Magneto-optics of massless electrons in Cd_3As_2

Milan Orlita

Laboratoire National des Champs Magnétiques Intenses
CNRS, Grenoble, France

NGS17, 25 July 2016

Collaborators:

Optical spectroscopy:

M. Hakl, C. Faugeras, G. Martinez, M. Potemski	LNCMI, CNRS, Grenoble, France
A. Akrap, I. Crassee, D. van der Marel	Université de Genève, Switzerland
C. C. Homes	Brookhaven national Laboratory, USA
J. Kuba	CEITEC & BUT, Brno, Czech Republic
L. Wu, N. P. Armitage	Johns Hopkins University, Baltimore, USA

Theory:

S. Tchoumakov, M. O. Goerbig	LPS, CNRS, Paris Orsay, France

X-ray:

O. Caha, J. Novák	CEITEC & Masaryk University, Brno, Czech Republic
S. Koohpayeh	Johns Hopkins University, Baltimore, USA

Sample growth:

A. Arushanov, A. Nateprov	Institute of Applied Physics, ASM, Moldova
Q. D. Gibson, R. J. Cava	Princeton University, USA

Transport:

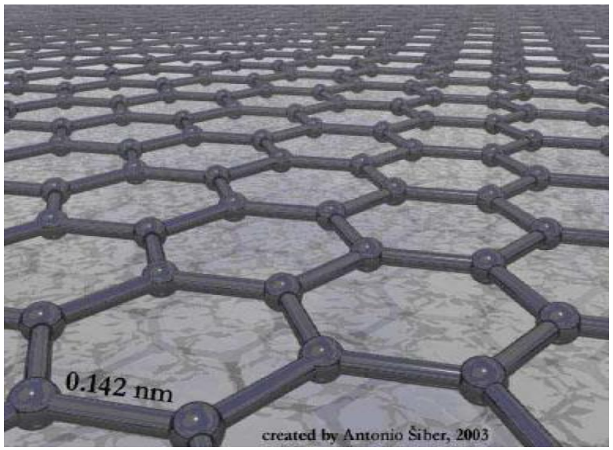
B. A. Piot	LNCMI, CNRS, Grenoble, France
F. Teppe, W. Desrat	LCC, CNRS & Université Montpellier, France

Outline:

- Massless electrons in solid-state physics (reminder)
- 3D massless electrons in Cd_3As_2
- Conclusions

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

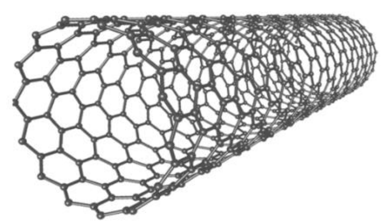
3D

Graphite

3D

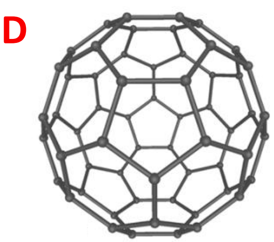
Carbon nanotube

1D



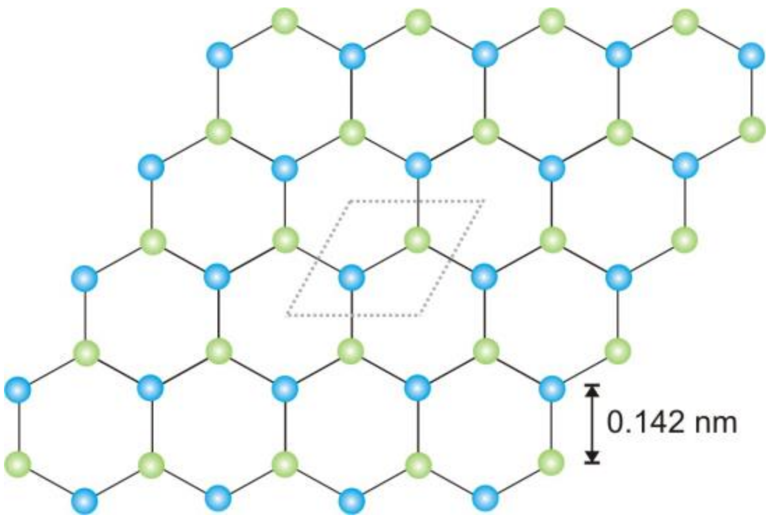
Fulleren

0D

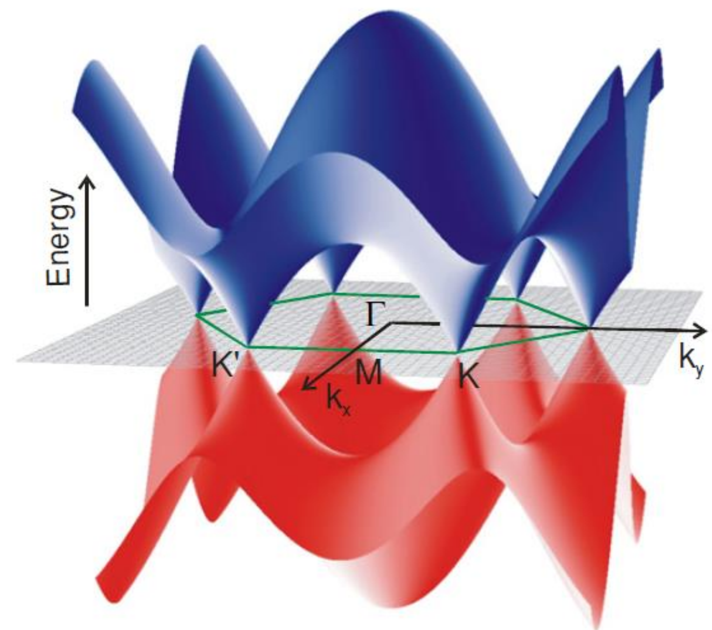


Electronic band structure of graphene

Crystal lattice:



Electronic bands:



Linearity of bands around K points:

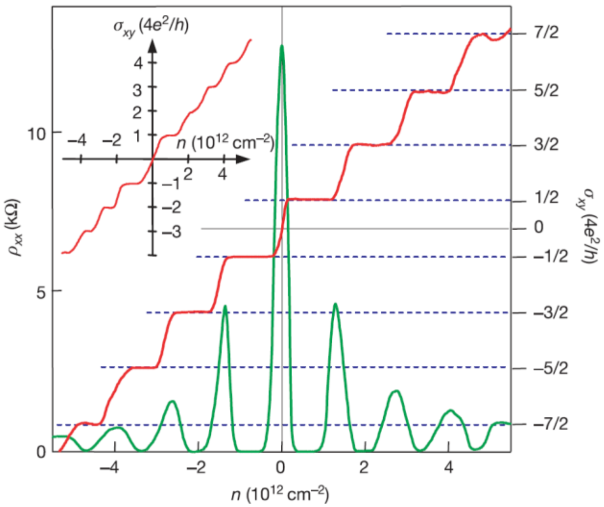
$$E(\mathbf{k}) \approx \pm\hbar v_F|\mathbf{k}| = \pm v_F|\mathbf{p}|$$

Electrons in graphene =
charged massless (relativistic) particles

$$E^2 = p^2c^2 + m_0^2c^4$$

Highlights of graphene physics

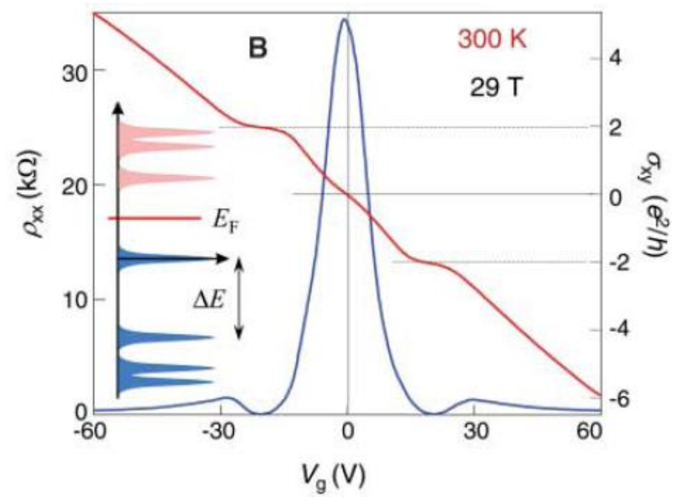
“Half-integer” and fractional QHE:



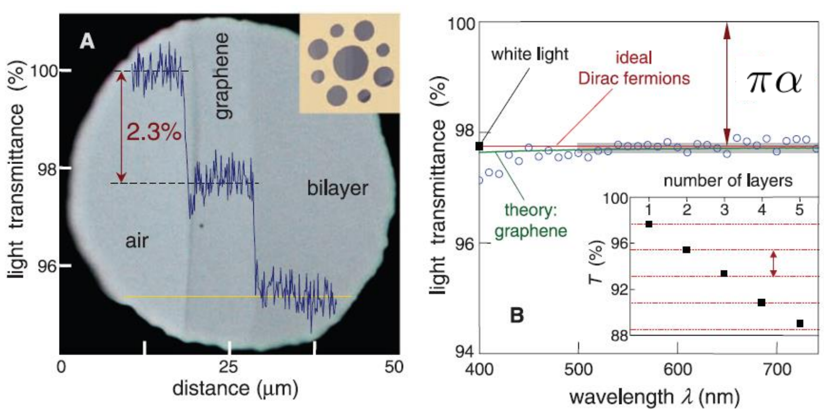
K. Novoselov et al., Nature 438, 197 (2005)
Y. Zhang et al., Nature 438, 201 (2005)
K. I. Bolotin et al.,, Nature 462, 196 (2009)

Room temperature QHE:

K. Novoselov et al., Science 315, 1379 (2007)



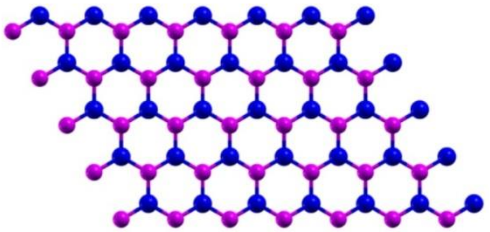
Universal dynamic conductivity:



R. R. Nair et al., Science 320, 1308 (2008)
A. B. Kuzmenko et al., Phys. Rev. Lett. 100, 117401 (2008)

Other materials with massless particles

Silicene, germanene, phosphorene (?)

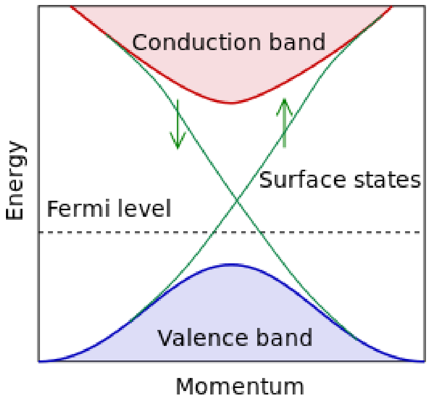


S. Cahangirov et al., Phys. Rev. Lett. 102, 236804 (2009)
H. Liu et al., ACS Nano 8, 4033 (2014)

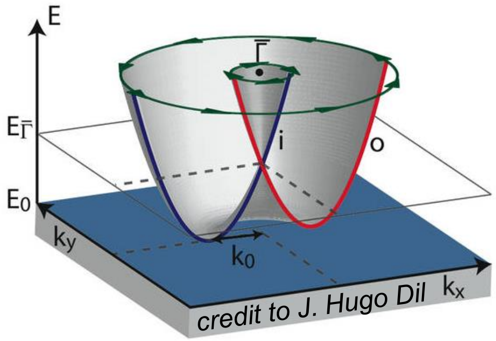
Artificial graphene, molecular graphene

C.-H. Park et al., PRL 101, 126804 (2008)
M. Gibertini et al., Phys. Rev. B 79, 241406 (2009)
L. Nádvorník et al., New J. Phys. 14, 053002 (2012)
K. K. Gomes et al., Nature 483, 306 (2012)

Topological insulators (HgTe QWs, Bi_2Se_3, Bi_2Te_3, Bi_xSb_{1-x} etc.)



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)



Semiconductors with a giant Rashba-type spin splitting (BiTeX, X = I, Cl or Br)

K. Ishizaka et al., Nature Materials 10, 521 (2011)
S. Bordacs et al., Phys. Rev. Lett. 111, 166403 (2013)

Massless particles in 3D: Dirac and Weyl semimetals…

3D Dirac semimetals
(with spin-degenerate 3D conical bands
protected by lattice symmetry)

Na_3Bi, Cd_3As_2

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)

3D Weyl semimetals
(3D conical bands with no spin degeneracy =
with either time- or inversion-symmetry lifted)

TaAs, NbAs, TaP

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)

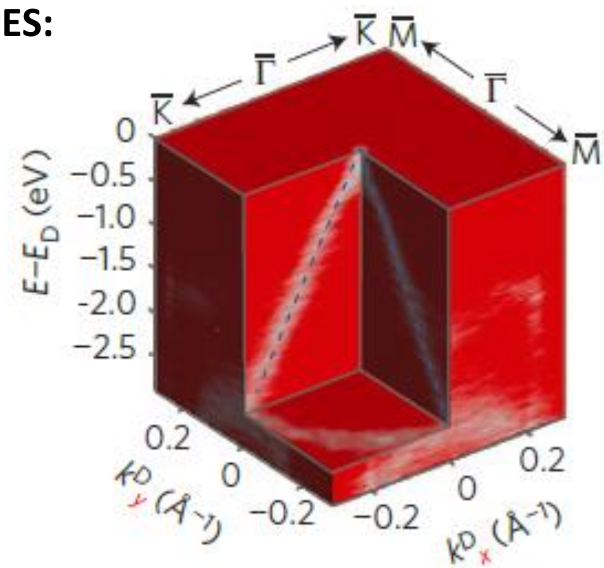
Dirac semimetal Cd_3As_2 = stable 3D analogue of graphene

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

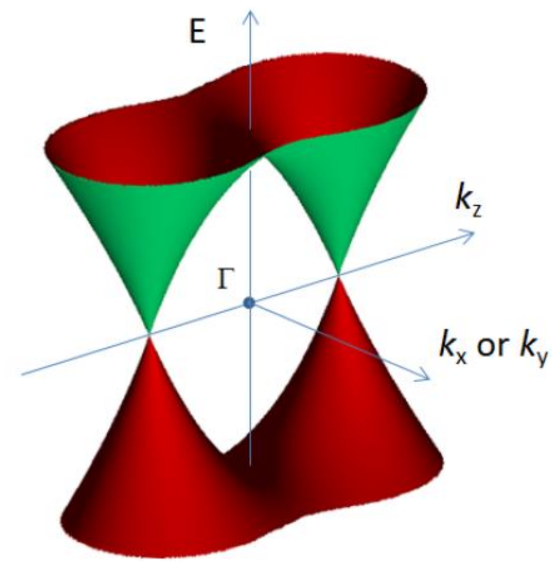
A stable three-dimensional topological Dirac semimetal Cd_3As_2

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. 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)

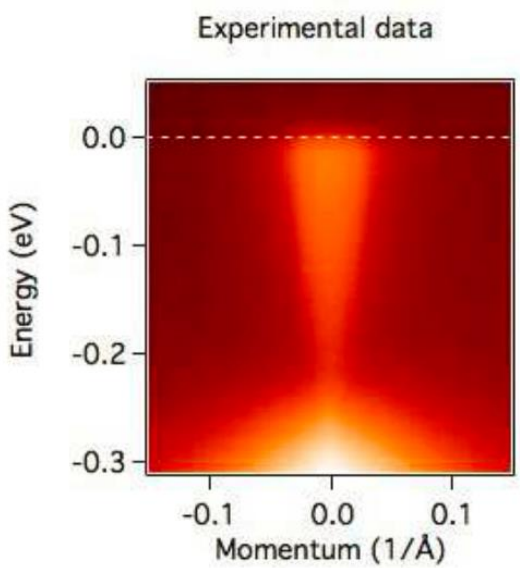
Dirac semimetal Cd_3As_2 = stable 3D analogue of graphene

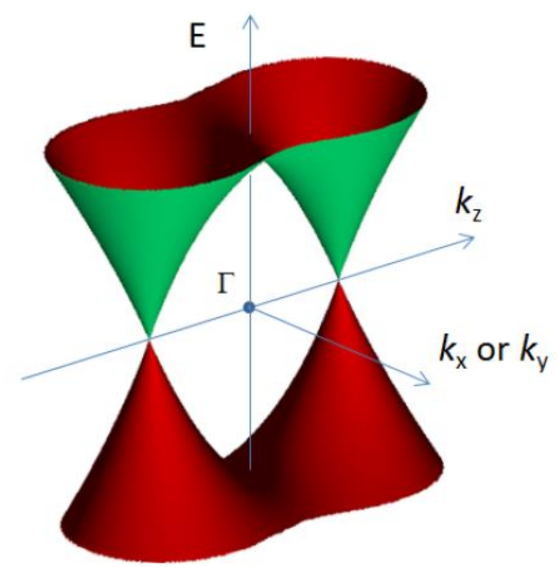
nature materials
LETTERS
PUBLISHED ONLINE: 25 MAY 2014 | DOI: 10.1038/NMAT3990

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:





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)

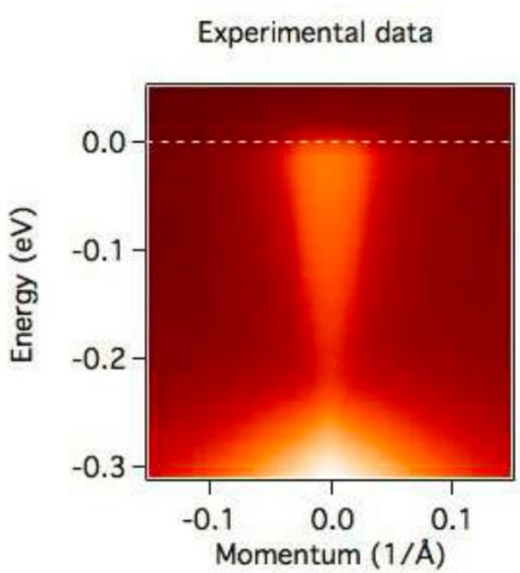
Dirac semimetal Cd_3As_2 = stable 3D analogue of graphene

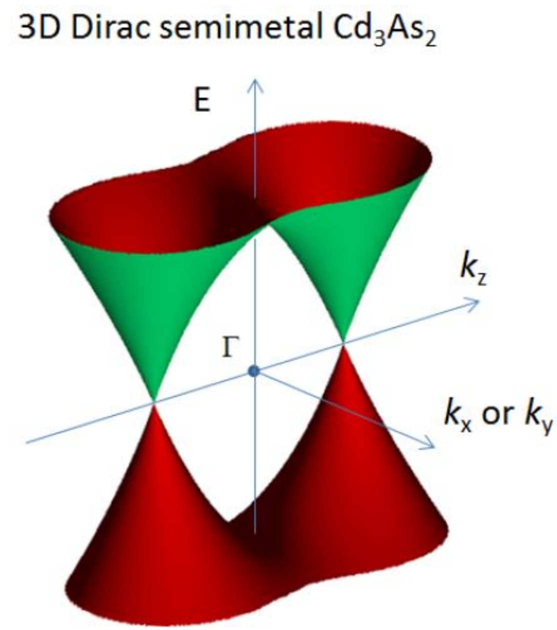
nature materials
LETTERS
PUBLISHED ONLINE: 25 MAY 2014 | DOI: 10.1038/NMAT3990

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:





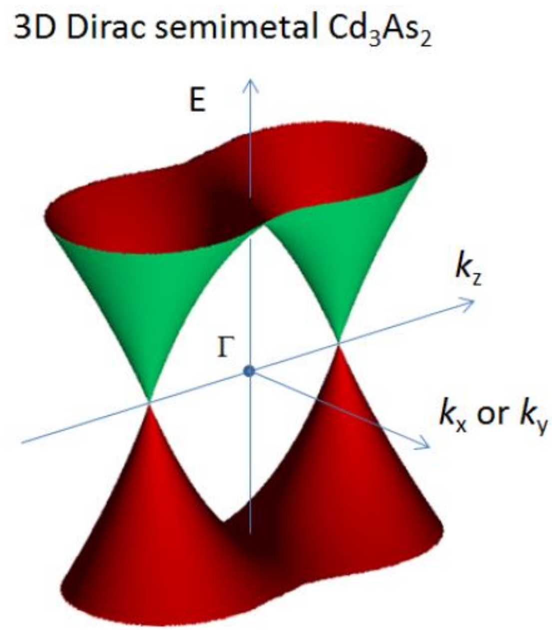
Z. K. Liu et al., Nature Mater. 13, 677 (2014)
S. Jeon et al., Nature Mater. 13, 851 (2014)
S. Borisenko et al., Phys. Rev. Lett. 113, 027603 (2014)
M. Neupane et al., Nature Comm. 5, 3786 (2014)

Dirac semimetal Cd_3As_2 = stable 3D analogue of graphene

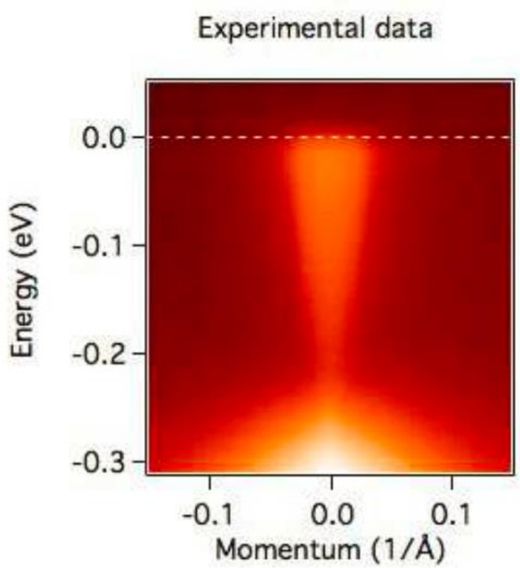
nature materials
LETTERS
PUBLISHED ONLINE: 25 MAY 2014 | DOI: 10.1038/NMAT3990

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★]



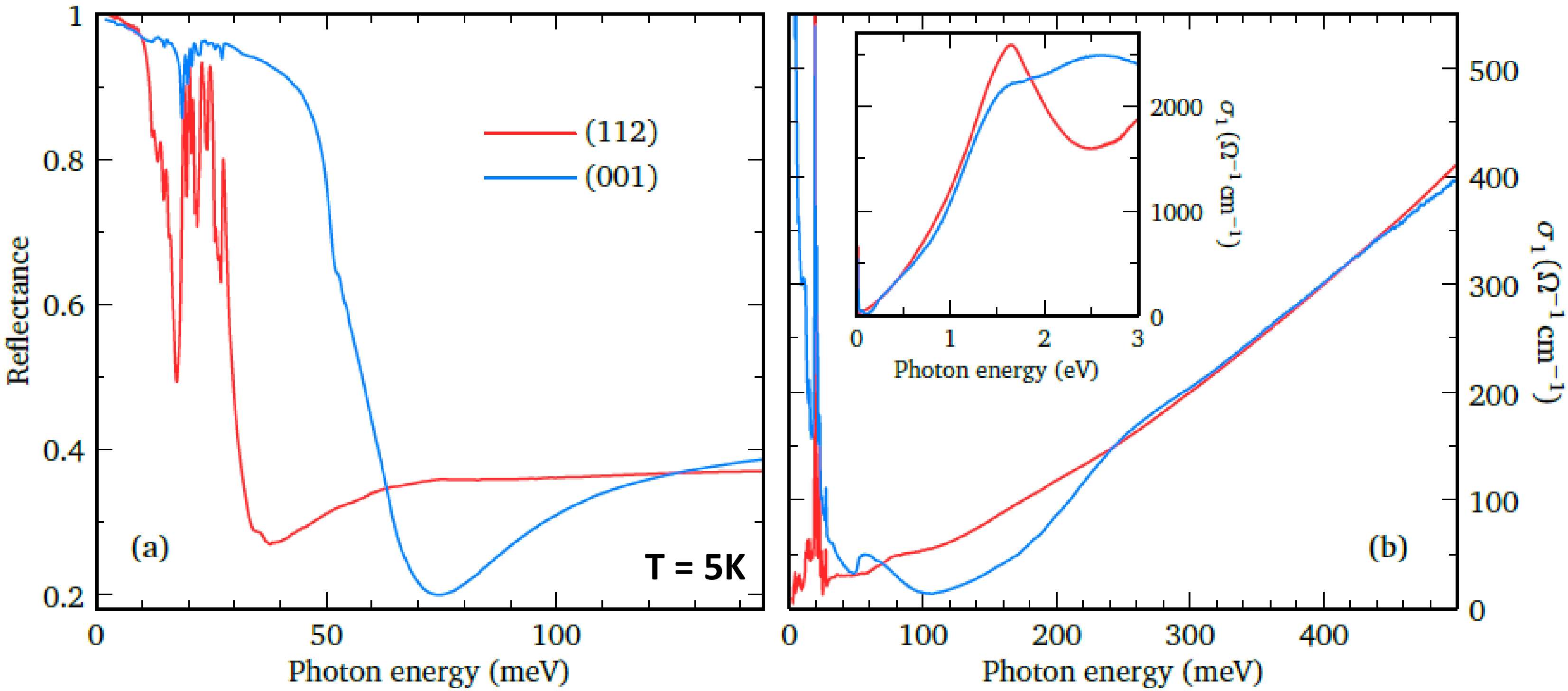
ARPES:



…but really not in line with other studies:

I. Rosenman, J. Phys. Chem. Solids 30, 1385 (1969)
M. J. Aubin, et al., Phys. Rev. B 23, 3602 (1981)
H. Schleijpen et al., Int. J. Infrared Milli. 5, 171 (1984)
S. Jeon et al., Nature Mater. 13, 851 (2014)

Cd_3As_2 – Infrared reflectance at B=0

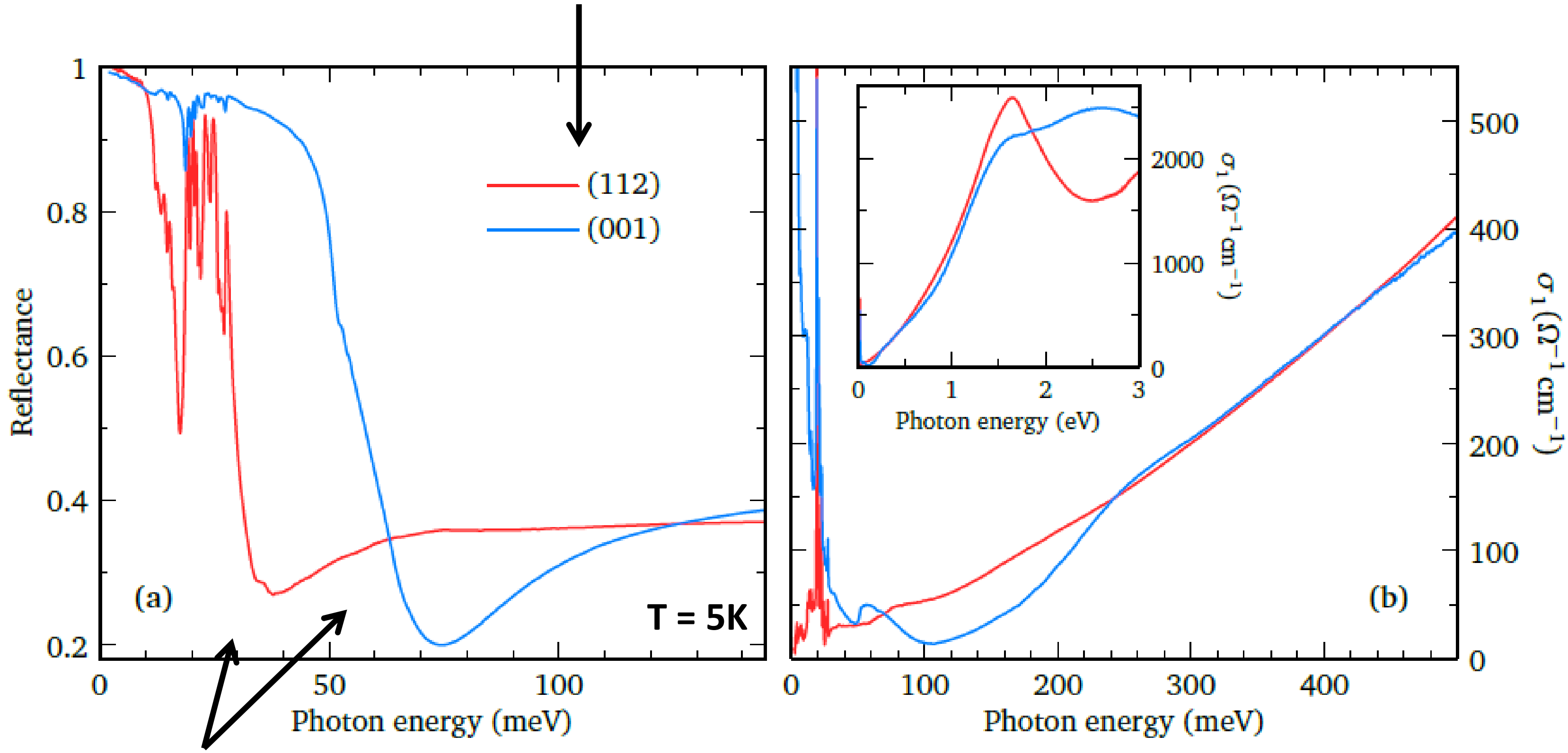


...in collaboration with C. C. Homes (Brookhaven)

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

Cd_3As_2 – Infrared reflectance at B=0

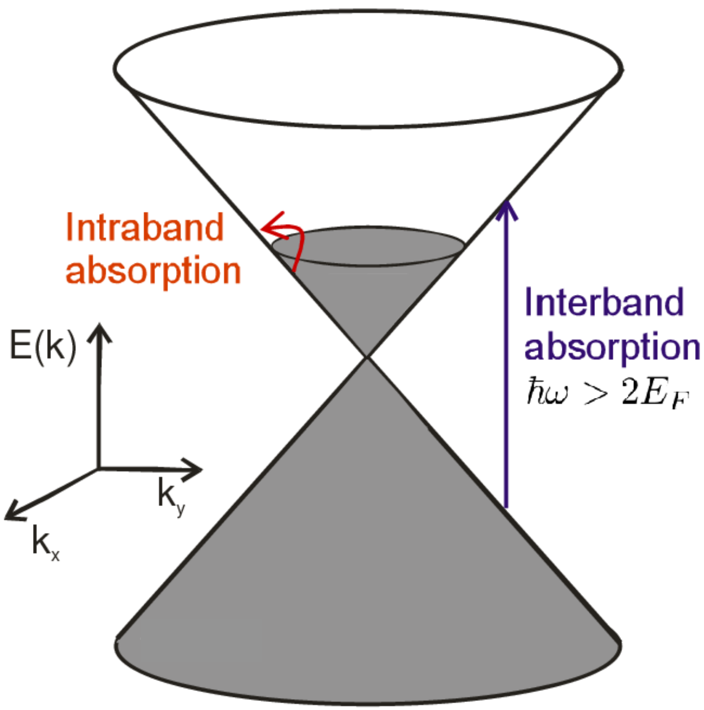
Two different crystallographic orientations of tetragonal Cd_3As_2

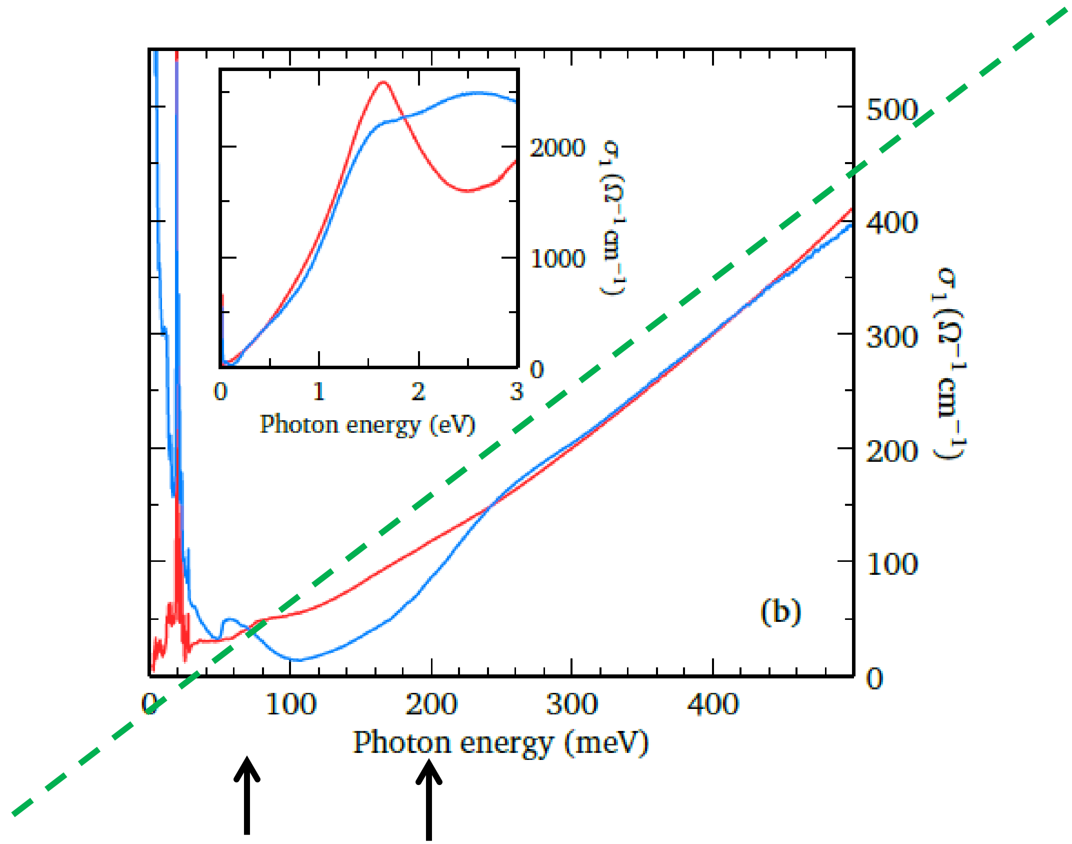


Plasma edges
(different carrier densities)

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

Cd_3As_2 – Infrared reflectance at B=0





Onsets of interband absorption (Pauli blocking)

see also T. Timusk et al., Phys. Rev. B 87, 235121 (2013)
M. Orlita et al., Nature Phys. 10, 233 (2014)

A. Akrap et al., submitted (2016)

Cd_3As_2 – Infrared reflectance at B=0

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

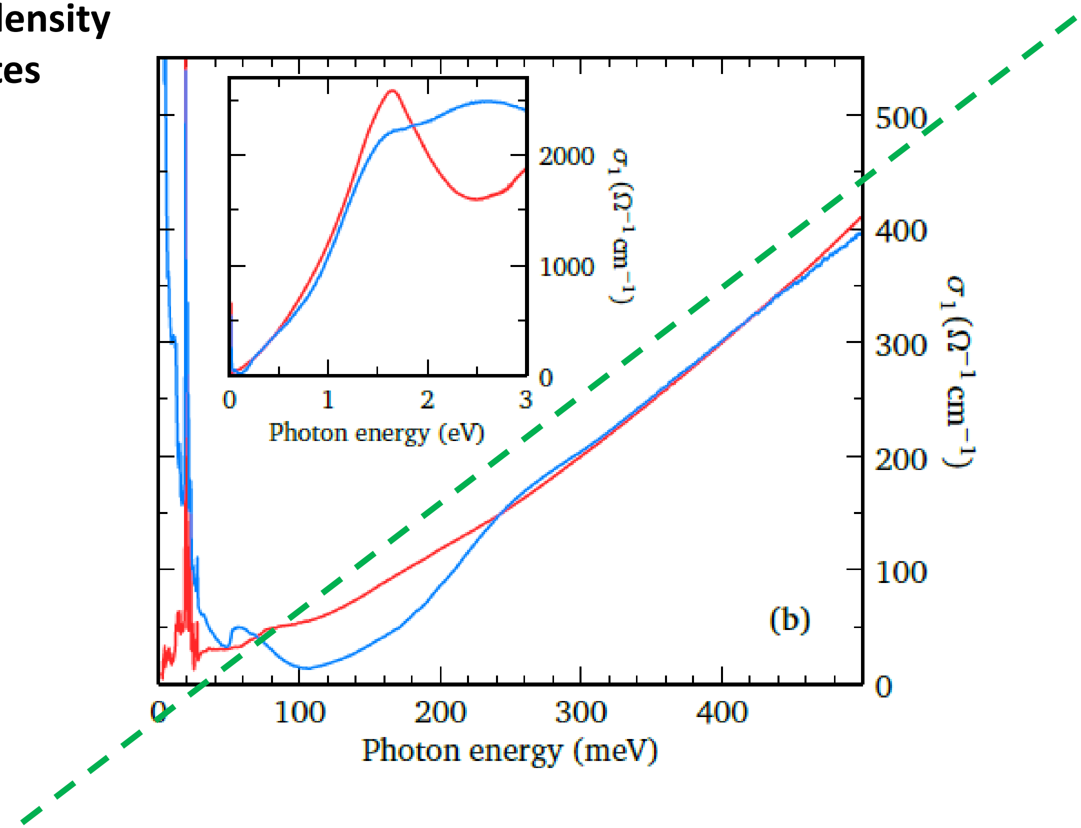
joint density of states

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

For conical bands in 3D:

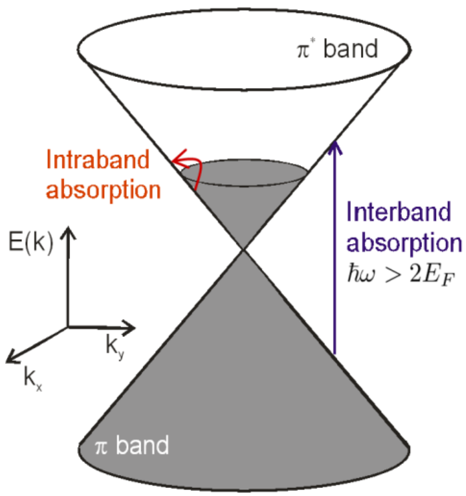
$$\mathcal{D}(\omega) \propto \omega^2$$

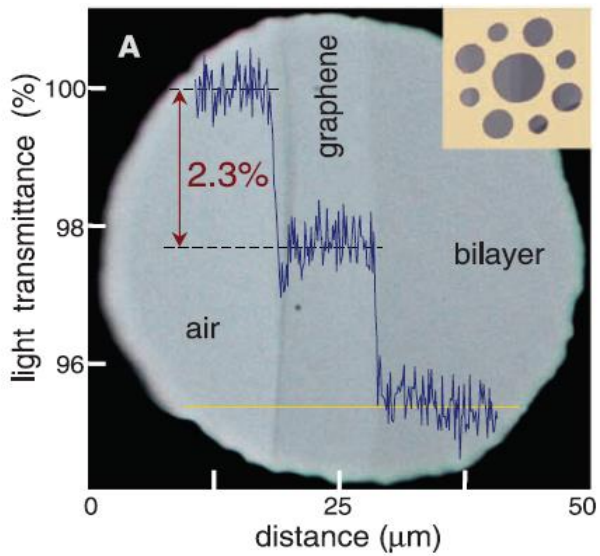
Absorption coefficient (optical conductivity) linear in photon frequency!

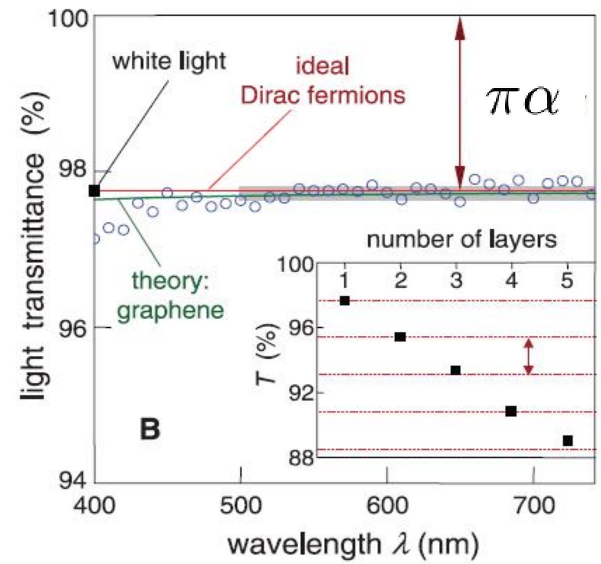


see also T. Timusk et al., Phys. Rev. B 87, 235121 (2013)
M. Orlita et al., Nature Phys. 10, 233 (2014)

Absorption of light in graphene





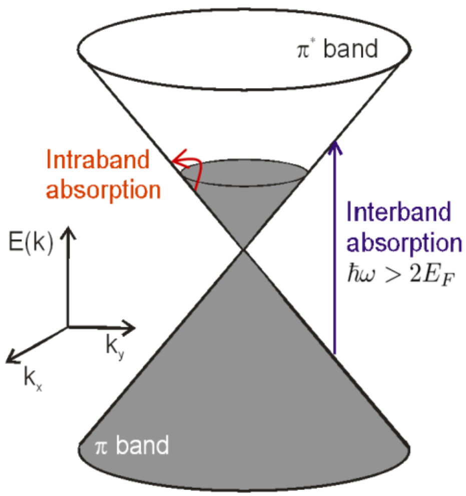


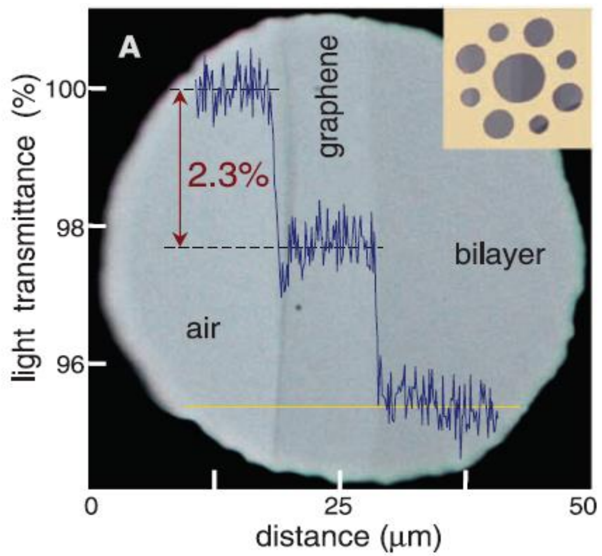
“Flat” absorption of light (2.3%) defined only by the fine structure constant:

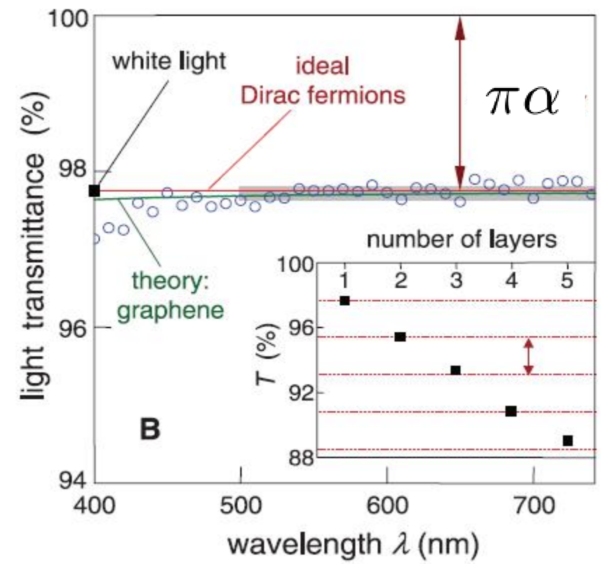
$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \doteq \frac{1}{137}$$

R. R. Nair et al., Science 320, 1308 (2008)
A. B. Kuzmenko et al., Phys. Rev. Lett. 100, 117401 (2008)

Absorption of light in graphene







Absorption of light in solids (Fermi's golden rule):

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

For conical bands in 2D:

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

Dispersionless (interband) absorption of light…

Cd_3As_2 – Optical response at B=0

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

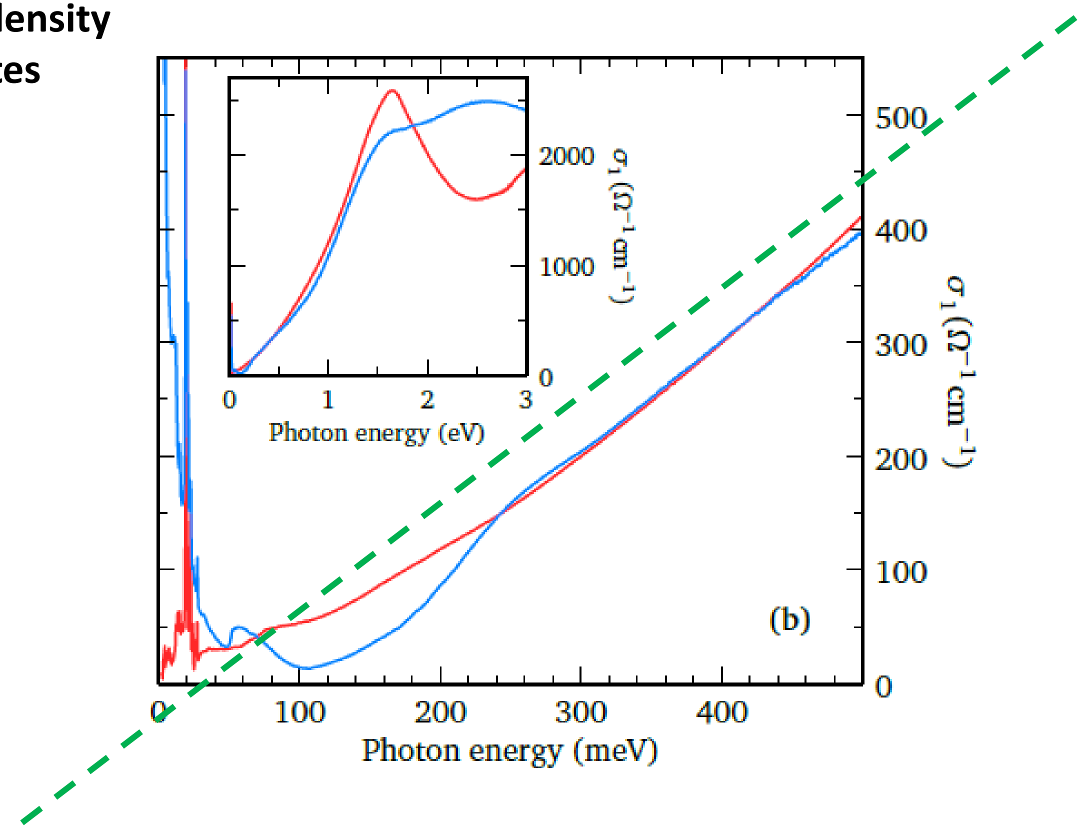
joint density of states

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

For conical bands in 3D:

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

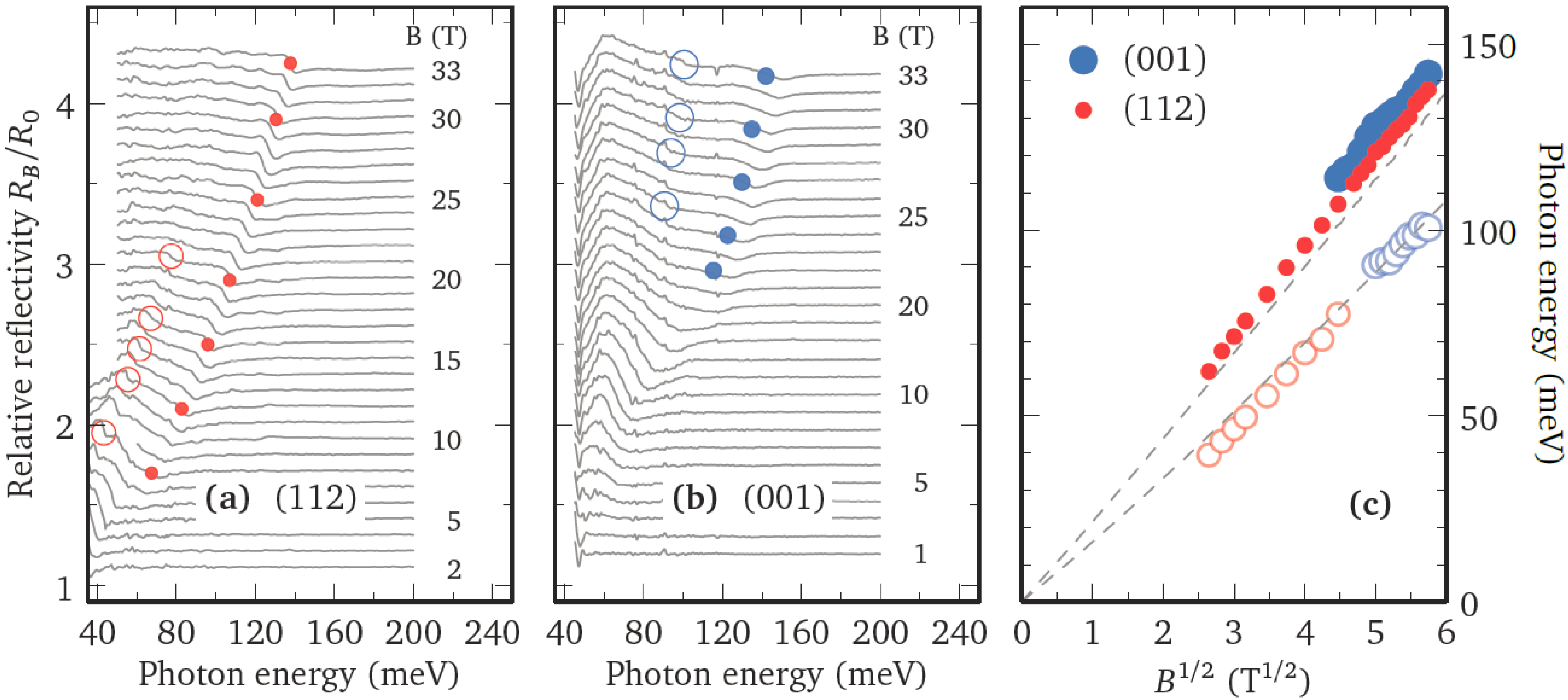
Absorption coefficient linear in photon frequency!



see also T. Timusk et al., Phys. Rev. B 87, 235121 (2013)
M. Orlita et al., Nature Phys. 10, 233 (2014)

Cd_3As_2 – High-field magneto-reflectivity

T = 5K

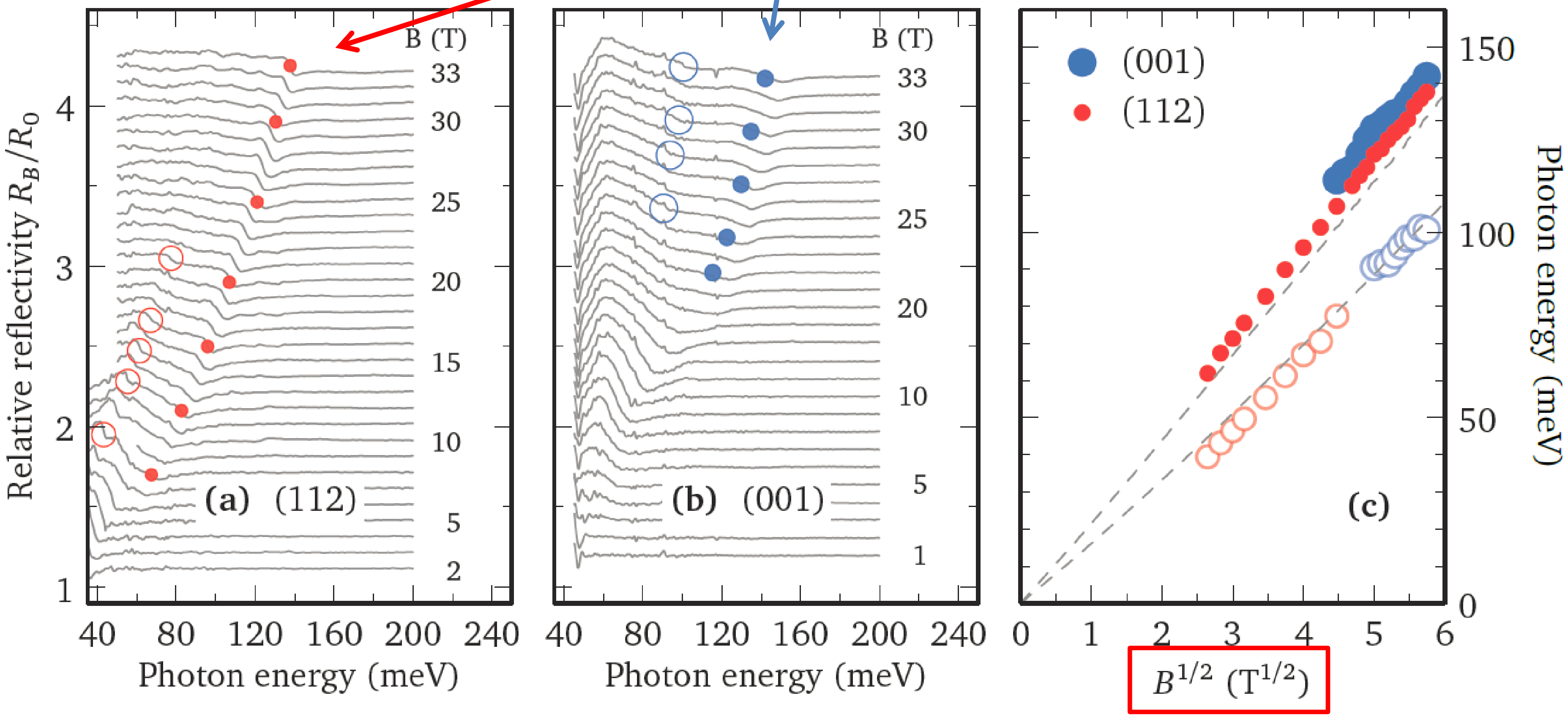


A. Akrap et al., arXiv:1604.00038 (2016)

Cd_3As_2 – High-field magneto-reflectivity

Cyclotron resonance (CR) in the quantum limit

T = 5K

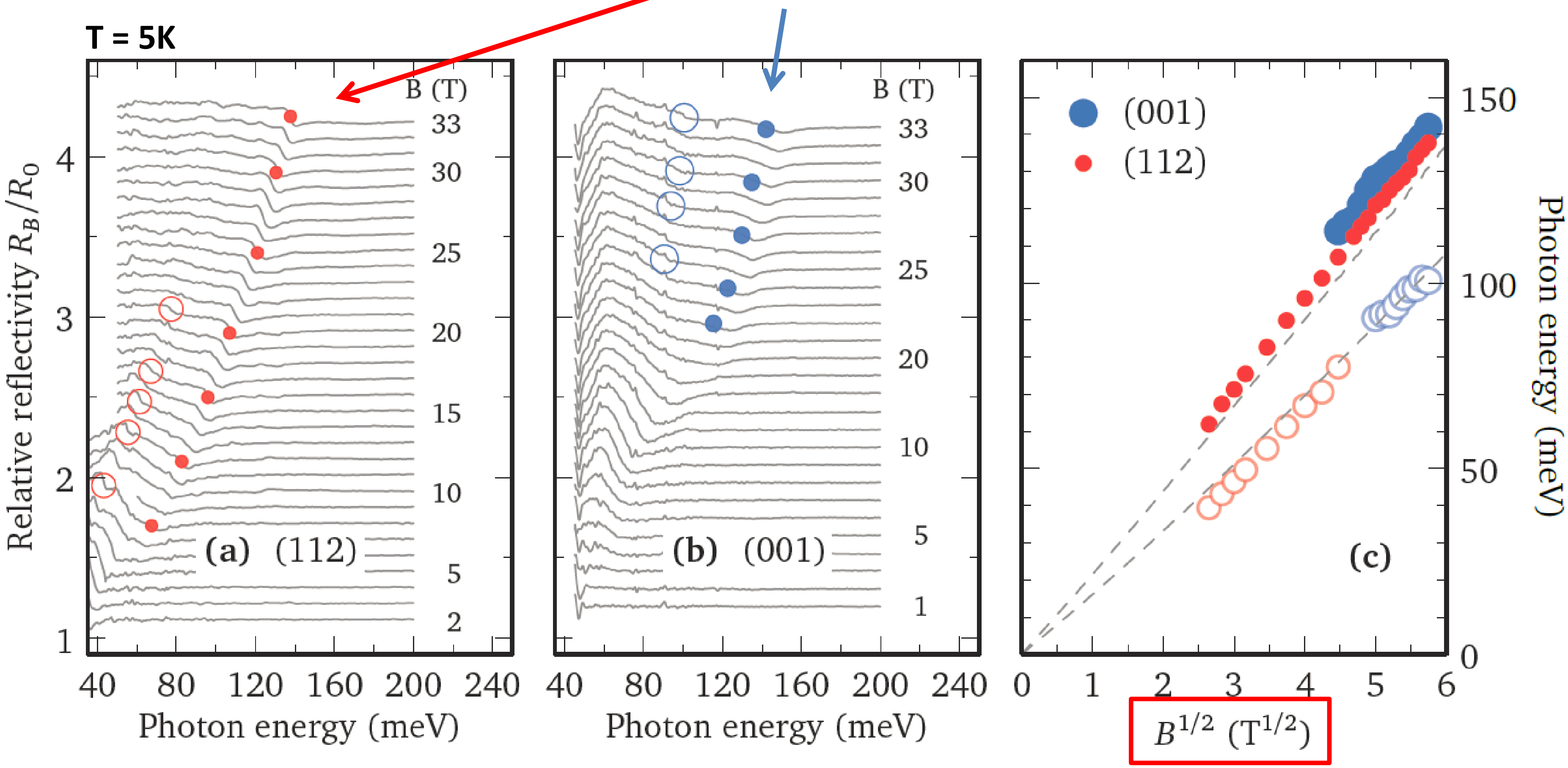


A. Akrap et al., arXiv:1604.00038 (2016)

Cd_3As_2 – High-field magneto-reflectivity

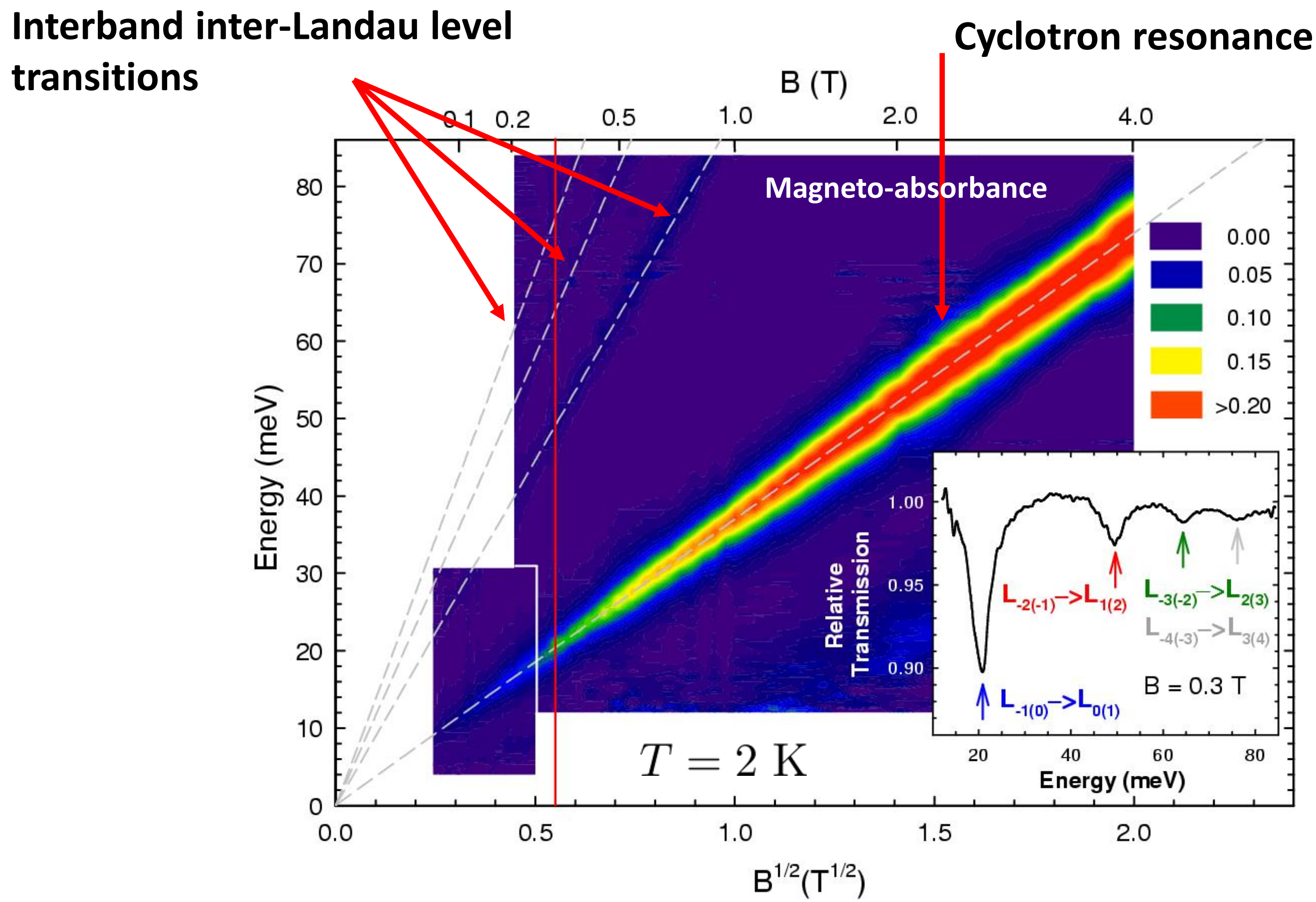
Cyclotron resonance (CR) in the quantum limit

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

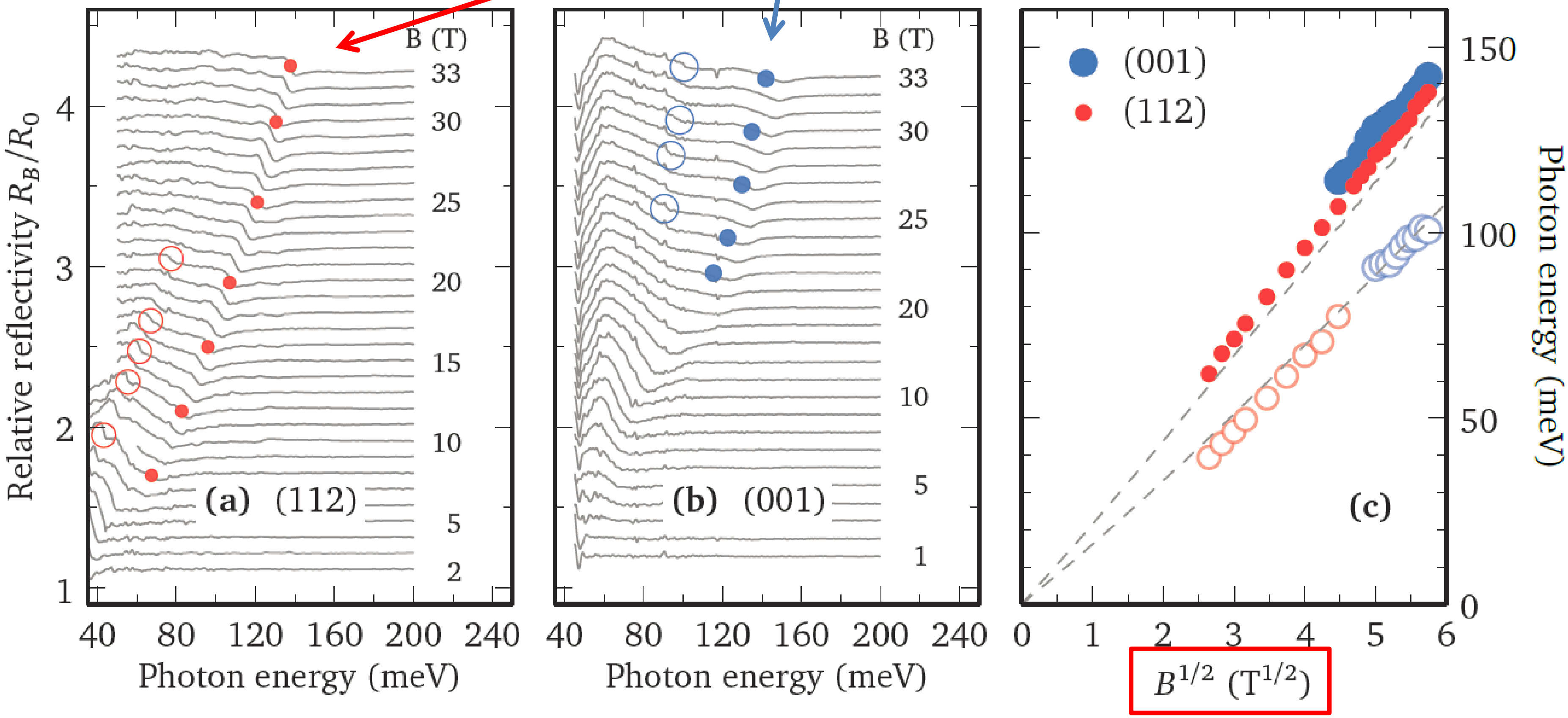
Selection rules: $$|n| \to |n| \pm 1$$

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

Cd_3As_2 – High-field magneto-reflectivity

Cyclotron resonance (CR) in the quantum limit

T = 5K

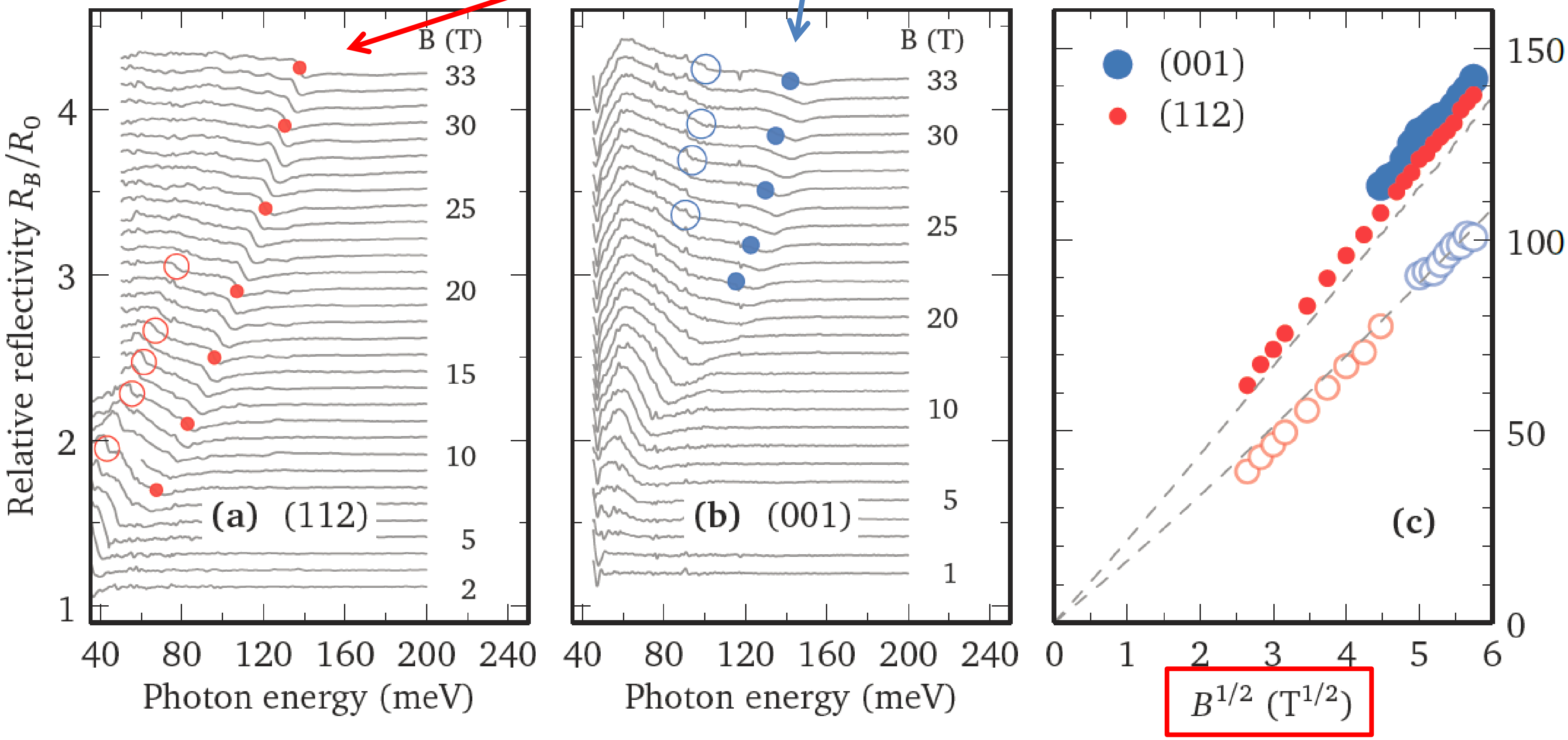


Magneto-optical response linear in $\sqrt{B}$ = typical signature of massless particles

Cd_3As_2 – High-field magneto-reflectivity

Cyclotron resonance (CR) in the quantum limit

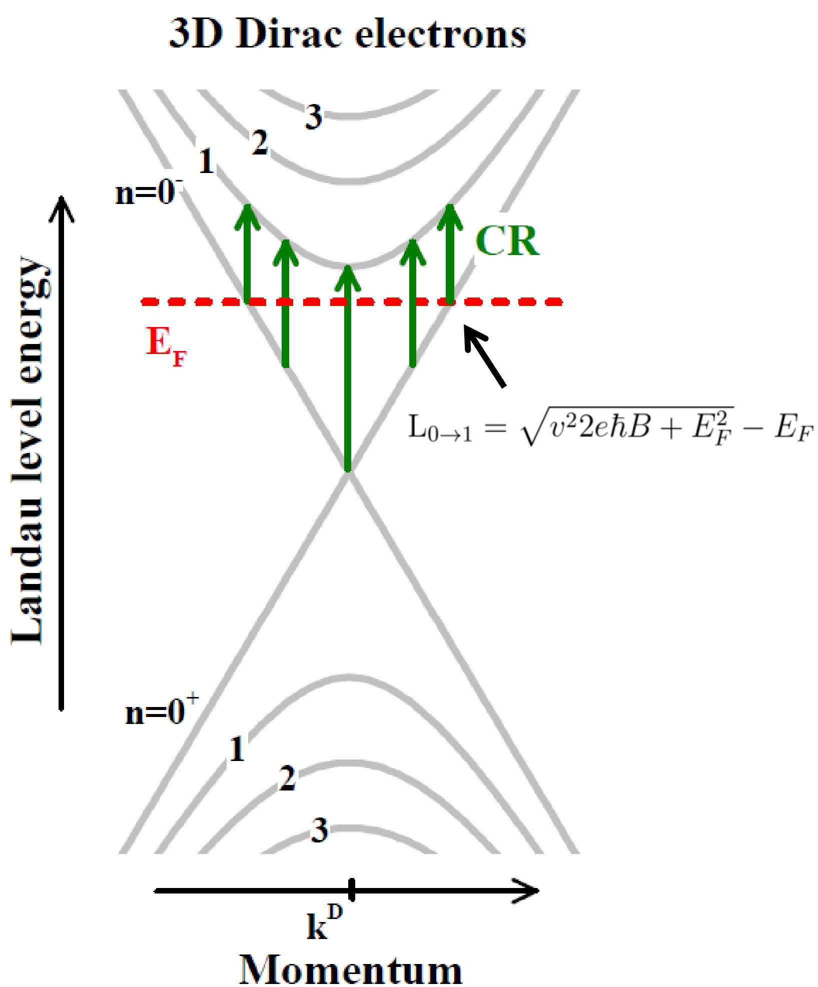
T = 5K

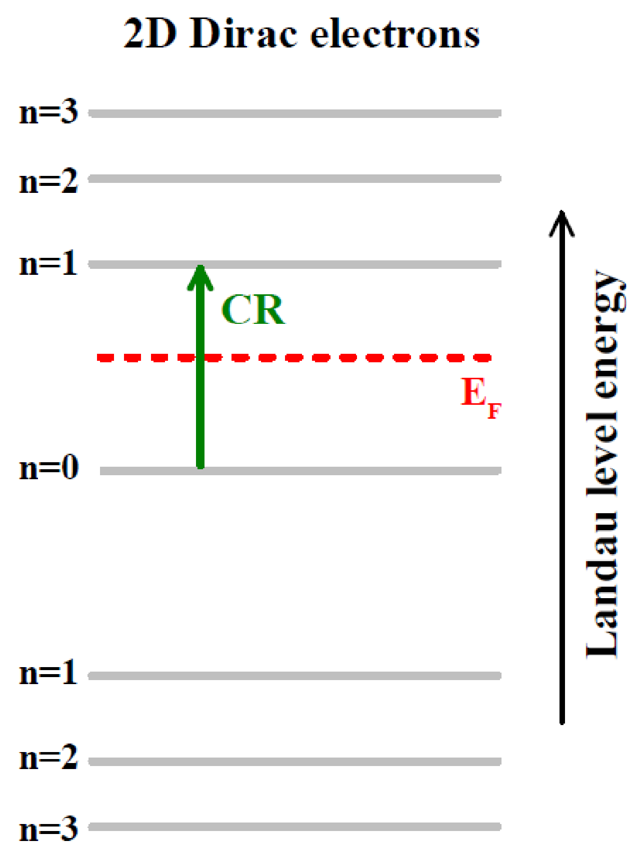


Magneto-optical response linear in $\sqrt{B}$ = typical signature of massless particles

....massless yes, but not 3D Dirac

Dirac electrons – Landau level spectrum



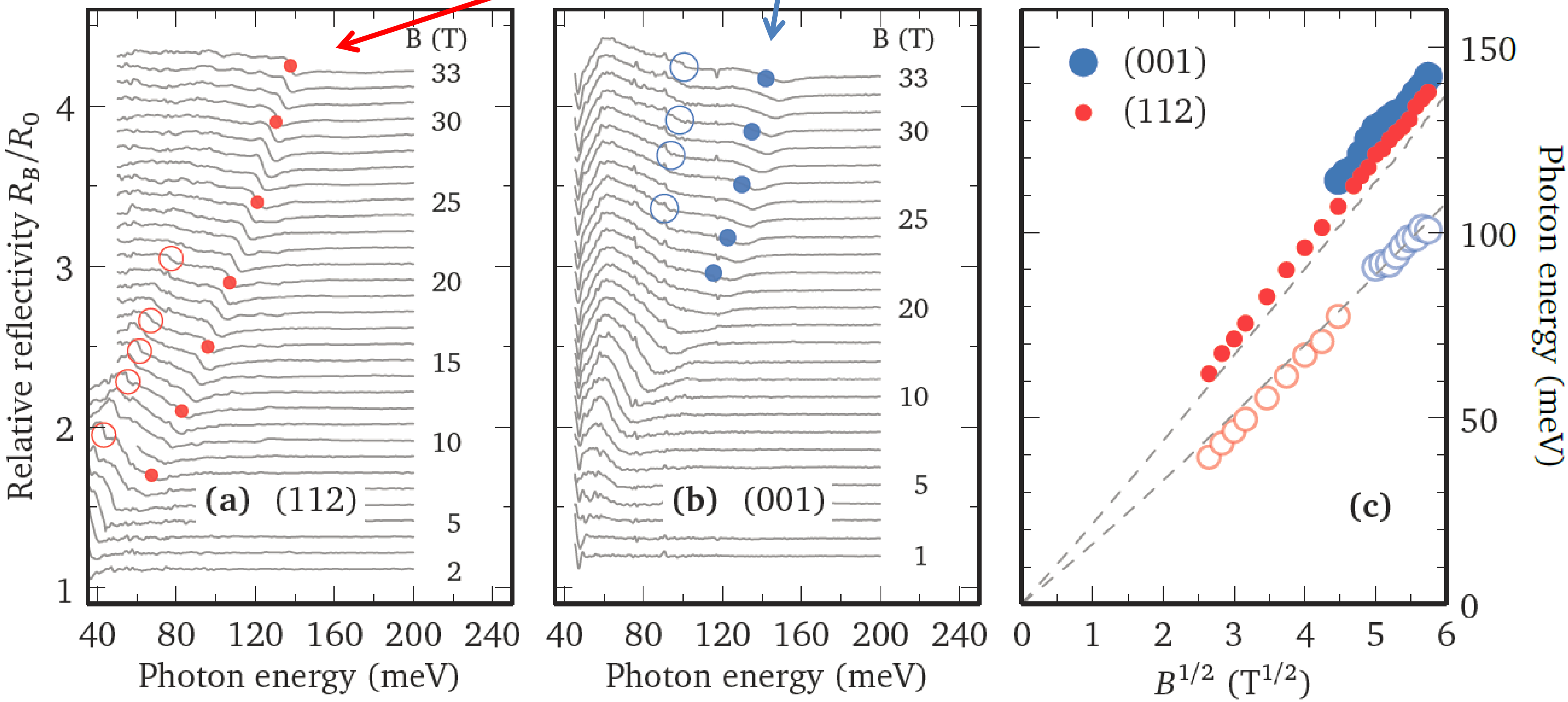


$$E_n = \pm v\sqrt{2e\hbar Bn + \hbar^2 k^2}$$

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

Cd_3As_2 – High-field magneto-reflectivity

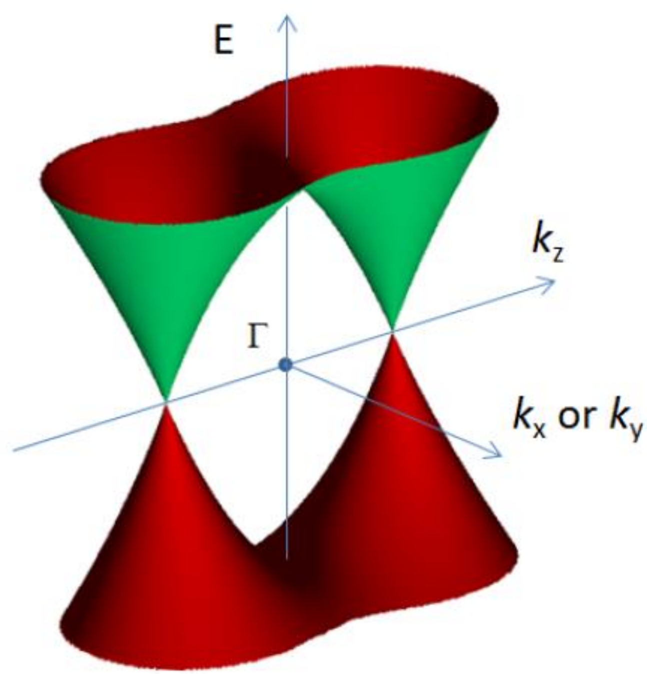
Cyclotron resonance (CR) in the quantum limit



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

....massless yes, but not 3D Dirac

Cd_3As_2 – Electronic band structure



What kind of massless carriers do we see?

How the band structure looks like?

Is Cd_3As_2 indeed a 3D Dirac semimetal?

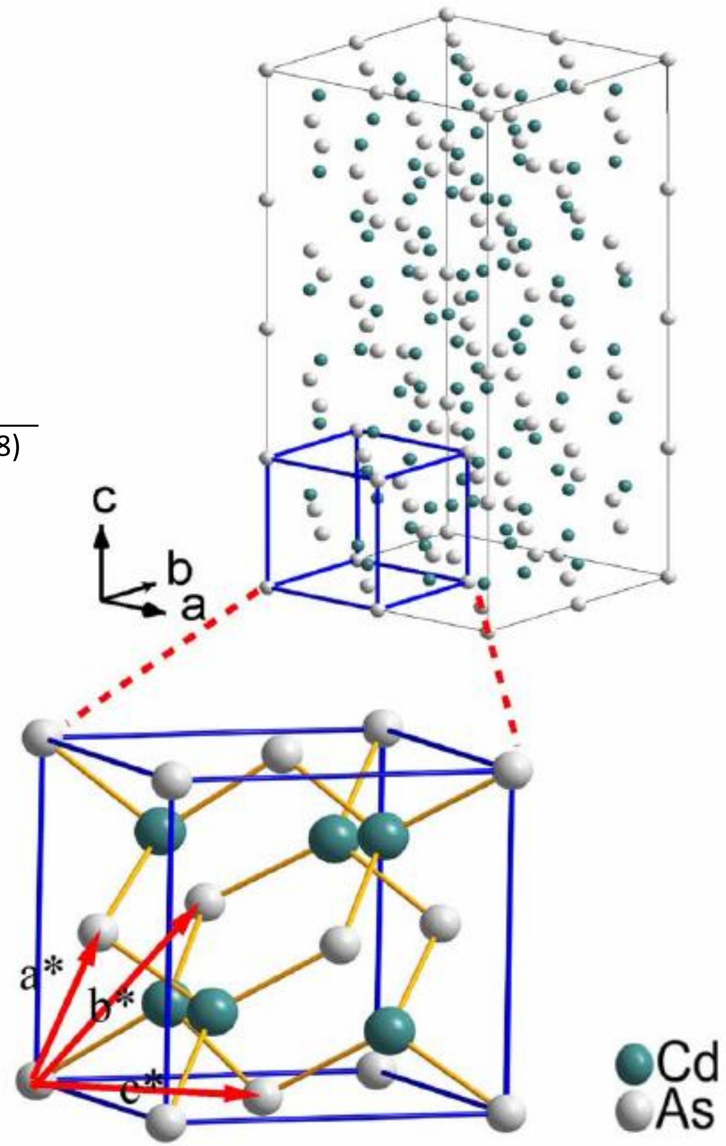
Cd_3As_2 – Crystallographic structure

Tetragonal lattice with a large unit cell (~160 atoms)

G. Steigmann and J. Goodyear, Acta Crystallogr. B 24, 1062 (1968)
M. N. Ali et al. Inorganic Chemistry 53, 4062 (2014)

Ab initio calculations difficult for such a huge cell…

Z. Wang et al. Phys. Rev. B 88, 125427 (2013)



H. Yi et al., Sci. Rep. 4, 6106 (2014)

Cd_3As_2 – Crystallographic structure

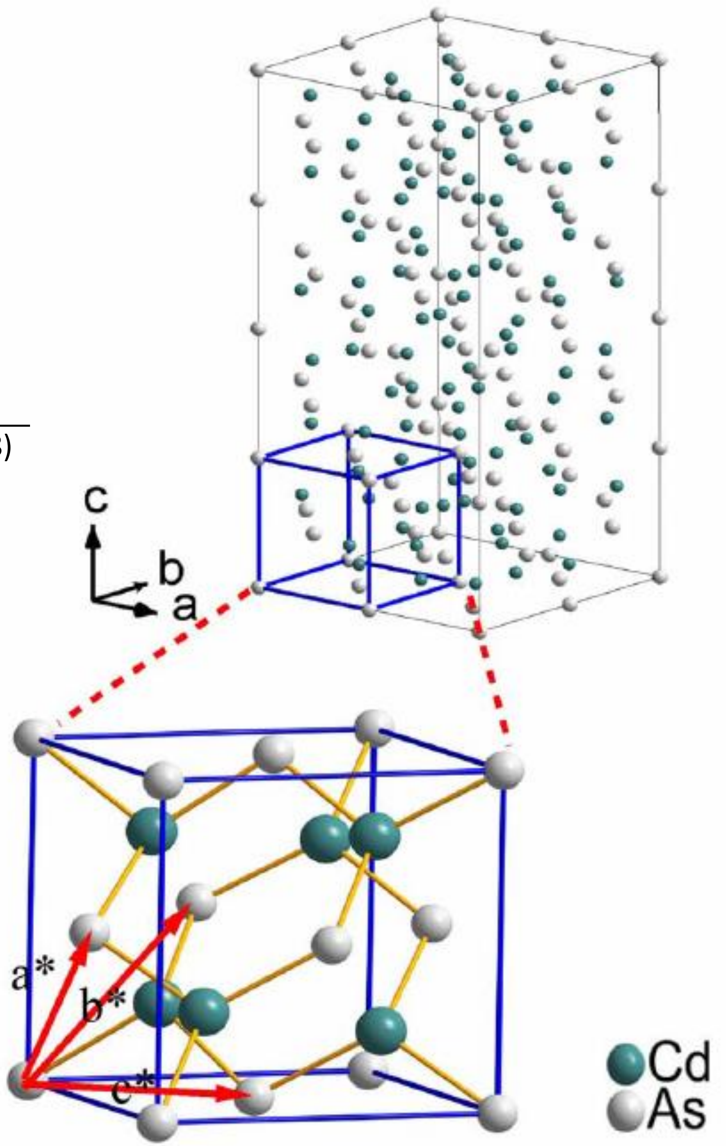
Tetragonal lattice with a large unit cell (~160 atoms)

G. Steigmann and J. Goodyear, Acta Crystallogr. B 24, 1062 (1968)
M. N. Ali et al. Inorganic Chemistry 53, 4062 (2014)

Ab initio calculations difficult for such a huge cell…

Z. Wang et al. Phys. Rev. B 88, 125427 (2013)

Composed from distorted cubic sub-cells
= "almost" zinc-blende lattice



H. Yi et al., Sci. Rep. 4, 6106 (2014)

Bodnar 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

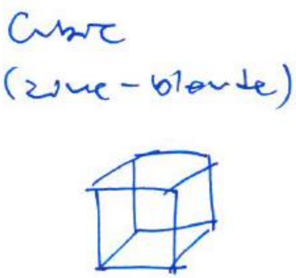
Department of Solid State Physics, Polish Academy of Sciences, Zabrze, Poland

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

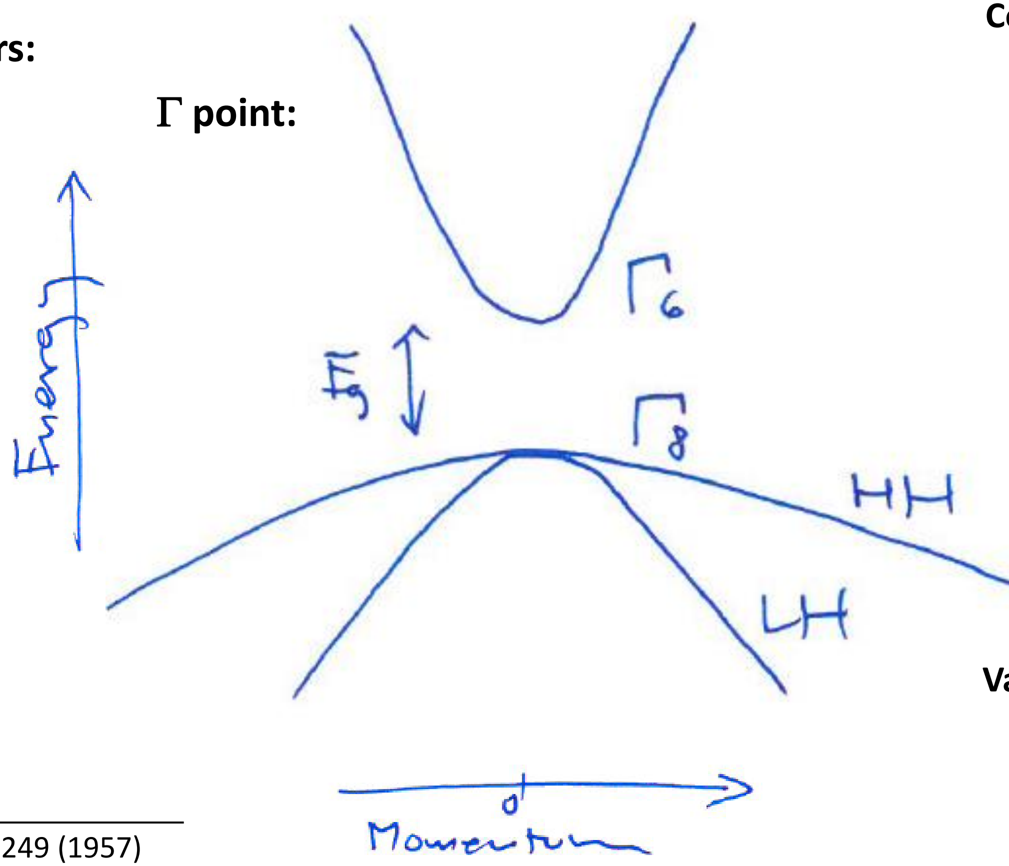
Bodnar model of electronic bands in Cd_3As_2

Standard Kane model for zinc-blende semiconductors:



Γ point:

Conduction band



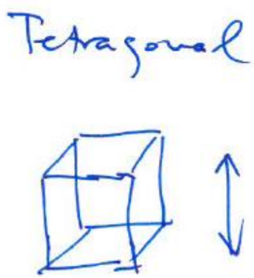
Valence bands

E. O. Kane, J. Phys. Chem. Solids 1, 249 (1957)

Valid for, e.g., GaAs, InAs, InSb, CdTe….

Bodnar model of electronic bands in Cd_3As_2

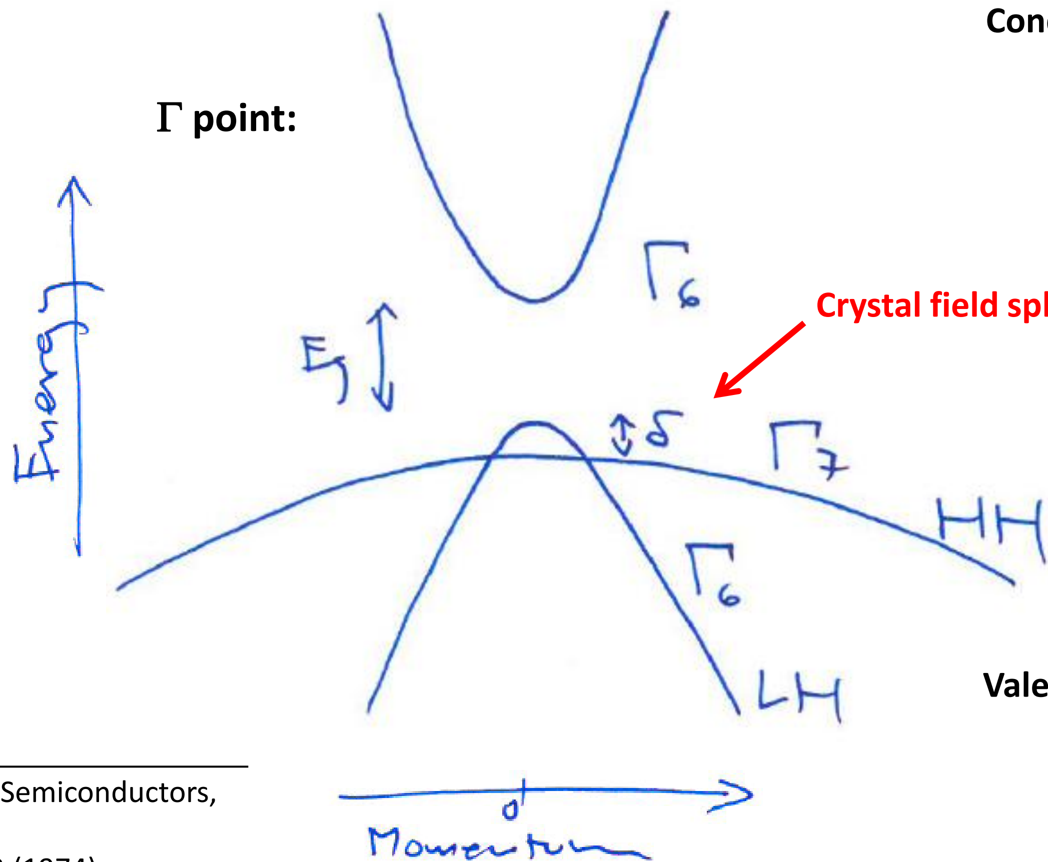
Kane model with a weak tetragonal distortion:



Γ point:

Conduction band

Crystal field splitting



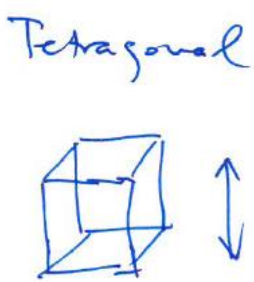
Valence bands

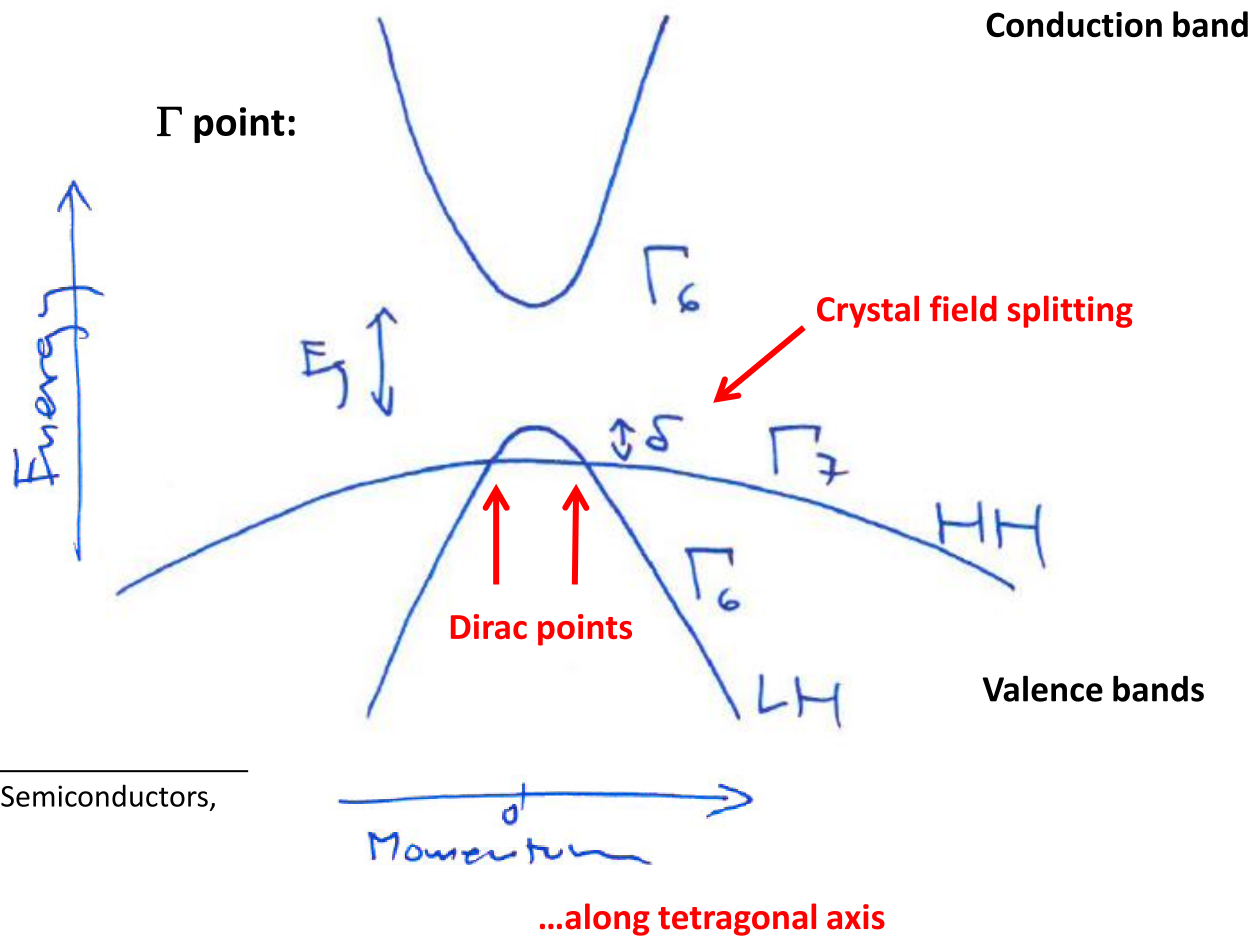
…along tetragonal axis

J. Bodnar, in Proc. III Conf. Narrow-Gap Semiconductors, Warsaw,(Elsevier, 1977) p. 311
see also H. Kildal, Phys. Rev. B 10, 5082 (1974).

Bodnar model of electronic bands in Cd_3As_2

Kane model with a weak tetragonal distortion:

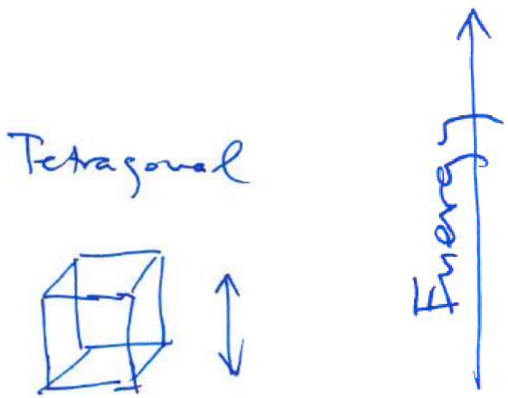




J. Bodnar, in Proc. III Conf. Narrow-Gap Semiconductors, Warsaw,(Elsevier, 1977) p. 311

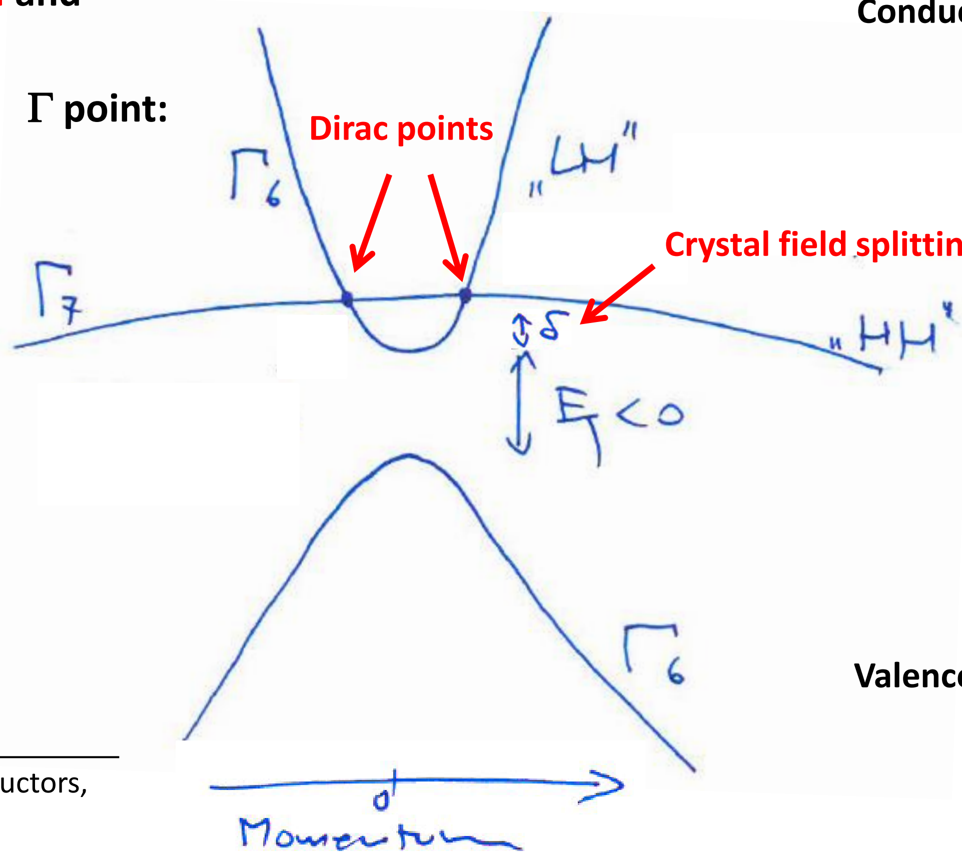
Bodnar model of electronic bands in Cd_3As_2

Kane model with a band inversion and a weak tetragonal distortion:



Γ point:

Conduction band



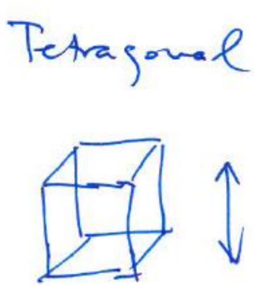
Valence bands

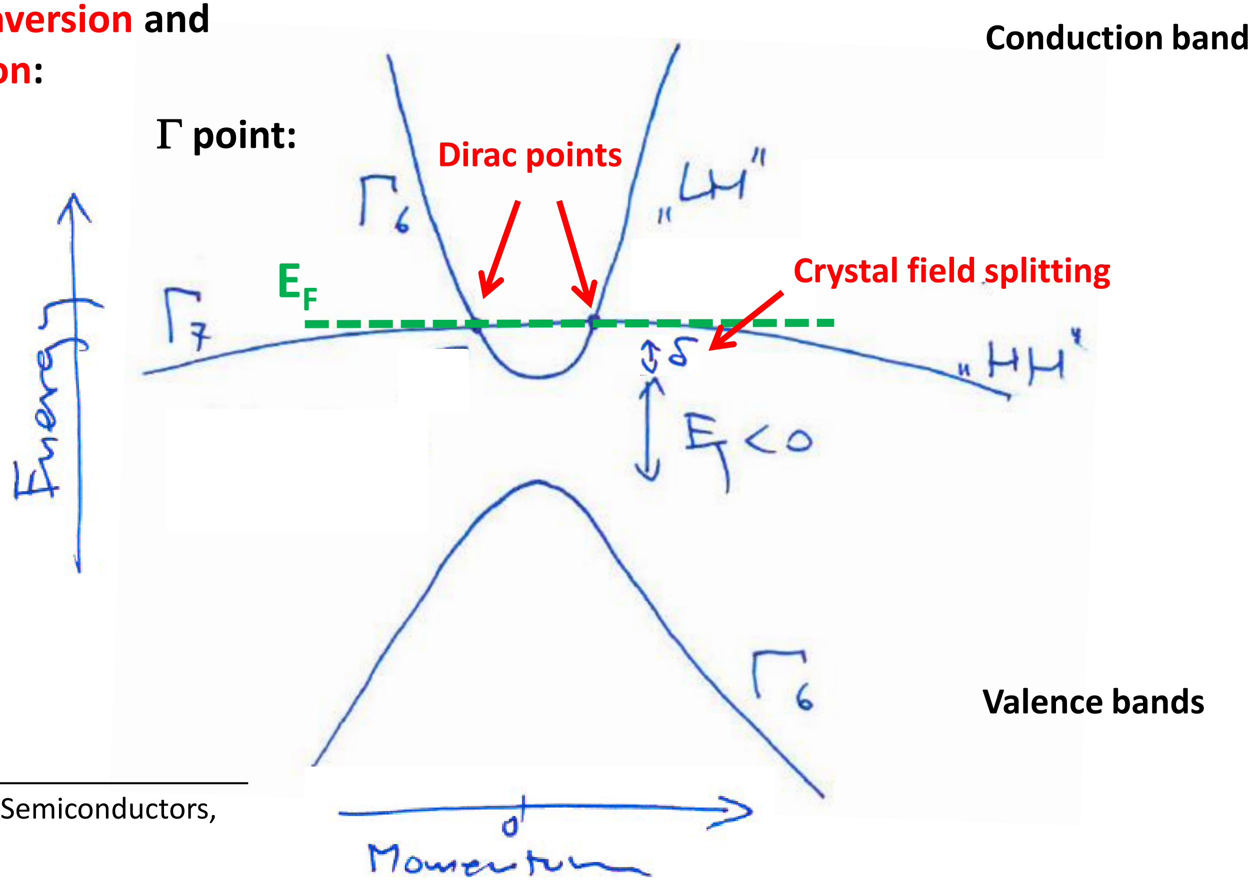
...along tetragonal axis

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

Bodnar model of electronic bands in Cd_3As_2

Kane model with a band inversion and a weak tetragonal distortion:

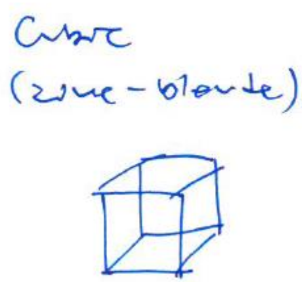




J. Bodnar, in Proc. III Conf. Narrow-Gap Semiconductors, Warsaw,(Elsevier, 1977) p. 311

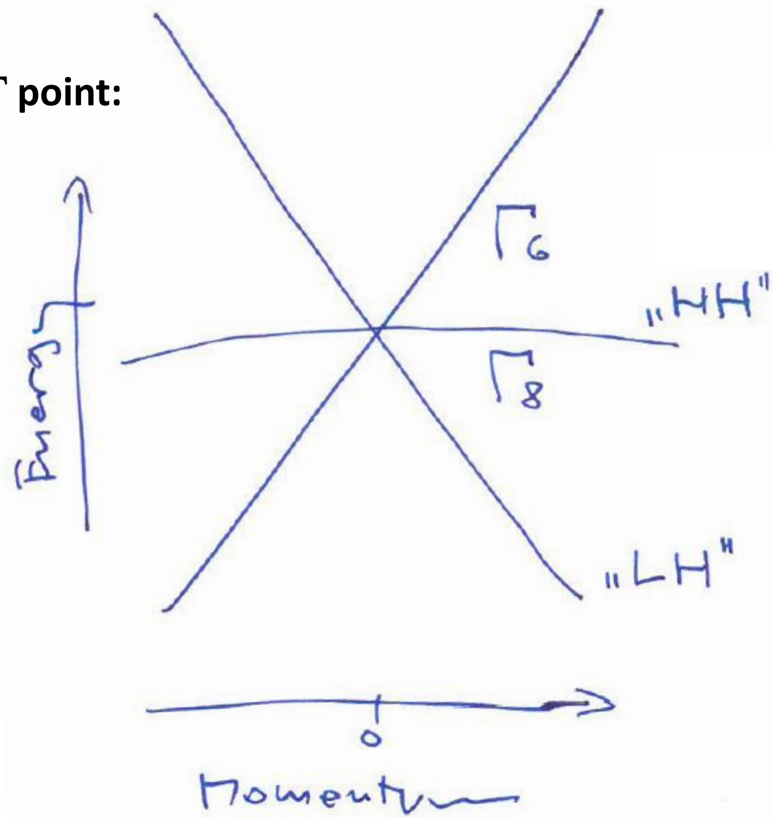
Bodnar model of electronic bands in Cd_3As_2

Standard Kane model
with a vanishing band gap:



Γ point:

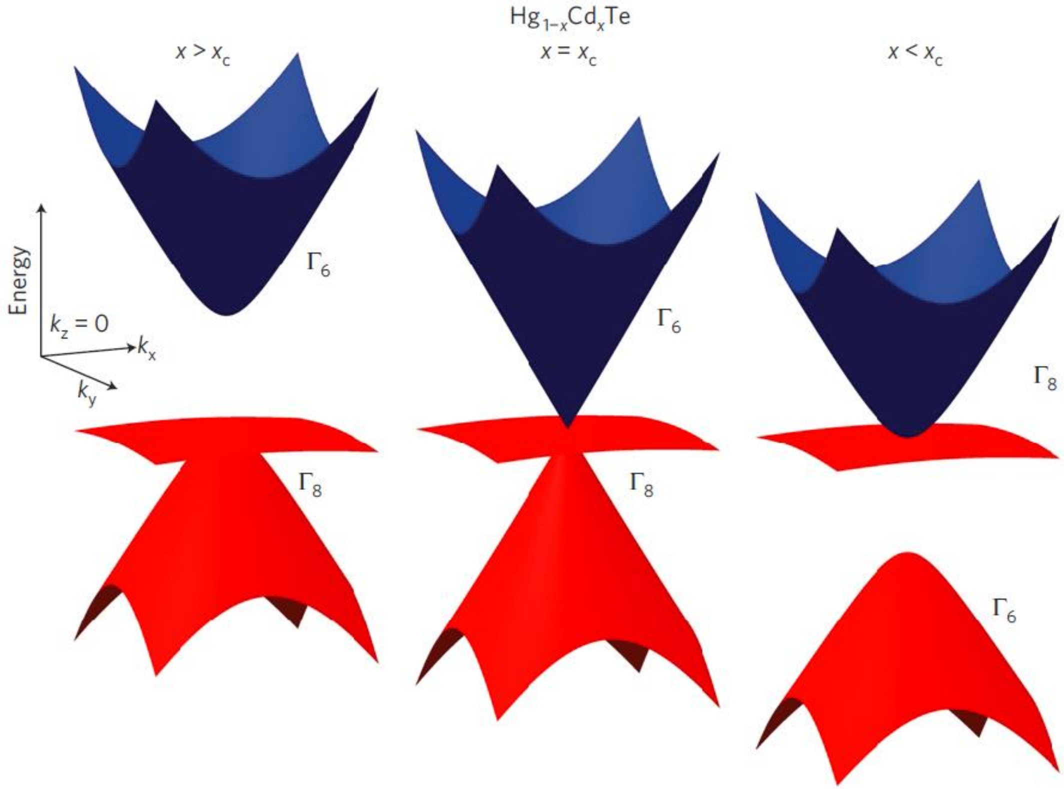
Conduction band



Valence bands

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)

Massless Kane electrons in gapless HgCdTe

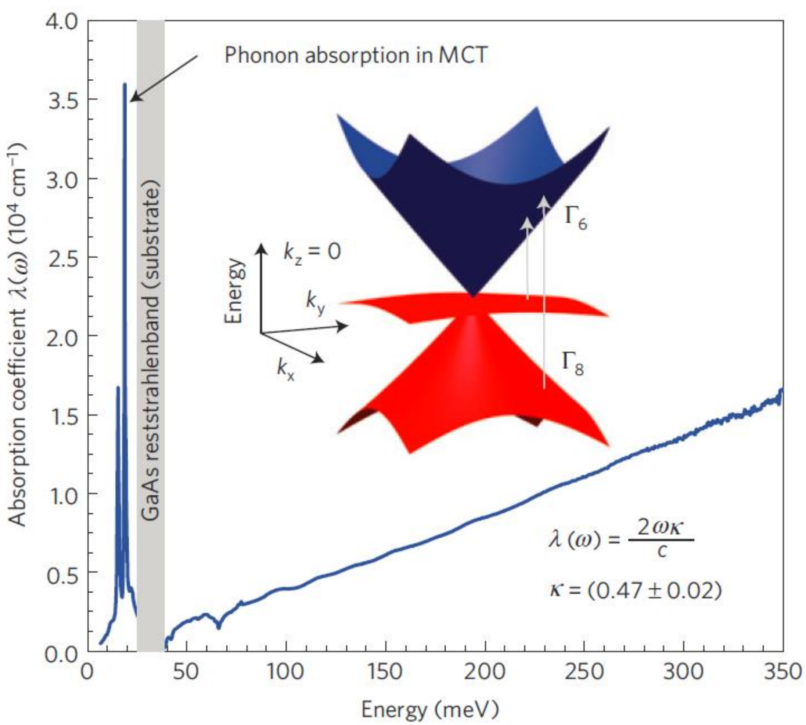


E. O. Kane, J. Phys. Chem. Solids 1, 249 (1957)
P. Kacman and W. Zawadzki, phys. stat. sol. (b) 47, 629 (1971)
M. Orlita et al., Nature Phys. 10, 233 (2914)

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

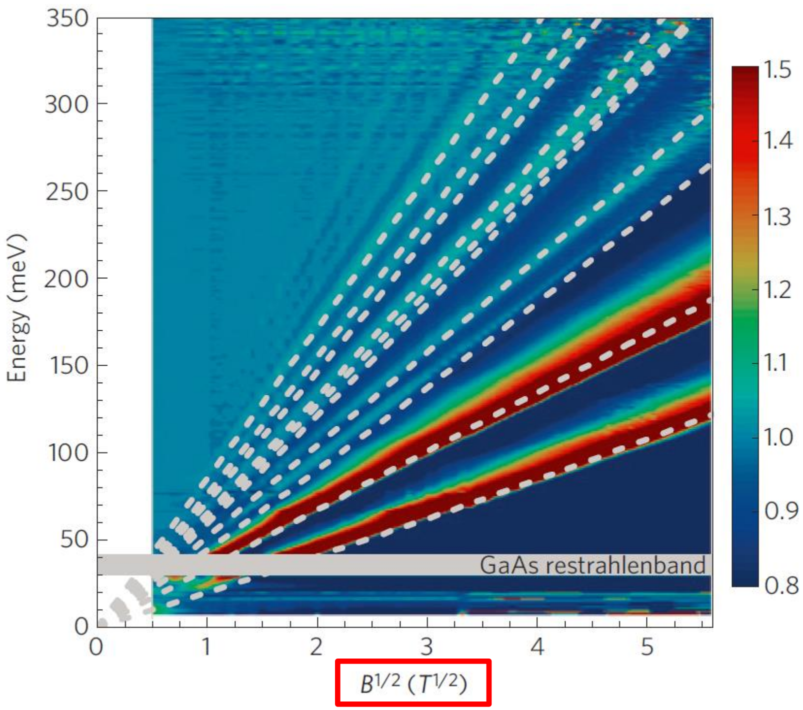
Massless Kane electrons in gapless HgCdTe

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

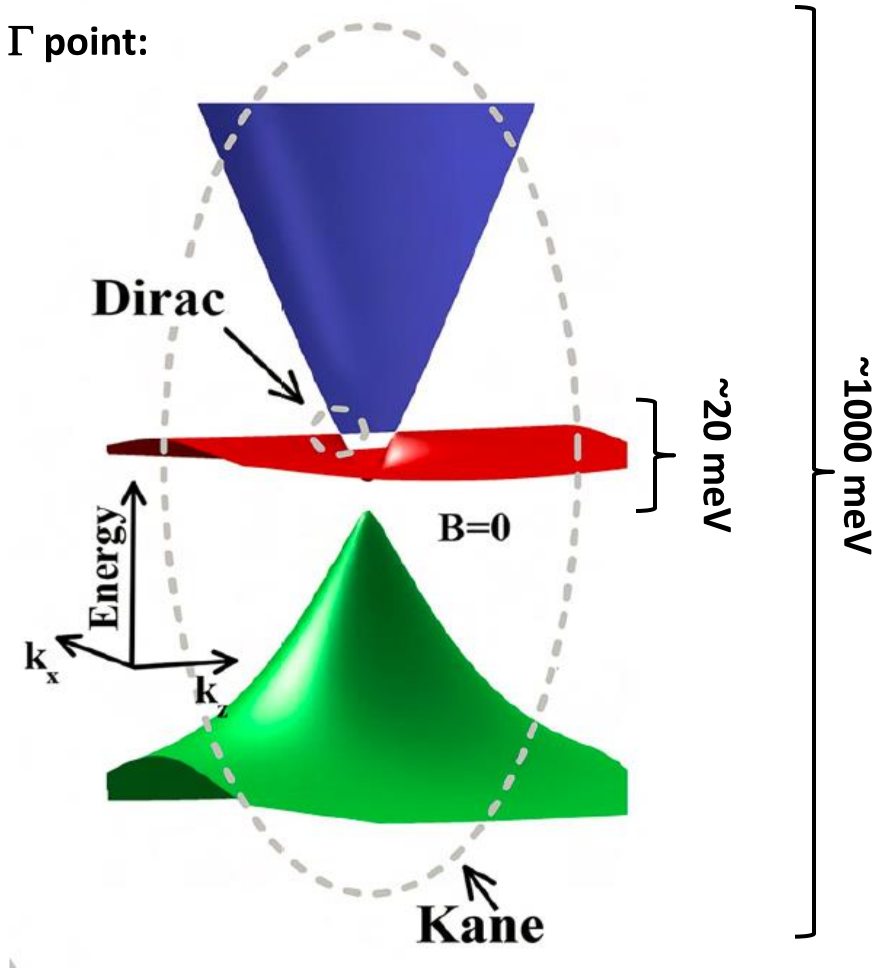
…due crossing of heavy and light hole band in a tetragonally distorted zinc-blende semiconductor

A single cone of massless Kane electrons, no symmetry protection

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

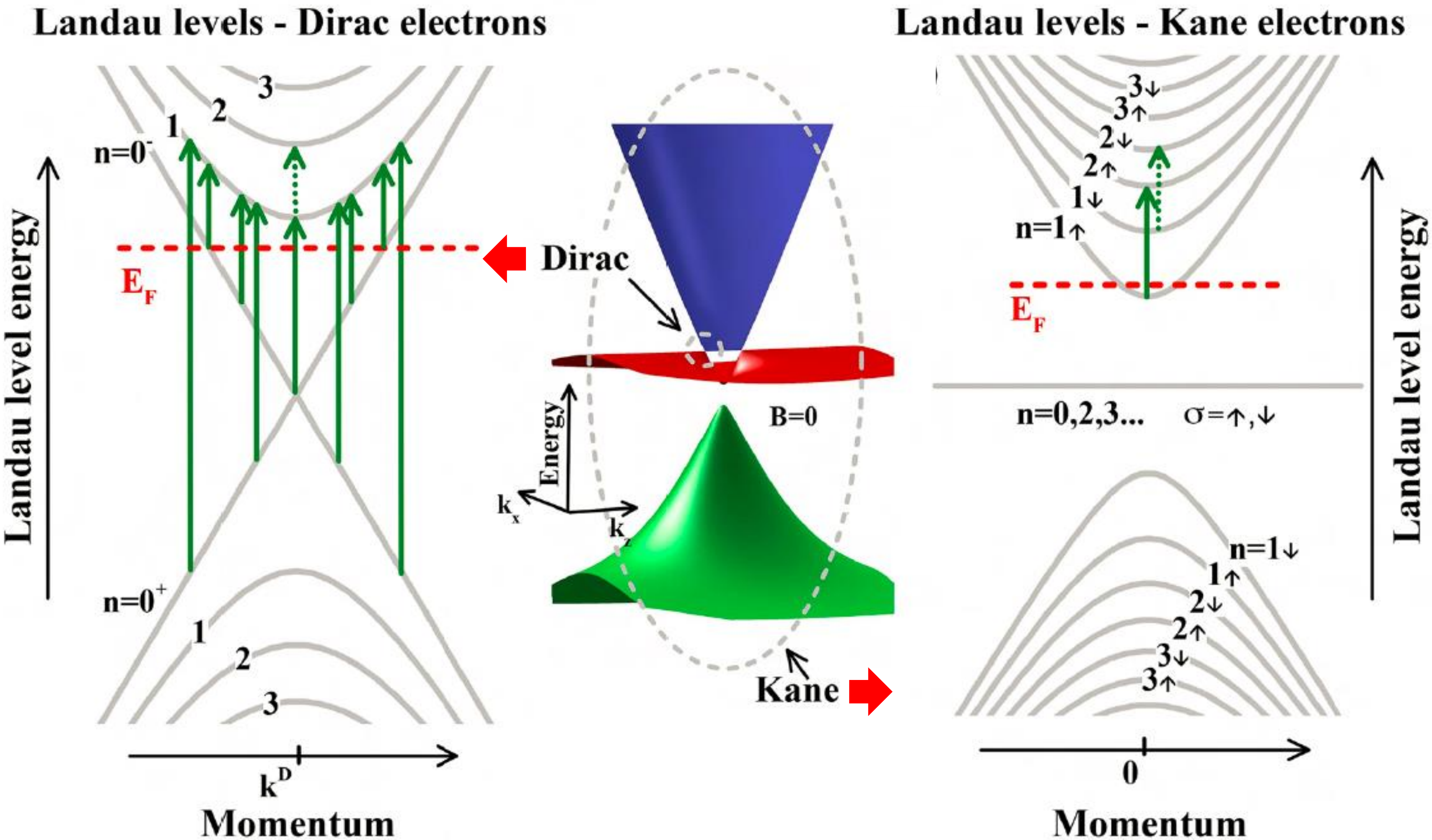
J. Bodnar, in Proc. III Conf. Narrow-Gap Semiconductors, Warsaw,(Elsevier, 1977) p. 311

Γ point:



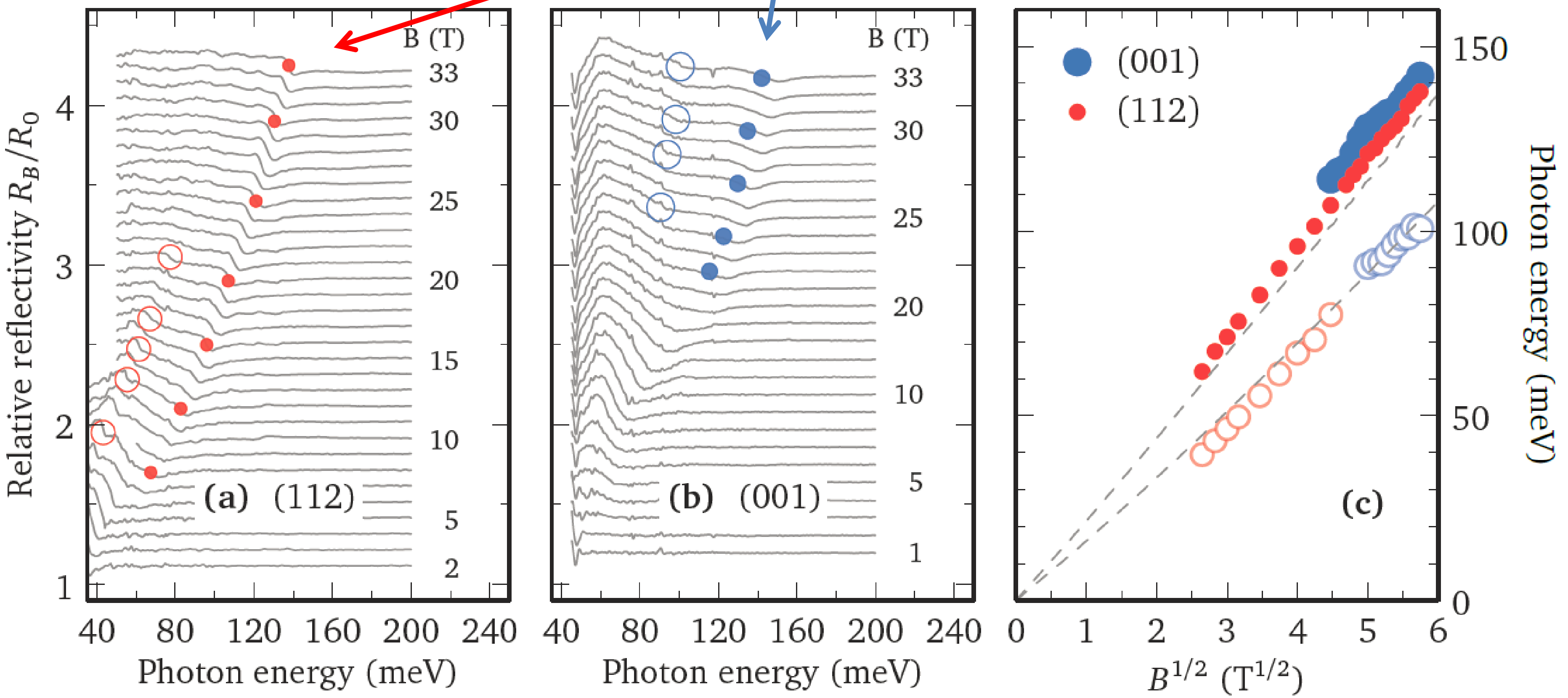
A. Akrap et al., arXiv:1604.00038 (2016)

3D massless Dirac/Kane electrons – Landau levels



Cd_3As_2 – High-field magneto-reflectivity

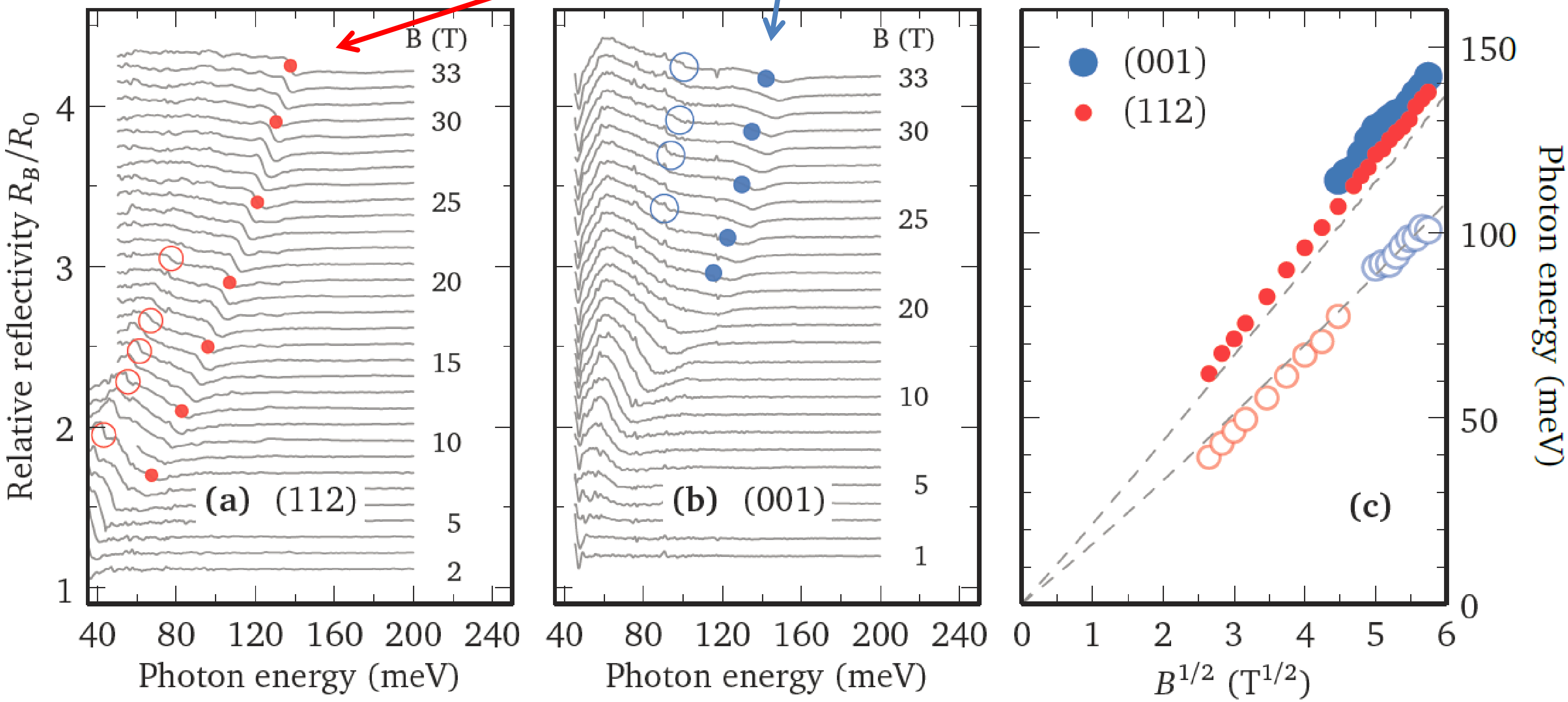
Cyclotron resonance (CR) in the quantum limit



Magneto-optical signature of massless Kane electrons

Cd_3As_2 – High-field magneto-reflectivity

Cyclotron resonance (CR) in the quantum limit



Magneto-optical signature of massless Kane electrons

…also observed by ARPES, STS/STM, transport…

Conclusions

Discovery/fabrication of graphene triggered vast search for other materials with analogous properties

Silicene, germanene, topological insulators, molecular graphene, artificial graphene, semiconductors with giant Rashba-type spin splitting…

Z. K Liu et al., Science 343, 864 (2014)
M. Orlita et al., Nature Physics 10, 233 (2014)
Z. K. Liu et al., Nature Mater. 13, 677 (2014)
S. Jeon et al., Nature Mate. 13, 851 (2014)
R. Y. Chen et al., Phys. Rev. Lett. 115, 176404 (2015)
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)

Materials with 3D conical bands reported

Na_3Bi, $\mathbf{Cd_3As_2}$, zero-gap HgCdTe, $ZrTe_5$, TaAs, NbAs

Cd_3As_2 is a symmetry-protected 3D Dirac semimetal

...but only ("trivial") 3D massless Kane electrons observed experimentally so far

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

Acknowledgements:

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