Phase transitions in two tunnel-coupled HgTe quantum wells.

Bilayer graphene analogy and beyond.

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Laboratoire Charles Coulomb, UMR 5221
Montpellier, FRANCE

Sci. Rep. **6**, 30755 (2016); ArXiv:1604.02423

Talk outline

- ❑ Introduction: electronic states in single HgTe QWs
- ❑ Why Double HgTe QWs? Initial motivation.

Original results

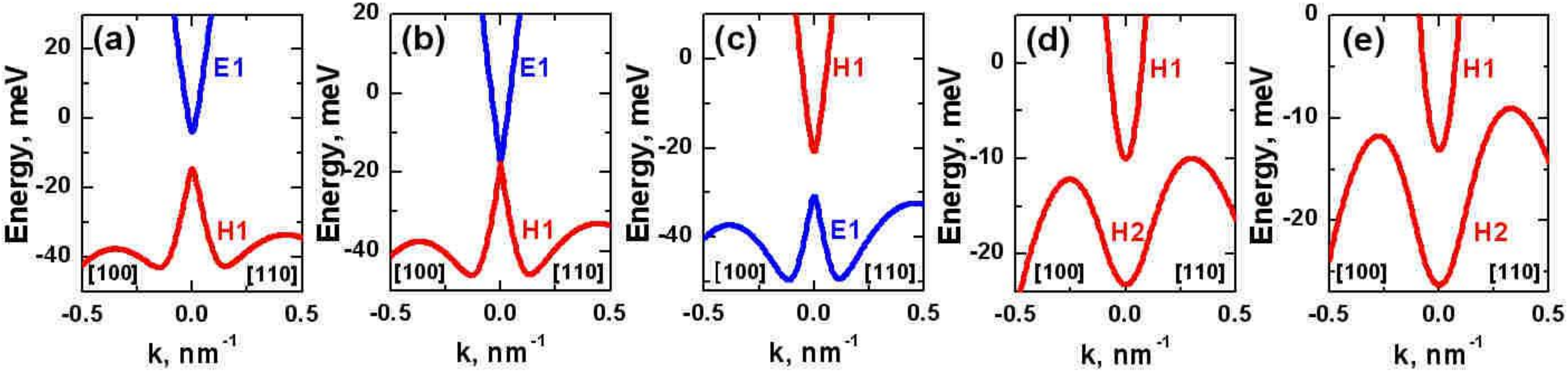
- ❑ Transition from direct to inverted band structure
- ❑ Massless fermions at inverted band structure
- ❑ ‘Bilayer graphene’ phase in Double HgTe QW
- ❑ Generalization of BHZ model. Picture of edge states

Experimental results from Montpellier

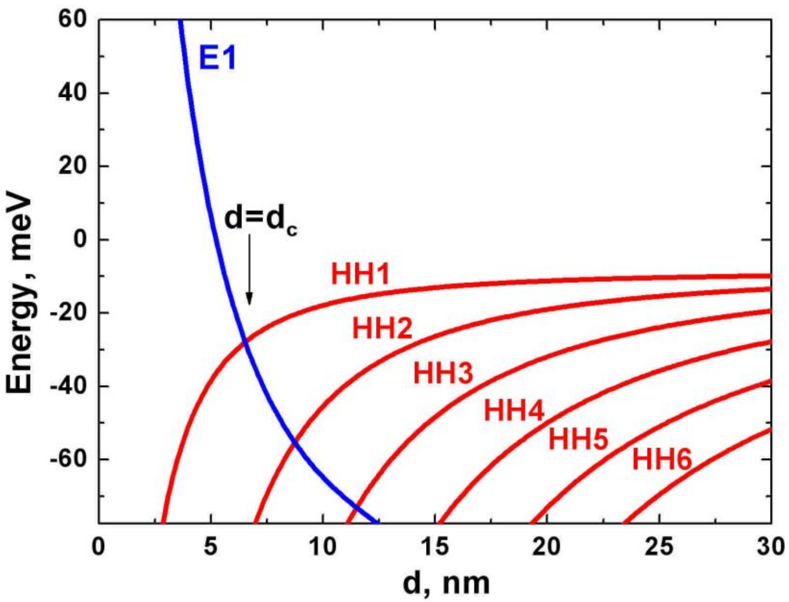
- ❑ Landau Level spectroscopy of ‘bilayer graphene’ phase

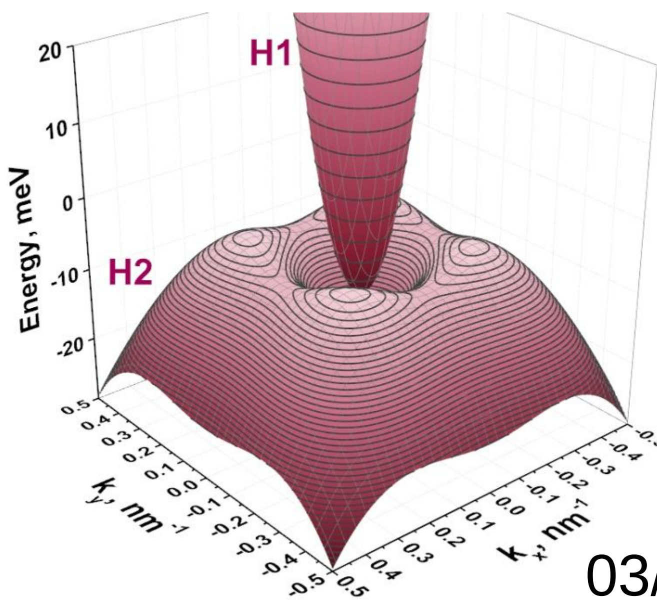
Phases in HgTe QWs

$d<d_c$	$d=d_c$	$d>d_c$	$d=d_{sm}$	$d>d_{sm}$



Band insulator	Dirac cone	Topological insulator	Gapless state	Semimetal phase





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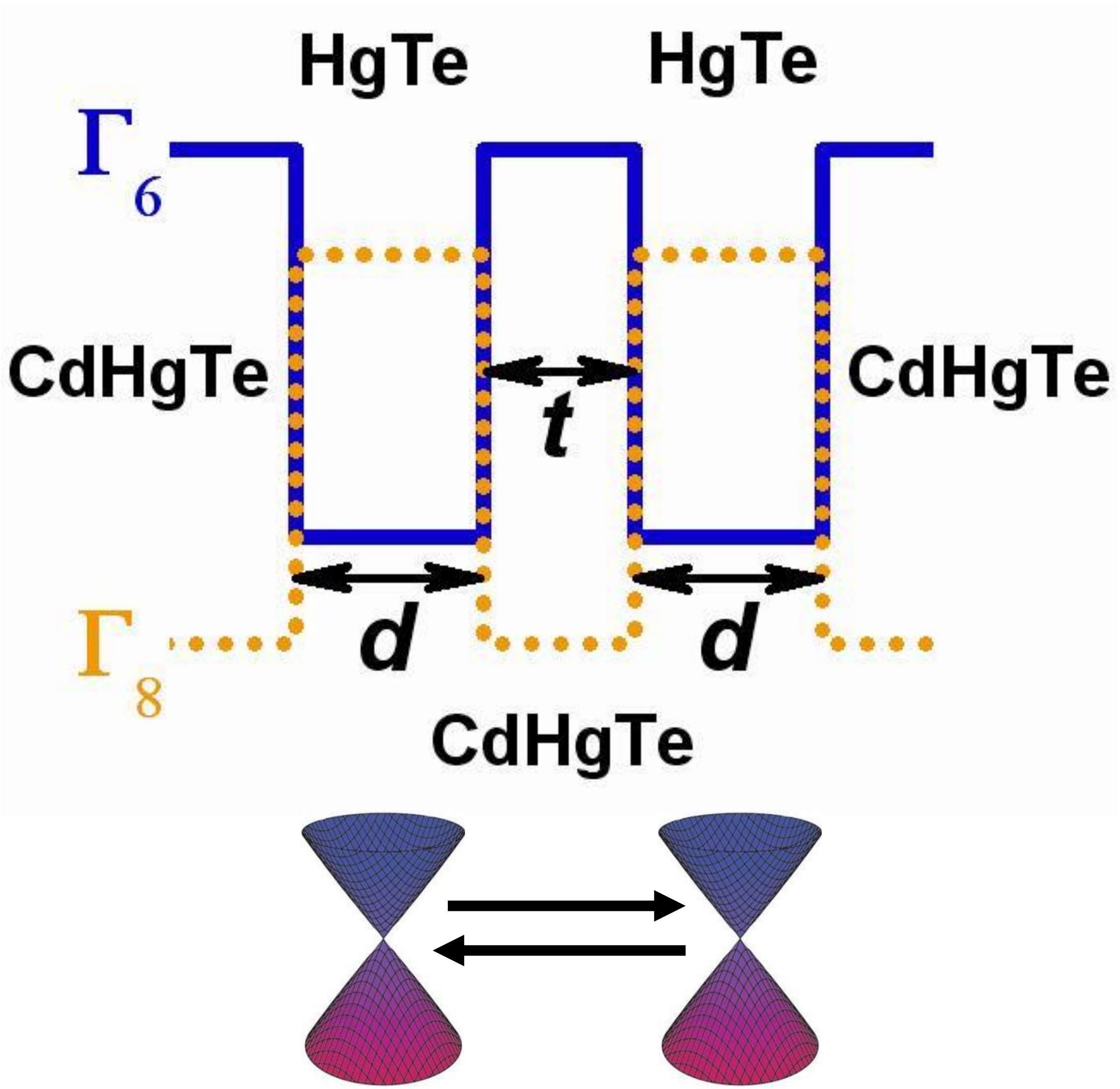
Initial motivation: few philosophical questions

Double HgTe QW



Bilayer graphene?

Tunneling between edge states?

New ‘topological’ phases?

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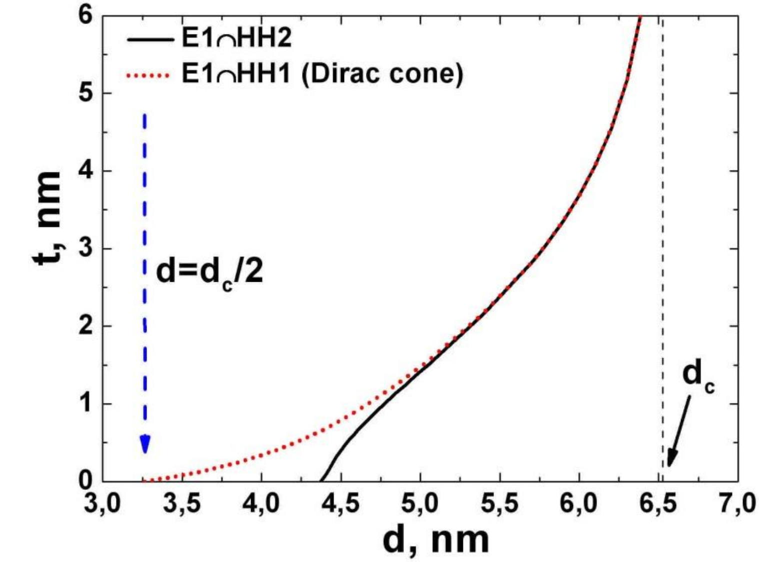
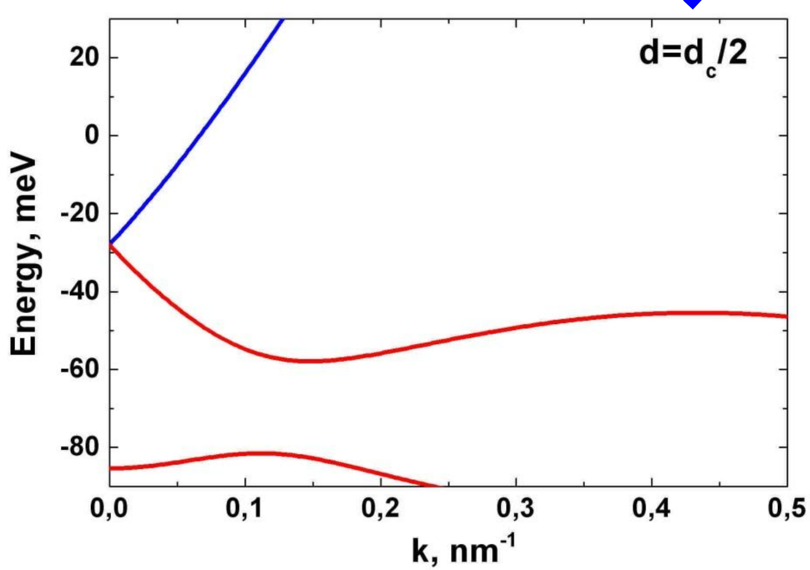
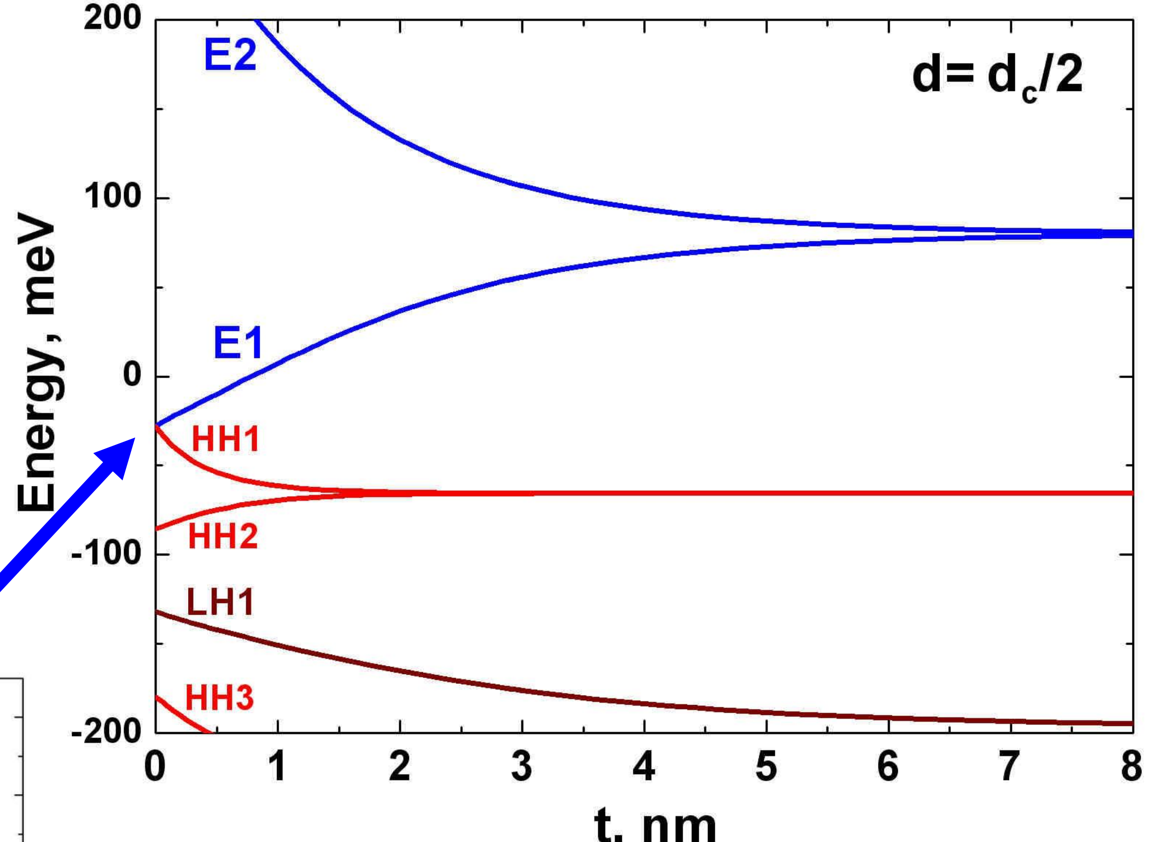
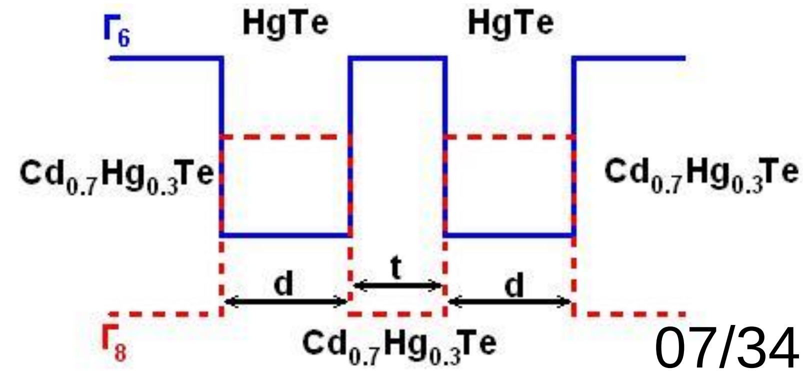
Band ordering at $d=d_c/2$

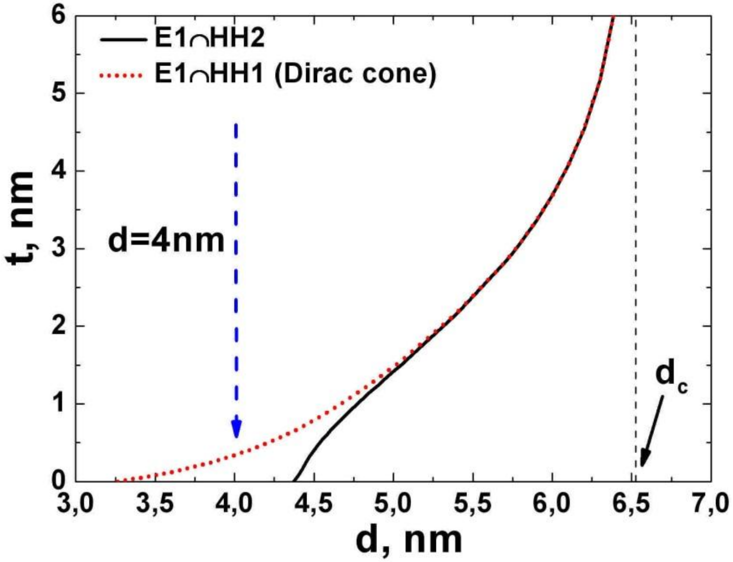


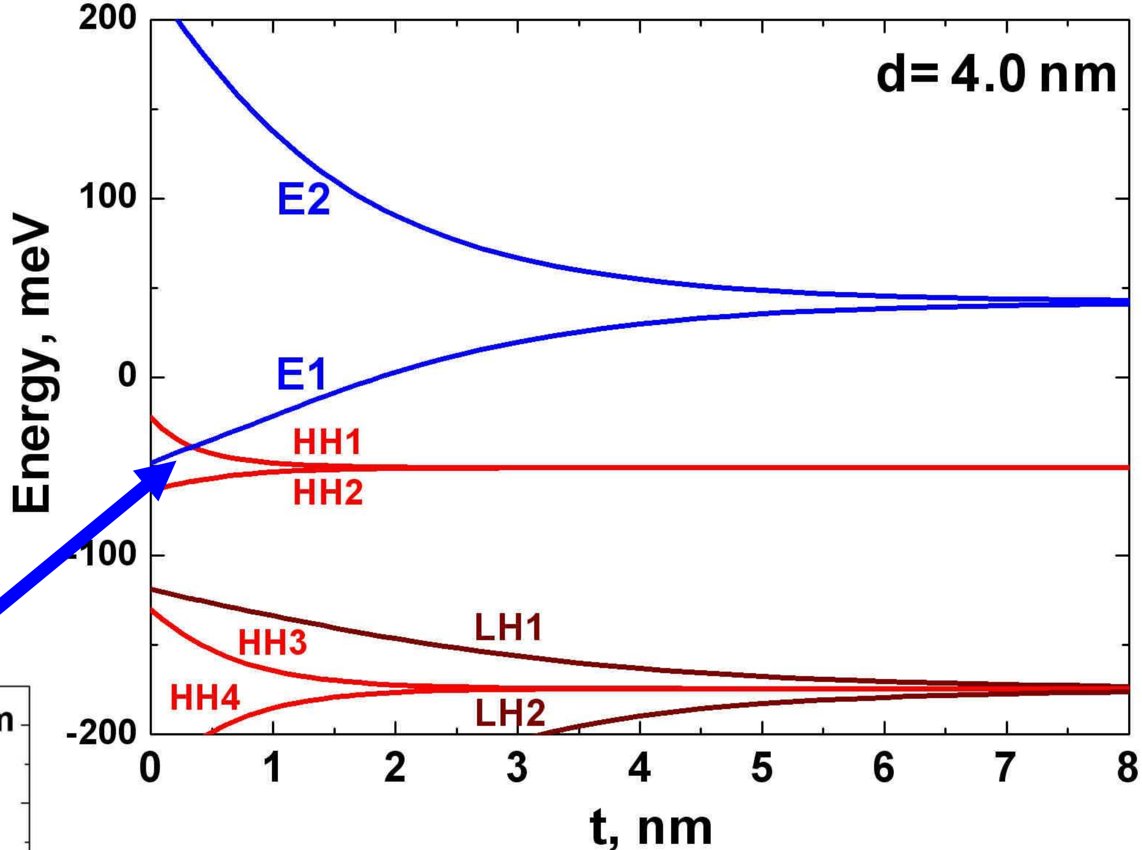


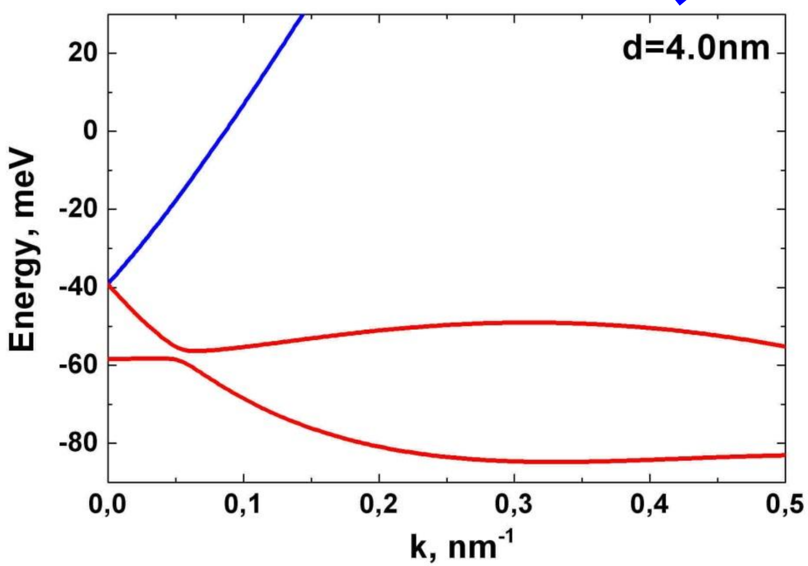


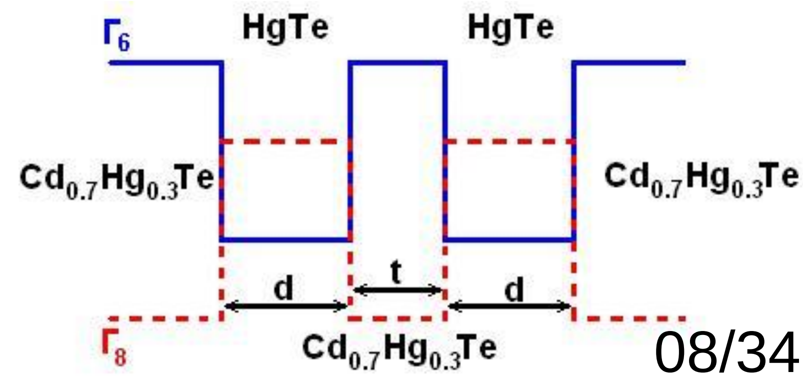


Band ordering at d=4.0nm

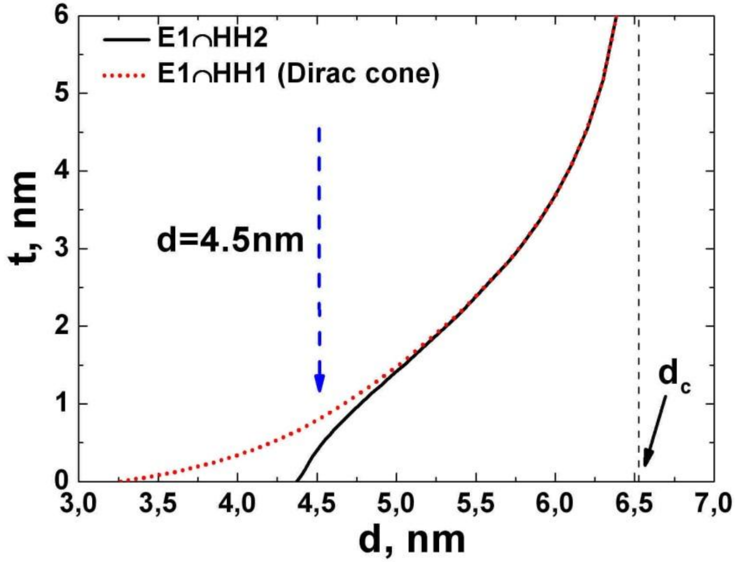


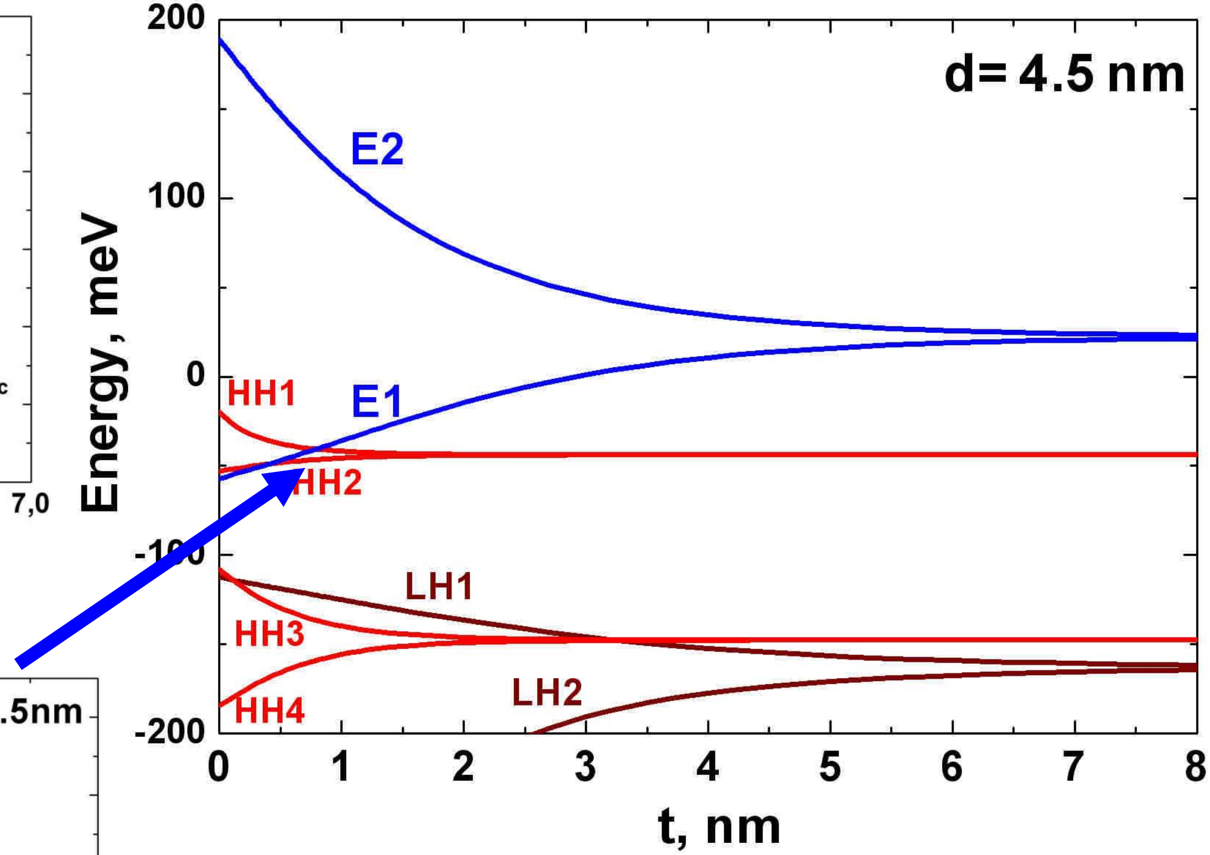


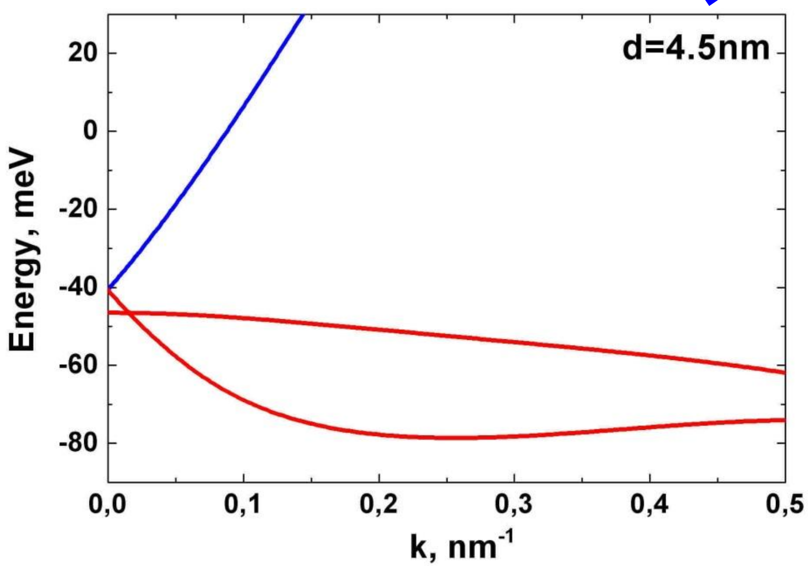


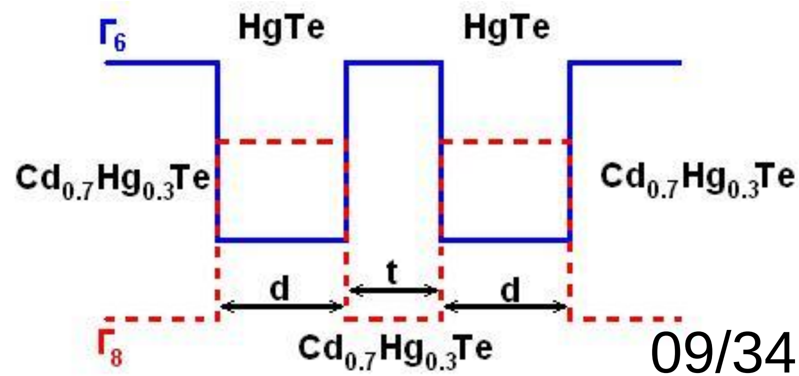


Band ordering at d=4.5nm

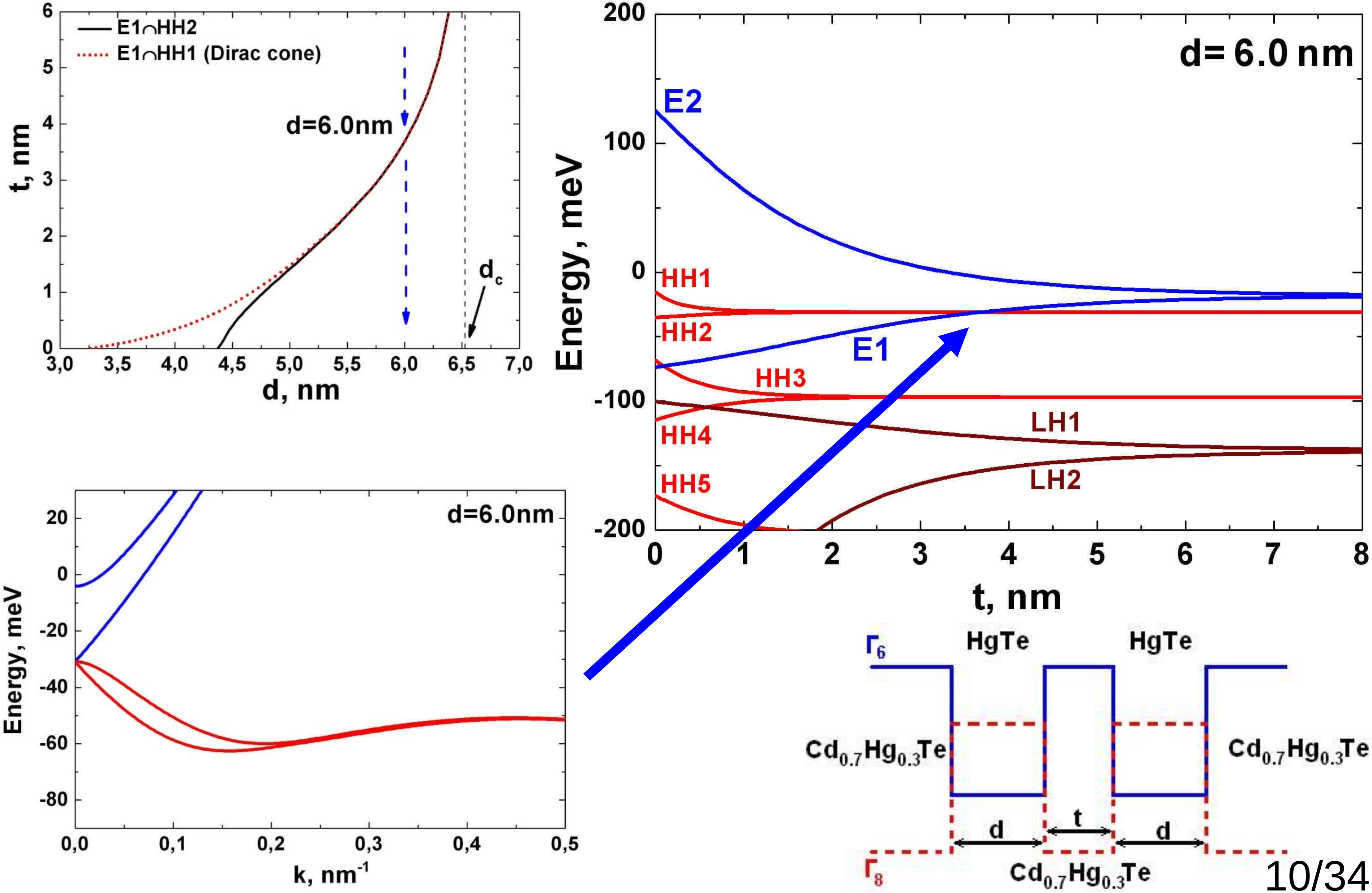




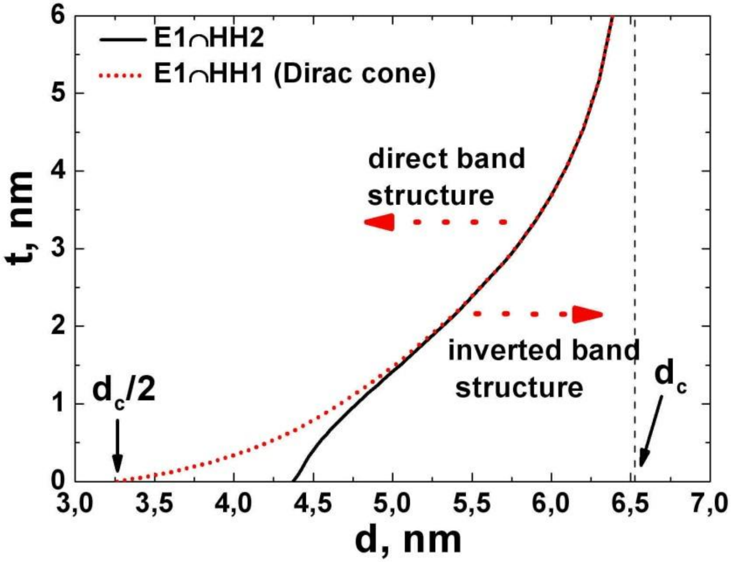


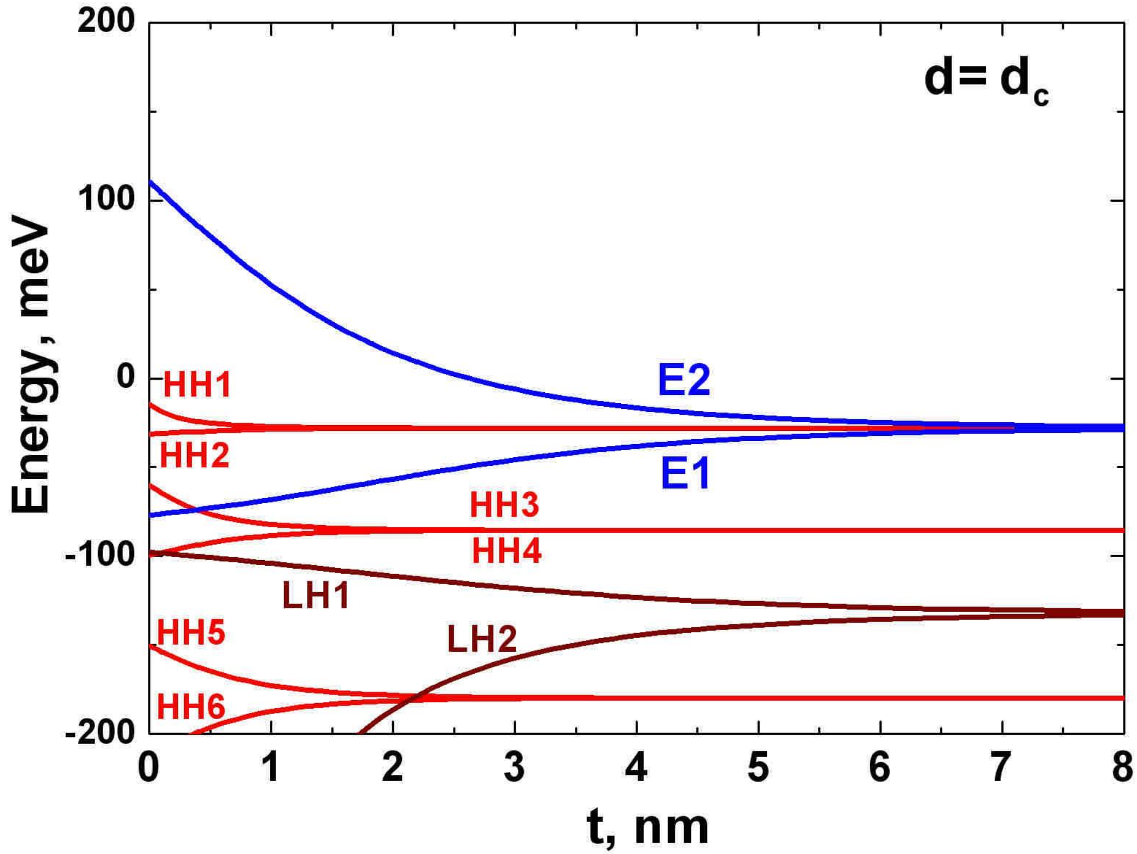


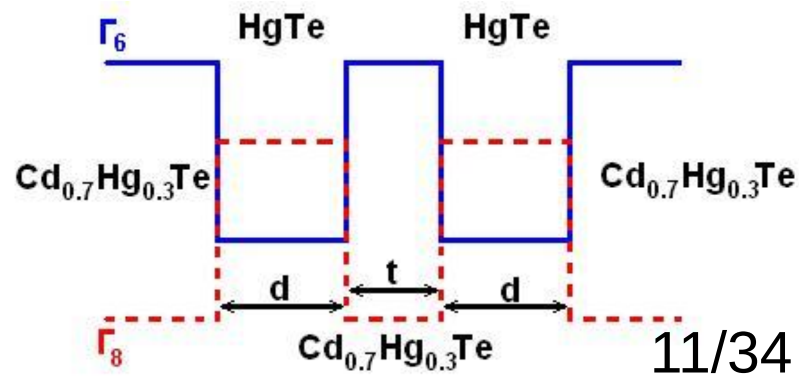
Band ordering at d=6.0nm



Band ordering at $d=d_c$







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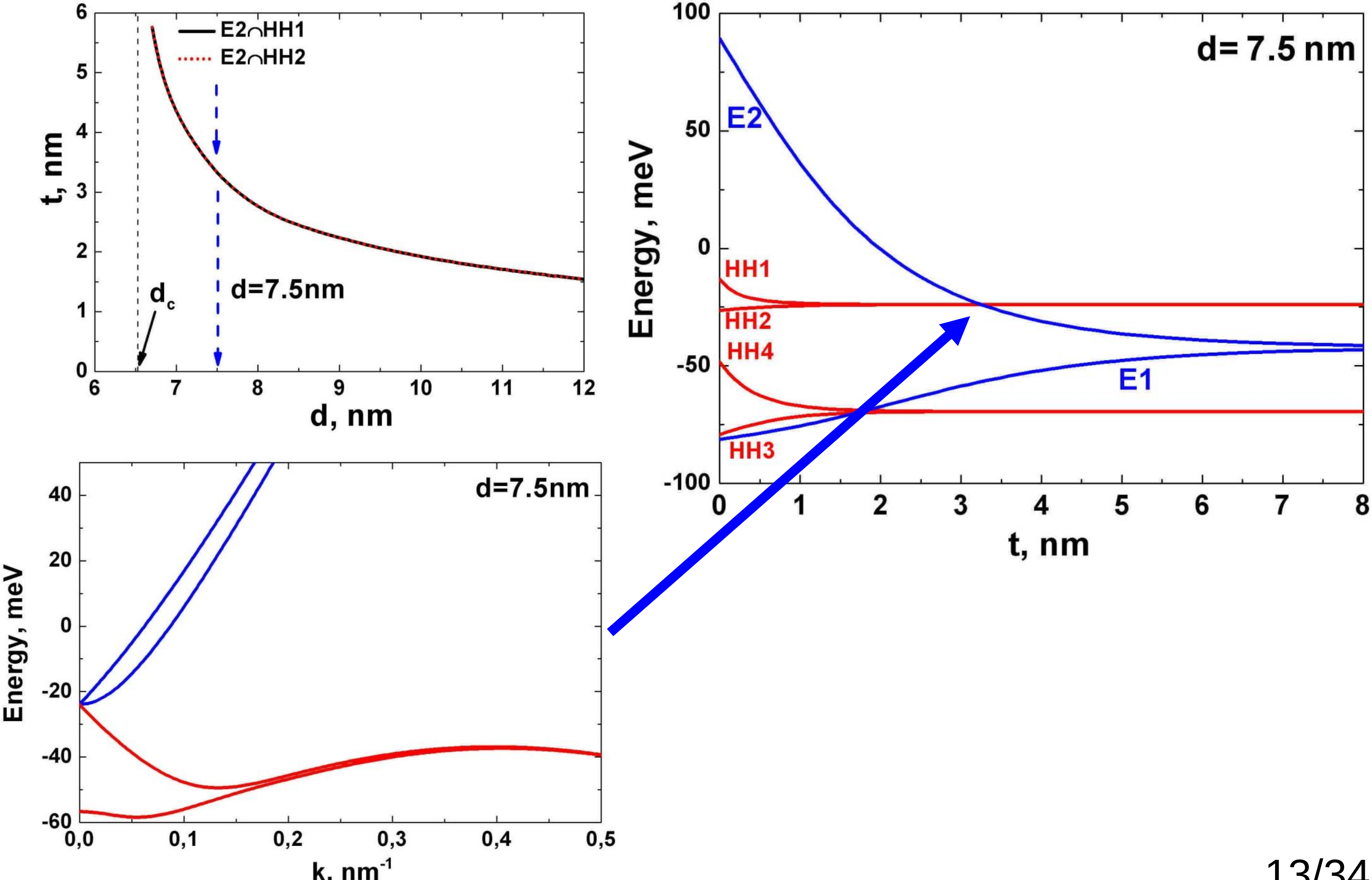
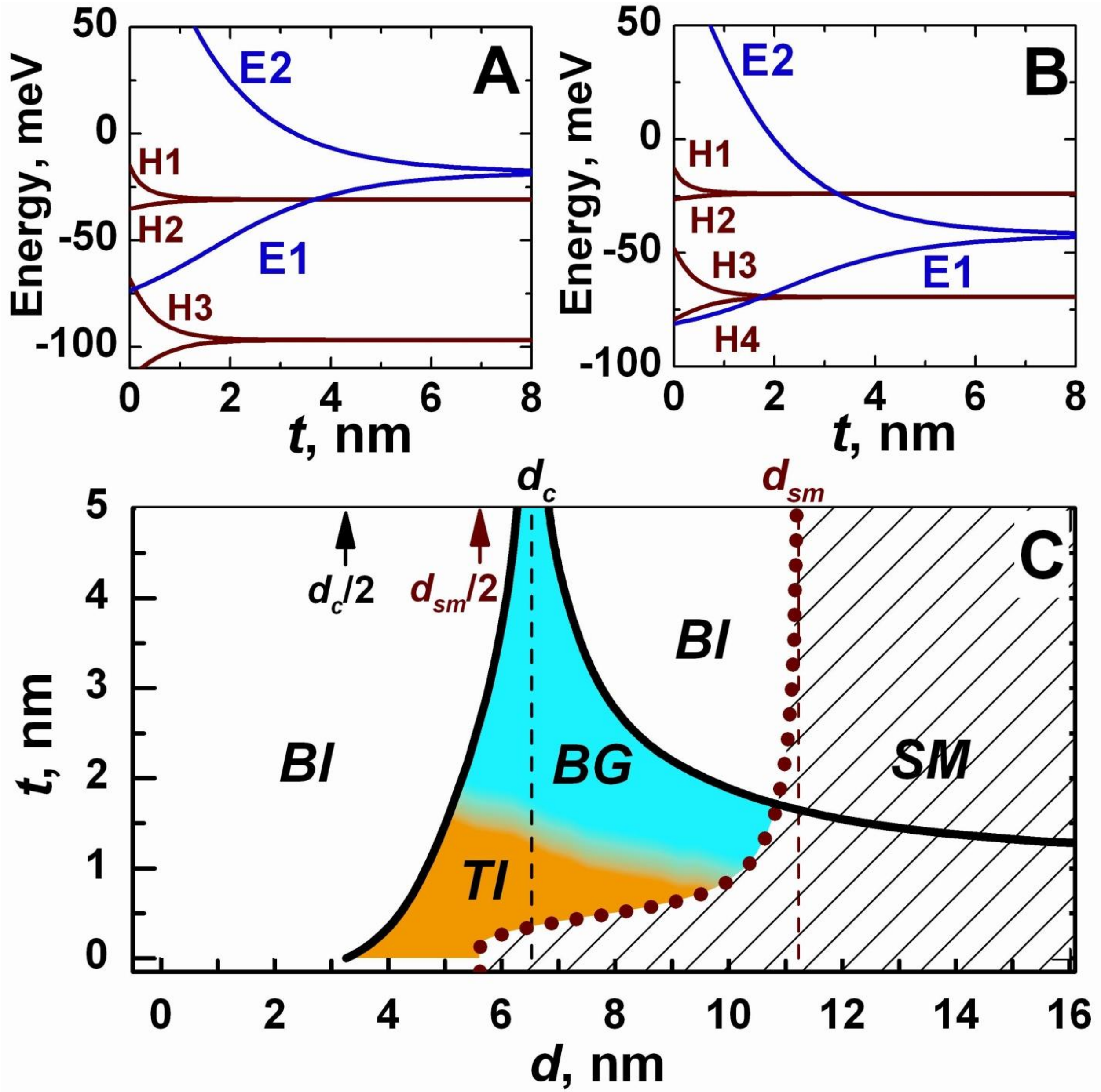
Massless fermions at inverted band structure



Phase diagram in HgTe/Cd(Hg)Te QW



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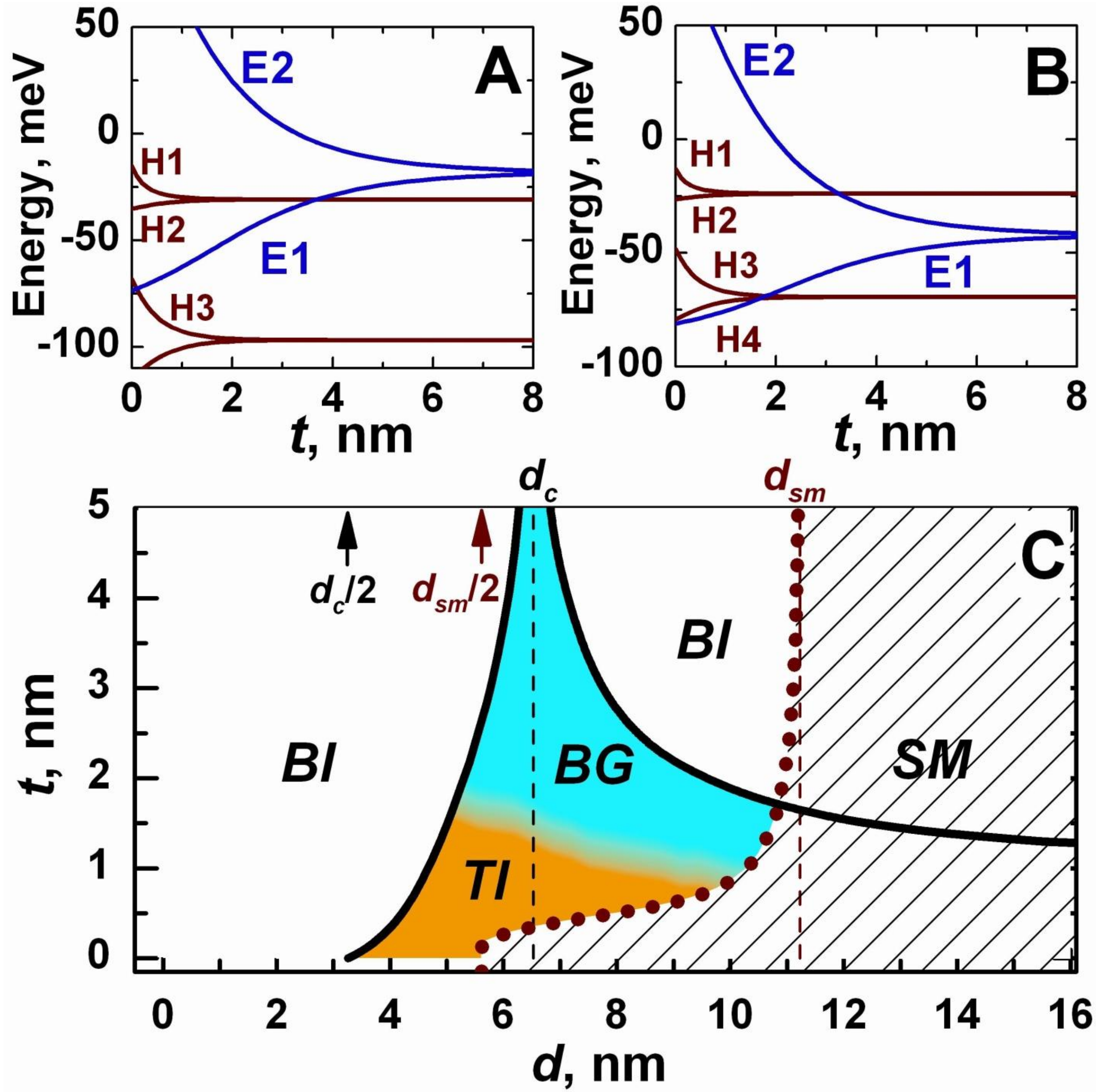
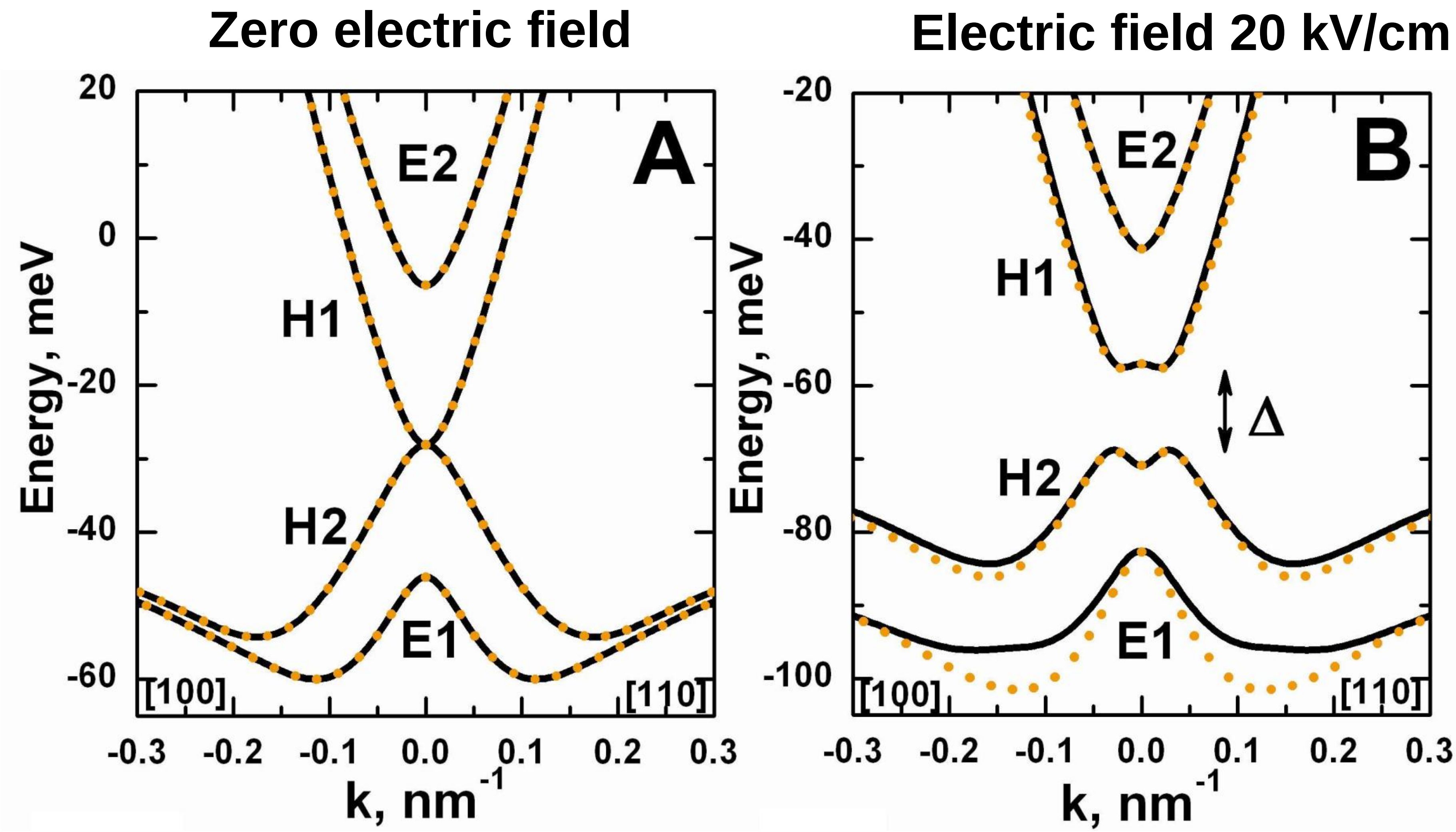
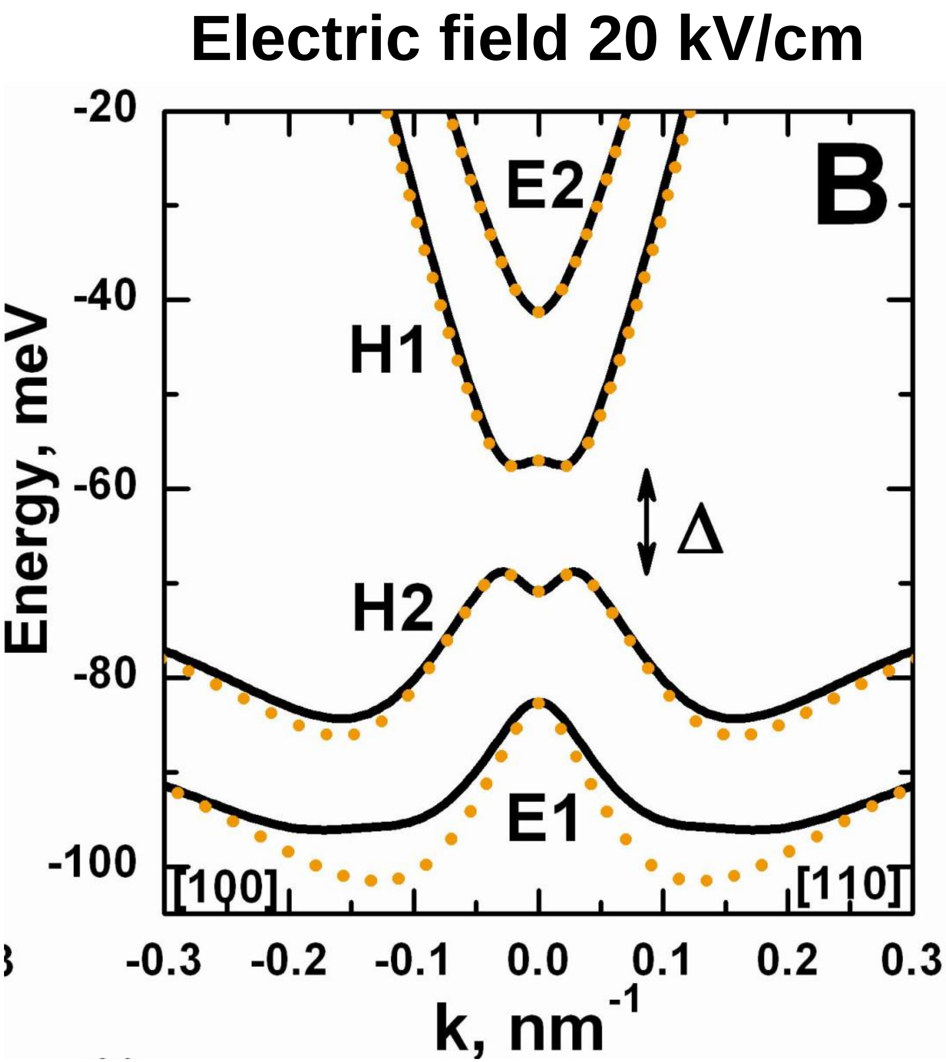


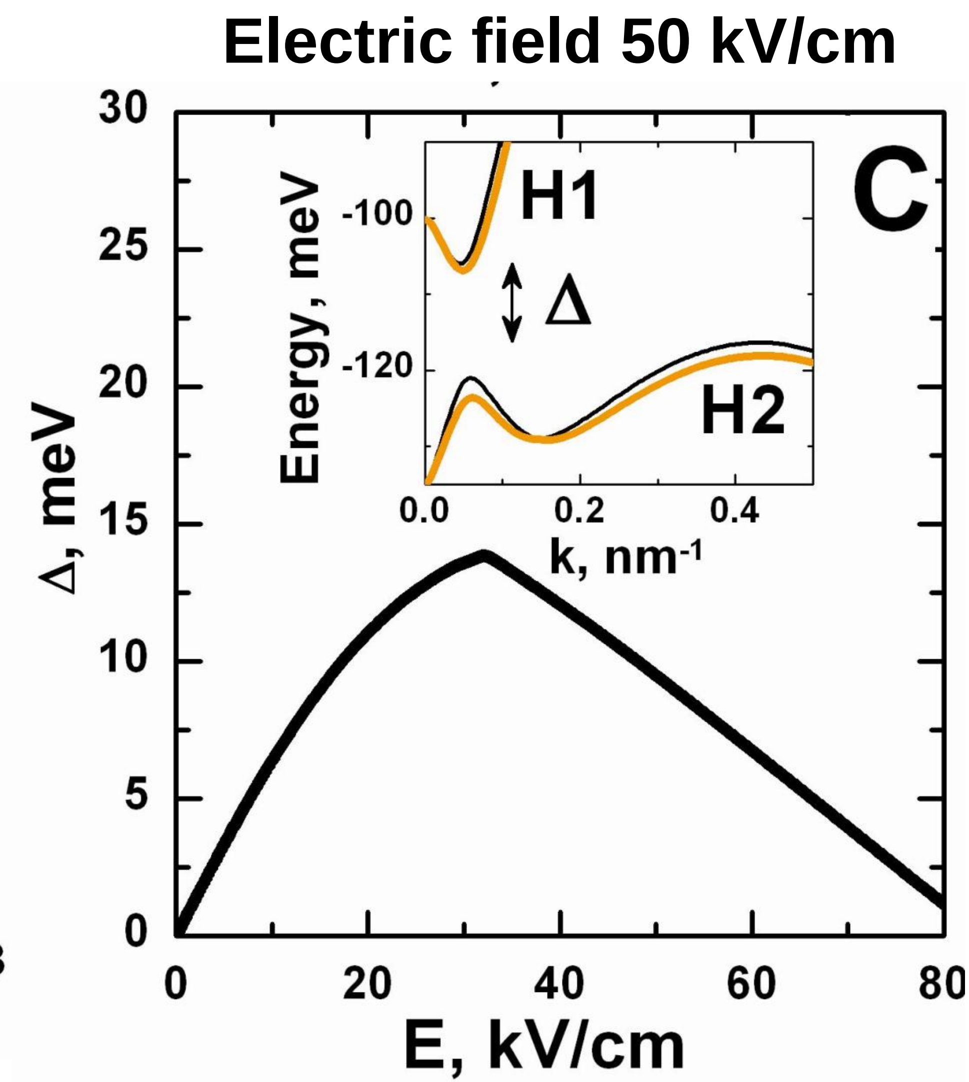
I. 'Bilayer graphene' phase at $d = d_c$



1) Spectrum consists two gapless isotropic parabolas
2) Non-zero band gap can be induced by breaking inversion symmetry between HgTe layers

II. 'Bilayer graphene' phase at $d = d_c$

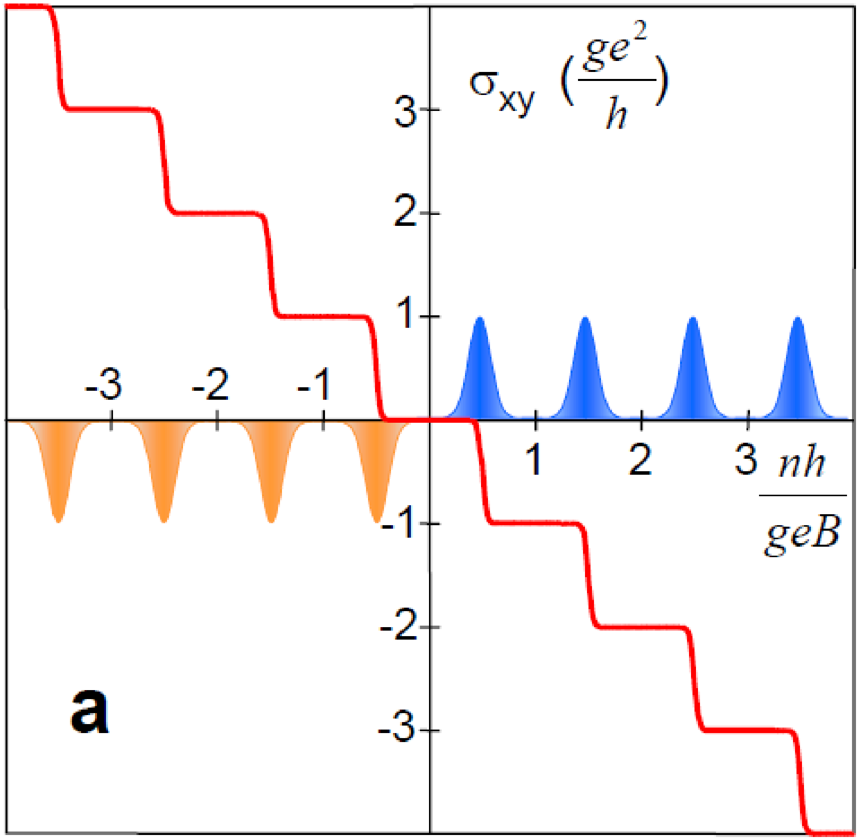




3) Electrically-tunable band gap

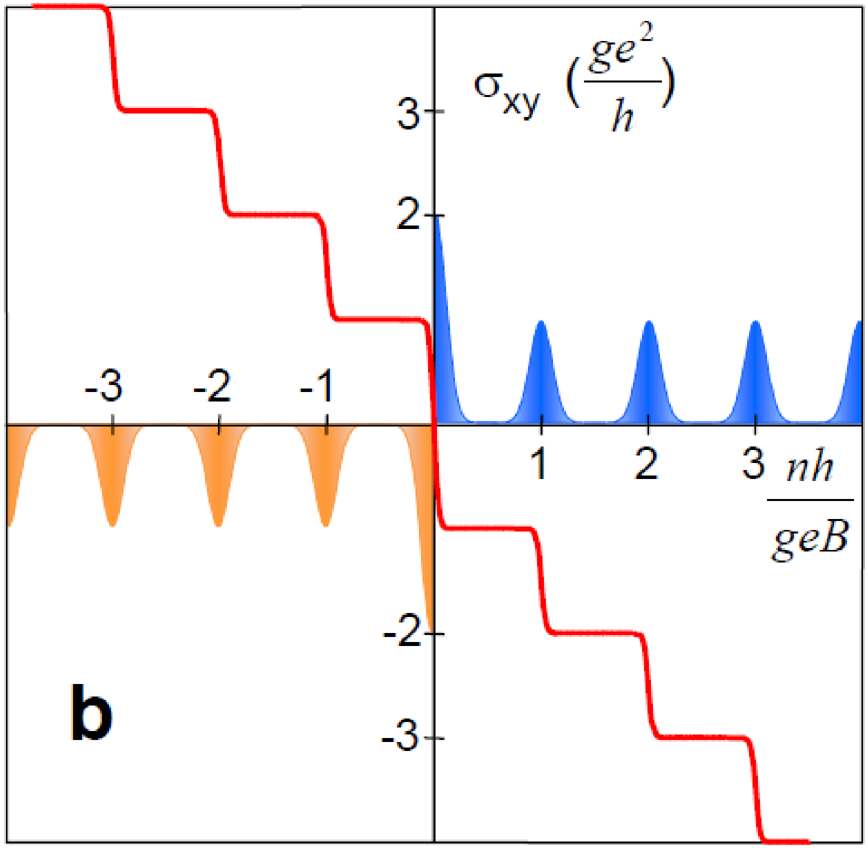
III. 'Bilayer graphene' phase at d = d_c. Unconventional quantum Hall effect.

Conventional 2DEG



Filling factor

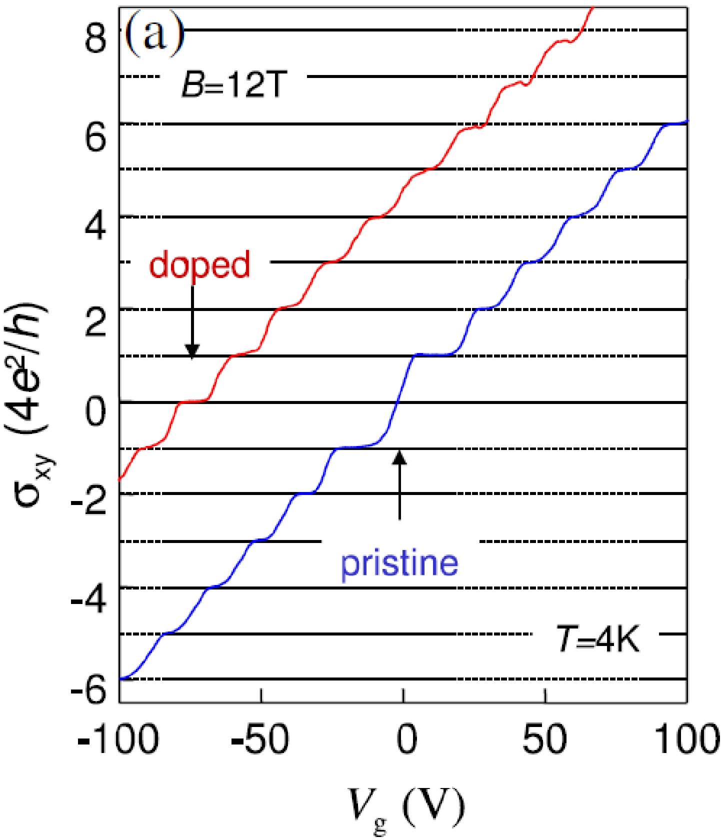
Natural BG

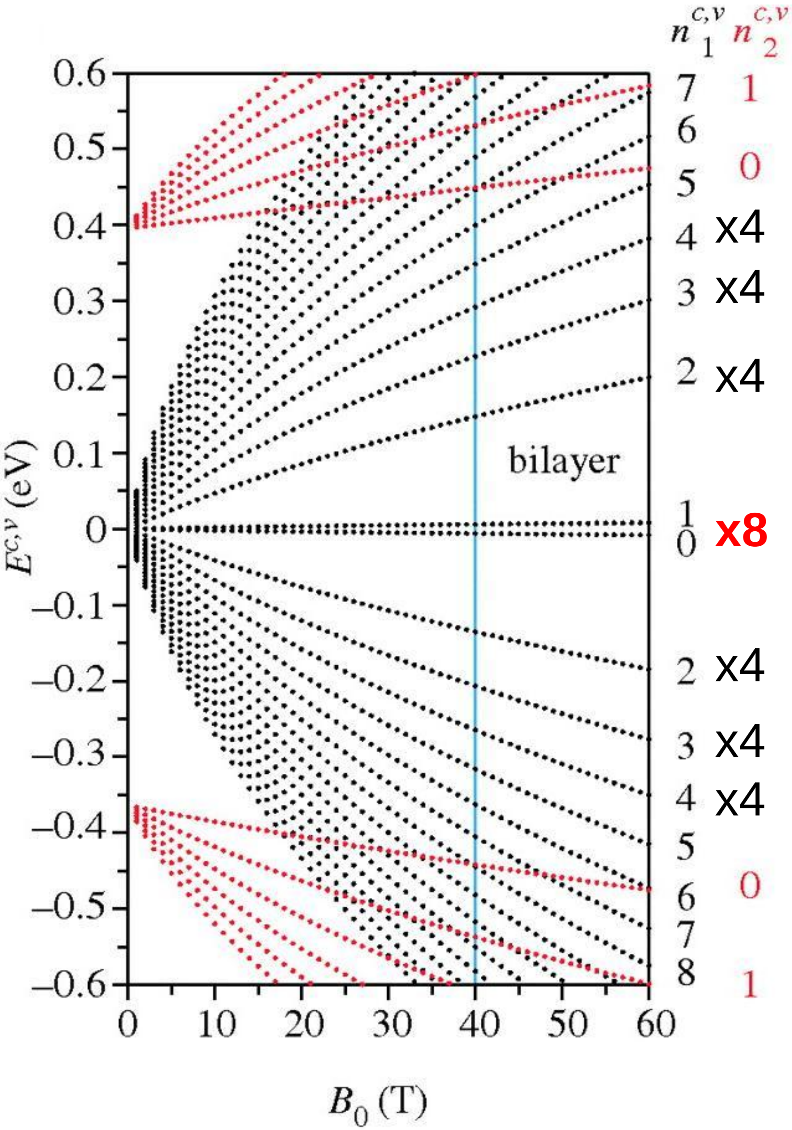


Filling factor

K. S. Novoselov, *et al*. *Nature Physics* **2**, 177 (2006).

III. 'Bilayer graphene' phase at $d = d_c$. Unconventional quantum Hall effect.



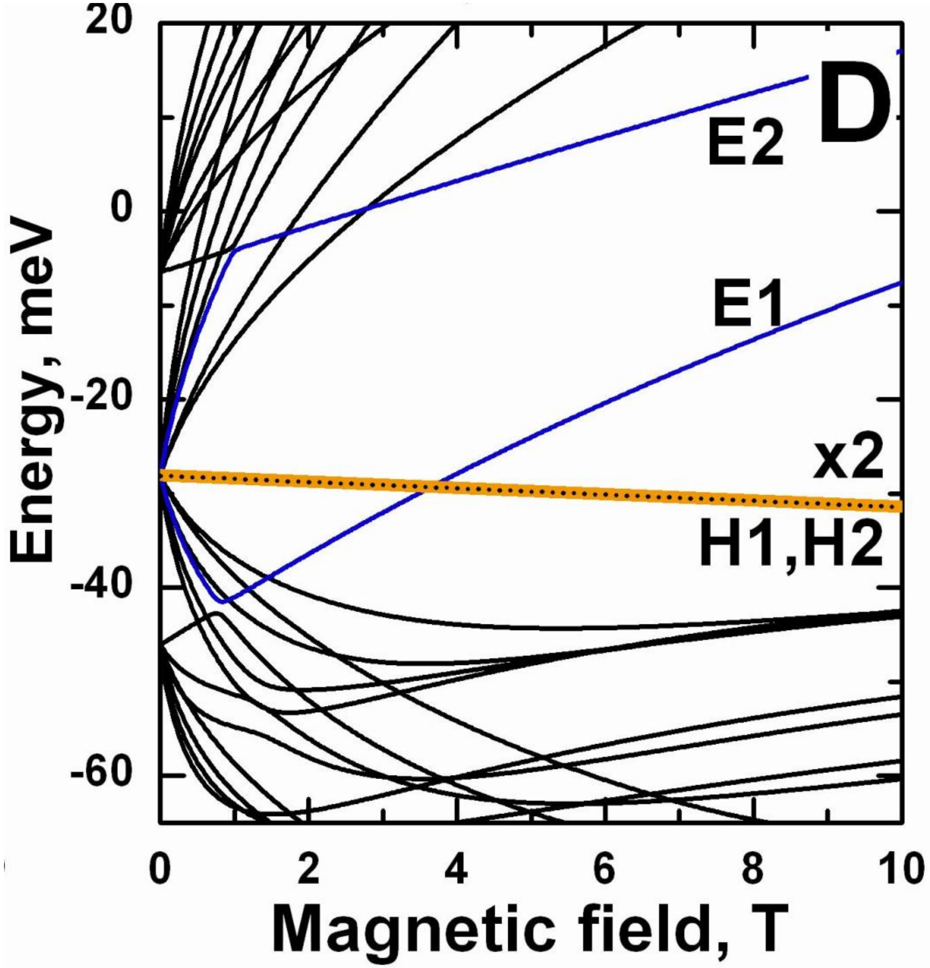


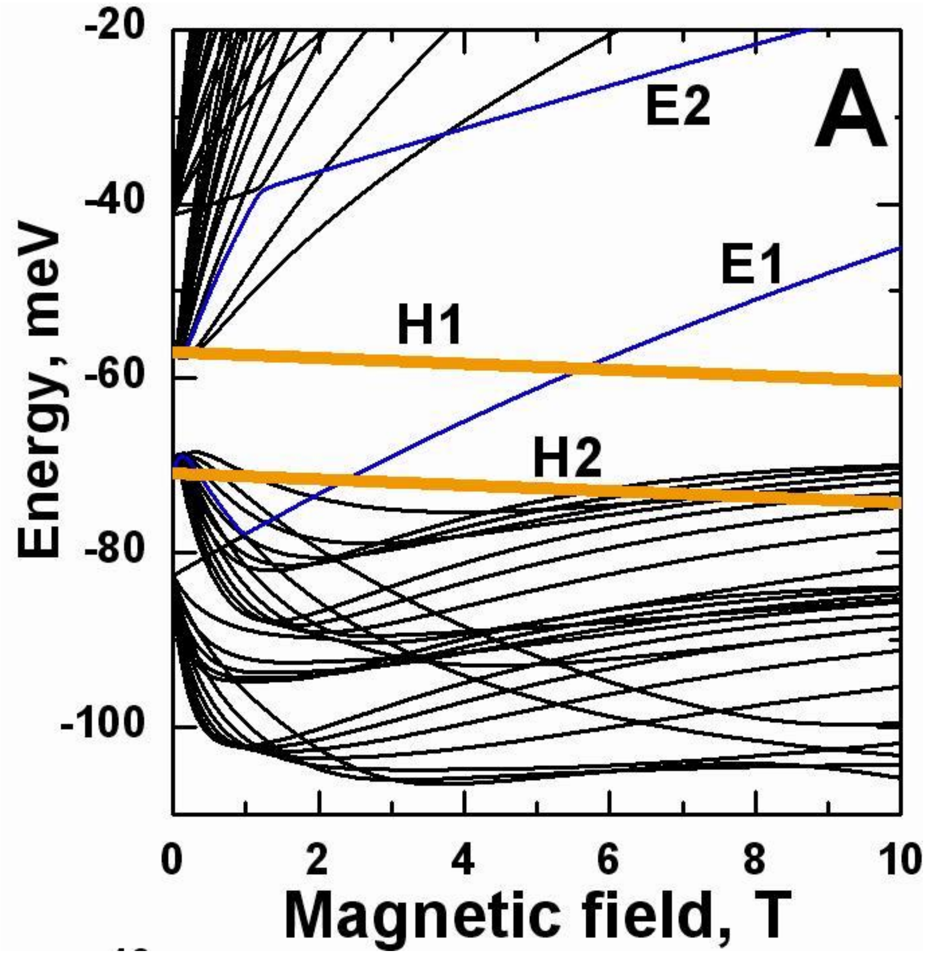
- Doubled degeneracy order of zero-energy LL
- SIA destroys unconventional QHE

E. V. Castro *et al. Phys. Rev. Lett.* **99**, 216802 (2007).

E. McCann, V. I. Fal'ko. *Phys. Rev. Lett.* **96**, 086805 (2006).

III. ‘Bilayer graphene’ phase at $d = d_c$. Unconventional quantum Hall effect.





4) Prediction unconventional QHE in double HgTe QWs as in natural BG

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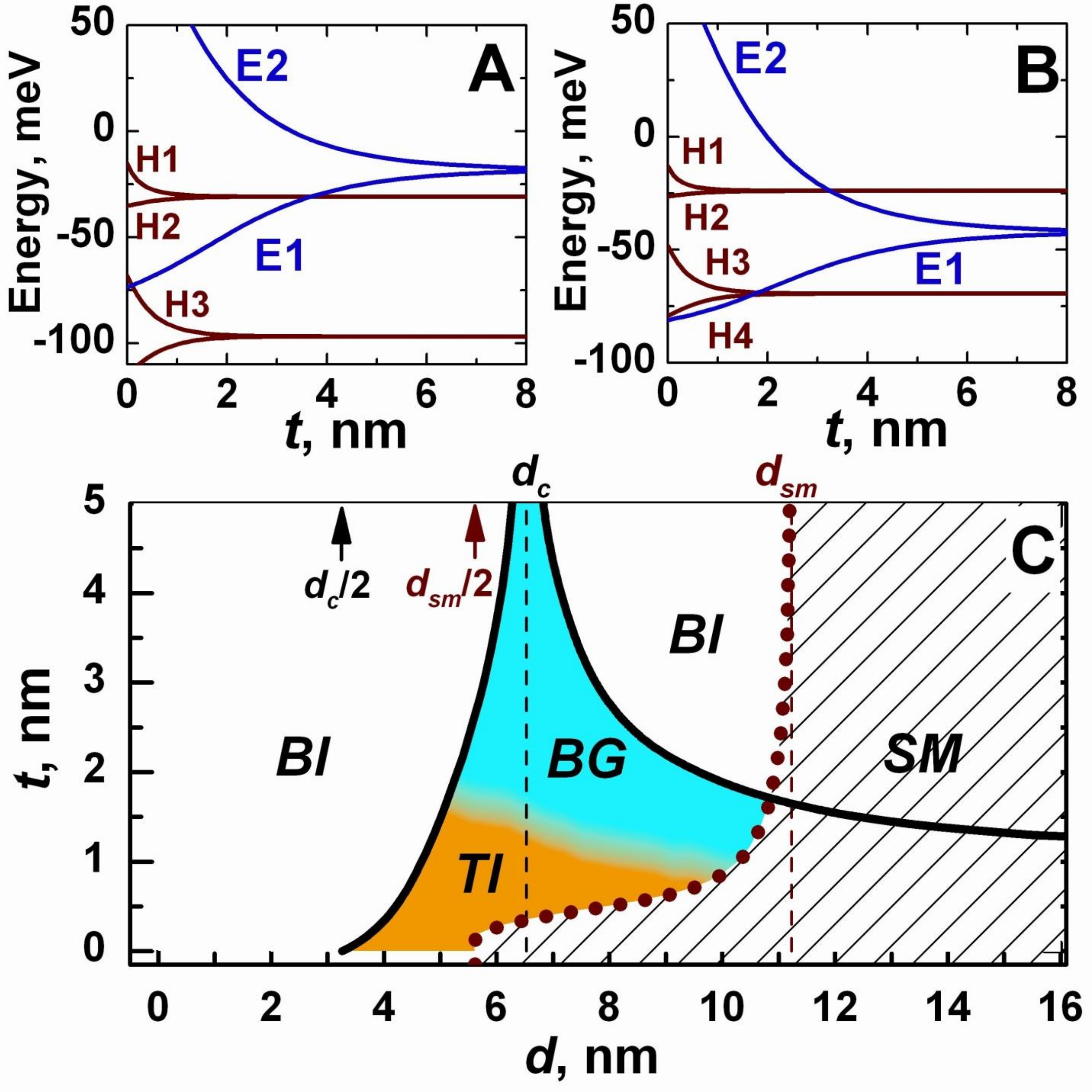


Generalization of BHZ model.

Straightforward derivation from the Kane Hamiltonian

Kramer's partners

|E1,+> |H1,+> |E2,-> |H2,->

$$H_{\uparrow}(\mathbf{k})$$

|E1,-> |H1,-> |E2,+> |H2,+>

$$H_{\downarrow}(\mathbf{k}) = H_{\uparrow}^{+}(-\mathbf{k})$$

BHZ model with M_1 parameter

|E1,+> |H1,+> |H2,-> |E2,->

$$H(k_x, k_y) = \begin{pmatrix} \varepsilon_{E1}(k) & -A_1 k_+ & R_1 k_-^2 & S_0 k_- \\ -A_1 k_- & \varepsilon_{H1}(k) & 0 & R_2 k_-^2 \\ R_1 k_+^2 & 0 & \varepsilon_{H2}(k) & A_2 k_+ \\ S_0 k_+ & R_2 k_+^2 & A_2 k_- & \varepsilon_{E2}(k) \end{pmatrix},$$

BHZ model with M_2 parameter

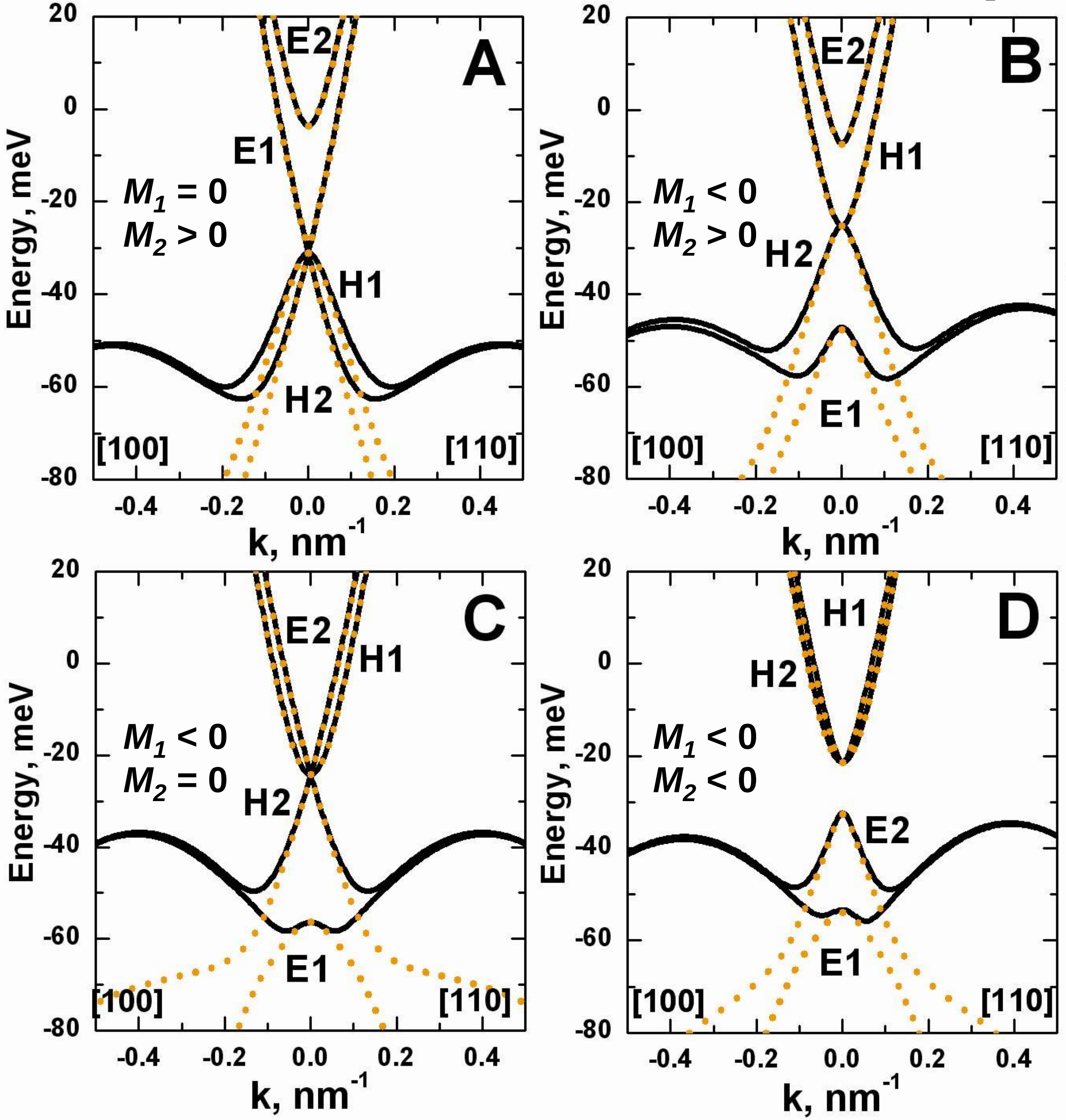
$$\varepsilon_{E1}(k) = C + \frac{\Delta_{H1H2}}{2} + 2M_1 + B_{E1}(k_x^2 + k_y^2),$$

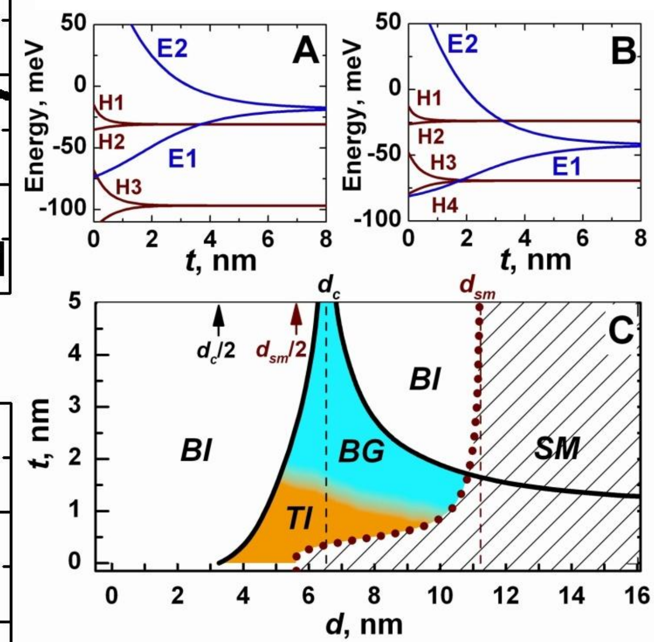
$$\varepsilon_{H1}(k) = C + \frac{\Delta_{H1H2}}{2} + B_{H1}(k_x^2 + k_y^2),$$

$$\varepsilon_{E2}(k) = C - \frac{\Delta_{H1H2}}{2} + 2M_2 + B_{E1}(k_x^2 + k_y^2)$$

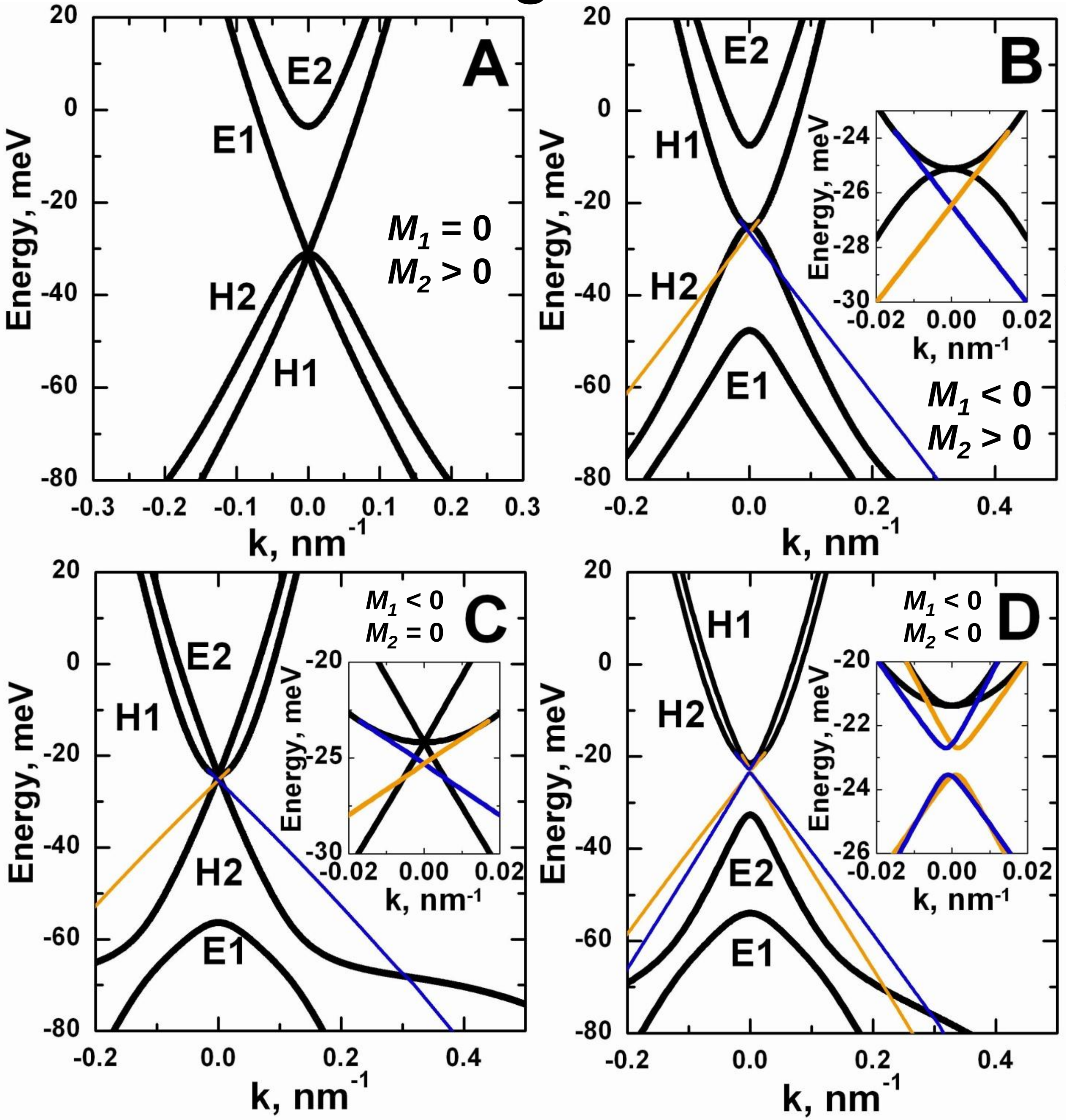
$$\varepsilon_{H2}(k) = C - \frac{\Delta_{H1H2}}{2} + B_{H2}(k_x^2 + k_y^2),$$

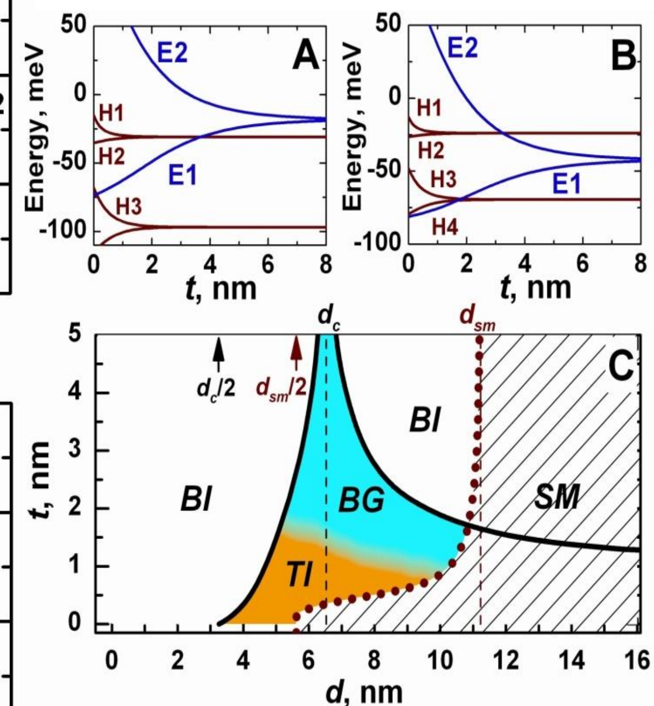
Kane Hamiltonian vs simplified model





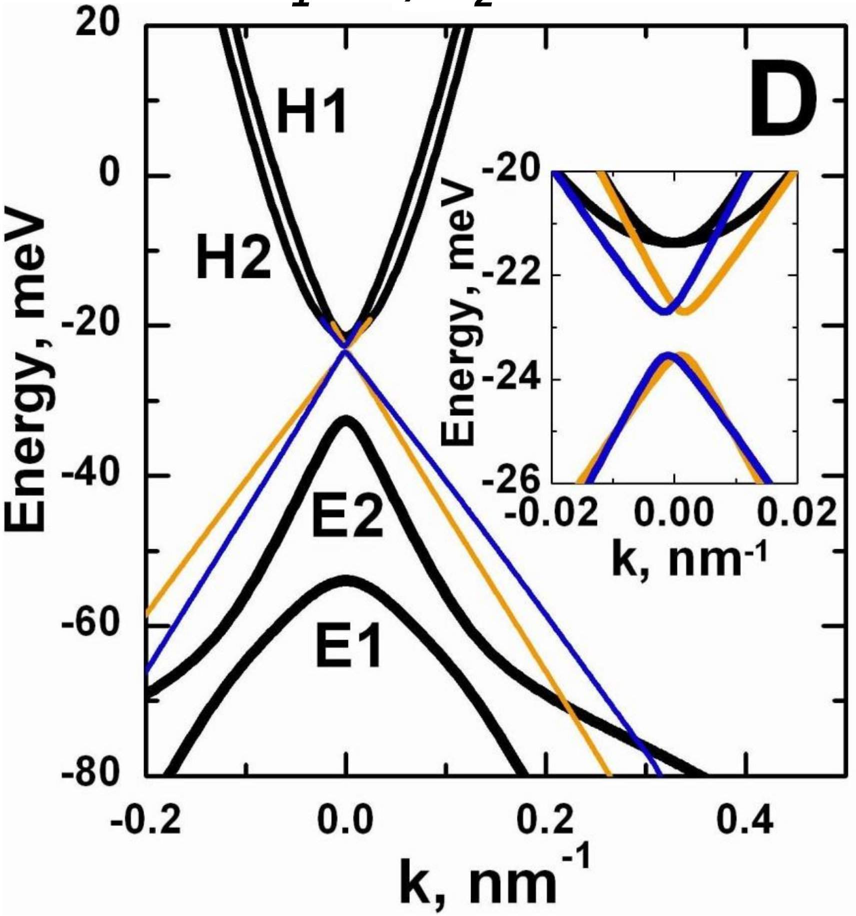
Picture of edge states in double HgTe QWs

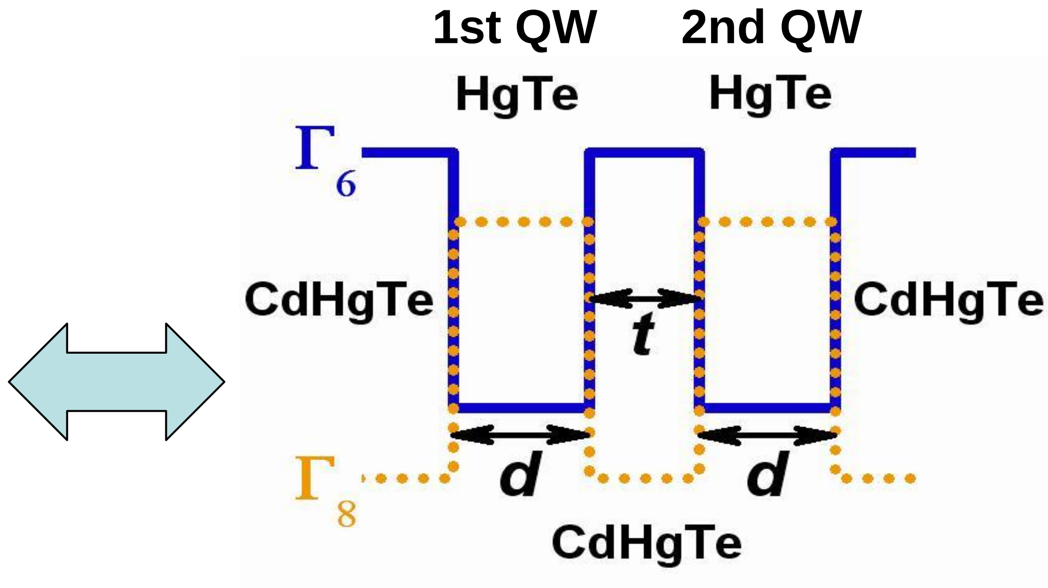




Band gap in the case of «double inversion»

$M_1 < 0$, $M_2 < 0$





$M_1 < 0$ $M_2 < 0$

Does «simple interpretation» exist?

Band gap in the case of «double inversion»

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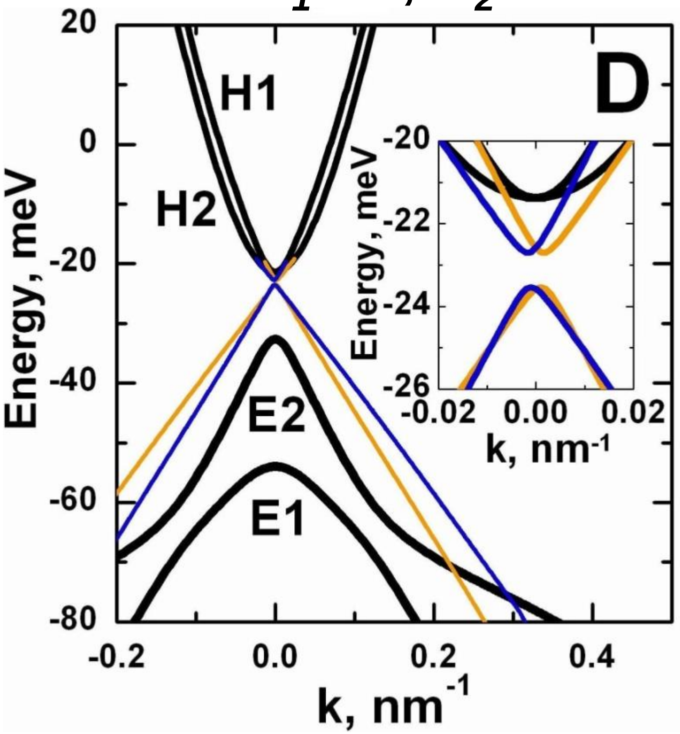
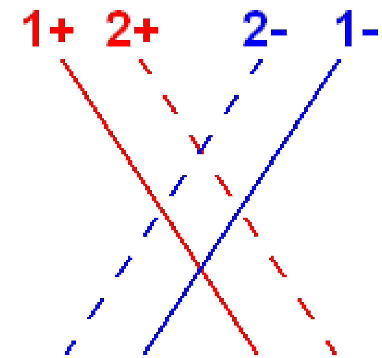
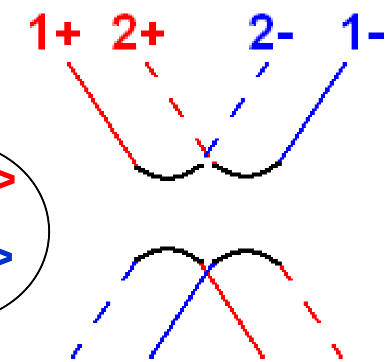


«Spin- conserving tunneling»



«Spin-dependent tunneling»

|E1,+> |H1,+> ⇔ |H2,-> |E2,->



BHZ model with M_1 parameter

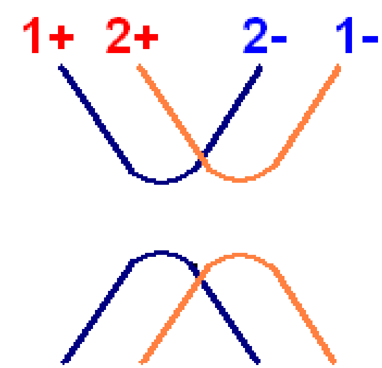
|E1,+> |H1,+> |H2,-> |E2,->

$$\begin{pmatrix} \varepsilon_1(k)+M_1-B_1k^2 & A_1k_+ & S_0k_-^2 & -R_0k_- \\ A_1k_- & \varepsilon_1(k)-M_1+B_1k^2 & 0 & \tilde{S}_0k_-^2 \\ S_0k_+^2 & 0 & \varepsilon_2(k)-M_2+B_2k^2 & -A_2k_+ \\ -R_0k_+ & \tilde{S}_0k_+^2 & -A_2k_- & \varepsilon_2(k)+M_2-B_2k^2 \end{pmatrix}$$

BHZ model with M_2 parameter

Kramer's partners

|E1,+>	|E1,->
|H1,+>	|H1,->
|E2,->	|E2,+>
|H2,->	|H2,+>



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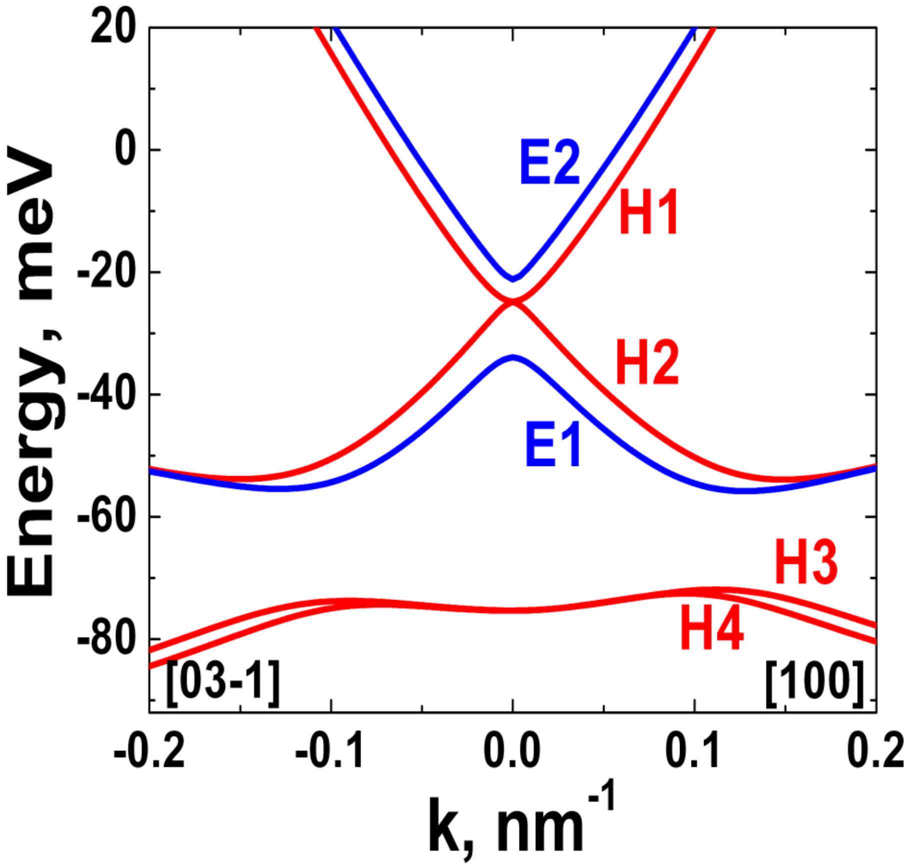
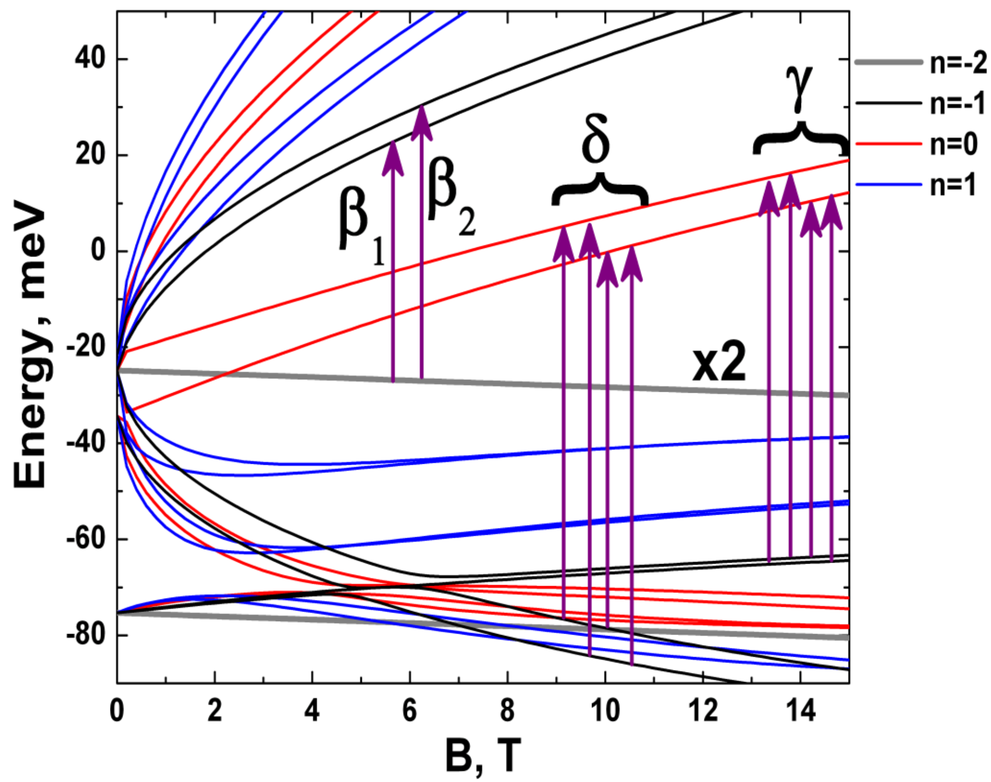
Landau Level spectroscopy of ‘bilayer graphene’





Samples

Made in Novosibirsk

N.N. Mikhailov,
S.A. Dvoretskii

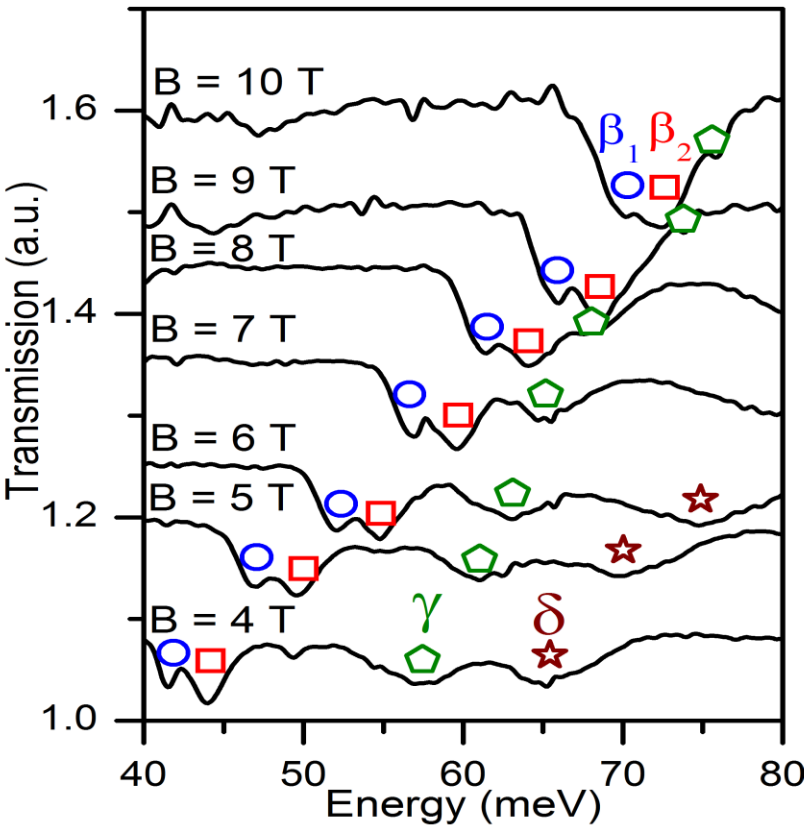
Measurements

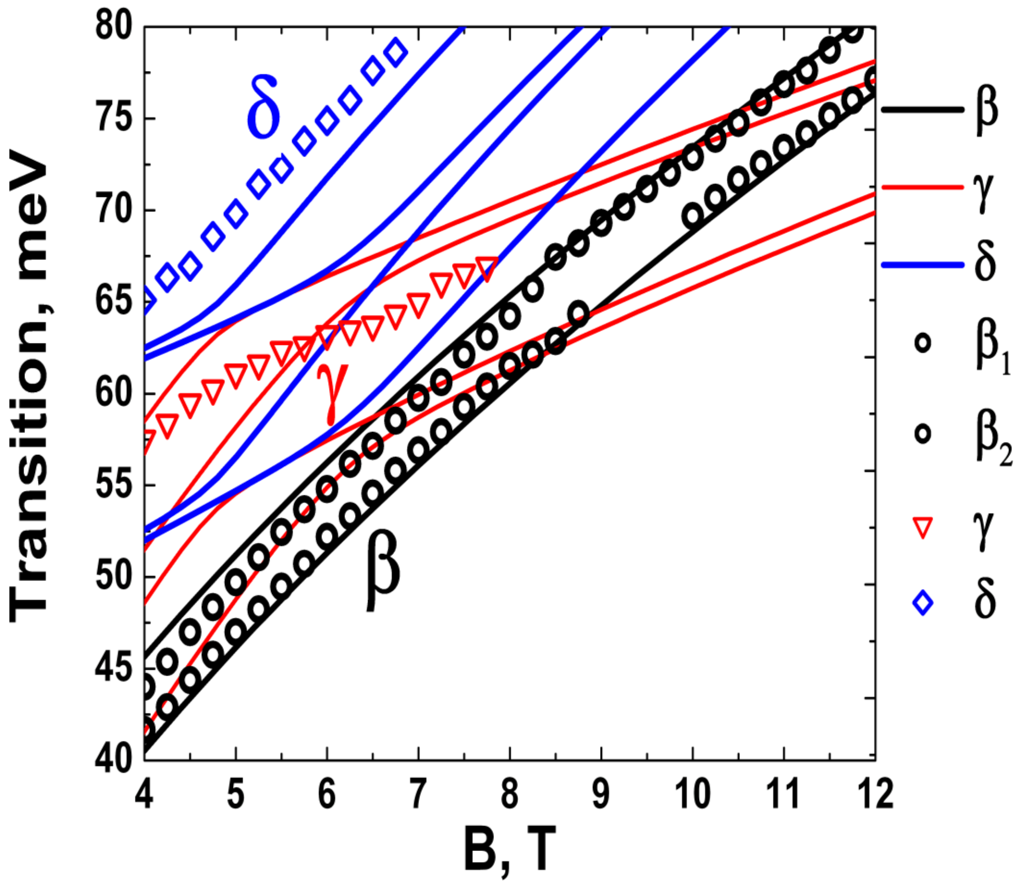
Made in Montpellier

S. Ruffenach, C. Consejo,
F. Teppe

LABORATOIRE CHARLES COULOMB MONTPELLIER

Landau Level spectroscopy of 'bilayer graphene'





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Acknowledgements

V.I. Gavrilenko

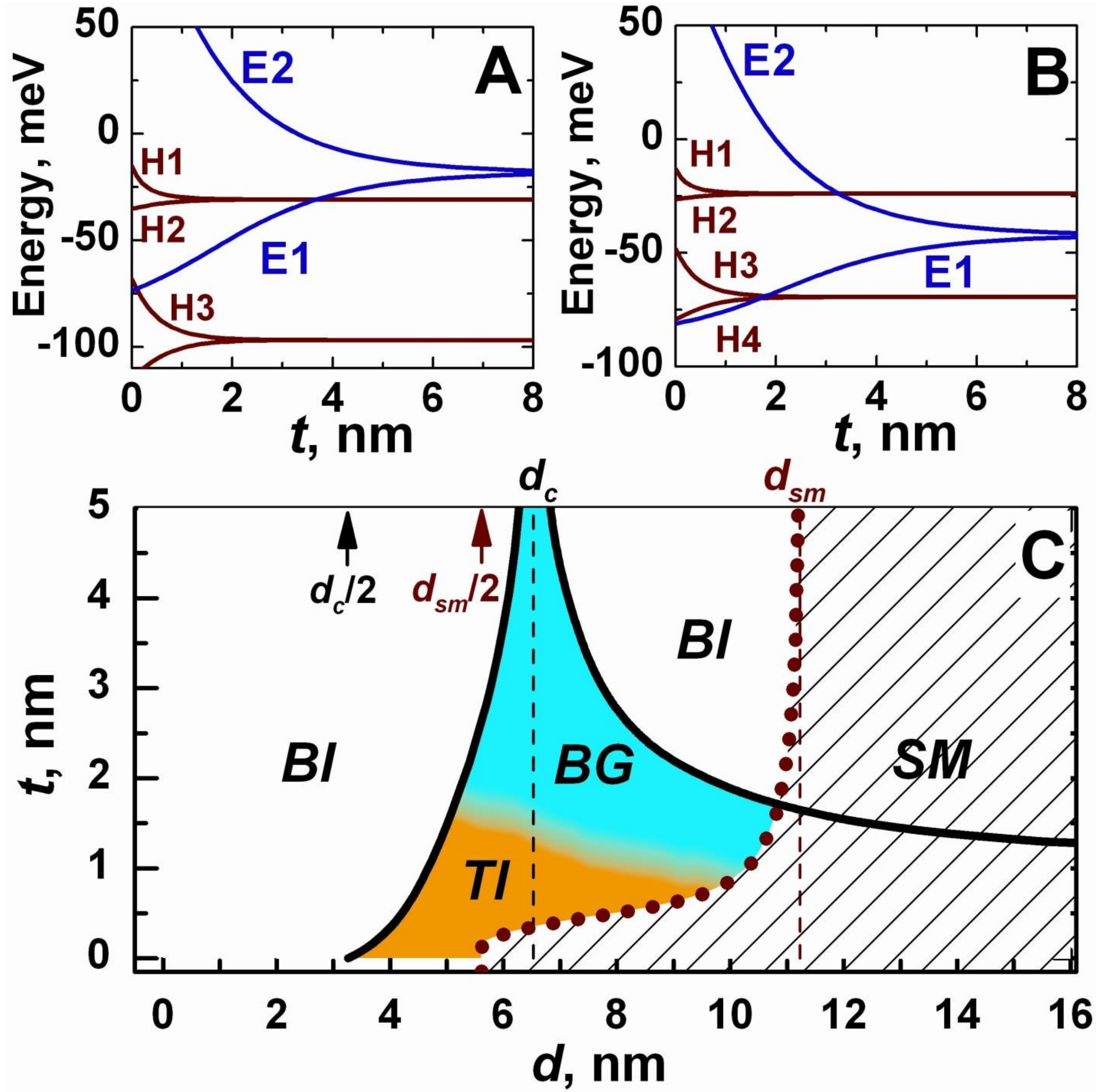
Laboratoire Charles Coulomb, UMR 5221
Montpellier

A. Fedorenko, T. Louvet, D. Carpentier

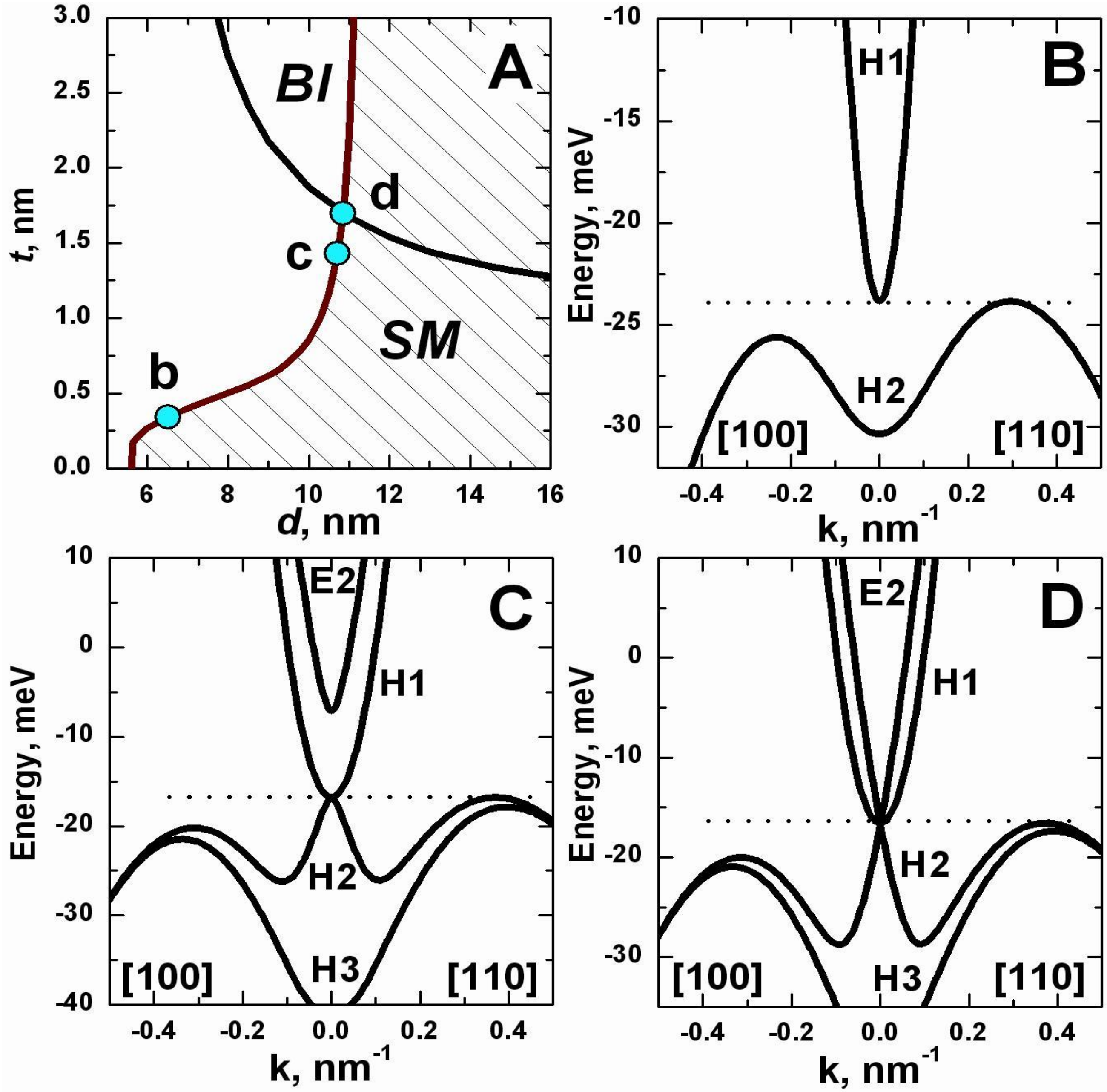
Physics Laboratory at ENS de *Lyon*

Thank you for your attention!

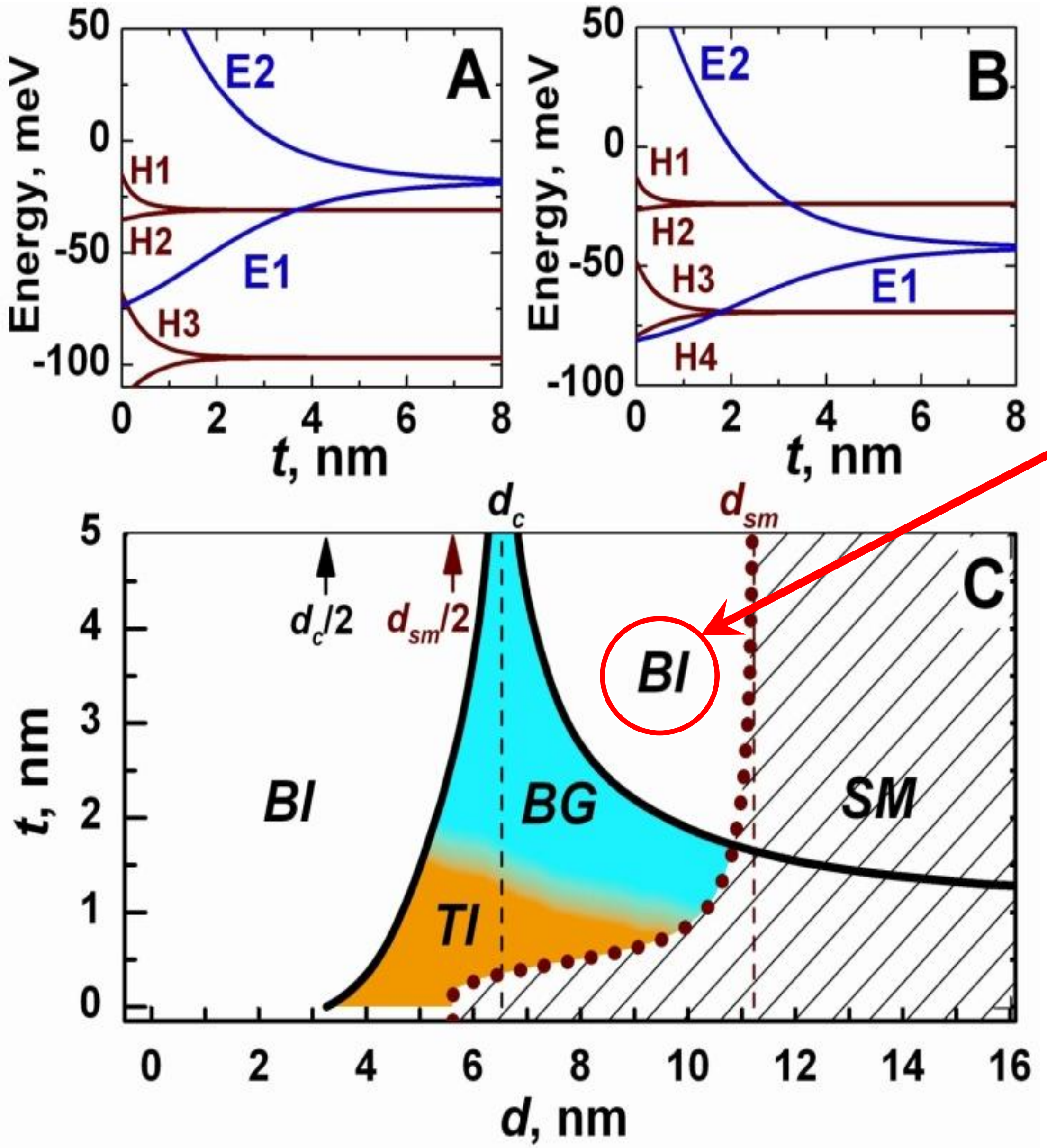
Phase diagram in HgTe/Cd(Hg)Te QW



Semimetal phase in HgTe/Cd(Hg)Te QW



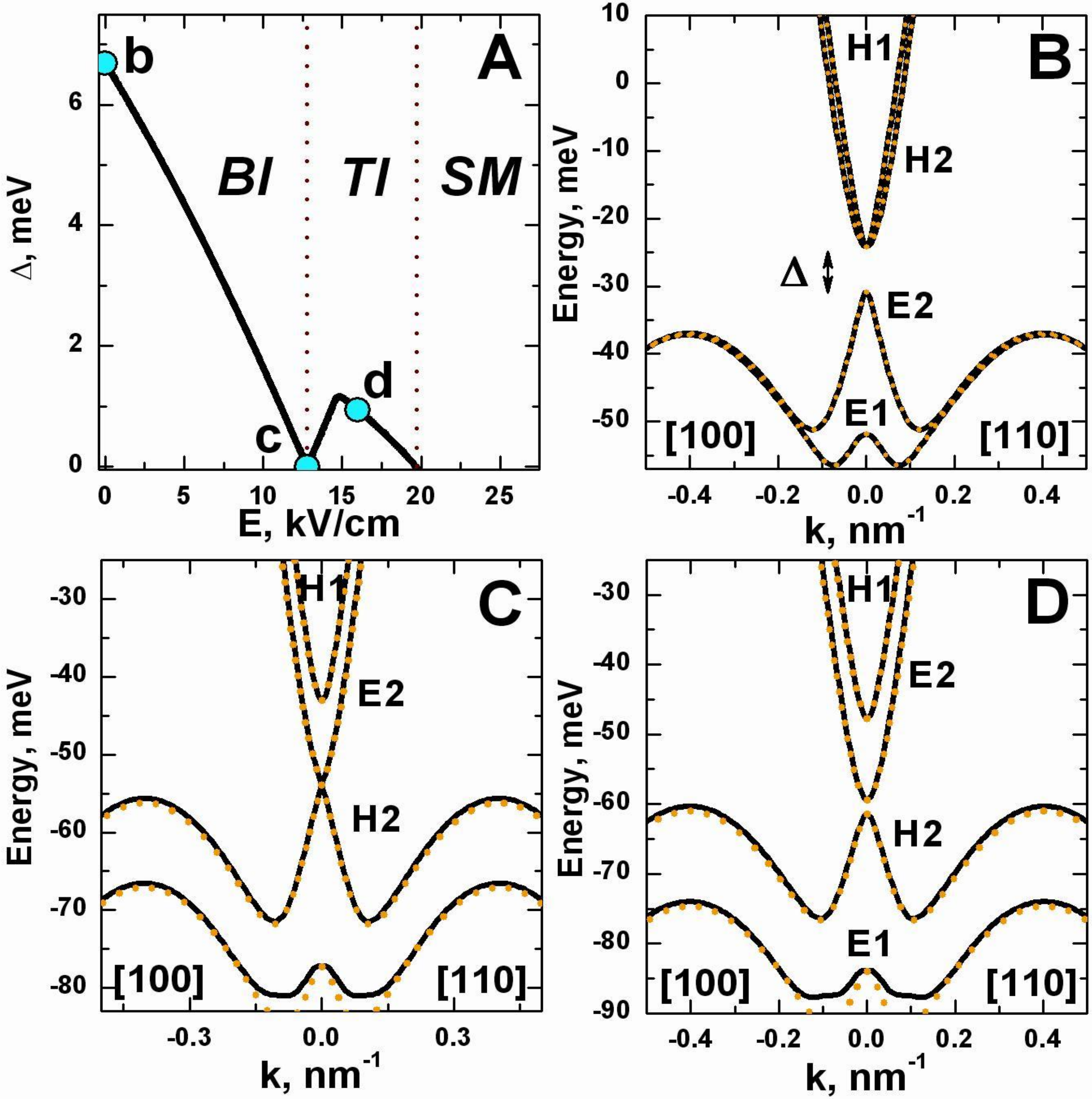
Specific band insulator phase at inverted band structure QWs



This BI phase shares some properties of natural BG:

1) Electrically-tunable band gap
2) Unconventional QHE

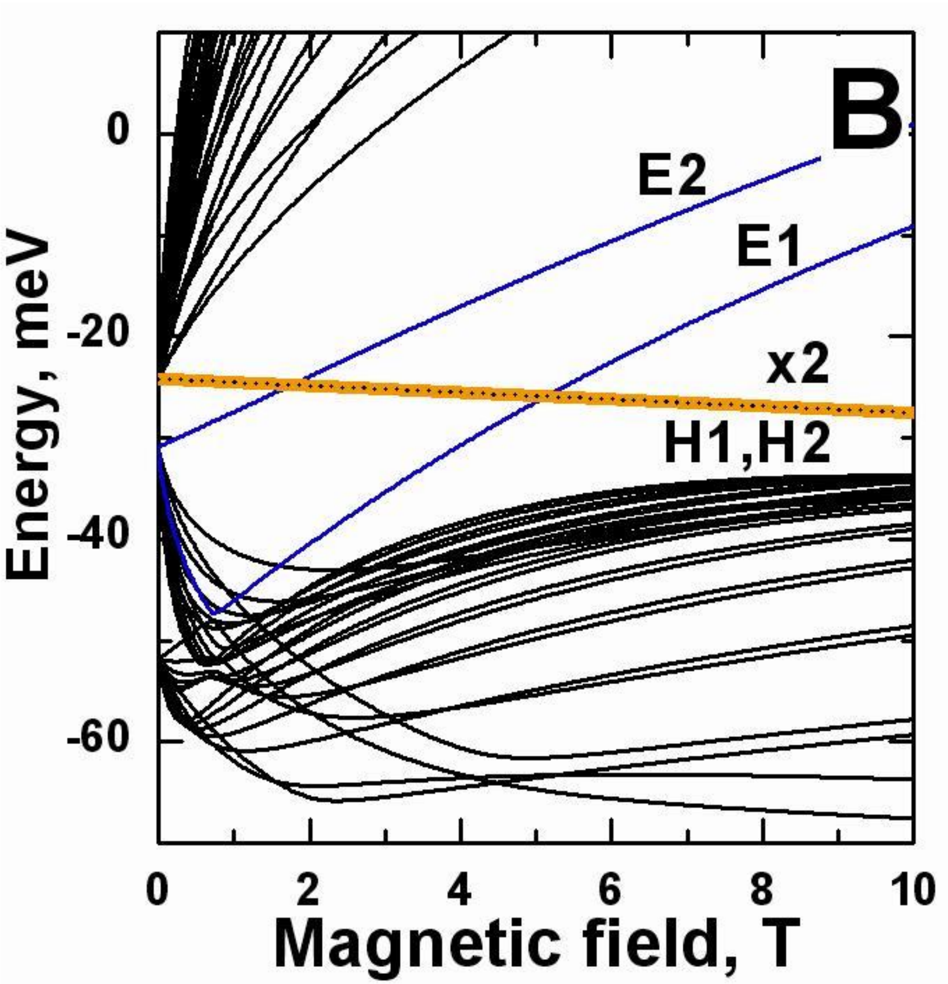
Electrically-tunable band gap in BI phase at $d>d_c$



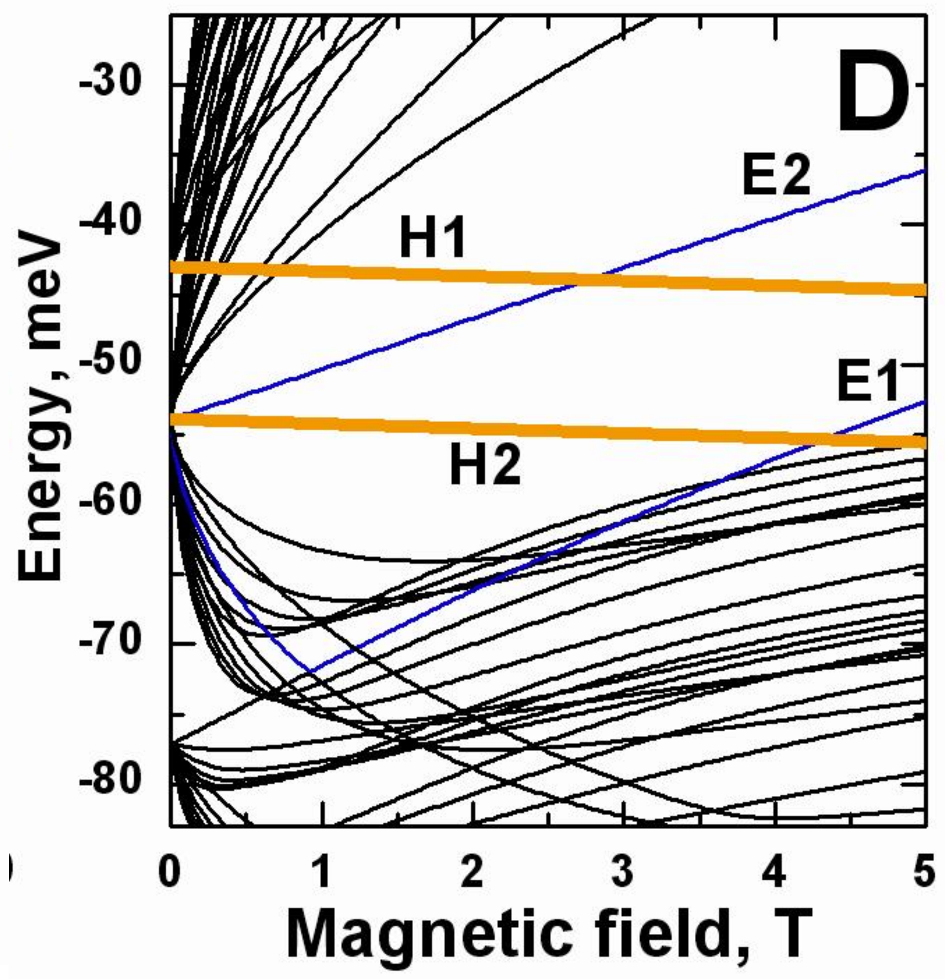
Electrical-field-driven transition between BI and TI phase

Unconventional QHE in BI phase at $d>d_c$

Zero electric field



Electric field ≈ 12.8 kV/cm



- Doubled degeneracy order of zero-mode LL
- SIA destroys unconventional QHE