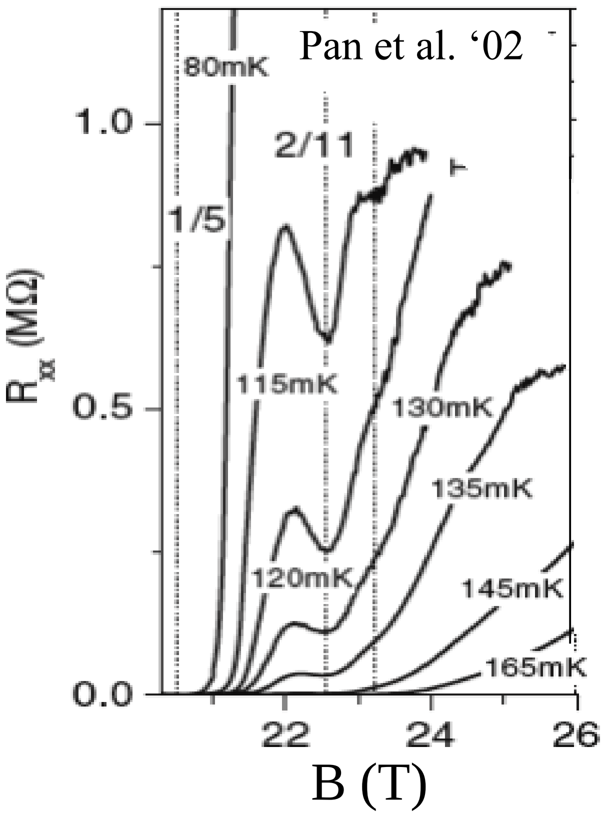
Microwave studies of Wigner solid phases in bilayer systems

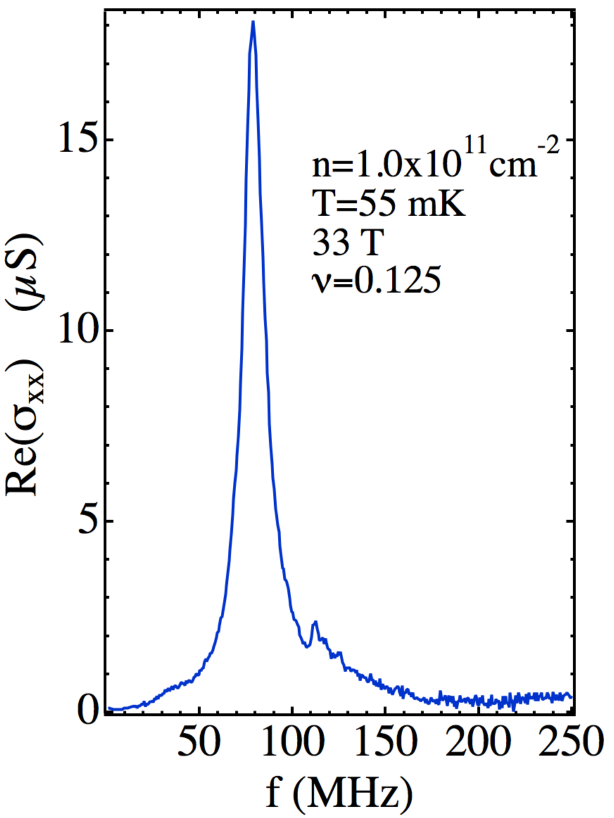
L. W. Engel, NHMFL/FSU

A. T. Hatke, NHMFL/FSU

Y. Liu, M. Shayegan, L. N. Pfeiffer,
K. W. West and K. W. Baldwin, Princeton

High B Termination of FQH series: insulator and resonance





- experiment: insulation + resonance n ~ 1/5
- Resonance: signature of pinned Wigner crystal
- resonance understood as pinning mode, in which solid oscillates within disorder potential

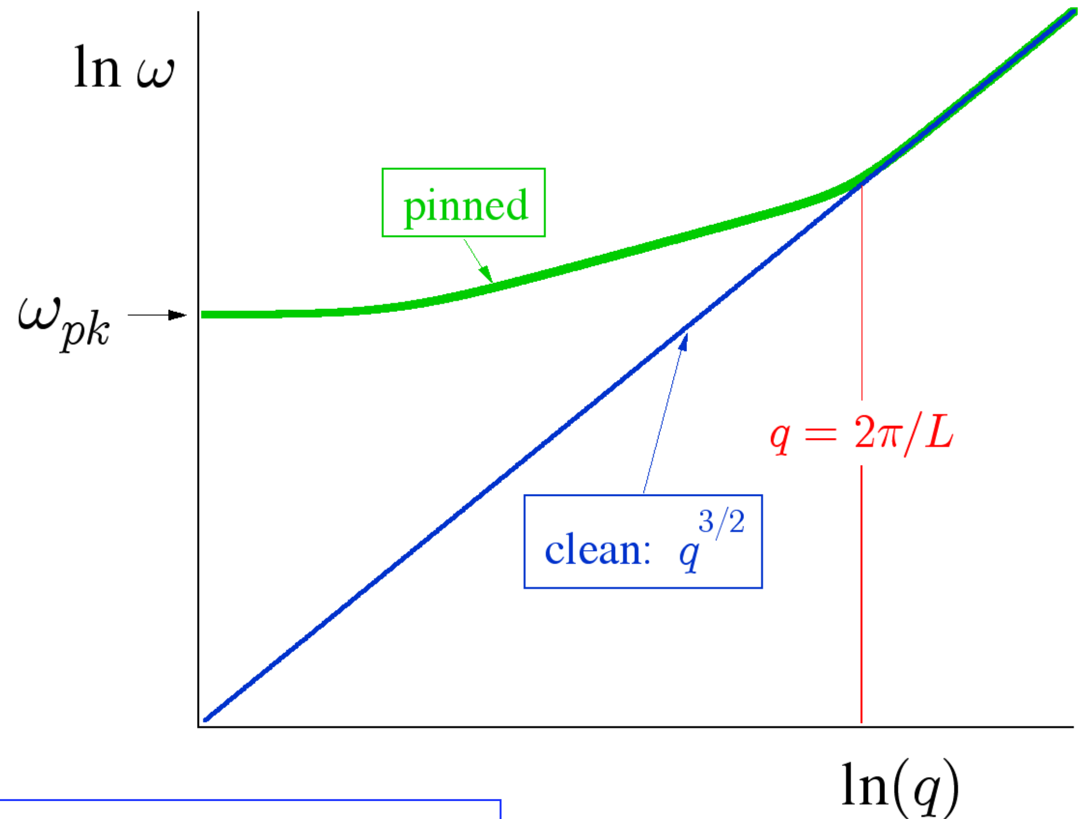
Resonance: pinning mode interpretation

Disorder induces "Pinning" Mode: small oscillation about pinned positions

Disorder

$\Rightarrow L$

$\Rightarrow \omega_{pk} \sim \omega(q \sim 2\pi/L)$

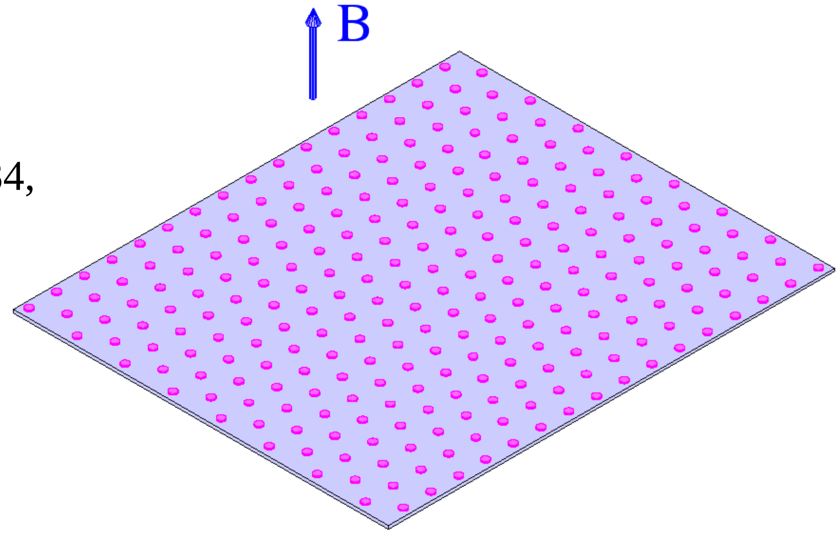


Classical Wigner crystal in high B:
Without disorder: $\omega \sim q^{3/2}$ B
With disorder: saturates at low q ~ $2\pi/L$

Wigner solids in QHE systems

Predicted low-ν state:

Lam and Girvin; Levesque, Weis, MacDonald `84,
Lozovik and Yudson `75,
Yang and Rezayi, ‘02

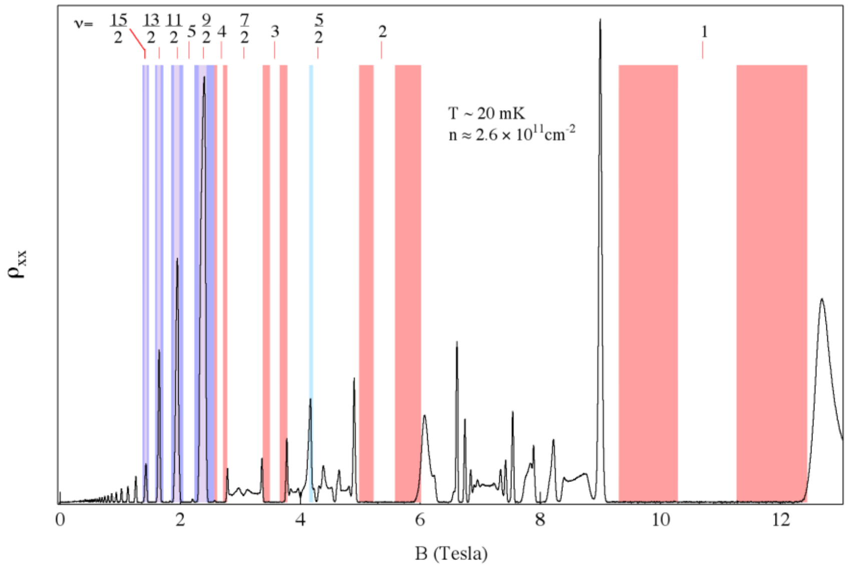


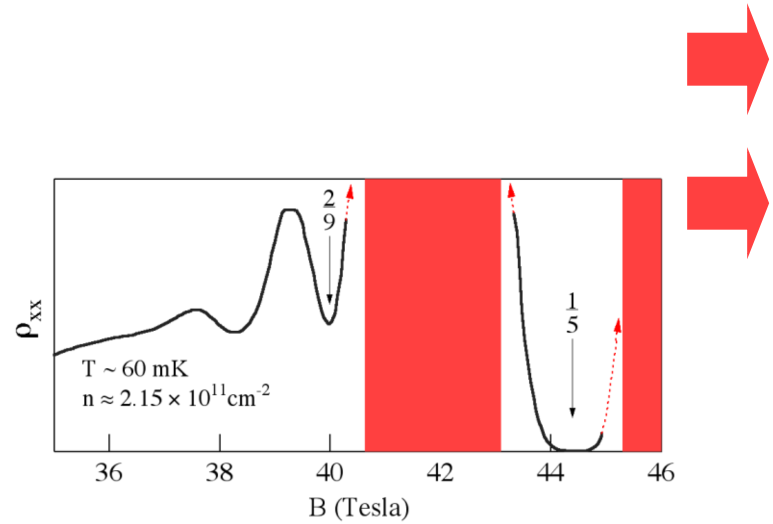
- Spatial charge distribution effect on NMR lineshape:
  L. Tiemann, T. D. Rhone, N. Shibata, and K. Muraki,
  Nat. Phys. ‘14.

- Tunneling approach (Ashoori, arxiv)

- Composite Fermion Wigner crystal
  Archer, Park, Jain, PRL ’13 ; Rhim, Jain, Park, PRB ’15

Resonance: pinning mode of **electron solid,** ν ranges of resonances





- Integer Quantum Hall Effect Wigner Crystal
- Bubble phase
- Stripe phase (anisotropic)
- N=1 Landau level bubble phase

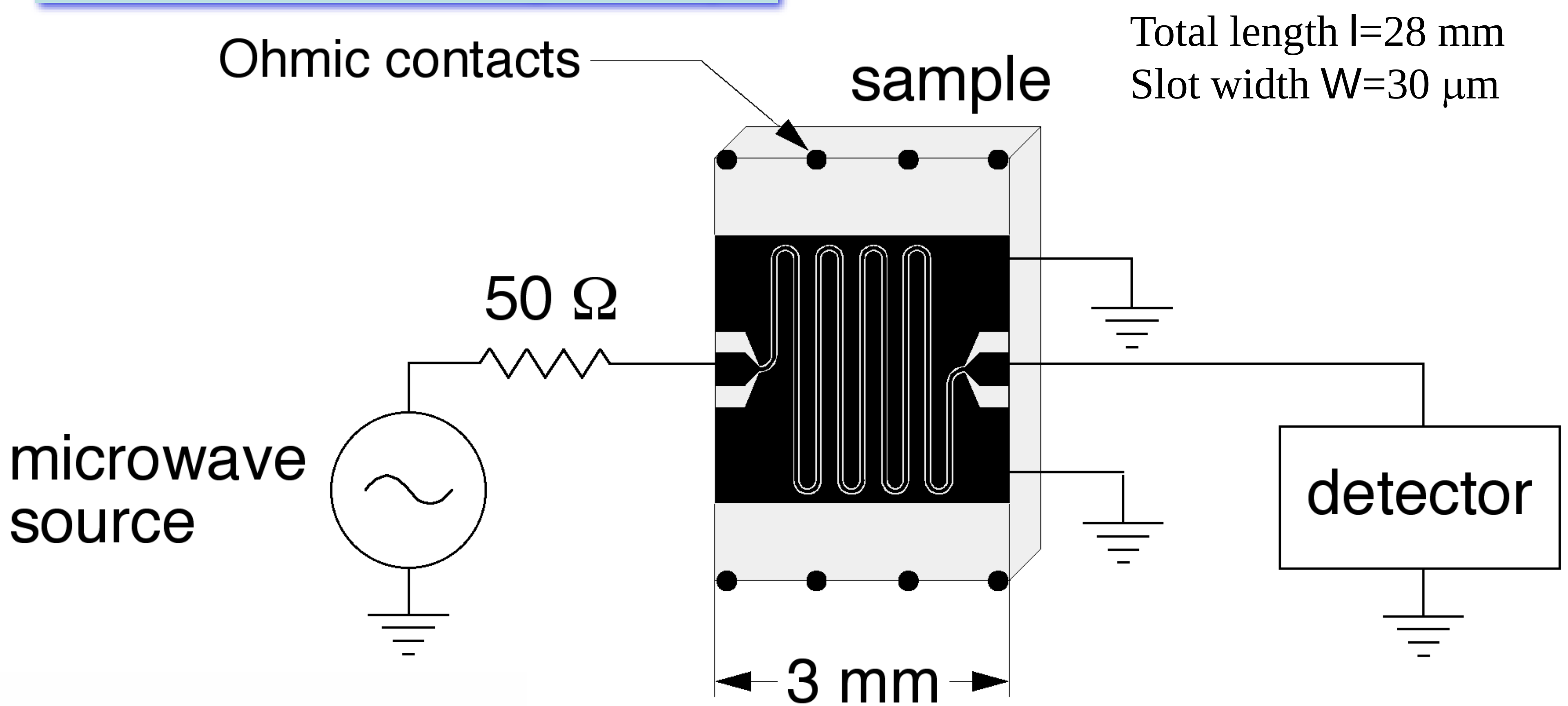
- High B Wigner Crystal

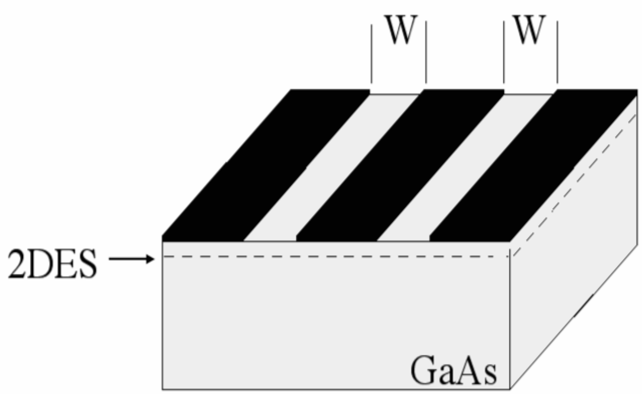
2010: within 1/3 FQHE

"solid" phases found in many conditions.

Resonance depends on disorder and solid stiffness:
phase transitions, to/ between solids at ν , T where dc just shows QHE or IP

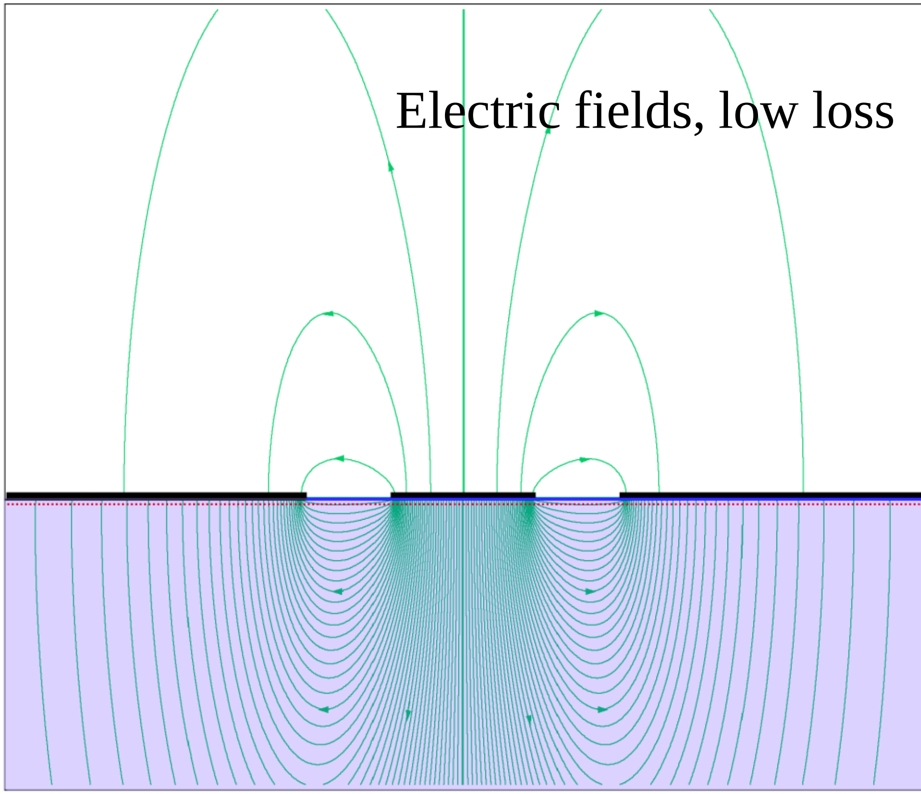
Microwave measuring technique

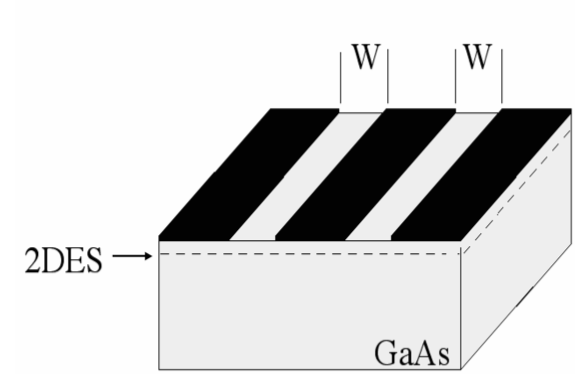




- Metal film makes coplanar waveguide (CPW) transmission line
- Center conductor driven, side planes grounded "like coax"
- σ_{xx} from 2DES effect on signal

Microwave measurement, coupling to 2DES





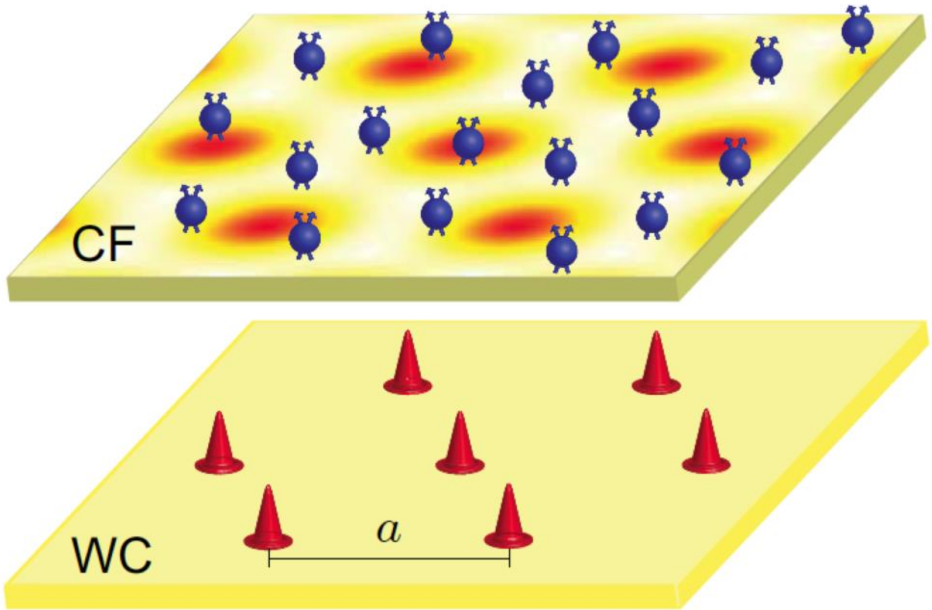
- Relevant 2DES is under the slots
- CPW - 2DES coupling is capacitive

- f-independent extinction $P = \exp(-Z_0 \mathrm{Re}(\sigma_{xx}) N_{sq})$
- Z_0 characteristic impedance for $\sigma_{xx}=0$, $N_{sq}=2l/W$, l is line length
- Formula is for high *f* , low loss limit.

Outline

- Double quantum well CF liquid+ WS
- Multiple Wigner solid phases in bilayer-regime wide QW

Wigner Solid + Composite Fermion Liquid



n_H

n_L

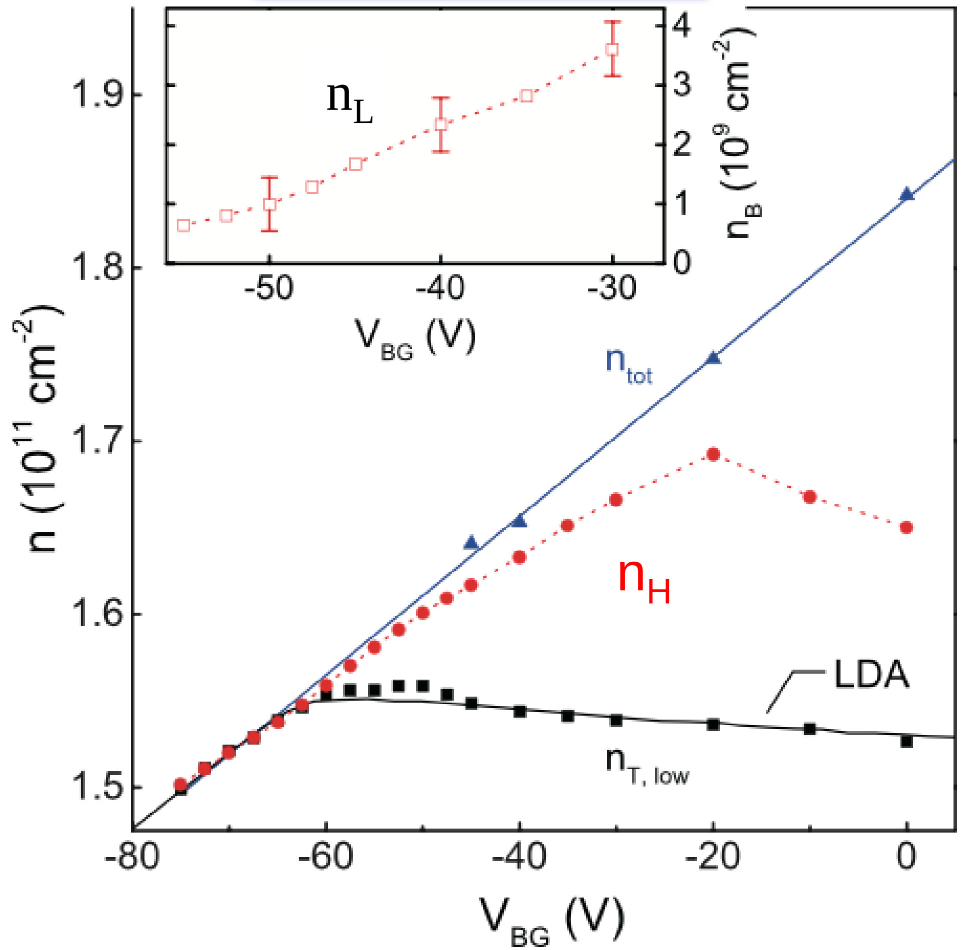
Double quantum well: 10 nm barrier, 30 nm wells

Highly unbalanced layer densities: $n_H \sim 1.5 \times 10^{11}$, $n_L \sim 2 \times 10^{10}$ cm^{-2}

Bottom (minority) layer: WS, top (majority) layer: FQHE regime.

Original purpose (Shayegan group): geometric resonances of CFs
arxiv 1410.3435 (Deng,Liu,Jo,Pfeiffer,West, Baldwin,Shayegan)

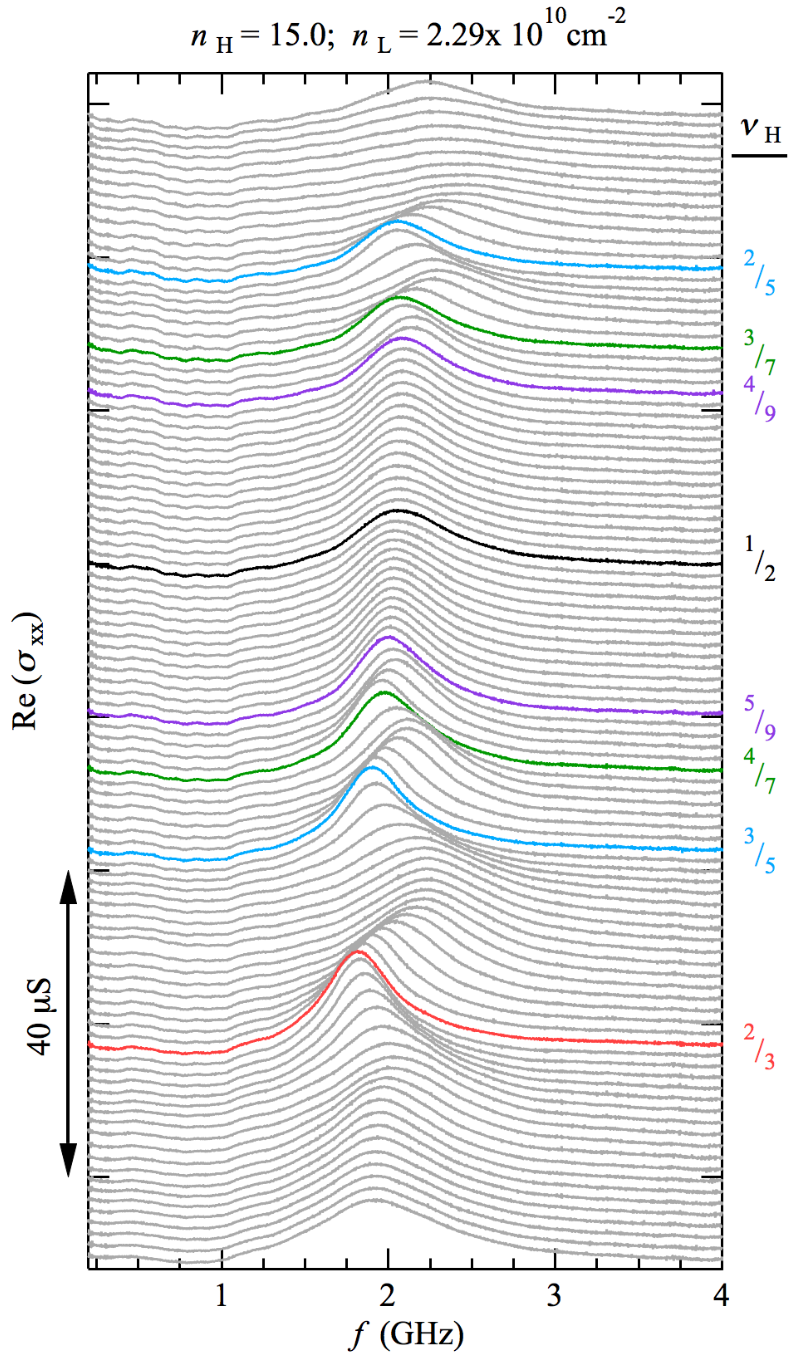
Determining n_L



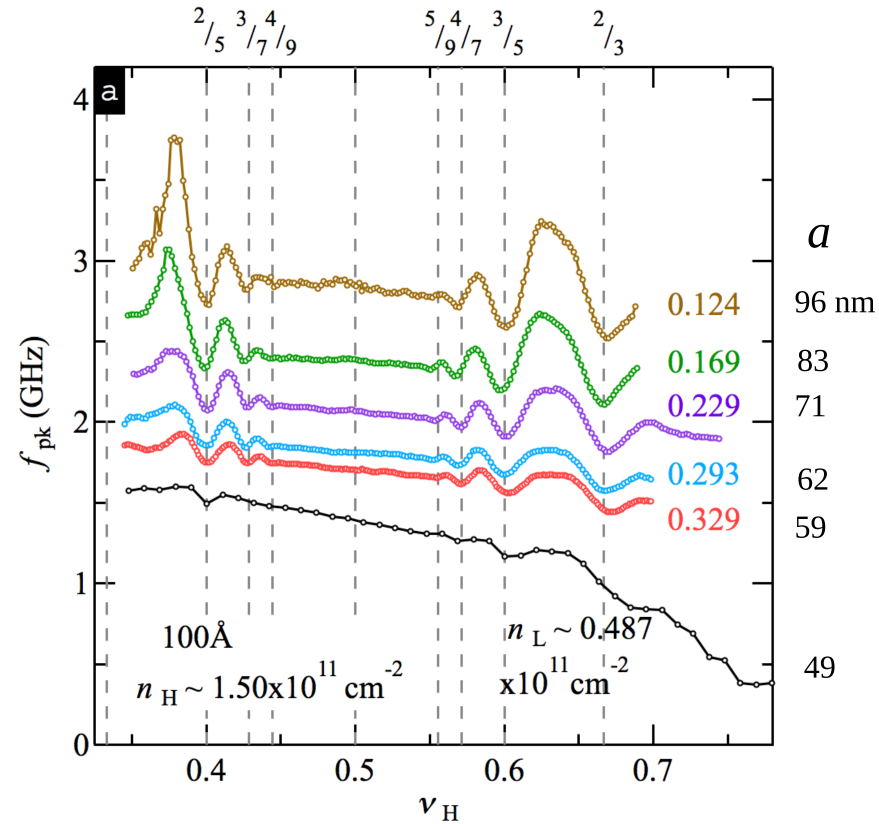
$$n_L = n_{tot} - n_H$$

- Charge transfer for $\nu\sigma 1$; gone for lower ν.
- n_L by subtraction of n_L (by FQHE) from SdH total density
- arxiv 1410.3435 (Deng,Liu,Jo, Pfeiffer,West, Baldwin,Shayegan)

Minority layer pinning mode spectra

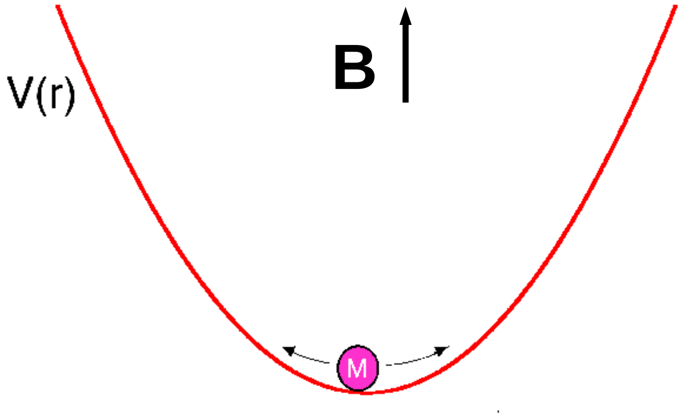


Top layer does *not* shield from MWs



f_{pk} responds to FQHE in majority layer
Interlayer coupling, small enough n_L :
Lattice constant *a* exceeding
separation d≈40nm

Sum rule: Harmonic oscillator model of pinning mode



Charge in "pinning" potential

$$V(x,y) = \frac{M\omega_0^2(x^2+y^2)}{2}$$

"pinning" frequency ω_0,
cyclotron frequency ω_c=eB/m*

Two modes: $\omega_+ \geq \omega_c$

$\omega_- = \omega_0^2/\omega_c$ (for $\omega_0 \ll \omega_c$)

Microwave resonance

Observed resonance frequency: $f_{pk}=\omega_0^2/2\pi\omega_c$

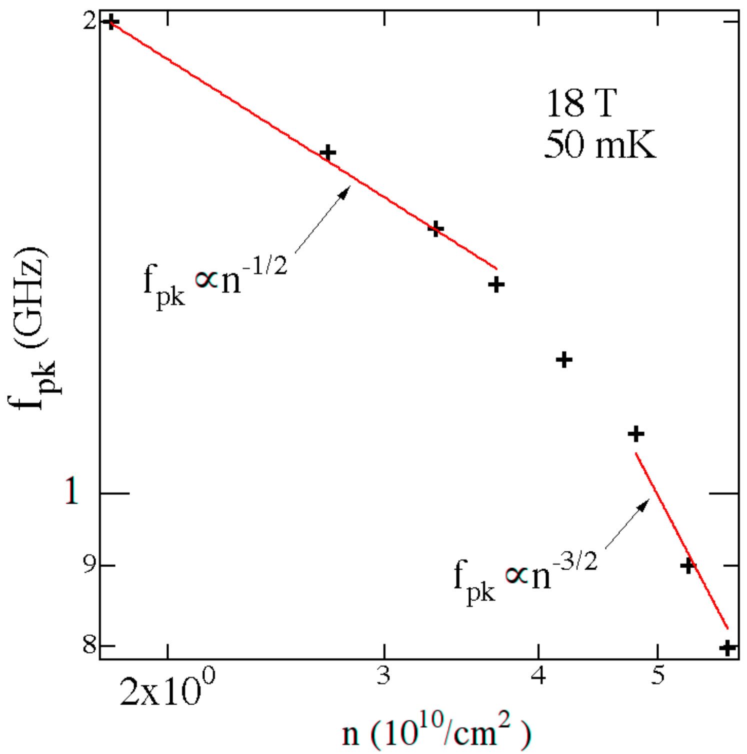
ω_- sum rule: $S_- = \int_0^\infty \mathrm{Re}[\sigma_{xx}(f)]df$ = $n_{osc} e\pi f_{pk}/2B$

from measured S/f_{pk} , participating carrier density: $n_{osc}=2BS_-/e\pi f_{pk}$

Participation ratio $/ = n_{osc}/n$

Fukuyama and Lee;
Millis, Normand, Littlewood

f_{pk} increases as n decreases: Weak pinning



Generic behavior

Reducing n ⇒weaker carrier-carrier interaction

⇒Carriers "fall further into impurity potential"

⇒Average pinning, so f_{pk} increases

- In weak pinning: $f_{pk} \sim 1/C_t$ inversely as shear modulus.

n_{osc} characterizes effect of majority-layer state: image charge

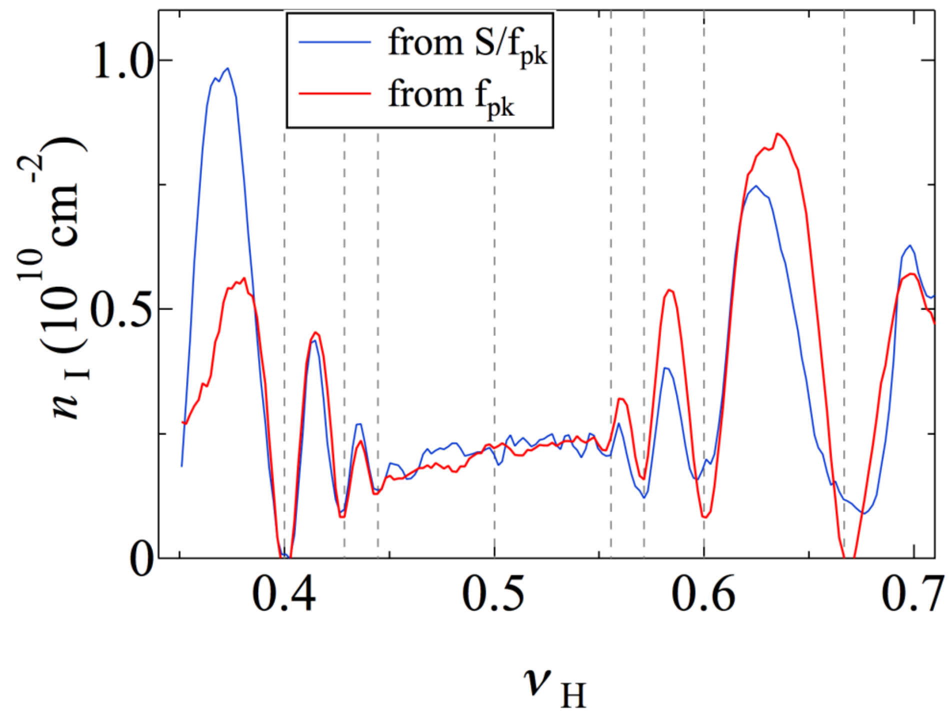
Two ways to get participating density n_{osc} from resonance :

i. $n_{osc} \propto f_{pk}^{-2}$: empirically established

ii. $n_{osc} = 2BS/e\pi f_{pk}$: sum rule for n, S is integrated Re $\sigma_{xx}(f)$

$$n_I = n_L - n_{osc}$$

$n_L = 2.29 \times 10^{10} cm^{-2}$



n_I : "image charge" density, reduction in resonance-measured density from true density, n_L

- local compressibility measurement

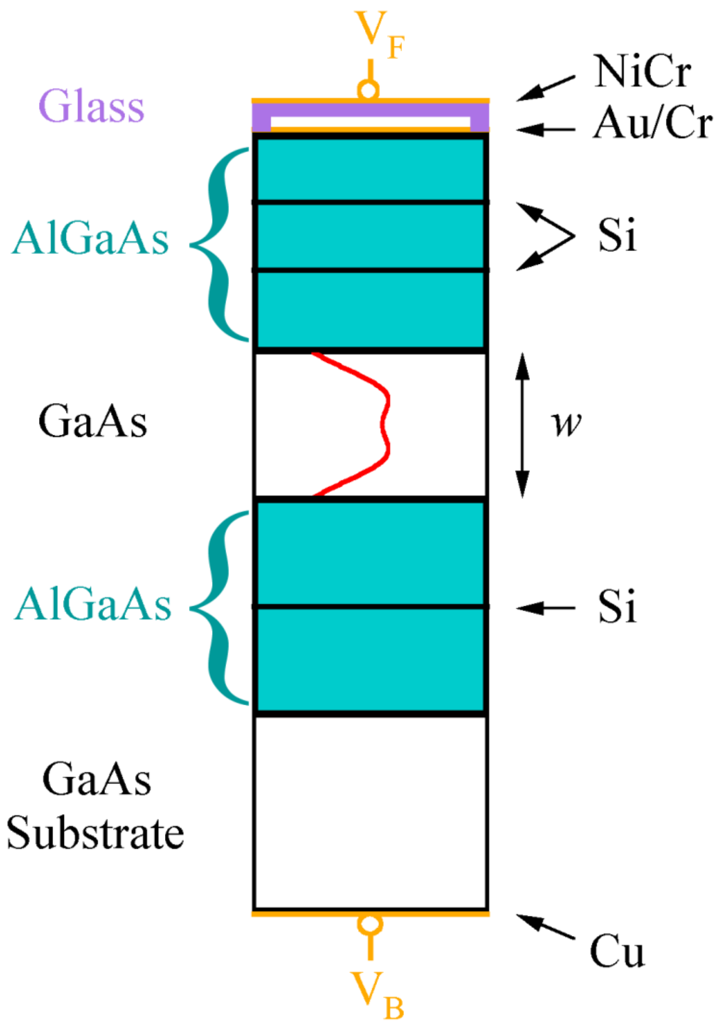
Two independent ways to get n_I

In pinning theory (Chitra et al 2001,Fertig 2000, Fogler 2001)
f_{pk} comes from static quantity
Larkin length + Lorenz force +shear modulus

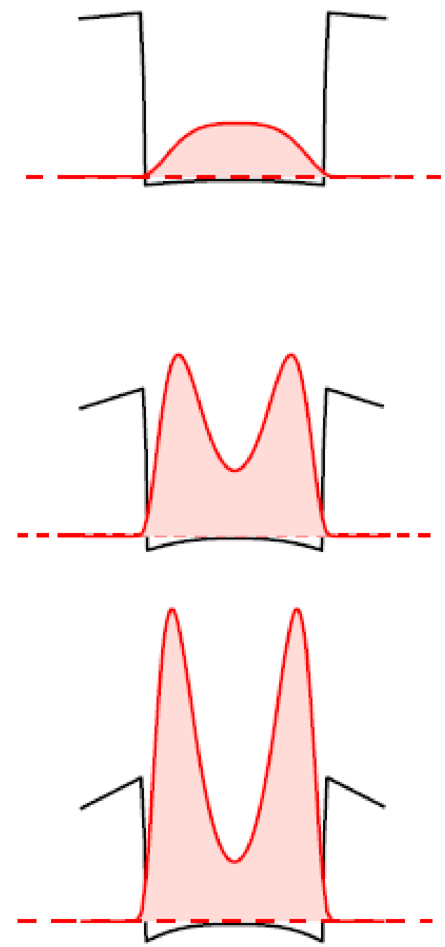
Sum rule measures all oscillating charge

“image” charge in majority layer appears to oscillate along with WS charges.

Wide quantum well



Increasing density, *n*

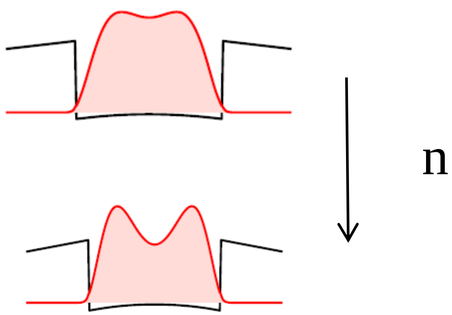


Low *n*, narrower
Single layer

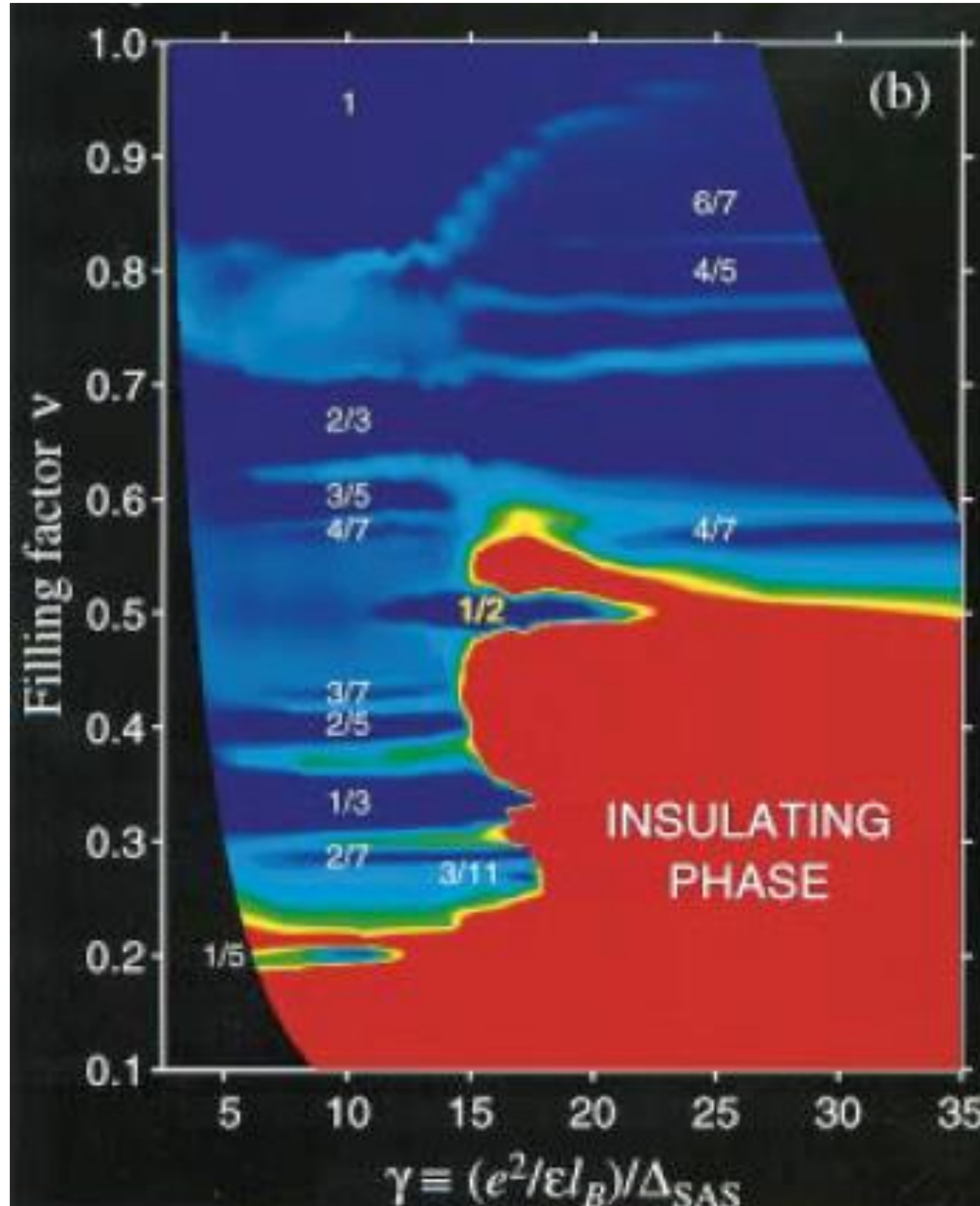
High *n*, wider
increased tendency
to form bilayer states

Air-gapped glass top gate: necessary for microwaves

Wide quantum wells WQW

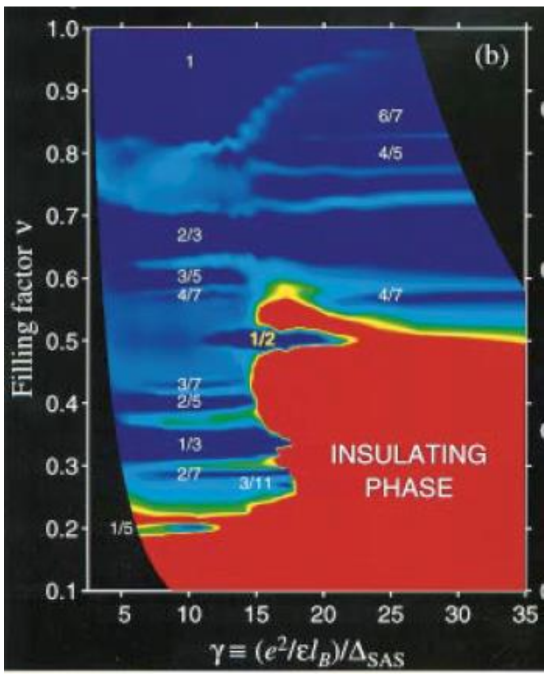


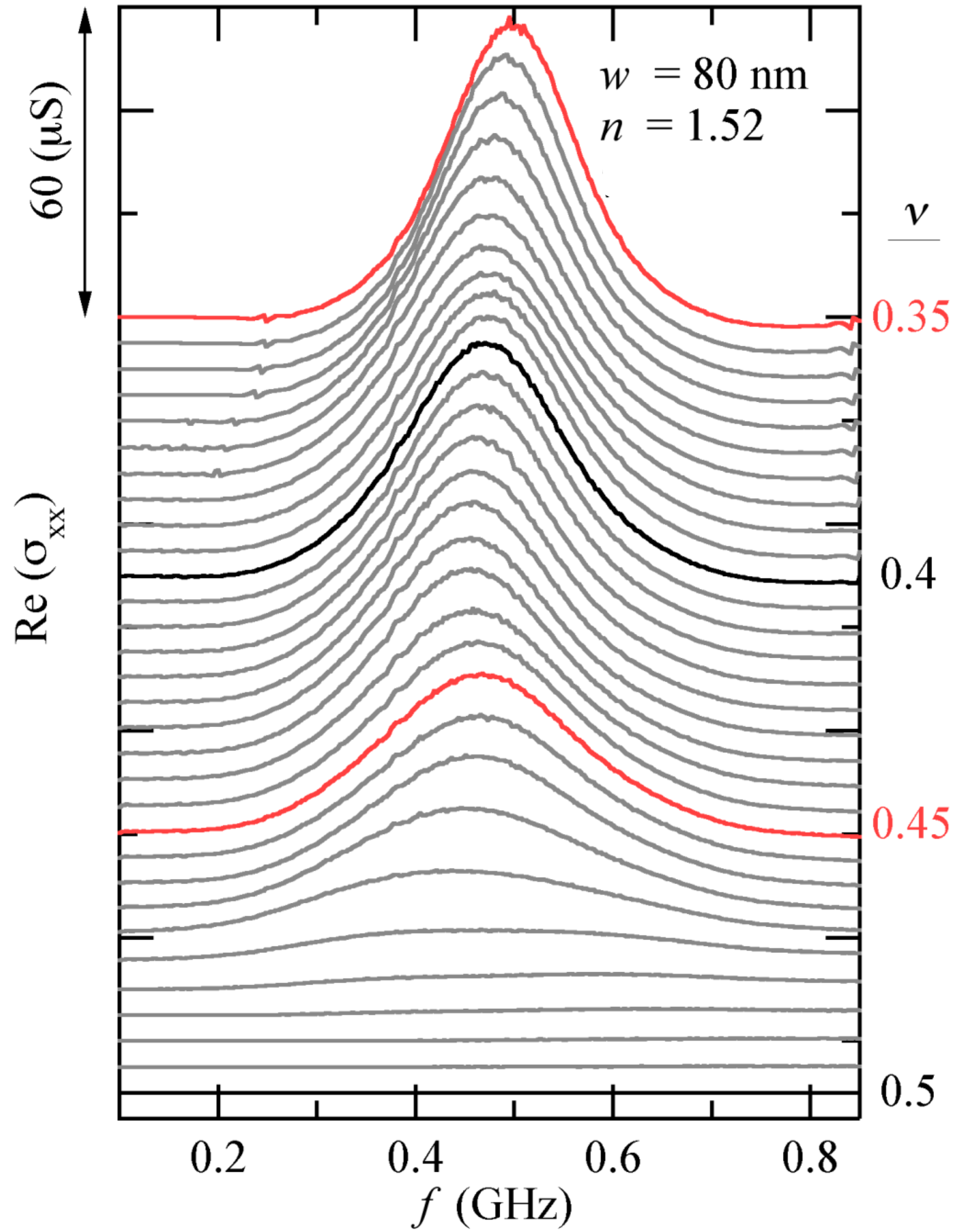
- two-component for
  $\gamma = E_c/\Delta = e^2/4\pi\varepsilon_0\varepsilon l_B\Delta >\sim 16$
  γ: measure of *bilayerness*
- transition to solid
  - single layer : ν~1/5
  - parallel single layers ν~2/5 (1/5 per layer)
- Interlayer correlated:
  - eg ½ FQHE



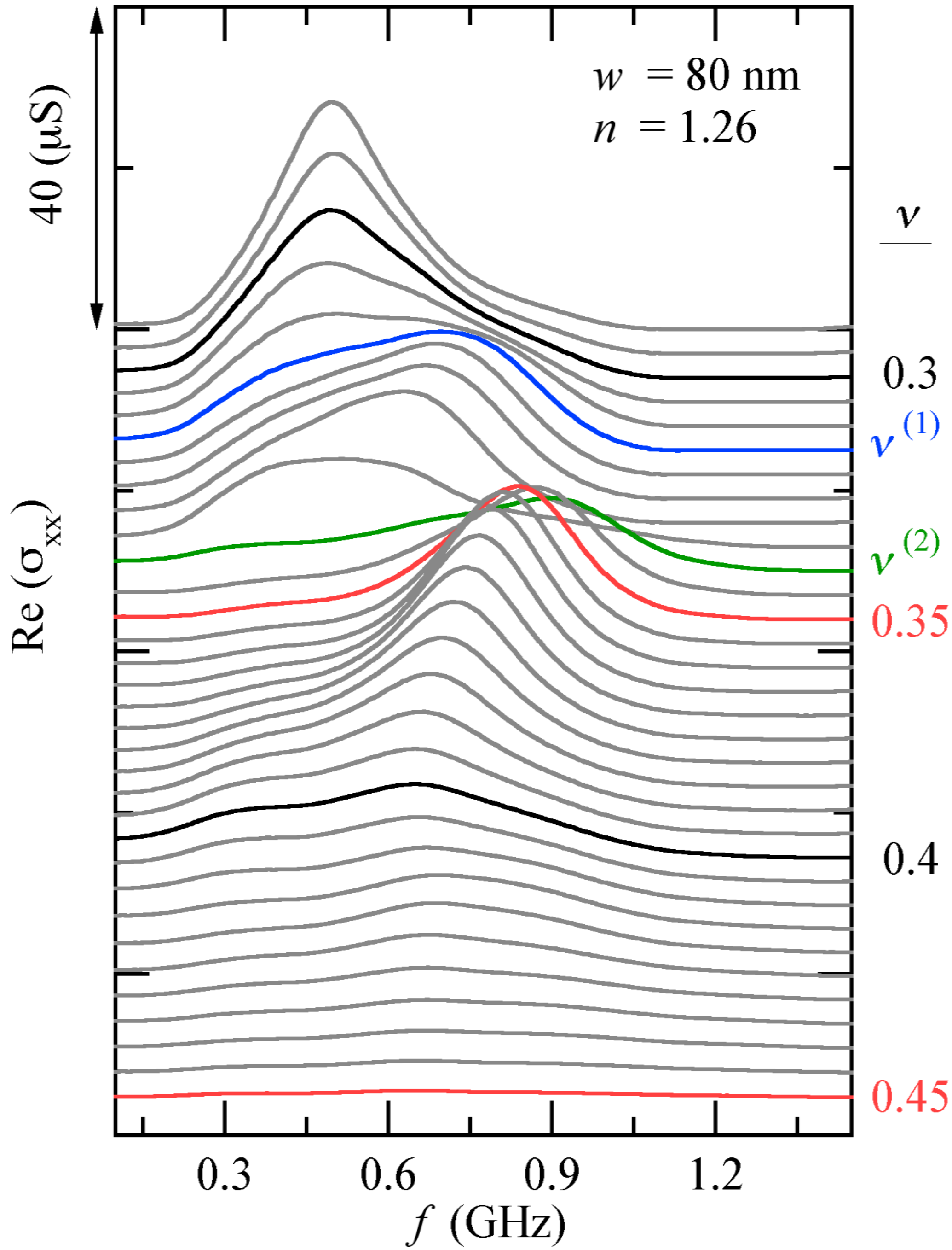
Manoharan, Suen, Santos, Shayegan PRL '96

Resonance onset

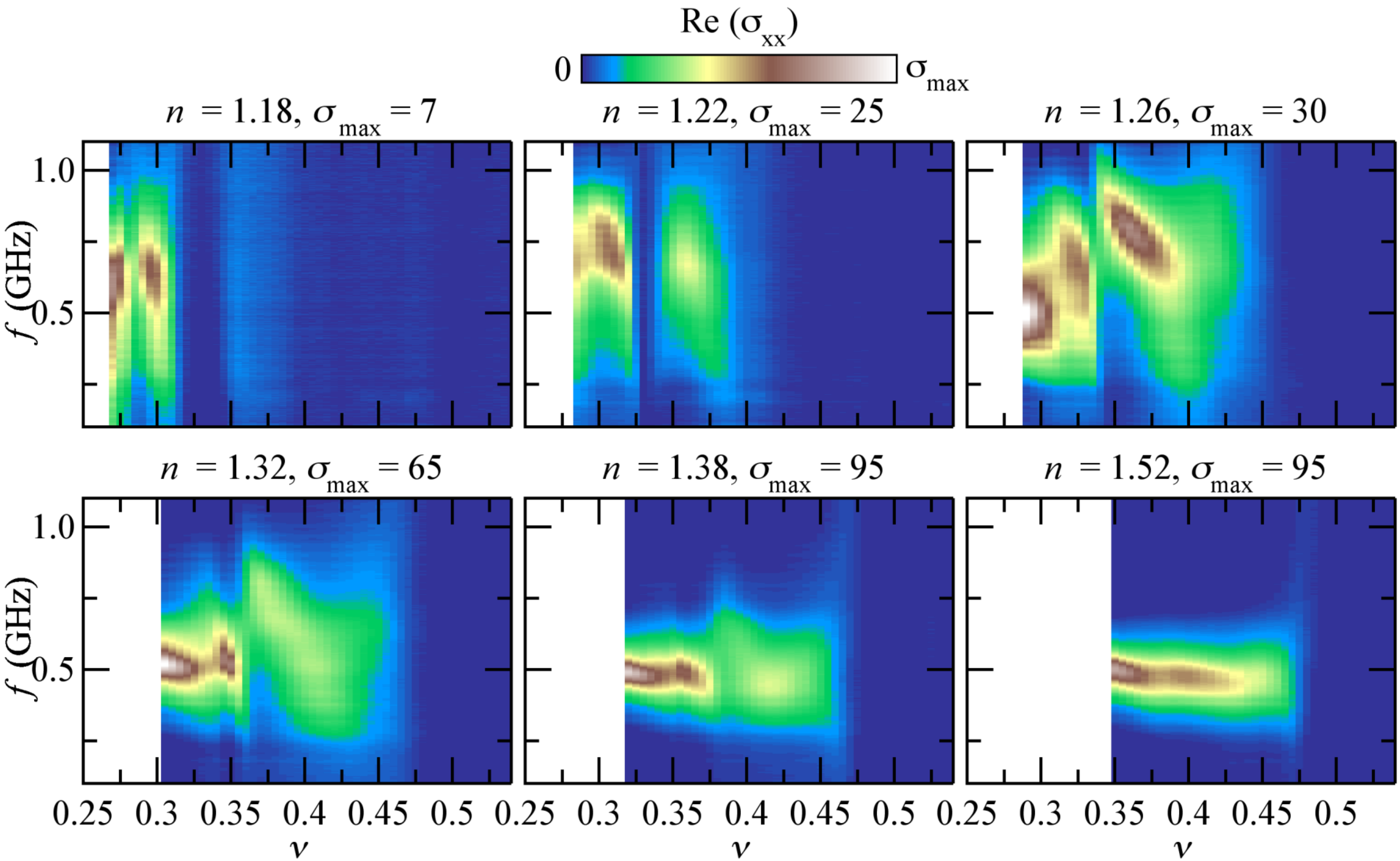




Phase transitions

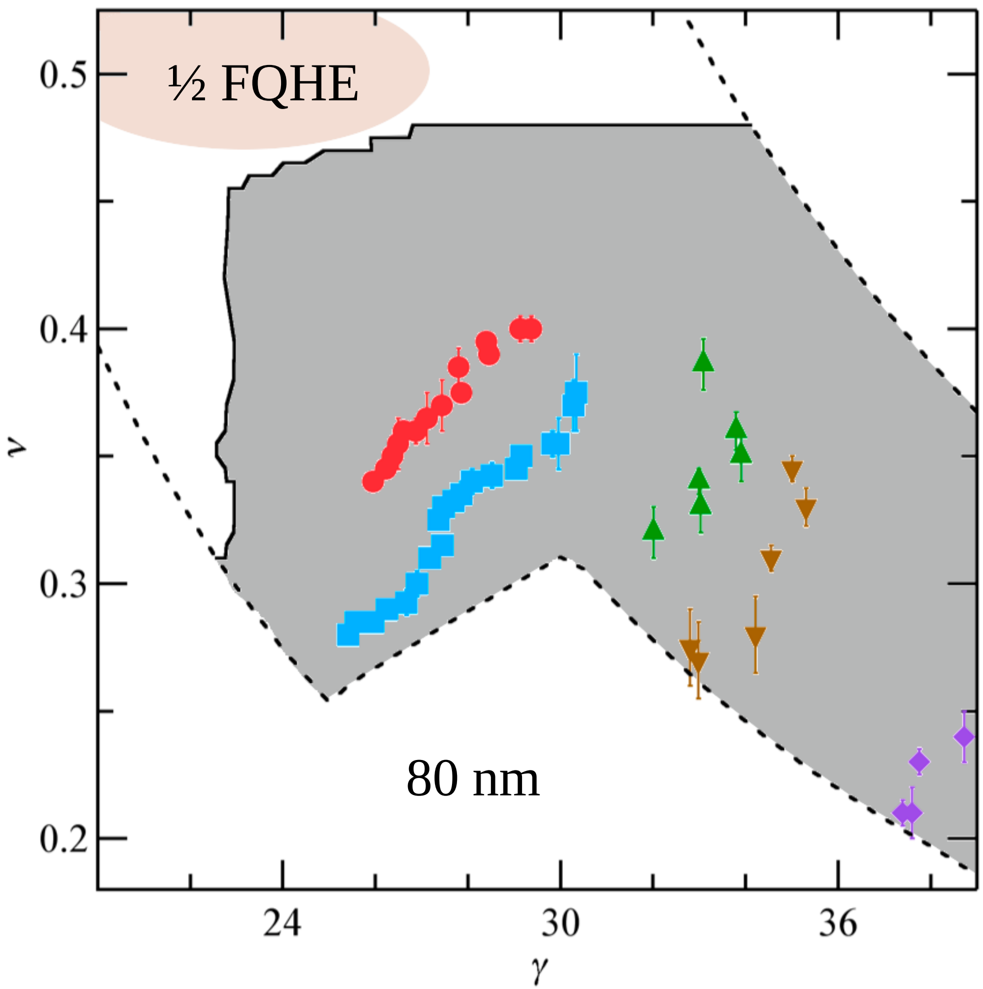


Microwave Spectra (w = 80 nm)

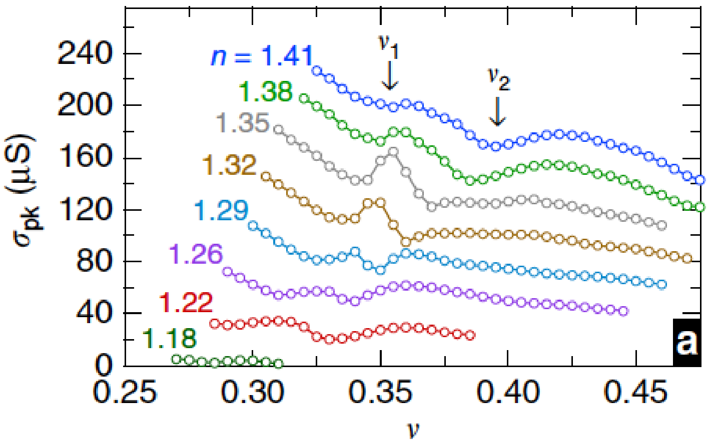


Hatke, Liu, Engel, Shayegan, Pfeiffer, West, Baldwin, Nature Comm. **6**, 7071 (2015)

five phase transitions in terminating insulator

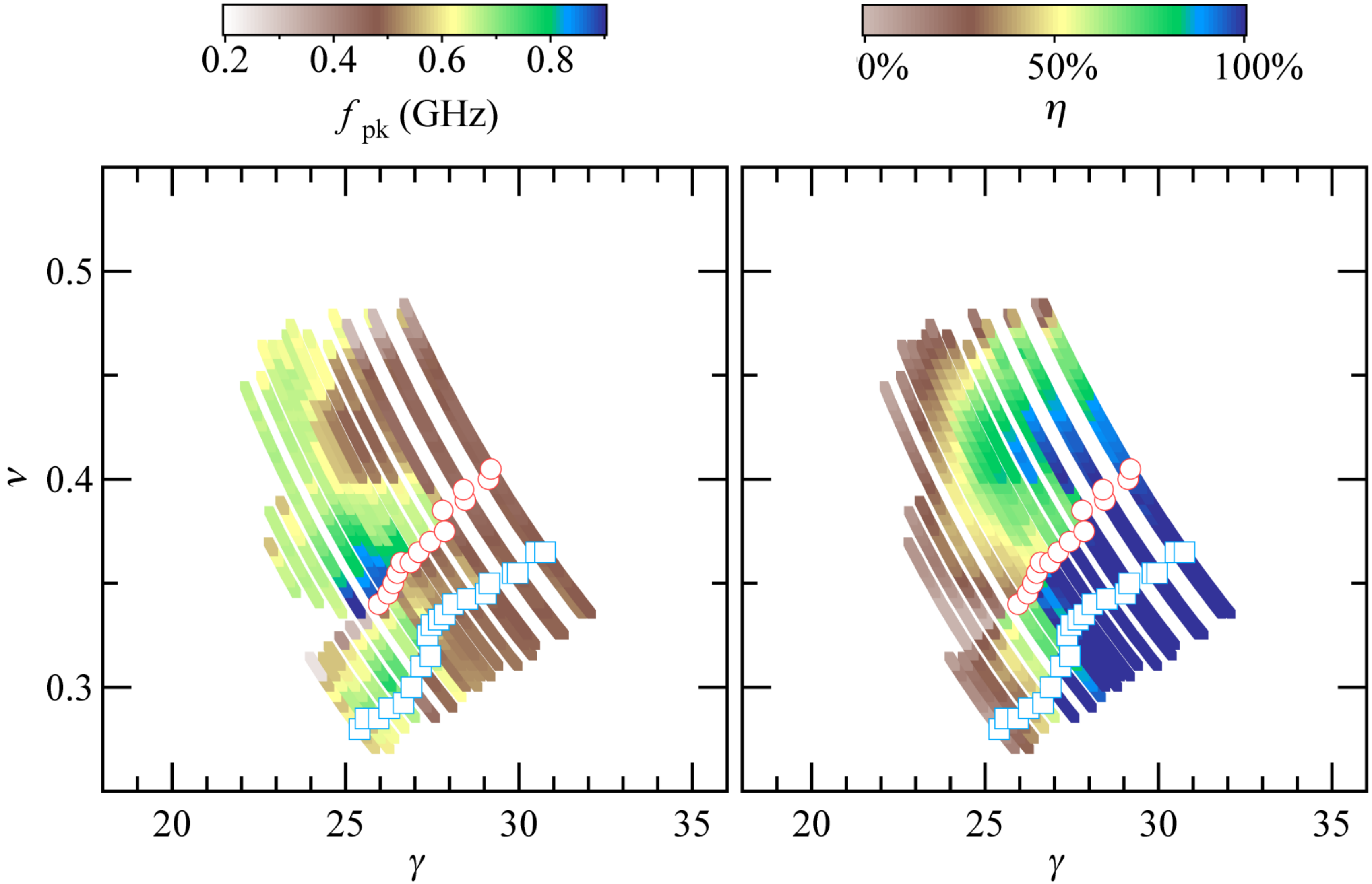


$\nu = nh/eB,\ \gamma = E_c/\Delta_{SAS}$



dashed lines: experimental limits

Phase Diagram (80 nm)

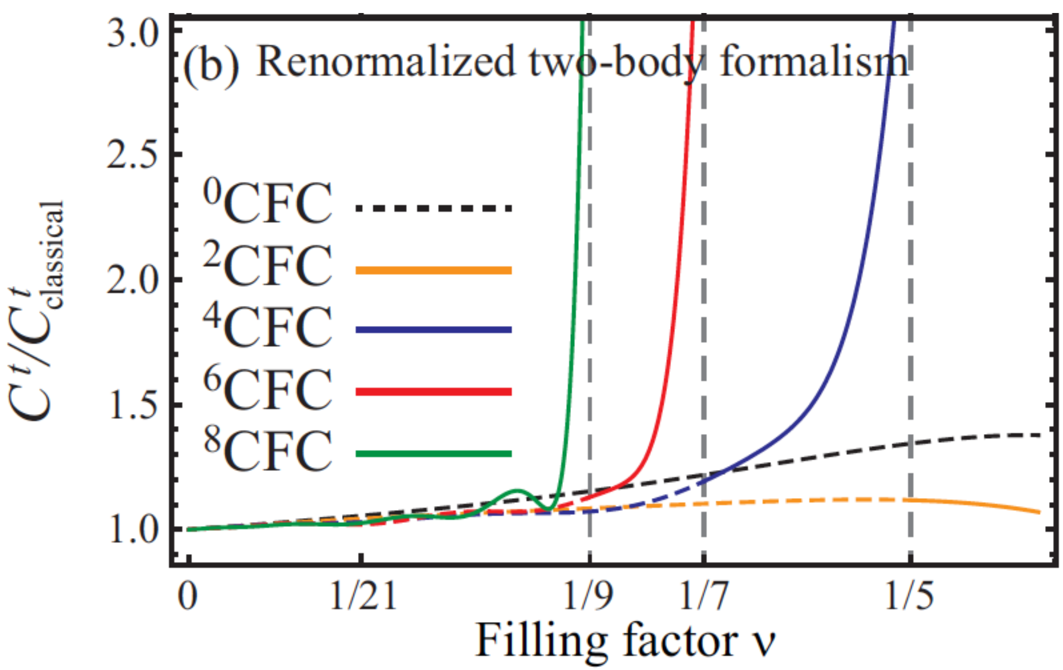


$\nu = nh/eB$, $\gamma = E_c/\Delta_{SAS}$, η = % participation

Possible explanations

- CFWC: Composite Fermion flux number (2p) transitions
  Archer, Park, Jain, PRL '13 ; Rhim, Jain, Park, PRB '15
  p → 2,3,4, as ν goes below~ 1/5,1/7, 1/9
- Single layer no disorder

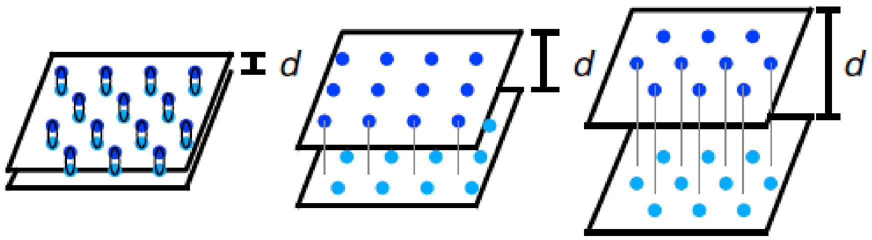
- Shear modulus has discontinuity at transitions

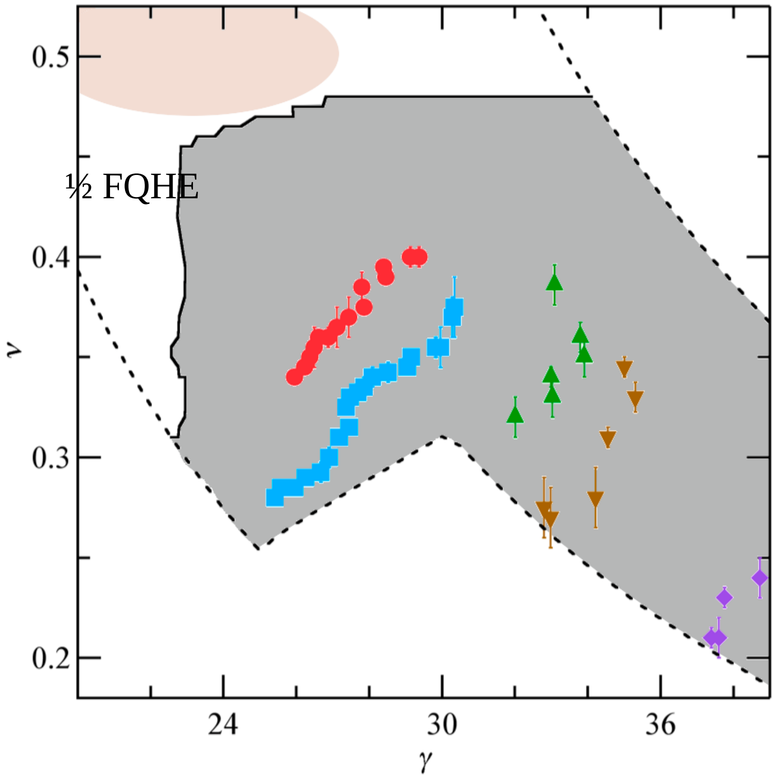


Possible explanations

- Bilayer structural

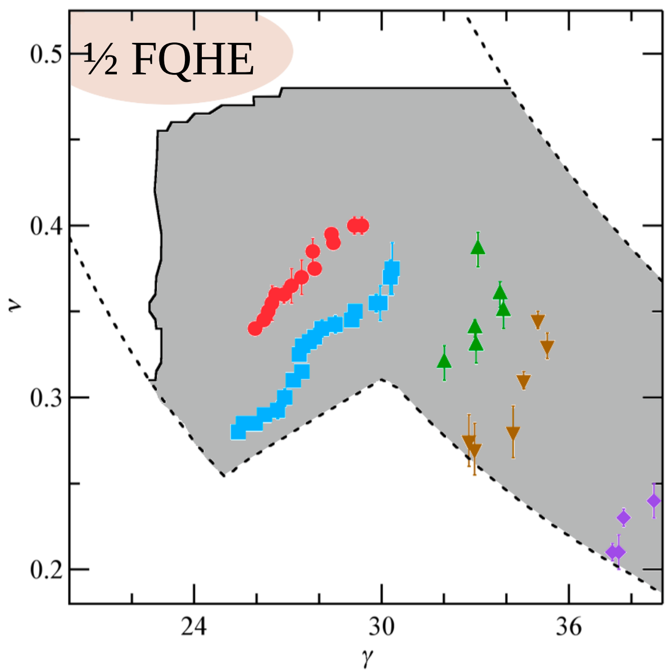
  HF theory : Narasihhan Ho, '95 ,
  Cote, Fertig, '95

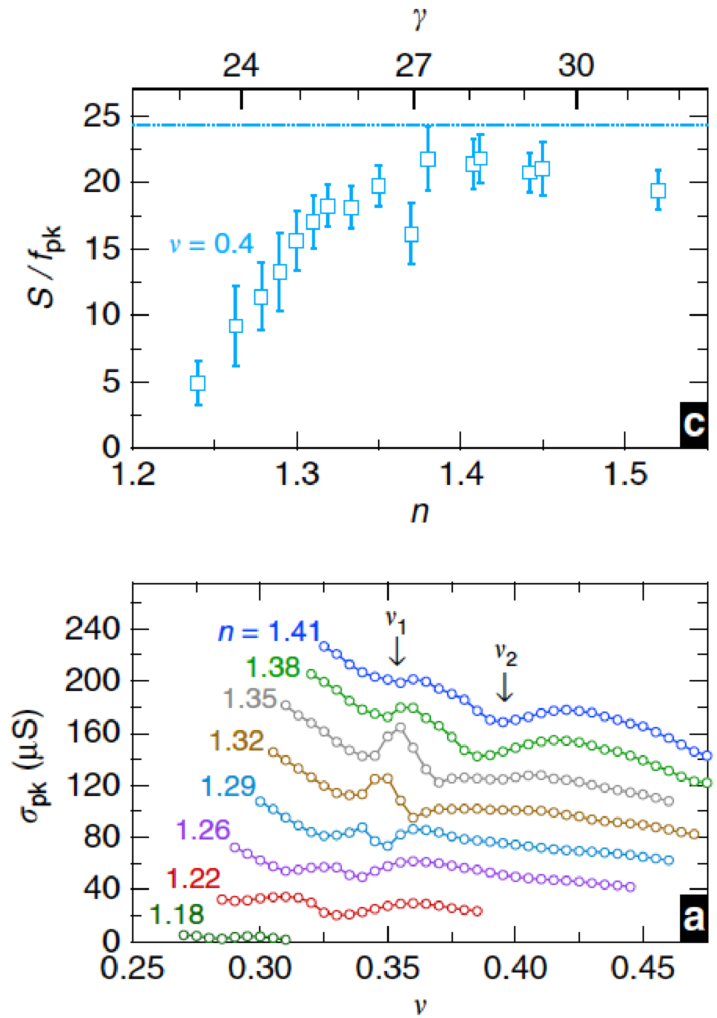




Wrong *trajectory*

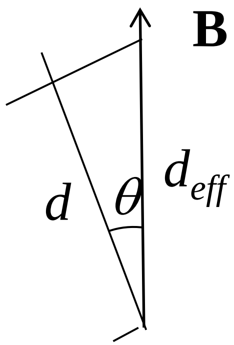
Admixture/microemulsion

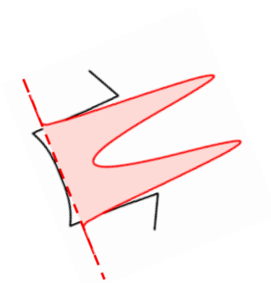


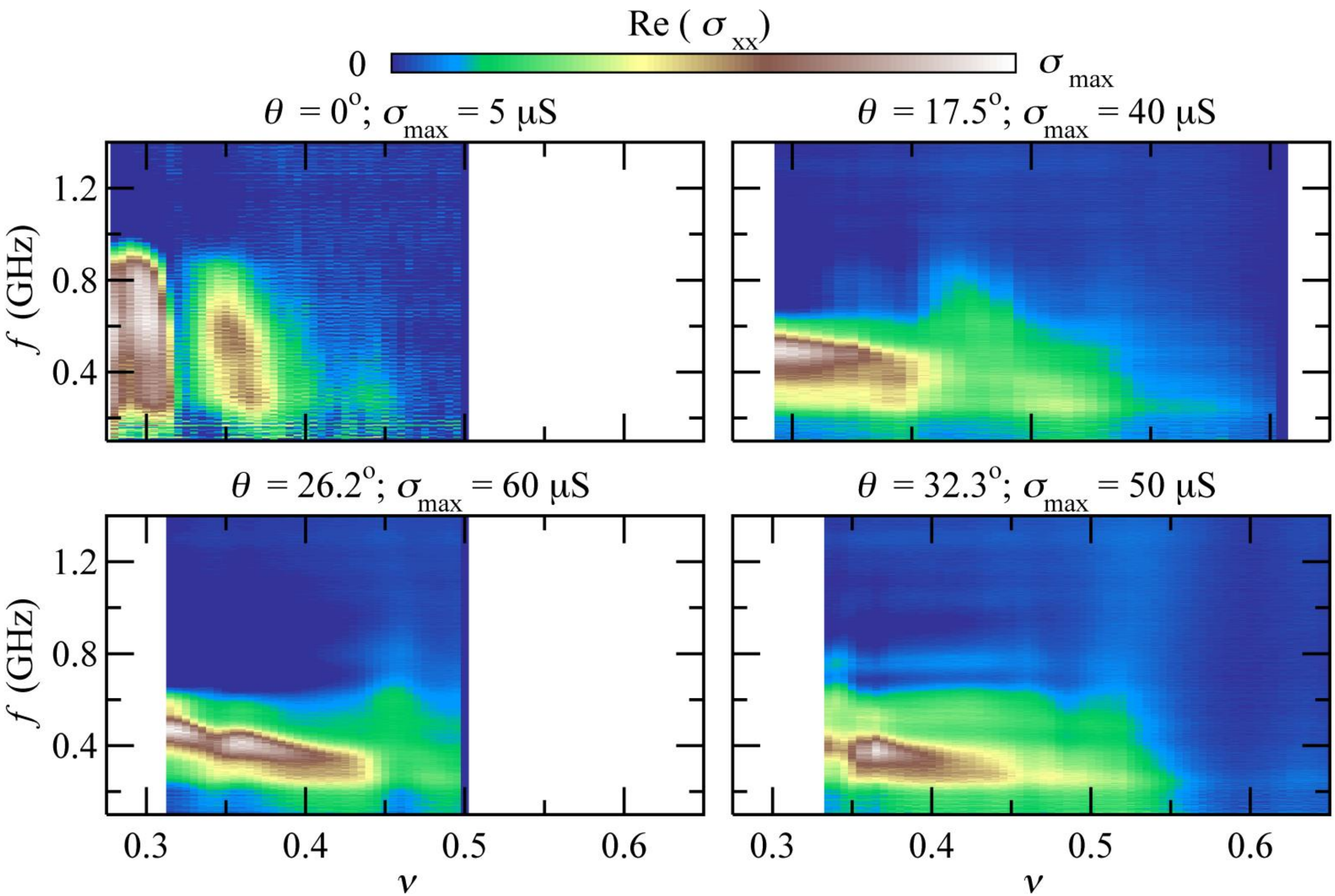


- Resonance turns on gradually as γ increases
- Transitions most pronounced at moderate γ
- Role of liquid or other nonresonant component
- Admixture/microemulsion, (Kivelson, Spivak)

Tilt sample in field:Microwave Spectra (w = 80 nm)



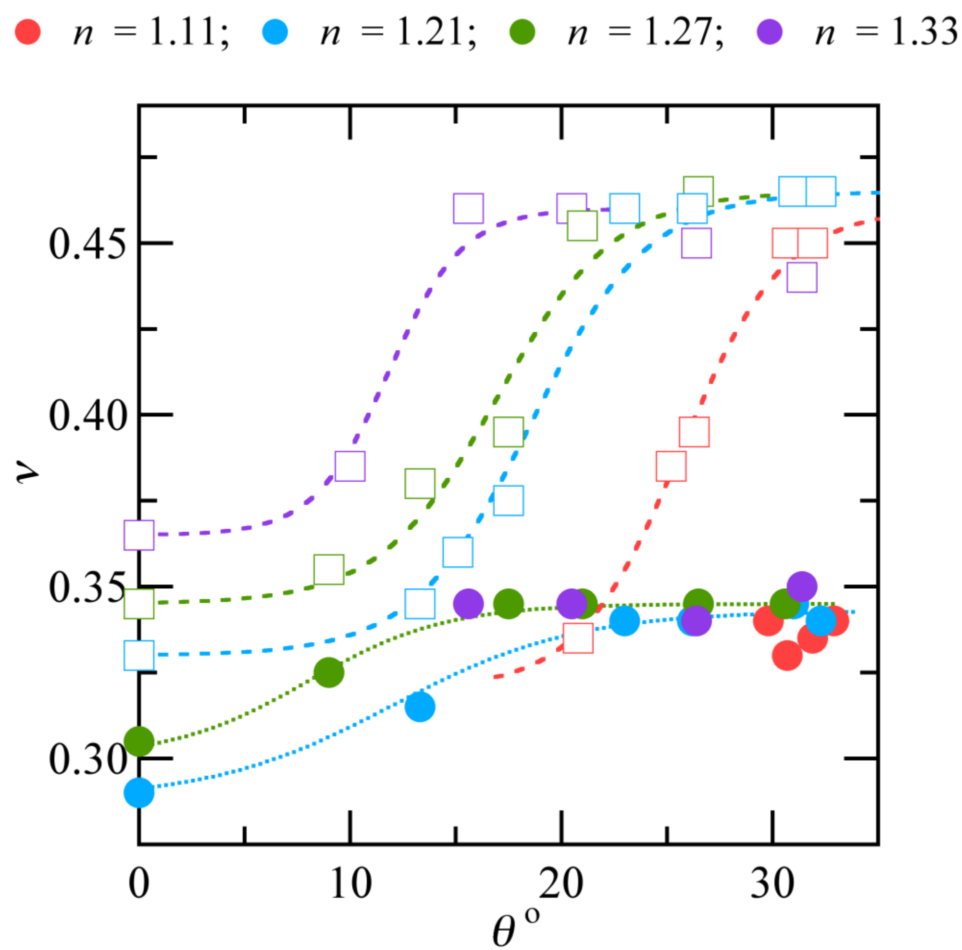




n=1.21

In-plane B increases sharpness, hence peak Re σ_{xx}.

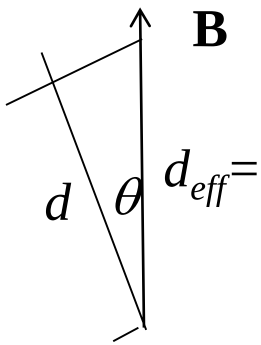
Transition movement (80 nm)



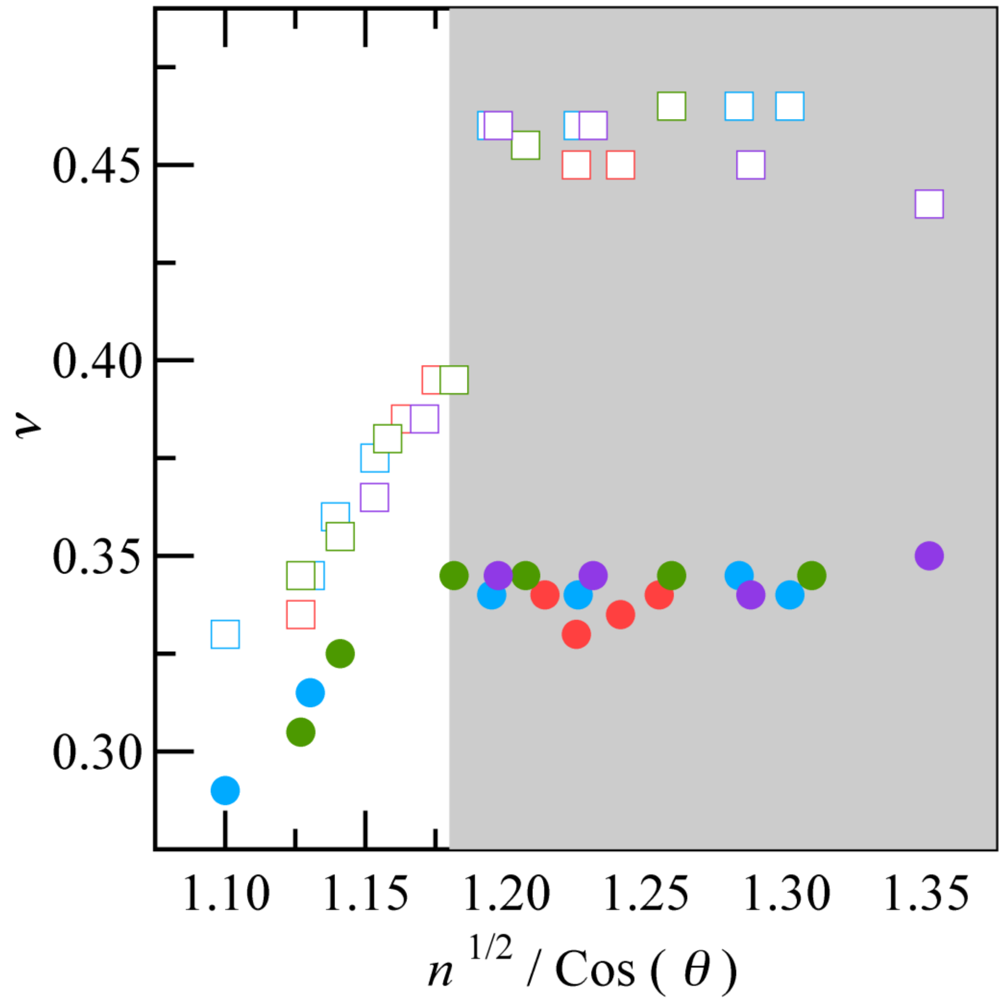
Increasing n or θ (bilayerness):

- Phase transition position moves to higher ν
- Reduction in tunneling
- Not consistent with HF predictions

Data collapse (80 nm)



$n^{1/2}/\cos\theta \sim d_{eff}/a$



Two regimes:

- Low θ: modification of Δ_{SAS}
- High θ: n and θ independent transitions---ν determined

Summary

- DQW: CF liquid +WS

  ν_H ®n_I

- Resonance associated with a bilayer electron solid in a wide quantum well
  - Deep in the insulating state: *five* phase transitions

    Possibilities…
    - CF vortex number transitions
    - Liquid/solid emulsion
    - Bilayer stacking transitions
  - ν characterizes transitions at high in-plane field

Hatke, Liu, Engel, Shayegan, Pfeiffer, West, Baldwin, Nature Comm. **6**, 7071 (2015)
Hatke, Liu, Engel, Shayegan, Pfeiffer, West, Baldwin, arXiv: 1504.08182