Magneto-optics of massless and massive electrons

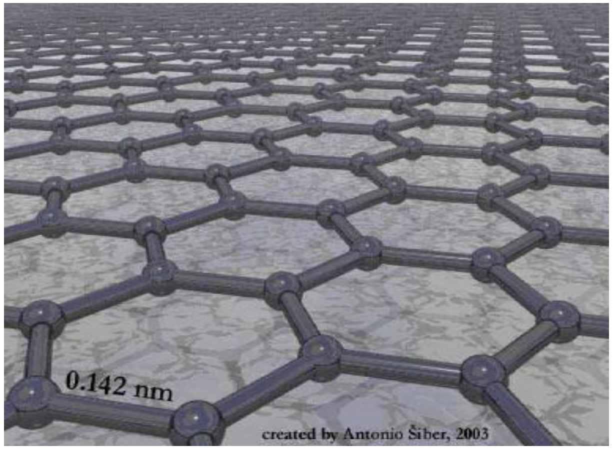
Milan Orlita

Laboratoire National des Champs Magnétiques Intenses
CNRS, Grenoble, France

LEES, 30 May 2016

Graphene

2D



2D crystal made of carbon atoms organized in hexagonal lattice

Theoretically known over sixty years…

P. R. Wallace, Phys. Rev. 71, 622 (1947)

Isolated/fabricated in 2004/2005

K. S. Novoselov et al., Science 306, 666 (2004)
K. S. Novoselov et al., Nature 438, 197 (2005)

Diamond

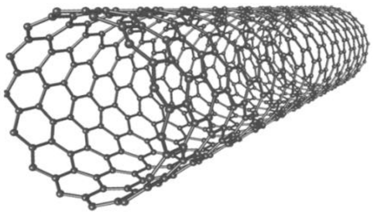
3D

Graphite

3D

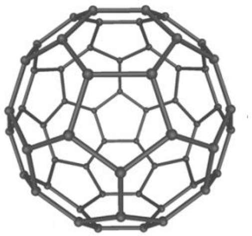
Carbon nanotube

1D



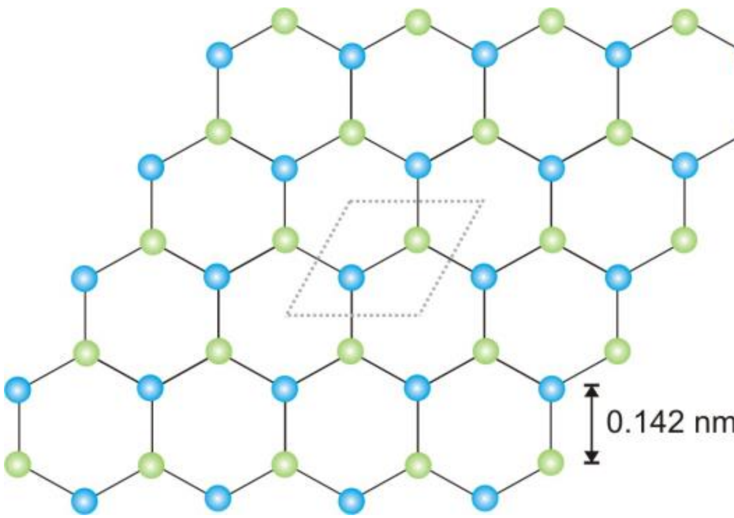
Fulleren

0D

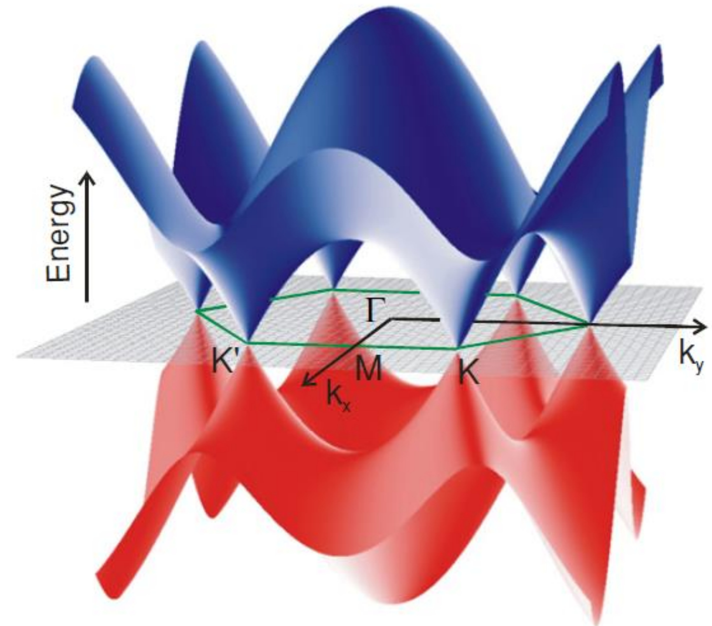


Electronic band structure of graphene

Crystal lattice:



Electronic bands:



Linearity of bands around K points:

$$E(\mathbf{k}) \approx \pm \hbar v |\mathbf{k}| = \pm v |\mathbf{p}|$$

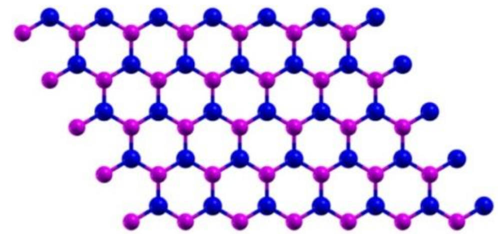
Electrons in graphene =
charged massless (relativistic) particles

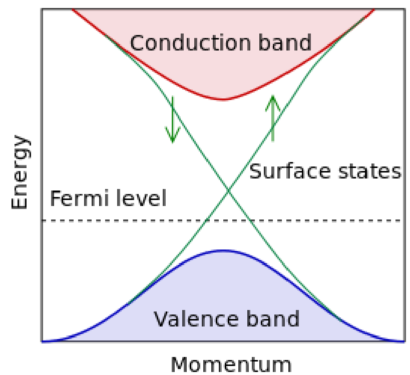
$$E^2 = p^2 c^2 + \cancel{m_0^2 c^4}$$

Dirac-type materials: Dimension, symmetry, number of nodes…

Graphene, silicene, artificial graphene…

S. Cahangirov et al., Phys. Rev. Lett. 102, 236804 (2009)
H. Liu et al., ACS Nano 8, 4033 (2014)
C.-H. Park et al., PRL 101, 126804 (2008)
M. Gibertini et al., Phys. Rev. B 79, 241406 (2009)





Topological and topological crystallline insulators

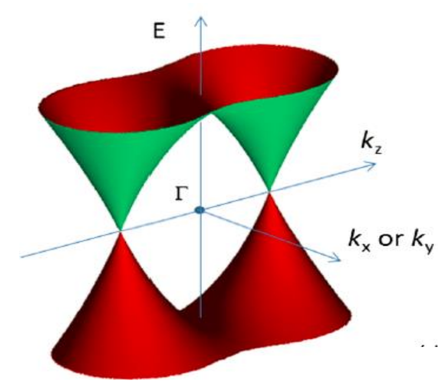
HgTe QWs, Bi_2Se_3, Bi_2Te_3, Bi_xSb_{1-x}, PbSnTe…

M. König et al., Science 318, 776 (2007)
D. Hsieh et al., Nature 452, 970 (2008)
H. Zhang et al., Nature Phys. 5, 438 (2009)
L. Fu, Phys. Rev. Lett. 106, 106802 (2011)

3D Dirac and Weyl semimetals

Na_3Bi, Cd_3As_2, TaAs, NbAs…

Z. K Liu et al., Science 343, 864 (2014)
Z. K. Liu et al., Nature Mater. 13, 677 (2014)
S. Jeon et al., Nature Mater. 13, 851 (2014)
S. Borisenko et al., Phys. Rev. Lett. 113, 027603 (2014)
M. Neupane et al., Nature Comm. 5, 3786 (2014)
B. Q. Lv et al., Nature Phys. 11, 724 (2015)
L. X. Yang et al., Nature Phys. 11, 728 (2015)
S.-Y. Xu et al., Nature Phys. 11, 748 (2015)



Outline:

Magneto-optics of massive Dirac electrons in Bi_2Se_3

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

C. Faugeras, B. A. Piot, G. Martinez, A.-L. Barra, M. Potemski	LNCMI, CNRS, Grenoble, France
P. Neugebauer	Stuttgart University, Germany
T. Brauner	University of Stavanger, Norway
E. M. Hankiewicz, S. Schreyeck, S. Grauer, C. Gould, C. Brüne, K. Brunner, and L. W. Molenkamp	Würzburg University, Germany

Magneto-optics of massless electrons in Cd_3As_2

A. Akrap et al., arXiv:1604.00038 (2016)

M. Hakl, C. Faugeras, B. A. Piot, G. Martinez, M. Potemski	LNCMI, CNRS, Grenoble, France
A. Akrap, I. Crassee, D. van der Marel	Université de Genève, Switzerland
S. Tchoumakov, M. O. Goerbig	LPS-CNRS, Paris Orsay, France
C. C. Homes	Brookhaven national Laboratory, USA
A. Arushanov, A. Nateprov	Institute of Applied Physics, ASM, Moldova
Q. D. Gibson, R. J. Cava	Princeton University, USA
J. Kuba, O. Caha, J. Novák	CEITEC & Masaryk University, Brno, Czech Republic
S. Koohpayeh, L. Wu, N. P. Armitage	Johns Hopkins University, Baltimore, USA
F. Teppe, W. Desrat	LCC-CNRS & Université Montpellier, France

Outline:

Magneto-optics of massive Dirac electrons in Bi_2Se_3

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

C. Faugeras, B. A. Piot, G. Martinez, A.-L. Barra, M. Potemski	LNCMI, CNRS, Grenoble, France
P. Neugebauer	Stuttgart University, Germany
T. Brauner	University of Stavanger, Norway
E. M. Hankiewicz, S. Schreyeck, S. Grauer, C. Gould, C. Brüne, K. Brunner, and L. W. Molenkamp	Würzburg University, Germany

Magneto-optics of massless electrons in Cd_3As_2

A. Akrap et al., arXiv:1604.00038 (2016)

M. Hakl, C. Faugeras, B. A. Piot, G. Martinez, M. Potemski	LNCMI, CNRS, Grenoble, France
A. Akrap, I. Crasse	witzerland
S. Tchoumakov, M	rance
C. C. Homes	boratory, USA
A. Arushanov, A. N	sics, ASM, Moldova
Q. D. Gibson, R. J.	A
J. Kuba, O. Caha, J. Novak	CEITEC & Masaryk University, Brno, Czech Republic
S. Koohpayeh, L. Wu, N. P. Armitage	Johns Hopkins University, Baltimore, USA
F. Teppe, W. Desrat	LCC-CNRS & Université Montpellier, France

A. Akrap, Wednesday 1/6/16, 9:50

Outline:

Magneto-optics of massive Dirac electrons in Bi_2Se_3

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

C. Faugeras, B. A. Piot, G. Martinez,
A.-L. Barra, M. Potemski
P. Neugebauer
T. Brauner
E. M. Hankiewicz, S. Schreyeck, S. Grauer,
C. Gould, C. Brüne, K. Brunner, and L. W. Molenkamp

LNCMI, CNRS, Grenoble, France
Stuttgart University, Germany
University of Stavanger, Norway
Würzburg University, Germany

Magneto-optics of massless electrons in Cd_3As_2

A. Akrap et al., arXiv:1604.00038 (2016)

M. Hakl, C. Faugeras, B. A. Piot,
G. Martinez, M. Potemski
A. Akrap, I. Crassee, D. van der Marel
S. Tchoumakov, M. O. Goerbig
C. C. Homes
A. Arushanov, A. Nateprov
Q. D. Gibson, R. J. Cava
J. Kuba, O. Caha, J. Novák
S. Koohpayeh, L. Wu, N. P. Armitage
F. Teppe, W. Desrat

LNCMI, CNRS, Grenoble, France
Université de Genève, Switzerland
LPS-CNRS, Paris Orsay, France
Brookhaven national Laboratory, USA
Institute of Applied Physics, ASM, Moldova
Princeton University, USA
CEITEC & Masaryk University, Brno, Czech Republic
Johns Hopkins University, Baltimore, USA
LCC-CNRS & Université Montpellier, France

Relativistic quantum electrodynamics in condensed-matter physics…

Relativistic quantum electrodynamics in condensed-matter physics…

Dirac Hamiltonian (4x4): $$H_D = m_D c^2 \overleftrightarrow{\beta} + c\overleftrightarrow{\alpha}.\vec{p}$$

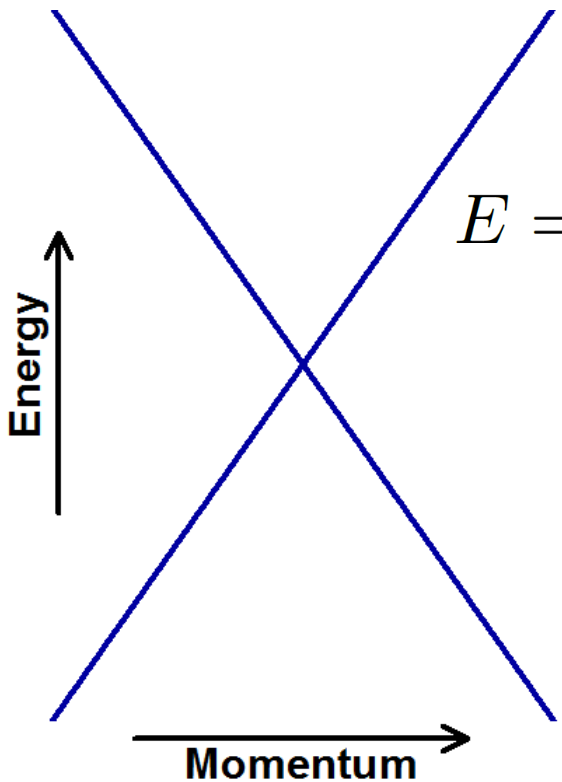
Relativistic quantum electrodynamics in condensed-matter physics…

Dirac Hamiltonian (4x4):

$$H_D = \cancel{m_D c^2 \overleftrightarrow{\beta}} + c\overleftrightarrow{\alpha}.\vec{p}$$

Dirac mass (= rest mass)

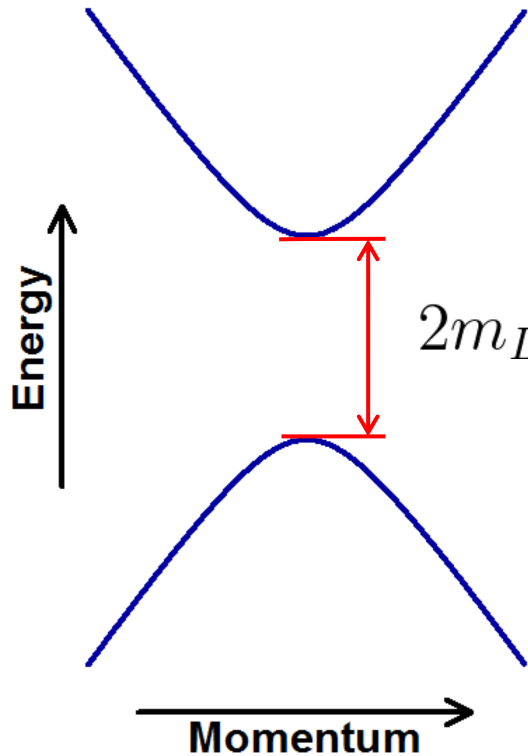
$$m_D = 0$$



$$E = \pm c|\vec{p}|$$

Relativistic quantum electrodynamics in condensed-matter physics…

Dirac Hamiltonian (4x4): $H_D = m_D c^2 \overset{\leftrightarrow}{\beta} + c\overset{\leftrightarrow}{\alpha}.\vec{p}$

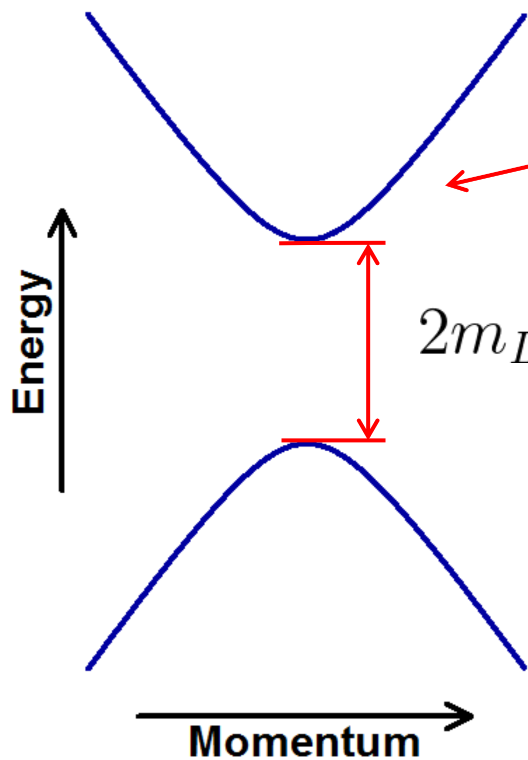


$$E^2 = m_D^2 c^4 + c^2 p^2$$

$2m_D c^2$ **Energy gap (particle-antiparticle)**

Relativistic quantum electrodynamics in condensed-matter physics…

Dirac Hamiltonian (4x4): $$H_D = m_D c^2 \overset{\leftrightarrow}{\beta} + c\overset{\leftrightarrow}{\alpha}.\vec{p}$$



$$2m_D c^2$$

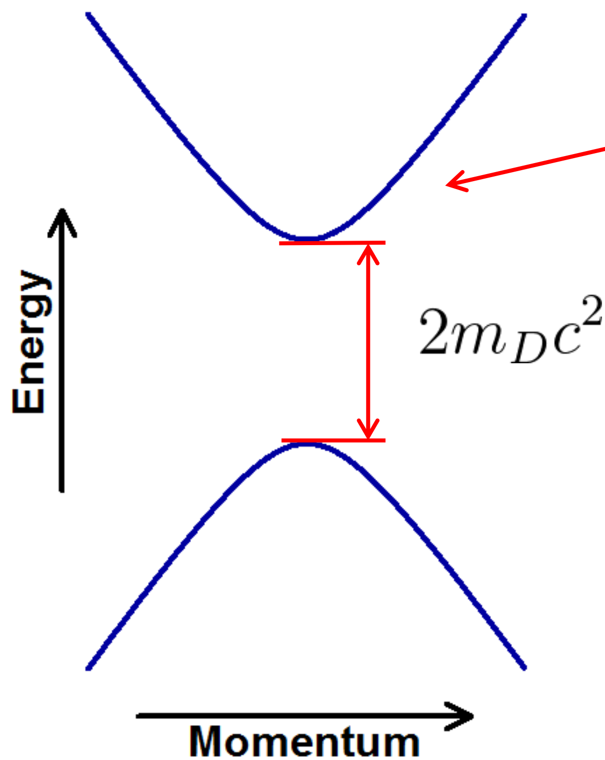
Particle mass m_D
(in the classical limit)

Energy gap, particles masses, and g factors determined by two parameters…

$$m_D, c$$

Relativistic quantum electrodynamics in condensed-matter physics…

Dirac Hamiltonian (4x4): $$H_D = m_D c^2 \overleftrightarrow{\beta} + c\overleftrightarrow{\alpha}.\vec{p}$$



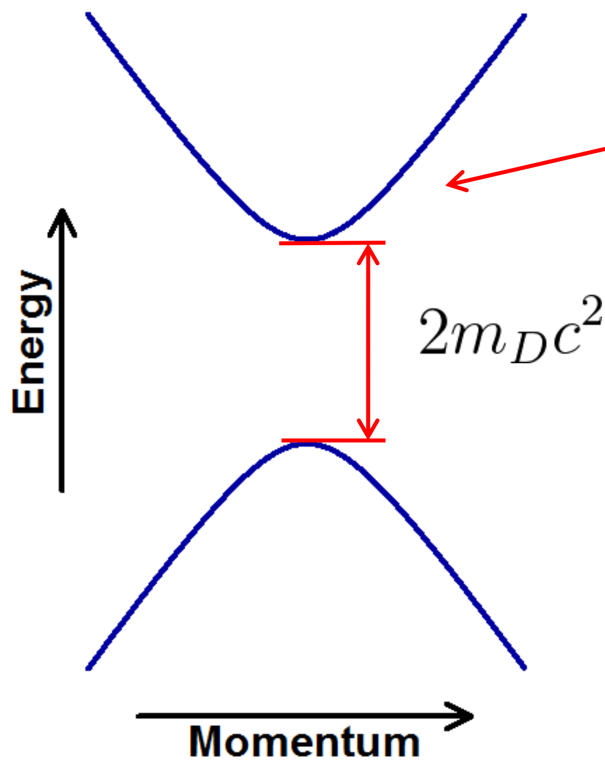
Particle mass m_D
(in the classical limit)

g factor (particle & antiparticle)

$$g = 2\frac{m_0}{m_D}$$

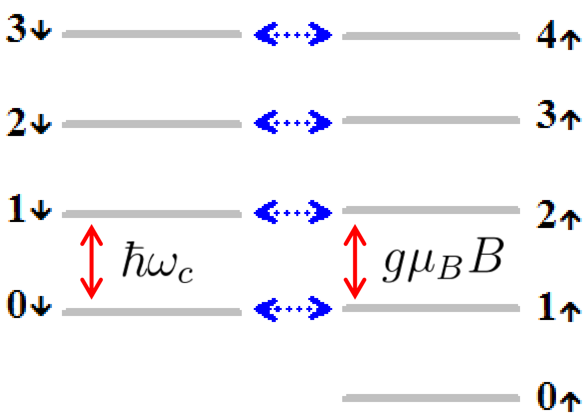
Relativistic quantum electrodynamics in condensed-matter physics…

Dirac Hamiltonian (4x4): $$H_D = m_D c^2 \overleftrightarrow{\beta} + c\overleftrightarrow{\alpha}.\vec{p}$$



Particle mass m_D
(in the classical limit)

Landau level spectrum:

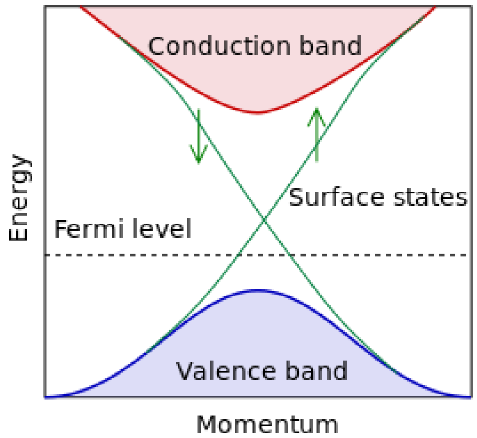


cyclotron energy = spin-splitting

Electronic bands in 3D topological insulators (Bi_2Se_3 family)

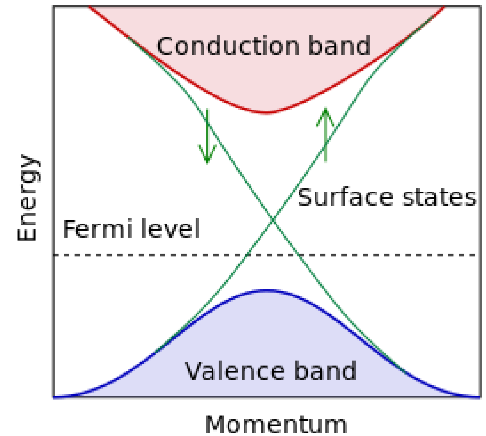
Topological insulators = narrow gap semiconductors with conducting Dirac-type surface states

Bi_2Se_3, Bi_2Te_3, Sb_2Te_3, Bi_xSb_{1-x}



Electronic bands in 3D topological insulators (Bi_2Se_3 family)

Topological insulators = narrow gap semiconductors with conducting Dirac-type surface states

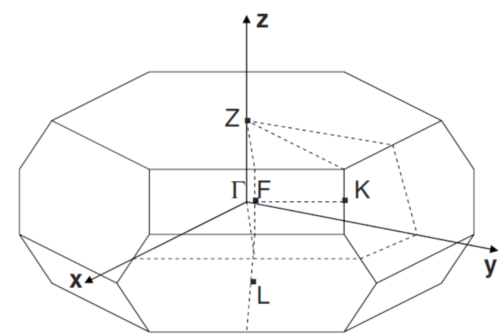


Bi_2Se_3, Bi_2Te_3, Sb_2Te_3, Bi_xSb_{1-x}

Effective 3D Dirac Hamiltonian at the Γ point:

$$H_D = Cp^2\overleftrightarrow{I} + (m_D v_D^2 + Mp^2)\overleftrightarrow{\beta} + v_D\overleftrightarrow{\alpha}.\vec{p}$$

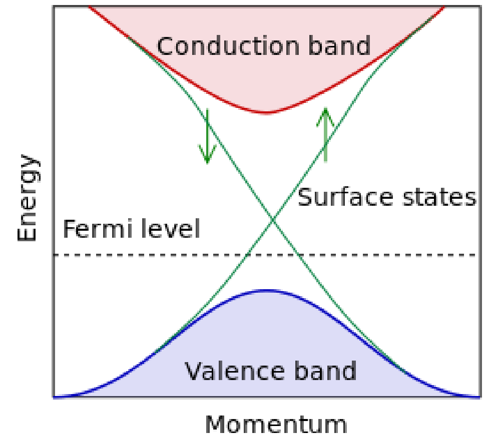
e-h asymmetry — **band inversion**



H. Zhang et al., Nature Phys. 5, 438 (2009)
C.-X. Liu et al., Phys. Rev. B 82, 045122 (2010)

Electronic bands in 3D topological insulators (Bi_2Se_3 family)

Topological insulators = narrow gap semiconductors with conducting Dirac-type surface states



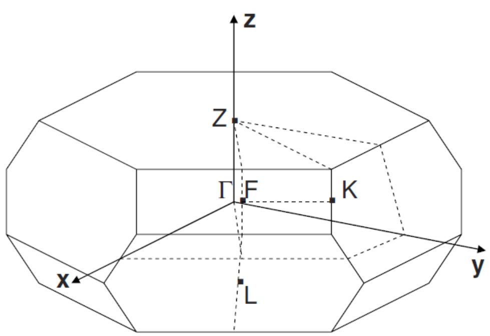
Bi_2Se_3, Bi_2Te_3, Sb_2Te_3, Bi_xSb_{1-x}

Effective 3D Dirac Hamiltonian at the Γ point:

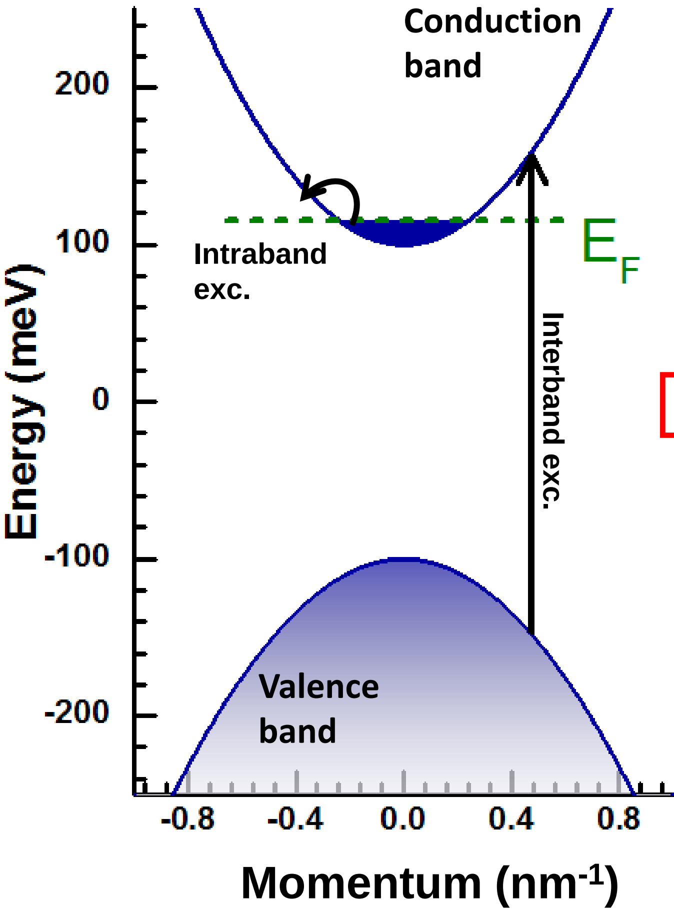
$$H_D = Cp^2 \overleftrightarrow{I} + (m_D v_D^2 + Mp^2)\overleftrightarrow{\beta} + v_D \overleftrightarrow{\alpha}.\vec{p}$$

Electronic bands (electron and hole branches):

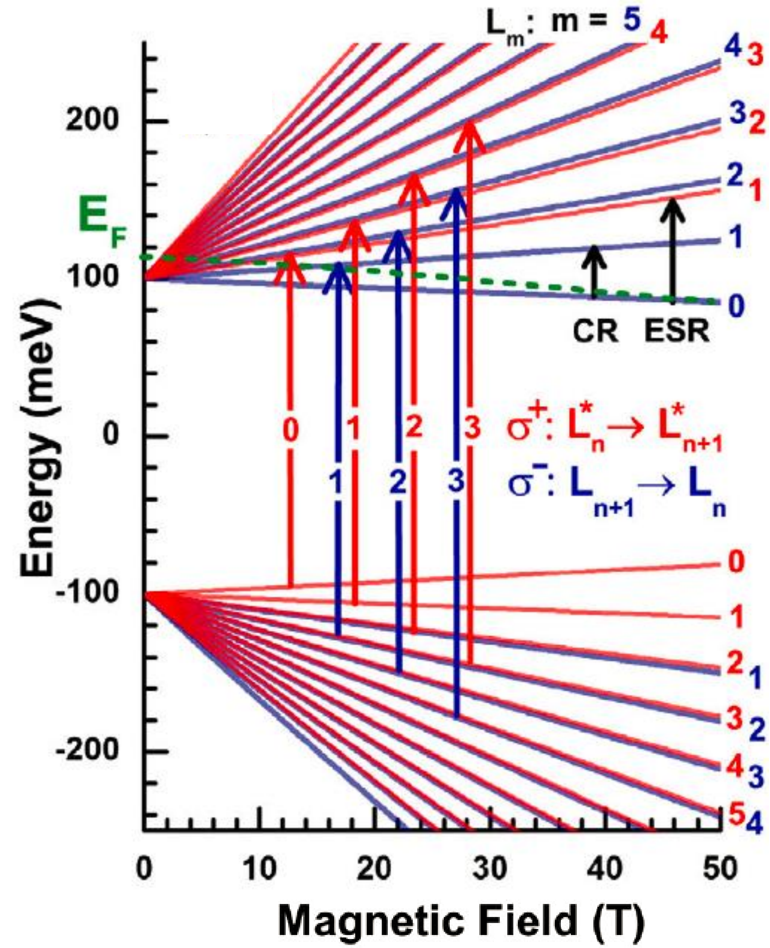
$$E = Cp^2 \pm \sqrt{(m_D v_D^2 + Mp^2)^2 + v_D^2 p^2}$$



Landau level spectroscopy

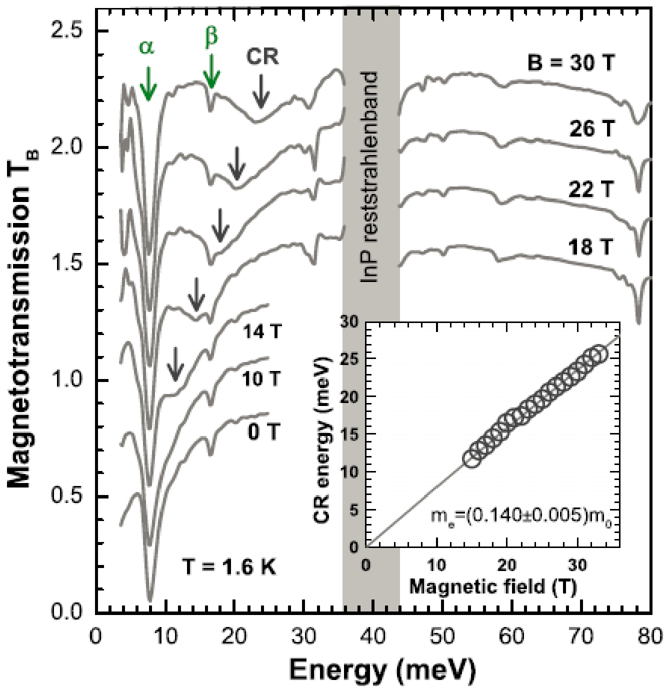


Magnetic field

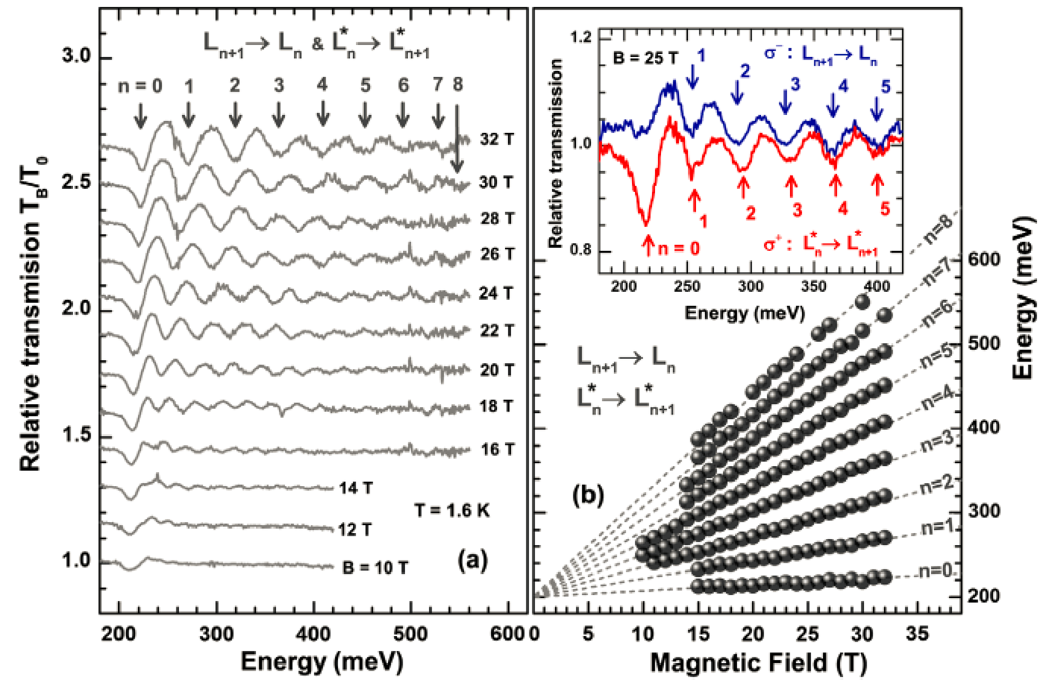


Thin layer of Bi_2Se_3: Infrared magneto-transmission

Cyclotron resonance:



Interband inter-Landau level excitations:



Bi_2Se_3 on InP(B) substrate
thickness 270 nm, n~5×10 ^{17}cm-2

Magneto-transmission experiment on thin MBE-grown layers of Bi_2Se_3

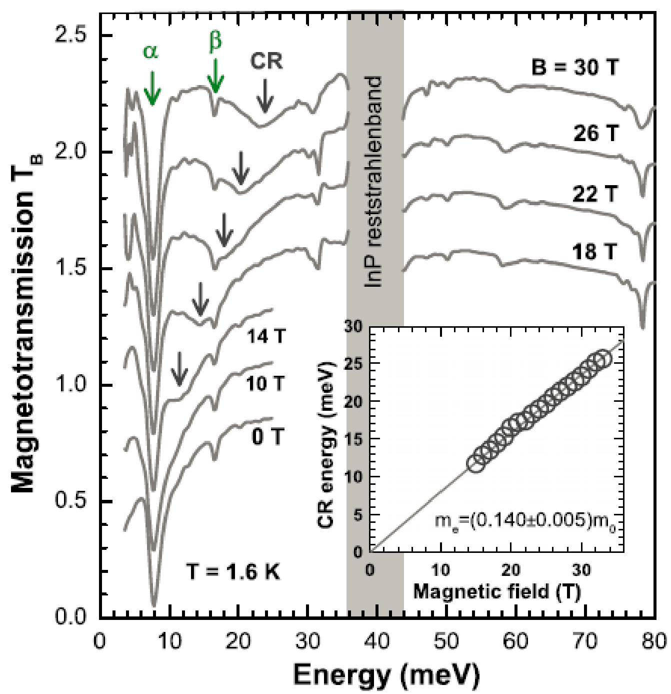
Group of L. W. Molenkamp

Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG

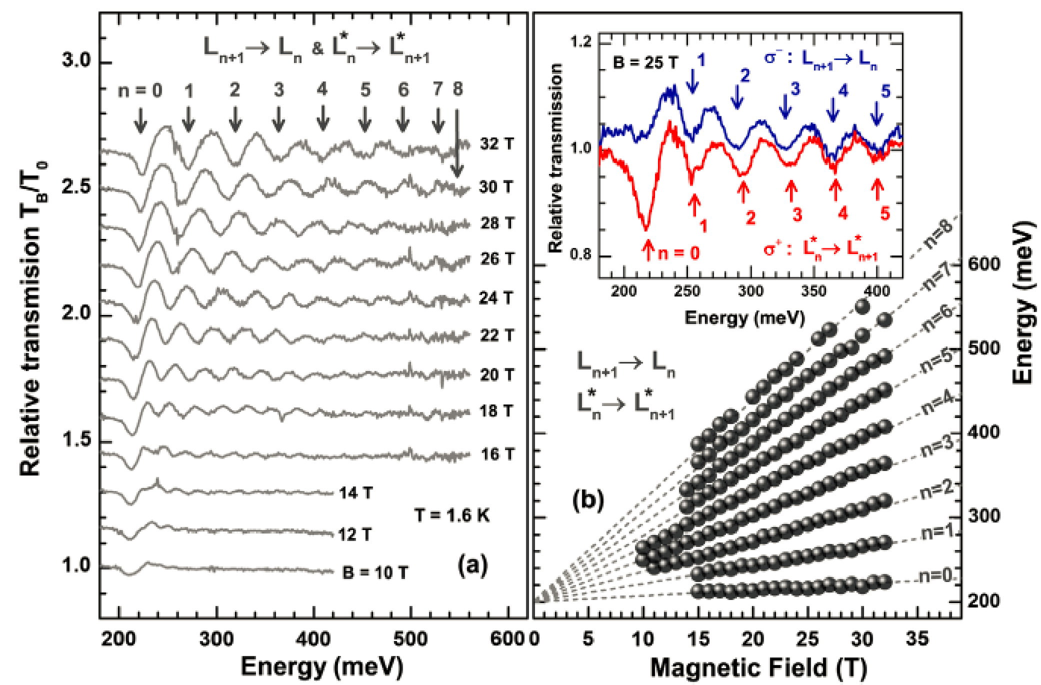
M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

Thin layer of Bi_2Se_3: Infrared magneto-transmission

Cyclotron resonance:



Interband inter-Landau level excitations:



Bi_2Se_3 on InP(B) substrate
thickness 270 nm, n~5×10 ^{17}cm-2

Conduction and valence band parabolic

Low electron hole asymmetry $m_e \approx m_h$

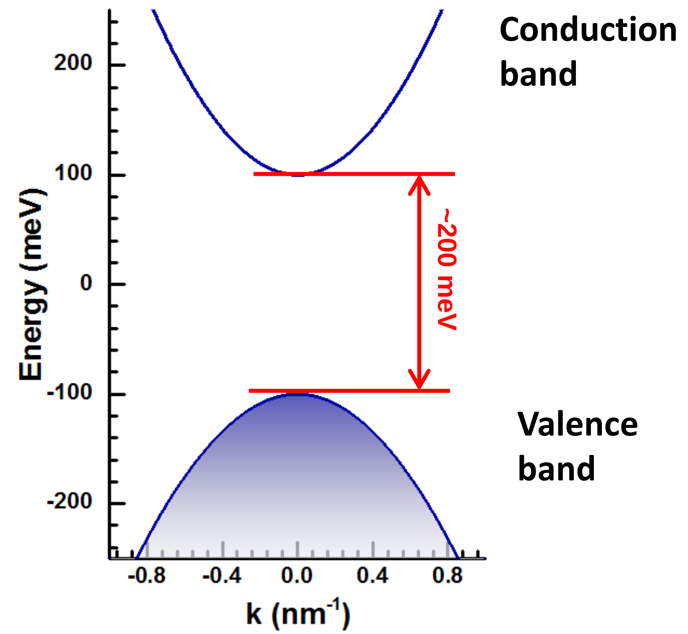
Band gap ~ 200 meV

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

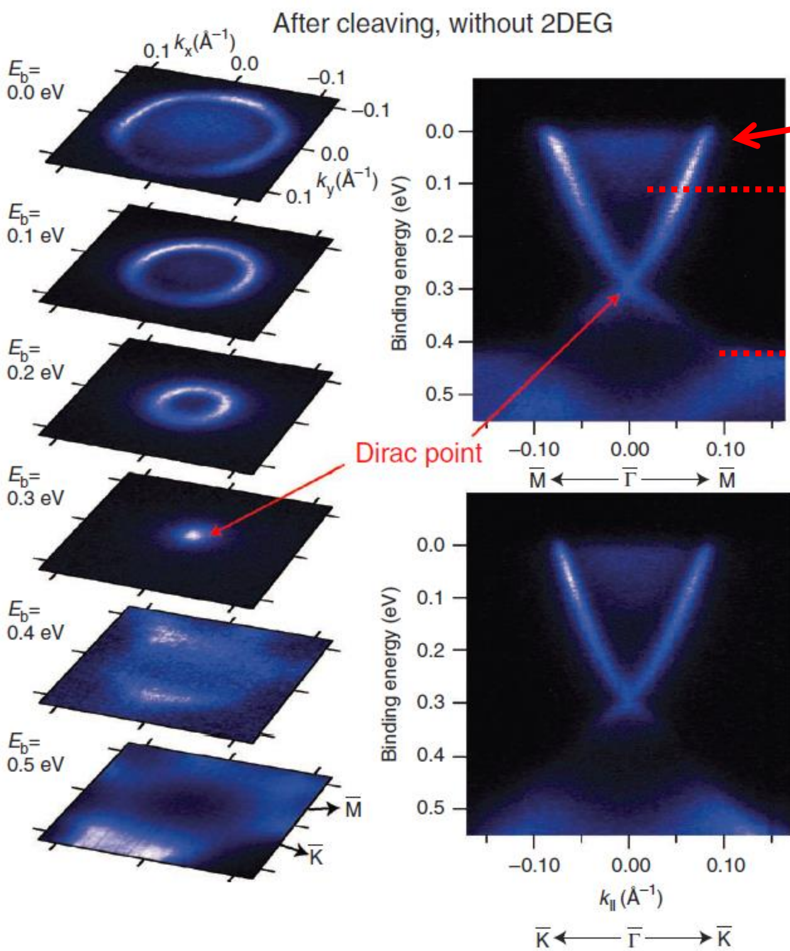
Electronic bands in bulk Bi_2Se_3 (Γ point)

Experiment (magneto-optics):

Conduction and valence band parabolic
High electron-hole symmetry



Digression: Band structure of Bi_2Se_3 in ARPES



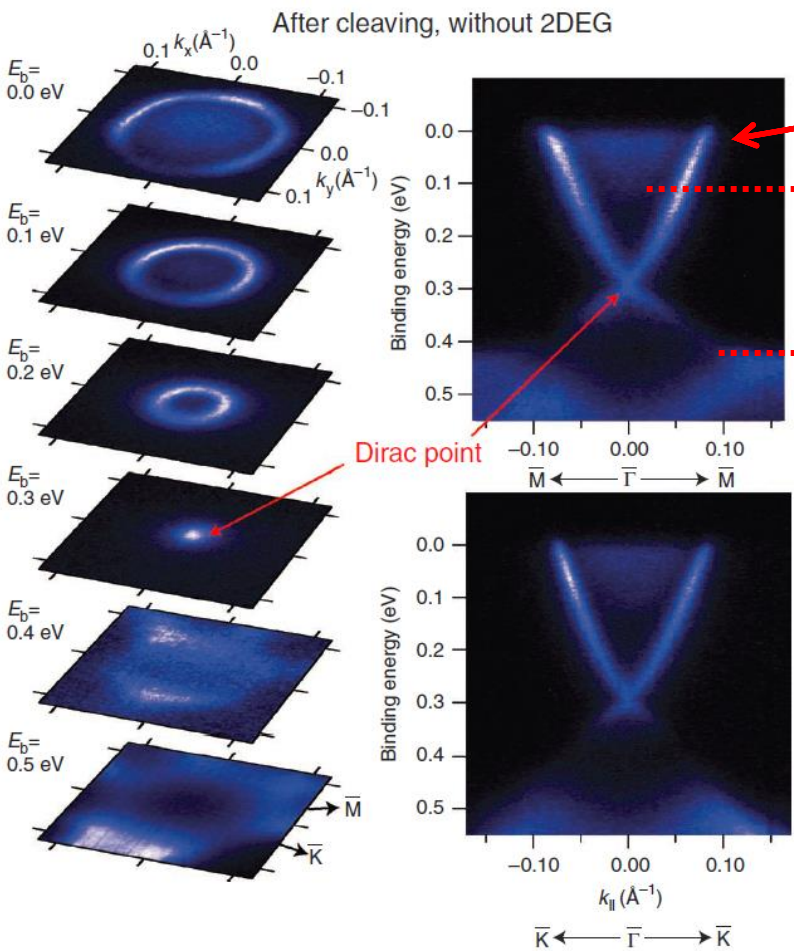
Parabolic conduction band

Indirect band gap (300-350 meV)

“Camelback” valence band

M. Bianchi et al., Nature Comm. 1, 128 (2010)

Digression: Band structure of Bi_2Se_3 in ARPES



Parabolic conduction band

Indirect band gap (300-350 meV)

"Camelback" valence band

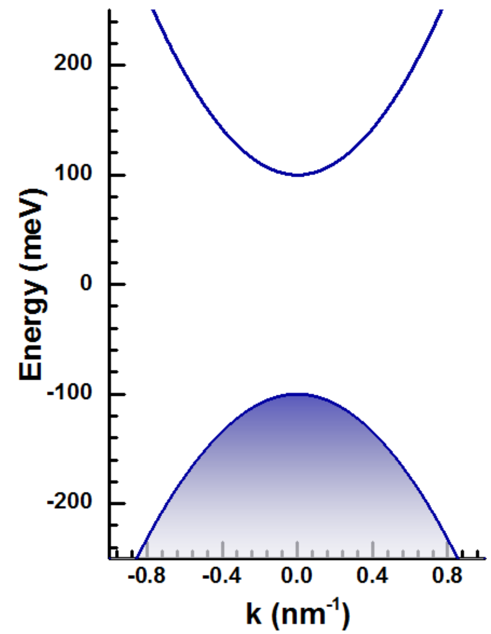
Surface versus bulk?

M. Bianchi et al., Nature Comm. 1, 128 (2010)

Electronic bands in bulk Bi_2Se_3 (Γ point)

Experiment (magneto-optics):

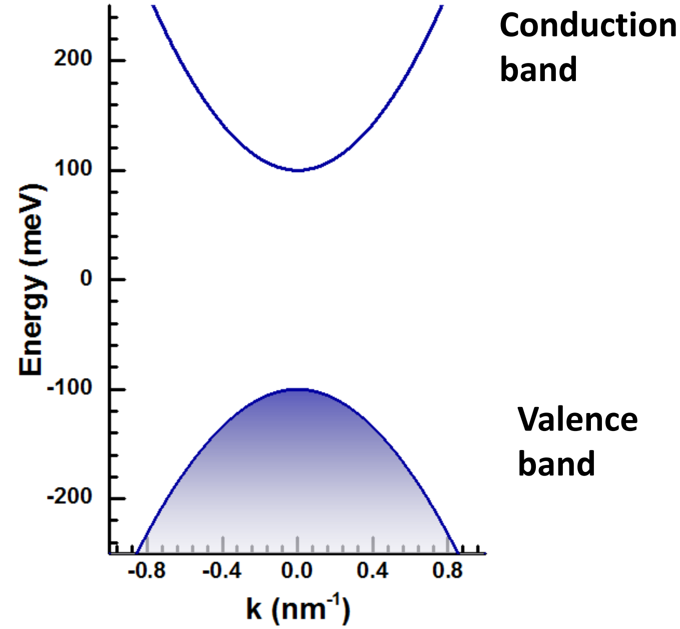
Conduction and valence band parabolic
High electron-hole symmetry



Electronic bands in bulk Bi_2Se_3 (Γ point)

Experiment (magneto-optics):

Conduction and valence band parabolic
High electron-hole symmetry



Theory:

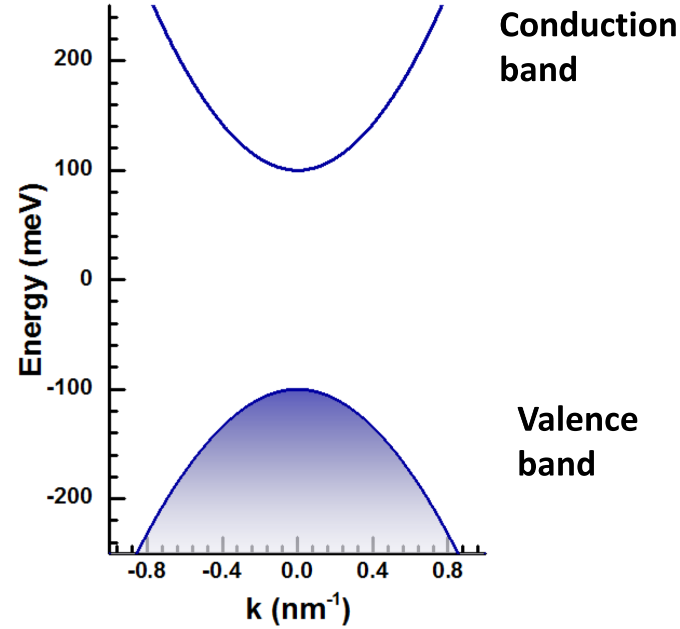
$$E = Ck^2 \pm \sqrt{(m_D v_D^2 + Mk^2)^2 + v_D^2 \hbar^2 k^2}$$

H. Zhang et al., Nature Phys. 5, 438 (2009)
C.-X. Liu et al., Phys. Rev. B 82, 045122 (2010)

Electronic bands in bulk Bi_2Se_3 (Γ point)

Experiment (magneto-optics):

Conduction and valence band parabolic
High electron-hole symmetry



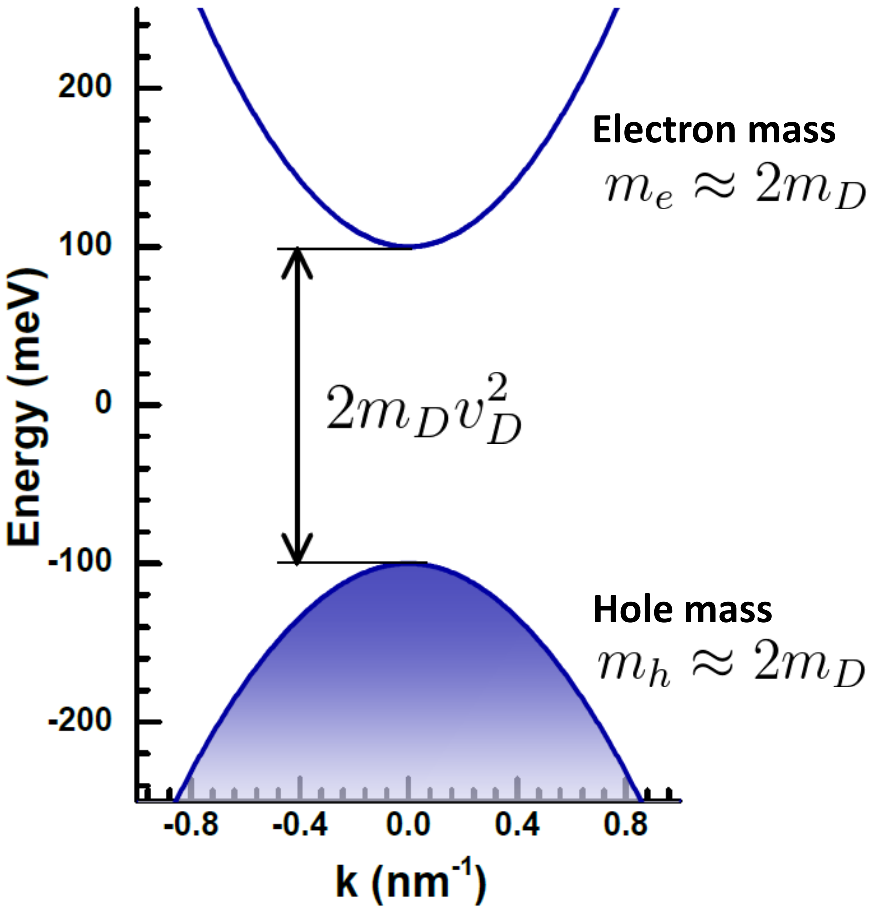
Theory:

$$E = \cancel{Ck^2} \pm \sqrt{(m_D v_D^2 + Mk^2)^2 + v_D^2 \hbar^2 k^2}$$

$$-\frac{\hbar^2}{4m_D} = M$$

H. Zhang et al., Nature Phys. 5, 438 (2009)
C.-X. Liu et al., Phys. Rev. B 82, 045122 (2010)

Electronic bands in bulk Bi_2Se_3 (Γ point)

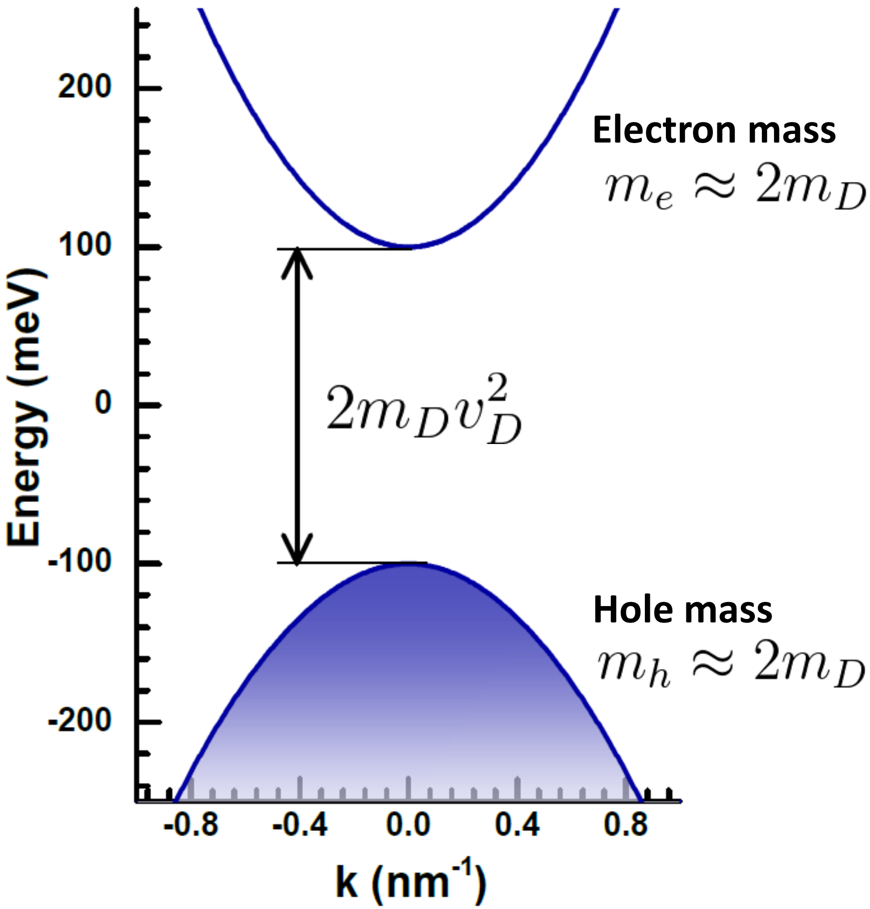


M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

Energy gap, particles masses and g factors in Bi_2Se_3 determined by only two parameters…

$$m_D, v_D$$

Electronic bands in bulk Bi_2Se_3 (Γ point)



Energy gap, particles masses and g factors in Bi_2Se_3 determined by only two parameters…

$$m_D, v_D$$

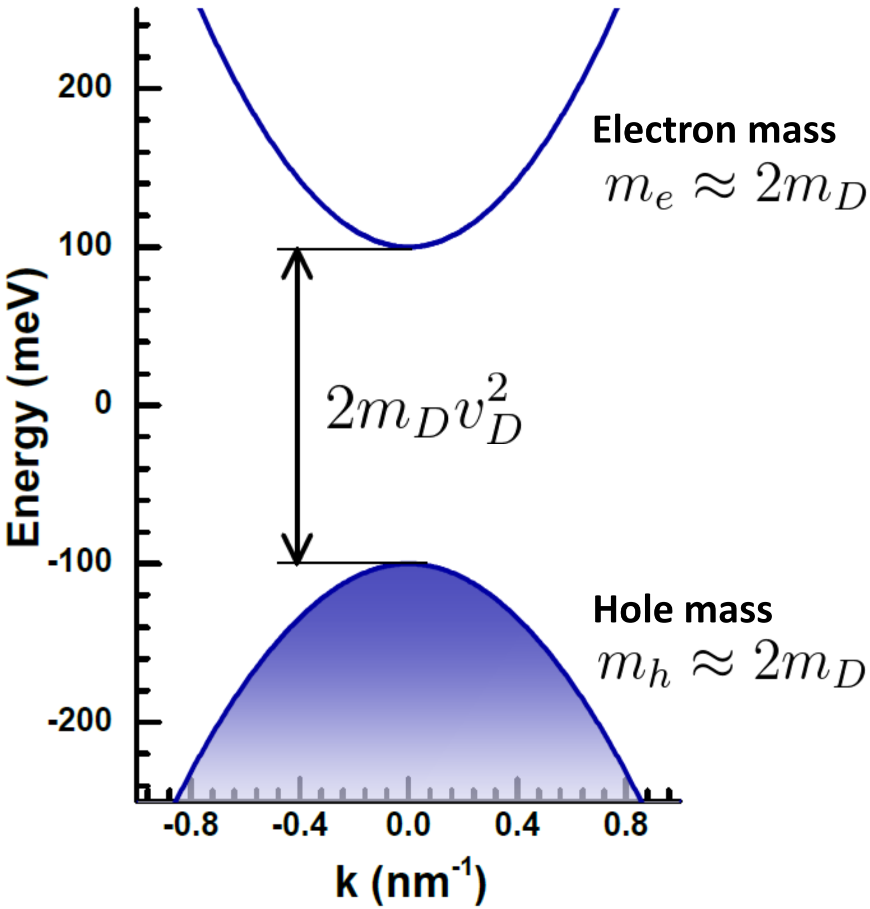
g factor:

$$g_e \approx g_h \approx 2\frac{m_0}{m_D} \approx 25$$

(for $m_D \approx 0.08m_0$)

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

Electronic bands in bulk Bi_2Se_3 (Γ point)



M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

Energy gap, particles masses and g factors in Bi_2Se_3 determined by only two parameters…

$$m_D, v_D$$

g factor:

$$g_e \approx g_h \approx 2\frac{m_0}{m_D} \approx 25$$

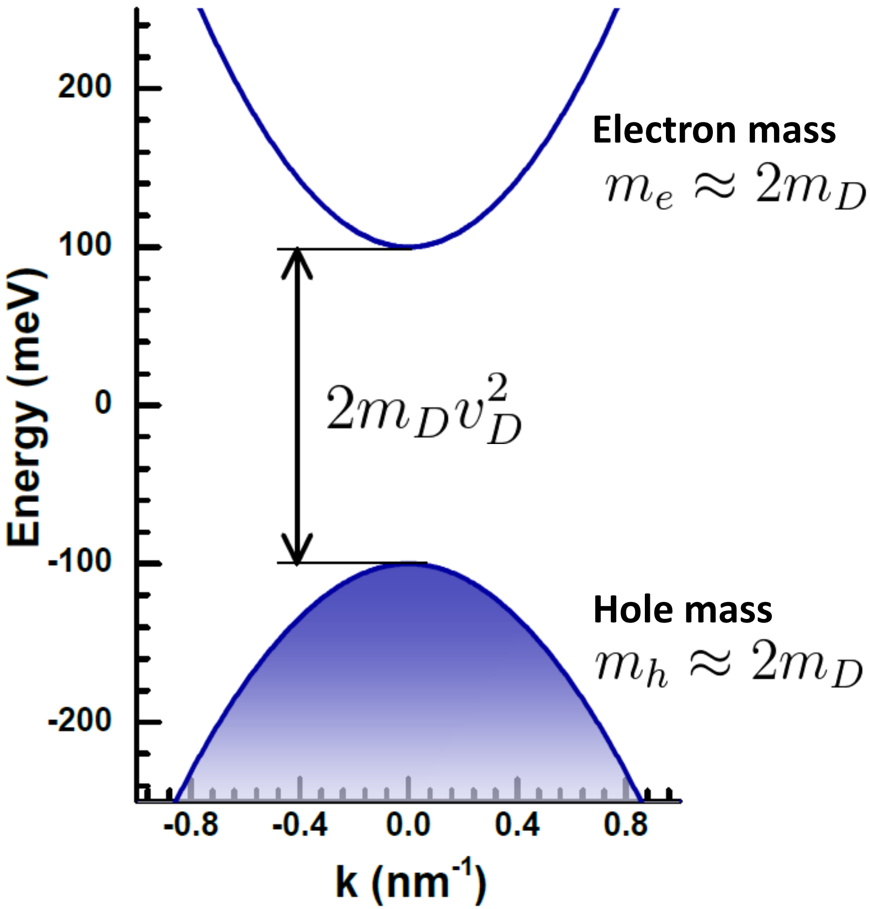
(for $m_D \approx 0.08 m_0$ **)**

Electron g factor from EPR:

$$g^{\mathrm{ESR}} = 27.5$$

A. Wolos et al., AIP Conf. Proc. 1566, 197 (2013)
A. Wolos et al., Phys. Rev. B 93, 155114 (2016)

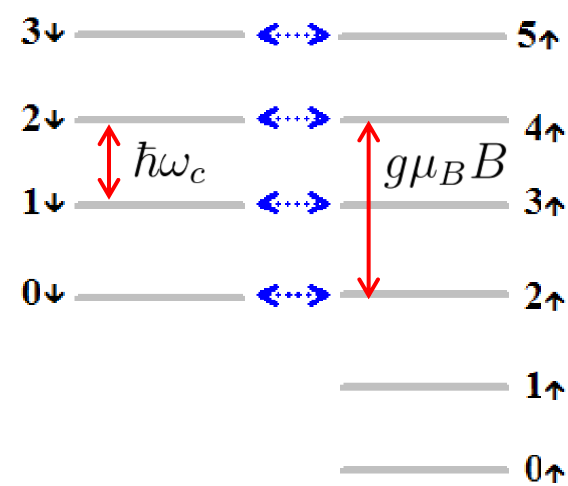
Electronic bands in bulk Bi_2Se_3 (Γ point)



Energy gap, particles masses and g factors in Bi_2Se_3 determined by only two parameters…

$$m_D, v_D$$

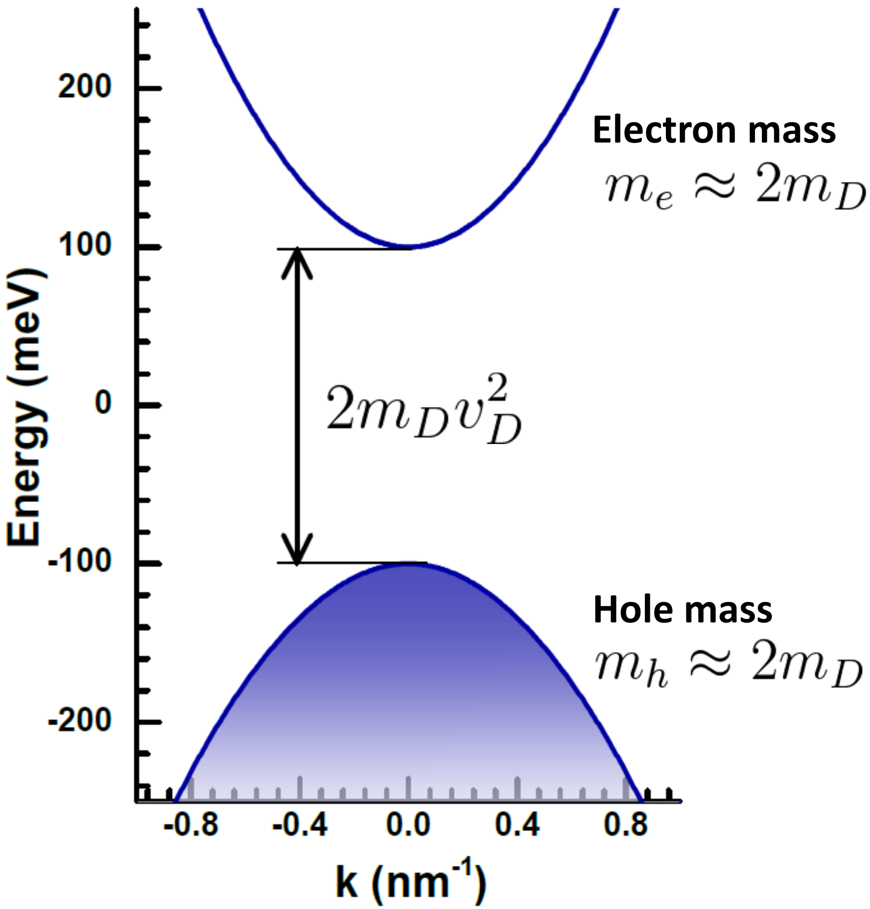
Landau level spectrum:



2× cyclotron energy = spin-splitting

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

Electronic bands in bulk Bi_2Se_3 (Γ point)



Electron mass
$m_e \approx 2m_D$

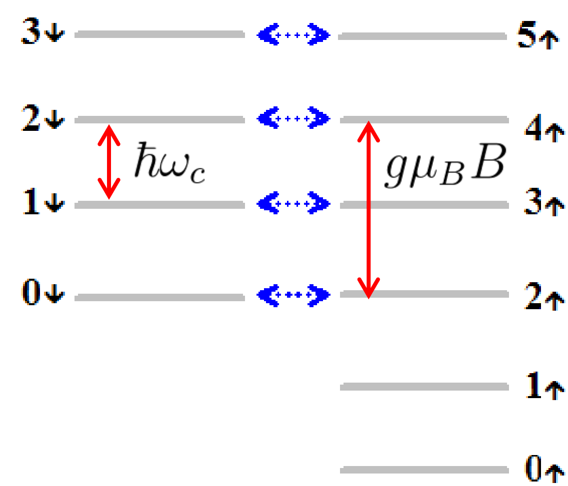
Hole mass
$m_h \approx 2m_D$

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

Energy gap, particles masses and g factors in Bi_2Se_3 determined by only two parameters…

$$m_D, v_D$$

Landau level spectrum:



Well-known empirical fact from magneto-transport…

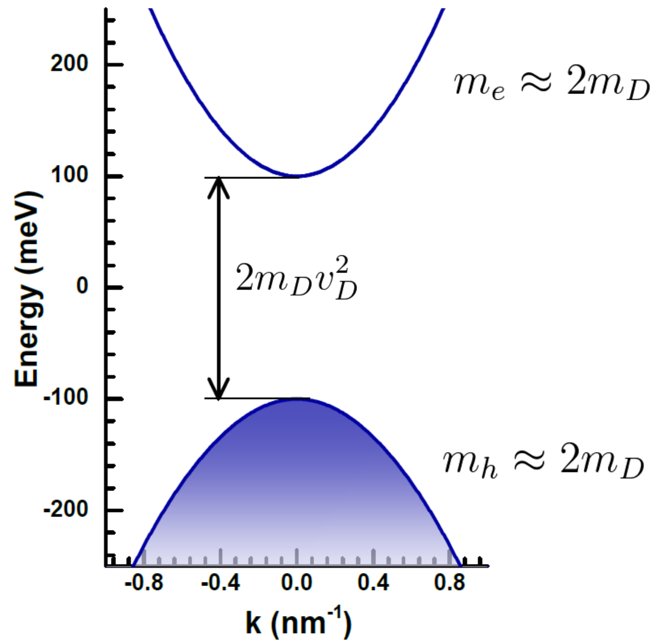
see e.g. H. Köhler and E. Wöchner, phys. stat. sol. (b) 67, 665 (1975)

Electronic bands in bulk Bi_2Se_3 : Conclusions

Electrons and holes in bulk Bi_2Se_3 closely resemble massive Dirac particles in quantum electrodynamics

Energy gap, particles masses and g factors in Bi_2Se_3 determined by only two parameters… m_D, v_D

In very good agreement with magneto-transport and EPR, but not ARPES.



M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)

Outline:

Magneto-optics of massive Dirac electrons in Bi_2Se_3

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)
L. Ohnoutek et al., Sci. Rep. 6, 19087 (2016)

C. Faugeras, B. A. Piot, G. Martinez,
A.-L. Barra, M. Potemski — LNCMI, CNRS, Grenoble, France
P. Neugebauer — Stuttgart University, Germany
T. Brauner — University of Stavanger, Norway
E. M. Hankiewicz, S. Schreyeck, S. Grauer,
C. Gould, C. Brüne, K. Brunner, and L. W. Molenkamp — Würzburg University, Germany

Magneto-optics of massless electrons in Cd_3As_2

A. Akrap et al., arXiv:1604.00038 (2016)

M. Hakl, C. Faugeras, B. A. Piot,
G. Martinez, M. Potemski — LNCMI, CNRS, Grenoble, France
A. Akrap, I. Crassee, D. van der Marel — Université de Genève, Switzerland
S. Tchoumakov, M. O. Goerbig — LPS-CNRS, Paris Orsay, France
C. C. Homes — Brookhaven national Laboratory, USA
A. Arushanov, A. Nateprov — Institute of Applied Physics, ASM, Moldova
Q. D. Gibson, R. J. Cava — Princeton University, USA
J. Kuba, O. Caha, J. Novák — CEITEC & Masaryk University, Brno, Czech Republic
S. Koohpayeh, L. Wu, N. P. Armitage — Johns Hopkins University, Baltimore, USA
F. Teppe, W. Desrat — LCC-CNRS & Université Montpellier, France

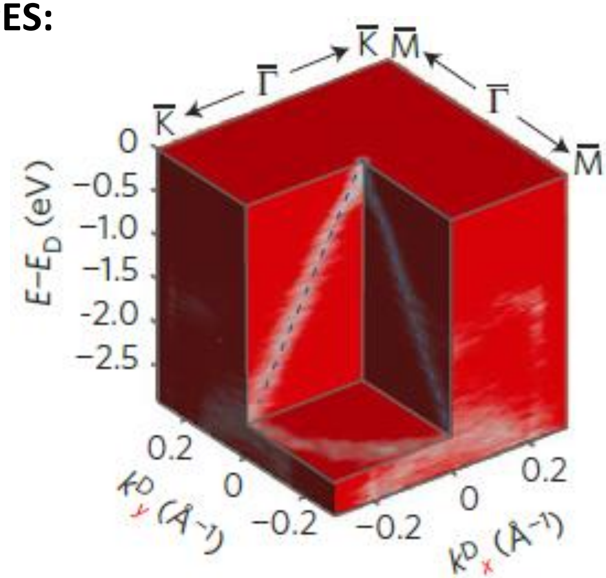
Dirac semimetal Cd_3As_2 = stable 3D analogue of graphene

nature materials
LETTERS
PUBLISHED ONLINE: 25 MAY 2014 | DOI: 10.1038/NMAT3990

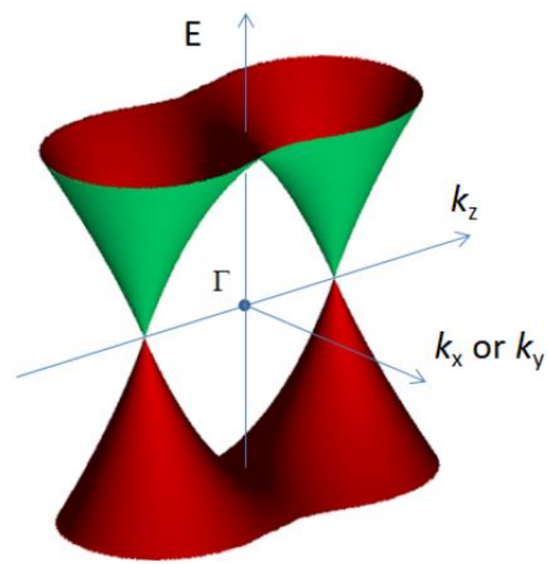
A stable three-dimensional topological Dirac semimetal Cd_3As_2

Z. K. Liu[1†], J. Jiang[2,3†], B. Zhou[2,4†], Z. J. Wang[5†], Y. Zhang[1,4], H. M. Weng[5], D. Prabhakaran[2], S-K. Mo[4], H. Peng[2], P. Dudin[6], T. Kim[6], M. Hoesch[6], Z. Fang[5], X. Dai[5], Z. X. Shen[1], D. L. Feng[3], Z. Hussain[4] and Y. L. Chen[1,2,4,6★]

ARPES:



3D Dirac semimetal Cd_3As_2



Z. K. Liu et al., Nature Mater. 13, 677 (2014)
S. Borisenko et al., Phys. Rev. Lett. 113, 027603 (2014)
M. Neupane et al., Nature Comm. 5, 3786 (2014)

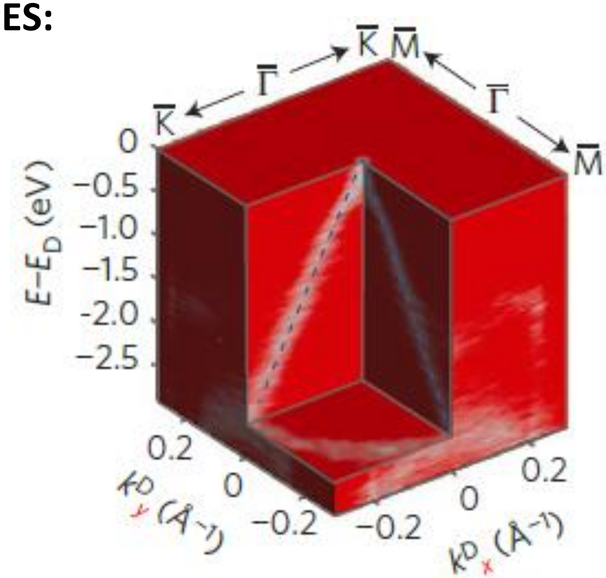
Dirac semimetal Cd_3As_2 = stable 3D analogue of graphene

nature materials
LETTERS
PUBLISHED ONLINE: 25 MAY 2014 | DOI: 10.1038/NMAT3990

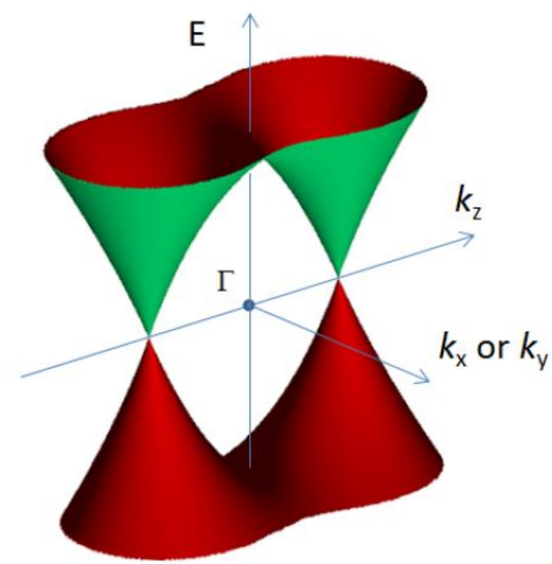
A stable three-dimensional topological Dirac semimetal Cd_3As_2

Z. K. Liu[1†], J. Jiang[2,3†], B. Zhou[2,4†], Z. J. Wang[5†], Y. Zhang[1,4], H. M. Weng[5], D. Prabhakaran[2], S-K. Mo[4], H. Peng[2], P. Dudin[6], T. Kim[6], M. Hoesch[6], Z. Fang[5], X. Dai[5], Z. X. Shen[1], D. L. Feng[3], Z. Hussain[4] and Y. L. Chen[1,2,4,6★]

ARPES:



3D Dirac semimetal Cd_3As_2

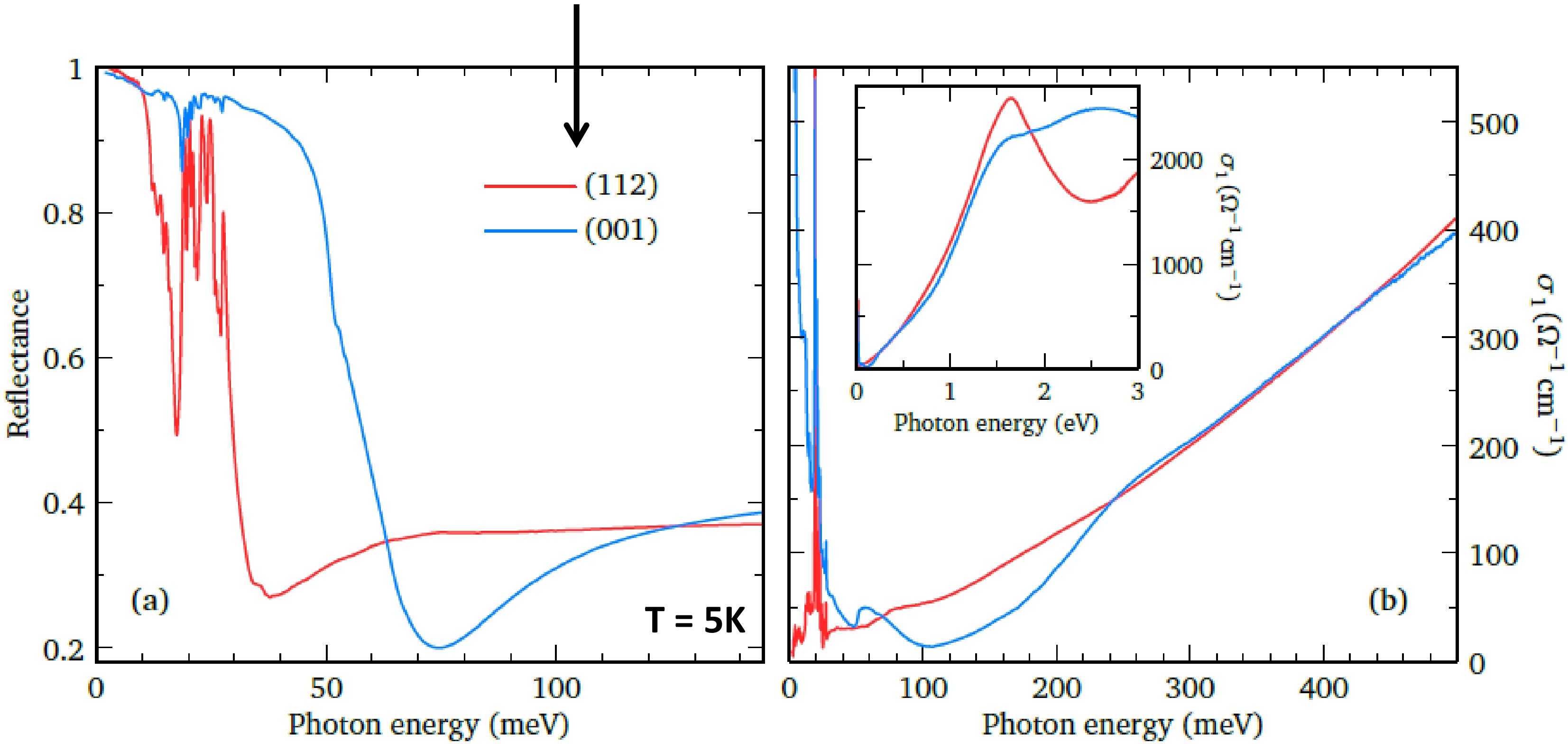


…but really not in line with other studies, e.g. recent STS/STM experiments

S. Jeon et al., Nature Mater. 13, 851 (2014)

Cd_3As_2 – Infrared reflectance at B=0

Two different crystallographic orientations of tetragonal Cd_3As_2



...in collaboration with C. C. Homes (Brookhaven)

A. Akrap et al., arXiv:1604.00038 (2016)

Cd_3As_2 – Infrared reflectance at B=0

Absorption of light in solids (e.g., Fermi's golden rule):

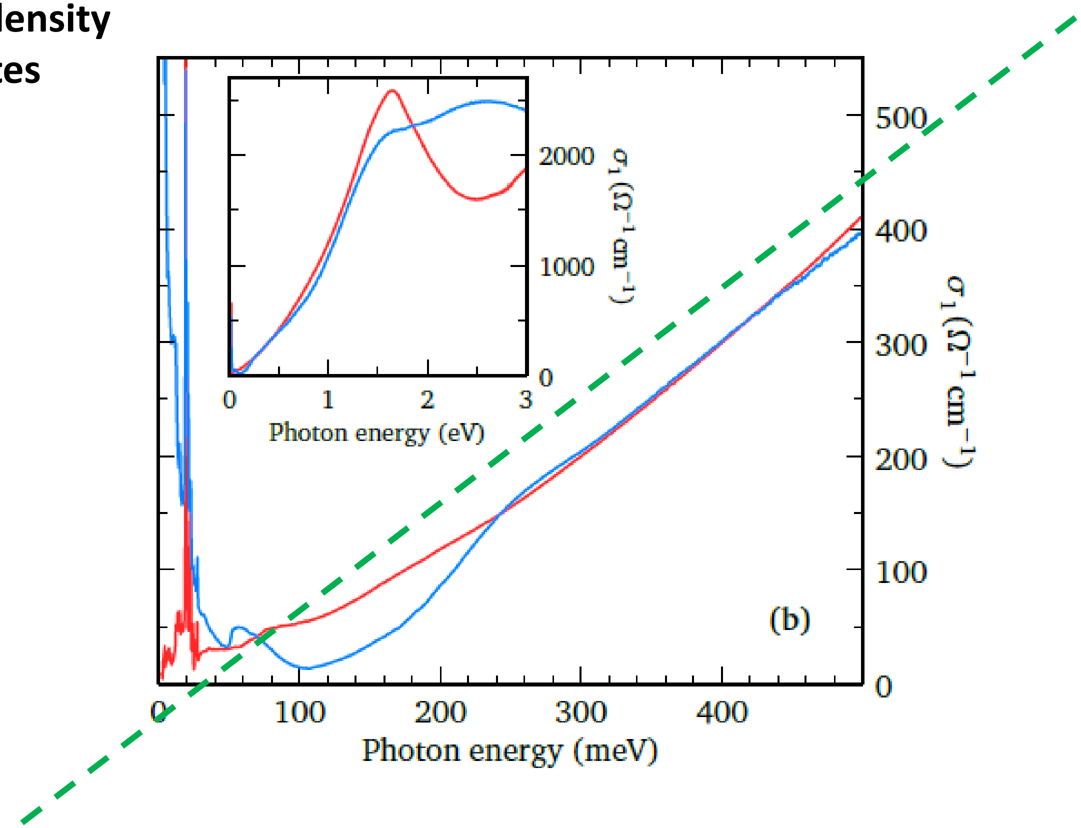
joint density of states

$$\sigma_1(\omega) \propto \frac{\mathcal{D}(\omega)}{\omega}$$

For conical bands in 3D:

$$\mathcal{D}(\omega) \propto \omega^2$$

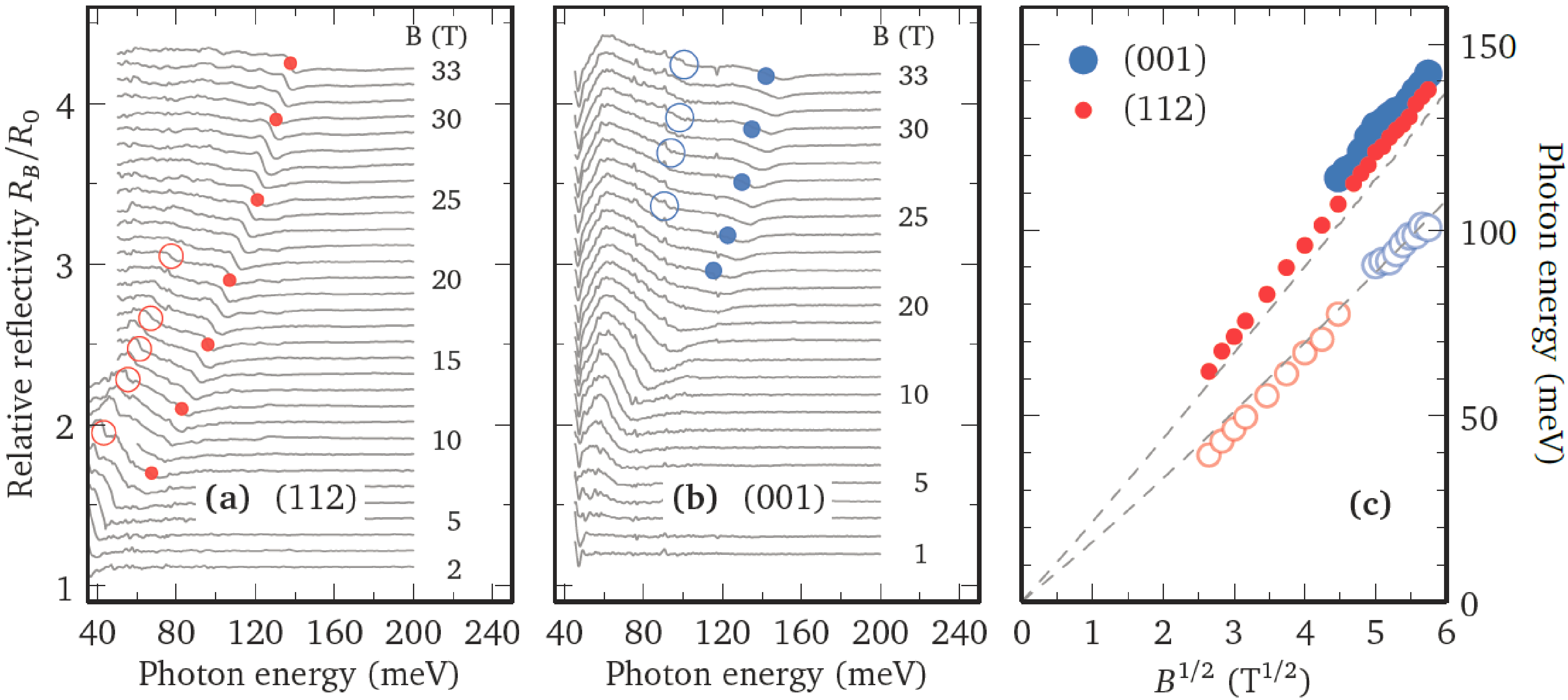
Absorption coefficient (optical conductivity) linear in photon frequency!



see also D. Neubauer et al. , Phys. Rev. B 93, 121202 (2016)

Cd_3As_2 – High-field magneto-reflectivity

T = 5K

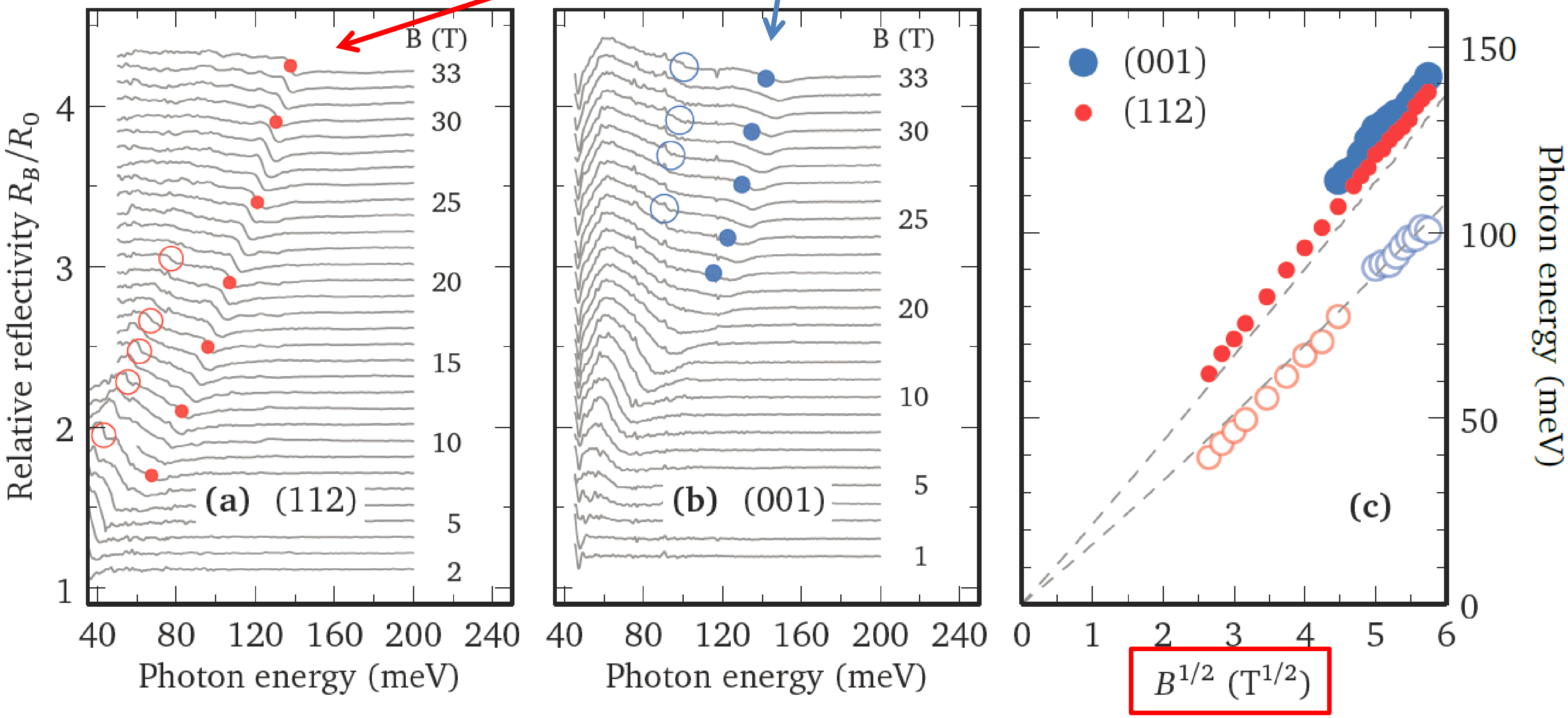


A. Akrap et al., arXiv:1604.00038 (2016)

Cd_3As_2 – High-field magneto-reflectivity

Cyclotron resonance (CR) in the quantum limit

T = 5K

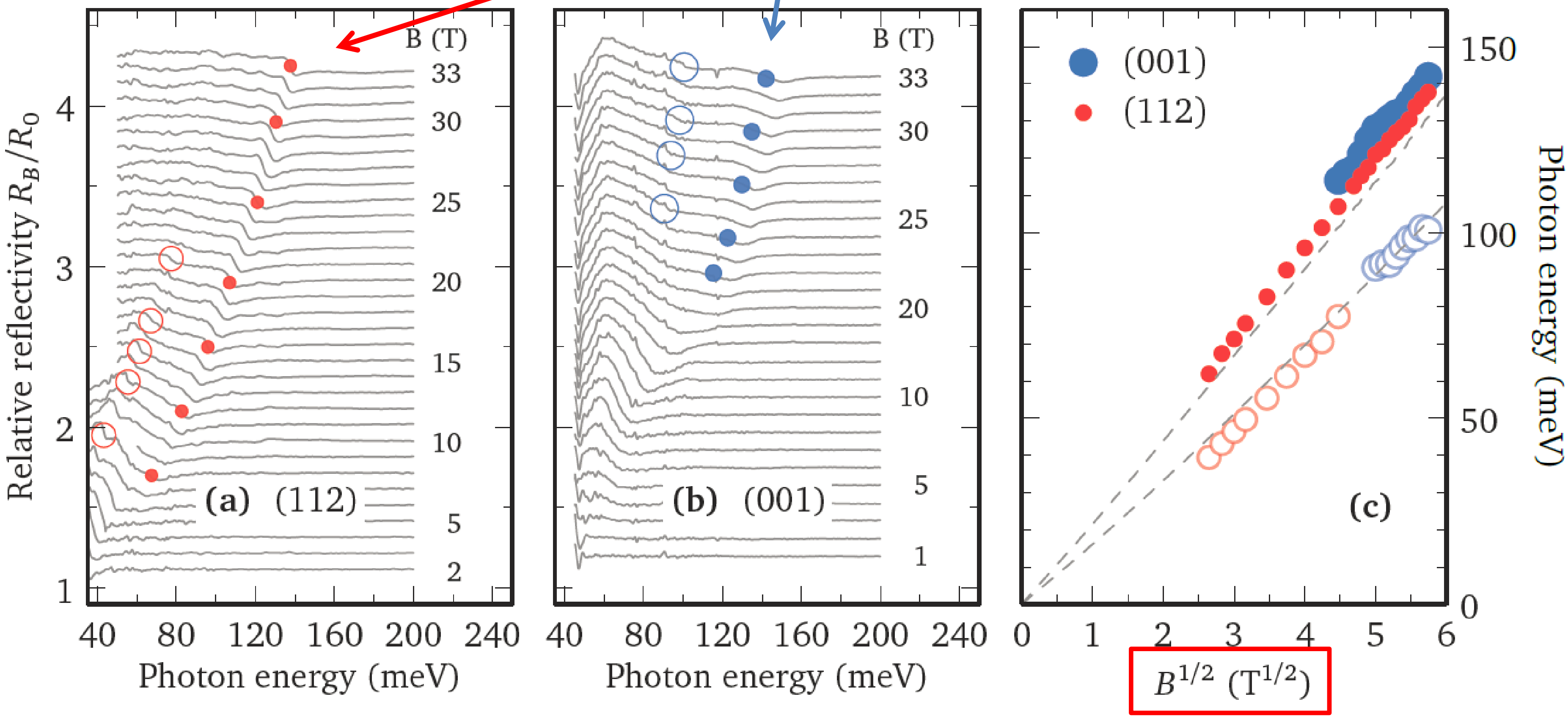


A. Akrap et al., arXiv:1604.00038 (2016)

Cd_3As_2 – High-field magneto-reflectivity

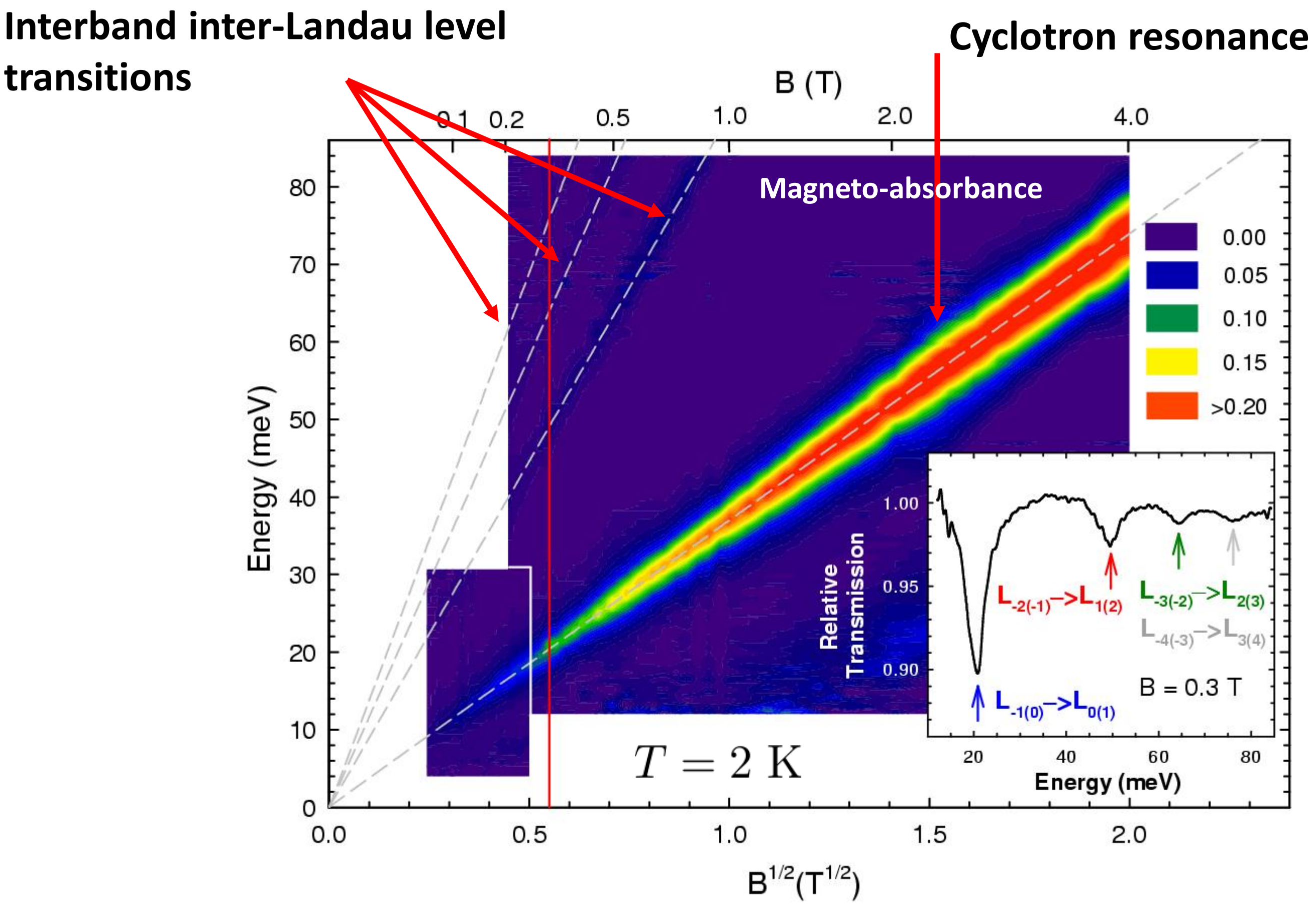
Cyclotron resonance (CR) in the quantum limit

T = 5K



Magneto-optical response linear in $\sqrt{B}$ = typical signature of massless particles

Magneto-transmission of (multilayer epitaxial) graphene



Energy spectrum:

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

Velocity:

$$v = 1.02 \times 10^6 \text{ m/s}$$

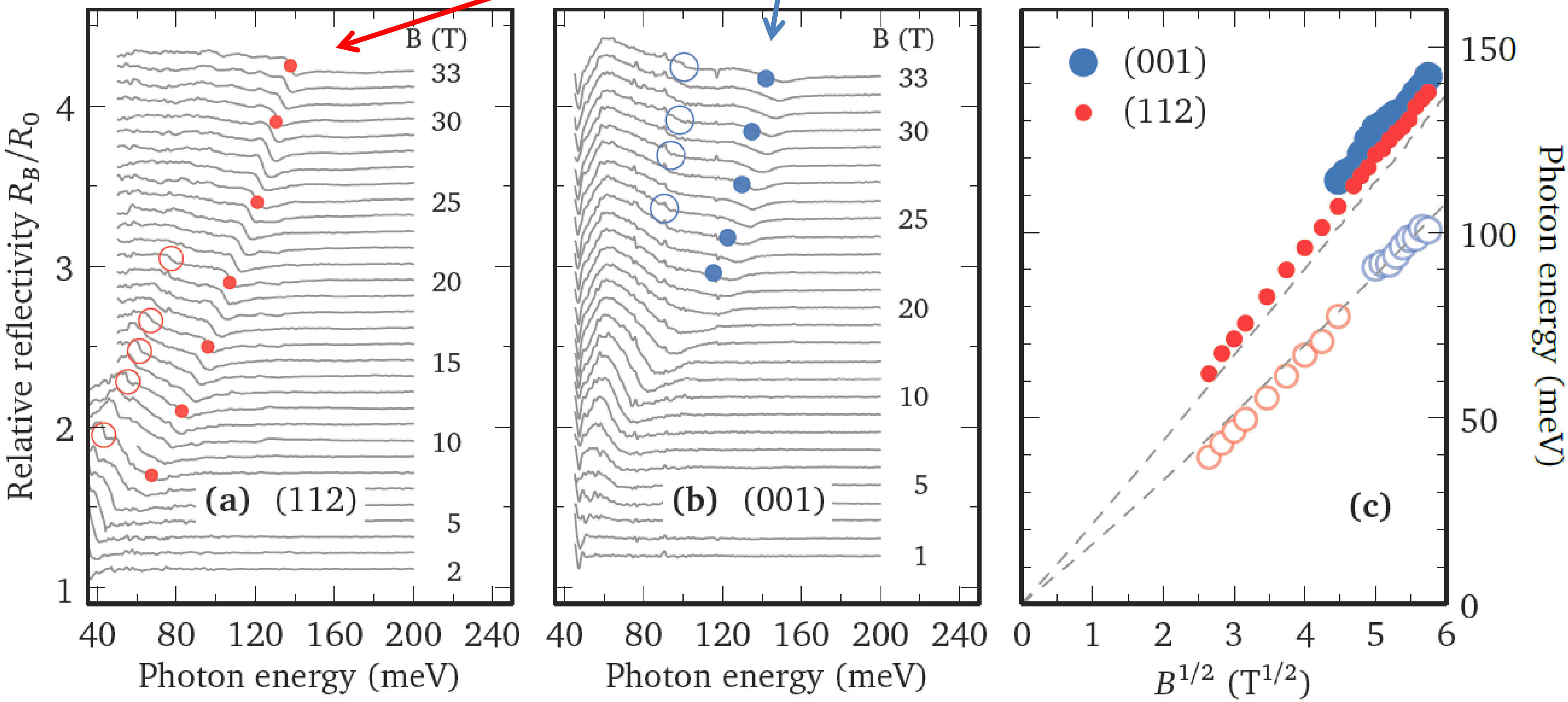
Selection rules:

$$|n| \rightarrow |n| \pm 1$$

M. Orlita et al., Phys. Rev. Lett. 101, 267601 (2008)

Cd_3As_2 – High-field magneto-reflectivity

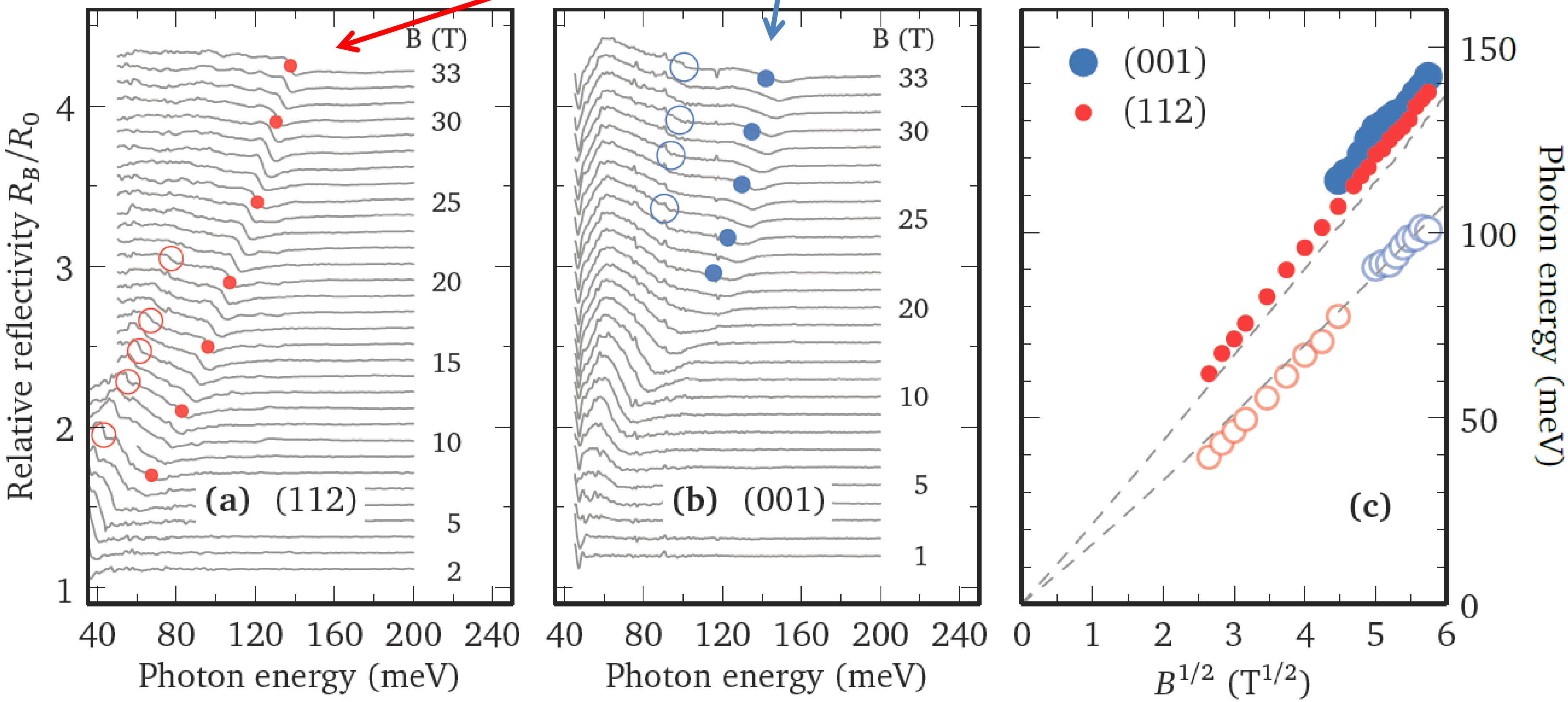
Cyclotron resonance (CR) in the quantum limit



Magneto-optical response linear in $\sqrt{B}$ = typical signature of massless particles

Cd_3As_2 – High-field magneto-reflectivity

Cyclotron resonance (CR) in the quantum limit

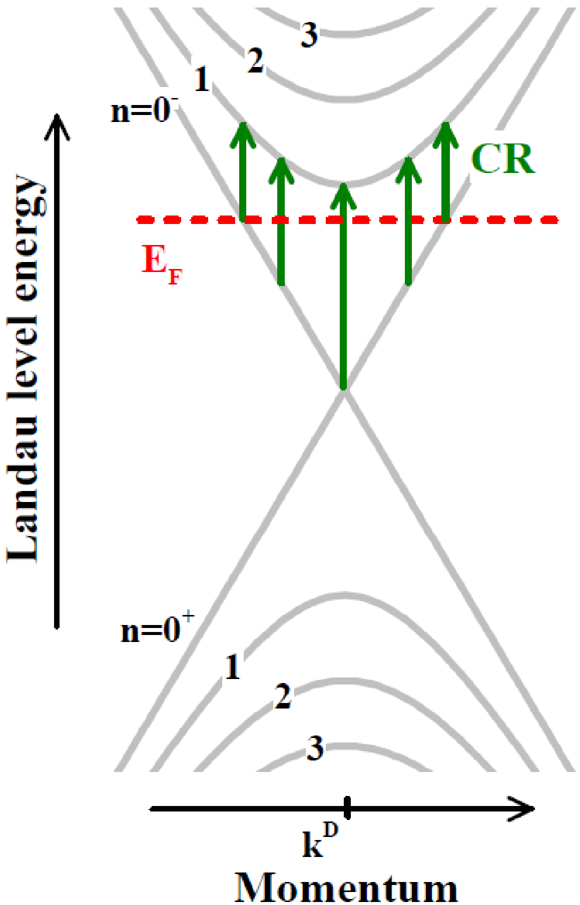


Magneto-optical response linear in $\sqrt{B}$ = typical signature of massless particles

….massless yes, but not 3D Dirac

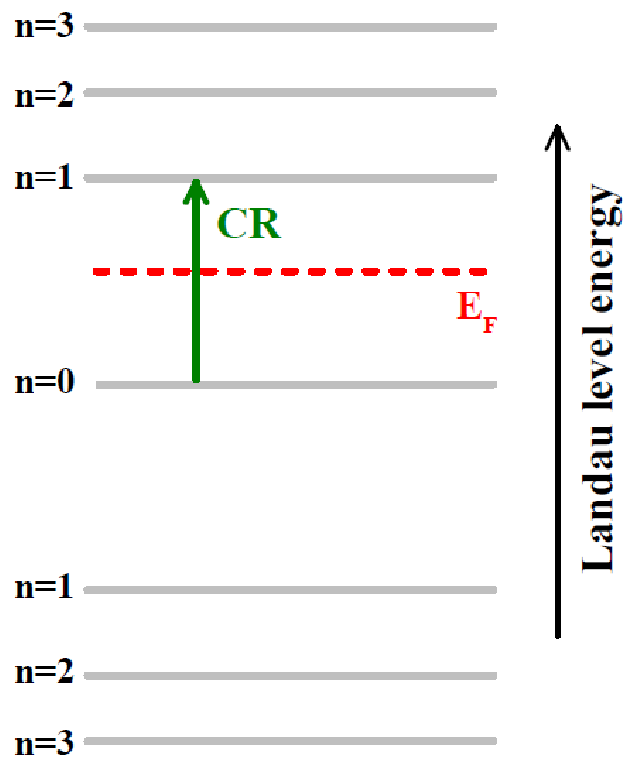
Dirac electrons – Landau level spectrum

3D Dirac electrons



$$E_n = \pm v\sqrt{2e\hbar Bn + \hbar^2 k^2}$$

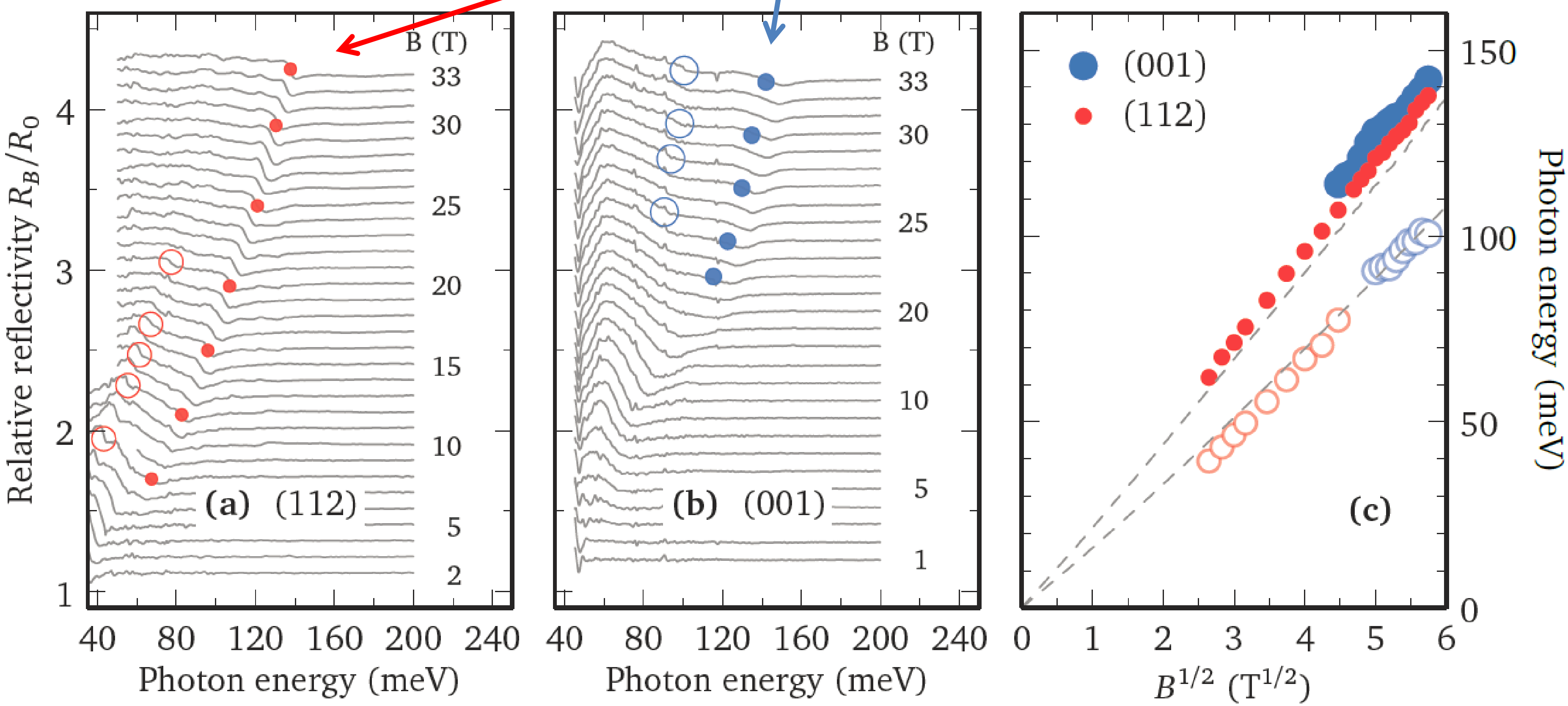
2D Dirac electrons



$$E_n = \pm v\sqrt{2e\hbar Bn}$$

Cd_3As_2 – High-field magneto-reflectivity

Cyclotron resonance (CR) in the quantum limit



Magneto-optical response linear in $\sqrt{B}$ = typical signature of massless particles

….massless yes, but not 3D Dirac

Bodnar’s model of electronic bands in Cd_3As_2

BAND STRUCTURE OF Cd_3As_2 FROM SHUBNIKOV-de HAAS
AND de HAAS - van ALPHEN EFFECTS

J. BODNAR

Department of Solid State Physics, Polish Academy of Sciences,
Zabrze, Poland

Experimental values of SdH and dHvA periods and cyclotron effective masses found by Rosenman and Doi et al. have been compared with the theoretical predictions derived in this work for a tetragonal narrow gap semiconductor. By the least square fit method the values of band parameters were obtained. It has been established that Cd_3As_2 has inverted band structure resembling HgTe under tensile stress.

J. Bodnar, Proc. III Conf. Narrow-Gap Semiconductors, Warsaw,(Elsevier, 1977) p. 311

Electronic bands in Cd_3As_2

Two energy scales of conical bands:

Two symmetry-protected Dirac cones at low energies

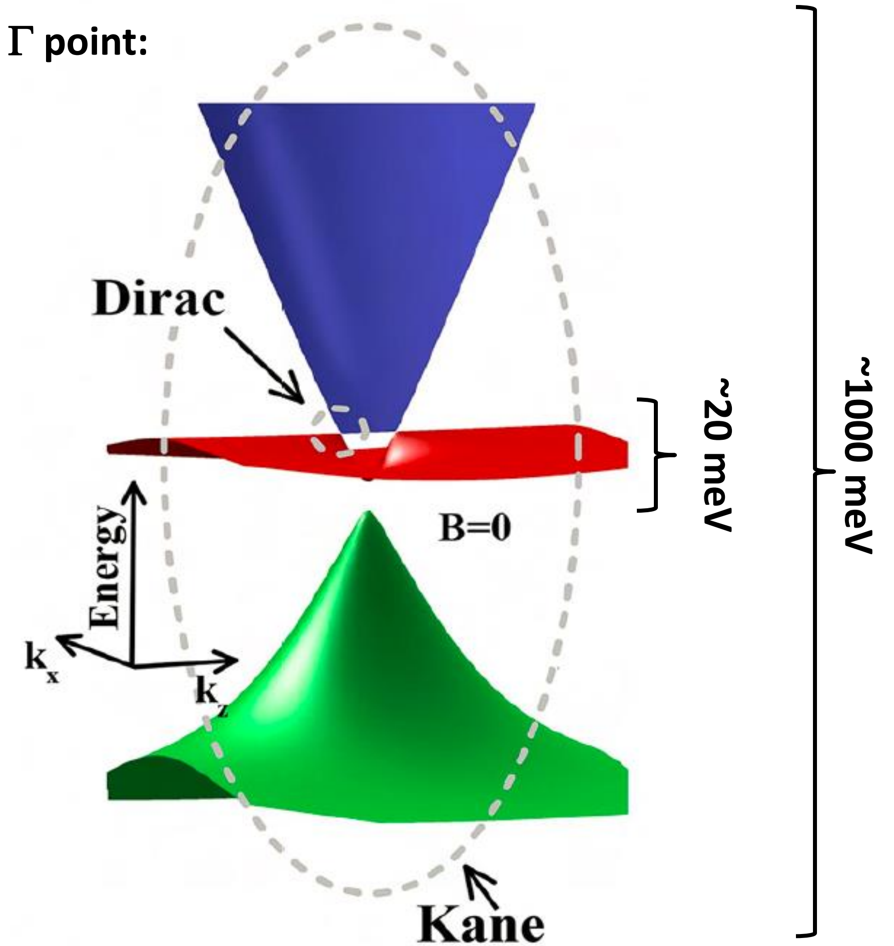
…due crossing of heavy and light hole band in a tetragonally distorted zinc-blende semiconductor

A single cone of massless Kane electrons, no symmetry protection

…appearing in zinc-blende semiconductors with a vanishing band gap

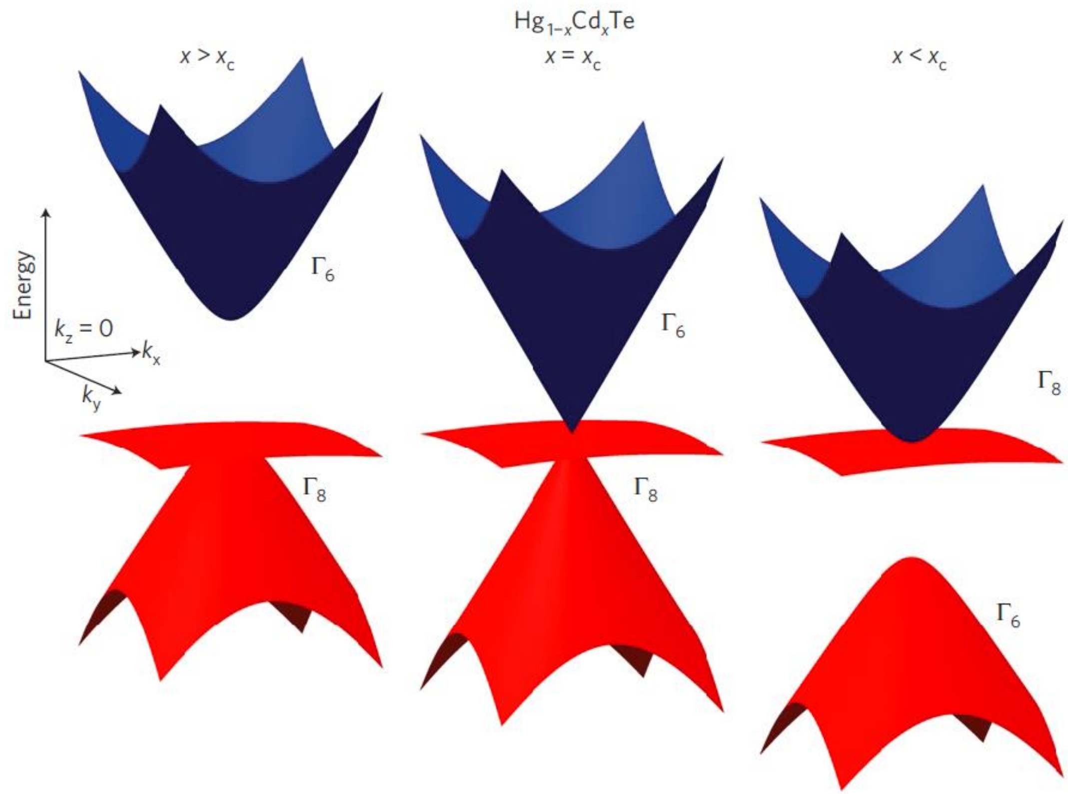
J. Bodnar, in Proc. III Conf. Narrow-Gap Semiconductors, Warsaw,(Elsevier, 1977) p. 311

Γ point:



A. Akrap et al., arXiv:1604.00038 (2016)

Massless Kane electrons in gapless HgCdTe

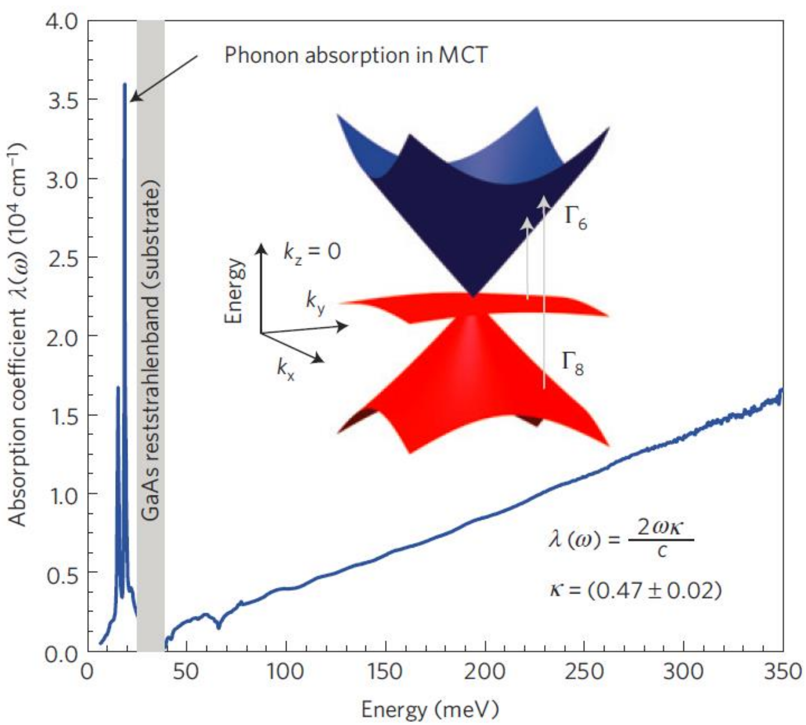


E. O. Kane, J. Phys. Chem. Solids 1, 249 (1957)
P. Kacman and W. Zawadzki, phys. stat. sol. (b) 47, 629 (1971)
M. Orlita et al., Nature Phys. 10, 233 (2914)

A single conical band in the center of Brillouin zone (due to accidental degeneracy of levels) hosting massless Kane electrons

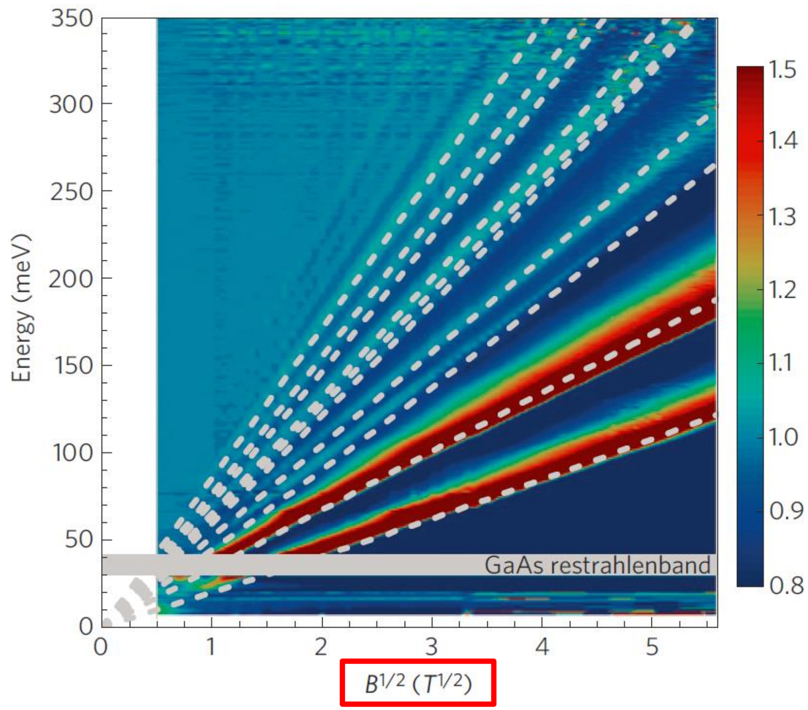
Massless Kane electrons in gapless HgCdTe

Absorption coefficient linear in photon energy:



M. Orlita et al., Nature Phys. 10, 233 (2014)

Magneto-optical response linear in $\sqrt{B}$:



Electronic bands in Cd_3As_2

Two energy scales of conical bands:

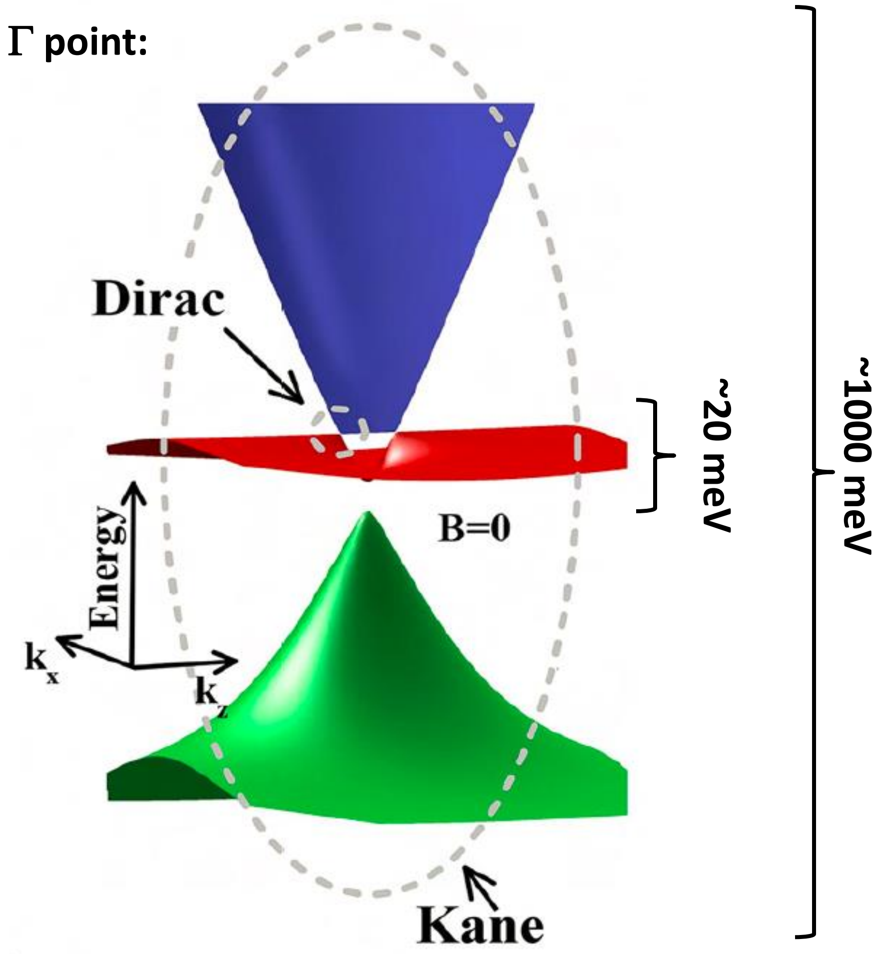
Two symmetry-protected Dirac cones at low energies

…due crossing of heavy and light hole band in a tetragonally distorted zinc-blende semiconductor

A single cone of massless Kane electrons, no symmetry protection

…appearing in zinc-blende semiconductors with a vanishing band gap

J. Bodnar, in Proc. III Conf. Narrow-Gap Semiconductors, Warsaw,(Elsevier, 1977) p. 311



A. Akrap et al., arXiv:1604.00038 (2016)

Electronic bands in Cd_3As_2

Two energy scales of conical bands:

Two symmetry-protected Dirac cones at low energies

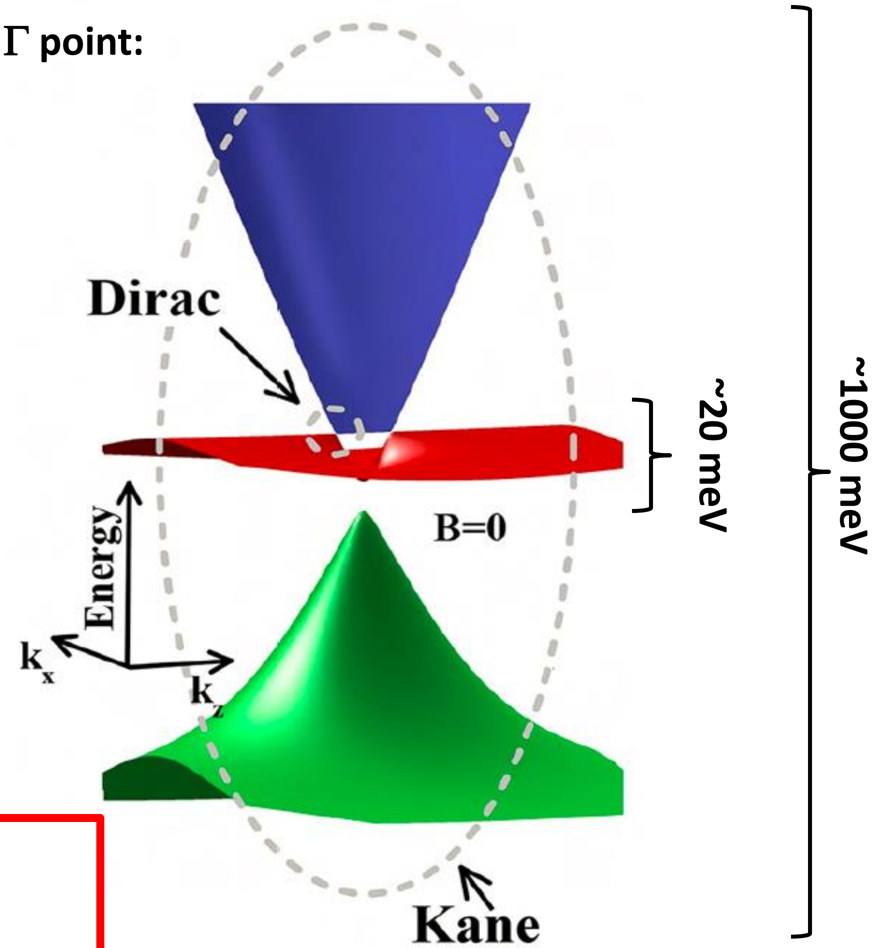
…due crossing of heavy and light hole band in a tetragonally distorted zinc-blende semiconductor

A single cone of massless Kane electrons, no symmetry protection

…appearing in zinc-blende semiconductors with a vanishing band gap

A. Akrap, Wednesday 1/6/16, 9:50

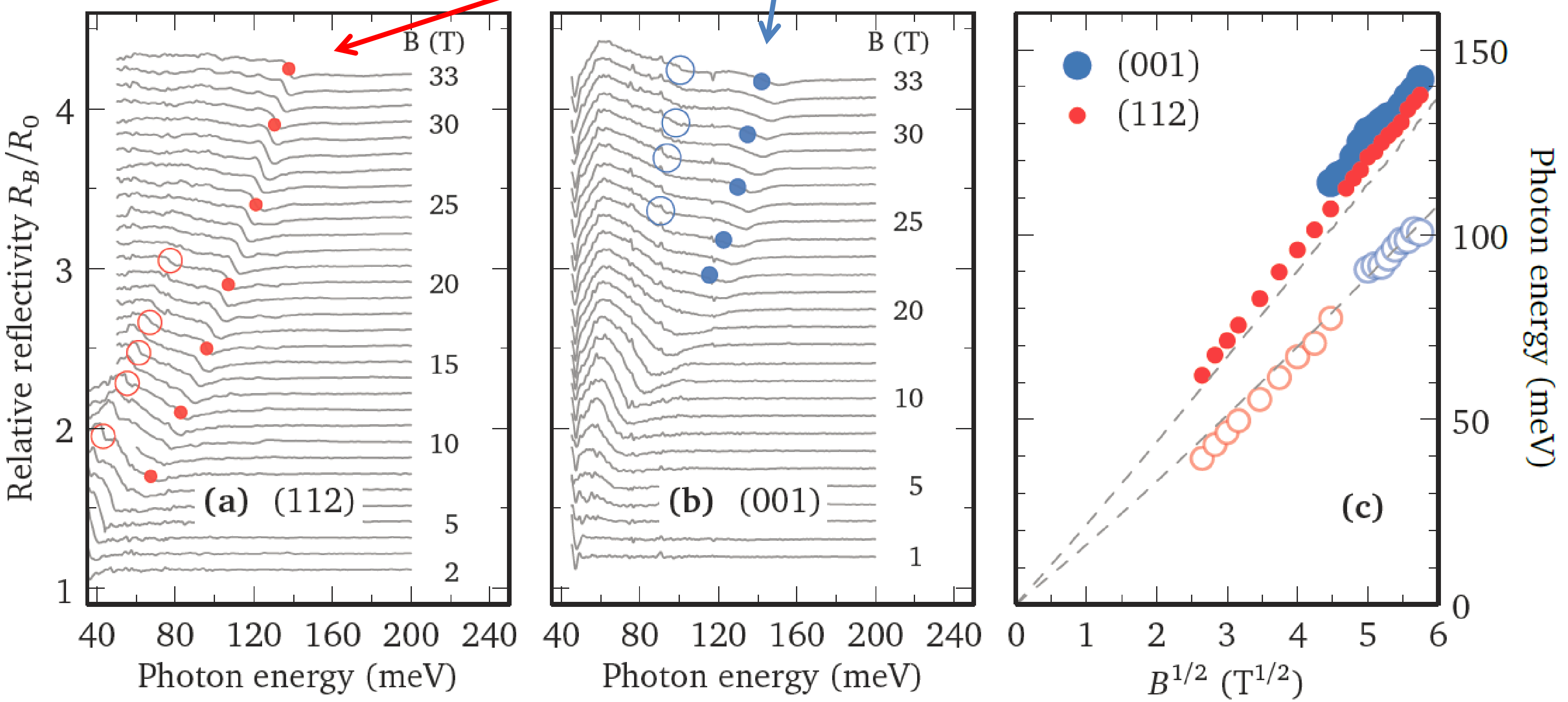
Γ point:



A. Akrap et al., arXiv:1604.00038 (2016)

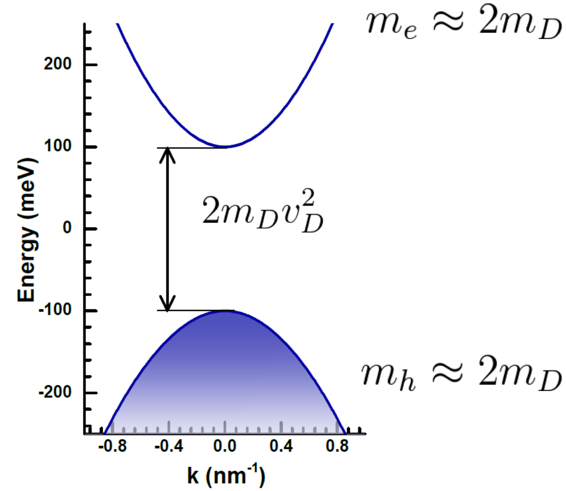
Cd_3As_2 – High-field magneto-reflectivity

Cyclotron resonance (CR) in the quantum limit



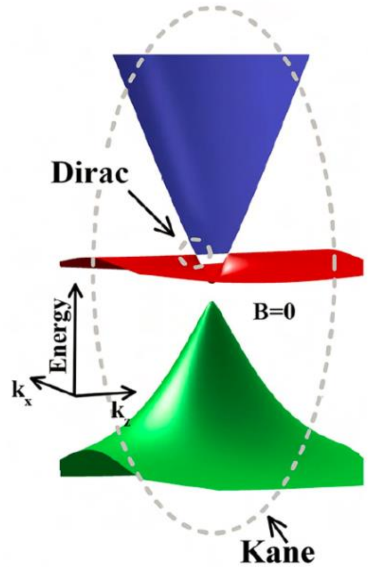
Magneto-optical signature of massless Kane electrons

Conclusions



Electrons and holes in bulk Bi_2Se_3 closely resemble massive Dirac particles in quantum electrodynamics

M. Orlita et al., Phys. Rev. Lett. 114, 186401 (2015)



The band structure of Cd_3As_2 hosts two kinds of 3D conical features:

3D massless Dirac and Kane electrons at a “small” and “big” energy scale, respectively

A. Akrap et al., arXiv:1604.00038 (2016)

Acknowledgements: ERC-2012-AdG-320590 MOMB (M. Potemski), Lia TeraMIR, TWINFUSYON