Non-collinear magnetic phases and edge states in graphene quantum Hall bars

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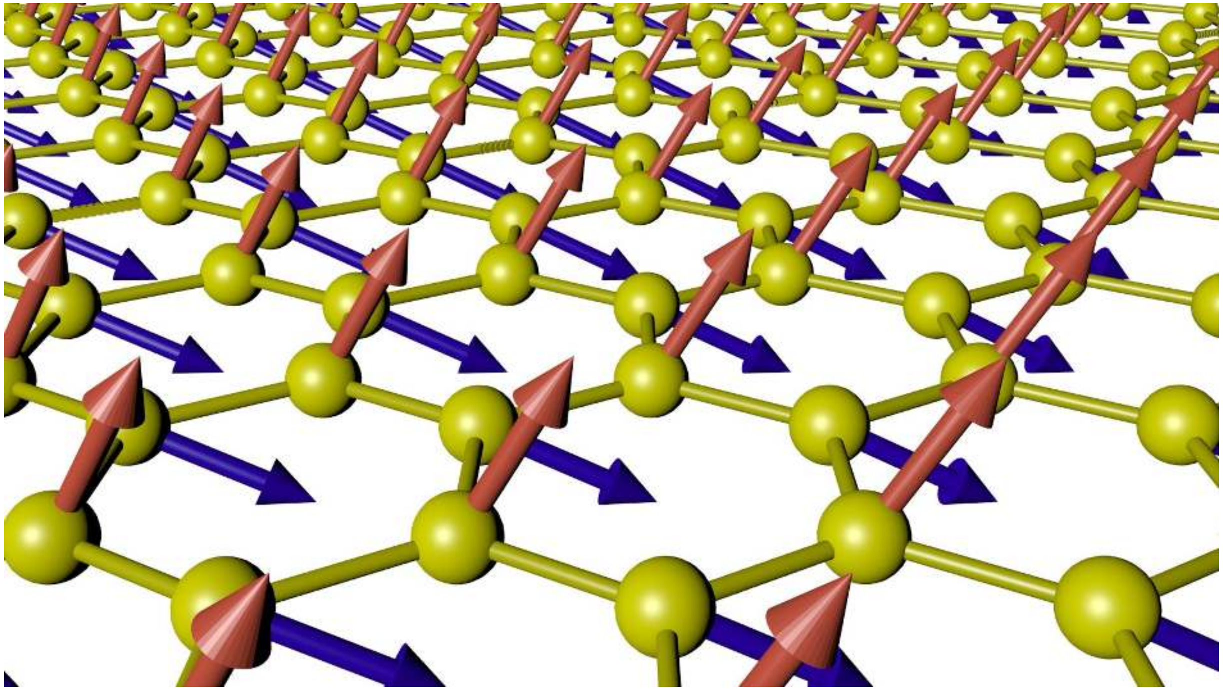
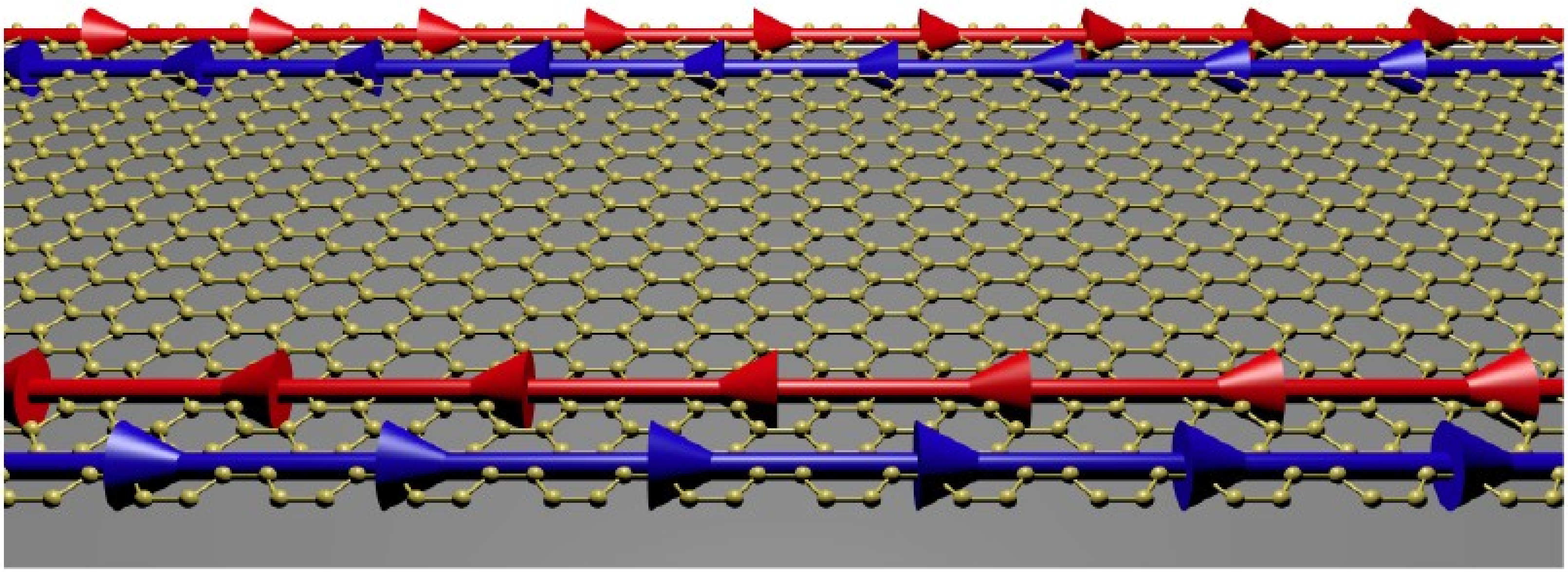


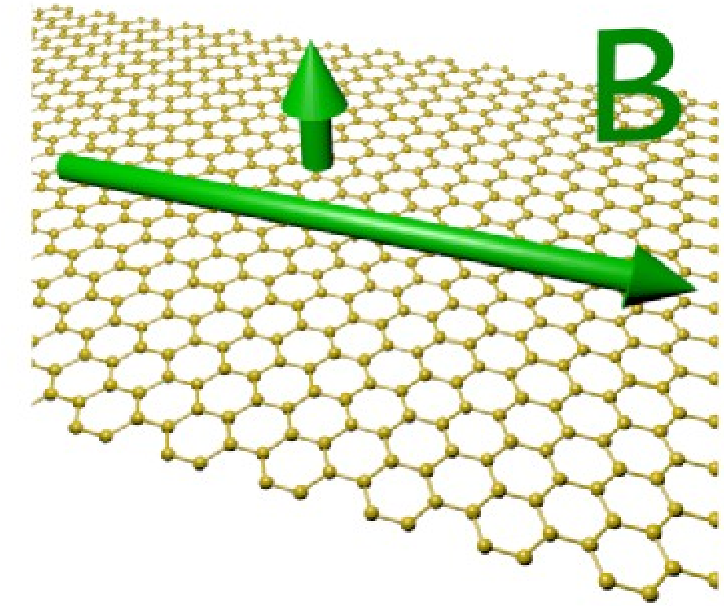
Looking for Quantum Spin Hall



Theory	Levitov et al, PRL (2006)
Experiment	A. F. Young et al, Nature (2014)
Time to go for the modeling!	J. L. Lado and J. F. Rossier, arXiv (2014)

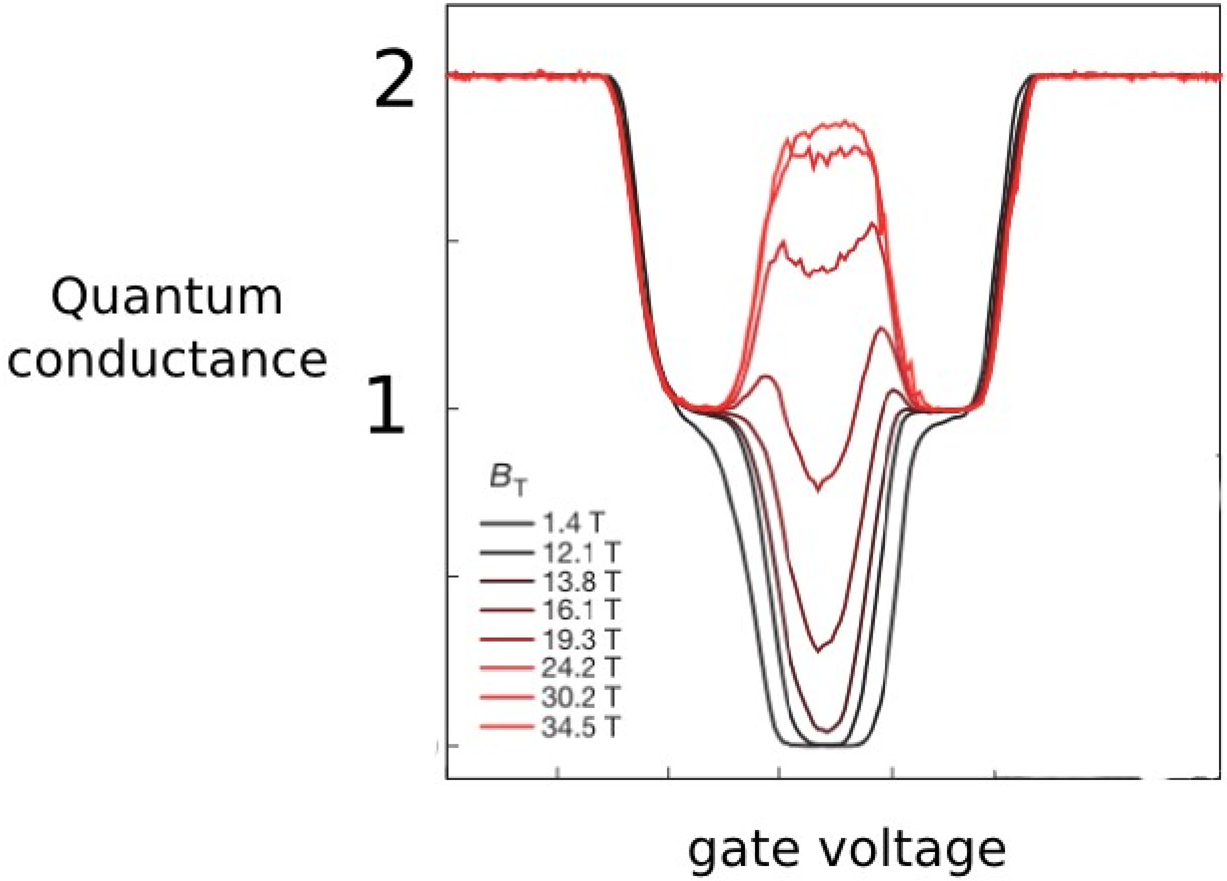
The experimental set-up

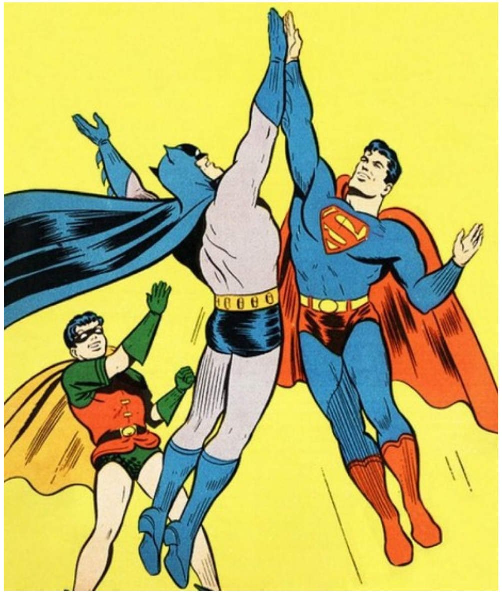
- High quality graphene
- Off-plane magnetic field
- In-plane magnetic field
- Variable doping via gate



A. F. Young et al, Nature (2014)

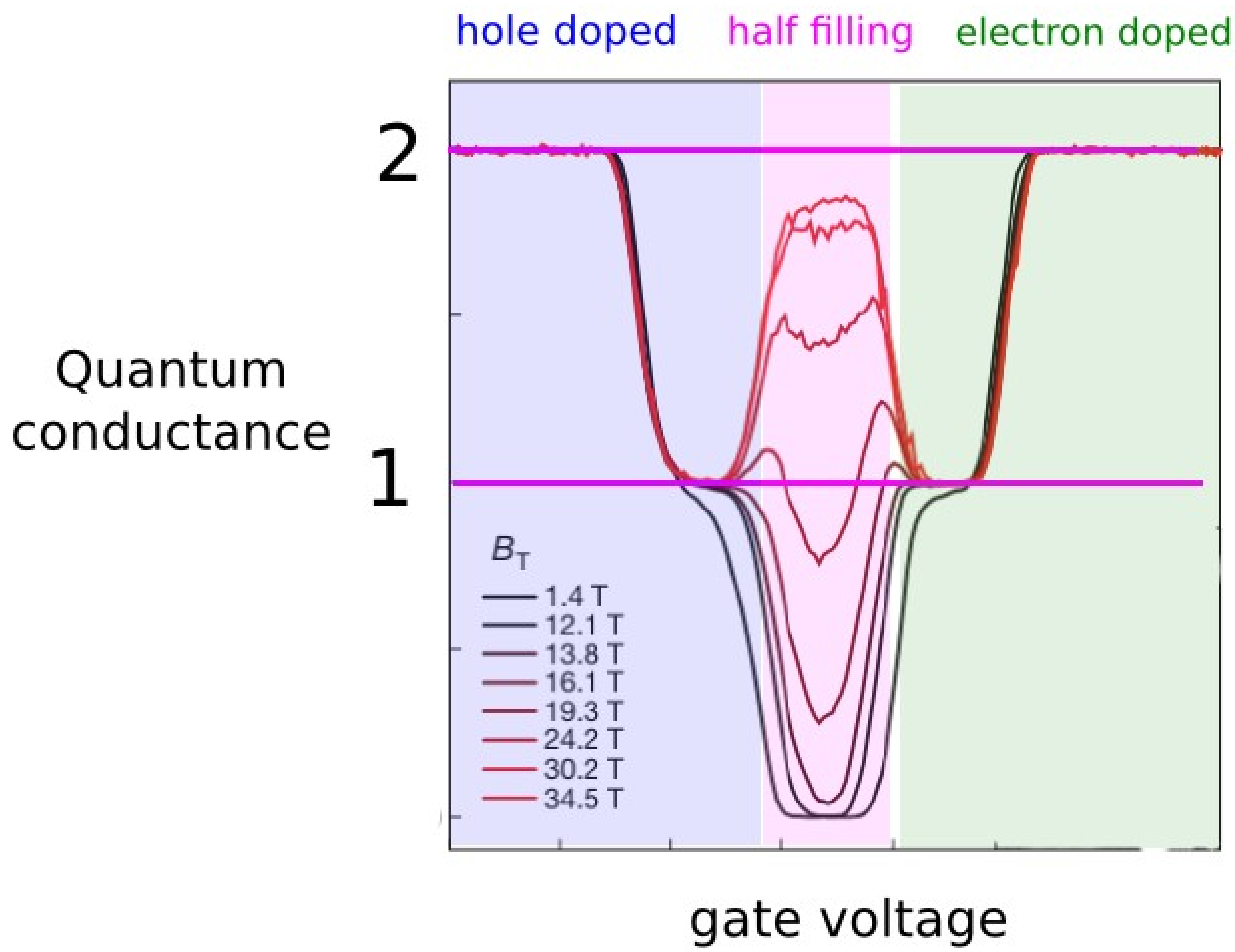
Different quantum Hall regimes





A. F. Young et al, Nature (2014)

Different quantum Hall regimes



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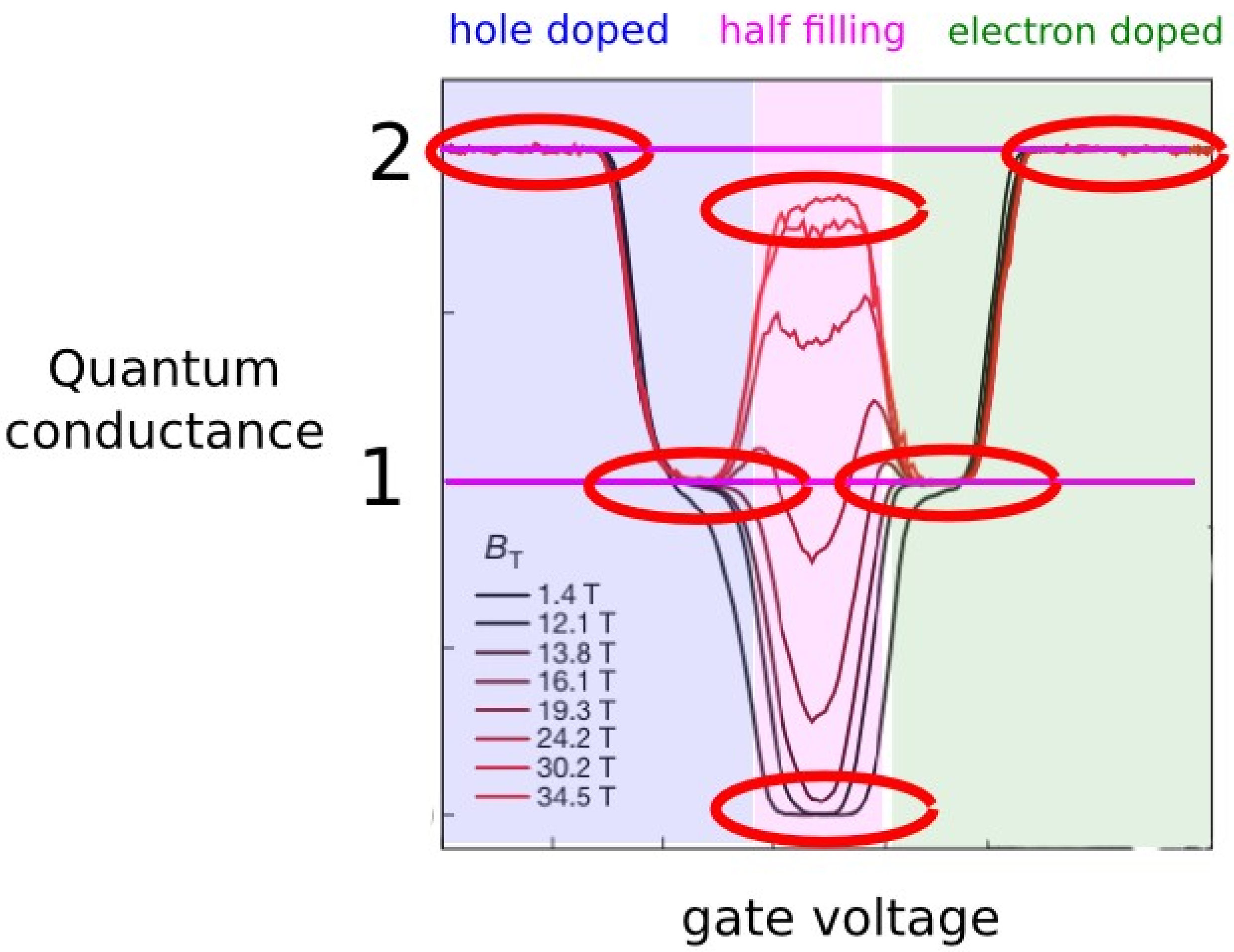
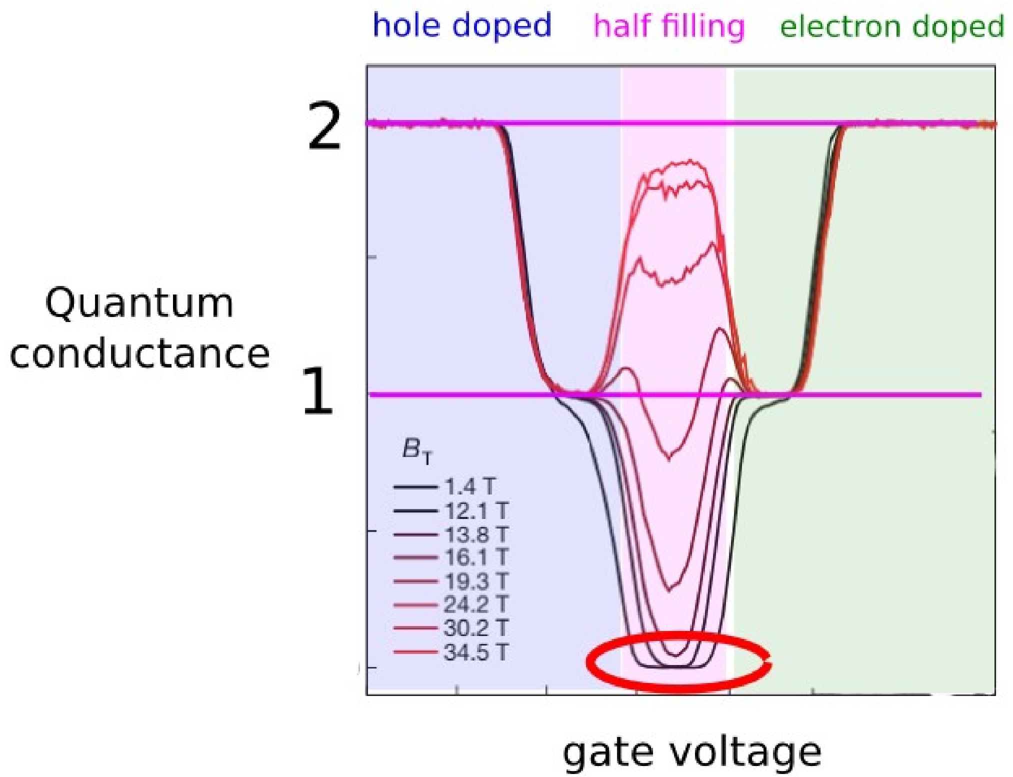
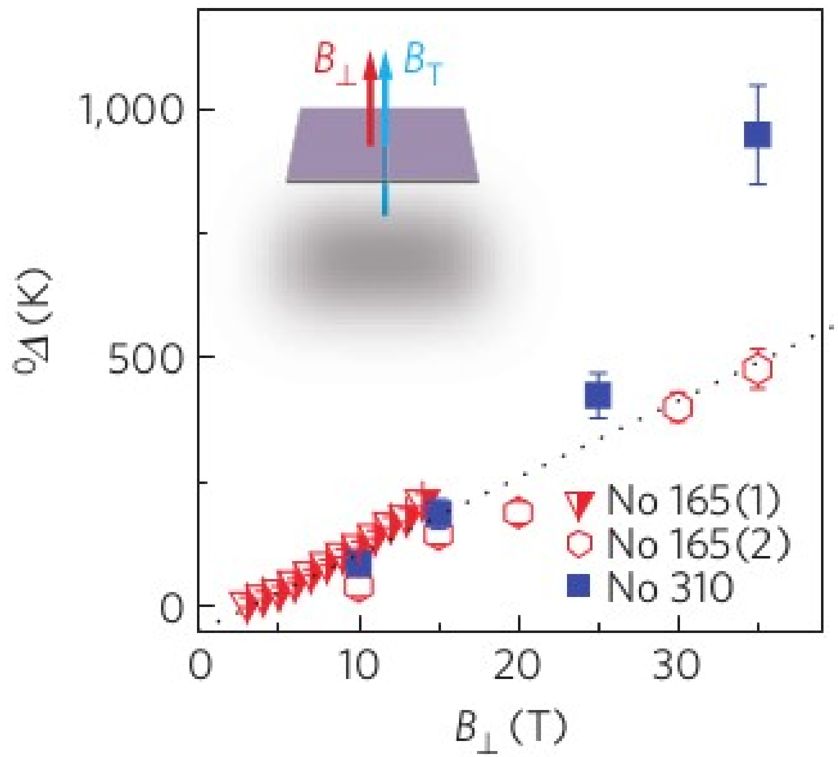
Different quantum Hall regimes



A. F. Young et al, Nature (2014)

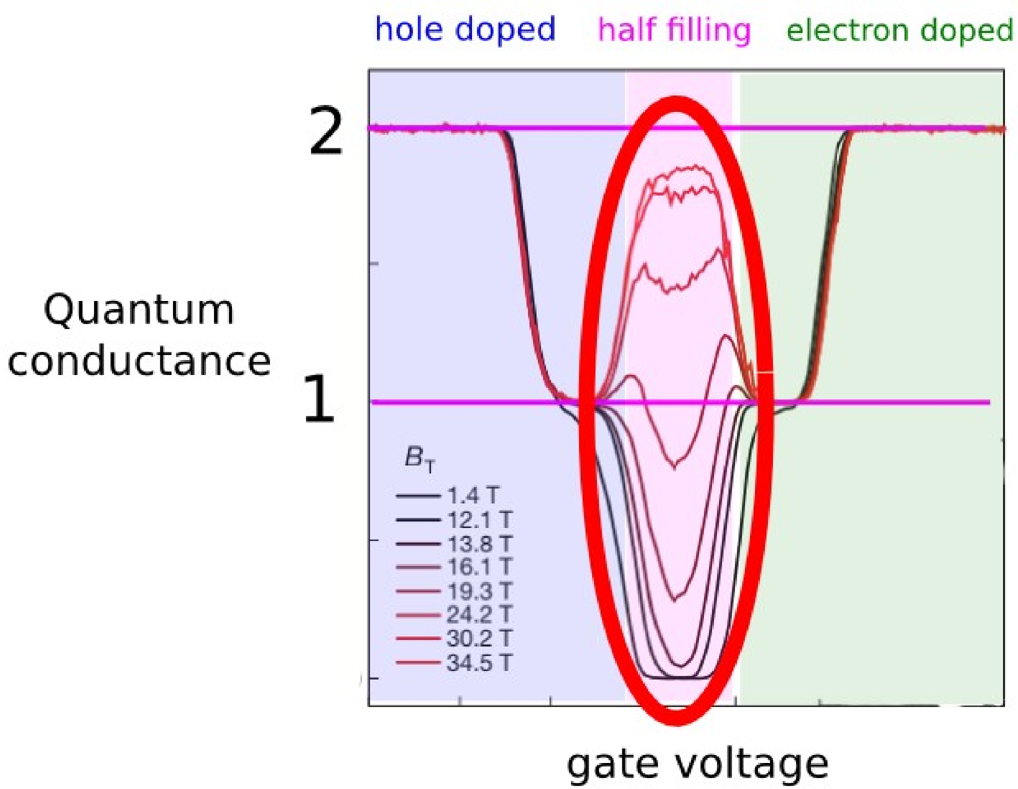
Gap increases at half filling

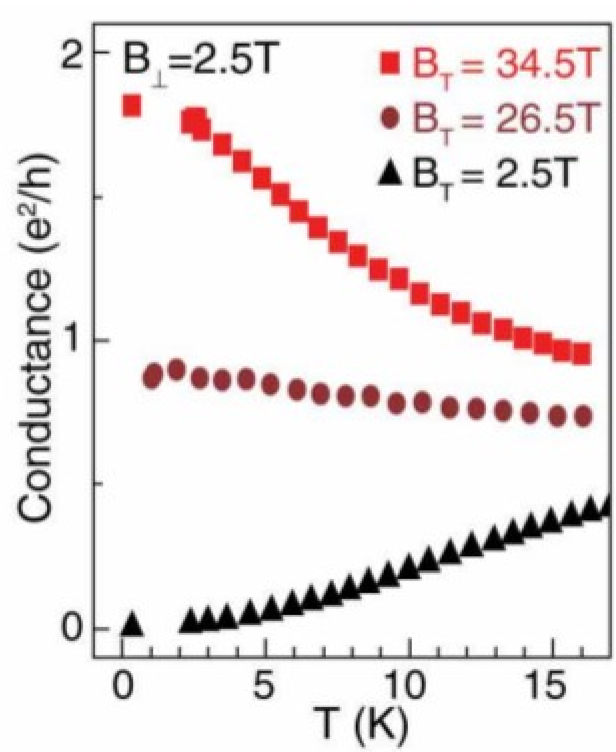




<u>**Gap increases linearly with off-plane field**</u>

Insulating to metallic



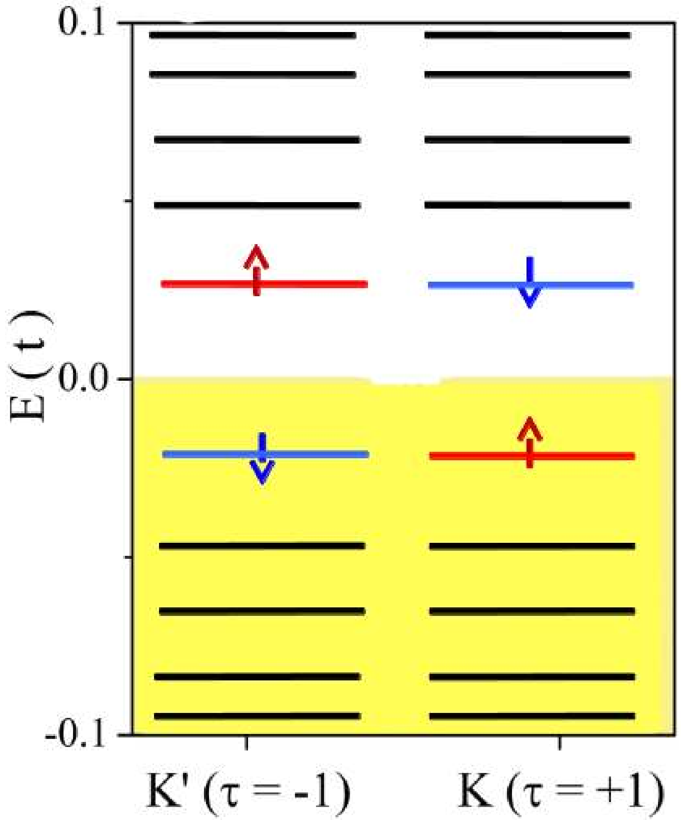


A. F. Young et at, Nature (2014)

Low BT → Insulating **High BT → Metallic**

The Landau level picture

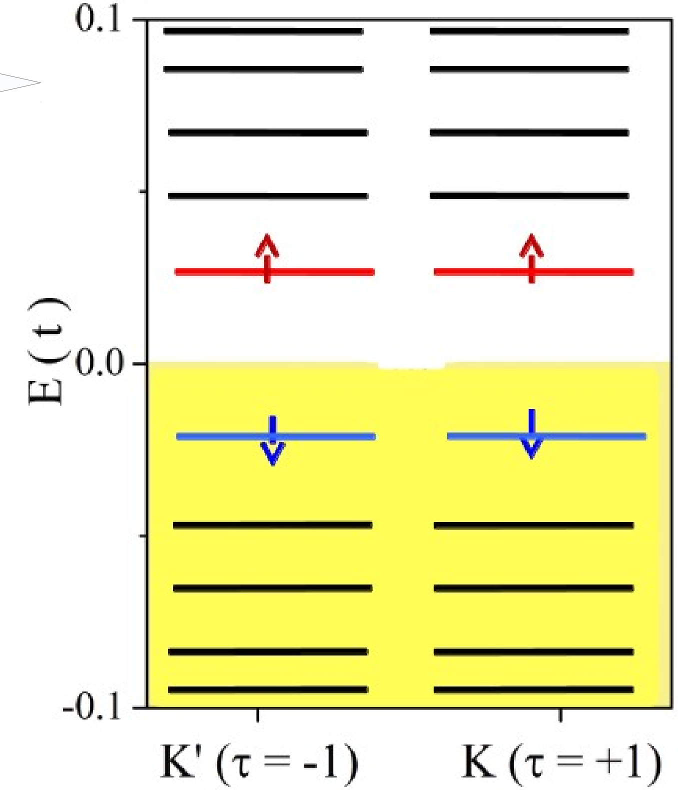
Antiferromagnetic



Spin Chern number = 0

Increasing Zeeman

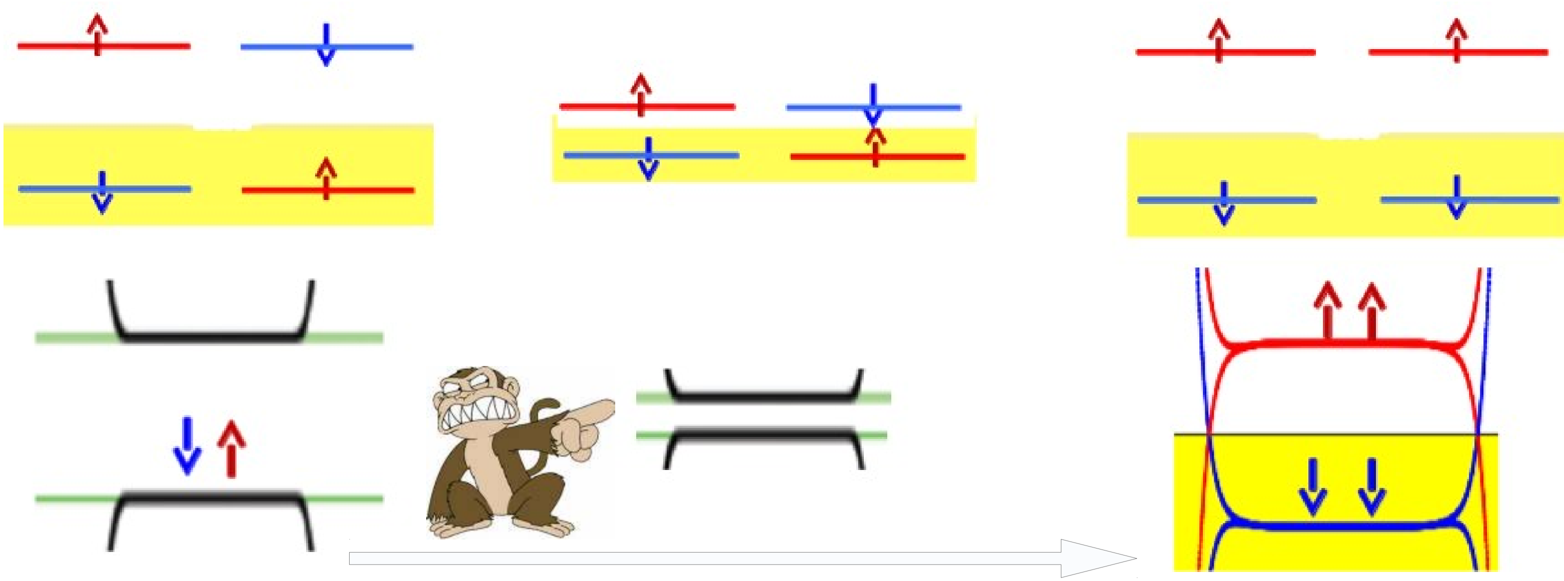
Ferromagnetic



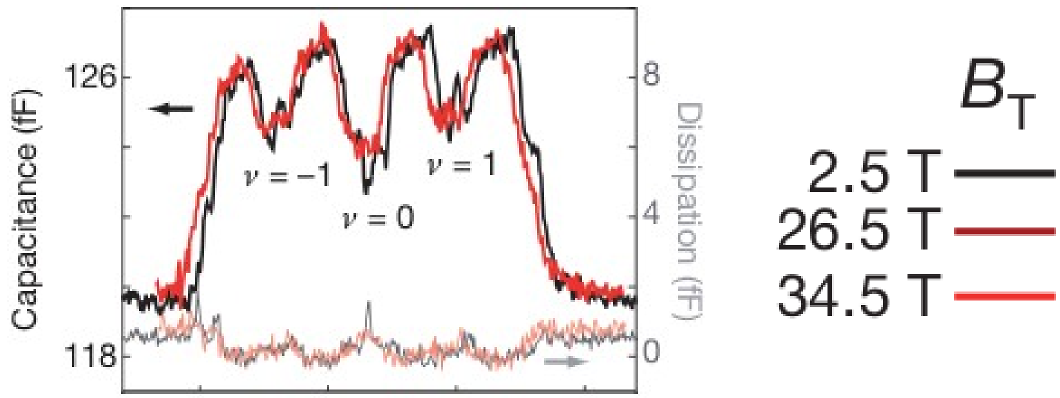
Spin Chern number = 2

Levitov et al, PRL (2006)

Collinear picture fails



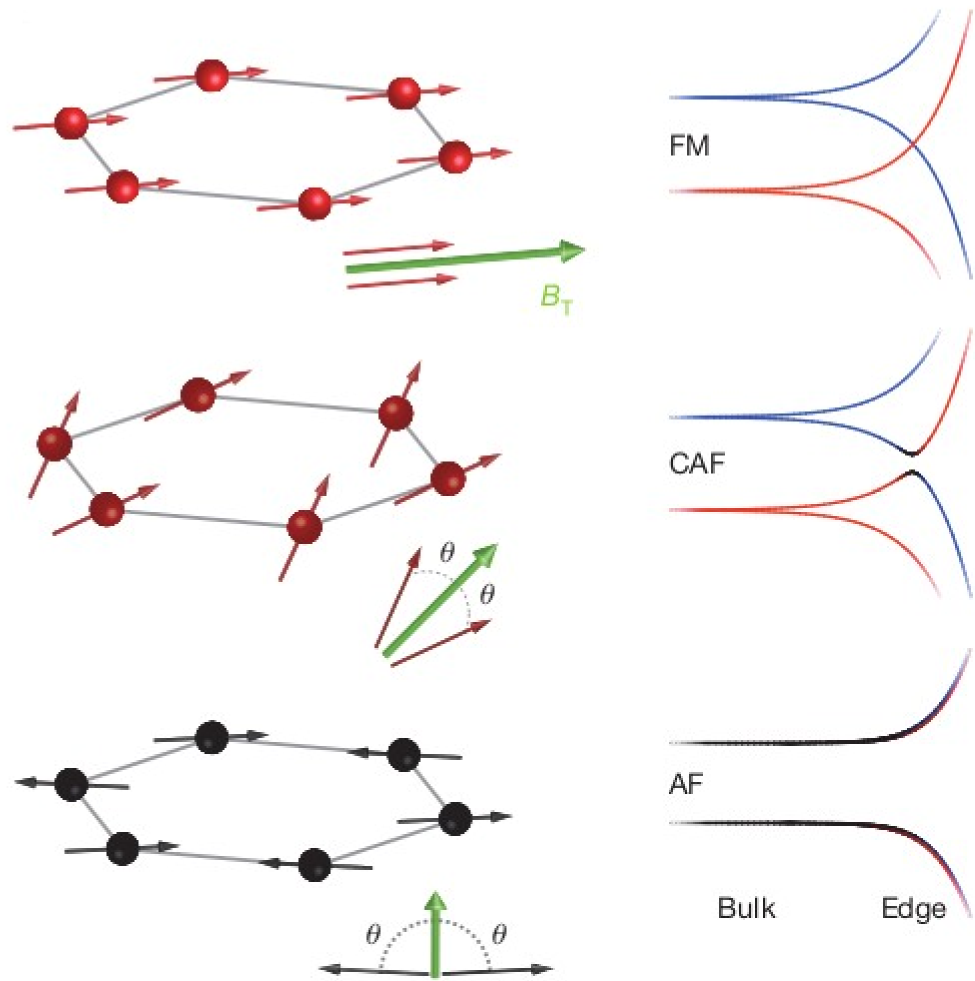
Increasing Zeeman



Bulk gap doesn't close!

A. F. Young et al, Nature (2014)

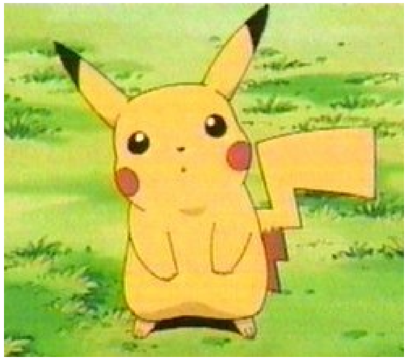
Canted magnetism



A. F. Young et al, Nature (2014)

To explain list

- Transition from G=0 to G=2 at half filling
- Linear scaling of the gap at half filling
- Edge gap closing without bulk gap closing
- G=1 away from half filling
- Not perfectly quantized G=2 spin Hall



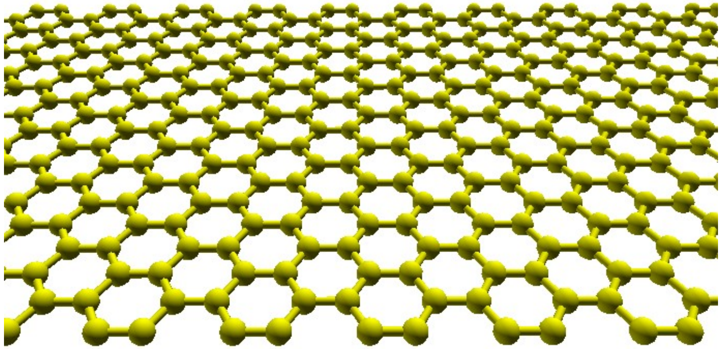
One ~~ring~~ model to rule them all

$$\mathcal{H} = \boxed{\mathcal{H}_0(B_z)} + \boxed{g\mu_B \vec{B}\cdot\vec{S}} + \boxed{U\sum_i n_{i,\uparrow}n_{i,\downarrow}}$$

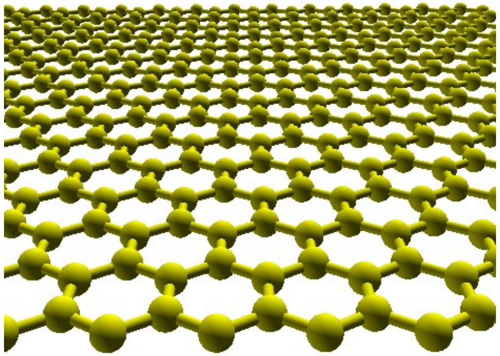
spin Zeeman field

nearest neighbor hopping
(with Peierls phase)

local e-e interaction
(Hubbard like)



ribbon geometry



Solving the model

$$\mathcal{H} = \mathcal{H}_0(B_z) + g\mu_B \vec{B}\cdot\vec{S} + U\sum_i n_{i,\uparrow}n_{i,\downarrow}$$

Mean field antsaz

$$H^{MF} = H_0 + g\mu_B \vec{B}\cdot\vec{S} + H_H + H_F + E_{DC}$$

Collinear (Hartree)

Exchange (Fock)

Double counting

Variational wave function

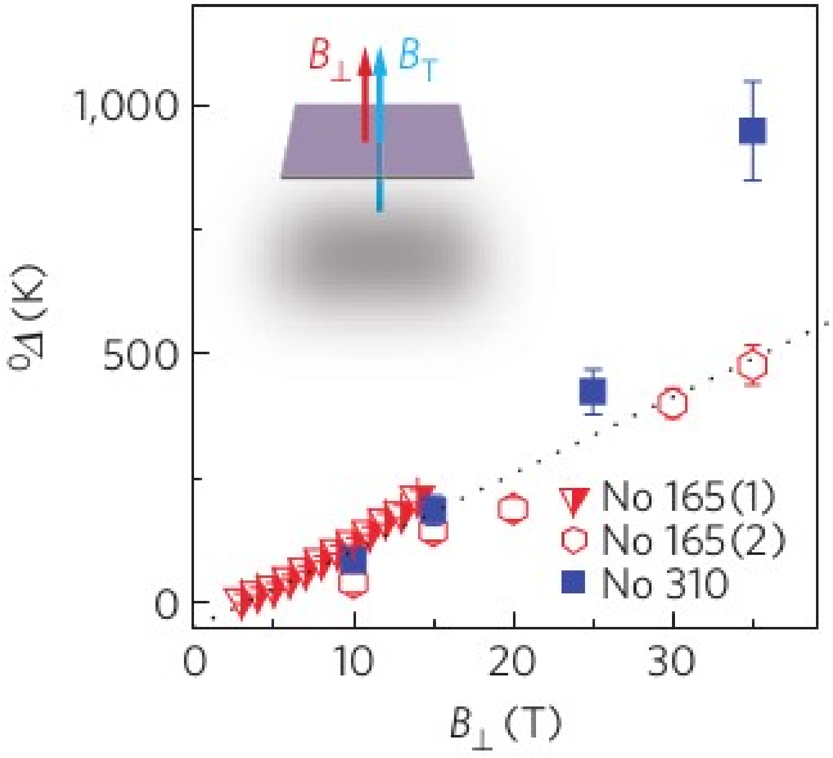
$$|\Omega\rangle = \prod_i \left(u_i c_{i\uparrow}^\dagger + v_i c_{i\downarrow}^\dagger\right)|0\rangle$$

Check list

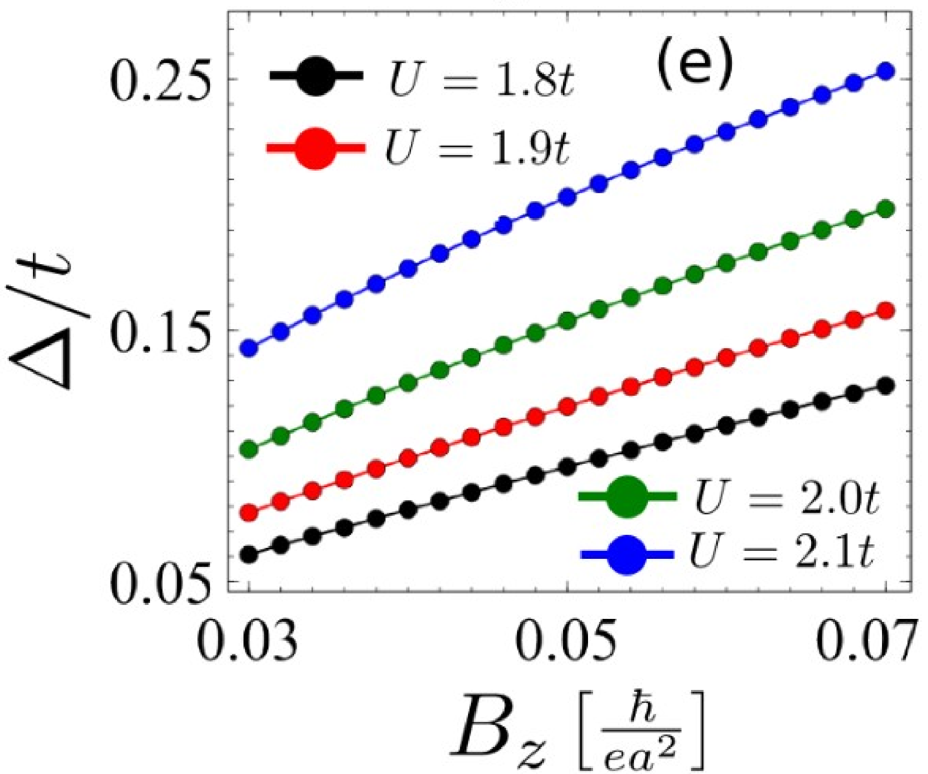
- Linear scaling of the gap at half filling
- Transition from G=0 to G=2 at half filling
- Edge gap closing without bulk gap closing
- G=1 and G=2 away from half filling
- Not perfectly quantized G=2 spin Hall

Gap increases (linearly) with Bz

Experiment

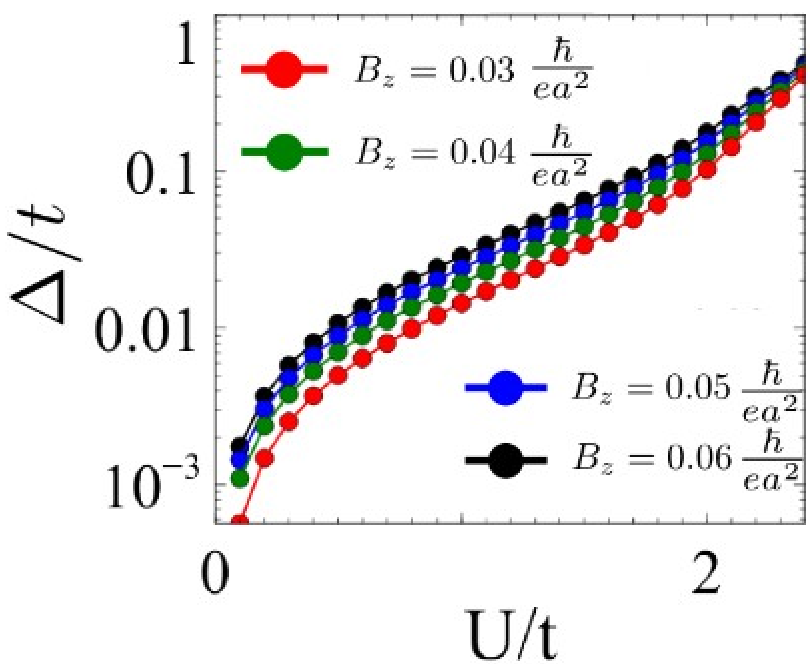


Theory



Gap increases (linearly) with Bz

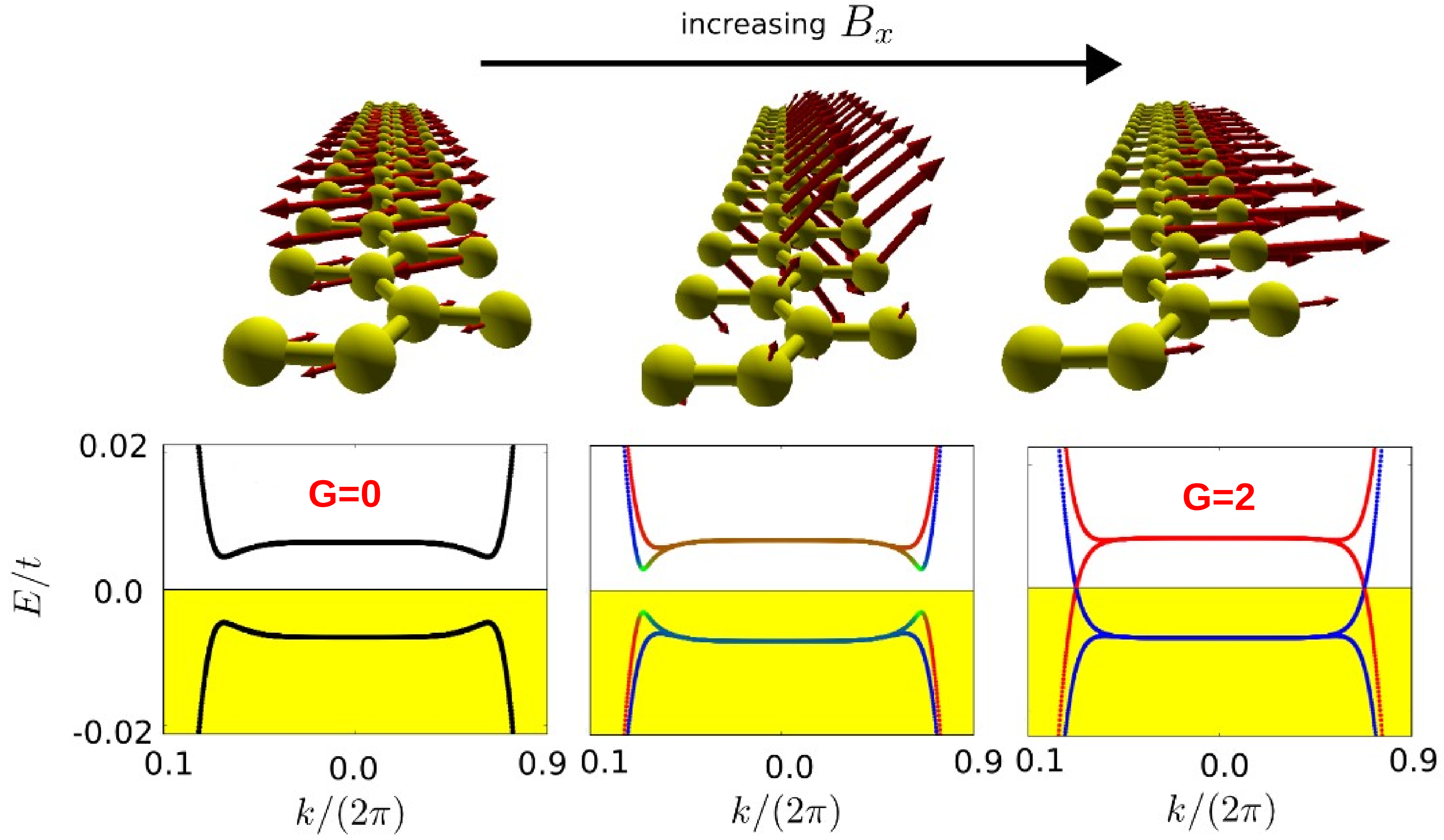
What about its magnitude?



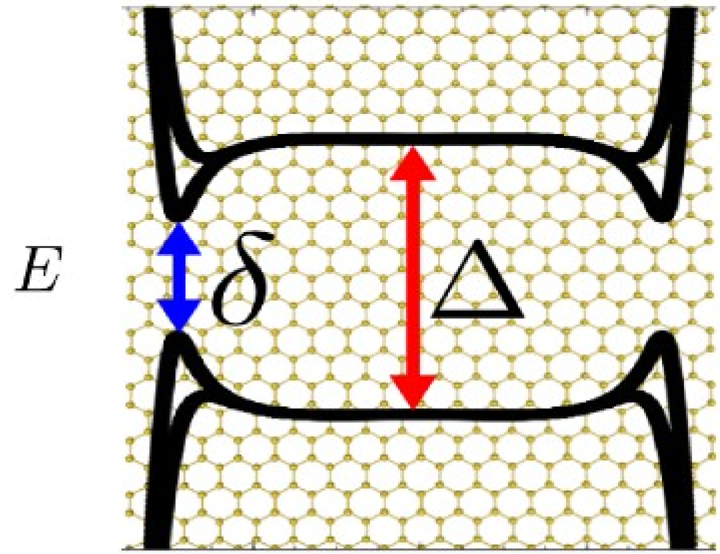
Strongly dependent on U

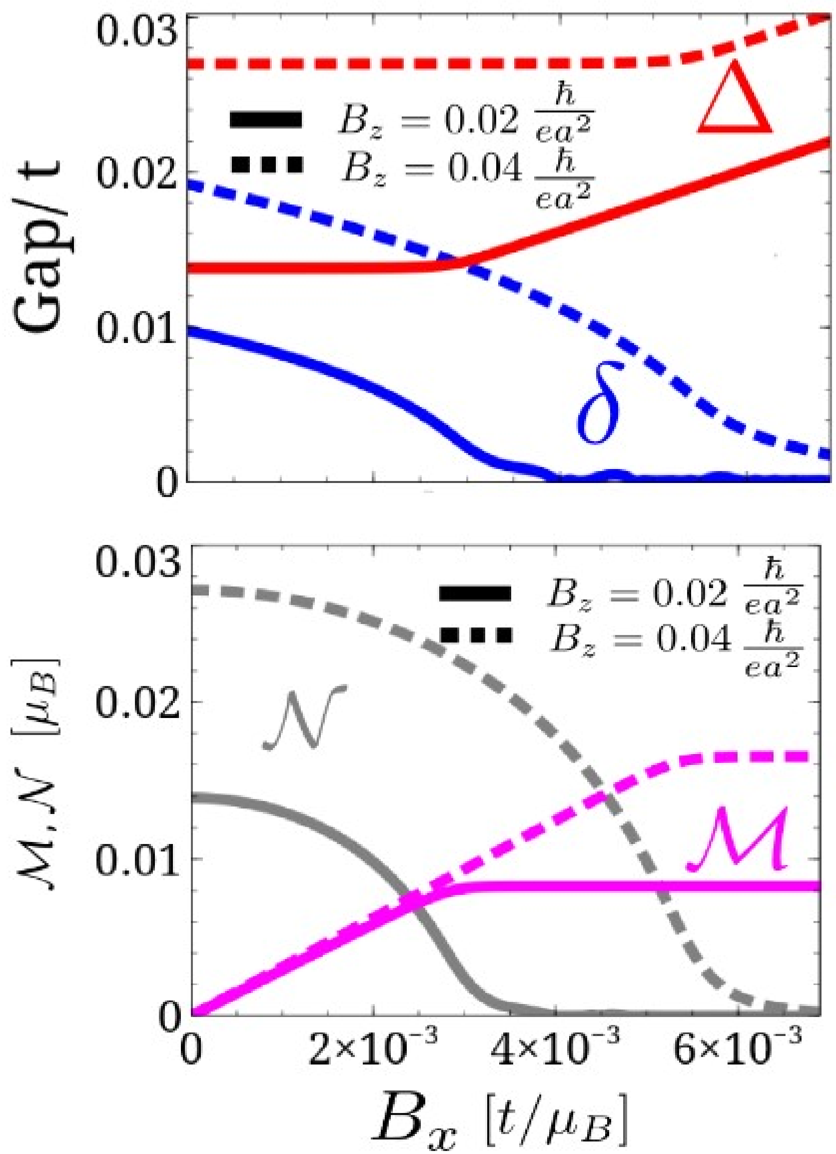
Experiemental gaps would be obtained with U around 6-7 eV

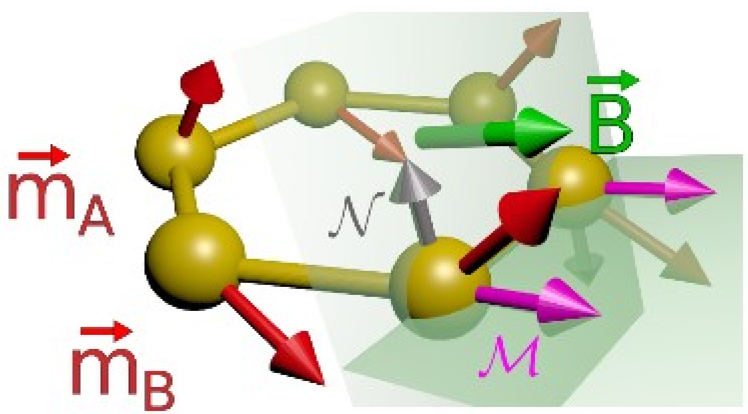
Transition at half filling with Bx



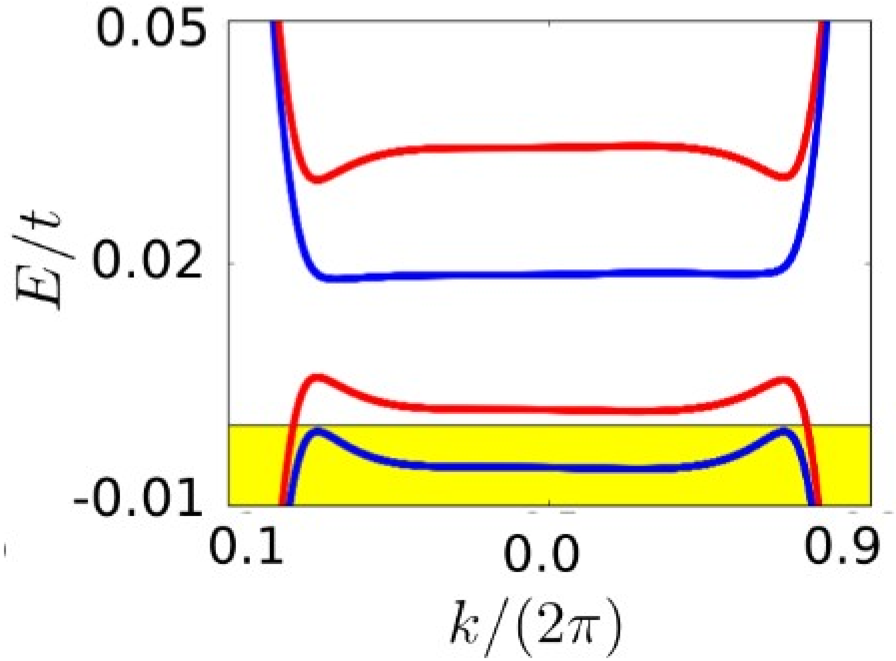
Transition at half filling with Bx

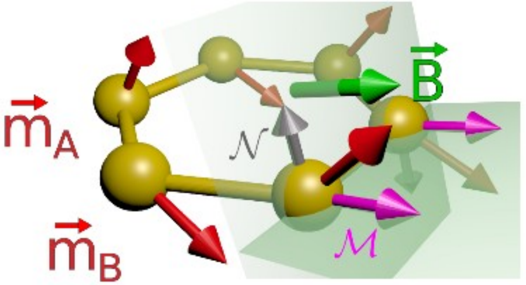


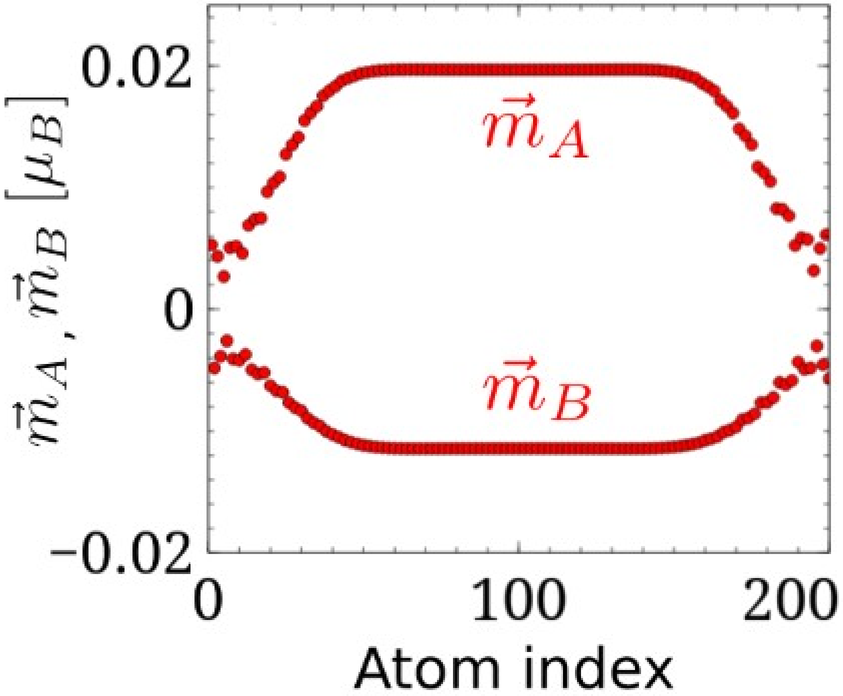




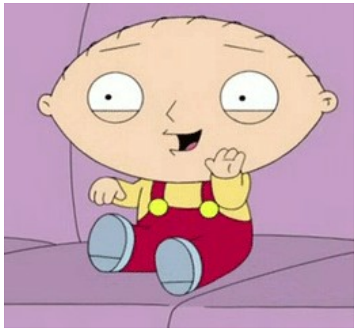
G=1 away from half filling



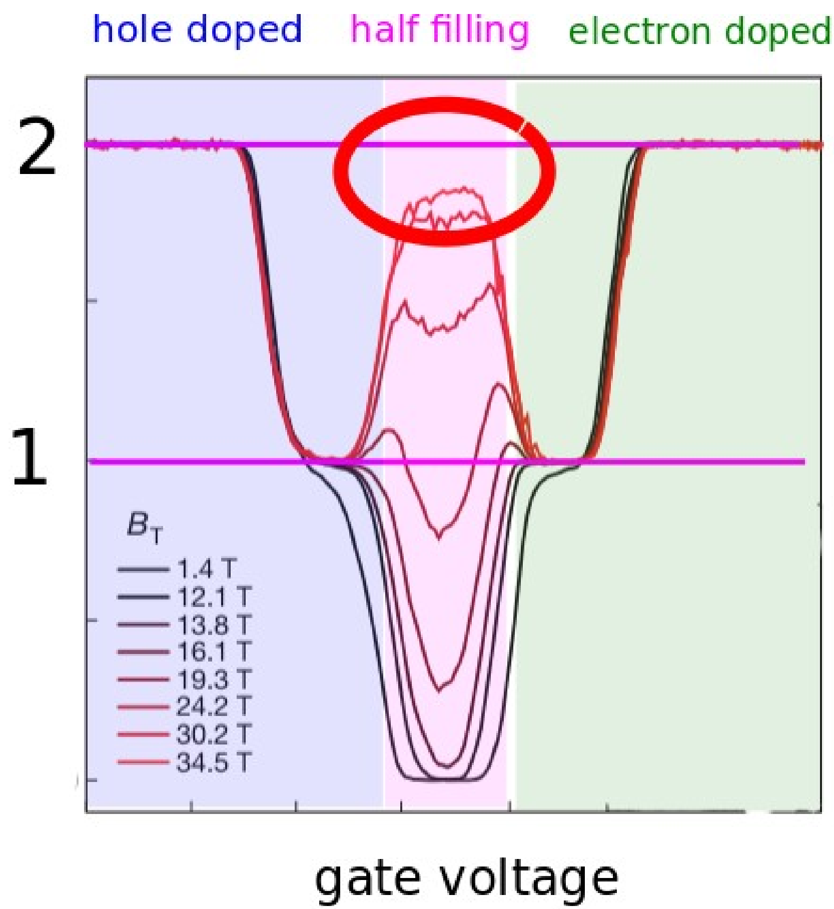




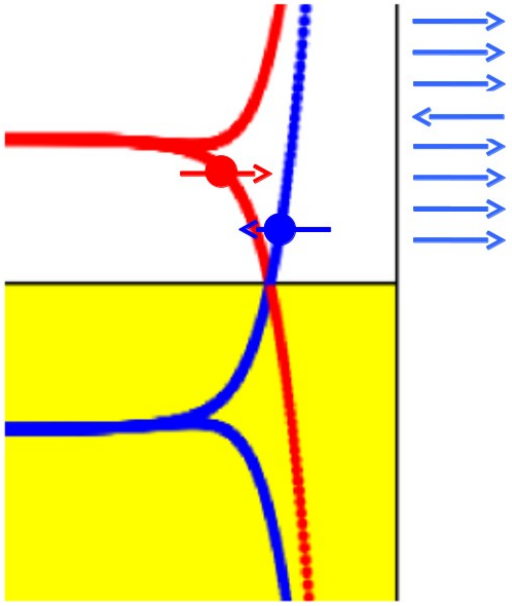
Ferrimagnetic state in graphene



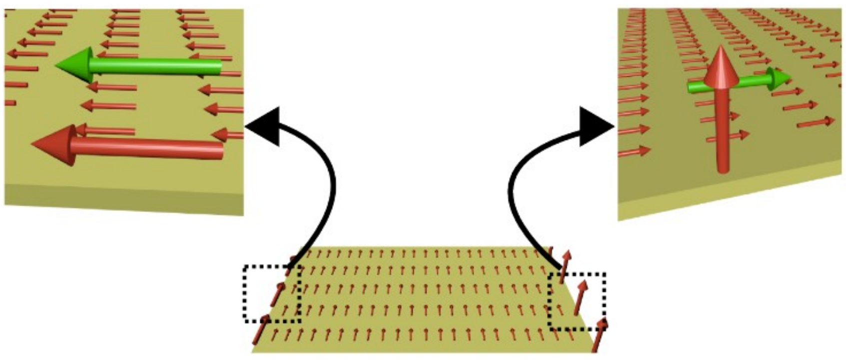
Spin flipping processes

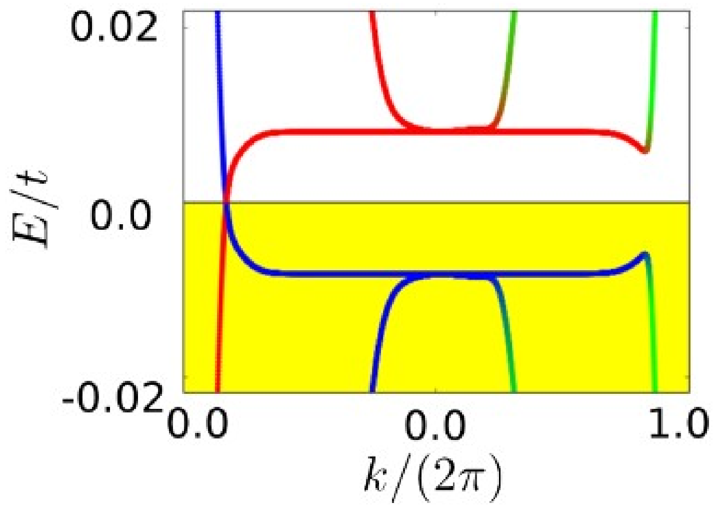


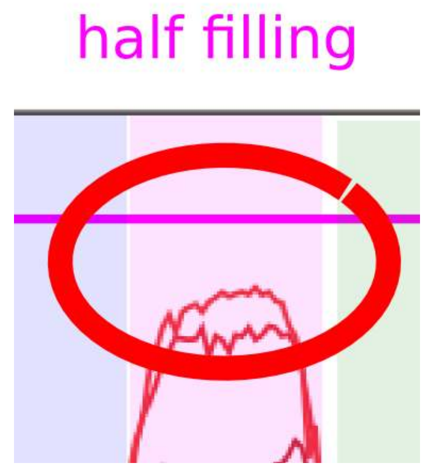
Why is it not perfect?

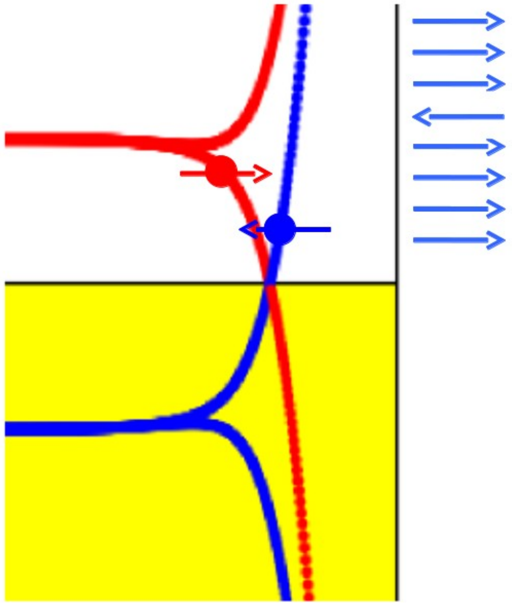


Spin flipping processes









Why it is not perfect?

<u>**Electron-magnon coupling**</u>

Done list

- **Transition from G=0 to G=2 at half filling**
- **Linear scaling of the gap at half filling**
- **Edge gap closing without bulk gap closing**
- **G=1 away from half filling**
- Not perfectly quantized

  G=2 spin Hall

Take home

- All the different integer quantum Hall phases in graphene are captured in one phenomenological model

$$\mathcal{H} = \mathcal{H}_0(B_z) + g\mu_B \vec{B} \cdot \vec{S} + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$

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