Chiral transport of hot carriers in graphene in the quantum Hall regime

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Classical Hall physics circa 1880

Wikipedia

Edwin Hall showed the transverse resistivity ρ_H of a thin metallic plate **varies linearly**

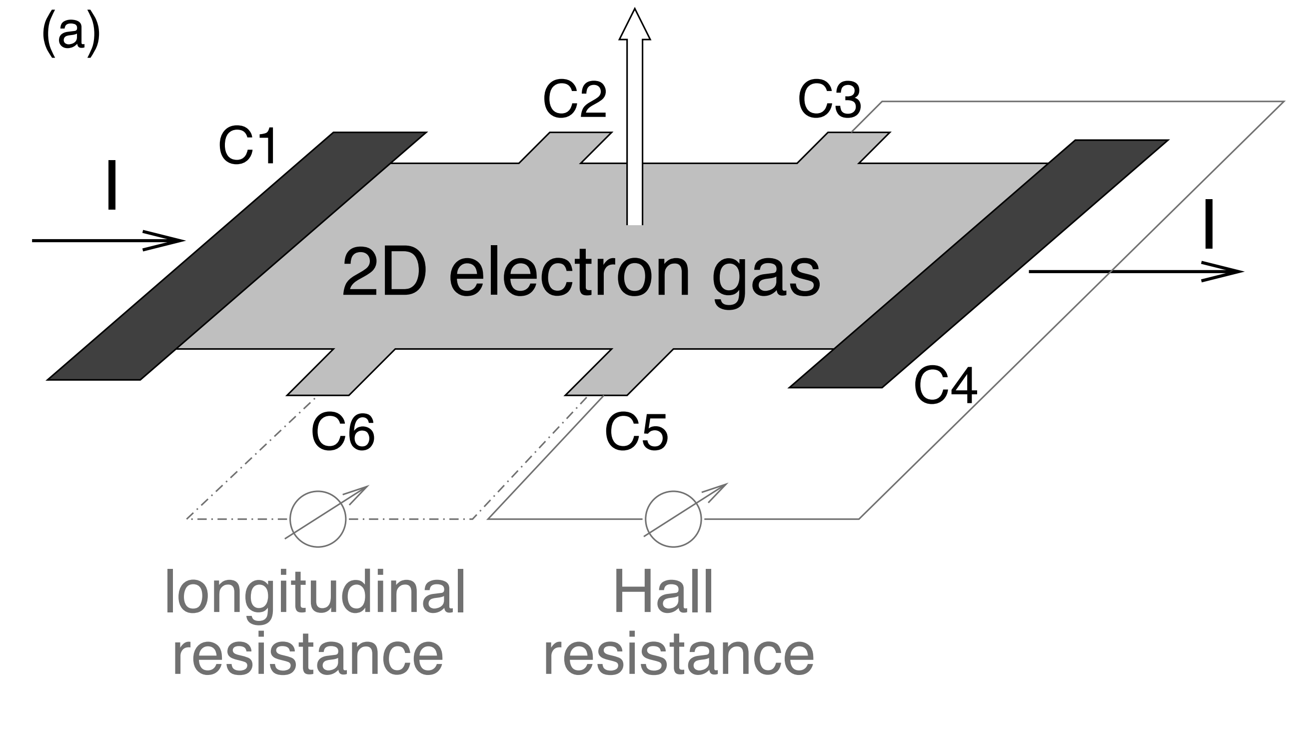
with the strength B of the perpendicular magnetic field

$$\rho_H = \frac{B}{q n_{el}}$$

q is the charge ($-e$ for electrons), n_{el} is the 2D carrier density.

The longitudinal resistivity is independent of B.

Just the Lorentz force changing the trajectory of a charged particle.



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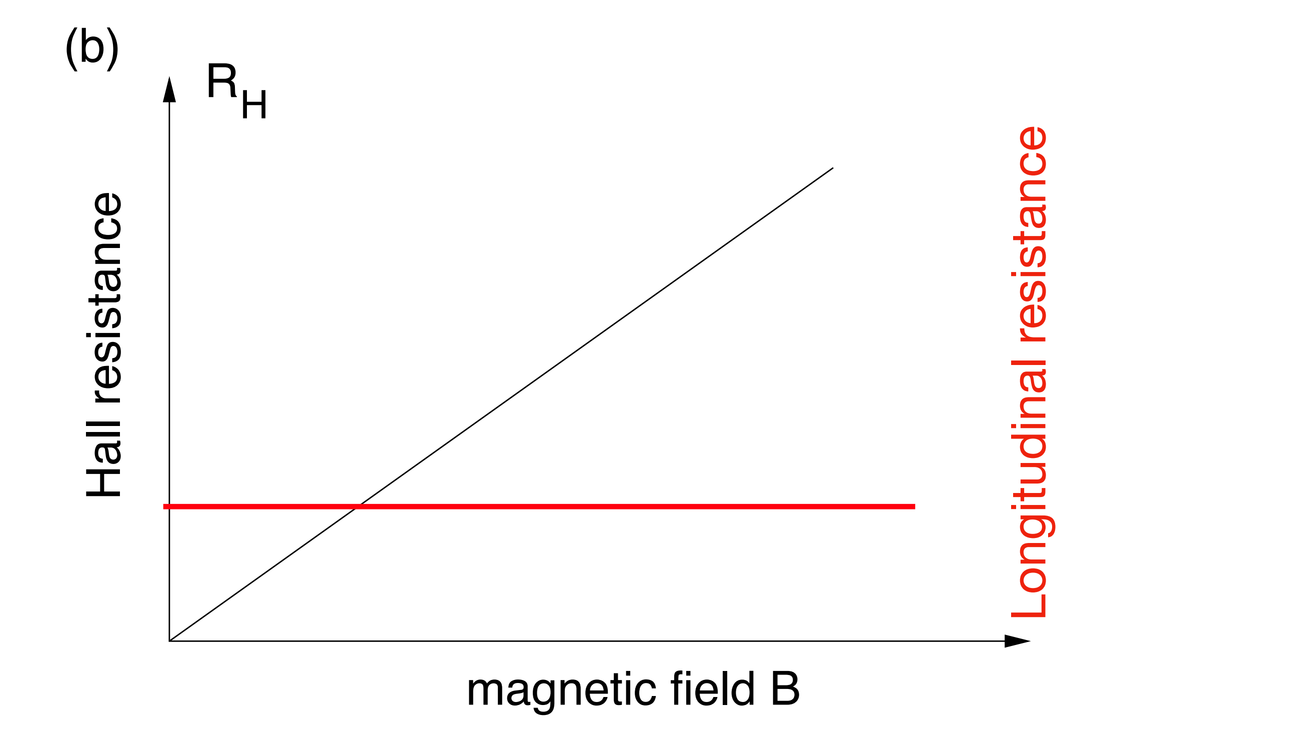

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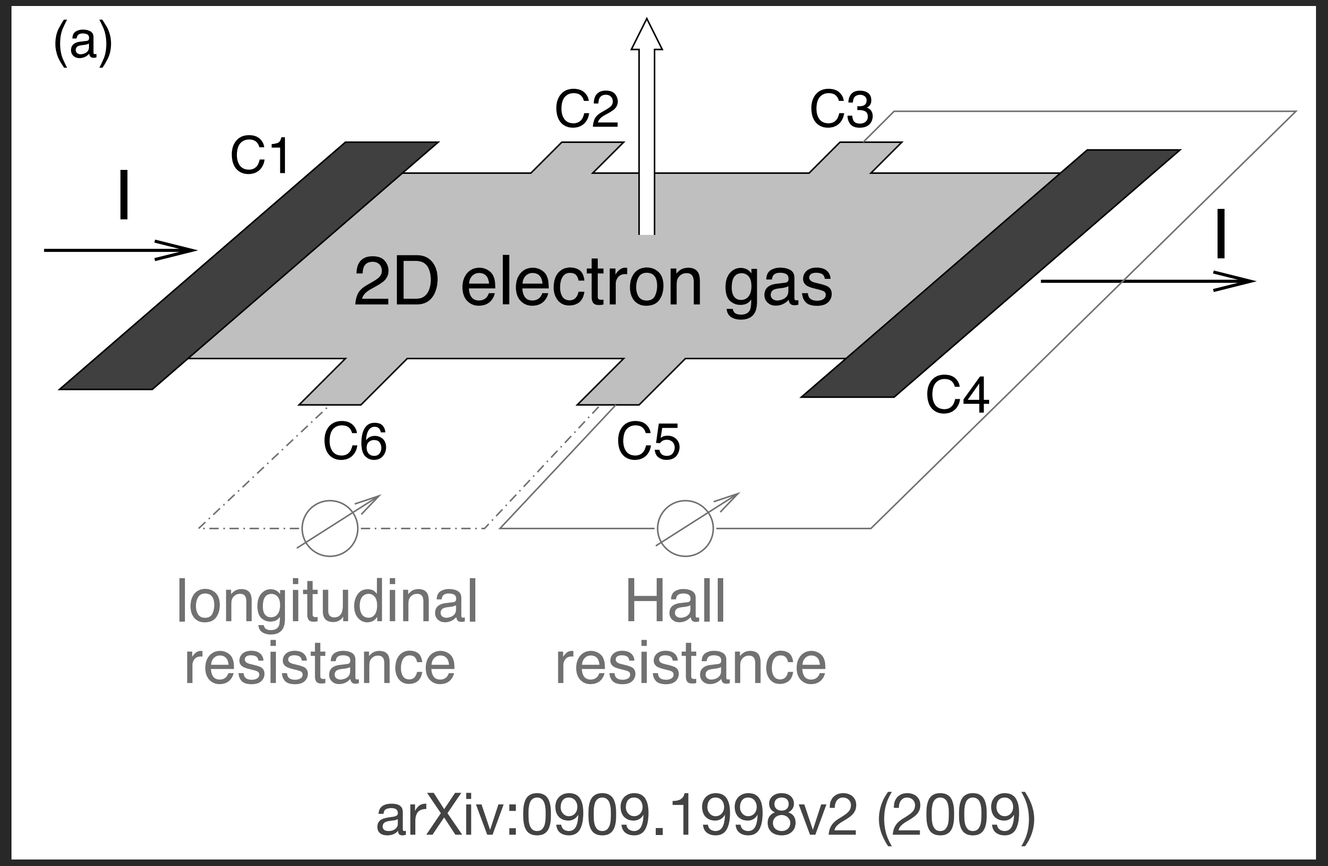

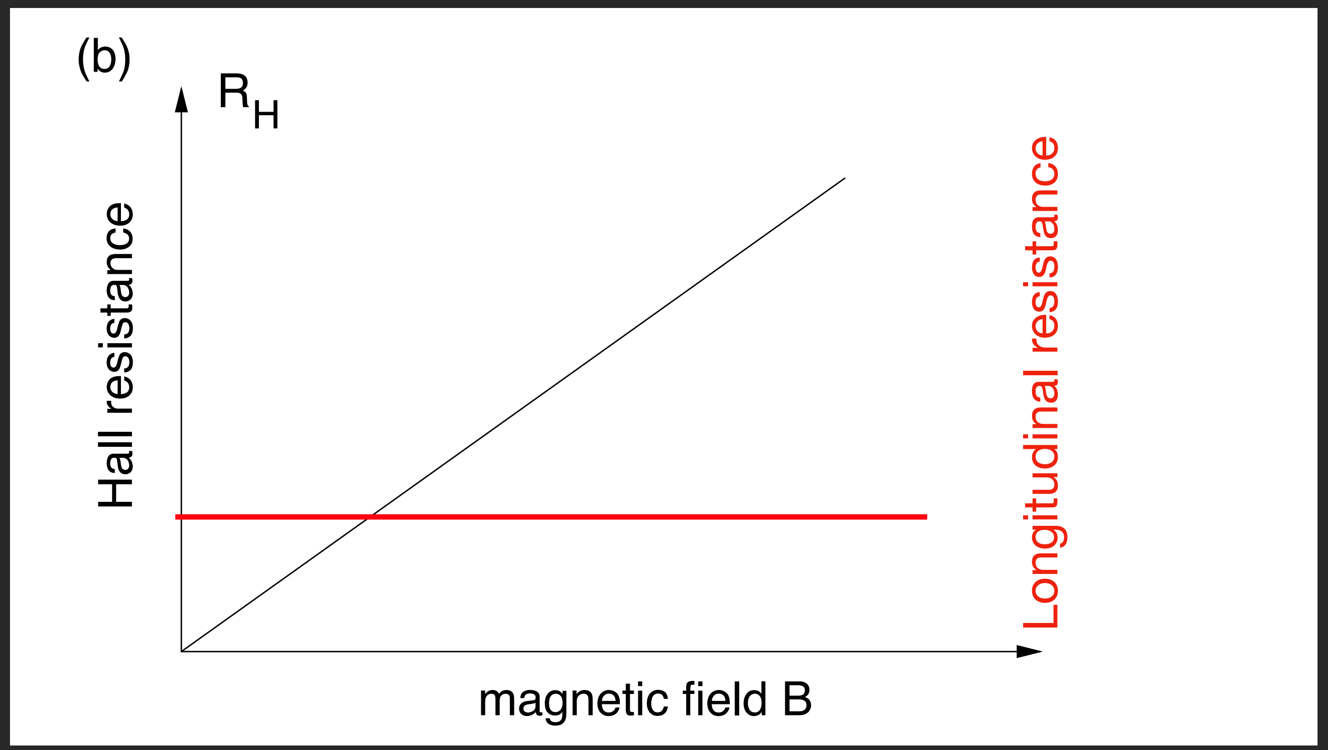

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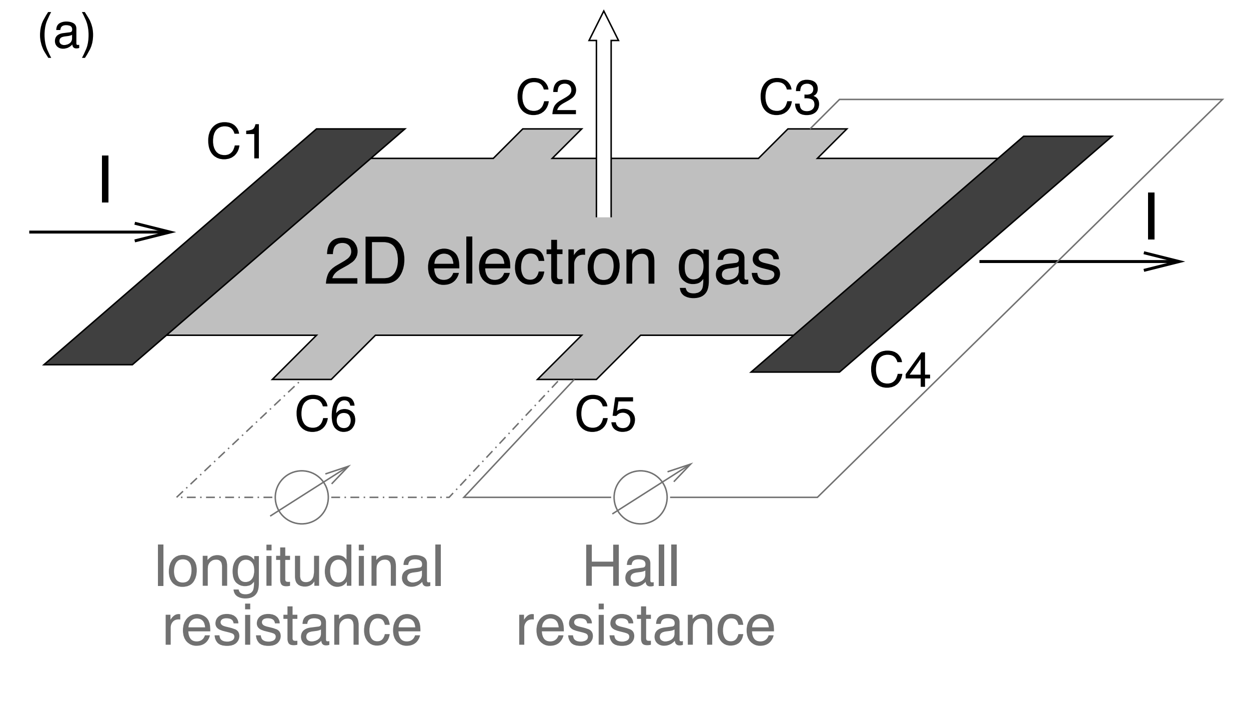
In the lab, we measure **Resistance** not **resistivity**, and $R = (L/A)\,\rho$ [l = length, A = cross section]

For a quasi 2D system, $R_H\, L = A$. $\rho = R$ making it robust with geometry change.

Another feature: In a semiconductor the carrier density and carrier mobility can found independent of each other.

Part 1: Integer Quantum Hall



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In a 2D system quantisation of allowed electron/hole energies can present

Parabolic bands: $\epsilon_n = \hbar\omega_C(n + 1/2)$,

n is an integer, cyclotron freq, $\omega_c = \dfrac{-qB}{m}$

iff charged-carrier scattering, τ^{-1} is weak, *i.e.*, $\omega_c\tau > 1$

Quantisation of Density of States, $\rho(\epsilon) = \sum_n g_n \delta\left(\epsilon - \epsilon_n\right)$ g_n- degeneracy

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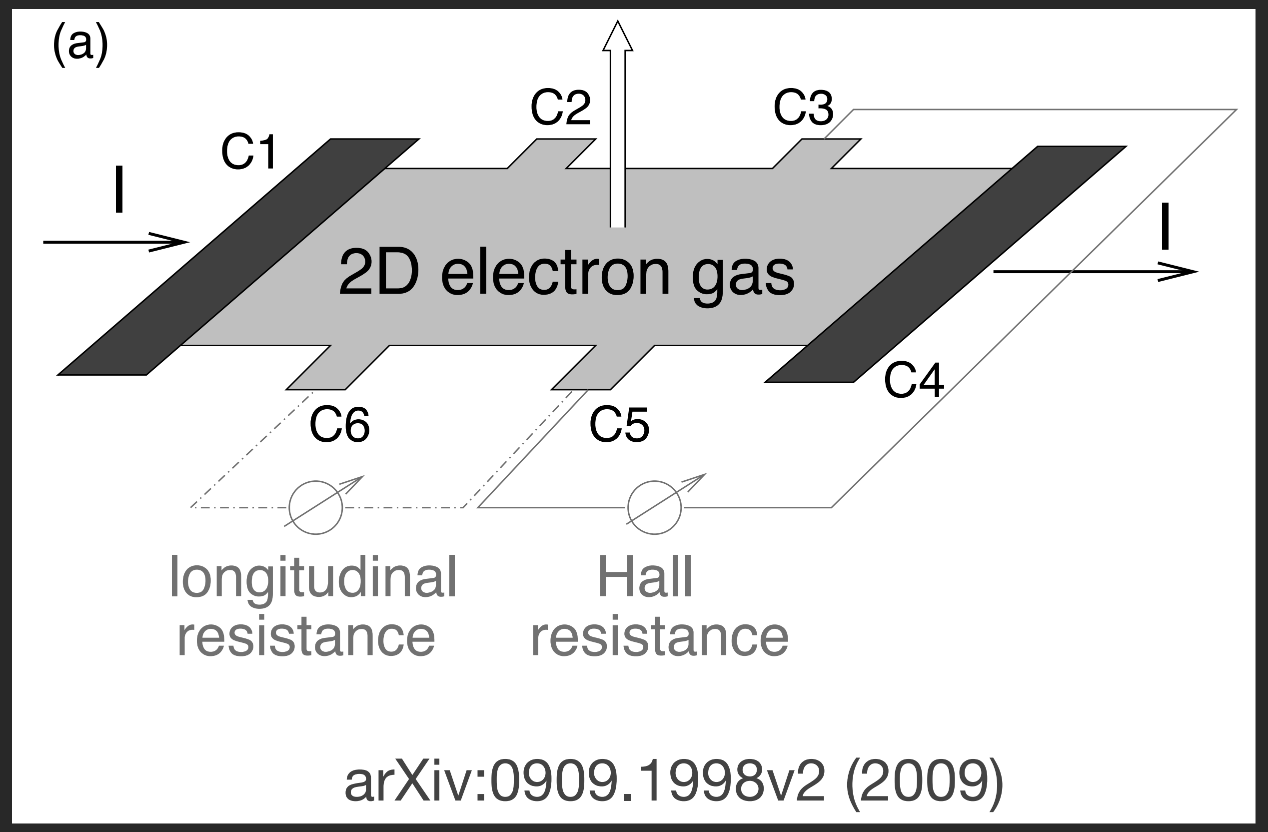

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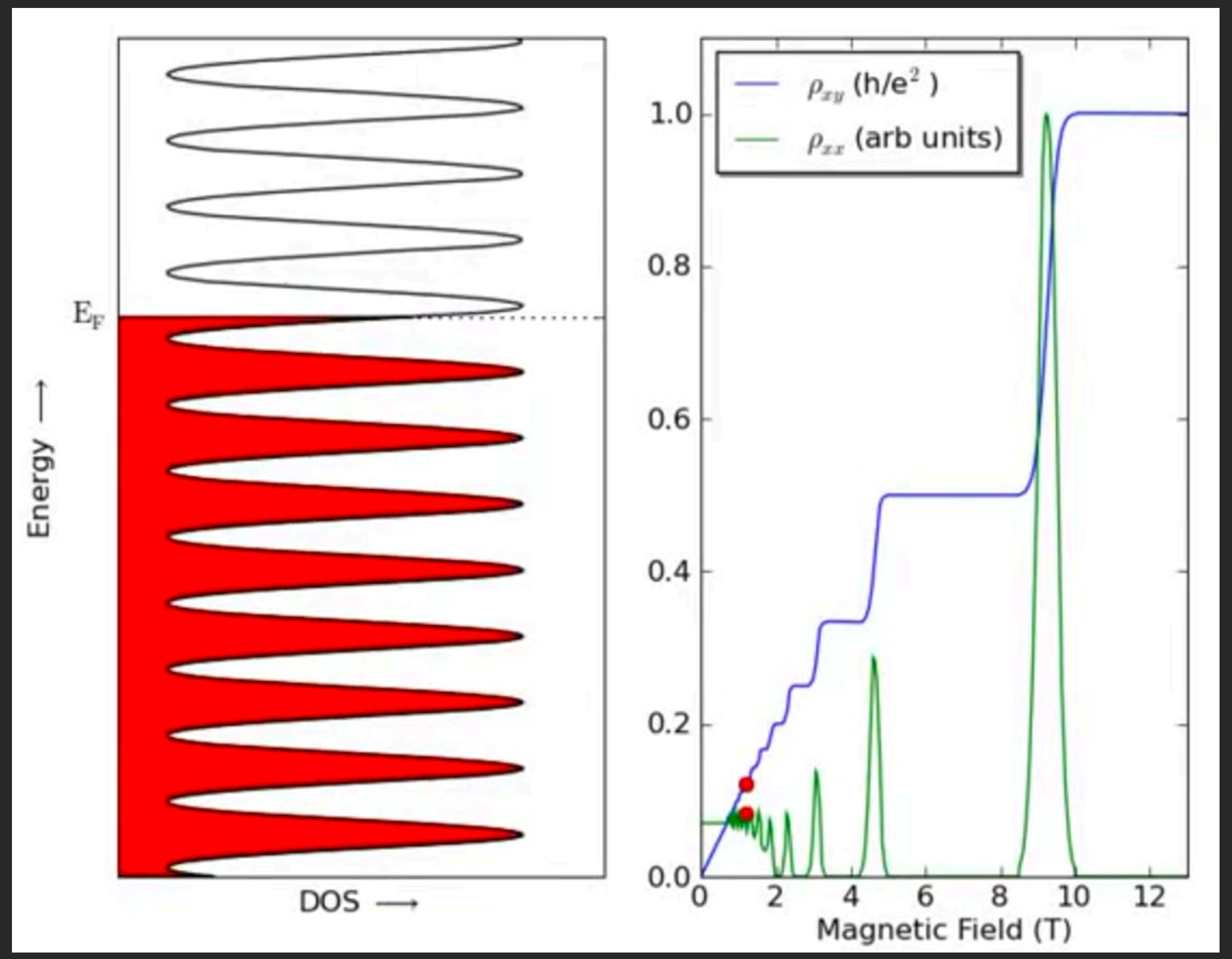

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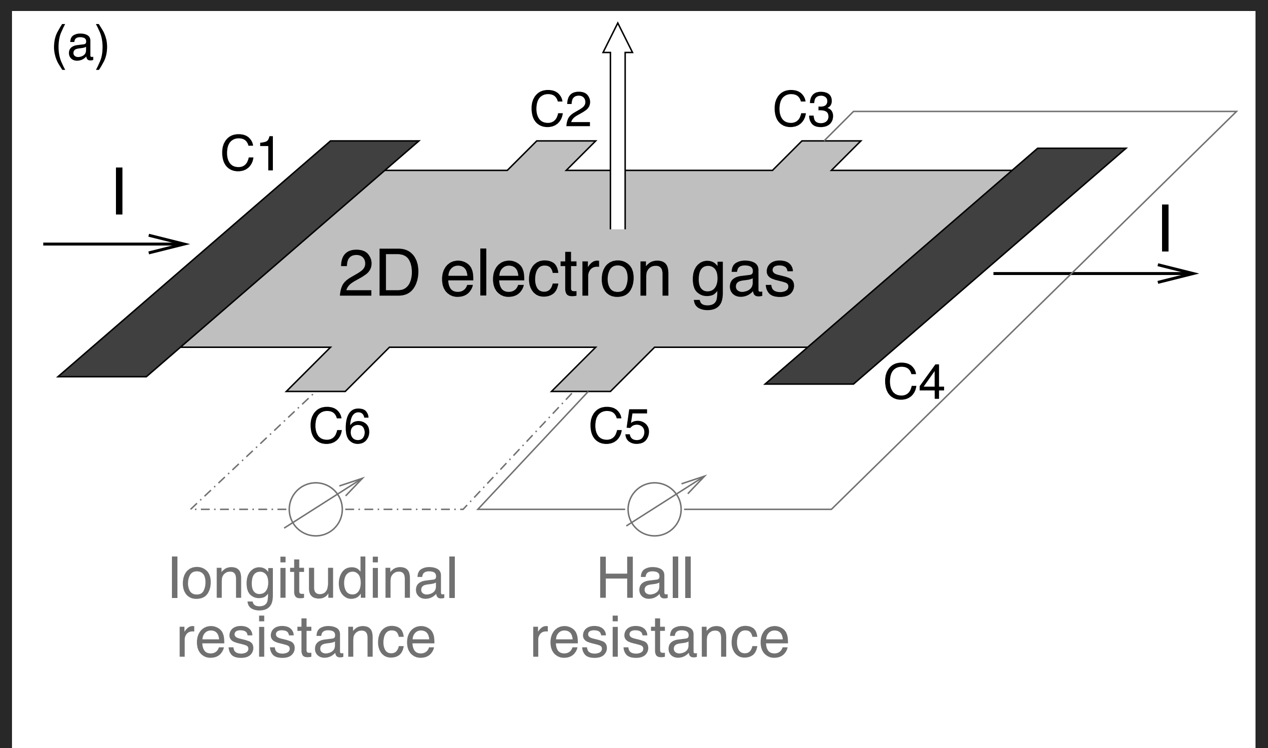

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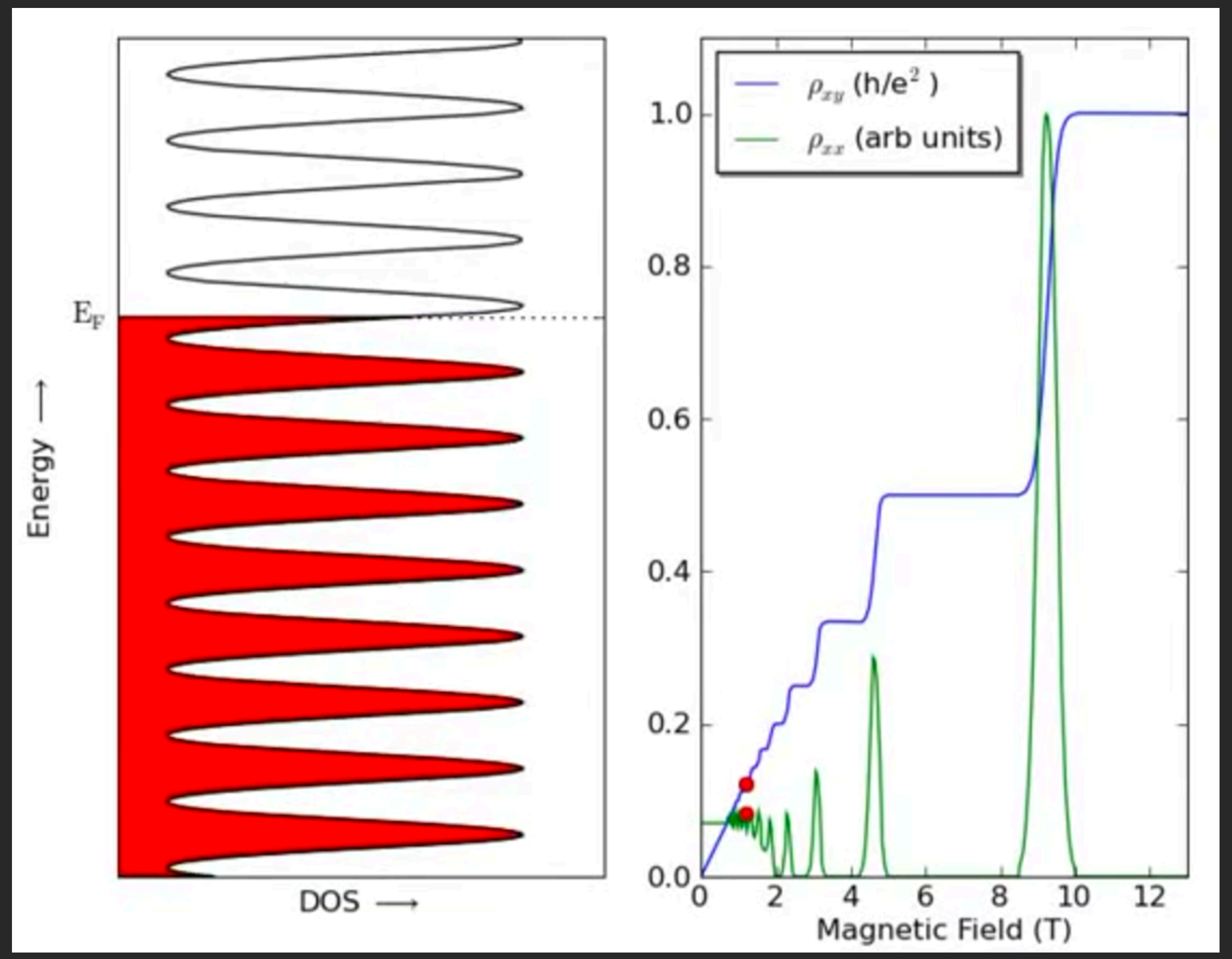

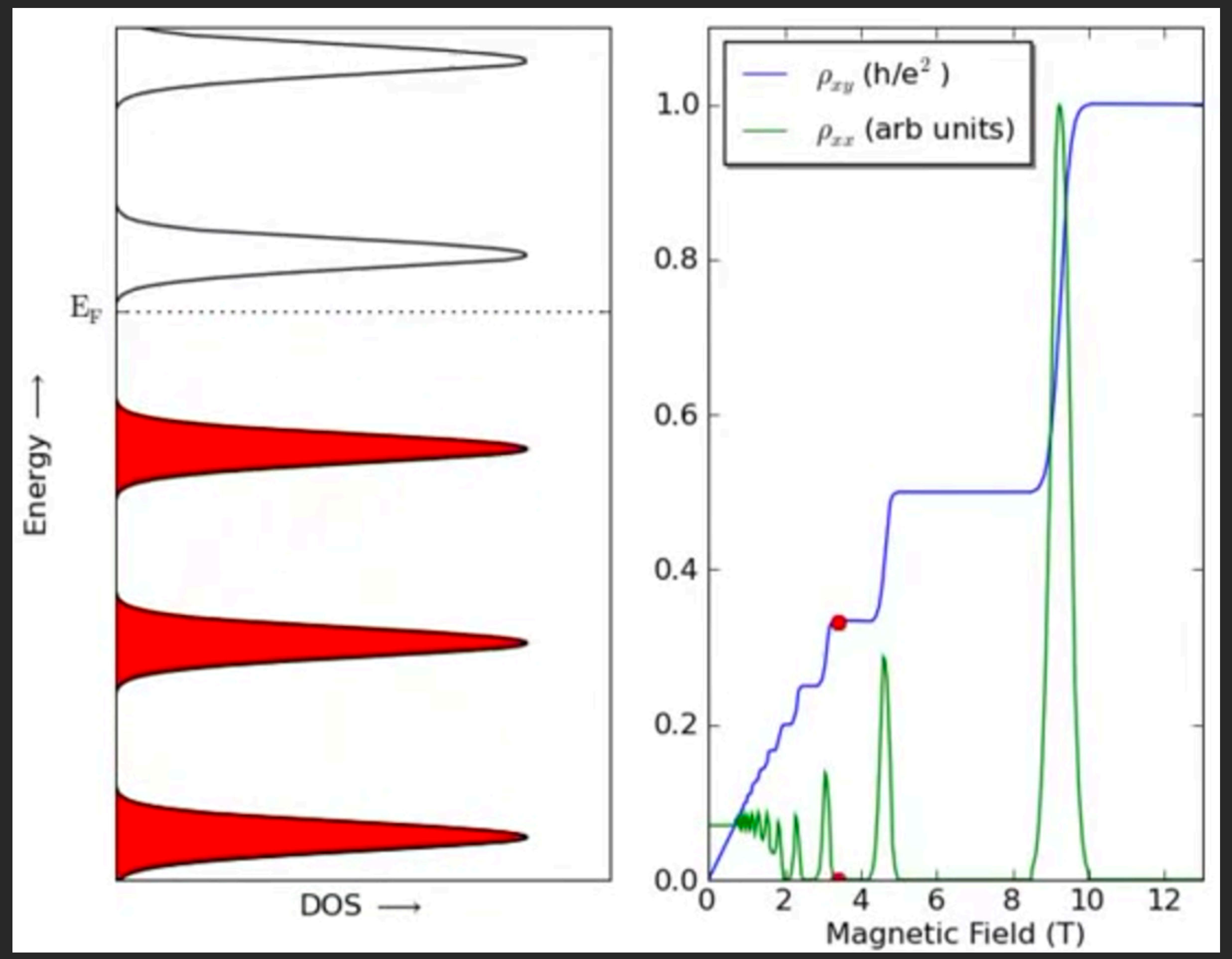

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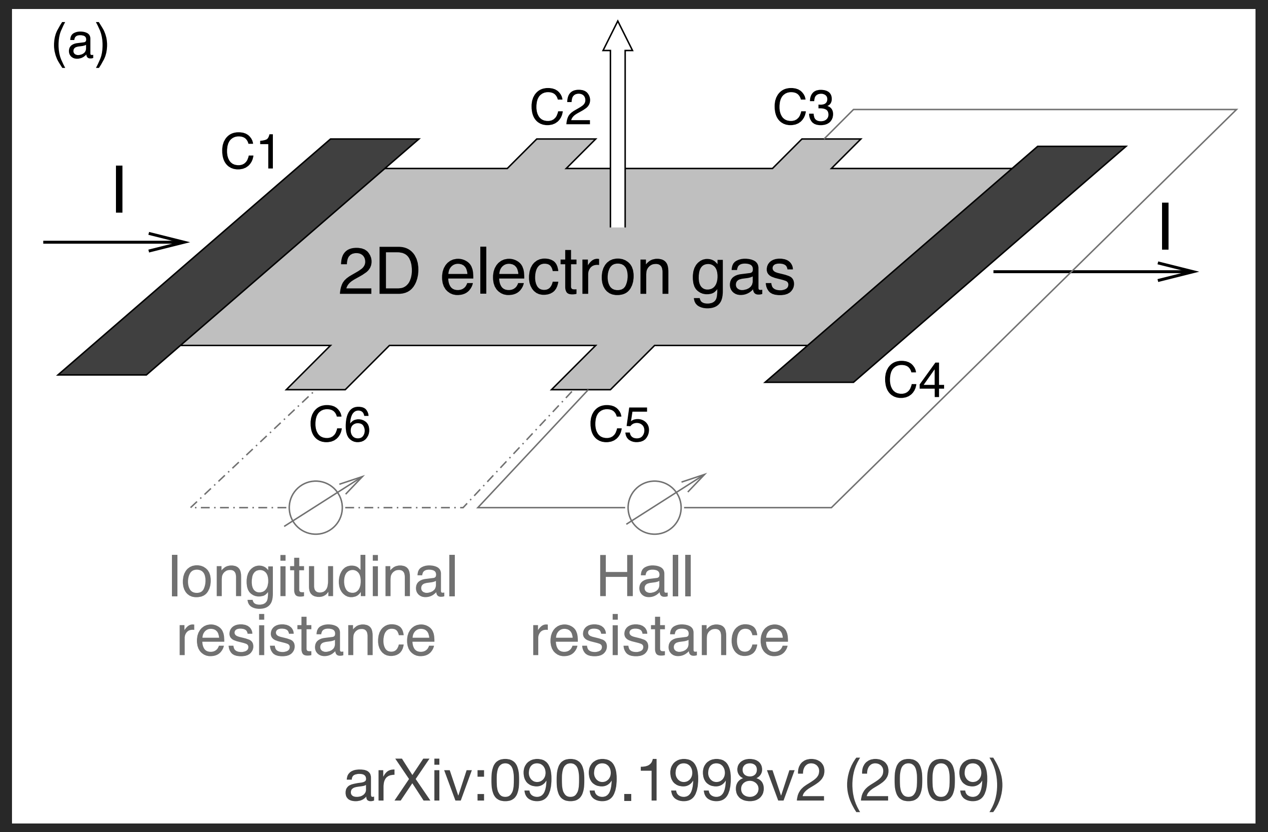

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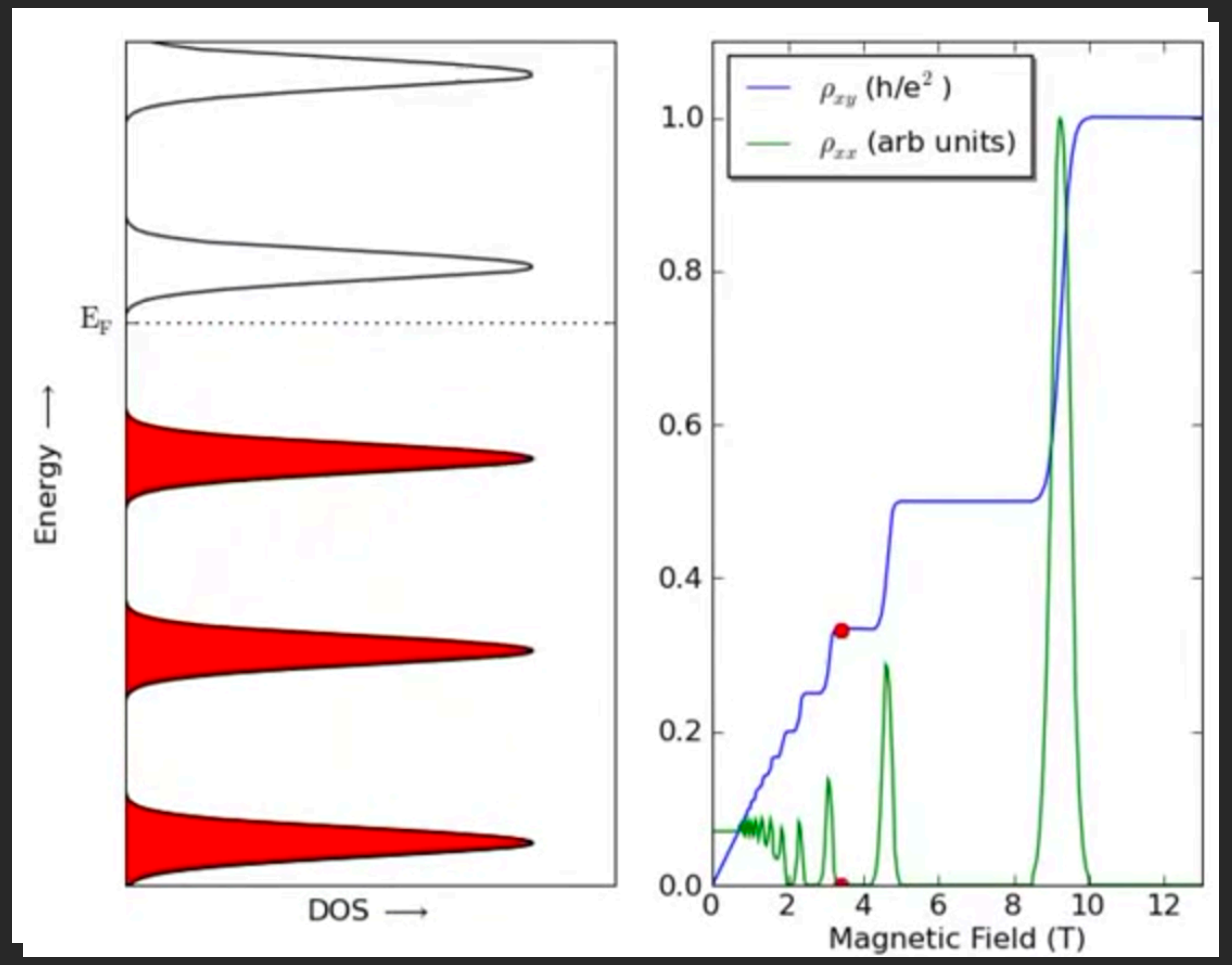

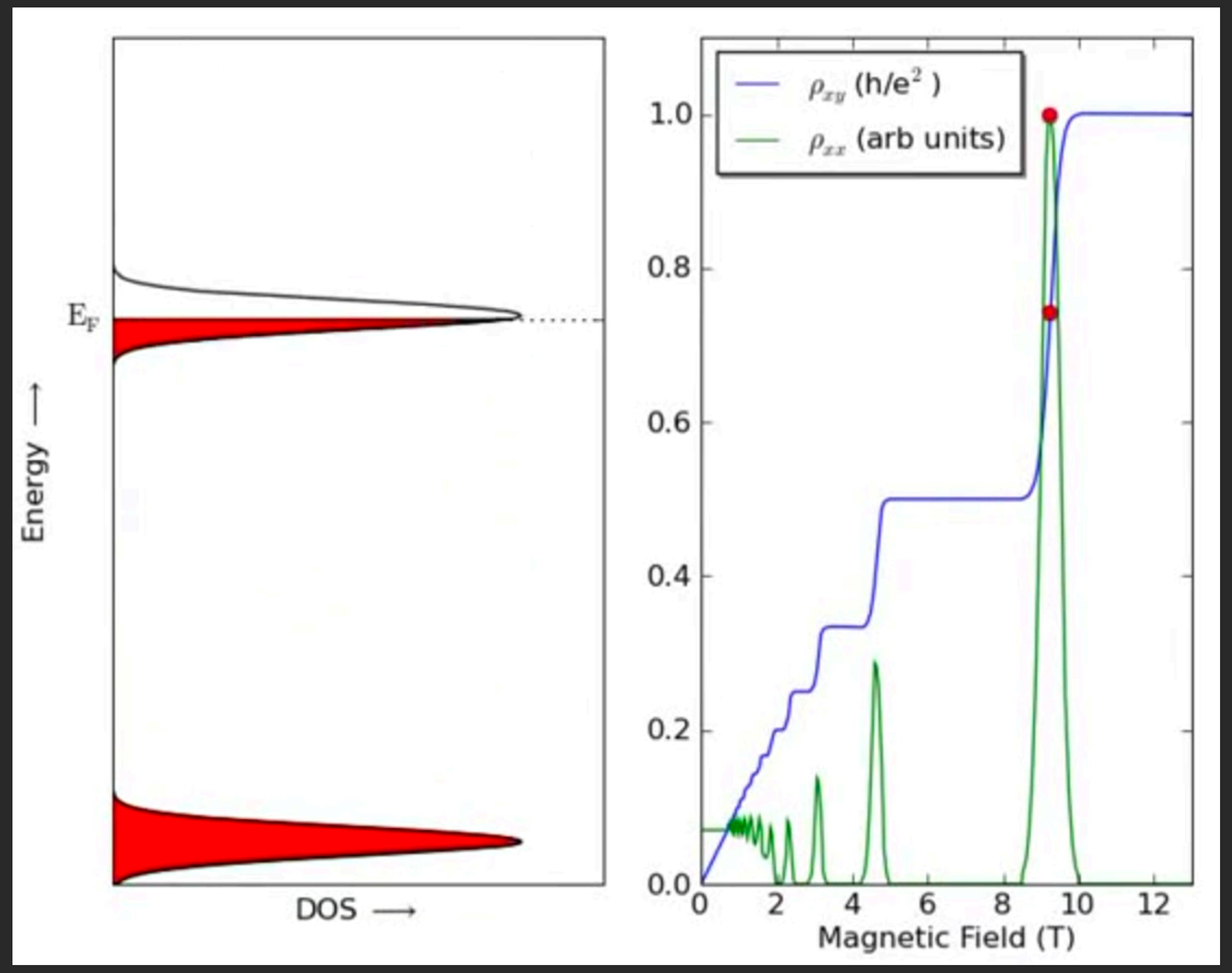

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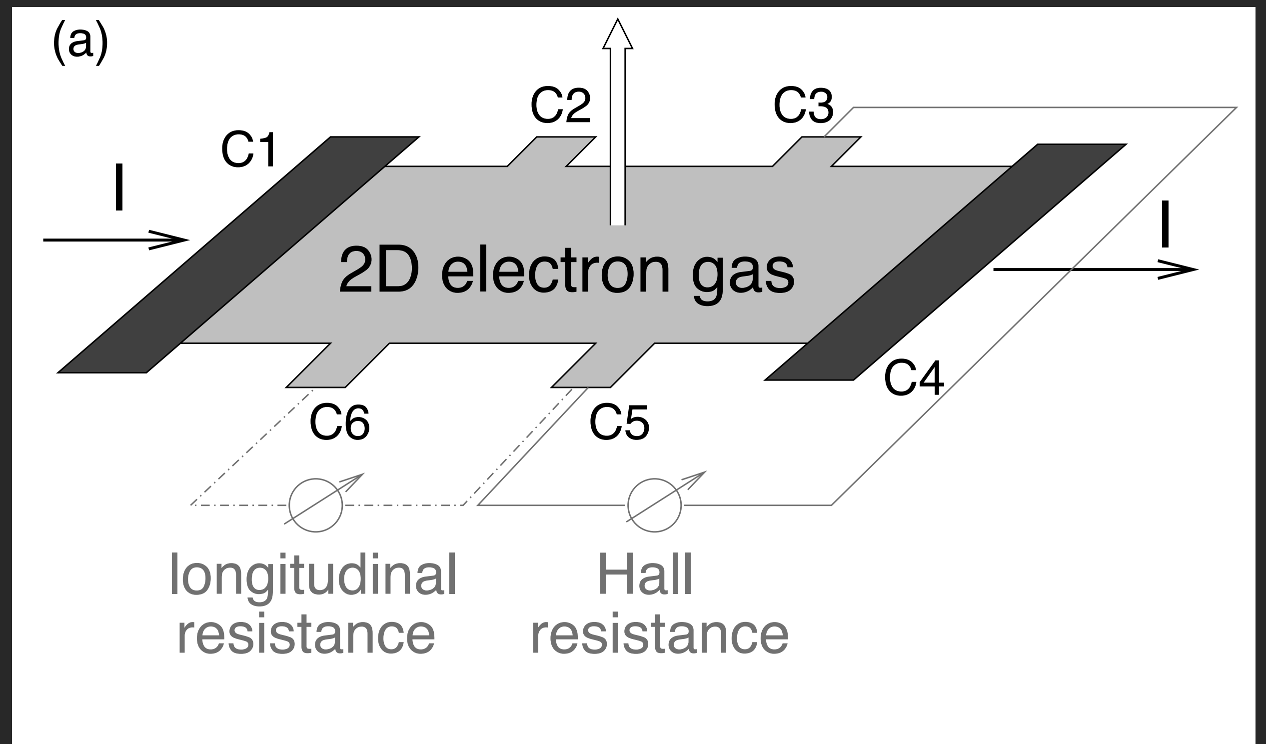

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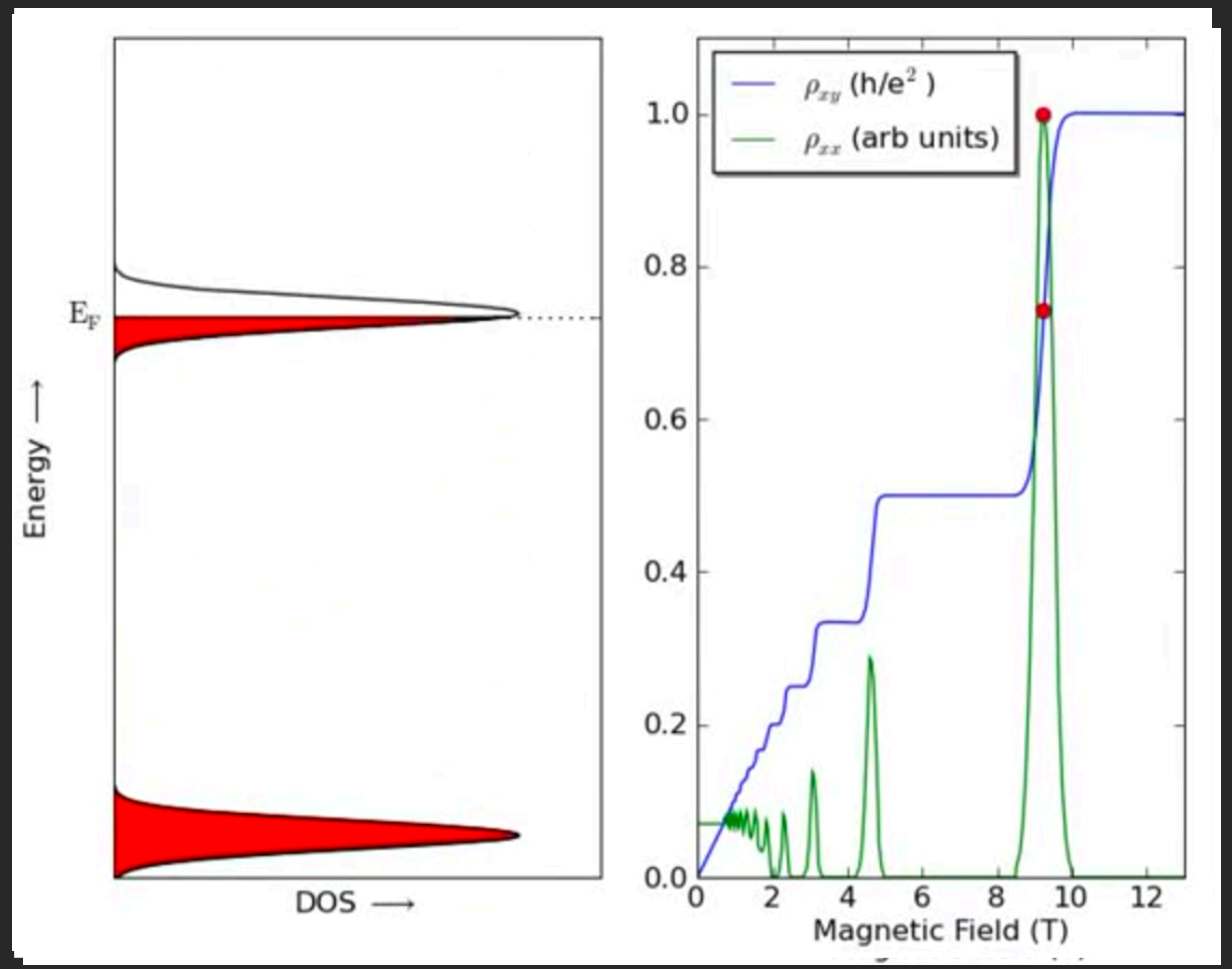
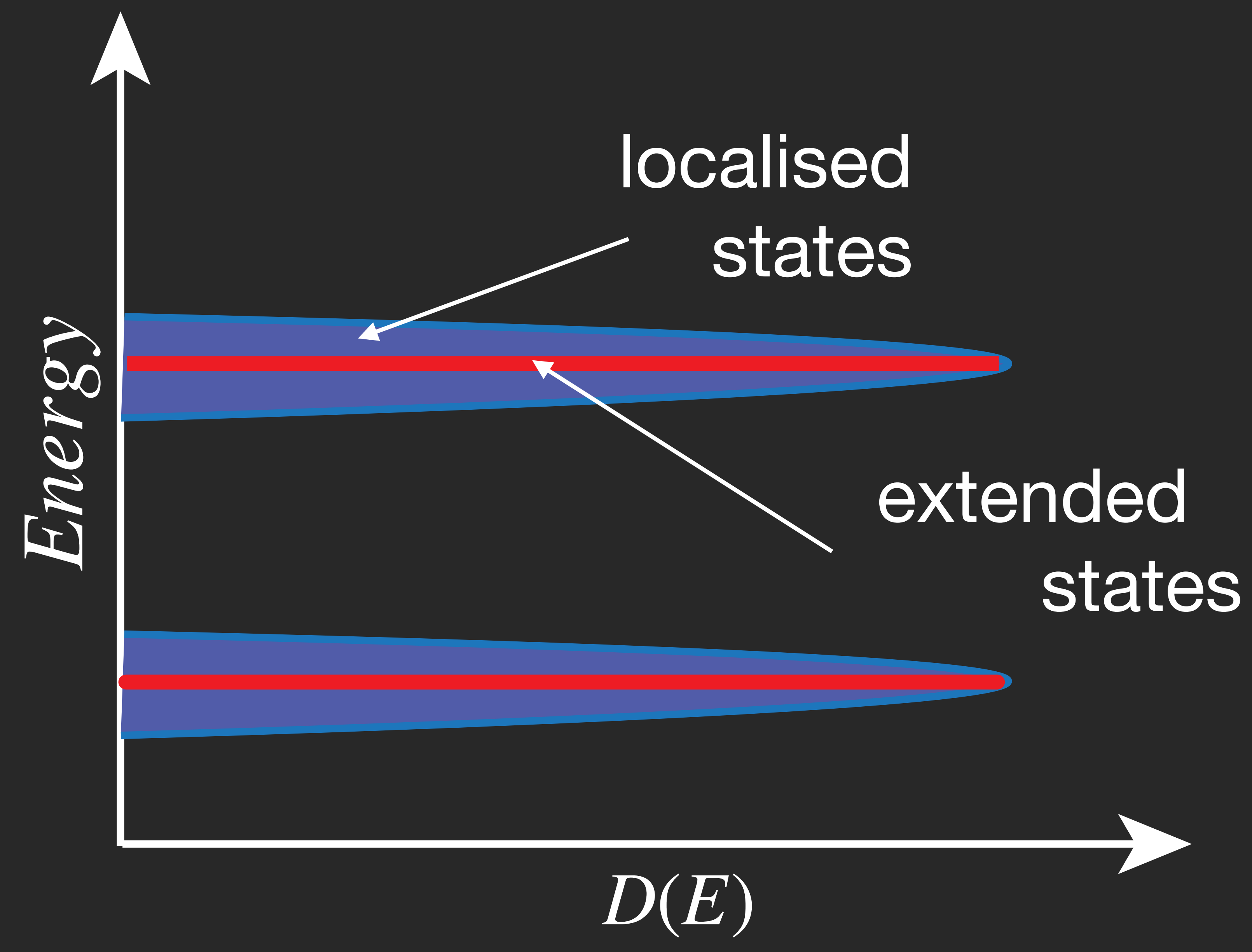


Peaks in the DOS are broadened by impurity scattering



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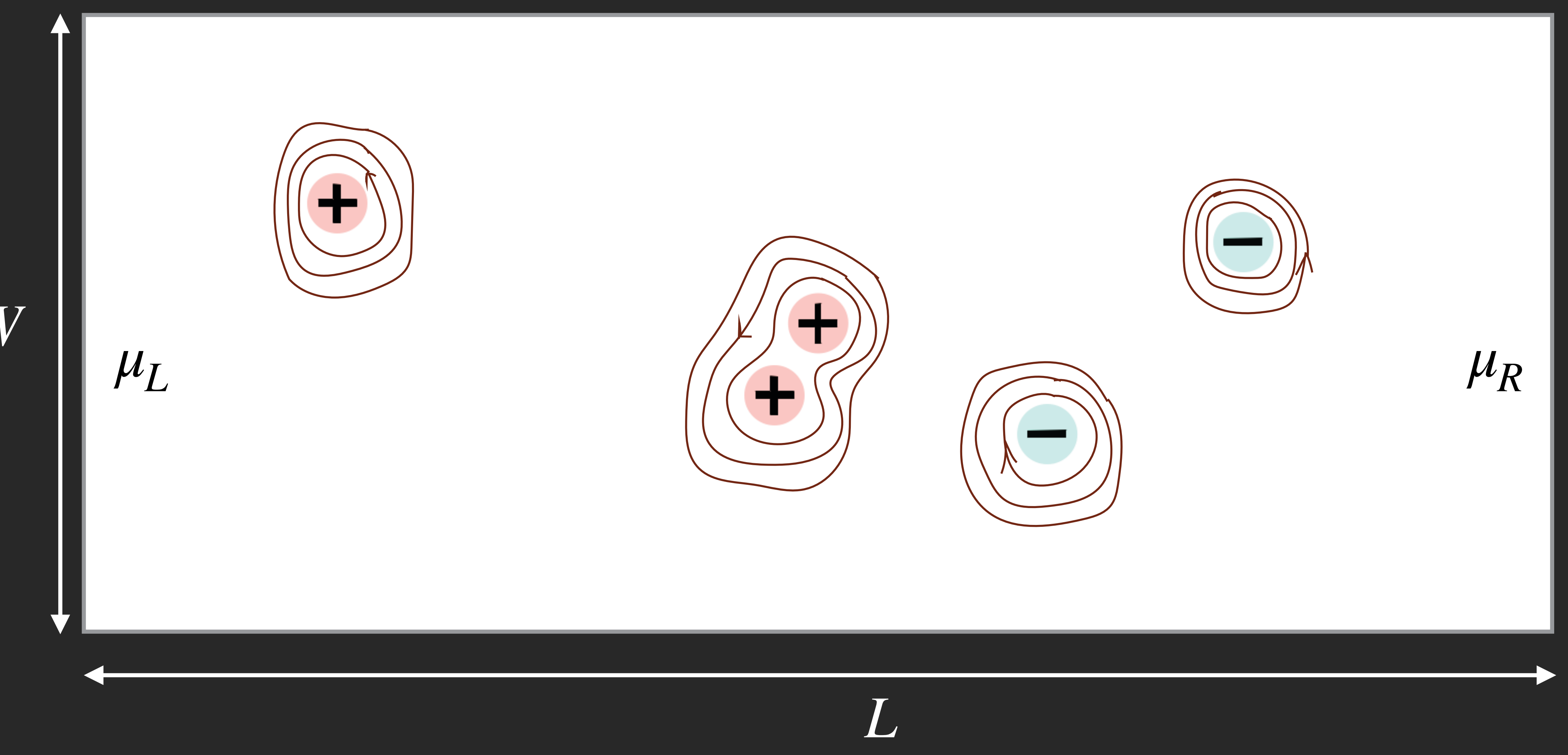
Integer Quantum Hall

- With low temperature, and low impurity scattering the DOS become quantised.



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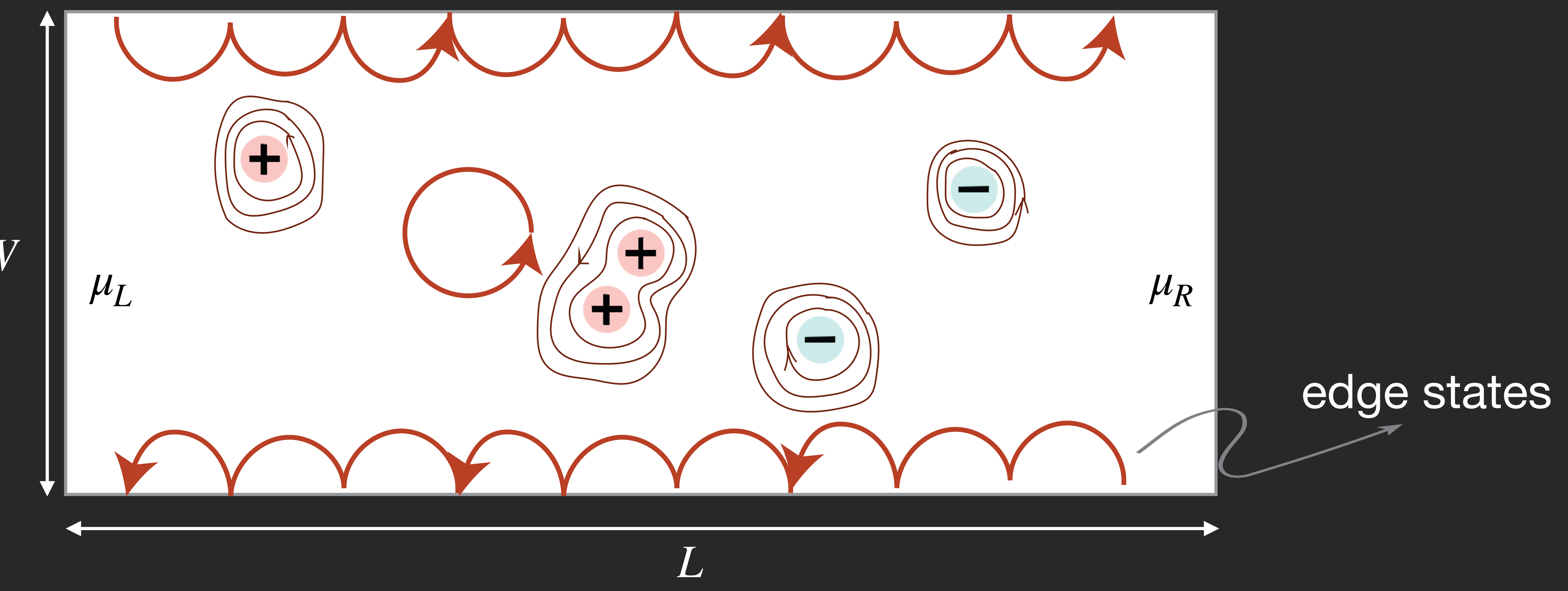

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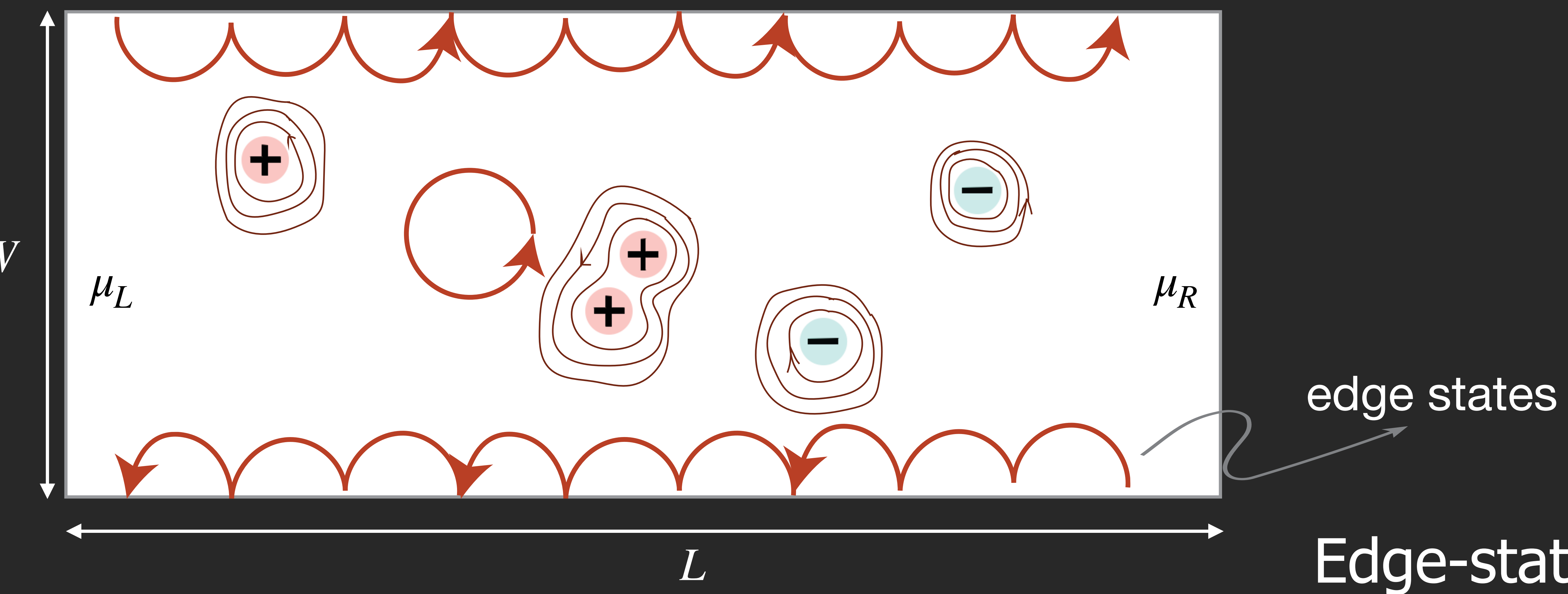
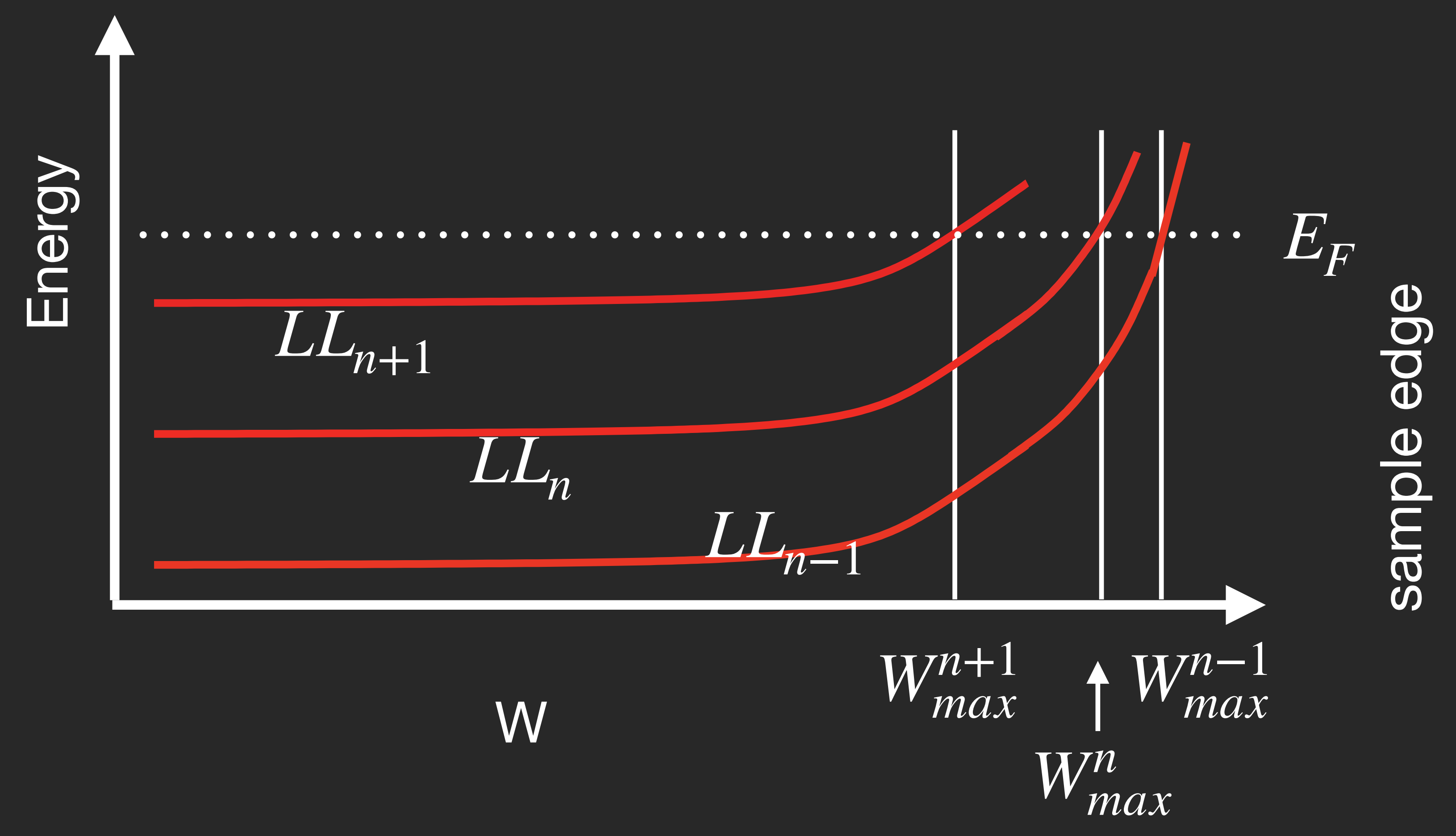
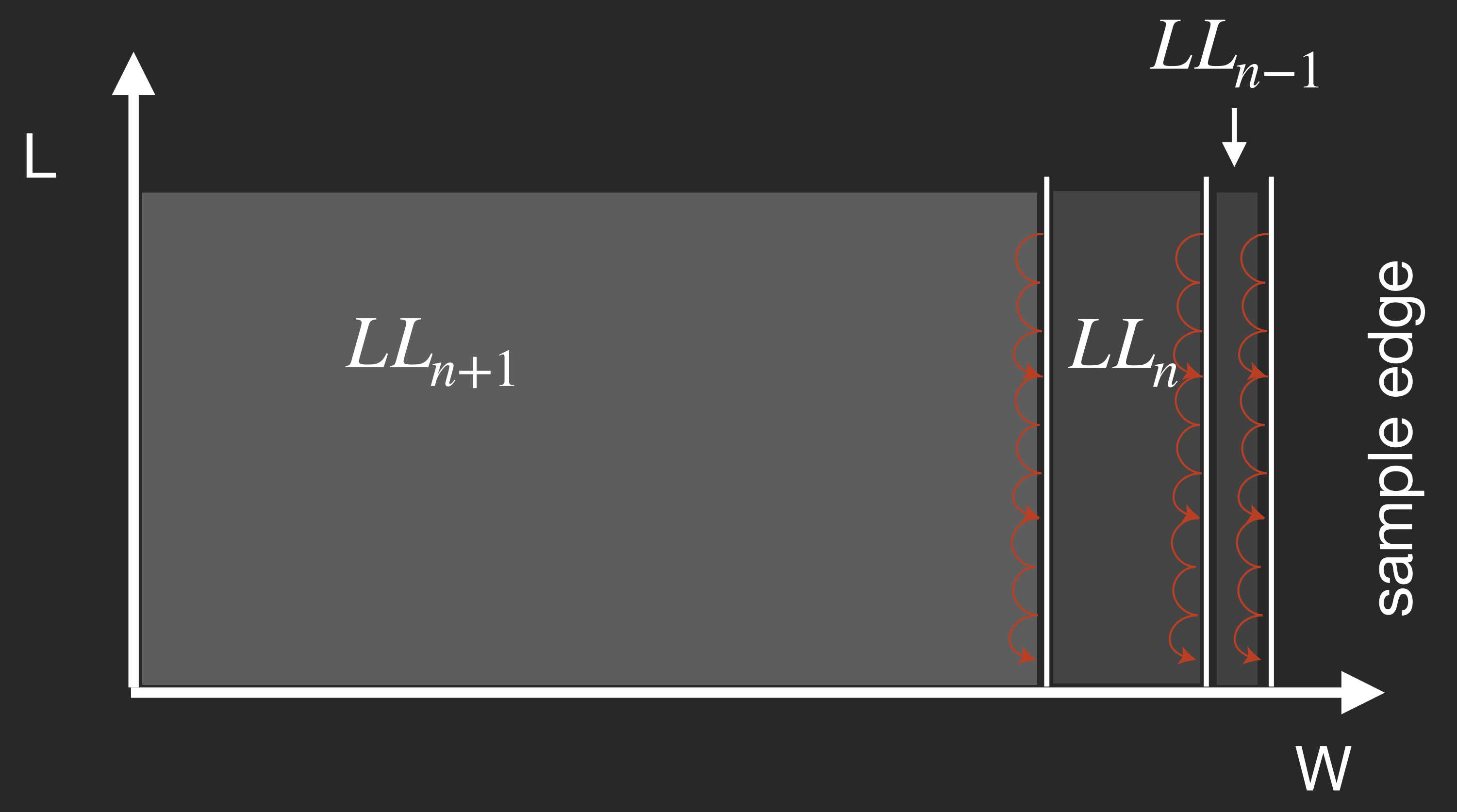


Edge-states due to sample-vacuum potential, and B-field.





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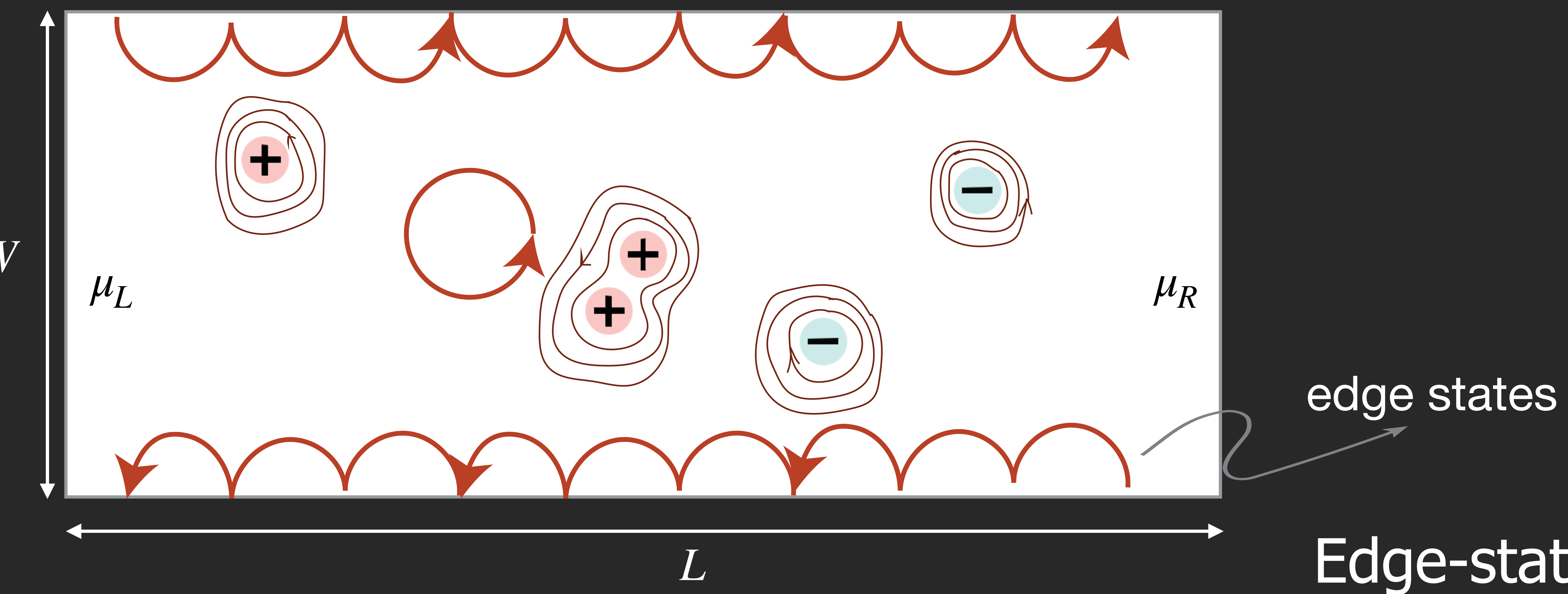

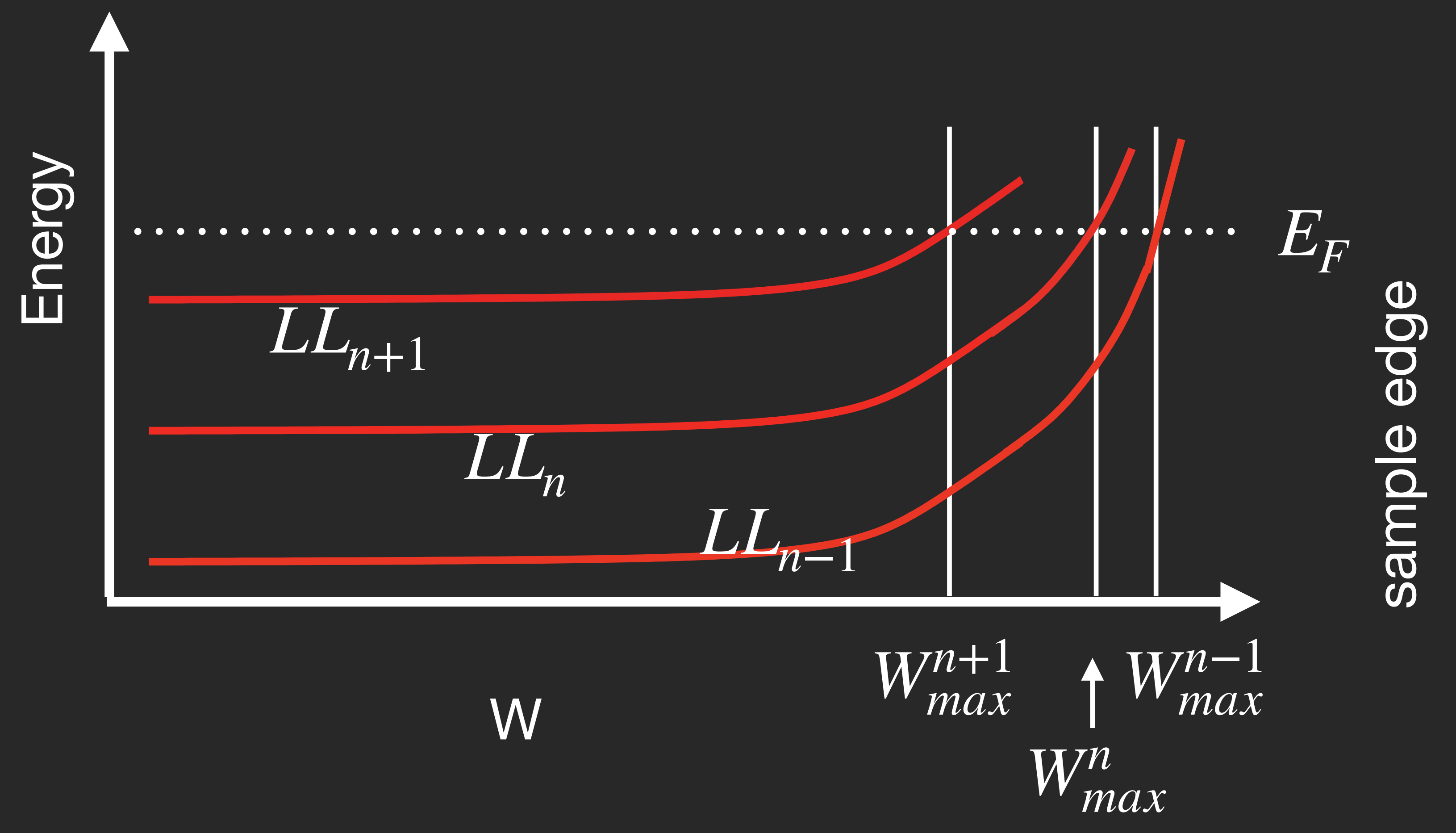

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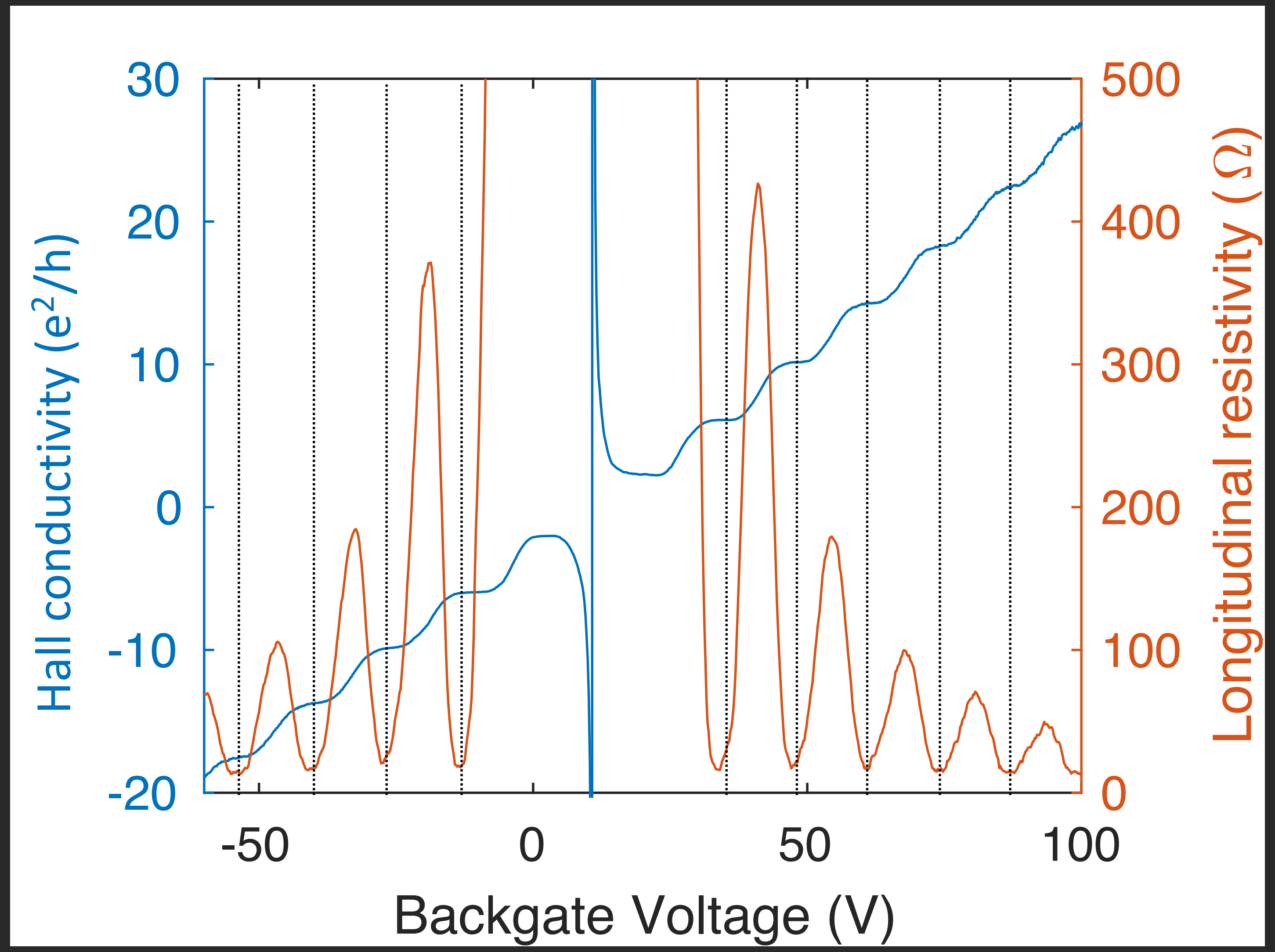
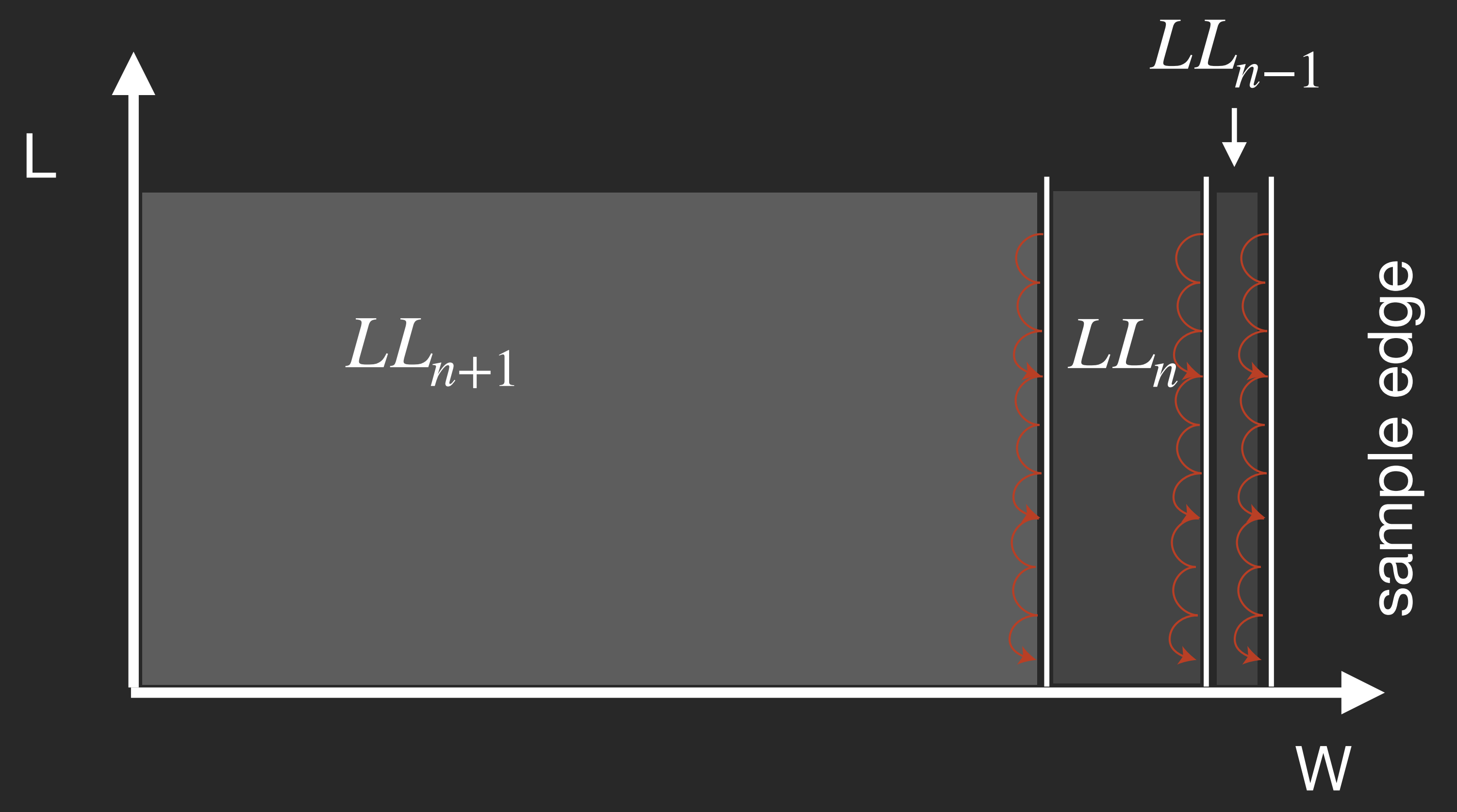


- The R_H plateaus are due to quantised DOS,
- The R_H slope is due to edge states.

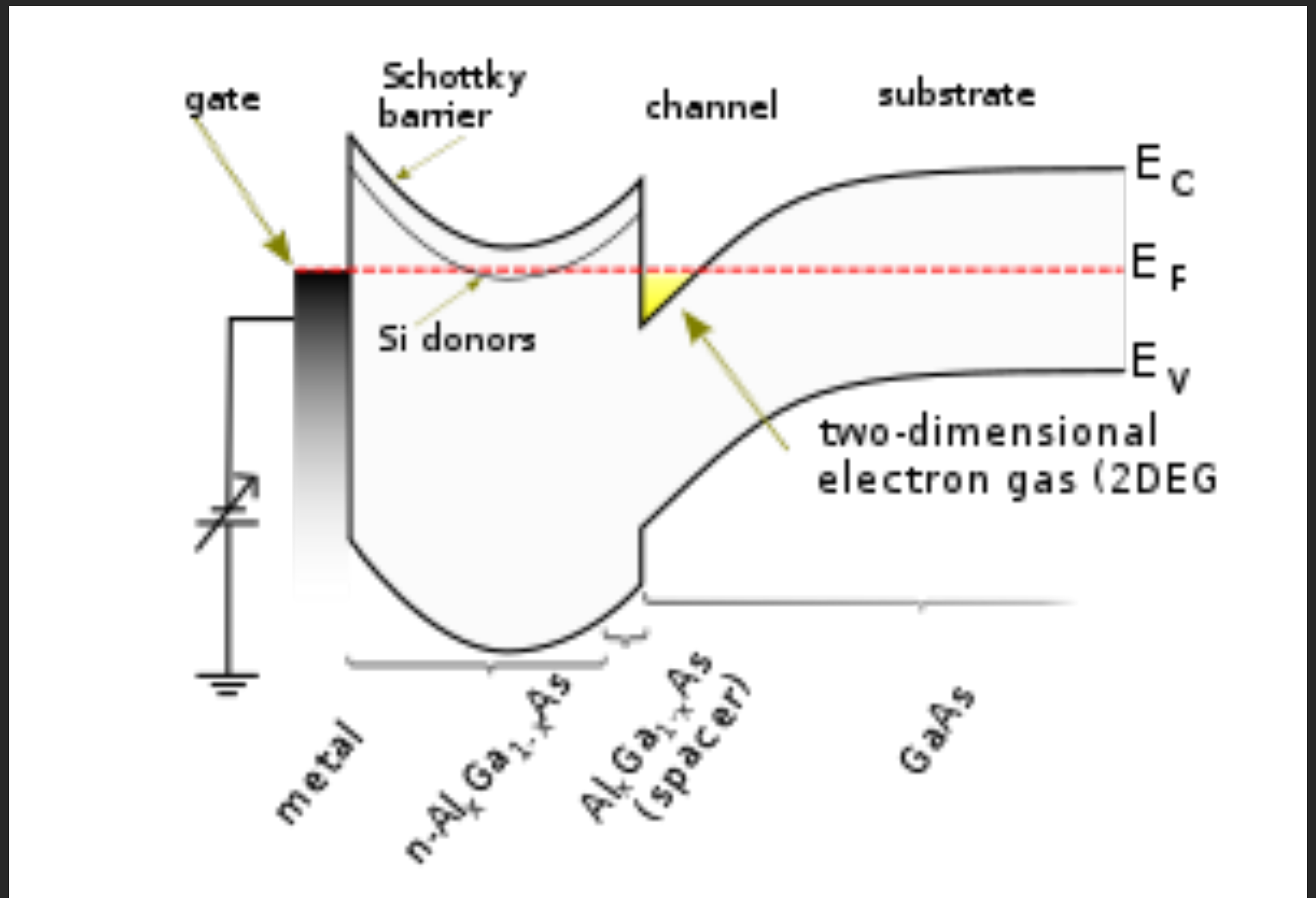


The III-V 2D Electron Gas (2DEG)

Initial integer quantum Hall (Stuttgart) - MOS structure

$\omega_c \tau > 1$ defines a critical magnetic field, $B_c \approx \dfrac{m}{e\tau} = \mu^{-1}$

With current III-V materials $\mu > 10^7 \mathrm{cm}^2/\mathrm{Vs}$ $B_c \approx 1\mathrm{mT}$



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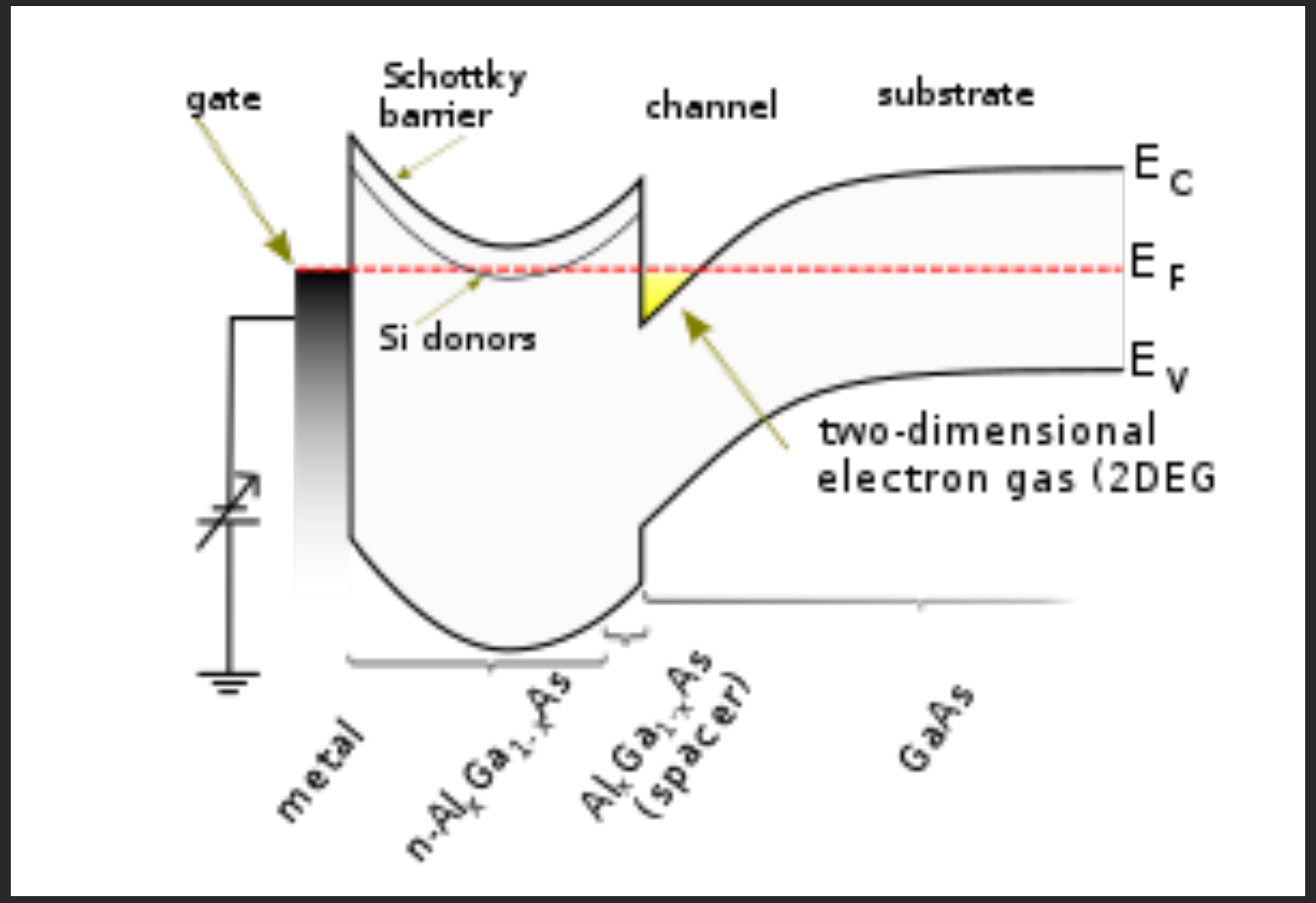

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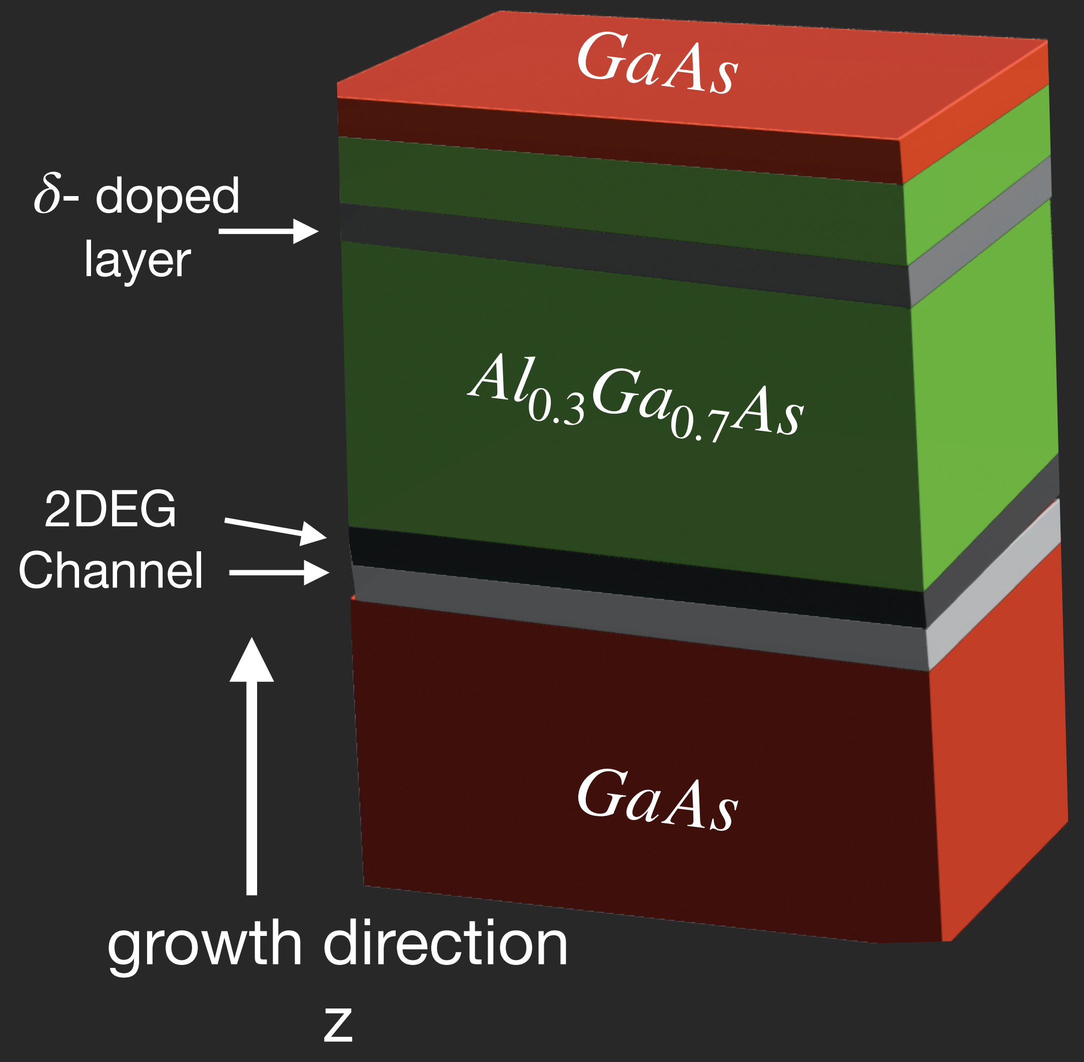

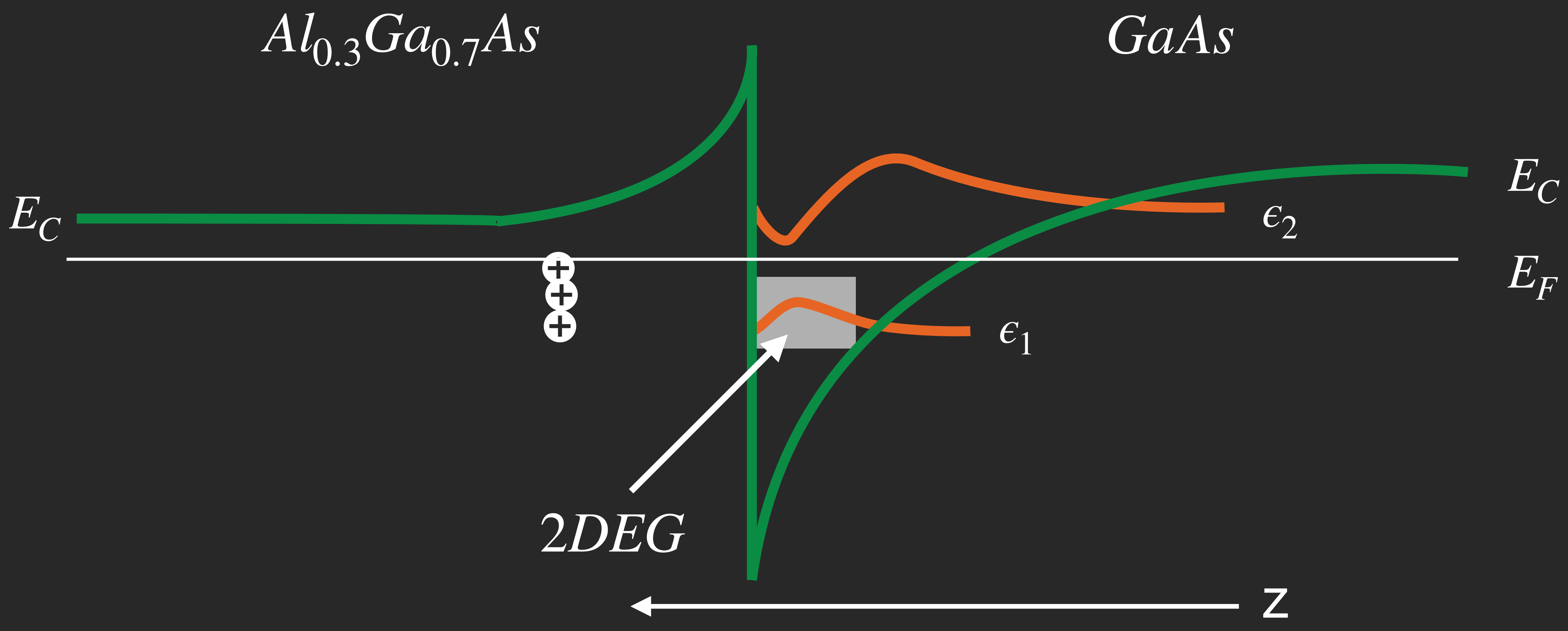

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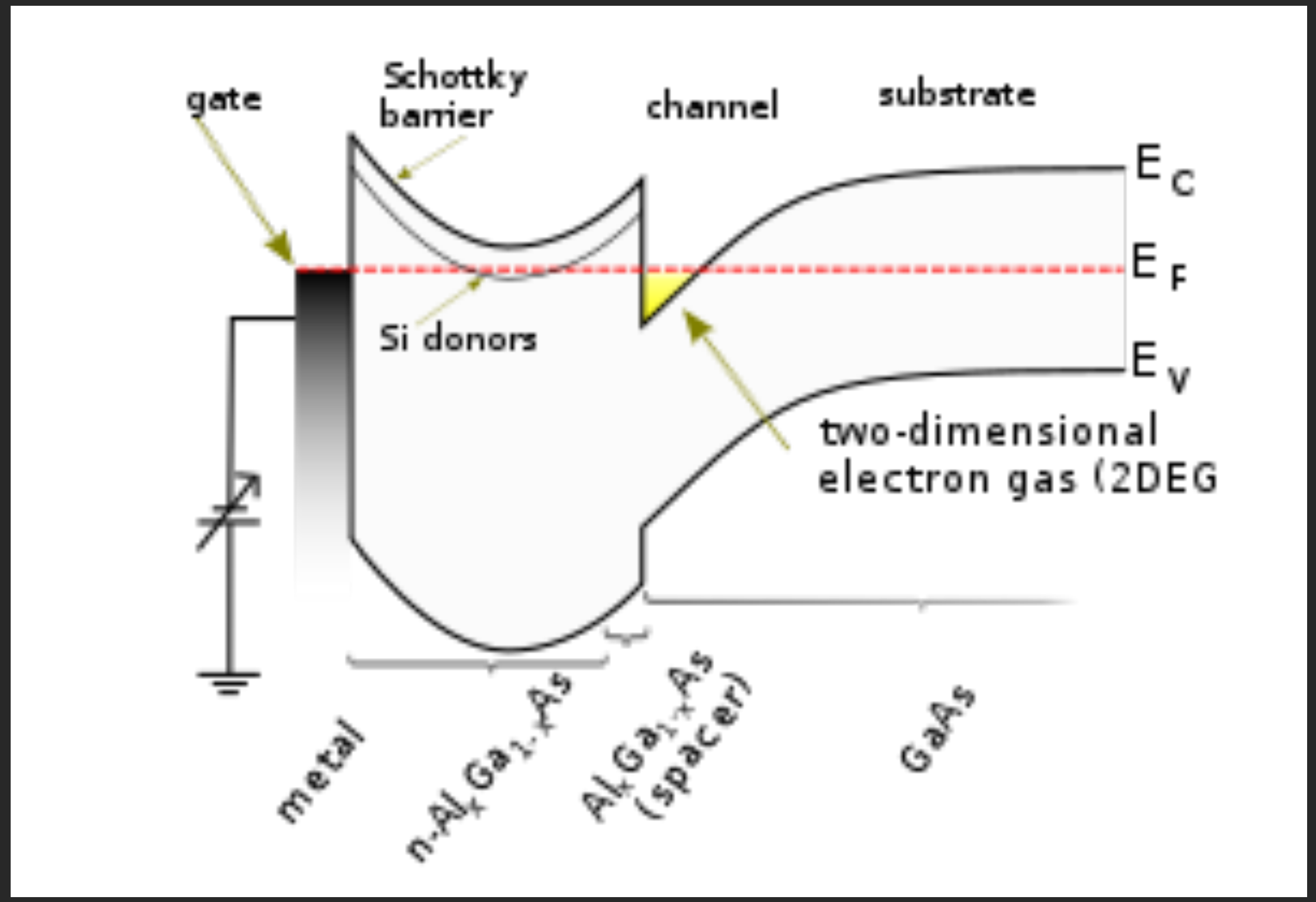

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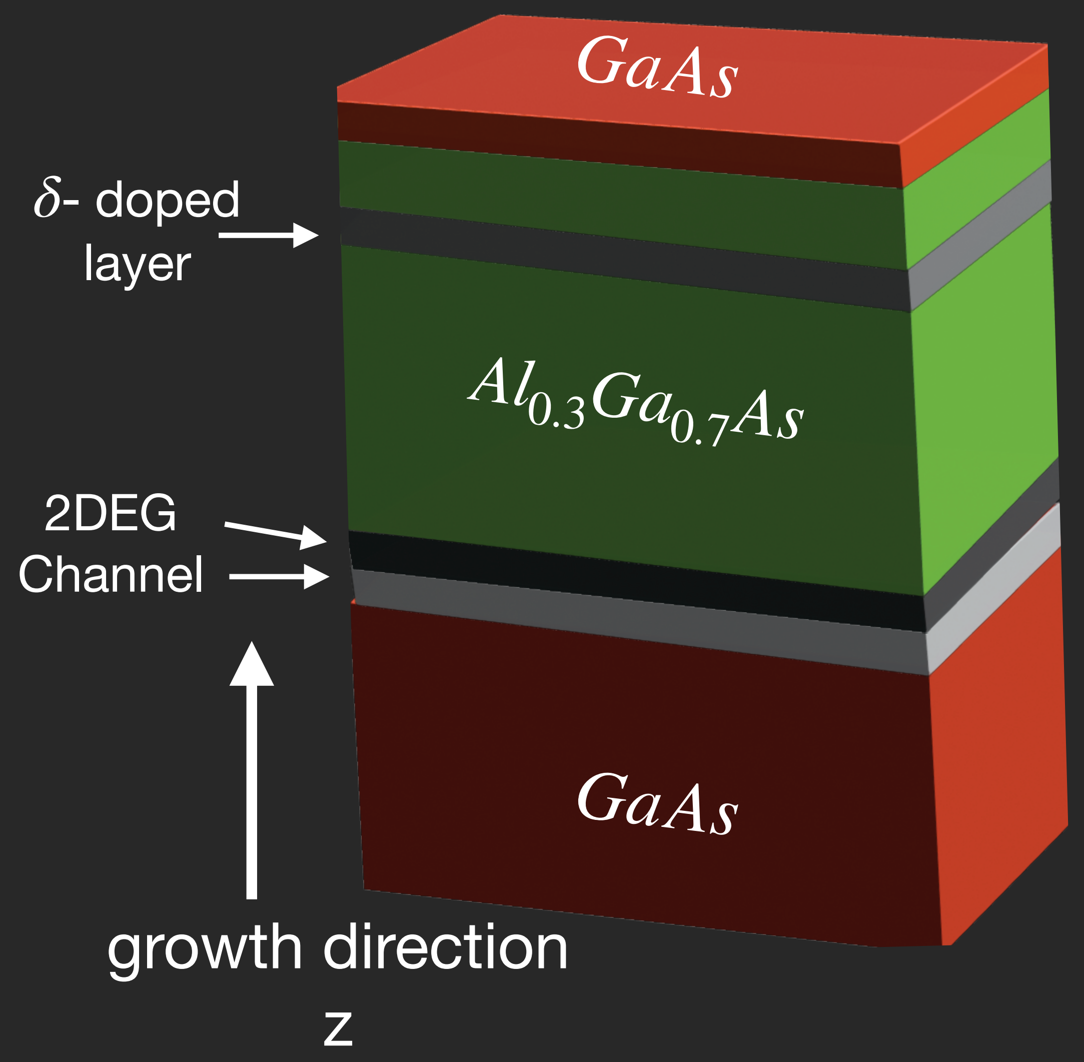

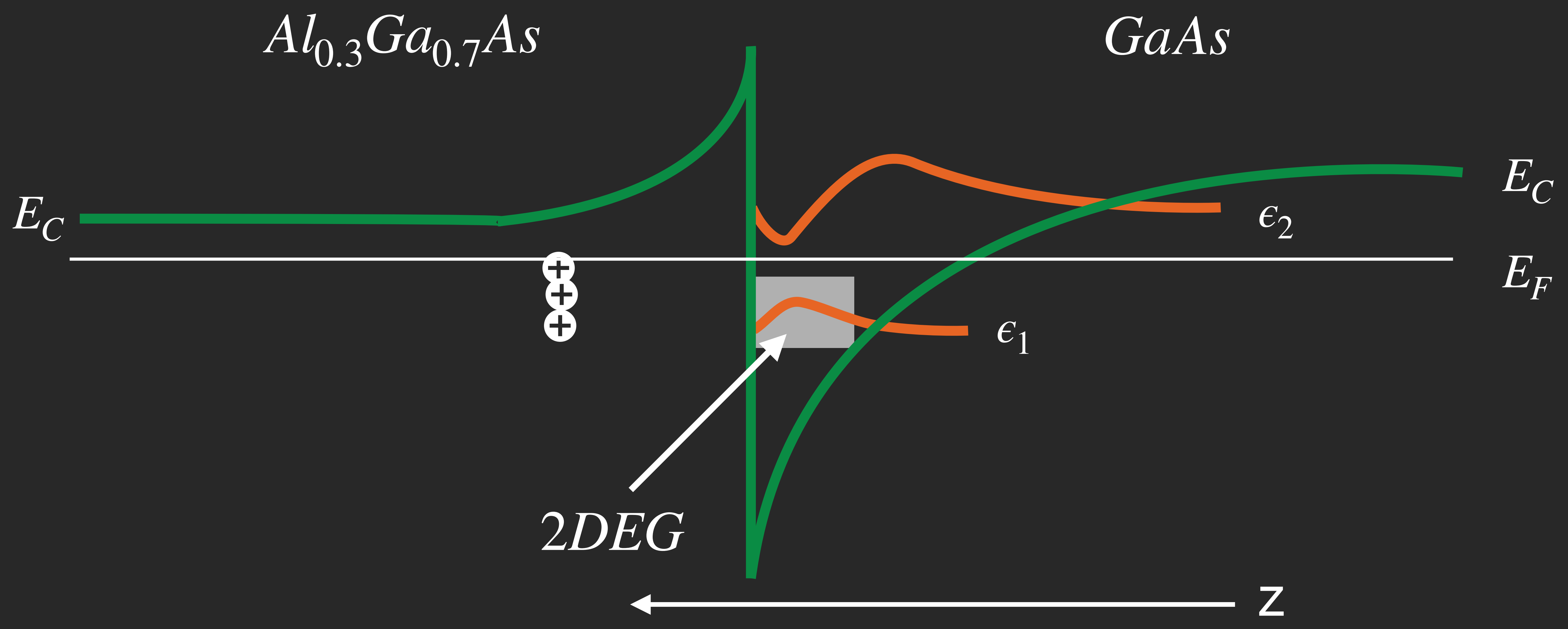

Let's look at a different way to make a 2-dimensional electron gas: Using Graphene

Part II: Graphene

Allotropes of carbon

all images: www.wikipedia.com

- Two “natural” forms of carbon—they are 3 dimensional:
  Diamond and **Graphite** have been well known for ages.
  One is one of the hardest of materials, the other, one of the softest.

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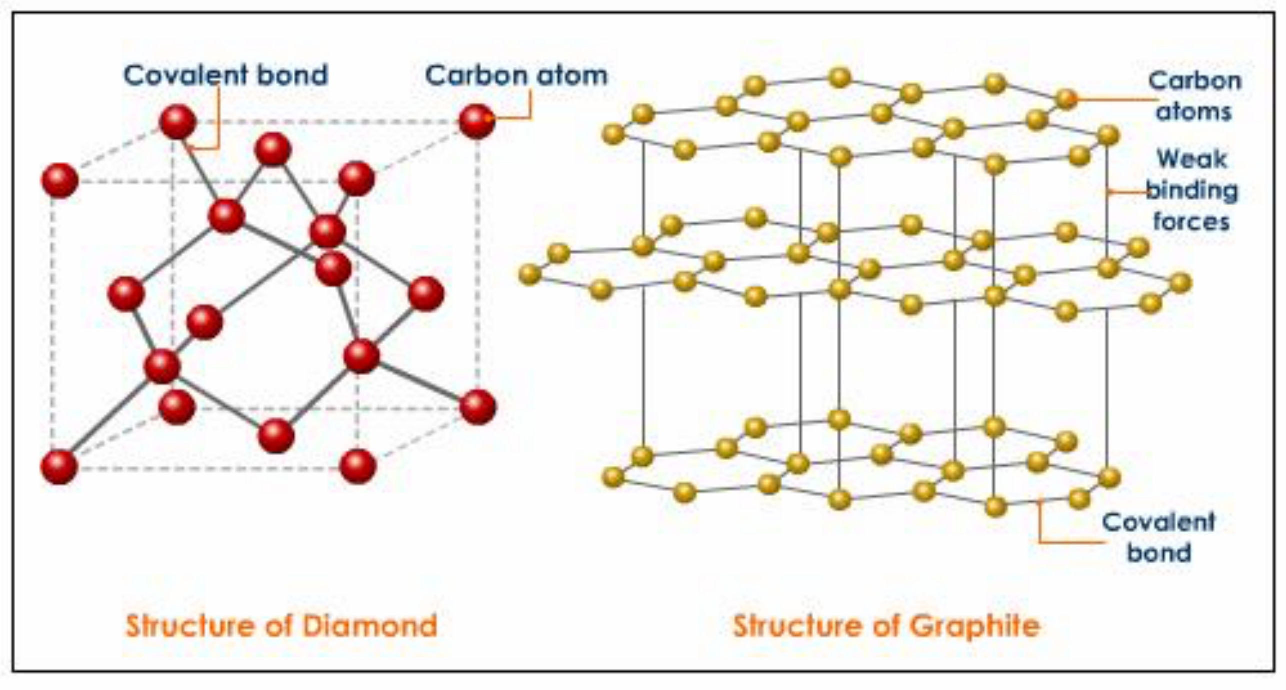

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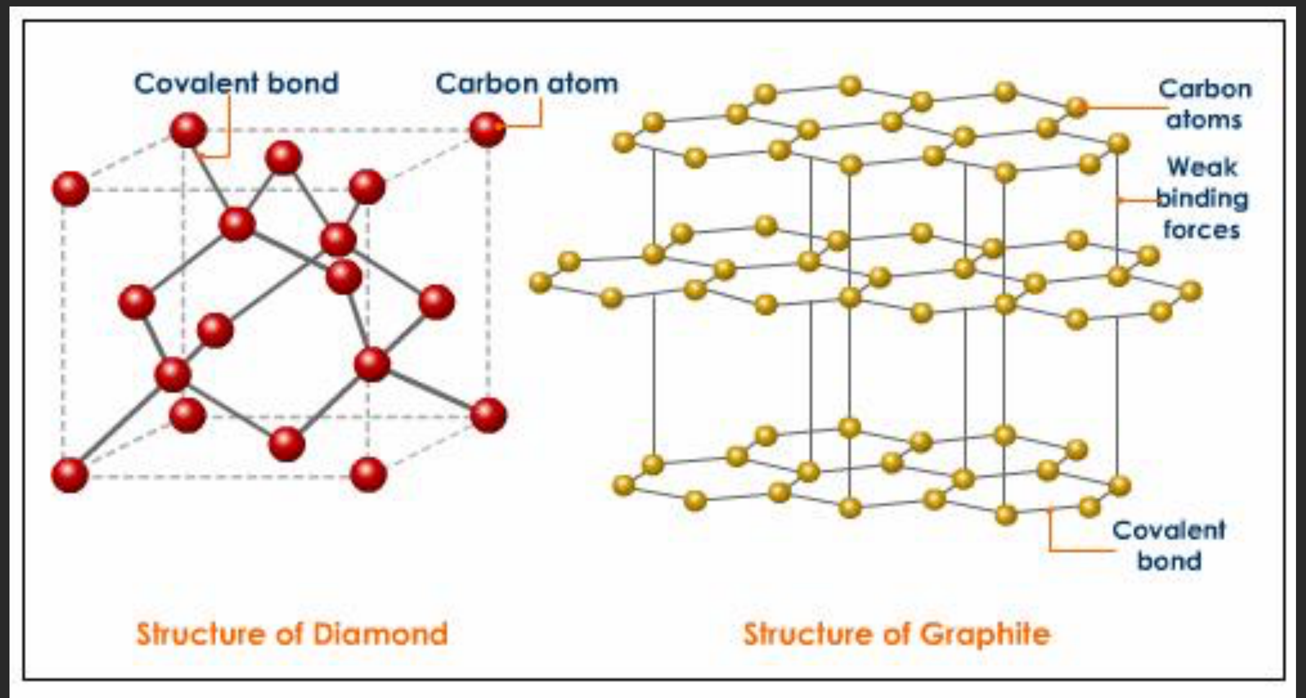

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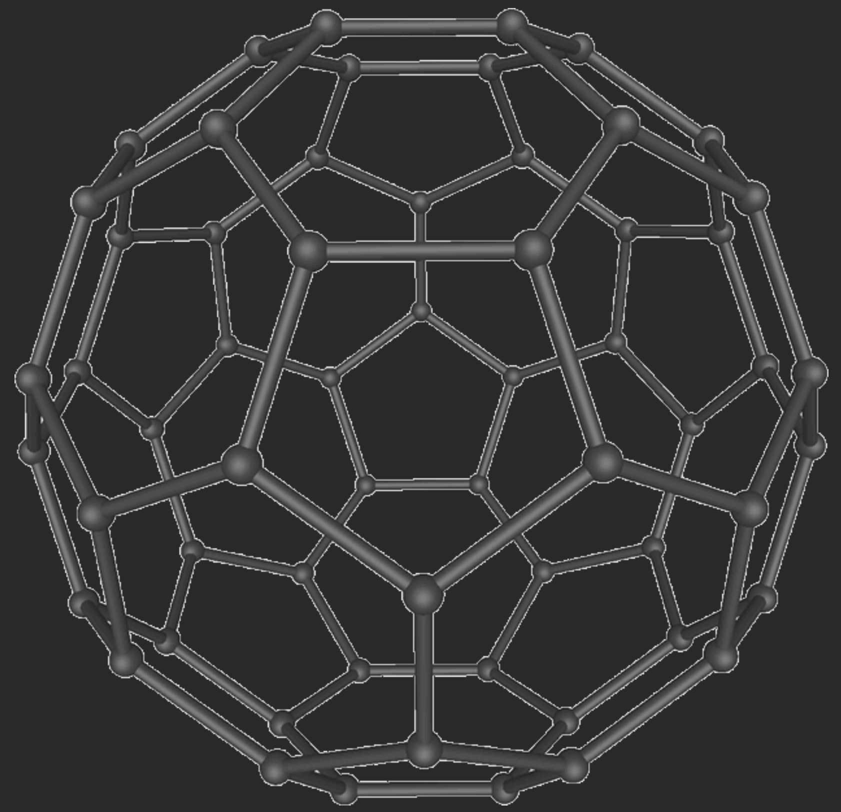

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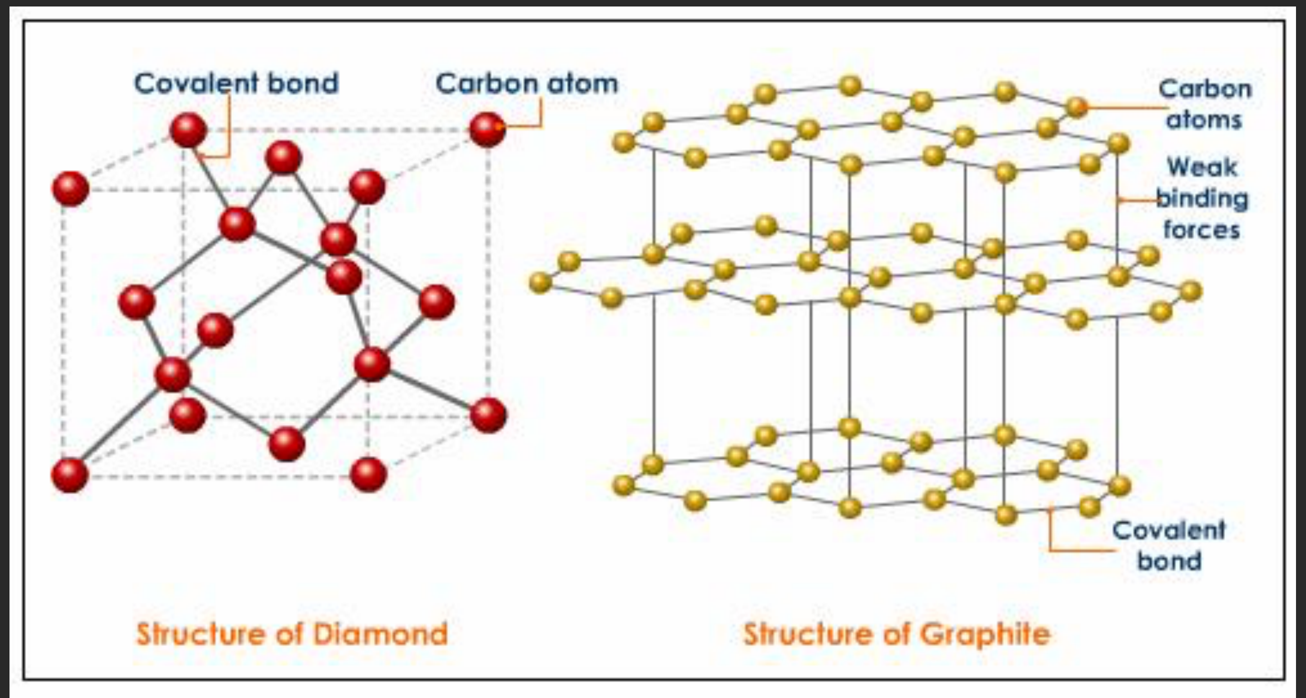

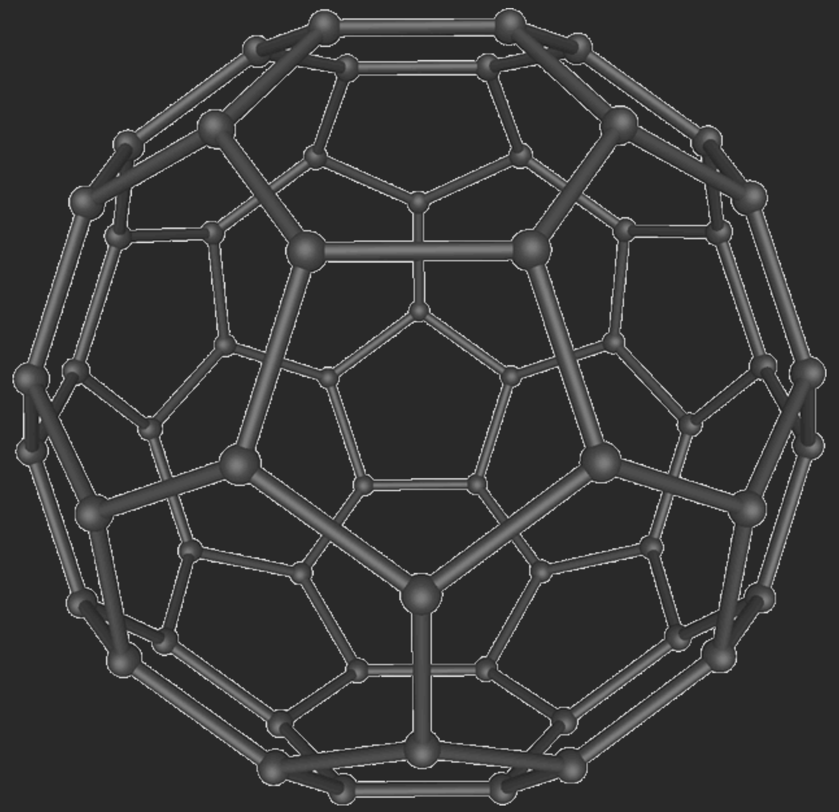

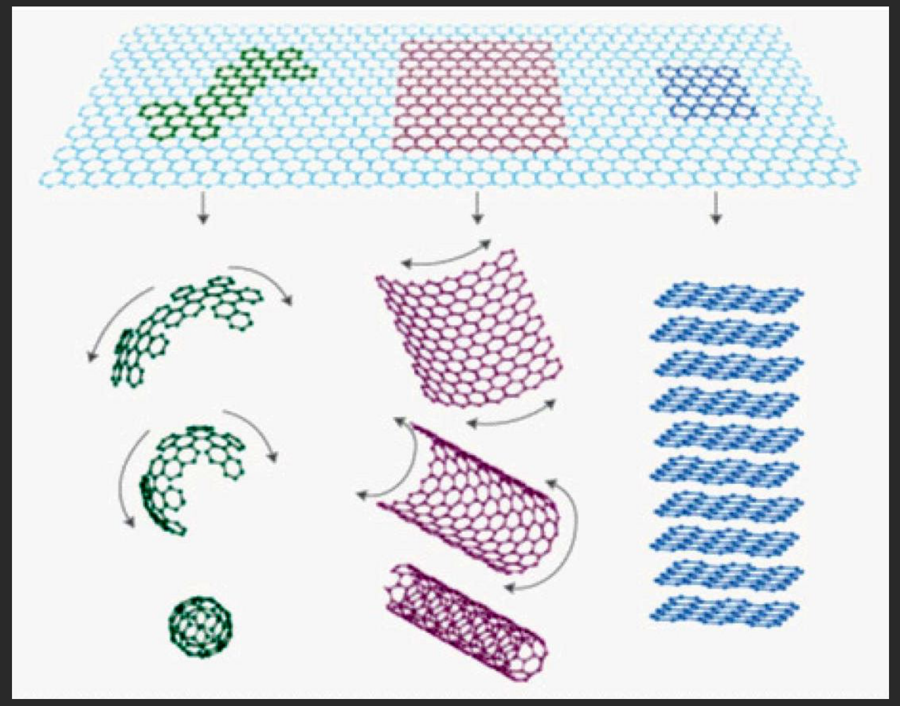

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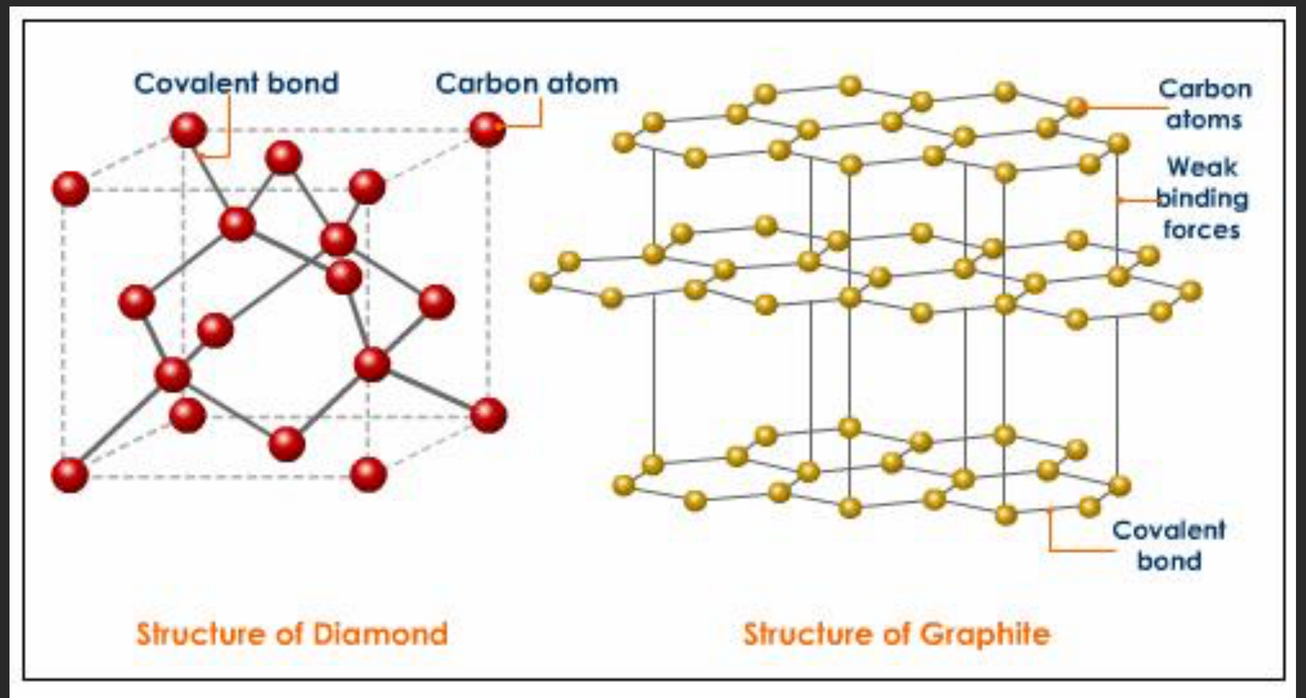

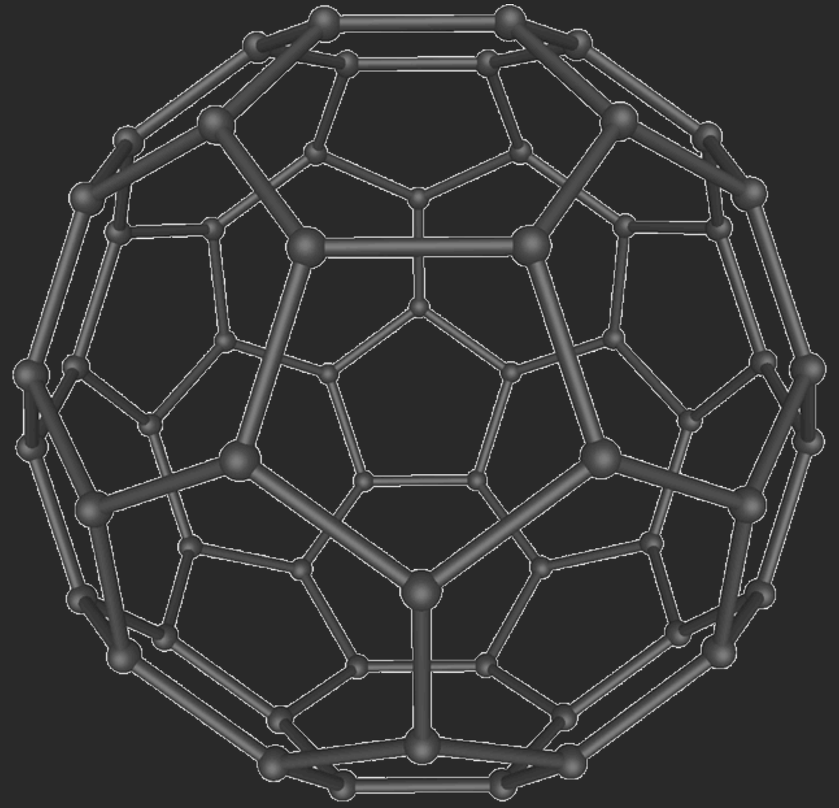
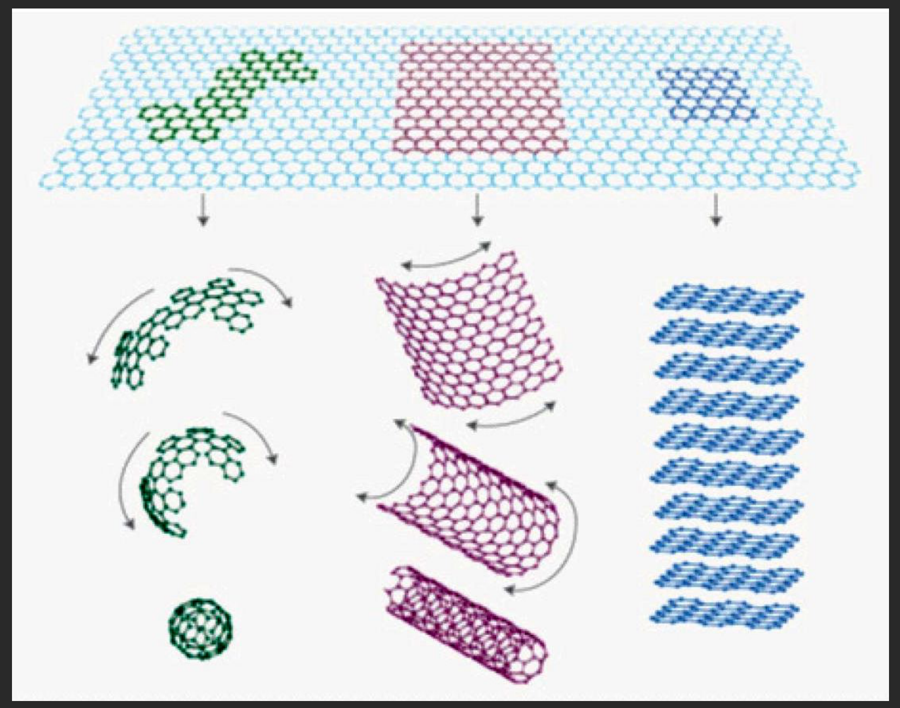

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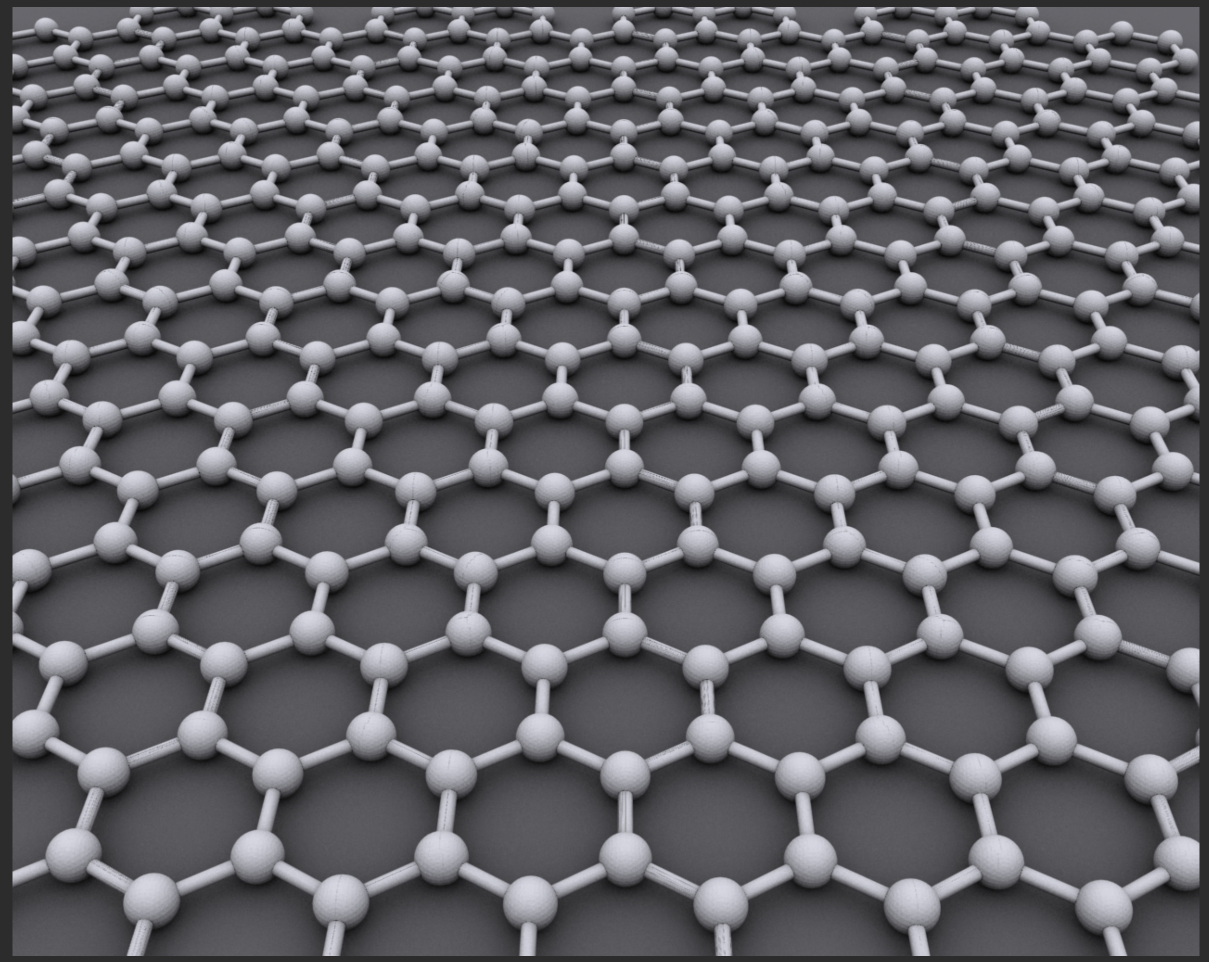
- Expect for diamond (sp^3), all allotropes are based on a 2D layer, we know as graphene.

The curious case of graphene



An isolated single 2D layer, graphene, was not seen until 2004.

K. S. Novoselov, *et al., Science*. **306,** 666 (2004).

Most believed 2D layers were not stable against thermal vibration.

sp^2 hybridise, plane bonding. Remaining $p-$orbital out of plane

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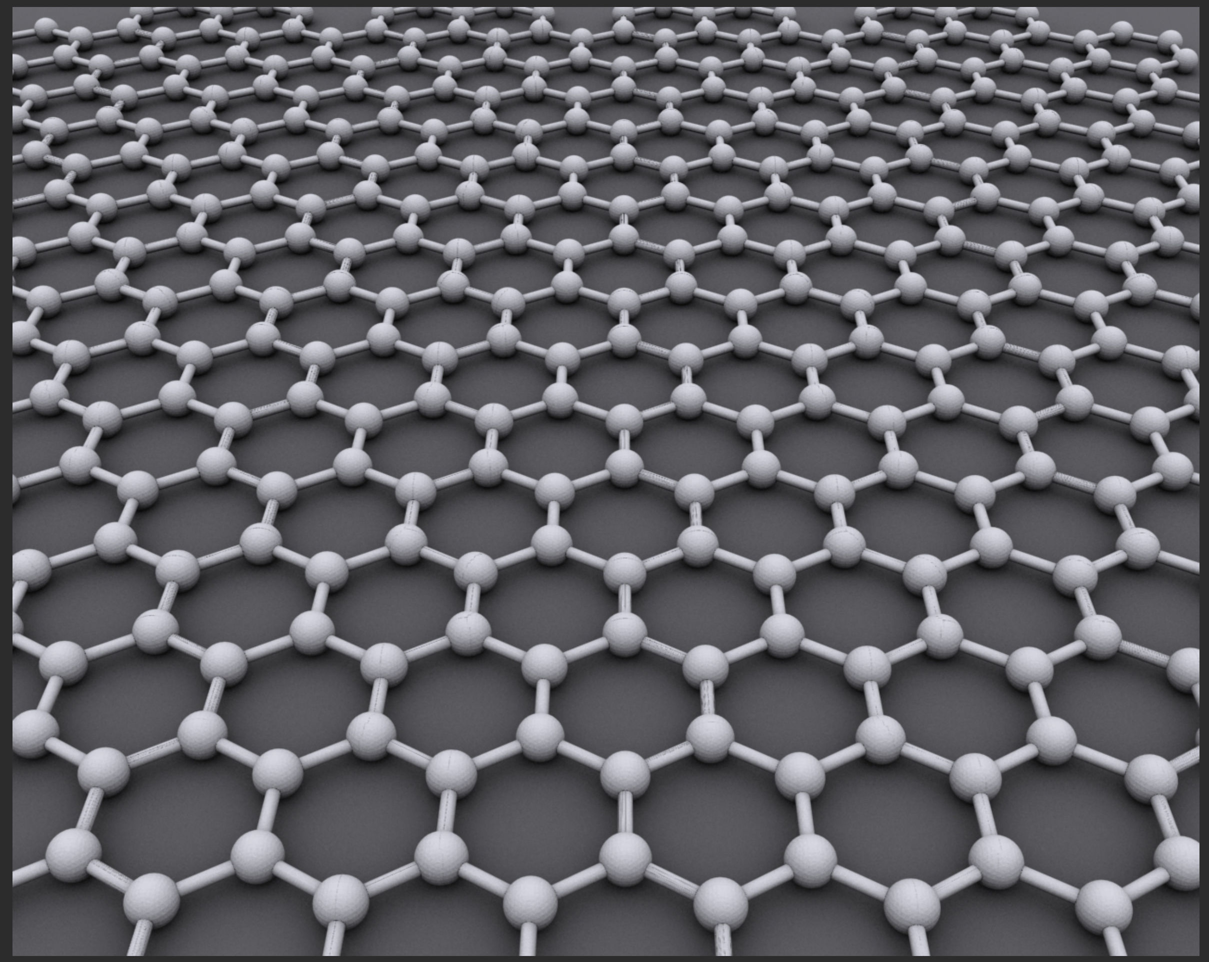

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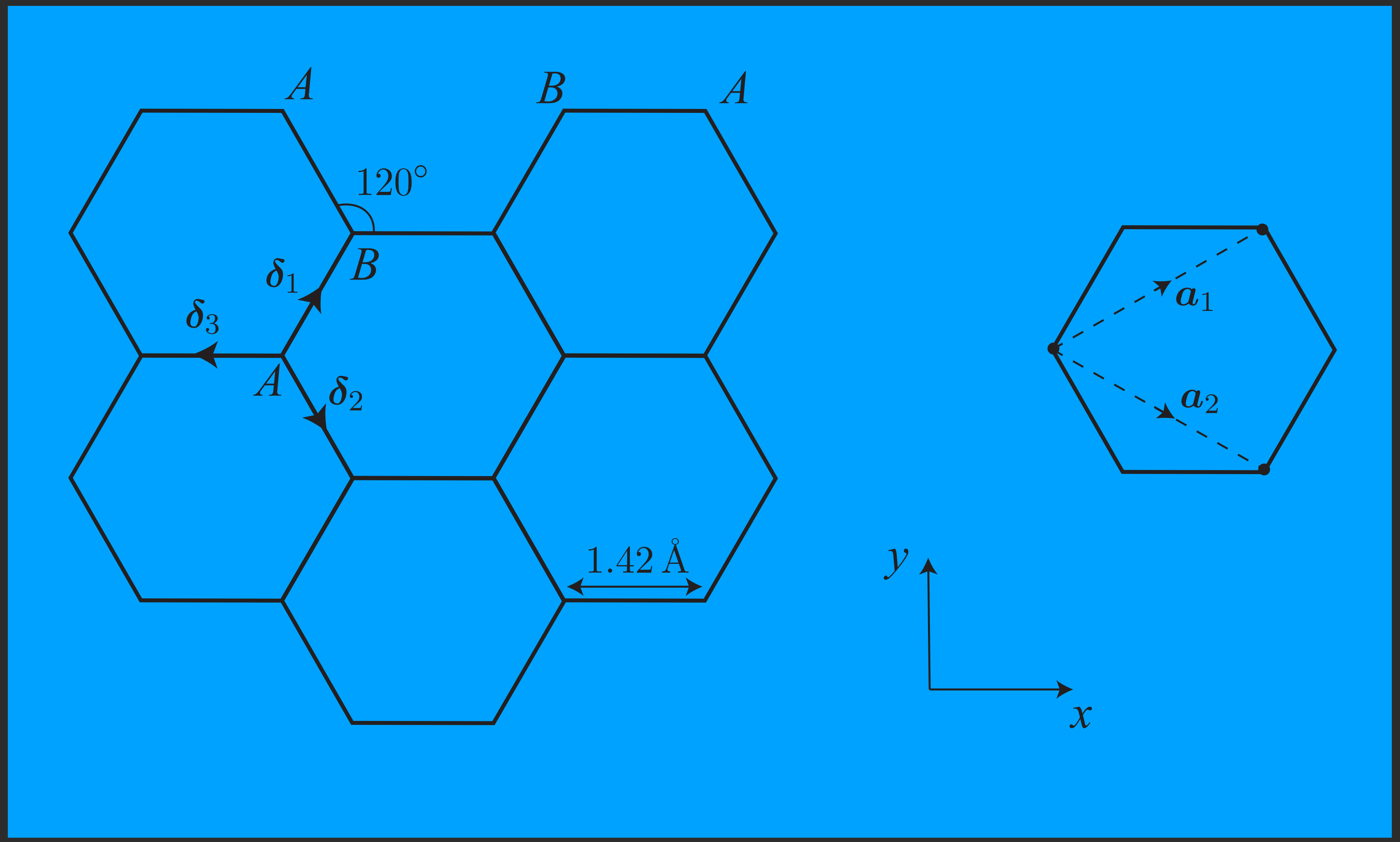
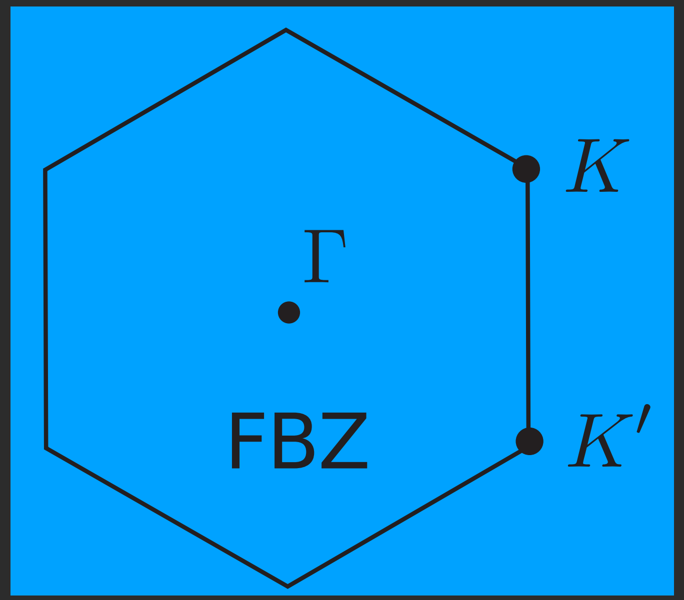


Two non-equivalent sublattices,
A and B, are mirror symmetric.

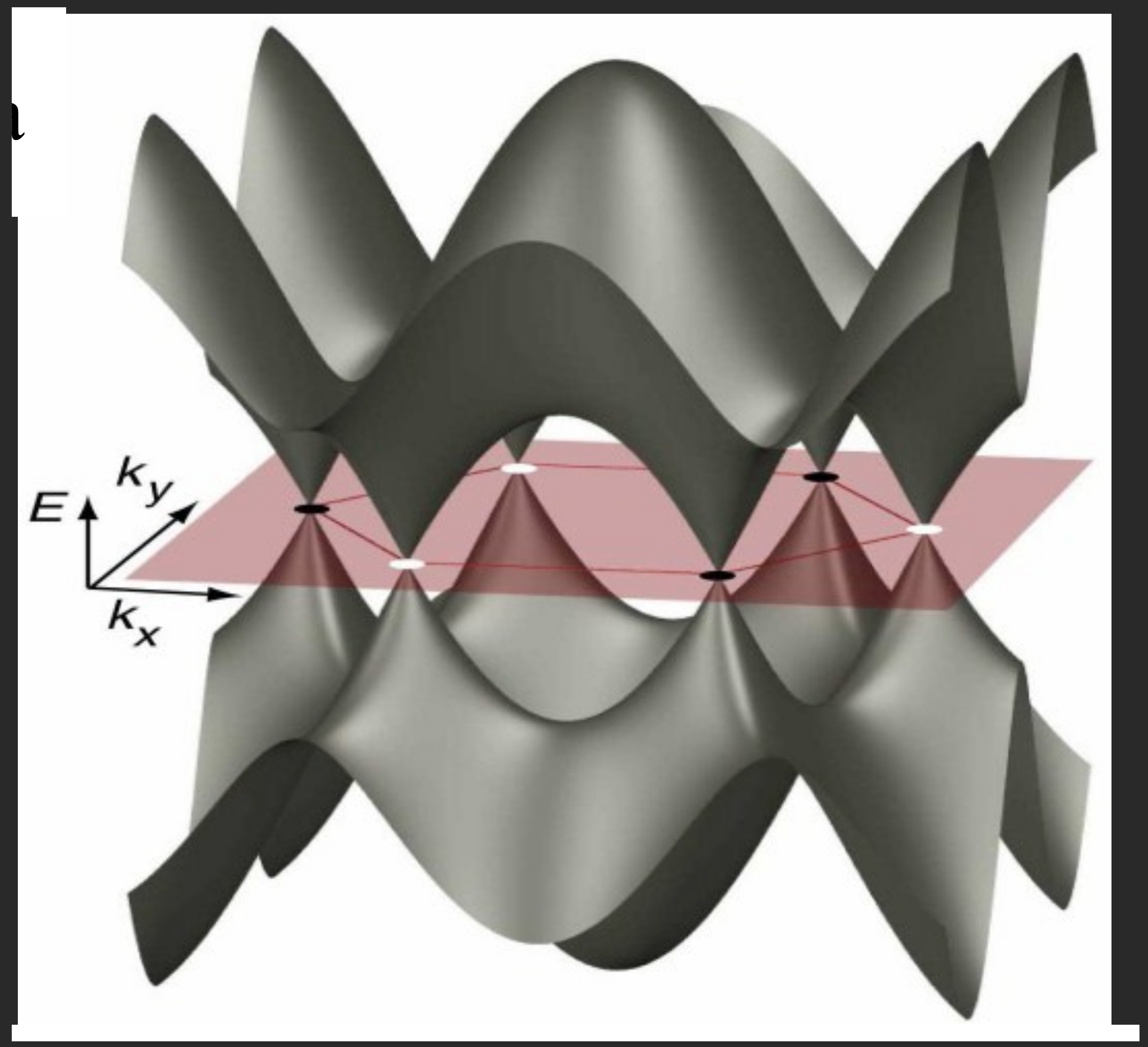


Reciprocal lattice — First Brillouin zone (FBZ),

Each sublattice point, *K* and *K*` in FBZ are :

$$K = \frac{2\pi}{3a}(1, \frac{1}{\sqrt{3}}), \qquad K' = \frac{2\pi}{3a}(1, -\frac{1}{\sqrt{3}})$$

Graphene band structure



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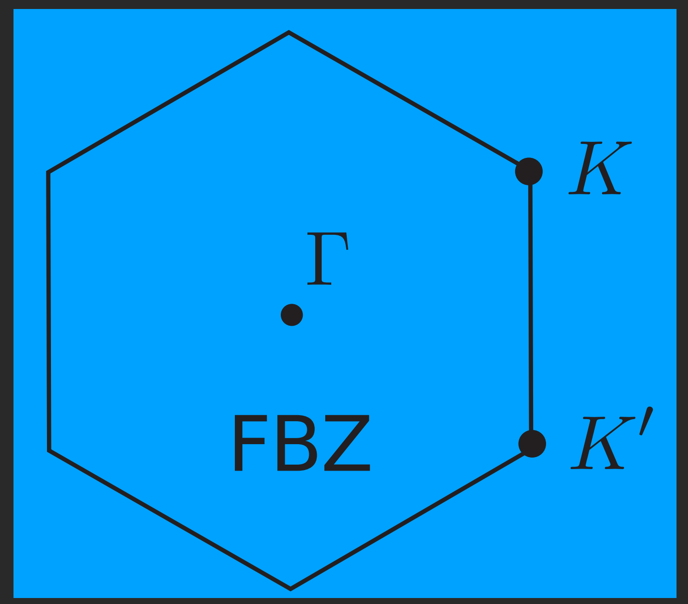

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- With no doping, no DOS at E_f.
- A perfect semi-metal.

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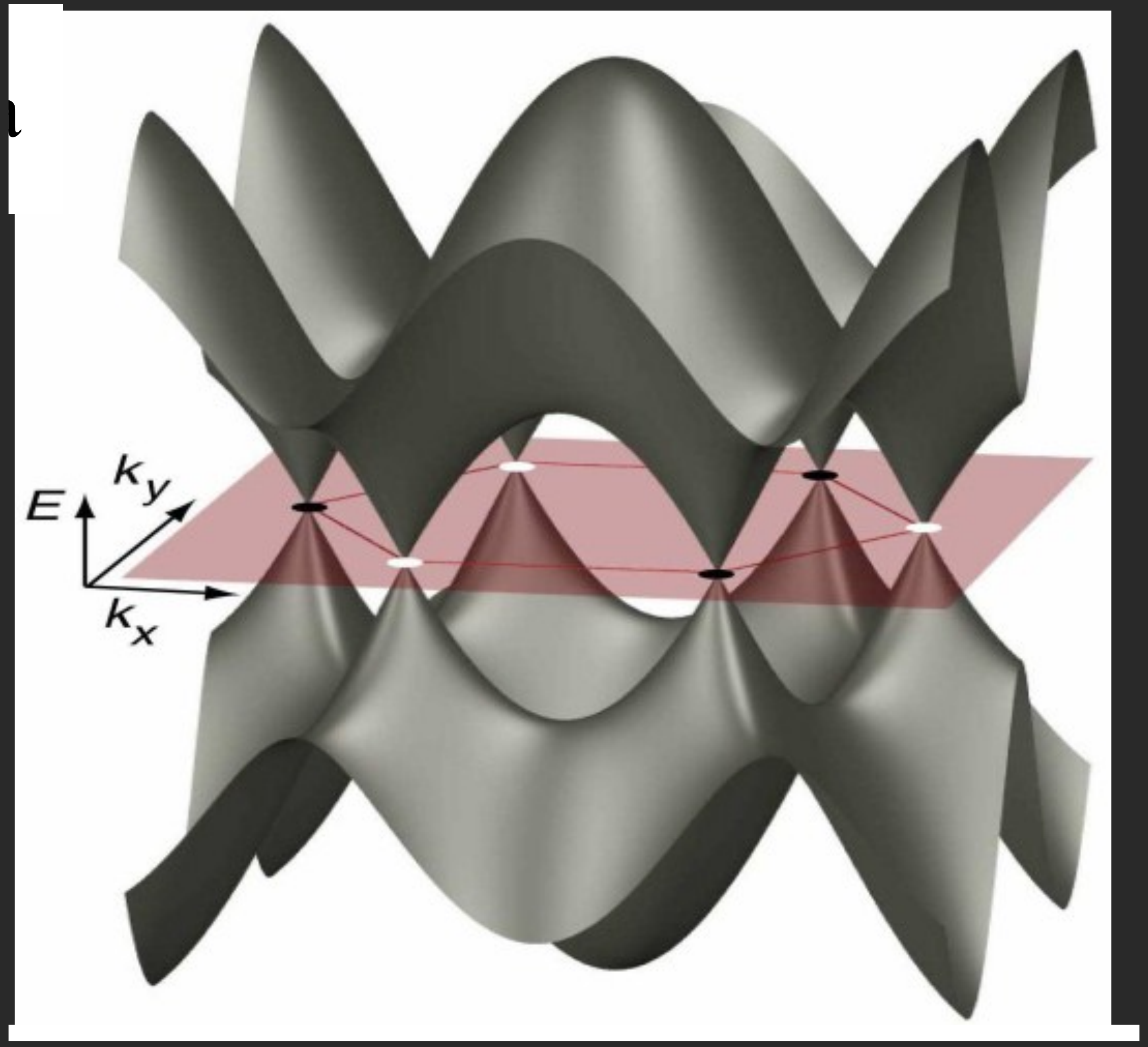

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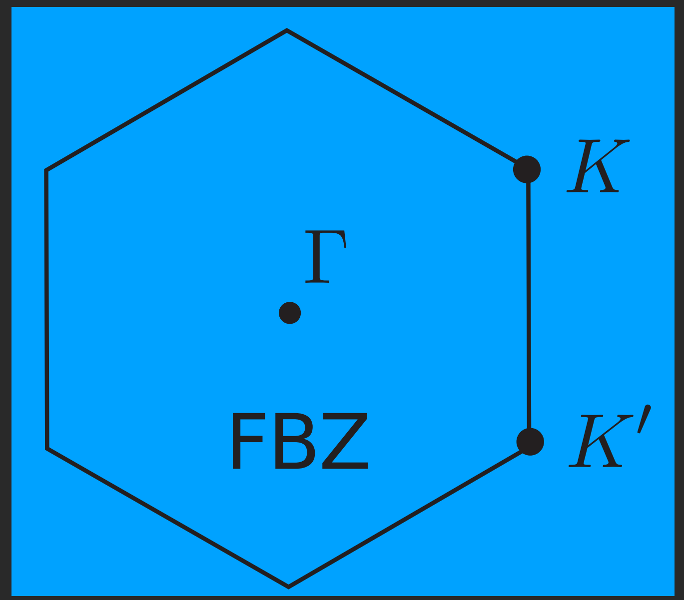

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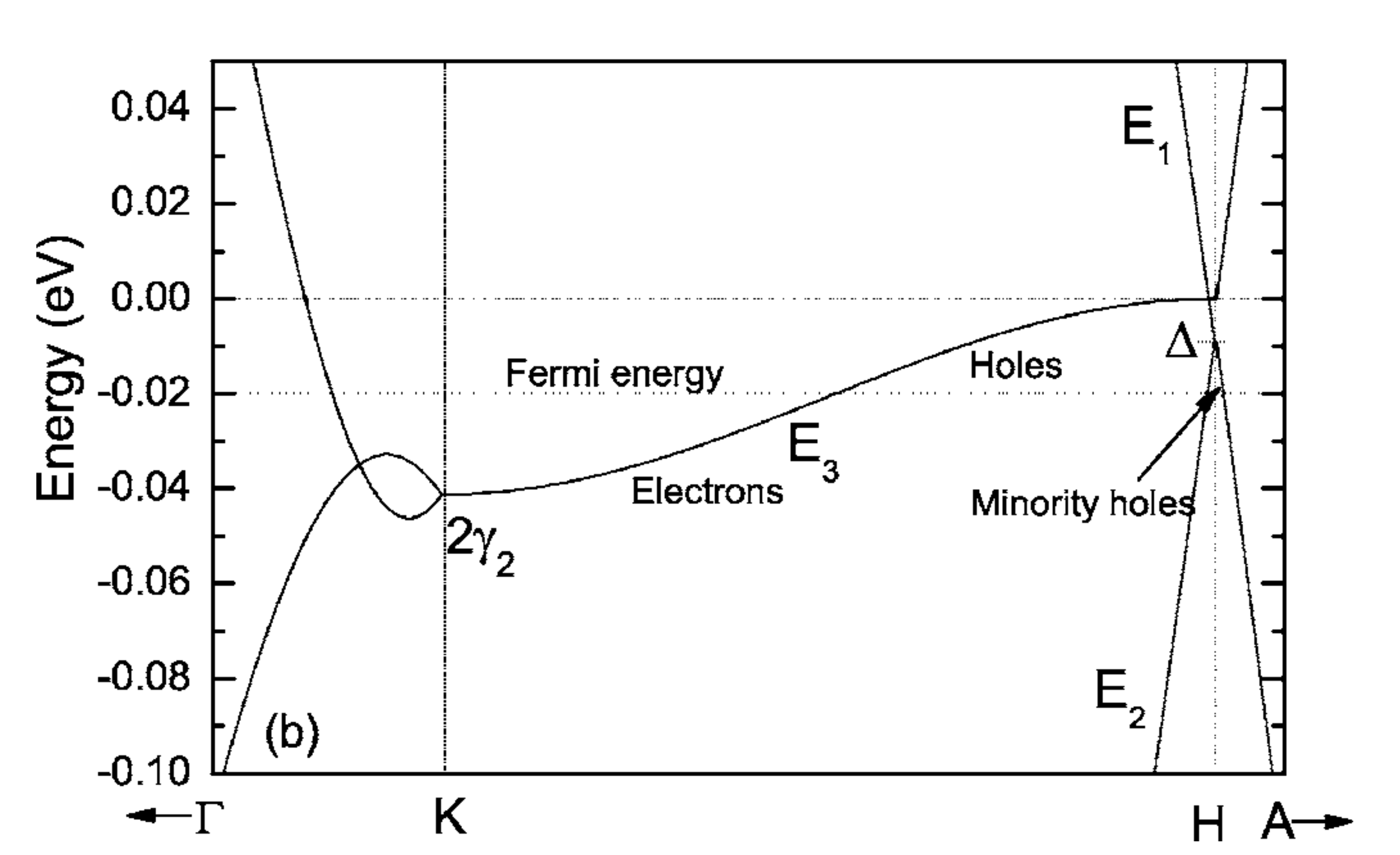
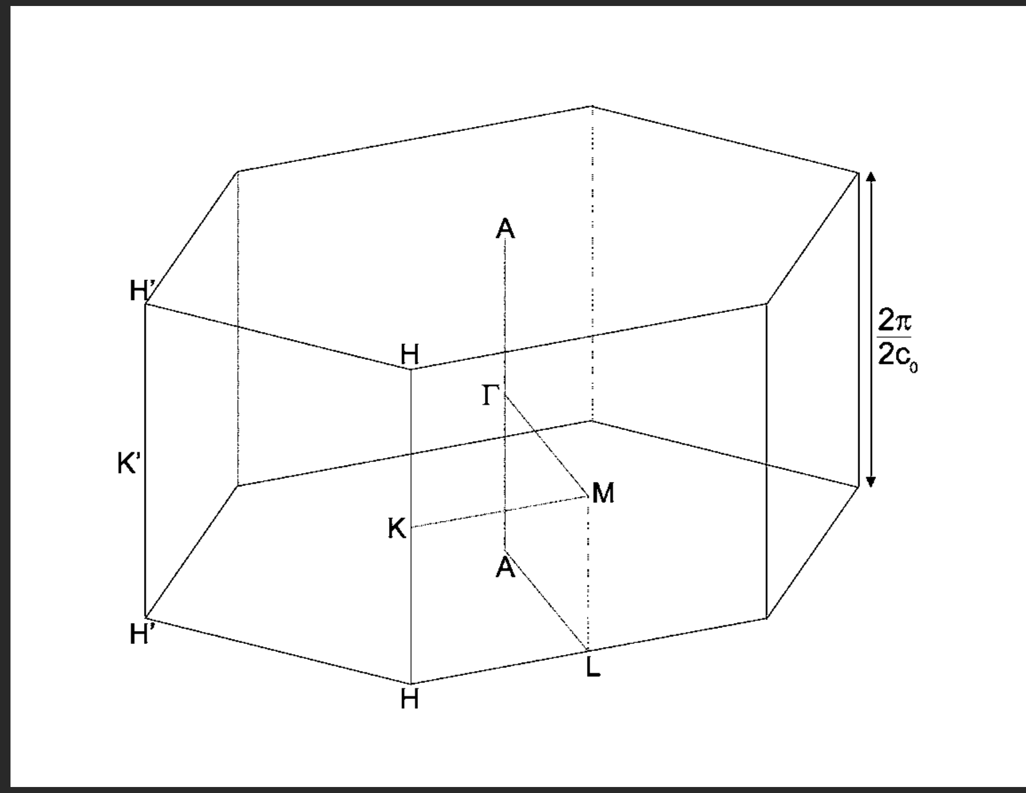
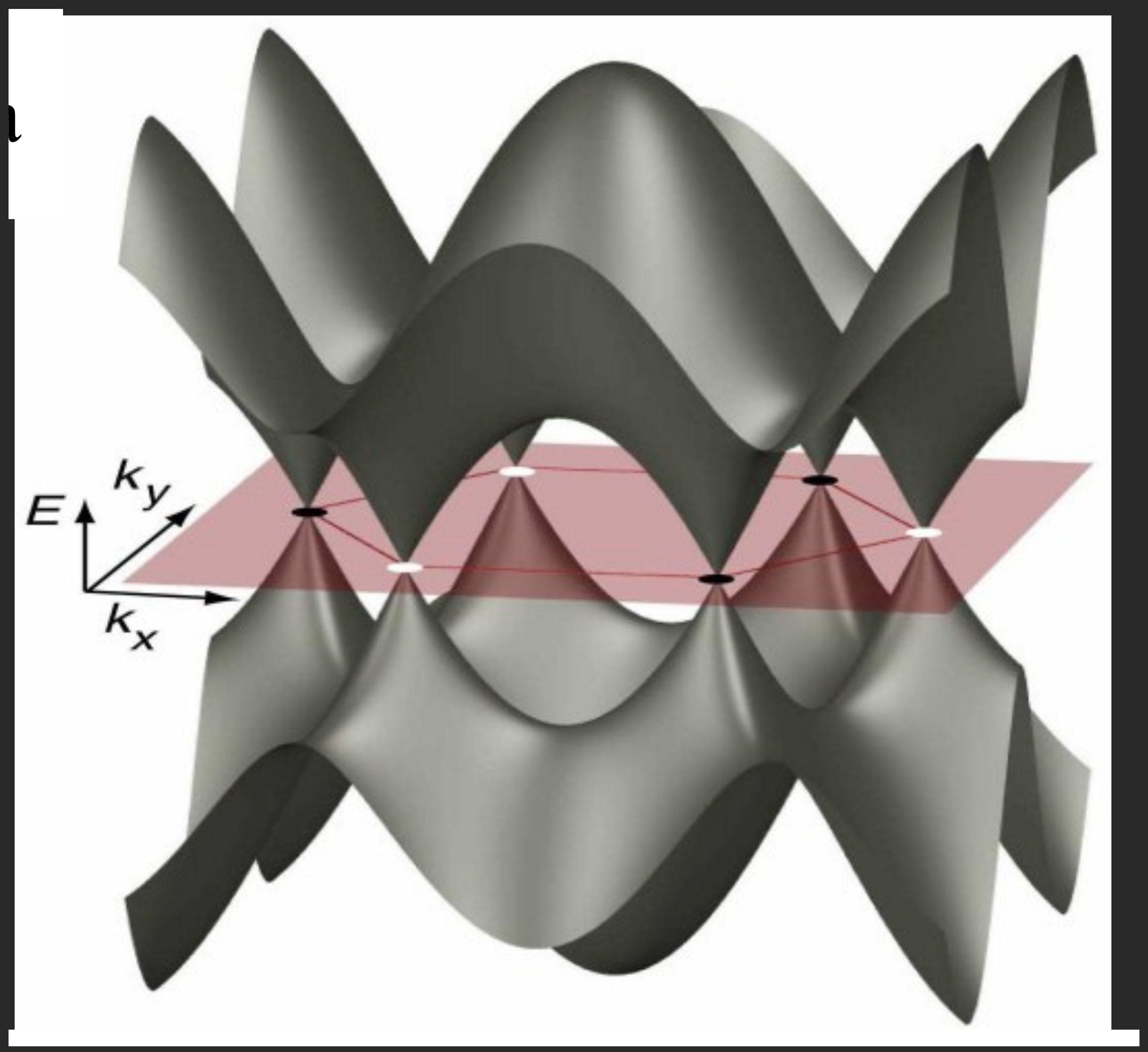
Reference: Graphite (bulk)



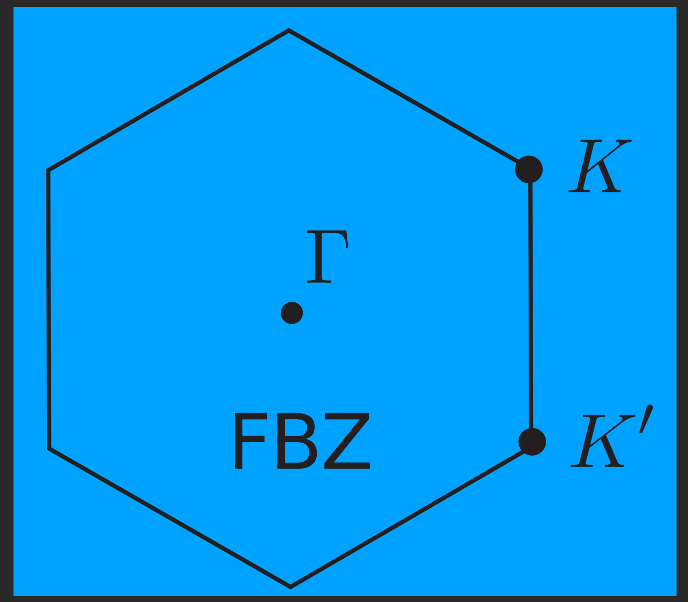
Partoens & Peeters, PRB, 74, 075404 2006



Graphene band structure

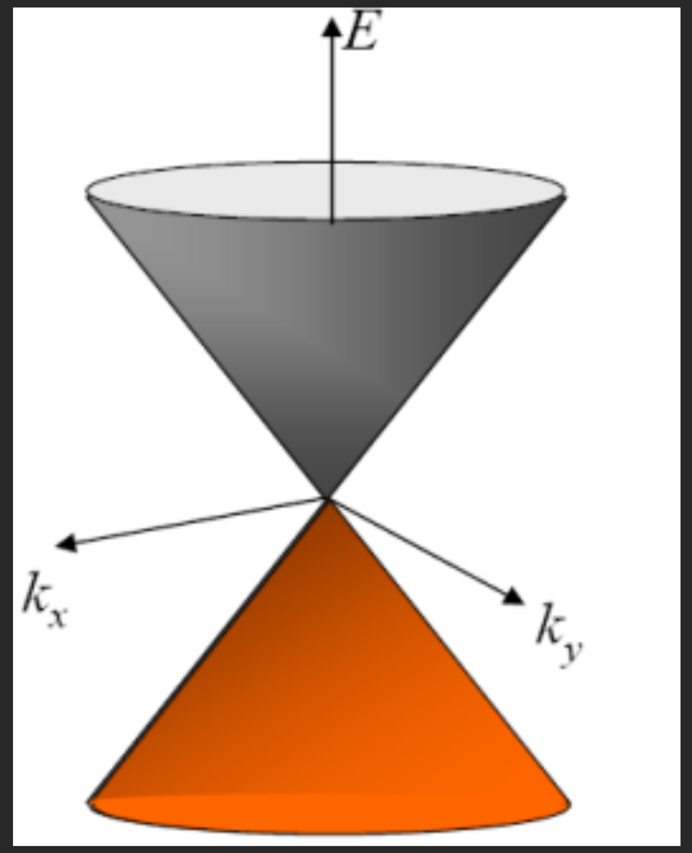


adapted from
C.W.J. Bennakker, Rev.Mod.Phys., 80, 1337 (2008)



- The valance and conduction bands meet at K, K` points.
- With no doping, no DOS at *E_f*.
- A perfect semi-metal.

$$\epsilon(q) \approx \hbar \nu_F (q_x - i q_y) \ + 0\ (1 + q/K)^2; \quad \nu_F = \frac{3ta}{2} \approx 10^6\ m/sec$$

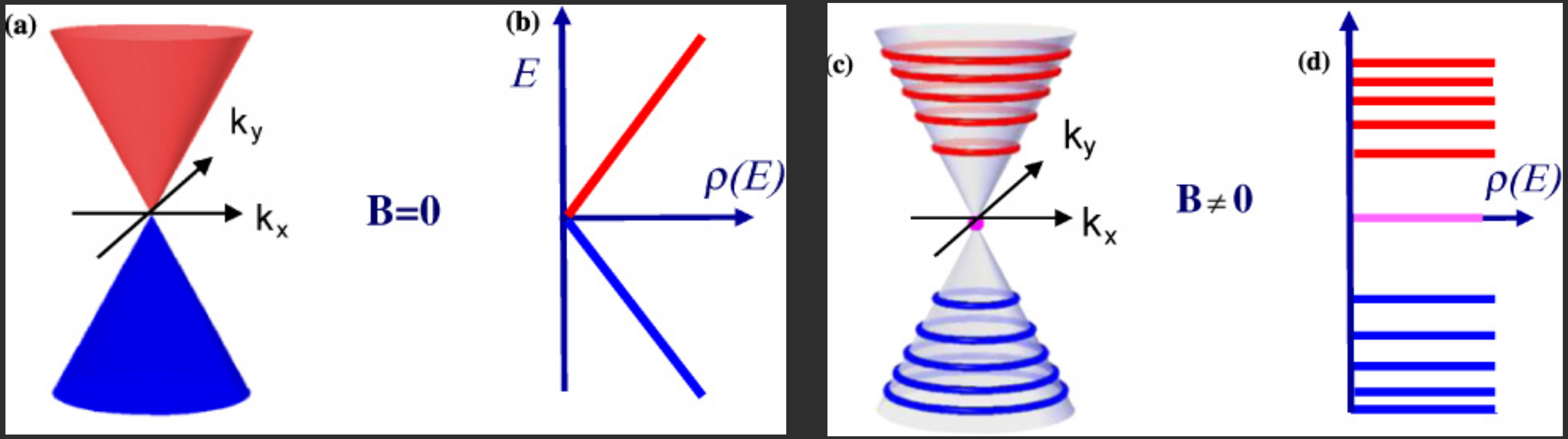


- Then the dispersion (wrt ***q***) near *K* is constant
- No band curvature.

Part III: Integer quantum Hall physics in graphene

- Add a perpendicular magnetic field, *B*
- Eigenenergies:

$$\epsilon_n = sign(n)\frac{\hbar \nu_F}{l_B}\sqrt{2\,|\,n\,|}\,; \quad l_B = \sqrt{\frac{\hbar}{eB}}$$



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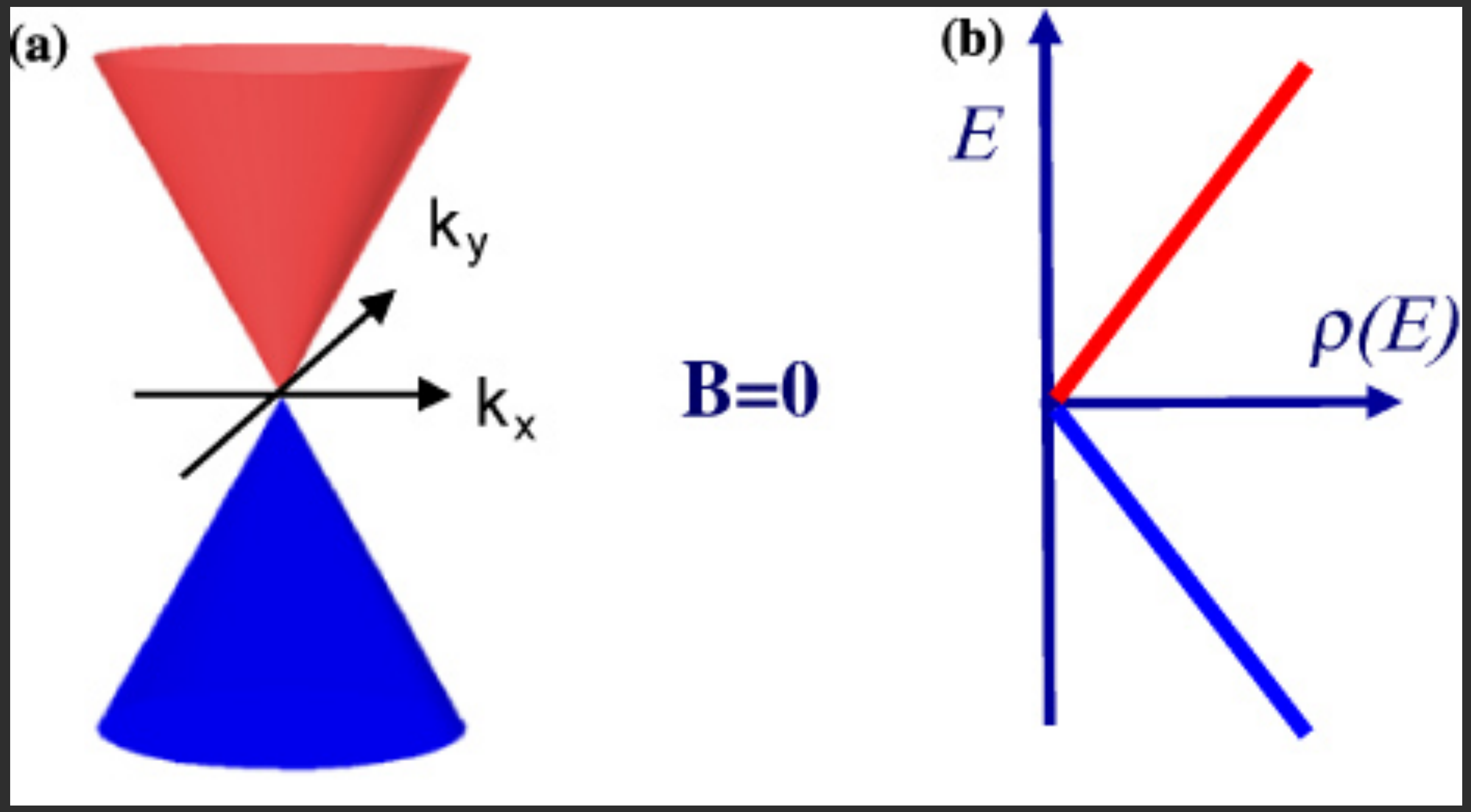
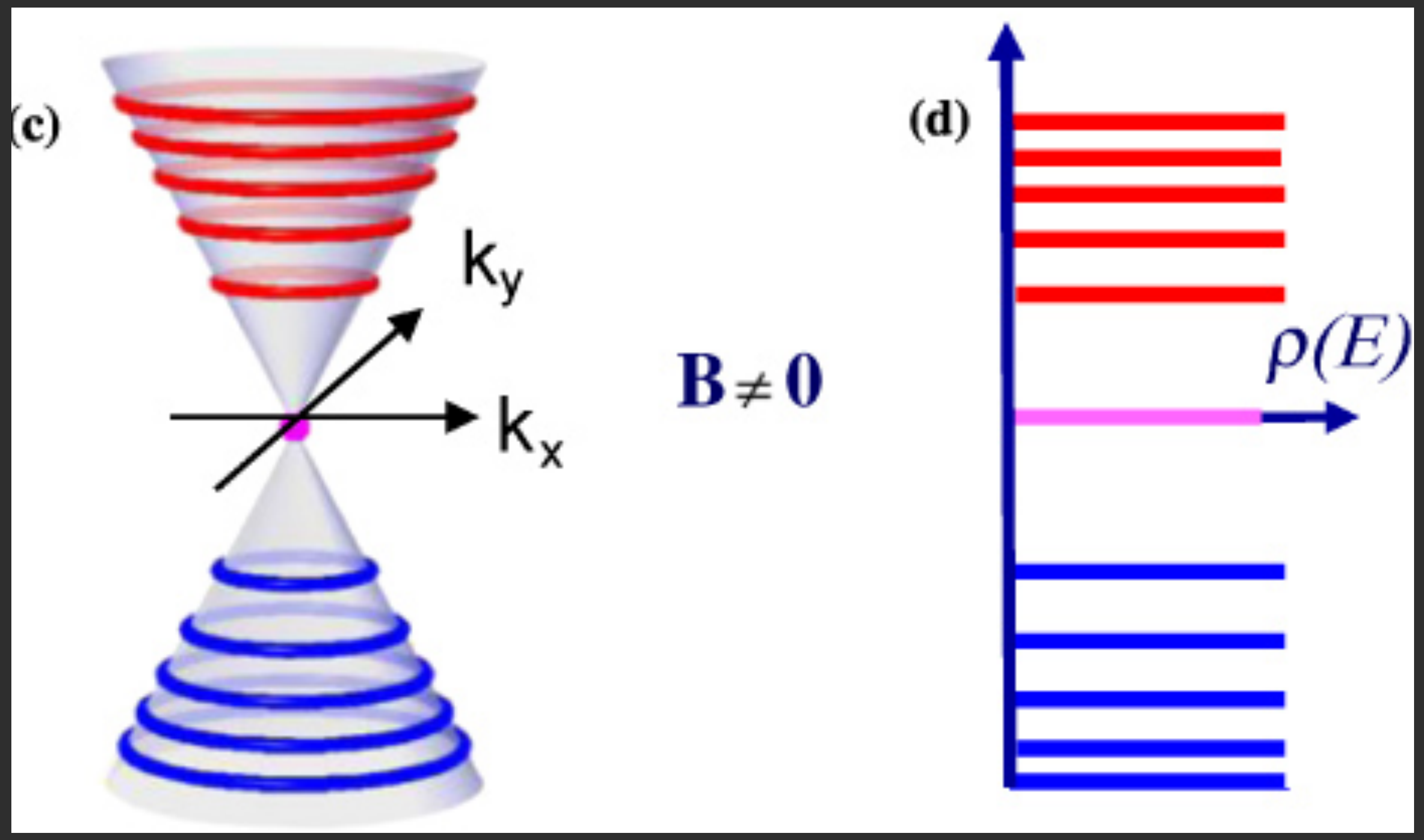
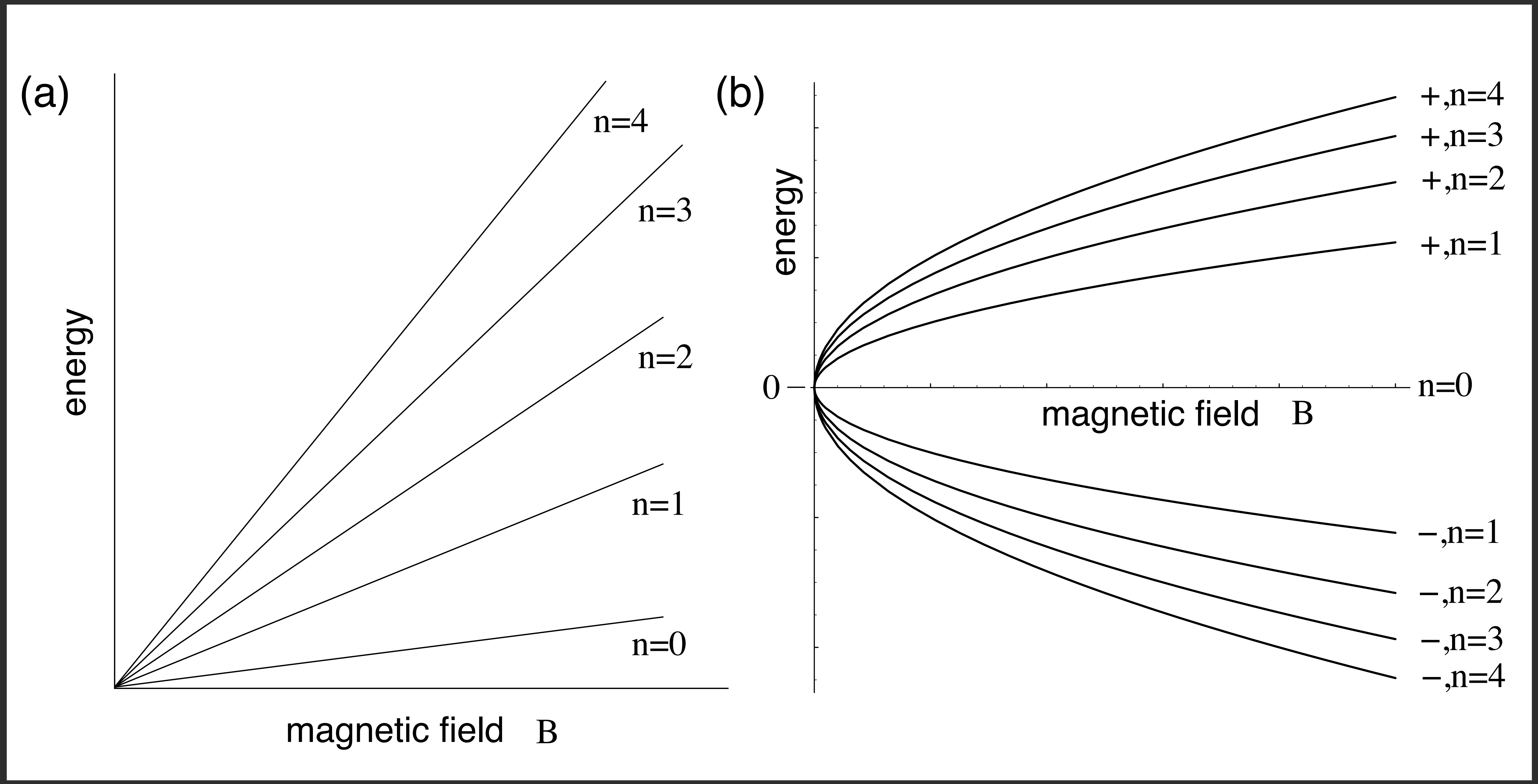




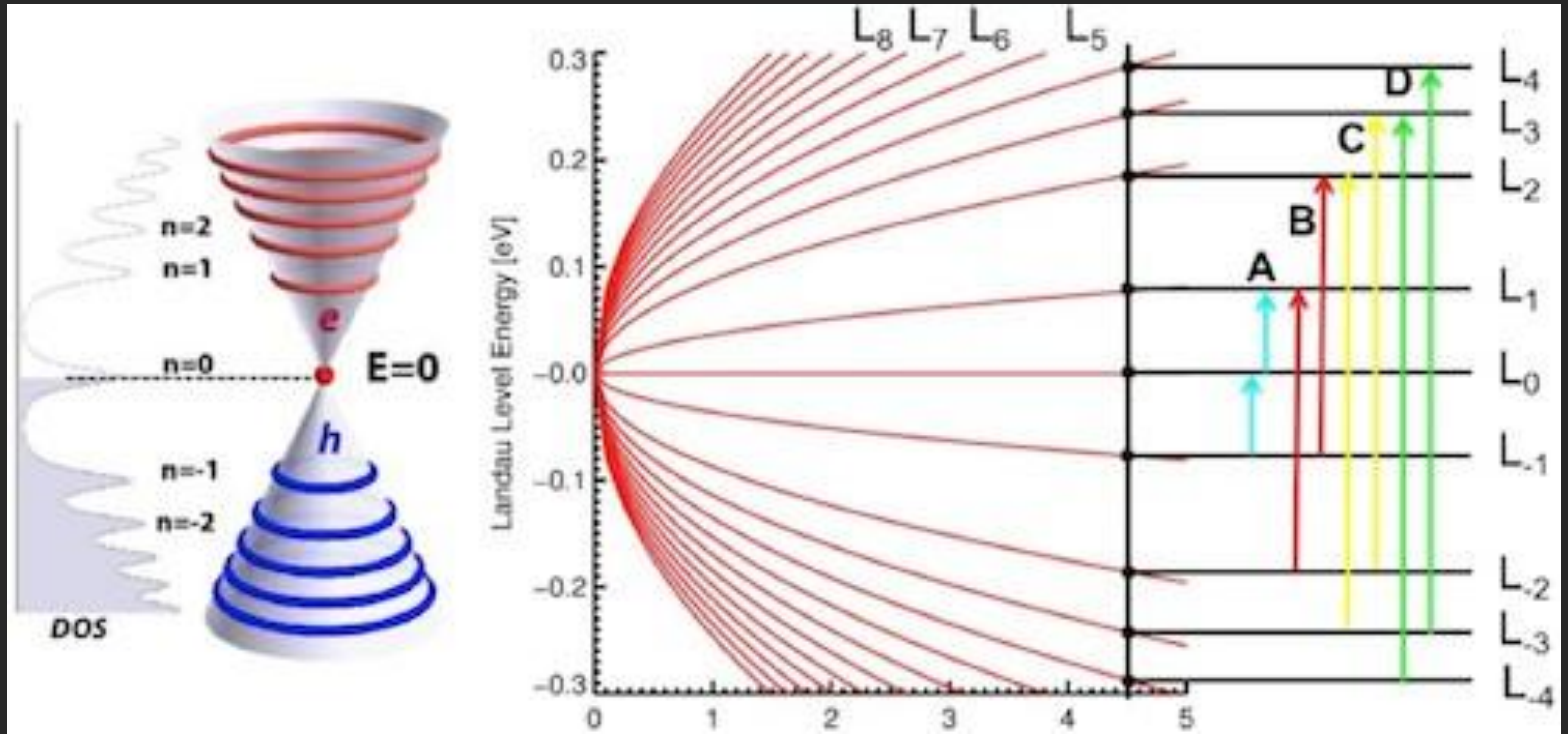
- *Normal* semiconductors:
- $\epsilon_n = \hbar\omega_c\,(n + 1/2) \propto B\,(n + 1/2)$

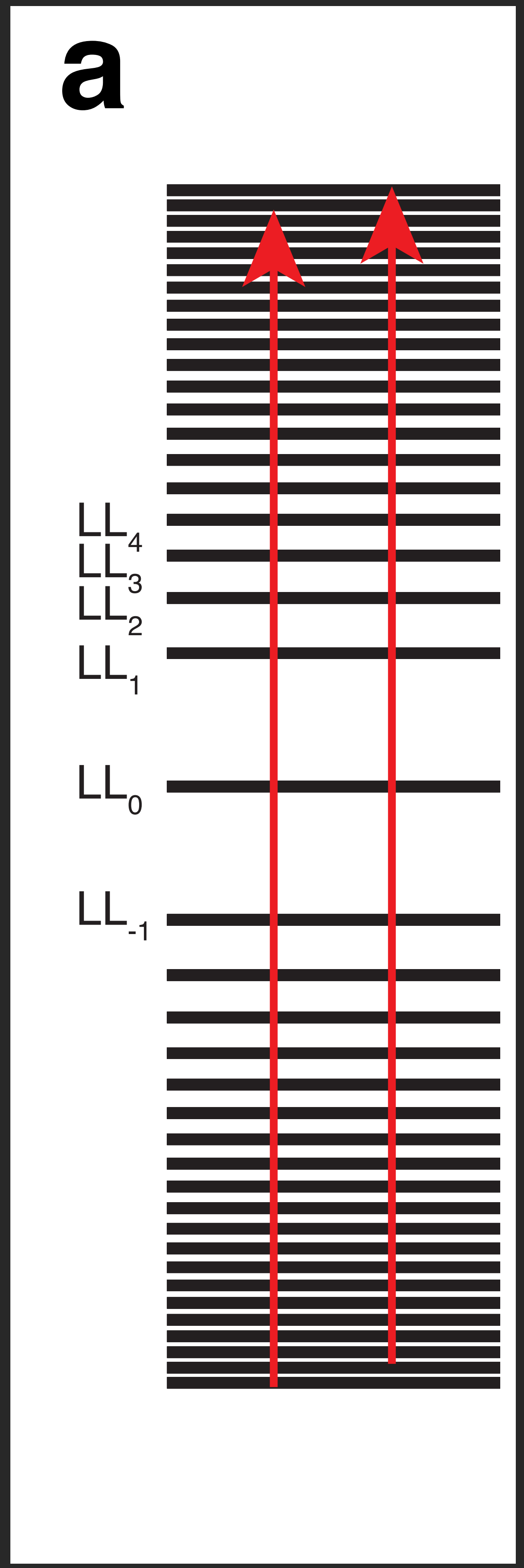
Parabolic band semiconductor

Dirac semiconductor



Part IV: In the non-equilibrium regime using light





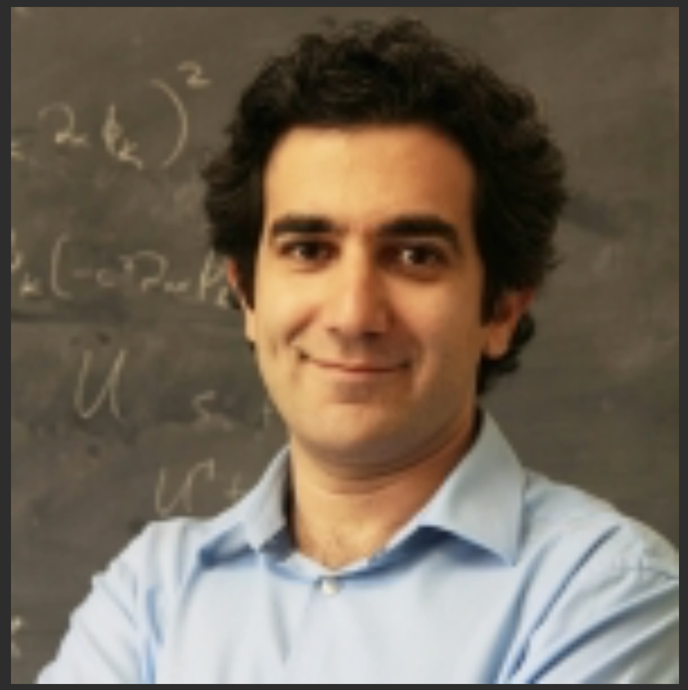
- The anharmonic energy level spacing in graphene allows unique energy transitions (within a factor of 2).
- Dipole-allowed transitions for $|n_f|$ - $|n_i|$ ± 1.

- With graphene in the integer quantum-Hall regime;
  Excite holes below E_f to empty electron states above E_f;
  Using selection rules: $|n_f|$ - $|n_i|$ ± 1.

Now an experiment, and a cast of characters

Bin Cao

Tobias Grass



Mohammad Hafez

Optical and electrical measurements:
Olivier Gazzano, Tobias Huber-Loyola, Markus Müller

Theory: Michael Gullens

Joint Quantum Institute,
NIST and University of Maryland
College, MD USA

Sample Prep: 1
Jiuning Hu, Dave Newell,
National Institute of Standards and Technology
Gaithersburg, MD USA

Sample Prep: 2:
Kishan Ashokbhai Patel,Luca Anzi, Roman Sordan
L-NESS, Department of Physics,
Politecnico di Milano, Como

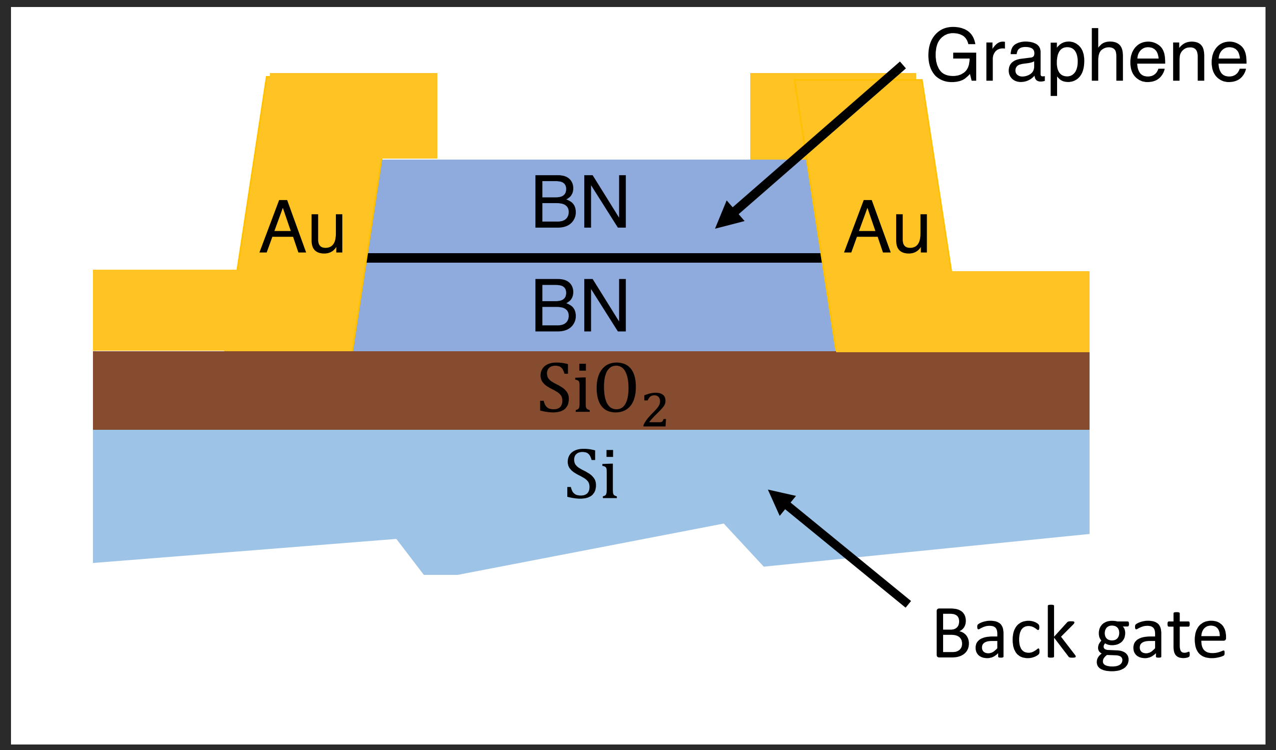
BN:
Kenji Watanabe, Takashi Taniguchi
National Institute for Materials Science,
Tsukuba, Japan

B. Cao, T. Grass, *et al.*, ACS Nano 2022, 16, 11, 18200–18209

The graphene sample

- **A typical structure**:
  Exfoliated hBN, graphene, BN encapsulated graphene
  Back-gated SiO_2 /Si, with metallic back contact
  Sizes range from 3 x 3 µm to 10 x 10 µm
  Ohmic contacts:
  Through an e-beam deposits Al hard mask
  Graphene & hBN etched selectively by O_2 and SF_6 RIE plasma
  Leaves pristine graphene exposed edges
  Ohmic contacts: Cr/Pd/Au (2/5/80 nm) patterned by e-beam lithography and e-beam

Two-terminal device with back gate



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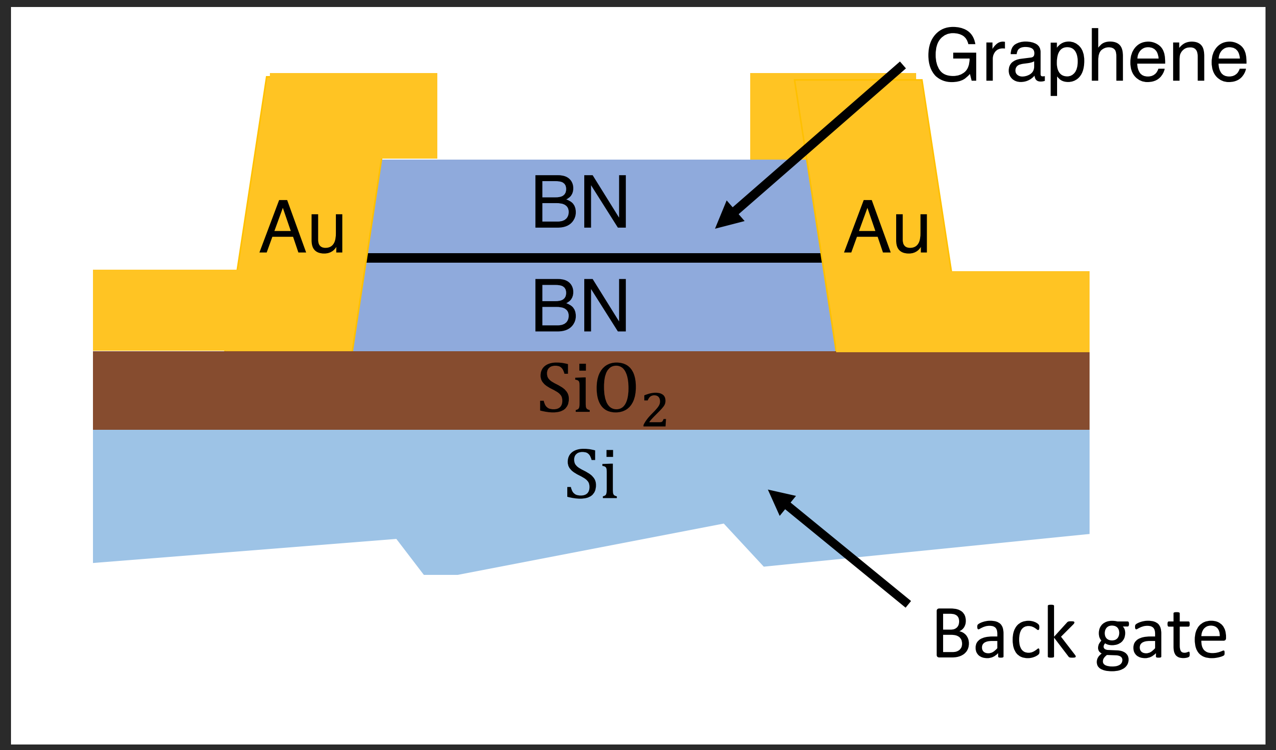
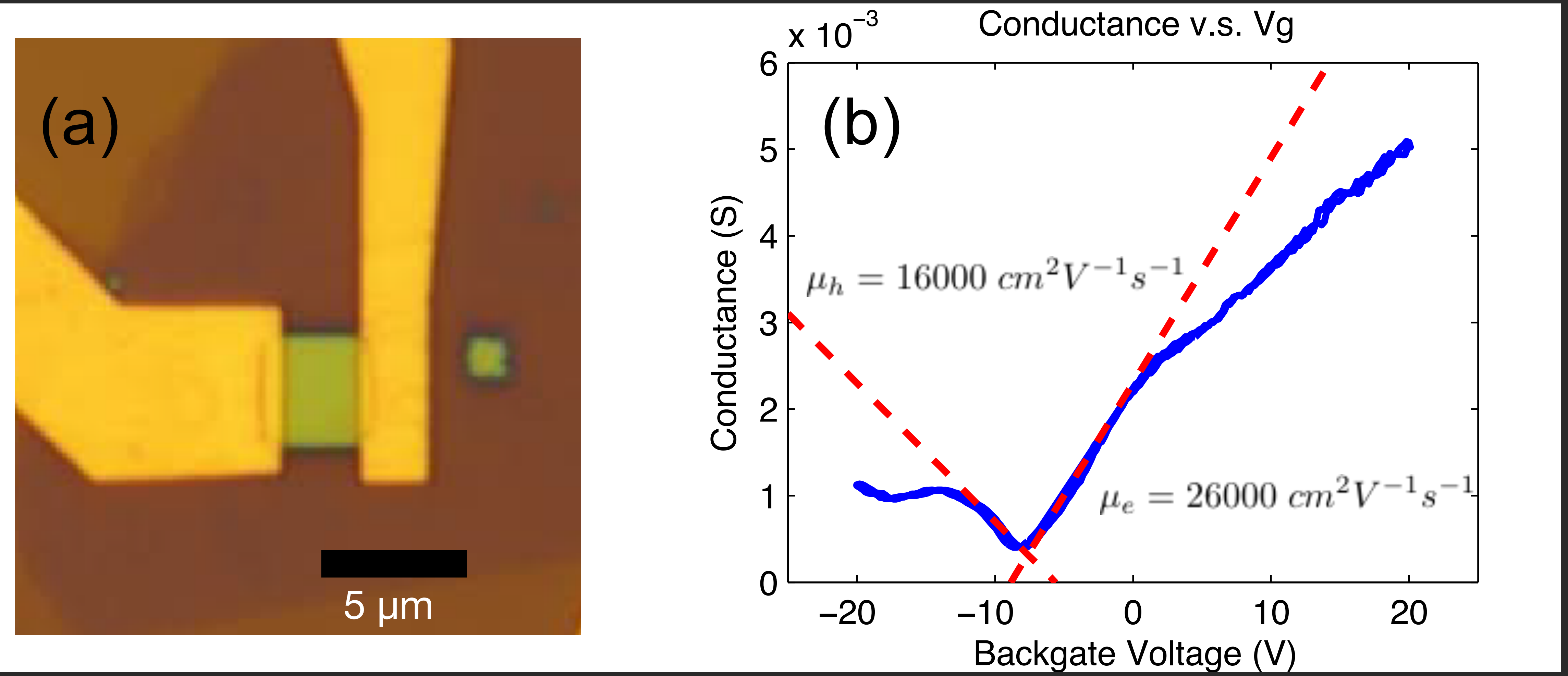
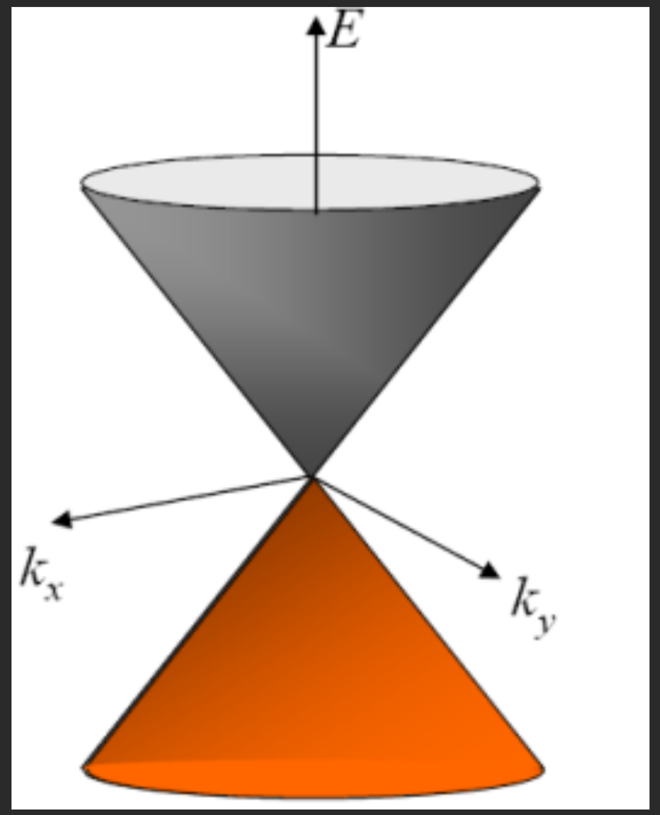


No B field, 4K Conductance



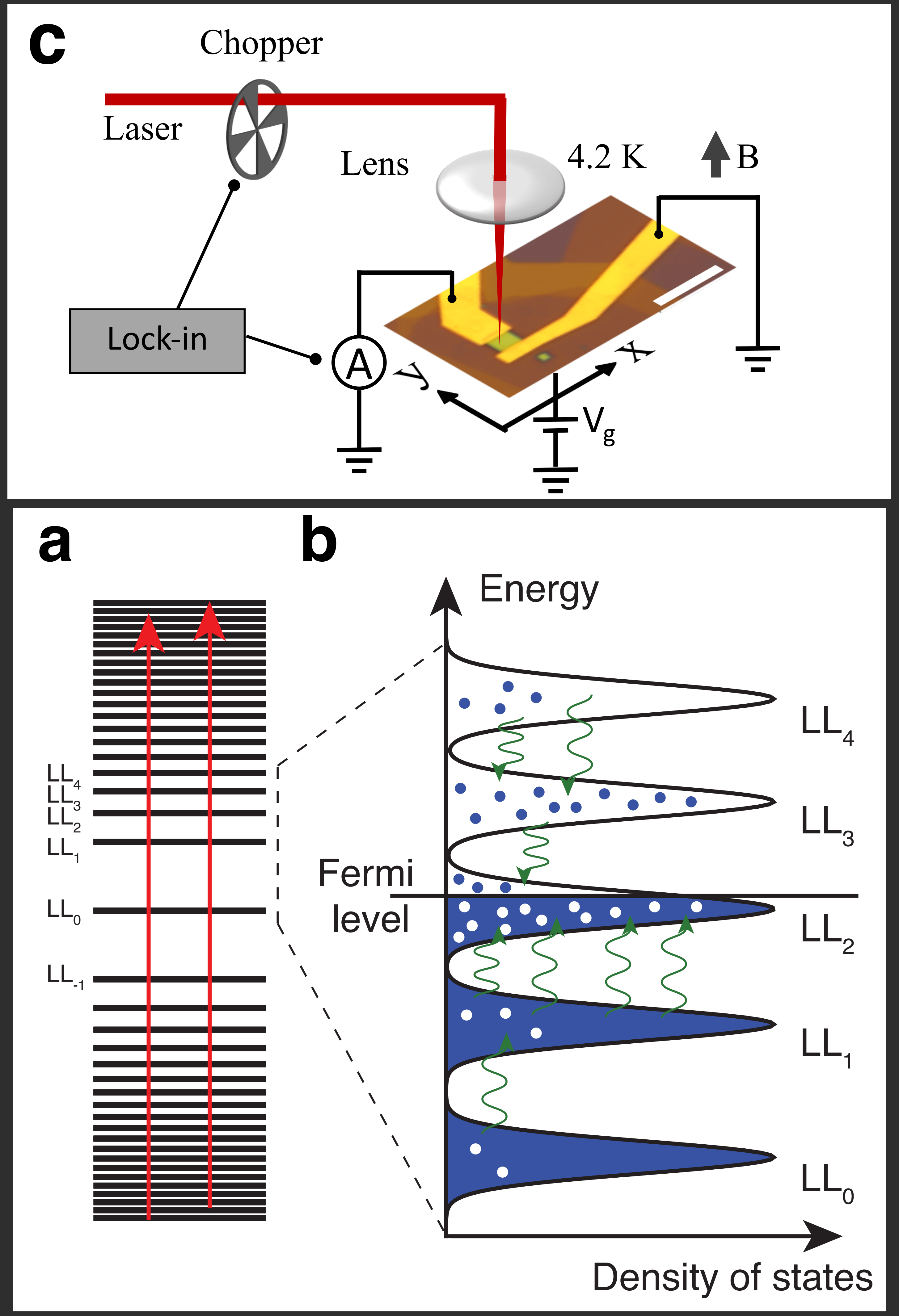


Size:
2.49µm∗3.87µm

$\mu_e = 26{,}000\ cm^2\ V^{-1}s^{-1}$
$\mu_h = 16{,}000\ cm^2\ V^{-1}s^{-1}$

Photocurrent in the IQH - Non-equilibrium transport

- Excite with 930 nm light, create e and h populations at $|n| \approx 36$;
- Fast (sub ps) relaxation and diffusion, creating photocurrents.



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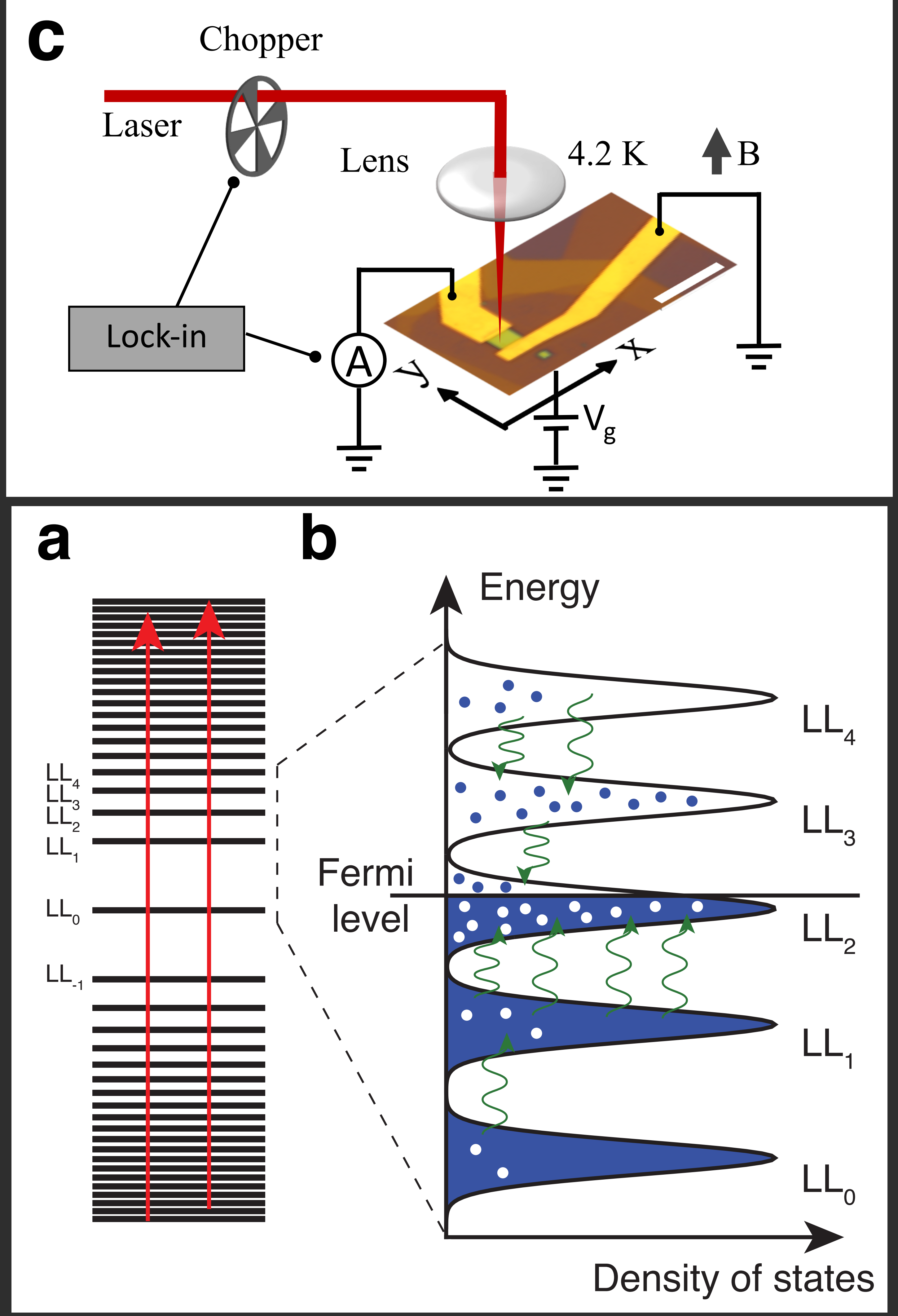
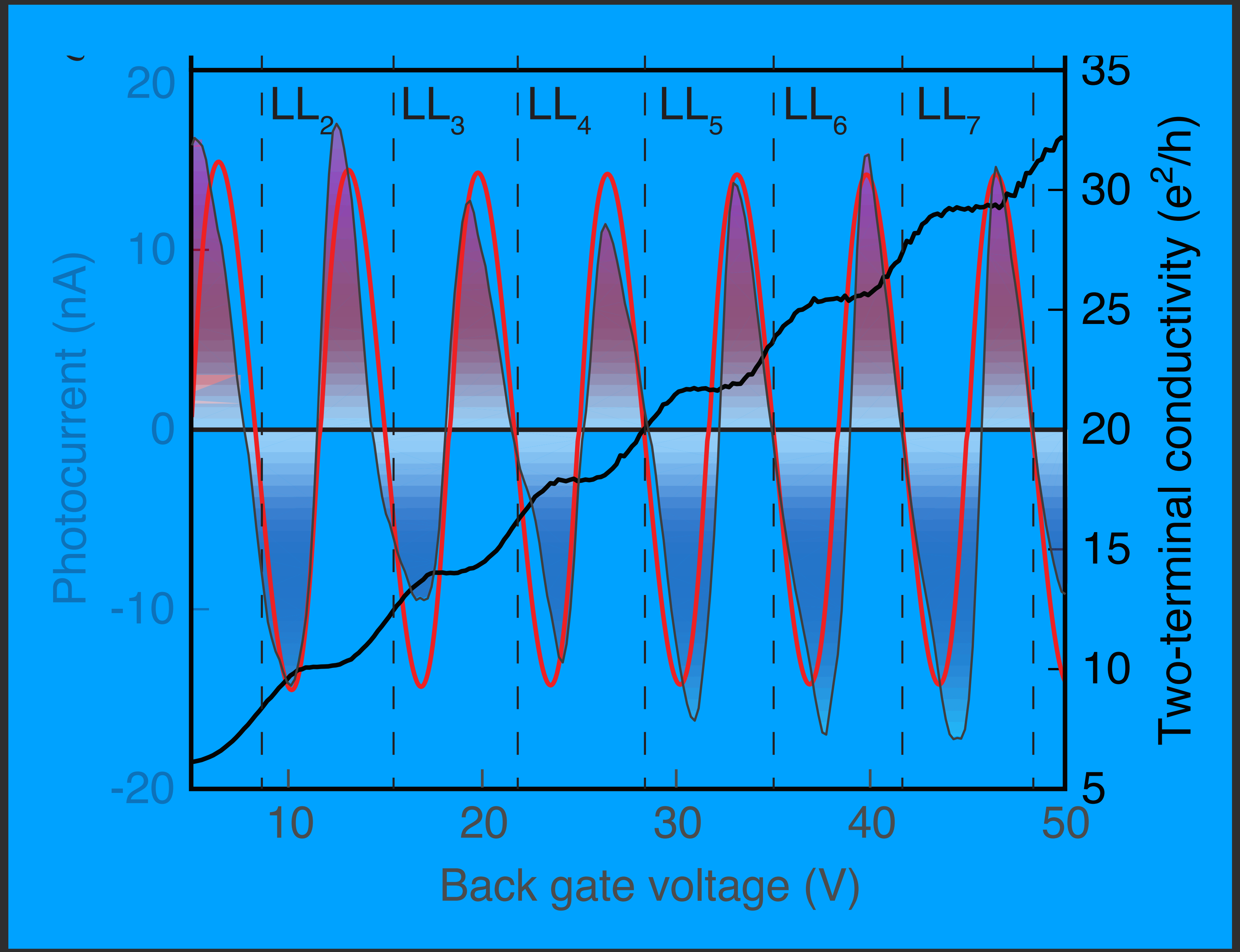


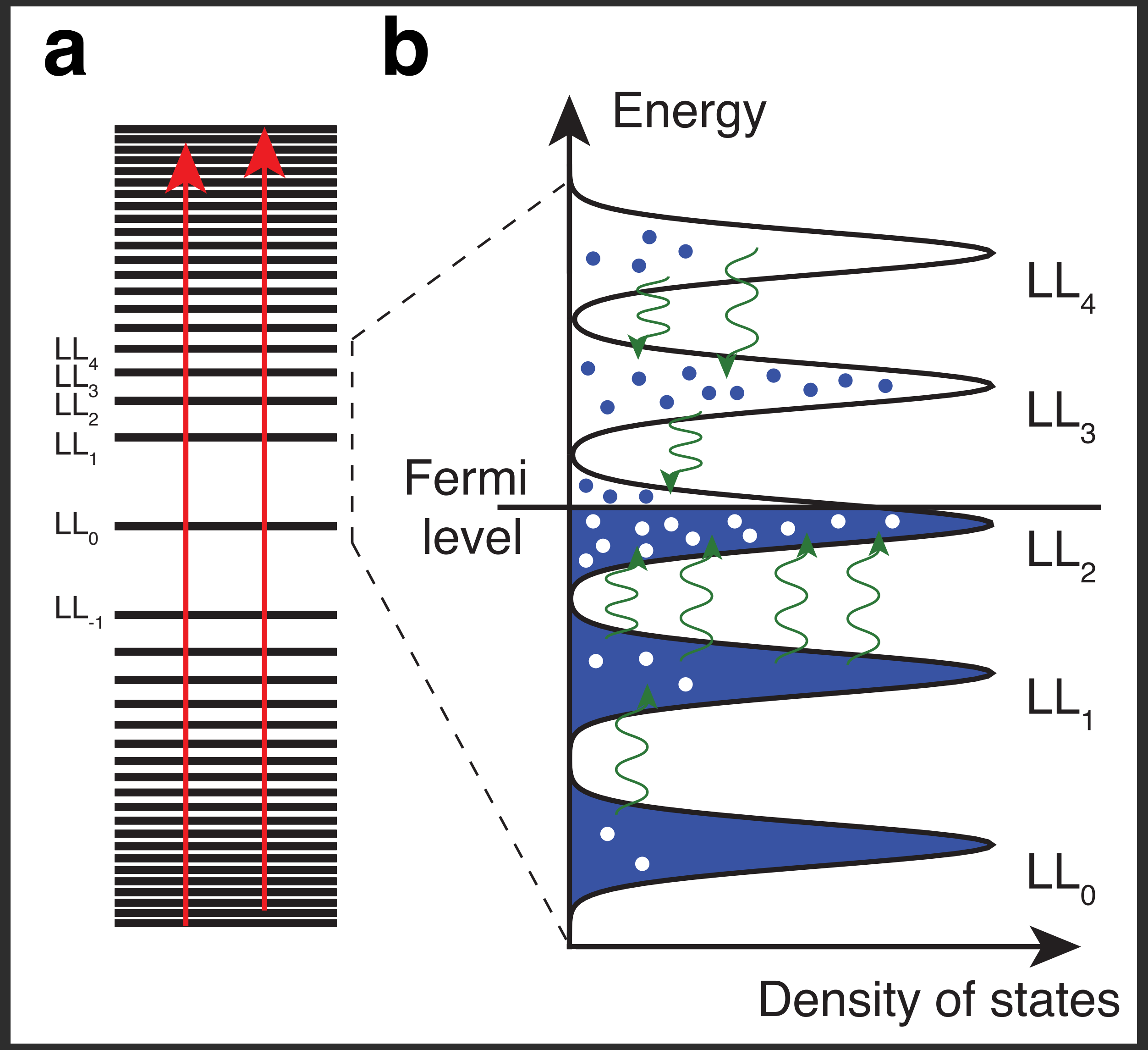
4.2K B= 4T



- Backgate voltage control E_f, no injected current.
- Photocurrent oscillations track LL's.
- Zeros in photocurrent are at half filling.

Why do we get any photocurrent?

- Why should we get any photocurrent?
- We create electrons & holes in equal amounts, they decay (~100 fs), and recombine.



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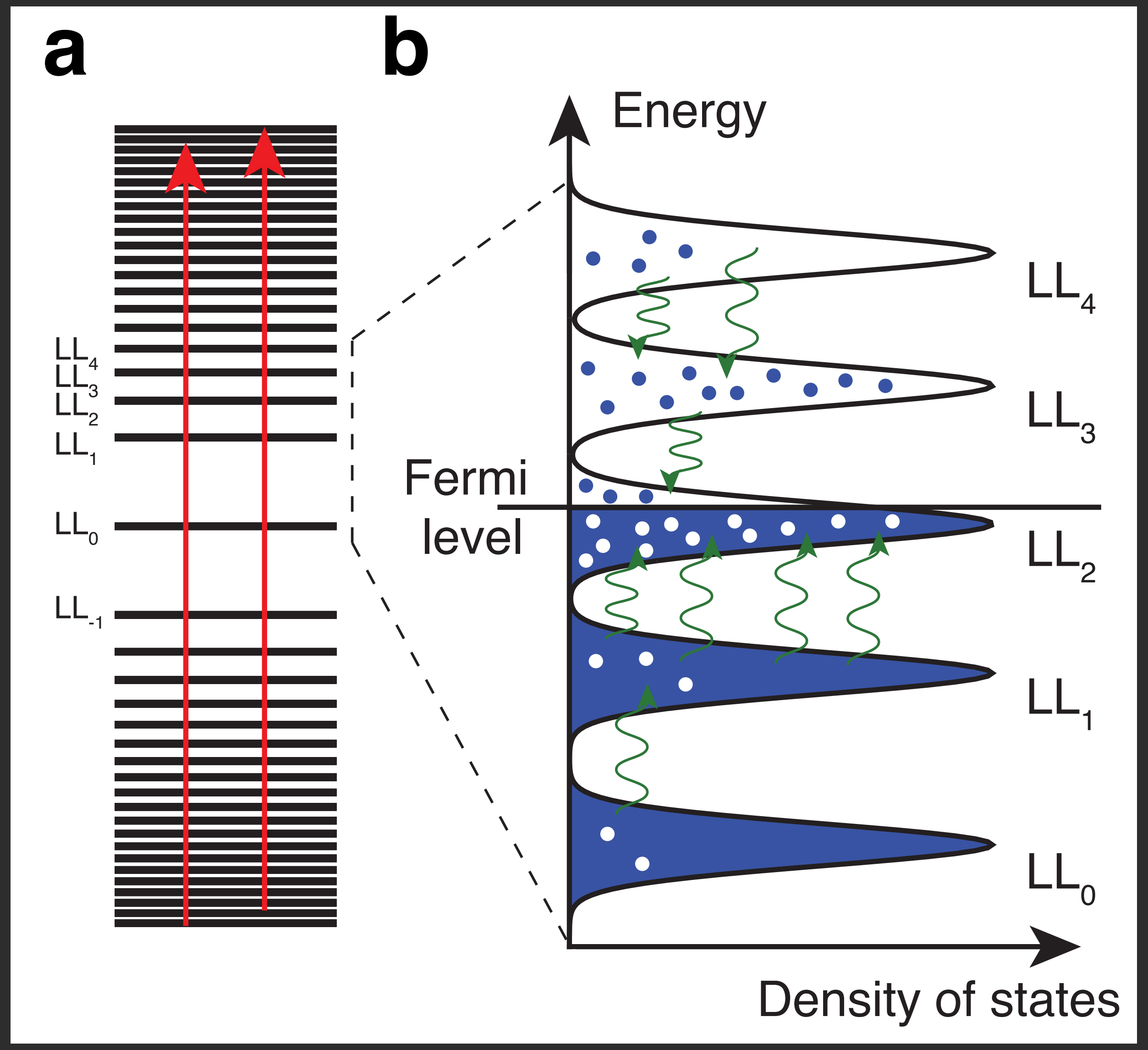

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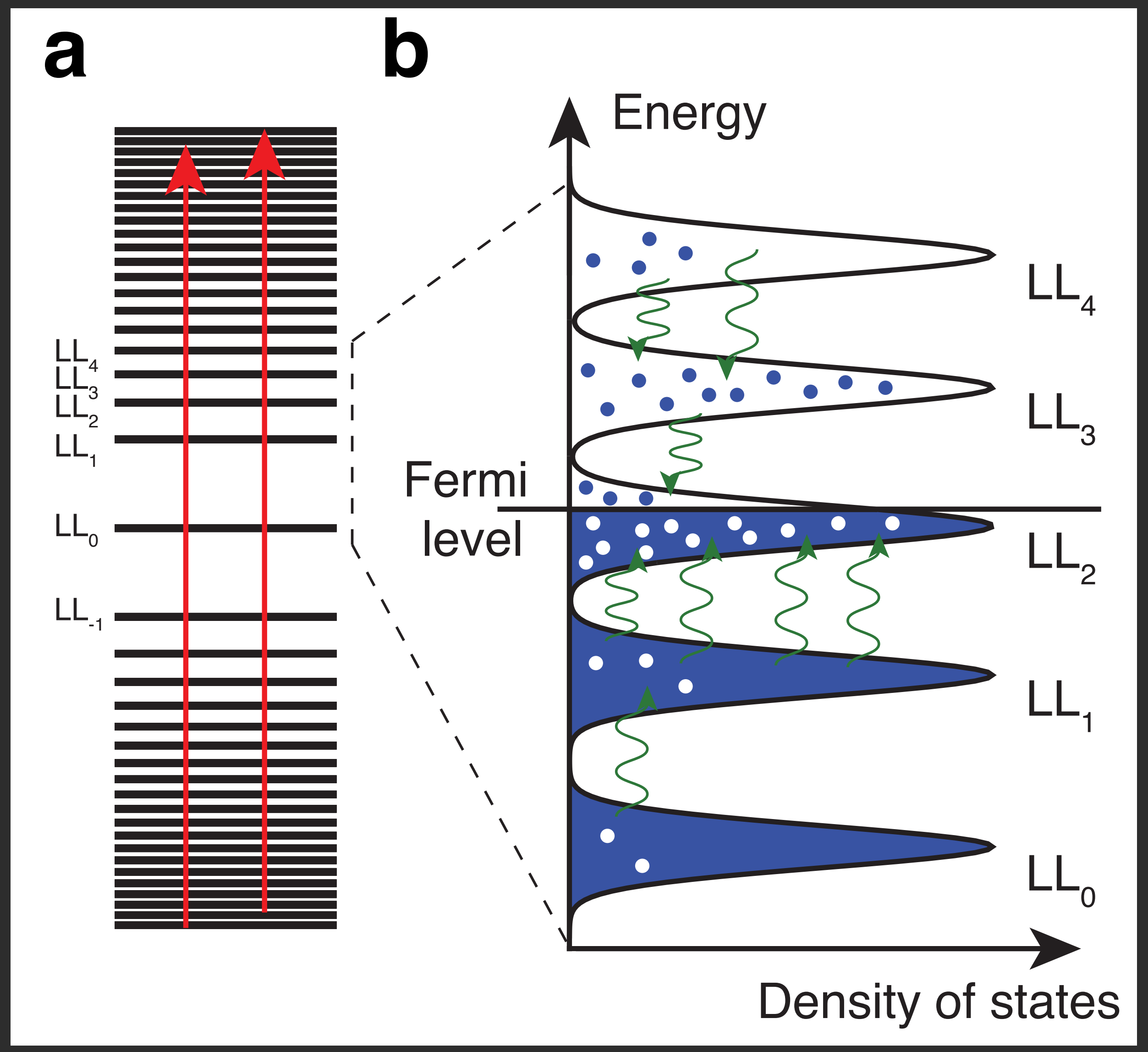

- Two processes: Relaxation of hot carriers to E_f or Diffusion of hot carriers to edges or contacts.
- *Relaxation process of excess hot carriers of one type depends on unbalanced number of available states at the Fermi level.*

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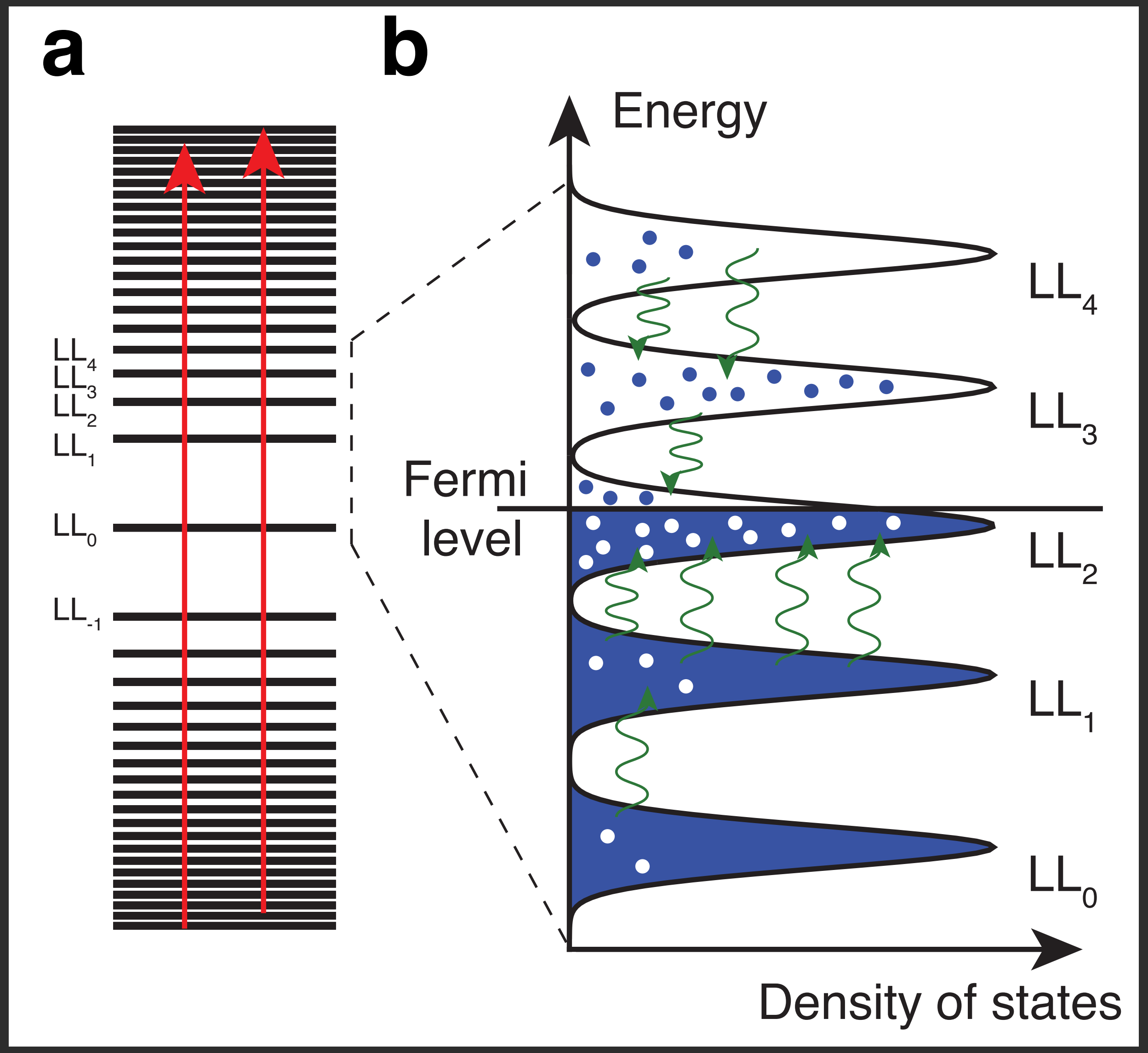

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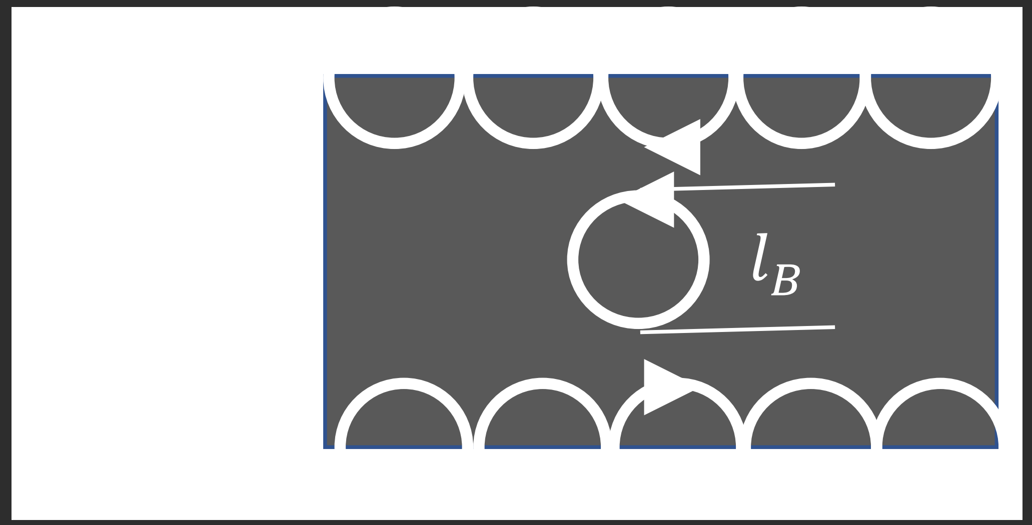
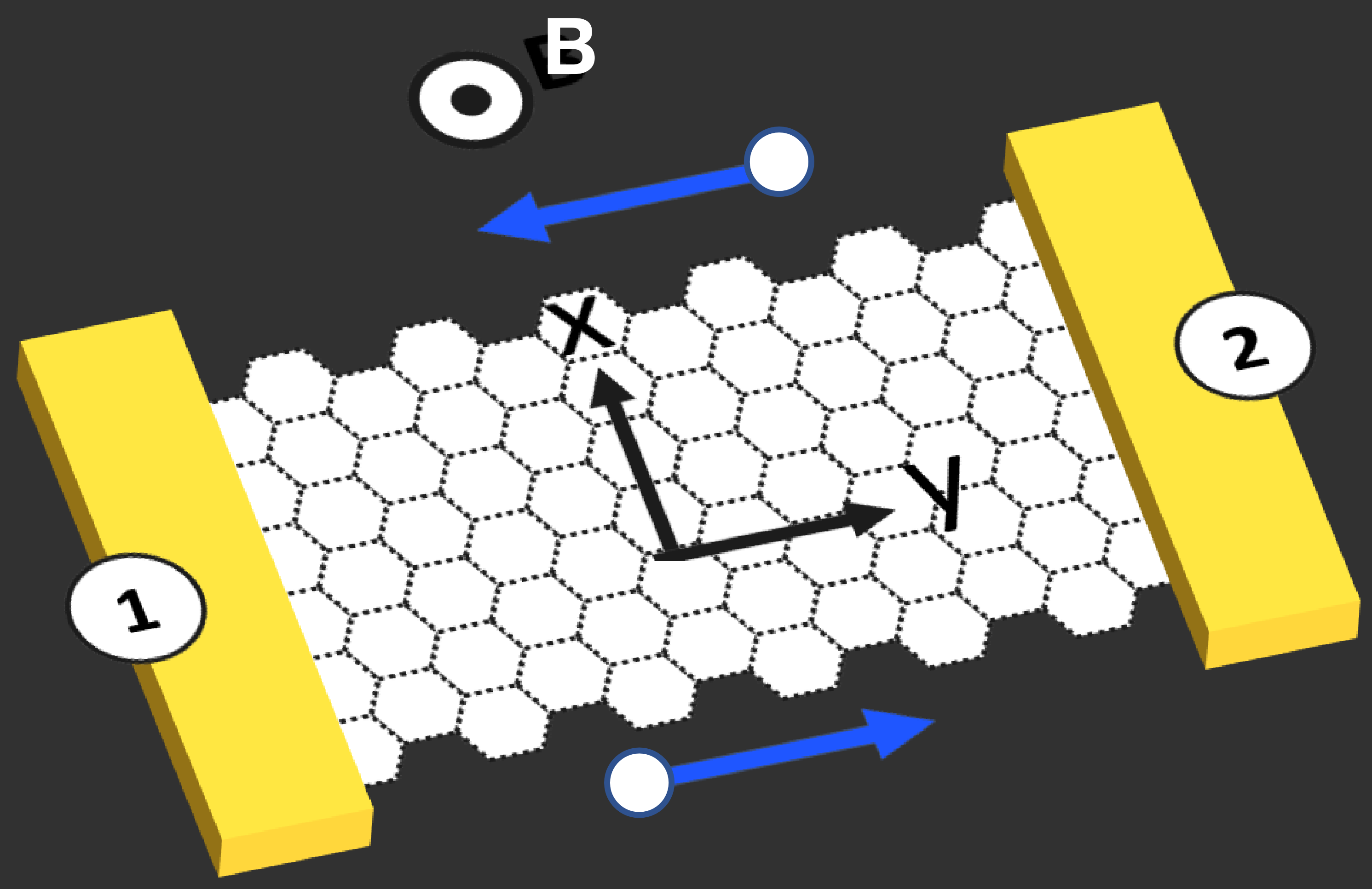
- *Relaxation process of excess hot carriers of one type depends on unbalanced number of available states at the Fermi level.*
- Photocurrent has two components:

Photocurrent
- Edge-state (Chiral)
- Diffusion (Not chiral)

Phys. Rev. B **90**, 075415 (2014)



Separate photocurrent contributions related to edge & extended states



- When B flips direction the edge state currents flip directions.
  I (B+) - I(B-) will add the edge-state currents.
- Diffusive extended-state currents (total electron and hole current) diffusing to contacts are unaffected by sign of B.

I (B+) - I(B-) negates diffusive extended state currents, but
I (B+) + I(B-) will add the currents.

Renormalise to focus on edge states: I (B+) - I(B-).

Chirality of edge-state photo-carriers

- Modify the energy spectrum mentioned earlier:

$$\epsilon_n = sign(n)\frac{\hbar\nu_F}{l_B}\sqrt{2\mid n\mid};$$

υ_F Fermi velocity,
l_B magnetic length,
n Landau level index

$$l_B = \sqrt{\frac{\hbar}{eB}}$$

$$\epsilon_n = sign(n)\frac{\hbar\nu_F}{l_B}\sqrt{2\mid n\mid} + \lambda sgn(q)V(x)$$

λ = +1 for conduction band
λ = -1 for valence band
q the carrier charge
V(x) the edge confining potential.

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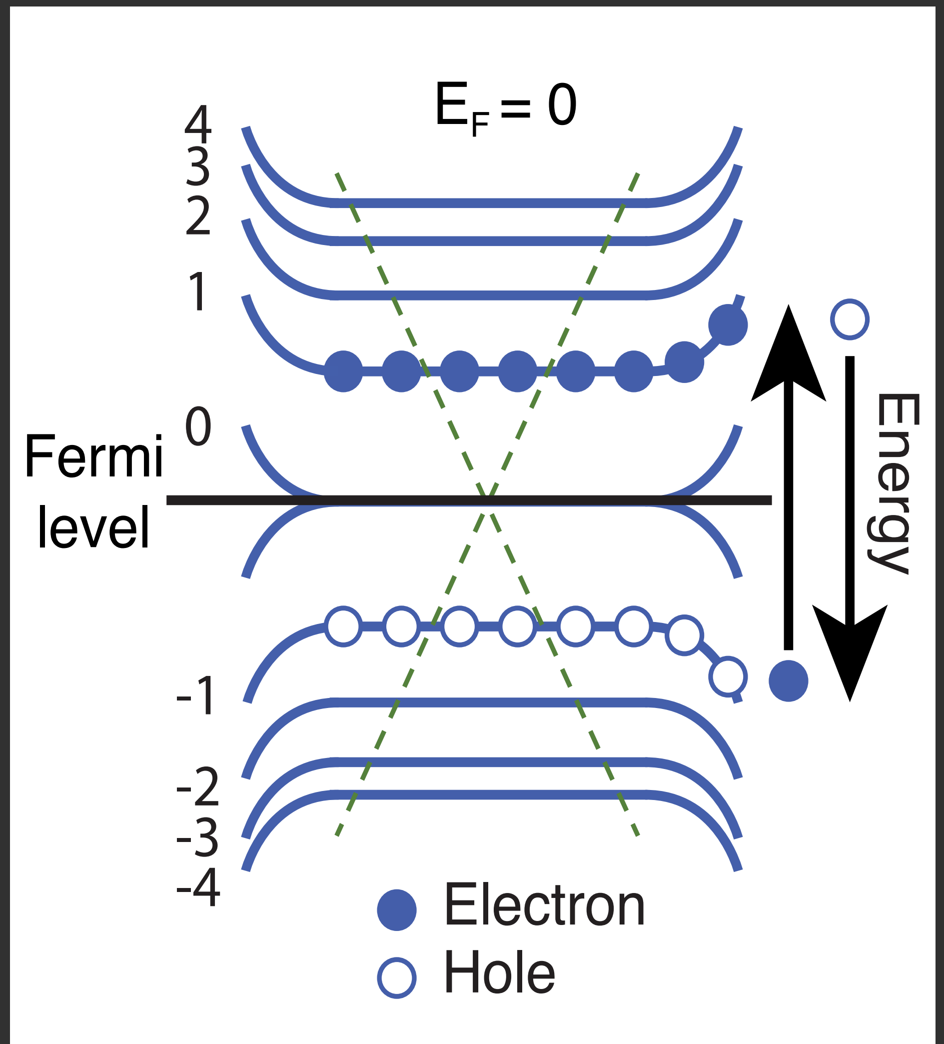
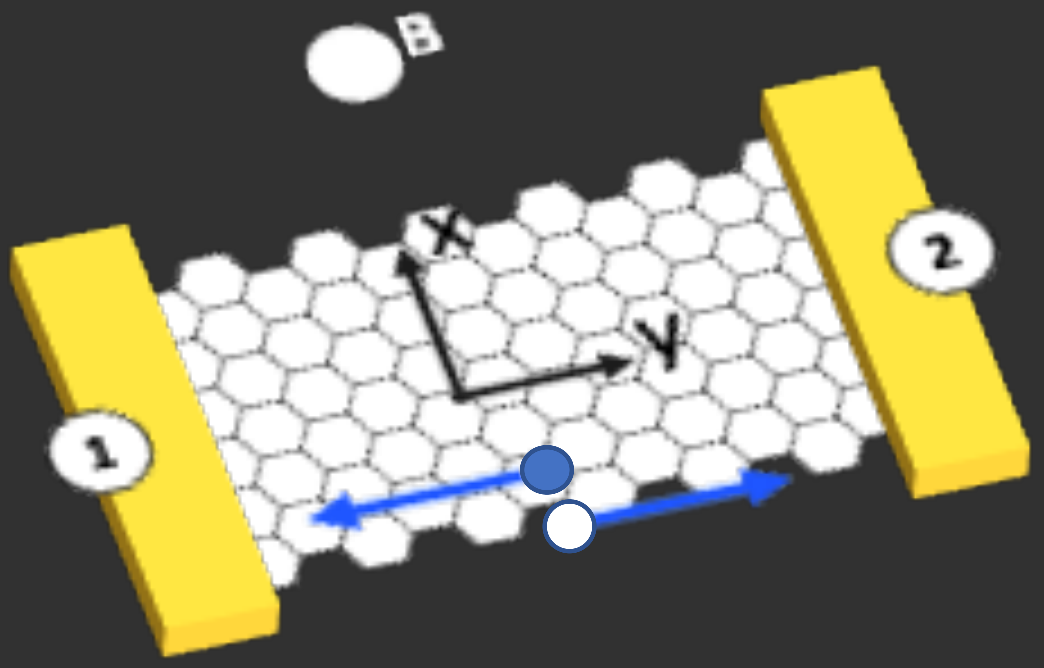
At the Dirac Point





Photocurrent

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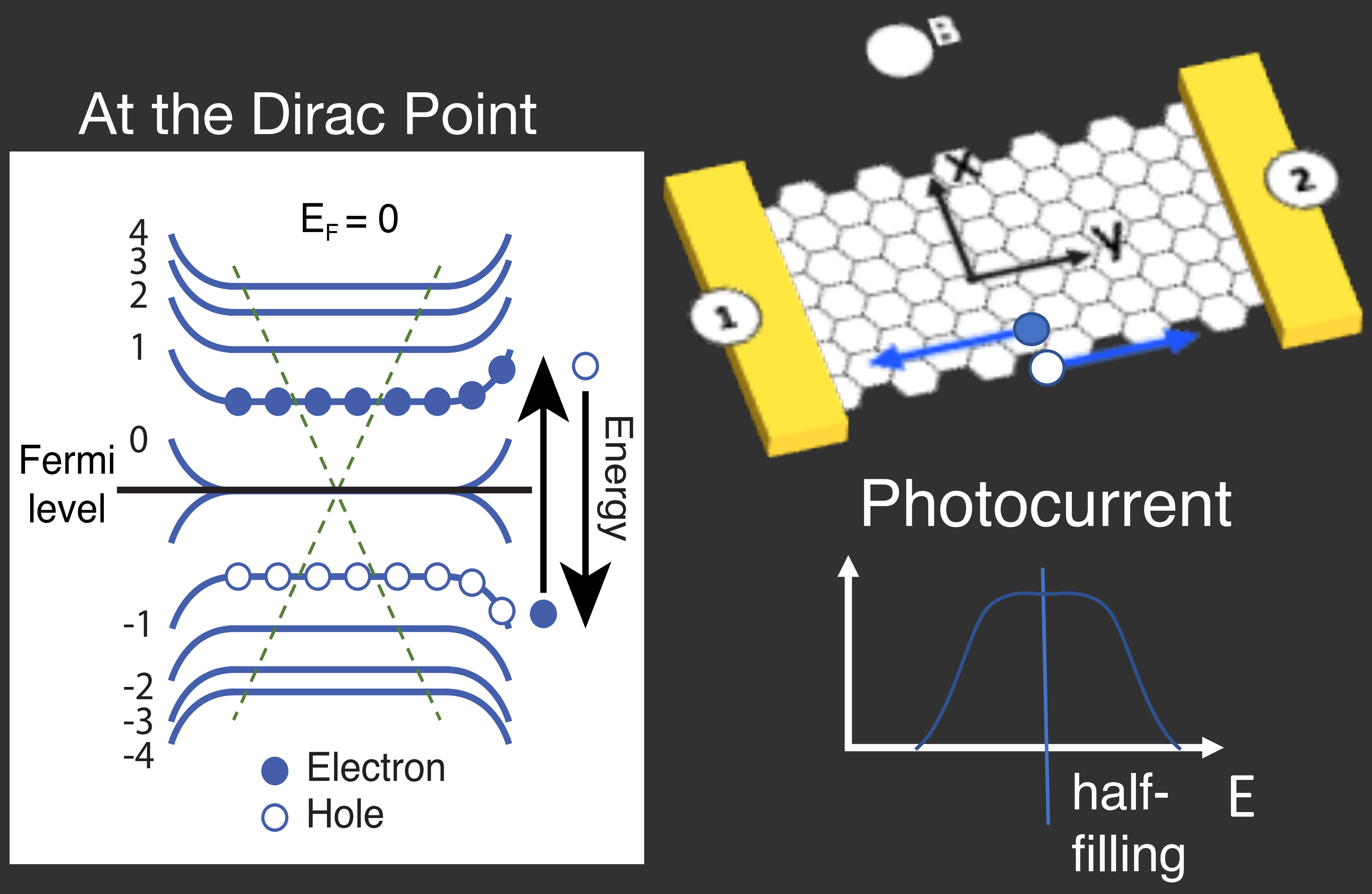
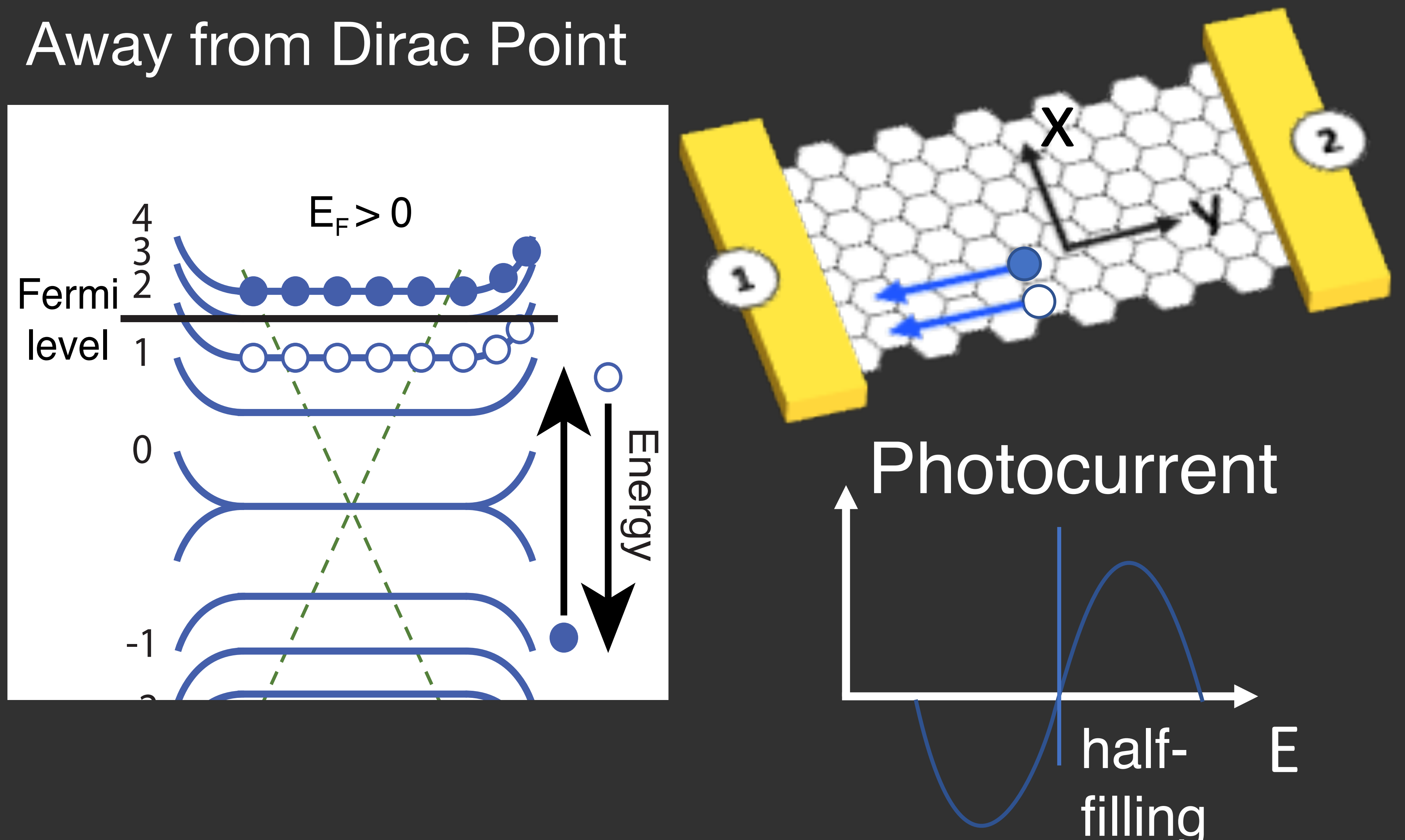
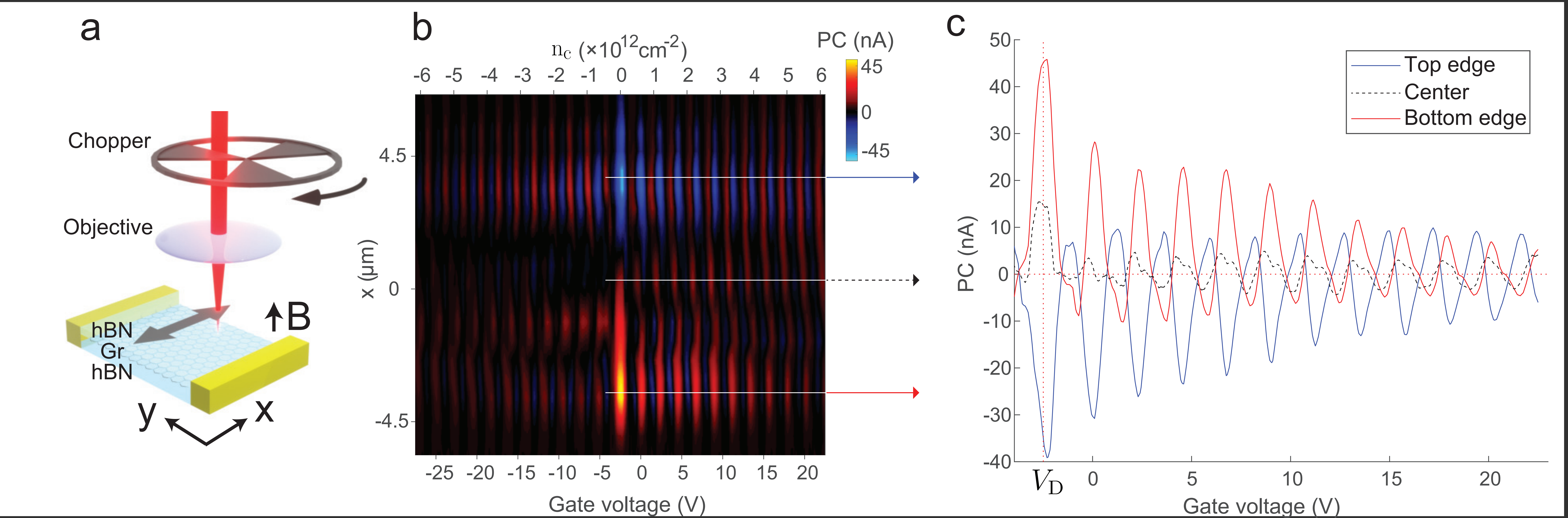


Away from Dirac Point



Edge-state currents from photoexciation



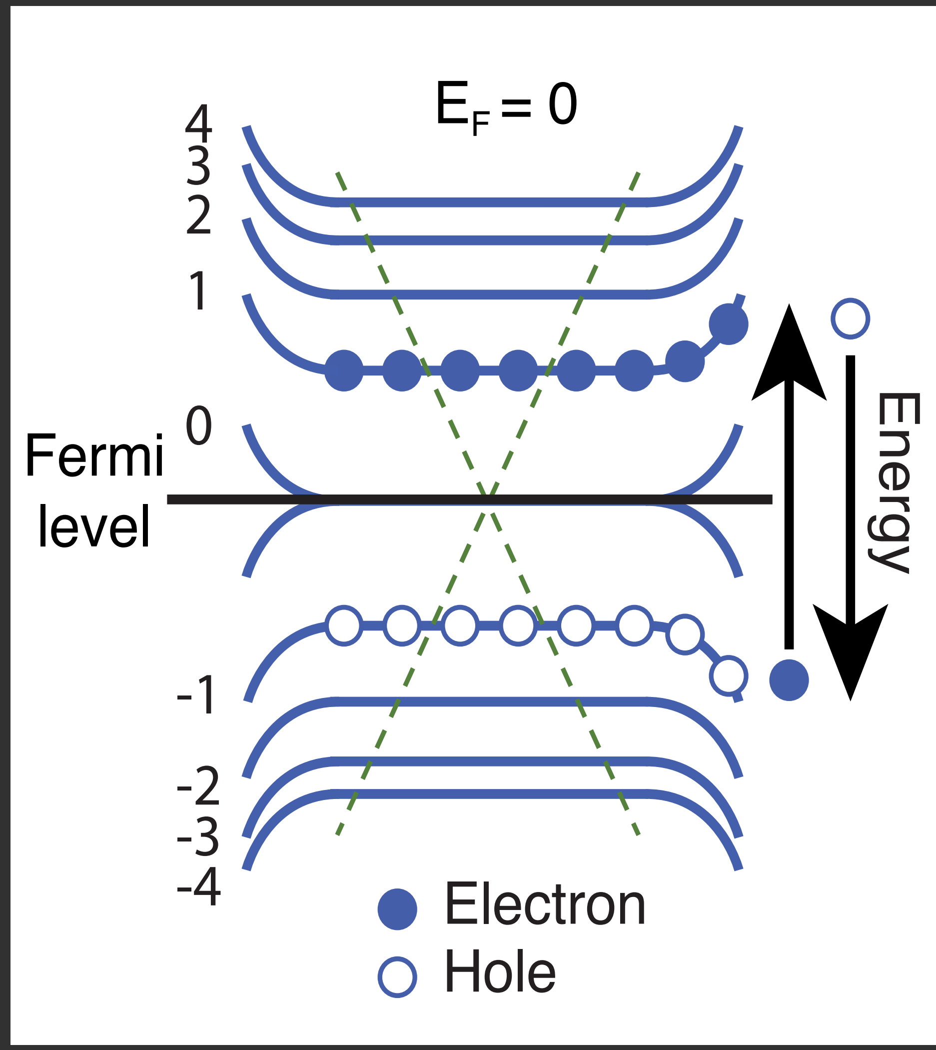
$$I\left(B^+ - B^-\right)$$

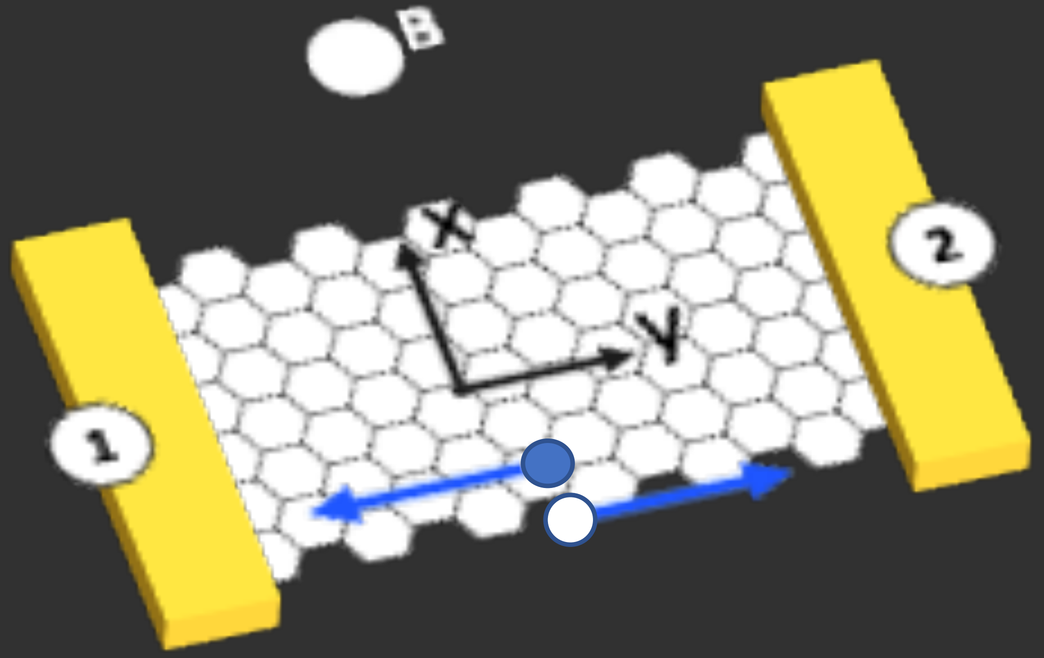
Edge-state current contributions

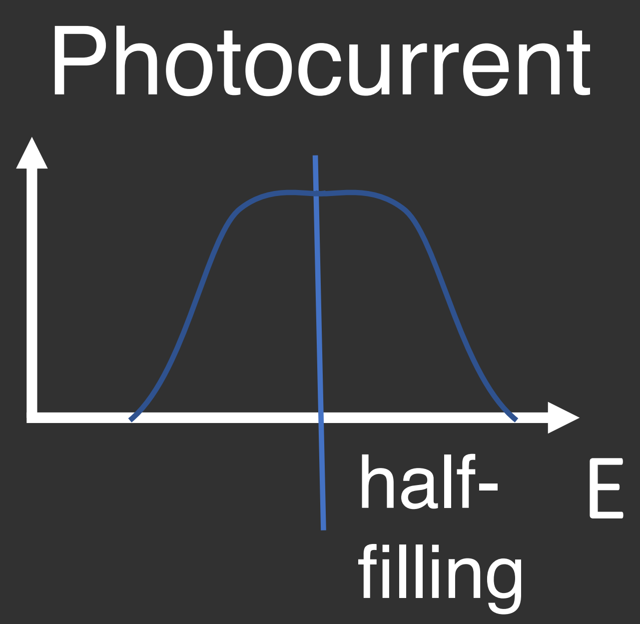
- Little B-field dependent transport in the sample center.
- Edge states currents are more concentrated at edges.

Edge-state photocurrent half-filling with LL

At the Dirac Point







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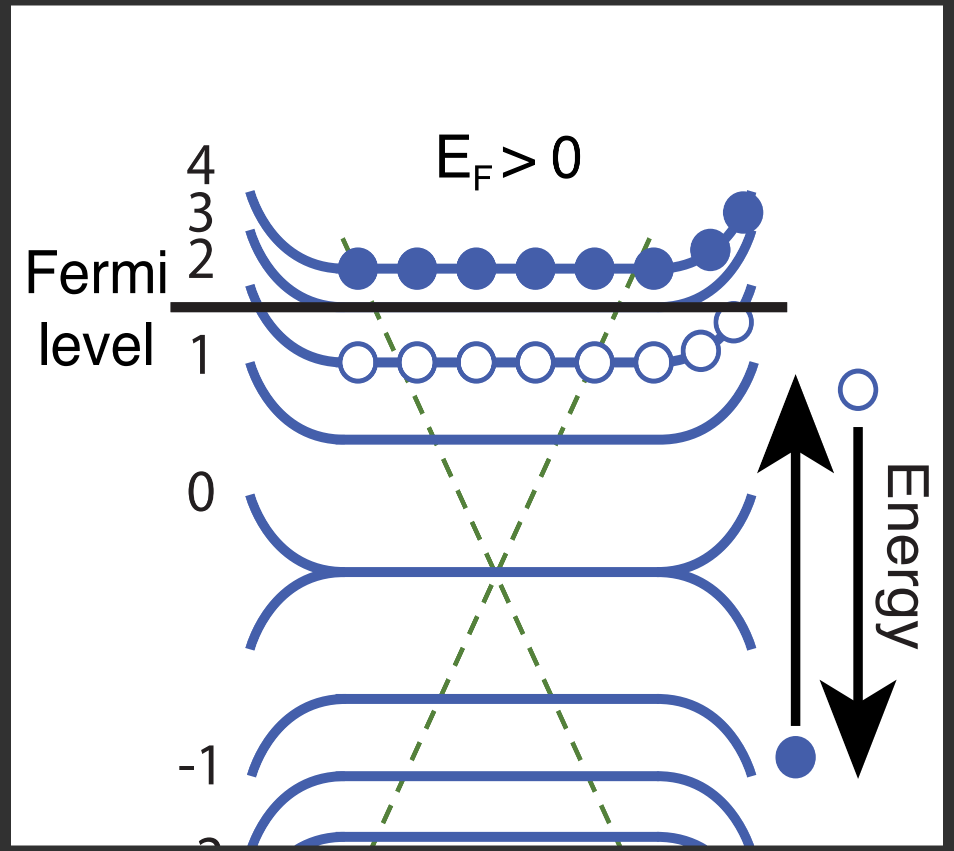
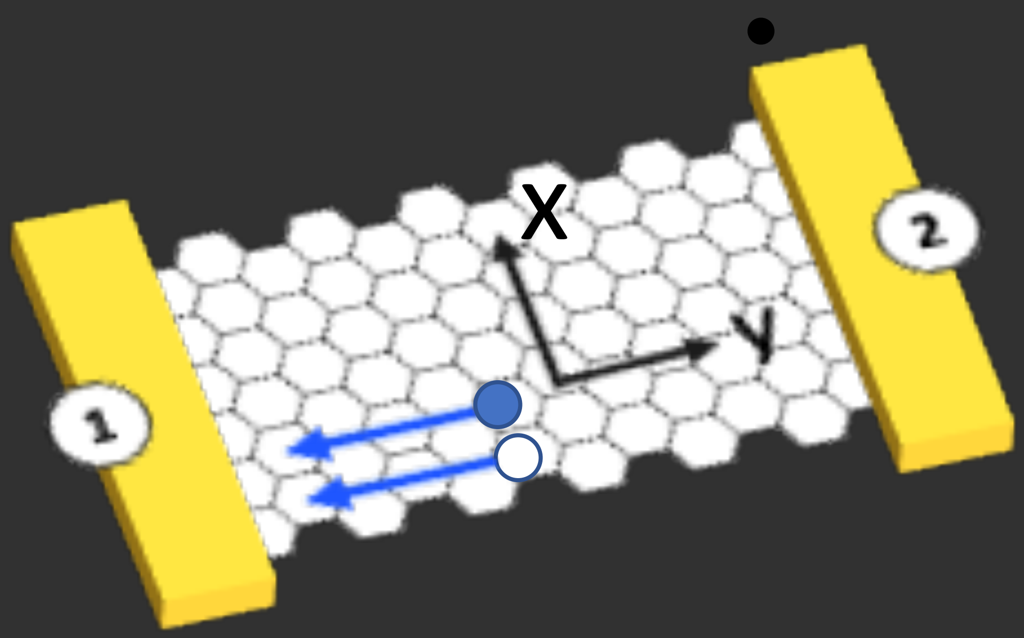
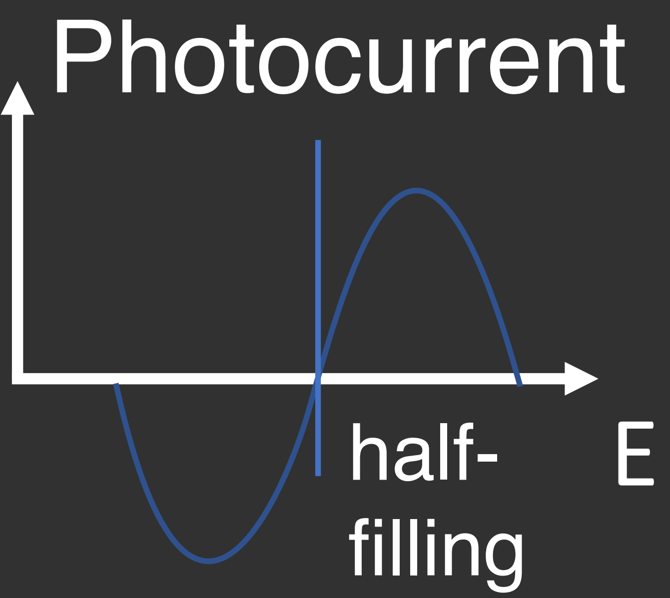
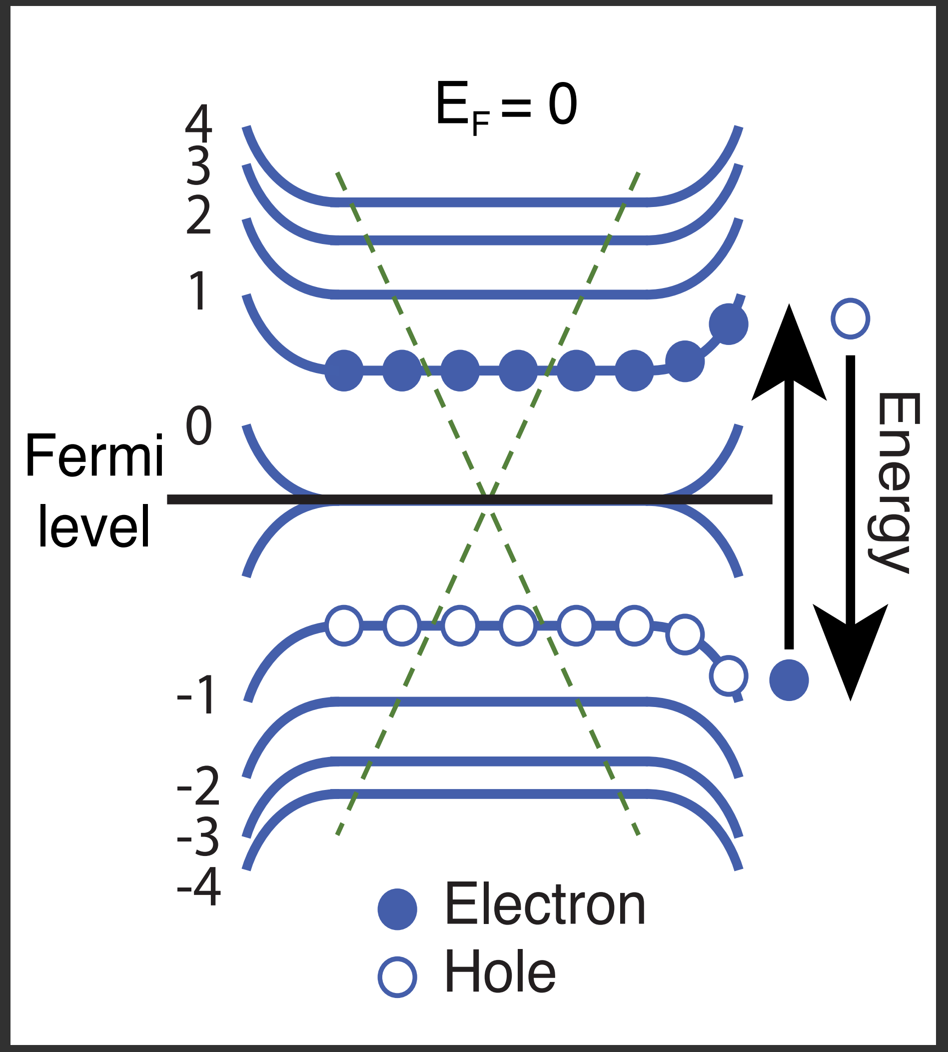


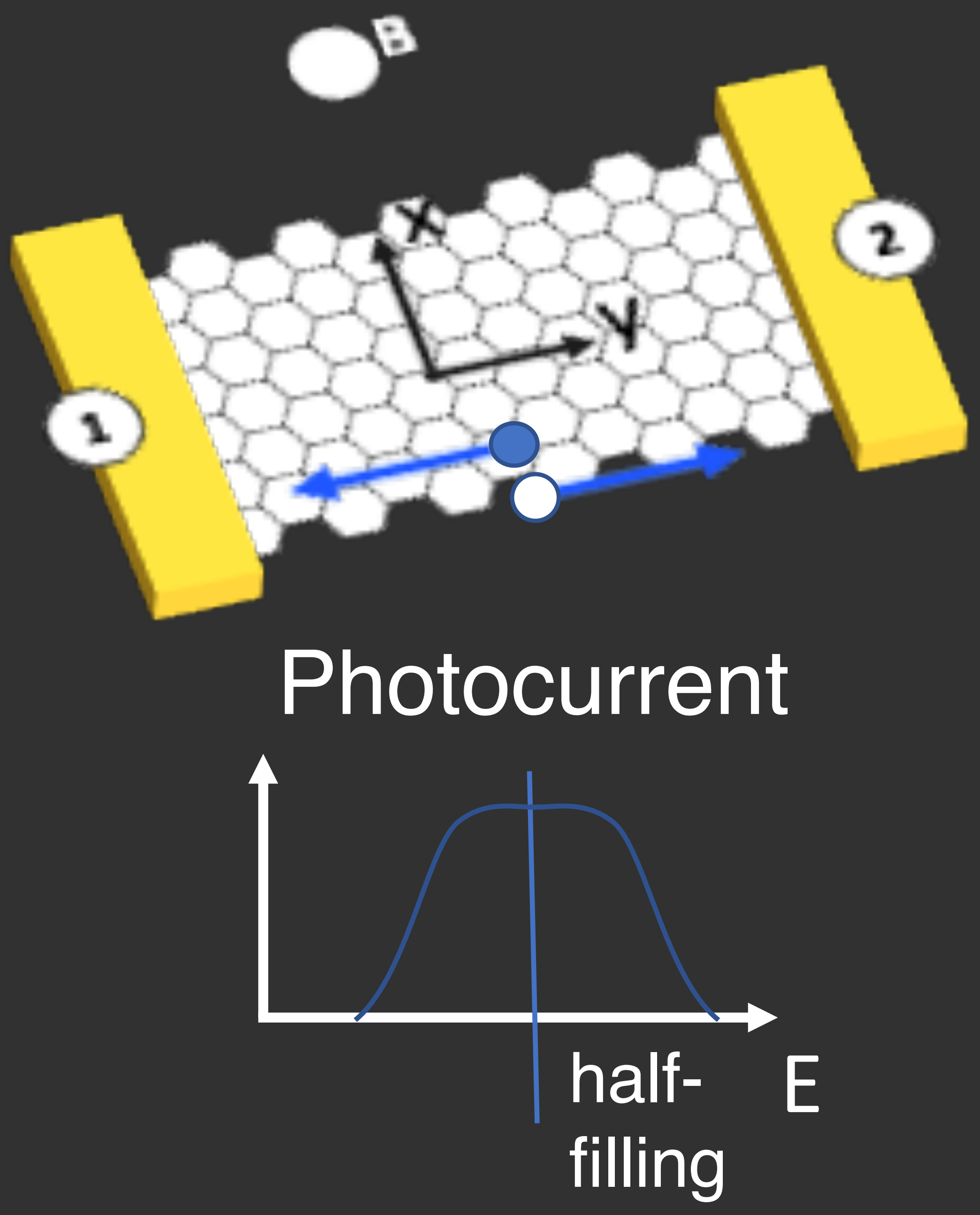




Edge-state photocurrent half-filling with LL

At the Dirac Point





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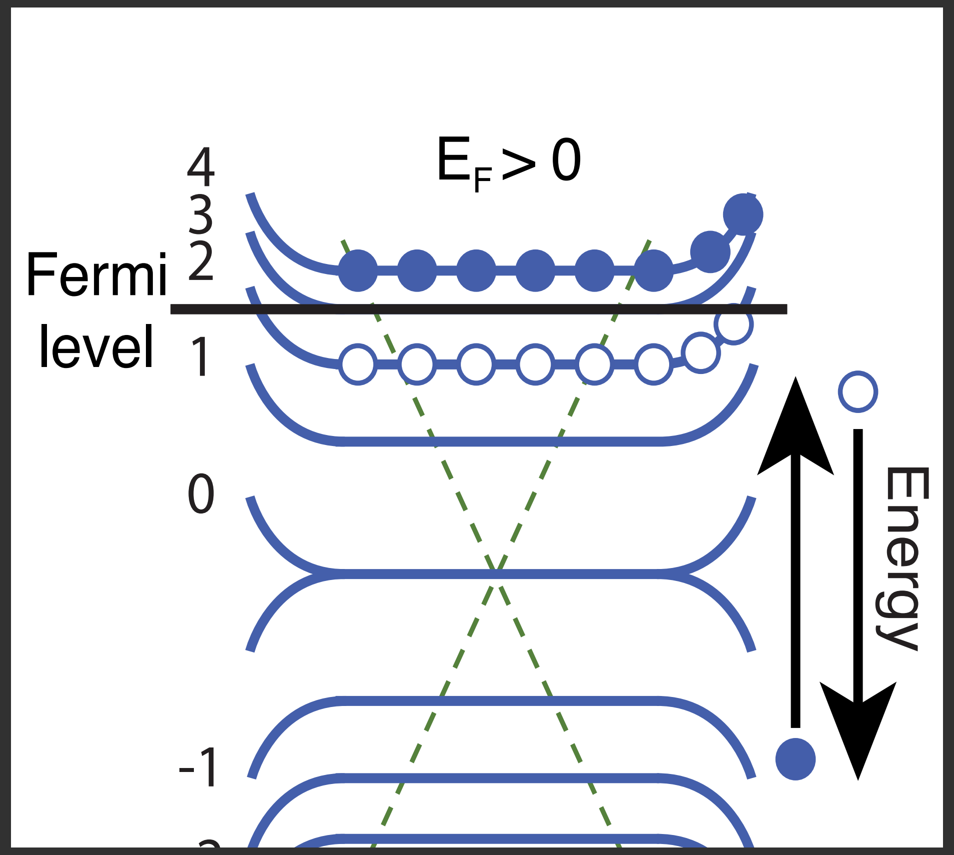
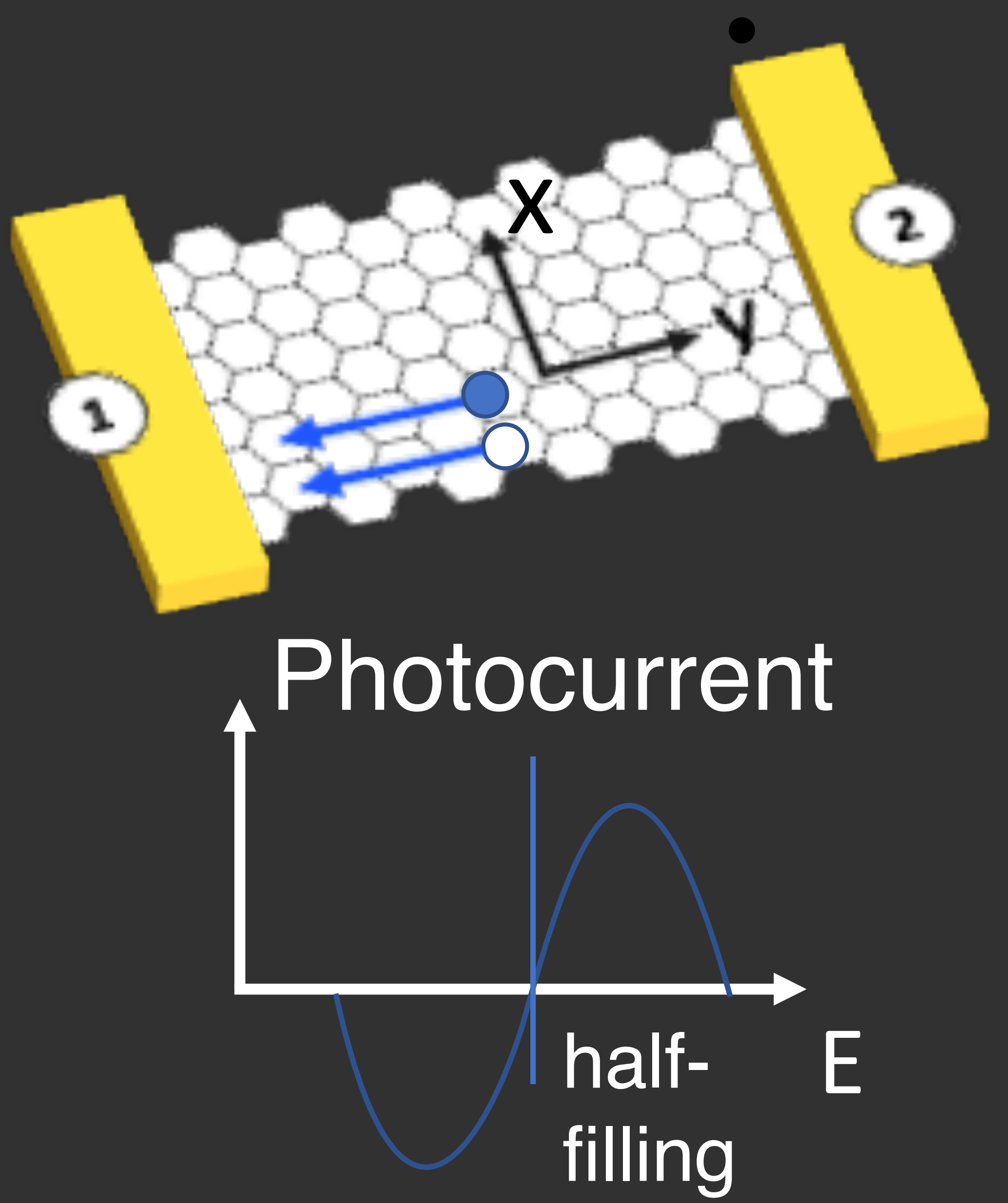
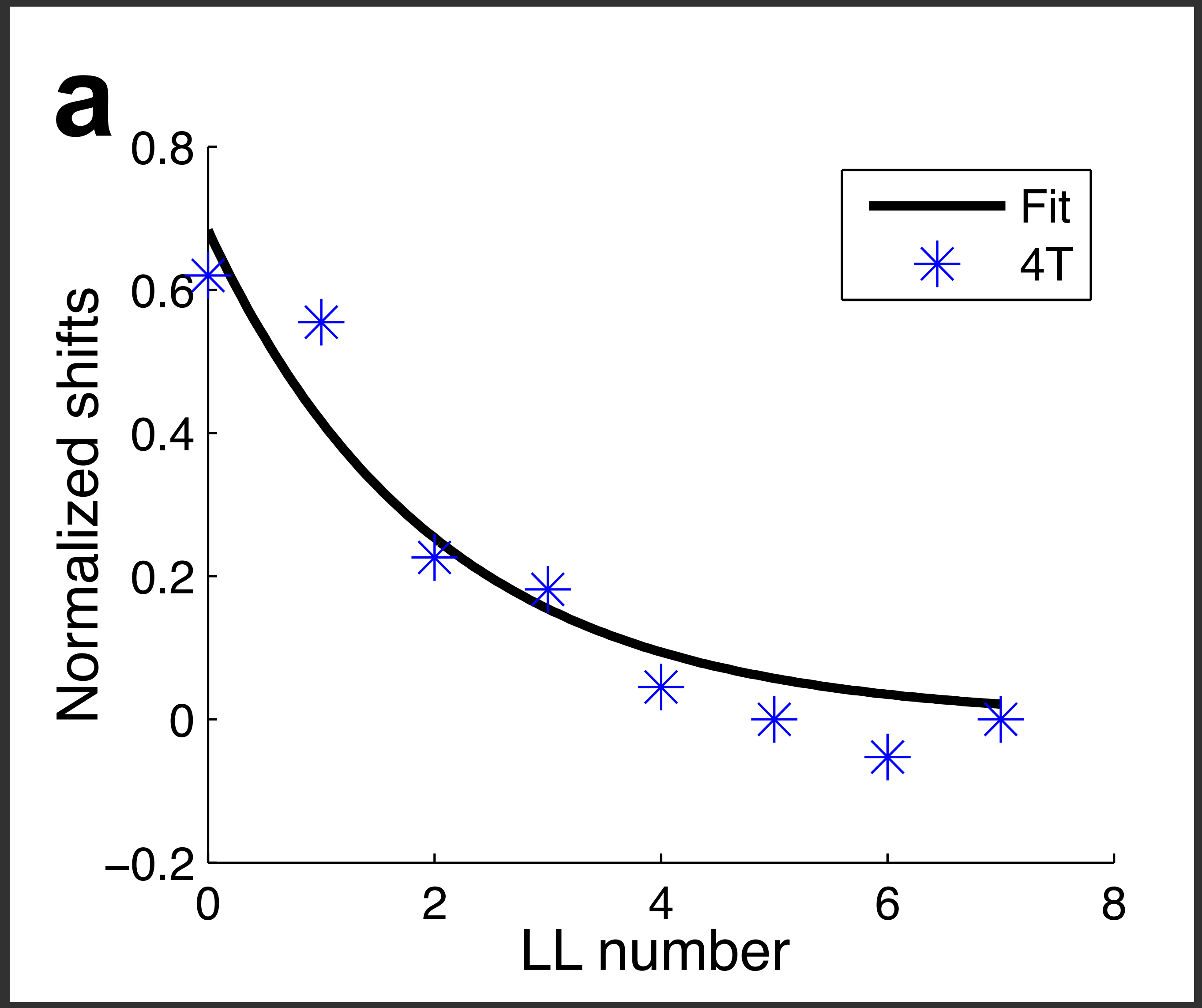
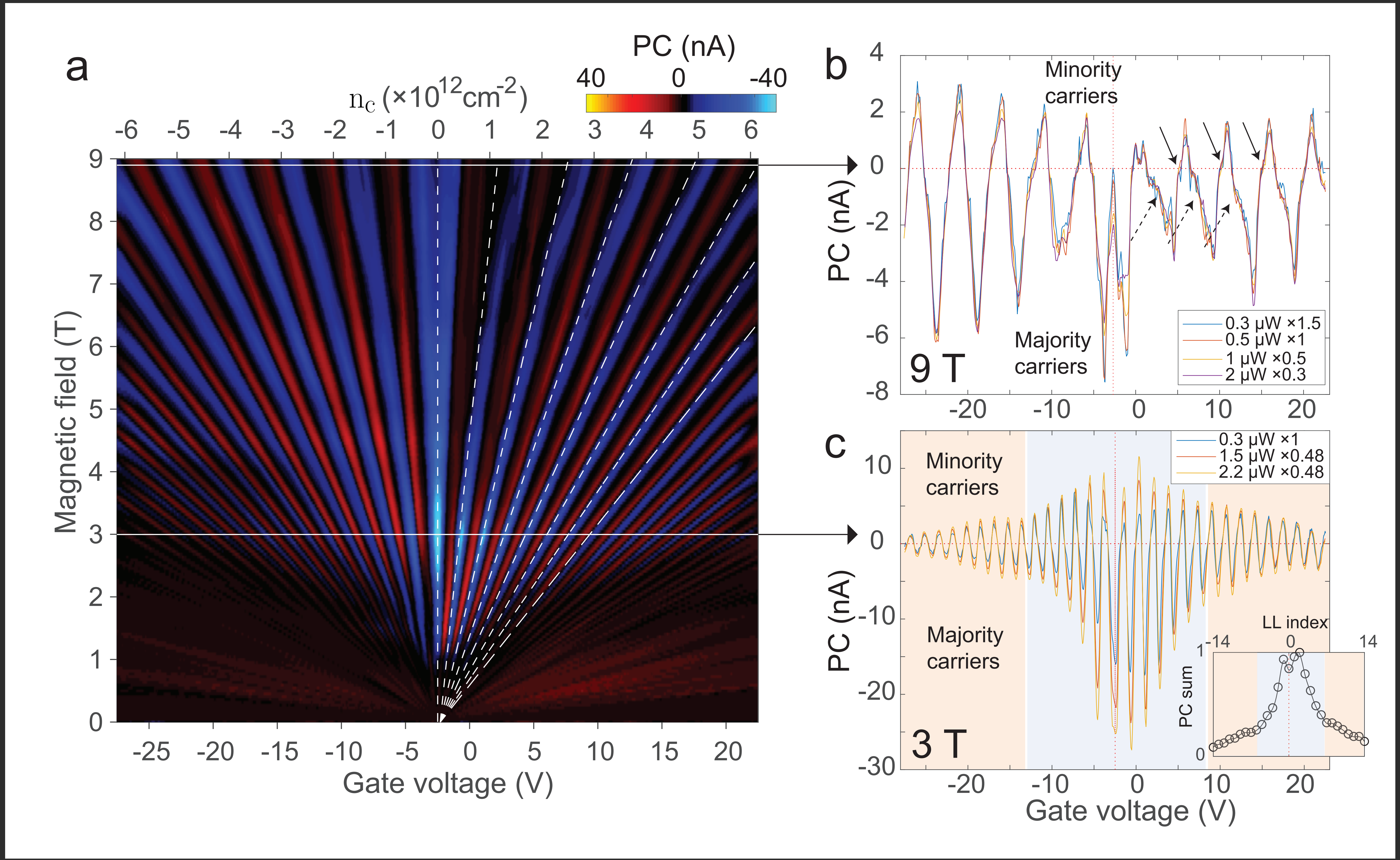




- At LL_0 half filling of LL is a PC peak
- While away from LL_0 PC is 0.
- Because of edge states have multi-LL components the PC moves from a peak value to 0 over several $LL's$.



Shape of the photocurrent envelop as a function of $B-$field
The case for carrier multiplication



9T region: The photocurrent is flat

Lower $B-$fields, 3T:

Large photocurrent majority (e^-) carrier envelope

But also a smaller PC minority carrier envelope.

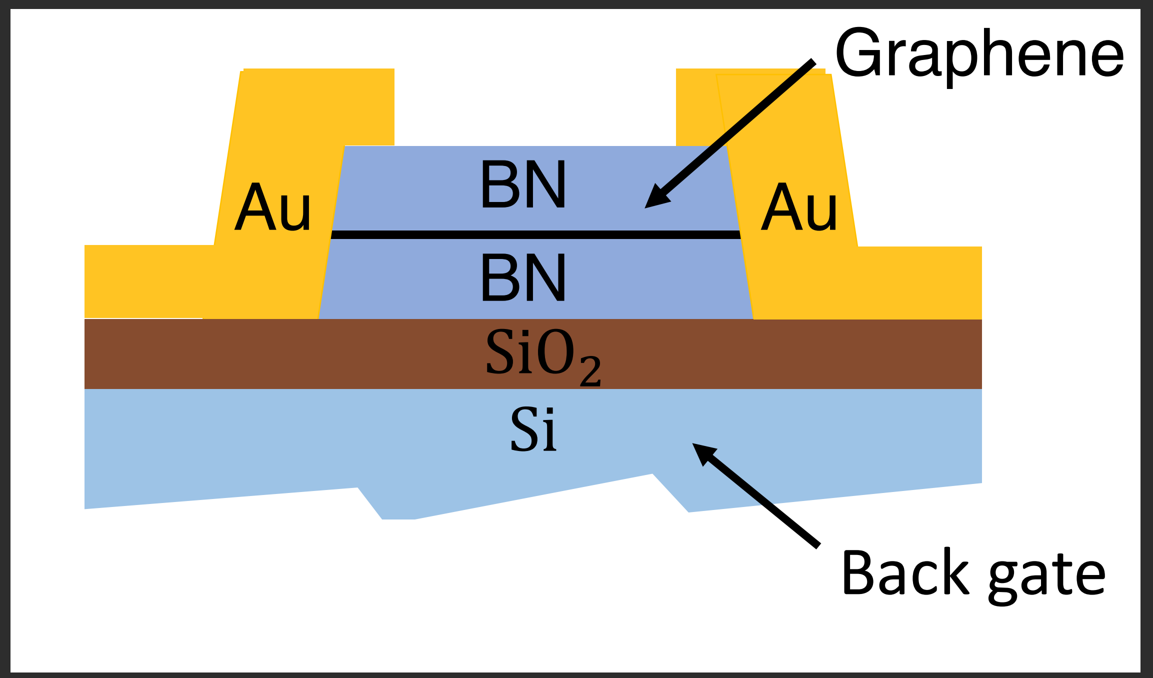
Carrier multiplication:

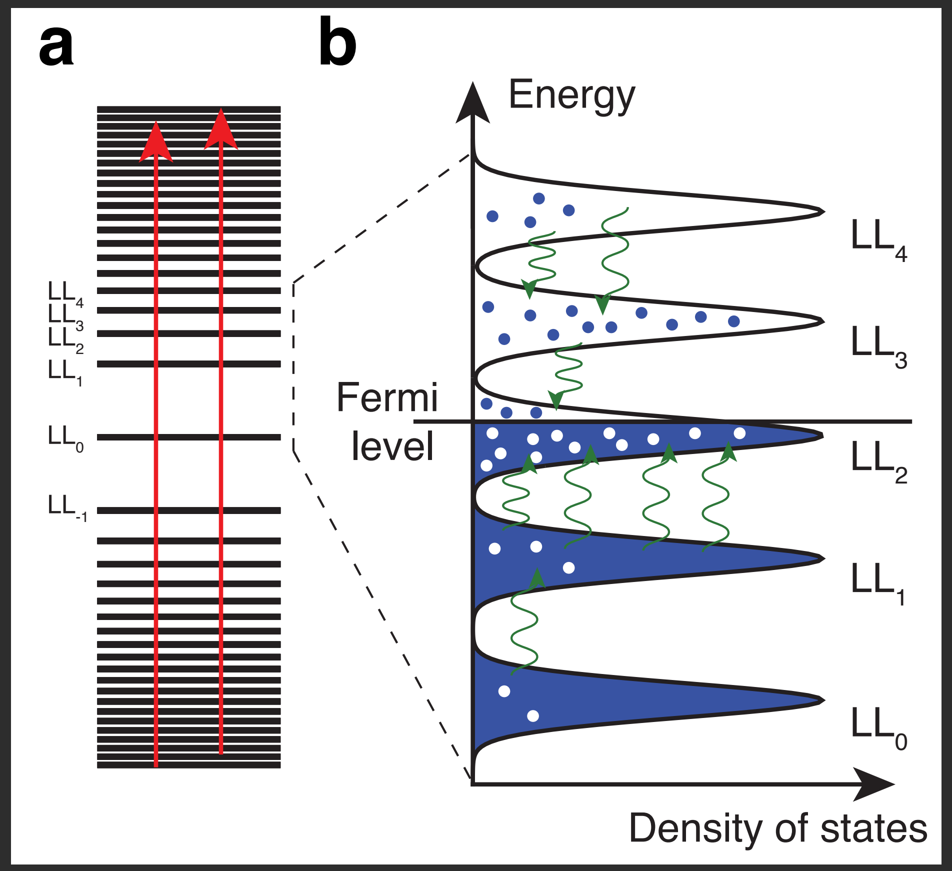
The majority carrier envelop could be due to e^- and h^+ adding around LL_0.

But the **minority carrier envelope can only be explained by carrier multiplication.**

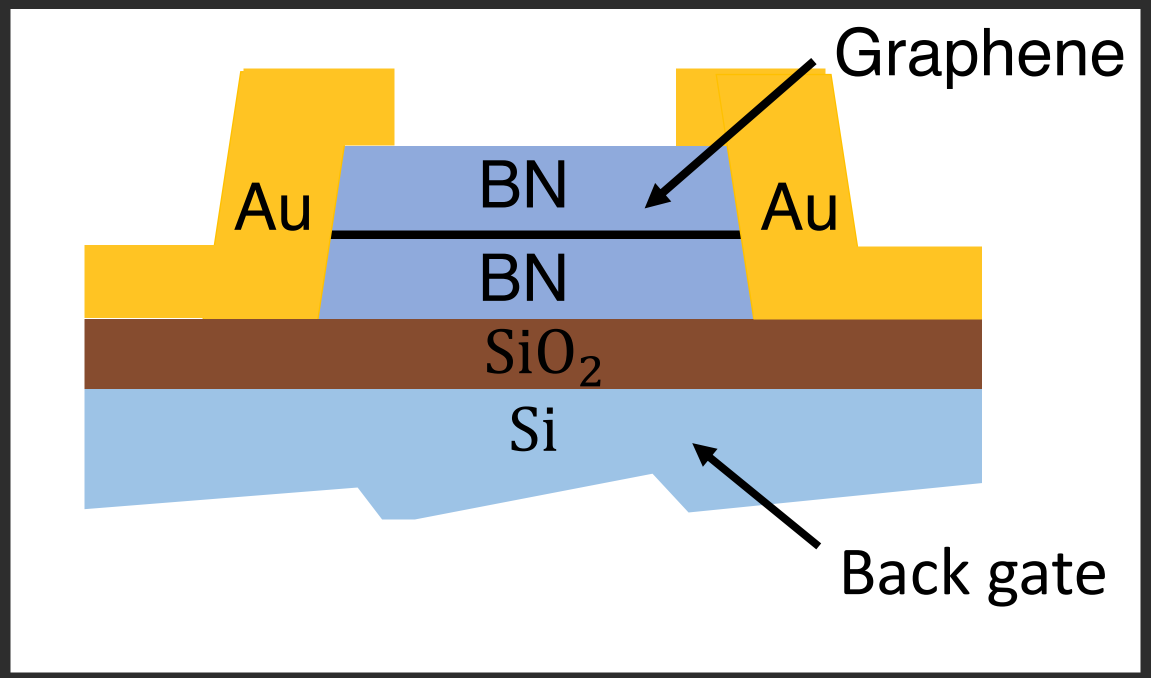
Summary and thoughts

- Using a graphene back-gated device structure at 4K
- Investigate integer quantum Hall physics with a non-equilibrium carrier distribution created by a laser





Summary and thoughts



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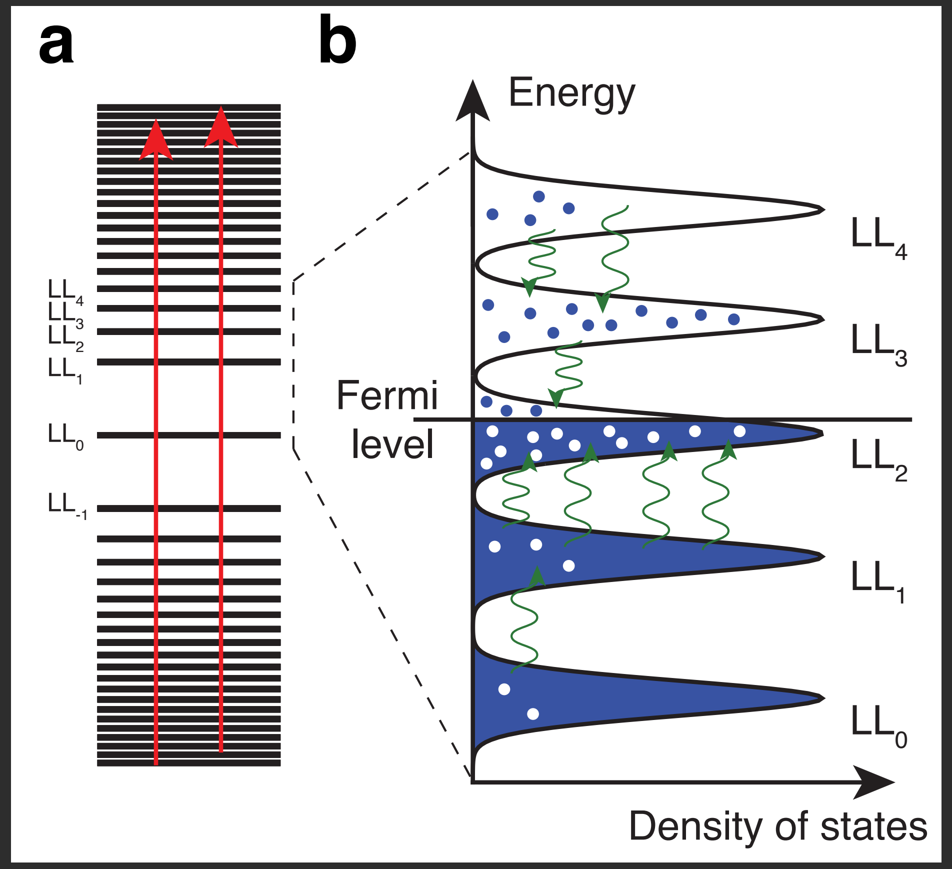
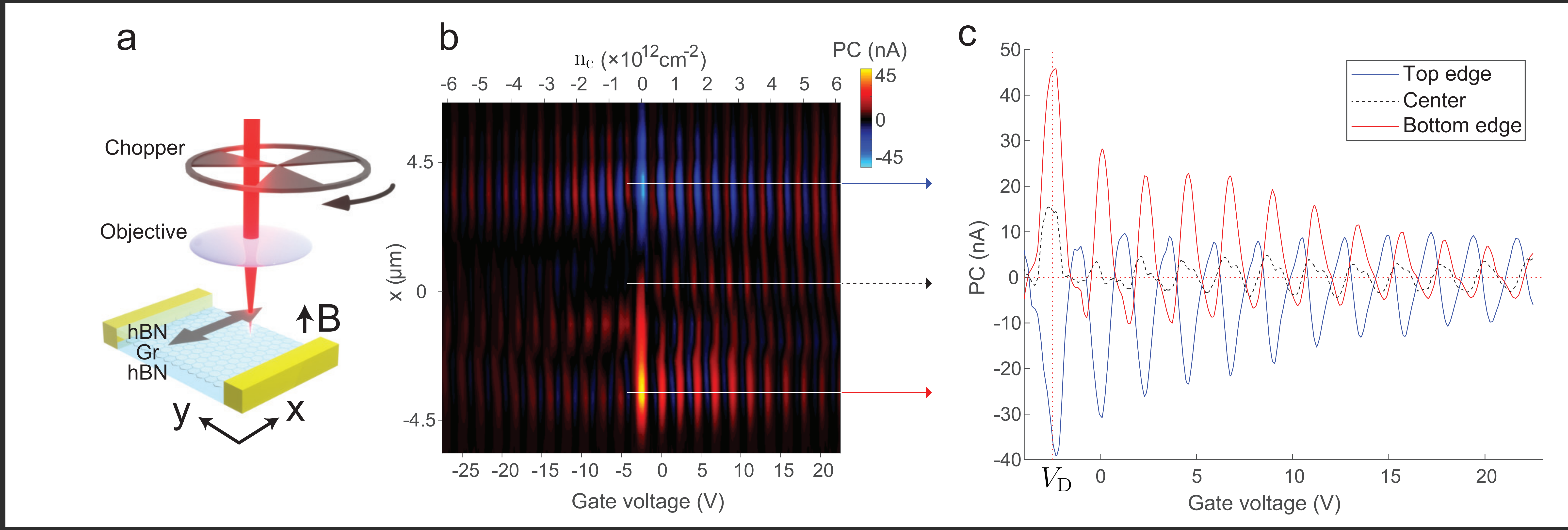
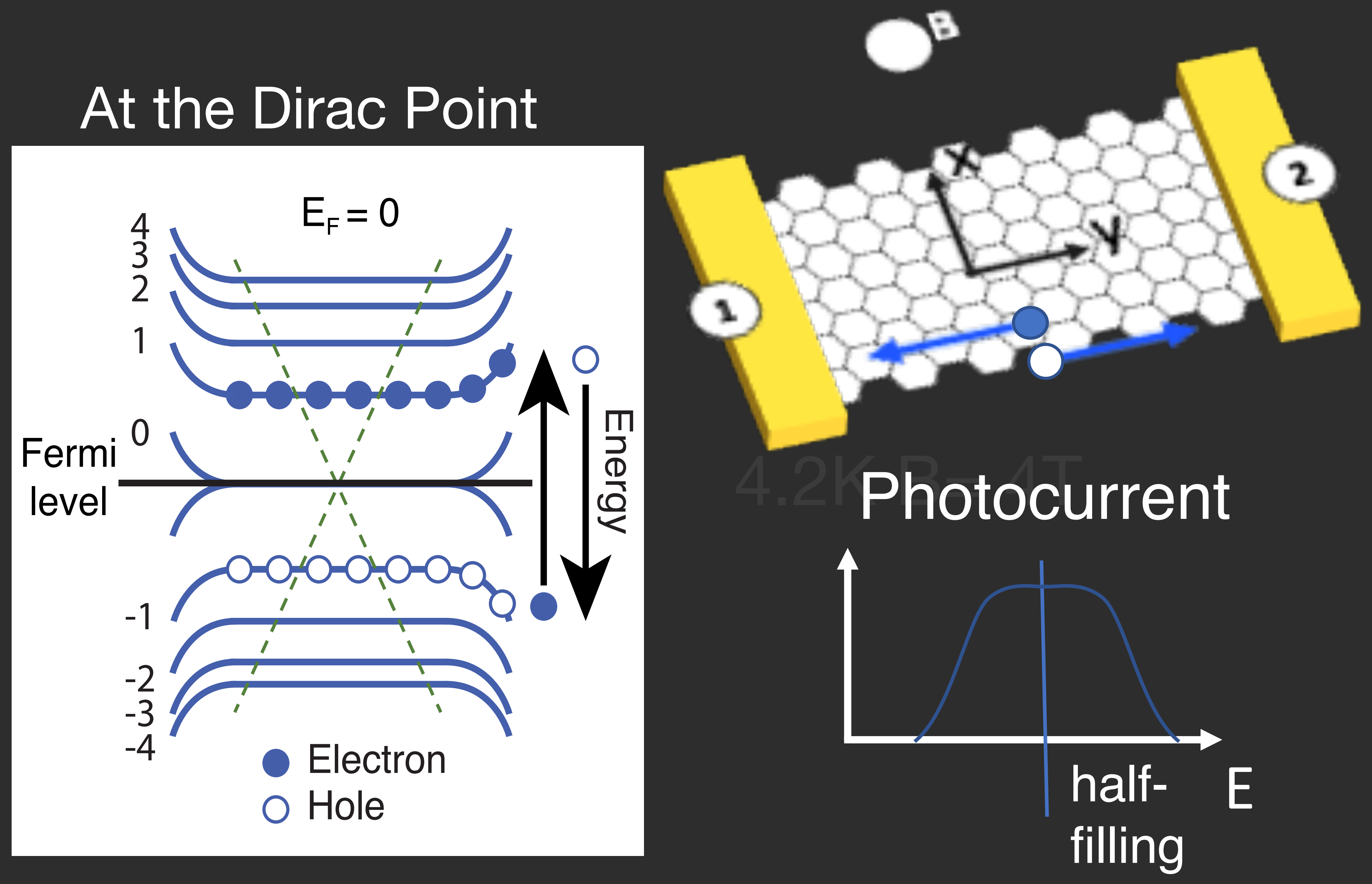
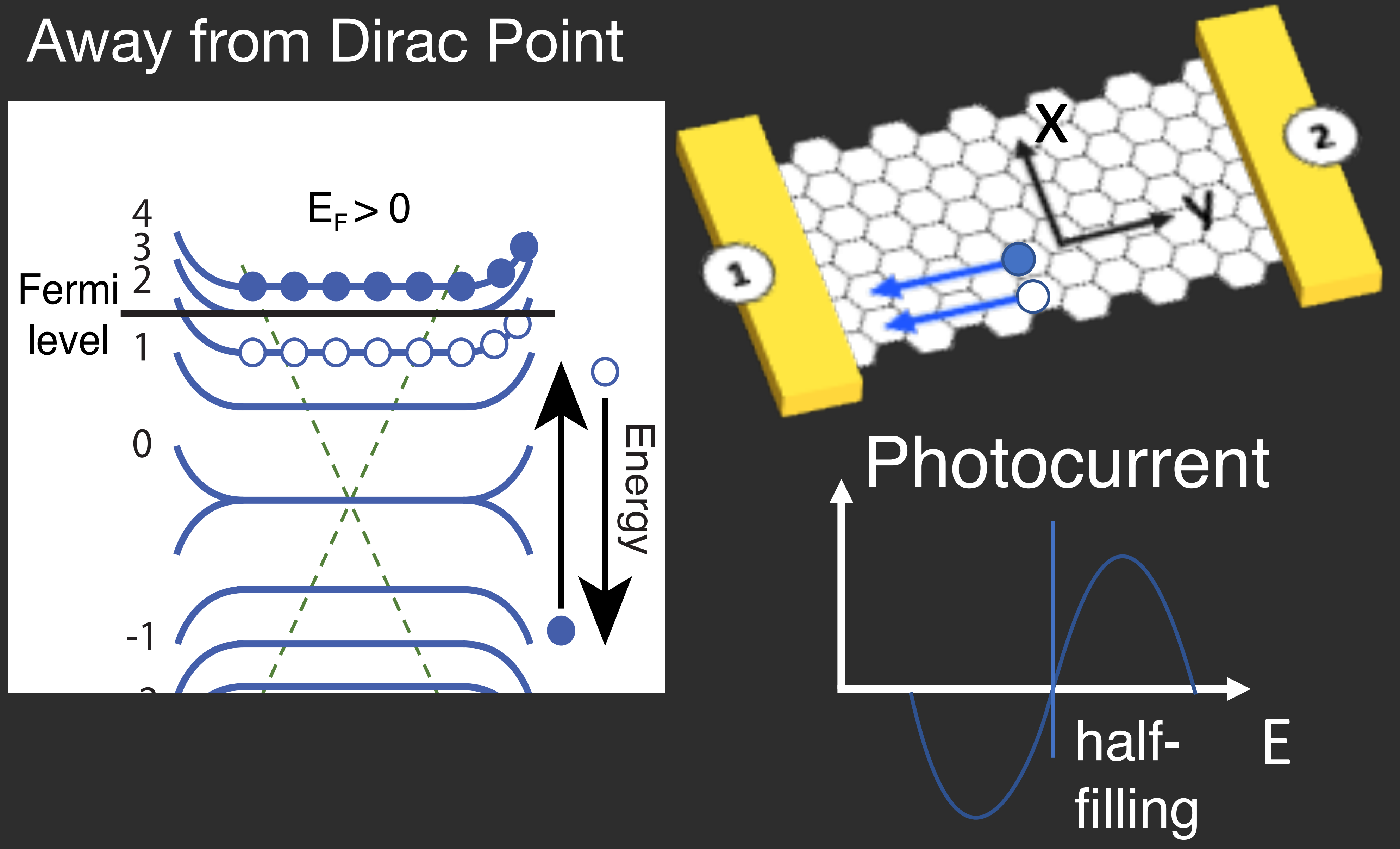




- Current occurs as carriers diffuse to edge-states before recombination
- Edge-state currents are linked to the changing availability of states for each carrier type with Fermi-level position in an LL.

- Both electron and hole currents are present in edge states.
- At the Dirac point their currents add as they come from different bands and both are majority carriers.
- Away from the Dirac point their currents subtract as the carriers are now in the same band.
- Strong evidence of carrier multiplication.





B. Cao, T. Grass, *et al.*, ACS Nano 2022, 16, 11, 18200–18209

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