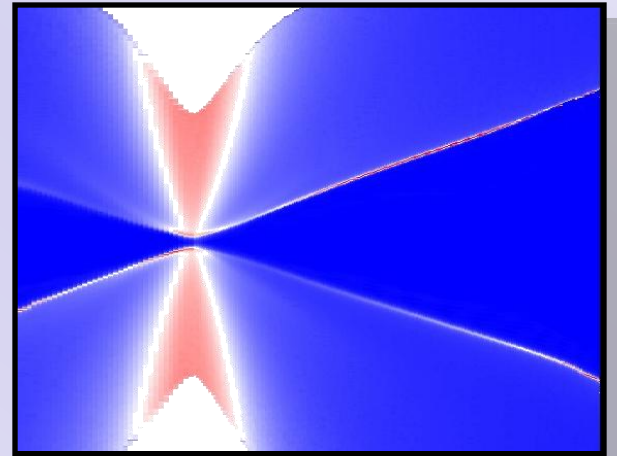
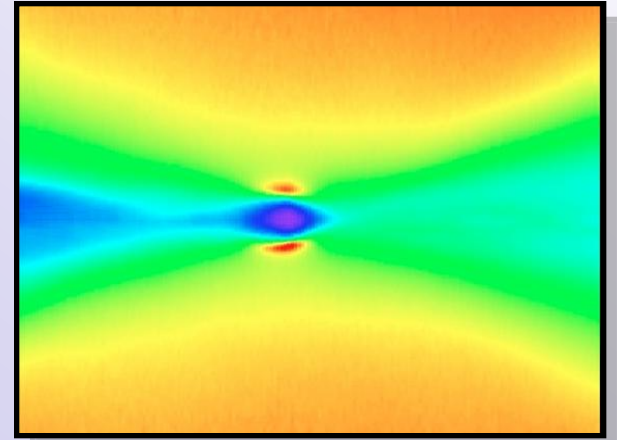
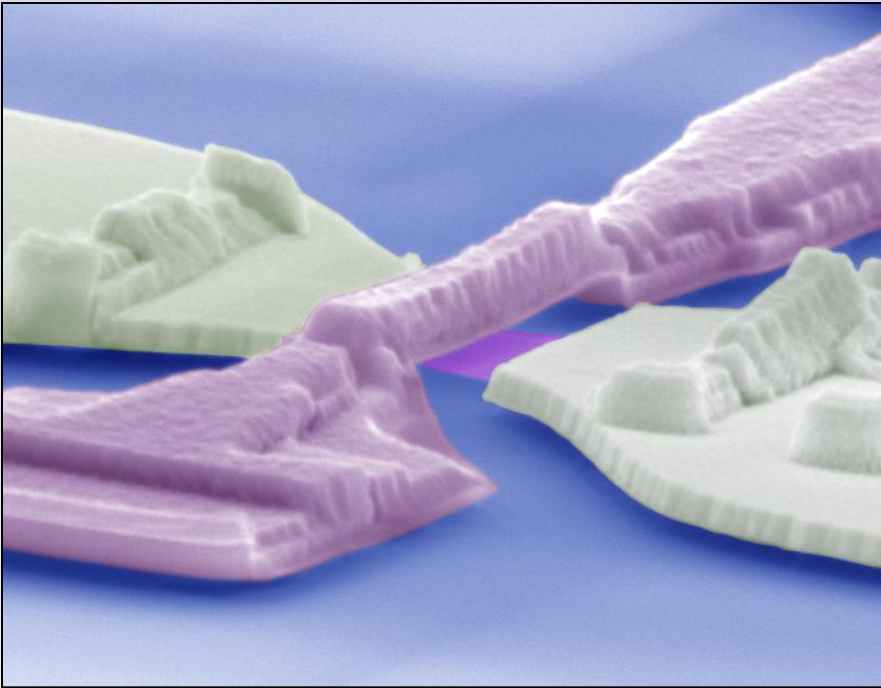


# Transport Spectroscopy of Symmetry-Broken Insulating States in Bilayer Graphene



# Contributors

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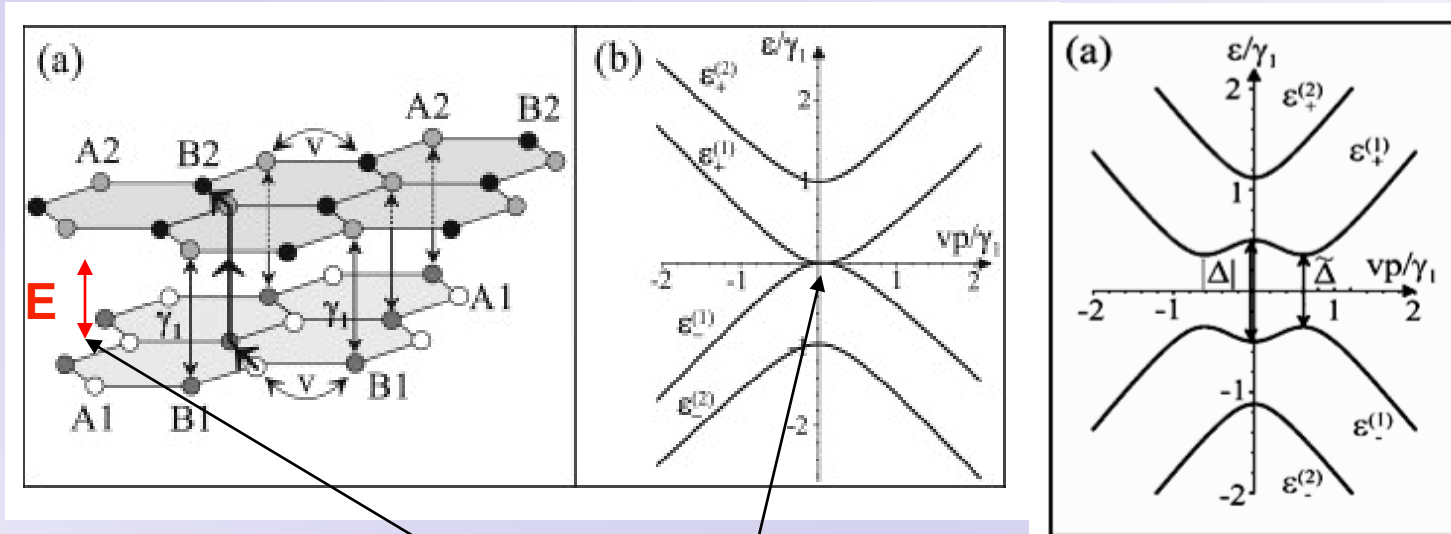
# Outline

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- Motivation
- Fabrication
- Observation of Insulating state
- Study of Insulating State
- Theory and Experiment
- Evidence for Phase Transition
- Conclusion

# The Band Structure of BLG

## Single Particle Picture



**Flat Bands**

**Electron-electron interactions**

E. McCann, V.I. Fal'ko, *Phys. Rev. Lett.* 2006

Y. Zhang, et al., *Nature* 2010

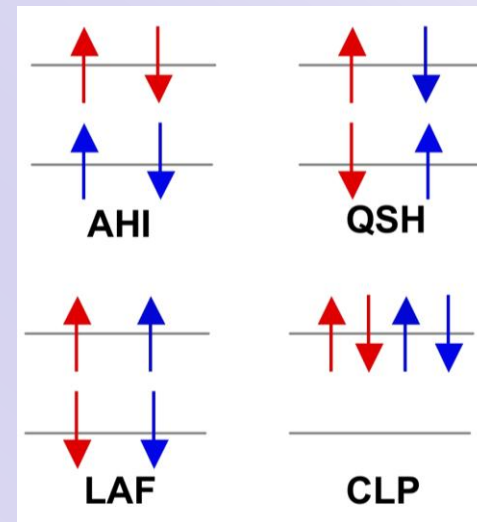
# Broken Symmetry States at CNP

	Nematic Order $\Gamma_1$	Anomalous Hall $\Gamma_2$	QSH	SDW (LAF)	CLP
Gapped?	No	Yes	Yes	Yes	Yes
2-terminal $\sigma_{min}$	finite	$4e^2/h$	$4e^2/h$	0	0
Broken Symmetries	in-plane rotation	Time reversal; Ising Valley	spin rotational; Ising Valley	Time reversal; spin rotation	inversion

<sup>1</sup>O. Vafek, *et al.*, *Phys. Rev. B*, 2010  
Y. Lemonik, *et al.*, *Phys. Rev. B*, 2010

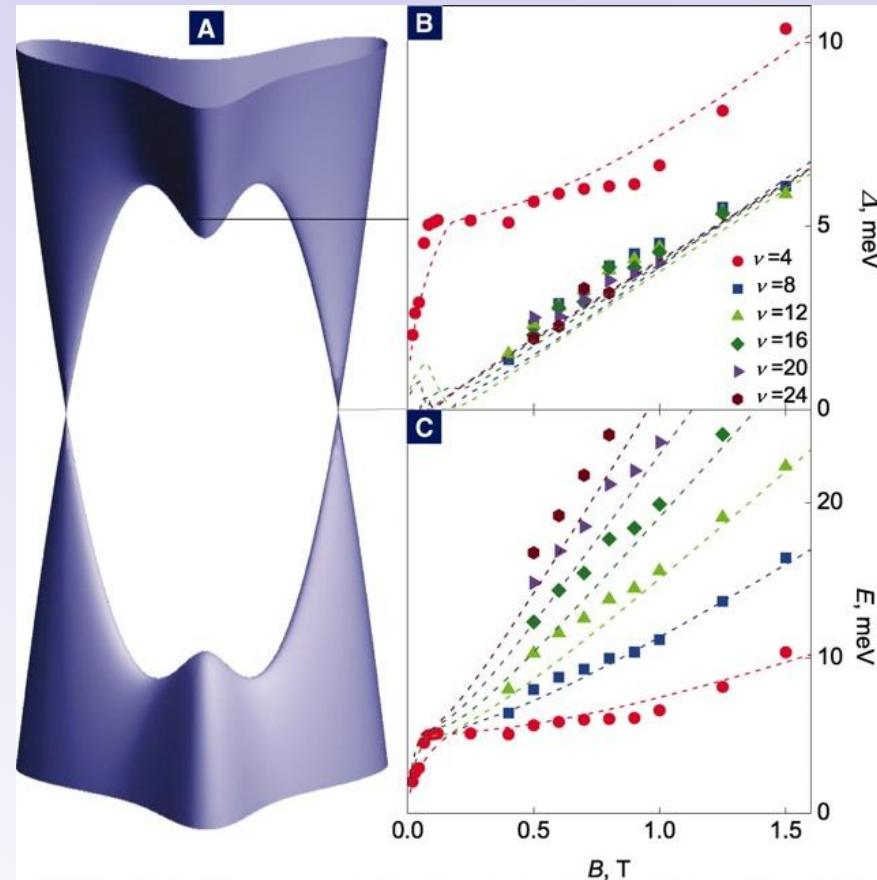
<sup>2</sup>R. Nandkishore & L. Levitov, *Phys. Rev. B*, 2010  
F. Zhang *et al.*, *Phys. Rev. Lett.*, 2011  
J. Jung *et al.*, *Phys. Rev. Lett.*, 2011

and many more!!!!



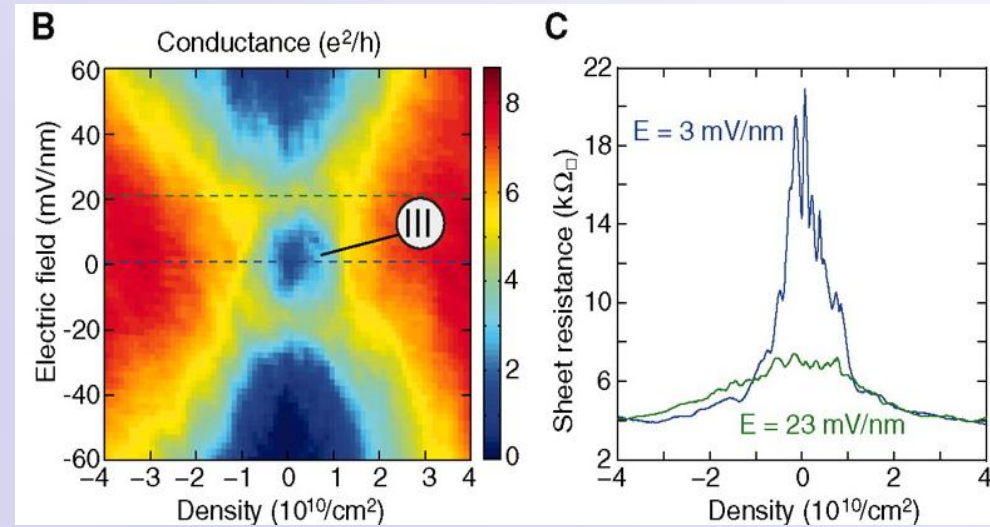
# Recent Experimental Progress

## Single Gate



Mayorov et al. *Science* 2011

## Dual Gate

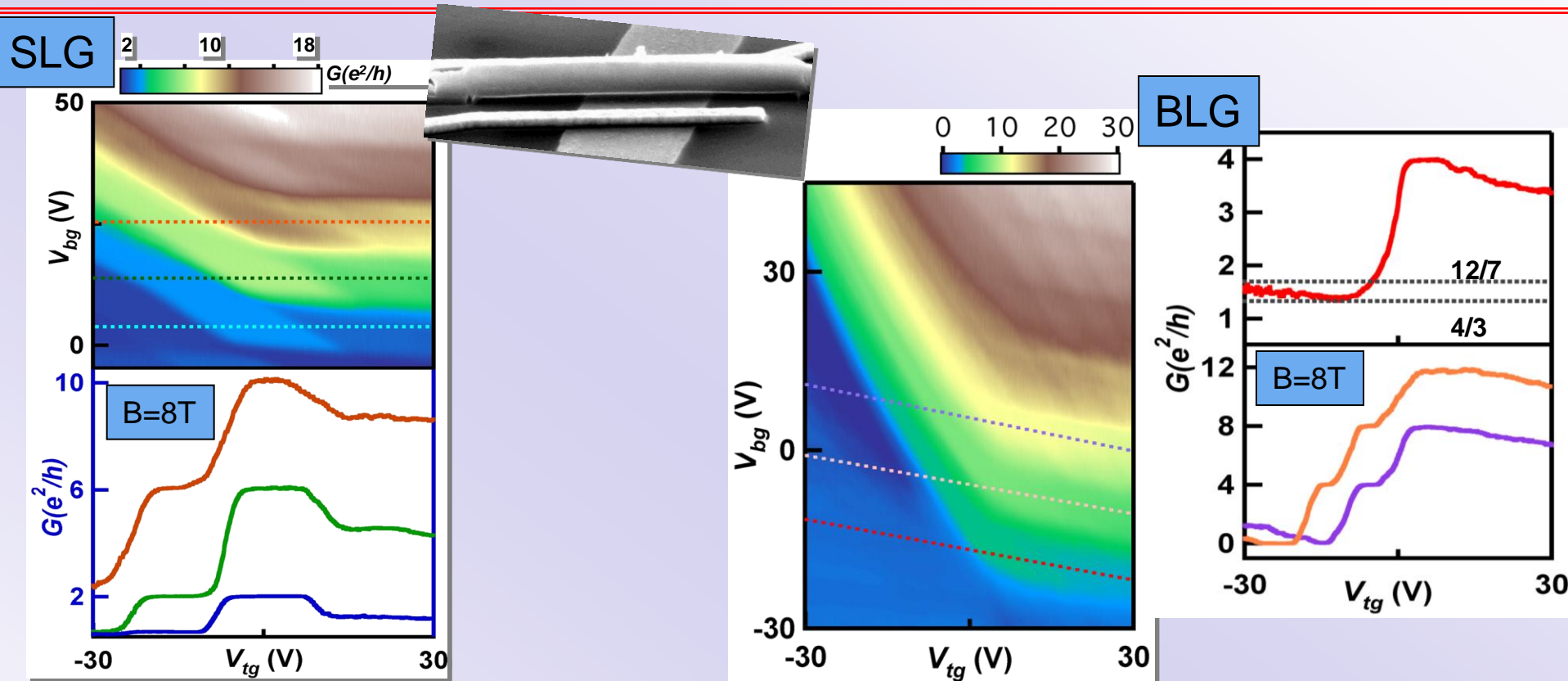


Weitz et al. *Science* 2010

Also see:

Freitag et al., arXiv:1104.3816, 2011

# Transport Data with Contactless top gate

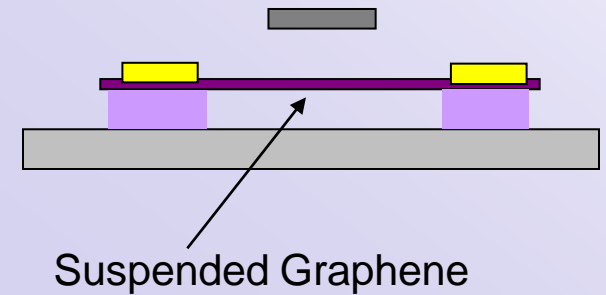
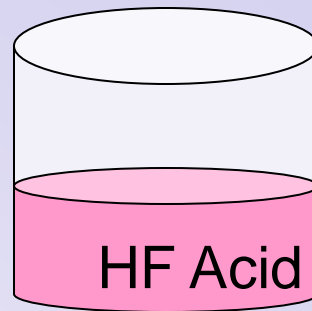
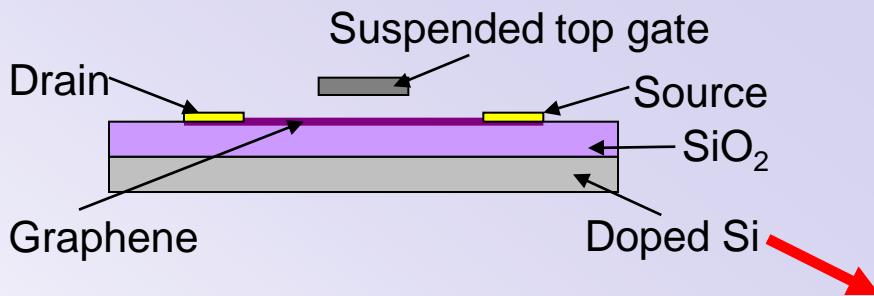
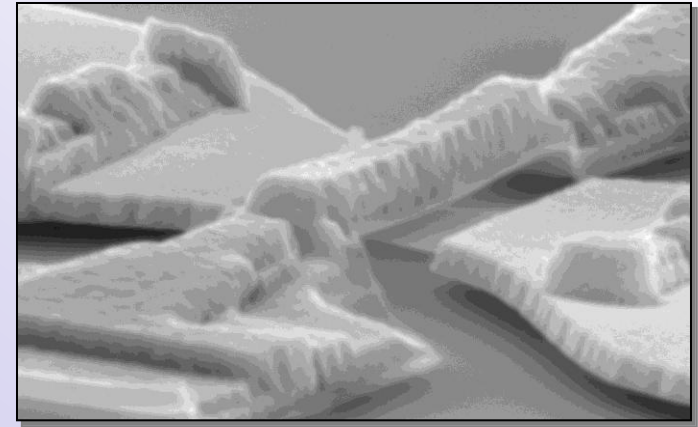
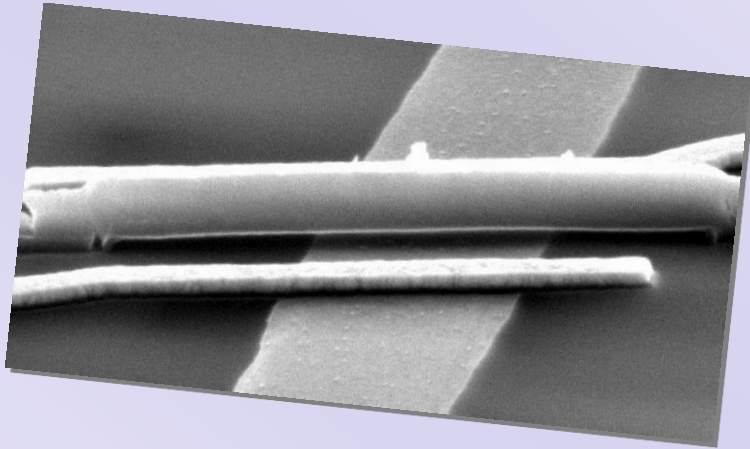


J. Velasco Jr. *et al.*, PRB(R) (2010)

L. Jing\*, J. Velasco Jr.\*, *et al.*, Nano Lett.(2010)

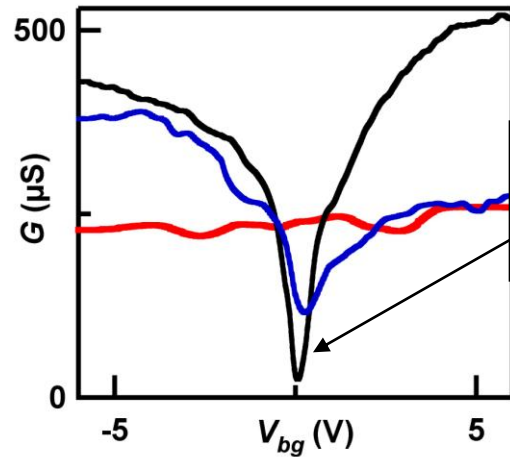
Also see:  
 J.R. Williams, L. DiCarlo and C.M. Marcus Science (2007)  
 D. Abanin, L. Levitov Science(2007)  
 B. Özyilmaz, P.J. Herrero, *et al*, Phys. Rev. Lett. (2007)

# Suspended Graphene and Top gate

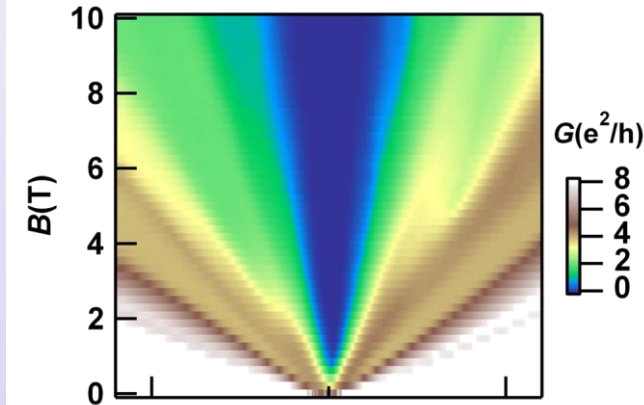
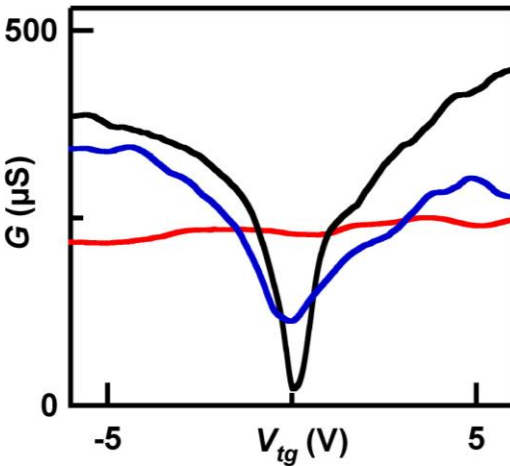




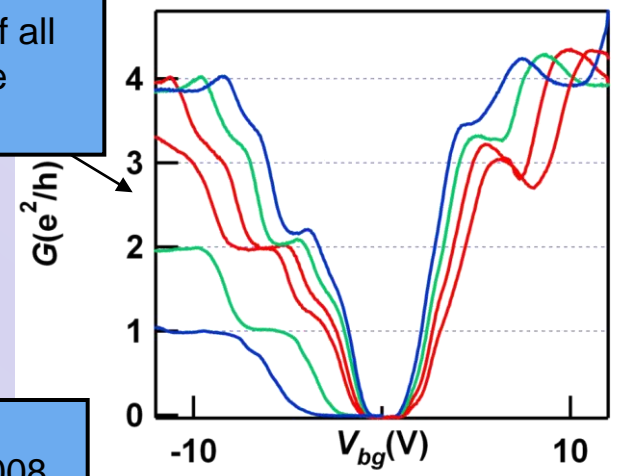
# High Device Quality



- Sharp Dirac point
- Highly symmetric  $G(V_g)$
- CNP close to  $V_g=0$

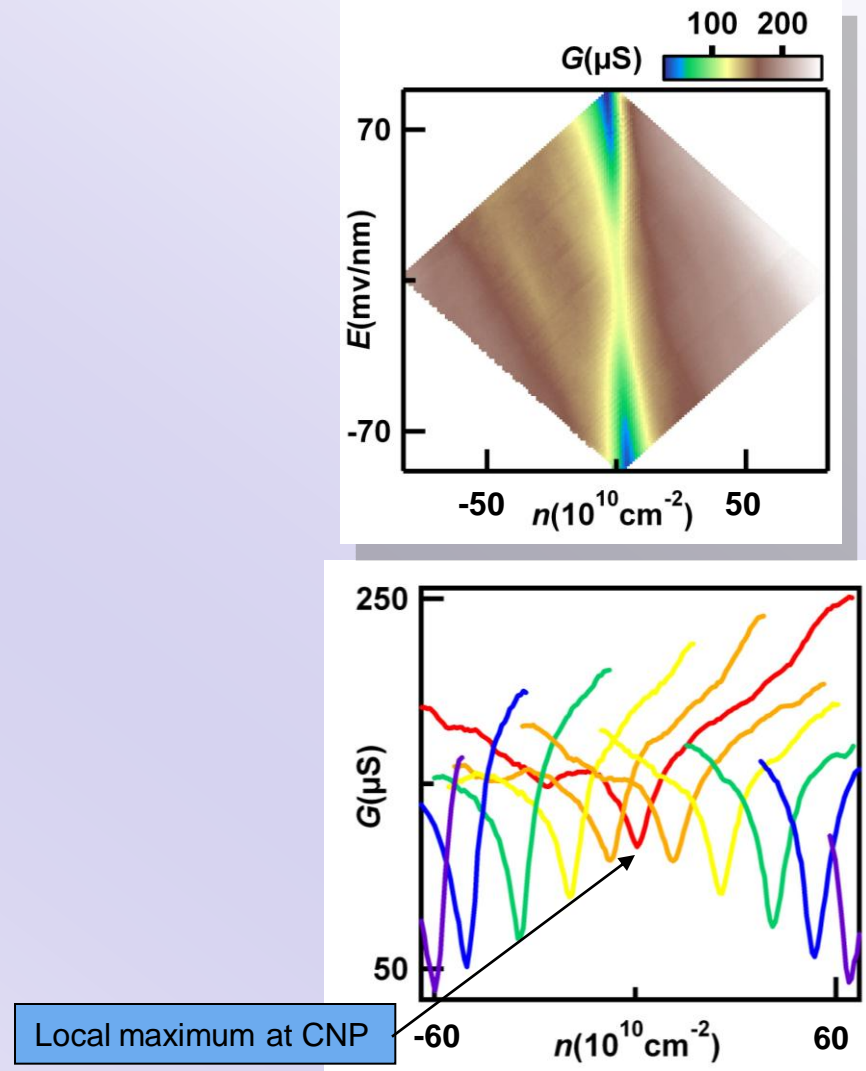
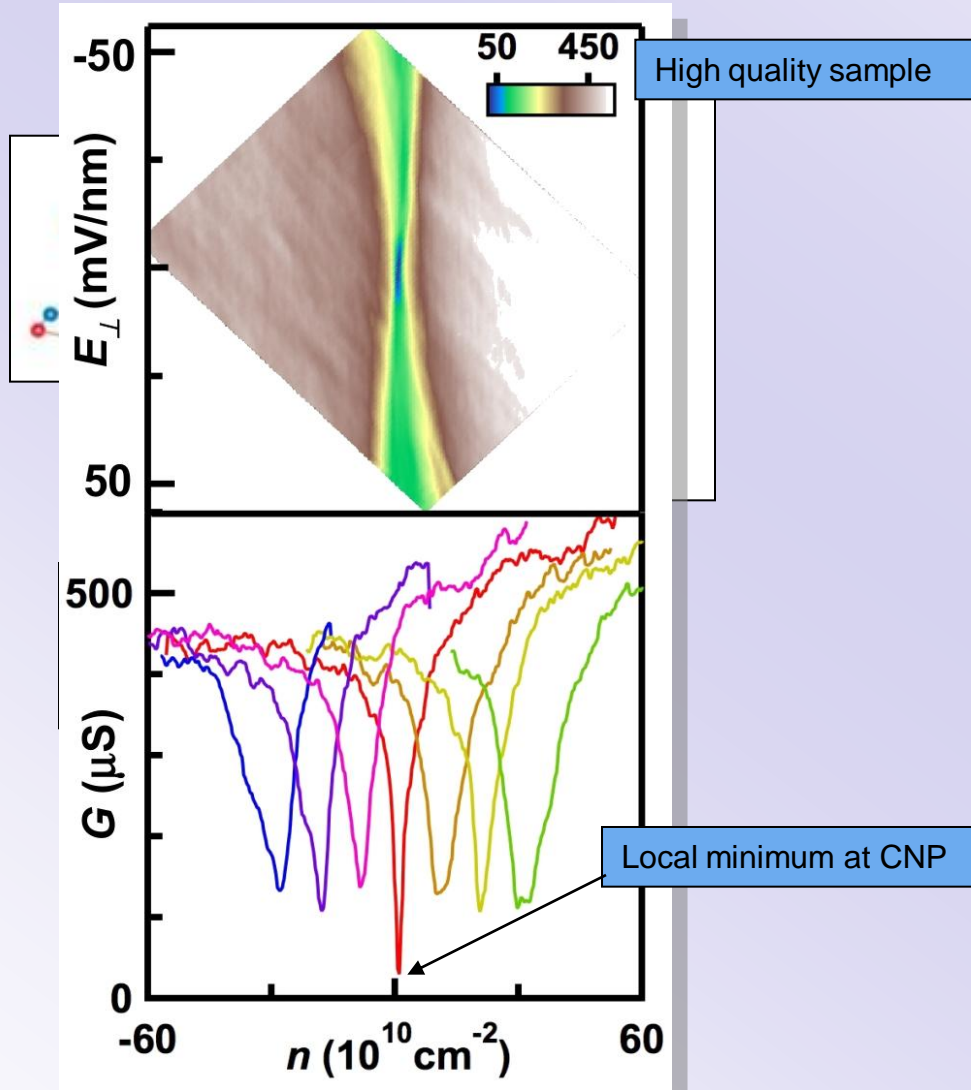


Breaking of all degenerate states

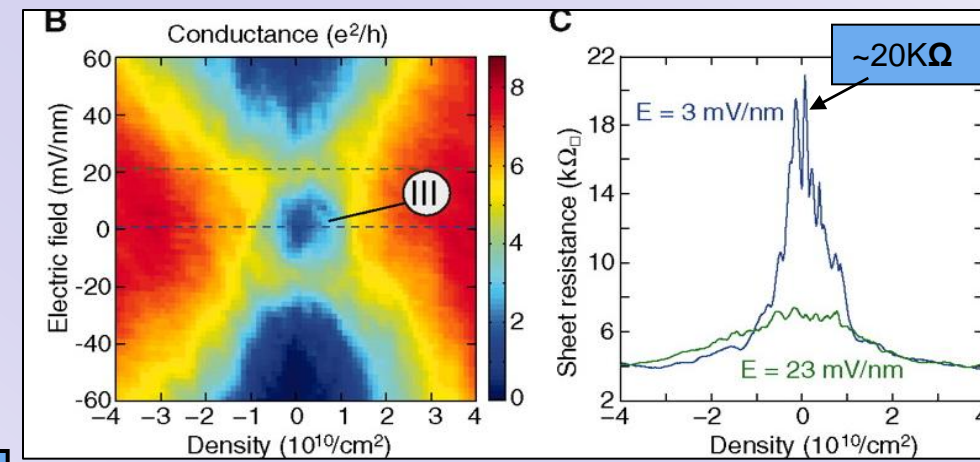
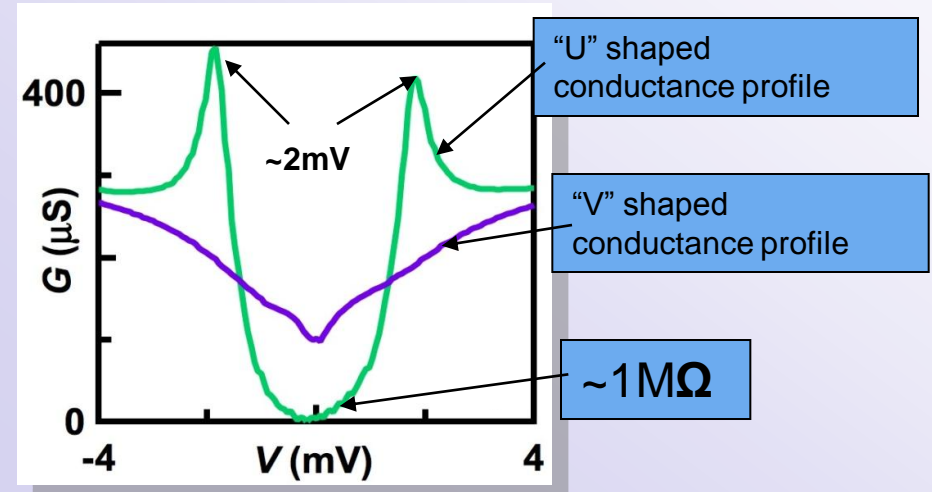
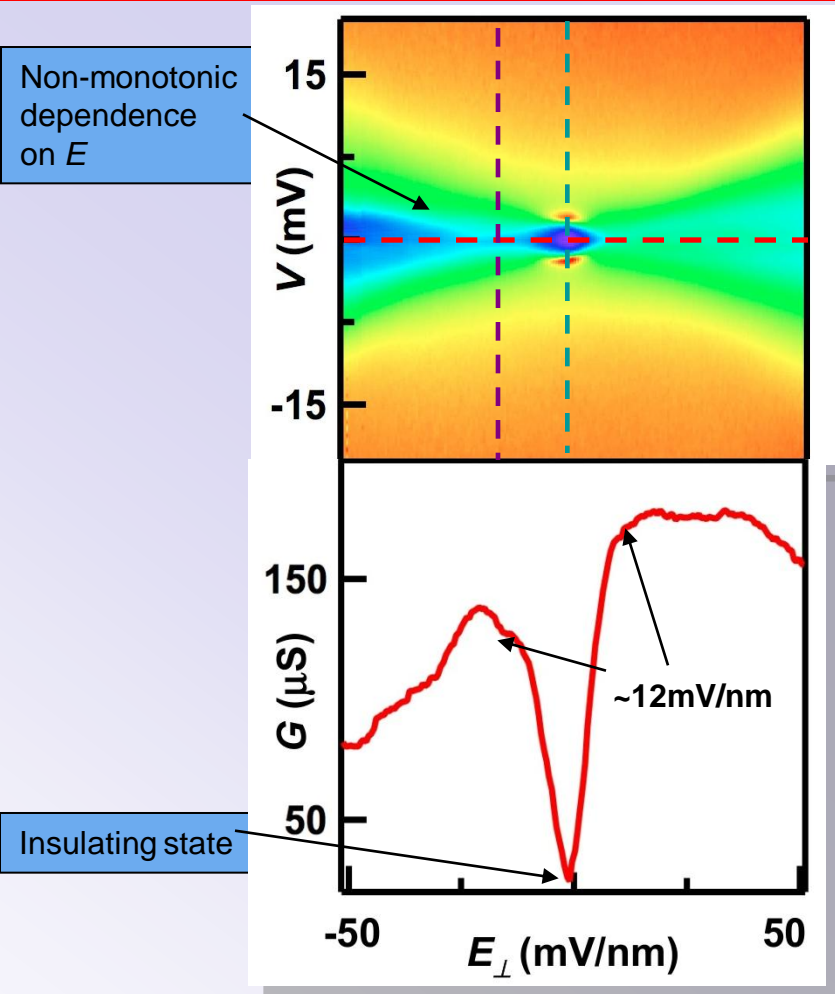


- Also See  
 Feldman et al., Nat. Phys. 2008  
 Zhao et al., Phys Rev Lett, 2008  
 Bao et al., Phys Rev Lett, 2010  
 Dean et al., Nat. Nano, 2010

# Observation of Insulating state



# Bias spectroscopy of Insulating state

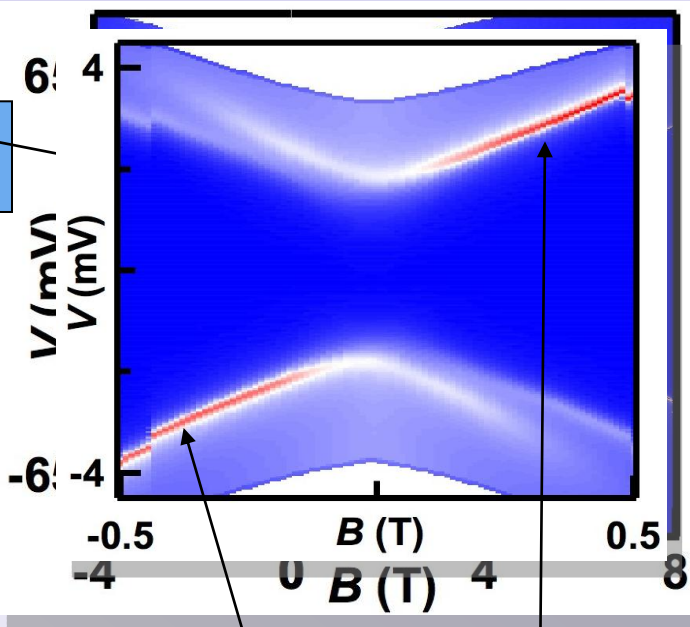


J. Velasco Jr. *et al.*, Nature Nanotechnology, in press (2012)

Weitz *et al.* Science 2010

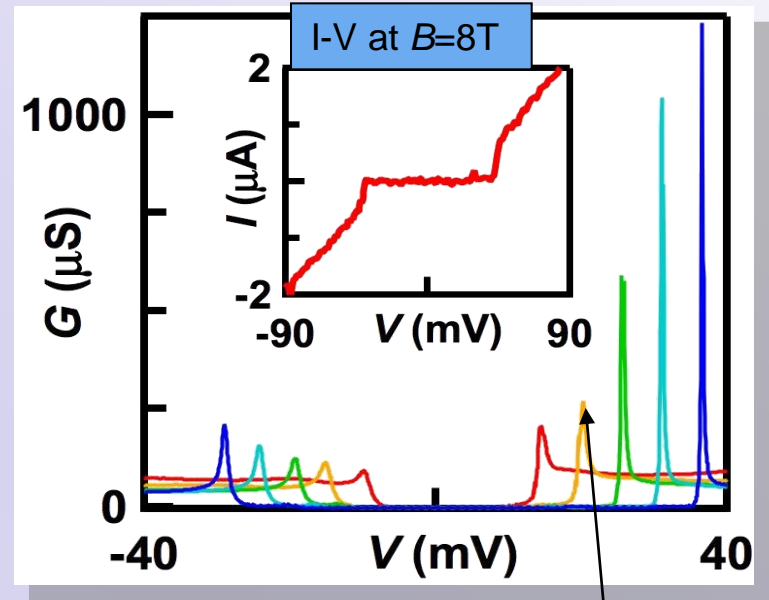
# Insulating state and $B$

Gapped state at  $B=0$  transitions smoothly to  $\nu=0$  quantum Hall state



Slope denotes Gap of 5.5 mV/T

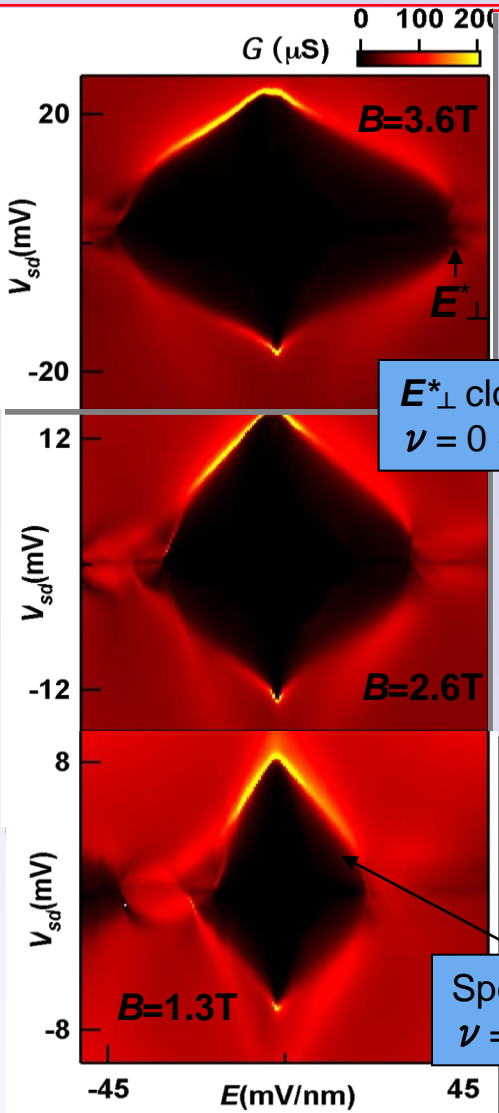
Asymmetry with respect to polarity of  $B$   
Gap opening is parabolic



Peaks increase in magnitude with increasing  $B$

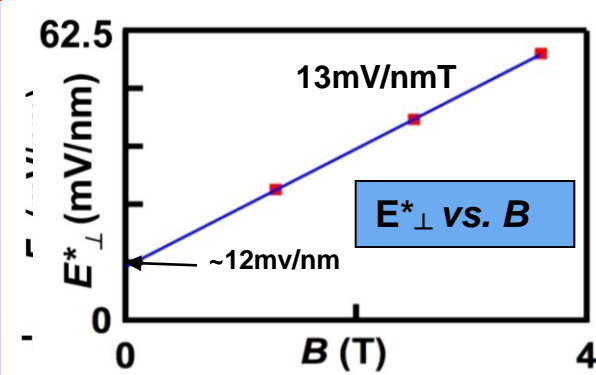
J. Velasco Jr. *et al.*, Nature Nanotechnology, in press (2012)

# Insulating state and applied fields

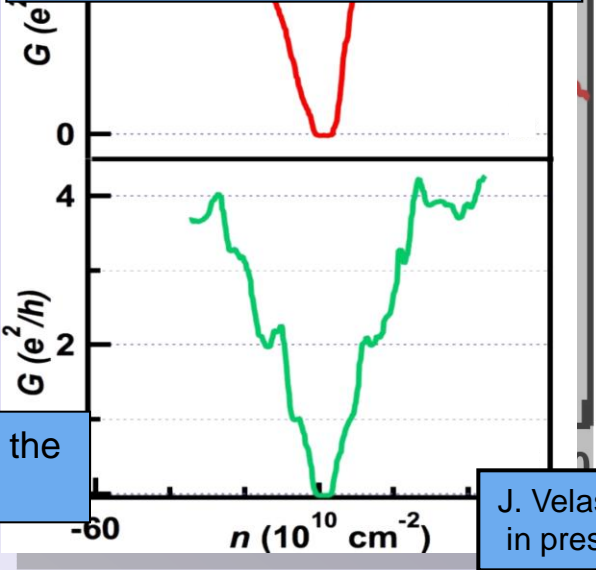


$E^*_\perp$  closes the  $\nu = 0$  gap

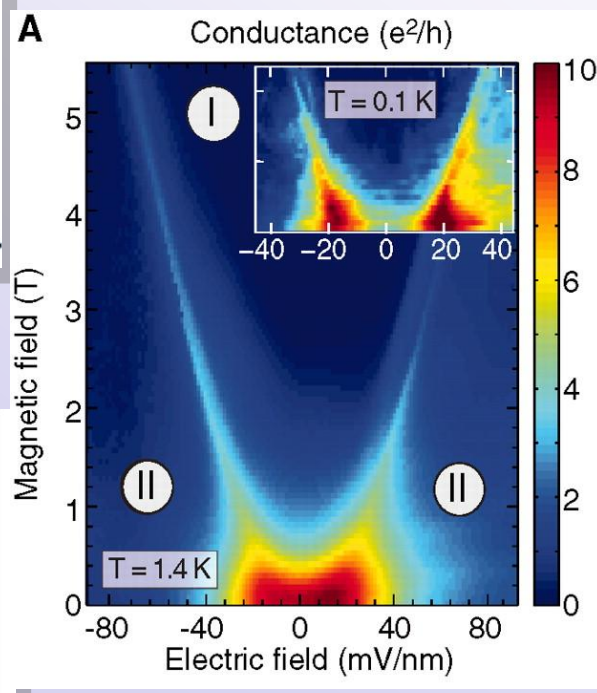
Spectroscopy of the  $\nu = 0$  gap



$E^*_\perp$  vs.  $B$   
Bias spectroscopy useful tool for measuring Quantum Hall gaps!



also see Weitz et al. *Science* 2010

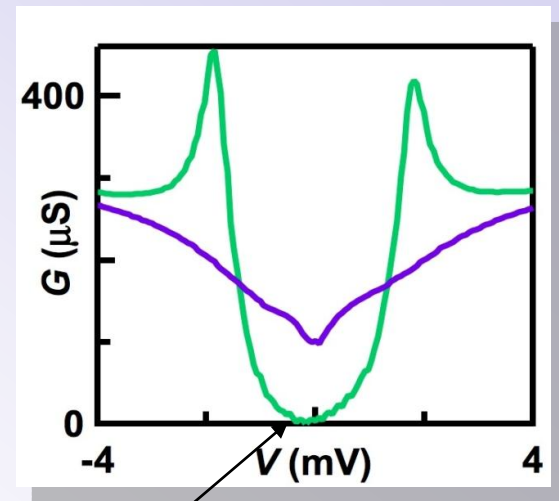


Slope and intercept match previous experiments by Yacoby group

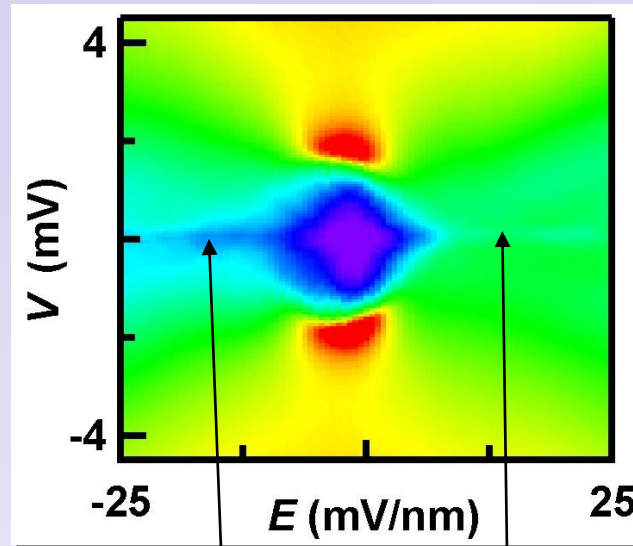
J. Velasco Jr. *et al.*, *Nature Nanotechnology*, in press (2012)

# Theory and Experiment

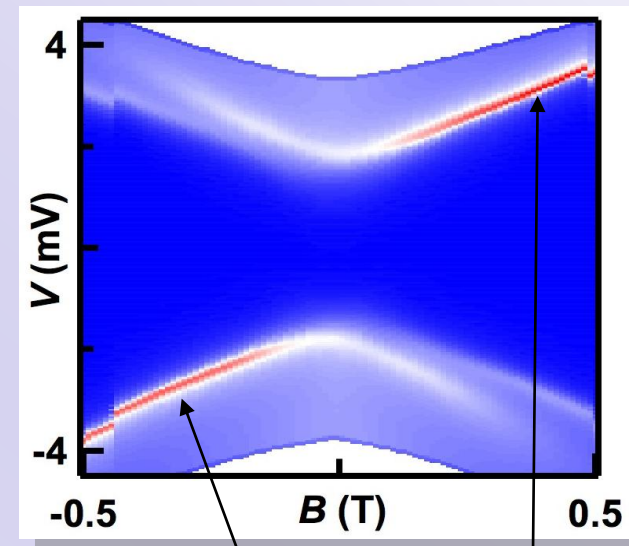
	<del>Nematic Order</del>	<del>Anomalous Hall</del>	<del>QSH</del>	SDW (LAF)	<del>CLP</del>
Gapped?	No	Yes	Yes	Yes	Yes
2-terminal $\sigma_{min}$	finite	$4e^2/h$	$4e^2/h$	0	0
Broken Symmetries	in-plane rotation	Time reversal; Ising Valley	spin rotational; Ising Valley	Time reversal; spin rotation	inversion



Insulating state

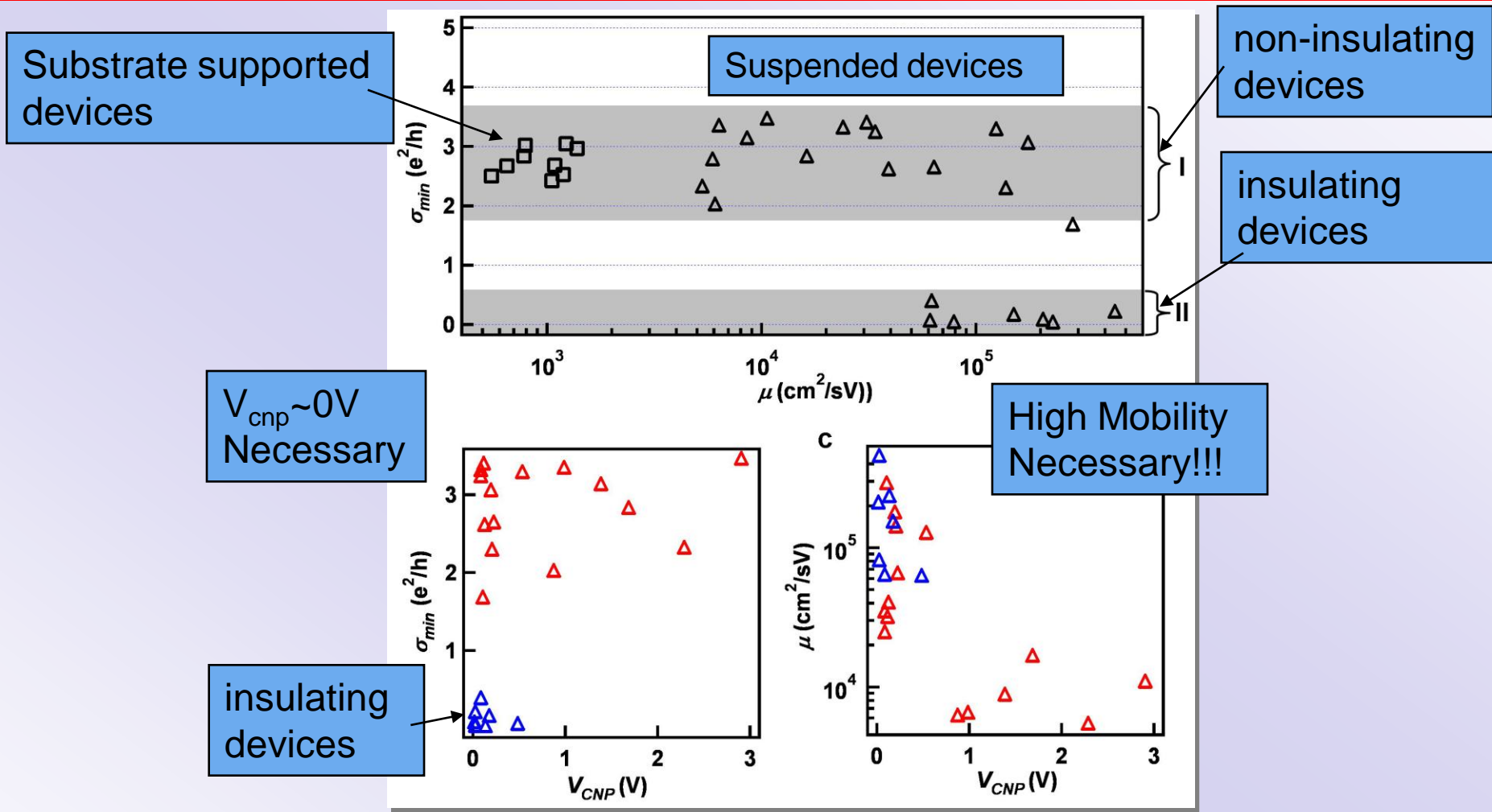


Symmetric closure of gap



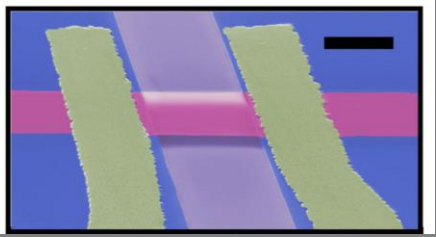
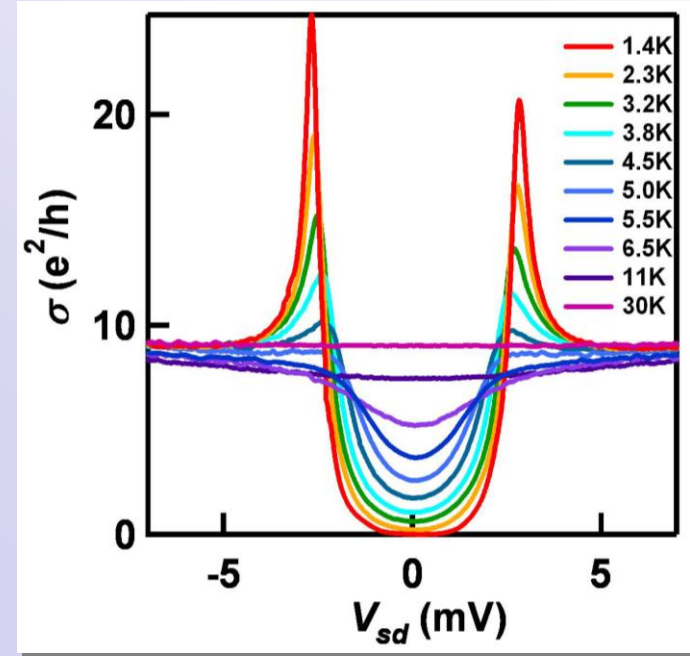
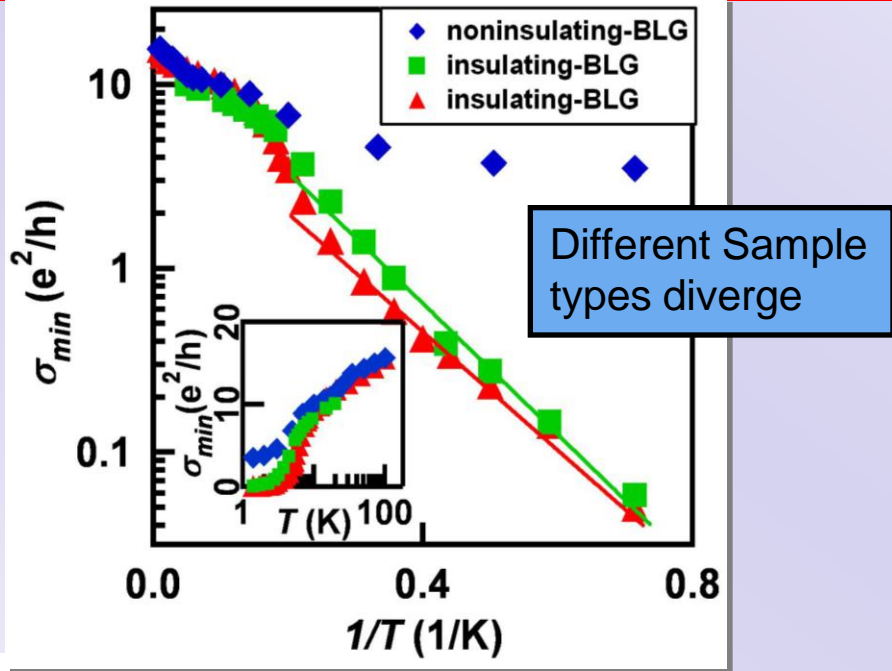
Asymmetric peaks

# Necessary Conditions for Insulating State



W. Bao\*, J. Velasco Jr.\*, F. Zhang\*, *et al.*, submitted

# Evidence for Phase Transition

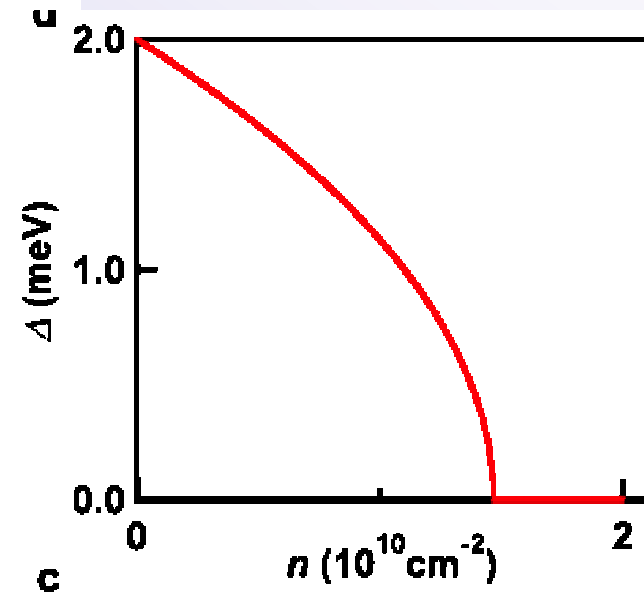
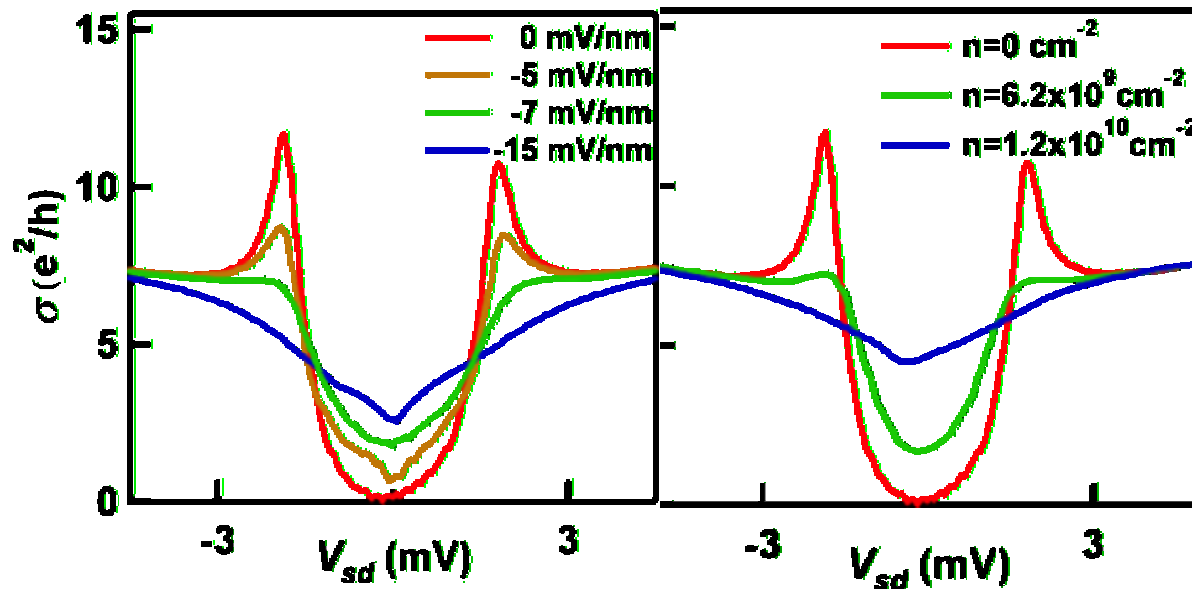


- "U" conductance profile is suppressed by temperature
- Suggests phase transition

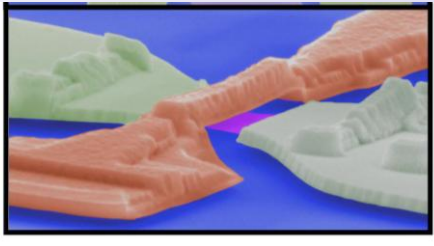
W. Bao\*, J. Velasco Jr.\*, F. Zhang\*, *et al.*, submitted



# Insulating State Tuned by $E$ and $n$



- “U” conductance profile is suppressed by  $T$ ,  $E$  and  $n$
- Suggests possible quantum phase transition



W. Bao\*, J. Velasco Jr.\*, F. Zhang\*, *et al.*, submitted

# Conclusion

- Observation of insulating state at CNP
- Bias spectroscopy at  $B=0$  shows a gapped insulating state
- In  $B$  the gap grows monotonically with field
- In both applied fields bias spectroscopy is useful for probing quantum Hall gaps
- LAF state captures most of data, more inquiry is needed!!!
- Evidence for a Phase Transition and gap is suppressed by  $E, T, n$

