Tuning the Fermi velocity in Dirac materials with an electric field

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UNIVERSIDAD COMPLUTENSE MADRID

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icmm Instituto de Ciencia de Materiales de Madrid

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OUTLINE

- ❑ Why?
- ❑ State-of-the-art
- ❑ Dirac materials
- ❑ Our proposal
- ❑ Conclusions

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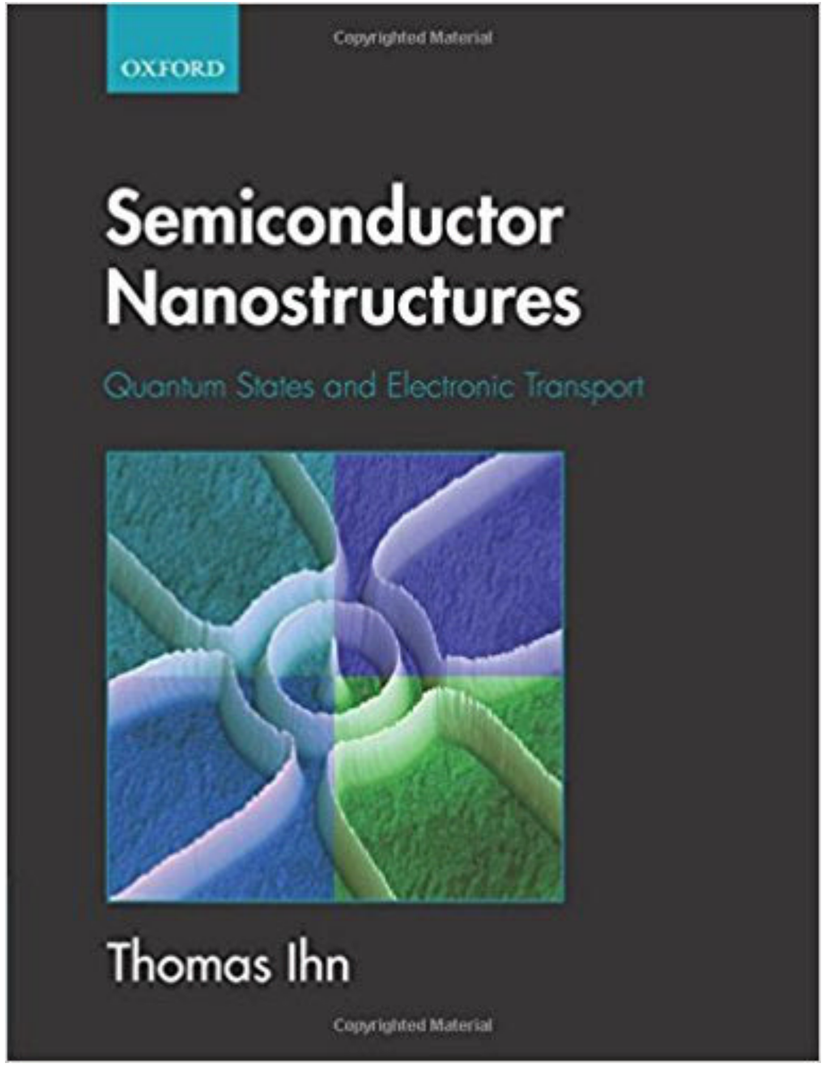
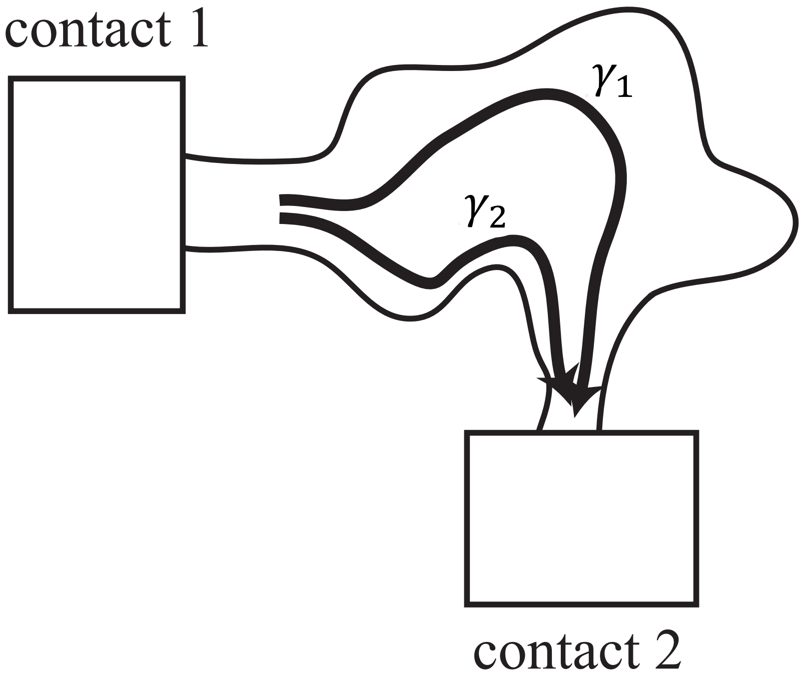
Quantum Transport



Ballistic Conductance Fluctuations



$$G_{\text{int}} = \sum_{mn} |t_m||t_n| \cos(\theta_m - \theta_n) \cos\left(\frac{eBA_{mn}}{\hbar}\right)$$

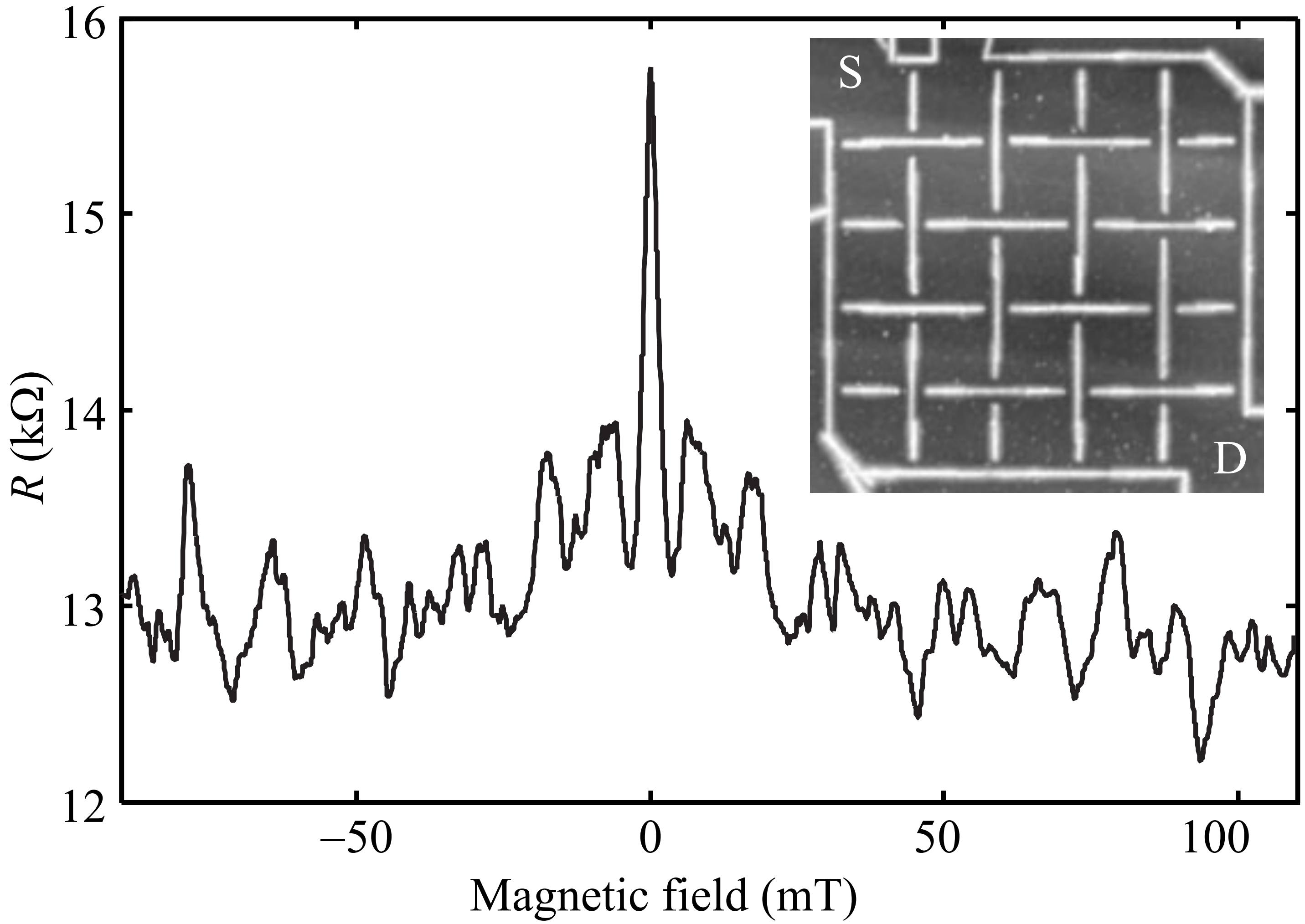


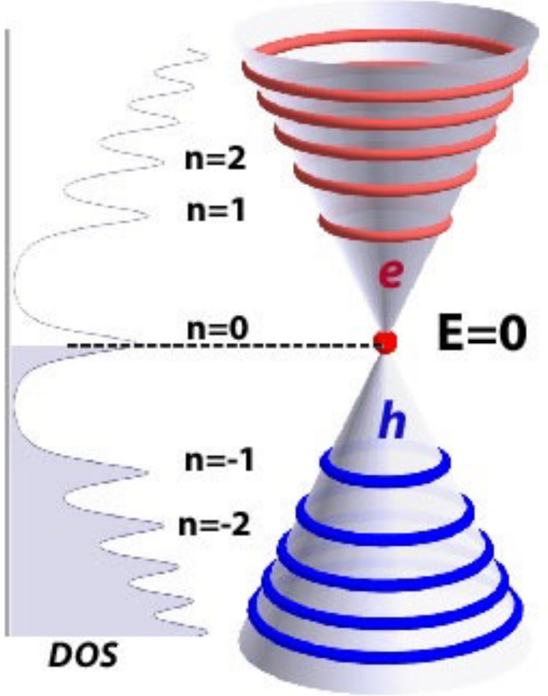
Fig. 14.25 Measurement of ballistic conductance fluctuations in a sample consisting of 25 mesoscopic squares, coupled via quantum point contacts. Current is driven from source (S) to drain (D). The sample was patterned using AFM lithography on a two-dimensional electron gas in the Ga[Al]As material system.

$$B = 0$$

$$G_{\text{int}} = \sum_{mn} |t_m||t_n| \cos(\underbrace{\theta_m - \theta_n})$$

Depends on v_F!

Quantum Hall Effect (Graphene)



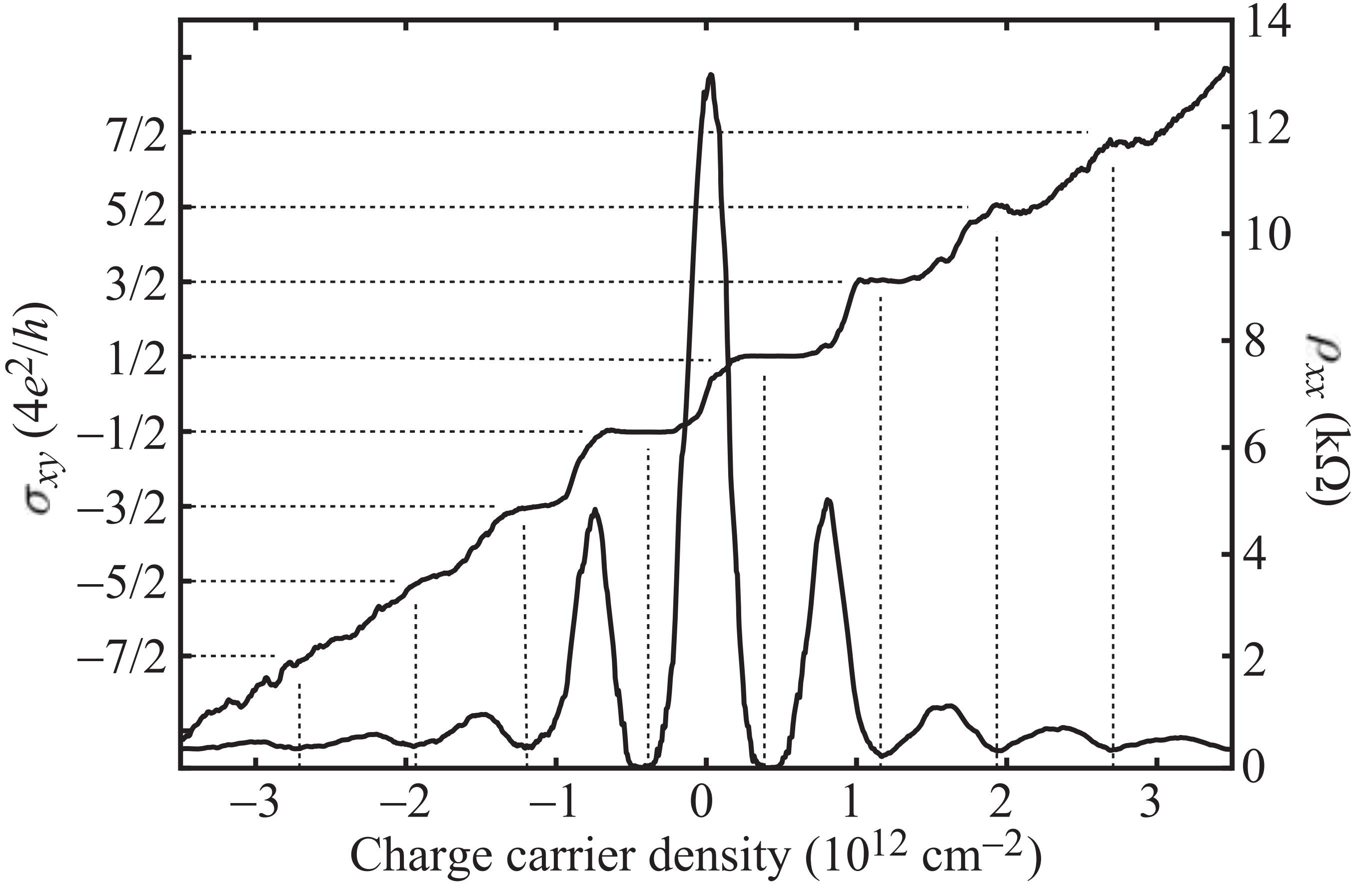
- Usual Landau levels

$$E_n = \hbar\omega_c\left(n + \frac{1}{2}\right)$$

- Graphene

$$E_n = \pm v_F\sqrt{2e\hbar|n|}$$

Quantum Hall Effect (Graphene)



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PRL 99, 256802 (2007) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2007

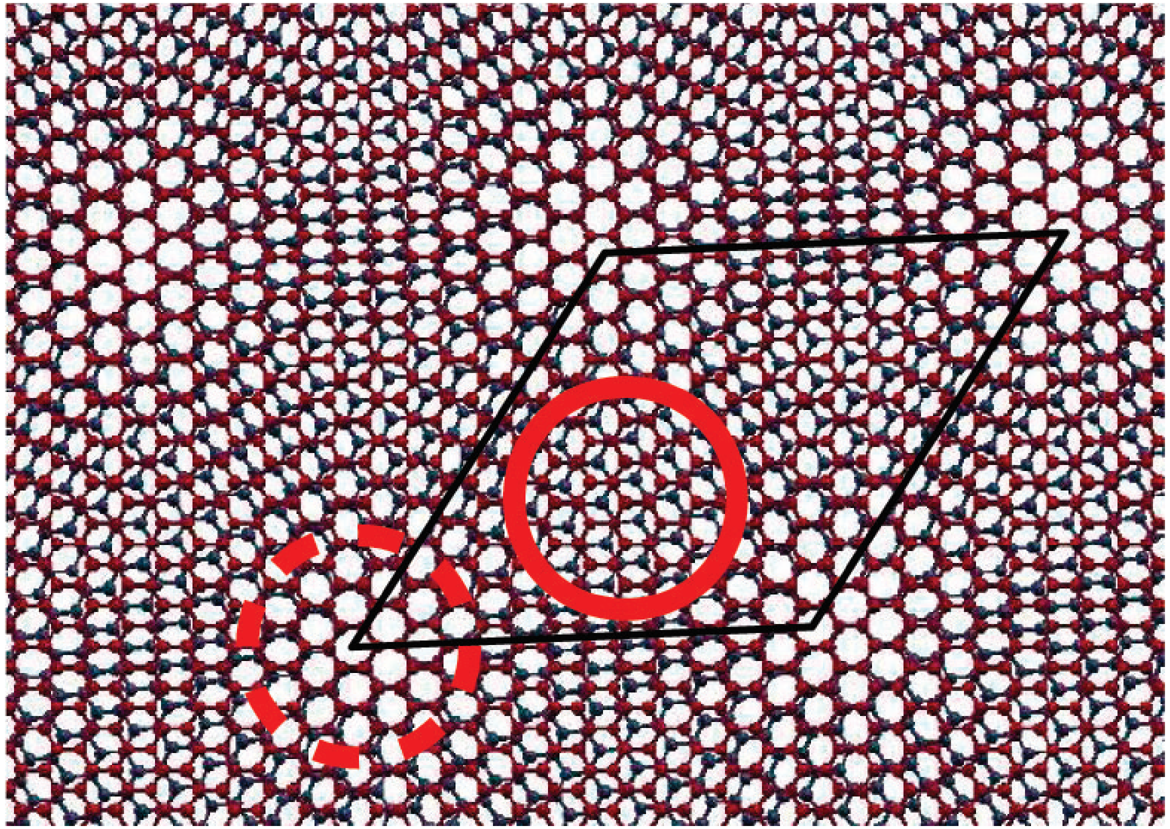
Graphene Bilayer with a Twist: Electronic Structure

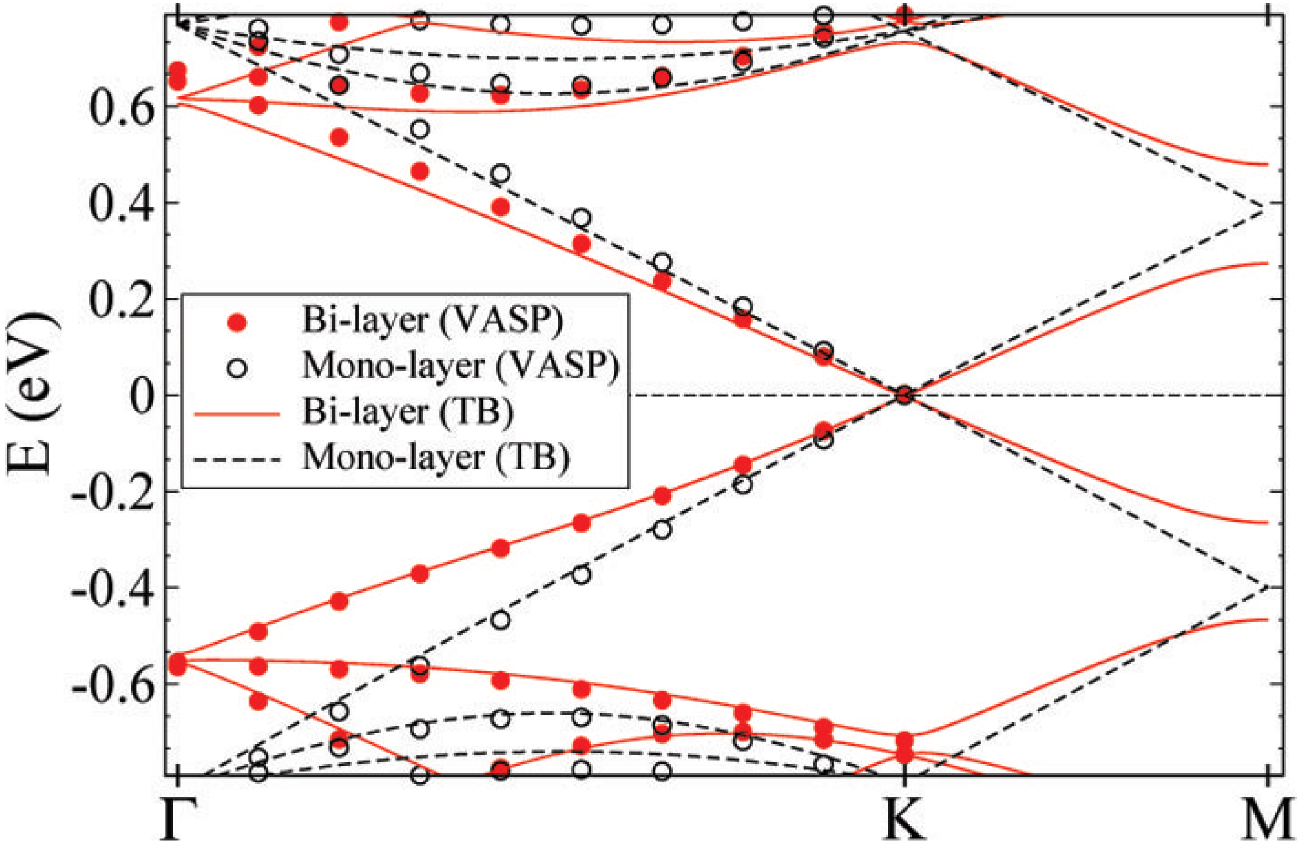
J. M. B. Lopes dos Santos,[1] N. M. R. Peres,[2] and A. H. Castro Neto[3]

NANO LETTERS
pubs.acs.org/NanoLett

Localization of Dirac Electrons in Rotated Graphene Bilayers

G. Trambly de Laissardière,*,† D. Mayou,*,† and L. Magaud*,†

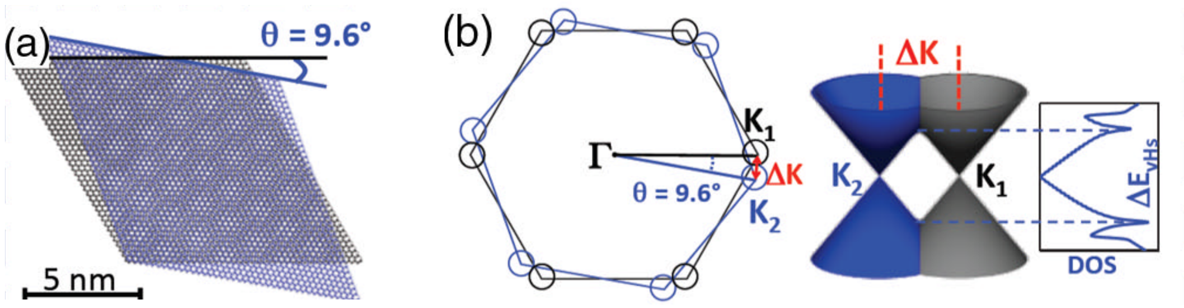




PRL **109,** 196802 (2012) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2012

Unraveling the Intrinsic and Robust Nature of van Hove Singularities in Twisted Bilayer Graphene by Scanning Tunneling Microscopy and Theoretical Analysis

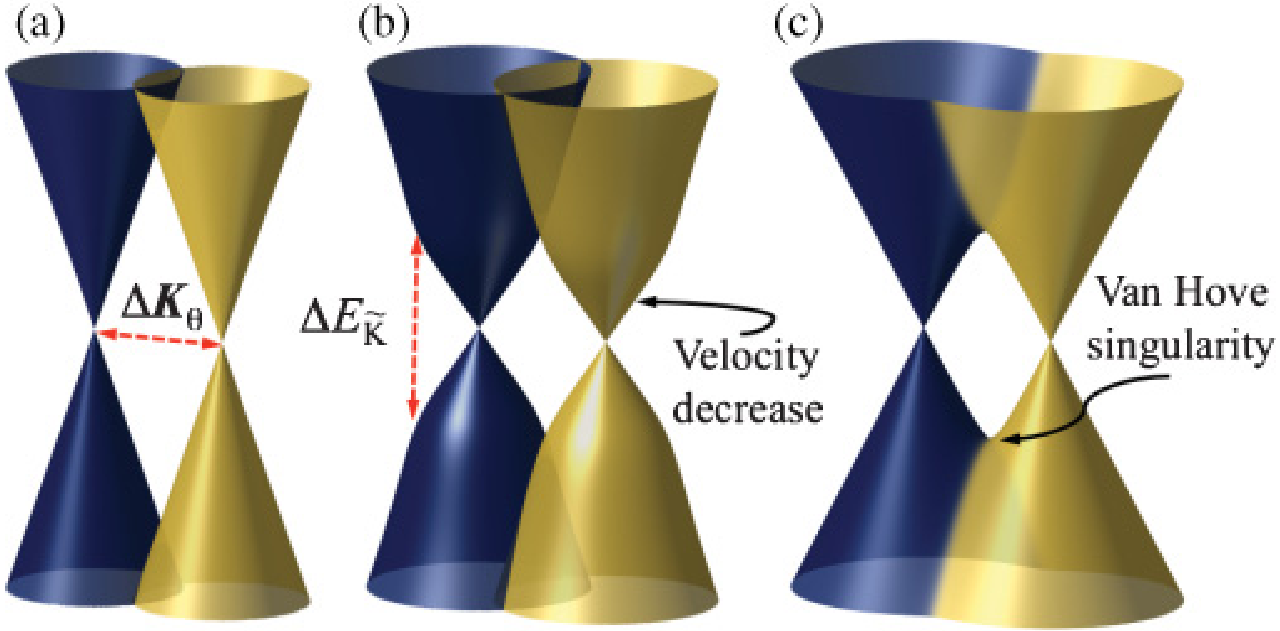
I. Brihuega,[1] P. Mallet,[2] H. González-Herrero,[1] G. Trambly de Laissardière,[3] M. M. Ugeda,[1] L. Magaud,[2] J. M. Gómez-Rodríguez,[1] F. Ynduráin,[1] and J.-Y. Veuillen[2,*]



PHYSICAL REVIEW B **83**, 205403 (2011)

Symmetry breaking in commensurate graphene rotational stacking: Comparison of theory and experiment

J. Hicks, M. Sprinkle, K. Shepperd, and F. Wang
A. Tejeda A. Taleb-Ibrahimi F. Bertran and P. Le Fèvre
W. A. de Heer C. Berger E. H. Conrad



nature physics
LETTERS
PUBLISHED ONLINE: 29 NOVEMBER 2009 | DOI: 10.1038/NPHYS1463

Observation of Van Hove singularities in twisted graphene layers

Guohong Li[1], A. Luican[1], J. M. B. Lopes dos Santos[2], A. H. Castro Neto[3], A. Reina[4], J. Kong[5] and E. Y. Andrei[1]★

NATURE PHYSICS | VOL 6 | FEBRUARY 2010 | www.nature.com/naturephysics 109

PRL 109, 196802 (2012) PHYSICAL REVIEW LETTERS week ending 9 NOVEMBER 2012

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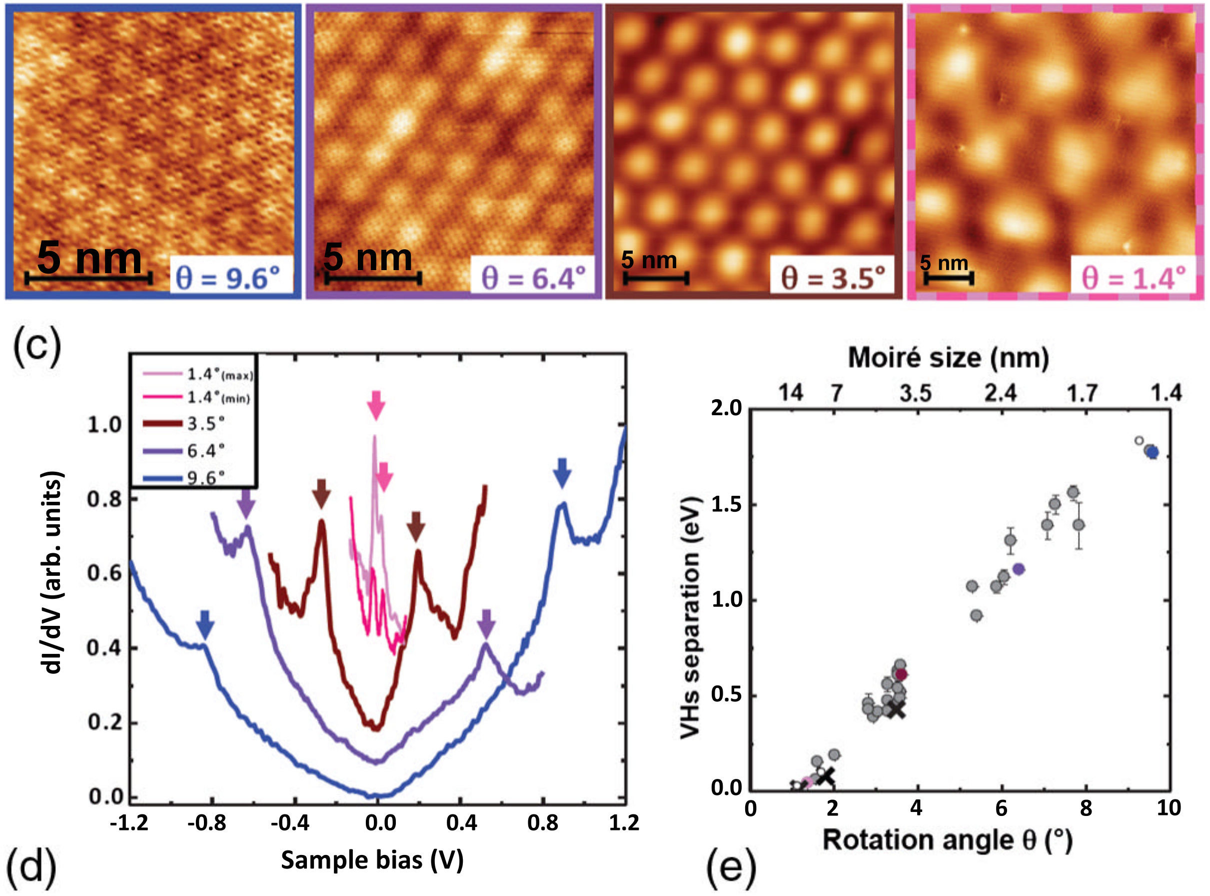


$$\Delta E_{\mathrm{vHs}} \propto v_F(\theta)$$

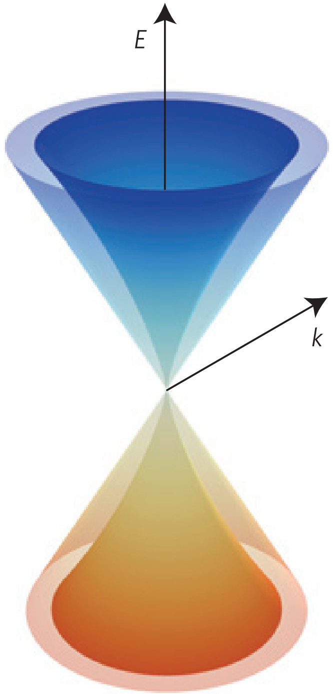
nature physics

LETTERS

PUBLISHED ONLINE: 24 JULY 2011 | DOI: 10.1038/NPHYS2049

Dirac cones reshaped by interaction effects in suspended graphene

D. C. Elias[1], R. V. Gorbachev[1], A. S. Mayorov[1], S. V. Morozov[2], A. A. Zhukov[3], P. Blake[3], L. A. Ponomarenko[1], I. V. Grigorieva[1], K. S. Novoselov[1], F. Guinea[4]* and A. K. Geim[1,3]



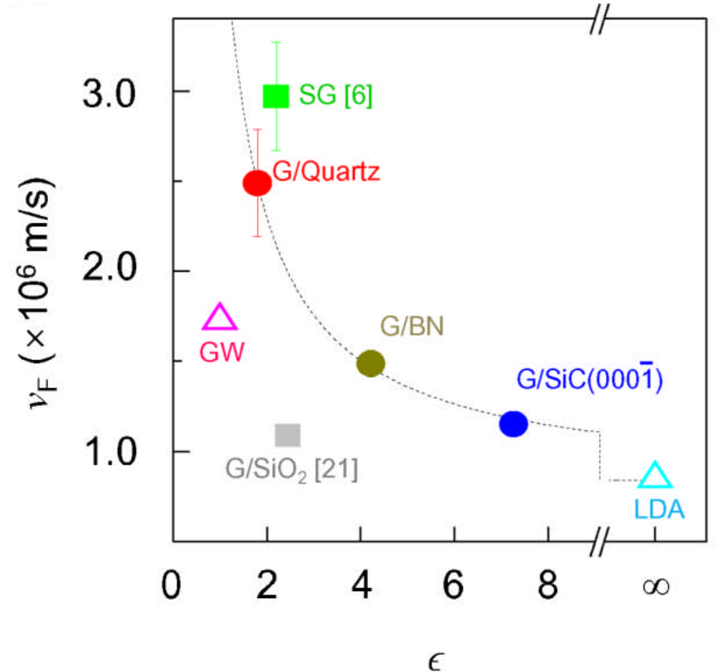
SCIENTIFIC REPORTS

OPEN

Fermi velocity engineering in graphene by substrate modification

SUBJECT AREAS:
ELECTRONIC MATERIALS AND DEVICES

Choongyu Hwang[1], David A. Siegel[1,2], Sung-Kwan Mo[3], William Regan[1,2], Ariel Ismach[4], Yuegang Zhang[4], Alex Zettl[1,2] & Alessandra Lanzara[1,2]



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REVIEW

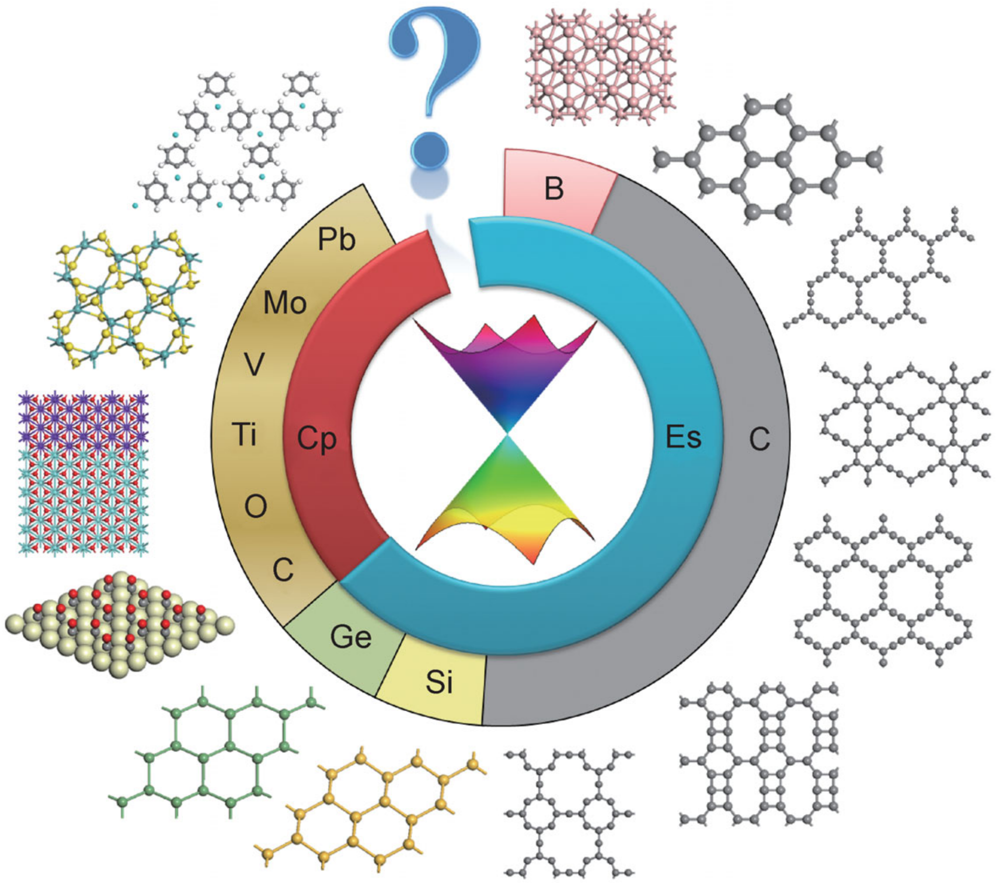
National Science Review
2: 22–39, 2015
doi: 10.1093/nsr/nwu080
Advance access publication 31 January 2015

PHYSICS

Special Topic: Graphene—From basic science to useful technology

The rare two-dimensional materials with Dirac cones

Jinying Wang, Shibin Deng, Zhongfan Liu and Zhirong Liu*



Advances in Physics, 2014
Vol. 63, No. 1, 1–76, http://dx.doi.org/10.1080/00018732.2014.927109

Taylor & Francis
Taylor & Francis Group

REVIEW ARTICLE

Dirac materials

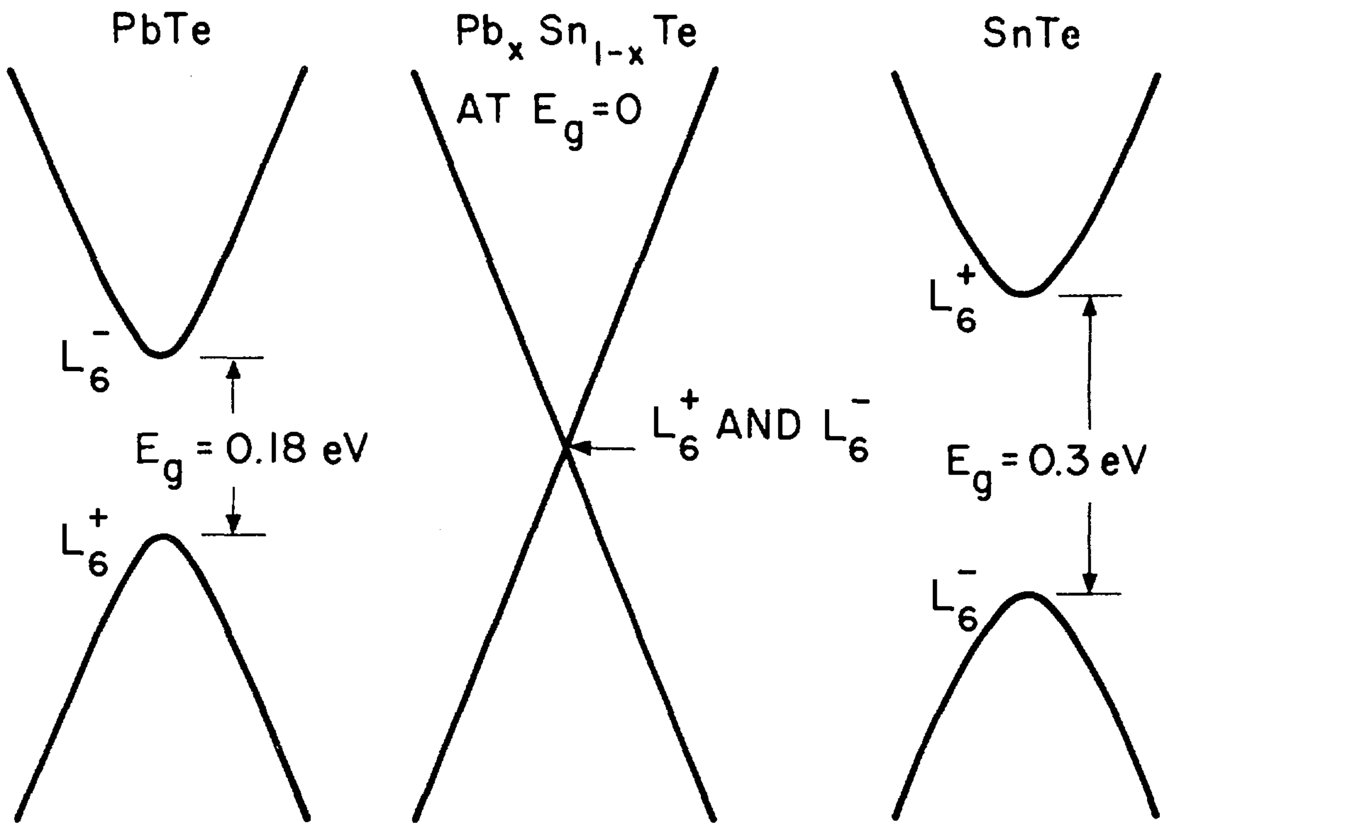
T.O. Wehling[a,b], A.M. Black-Schaffer[c] and A.V. Balatsky[d,e*]

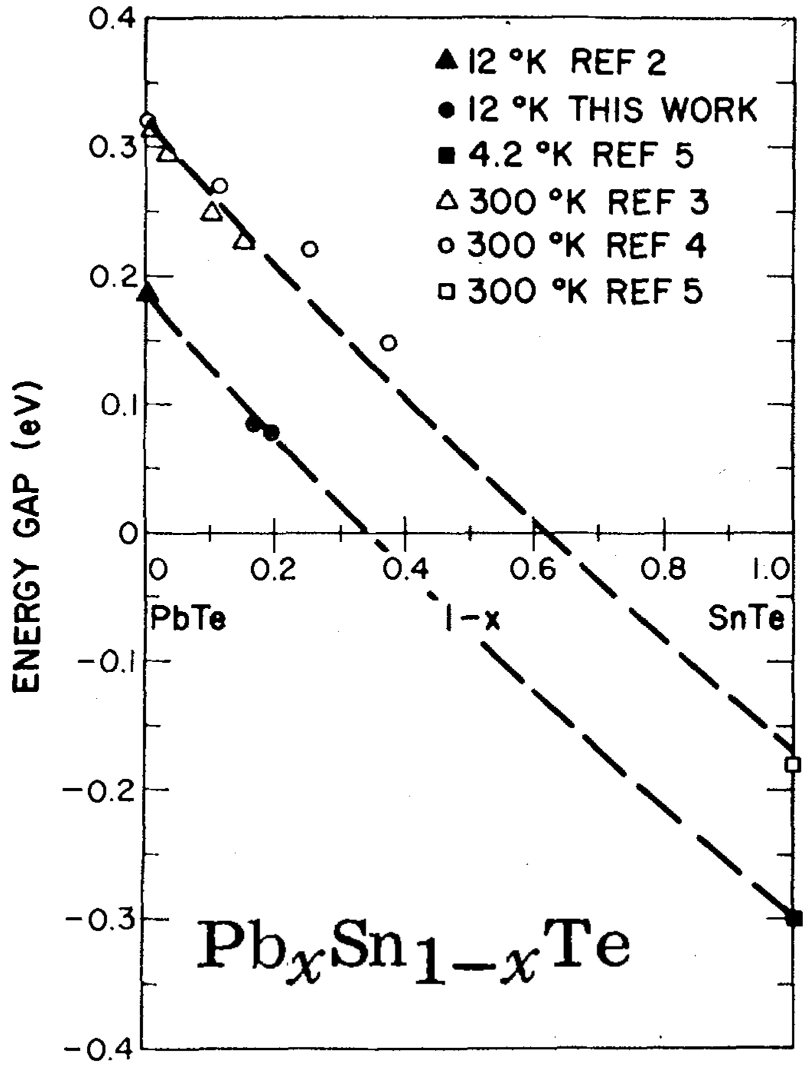
Table 1. Dirac materials indicated by material family, pseudo-spin realization in the Dirac Hamiltonian, and the energy scale for which the Dirac spectrum is present without any other states.

Material	Pseudo-spin	Energy scale	References
Graphene, silicene, germanene	Sublattice	$1-3$ eV	[5,6,17,19,36,37]
Artificial graphenes	Sublattice	$10^{-8}-0.1$ eV	[28,29,38–40]
Hexagonal layered heterostructures	Emergent	$0.01-0.1$ eV	[41–47]
Hofstadter butterfly systems Graphene–hBN heterostructures in high magnetic fields	Emergent	0.01 eV	[46]
Band inversion interfaces: SnTe/PbTe, CdTe/HgTe, PbTe	Spin–orbit ang. mom.	0.3 eV	[48–50]
2D topological insulators: HgTe/CdTe, InAs/GaSb, Bi bilayer, …	Spin–orbit ang. mom.	<0.1 eV	[7,8,22,24,51,52]
3D topological insulators: $Bi_{1-x}Sb_x$, Bi_2Se_3, strained HgTe, Heusler alloys, …	Spin–orbit ang. mom.	$\lesssim 0.3$ eV	[7,8,23,52–55]
Topological crystalline insulators: SnTe, $Pb_{1-x}Sn_xSe$	Orbital	$\lesssim 0.3$ eV	[56–59]
d-wave cuprate superconductors	Nambu pseudo-spin	$\lesssim 0.05$ eV	[60,61]
^3He	Nambu pseudo-spin	0.3 μeV	[2,3]
3D Weyl and Dirac SM Cd_3As_2, Na_3Bi	Energy bands	Unclear	[32–34]

BAND STRUCTURE AND LASER ACTION IN $Pb_xSn_{1-x}Te$

J. O. Dimmock, I. Melngailis, and A. J. Strauss





Two-dimensional massless electrons in an inverted contact

B. A. Volkov and O. A. Pankratov

Pis'ma Zh. Eksp. Teor. Fiz. **42**, No. 4, 145–148 (25 August 1985)

PHYSICAL REVIEW B VOLUME 35, NUMBER 12 15 APRIL 1987-II

Subbands in the gap in inverted-band semiconductor quantum wells

V. Korenman and H. D. Drew

PHYSICAL REVIEW B VOLUME 37, NUMBER 17 15 JUNE 1988-I

Interface states in band-inverted semiconductor heterojunctions

D. Agassi
V. Korenman

phys. stat. sol. (b) **186**, K49 (1994)

Subject classification: 73.20 and 73.40

Departamento de Física de Materiales, Facultad de Físicas, Universidad Complutense, Madrid[1])

Green Function Approach to Interface States in Band-Inverted Junctions

By

F. DOMÍNGUEZ-ADAME

PHYSICAL REVIEW B VOLUME 37, NUMBER 17 15 JUNE 1988-I

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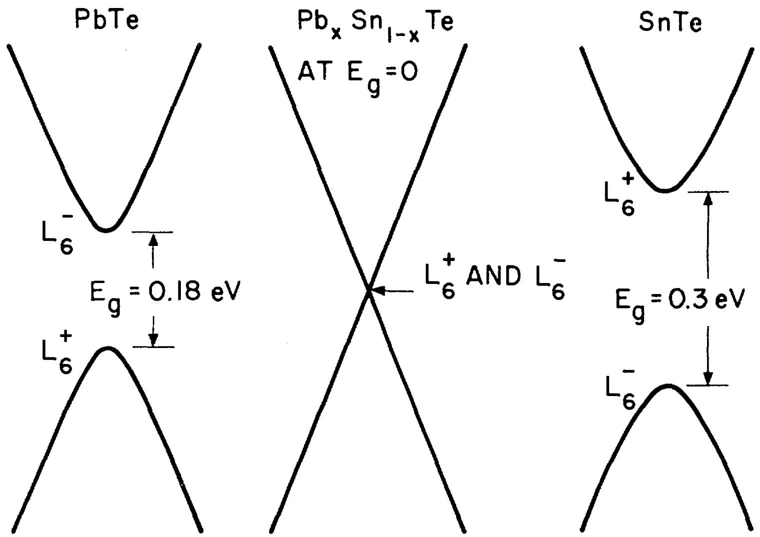
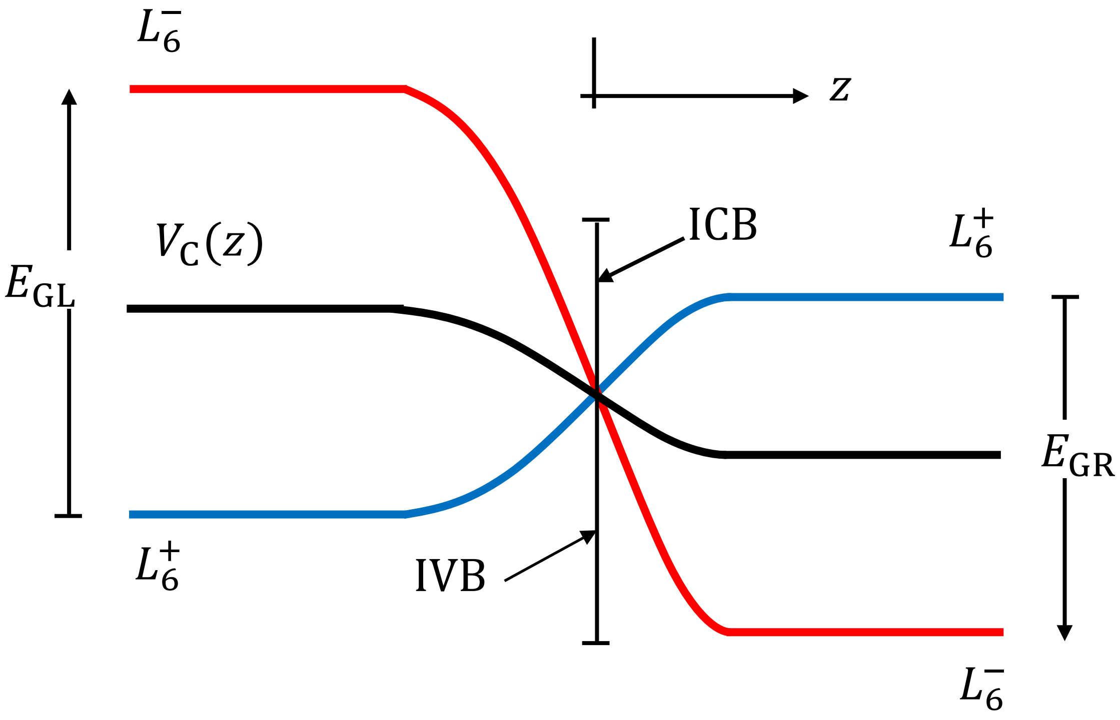
V. Korenman





Two-band model: Dirac-like Hamiltonian

$$\mathcal{H} = v_\perp \boldsymbol{\alpha}_\perp \cdot \boldsymbol{p}_\perp + v_z \alpha_z p_z + \frac{1}{2} E_G(z)\beta + V_C(z)$$

phys. stat. sol. (b) **186**, K49 (1994)

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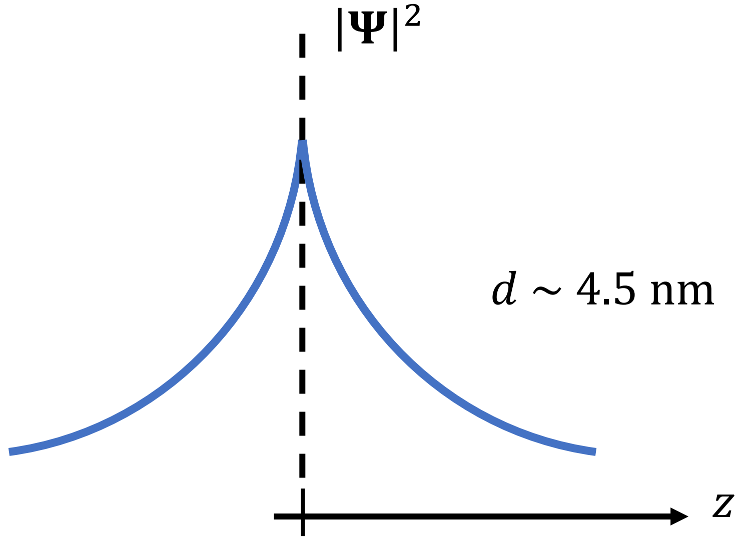
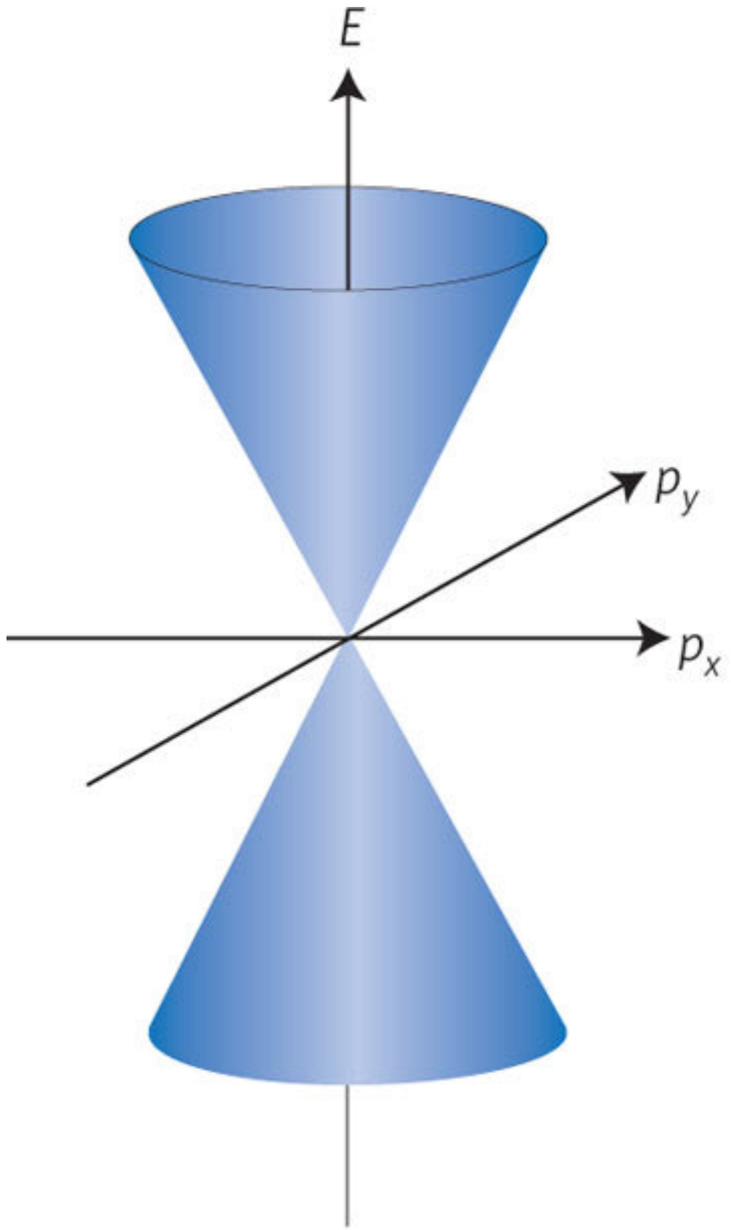
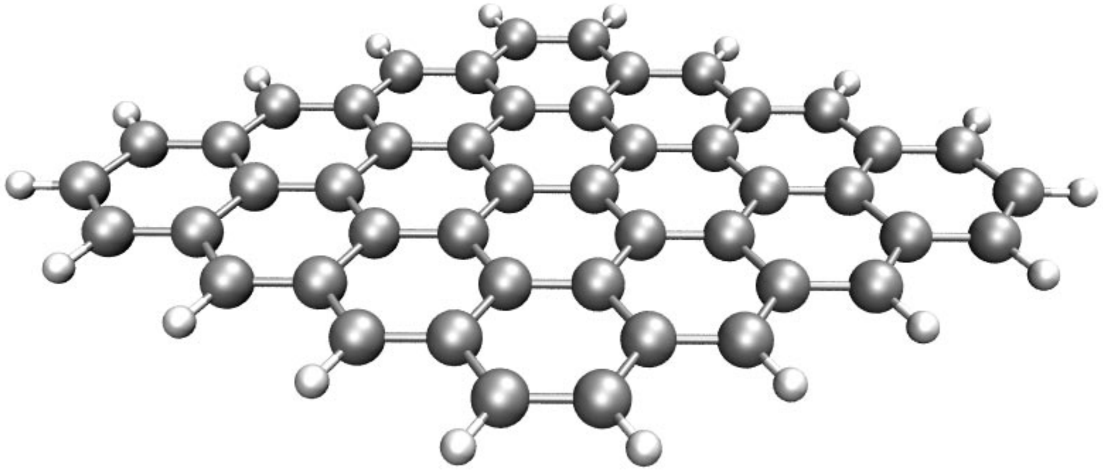
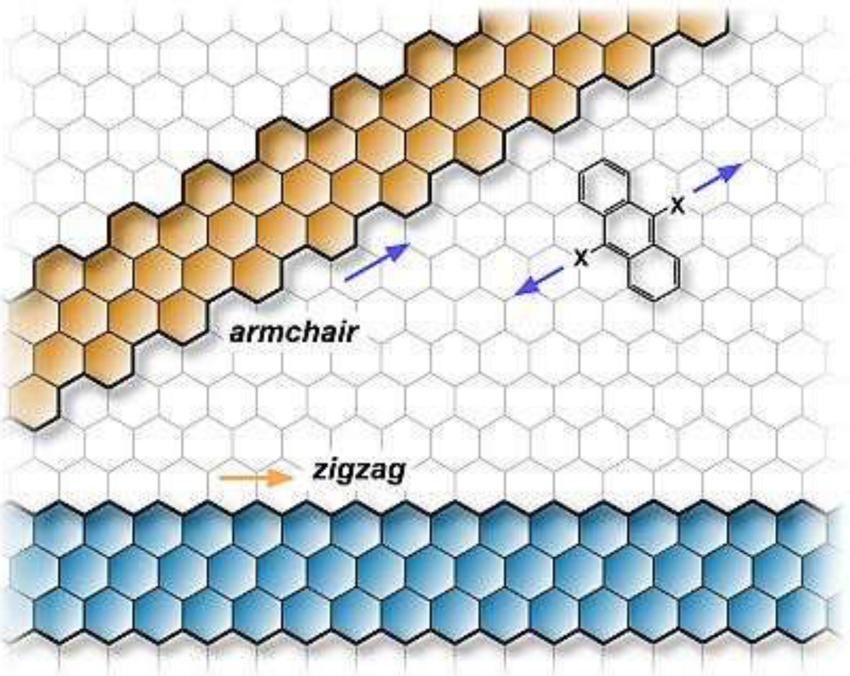
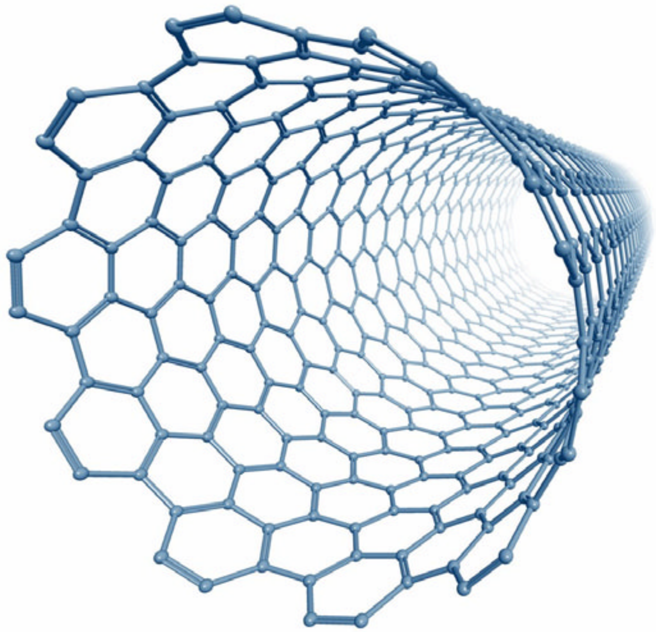







X
X
armchair
zigzag



OUTLINE

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- ❑ State-of-the-art
- ❑ Dirac materials
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Tuning the Fermi velocity in Dirac materials with an electric field

A. Díaz-Fernández[1,2,*], Leonor Chico[3,4], J. W. González[4,5], and F. Domínguez-Adame[1,2]

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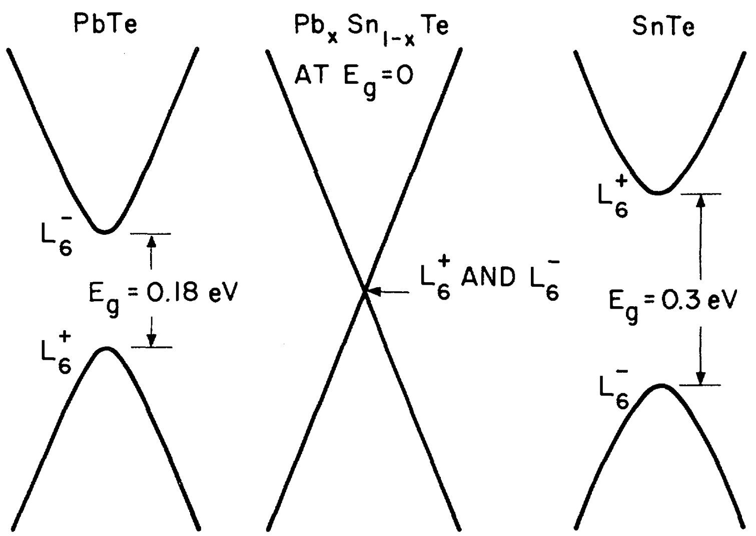

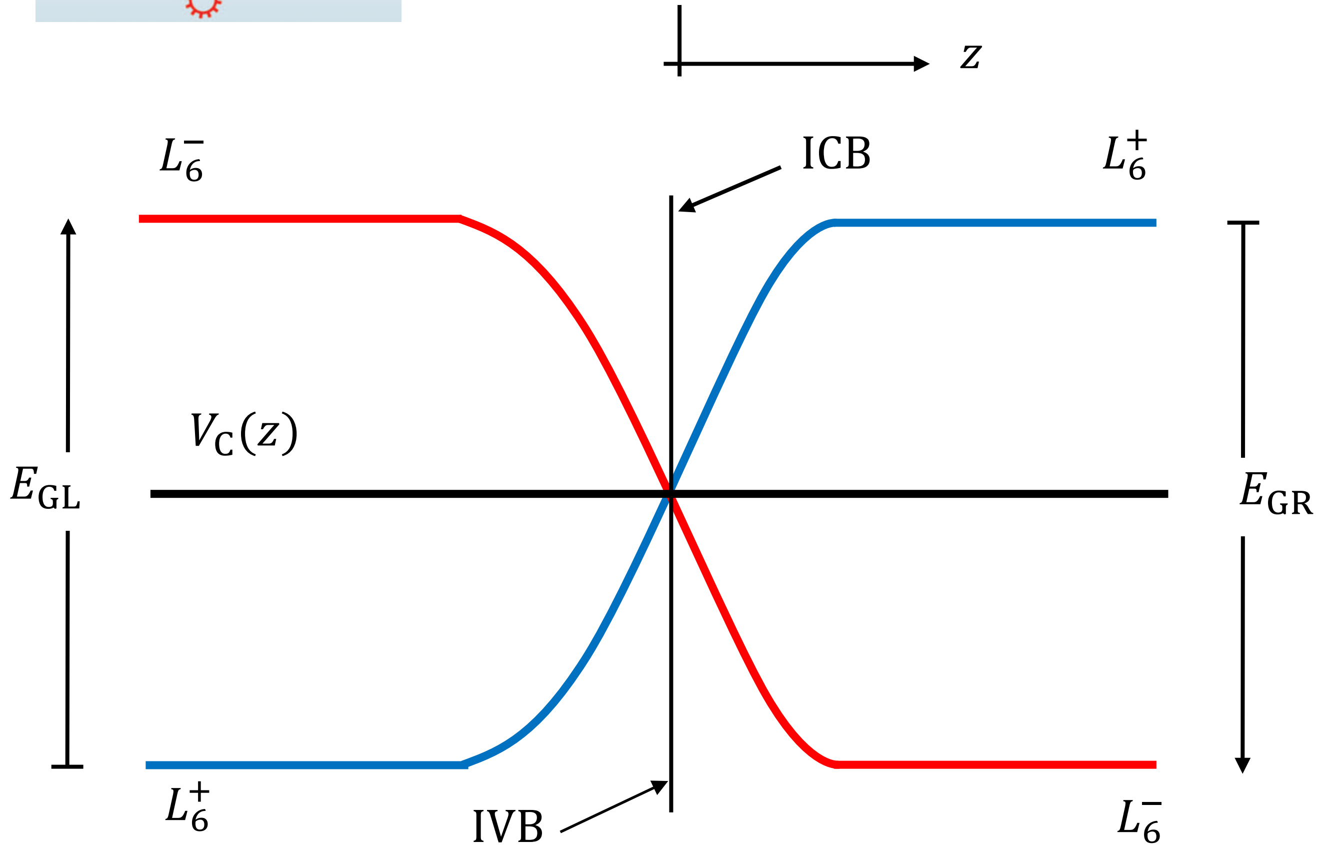

Approximations (can be relaxed):

- $E_{\mathrm{GL}} = -E_{\mathrm{GR}} = E_{\mathrm{G}}$ (symmetry)
- $V_{\mathrm{L}} = V_{\mathrm{R}} = 0$ (centred)
- $v_{\perp} = v_z = v$ (isotropy)

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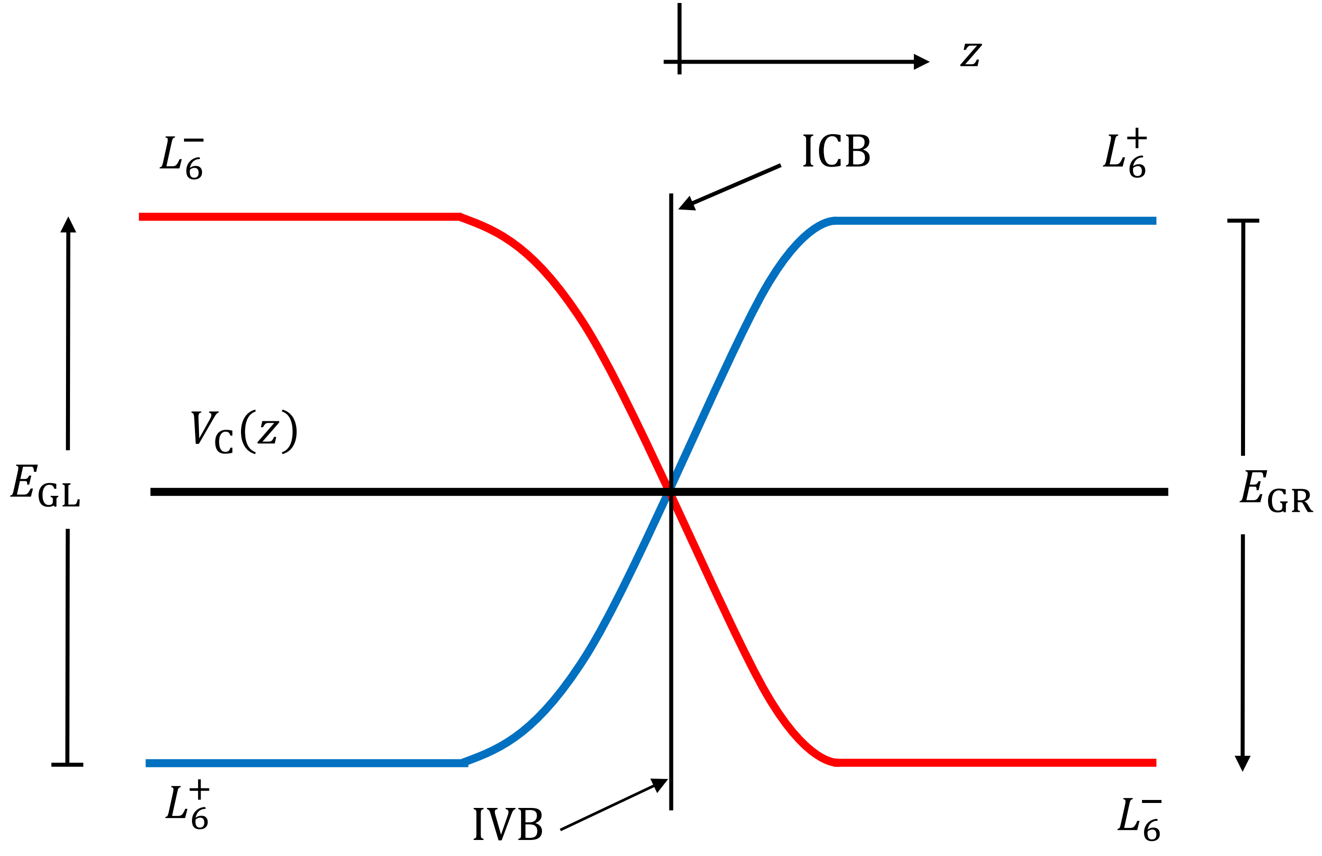

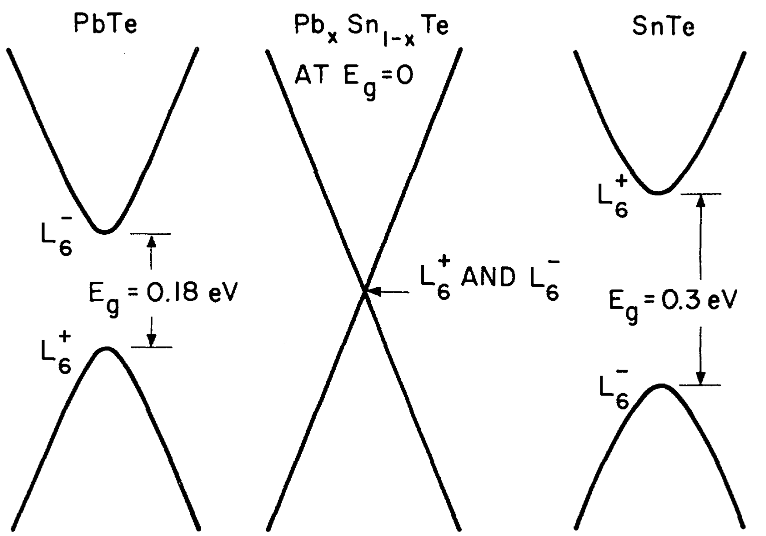

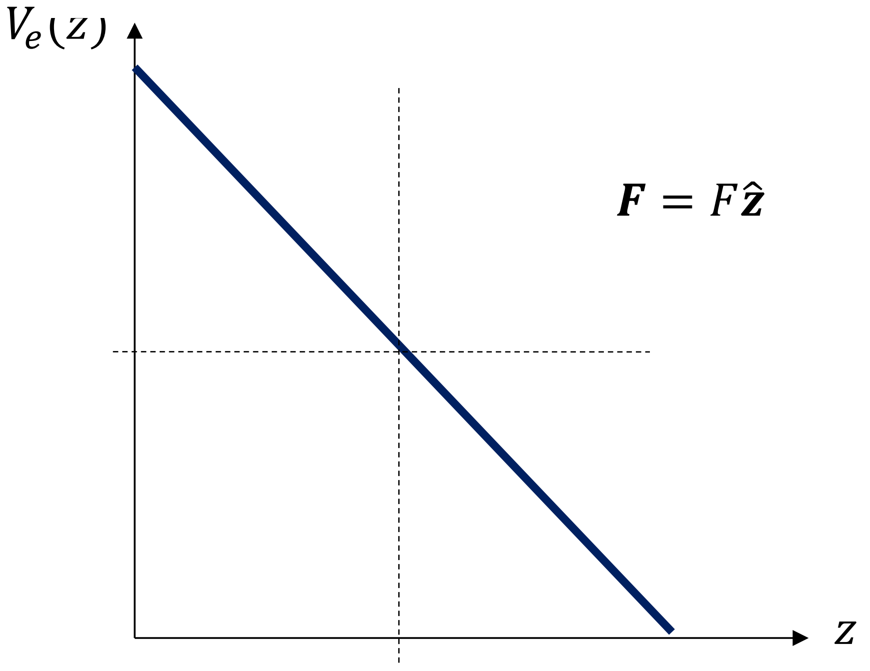

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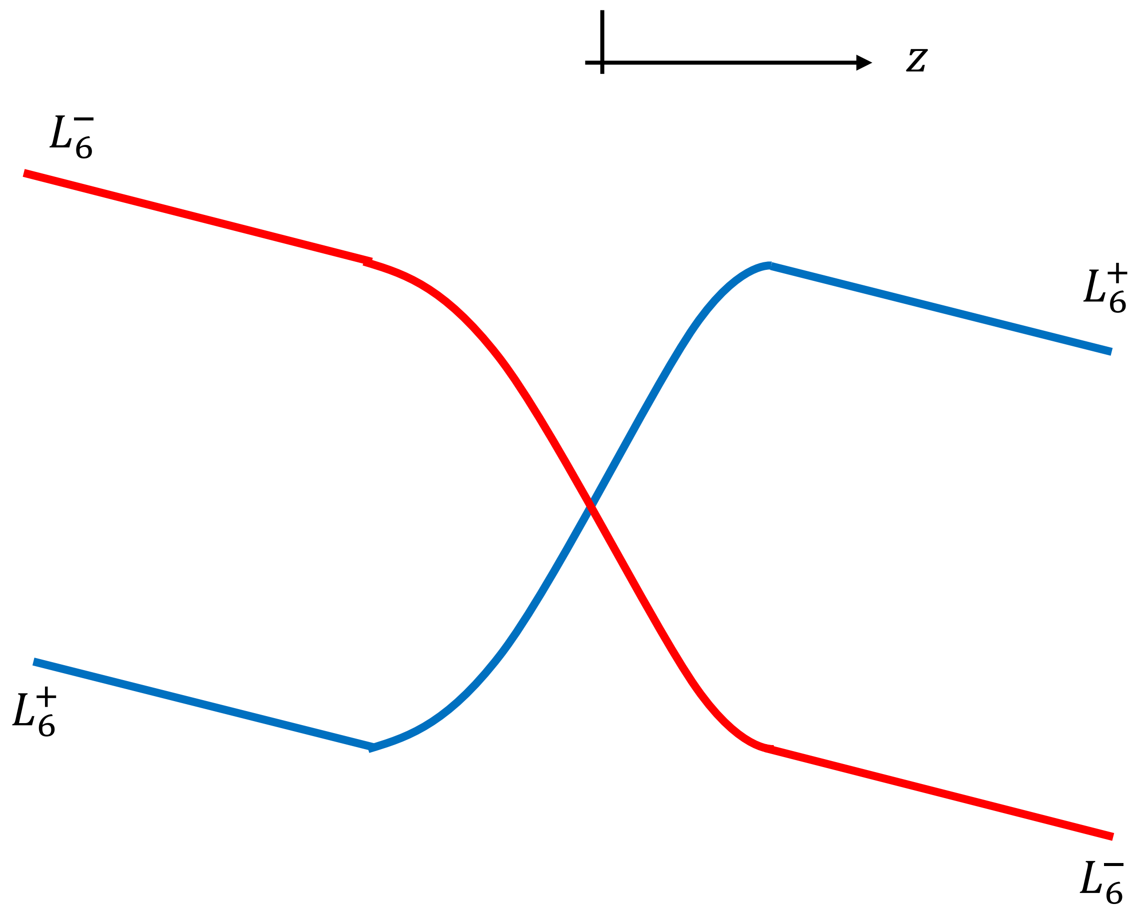

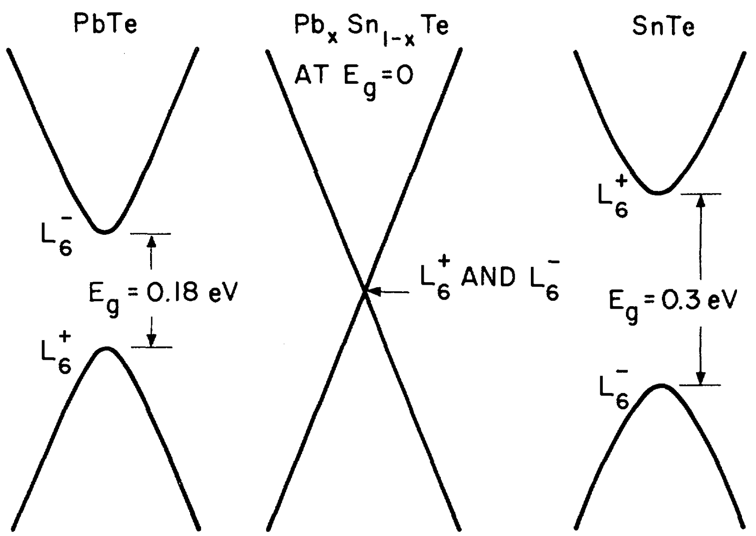

Approximations (can be relaxed):

- $F < F_C = \frac{E_G/2}{ed}$ $(\approx 170\ \mathrm{kV/cm})$

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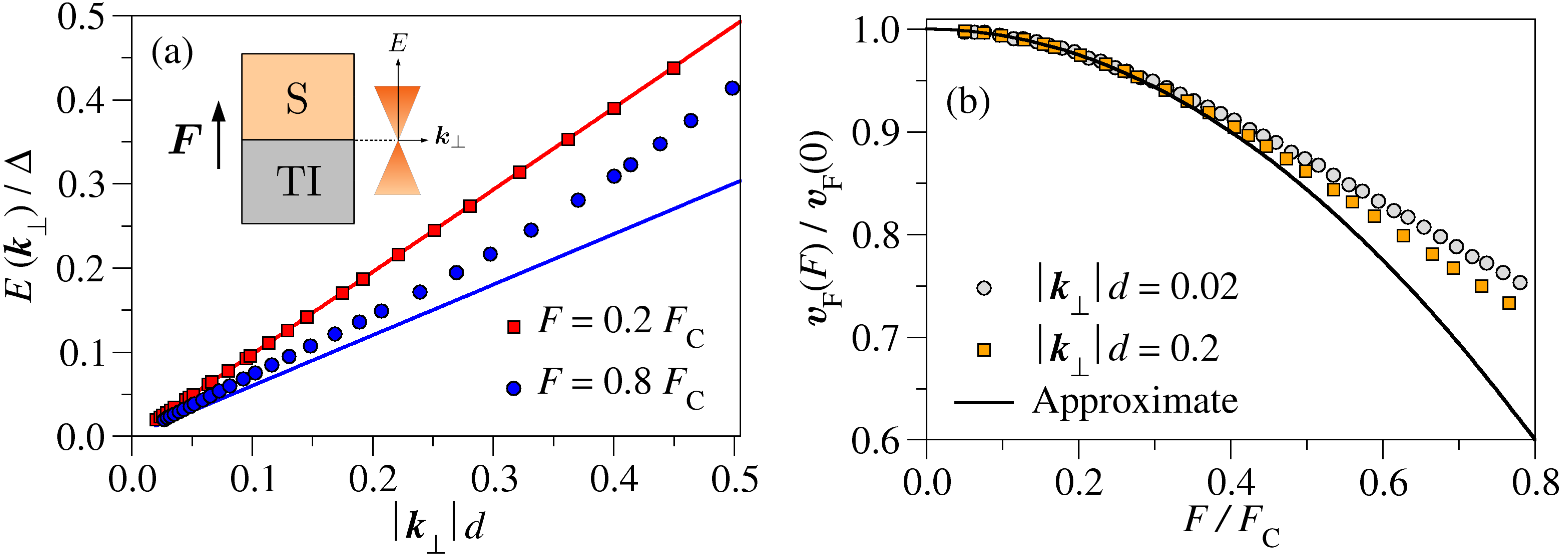
SCIENTIFIC REPORTS

$$E(F) = \pm\hbar v_{\mathrm{F}}(F)|\boldsymbol{k}_{\perp}|$$

$$v_{\mathrm{F}}(F) = v_{F}(0)\left(1 - \frac{5}{8}\frac{F^2}{F_{\mathrm{C}}^2}\right)$$



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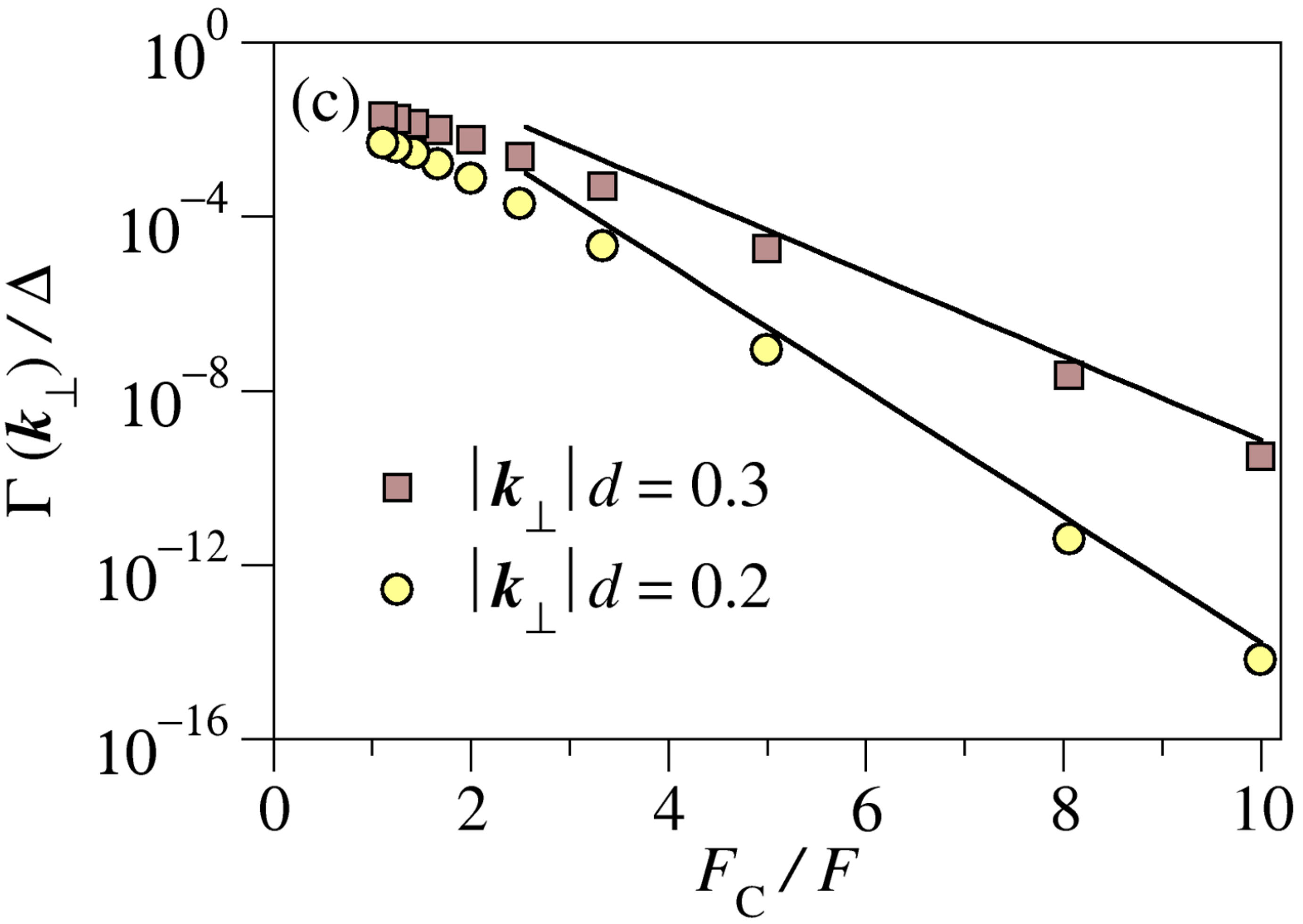

$$\Gamma \propto \exp\left(-\alpha \frac{F_C}{F}\right)$$

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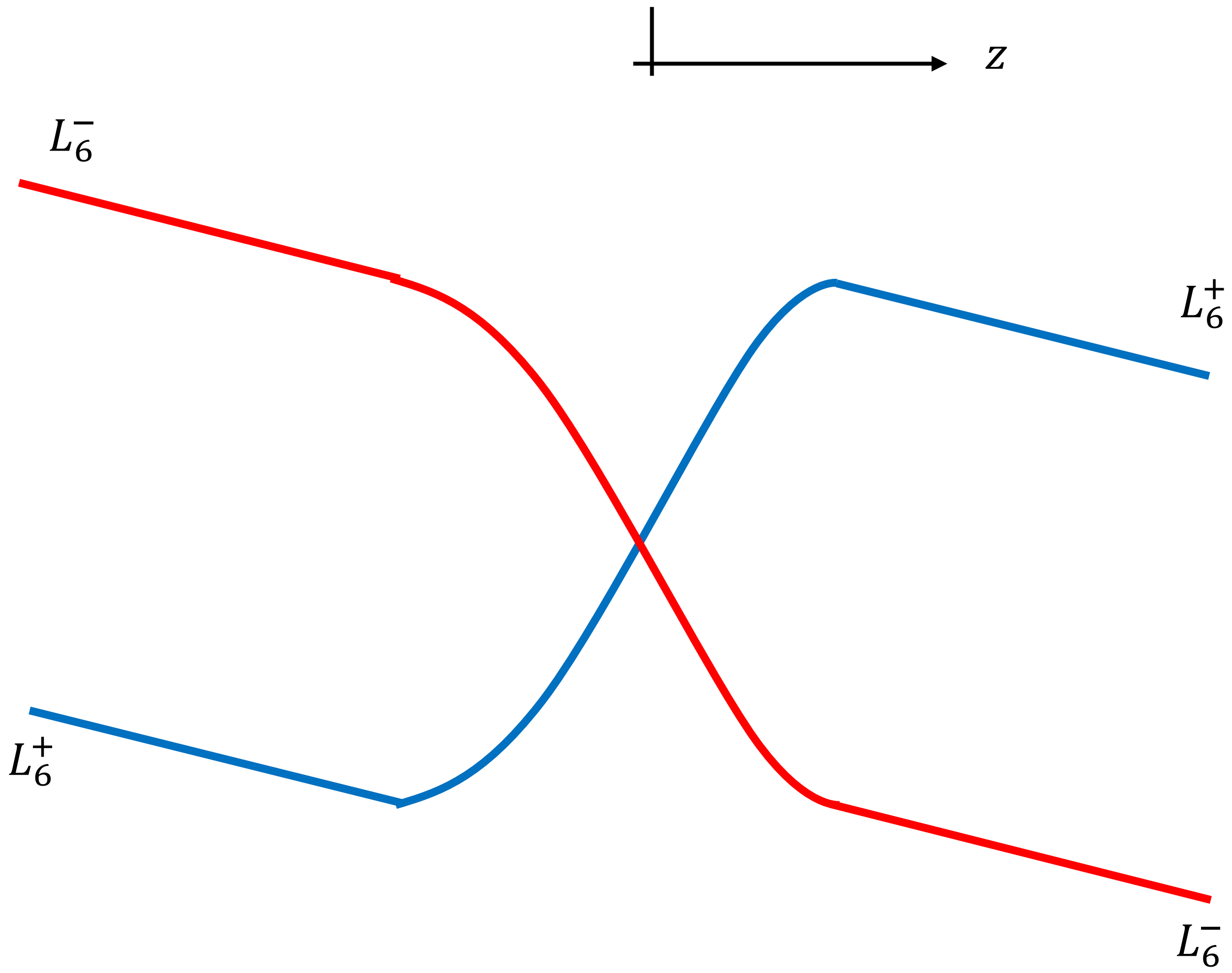
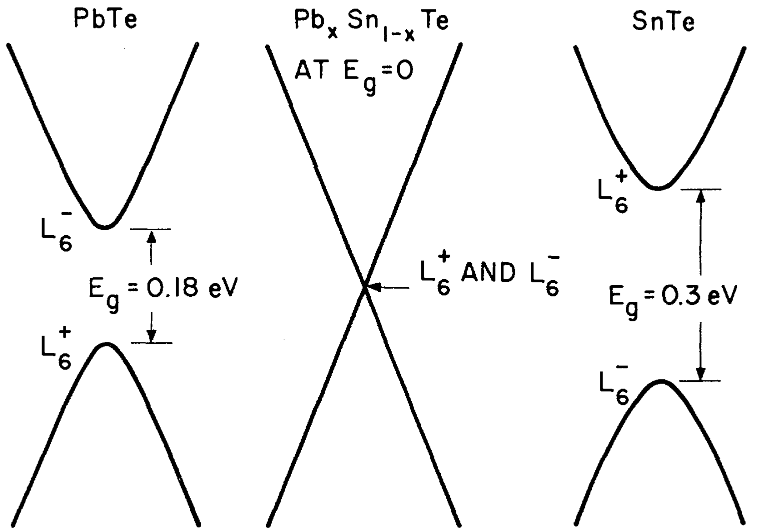
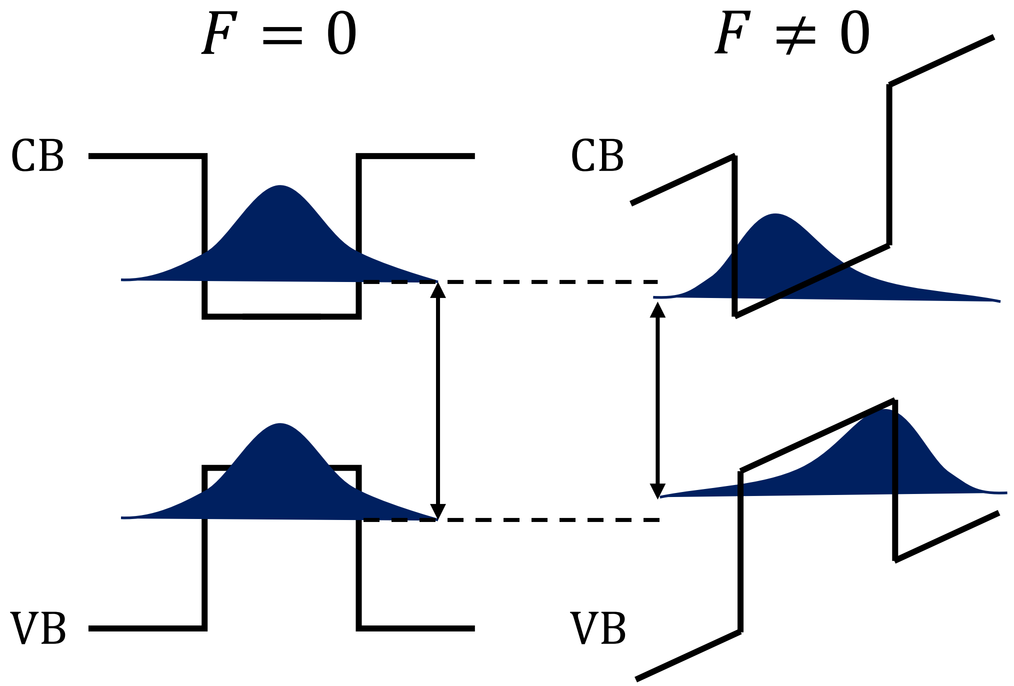
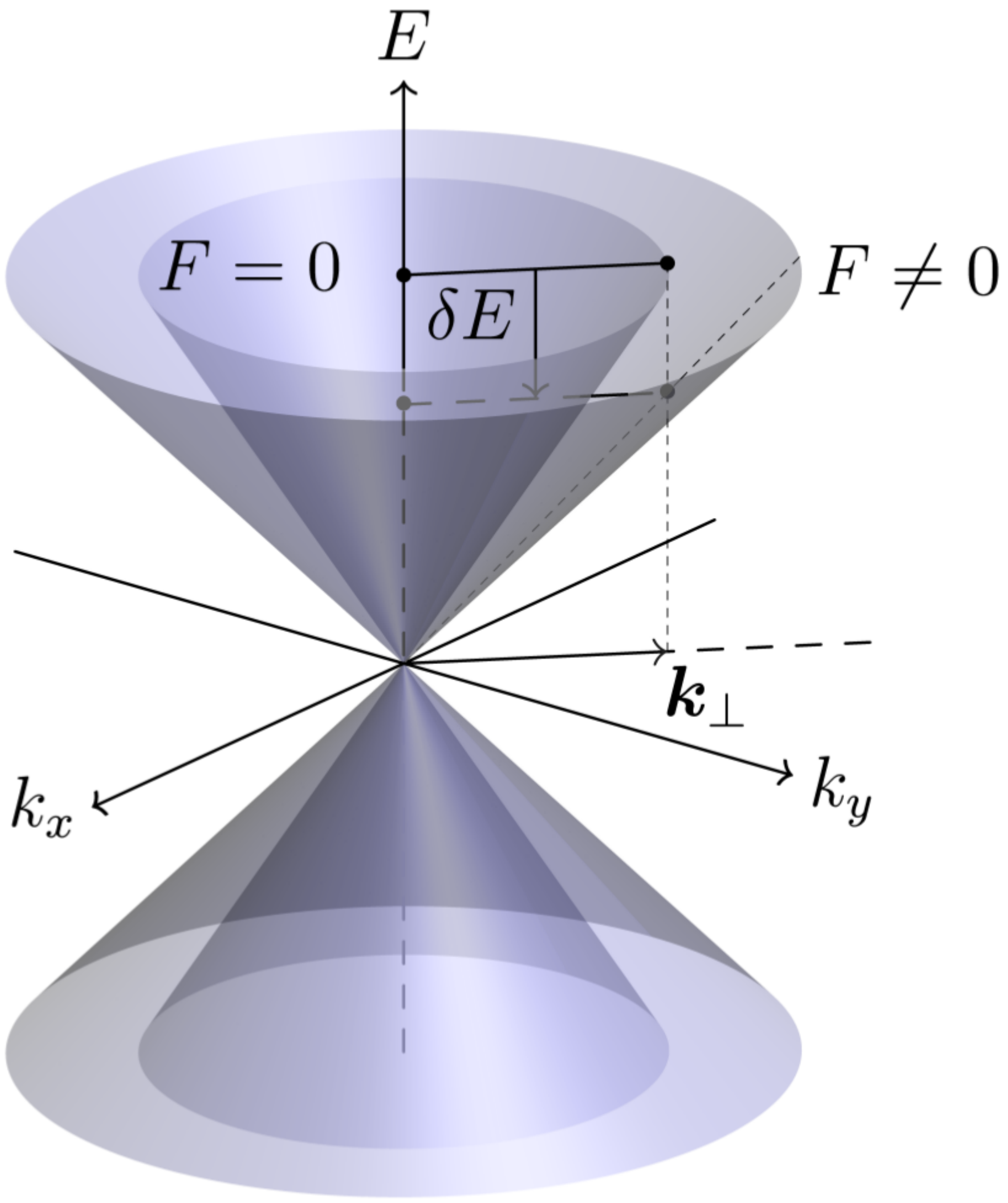




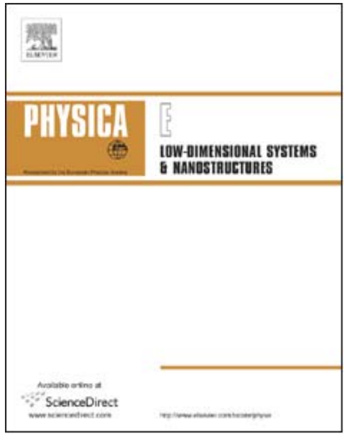


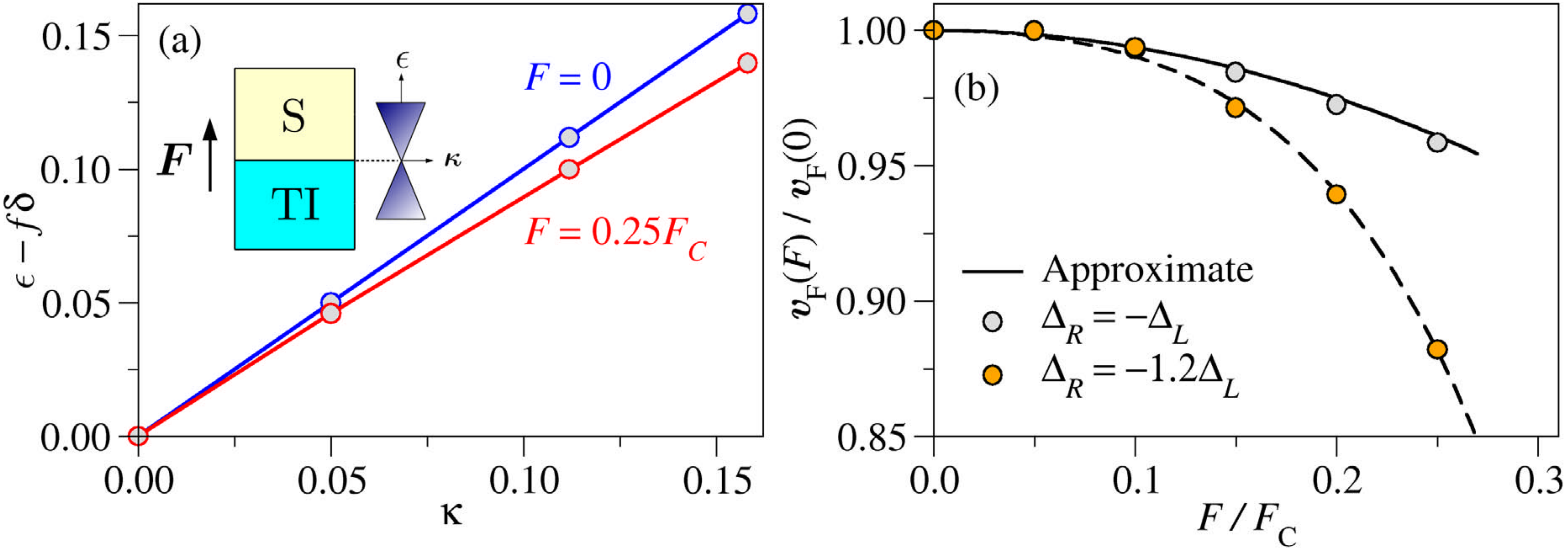


E
$F = 0$
$F \neq 0$
δE
$\boldsymbol{k}_\perp$
k_x
k_y

Quantum-confined Stark effect in band-inverted junctions

A. Díaz-Fernández, F. Domínguez-Adame





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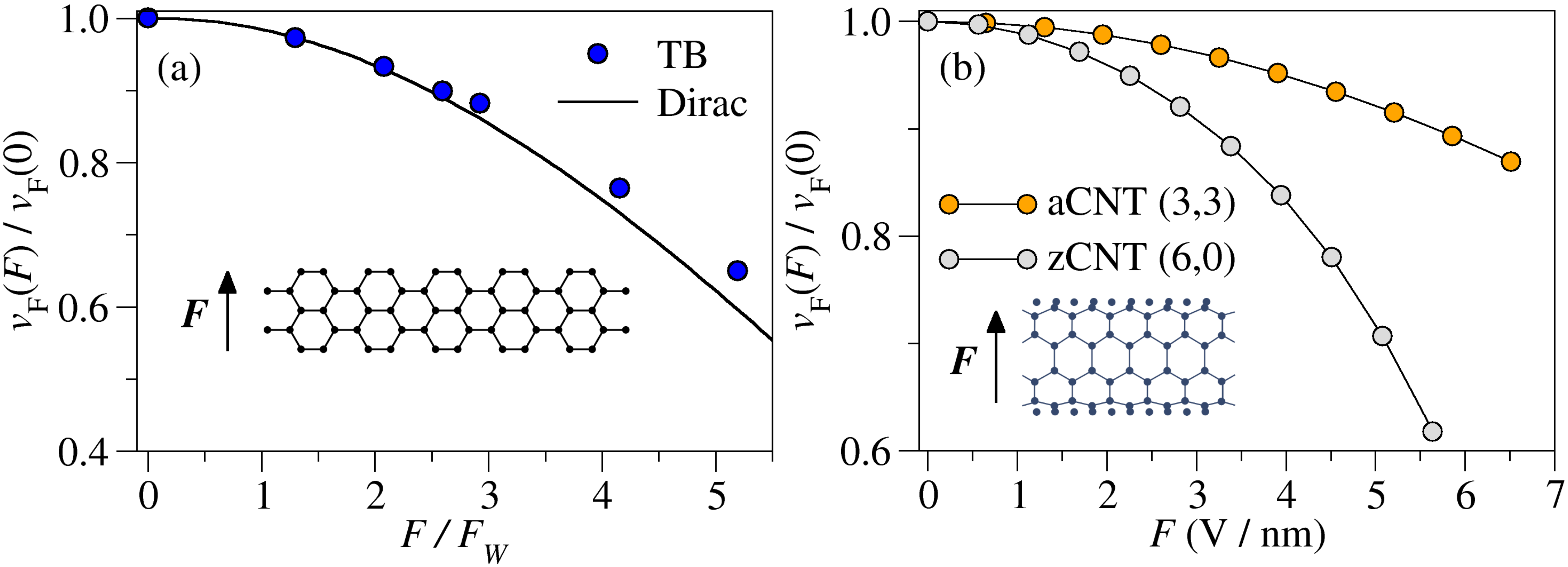

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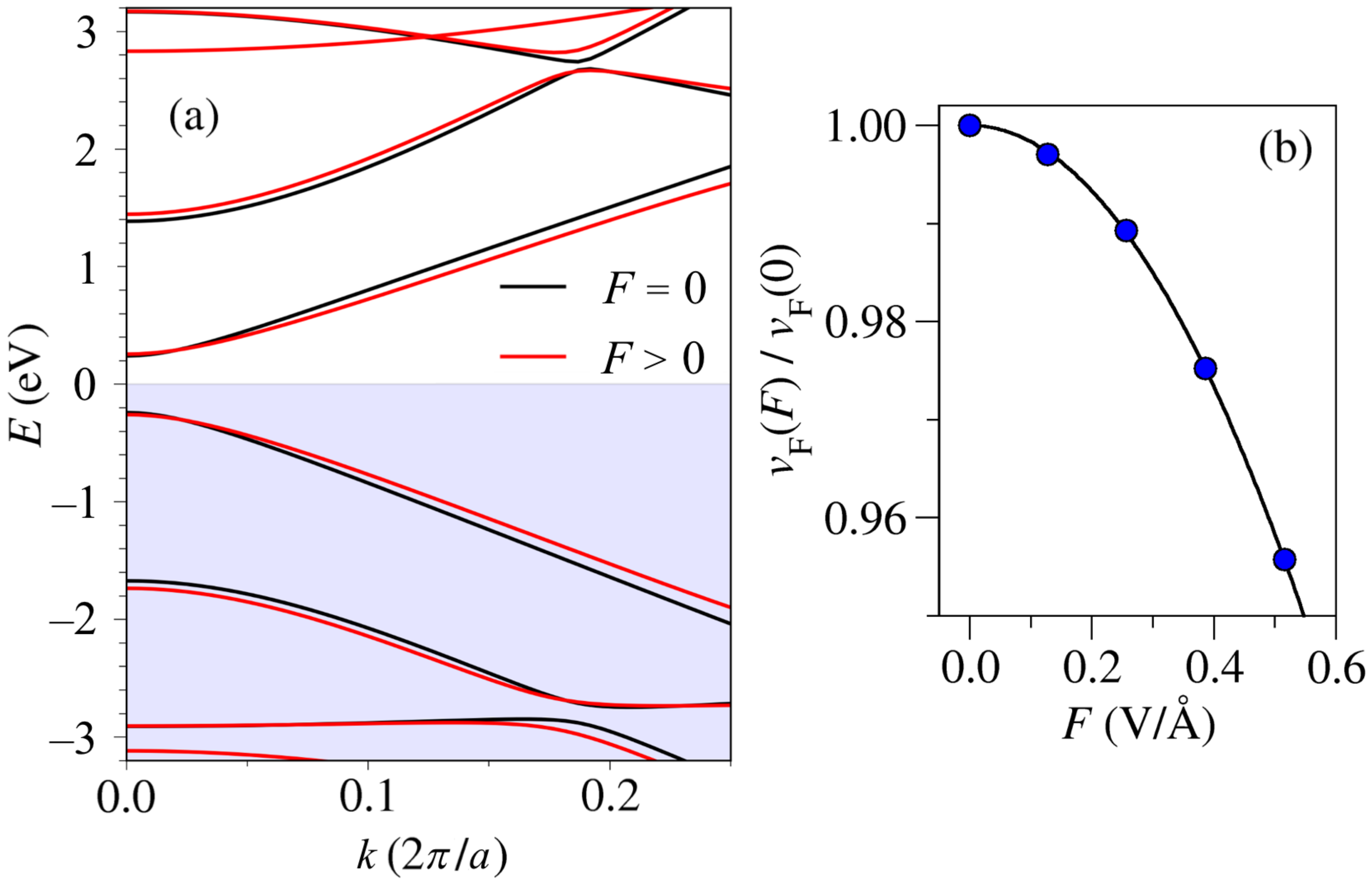

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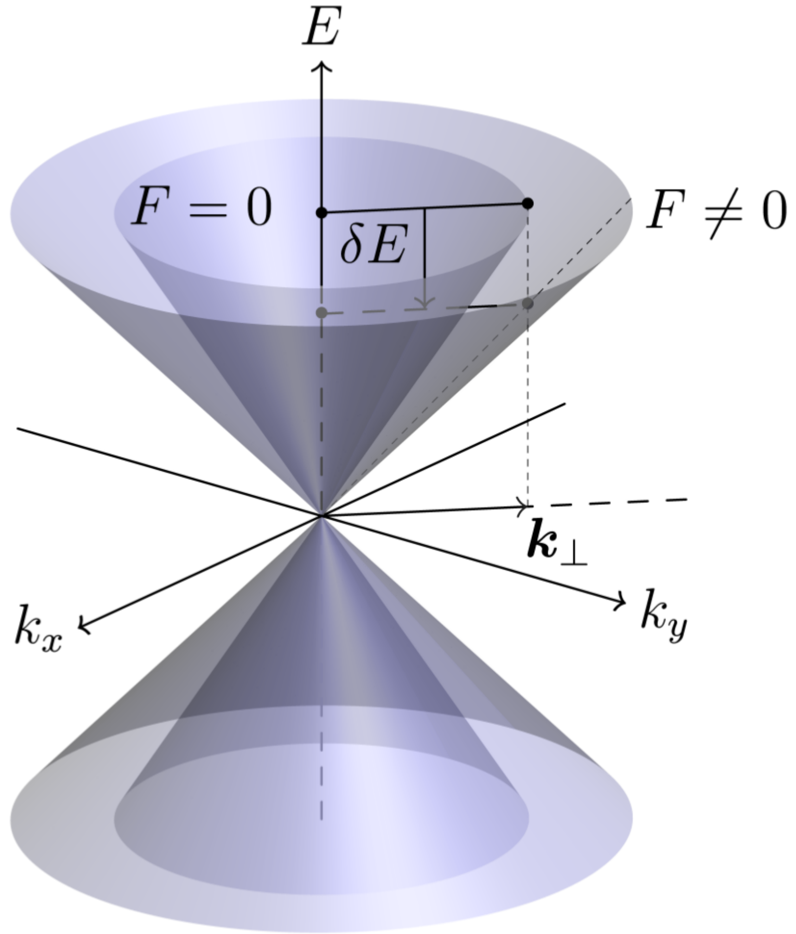
Conclusions

- ✓ Before ADF et al.: structural/many-body effects required (experimentally difficult)
- ✓ After ADF *et al.*: double-gated Dirac materials (experimentally simpler)



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