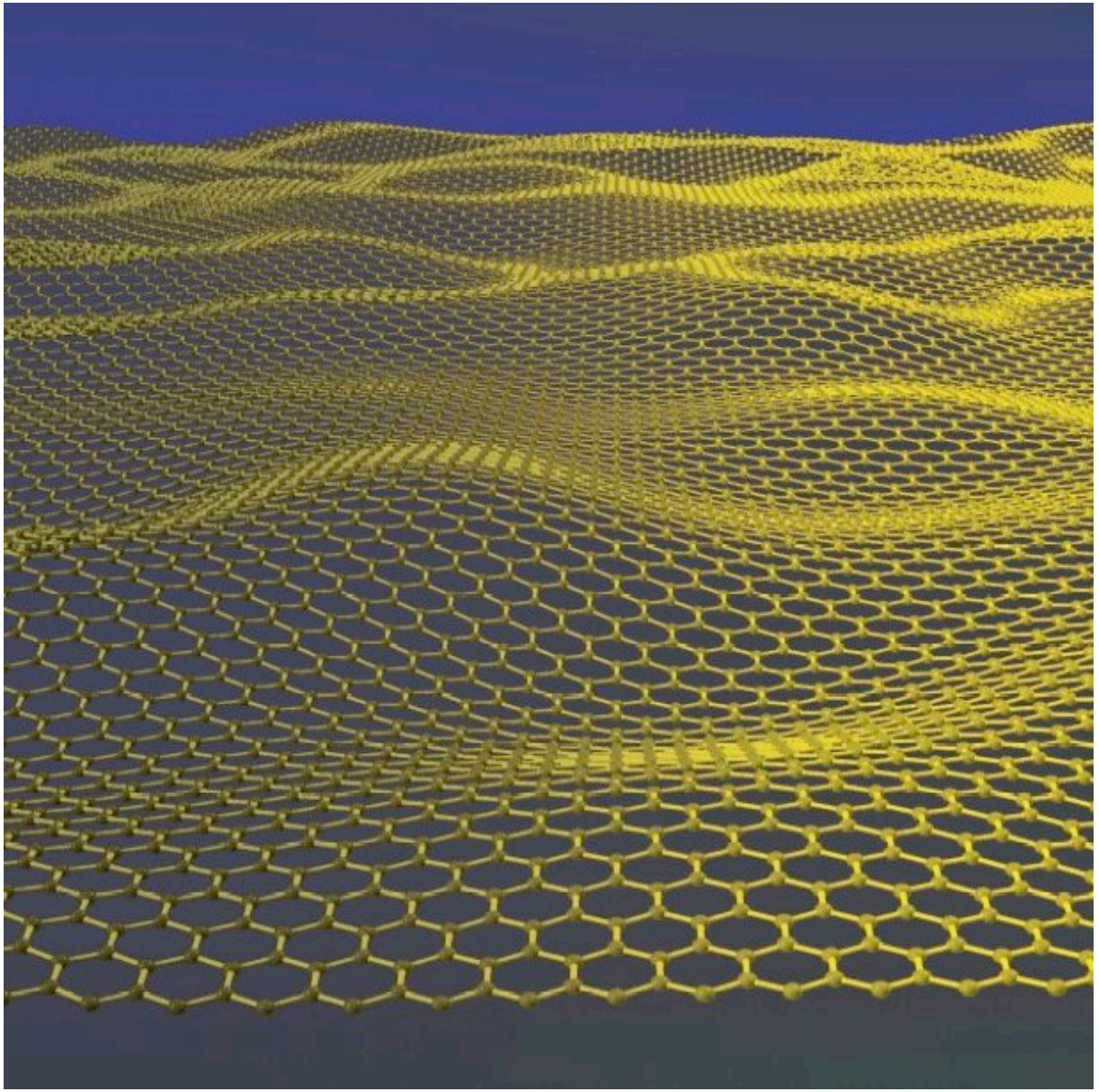
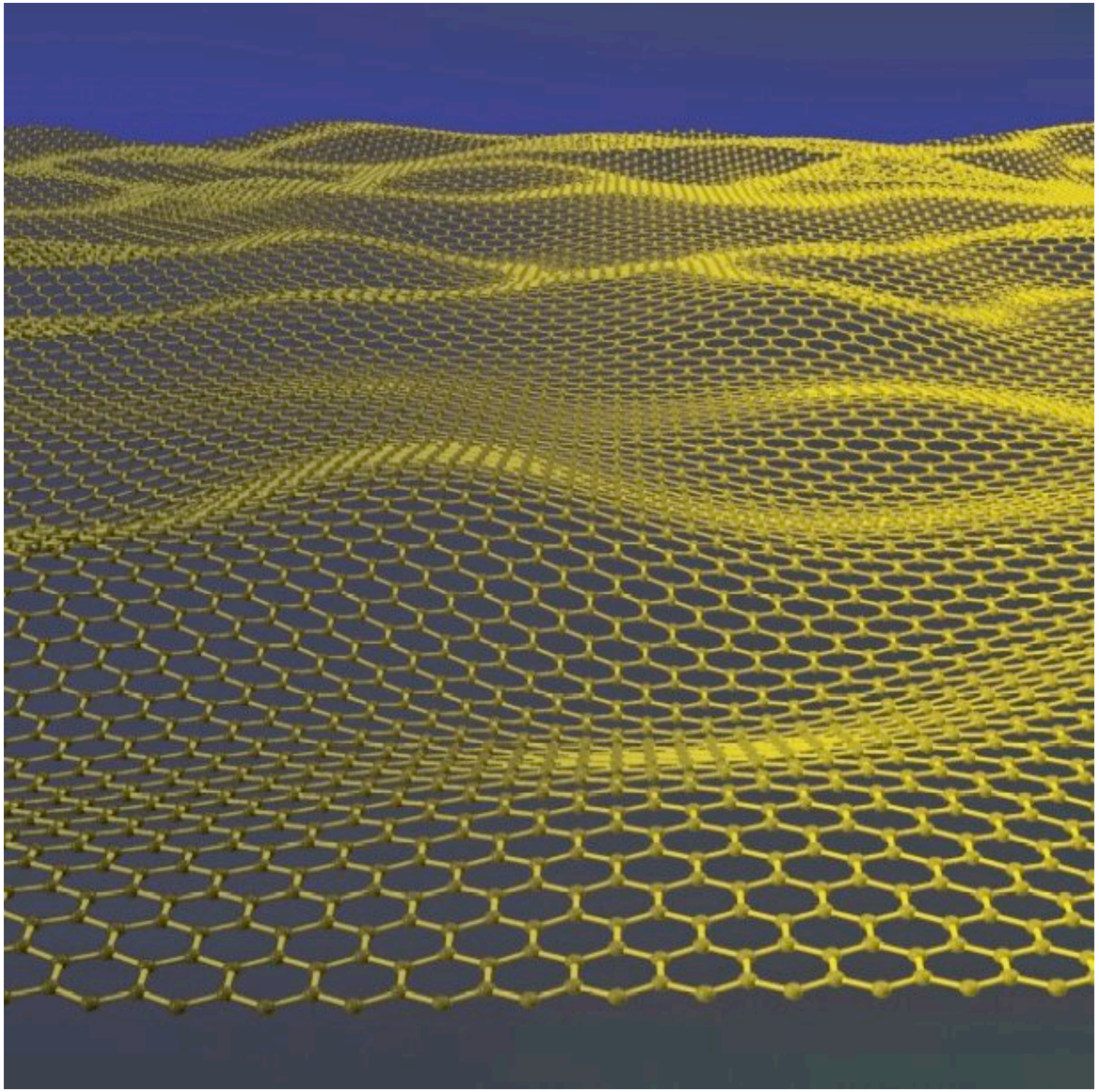
Carbon Flatland



Not your father's 2DEG



Socrates: Shall we set down astronomy among the subjects of study?

Glaucon: I think so, to know something about the seasons, the months and the years is of use for military purposes, as well as for agriculture and for navigation.

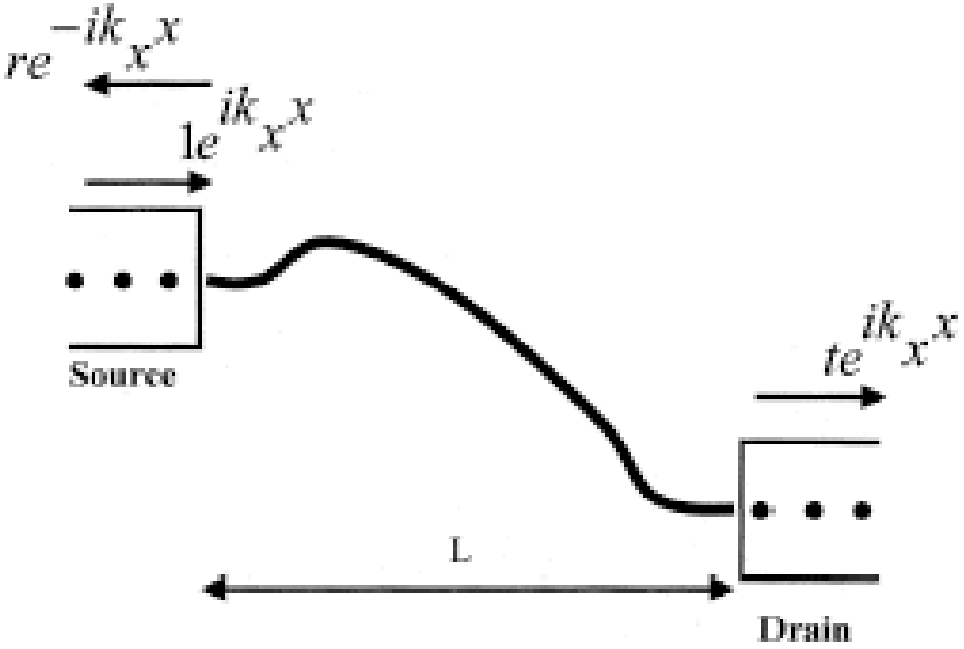
Socrates: It amuses me to see how afraid you are, lest the people should accuse you of recommending useless studies.

Socrates

Glaucon

Semiconductor Roadmap

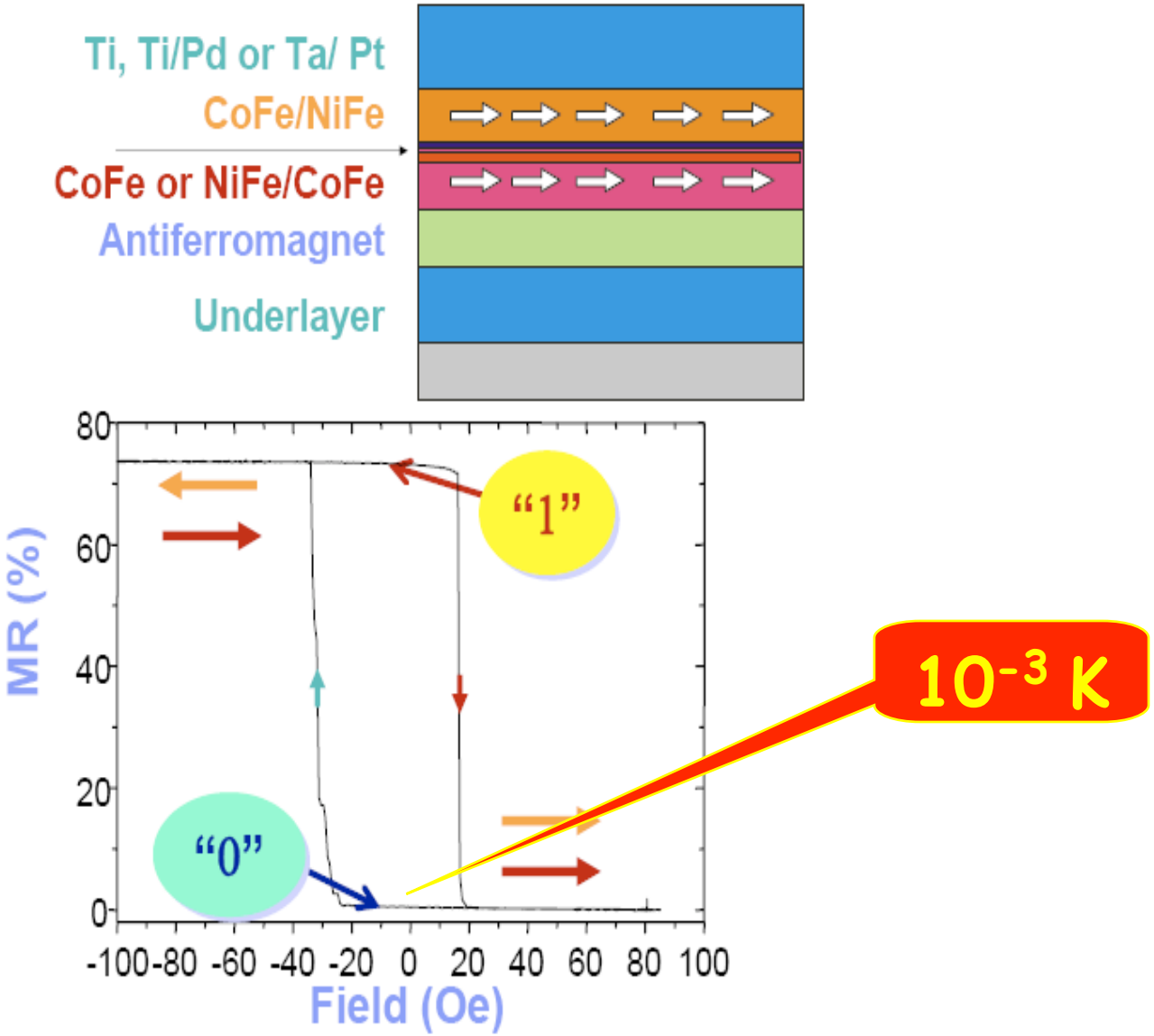
The Collective FET vision



$I \sim I_{sat} (1 - \exp(-eV/k_B T))$

$eV/k_B T >$ about 10

The Collective FET vision



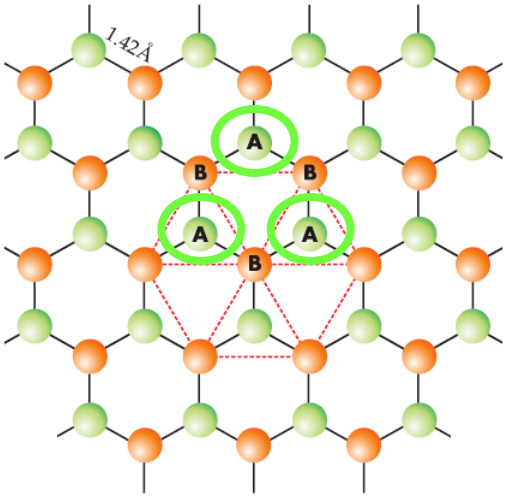
Pseudospins & Chirality

Bilayer Pseudospin Ferromagnetism

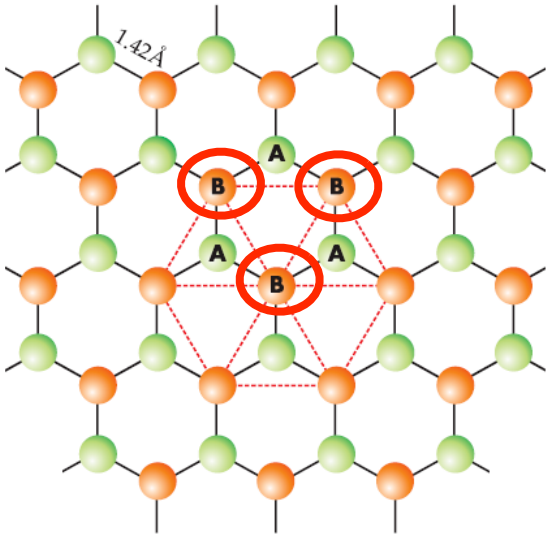
Bilayer Quantum Hall Effect

Chirality in Multilayers

Pseudospins - Graphene

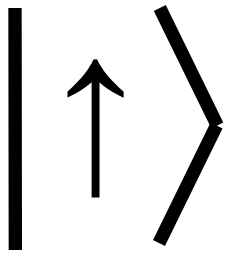


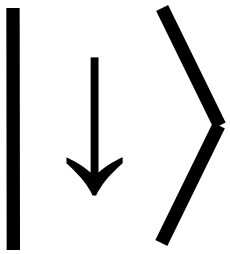
$|A\rangle$



$|B\rangle$

Electron Spins

 spin-up

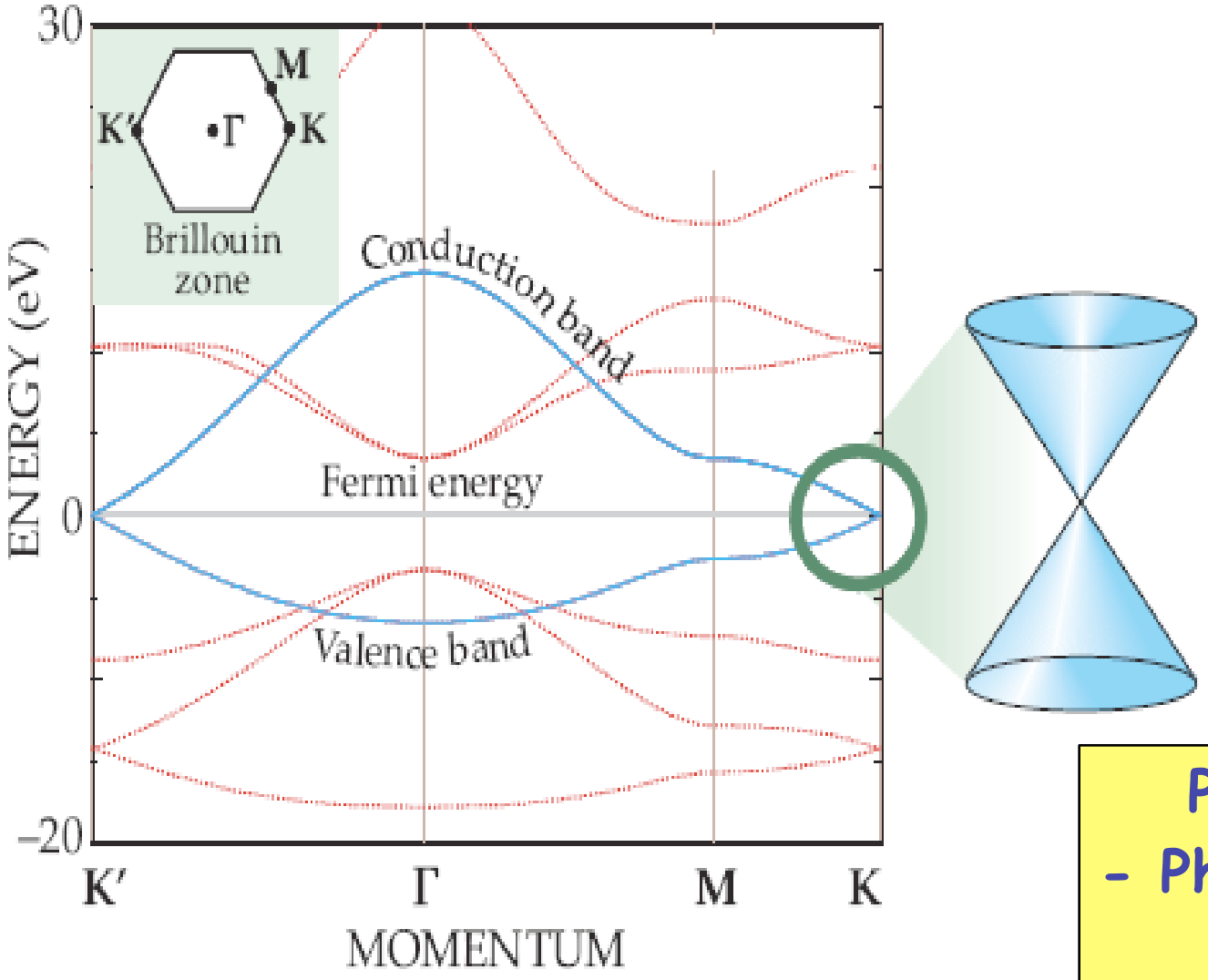
 spin-down

Zeeman doublet

`two-valued quantum degree of freedom'

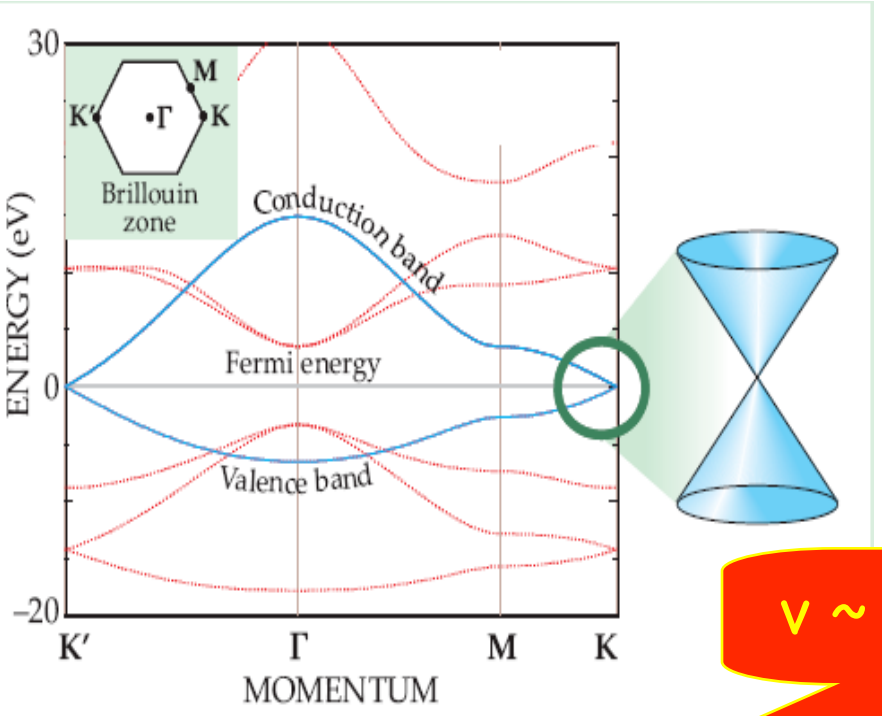
… Compton, Pauli, Goudsmit, Uhlenbech …

flatland band structure



Phil Wallace
- Physical Review -
1947

2D Massless Dirac Equation



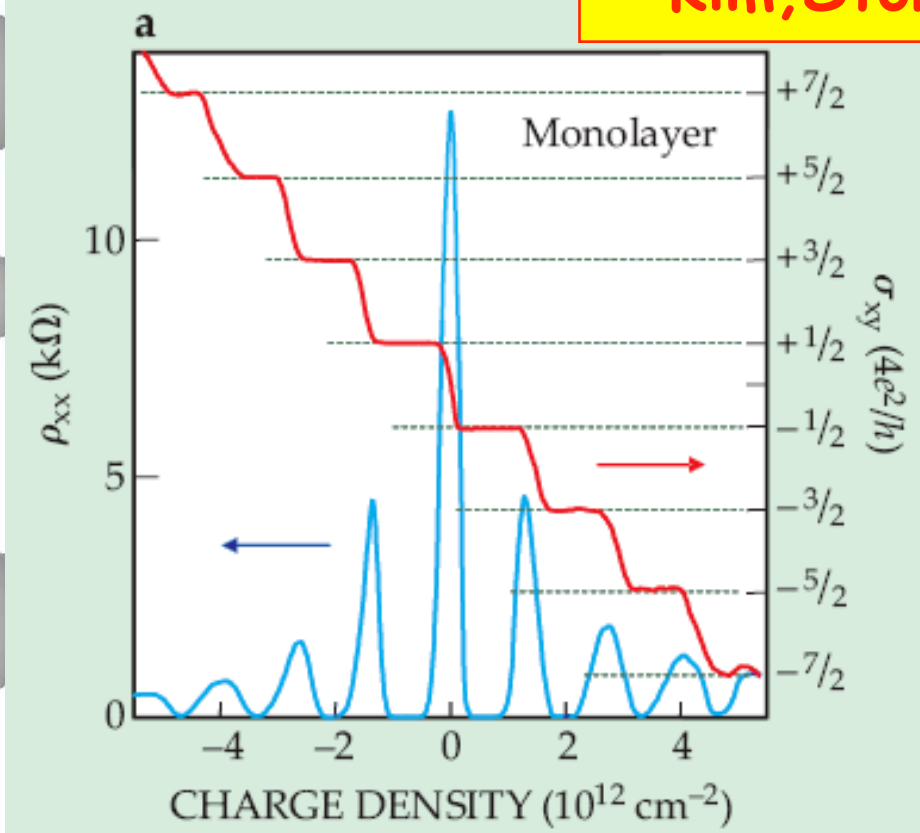
$v \sim 100\text{nm}/(10^{-13}\ \text{s})$

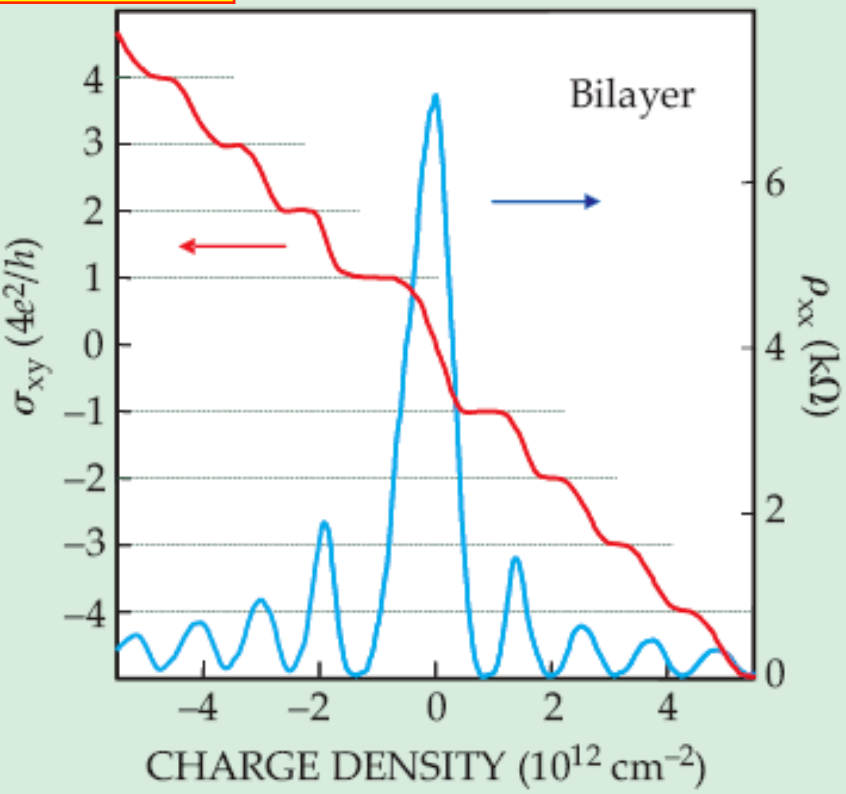
$$H = -v\hbar\mathbf{k}\cdot\boldsymbol{\tau}$$

Andrey Geim and AHM – Physics Today – August 2007

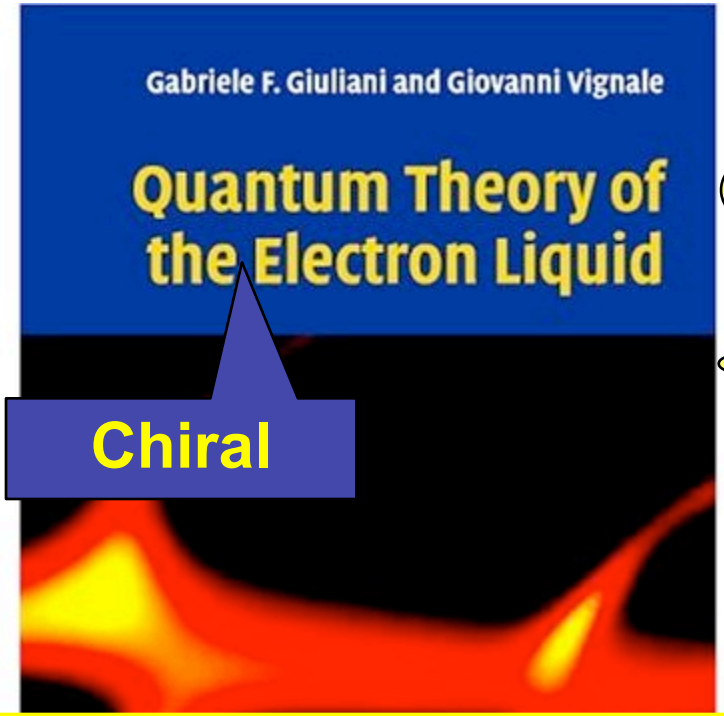
Graphene Quantum Hall Effect

Geim, Novoselov …
Kim,Stormer …





Electron Gas Theory



New and improved

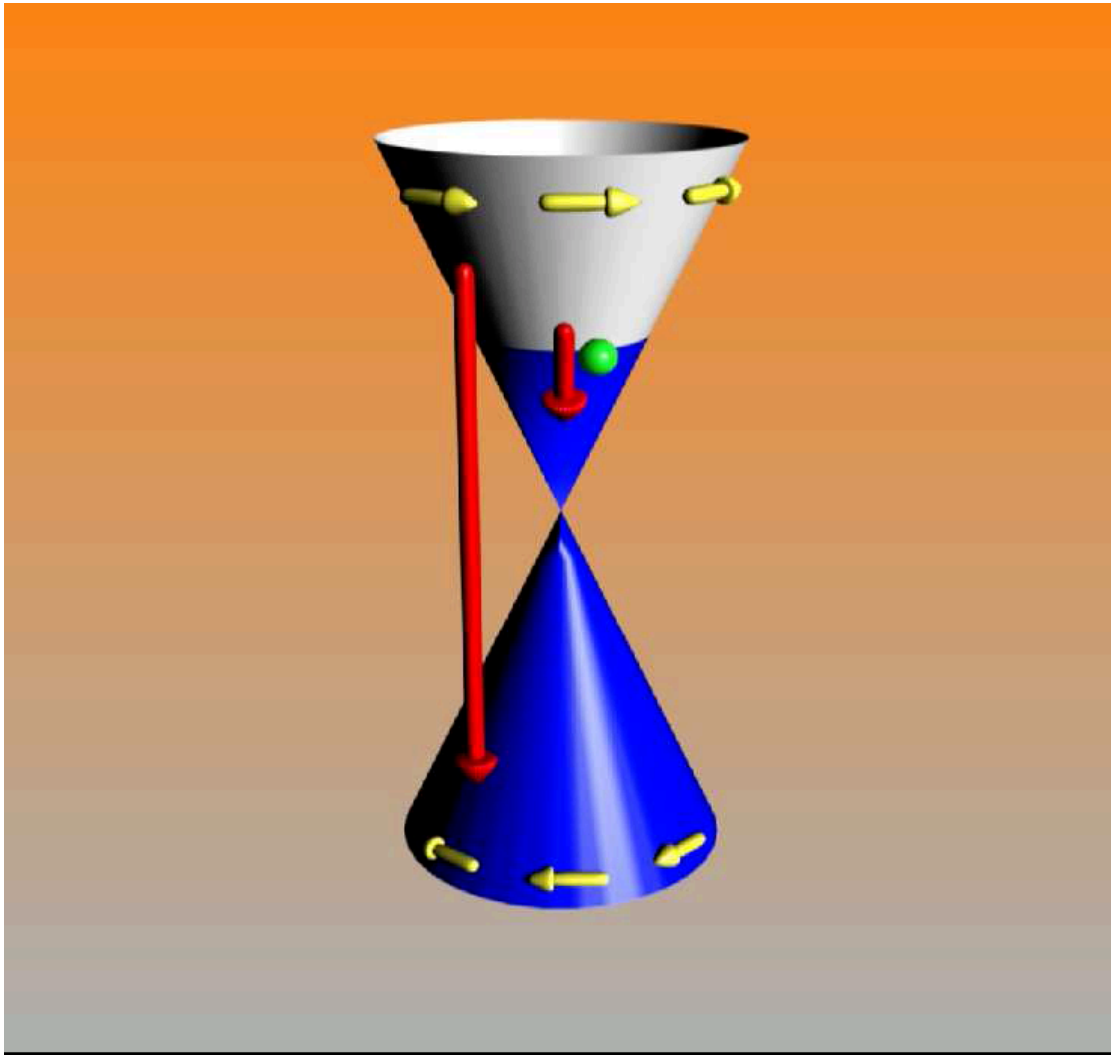
$$k^2 \rightarrow \sigma_x k_x + \sigma_y k_y$$

Electron-Electron Interactions

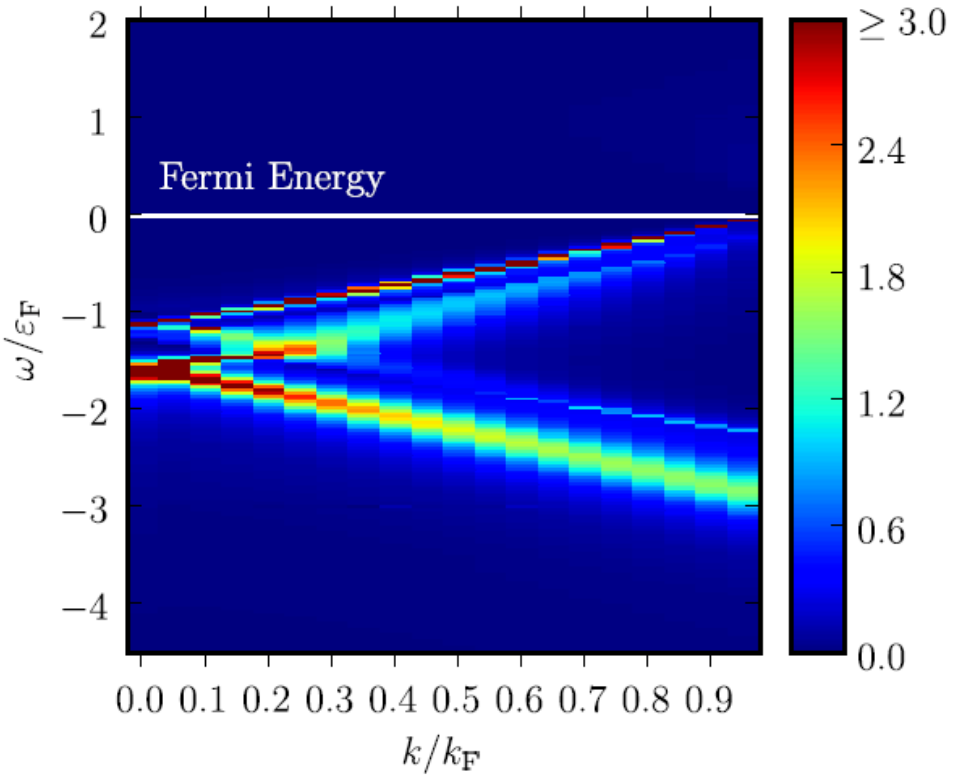
$$\alpha = e^2/\hbar c \approx 1/137$$

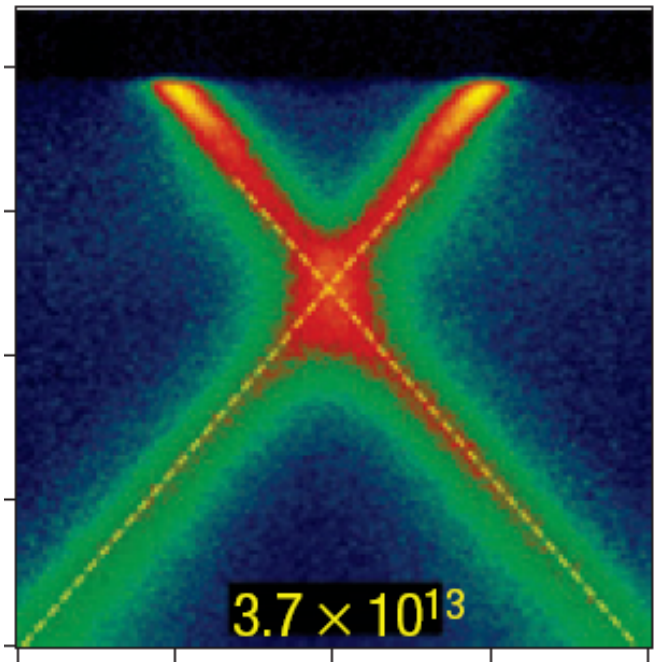
$$\alpha_{gr} = e^2/\epsilon\hbar v \approx 2$$

Chiral 2DES



ARPES





Theory
(Polini)

Experiment
(Rotenberg)

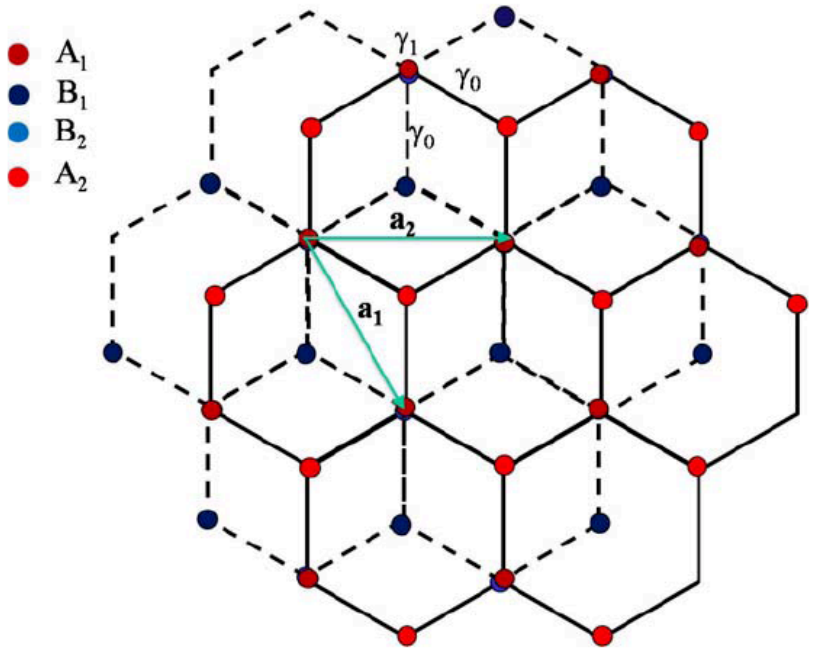
Pseudospins & Chirality

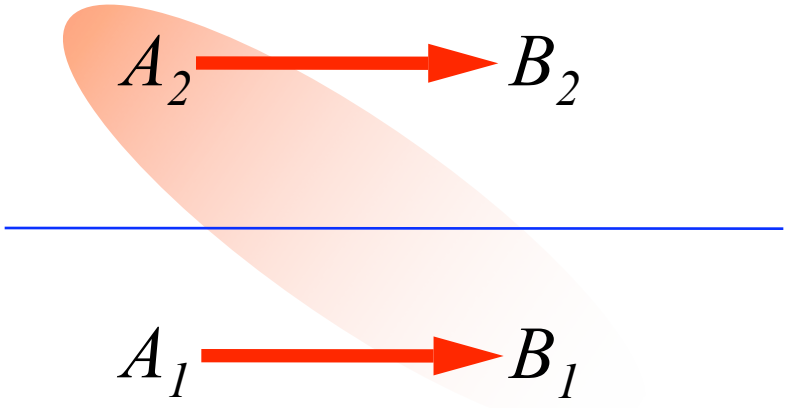
Bilayer Pseudospin Ferromagnetism

Bilayer Quantum Hall Effect

Chirality in Multilayers

Bilayer AB stacking

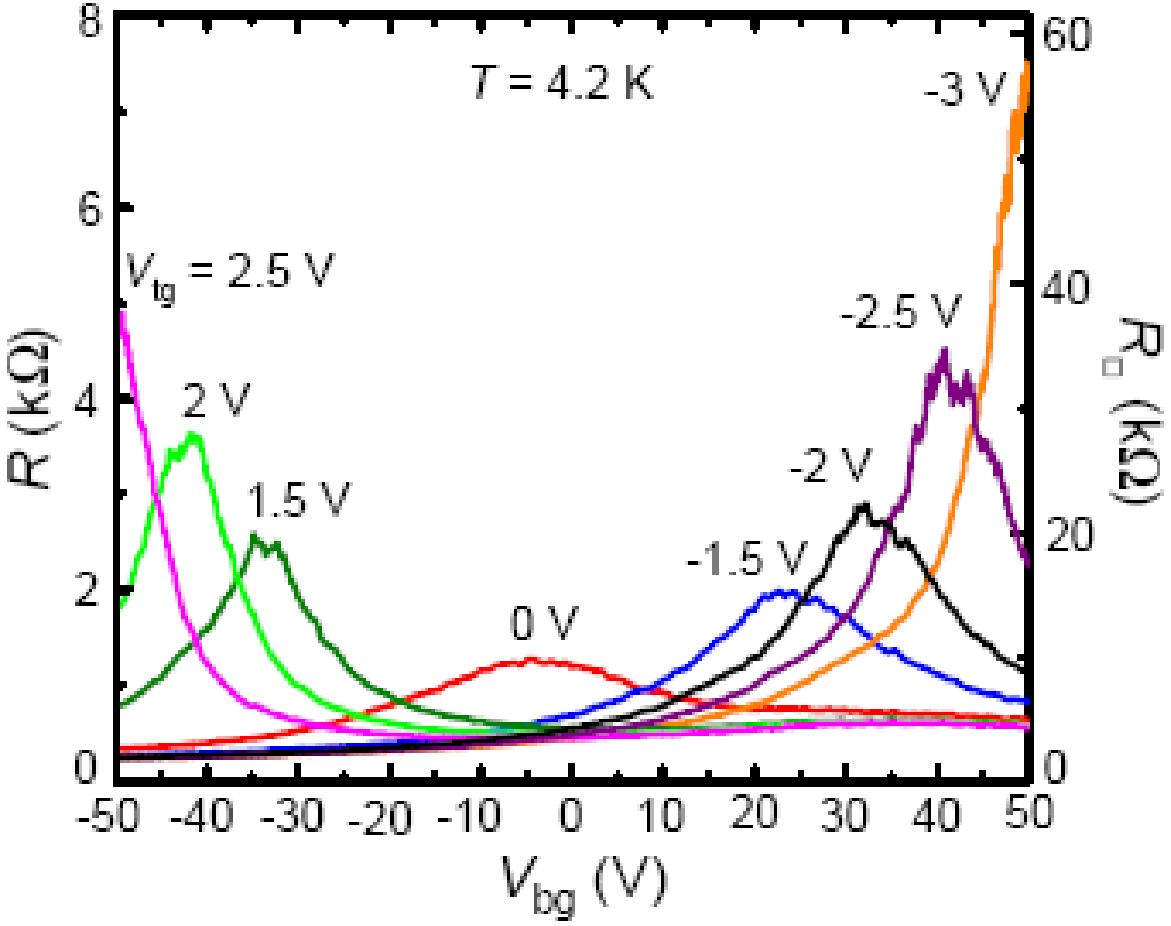




π = π_x+iπ_y
=perturbation

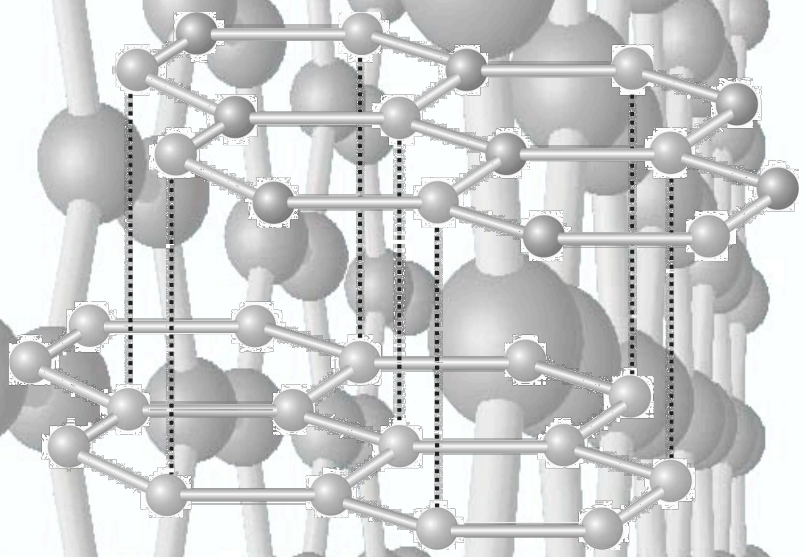
$$\mathcal{H}_{MD}(\boldsymbol{k}) = -\begin{pmatrix} 0 & v\pi^\dagger \\ v\pi & 0 \end{pmatrix} \begin{matrix} |A\rangle \\ |B\rangle \end{matrix}$$

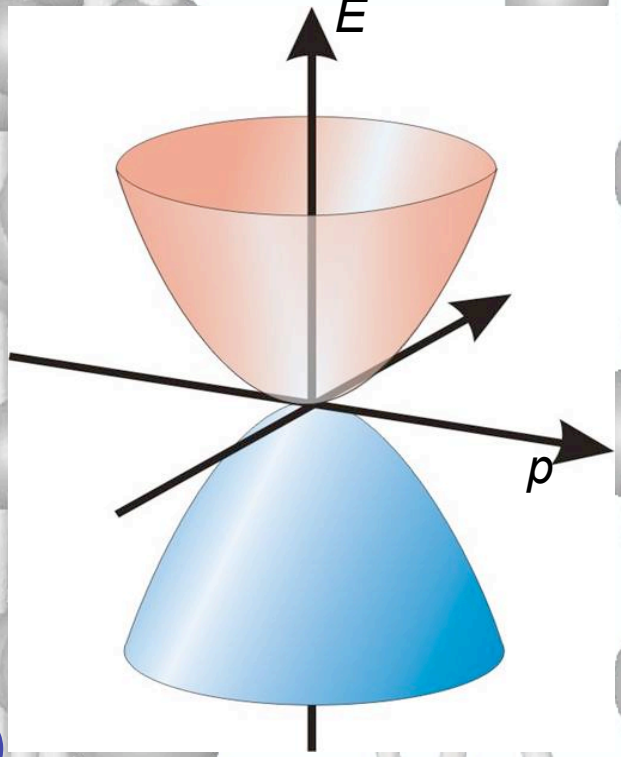
Bilayer Gaps

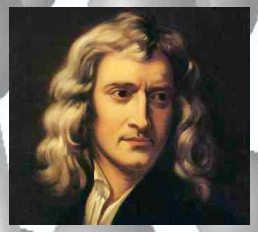


Vandersypen Delft

BILAYER GRAPHENE







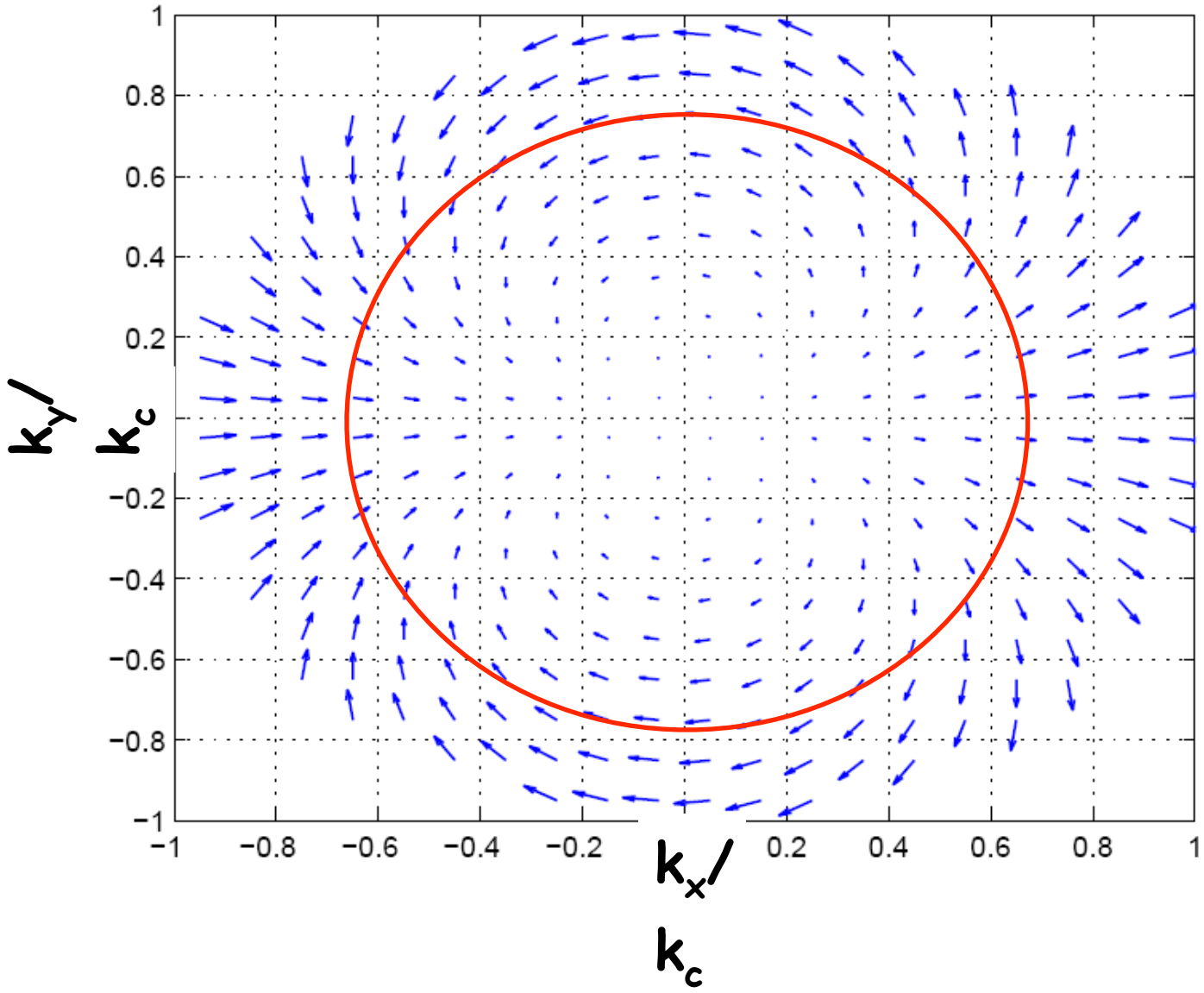
McGann & Falko PRL **96** (2006)

Novoselov et al. Nature Phys **2**, (2006)

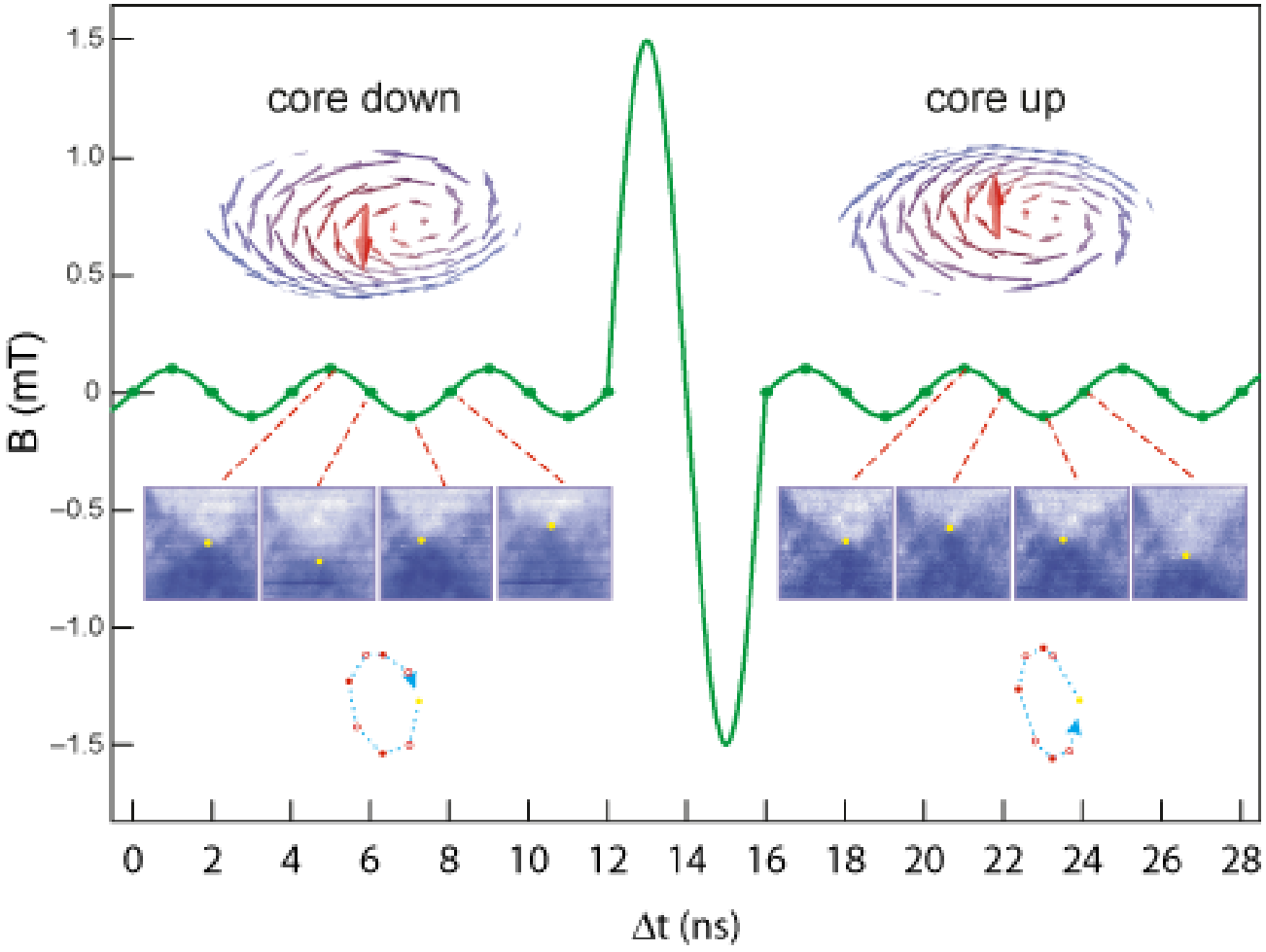
$$\vec{B}_{\text{band}}(\vec{k}) = \frac{\hbar^2 k^2}{2m^*}\left(\cos(2\phi_{\vec{k}}), \sin(2\phi_{\vec{k}}), 0\right)$$


no hands!
CAUTION!
Theorist
at
work

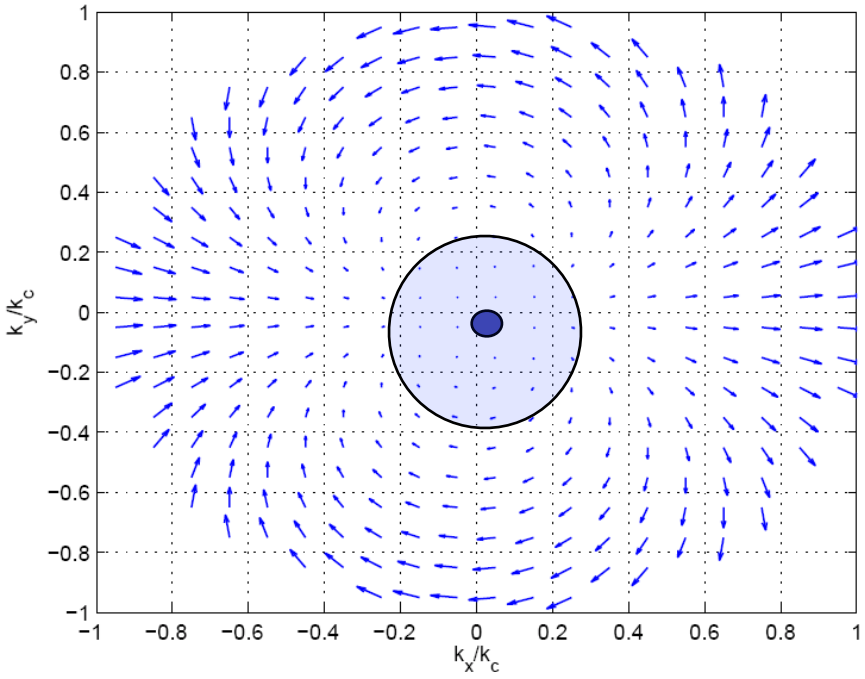
bilayer k-space vortex



Magnetic Vortex

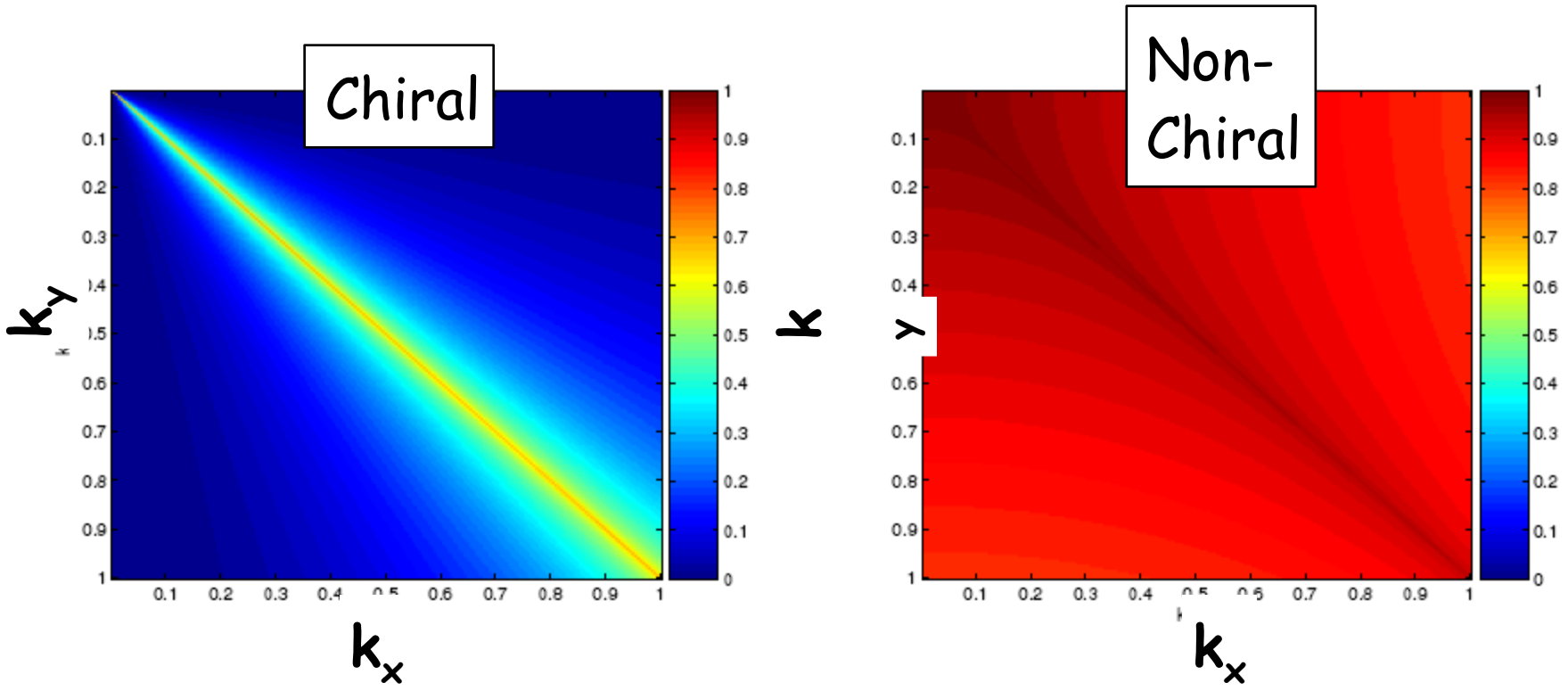


Pseudospin Exchange Fields



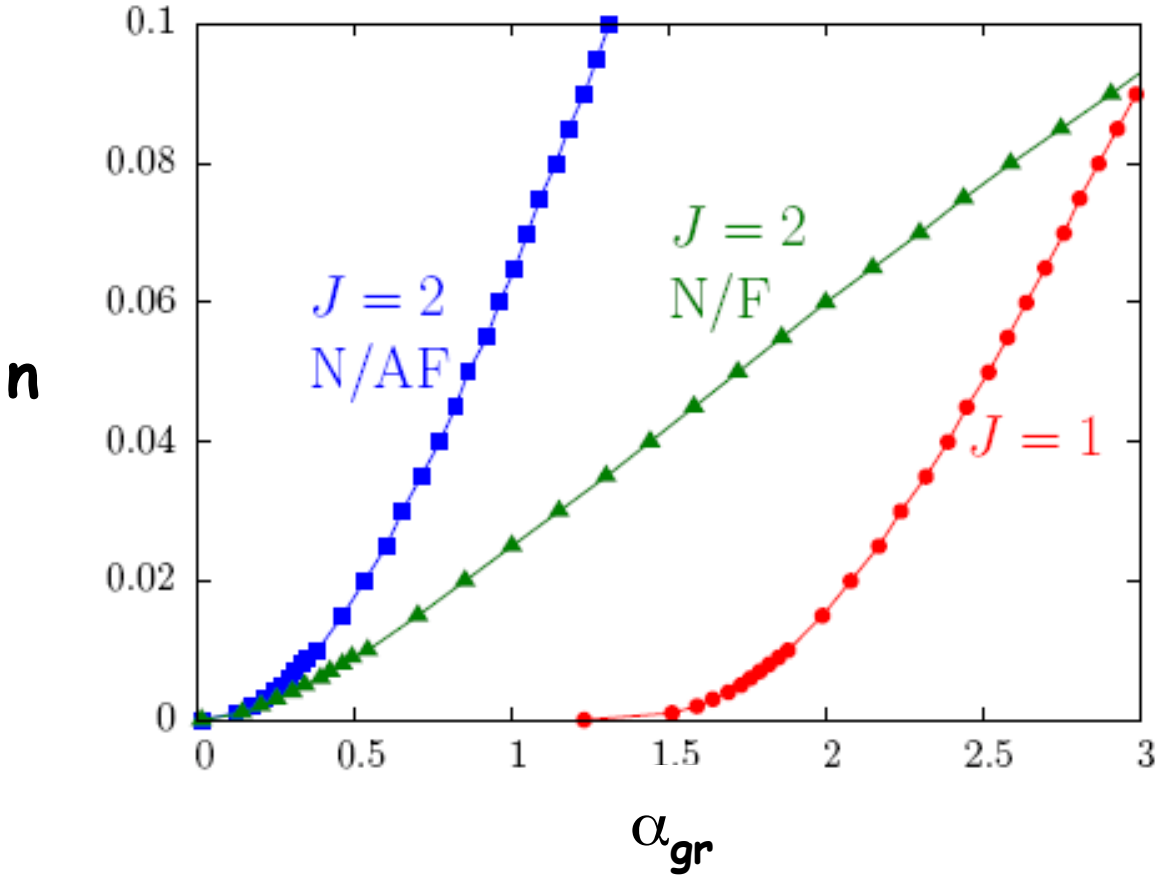
$$\vec{B}_{\mathrm{x}}(\vec{k}) = \frac{1}{2A} \sum_{\vec{k}'} V(\vec{k} - \vec{k}')\ \hat{n}(\vec{k}')$$

Σ_{xy}/Σ_z - Bilayer



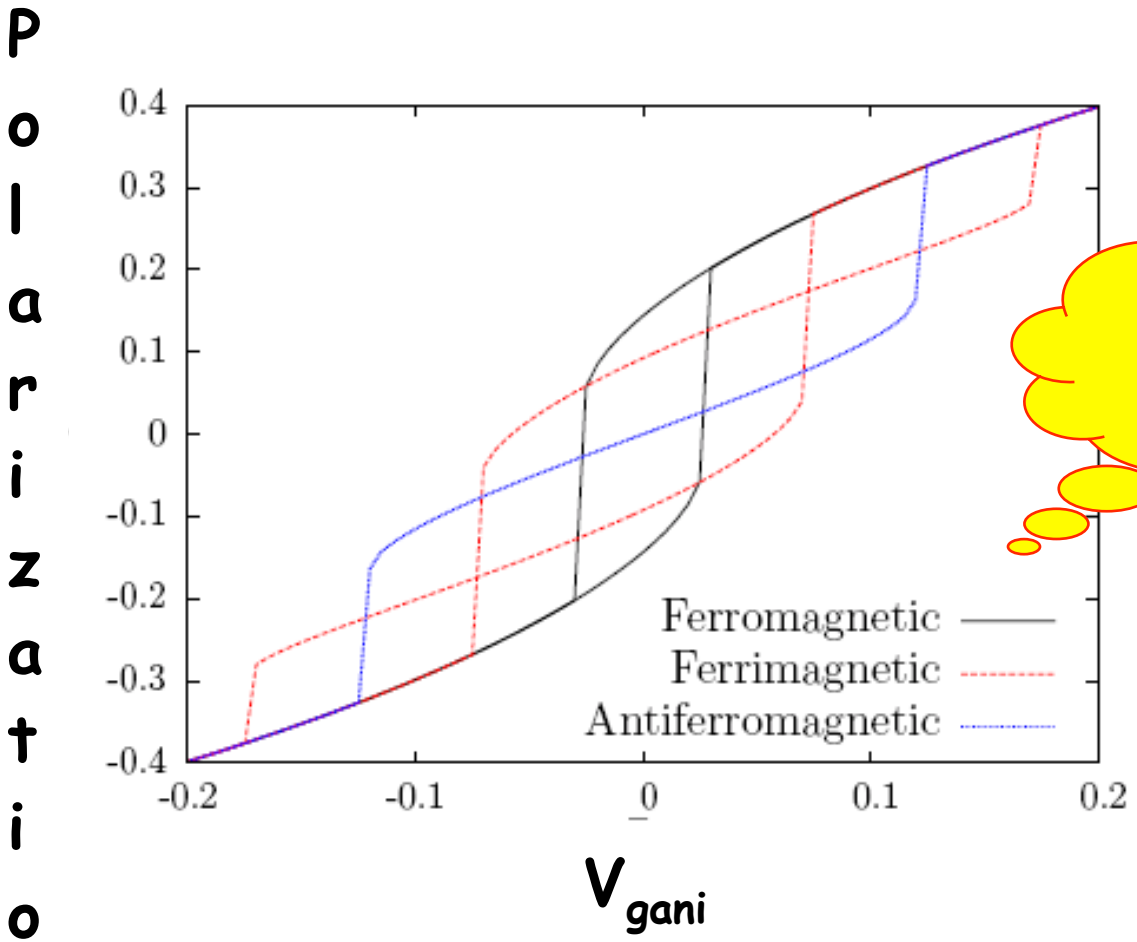
$$\left[\vec{B}_{\mathrm{band}}(\vec{k}) + \vec{B}_{\mathrm{x}}(\vec{k})\right] \times \hat{n}(\vec{k}) = 0$$

Phase Diagram



Min, Polini, Borghi, AHM – cond-mat/0707

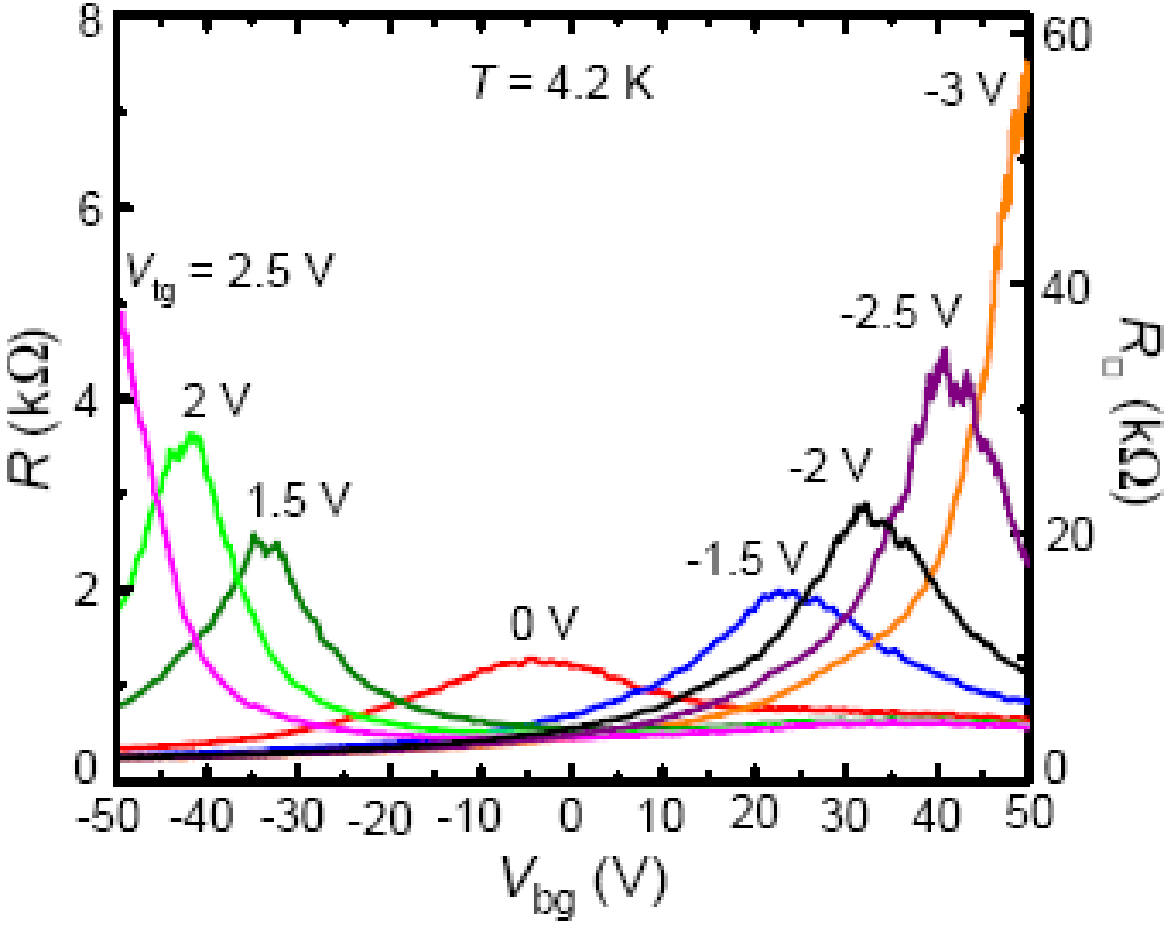
Gate Hysterisis



Collective FET?

Min, Polini, Borghi, AHM – cond-mat/0707

What about Lieven?



Vandersypen Delft

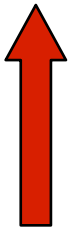
Pseudospins & Chirality

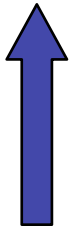
Bilayer Pseudospin Ferromagnetism

Bilayer Quantum Hall Effect

Chirality in Multilayers

N=4 Quantum Hall Ferromagnets

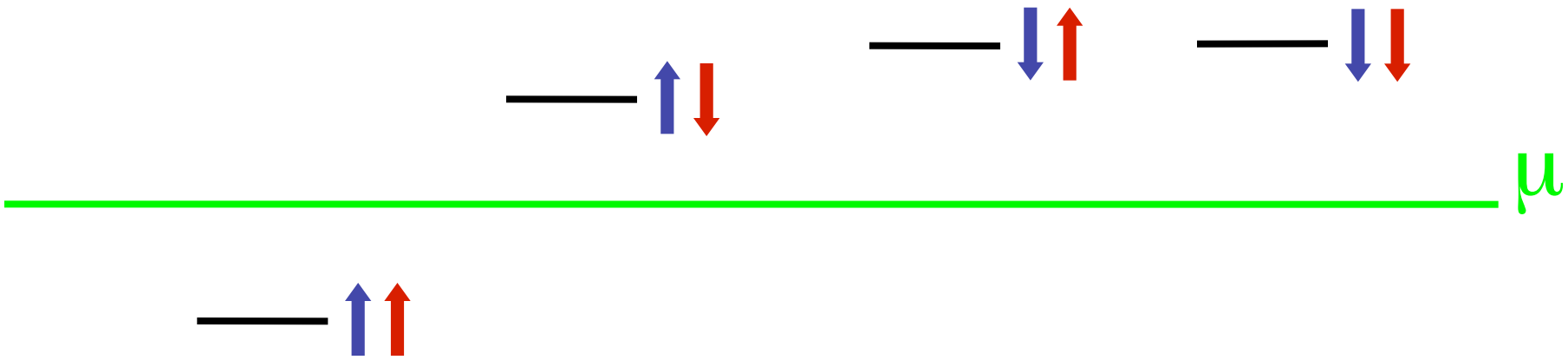
 = valley

 = spin

$$\mathcal{H}_{MD}(\boldsymbol{k}) = -\begin{pmatrix} 0 & v\pi^\dagger \\ v\pi & 0 \end{pmatrix} \begin{matrix} |A\rangle \\ |B\rangle \end{matrix}$$

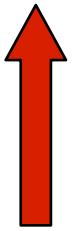
Levitov, Lee, Nomura, Alicea, Fisher, Balents, Sheng, Haldane
Columbia & Manchester

$\nu = -1$

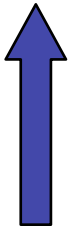


ν =

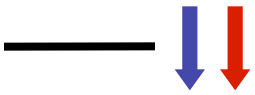
0



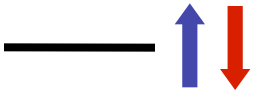
= valley



= spin



μ

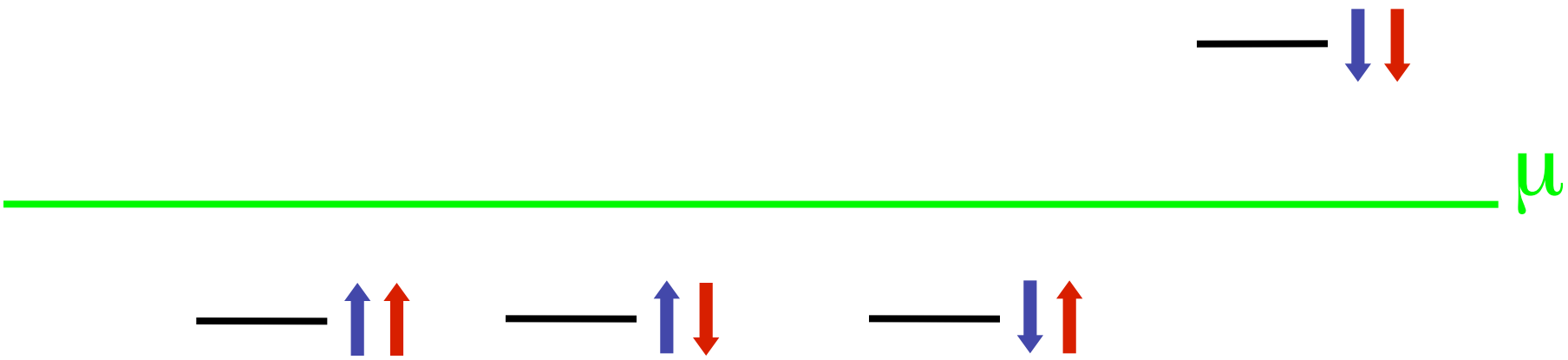


ν =

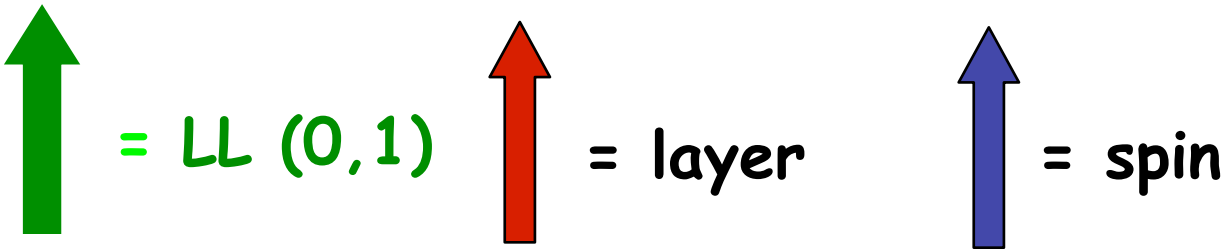
1

= valley

= spin



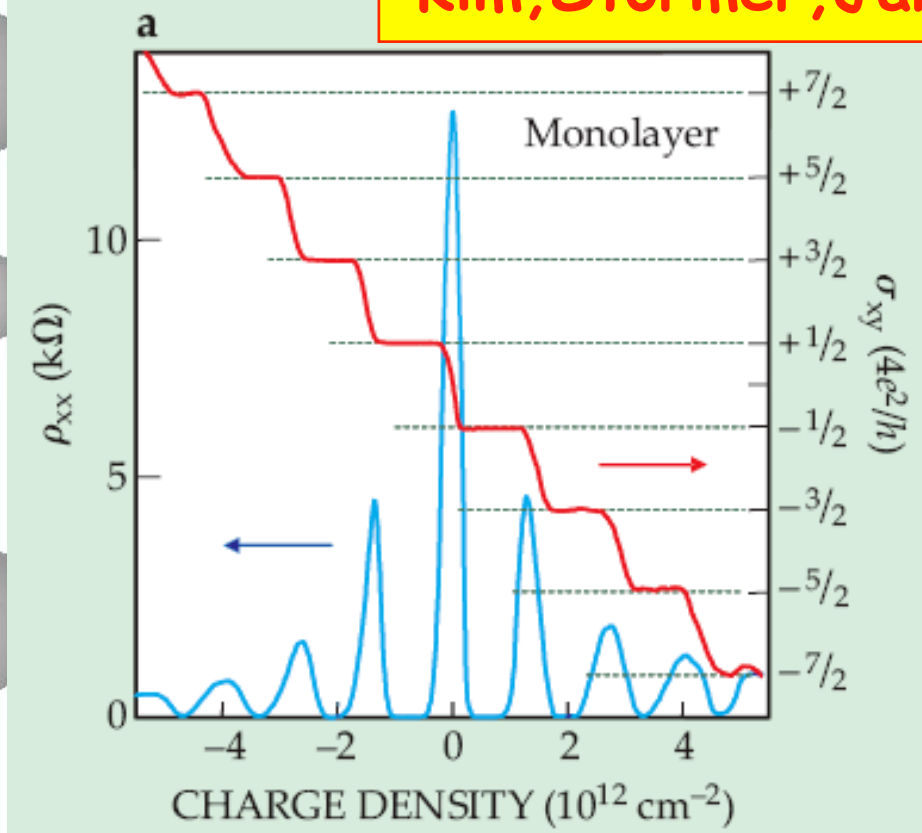
N=8 Quantum Hall Ferromagnets

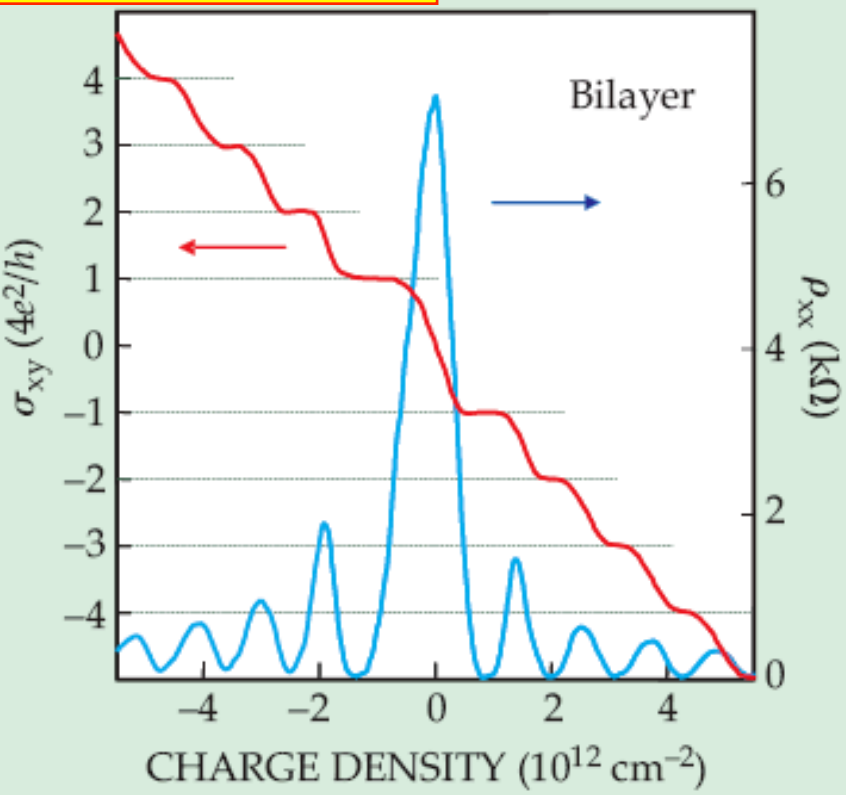


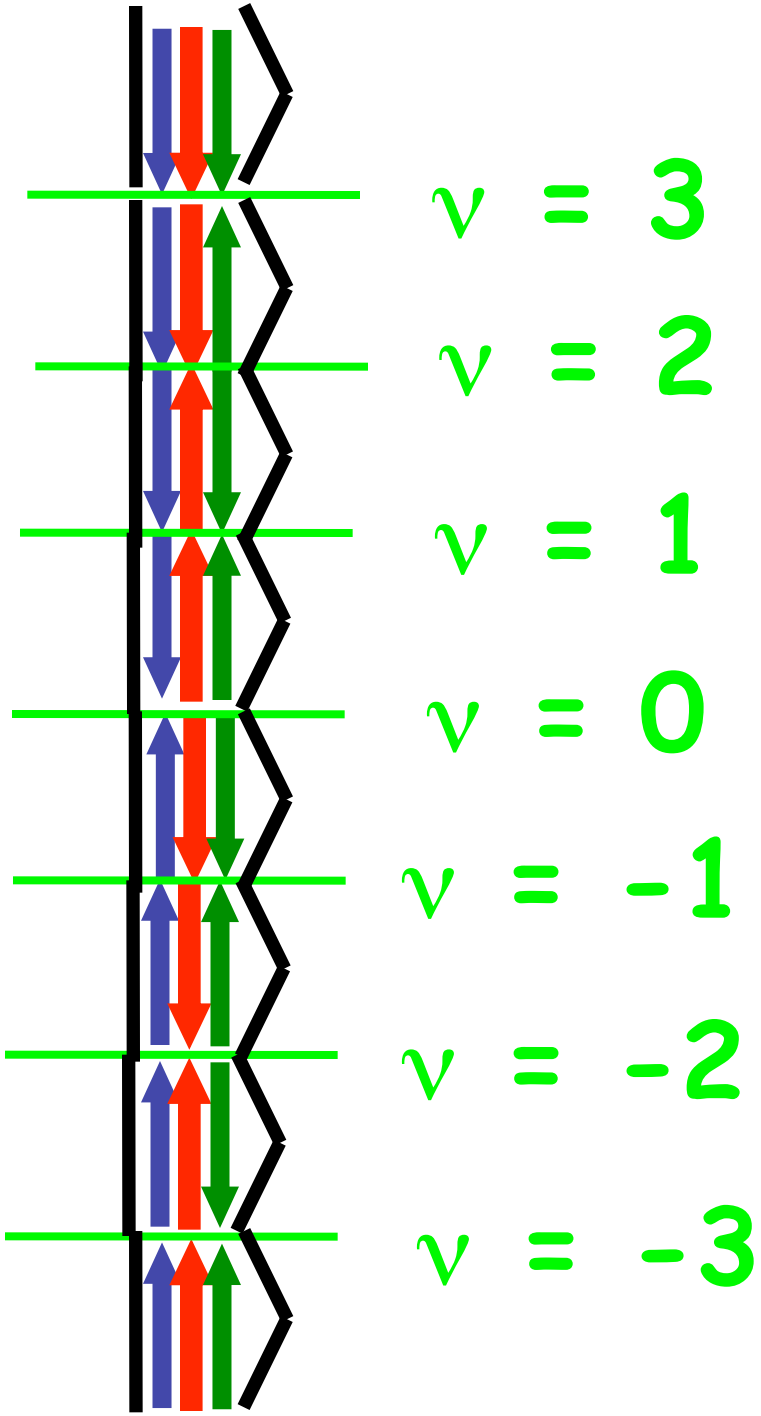
$$\mathcal{H} = -\hbar\omega_c \begin{pmatrix} 0 & a^2 \\ (a^\dagger)^2 & 0 \end{pmatrix} \begin{matrix} |A\rangle \\ |B\rangle \end{matrix}$$

Graphene Quantum Hall Effect

Geim, Novoselov …
Kim,Stormer,Jarillo-Herrero,…







Hunds Rules:

Spin

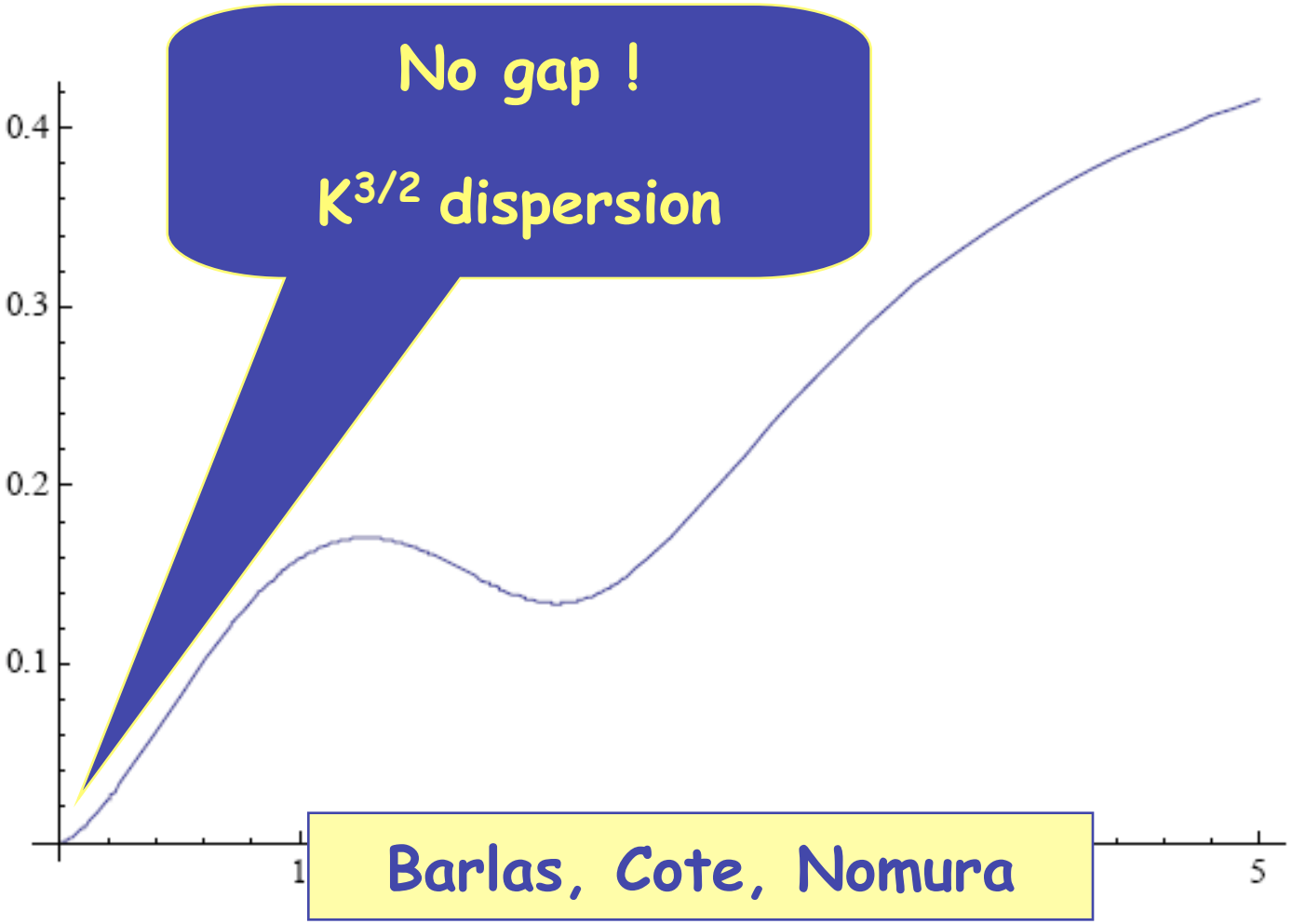
then

layer

then

LL

Bilayer ν = odd magnetorotons



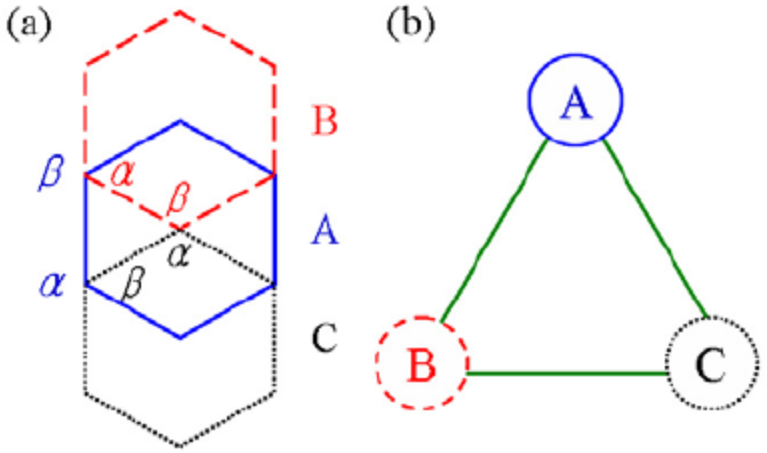
Pseudospins & Chirality

Bilayer Pseudospin Ferromagnetism

Bilayer Quantum Hall Effect

Chirality in Multilayers

Multilayer Stacking – A,B,C layers

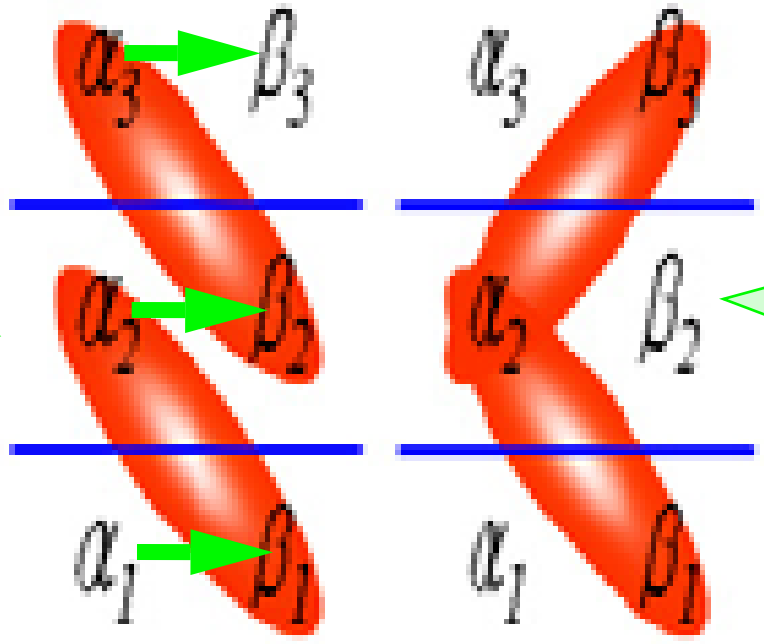


Koshino & Ando, PRB '07

Nakamura

3 layer stacks

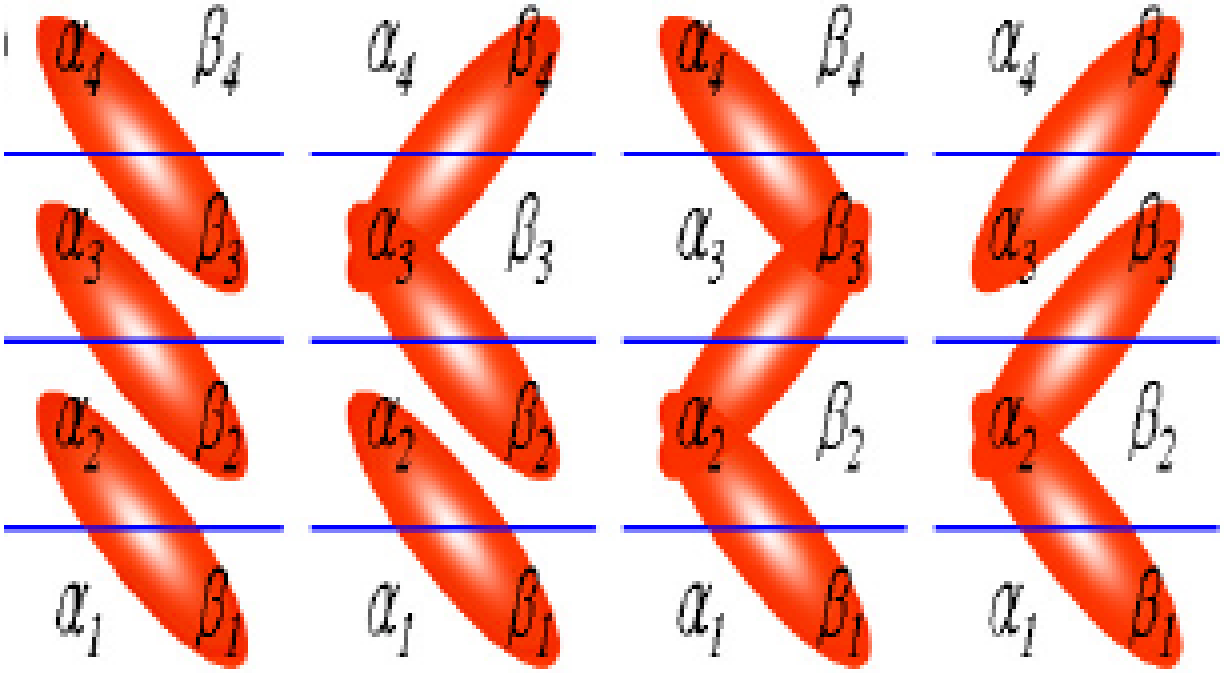
J=3



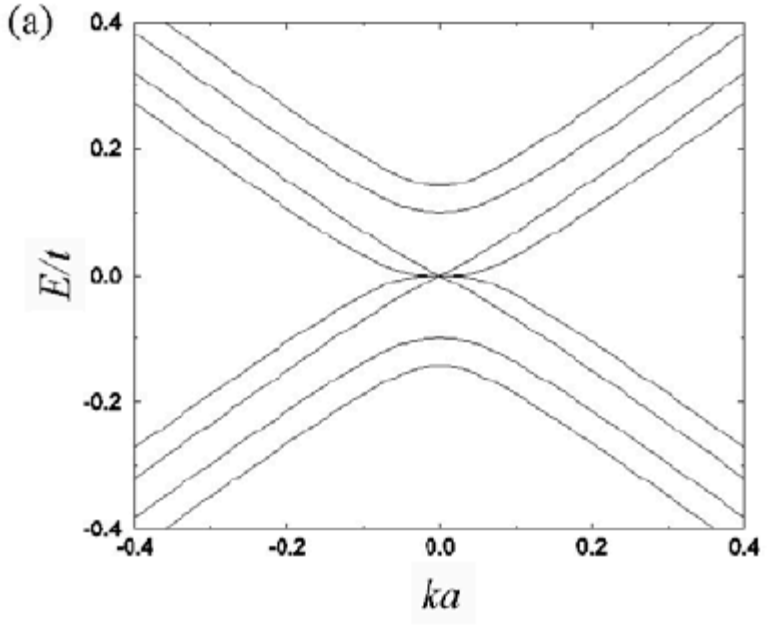
J=1
&
J=2

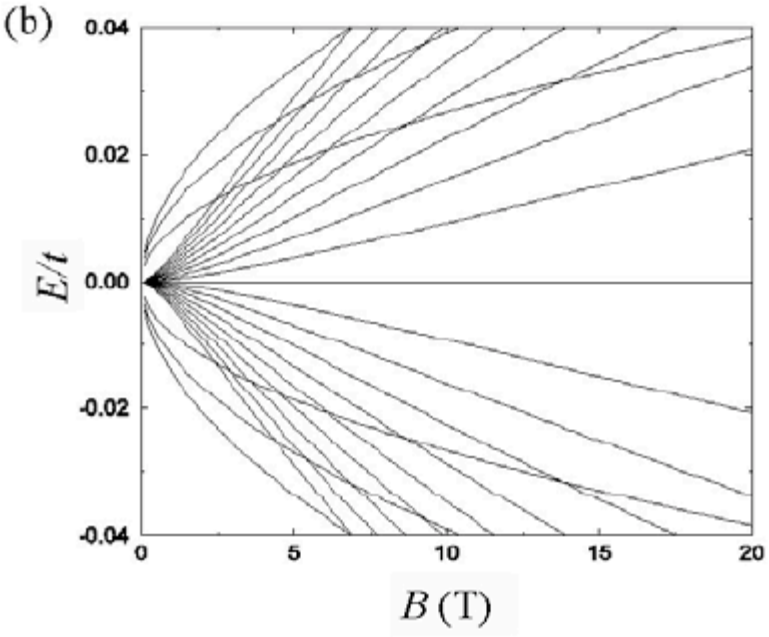
ABC ABA

4 layer stacks



ABCA	ABCB	ABAB	ABAC
J=4	J=1,J=3	J=2,J=2	J=1,J=3



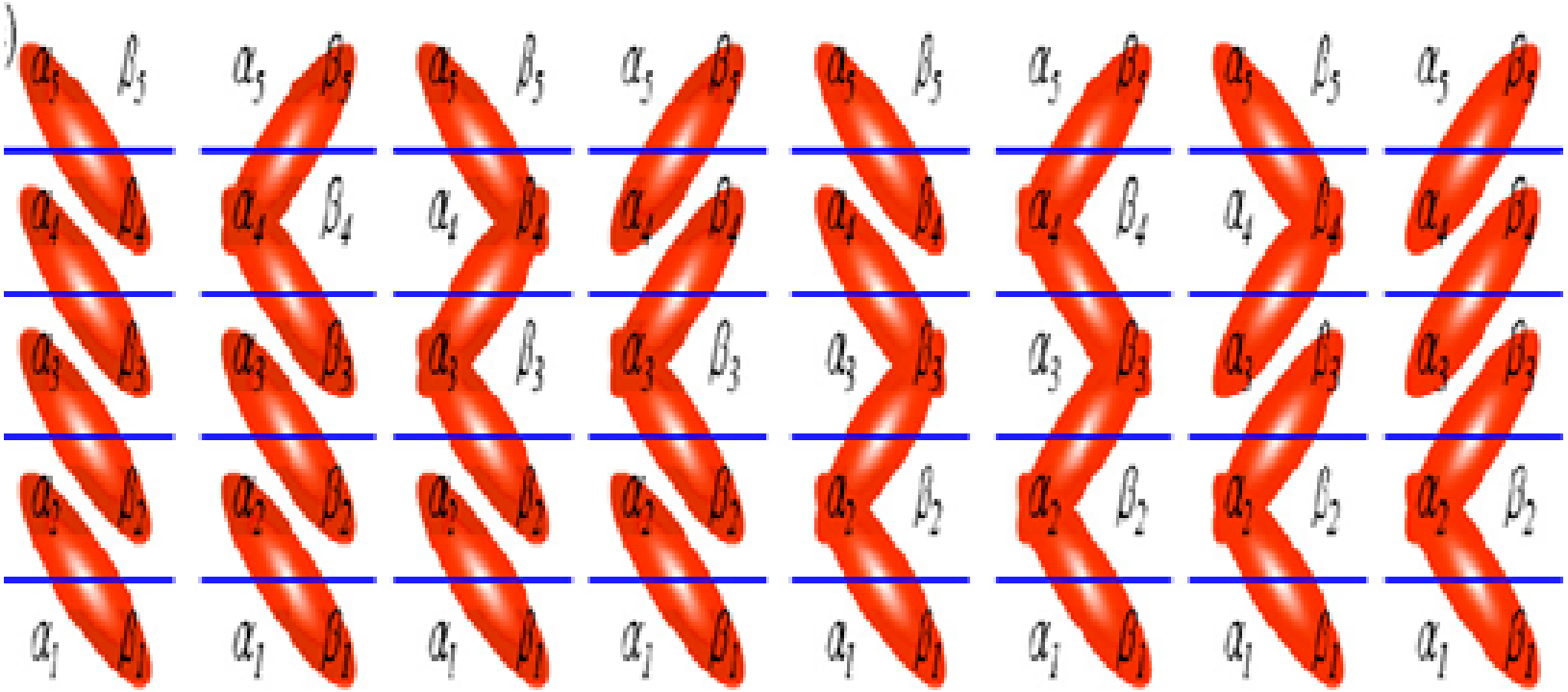


4-layer ABCB

J=1,3

$E \sim k^J \sim B^{J/2}$

5 layer stacks

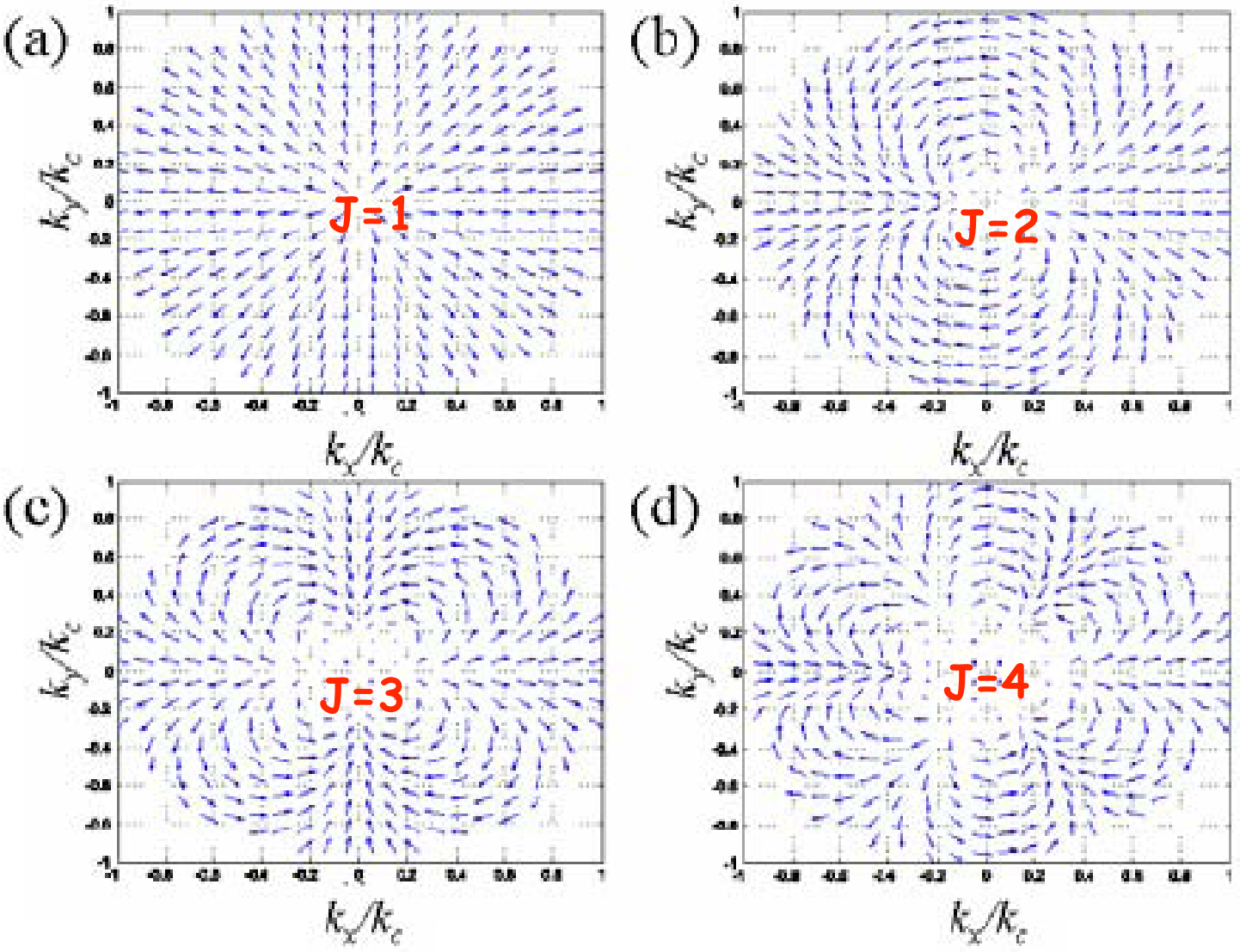


J=5	J=1, 4	J=2, 3	J=1, 4	J=2, 3	J=2,2,1	J=2,2,1	J=2, 3

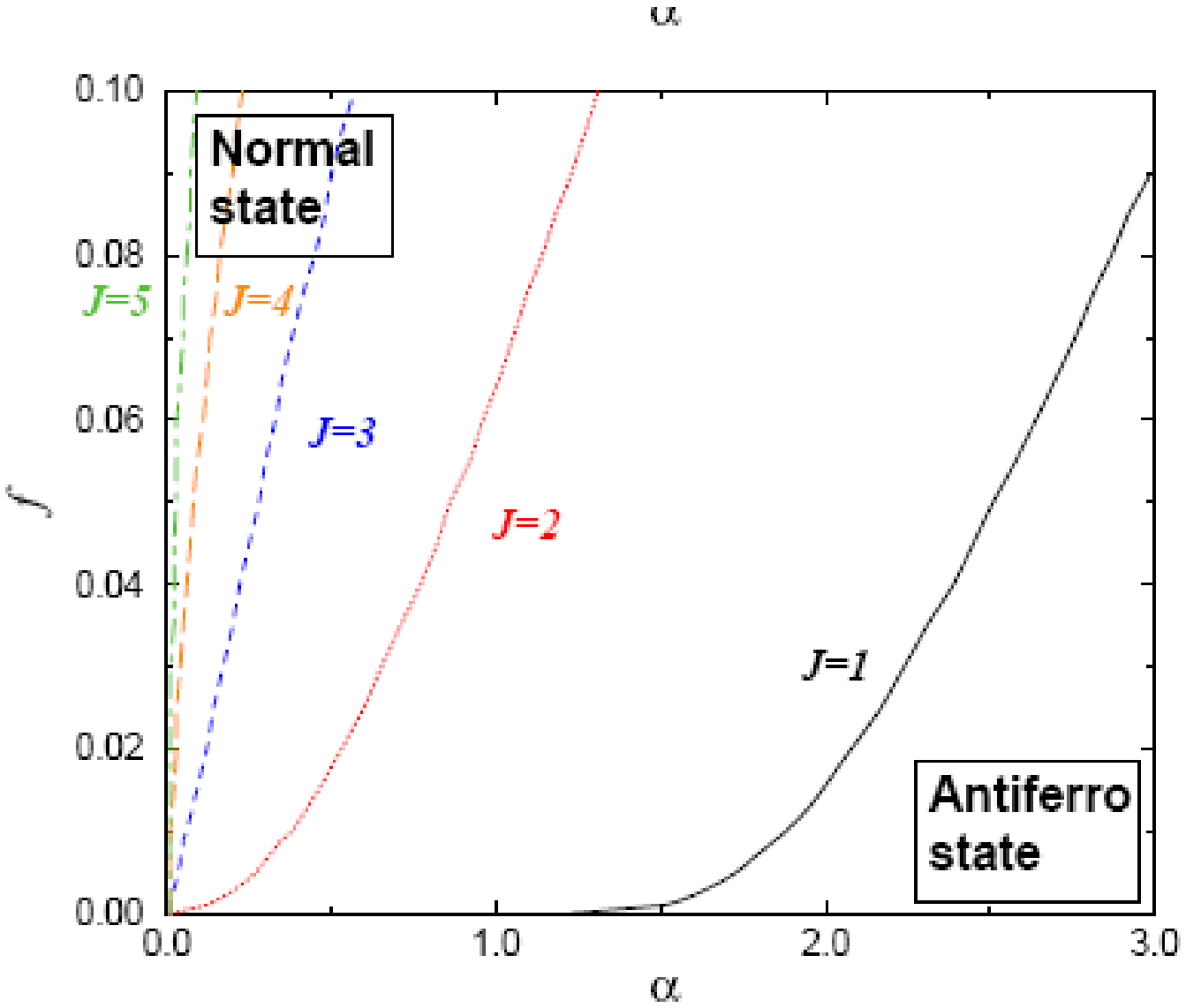
$$\sum_{i=1}^{N_D} J_i = N$$

Chiral Sum Rule

Higher J k-space vortices



Higher J Pseudospin Ferromagnets

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Massless Dirac Fermions in Flatland