Quantum oscillations without magnetic field

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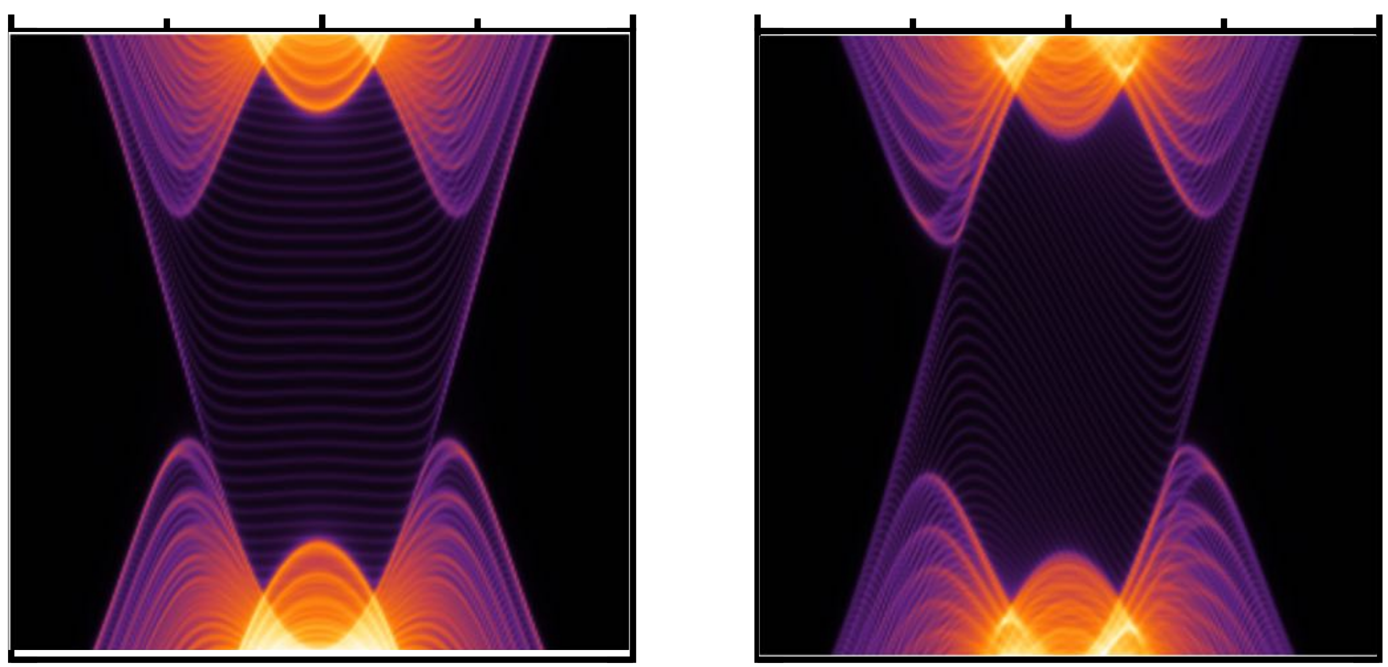
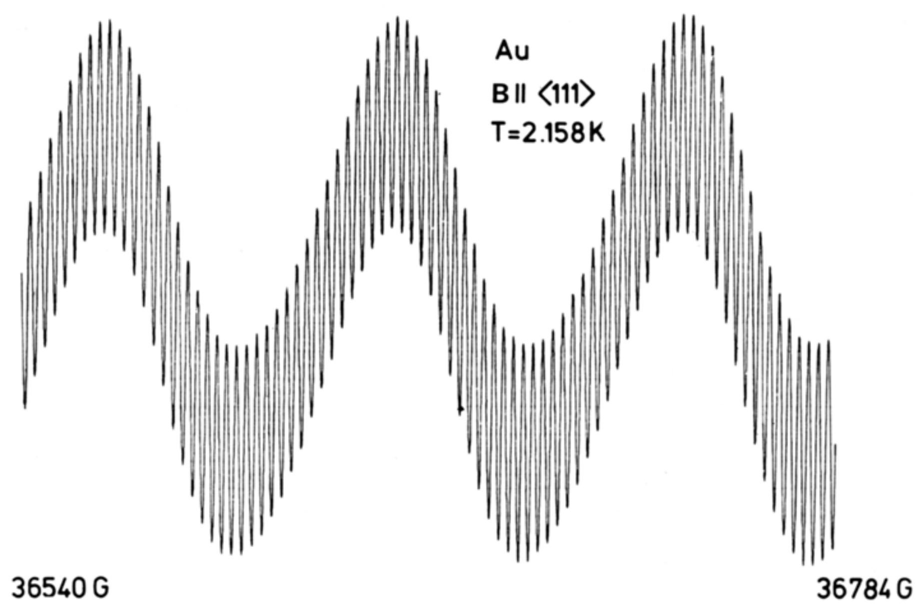
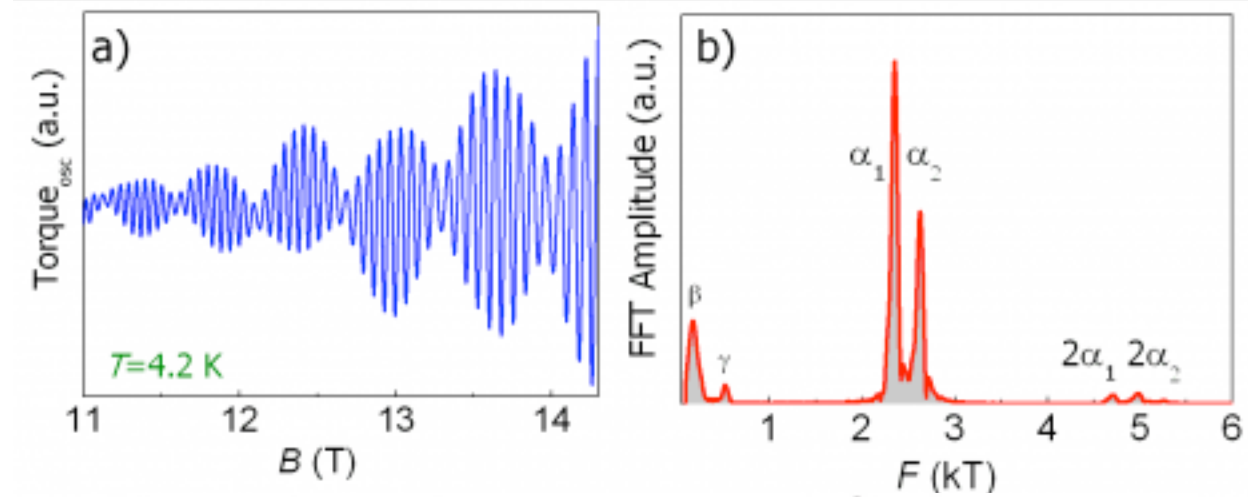
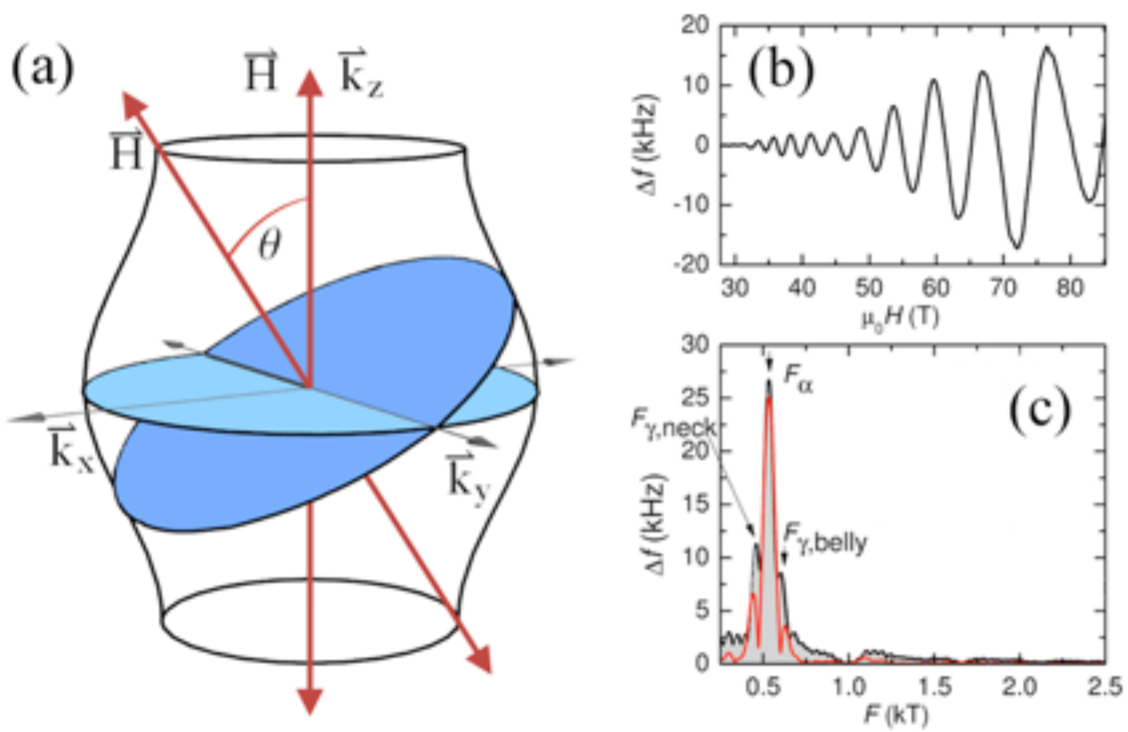
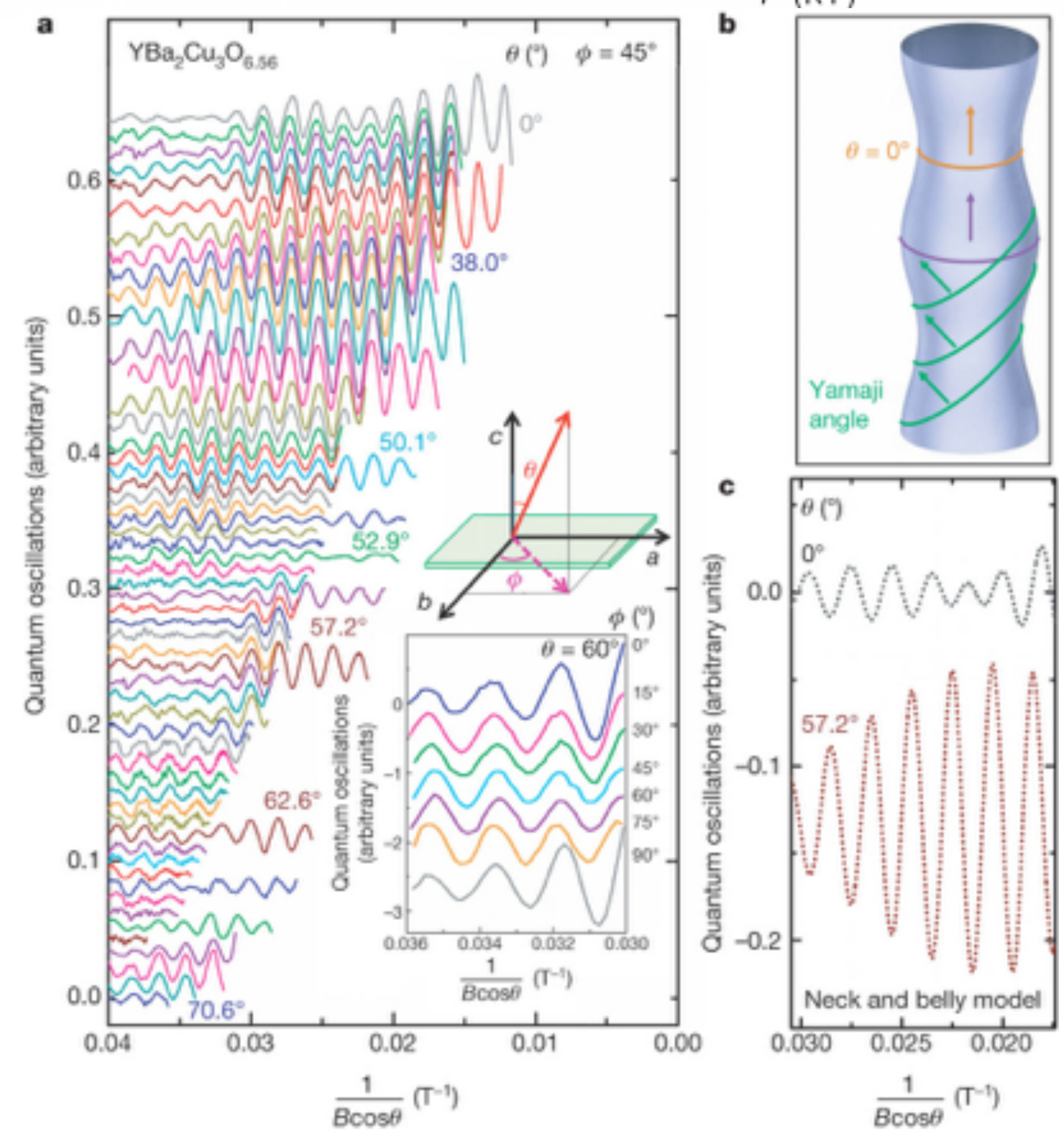


Quantum oscillations







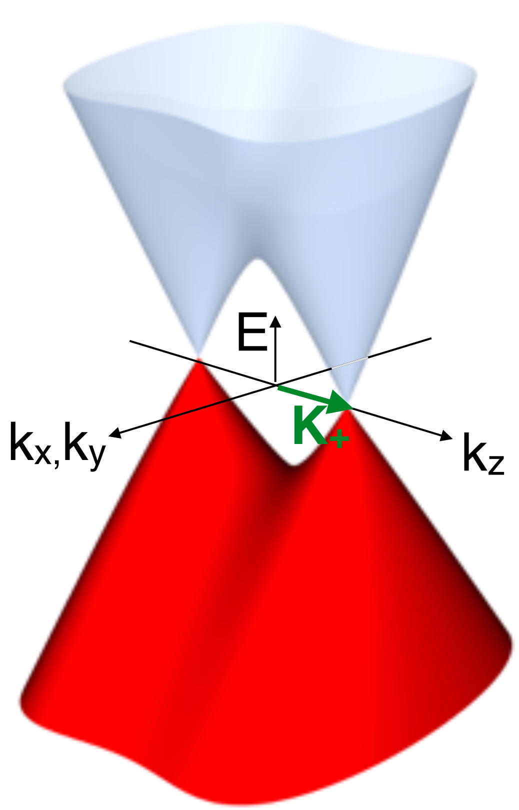


Quantum oscillations normally require magnetic field B

… except when B can be replaced by b.

b = strain-induced pseudomagnetic field

<u>Main result:</u> in Dirac and Weyl semimetals quantum oscillations can be generated by elastic strain in complete absence of magnetic field B



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nature physics

Energy gaps and a zero-field quantum Hall effect in graphene by strain engineering

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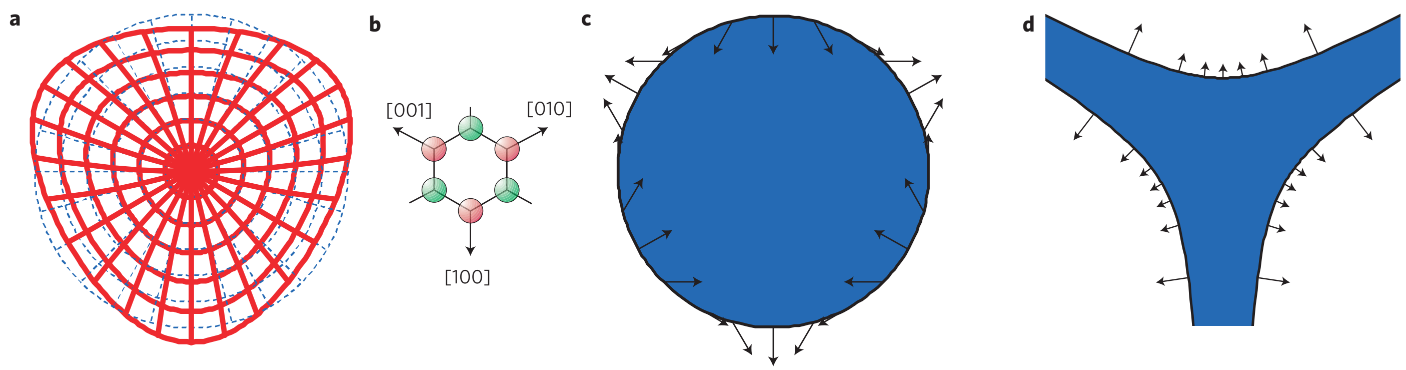

Figure 1 | Designed strain can generate a strictly uniform pseudomagnetic field in graphene. a, Distortion of a graphene disc which is required to generate uniform B_S. The original shape is shown in blue. **b**, Orientation of the graphene crystal lattice with respect to the strain. Graphene is stretched or compressed along equivalent crystallographic directions ⟨100⟩. Two graphene sublattices are shown in red and green. **c**, Distribution of the forces applied at the disc's perimeter (arrows) that would create the strain required in **a**. The uniform colour inside the disc indicates strictly uniform pseudomagnetic field. **d**, The shown shape allows uniform B_S to be generated only by normal forces applied at the sample's perimeter. The length of the arrows indicates the required local stress.

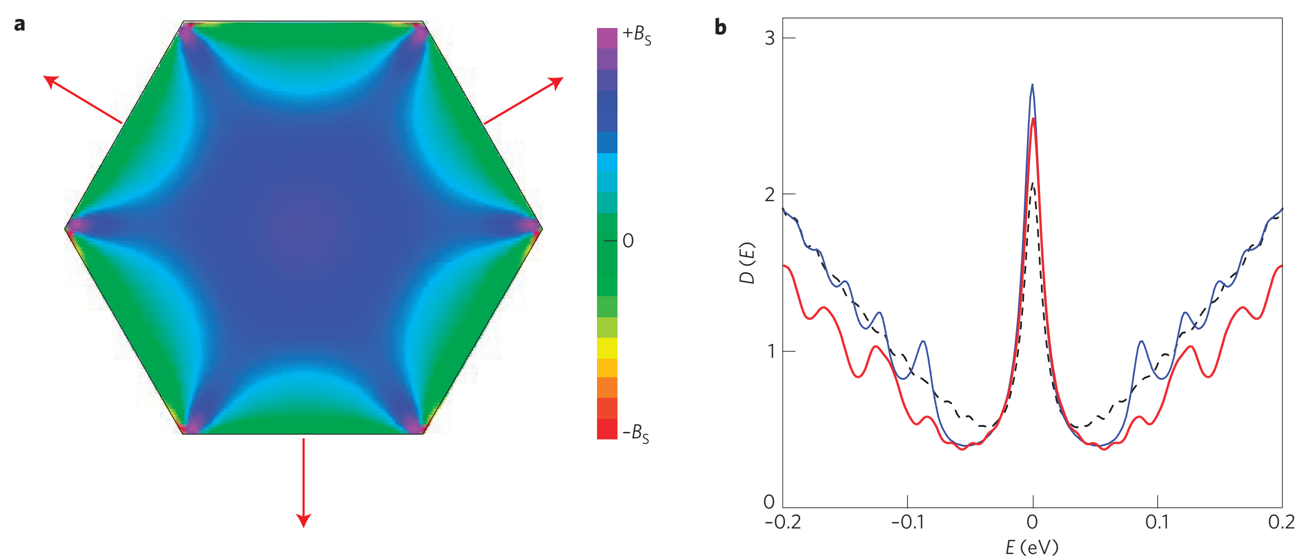

Figure 2 | Stretching graphene samples along ⟨100⟩ axes always generates a pseudomagnetic field that is fairly uniform at the centre. a, Distribution of B_S for a regular hexagon stretched by its three sides oriented perpendicular to ⟨100⟩. Other examples are given in the Supplementary Information. **b**, Normalized density of states for the hexagon in **a** with $L = 30$ nm and $\Delta_m = 1\%$. The black curve is for the case of no strain and no magnetic field. The peak at zero E is due to states at zigzag edges. The blue curve shows the Landau quantization induced by magnetic field $B = 10$ T. The pseudomagnetic field with $B_S \approx 7$ T near the hexagon's centre induces the quantization shown by the red curve. Comparison between the curves shows that the smearing of the pseudo-Landau levels is mostly due to the finite broadening $\Gamma = 2$ meV used in the tight-binding calculations (Γ corresponds to submicrometre mean free paths attainable in graphene devices). The inhomogeneous B_S plays little role in the broadening of the first few pseudo-Landau levels (see Supplementary Fig. S4).

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Strain-Induced Pseudo–Magnetic Fields Greater Than 300 Tesla in Graphene Nanobubbles

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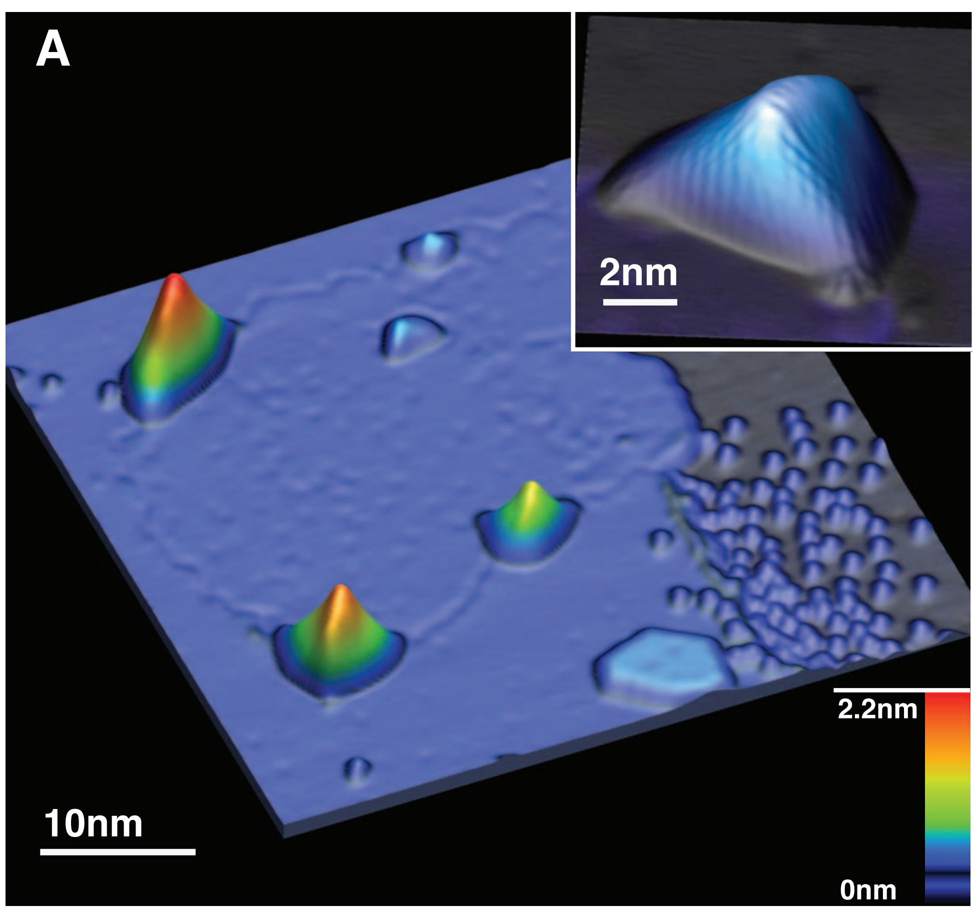
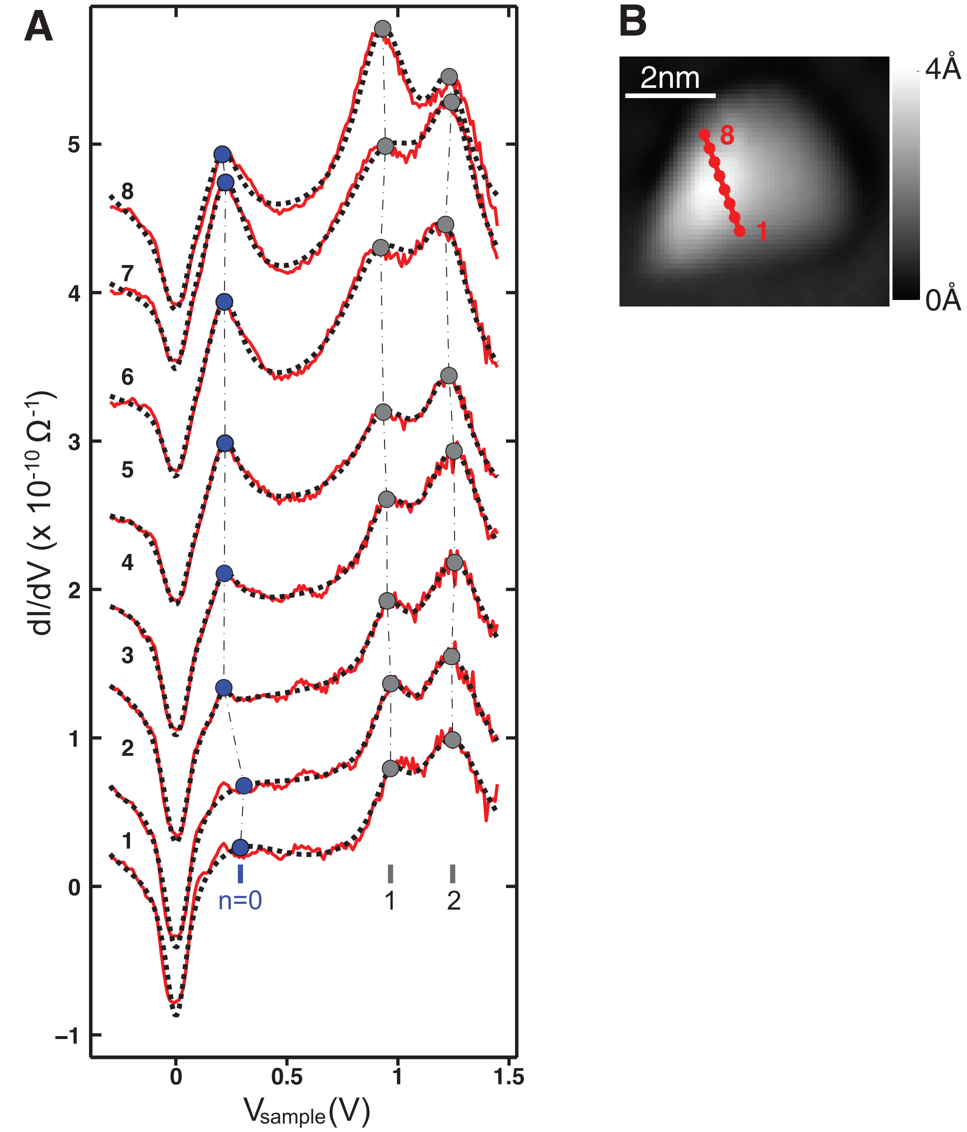
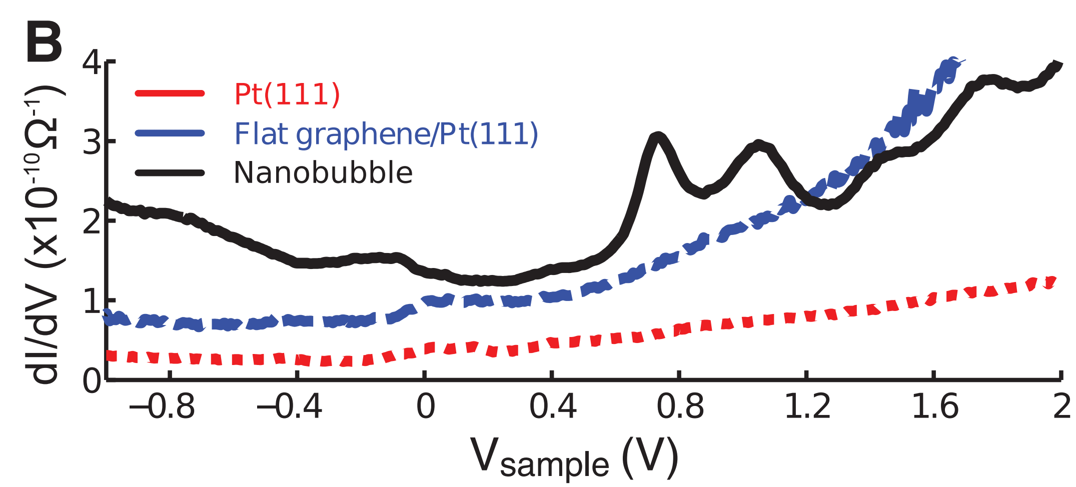
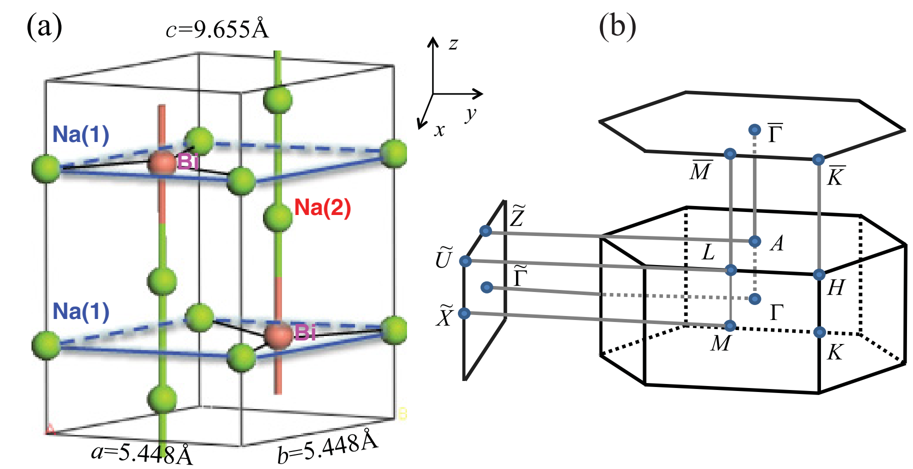
Recent theoretical proposals suggest that strain can be used to engineer graphene electronic states through the creation of a pseudo–magnetic field. This effect is unique to graphene because of its massless Dirac fermion-like band structure and particular lattice symmetry (C_{3v}). Here, we present experimental spectroscopic measurements by scanning tunneling microscopy of highly strained nanobubbles that form when graphene is grown on a platinum (111) surface. The nanobubbles exhibit Landau levels that form in the presence of strain-induced pseudo–magnetic fields greater than 300 tesla. This demonstration of enormous pseudo–magnetic fields opens the door to both the study of charge carriers in previously inaccessible high magnetic field regimes and deliberate mechanical control over electronic structure in graphene or so-called "strain engineering."







Back to 3D: Model for Cd_3As_2 and Na_3Bi



In the basis of spin-orbit coupled states

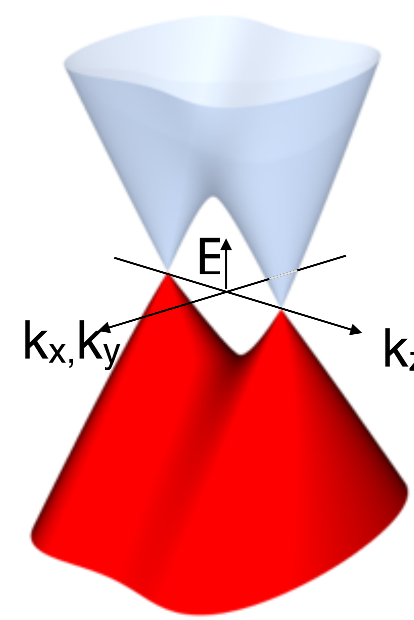
$$|P_{\frac{3}{2}},\tfrac{3}{2}\rangle, |S_{\frac{1}{2}},\tfrac{1}{2}\rangle, |S_{\frac{1}{2}},-\tfrac{1}{2}\rangle, |P_{\frac{3}{2}},-\tfrac{3}{2}\rangle$$

the tight-binding model reads:

$$H^{\text{latt}} = \epsilon_{\boldsymbol{k}} + \begin{pmatrix} h^{\text{latt}} & 0 \\ 0 & -h^{\text{latt}} \end{pmatrix}$$

$$h^{\text{latt}}(\boldsymbol{k}) = m_{\boldsymbol{k}}\tau^z + \Lambda(\tau^x \sin a_x k_x + \tau^y \sin a_y k_y),$$

$$m_{\boldsymbol{k}} = t_0 + t_1 \cos a k_z + t_2(\cos a k_x + \cos a k_y)$$



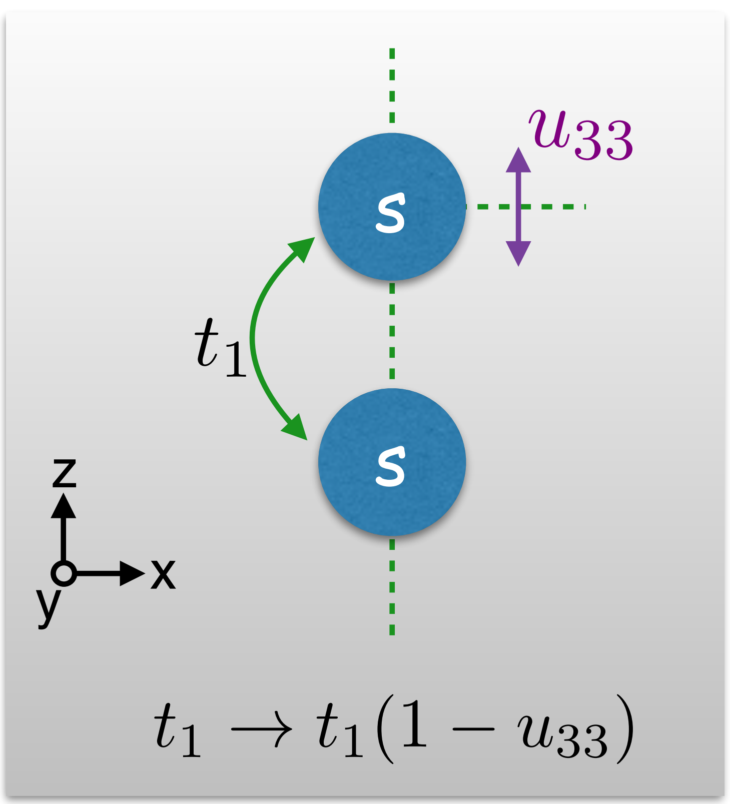
Z. Wang, H. Weng, Q. Wu, X. Dai, and Z. Fang, PRB 88, 125427 (2013)
Z. Wang, Y. Sun, X.-Q. Chen, C. Franchini, G. Xu, H. Weng, X. Dai, and Z. Fang, PRB 85, 195320 (2012)

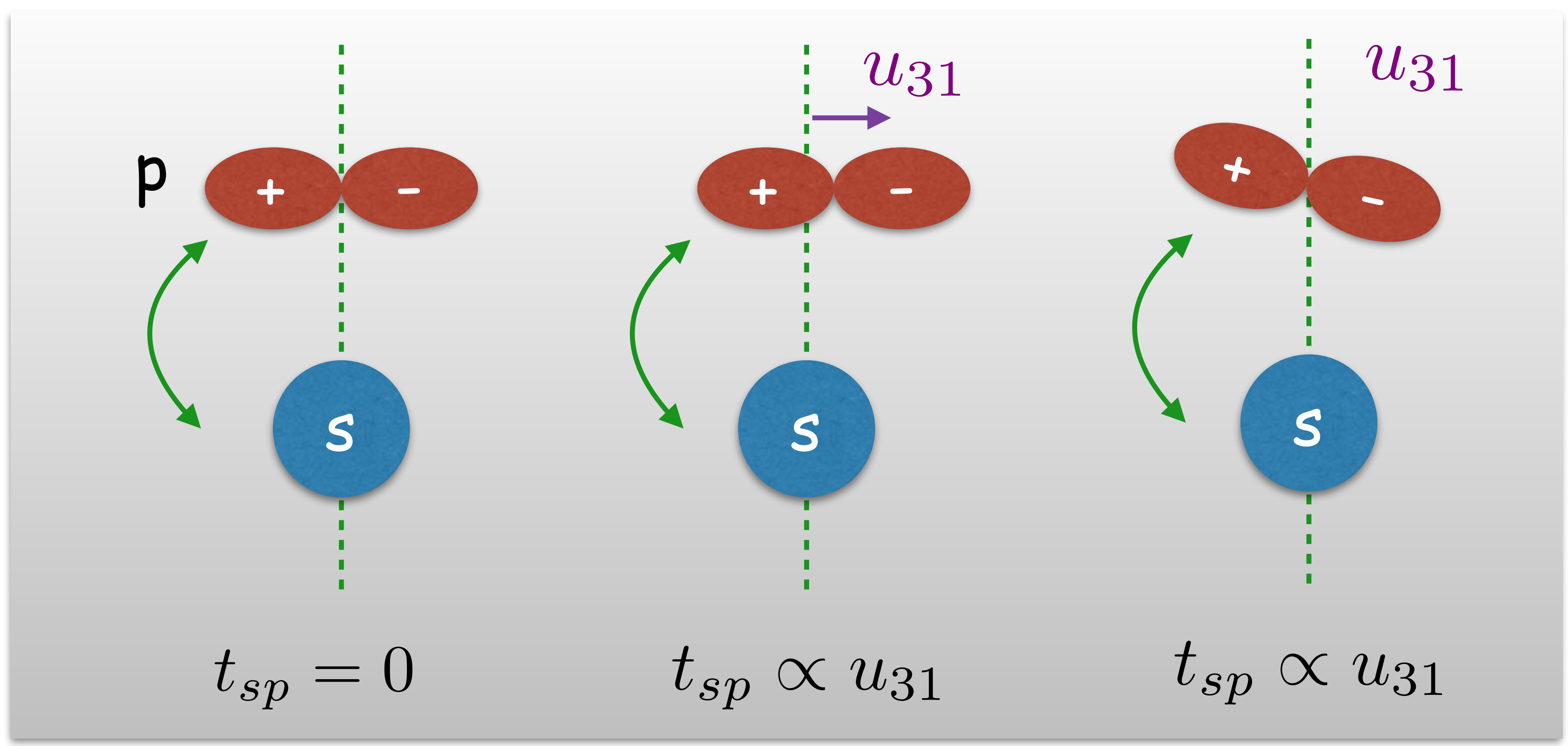
Effect of elastic strain on tunnelling amplitudes

The most important effect of elastic strain is incorporated by

$$t_1\tau^z \to t_1(1-u_{33})\tau^z + i\Lambda\sum_{j\neq 3} u_{3j}\tau^j,$$

where $u_{ij} = \frac{1}{2}(\partial_i u_j + \partial_j u_i)$ is the strain tensor and **u** is the displacement field.





H. Shapourian, T. L. Hughes, and S. Ryu, PRB 92, 165131 (2015)
A.Cortijo, Y. Ferreiro´s, K. Landsteiner, and M. A. H. Vozmediano, PRL 115, 177202 (2015)
H. Sumiyoshi and S. Fujimoto, PRL 116, 166601 (2016)

Strain = chiral gauge potential at low energies

Derive low-energy theory by expanding $h^{\text{latt}}(\boldsymbol{k})$ near Dirac points $\boldsymbol{k} = \boldsymbol{K}_\pm + \boldsymbol{q}$

$$h_\eta(\mathbf{q}) = v_\eta^j \tau^j \left(\hbar q_j - \eta \frac{e}{c} \mathcal{A}_j\right), \quad \eta = \pm$$

Here $\boldsymbol{v}_\eta = \hbar^{-1} a(\Lambda, \Lambda, -\eta t_1 \sin aQ)$ and

$$\vec{\mathcal{A}} = -\frac{\hbar c}{ea}\big(u_{13} \sin aQ, u_{23} \sin aQ, u_{33} \cot aQ\big).$$

$$\mathbf{K}_\pm = (0, 0, \pm Q)$$

Components u_{3j} of the strain tensor act on Dirac fermions as chiral gauge field.

Strain-induced field strength estimate

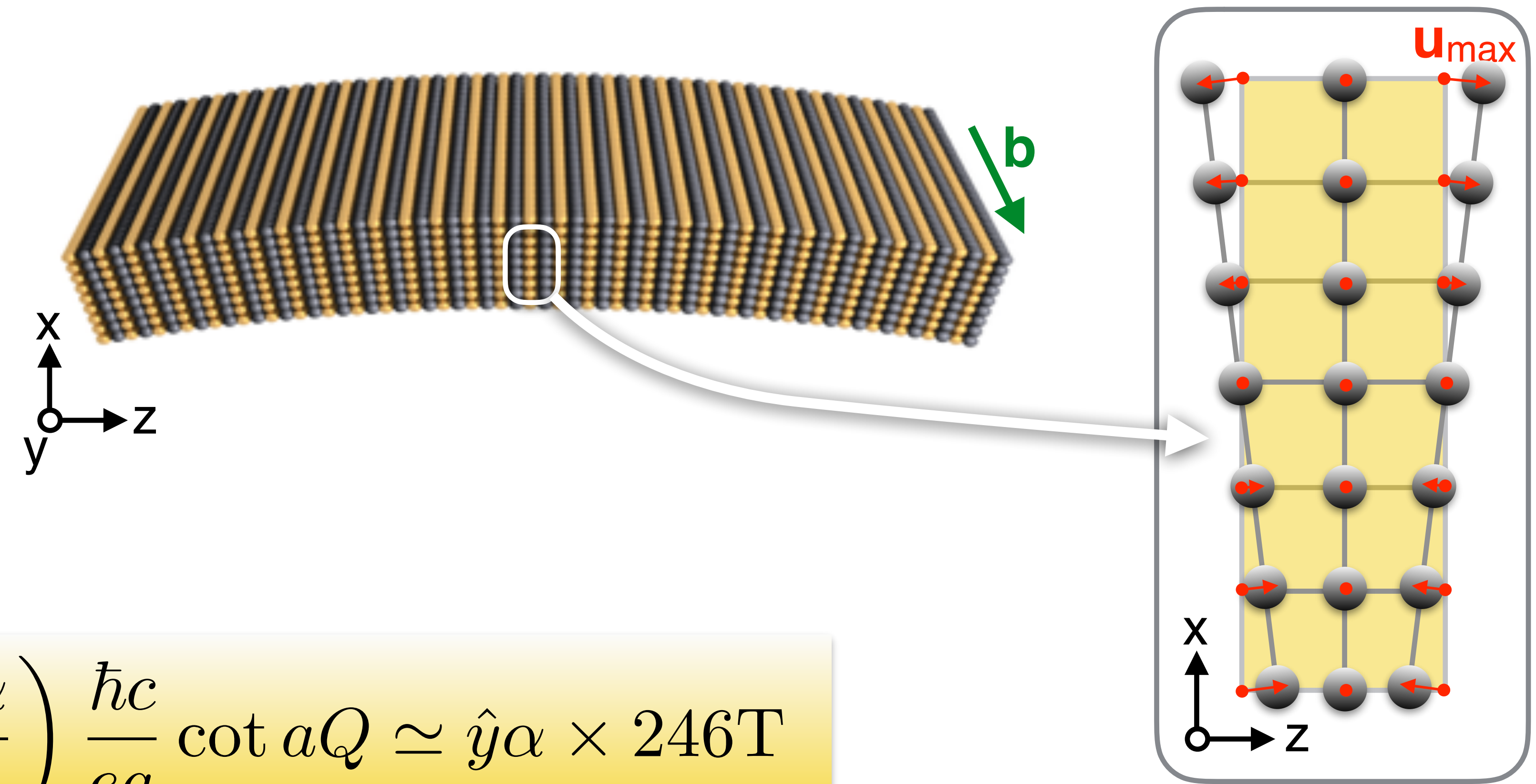
Displacement field

$$\boldsymbol{u} = (0, 0, 2\alpha xz/d)$$

gives strain tensor

$$u_{33} = 2\alpha x/d$$

and pseudomagnetic field



$$\mathbf{b} = \nabla \times \vec{A} = \hat{y}\left(\frac{2\alpha}{d}\right)\frac{\hbar c}{ea}\cot aQ \simeq \hat{y}\alpha \times 246\mathrm{T}$$

$$\alpha = u_{\max}/a$$

for Cd_3As_2 parameters with $aQ \simeq 0.132$.

What is the maximum strain Cd_3As_2 film can sustain?

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ARTICLE

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Giant negative magnetoresistance induced by the chiral anomaly in individual Cd_3As_2 nanowires

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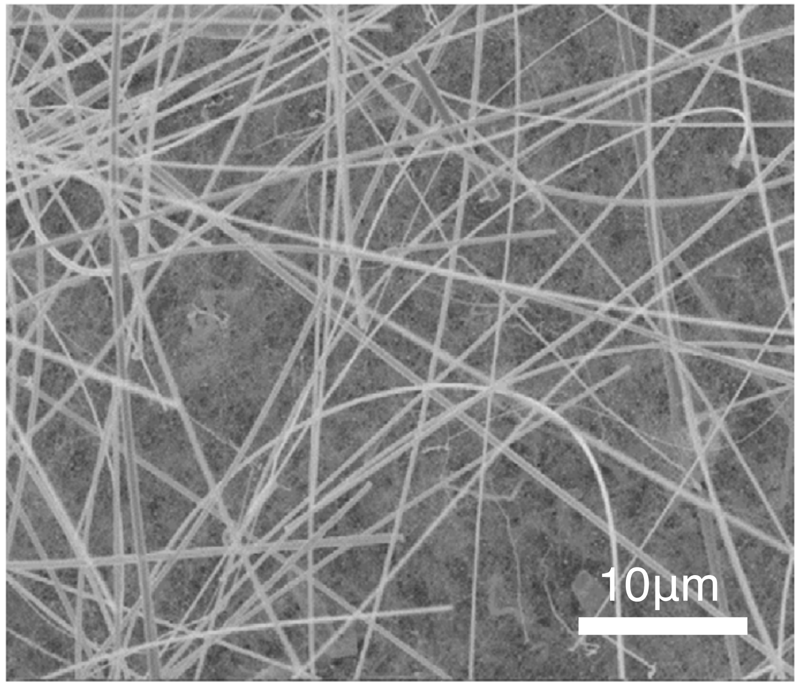
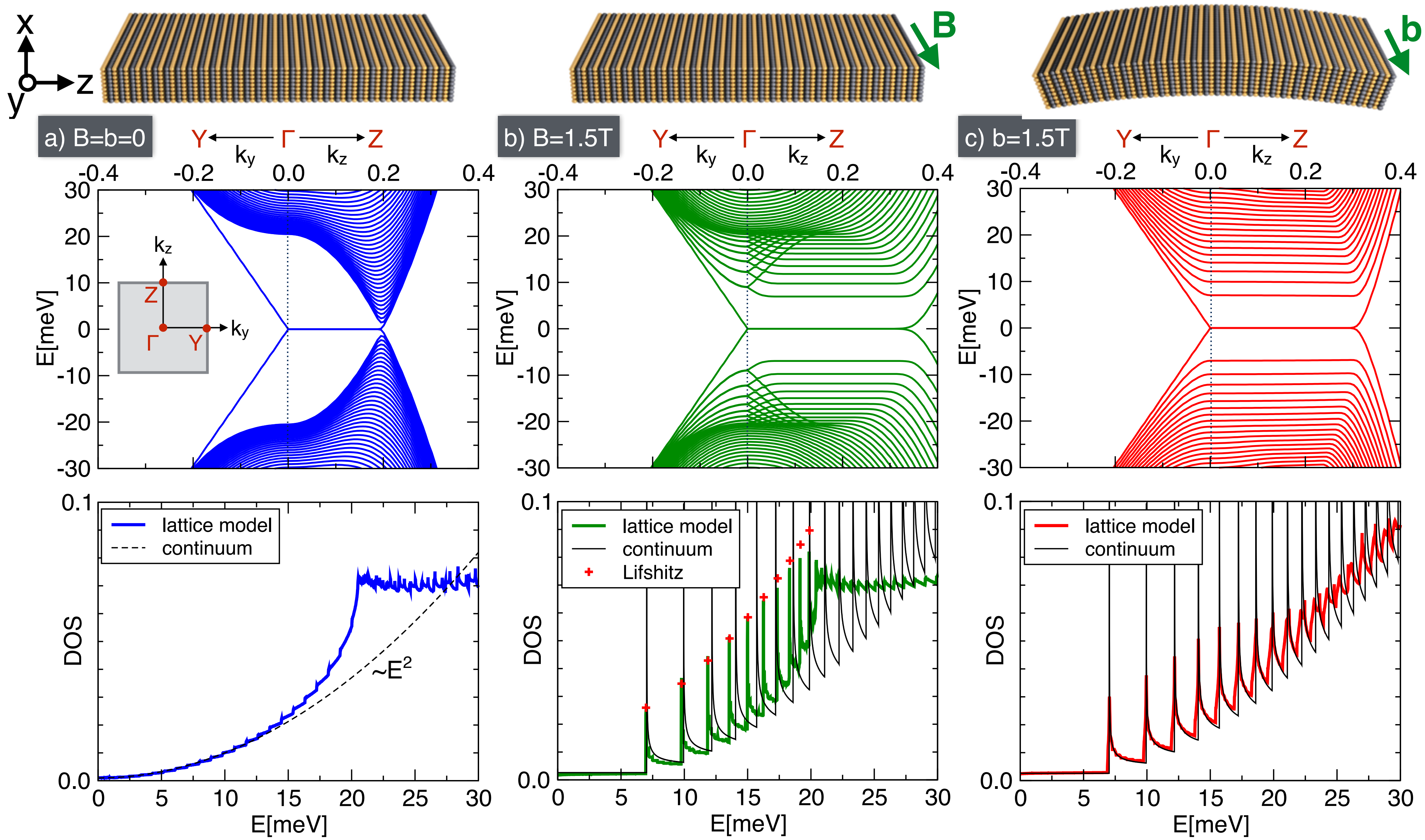
a

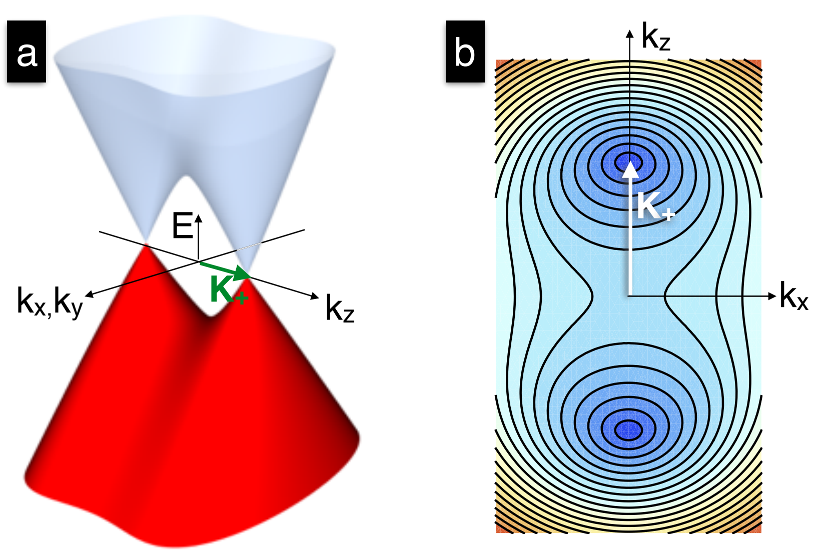


From the radius R of the bend and diameter d of nanowires we estimate that distortion α of several percent can be achieved. This gives maximum estimated pseudomagnetic field of 10-15T in Cd_3As_2.

This should be sufficient to observe strain-induced quantum oscillations.

Numerical results for Cd_3As_2 lattice model





Dirac Landau levels:

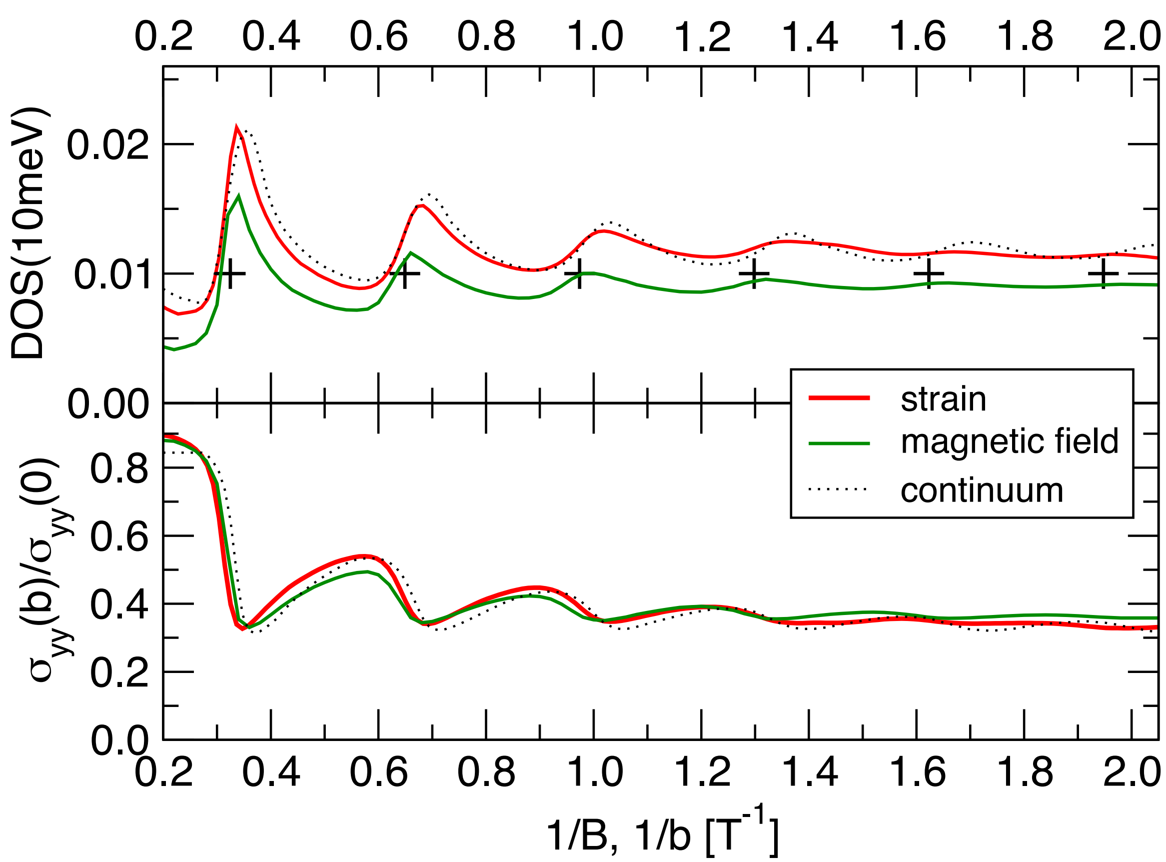
$$E_n(k_y) = \pm\hbar\sqrt{v_y^2 k_y^2 + 2n v_x v_z \frac{e|B|}{\hbar c}}, \quad n = 1, 2, \ldots,$$

Lifshitz-Onsager quantization:

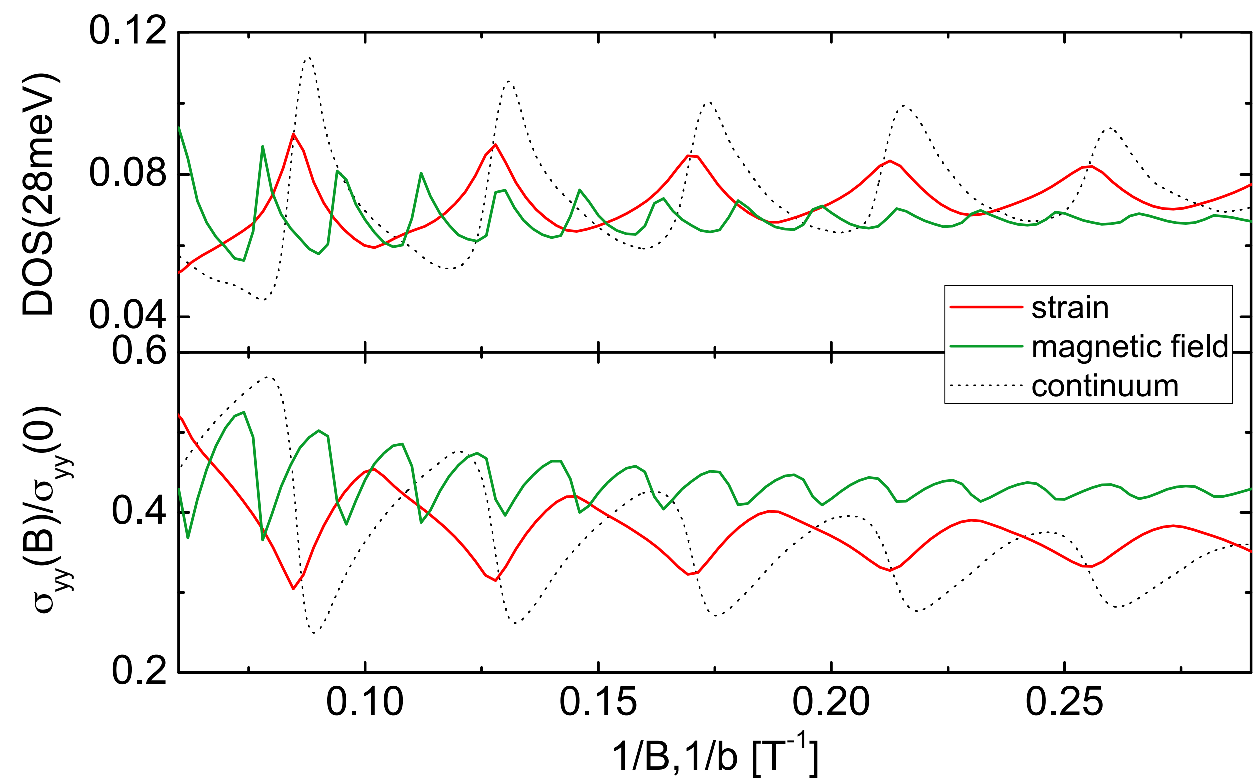
$$S(E_n) = 2\pi n(eB/\hbar c)$$

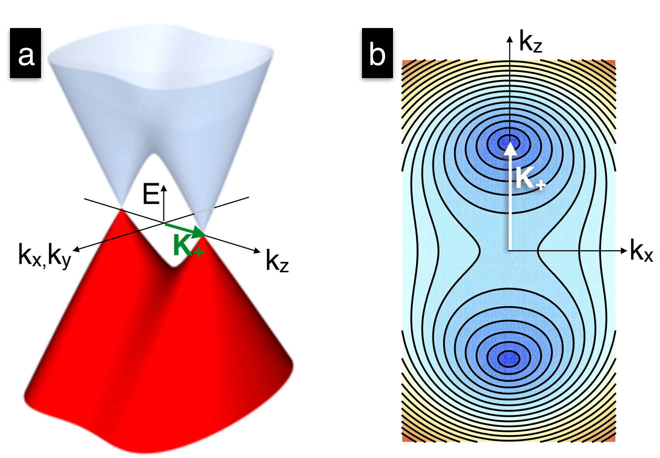
de Haas-van Alphen and Shubnikov-de Haas oscillations

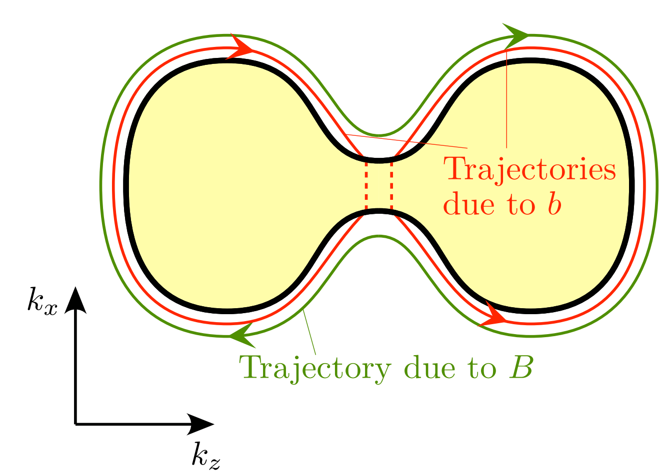
Below E_{Lif}



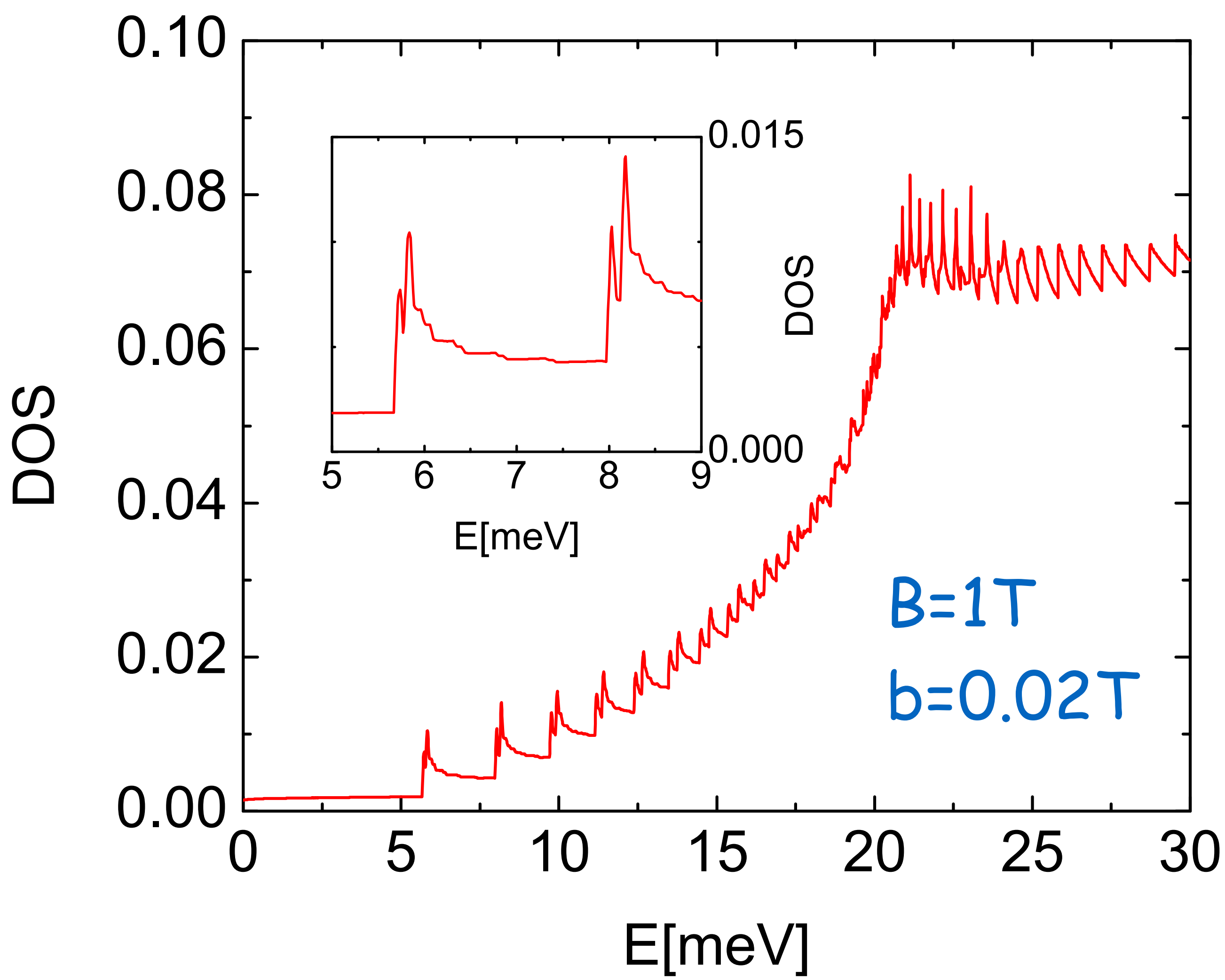
Above E_{Lif}

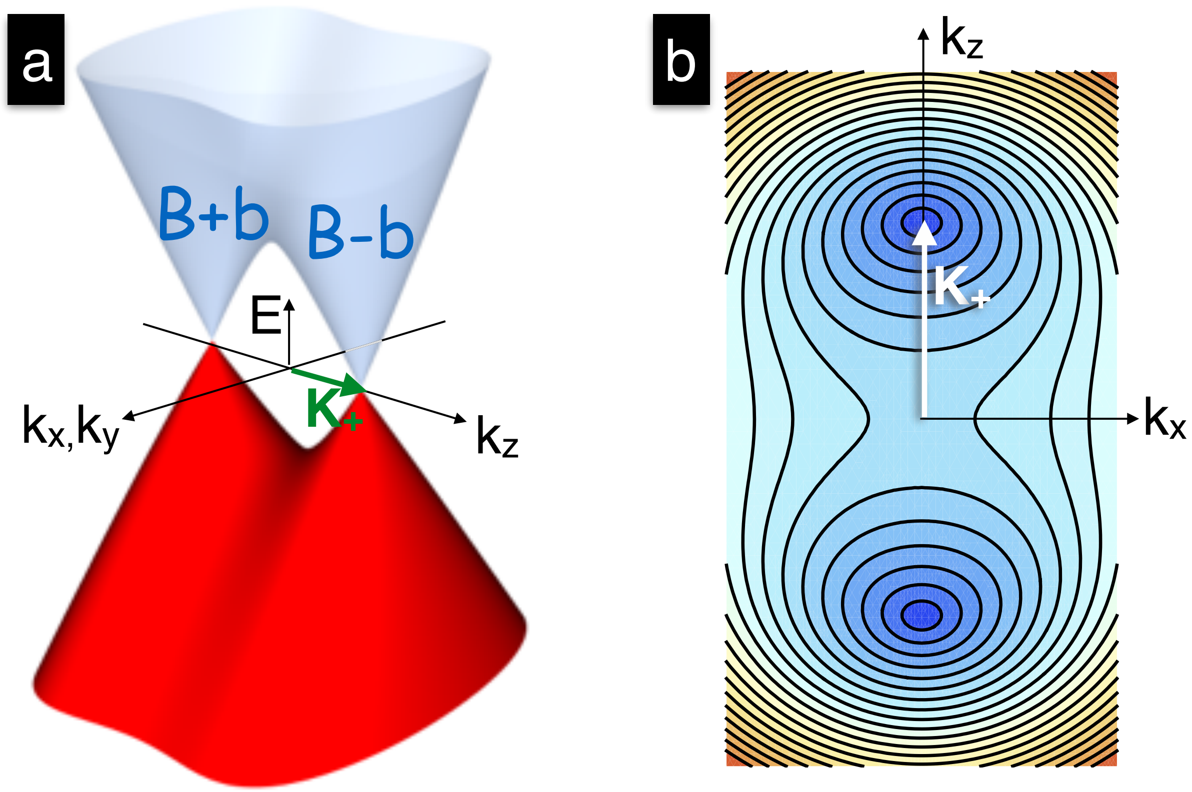






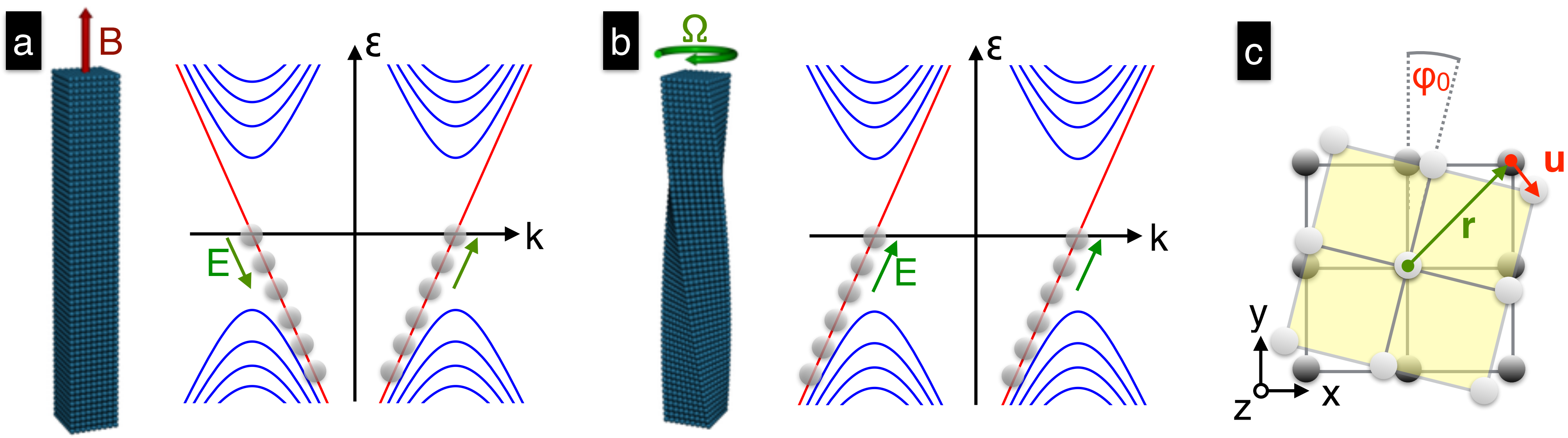
Equivalence of B and b for low-energy electrons





Chiral anomaly from strain-induced EM fields

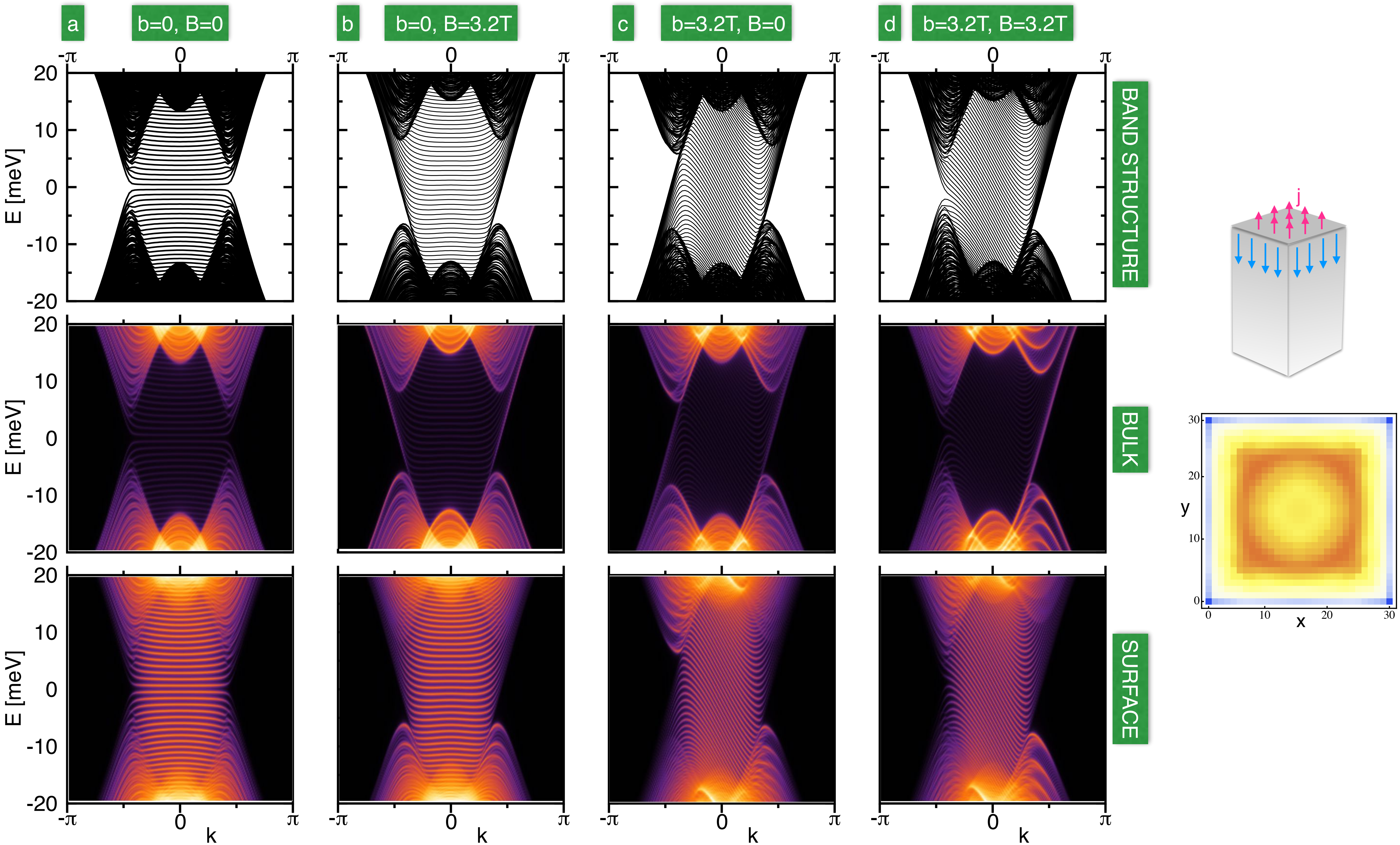
arXiv:1607.01810



$$\partial_t \rho_5 + \nabla \cdot \boldsymbol{j}_5 = \frac{e^2}{2\pi^2\hbar^2 c}(\boldsymbol{E}\cdot\boldsymbol{B} + \boldsymbol{e}\cdot\boldsymbol{b}),$$

$$\partial_t \rho + \nabla \cdot \boldsymbol{j} = \frac{e^2}{2\pi^2\hbar^2 c}(\boldsymbol{E}\cdot\boldsymbol{b} + \boldsymbol{e}\cdot\boldsymbol{B}).$$

C.-X. Liu, P. Ye, and X.-L. Qi, Phys. Rev. B 87, 235306 (2013).



a
b=0, B=0
b
b=0, B=3.2T
c
b=3.2T, B=0
d
b=3.2T, B=3.2T
BAND STRUCTURE
BULK
SURFACE
E [meV]
k
-π
0
π
20
10
0
-10
-20
j
y
x

Conclusions

- Similar to graphene elastic strain in Dirac and Weyl semimetals acts as chiral gauge potential
- This gives rise to **quantum oscillations** in complete absence of magnetic field
- Also generates an interesting novel manifestation of the **chiral anomaly**