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Holography, Supergravity and Graphene

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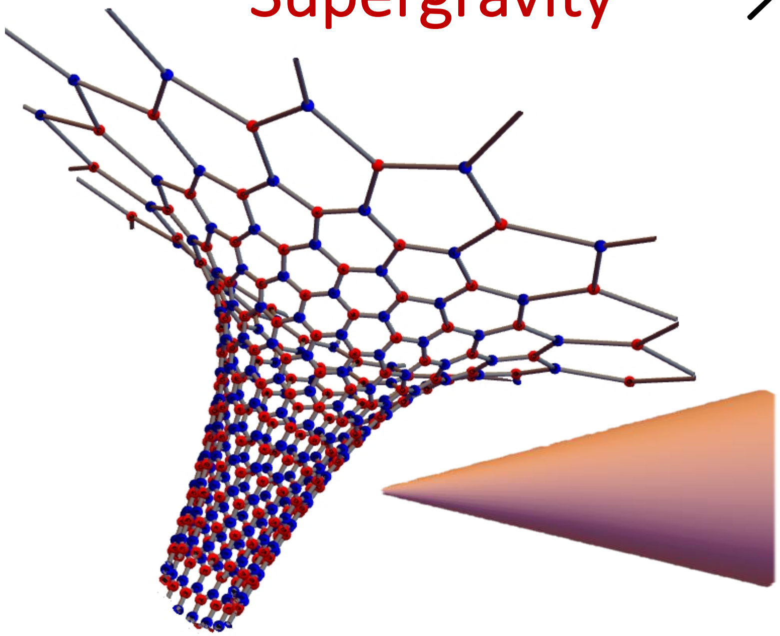
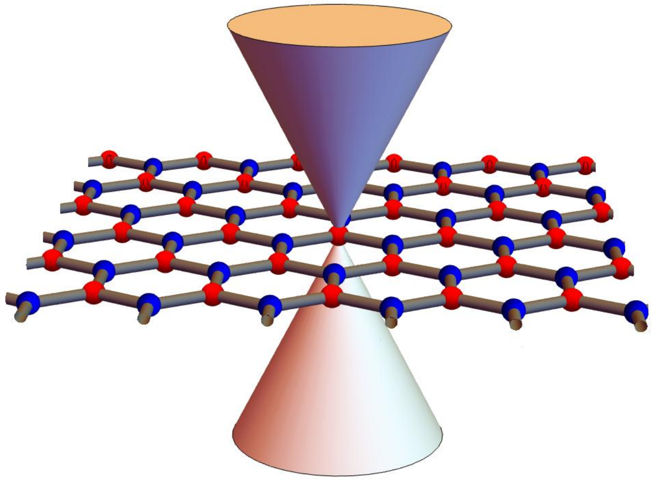
based on L. Andrianopoli, BLC, R. D'Auria, M. Trigiante, JHEP04(2018)007, arXiv:1801.08081;
L. Andrianopoli, BLC, R. D'Auria, A. Gallerati, R. Noris, M. Trigiante, J. Zanelli, JHEP01(2020)084, arXiv:1910.03508;
L. Andrianopoli, BLC, R. Matrecano, O. Mišković, R. Noris, R. Olea, L. Ravera, M. Trigiante, work in progress

Supergravity → Graphene





Main idea

Objective: Application of the dualities of supergravity to the study of graphene-like 2D materials in condensed matter.

- **The gauge/gravity correspondence relates a strongly coupled gauge theory to a weakly coupled classical gravity theory in one dimension higher.**

bulk		boundary
3+1-dim. Supergravity on an anti-de Sitter spacetime	$\xrightarrow{\textbf{holography}}$	**Electronic properties of a 2+1-dim. Layer of graphene**

- **Top-down approach: Large amout of supersymmetry makes the model very predictive**

Relation of the electronic properties of graphene to deformations of the lattice geometry

- **Relevance of supersymmetry in low-energy physics** → **Interdisciplinary approach**

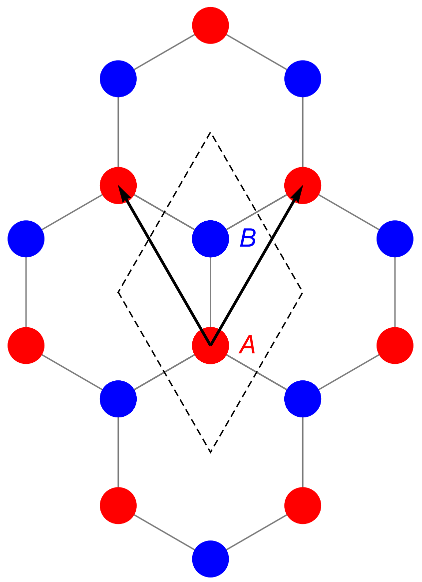
Graphene and the Dirac equation

The graphene honeycomb lattice

Graphene is a two-dimensional layer of carbon atoms (one single layer of graphite).

The carbon atoms in graphene form a honeycomb lattice with a hexagonal structure, due to the *sp*^{2} orbital hybridization.

Bipartite lattice composed by two triangular sublattices (sites A and sites B).

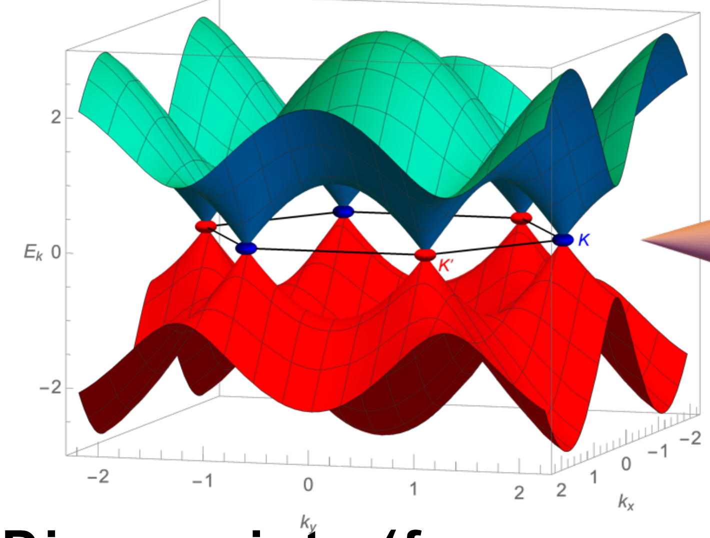


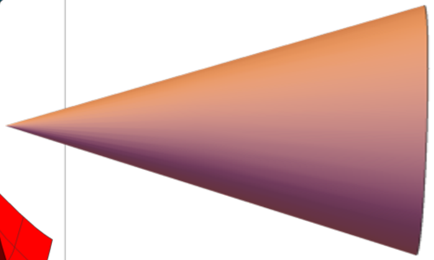
Belonging to site A or B defines an additional

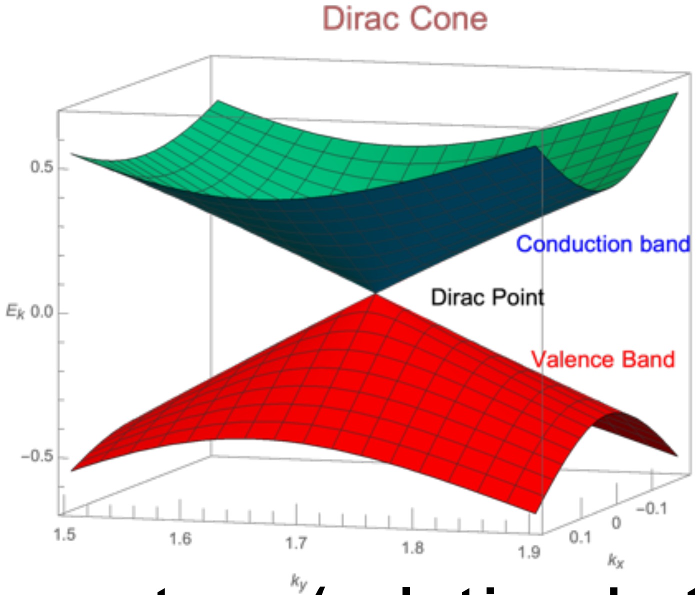
spin-like quantum number: Pseudospin.

The graphene Dirac cone

The Electron Band Structure of graphene







At the Dirac points (for a range of 1eV) the spectrum (relation between the energy E_k and the momentum k) is linear:

Dirac cone: $E_k = \pm \hbar c\,|k|$

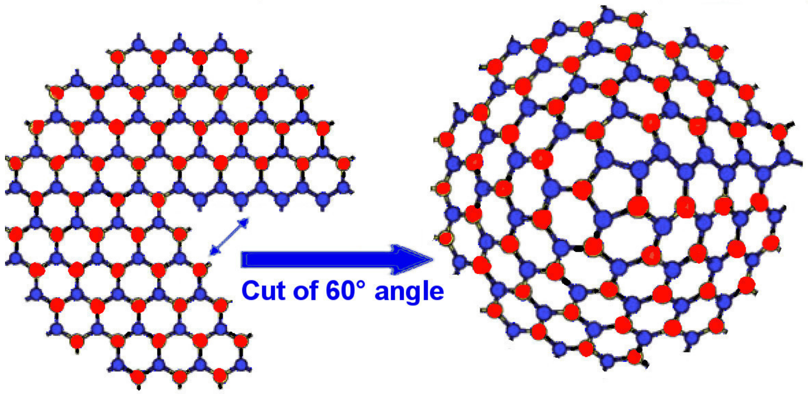
Electrons in graphene obey the same type of equations as

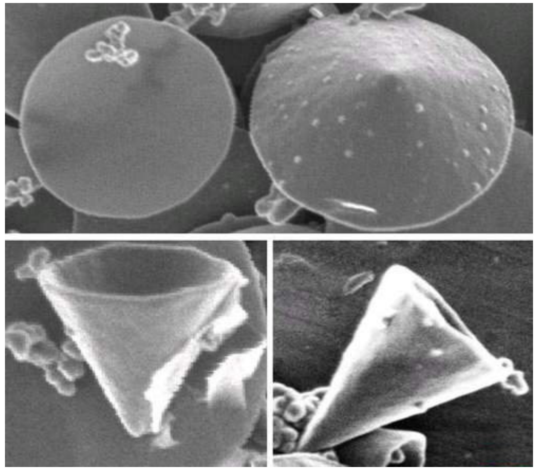
$\boxed{\textbf{relativistic Dirac massless particles}}$ **with**

Light speed $c \rightarrow v_F = 10^6 \, \frac{m}{s} = \frac{c}{300}$ **Fermi velocity**

Analogue relativity in Condensed Matter: Geometry

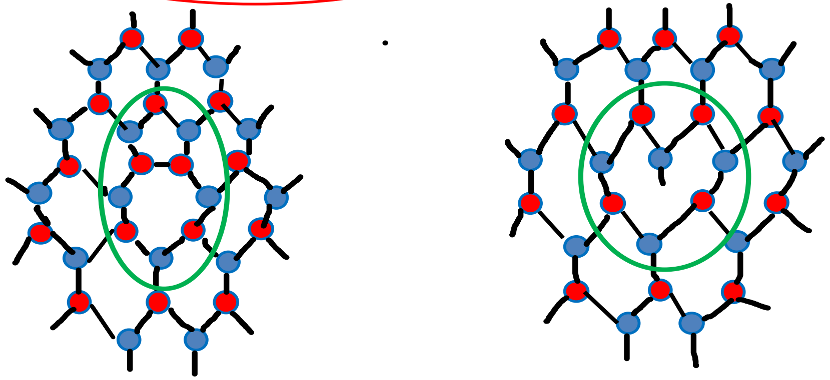
Lattice disclination → **Space Curvature**





Carbon nanocones
[Kenneth D. Knudsen, https://en.wikipedia.org/wiki/Carbon_nanocone, licensed under https://en.wikipedia.org/wiki/en:Creative_Commons]

Lattice dislocation → **Space Torsion**



Glide and shuffle dislocations in graphene, obtained from subsequent disclinations
[see e.g. A. Carpio, L.L. Bonilla, F. de Juan, M.A.H. Vozmediano, *Dislocations in graphene*, New J. Phys. 10 (2008); T.L. Hughes, R.G. Leigh and O. Parrikar, *Torsional Anomalies, Hall Viscosity and Bulk-boundary Correspondence in Topological States*, Phys. Rev. D 88 (2013) 025040, arXiv:1211.6442]

Generalized AVZ Model for Graphene

[L. Andrianopoli, BLC, R. D'Auria, M. Trigiante, *Unconventional Supersymmetry at the boundary of AdS_4 Supergravity*, JHEP04(2018)007, arXiv:1801.08081;
L. Andrianopoli, B.L. Cerchiai, R. D'Auria, A. Gallerati, R. Noris, M. Trigiante, J. Zanelli, *N-Extended D=4 Supergravity, Unconventional SUSY and Graphene*, JHEP01(2020)084, arXiv:1910.03508]

In the AVZ model [P.D. Alvarez, M. Valenzuela, J. Zanelli, *Supersymmetry of a different kind*, JHEP 1204 (2012) 058, arXiv:1109.3944] **the fermionic gauge field ψA is a composite field, and the propagating fermion χA originates from the radial component of the gravitino through the Ansatz**: (A=1,..,$\mathcal{N}$, $\mathcal{N}$ number of supersymmetries; i=0,1,2)

Supergravity Gravitino

Propagating fermion (pseudoparticle in graphene)

$$\boxed{\psi^A = i\,\gamma_i e^i \chi^A .}$$

gamma matrices and Vielbein describing the Geometry

Massive Dirac Equation in the AVZ model

The AVZ model can be obtained at the D=2+1 AdS_3 boundary from a supergravity on a (curved) AdS_4 spacetime in D=3+1 through an ultraspinning limit.

From the Maurer-Cartan equations of the supersymmetry algebra

Massive Dirac equation

$$\boxed{\not{\mathfrak{D}}\,\chi = -\frac{3}{2}\, i\, \tau\, \chi}$$

$\mathfrak{D}$ **covariant derivative**

mass $m = \frac{3}{2}\tau$ ⟵ **torsion**

Killing spinor equation for the boundary supersymmetry

Solutions of the Dirac equation correspond to supersymmetries of the system.

Electronic properties of the pseudoparticles, such as e.g. optical conductivity, are determined by supersymmetry. We have ongoing discussions with the condensed matter groups, both theoretical and experimental, at the Politecnico di Torino.

Some Properties of the AVZ model

- **There are no bosonic propagating degrees of freedom:**

  Number of bosons $\neq$ Number of fermions

Unconventional Supersymmetry

- **Supersymmetry is implemented purely as a gauge symmetry**

- **The AVZ Ansatz corresponds to an (unconventional) gauge fixing of supersymmetry in the framework of a BRST quantization** [L. Andrianopoli, BLC, P.A. Grassi, M. Trigiante, *The Quantum Theory of Chern-Simons Supergravity*, JHEP 1906 (2019) 036, arXiv:1903.04431]**.**

- **The supersymmetry parameter ϵ_A is proportional to the propagating fermion:**

$$\boxed{\epsilon_A \propto (\bar{\chi}\chi)\,\chi_A}$$

- **Mass is generated by the geometric properties of supergravity, such as torsion.**

Holography in the geometric framework

[L. Andrianopoli, BLC, R. Matrecano, O. Mišković, R. Noris, R. Olea, L. Ravera, M. Trigiante, work in progress]

- **We are explicitly computing the holographic map in a geometric formulation** [for a review on the geometric framework for supergravity, see R. D'Auria, *Geometric Supergravity*, hep-th2005.13593, review article from the book "Tullio Regge:an Eclectic Genius"; World Scientific Publishing Co. Pte.Ltd].
- **The gauge/gravity (AdS/CFT) correspondence relates a conformal gauge theory on the boundary to a classical gravity theory on anti de Sitter spacetime in one dimension higher.** [J.M. Maldacena, *The Large N limit of superconformal field theories and supergravity*, ATMP 2 (1998) 231, hep-th/9711200]

Non-perturbative Strong-weak duality

- **At low energies it implies a one-to-one correspondence between quantum operators in the boundary conformal field theory and fields of the bulk supergravity, which act as sources for the gauge theory.**
- **The radial coordinate moving towards the bulk is related to the energy of the gauge theory** [A.W. Peet, J.Polchinski, *UV / IR relations in AdS dynamics*, Phys. Rev. D 59, 065011 (1999), hep-th/9809022].
- **The AVZ model should correspond to a topologically inequivalent sector from an unconventional gauge fixing of supersymmetry** [L. Andrianopoli, BLC, P.A. Grassi, M. Trigiante, arXiv:1903.04431].

Final remarks

- **In the framework of holography, we have obtained a description of 2D graphene-like materials in a suitable AdS_3 patch at the boundary of an extended supergravity in one dimension higher with $\mathcal{N}$ supersymmetries.**

- **This top-down approach is more predictive than the common bottom-up one, because it is strongly constrained from the supersymmetry of the gravity theory.**

- **The model features supersymmetry, and it can be viewed as a top-down approach to understand the origin of the observed supersymmetric phenomenology in graphene** [S.-S. Lee, *Emergence of supersymmetry at a critical point of a lattice model*, Phys. Rev. B76 (2007) 075103, cond-mat/0611658].

- **The Haldane and Semenoff-type masses are identified with geometric properties of the model, such as torsion.**

- **In collaboration with O.Miškovic and R.Olea, we are actually explictly computing the holographic map, and we want to apply the holographic renormalization scheme to our AdS_4/graphene correspondence. In this framework the counterterms in the holographic renormalization should sum up to topological invariants** [R.Aros, M.Contreras, R.Olea, R.Troncoso, J.Zanelli, *Conserved charges for gravity with locally AdS asymptotics*, Phys.Rev.Lett. 84 (2000) 1647-1650, arXiv:gr-qc/9909015]**.**

Thank you!