Microwave spectroscopy of the low ν insulator in wide quantum wells

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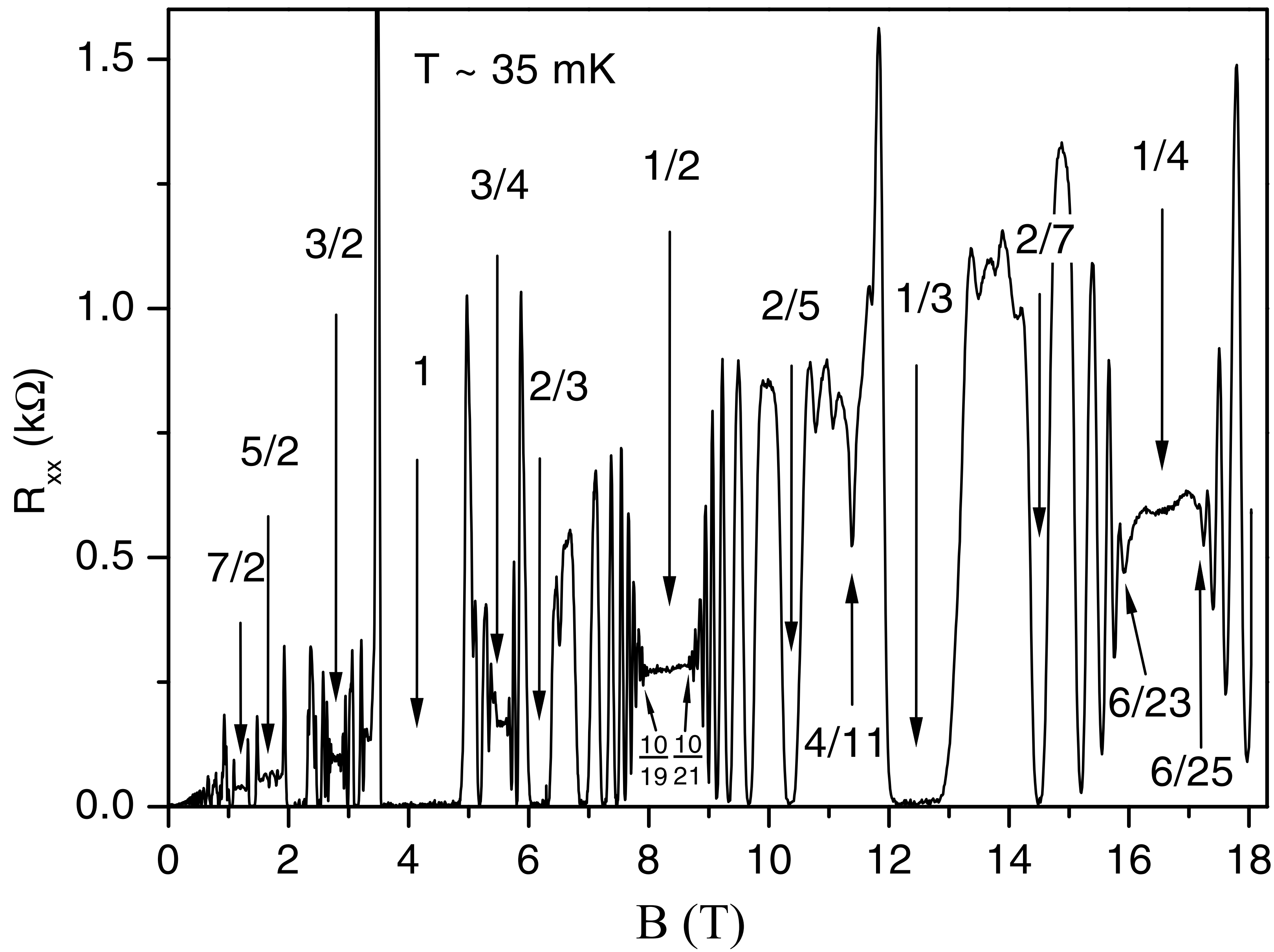
Gordon and Betty Moore Foundation GBMF2719

QT2DS, Luchon France, May 27th 2015

Talk overview

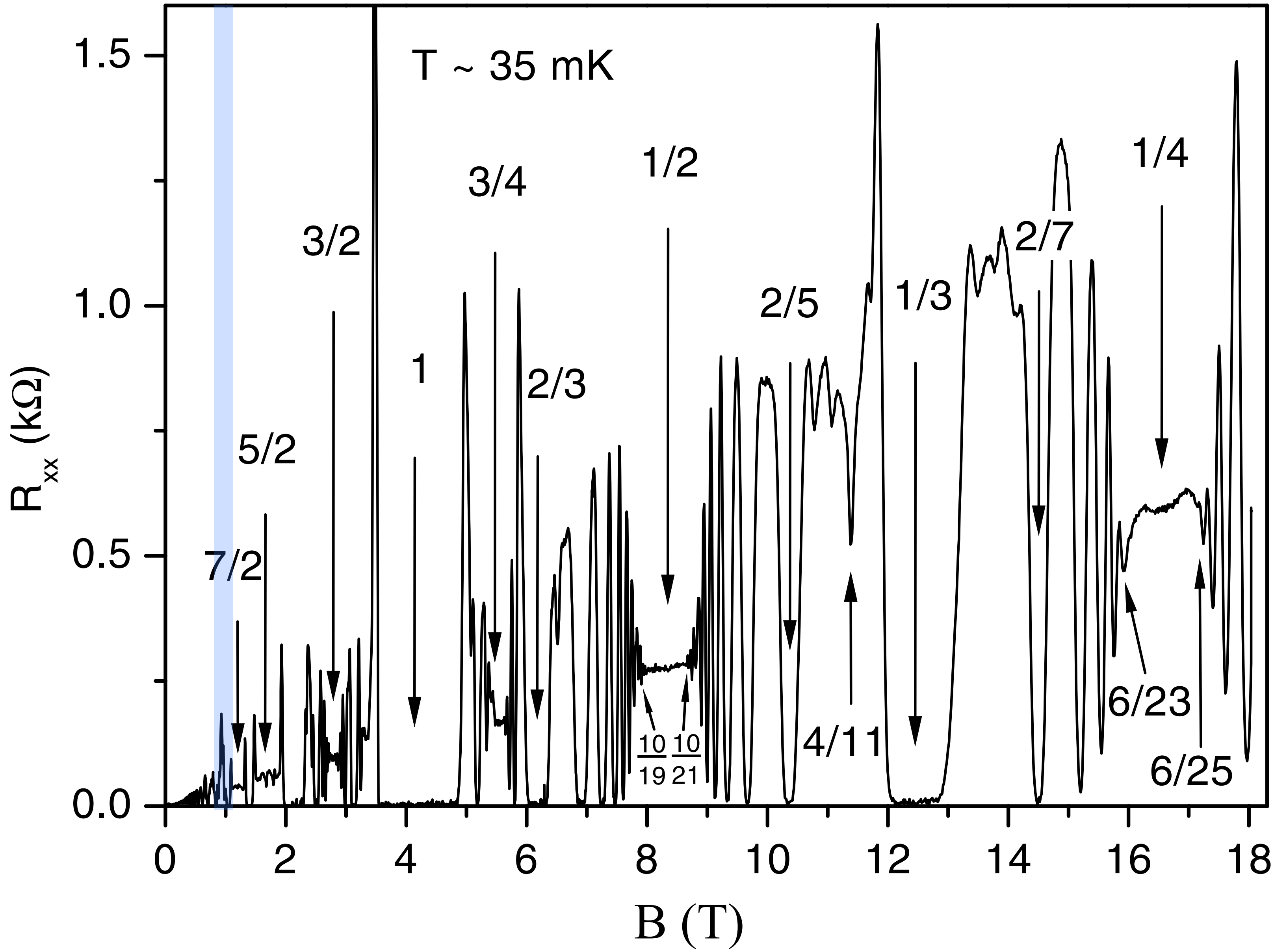
- Introduction
  - Microwave spectroscopy technique
  - Wide quantum well (WQW) system
- High magnetic field insulating state
  - Pinned bilayer Wigner solid in a WQW
  - Pinning mode resonance of a bilayer electron solid
    - Multiple phase transitions
- Fractional quantum Hall effect near $\nu = 1/2$
  - Solidification of 1/2 fractionally charged quasiholes

Decades of phases



Pan, Stormer, Tsui, Pfeiffer, Baldwin, West, PRL **88**, 176802 (2002)

Decades of phases



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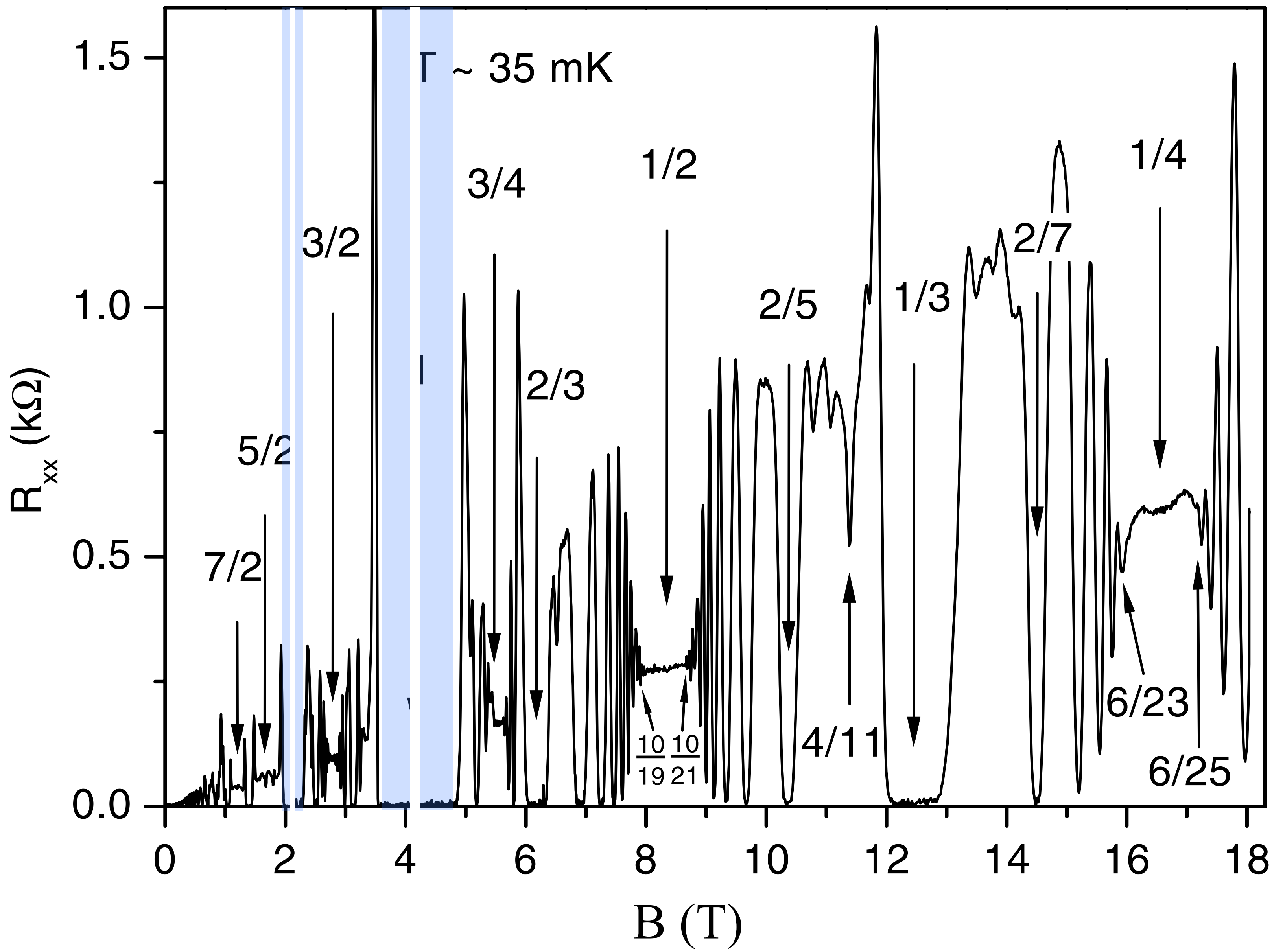

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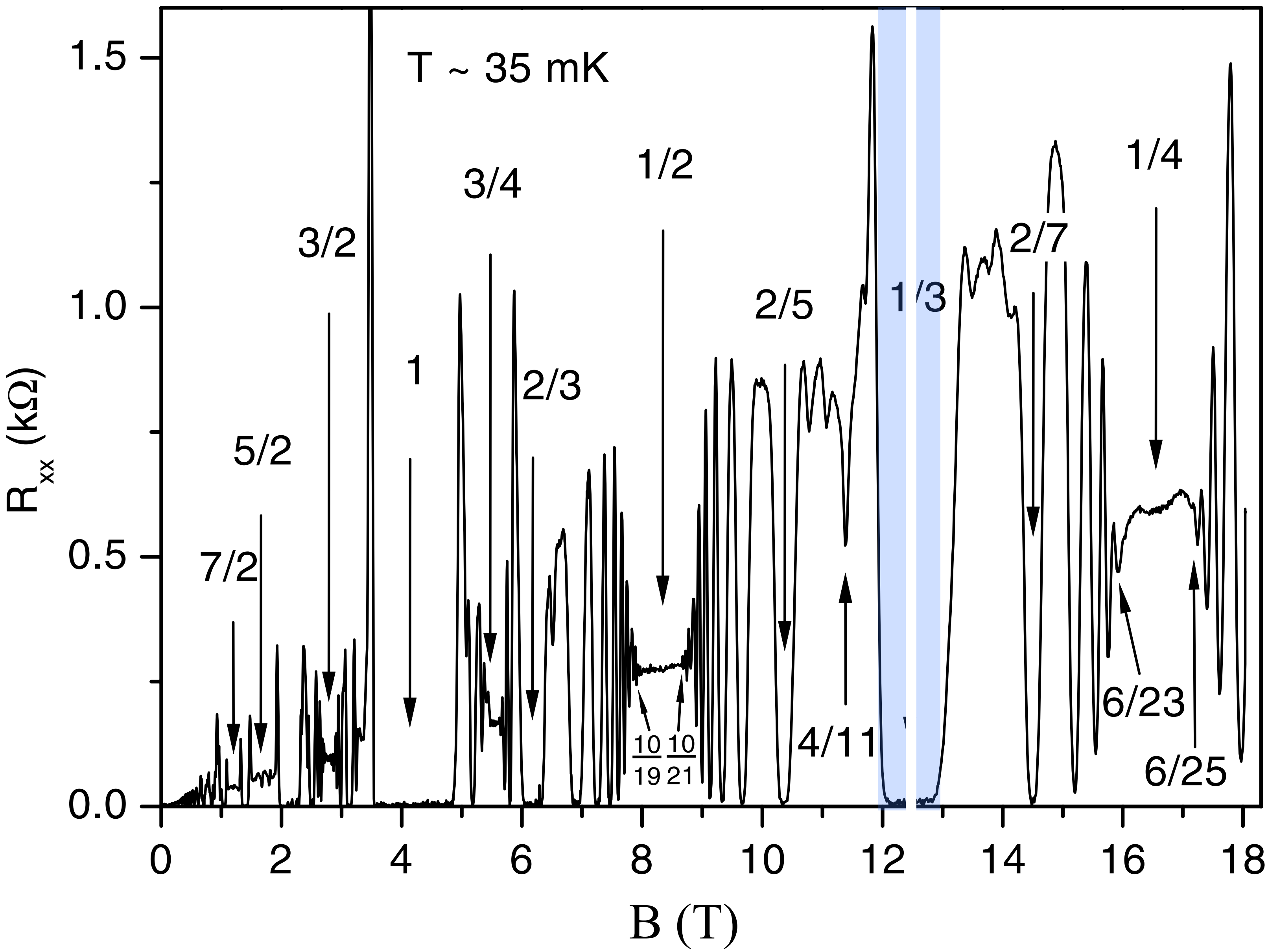
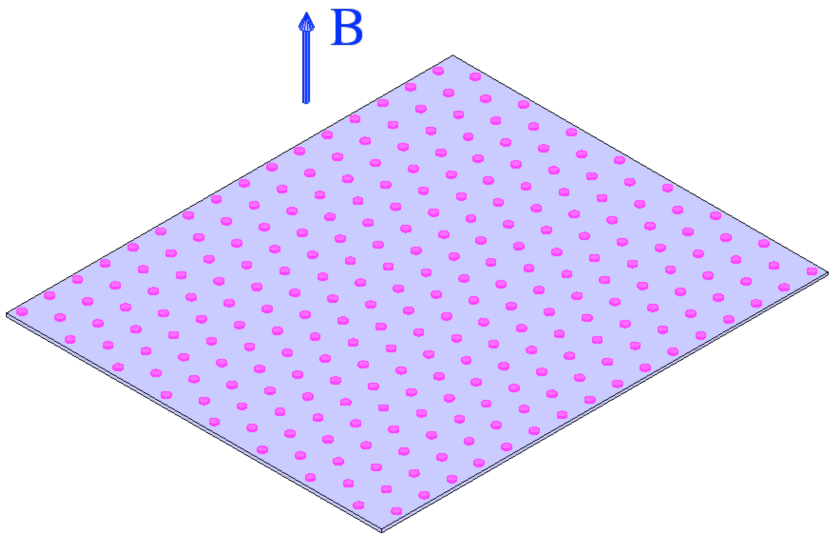
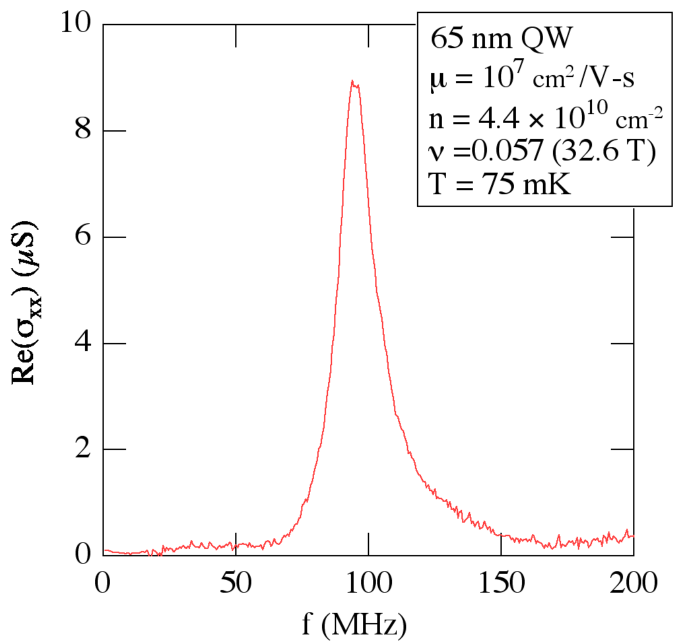


Pan, Stormer, Tsui, Pfeiffer, Baldwin, West, PRL **88**, 176802 (2002)

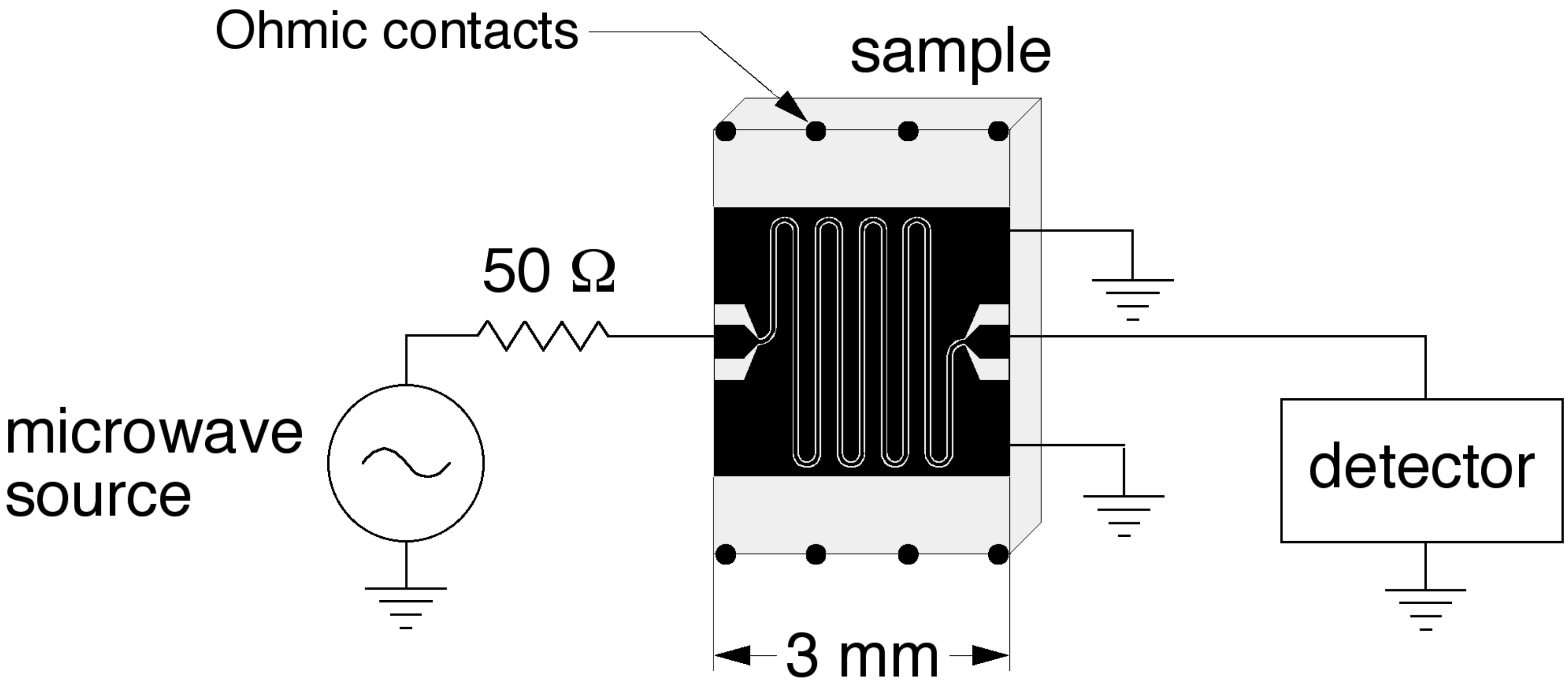
High *B* Wigner solid

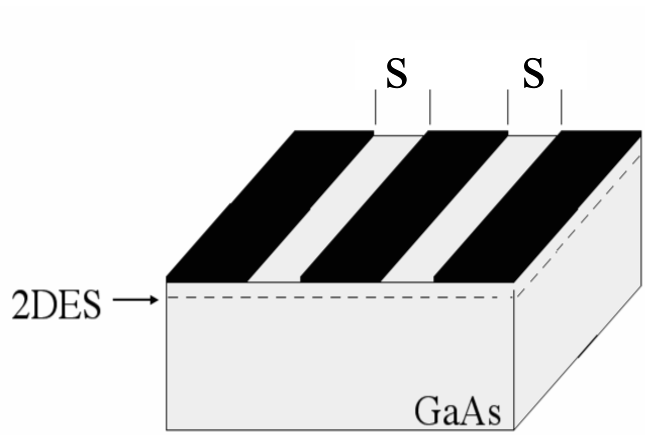




- Wigner solidification at $\nu \sim 1/5$ in single layer
- Solid pinned by disorder
- Microwaves measure a pinning mode resonance
  - Measuring a resonance with a peak frequency
    - Sensitive to crystal structure, interactions, and disorder

Experimental setup



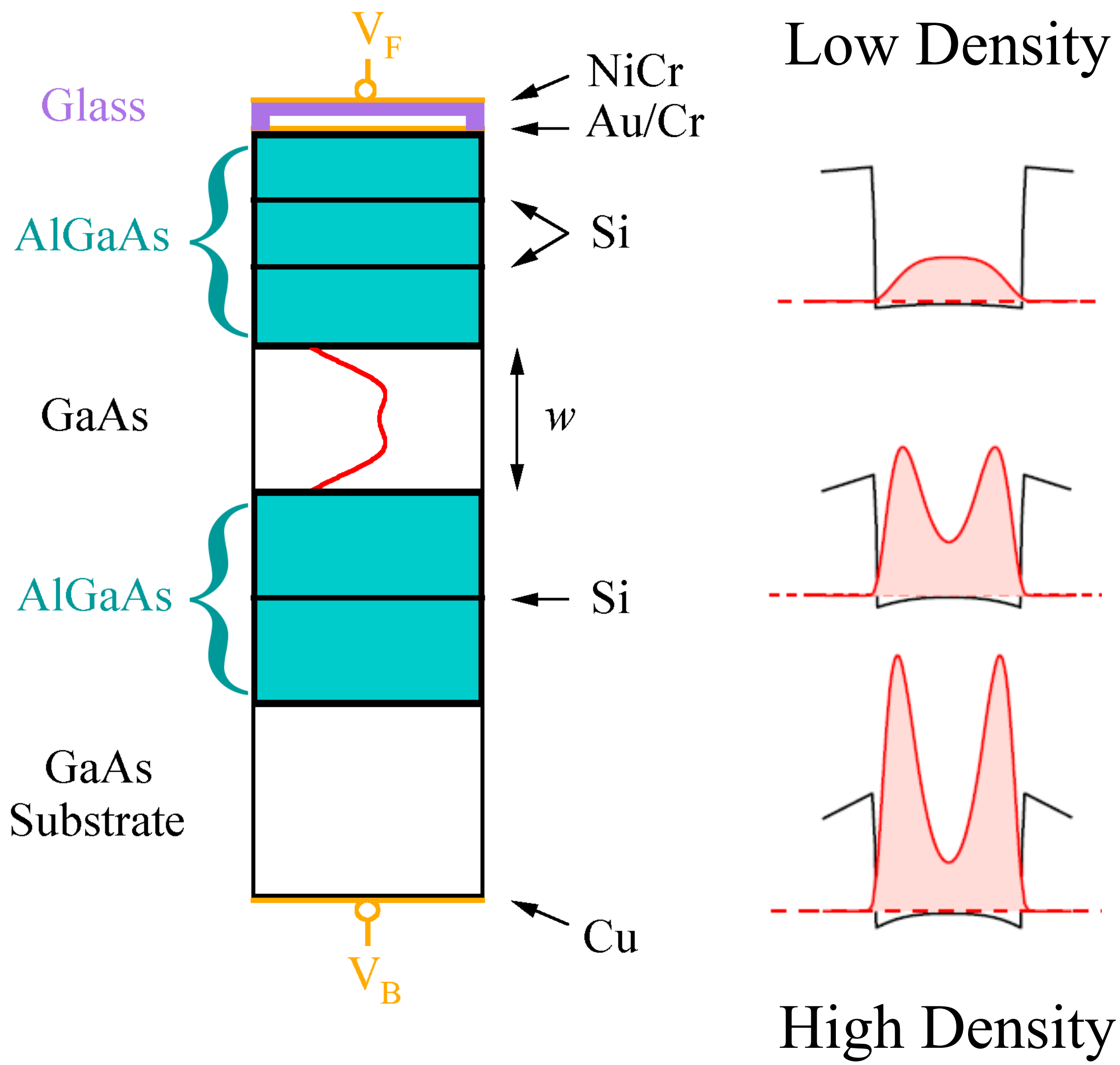


- Conductivity:

$$\sigma(f) = \frac{s}{lZ_0} \ln \frac{t}{t_0}$$

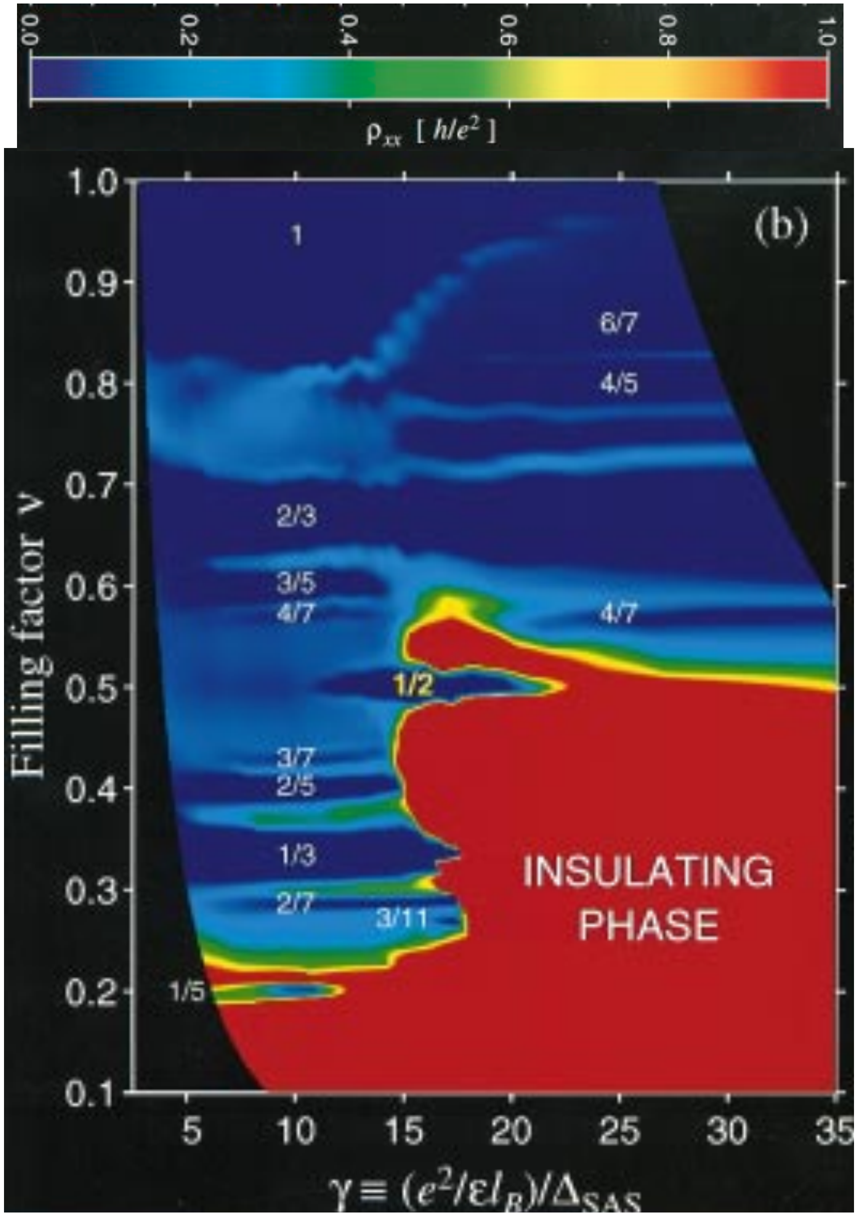
- $T \sim 50$ mK, $f \sim 1$ GHz

Wide quantum well



- GaAs/AlGaAs quantum wells
- Low density
  - Single layer
- High density
  - Bilayer effects have increasing importance

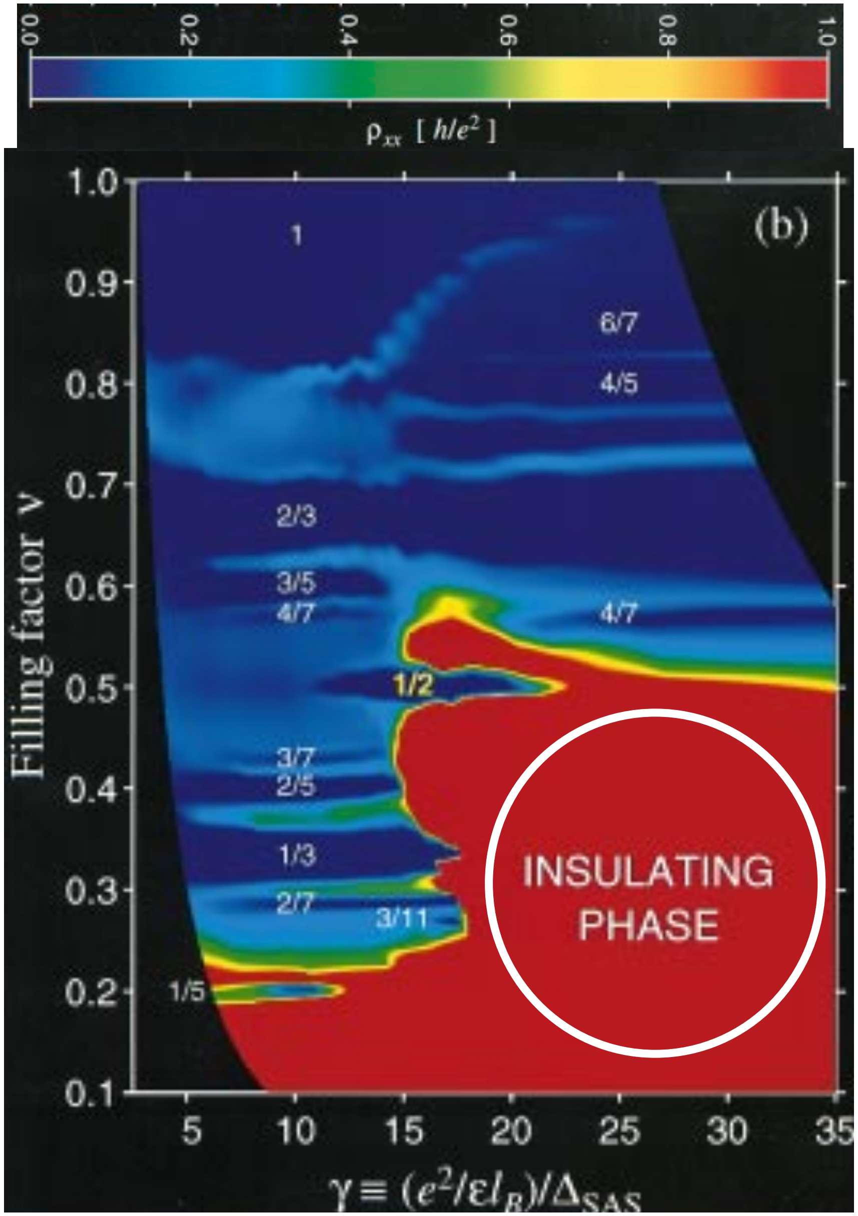
Bilayer electron solid (w = 75 nm)



- γ controls "bilayerness"
  - E_c ~ charge separation
  - Δ_{SAS} ~ charge uniformity
- Low γ (single layer):
  - Insulating phase: $\nu < 1/5$
- Intermediate γ (correlated double layer):
  - Insulating phase: $\nu < 1/2$

[1] Manoharan, Suen, Santos, Shayegan, PRL **77**, 1813 (1996)

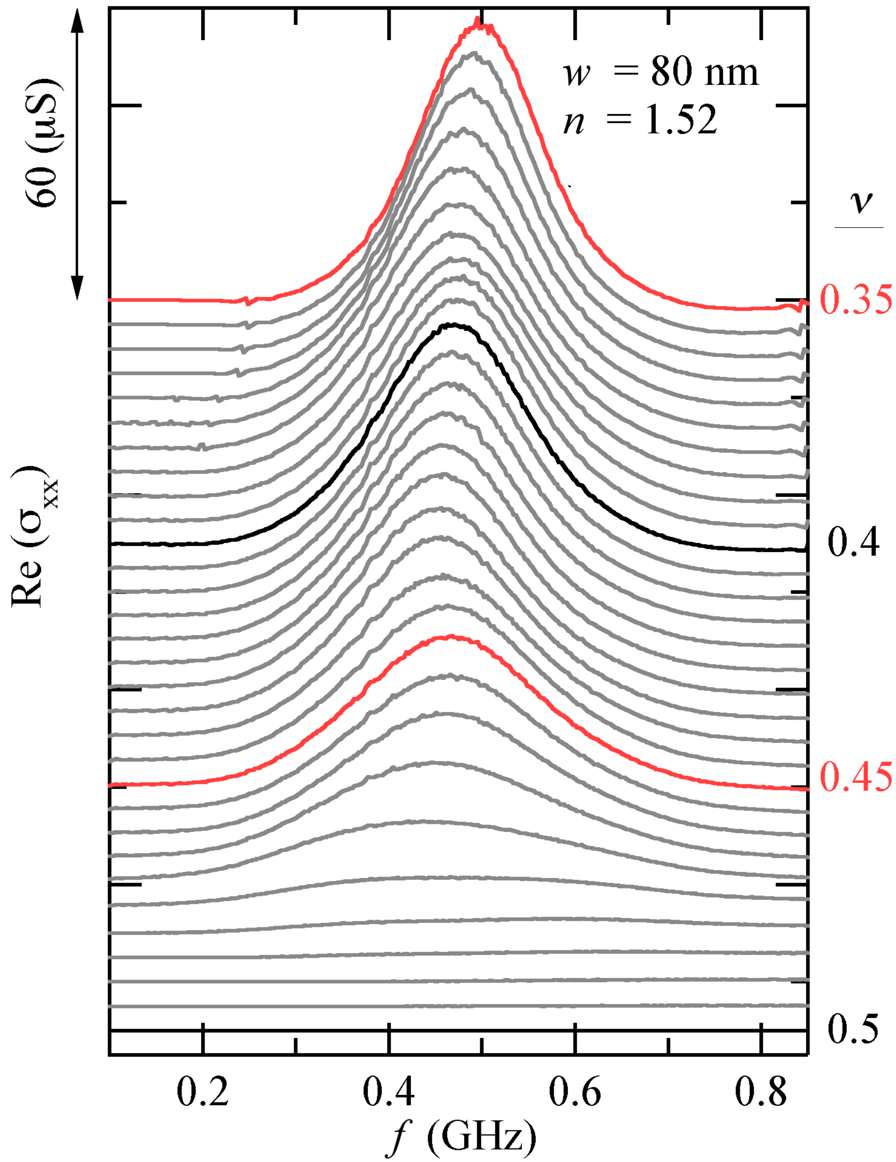
Bilayer electron solid (w = 75 nm)



- γ controls "bilayerness"
- Low γ (single layer):
  - Insulating phase: $\nu < 1/5$
- High γ (double layer):
  - Insulating phase: $\nu < 2/5$
- Intermediate γ (correlated double layer):
  - Insulating phase: $\nu < 1/2$

[1] Manoharan, Suen, Santos, Shayegan, PRL **77**, 1813 (1996)

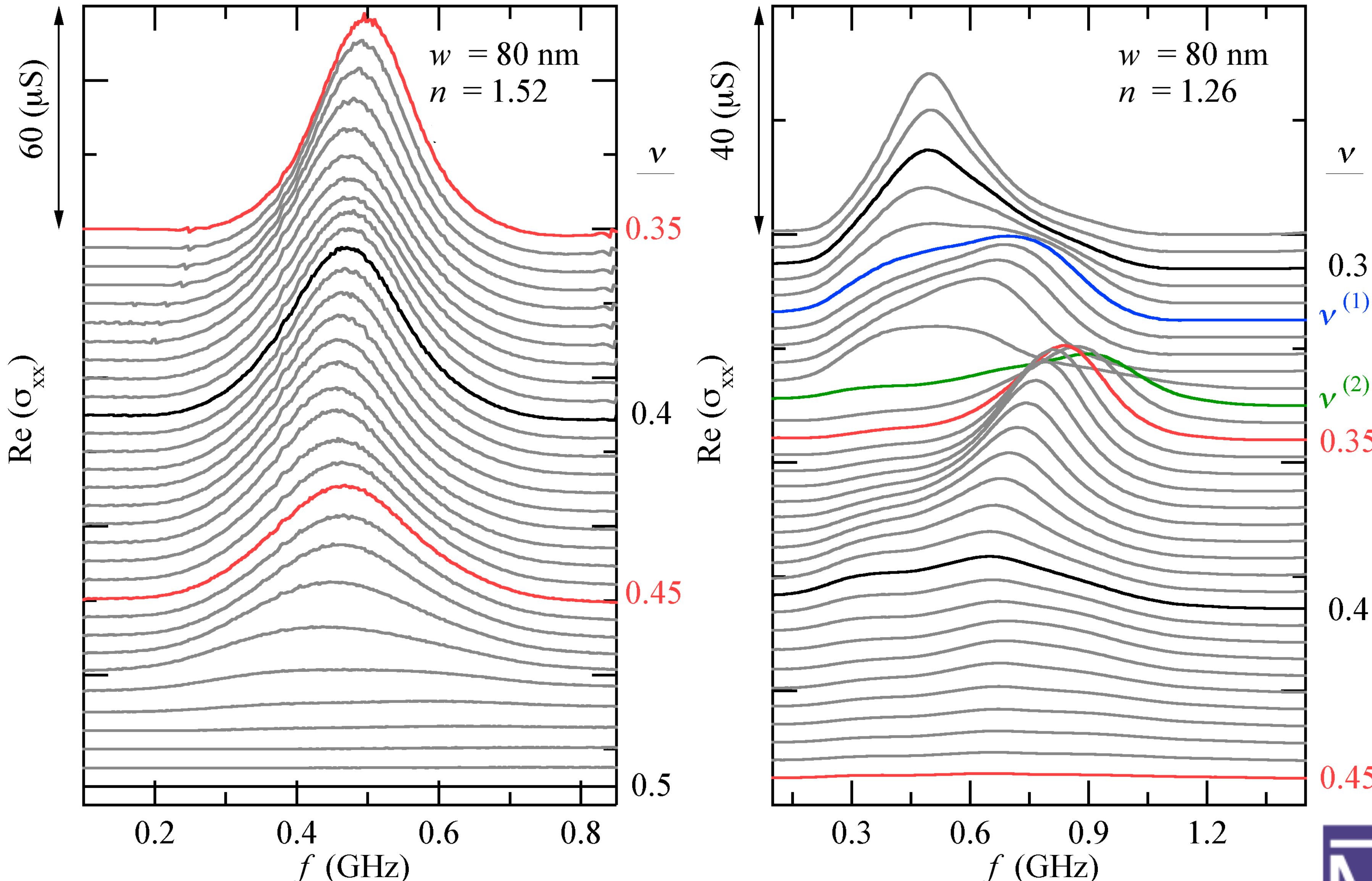
Microwave Spectra (w = 80 nm)



- Microwave spectra reveal a resonance deep in the bilayer insulator
- Bilayer electron solid with $f_{pk} \sim 0.5$ GHz
  - Little change in f_{pk}

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

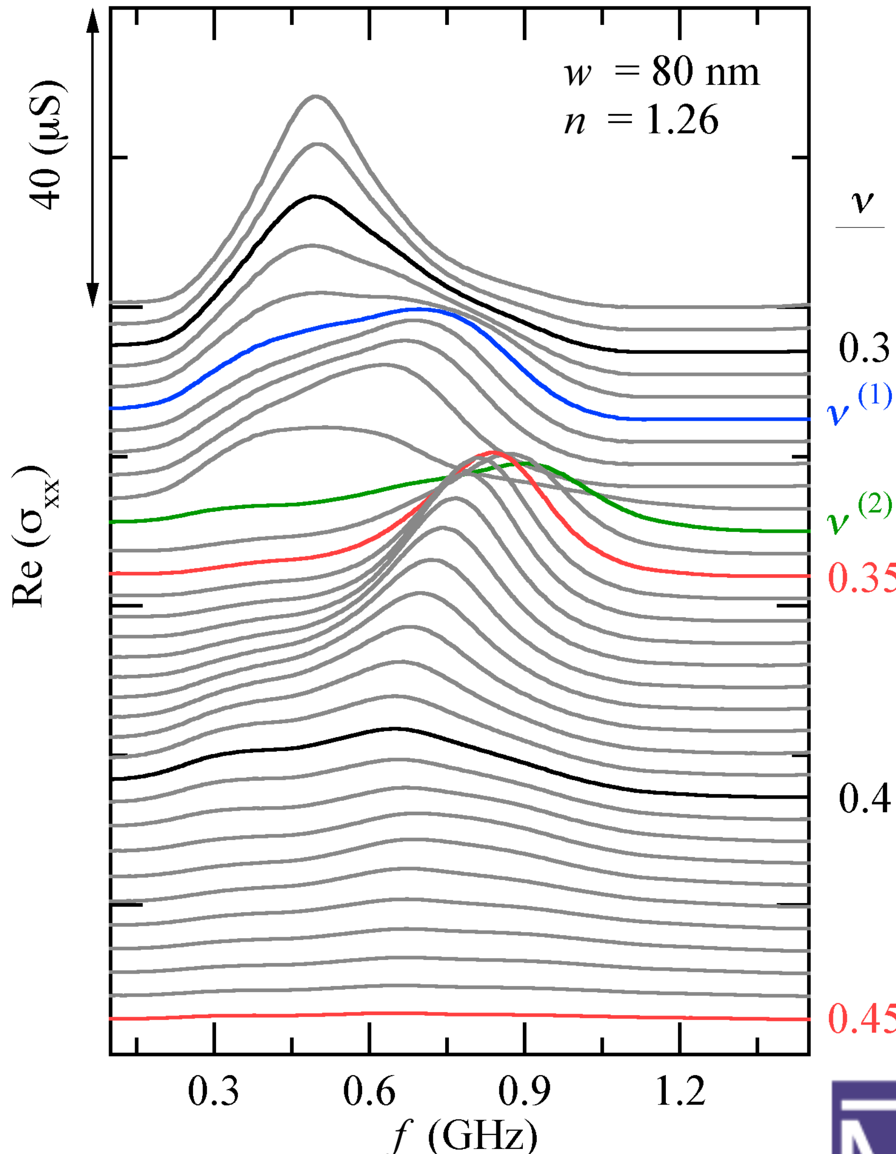
Microwave Spectra (*w* = 80 nm)



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

Microwave Spectra (w = 80 nm)

- $\nu = 0.29$: bilayer electron solid
  - $f_{pk} \sim 0.5$ GHz
- Phase transition with increasing ν
  - f_{pk} jumps at $\nu^{(1)} = 0.315$
    - $f_{pk} \sim 0.7$ GHz
  - f_{pk} jumps at $\nu^{(2)} = 0.34$
    - $f_{pk} \sim 0.9$ GHz



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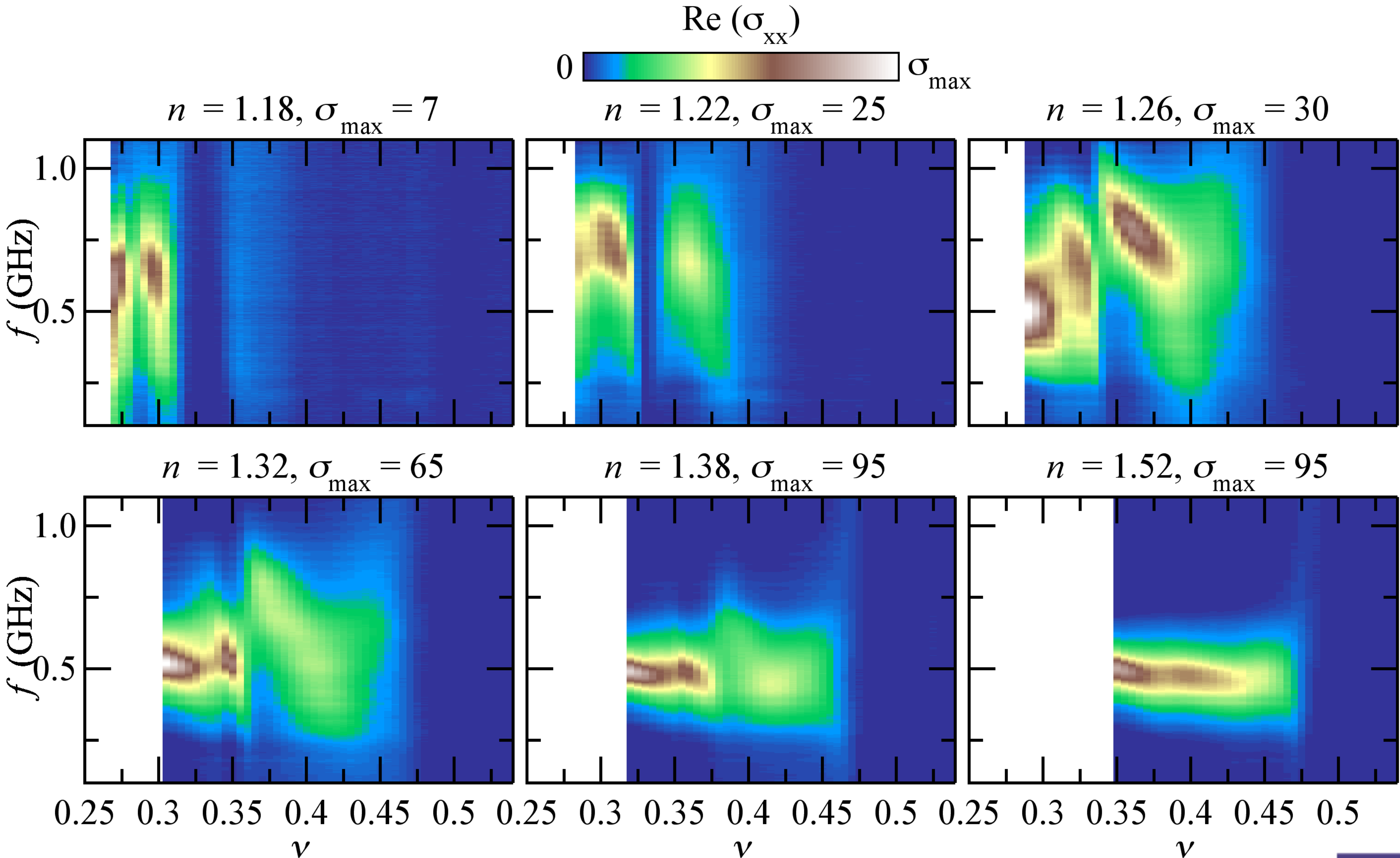

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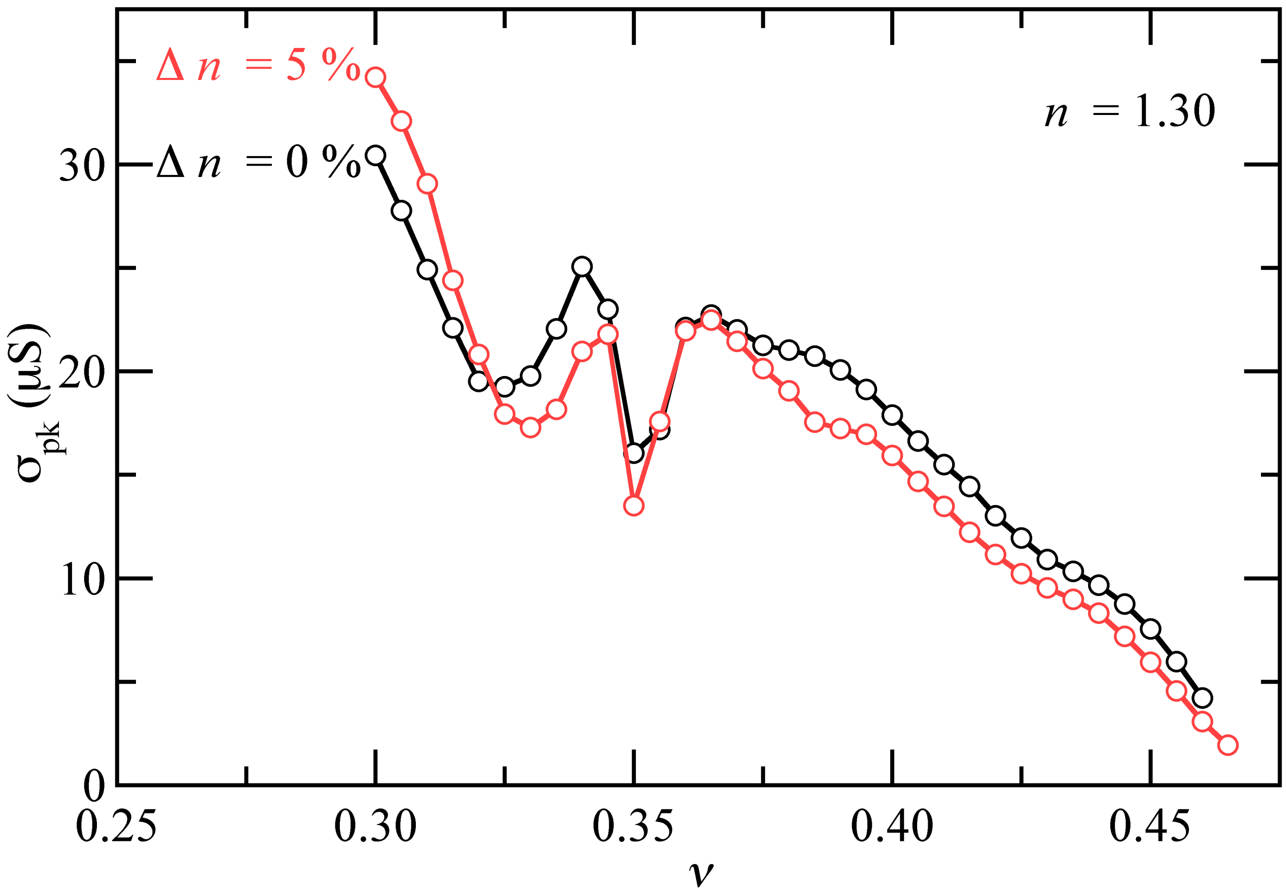

- Slight asymmetry has minimal effect

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

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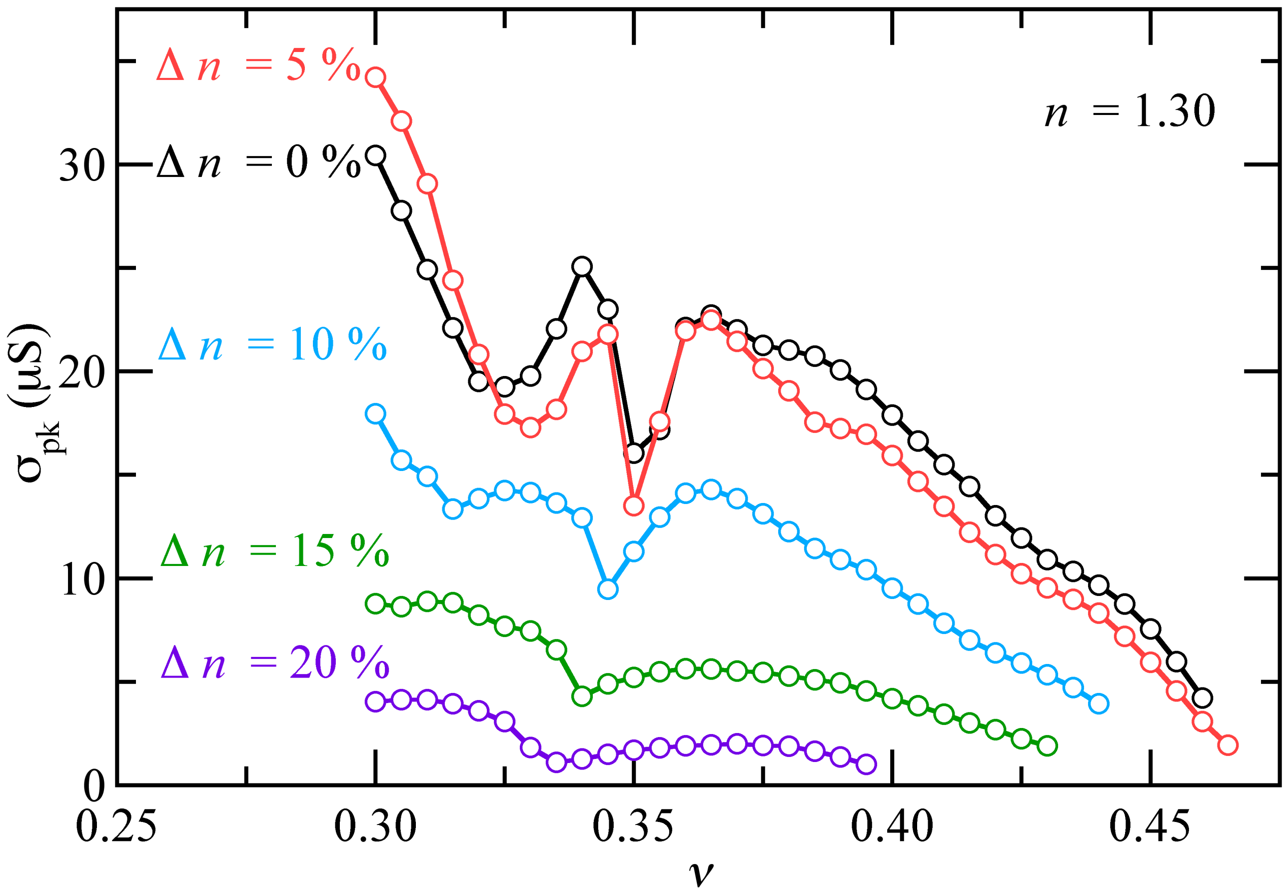
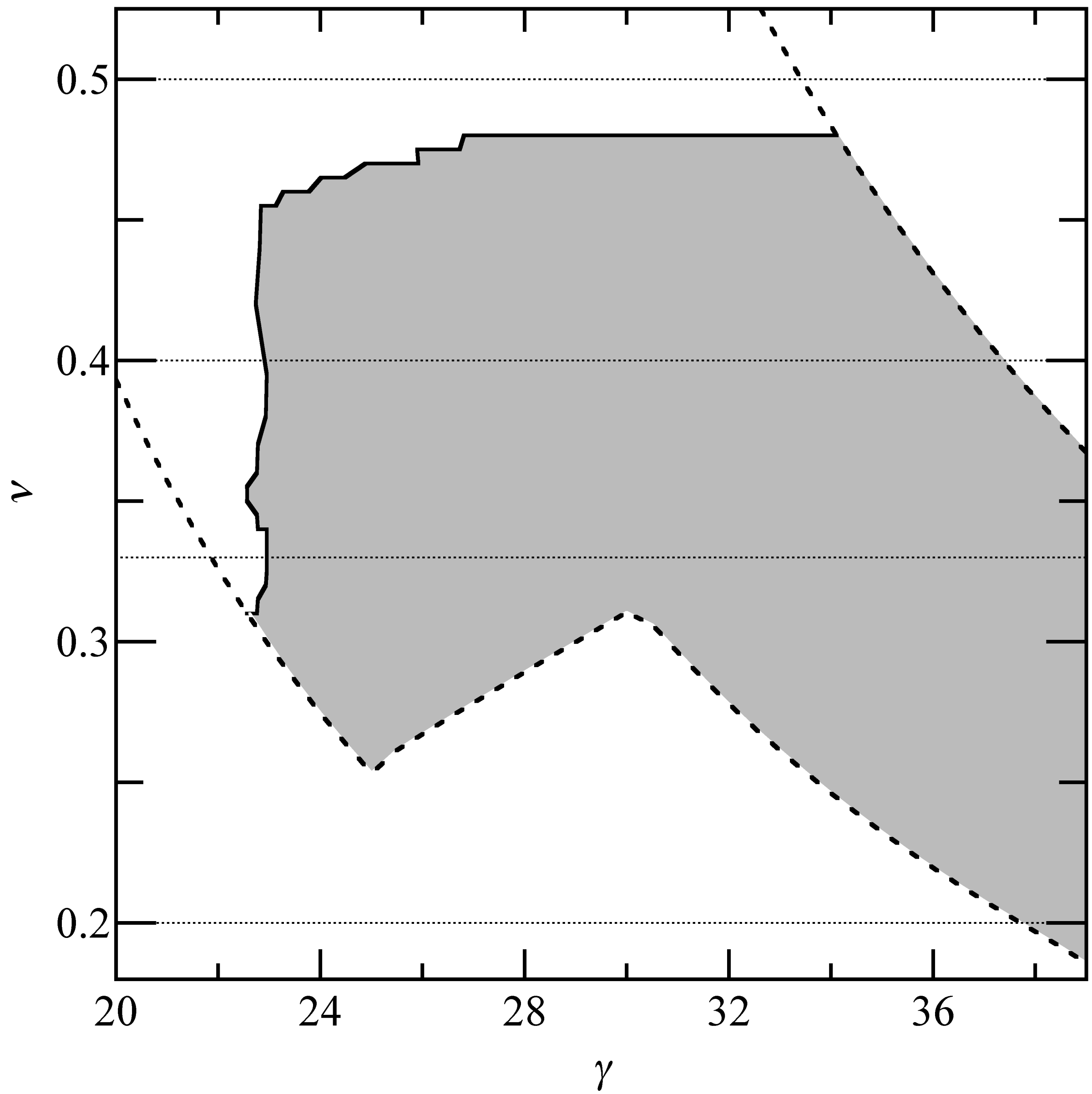


- Slight asymmetry has minimal effect
- Hard asymmetry destroys bilayer state

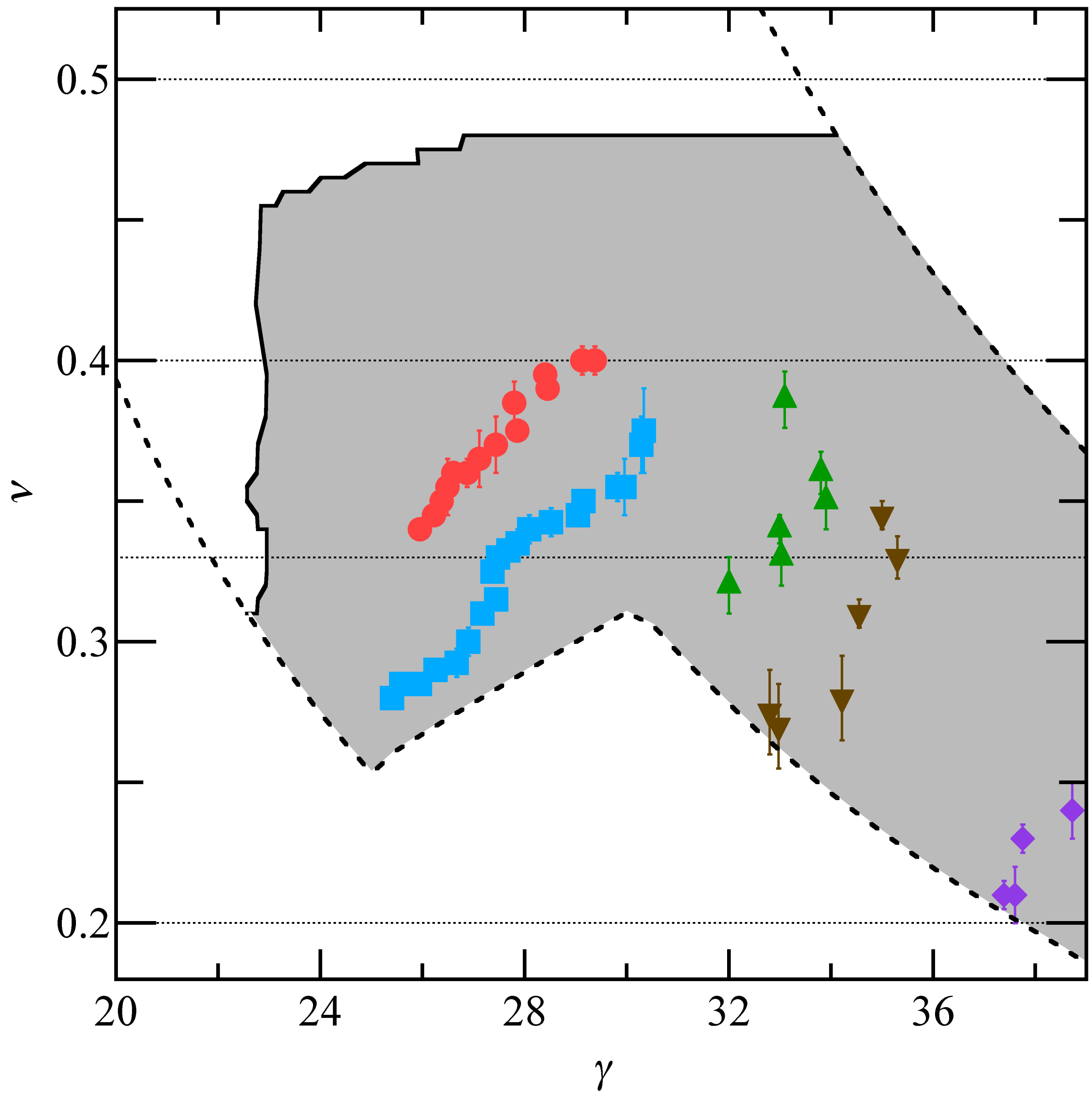
Hatke, Liu, Engel, Shayegan, Pfeiffer, West, Baldwin, Nature Comm. **6**, 7071 (2015)

Phase Diagram (w = 80 nm)



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

Phase Diagram (w = 80 nm)



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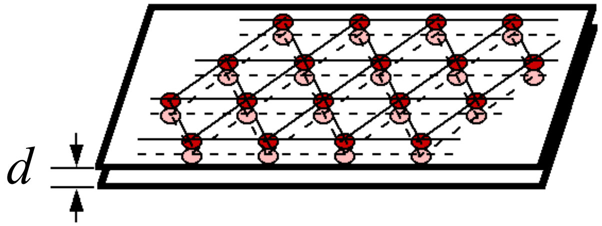
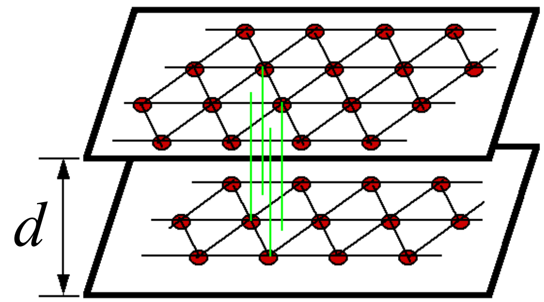
Bilayer stacking transition



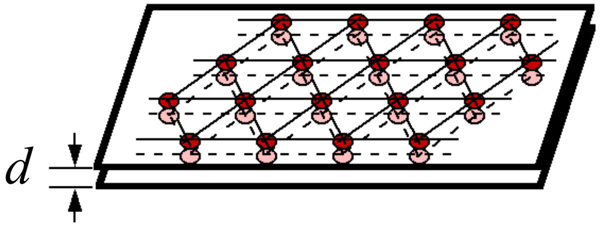
One-component triangular



Staggered Triangular

Narasimhan, Ho, PRB **52**, 12291 (1995)

Bilayer stacking transition



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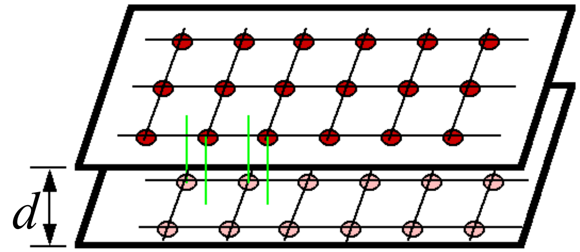
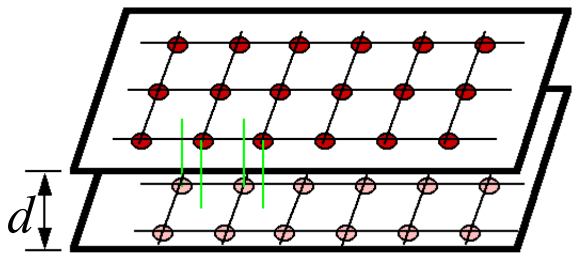
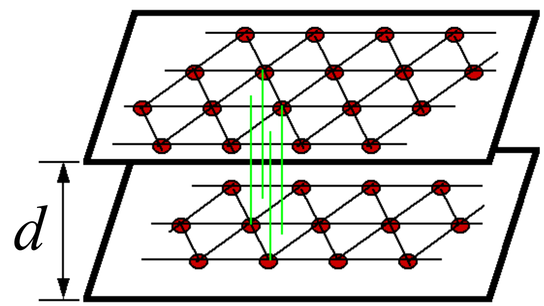


Centered square



Centered Square



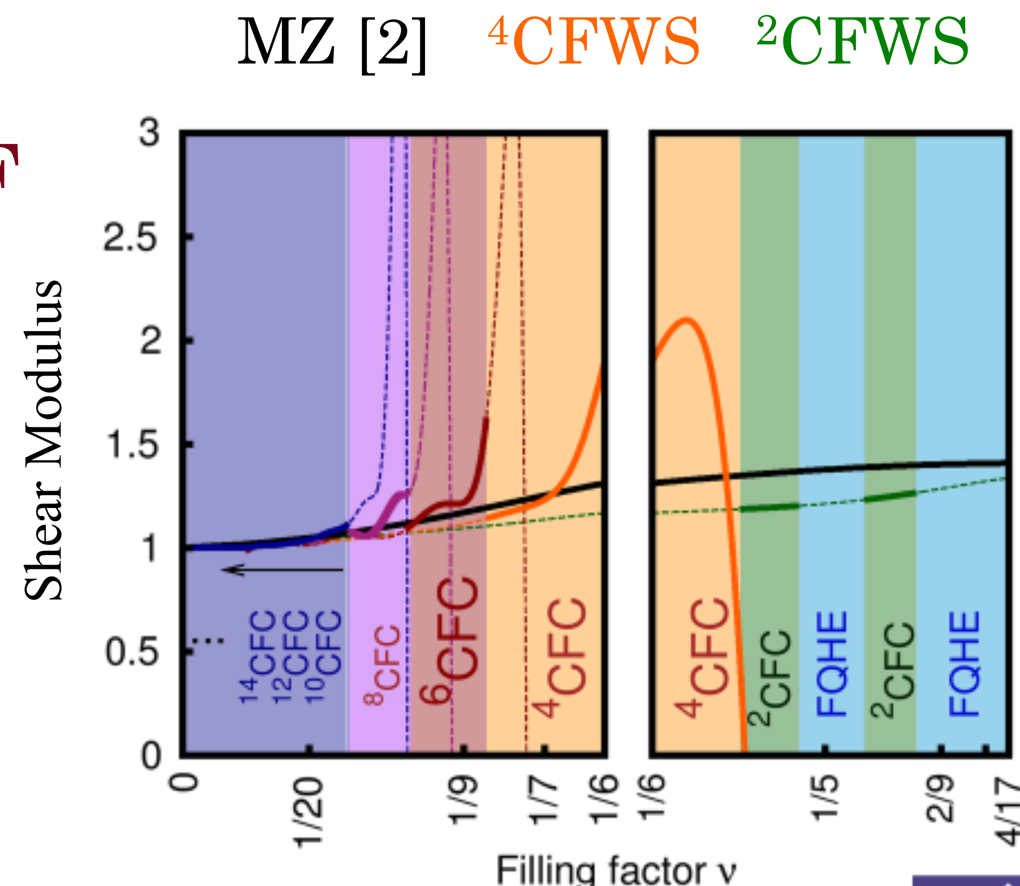
Staggered Triangular

Narasimhan, Ho, PRB **52**, 12291 (1995)

Transitions in a single layer

- ν of single layer is half total ν
- 1 electron + 2p flux quantum = CF

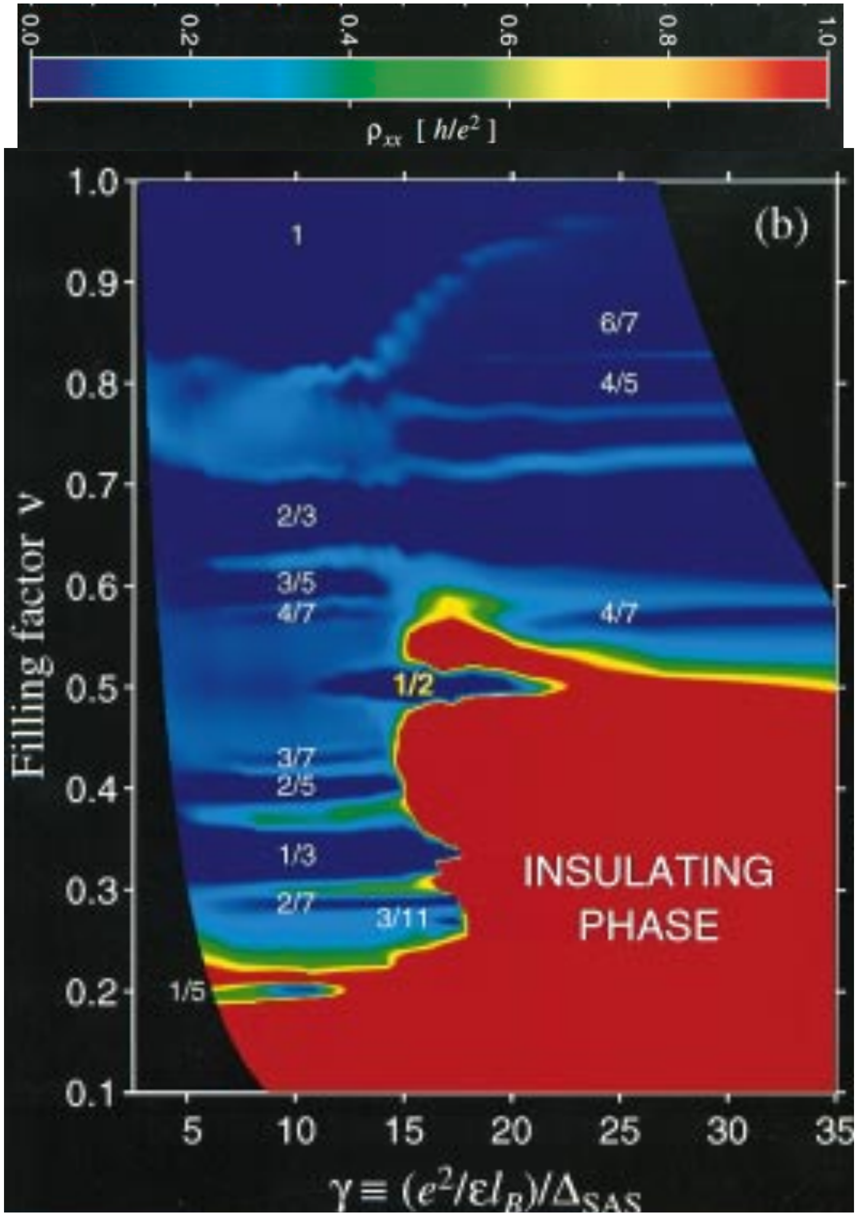
- Series of distinct CF WS phases ^{2p}CFWS
  - p increases with decrease of ν



- Transition from 2p = 2 to 4
  - $\nu \sim 1/5$ to $1/6$

[1] Archer, Park, Jain, PRL **111**, 146804 (2013)
[2] Maki, Zotos, PRB **28**, 4349 (1983)

Bilayer electron solid (w = 75 nm)



Manoharan, Suen, Santos, Shayegan, PRL **77**, 1813 (1996)

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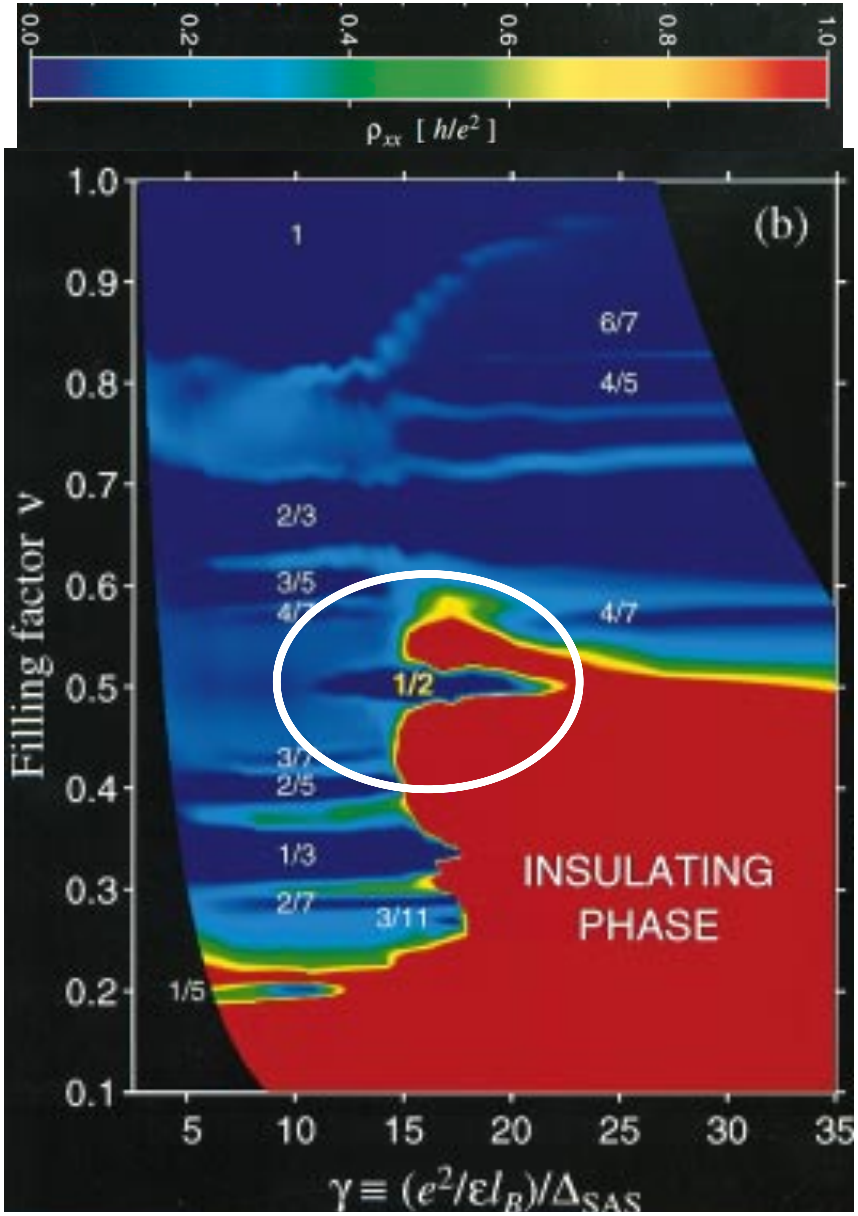
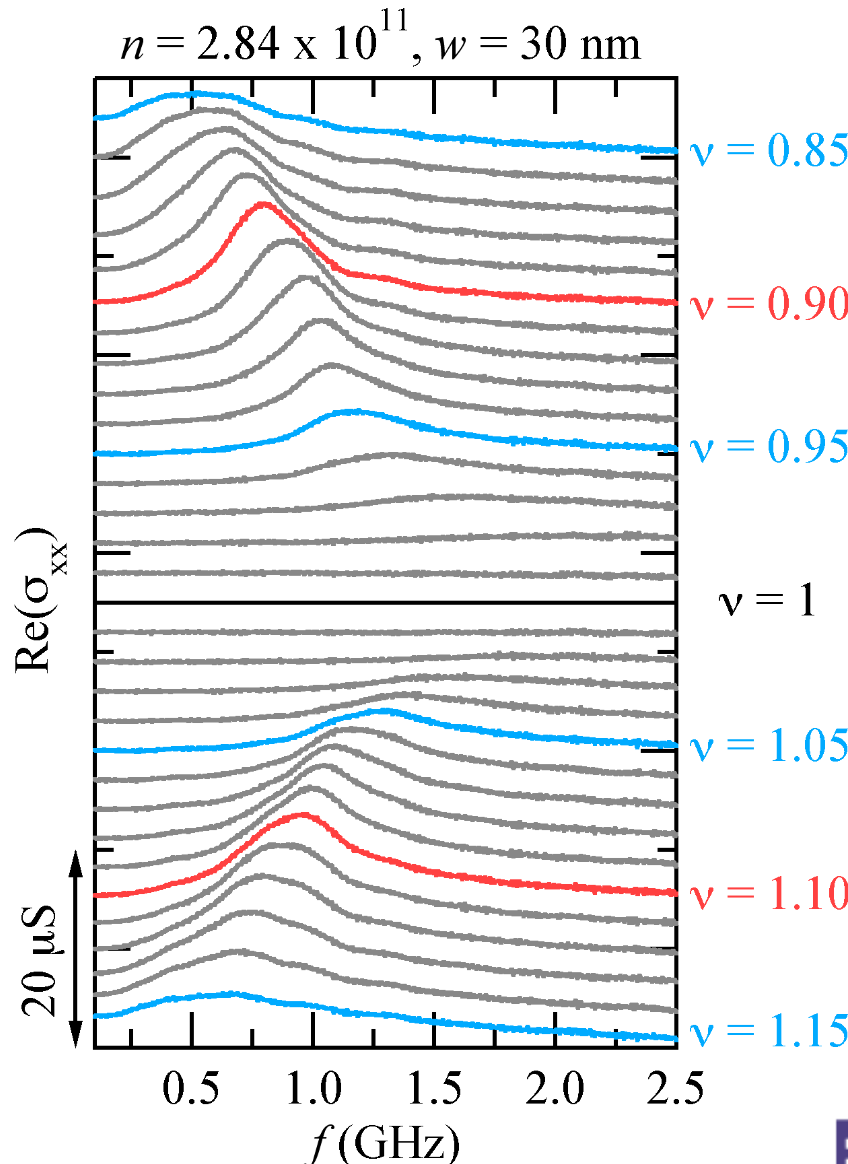


Manoharan, Suen, Santos, Shayegan, PRL **77**, 1813 (1996)

Microwave spectra – pinned WS within QHE

- Resonance appears on either side of ν = 1
  - Symmetrical
  - f_{pk}, peak position, shifts down as ν moves away from 1
- Understood as due to pinned WS



Chen, Lewis, Engel, Tsui, Ye, Pfeiffer, West, PRL **91**, 016801 (2003)

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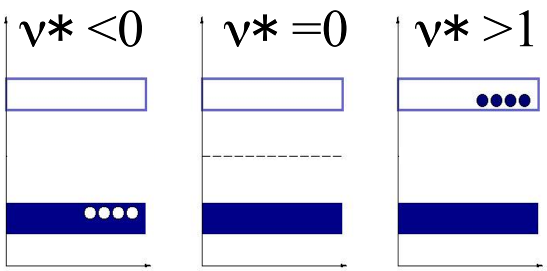
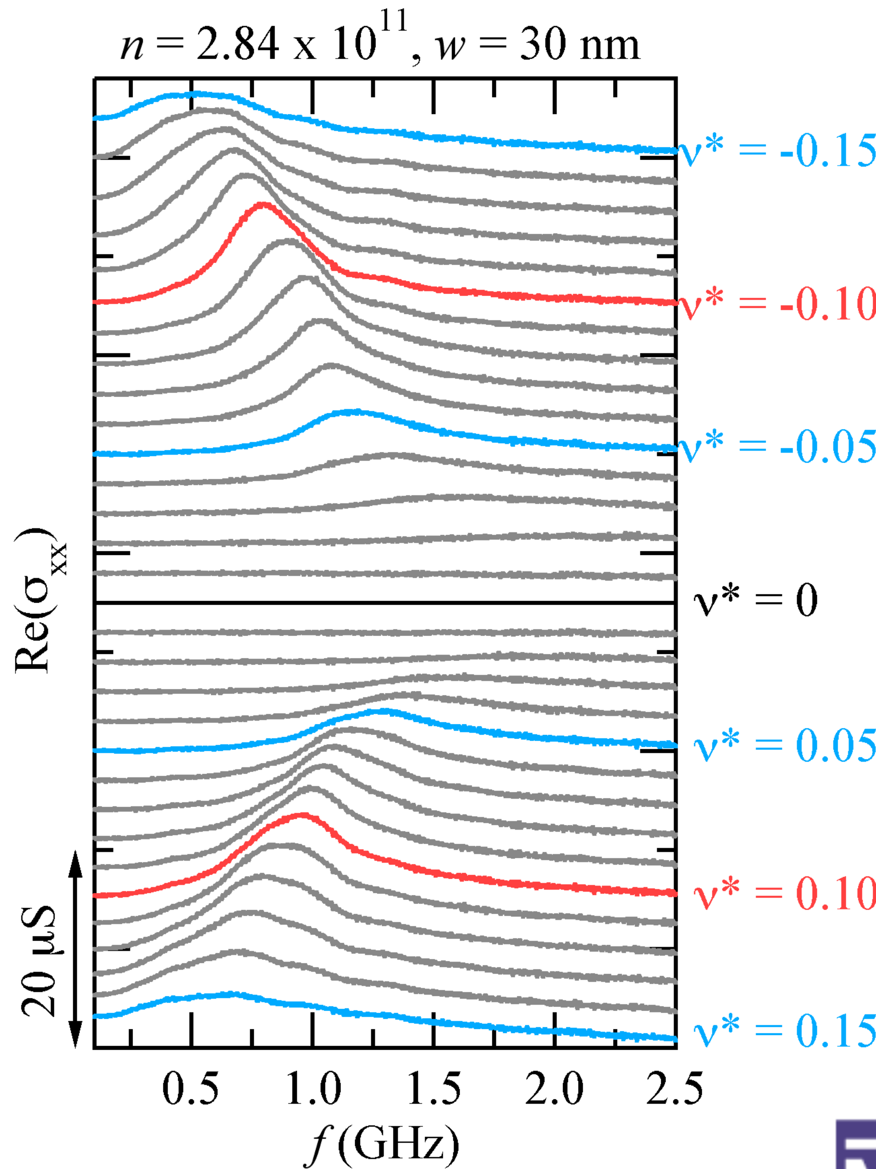
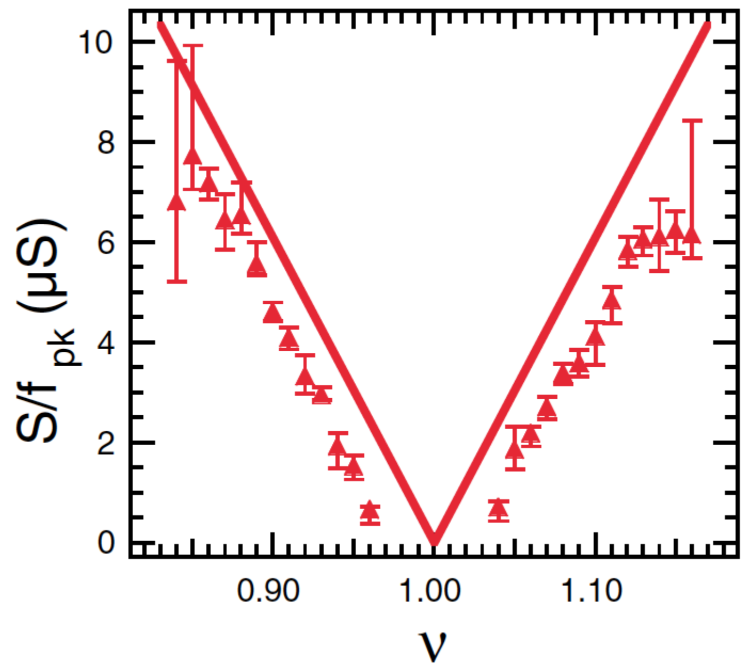


$$\upsilon^* = \upsilon - J; \quad n^* = \frac{\upsilon^*}{\upsilon} n$$



Chen, Lewis, Engel, Tsui, Ye, Pfeiffer, West, PRL **91**, 016801 (2003)

Sum rule

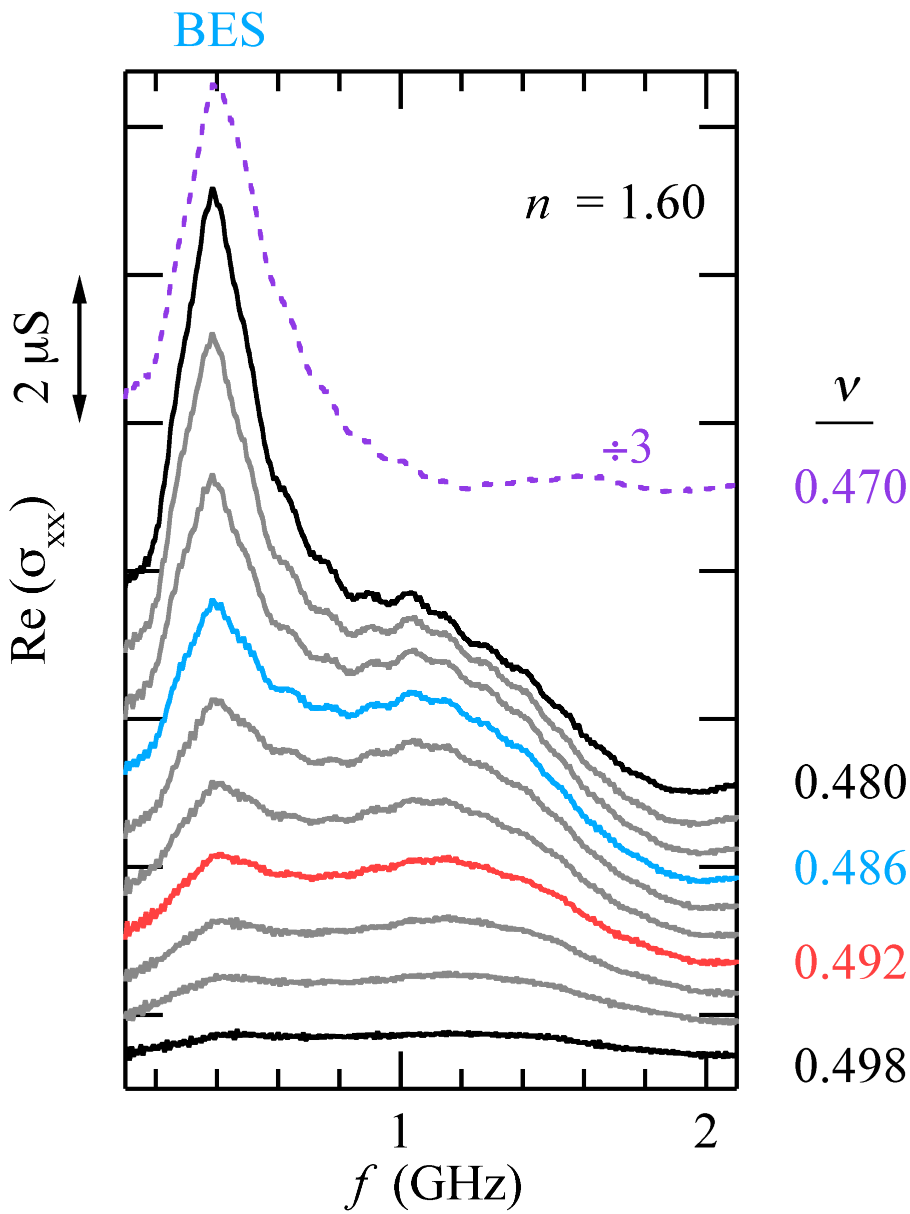


- Oscillator model of the pinning mode:

$$\left(\frac{S}{f_{pk}}\right)^{th} \equiv \frac{e^2 \pi \tilde{\nu}}{2h}; \quad \begin{array}{ll} \tilde{\nu} = \nu & \text{Electrons} \\ \tilde{\nu} = \nu^* \equiv |\nu - 1| & \text{Quasicarriers} \end{array}$$

Chen, Lewis, Engel, Tsui, Ye, Pfeiffer, West, PRL **91**, 016801 (2003)
Fukuyama and Lee, PRB **18**, 6245 (1978)

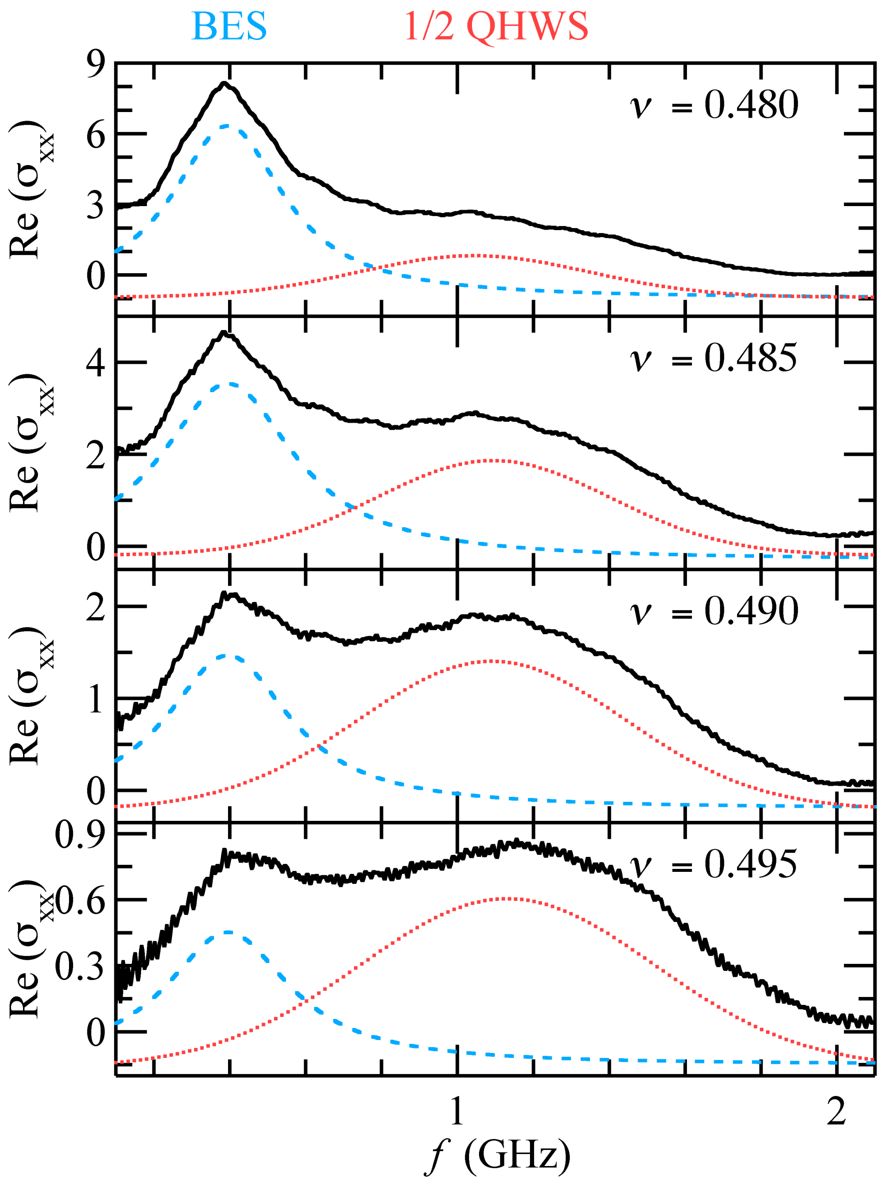
Microwave spectra near $\nu = 1/2$



- Low ν:
  - Sharp low f resonance
  - Broad high f resonance
- Increasing ν:
  - Low f resonance:
    - Amplitude monotonically decreases
  - High f resonance:
    - Nonmonotonic amplitude

Hatke, Liu, Engel, Shayegan, Pfeiffer, West, Baldwin, arXiv: 1504.08182

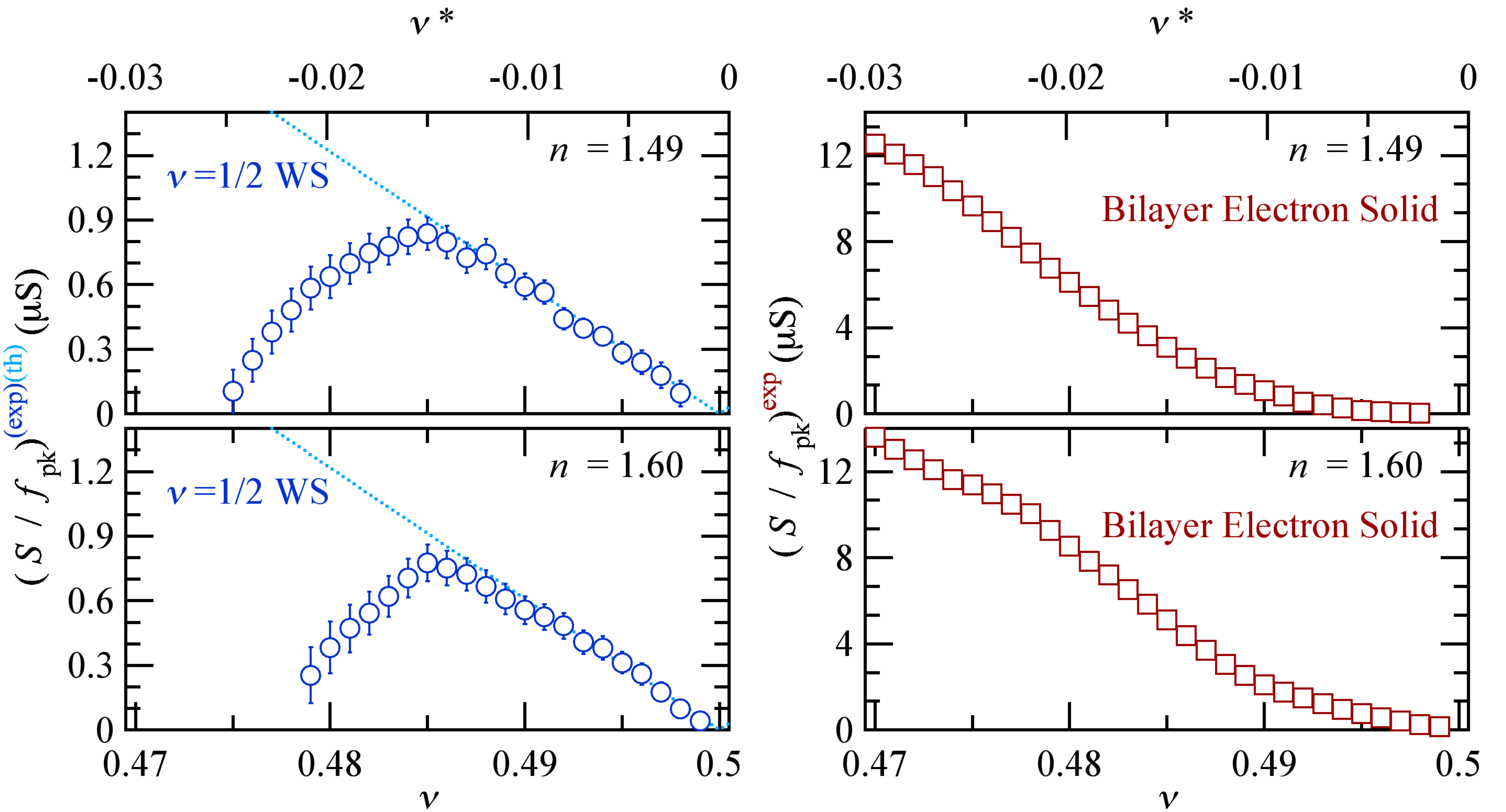
Microwave spectra near $\nu = 1/2$



- Decompose spectra into two parts
  - $f_{pk} \sim 0.4$ GHz
    - Bilayer Electron Solid (BES)
  - $f_{pk} \sim 1.2$ GHz
    - 1/2 charged quasihole Wigner solid (1/2 QHWS)

Hatke, Liu, Engel, Shayegan, Pfeiffer, West, Baldwin, arXiv: 1504.08182

Sum Rule Comparison



$$\left(\frac{S}{f_{pk}}\right)^{th} \equiv \frac{e^2 \pi \tilde{\nu}}{2h}; \qquad \tilde{\nu} = \nu$$

$$\tilde{\nu} = \nu^* \equiv \nu - 1/2$$

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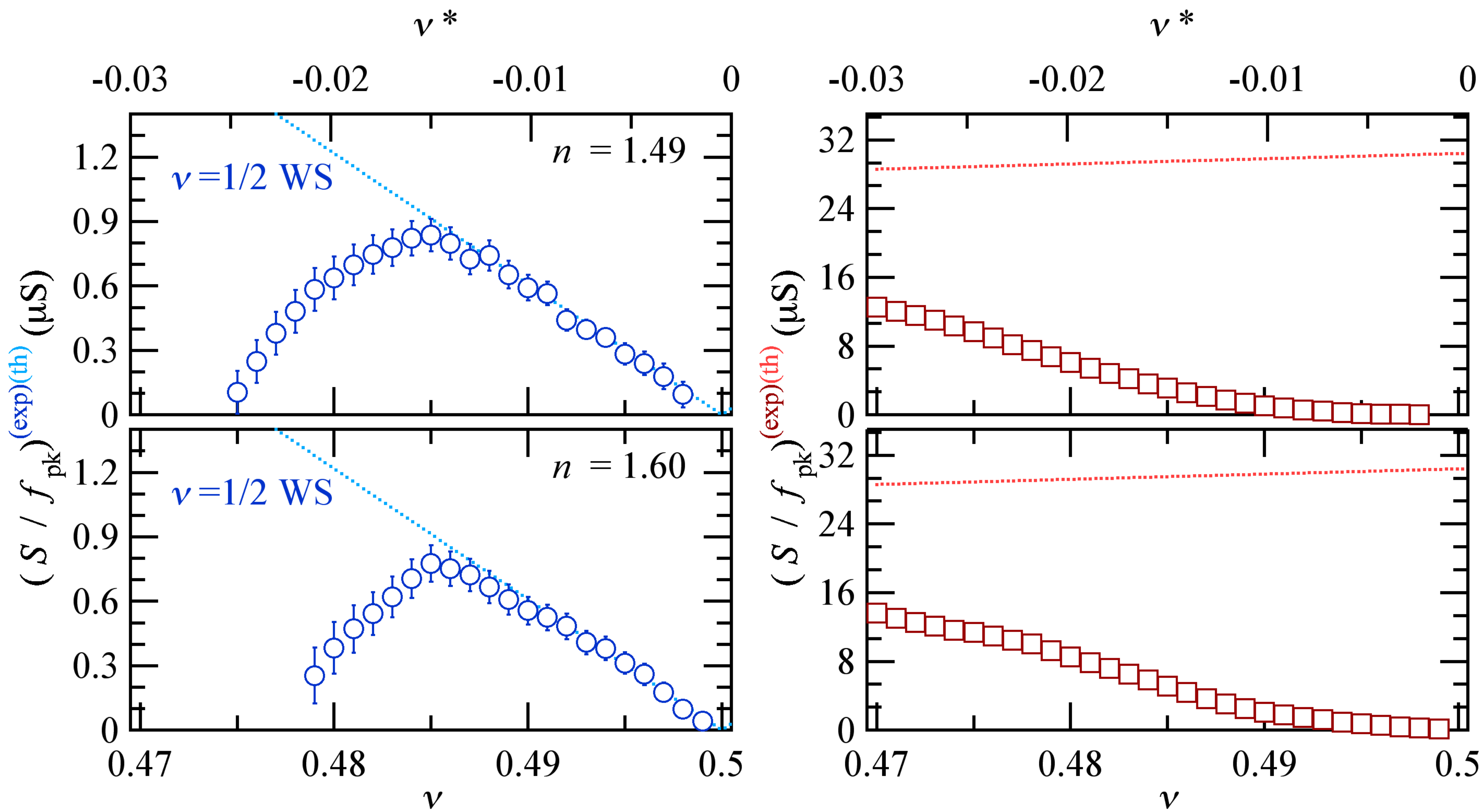
Sum Rule Comparison



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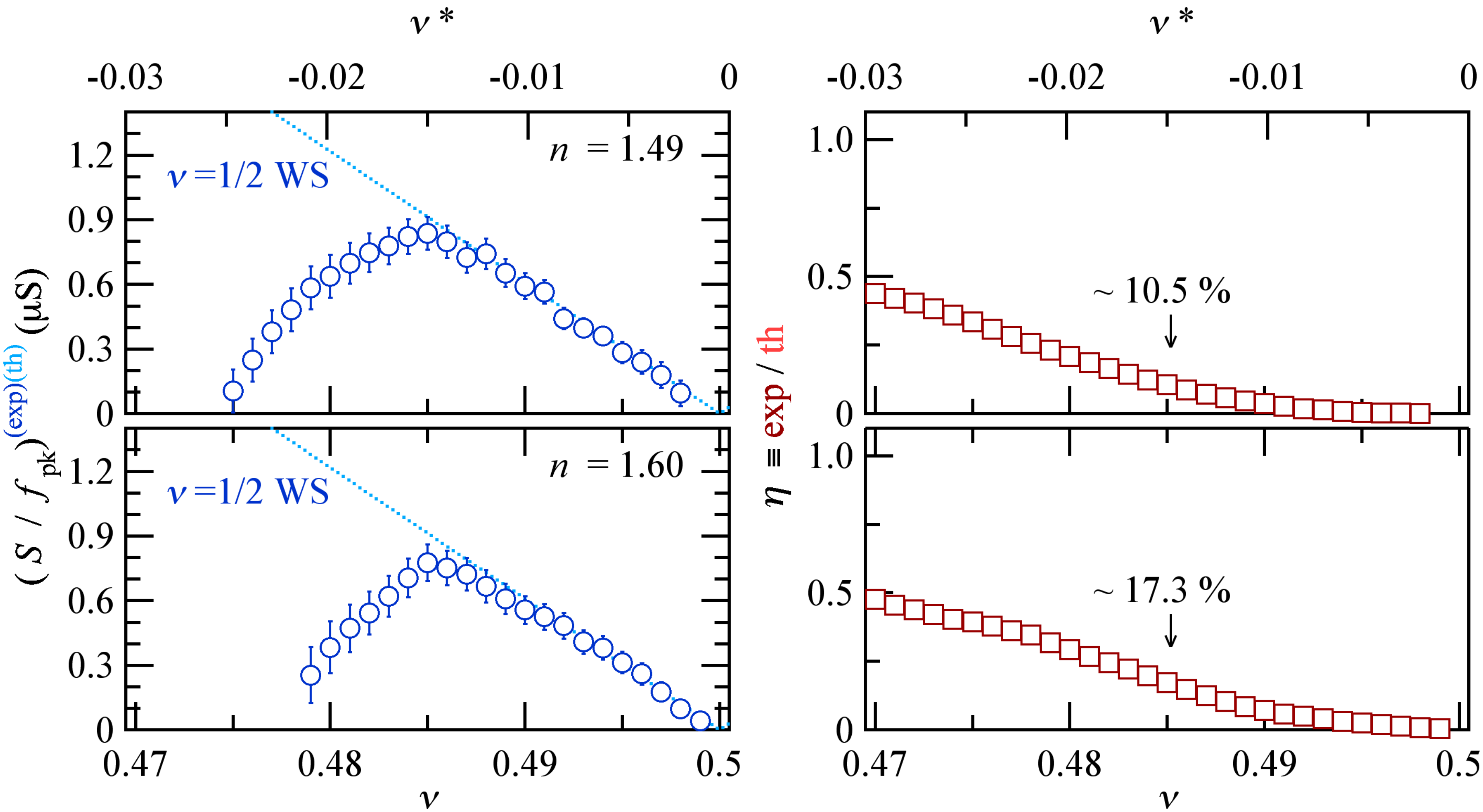

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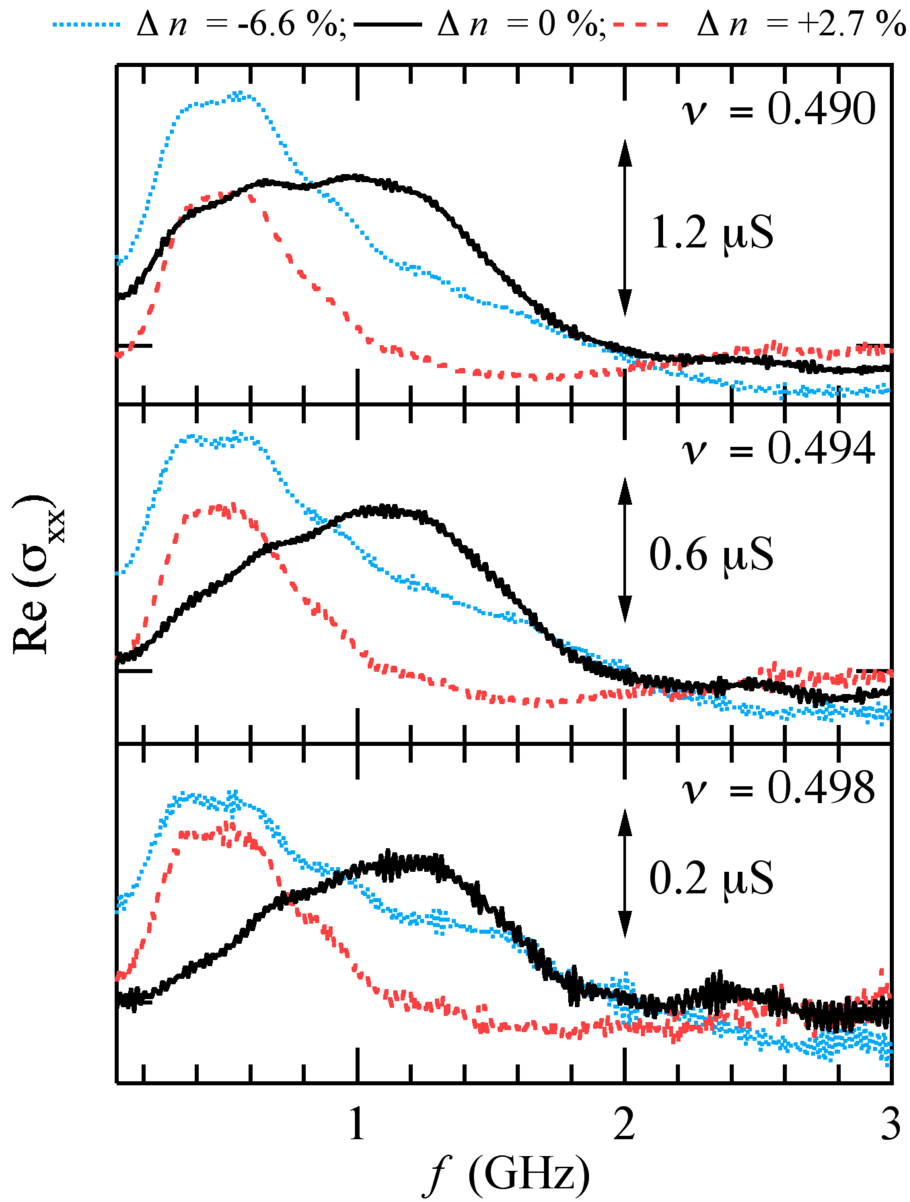
Hatke, Liu, Engel, Shayegan, Pfeiffer, West, Baldwin, arXiv: 1504.08182

Forced charge asymmetry



Hatke, Liu, Engel, Shayegan, Pfeiffer, West, Baldwin, arXiv: 1504.08182

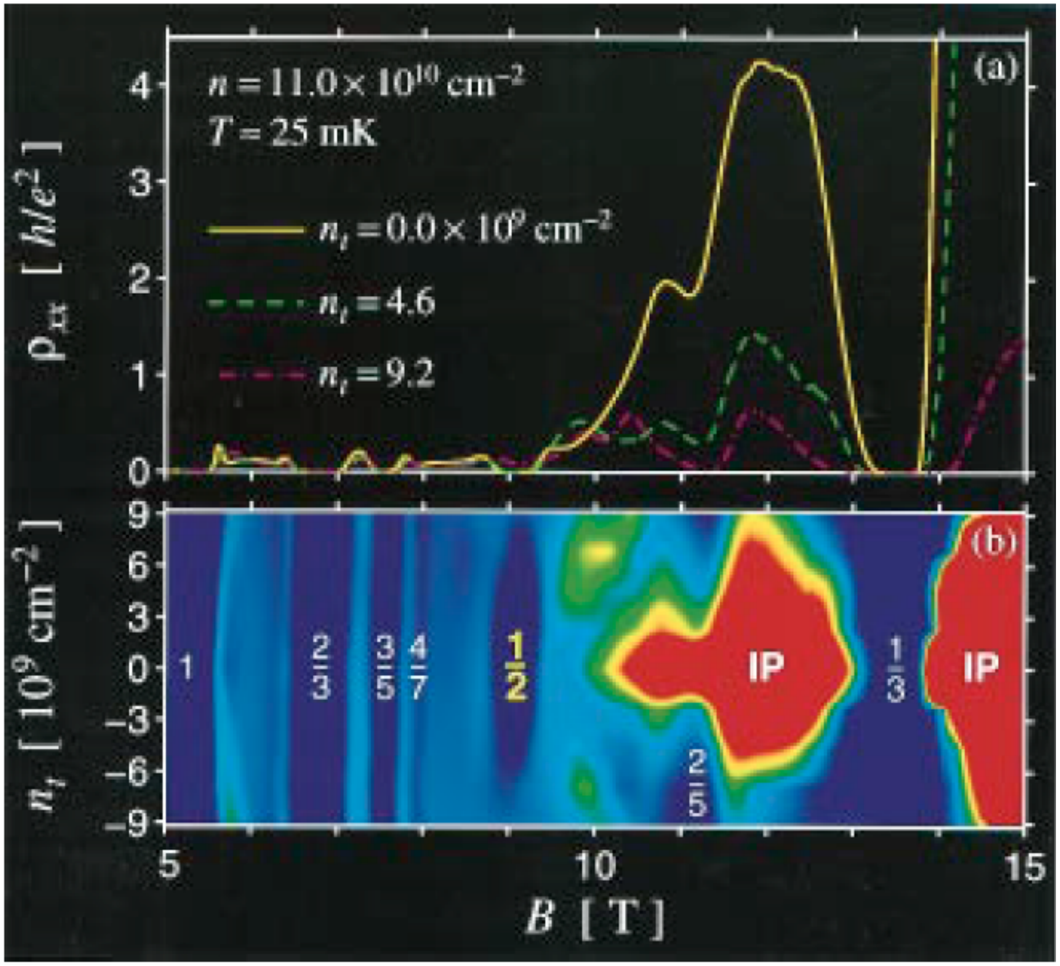
Summary

- Resonance associated with a bilayer electron solid in a wide quantum well
  - Deep in the insulating state: *five* phase transitions
- Solidification of 1/2 charged quasiholes
  - Mixed solid phase with bilayer electron solid

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

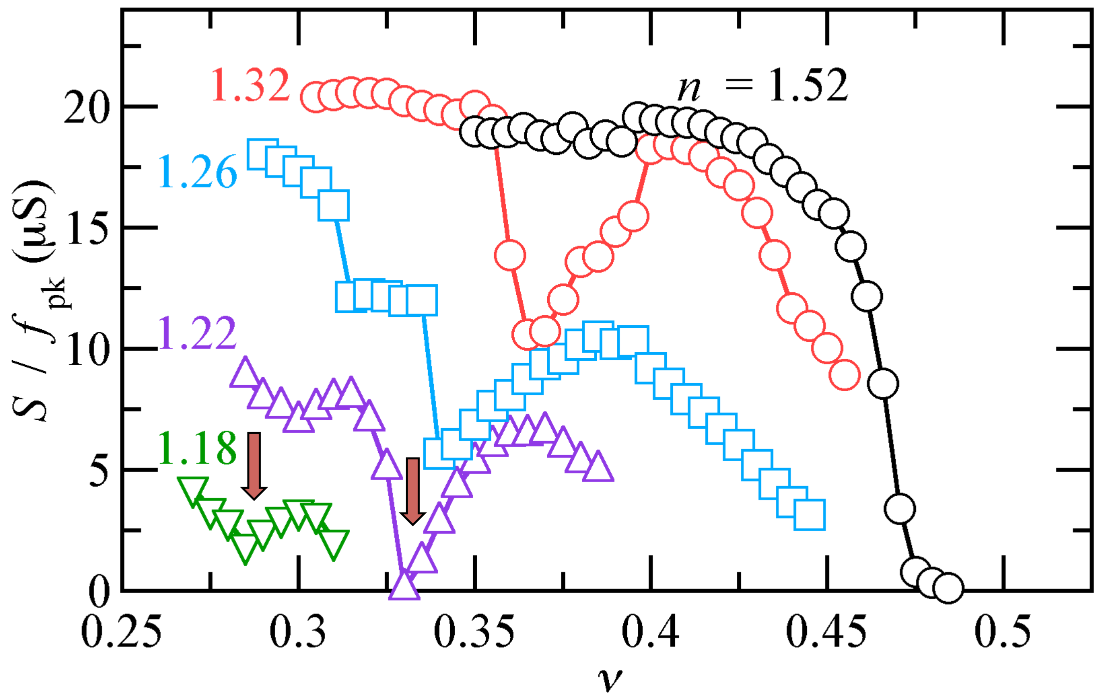
Asymmetry of $\nu = 1/2$ FQHE (DC, w = 75 nm)

- 1C $\nu = 1/3$ FQHE is strengthened
- 2C insulating phase weakened
- Destabilization of $\nu = 1/2$ FQHE at 3% charge imbalance



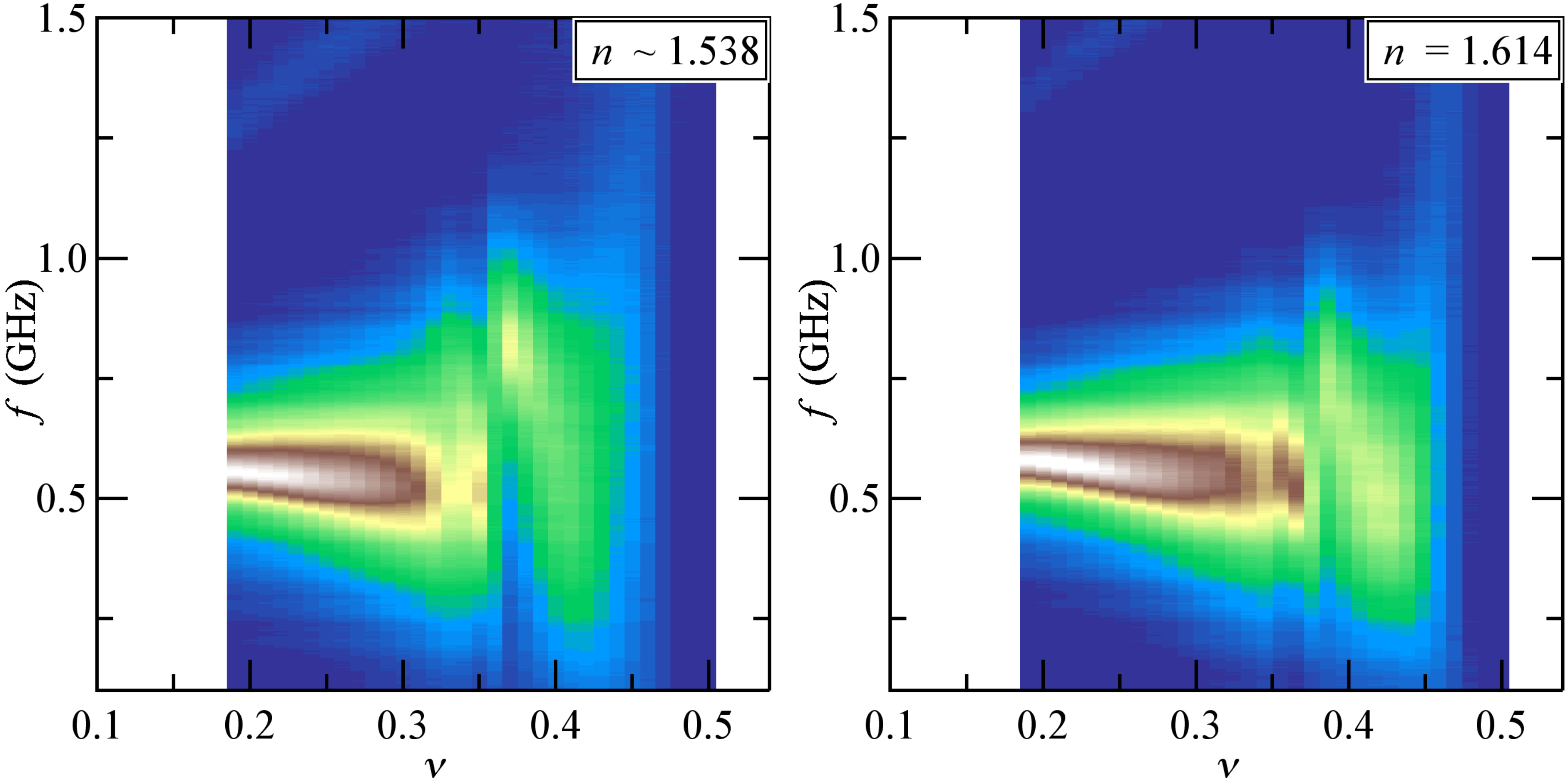
[1] Manoharan, Suen, Santos, Shayegan, PRL **77**, 1813 (1996)

Integrated Intensity (Symmetric)



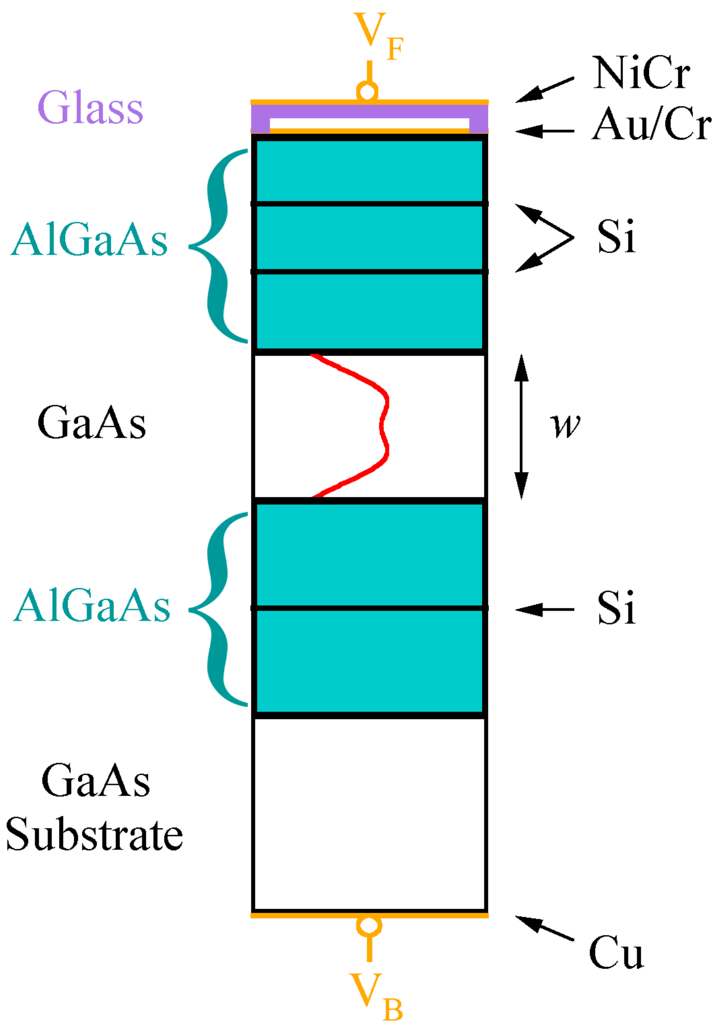
- Phase transition = S/f_{pk} minimum or step
  - $S = \int \mathrm{Re}\,(\sigma_{xx})$
- Integrated intensity sum rule: $S/f_{pk} = n^* e^2 \pi / 2h$

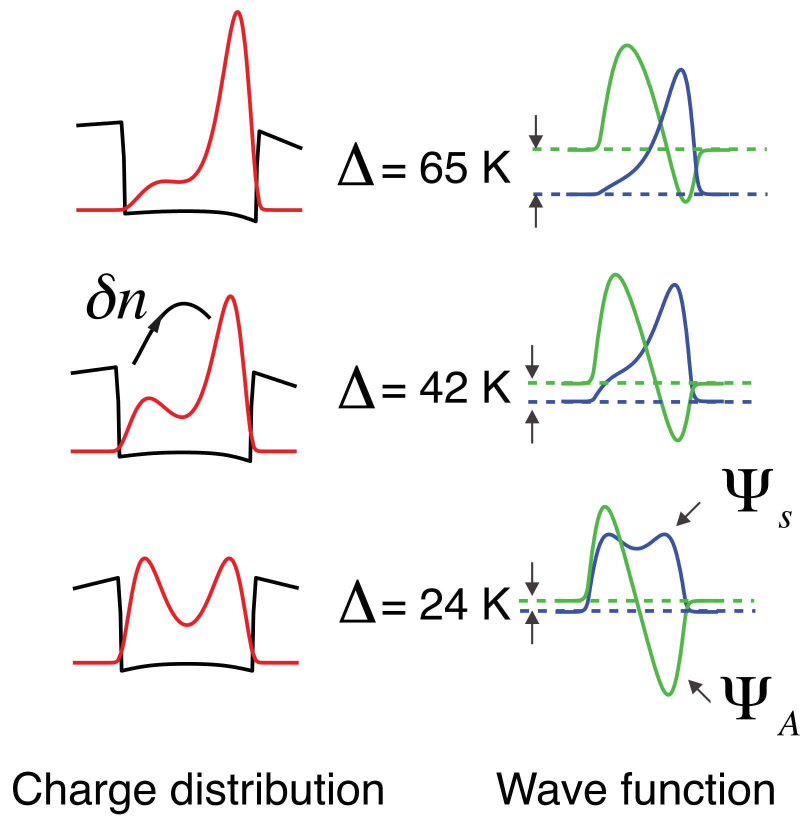
[1] Fukuyama and Lee, PRB **18**, 6245 (1978)
[2] Zhu, Chen, Jiang, Engel, Tsui, Pfeiffer, West, PRL **105**, 126803 (2010)



n ~ 1.538
n = 1.614
f (GHz)
1.5
1.0
0.5
0.1
0.2
0.3
0.4
0.5
ν

Wide quantum well structure





- Well width: w = 54 & 65 nm