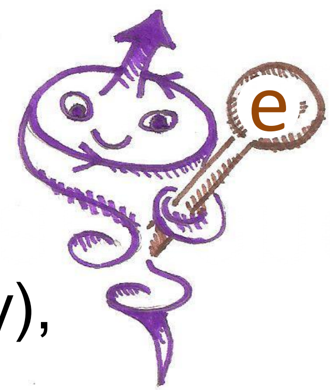
Bilayer Graphene as a Playground for Exotic Magnetic Phases



Collaborators

Ganpathy Murthy (U Kentucky),
Herb Fertig (Indiana U)

Useful discussions:

Jun Zhu, Jing Li,
Andrea Young,
Mike Zaletel

United States – Israel
Binational Science Foundation

The Quantum Hall Effect in graphene

$$E_n = \frac{\sqrt{2}\hbar v_F}{l_B}\sqrt{|n|}$$

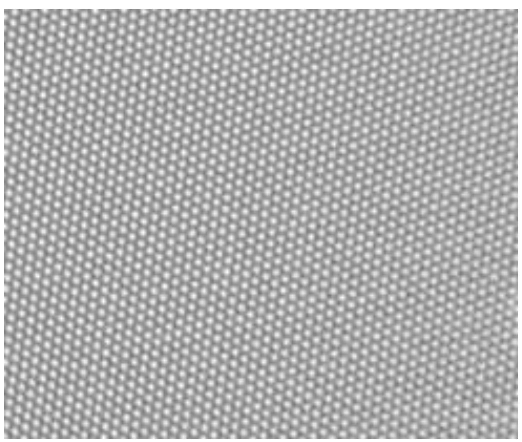
n=2

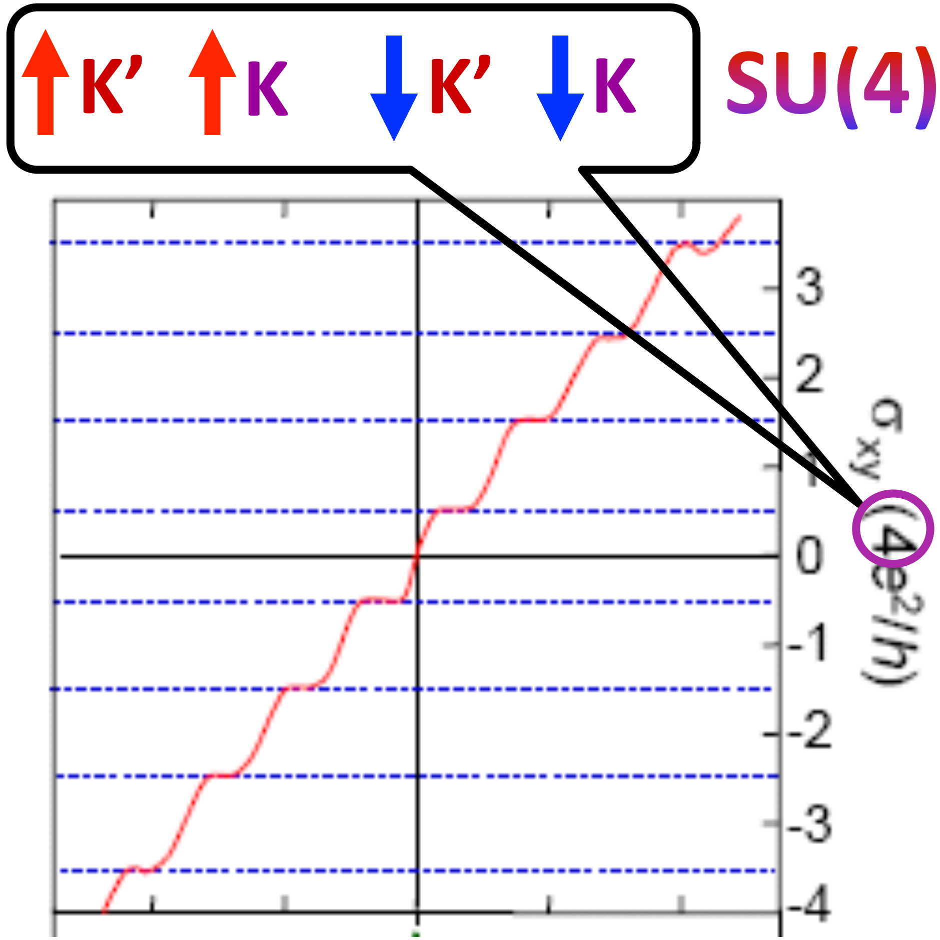
n=1

n=0

n=-1

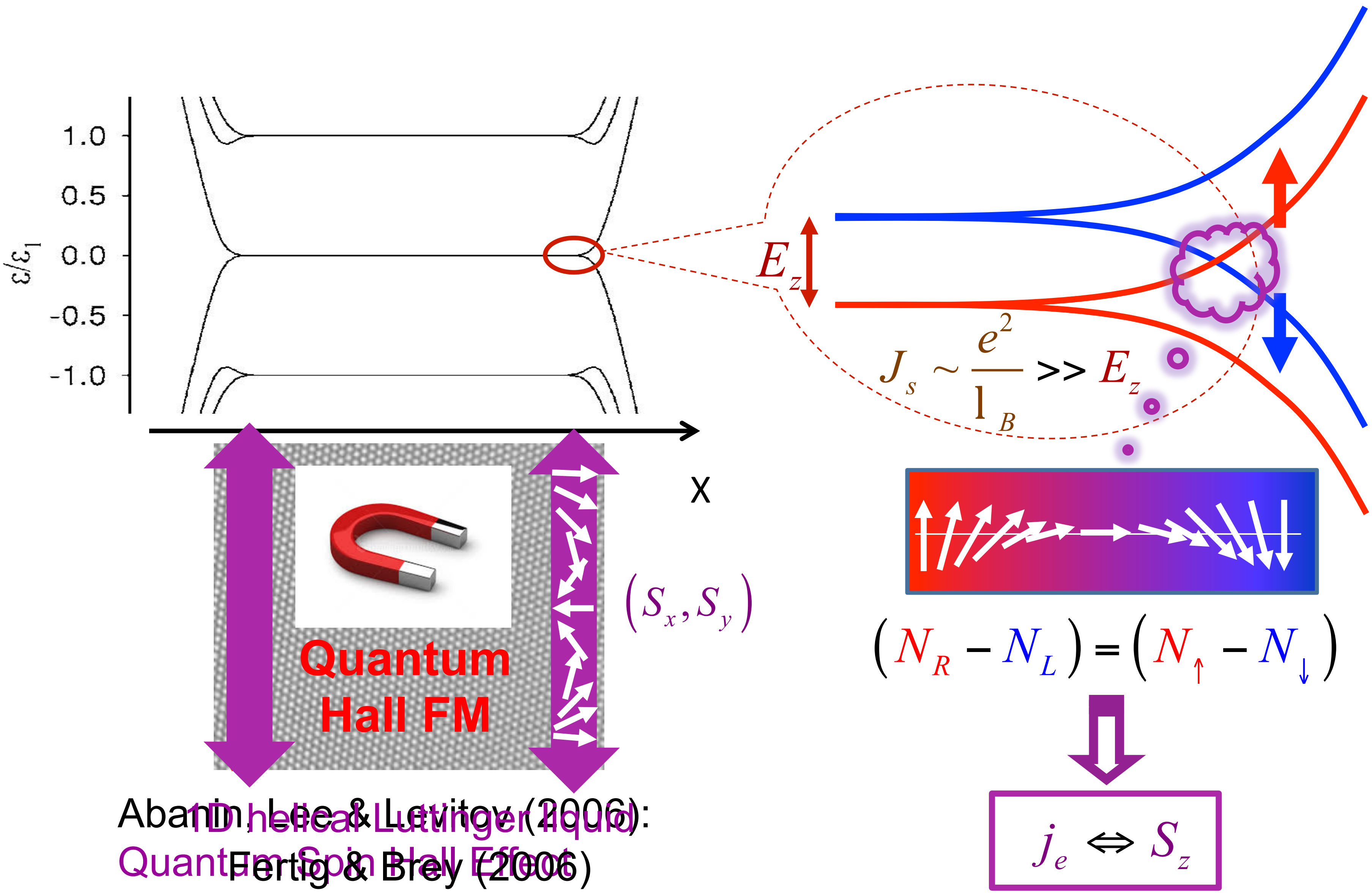
n=-2





Novoselov, Geim et al., Nature **438**, 197 (05)

The $\nu = 0$ QH State in Graphene



Abanin, Lee & Levitov (2006):

Fertig & Brey (2006)

1D helical Luttinger liquid

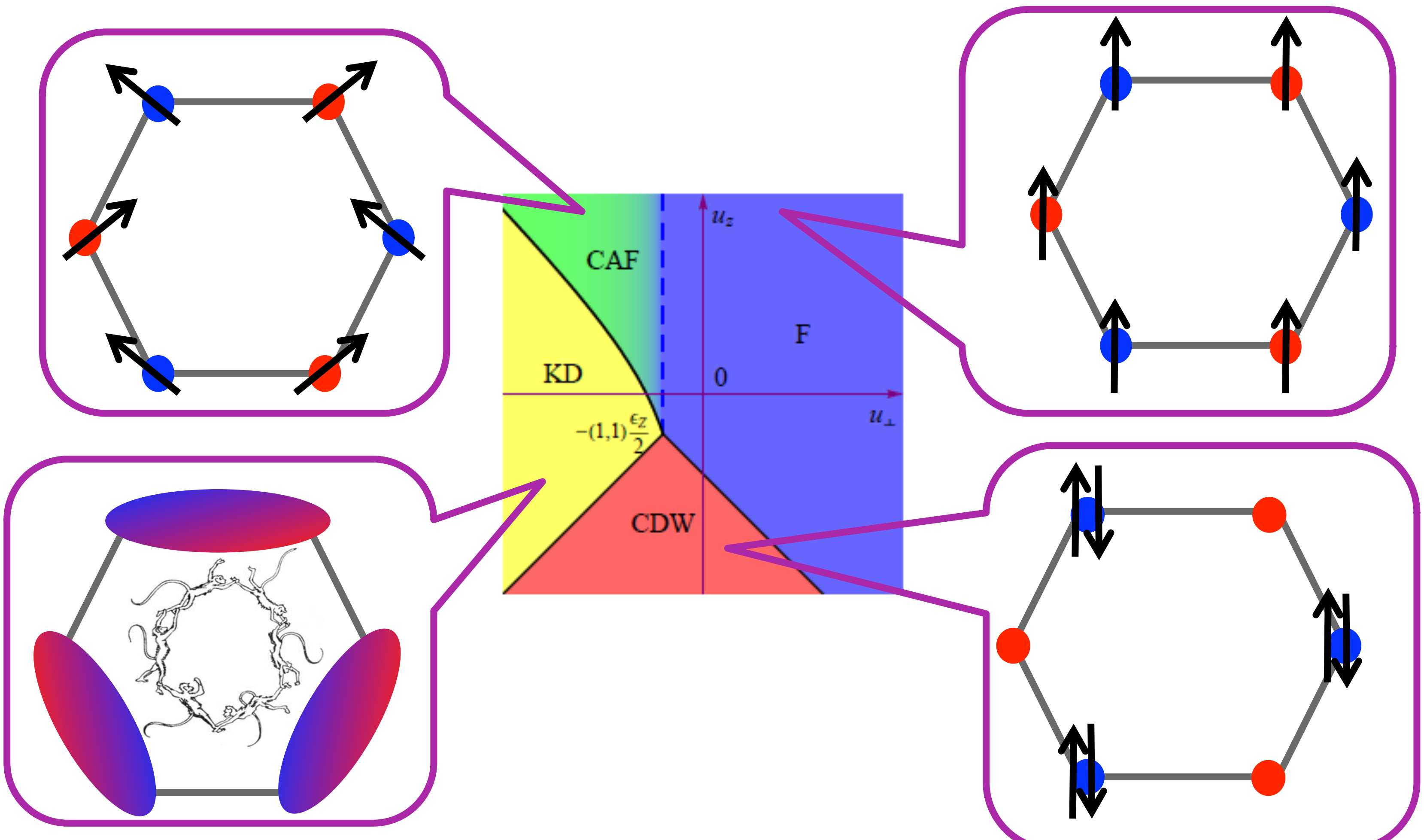
Quantum Spin Hall Effect

Experimentally: $\nu = 0$ an INSULATOR!

Jung & MacDonald, Nandkishore & Levitov (2009):

Variety of SU(4) symmetry-broken ground states in the bulk

Kharitonov (2012): Coulomb + lattice-scale interactions

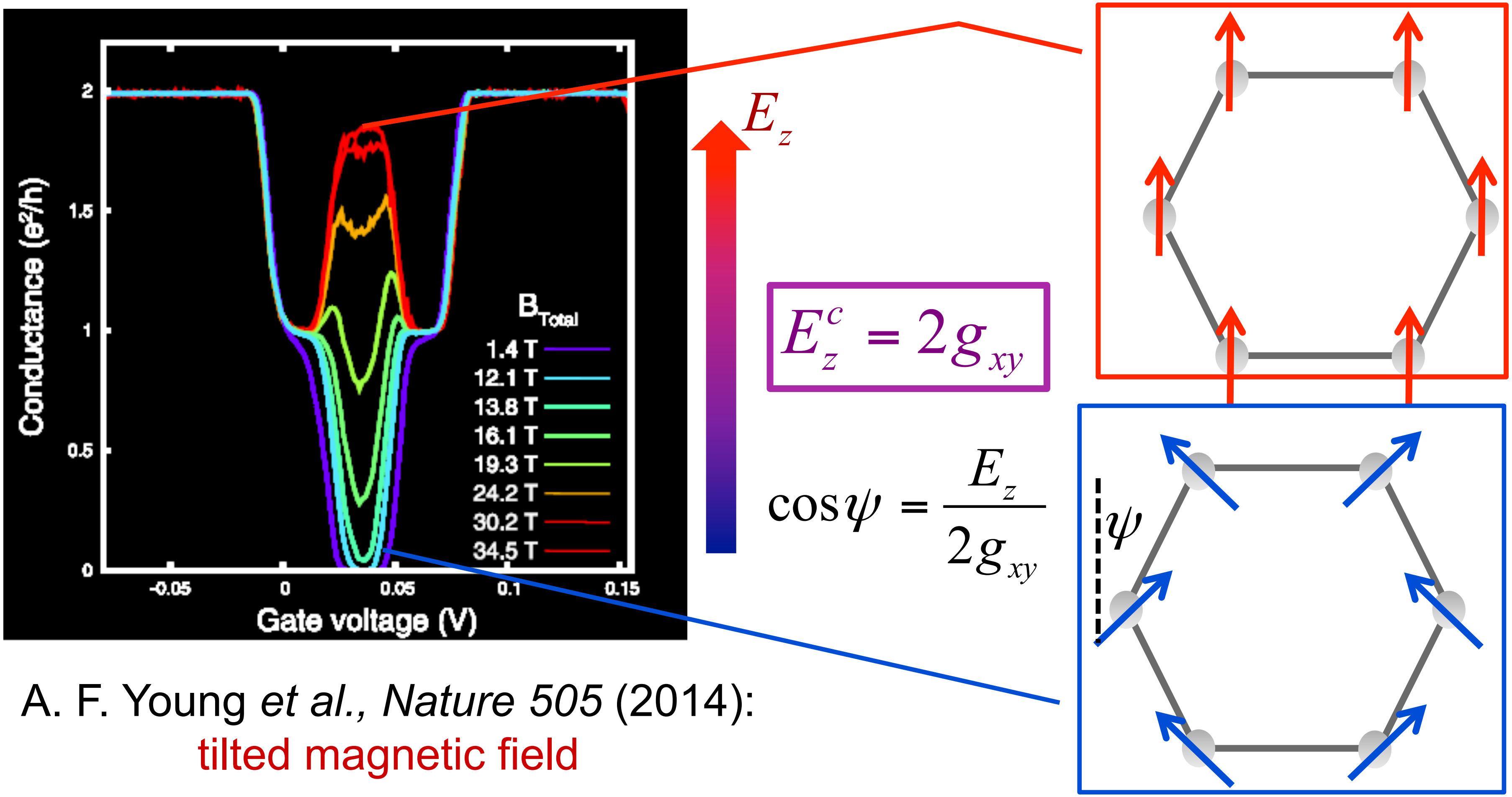


Experimentally: $\nu = 0$ an INSULATOR!

Jung & MacDonald, Nandkishore & Levitov (2009):

Variety of SU(4) symmetry-broken ground states in the bulk

Kharitonov (2012): Canted Anti-Ferromagnet ➡ Ferromagnet



$$E_z^c = 2g_{xy}$$

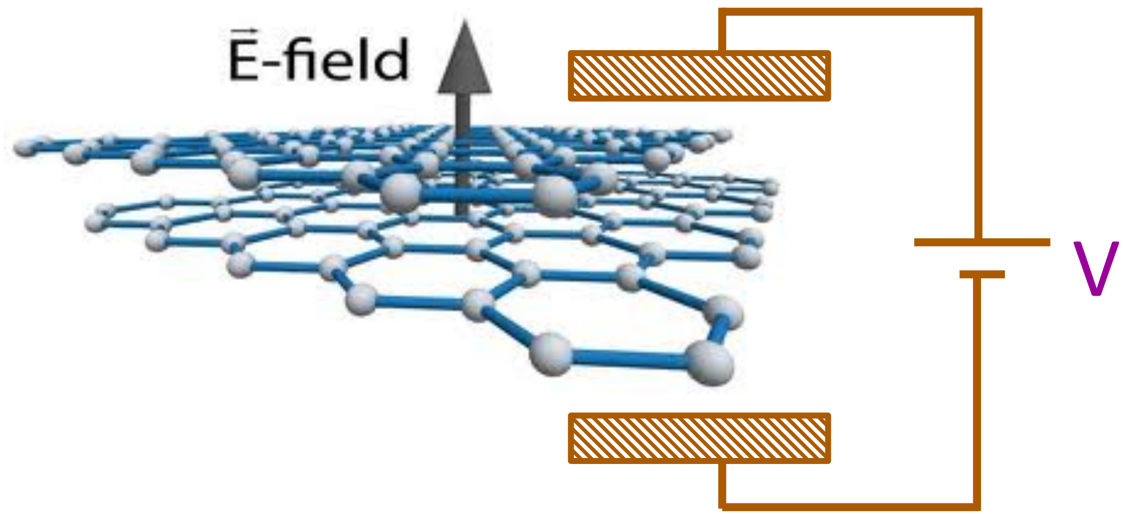
$$\cos\psi = \frac{E_z}{2g_{xy}}$$

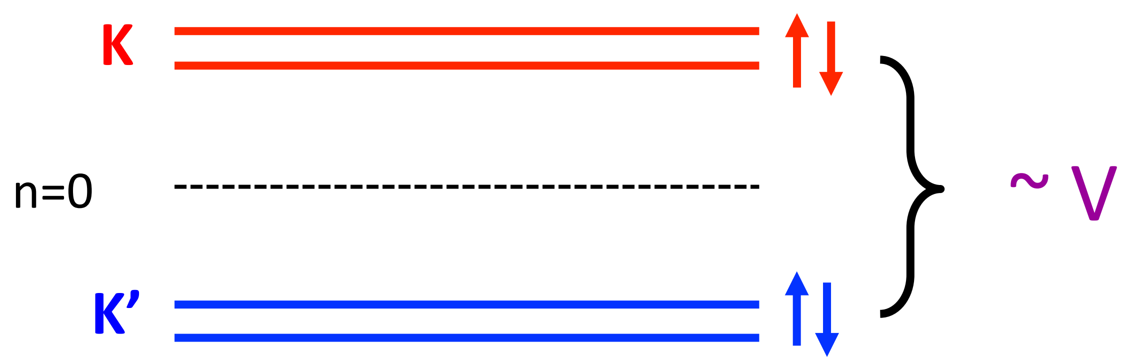
A. F. Young *et al.*, *Nature 505* (2014):

tilted magnetic field

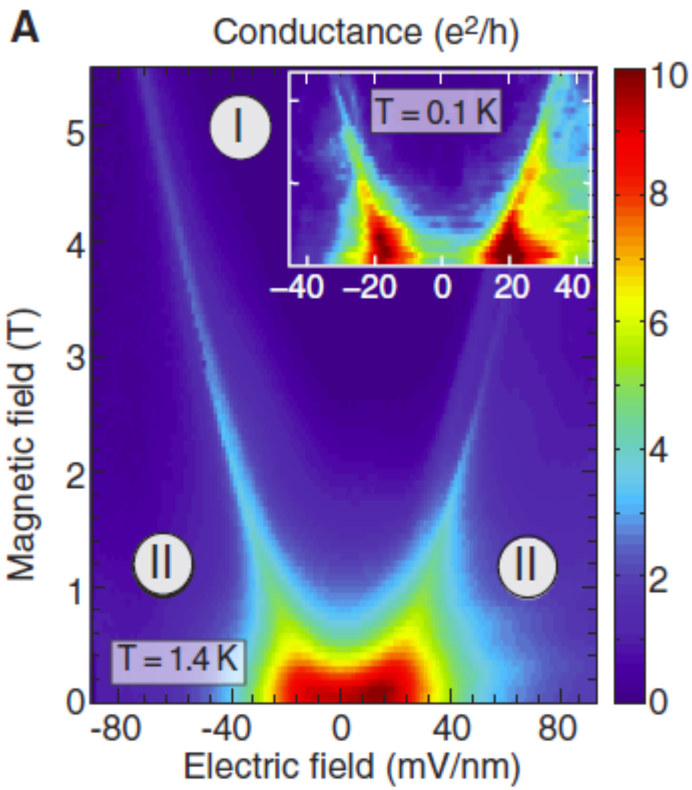
Bilayer Graphene

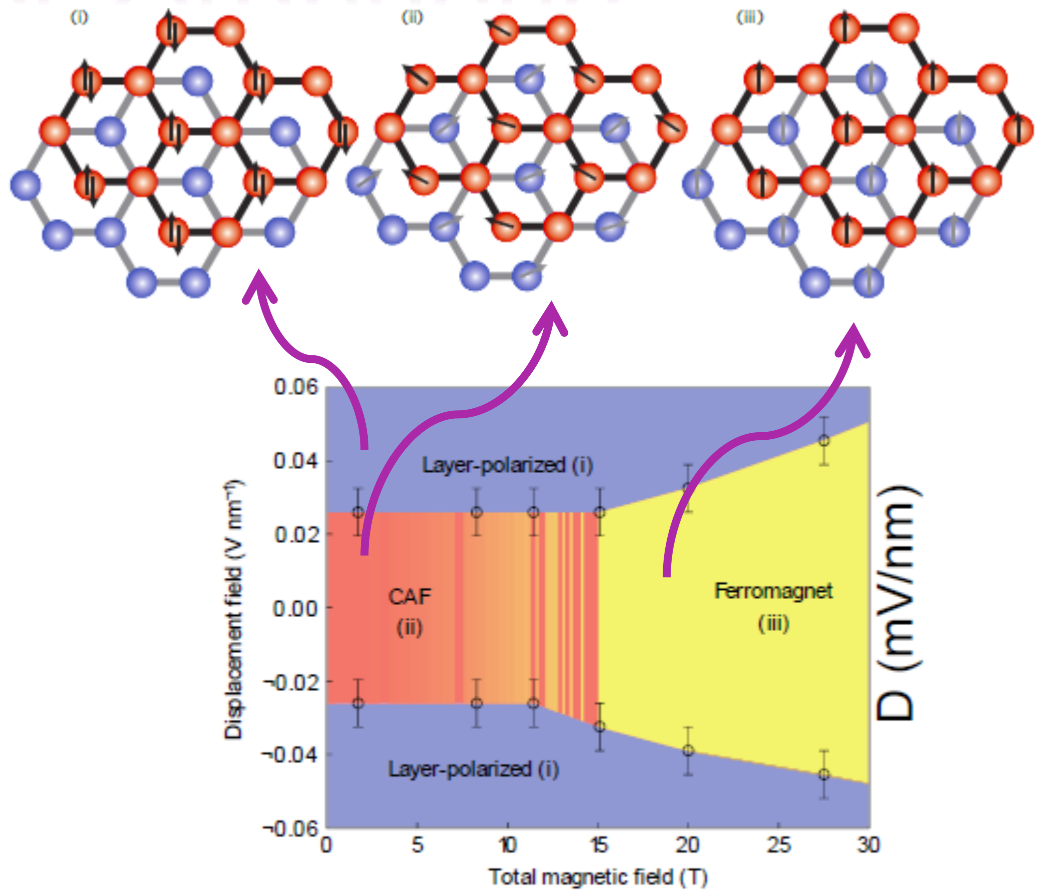
$B_{eff} \Longrightarrow$ Perpendicular electric field





Bilayer Graphene

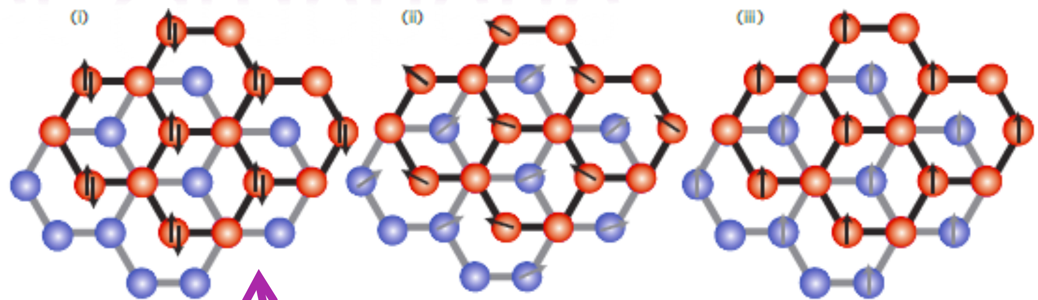


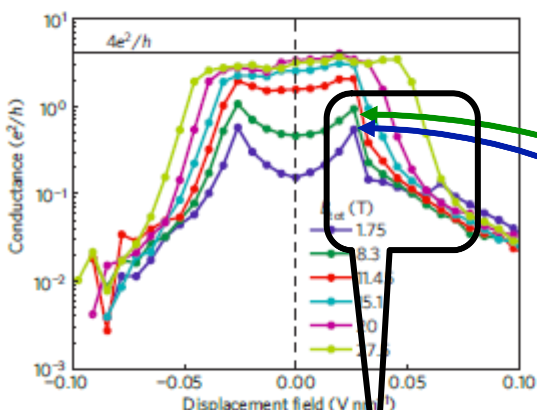


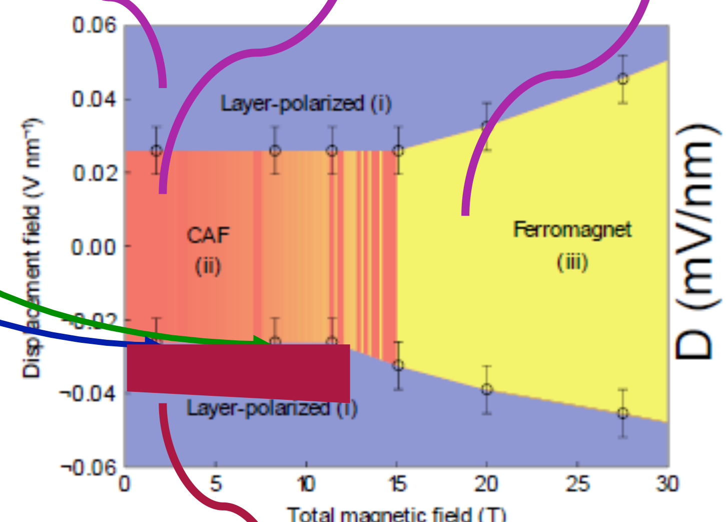
R. T. Weitz *et al.* (Yacoby group), Science **330**, 812 (2010)

P. Maher *et al.* (Kim group), Nature Phys. **9**, 154 (2013)

Bilayer Graphene





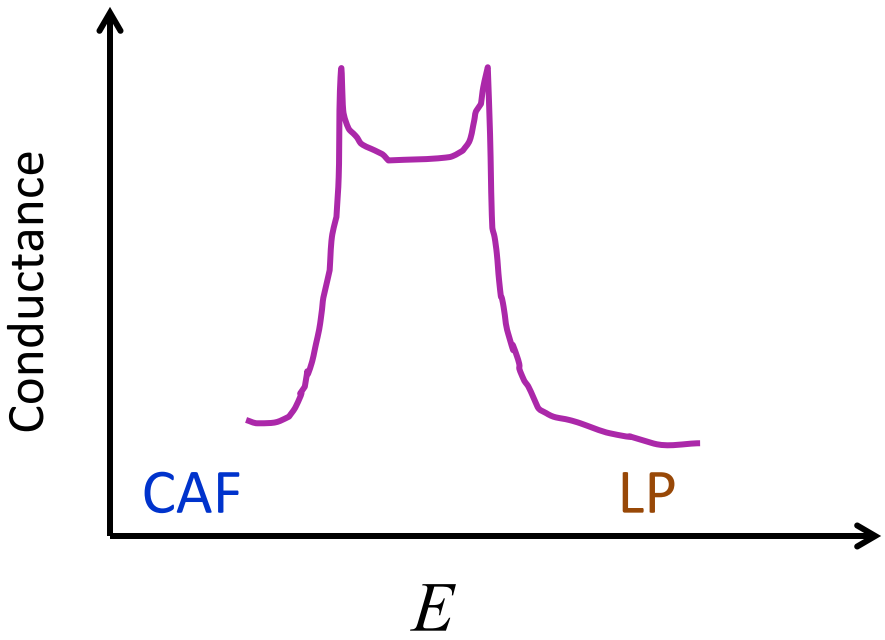


P. Maher *et al.* (Kim group),
Nature Phys. 9, 154 (2013)

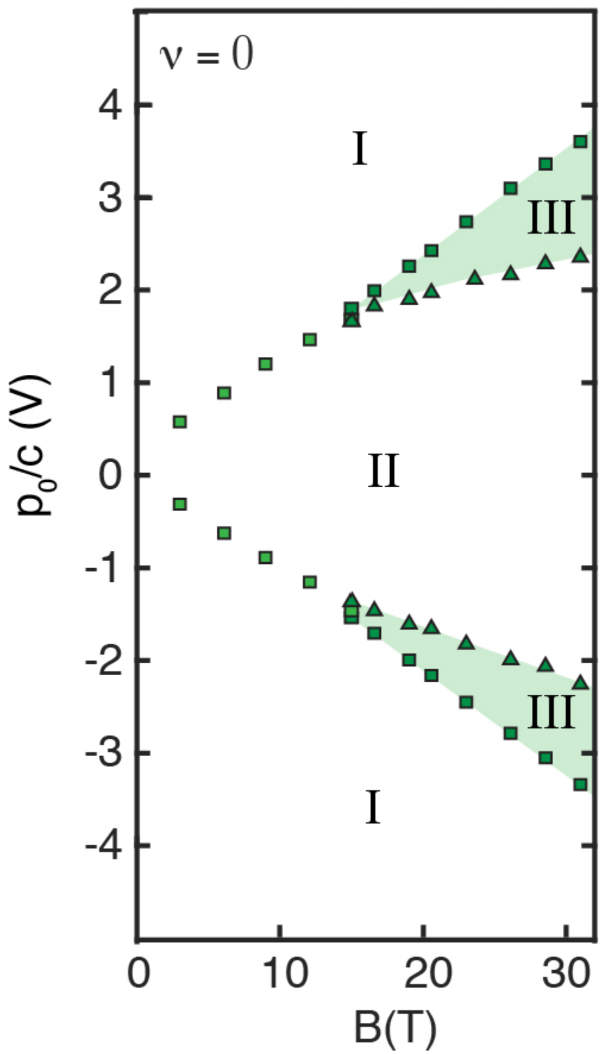
Intermediate phase?

Bilayer Graphene

Jun Zhu's lab, Penn State (preliminary data, in part of samples):



Bilayer Graphene

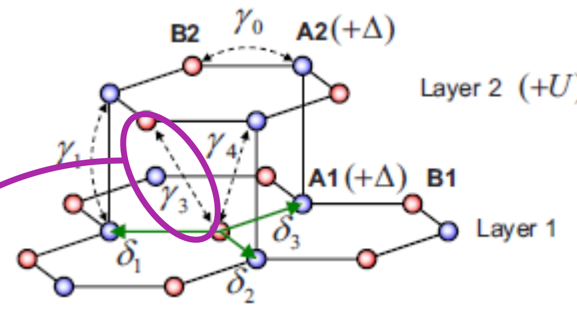


Compressibility and relative capacitance measurements:

B. M. Hunt *et al.* (Andrea Young's group at UCSB), arXiv:1607.06461

Our Theory

$$H = H_0 + H_{\text{int}}$$



$$H_0 = \sum_X H_X - g\mu_B B_T \sigma_X^z$$

$$H_X = \begin{pmatrix} E + \Delta a^\dagger a & -\omega_c\left(a^2 + \lambda a^\dagger\right) \\ -\omega_c\left(\left(a^\dagger\right)^2 + \lambda a\right) & -E + \Delta a a^\dagger \end{pmatrix}$$

$$a = \frac{1}{\sqrt{2}}\left(l\frac{\partial}{\partial x} + \frac{(x - X)}{l}\right)$$

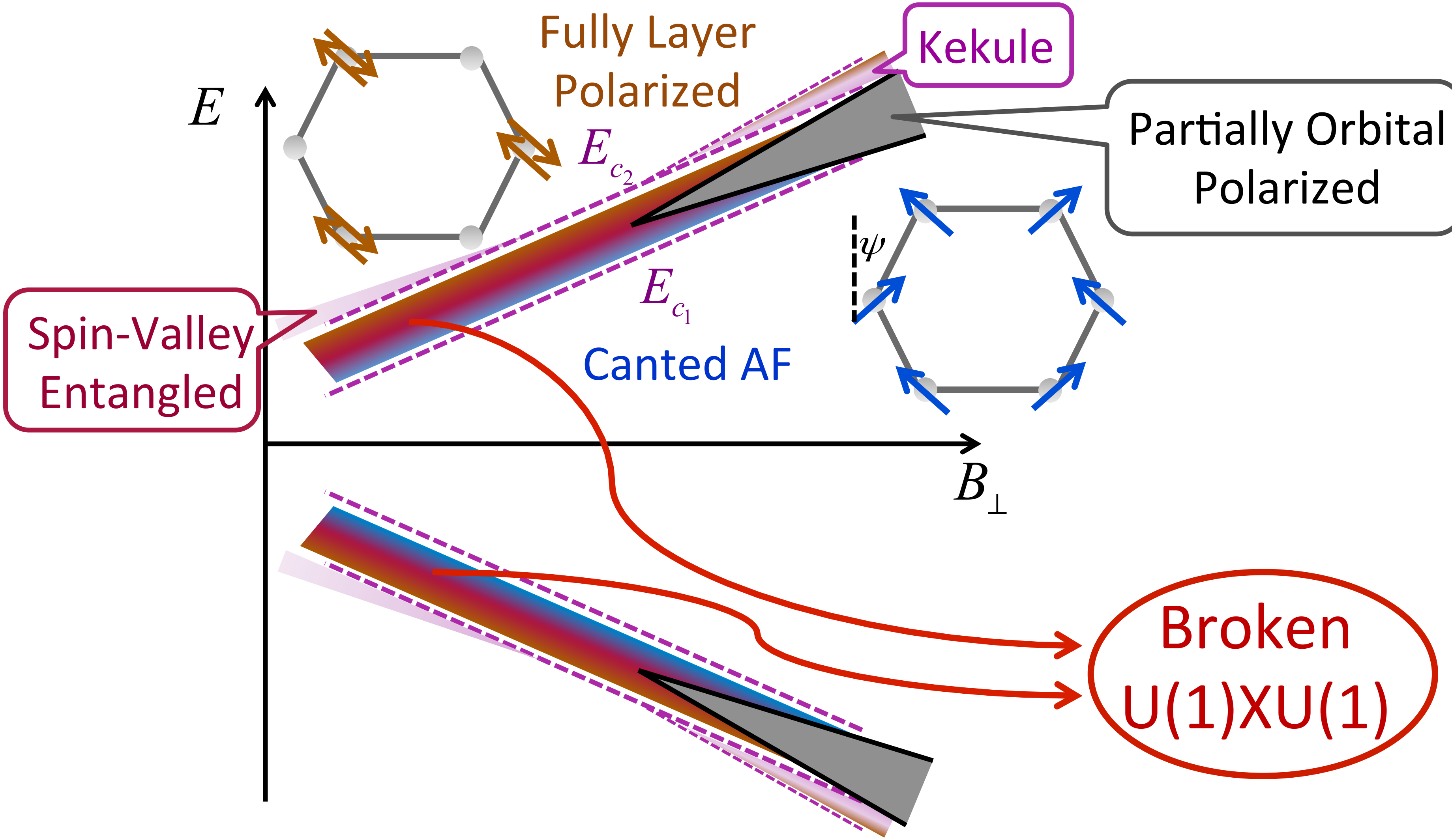
$$l = \sqrt{\frac{\mathrm{hc}}{eB_\perp}} \qquad X = l^2 k_y$$

$$H_{\text{int}} = \sum_{X,X'} g_0 n_X n_{X'} + g_{xy}\left(\tau_X^x \tau_{X'}^x + \tau_X^y \tau_{X'}^y\right) + g_z \tau_X^z \tau_{X'}^z + g_{nz} O_X^z O_{X'}^z$$

$$\omega_c, \Delta \sim B_\perp \qquad g_\alpha \sim \frac{e^2 a_0}{l^2} \sim B_\perp \qquad \boxed{\lambda \sim \frac{1}{\sqrt{B_\perp}}}$$

~ 1 for $B_\perp$
A few Tesla

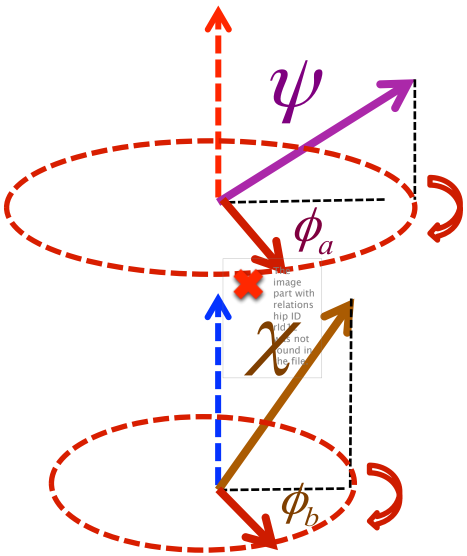
Our Theory:
Possible phase diagram



Spin-Valley entangled

$$|a\rangle = \cos\left[\frac{\psi}{2}\right]|\uparrow, K\rangle - e^{i\phi_a}\sin\left[\frac{\psi}{2}\right]|\downarrow, K'\rangle$$

$$|b\rangle = -\cos\left[\frac{\chi}{2}\right]|\uparrow, K'\rangle + e^{i\phi_b}\sin\left[\frac{\chi}{2}\right]|\downarrow, K\rangle$$

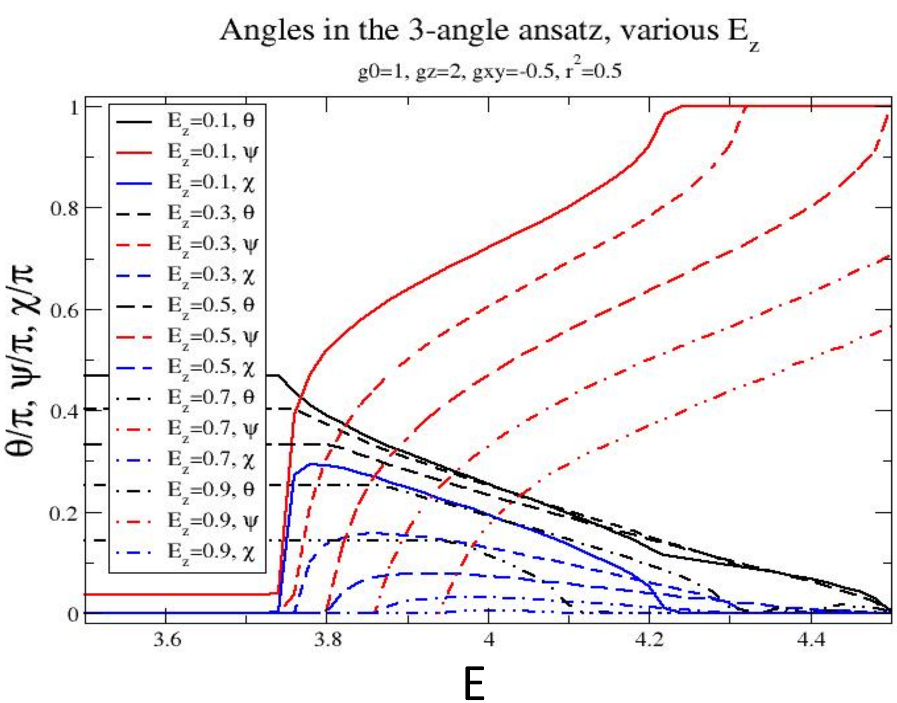


"Broken U(1)XU(1)":

$$|a\rangle = \cos\left[\frac{\psi}{2}\right]|\uparrow, K\rangle - e^{i\phi_a}\sin\left[\frac{\psi}{2}\right]|\downarrow, K'\rangle$$

$$|b\rangle = -\cos\left[\frac{\chi}{2}\right]|\uparrow, K'\rangle + e^{i\phi_b}\sin\left[\frac{\chi}{2}\right]|\downarrow, K\rangle$$

$$\cos\left[\frac{\theta}{2}\right]|a\rangle + e^{i\phi_c}\sin\left[\frac{\theta}{2}\right]|b\rangle$$



Two independent U(1)-angles:

$$\phi_a, \phi_b, \phi_c \Rightarrow \varphi, \eta$$

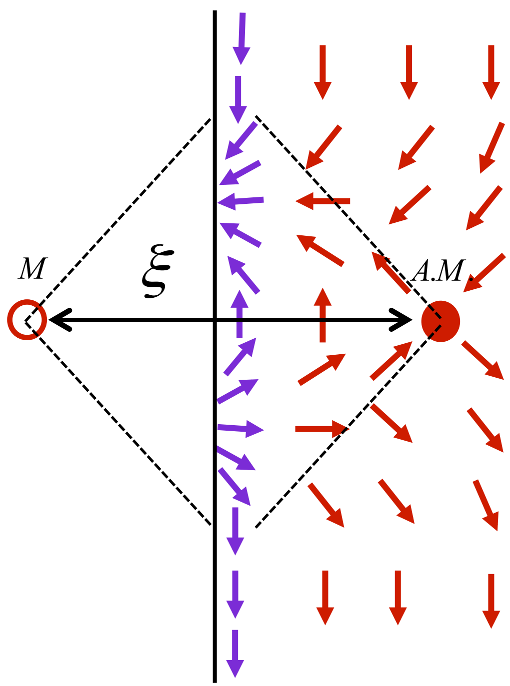
Collective Charged Mode on the Edge

(Murthy, ES, Fertig 2014; Tikhonov, ES, Murthy, Fertig 2016)

Meron-Antimeron pair

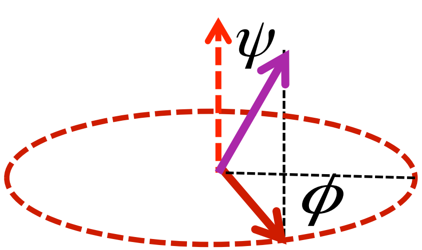
$$Q = 1e \Leftrightarrow \text{Pontryagin number}$$

$$\Delta_{edge} = E_M + E_{A.M.} \sim \rho_b \ln \rho_b$$



Bulk pseudospin stiffness:

$$\rho_b \propto \sin^2 \psi$$



Summary

- The $\nu = 0$ QH state in bilayer graphene has a rich phase diagram, dictated by interplay of H_{int}, E, B and the trigonal warping parameter λ .
- Possible spin-valley entangled intermediate phases between CAF and FLP: broken U(1)XU(1) symmetry
- Low-energy charged excitations: edge spin-textures, softening near the transitions