Graphene Wormholes: From General Relativity to Nano-Technologies

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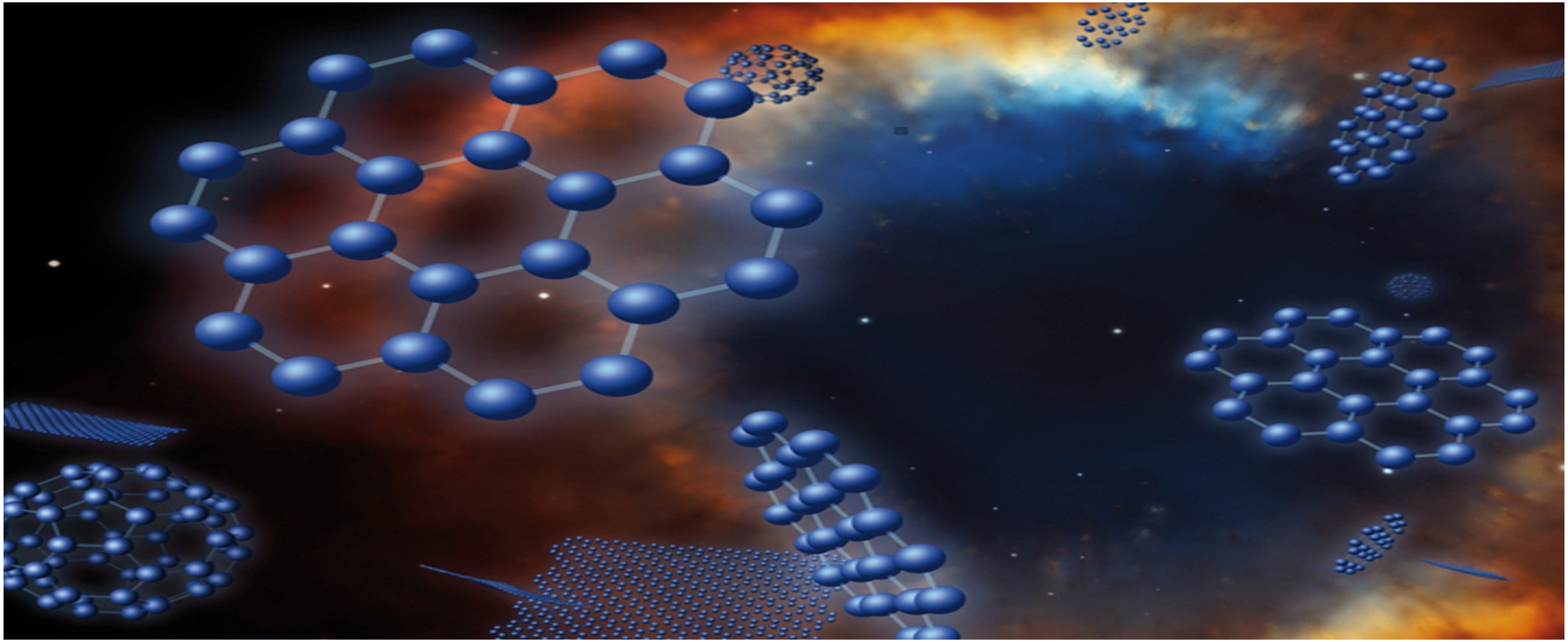

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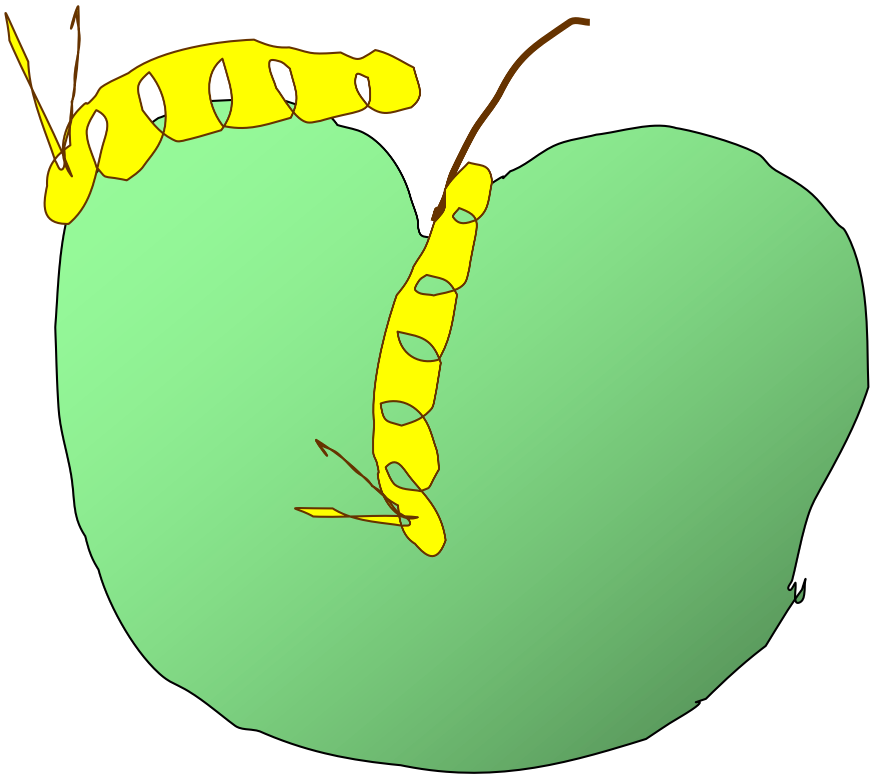
Summary

- Whormholes: some definitions
- Wormholes and time travels
- Troubles and issues
- The graphene
- Current densities in graphene
- Electric current vs time arrow
- Geometric defects instead of exotic matter
- The graphene wormhole
  (exact solutions and possible applications)
- Cosmology in the Lab
- Perpectives

Wormholes

- **The term WH was introduced by J. A. Wheeler in 1957**
- **Already in 1921 by H. Weyl (mass in terms of EM)**
- **The name WH comes from the following obvious picture.**



The worm could take a shortcut to the opposite side of the apple's skin by burrowing through its center, instead of traveling the entire distance around.

Whormole: definitions

- The wormholes are solutions of the Einstein field equations having a non-trivial topological structure linking separate points of spacetime, much like a tunnel with two ends.

- A wormhole may connect extremely long distances such as billions of light years; short distances such as a few meters; different universes; and/or different points in space-time.

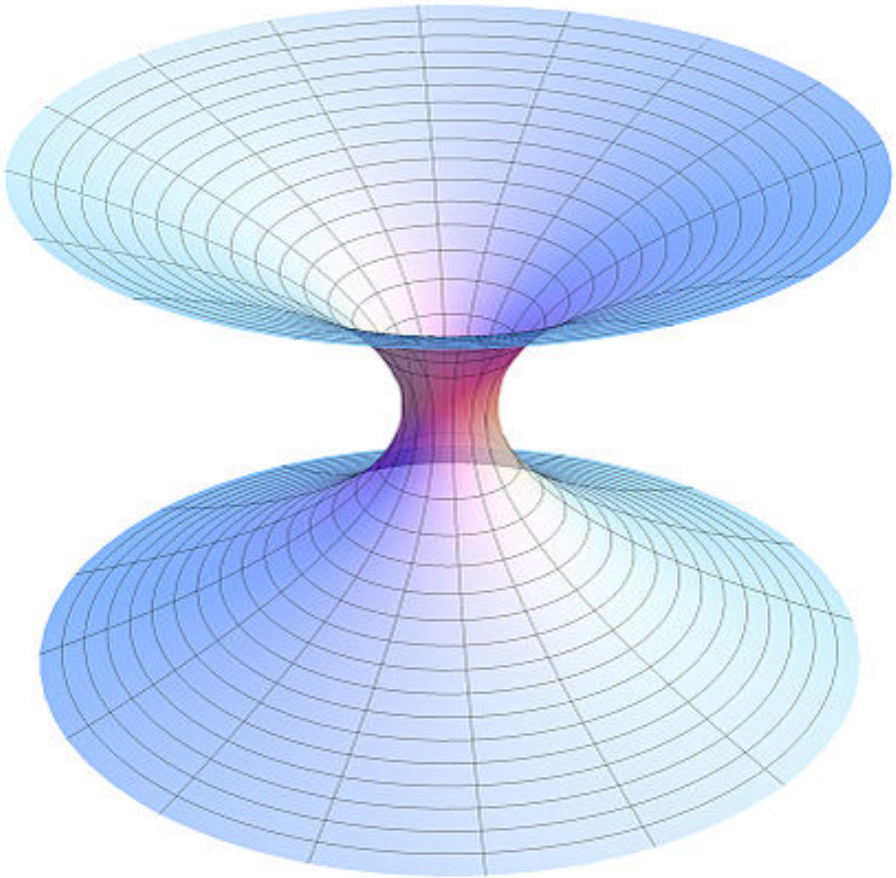
- They are related to space-time topology changes.

- Problems with causality notion.

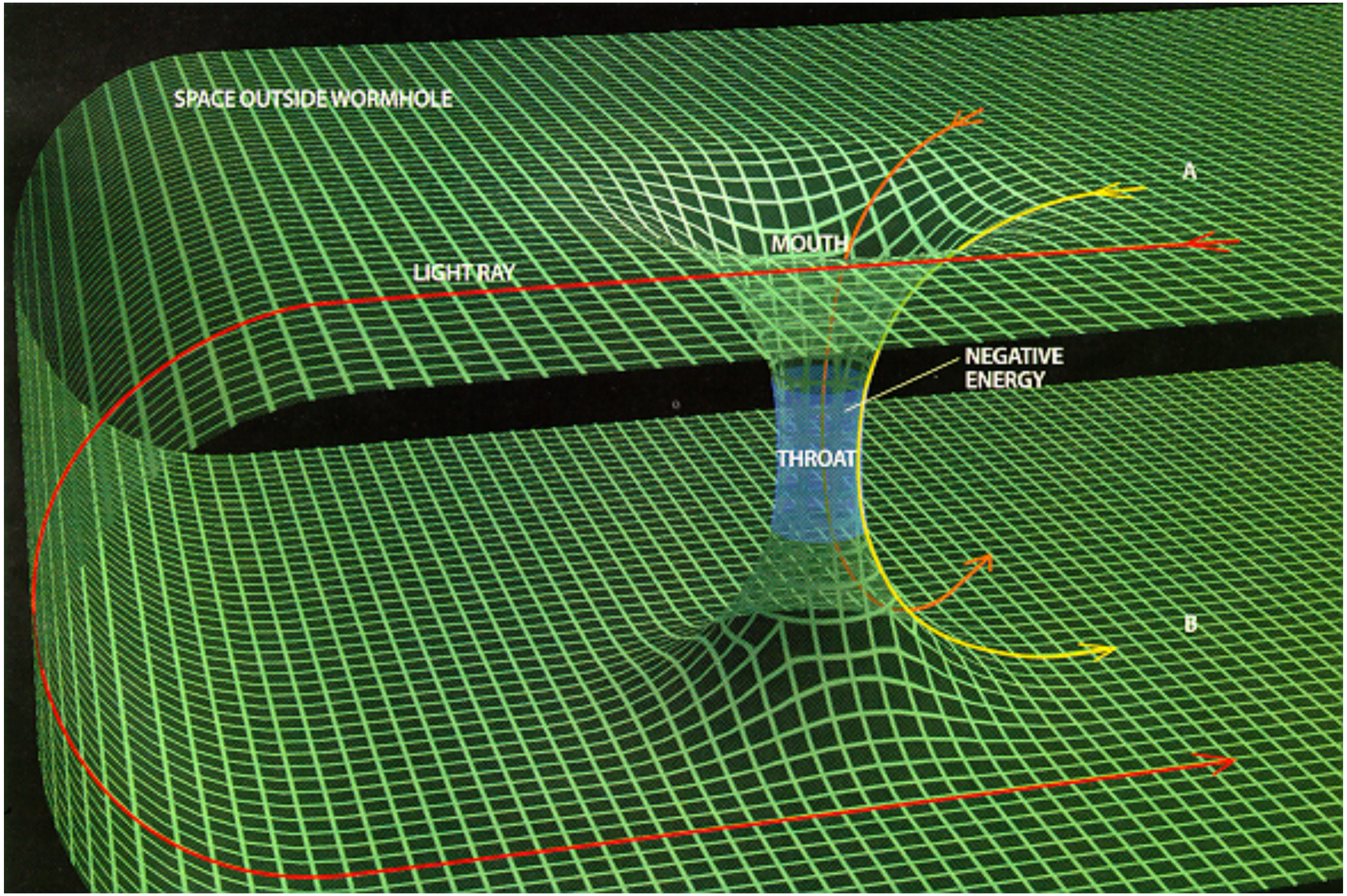
- Cronology Protection Conjecture.

- Their existence remains hypothetical at astrophysical level.

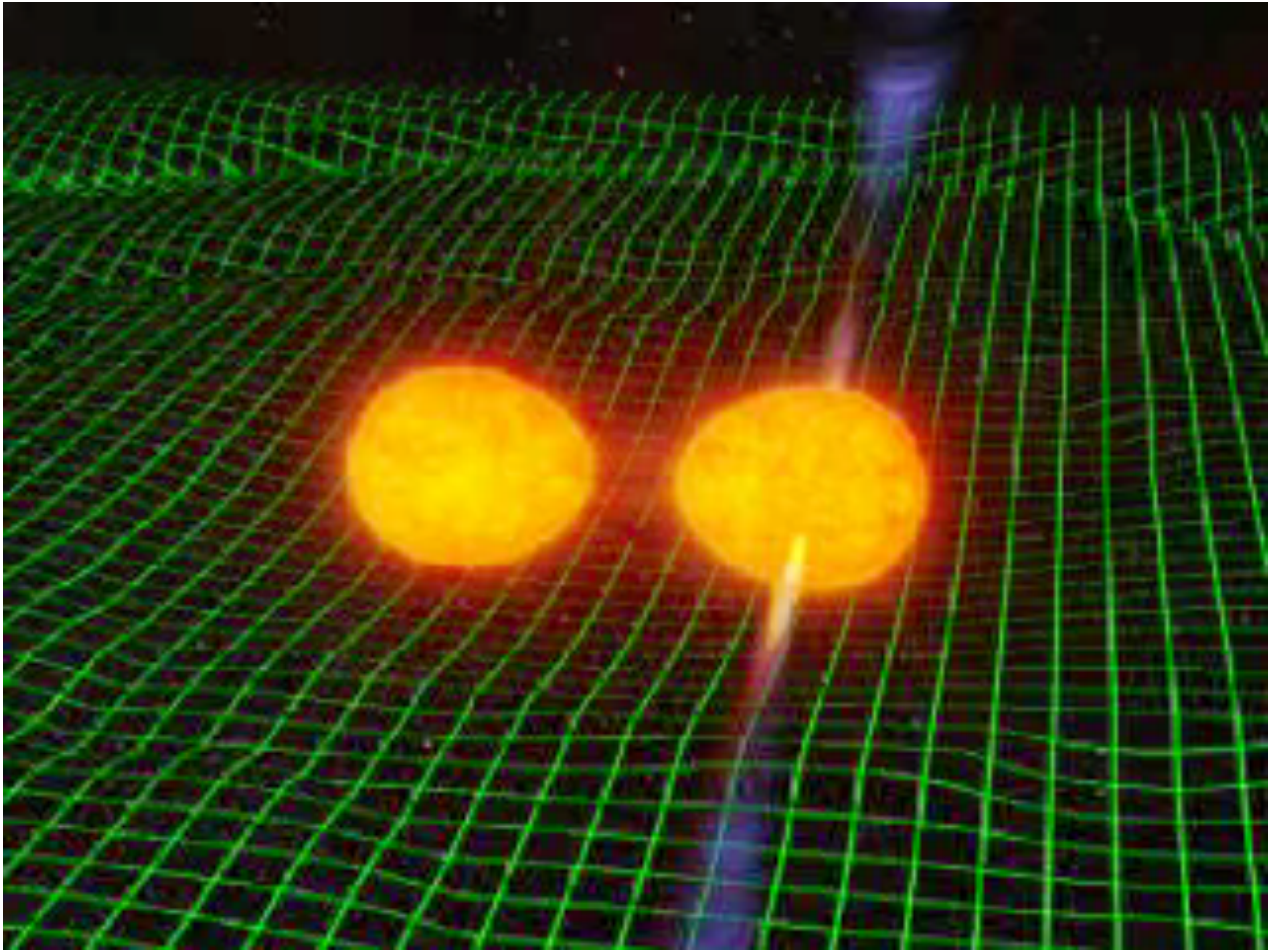
Einstein-Rosen bridge (1935)



Two Schwarzschild solutions joined by a throat



The traveler, just as a worm, could take a shortcut to the opposite side of the universe through a topologically nontrivial tunnel. A negative energy is requested to give rise to the topology change and the throat.

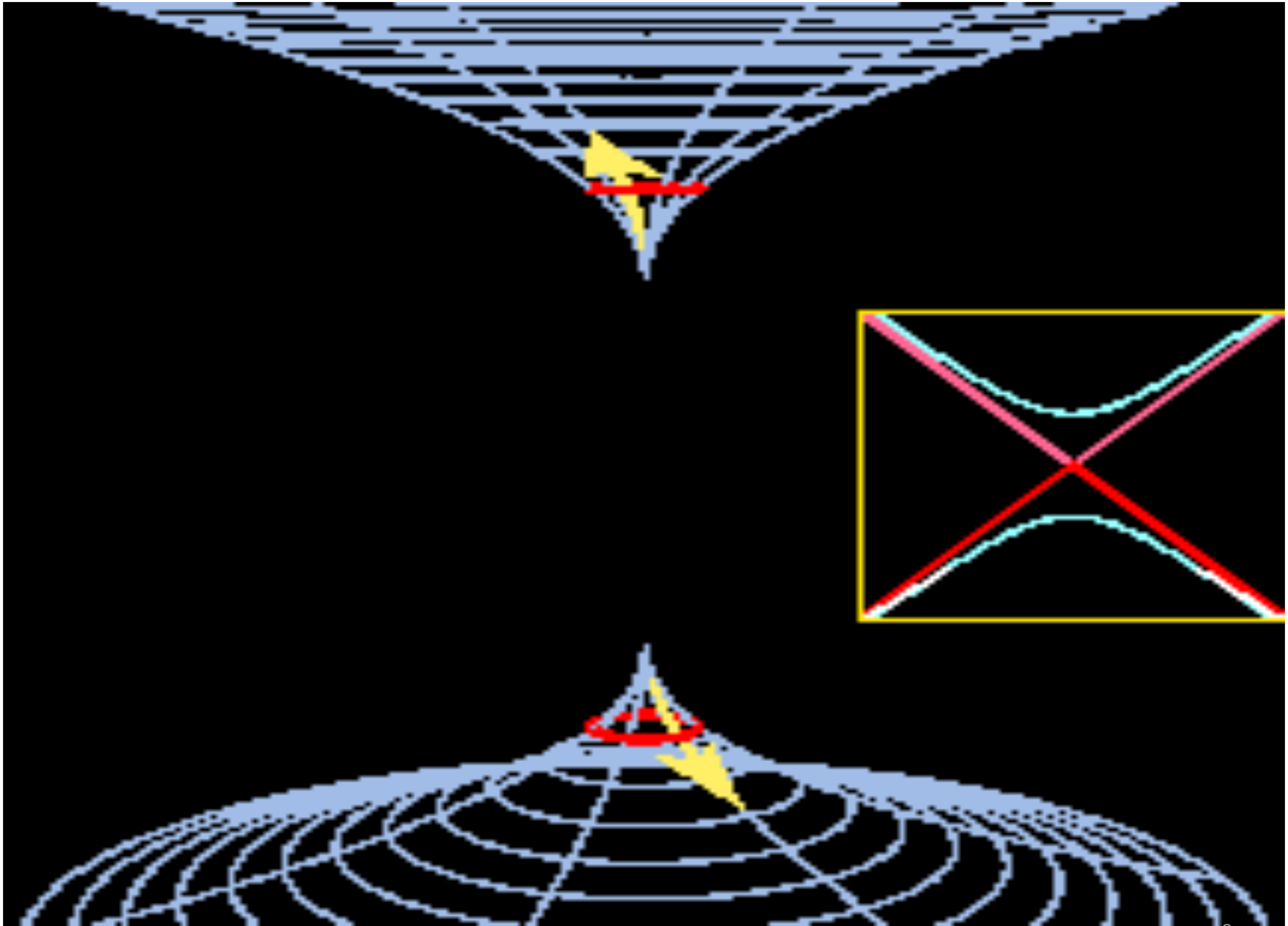


Traversable Wormholes

Morris-Thorne 1988

$$\boxed{ds^2 = -e^{2\Phi(r)}dt^2 + \frac{dr^2}{1 - \frac{b(r)}{r^2}} + r^2(d\vartheta^2 + \sin^2\vartheta\, d\varphi^2)}$$

Traversable WHs need **exotic matter** for stability. For standard matter energy conditions are violated!



- Several WH solutions exist, howver standard matter forbids their formation.
- Some kinds of **Dark Matter** could solve the problem but no final detection at fundamental level.
- We need huge energies and masses   (at least stellar masses) to give rise to WHs at astrophysical level.

…………………………BUT………………………………..

IN NATURE, ALL THAT IS NOT FORBIDDEN,
IT IS NECESSARY!
(E. Fermi)

- Einstein's Field Equations DO NOT forbid the WH formation!

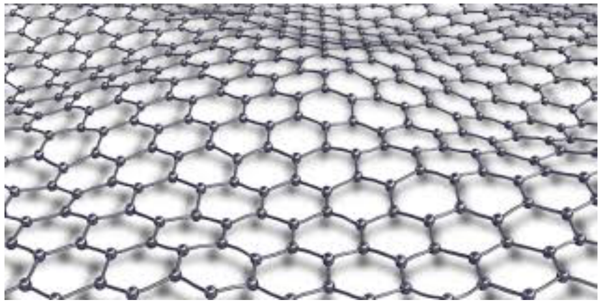
- Are there similar structures in which to generate topology changes as in space-time?

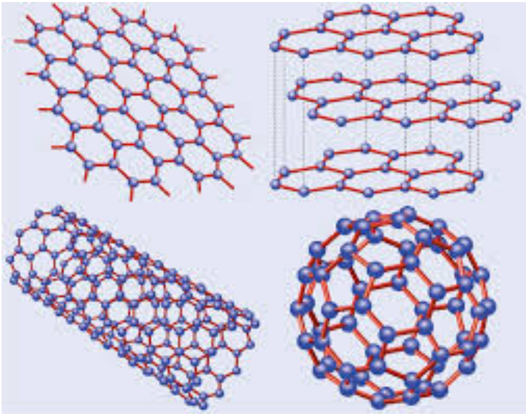
- Is it possible to change the geometry instead of searching for exotic matter?

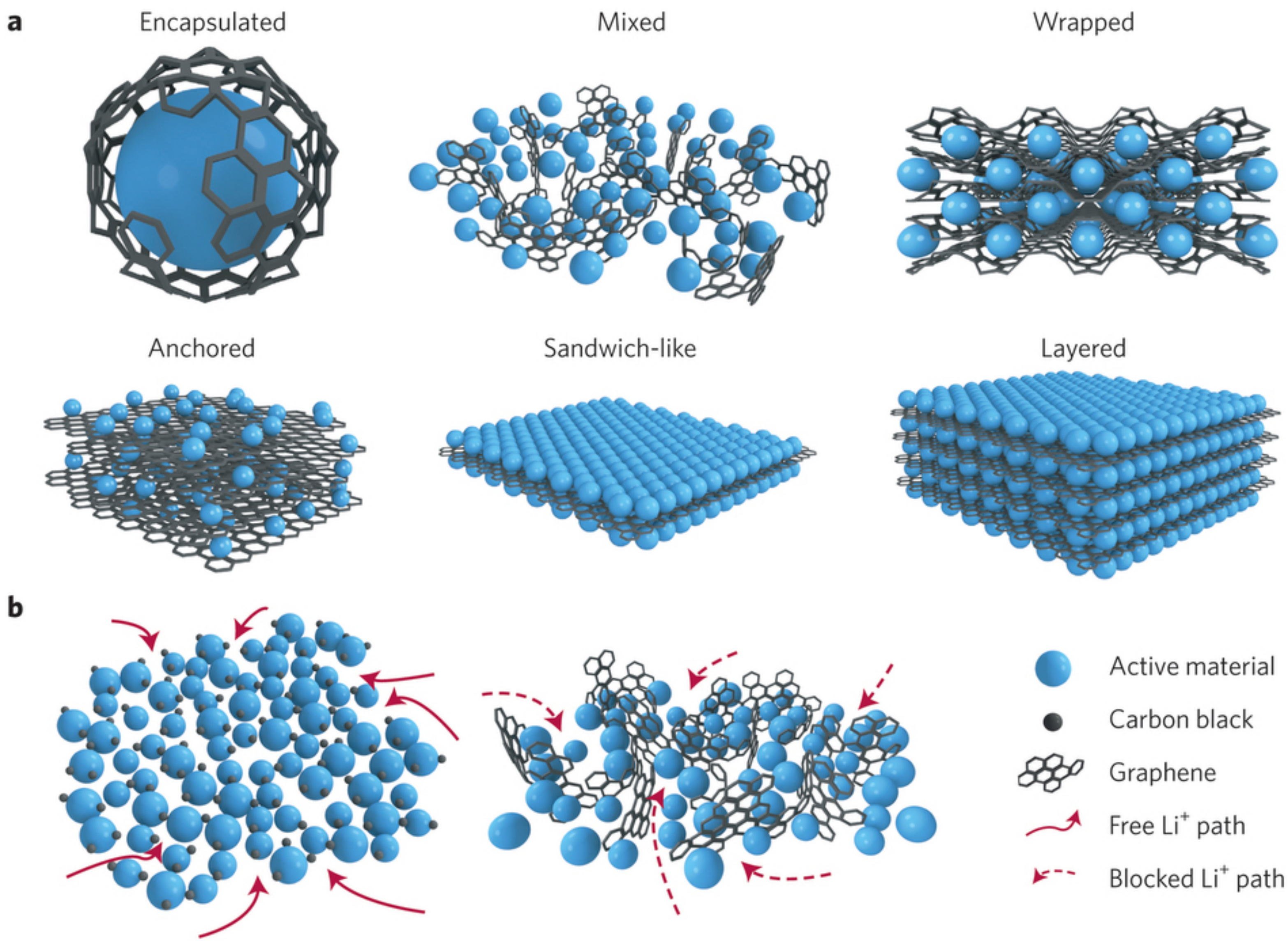
- Is it possible to find out analogue quantities that behave like the "**time arrow**"?

Graphene

Graphene is an allotrope of carbon in the form of a two-dimensional, atomic-scale, hexagonal lattice in which one atom forms each vertex. It is the basic structural element of other allotropes, including graphite, charcoal, carbon nanotubes and fullerenes. It can be considered as an indefinitely large aromatic molecule the ultimate case of the family of flat polycyclic aromatic hydrocarbons. Graphene has many unusual properties. It is about 200 times stronger than the strongest steel. It efficiently conducts heat and electricity and is nearly transparent. Graphene shows a large and nonlinear diamagnetism, greater than graphite and can be levitated by neodynium magnets. Scientists have theorized about graphene for years. It has unintentionally been produced in small quantities for centuries, through the use of pencils and other similar graphite applications. It was originally observed in electron microscopes in 1962, but it was studied only while supported on metal surfaces. The material was later rediscovered, isolated, and characterized in 2004 by Andre Geim and Konstantin Novoselov (Nobel Prize 2010).






a
Encapsulated
Mixed
Wrapped
Anchored
Sandwich-like
Layered
b
Active material
Carbon black
Graphene
Free Li$^+$ path
Blocked Li$^+$ path

Working Hypotheses

- Graphene behaves as a bidimensional spacetime
- We apply analogue Einstein field equations to graphene
- Instead of searching for **exotic matter**, we take into account the graphene **curvature** and its **geometric defects**
- Graphene defects and bonds generate **electric currents**.
- Coupled electrons give rise to **analogue gravitons** that bring information (current = information)
- Equations yield EXACT SOLUTIONS

↓

Graphene Wormhole


WHAT
DO I
NEED TO
KNOW?

Graphene geometry

Analogue Metric

$$A^{ab} = g^{ab} = h^{ab} = h_1^{ab'} \otimes h_2^{b'b} - h_2^{bb'} \otimes h_1^{ab'}$$
$$F_{abc} = \partial_a A_{bc} - \partial_b A_{ca} + \partial_c A_{ab} = 2(\partial_\mu g_{\nu\lambda} + \partial_\nu g_{\mu\lambda} - \partial_\lambda g_{\mu\nu}) = 2\Gamma_{\mu\nu\lambda}$$

$$\begin{aligned}\langle F^\rho{}_{\sigma\lambda}, F^\lambda{}_{\mu\nu}\rangle &= \langle [X^\rho, X_\sigma, X_\lambda], [X^\lambda, X_\mu, X_\nu]\rangle \\ &= [X_\nu, [X^\rho, X_\sigma, X_\mu]] - [X_\mu, [X^\rho, X_\sigma, X_\nu]] \\ &\quad + [X^\rho, X_\lambda, X_\nu][X^\lambda, X_\sigma, X_\mu] - [X^\rho, X_\lambda, X_\mu][X^\lambda, X_\sigma, X_\nu] \\ &= \partial_\nu \Gamma^\rho_{\sigma\mu} - \partial_\mu \Gamma^\rho_{\sigma\nu} + \Gamma^\rho_{\lambda\nu}\Gamma^\lambda_{\sigma\mu} - \Gamma^\rho_{\lambda\mu}\Gamma^\lambda_{\sigma\nu} = R^\rho_{\sigma\mu\nu},\end{aligned}$$

Analogue Curvature

$$\langle F_{abc}, F^{bc}_{a'}\rangle = R^{anti-parallel}_{aa'} - R^{parallel}_{aa'}$$

$$\begin{aligned}R_{MN} = R_{aa'} + R_{ia'} + R_{ij'} = R^{anti-parallel}_{Free-Free} + R^{anti-parallel}_{Free-Bound} + R^{anti-parallel}_{Bound-Bound} \\ - R^{parallel}_{Free-Free} - R^{parallel}_{Free-Bound} - R^{parallel}_{Bound-Bound}.\end{aligned}$$

Same "**machinery**" of General Relativity

Graphene currents with parallel and anti-parallel electronic spins

$$\begin{aligned}\langle F^{abc},F_{abc}\rangle_{Free-Free} = & A^{ab} i\sigma^2_{ij}\partial^i_a\psi^j_b + \sigma^0_{ij}\psi^{\dagger a,i}\psi^j_a - \sigma^1_{ij}\psi^{\dagger a,i}\psi^j_a \\ & +\sigma^0_{i'i}(\psi^{\dagger a,i'} i\sigma^0_{i'j}\sigma^1_{jk}\partial^{a,j}\psi^k_a)(\psi^{\dagger i}_a i\sigma^0_{ij}\sigma^1_{jk}\partial^{a,j}\psi^k_a) \\ & +\sigma^1_{i'i}(\psi^{\dagger a,i'} i\sigma^0_{i'j}\sigma^1_{jk}\partial^{a,j}\psi^k_a)(\psi^{\dagger i}_a i\sigma^0_{ij}\sigma^1_{jk}\partial^{a,j}\psi^k_a) \\ & -\sigma^0_{i'i}(\psi^{\dagger a,i'} i\sigma^1_{i'j}\sigma^1_{jk}\partial^{a,j}\psi^k_a)(\psi^{\dagger i}_a i\sigma^1_{ij}\sigma^1_{jk}\partial^{a,j}\psi^k_a),\end{aligned}$$

$$\begin{aligned}\langle \partial^b\partial^a X^i, \partial_b\partial_a X^i\rangle = & \varepsilon^{abc}\varepsilon^{ade}(\partial_b\partial_c X^i_\alpha)(\partial_e\partial_d X^i_\beta) = \\ & \Psi^{\dagger a,U}\langle F_{abc},F^{a'bc}\rangle\Psi^L_{a'} + \Psi^{\dagger a,L}\langle F_{abc},F^{a'bc}\rangle\Psi^U_{a'} - \Psi^{\dagger a,U}\langle F_{abc},F^{a'bc}\rangle\Psi^U_{a'} \\ & -\Psi^{\dagger a,L}\langle F_{abc},F^{a'bc}\rangle\Psi^L_{a'} + \Psi^{\dagger a,L}\Psi^{\dagger d,U}\partial_d\partial^{d'}\langle F_{abc},F^{a'bc}\rangle\Psi^L_{a'}\Psi^U_{d'} \\ & -\Psi^{\dagger a,L}\Psi^{\dagger d,U}\partial_d\langle F_{abc},F^{a'bc}\rangle\Psi^L_{a'} - \Psi^{\dagger a,U}\Psi^{\dagger d,L}\partial_d\langle F_{abc},F^{a'bc}\rangle\Psi^U_{a'} \\ & +\psi^{\dagger i,U}\langle F_{ijk},F^{i'jk}\rangle\psi^L_{i'} + \psi^{\dagger i,L}\langle F_{ijk},F^{i'jk}\rangle\psi^U_{i'} - \psi^{\dagger i,U}\langle F_{ijk},F^{i'jk}\rangle\psi^U_{i'} \\ & -\psi^{\dagger i,L}\langle F_{ijk},F^{i'jk}\rangle\psi^L_{i'} + \psi^{\dagger i,L}\psi^{\dagger m,U}\partial_m\partial^{m'}\langle F_{ijk},F^{i'jk}\rangle\psi^L_{i'}\psi^U_{m'} \\ & -\psi^{\dagger i,L}\psi^{\dagger m,U}\partial_m\langle F_{ijk},F^{i'jk}\rangle\psi^L_{i'} - \psi^{\dagger i,U}\psi^{\dagger m,L}\partial_m\langle F_{ijk},F^{i'jk}\rangle\psi^U_{i'} \\ & +\Psi^{\dagger a,U}\langle F_{abc},F^{i'bc}\rangle\psi^L_{i'} + \Psi^{\dagger a,L}\langle F_{abc},F^{i'bc}\rangle\psi^U_{i'} - \Psi^{\dagger a,U}\langle F_{abc},F^{i'bc}\rangle\psi^U_{i'} \\ & -\Psi^{\dagger a,L}\langle F_{abc},F^{i'bc}\rangle\psi^L_{i'} + \Psi^{\dagger a,L}\Psi^{\dagger d,U}\partial_d\partial^{i'}\langle F_{abc},F^{j'bc}\rangle\psi^L_{j'}\psi^U_{i'} \\ & -\Psi^{\dagger a,L}\Psi^{\dagger d,U}\partial_d\langle F_{abc},F^{i'bc}\rangle\psi^L_{i'} - \Psi^{\dagger a,U}\Psi^{\dagger d,L}\partial_d\langle F_{abc},F^{i'bc}\rangle\psi^U_{i'}. \qquad \text{(A.2)}\end{aligned}$$

Differences with respect to the Einstein Gravity

Two kinds of effective gravity emerge:

- One is generated by parallel spins, the other by antiparallel spins.

- **Three types of curvatures**:

- Interaction of free electrons.
- Interactions of free-bound electrons
- Interactions of bound-bound electrons.

- Antiparallel electrons give positive curvature, parallel electrons give negative curvature.
- We can have **ATTRACTIVE and REPULSIVE GRAVITY**

This feature gives **stable** and **traversable** WHs!

Differences with respect to the Einstein Gravity

Modified gravitational Action

$$
\begin{aligned}
E_{system} &= \int d^4x \rho \\
&= \int d^4x \sqrt{-g} \Big\{ -(1-m_g^2)\Big[(R^{parallel}_{Free-Free})^2 + (R^{anti-parallel}_{Free-Free})^2 + (R^{parallel}_{Free-Bound})^2 \\
&\quad + (R^{anti-parallel}_{Free-Bound})^2 + (R^{parallel}_{Bound-Bound})^2 + (R^{anti-parallel}_{Bound-Bound})^2 \\
&\quad + (R^{parallel}_{Free-Free} R^{anti-parallel}_{Free-Free})\, \partial^2 (R^{parallel}_{Free-Free} + R^{anti-parallel}_{Free-Free}) \\
&\quad + (R^{parallel}_{Free-Bound} R^{anti-parallel}_{Free-Bound})\, \partial^2 (R^{parallel}_{Free-Bound} + R^{anti-parallel}_{Free-Bound}) \\
&\quad + (R^{parallel}_{Bound-Bound} R^{anti-parallel}_{Bound-Bound})\, \partial^2 (R^{parallel}_{Bound-Bound} + R^{anti-parallel}_{Bound-Bound}) \Big] \\
&\quad + m_g^2 \lambda^2 \delta^{\mu_1\nu_1}_{\rho_1\sigma_1} \Big[R^{anti-parallel,\rho_1\sigma_1}_{Free-Free,\mu_1\nu_1} + R^{anti-parallel,\rho_1\sigma_1}_{Bound-Bound,\mu_1\nu_1} + R^{anti-parallel,\rho_1\sigma_1}_{Free-Bound,\mu_1\nu_1} \\
&\quad - R^{parallel,\rho_1\sigma_1}_{Free-Free,\mu_1\nu_1} + R^{parallel,\rho_1\sigma_1}_{Bound-Bound,\mu_1\nu_1} + R^{parallel,\rho_1\sigma_1}_{Free-Bound,\mu_1\nu_1} \Big] \Big\},
\end{aligned}
$$

$$\boxed{m_g^2 = (\lambda)^2 \det([X^j_\alpha T^\alpha, X^k_\beta T^\beta, X^{k'}_\gamma T^\gamma])}$$

Effective "graviton" mass.
In Einstein's gravity,
the graviton is massless

Geometric structure of graphene

Combining electrons

$$\Psi^{\dagger a,L}\psi_a^U = \Psi^{\dagger a,U}\psi_a^L = \Psi^{\dagger a,L}\Psi_a^U = \Psi^{\dagger a,U}\Psi_a^L = \psi^{\dagger a,U}\psi_a^L = \psi^{\dagger a,L}\psi_a^U = l_1$$

$$\Psi^{\dagger a,U}\psi_a^U = \Psi^{\dagger a,L}\psi_a^L = \Psi^{\dagger a,U}\Psi_a^U = \Psi^{\dagger a,L}\Psi_a^L = \psi^{\dagger a,U}\psi_a^U = \psi^{\dagger a,L}\psi_a^L = l_2,$$

- l_1 coupling for anti-parallell spin electrons
- l_2 coupling for parallel spin electrons

combining the couplings we get

Repulsion $$R^{parallel}_{Free-Free} = R^{parallel}_{Free-Bound} = R^{parallel}_{Bound-Bound} \approx l_2 - l_2'$$

Attraction $$R^{anti-parallel}_{Free-Free} = R^{anti-parallel}_{Free-Bound} = R^{anti-parallel}_{Bound-Bound} \approx l_1 + l_1'.$$

Graphene Dynamics

Action for an atom in the graphene

$$S_{co-atom} \approx V \int d\cos\theta\, \Sigma_{n=1}^{p} \Big\{ 6m_g^2\lambda^2 \left[l_1 - l_2 - l_1' + l_2' + (l_1')^2 - (l_2')^2 \right] \\ -3(1-m_g^2) \left[2l_1^2 + 2l_2^2 + 2(l_1')^2 + 2(l_2')^2 + l_1^2 l_2^2 (l_1^2 + l_2^2)'' \right] \Big\}^{\frac{1}{2}}$$

- l_2 is the coupling for parallel spins, l_1 is the coupling for antiparallel spins
- V is the atomic volume
- The couplings depend on the angle θ between two electrons in a graphene atom.

Graphene Equations

Equations of motions of electrons in graphene:

$$\Big\{m_g^2 l_1' \left[\lambda^2-(1+2l_1^2 l_2^2)\right]\left\{6m_g^2\lambda^2[l_1-l_2-l_1'+l_2'+(l_1')^2-(l_2')^2]\right.$$
$$\left.-3(1-m_g^2)\left[2l_1^2+2l_2^2+2(l_1')^2+2(l_2')^2+l_1^2l_2^2(l_1^2+l_2^2)''\right]\right\}^{-\frac{1}{2}}\Big\}'=$$
$$\left\{(1-m_g^2)l_1\left[1+3l_2^2(l_1^2+l_2^2)''\right]+m_g^2\lambda^2\right\}\left\{6m_g^2\lambda^2[l_1-l_2-l_1'+l_2'+(l_1')^2-(l_2')^2]\right.$$
$$\left.-3(1-m_g^2)[2l_1^2+2l_2^2+2(l_1')^2+2(l_2')^2+l_1^2l_2^2(l_1^2+l_2^2)'']\right\}^{-\frac{1}{2}},$$

$$\Big\{l_2'\left[(1-m_g^2)(1-2l_1^2l_2^2)-m_g^2\lambda^2\right]\left\{6m_g^2\lambda^2[l_1-l_2-l_1'+l_2'+(l_1')^2-(l_2')^2]\right.$$
$$\left.-3(1-m_g^2)[2l_1^2+2l_2^2+2(l_1')^2+2(l_2')^2+l_1^2l_2^2(l_1^2+l_2^2)'']\right\}^{-\frac{1}{2}}\Big\}'=$$
$$\left\{(1-m_g^2)l_2[1-3l_1^2(l_1^2+l_2^2)'']-m_g^2\lambda^2\right\}\left\{6m_g^2\lambda^2[l_1-l_2-l_1'+l_2'+(l_1')^2-(l_2')^2]\right.$$
$$\left.-3(1-m_g^2)[2l_1^2+2l_2^2+2(l_1')^2+2(l_2')^2+l_1^2l_2^2(l_1^2+l_2^2)'']\right\}^{-\frac{1}{2}}.$$

solutions

$$l_1 \approx \cos(\theta_1)$$
$$l_2 \approx \cos(\theta_2) = (1-m_g^2)\cos(\theta_1) - m_g^2\lambda^2\sin(\theta_1).$$

..and then

$$\Psi = \psi \approx \sqrt{\cos(\theta)}.$$

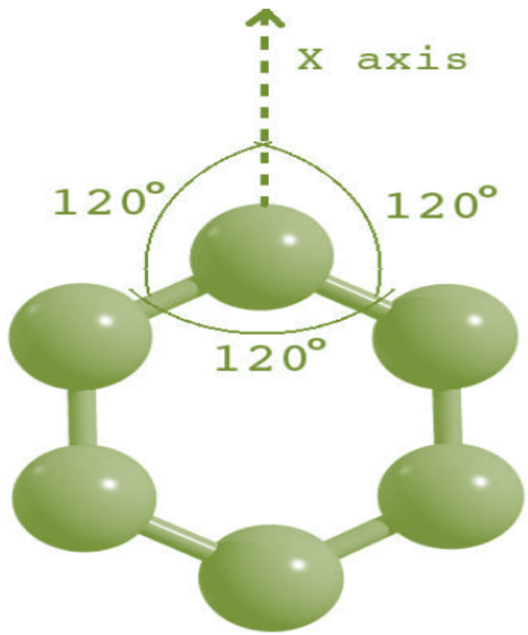
…we can evaluate curvature and current densities

Graphene without defects (hexagonal)

$$\boxed{\begin{aligned} R^{anti-parallel}_{Free/Bound-Free/Bound} &= l_1^{1-1} + l_1^{1-2} + l_1^{1-3} + (l_1')^{1-1} + (l_1')^{1-2} + (l_1')^{1-3} = 0 \\ R^{parallel}_{Free/Bound-Free/Bound} &= l_2^{1-1} + l_2^{1-2} + l_2^{1-3} - (l_2')^{1-1} - (l_2')^{1-2} - (l_2')^{1-3} = 0, \end{aligned}}$$

$$\boxed{J \approx 0.}$$

For graphene without defects, the **current density is zero**. Electrons do not move in any direction.

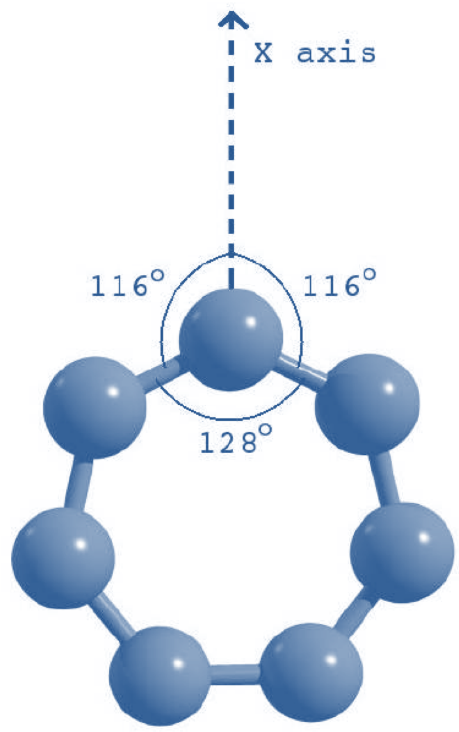


Graphene with heptagonal defects

$$R^{anti-parallel}_{Free/Bound-Free/Bound} = l_1^{1-1} + l_1^{1-2} + l_1^{1-3} + (l_1')^{1-1} + (l_1')^{1-2} + (l_1')^{1-3} = 0.132$$
$$R^{parallel}_{Free/Bound-Free/Bound} = l_2^{1-1} + l_2^{1-2} + l_2^{1-3} - (l_2')^{1-1} - (l_2')^{1-2} - (l_2')^{1-3} = -0.048.$$

$$\boxed{J \approx 0.458.}$$

Electrons are repelled by neighbor molecules and move along the X-axis (the curvature produced by parallel spins is larger than the curvature produced by anti-parallel spins and therefore a negative force is applied to electrons and they move in opposite directions with respect to the molecule). **The current density is positive.**

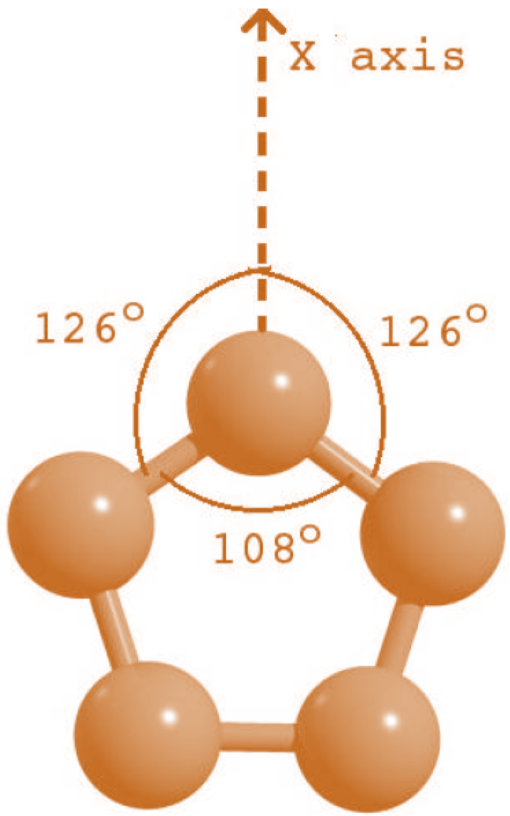


Graphene with pentagonal defects

$$R^{anti-parallel}_{Free/Bound-Free/Bound} = l_1^{1-1} + l_1^{1-2} + l_1^{1-3} + (l_1')^{1-1} + (l_1')^{1-2} + (l_1')^{1-3} = -0.174$$
$$R^{parallel}_{Free/Bound-Free/Bound} = l_2^{1-1} + l_2^{1-2} + l_2^{1-3} - (l_2')^{1-1} - (l_2')^{1-2} - (l_2')^{1-3} = 0.063.$$

$$\boxed{J \approx -0.539.}$$

The negative value of the current density implies that the electrons are absorbed by pentagonal defects and move along the negative X-axis, i.e. this type of defects induces a force to the free electrons and leads them to move towards the molecule. **The current density is negative.**

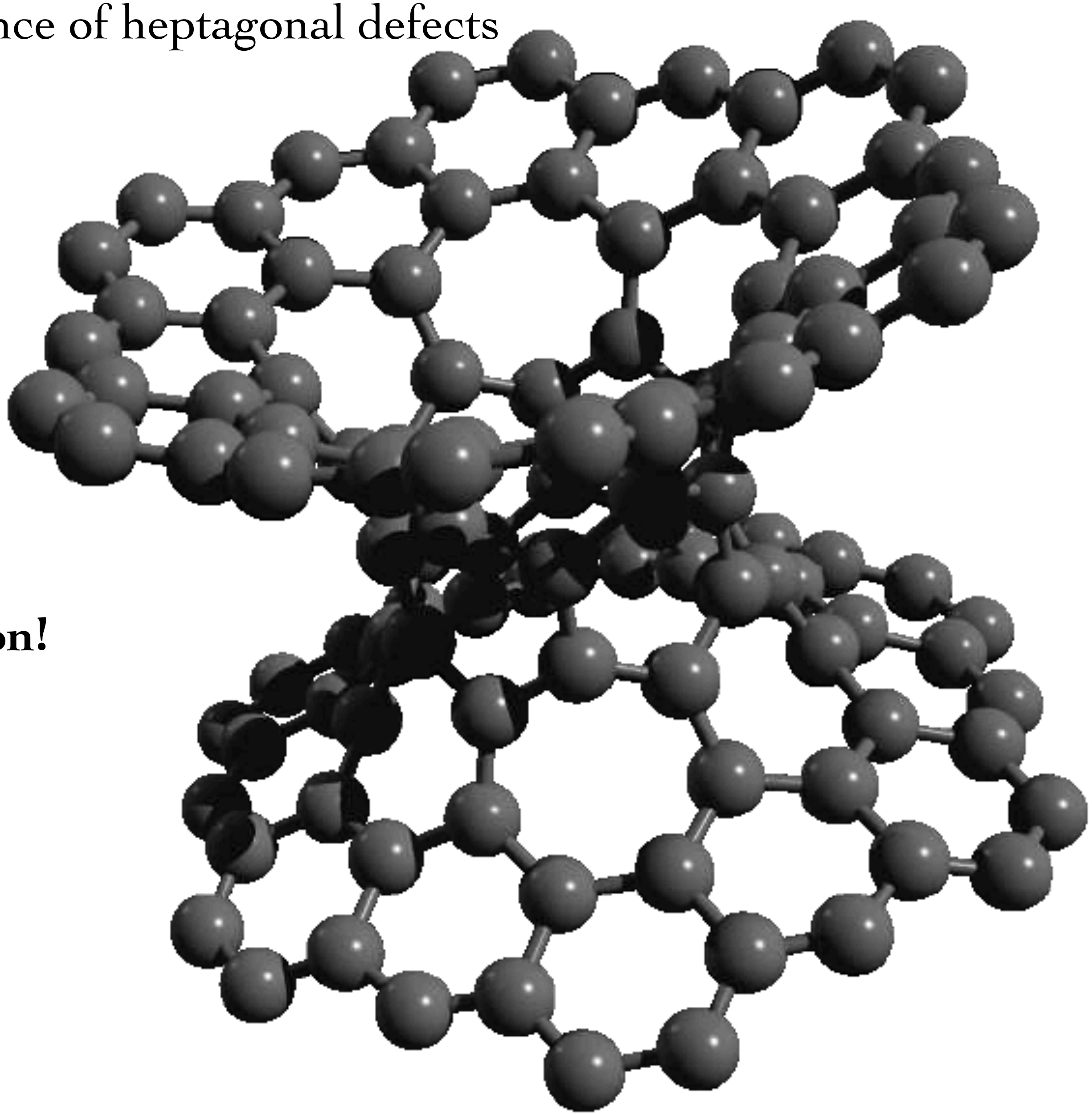


The graphene wormhole

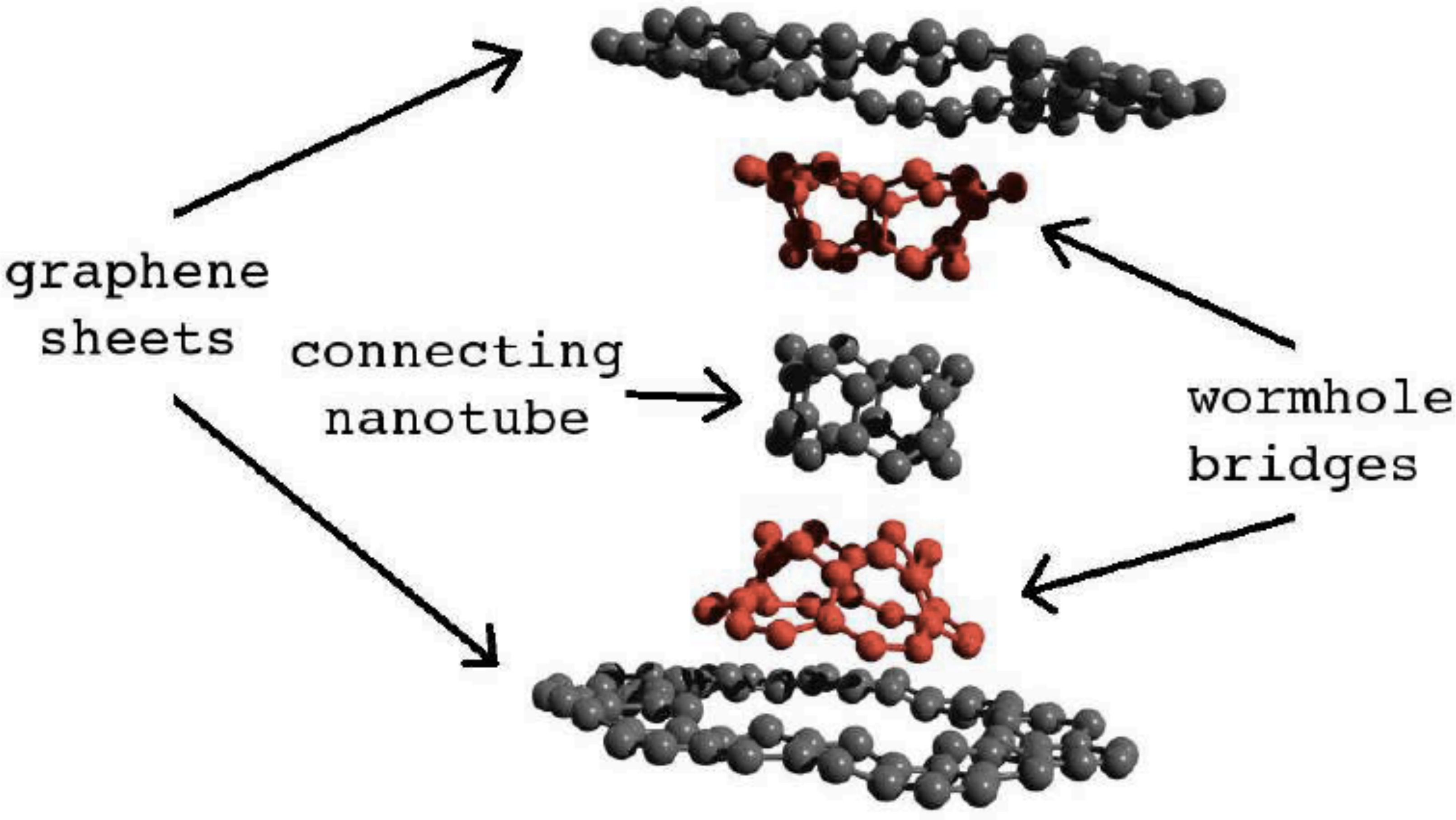
Such an object is created when the structure of the plain graphene is disrupted by the presence of heptagonal defects

We take into account the case of 12 defects.

This is an **exact solution!**



The graphene wormhole



The current density in a graphene wormhole

- The number of defects in the graphene wormhole can differ from 2 to 12 defects, i.e. from 1 to 6 defects at each side. The process can be iterative with *n*+6

$$\boxed{J \approx 6 \cdot 0.458 = 2.748.}$$

- The upper and lower sheets have not the geometry of the plain graphene, and the corresponding current density changes, as well as the current density close to the middle of the connecting nanotube.

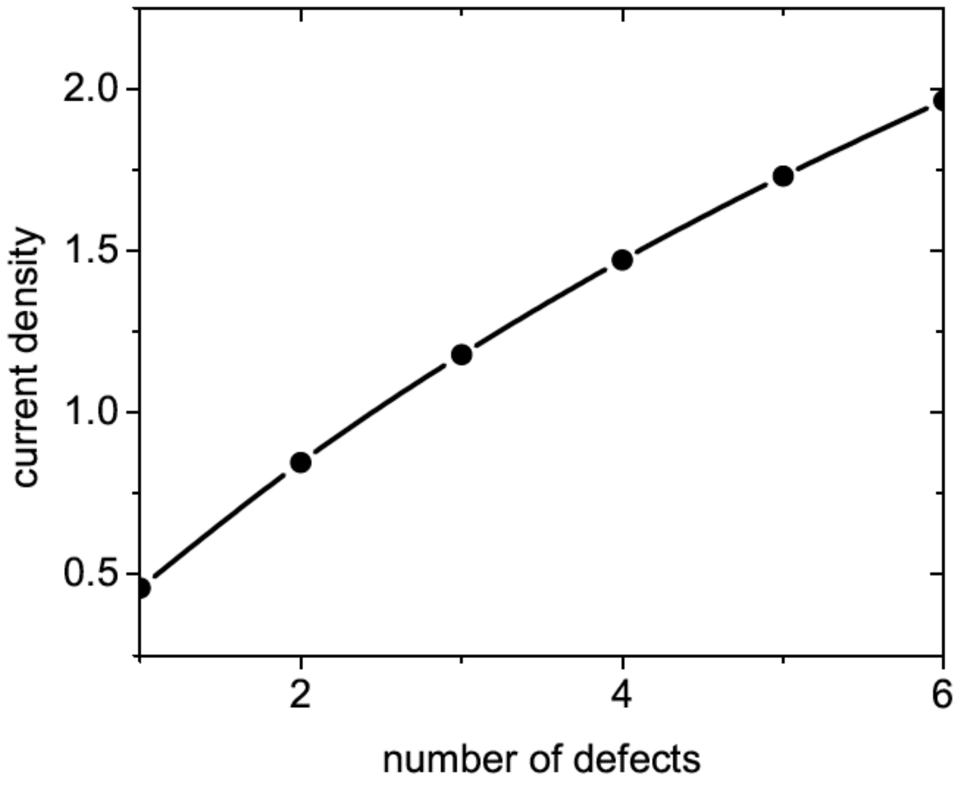
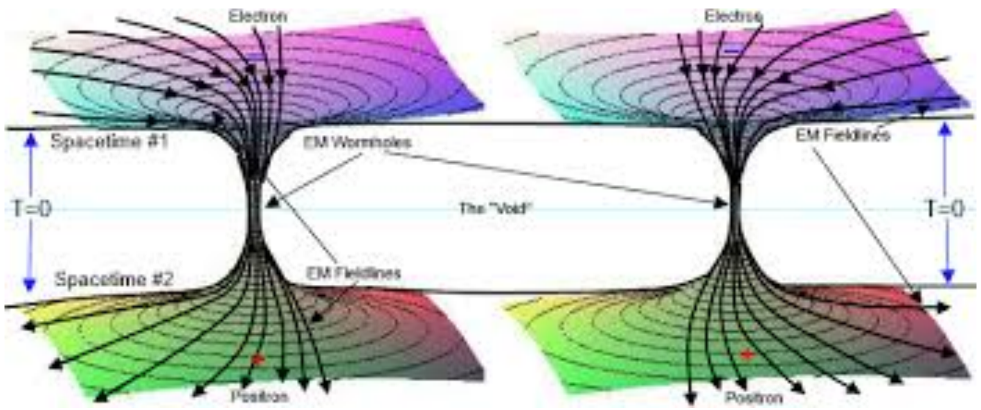


Table of Analogies

- Graphene sheet → Space-time sheet
- Graphene wormhole → Space-time wormhole
- Curvature terms → Exotic matter
- Current densities → Information, flux of particles
- **Electronic circuits → 2 anti-parallel doped WHs**
- Circulating currents → Close Time Curves
- Cooper pairs → Gravitons



Cosmology meets superconductivity in the LAB

New Perspectives…..

Open Issues

- Wormhole solutions can be reproduced in Lab?
- Yes…by graphene structures!
- The role of spacetime curvature is replaced by the interactions between electrons that can be free-free, bound-bound, free-bound.
- It is possible to achieve stable configurations (Einstein-Rosen bridge)
- Current densities represent **information** flowing into the wormhole troath
- Main role is played by the defects (pentagonal, eptagonal etc…) that determine the intensity and the direction of current densities

The goals:

- **Achieving an analogue wormhole by graphene**
- **Stabilize it and controlling the system**
- **Give exact estimation of currents**
- **Standardize the procedure at industrial level**

How generate the supporting structure…

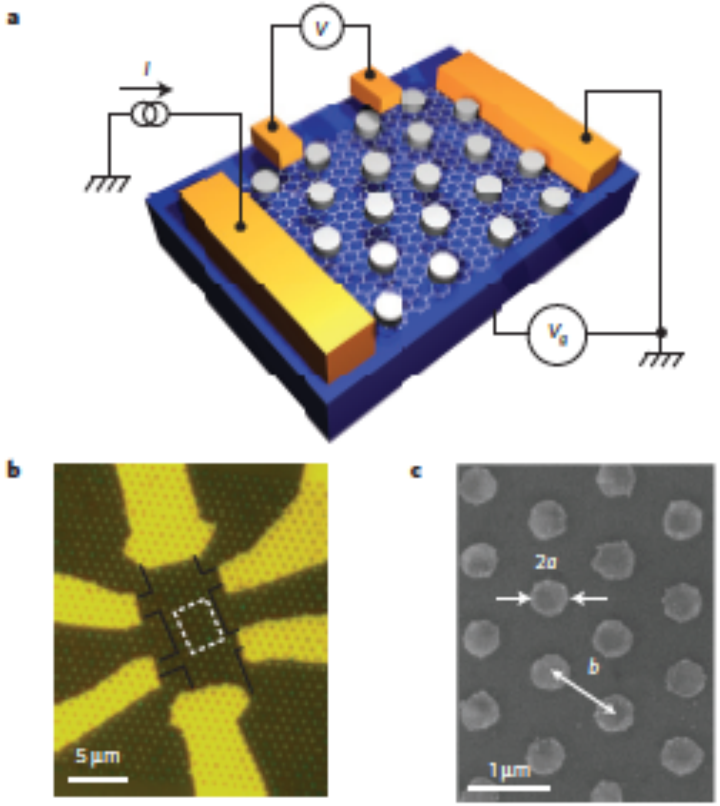
some examples in literature

ARTICLES
PUBLISHED ONLINE: 30 MARCH 2014 | DOI: 10.1038/NPHYS2929

nature physics

Collapse of superconductivity in a hybrid tin–graphene Josephson junction array

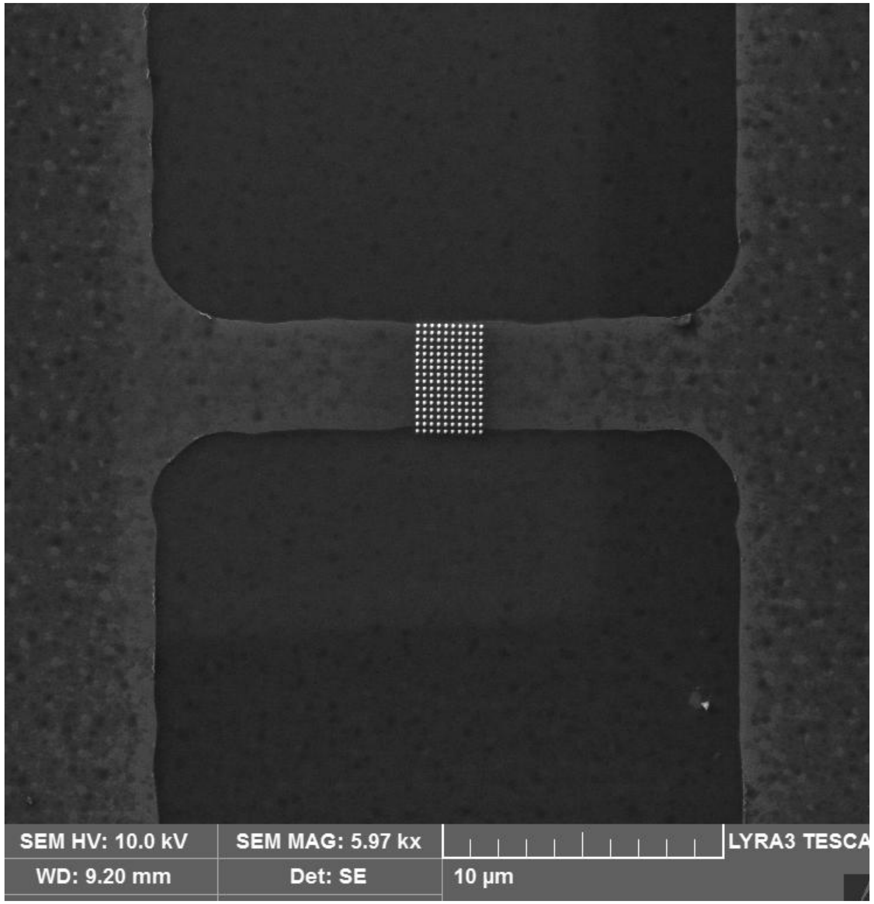
Zheng Han[1,2], Adrien Allain[1,2], Hadi Arjmandi-Tash[1,2], Konstantin Tikhonov[3,4], Mikhail Feigel'man[3,5], Benjamin Sacépé[1,2] and Vincent Bouchiat[1,2*]

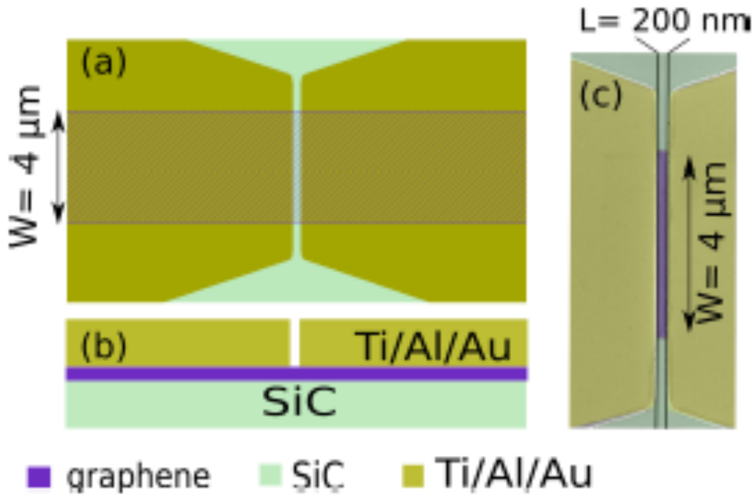


Methods

We used CVD-grown monolayer graphene sheets transferred onto 285 nm oxidized silicon wafer as a 2D diffusive metal. As shown in Fig. 1, the sample was patterned by standard e-beam lithography into a Hall bar geometry (central square area 6 µm²) and contacted with normal leads (Ti/Au bilayers, 5 nm/50 nm thick). The entire graphene surface was then decorated in a second lithography step by an array of 50-nm-thick Sn discs.

Our DEMONSTRATOR





PHYSICAL REVIEW B **94**, 054525 (2016)

Josephson effect in graphene

Al-graphene-Al

Collaboration between Napoli and Chalmers (Sweden).
We used an already available technology in order to get the graphene suspension

LETTERS

Vol 446|1 March 2007|doi:10.1038/nature05545

The structure of suspended graphene sheets

Jannik C. Meyer[1], A. K. Geim[2], M. I. Katsnelson[3], K. S. Novoselov[2], T. J. Booth[2] & S. Roth[1]

Selected for a Viewpoint in *Physics*

PRL 101, 096802 (2008) PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2008

Temperature-Dependent Transport in Suspended Graphene

K. I. Bolotin,[1] K. J. Sikes,[2] J. Hone,[3] H. L. Stormer,[1,2,4] and P. Kim[1]

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[2]*Department of Applied Physics, Columbia University, New York, New York 10027, USA*

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'4, USA

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PRL 105, 256806 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Local Compressibility Measurements of Correlated States in Suspended Bilayer Graphene

J. Martin, B. E. Feldman, R. T. Weitz, M. T. Allen, and A. Yacoby

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(Received 8 September 2010; published 15 December 2010)

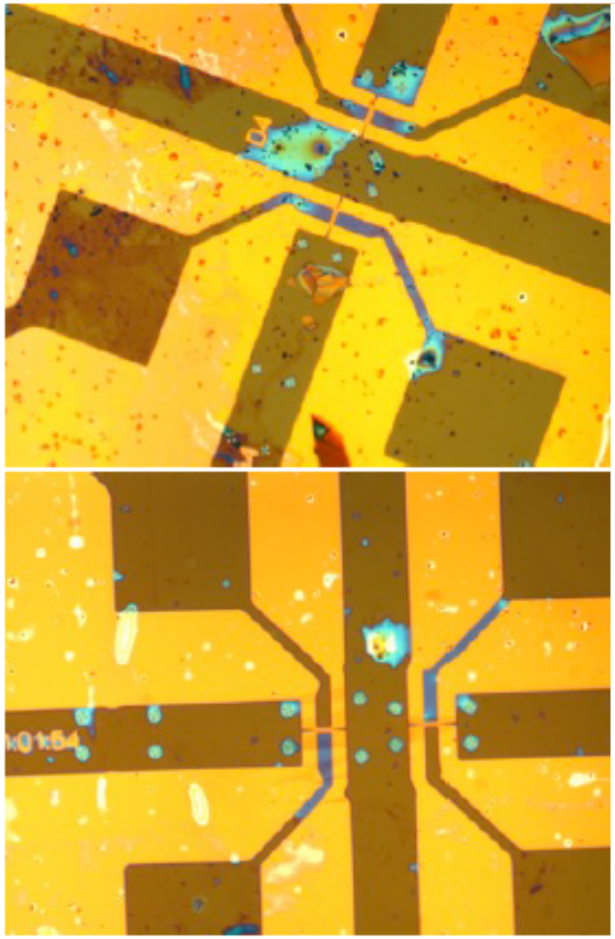
nature materials LETTERS

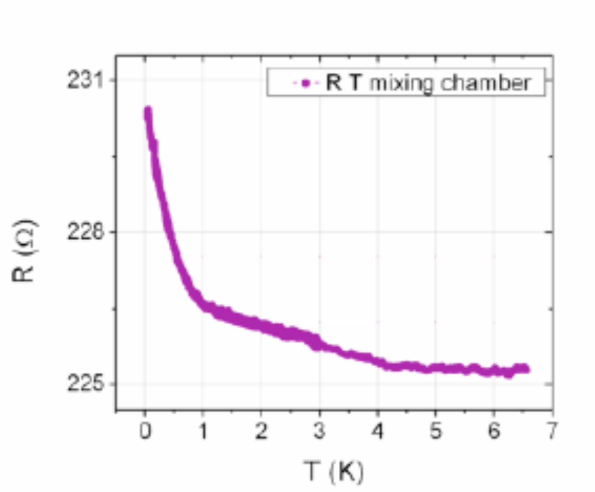
PUBLISHED ONLINE: 1 JULY 2012 | DOI: 10.1038/NMAT3370

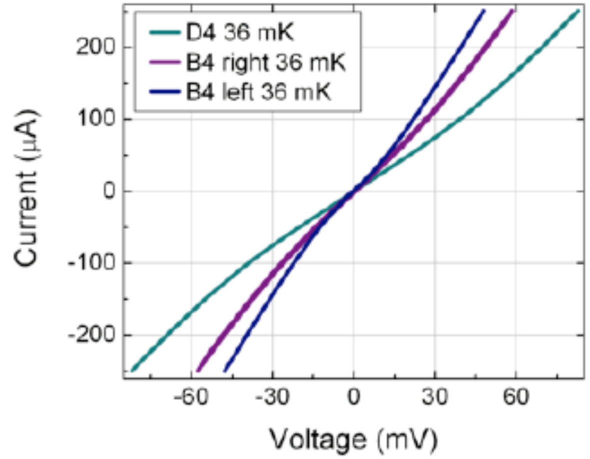
The nature of strength enhancement and weakening by pentagon–heptagon defects in graphene

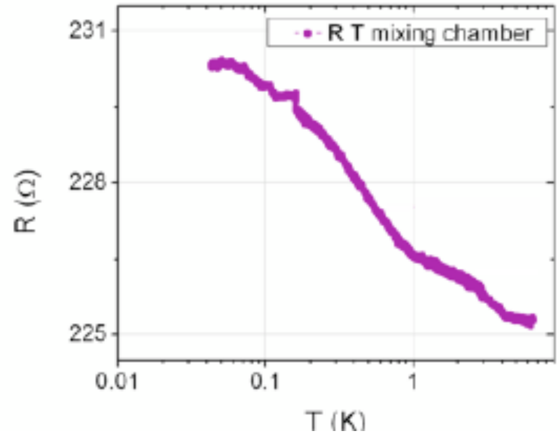
Yujie Wei[1]*, Jiangtao Wu[1], Hanqing Yin[1], Xinghua Shi[1], Ronggui Yang[2]* and Mildred Dresselhaus[3]

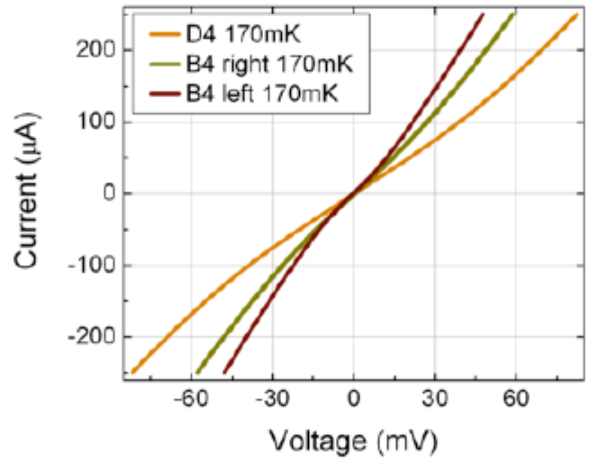
Expertise in Napoli



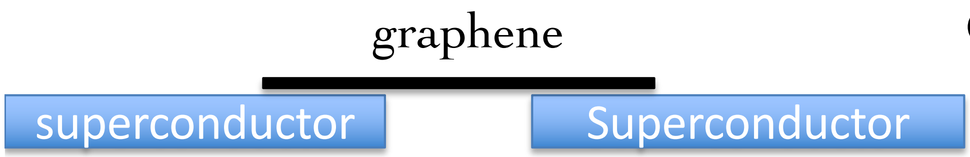






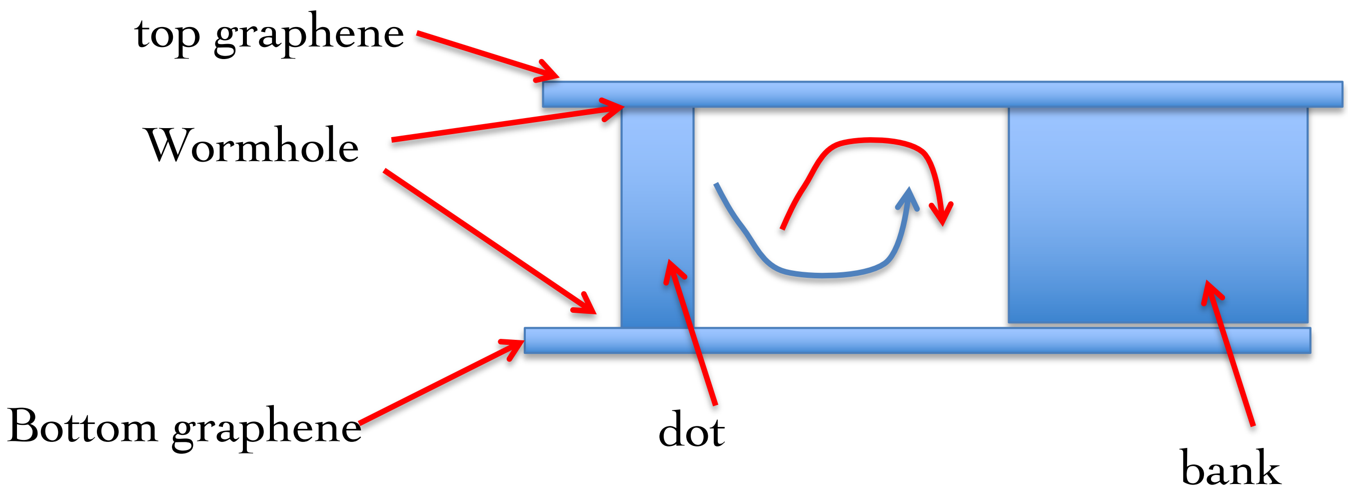


Graphene suspended on YBCO



Collaboration between Napoli and Chalmers

The "industrial" idea is to measure and control the flow of current within the WH and to produce a superconducting device



This is the pattern of a wormhole device that could be used to produce circular currents depending on the doping of graphene sheets. Advantages: zero resistance, very small currents (nanoampere).

"I do not know what it is for, but someone, in the future, can put a fee on it "
(M. Faraday)

Summary and Perspective

- For graphene structures, the exchange of gauge fields between electrons gives rise to effective gravitons.
- Such an exchange leads to the emergence of conductivity
- Three types of curvature: i) between free electrons, ii) between bound electrons, iii) between free and bound electrons.
- These fields create a sort of an effective gravity with positive curvature between parallel spins, and anti-gravity with negative curvature between parallel spins.
- The current density of free electrons is obtained in terms of inequality between curvatures of parallel spins and those between anti-parallel spins.

Summary and Perspectives

- Curvature and parameters of graphene molecule give the current density in terms of the angles between atoms with respect to the center of graphene molecule
- Using M-theory, an action for conductivity in a graphene system is defined in terms of gauge fields and fermions.
- We obtained the relation between gauge fields and curvature of parallel spins and anti-parallel spins.
- Curvature produced between parallel spins has an opposite sign with respect to the curvature which is generated between anti-parallel spins.
- Curvature has a direct relation with the effective energy-momentum tensor. In particular R^2 terms give rise to a curvature energy-momentum tensor. This fact allows no violation of energy conditions.
- Variations of momenta give rise to forces between spinors.
- The force between parallel spins has an opposite sign with respect to the force between anti-parallel spins. It can be observed in laboratory experiments.
- Using the relations between gauge fields, spinors and curvature, it is possible to obtain the energy of system in terms of difference between curvatures of parallel spins and anti-parallel spins.

Summary and Perspectives

- The current density can be calculated in terms of angles. For standard graphene with hexagonal molecules, the current density is zero and electrons move randomly and superconductivity disappears.
- For graphene with heptagonal defects, the current density is positive, it is possible to deduce that electrons are repelled by neighbor molecules and move outward from molecules (the curvature produced by parallel spins is larger than the curvature produced by anti-parallel spins and therefore a negative force is applied to electrons. As consequence, they move in opposite directions with respect to the molecule).
- For graphene with pentagonal defects, the current density is negative. Electrons are absorbed by pentagonal defects and move towards molecules. This type of defects induces a force to the free electrons and leads them to move towards the molecules.
- Increasing the number of defects, the current density increases and the graphene tends to become a superconductor.
- A symmetry breaking induced by effective gravitons produces the graphene wormhole which is **stable** and **traversable**.
- Stability is guaranteed by the curvature energy momentum tensor. No violation of energy conditions.

Summary and Perspectives

- In the graphene wormhole, the current density is zero in the upper and lower graphene sheets, then it rises up to positive value in the wormhole bridges.
- In the connecting nanotube, it decreases to the lower values.
- In the centre of the connecting nanotube, the current density is exactly zero due to the mutual elimination and the wormhole is stable!
- In pure graphene, due to its symmetry, the curvature of anti-parallel spins is cancelled out by the curvature of parallel spins, and the total current density of free electrons is zero.
- The free electrons do not move in any special direction and conductivity disappears.
- For graphene with some type of geometrical defects, anti-parallel spins come closer mutually, their curvature increases, and (modified) gravity emerges.
- Consequently, the current density grows and conductivity increases. Similarly, for some other types of defects, parallel spins approach each other, their negative curvature increases and (modified) anti-gravity appears.
- In this case, the sign of current density reverses, the electrons move in opposite direction, and a new conductivity appears along this new direction.
- It is possible to show that different defects produce different Extended Gravity models.
- This means that wormhole solutions can be "classified" according to the graphene geometrical defects (e.g. Chern-Simons, Gauss-Bonnet, Reissner-Nordstrom, etc.).
- Technological applications have to be characterized by sizing the devices and the current densities….WORK IN PROGRESS!

References

- S. Capozziello, T. Harko, T.S. Koivisto, F. S.N. Lobo, G. J. Olmo,
  Phys.Rev. D86 (2012) 127504

- S. Bahamonde, U. Camci, S. Capozziello, M. Jamil
  Phys.Rev. D94 (2016), 084042

- A. Sepehri, R. Pincak, K. Bamba, S. Capozziello, E. N. Saridakis
  Int.J.Mod.Phys. D26 (2017), 1750094

- S. Capozziello, F. S. N. Lobo, J. P. Mimoso
  Phys.Rev. D91 (2015) 124019

- S. Capozziello, F. S. N. Lobo, José P. Mimoso
  Phys.Lett. B730 (2014) 280-283

- S. Capozziello, R. Pincak , E. N. Saridakis
  Annals of Physics 390 (2018) 303