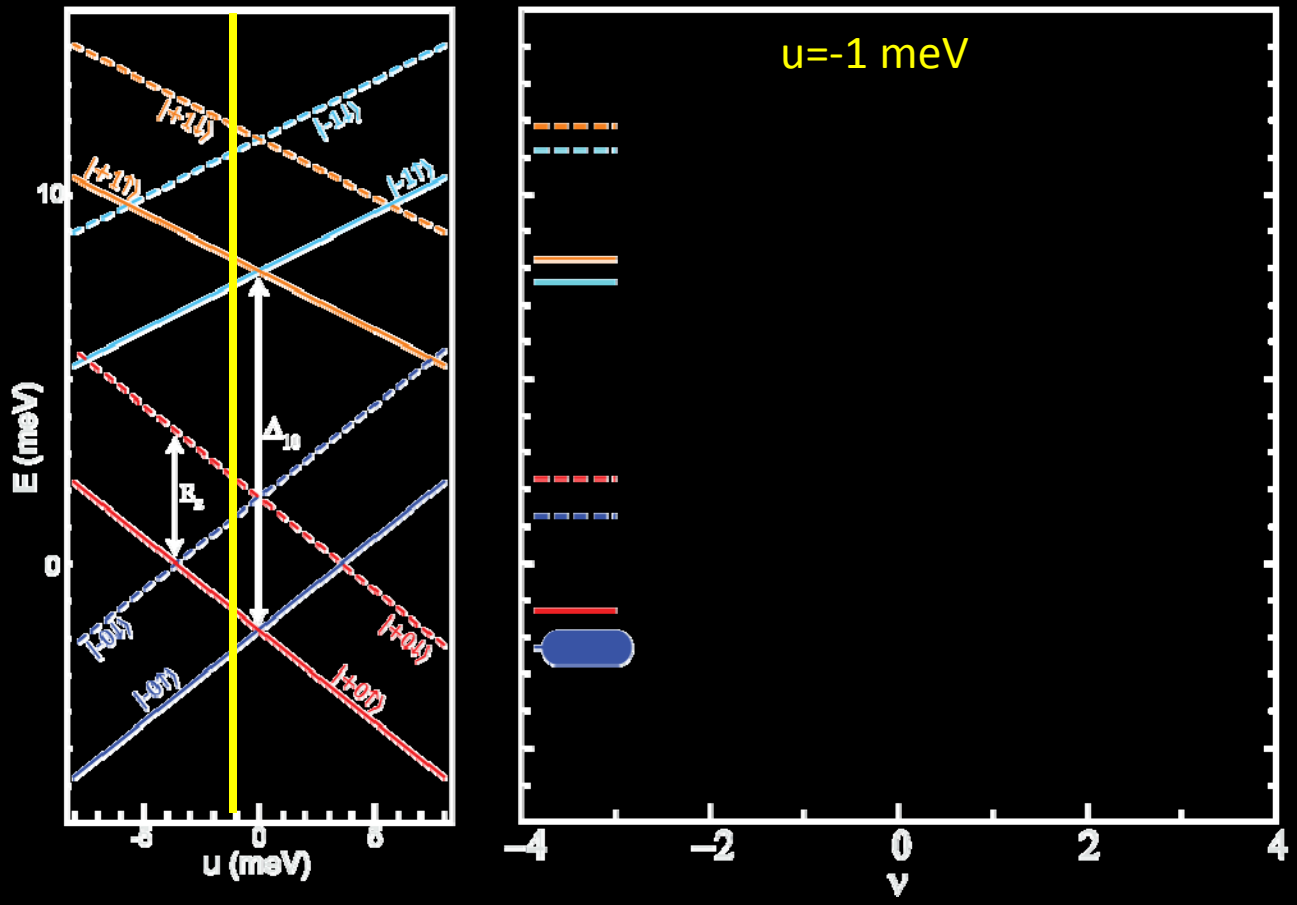
- Single particle energies: E_Z, Δ_{10}, and u



- Basic physics: competition btw. Δ_{10}, ξ_{10}

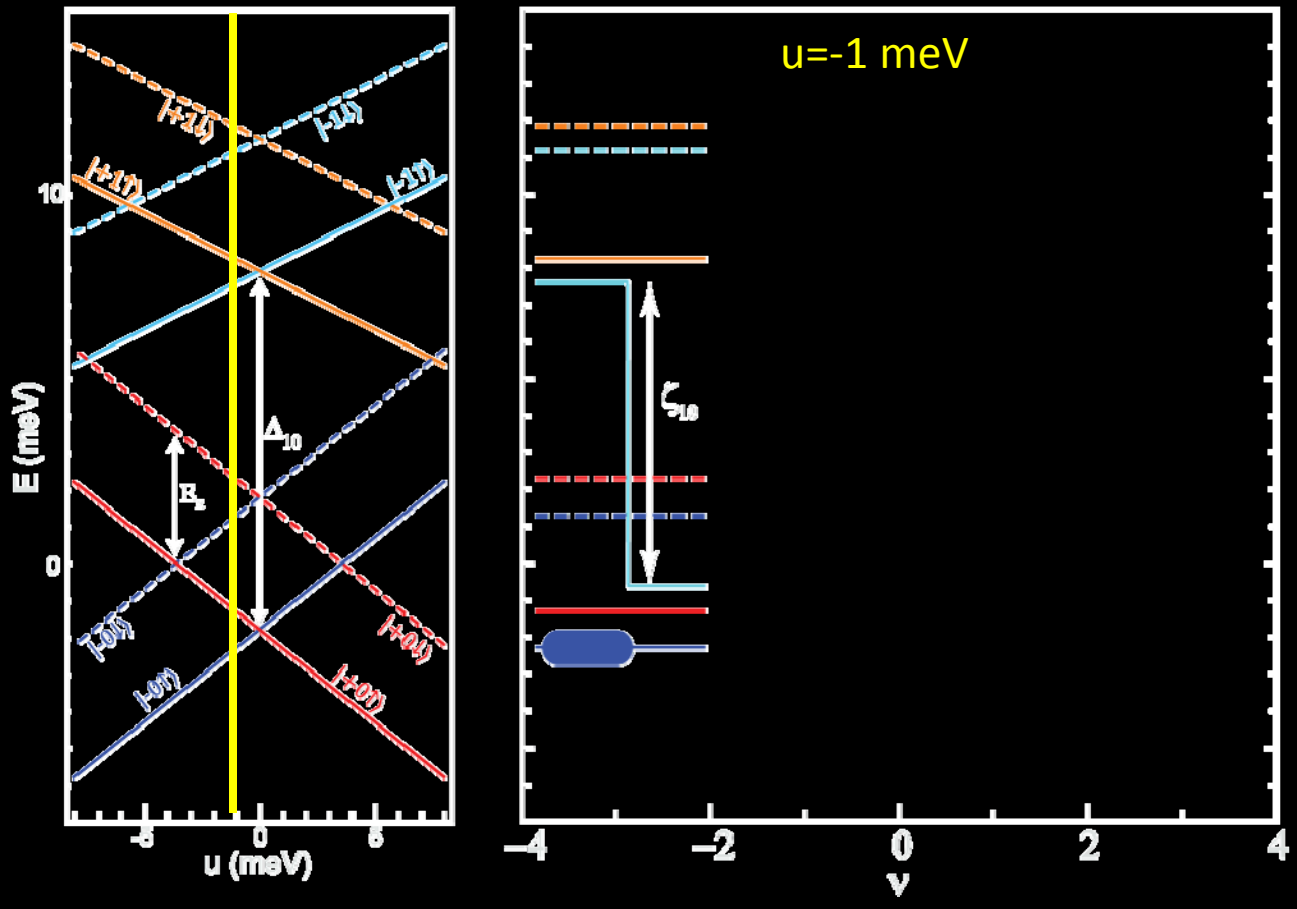
Constructing a model

- Fill lowest energy level first



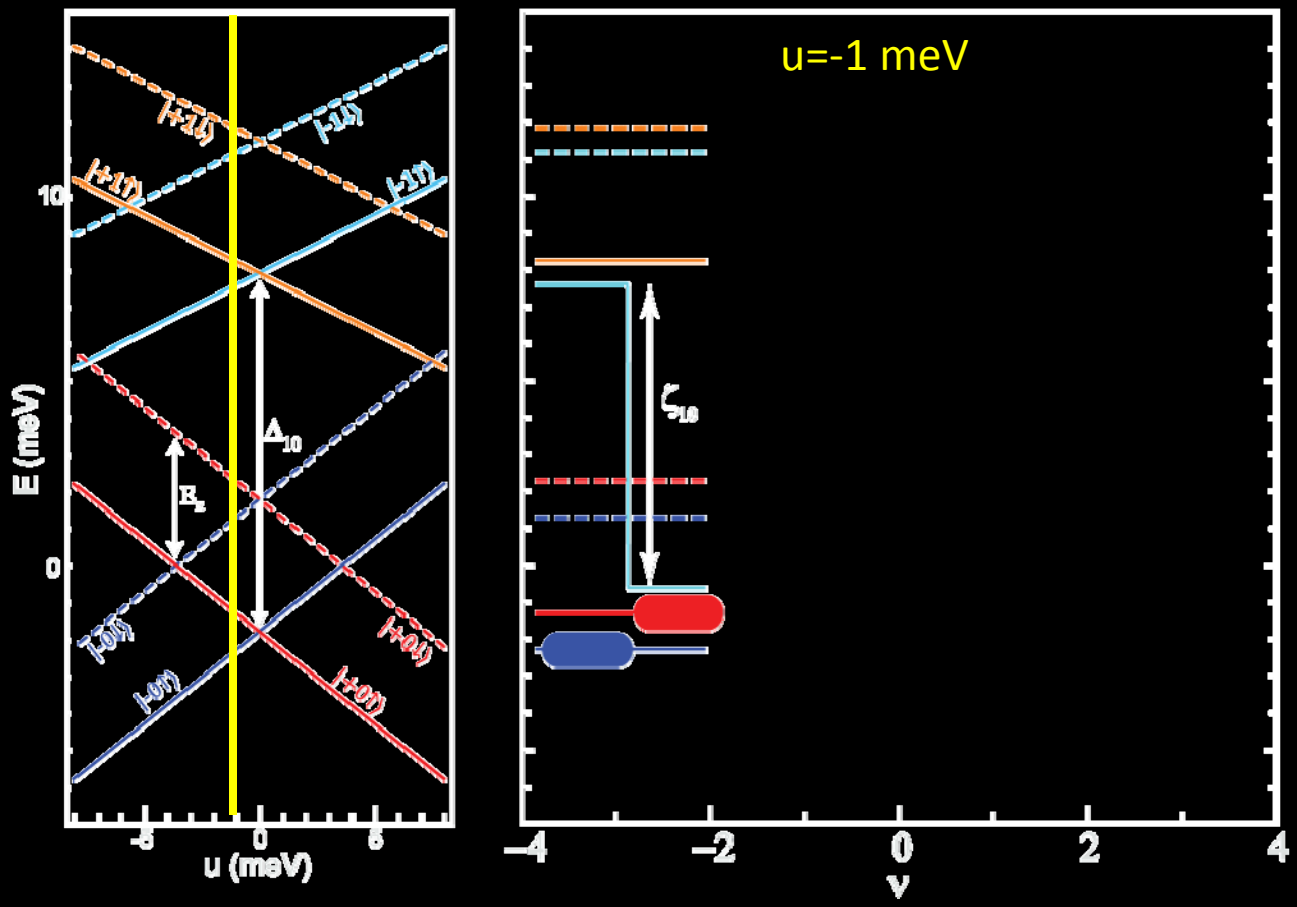
Constructing a model

- Filled $|0\rangle$ lowers empty $|1\rangle$

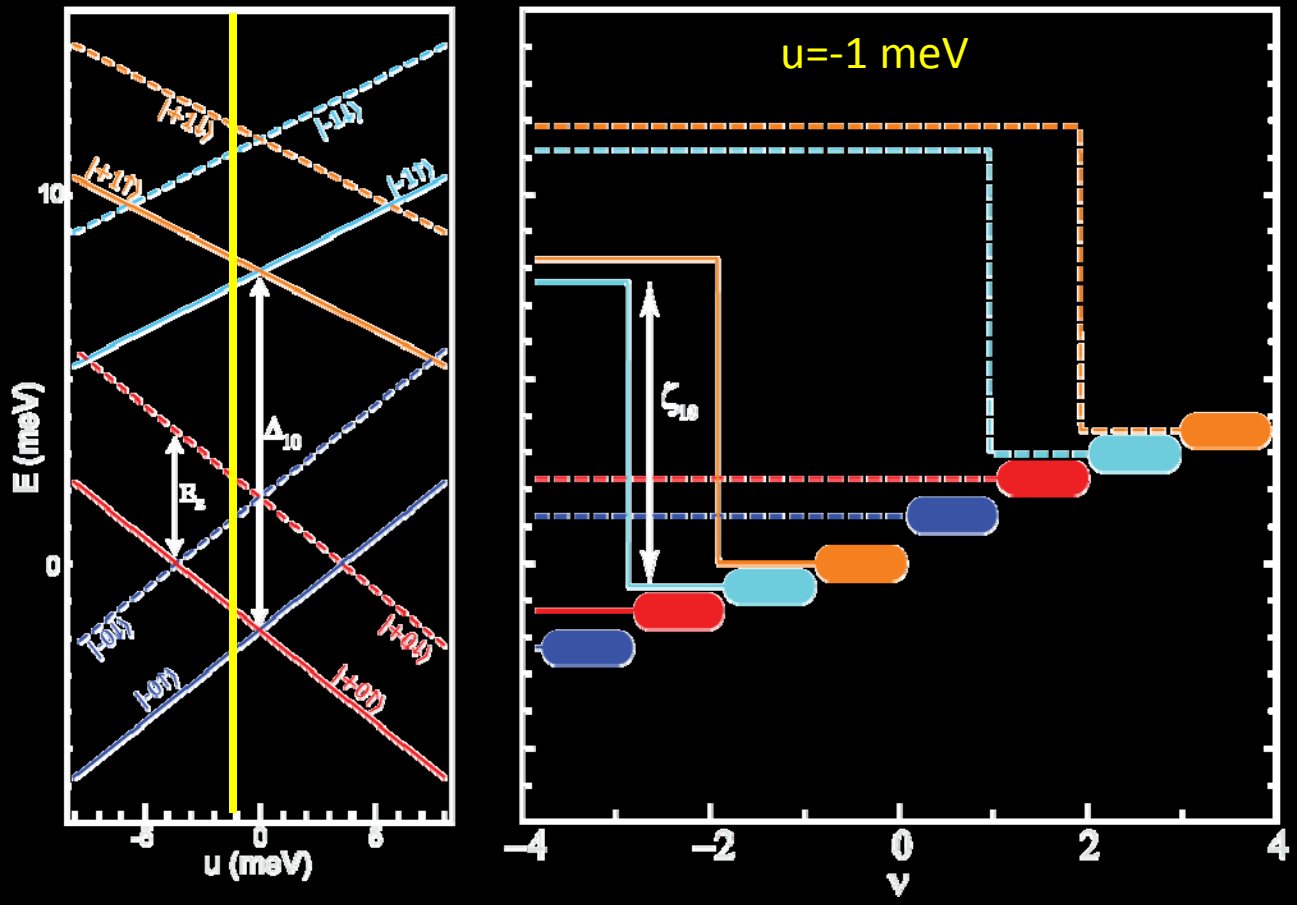


- Enough to overcome Δ_{10} anisotropy?

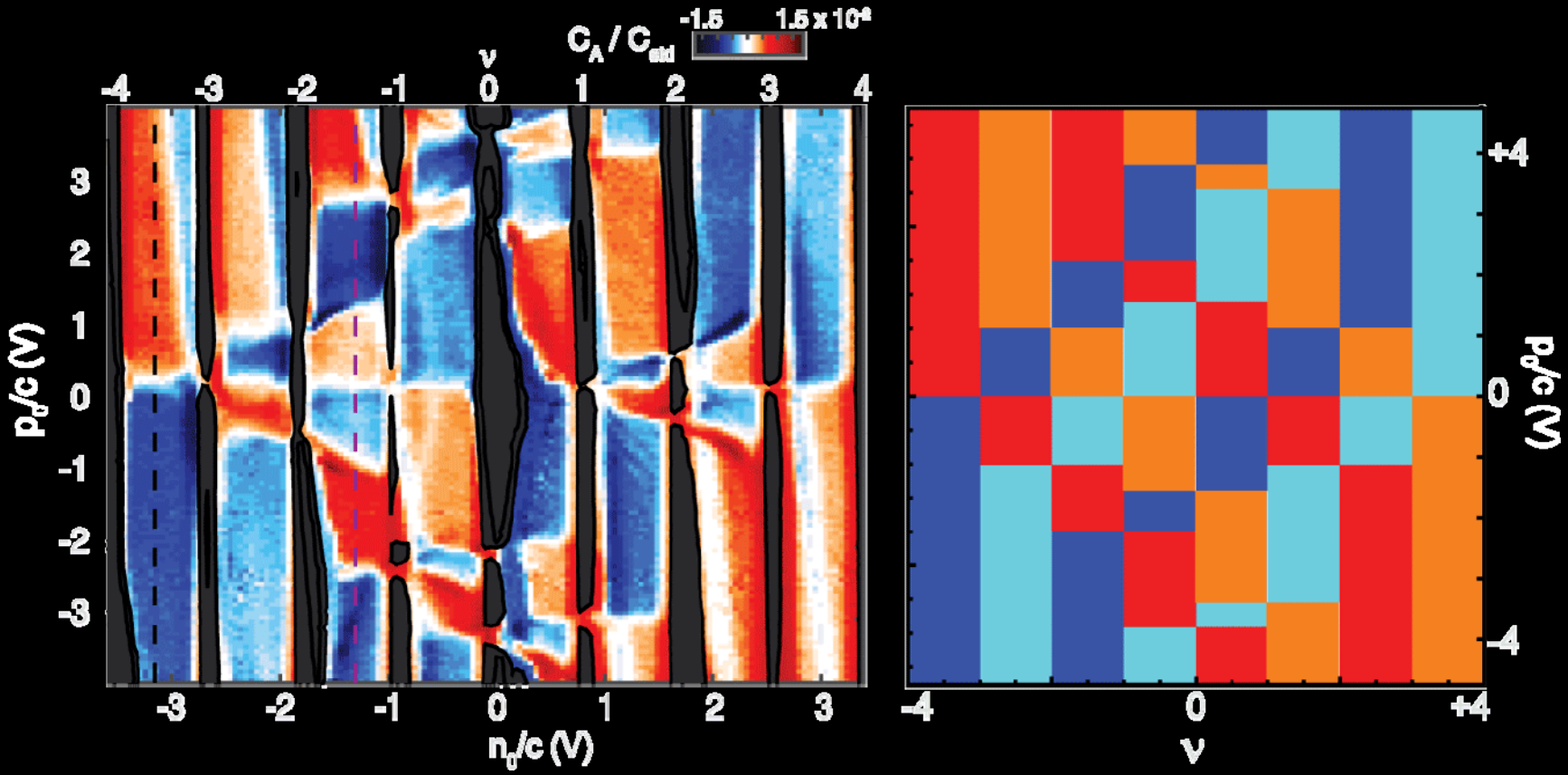
Constructing a model



Constructing a model



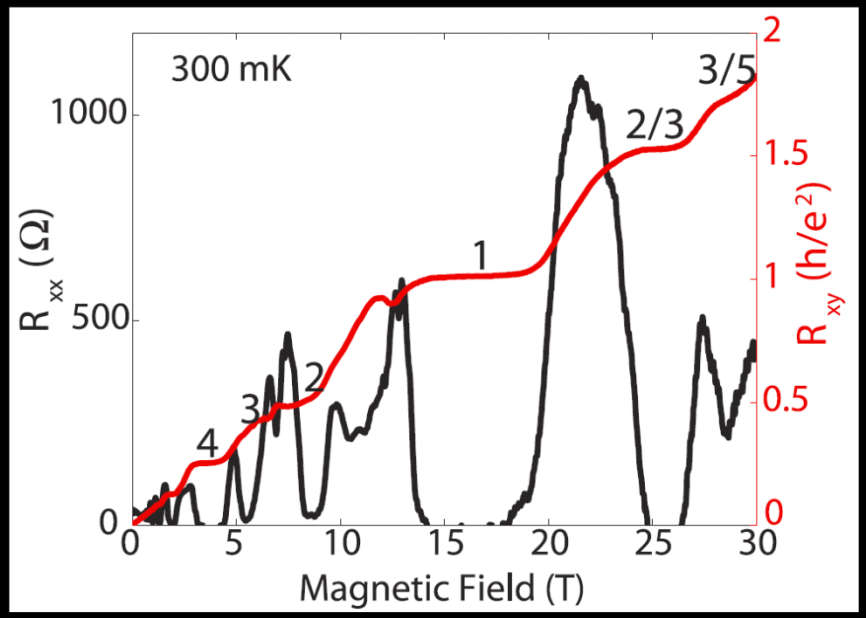
Phase diagram



- Large regions where isospin, orbital physics ‘inert’
- Others with dense orbital/isospin crossings
- Need large $\epsilon \approx 11$ to fit

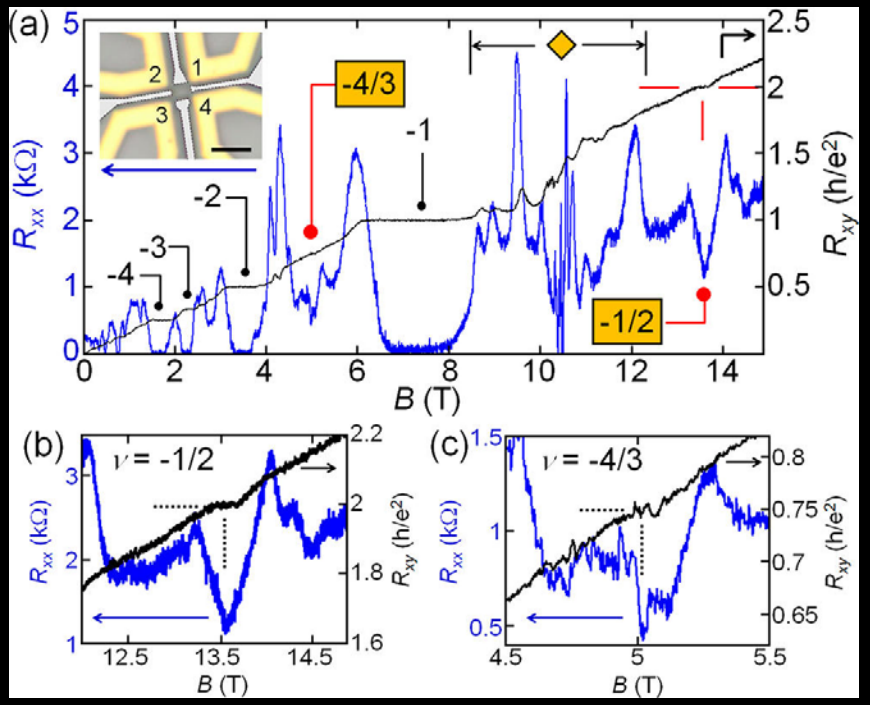
Bilayer graphene FQH: literature

FQHE: 1/3's and 1/5's



Maher 2014
Kou 2014

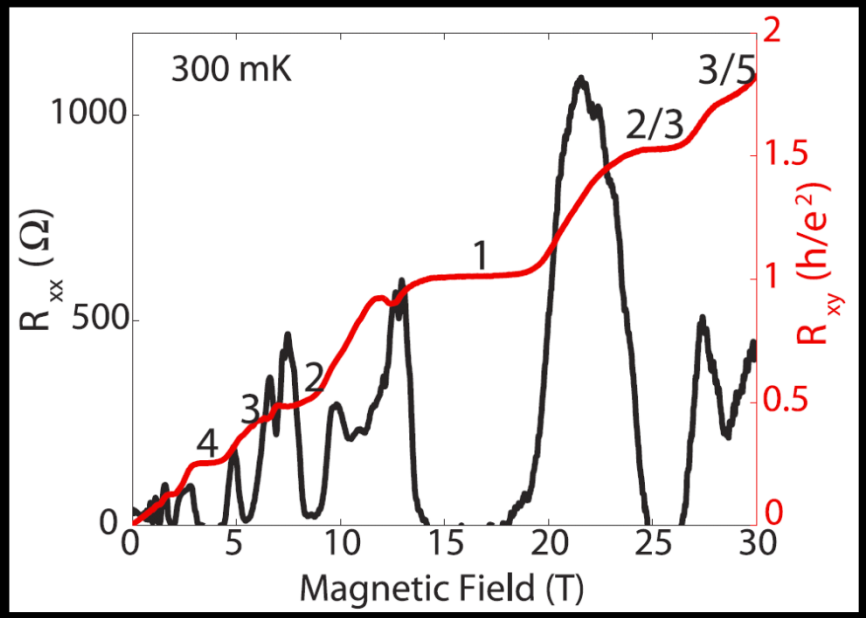
Even denominator – Pfaffian?



Ki 2014

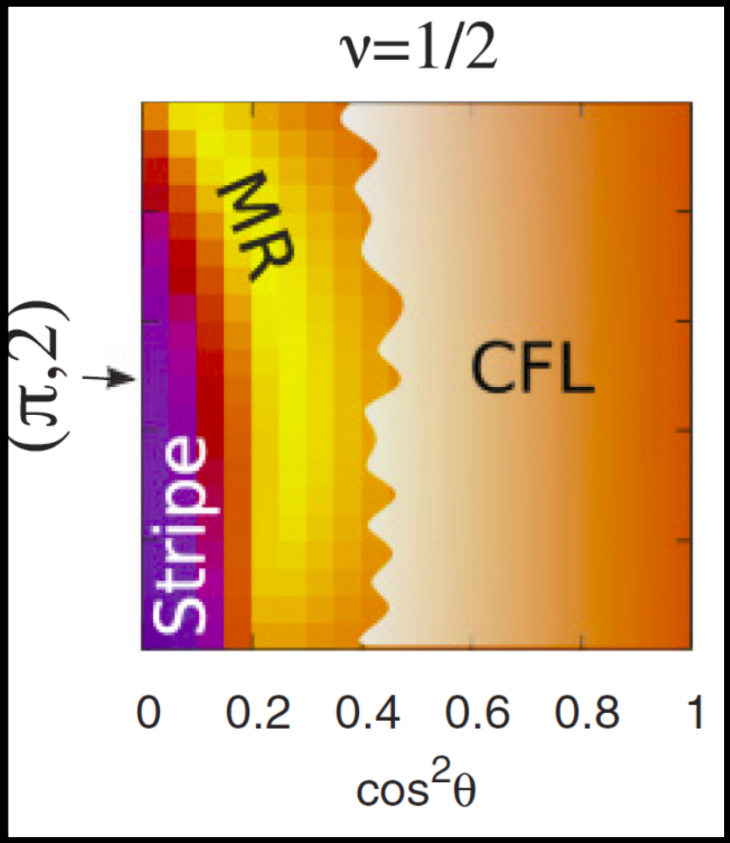
Bilayer graphene FQH: literature

FQHE: 1/3's and 1/5's



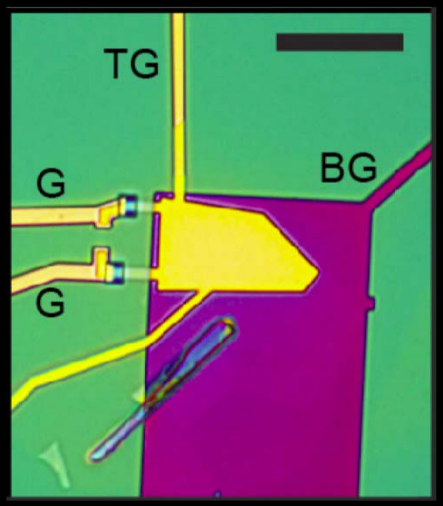
Maher 2014
Kou 2014

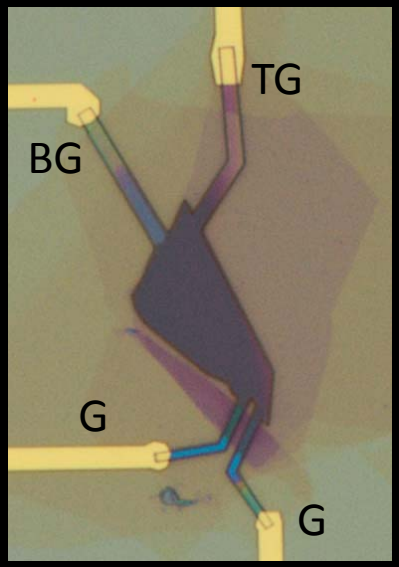
Even denominator – Pfaffian?

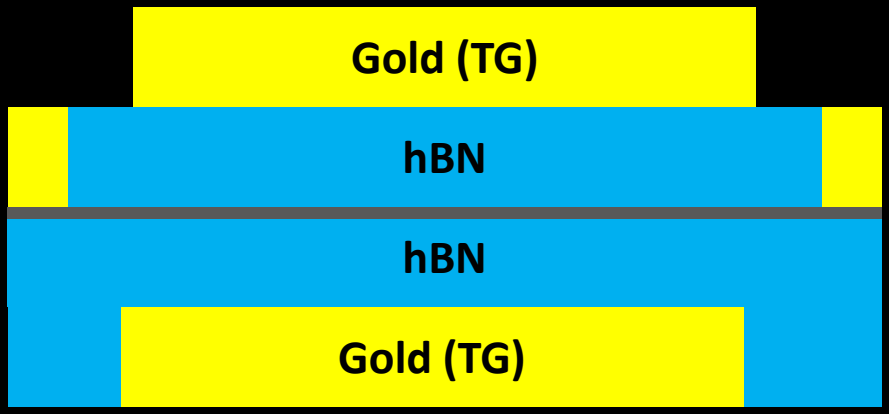


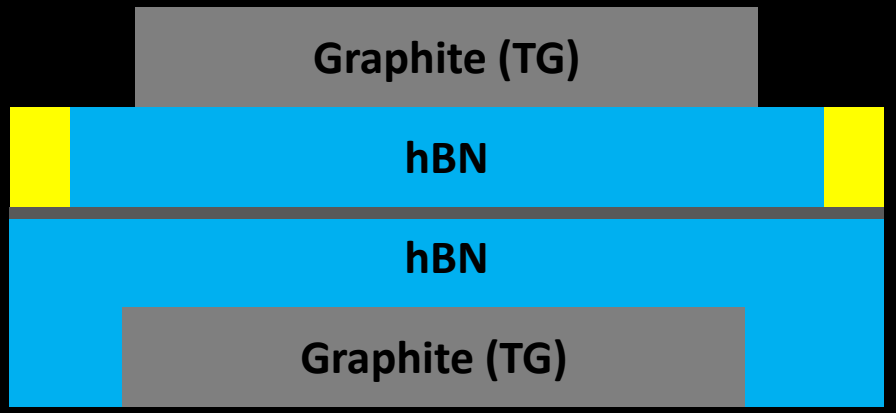
Papic 2011
Apalkov 2011
Papic 2014

What limits sample quality?



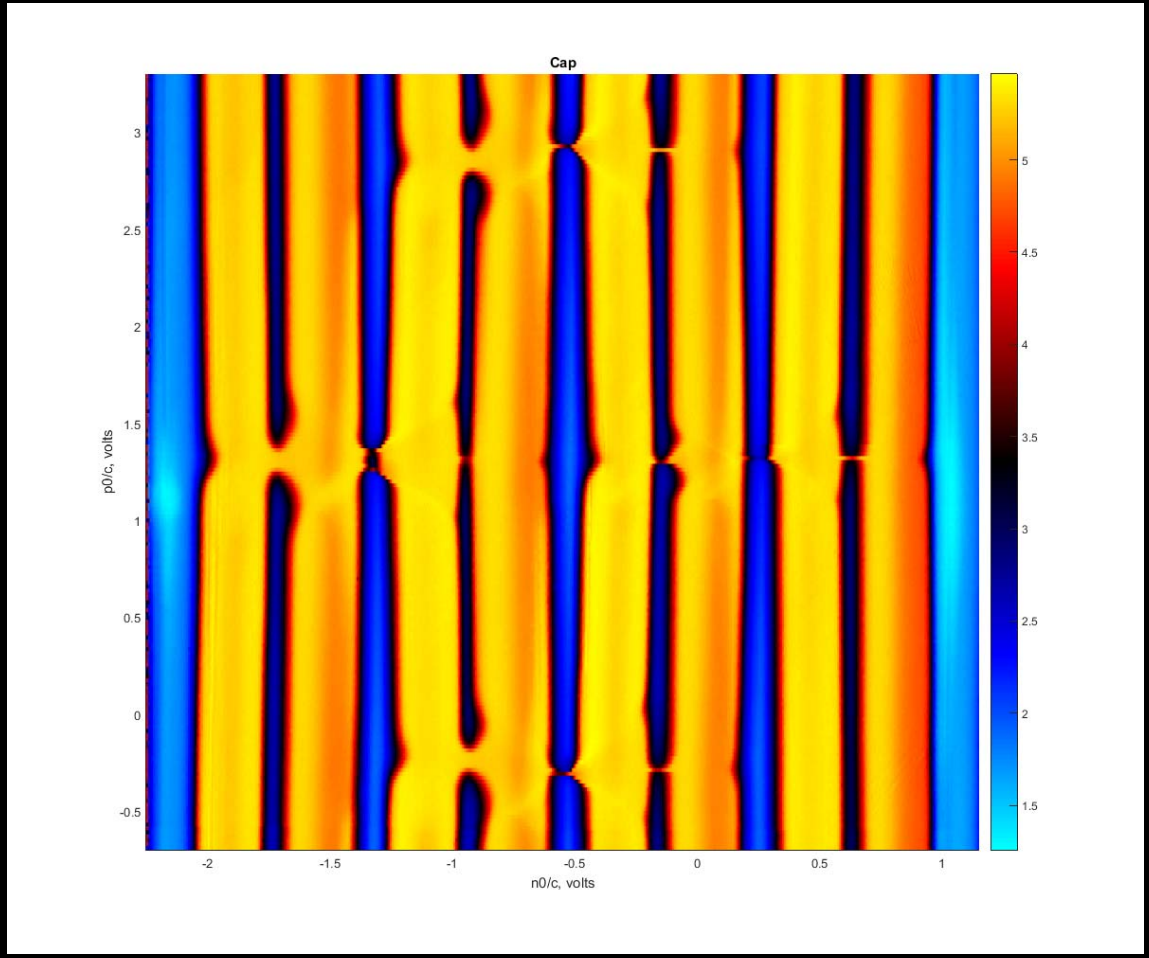




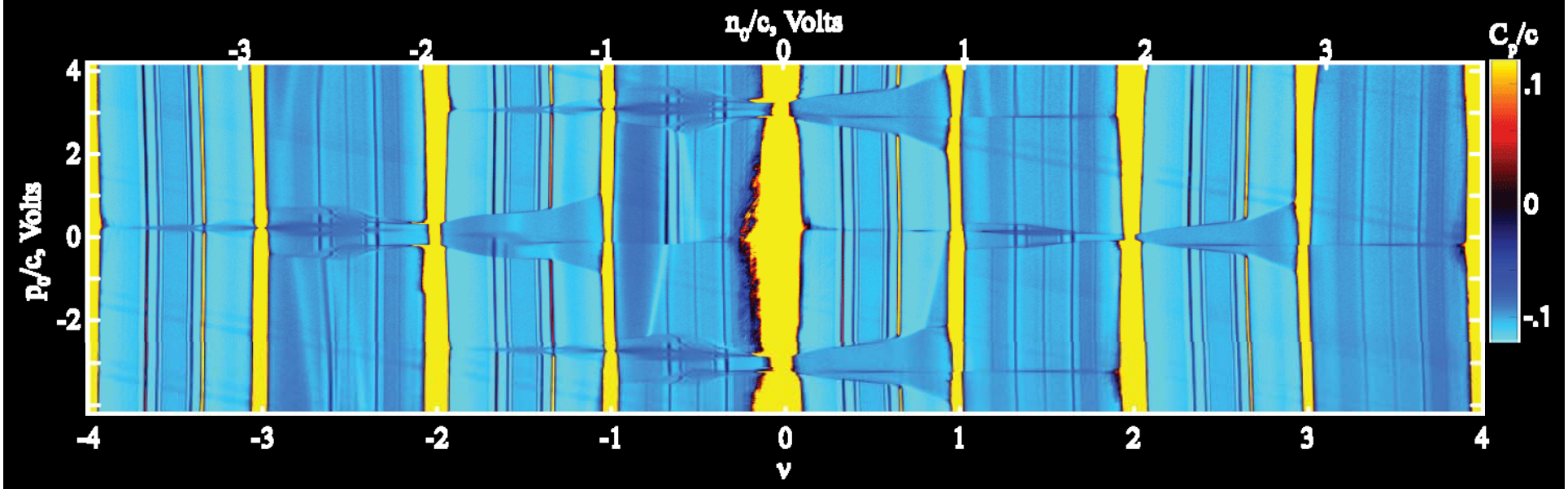


Metal gates – IQHE gaps

B=10T; $T \approx 50\ mK$, C_S

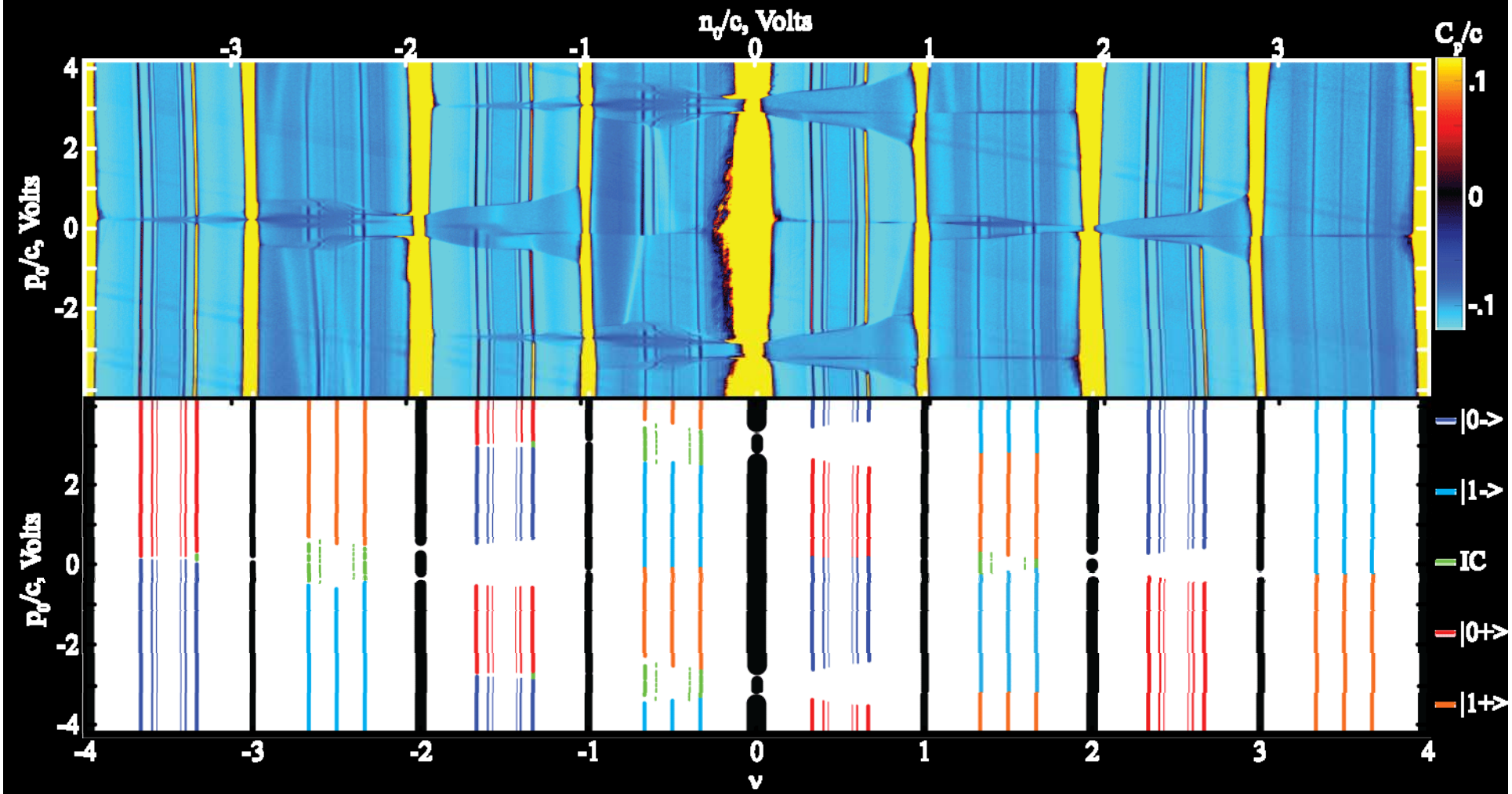


Graphite gates – FQHE!



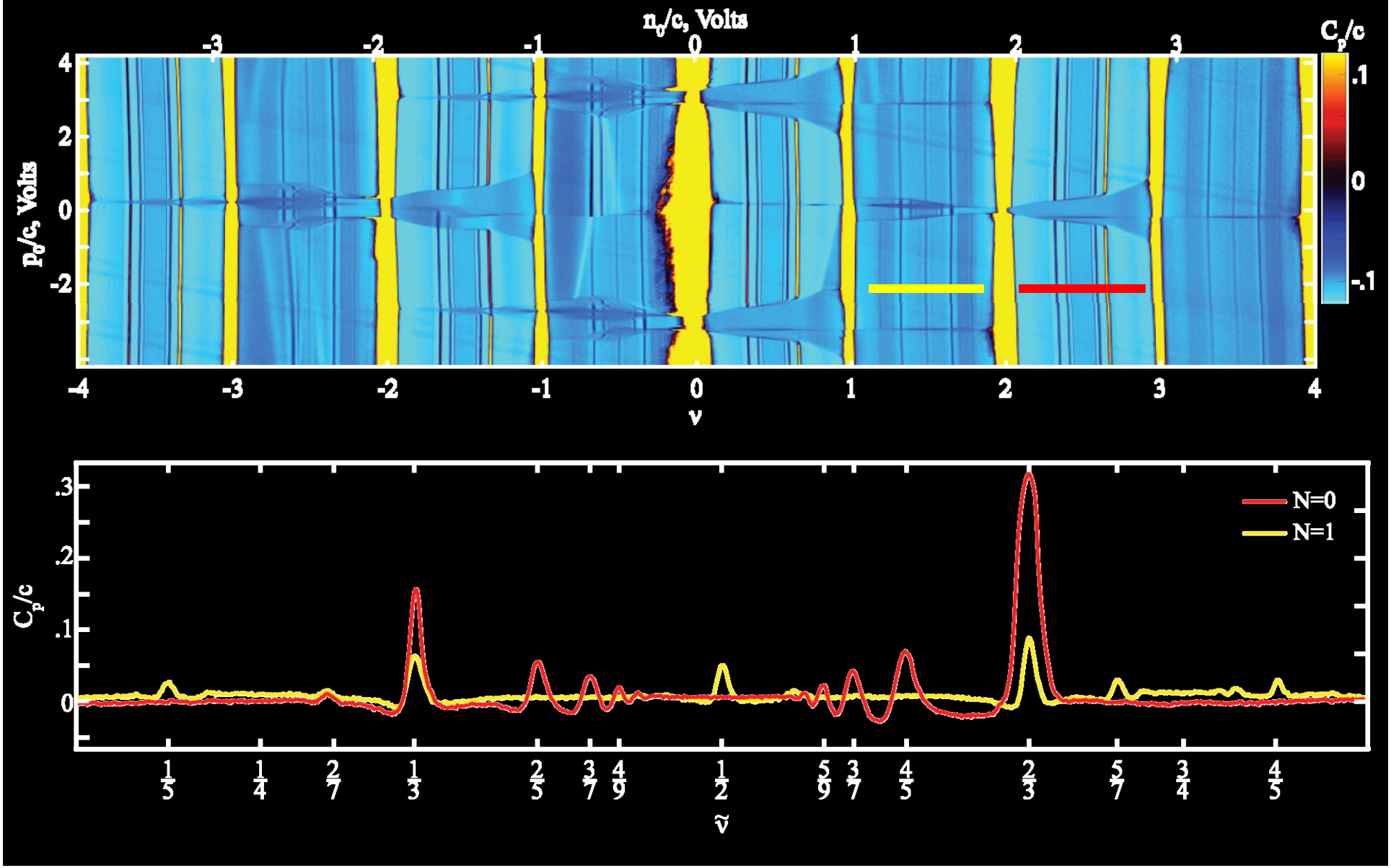
- Incompressible states at fractional filling throughout ZLL
- Many phase transitions – same # at integer ν, many more at fractional ν

Fractional quantum Hall effect

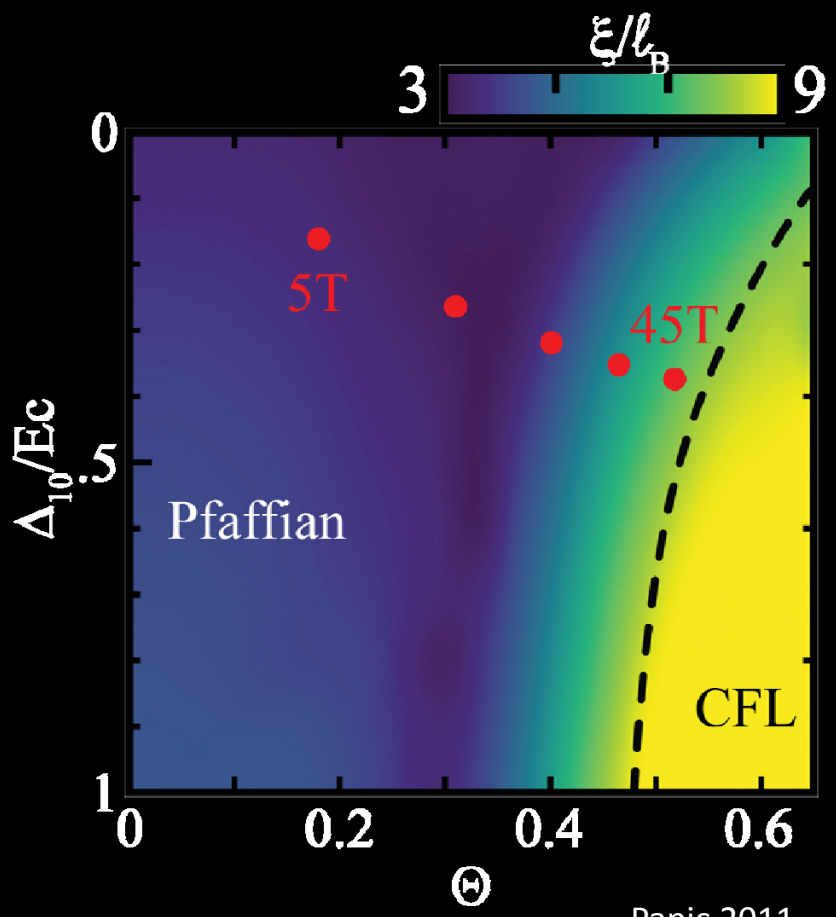


- Three generic ‘regimes’: $|0\rangle$, $|1\rangle$, interlayer correlated

Fractional quantum Hall effect



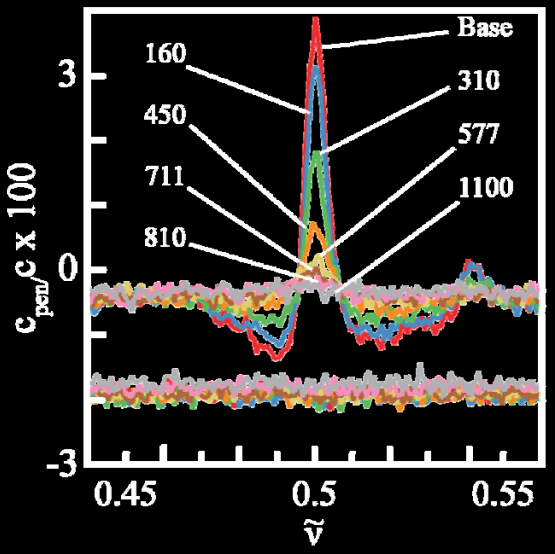
Pfaffian

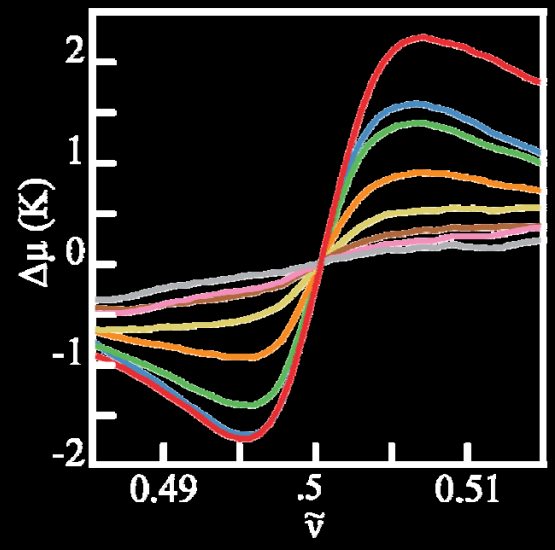


Papic 2011
Papic 2014

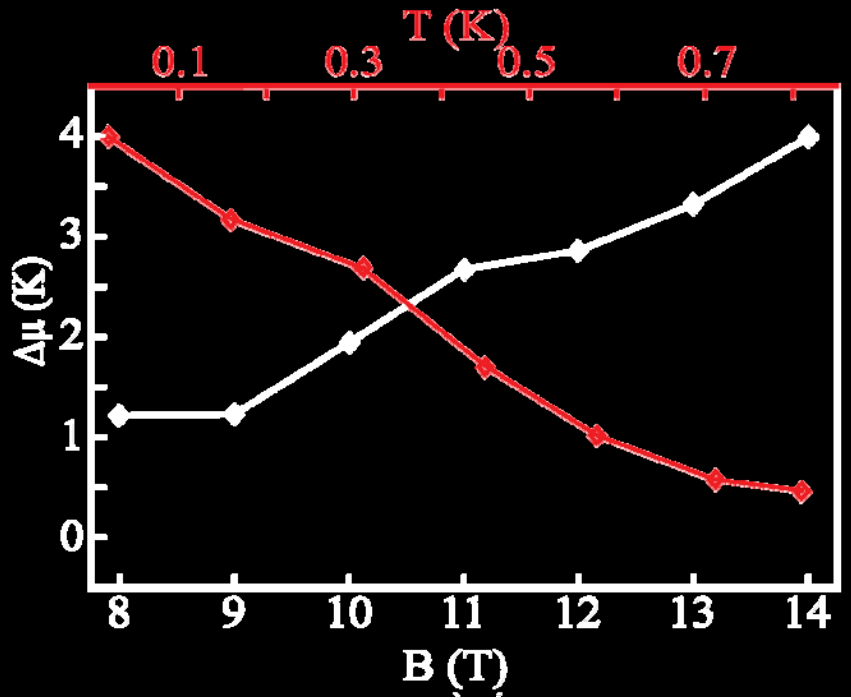
- Even denominator observed in most single component $|1\rangle$ regimes
- Pfaffian strongly favored in numerics
- Accurate LL mixing, wavefunction form factors

Pfaffian gap

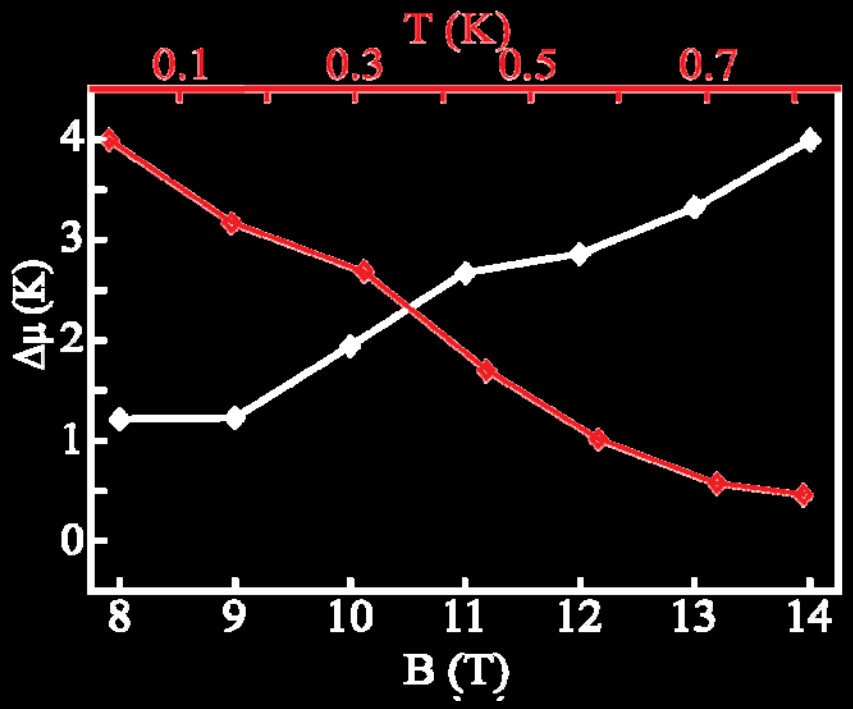


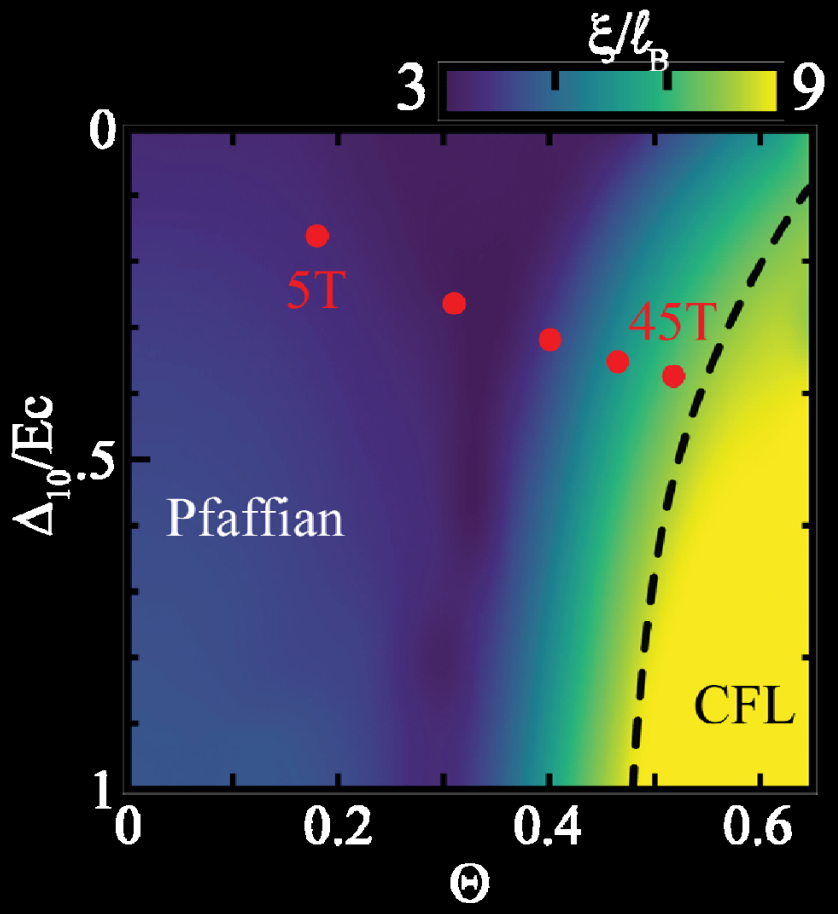


- $\frac{C_P}{c} \approx \frac{\partial \mu}{\partial n}$
- $\Delta\mu = \int \frac{\partial \mu}{\partial n} dn_0$
- $\frac{\mathrm{e}}{\mathrm{q}} \Delta\mu \simeq 4 \times \Delta_{act}$

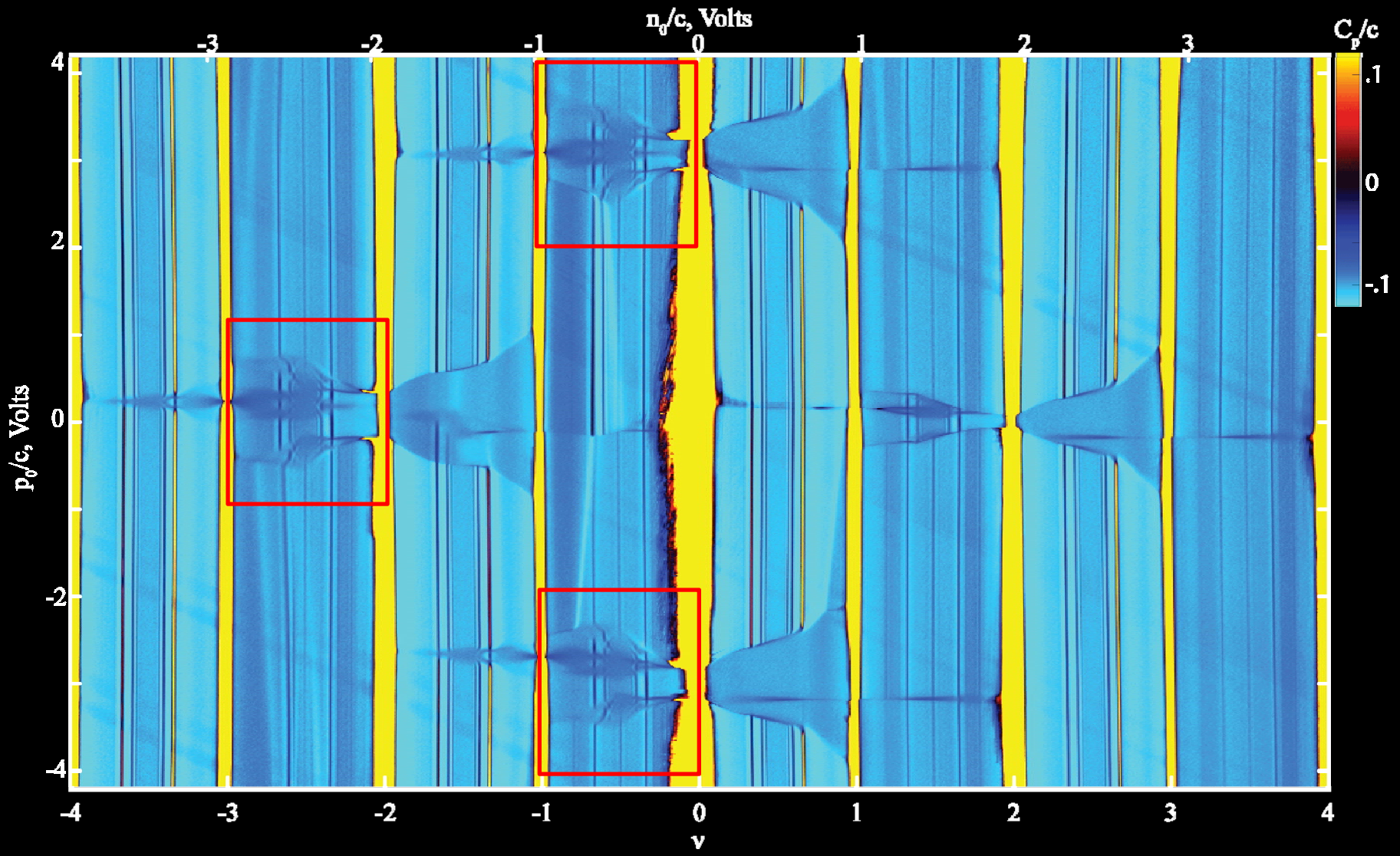


Pfaffian gap

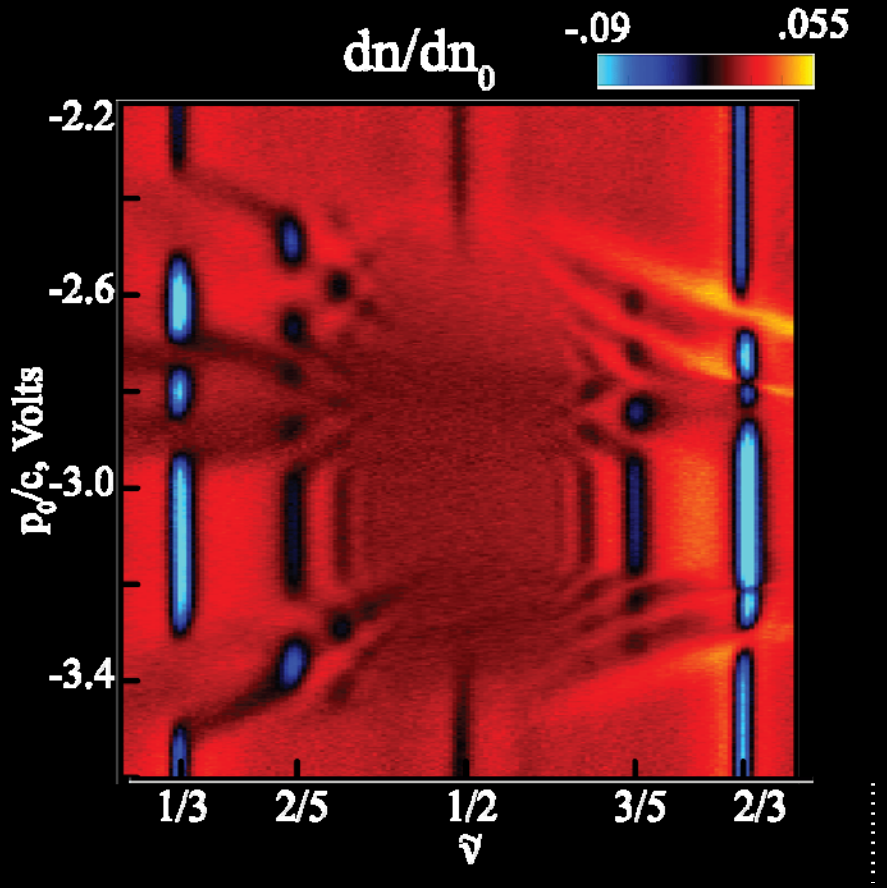


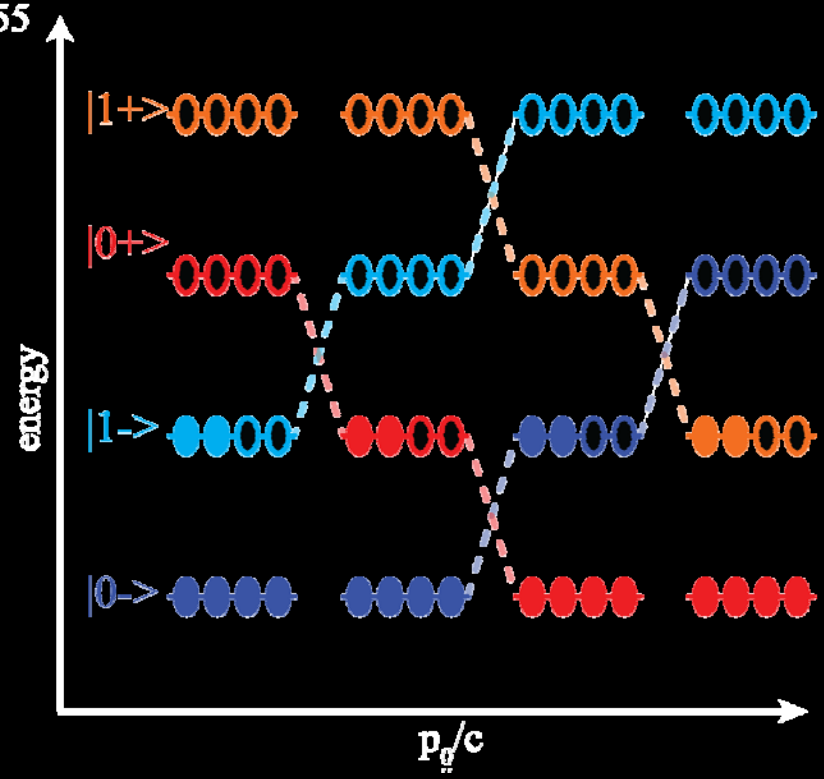


FQHE near level crossings

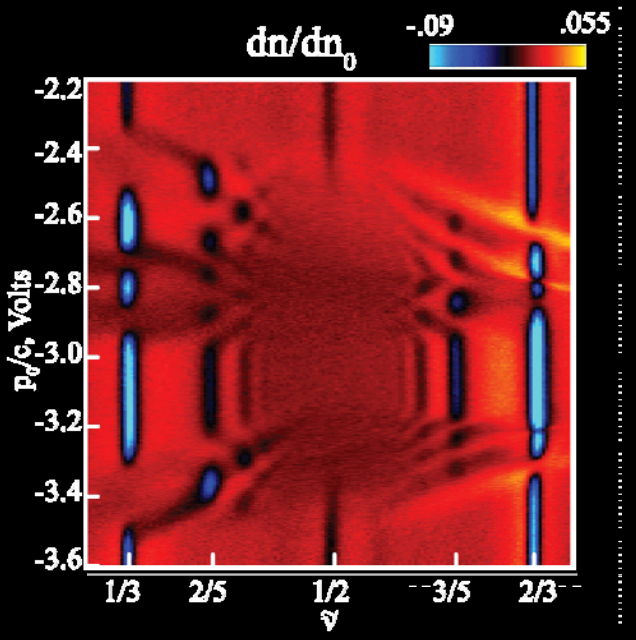


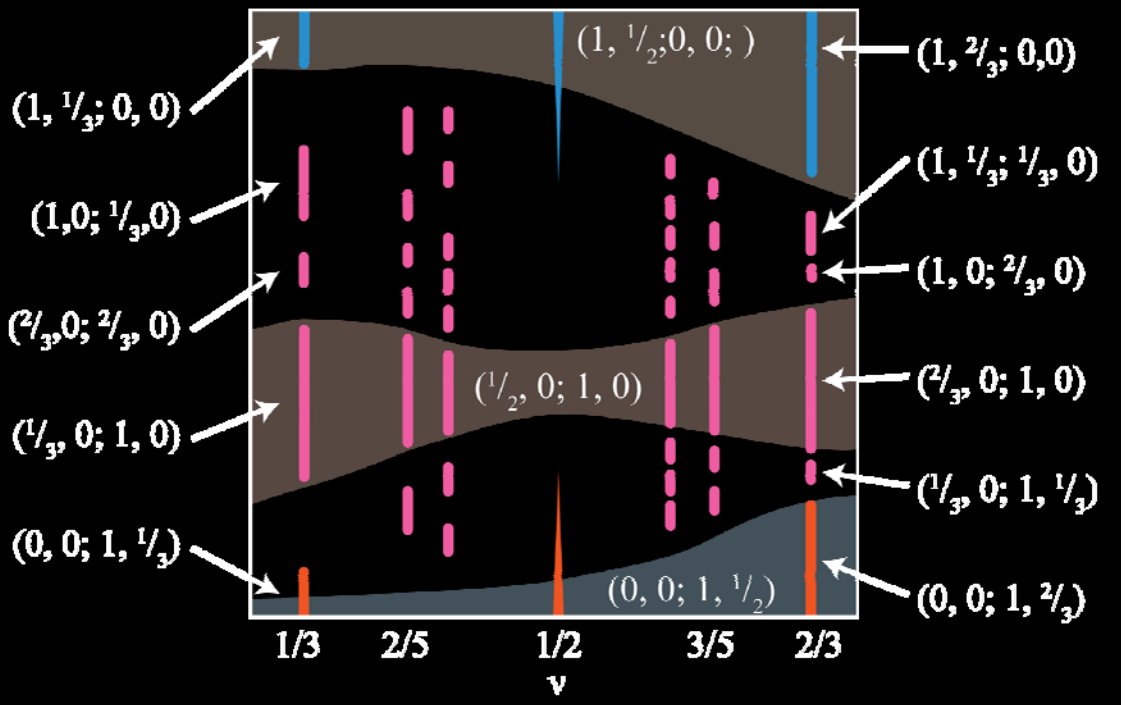
FQHE near level crossings



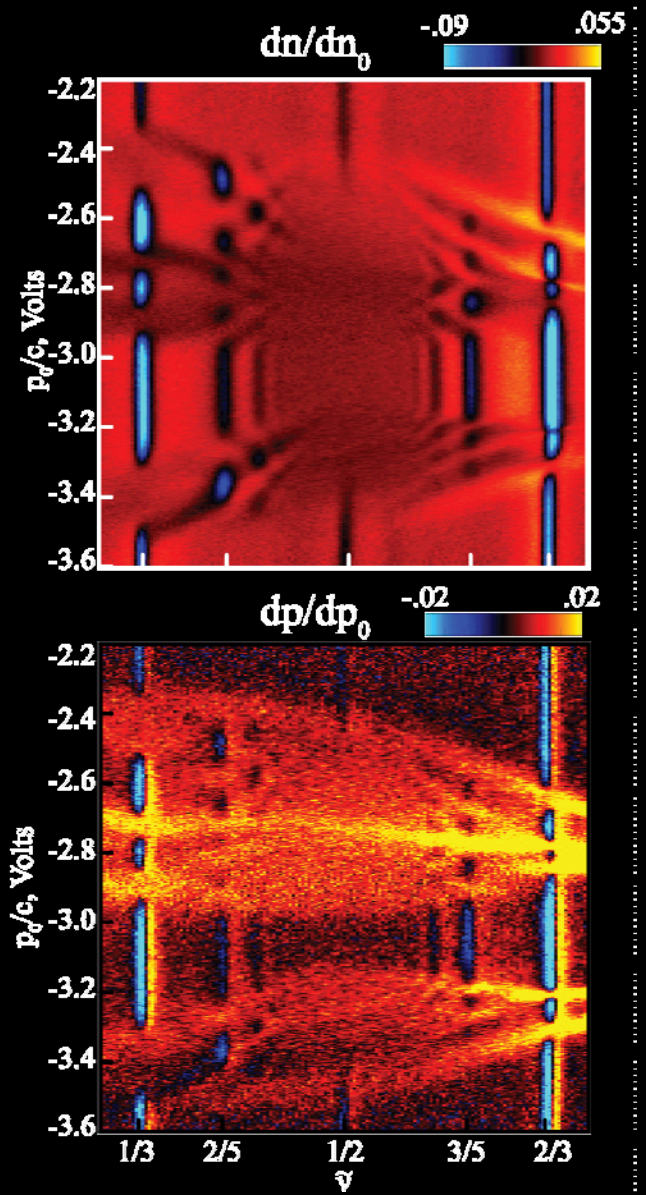


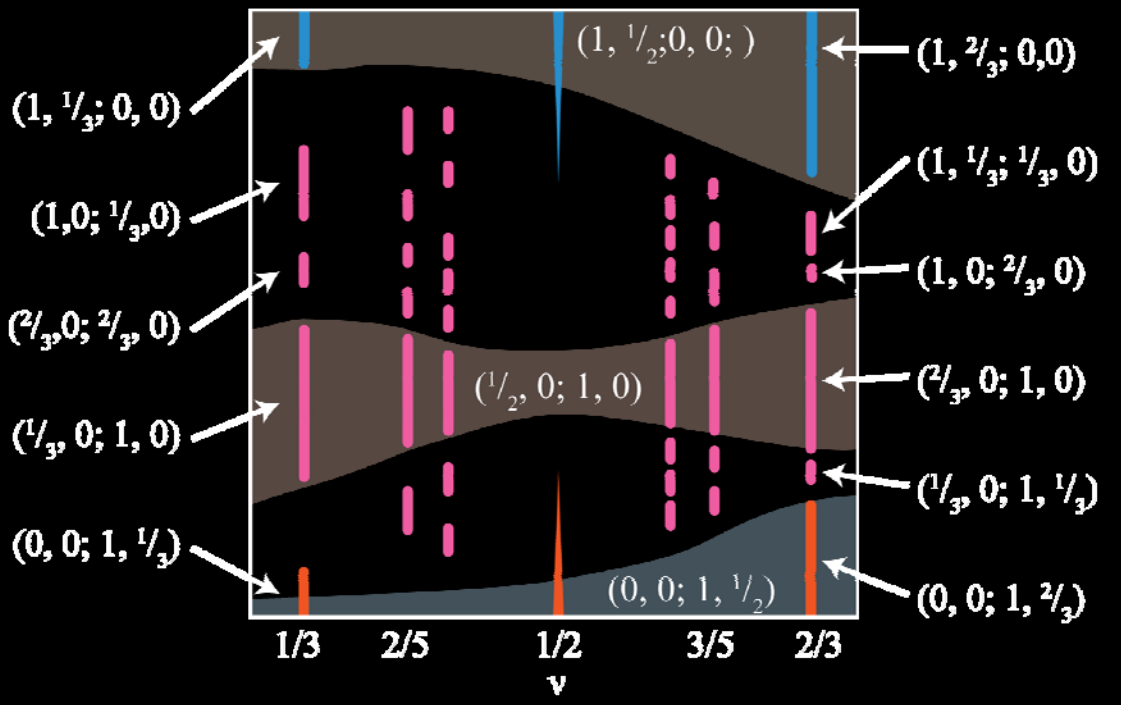
FQHE near level crossings





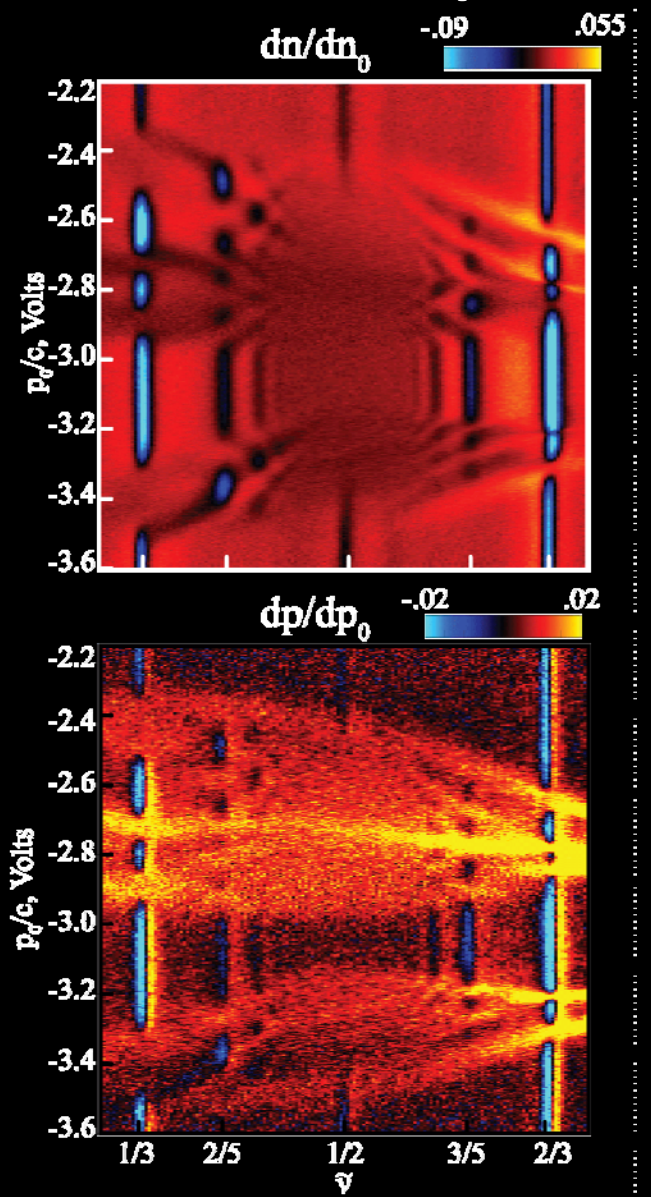
FQHE near level crossings

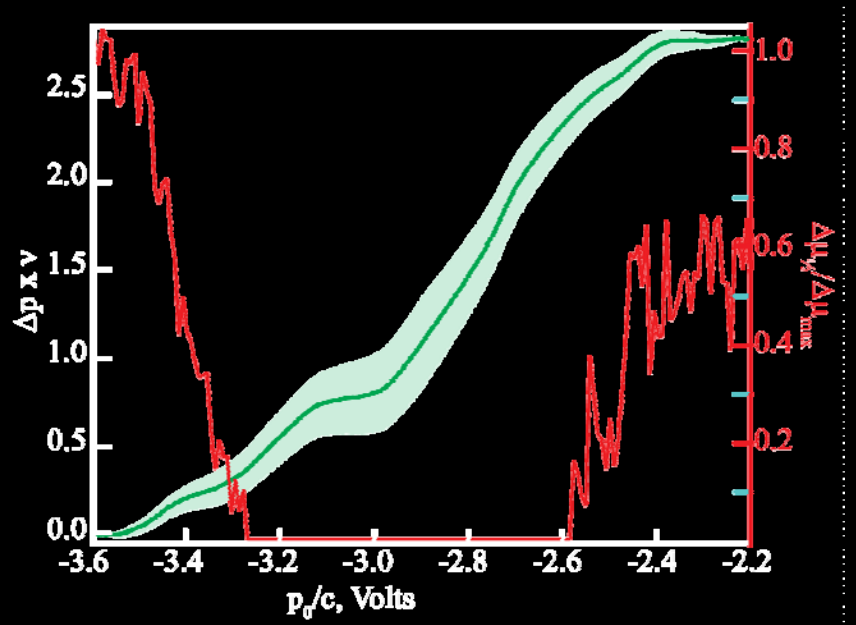




- Odd denominators: sharp phase transitions, hierarchy
- Even denominator: smooth?

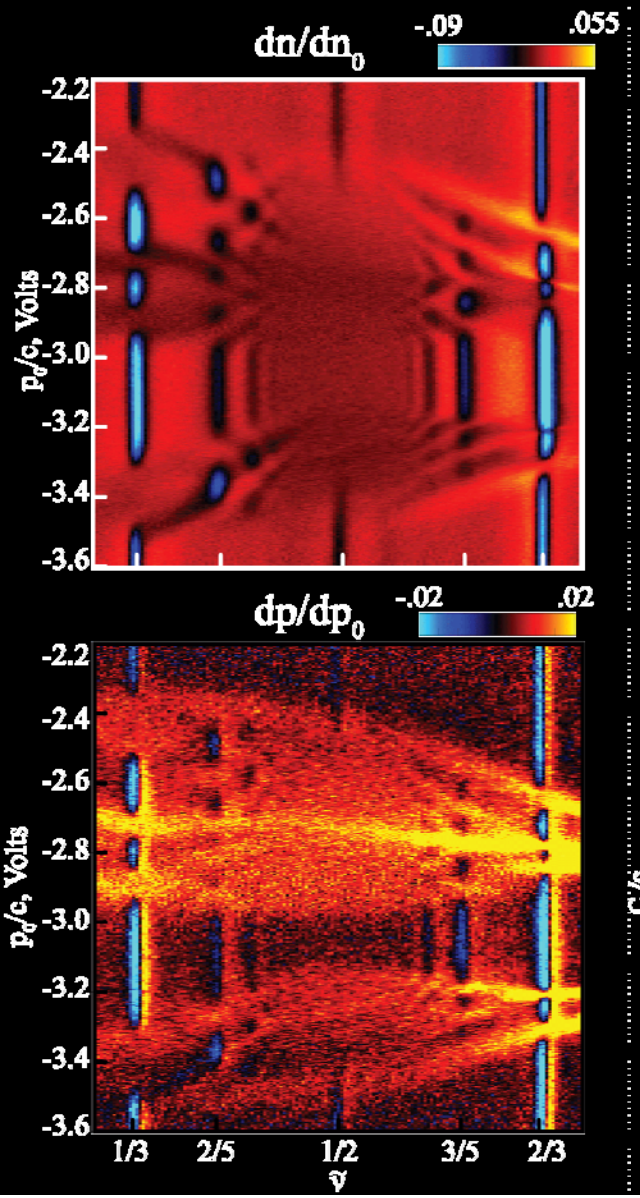
Depolarization at 1/2

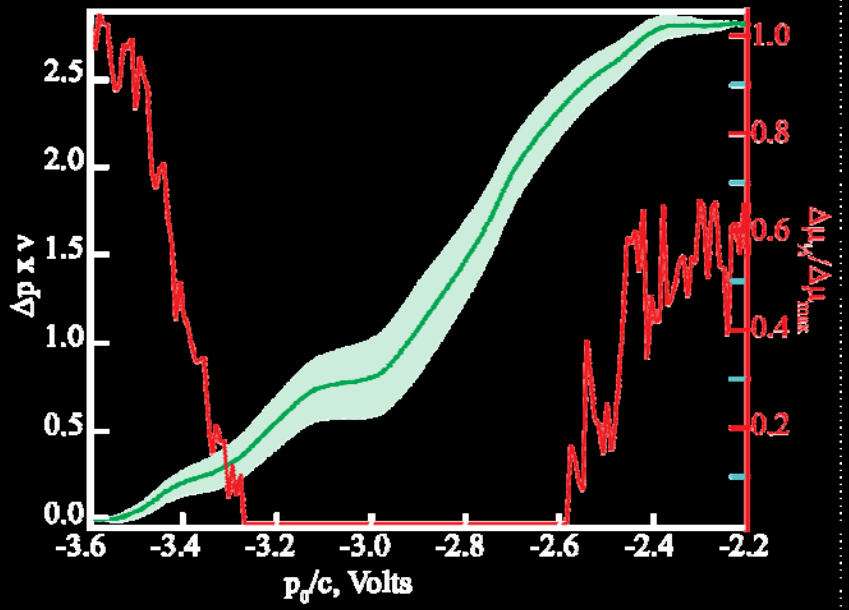


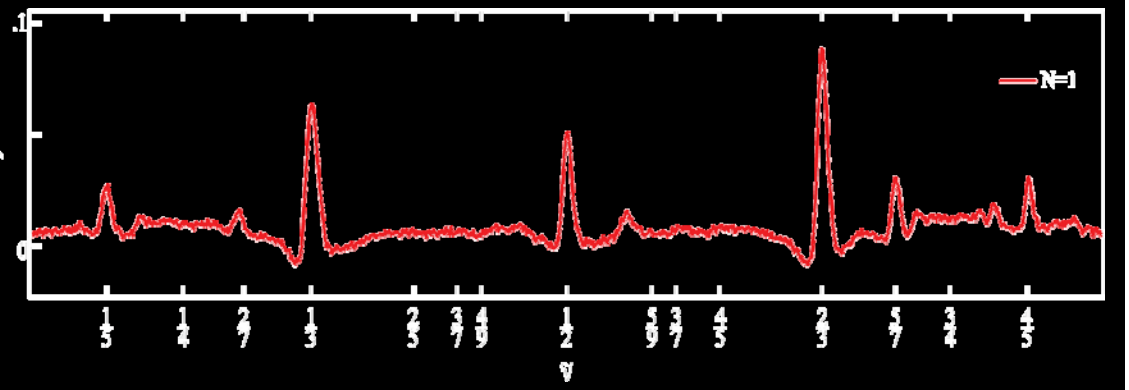


- Gap survives from $(\nu_+, \nu_-) = (1.5,0) \rightarrow (1.33, .17)$

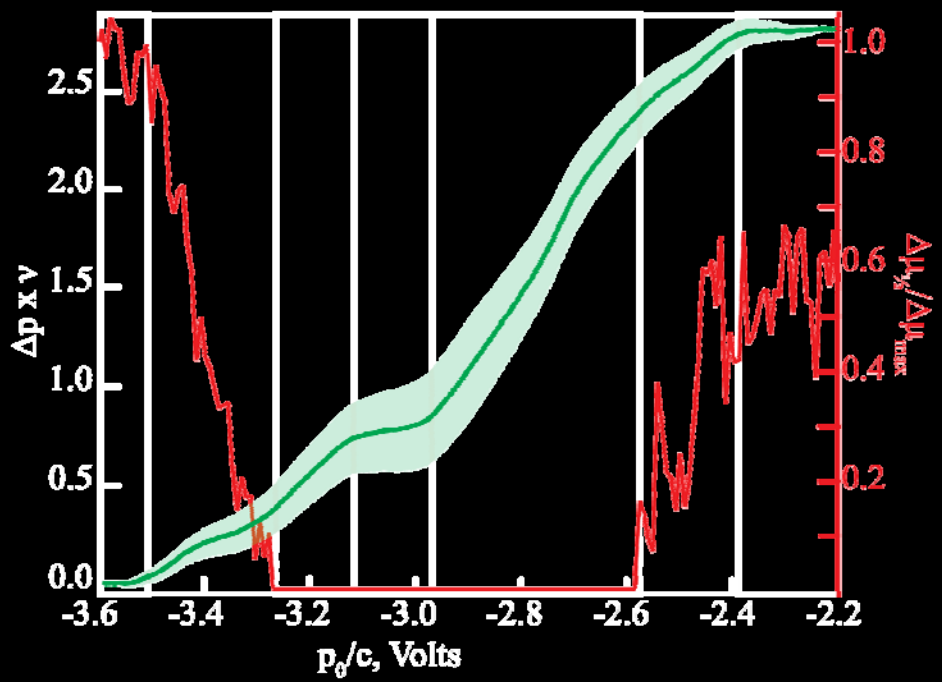
Depolarization at 1/2







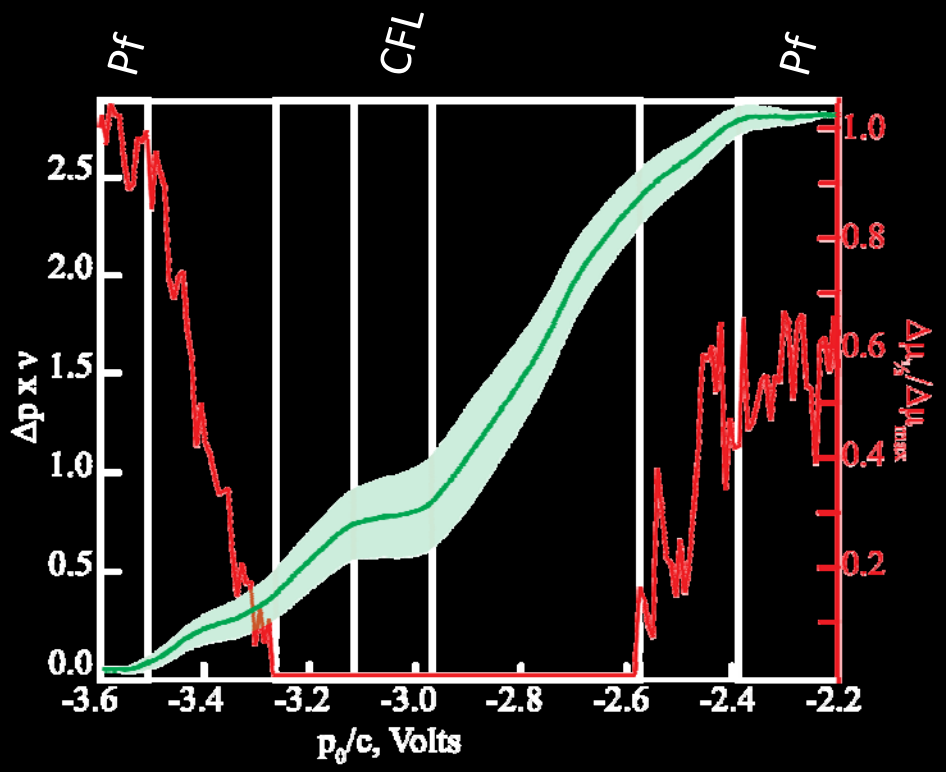
Depolarization at 1/2

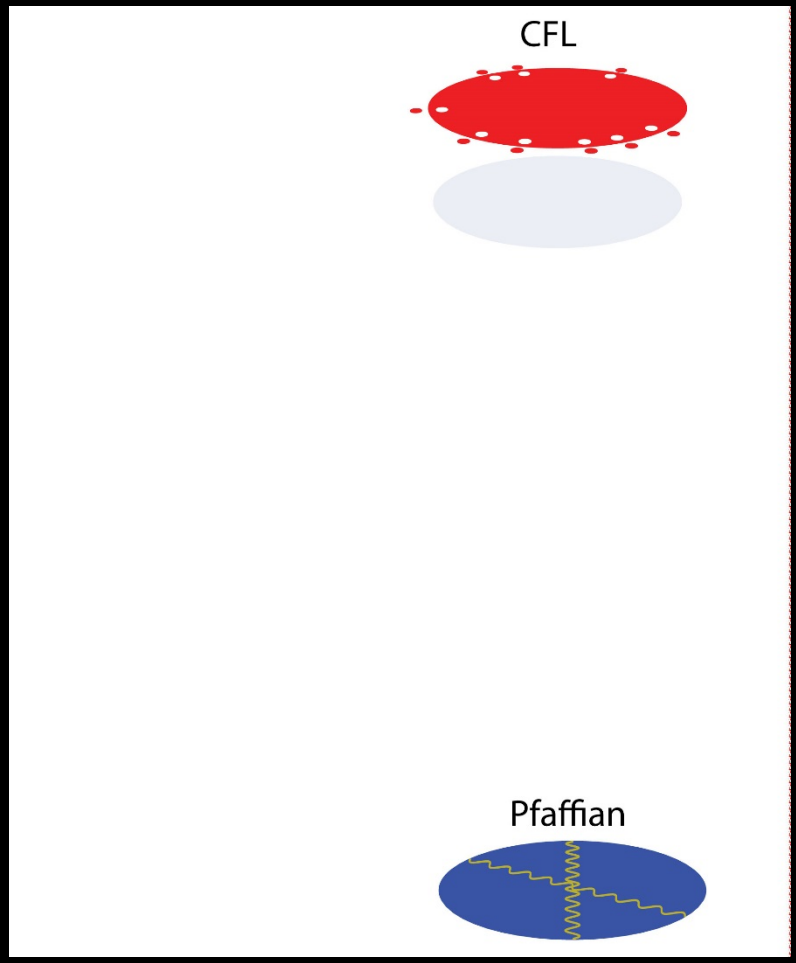


- Four phases:
  - Gapped, polarized $|1\rangle$
  - Gapped, mixed
  - Gapless, mixed
  - Gapless, polarized $|0\rangle$

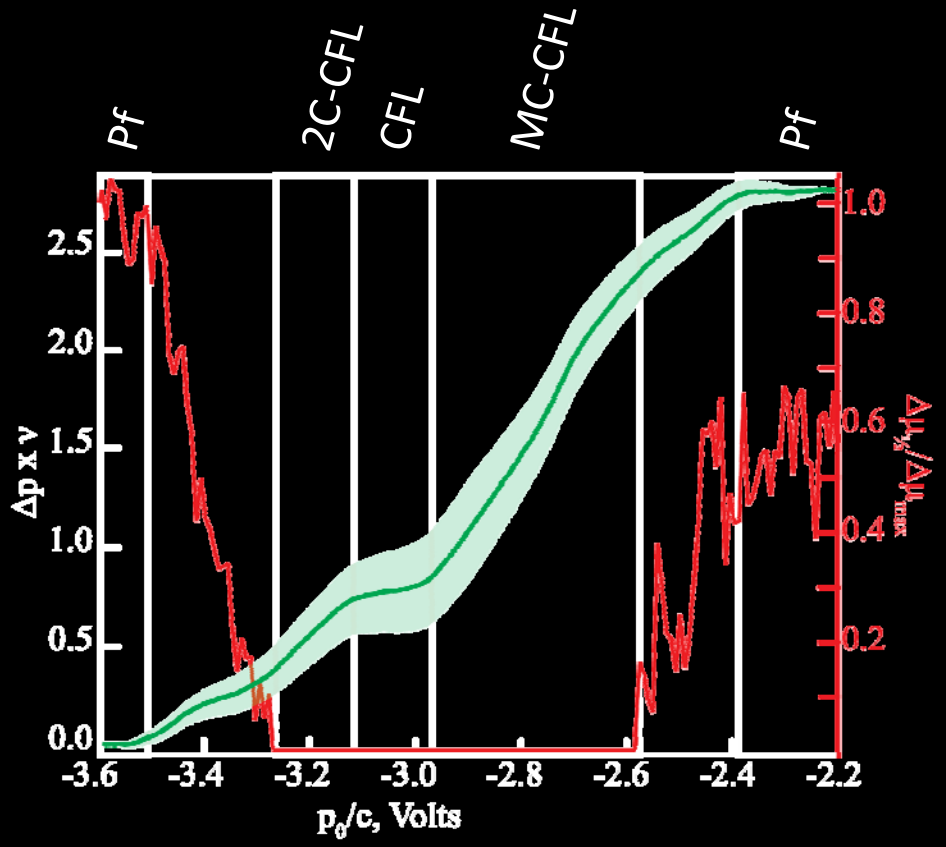
Barkeshli et al., in prep

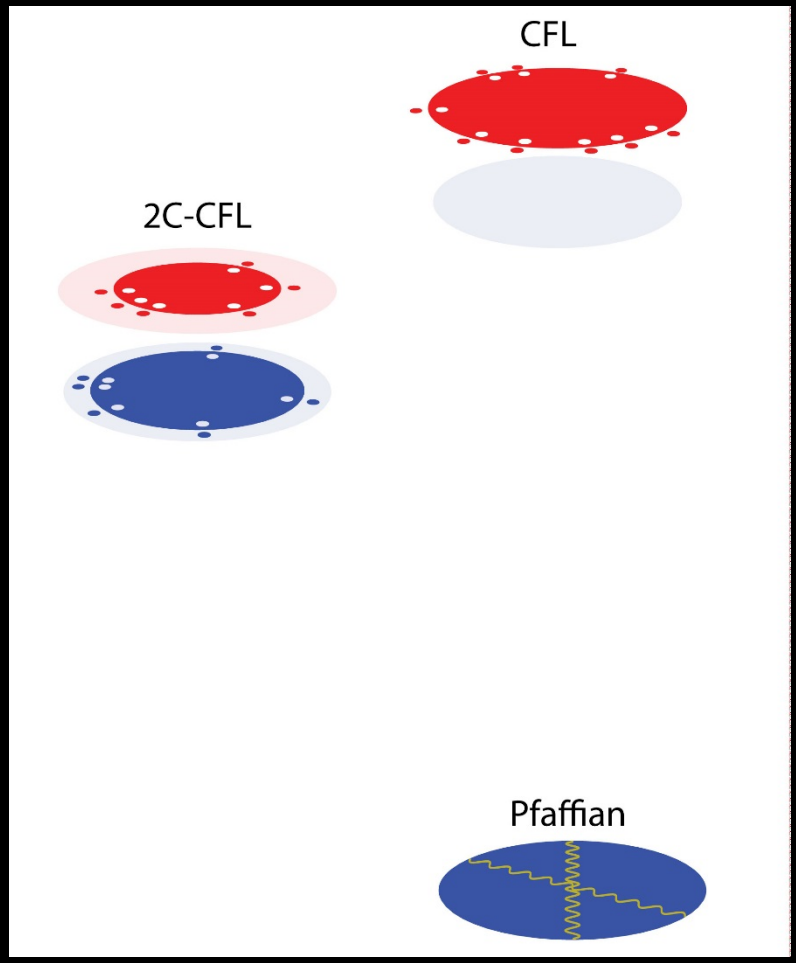
Depolarization at 1/2



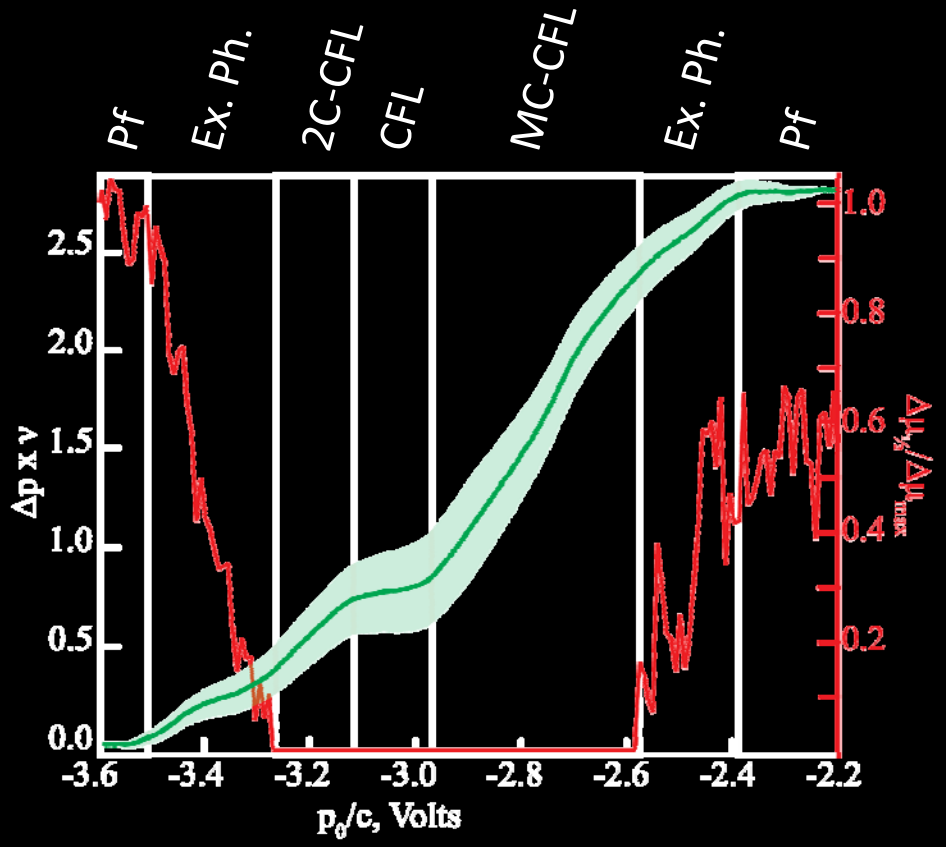


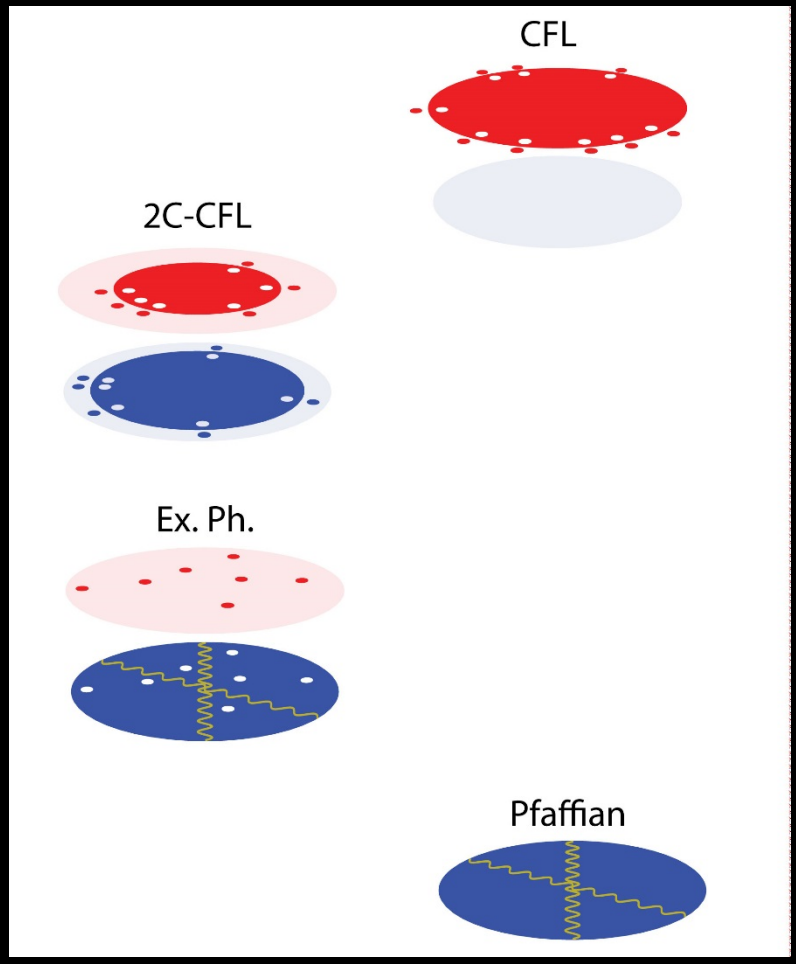
Depolarization at 1/2



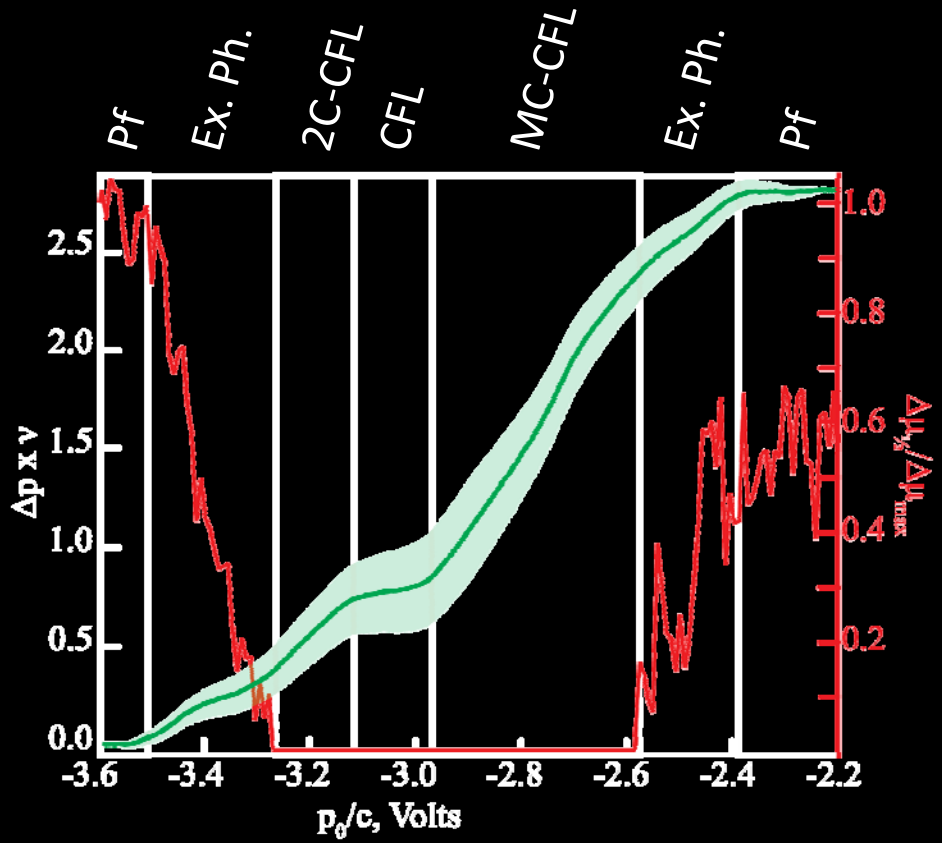


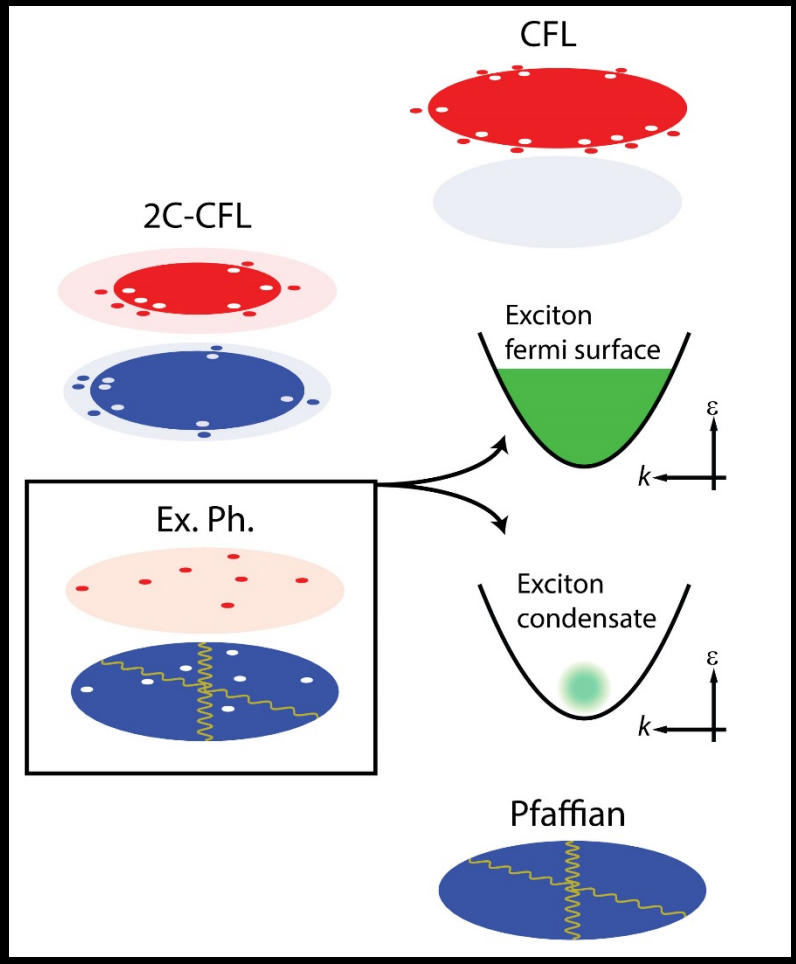
Depolarization at 1/2





Depolarization at 1/2





Outlook

- Bilayer hosts robust Pffaffian ground states
- All vdW architecture allows gating, locally
  - Time to revisit interferometry?
- T-dep μ ➔ n-dep S
  - Detect entropy of topological degeneracy?
- $|1\rangle \rightarrow |0\rangle$ transition at $\nu = \frac{1}{2}$: excitonic phase?
  - Anisotropic transport?
  - Double bilayers: drag, counterflow, etc.
  - Detect exciton FS?

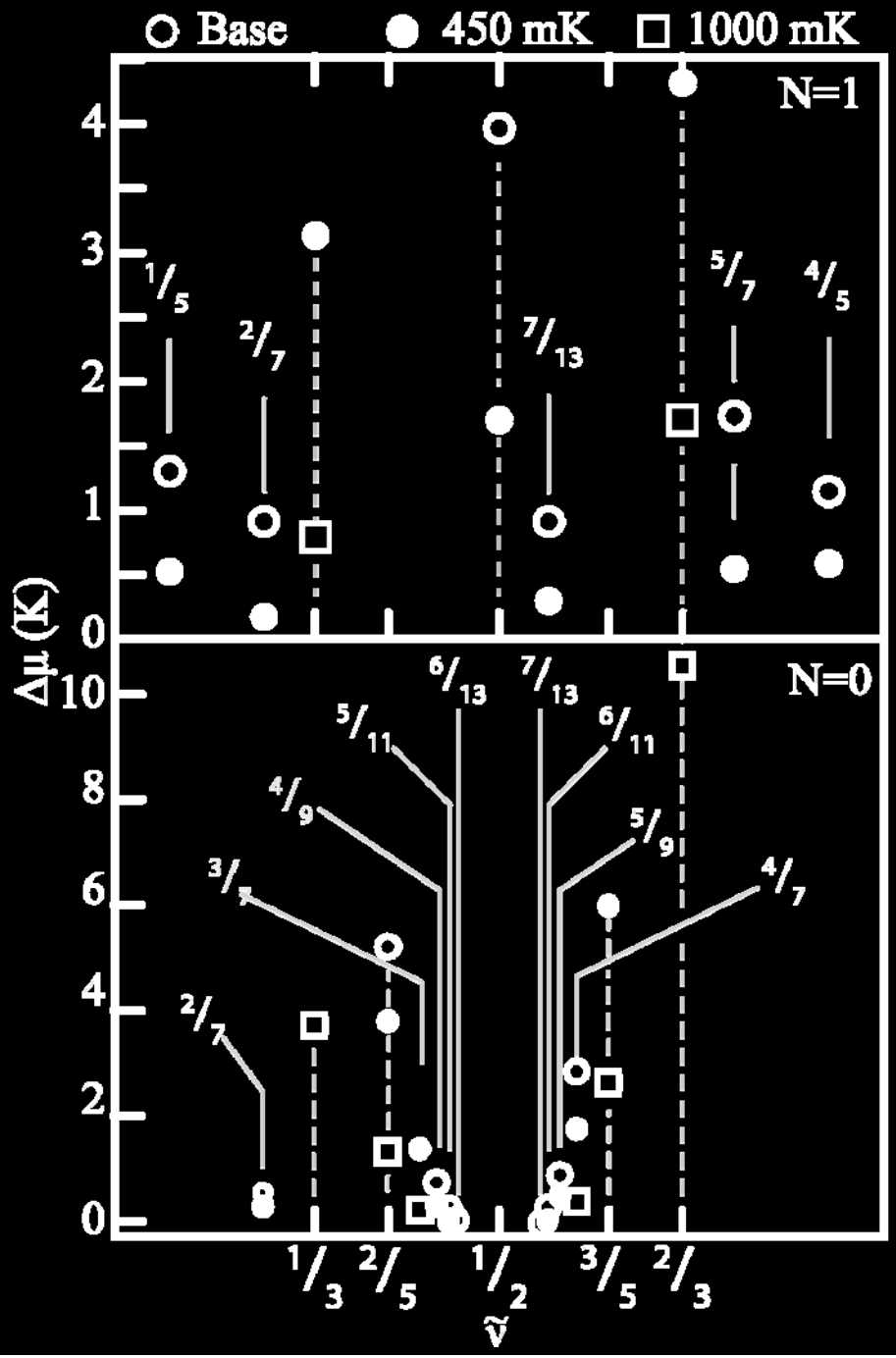
Acknowledgements

Integer QH

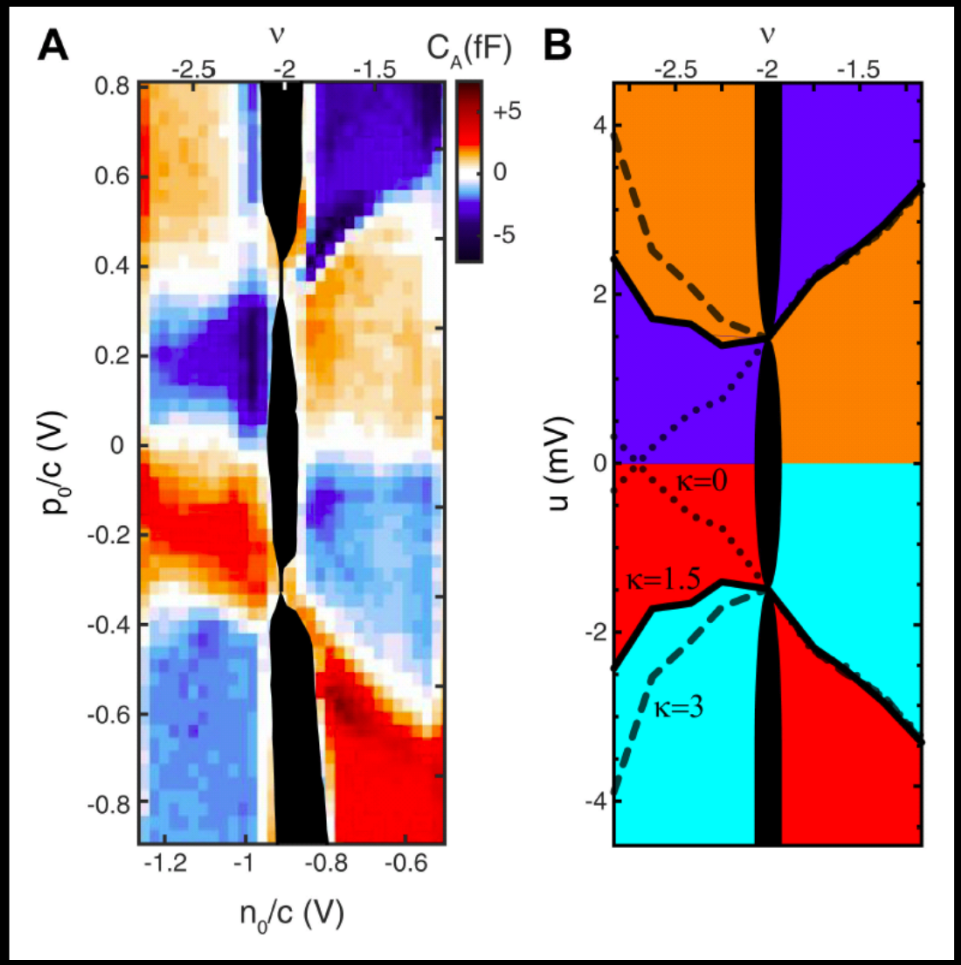
- **MIT**
  - **B. Hunt (CMU), R. Ashoori,** L. Levitov
- Columbia
  - L. Wang, J. Li, C. Dean, J. Hone
- NIMS
  - T. Taniguchi, K. Watanabe
- UCSB
  - Sasha Zibrov
- Station Q
  - Mike Zalatel

Fractional QH

- UCSB
  - Sasha Zibrov, Carlos Kometter
- Station Q
  - Mike Zalatel, Maissam Barkeshli, Chetan Nayak
- NIMS
  - T. Taniguchi, K. Watanabe

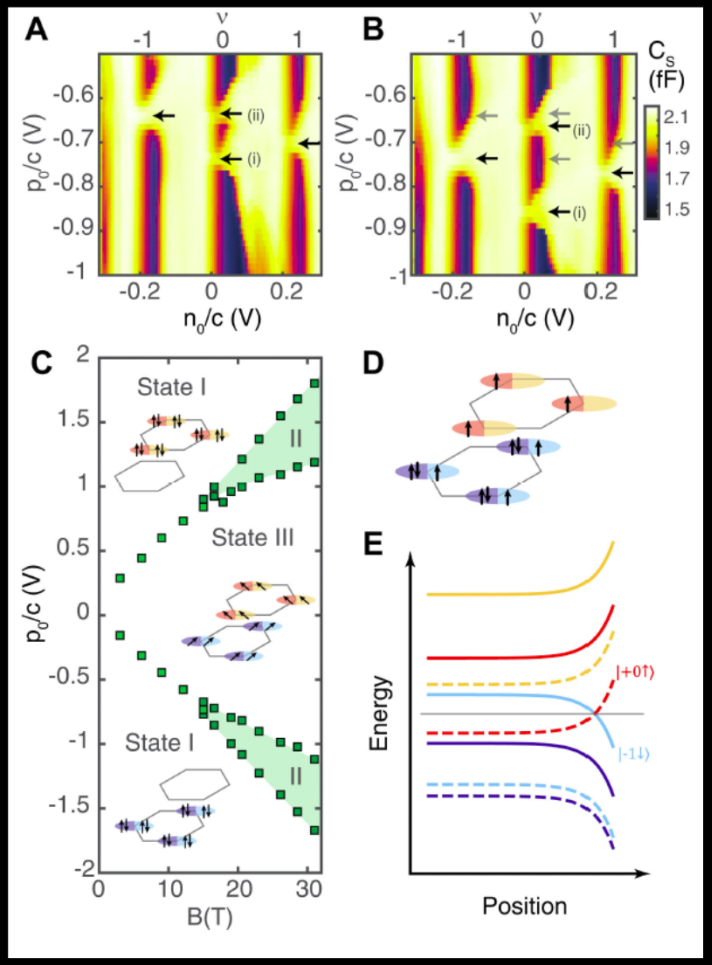

Base
450 mK
1000 mK
N=1
N=0
Δμ (K)
ν̃
1/5
2/7
7/13
5/7
4/5
6/13
7/13
5/11
6/11
4/9
5/9
3/7
4/7
2/7
1/3
2/5
1/2
3/5
2/3
0
2
4
6
8
10

Tilted phase transitions



- Phase transition: two degenerate states
- Tilt: energy per particle depends on particle number
- Correlation effect, DMRG says: very sensitive to details

Spin structure of ZLL



- Tilted field measurements: change Zeeman, nothing else
- Consistent with CAF state at $\nu = 0$, but new state appears
- Spin polarized: should be helical phase
- Need transport….