# Revisiting the pseudo-gauge fields in strained graphene

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**Výjezdní seminář ÚCJF - Malá Skála**
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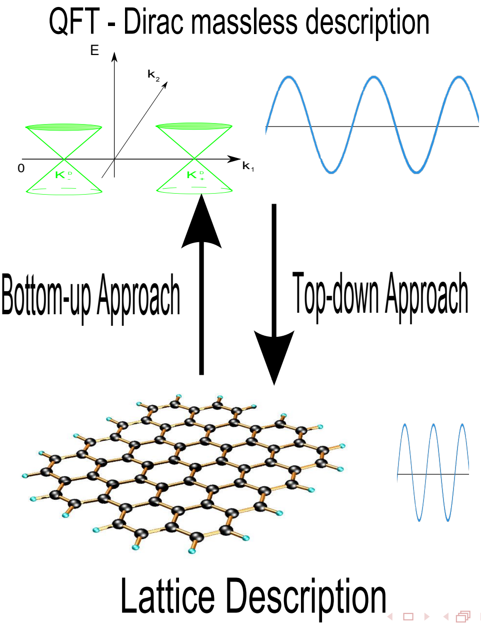
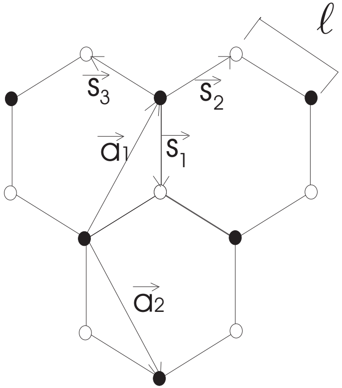

QFT - Dirac massless description
E
k2
k1
0
Bottom-up Approach
Top-down Approach
Lattice Description

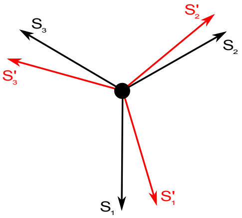
# The honeycomb graphene




● = sublattice $L_A$ ○ = sublattice $L_B$

# The strain tensor

$\vec{x'} = \vec{x} + \vec{u}(\vec{x})$ **Deformation vector**

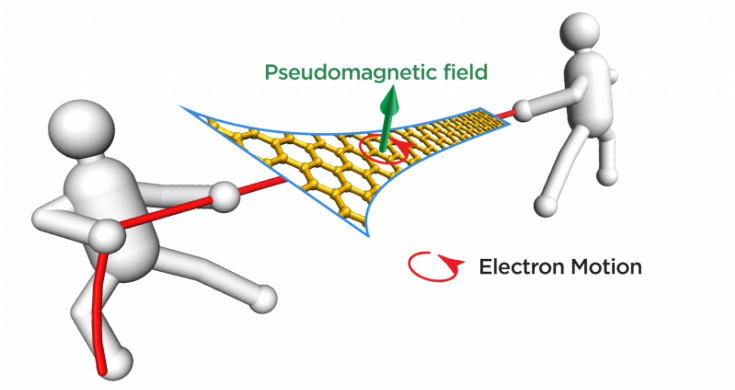



Near-neighbors infinitesimal vector transformation $\vec{s}'_i = (I + \bar{\bar{\epsilon}})\vec{s}_i$

$u^{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x^j} + \frac{\partial u_j}{\partial x^i}\right)$ **Strain tensor**

# The pseudo-gauge field

Experimentally (2010) was observed that the strain can mimic an effective magnetic field ($\sim$ 300 T)



# The pseudo-gauge field

Staring from the tight-binding Hamiltonian

$$H = -\sum_{\vec{r}\in L_A}\sum_{i=1}^{i=3}\left(a^\dagger(\vec{r})t_i b(\vec{r}+\vec{s}_i') + b^\dagger(\vec{r}+\vec{s}_i')t_i a(\vec{r})\right). \qquad (1)$$

$$t_i = \eta \exp\left[-\beta\left(\frac{|\vec{s}_i'|}{\ell} - 1\right)\right], \qquad (2)$$

$\eta$ nearest-neighbor hopping energy

$\beta = \left|\frac{\partial \ln \eta}{\partial \ln \ell}\right|$

$a, a^\dagger (b, b^\dagger)$ anticommuting annihilation and creation operators related to $L_A(L_B)$

# The pseudo-gauge field

$$H = -iv_F \int d^2x \psi_+^\dagger \vec{\sigma} \cdot \left( \vec{\nabla} + i\vec{A} \right) \psi_+ ,$$

where

$$\psi_\pm = \begin{pmatrix} b_\pm \\ a_\pm \end{pmatrix}$$

$$A^j = -\frac{\beta}{2\ell} \epsilon^{jp} K^{pmn} u_{mn}$$

**Pseudo-gauge field**

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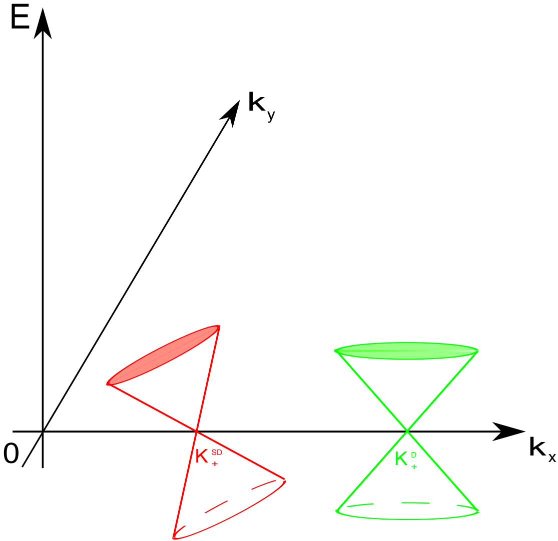
$$A^j = -\frac{\beta}{2\ell} \epsilon^{jp} K^{pmn} u_{mn}$$ **Pseudo-gauge field**

$$K^{jmn} = -\frac{4}{3\ell^3} \sum_{i=1}^{i=3} (s_i)^j (s_i)^m (s_i)^n$$ **Non-isotropic three-rank tensor**

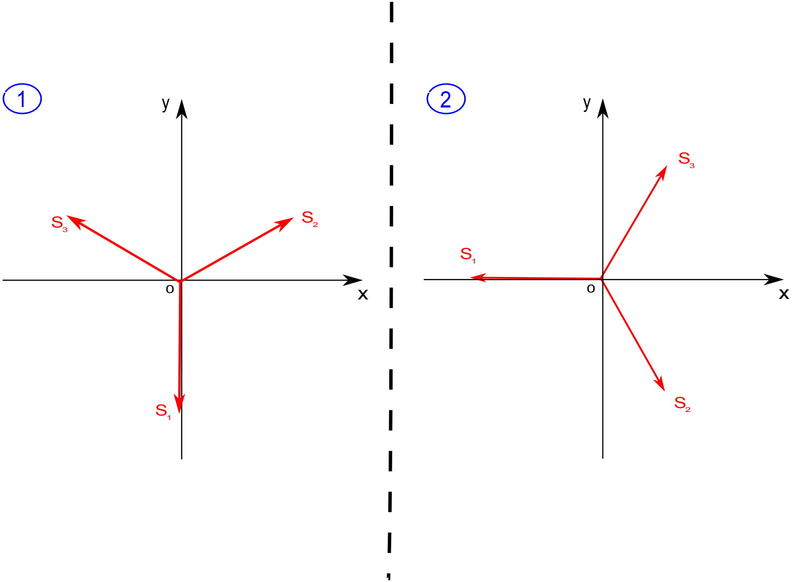
$$K^{222} = -K^{112} = -K^{121} = -K^{211} = 1$$

For this choice of basis vectors, we have $\vec{A} \propto \left(u_{xx} - u_{yy}, 2u_{xy}\right)$

# The effect of strain on the Fermi lightcones

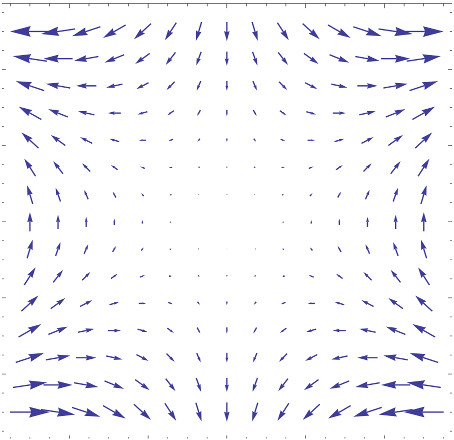


# Two graphene samples

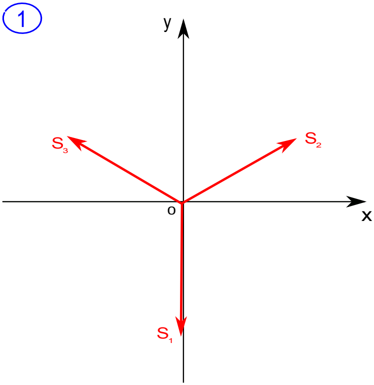


# Two graphene samples

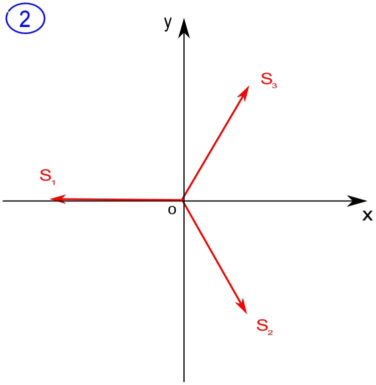
If we apply to both samples this deformation vector
$\vec{u} = (2xy, x^2 - y^2)u_0/4L$,



# Two graphene samples




$$|\vec{B}| = \frac{\beta}{\ell L} u_0$$




$$|\vec{B}| = 0$$

# Conclusions

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# Conclusions

- This pseudo-gauge field seems cannot be guessed from standard QFT in curved spacetime (top-down approach)
- It only can be deduced from the lattice structure to the long wave-length limit (bottom-up approach)
- It is a relic at low energy of the high-energy behavior of the system (memory of the lattice structure)
- This kind of effects could bring us the possibility to test particular features appearing in some fundamental HEP theories (e.g., Lorentz violating terms in Loop Quantum Gravity)

# More about:

**Graphene as table-top laboratory for high-energy physics**

- A. Iorio, G. Lambiase *Quantum field theory in curved space-times, Lobachevsky Geometry and all that*, Phys. Rev. D **90**, 025006.

**Pseudo-gauge fields induced by strain in graphene**

- N. Levy, et al. , Science **329** (2010) 544.
- M. A. H. Vozmediano, M. I. Katsnelson, F. Guinea, Phys. Rept. **496** (2010) 109.
- F. de Juan, M. Sturla, M. A. H. Vozmediano, Phys. Rev. Lett. **108** (2012) 227205

**Detailed discussion about 'memory tensors' in graphene**

- D. C. Cabra, et al., Phys. Rev. B **88** (2013) 045126.

**Detailed version of this work**

- A. Iorio, P. Pais, *Revisiting the gauge fields of strained graphene*, Phys. Rev. D **92** (2015) 125005 [arXiv:1508.00926].

Thank you!