Graphene 2018
June 26 - 29
Dresden (Germany)

Tailoring one-way transport and non-reciprocity in graphene-based devices

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This is shortened version of the full presentation.
The full presentation is available at
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Preamble:
The (forgotten) search of a transistor-like effect in a metal

Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1]* S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

We describe monocrystalline graphitic films, which are a few atoms thick but are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films are found to be a two-dimensional semimetal with a tiny overlap between valence and conductance bands, and they exhibit a strong ambipolar electric field effect such that electrons and holes in concentrations up to 10^{13} per square centimeter and with room-temperature mobilities of ~10,000 square centimeters per volt-second can be induced by applying gate voltage.

The ability to control electronic properties of a material by externally applied voltage is at the heart of modern electronics. In many cases, it is the electric field effect that allows one to vary the carrier concentration in a semiconductor device and, consequently, change an electric current through it. As the semiconductor industry is nearing the limits of performance improvements for the current technologies dominated by silicon, there is a constant search for new, nontraditional materials whose properties can be controlled by the electric field. The most notable recent examples of such materials are organic conductors (*1*) and carbon nanotubes (*2*). It has long been tempting to extend the use of the field effect to metals [e.g., to develop all-metallic transistors that could be scaled down to much smaller sizes and would consume less energy and operate at higher frequencies

[1]Department of Physics, University of Manchester, Manchester M13 9PL, UK. [2]Institute for Microelectronics Technology, 142432 Chernogolovka, Russia.

*To whom correspondence should be addressed. E-mail: geim@man.ac.uk

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The search of a transistor-like effect in a metal

Electric Field Effect in Atomically Thin Carbon Films

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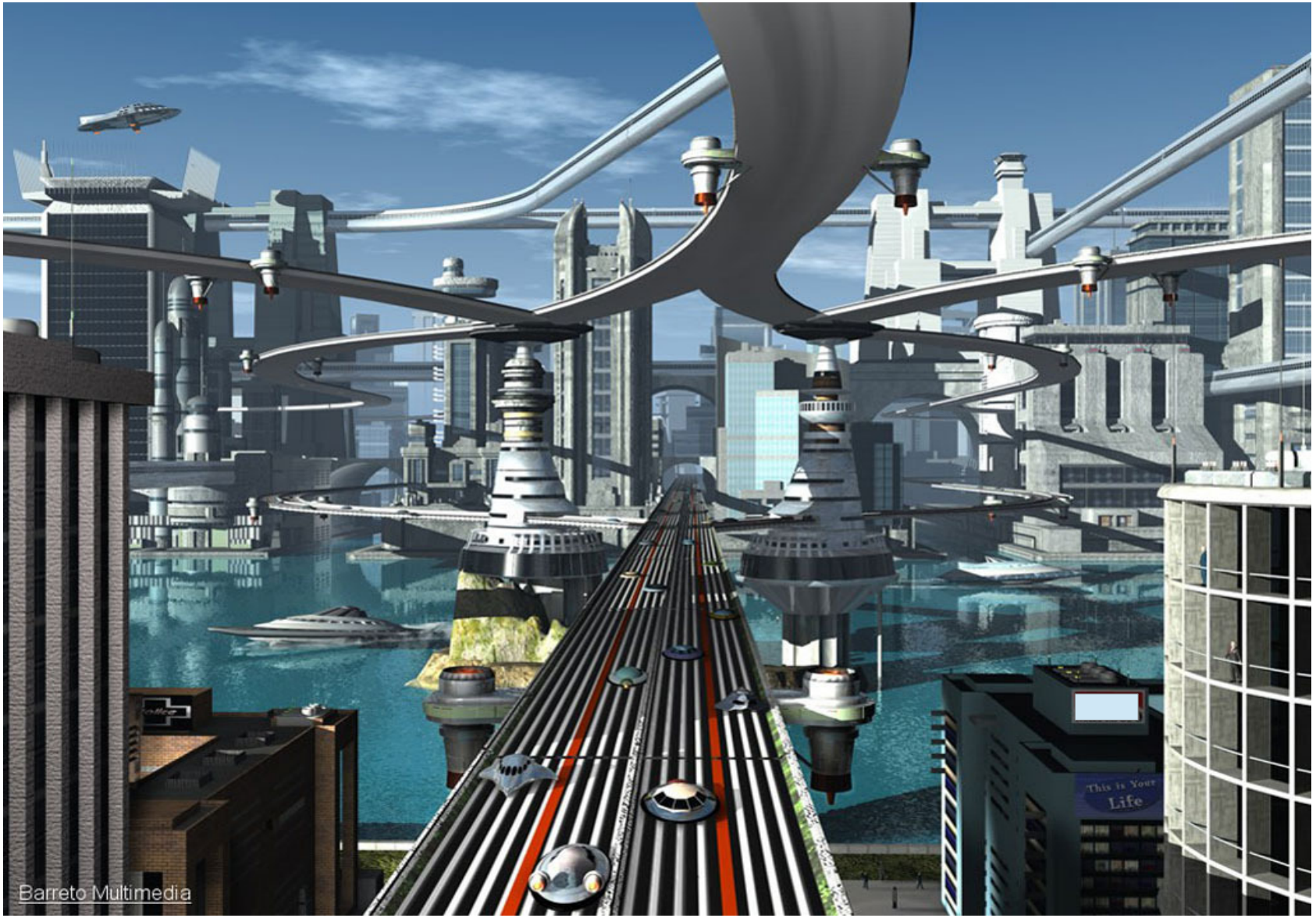
*"Graphene may be the best possible metal for **metallic transistor** applications…*
Graphene transistors show a rather modest on-off resistance ratio (less than 30 at 300 K), but this is a fundamental limitation for any material without a band gap exceeding kT."



Layertronics?

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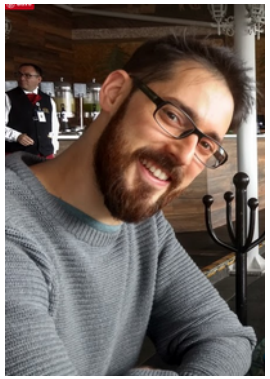
C. Balseiro
(CAB, Argentina)


Eric Suárez Morell
(UTFSM, Chile)


José Eduardo Barrios Vargas


Matías Berdakin

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S. Roche (ICN2)


75 °W
60 °W
45 °W
PERU
BOLIVIA
PARAGU
ARGENTINA
Arica
Iquique
Calama
Valle de la Luna
Antofagasta
Copiapó
La Serena
San Cristóbal Hill
Valparaíso
SANTIAGO
Talca
Concepción
Chillán
Los Ángeles
Temuco
Pucon
Valdivia
Quellón
Chaiten
Coihaique
Valparaíso
Cochrane
Torres del Paine
Puerto Natales
Los Pingüinos
Natural Monument
Punta Arenas
Atacama Desert
Andes
Chilean Fjords
Archipelago
Corcovado Gulf
Magallanes Str.
Falkland
75 °W
60 °W
45 °W


75 °W
60 °W
45 °W
PERU
BOLIVIA
BRAZIL
PARAGUAY
ARGENTINA
URUGUAY
Arica
Iquique
Calama
Valle de la Luna
Antofagasta
Copiapó
La Serena
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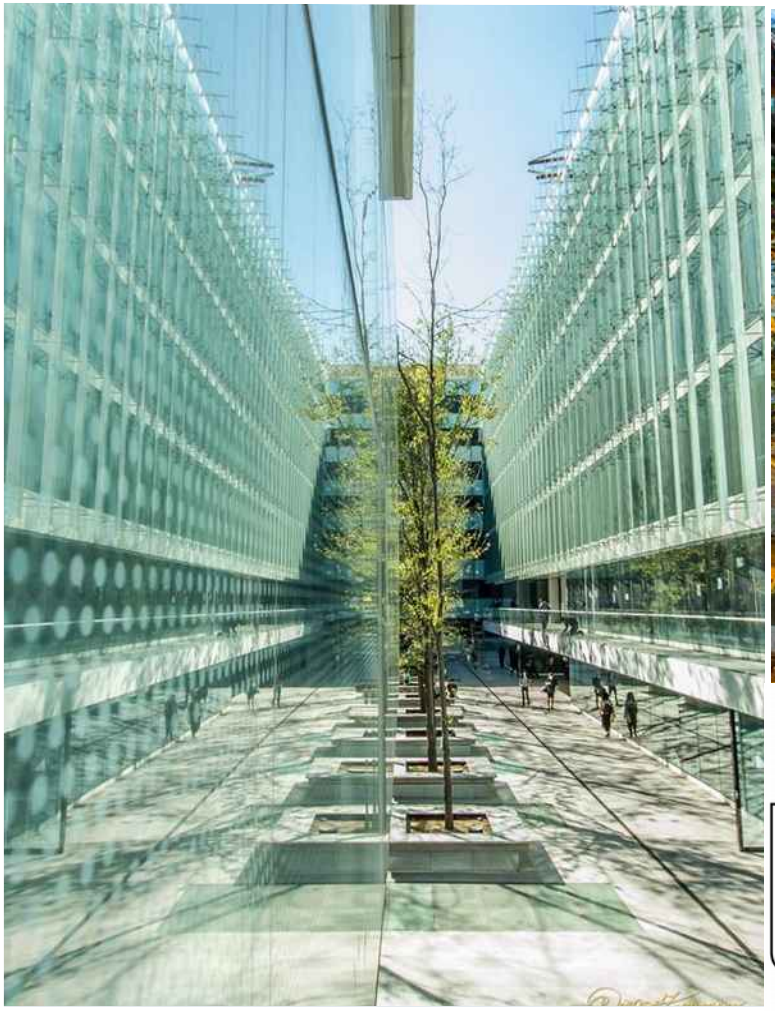
SANTIAGO
Talca
Concepción
Chillán
Los Ángeles
Temuco
Pucon
Valdivia
Quellón
Chaiten
Coihaique
Cochrane
Torres del Paine
Puerto Natales
Los Pingüinos
Natural Monument
Punta Arenas
Tropic of Capricorn
30 °S
75 °W
60 °W



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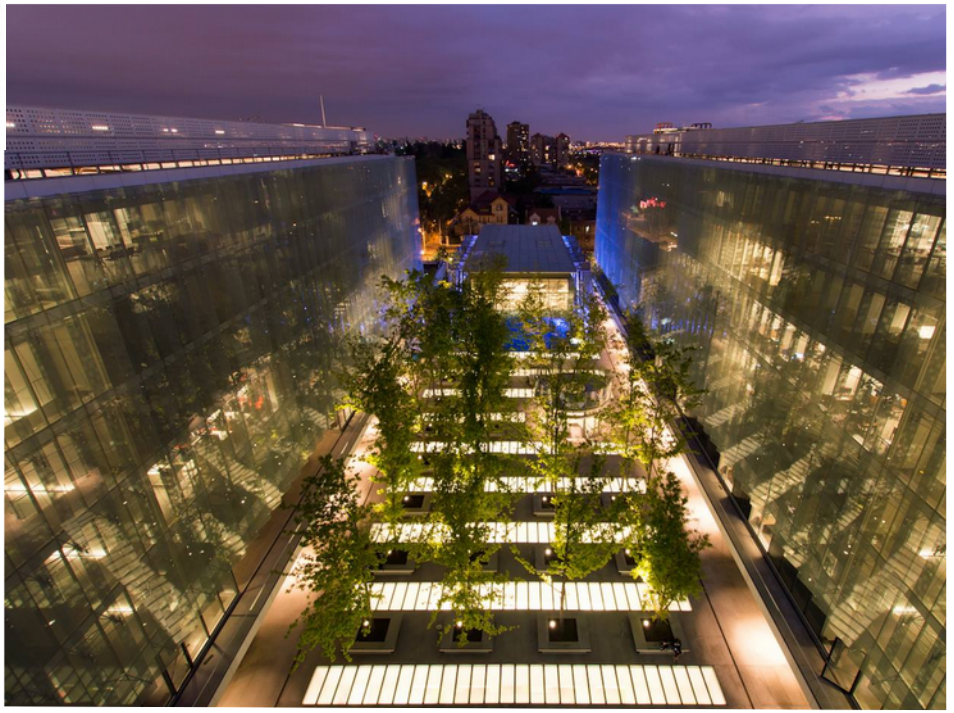


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for next year
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luisfoa@gmail.com
Let’s chat during the
conference.

Outline

Introduction:

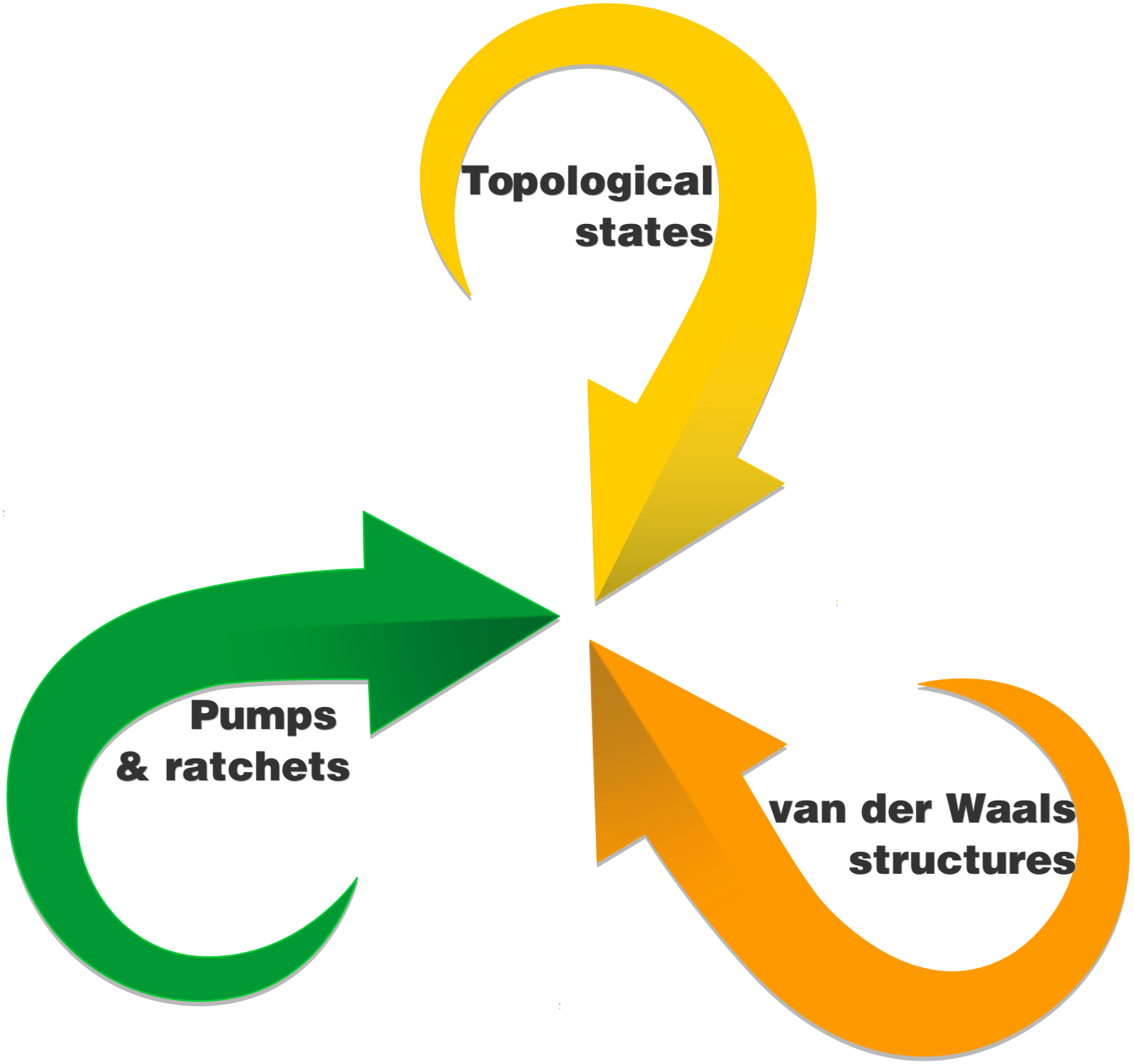
- Ingredients and Motivation
- Topological states of matter

Crafting one-way transport of charge, valley and spin

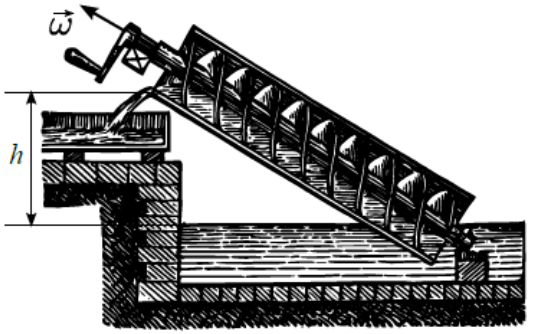
- Non-reciprocal bandstructure of the Haldane bilayer
- One-way transport
- Making it *anti-fragile*
- The spinfull case: bilayer with intrinsic spin-orbit interaction

Conclusions and final remarks

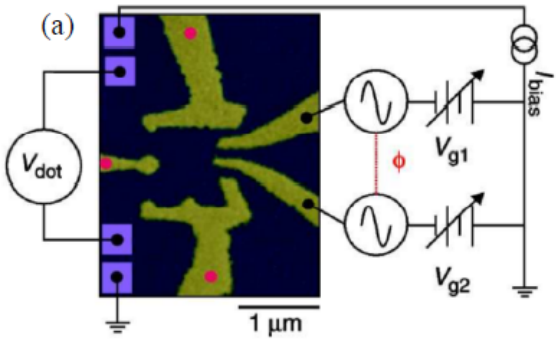
Our ingredients



Our ingredients



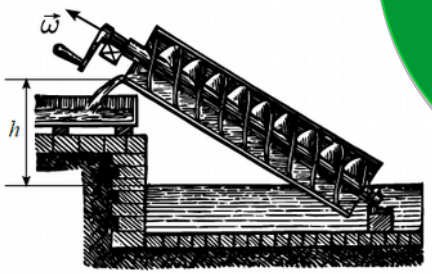
Archimedes., 3rd century BC



Switkes et al., Science 1999

Pumps & ratchets

van der Waals structures

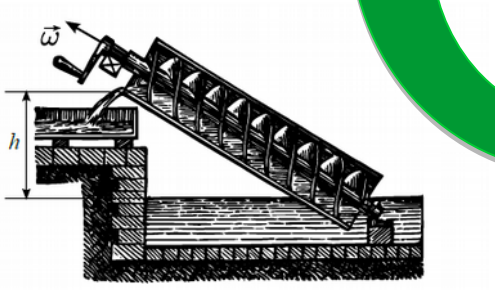


Our ingredients

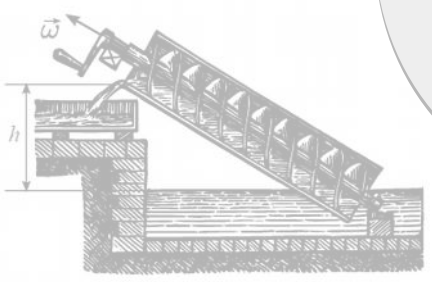
Topological states

Pumps & ratchets

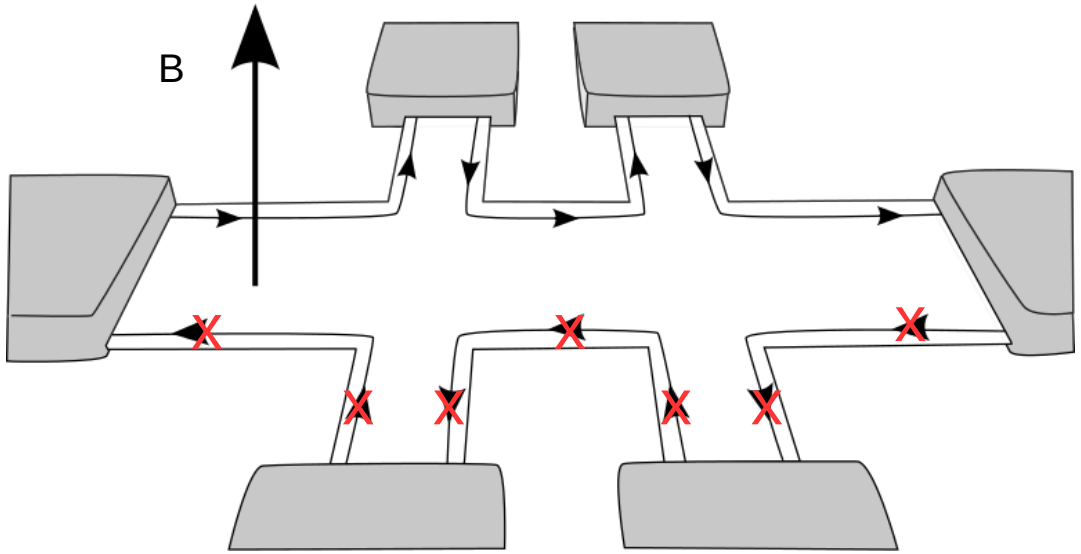
van der Waals structures



Our ingredients



What if … ?



This would violate the bulk-boundary correspondence

$$\mathcal{H} = \begin{pmatrix} \mathcal{H}_1 & \mathcal{H}_{1,2} \\ \mathcal{H}_{2,1} & \mathcal{H}_2 \end{pmatrix}$$

Idea: look for edge states coexisting with a continuum in bipartite systems.

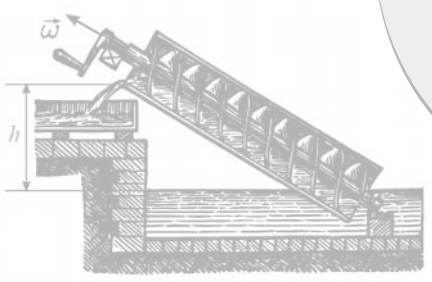
Perez-Piskunow, Foa Torres, Usaj, PRA **91**, 043625 (2015).
Baum et al. PRL **114**, 136801 (2015).

Our ingredients

Topological states

Pumps & ratchets

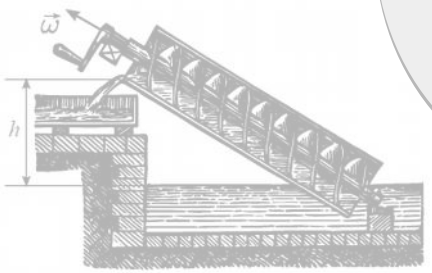
van der Waals structures



Our ingredients

Topological states

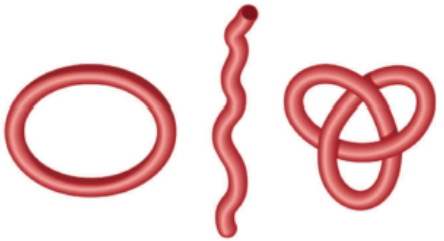
Pumps & ratchets



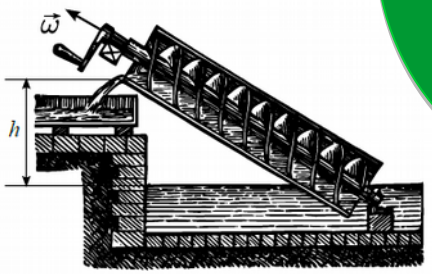
van der Waals structures

Our ingredients

Topological states

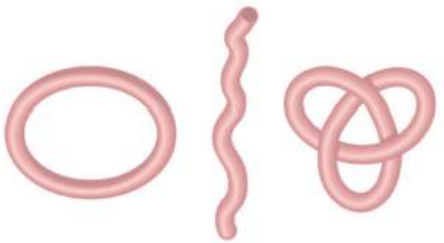


Pumps & ratchets



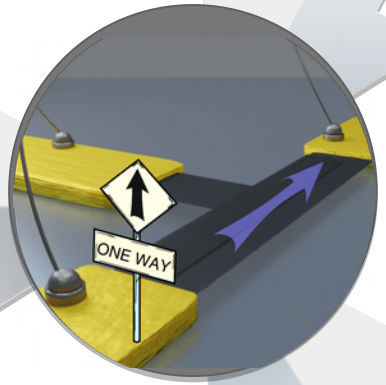
van der Waals structures

Our ingredients



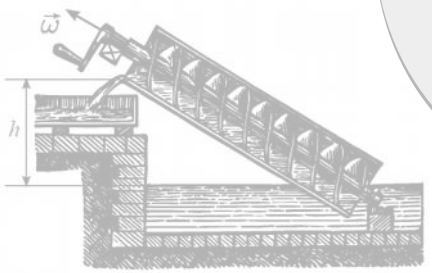
Topological states

The ‘ultimate’ steering



Pumps & ratchets

van der Waals structures



Isolator

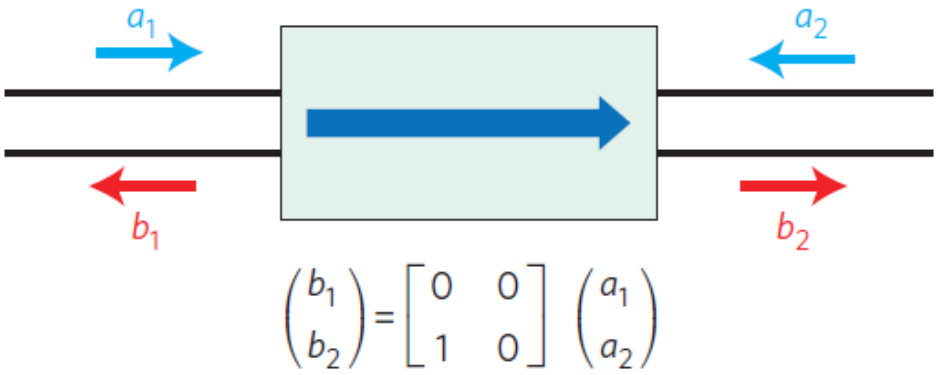


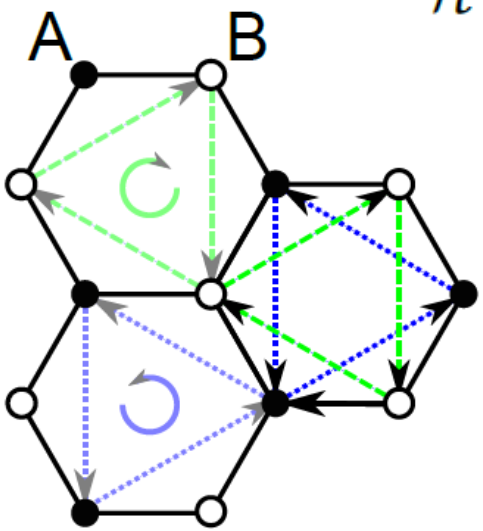
Figure 2 | The simplest isolator with two single-mode waveguide ports. The scattering matrix indicates that the isolator allows transmission in only one direction.

Jalas et al., “What is and what is not an optical isolator”, Nat. Photonics **7**, 579 (2013)

Crafting one-way transport of charge (and valley) and spin

Haldane model

Graphene + complex second-nearest neighbors term

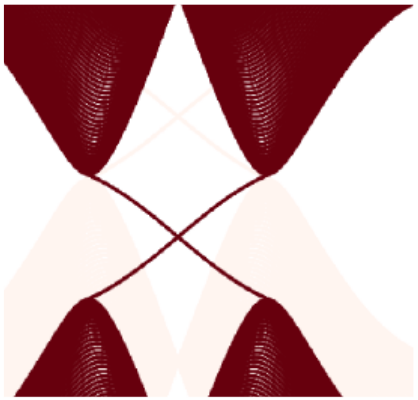


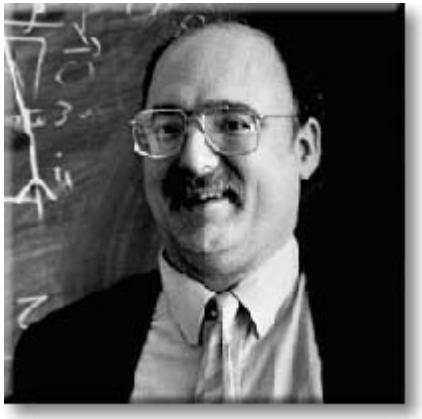
$$\mathcal{H} = \sum_i E_i \, c_i^\dagger c_i - \gamma_0 \sum_{\langle i,j \rangle} c_i^\dagger c_j - \mathrm{i}\gamma_H \sum_{\langle\langle i,j \rangle\rangle} \nu_{i,j} c_i^\dagger c_j$$

Haldane's term
second nearest neighbors
(complex)

Bulk gap + edge states

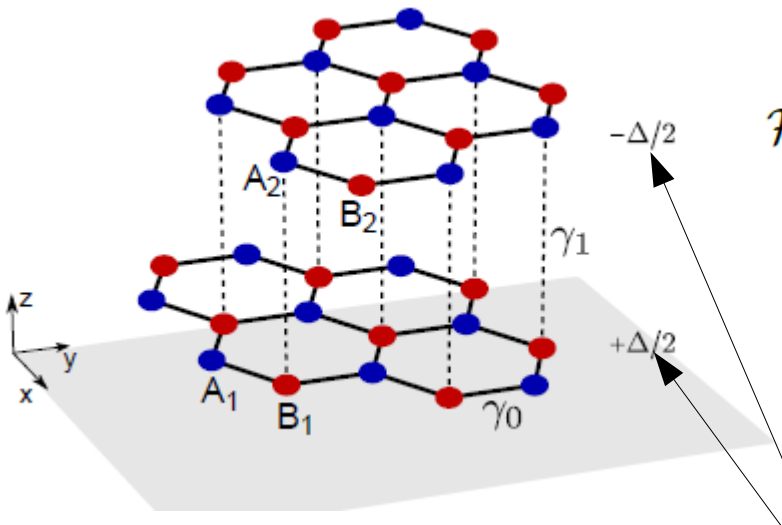
Similar to QHE
but without Landau levels





F. D. M. Haldane, PRL 61, 2015 (1988).

Bilayer with Haldane term



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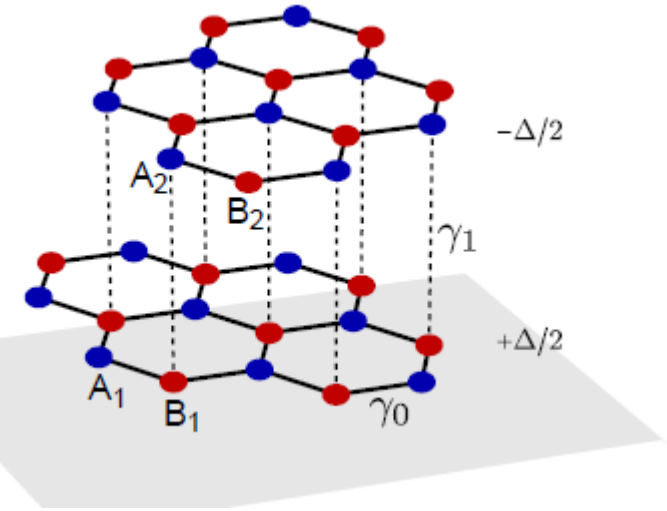
1) stacking

2) Perpendicular bias

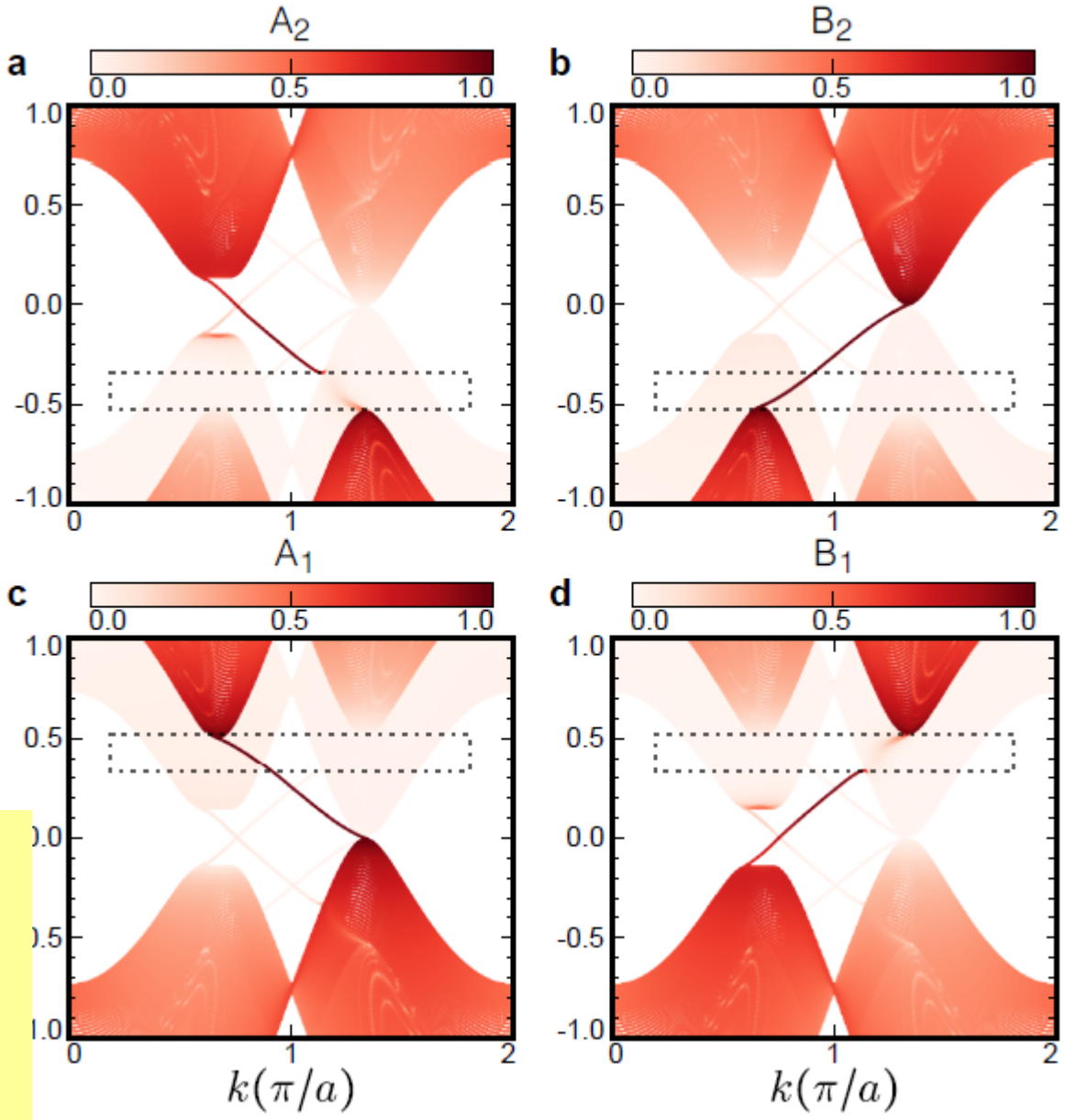
Bilayer with Haldane term

$\gamma_1 \neq 0$

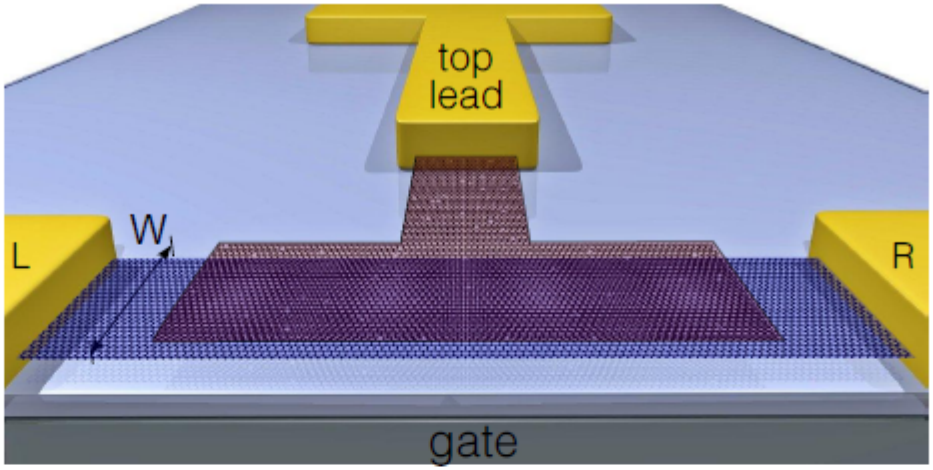


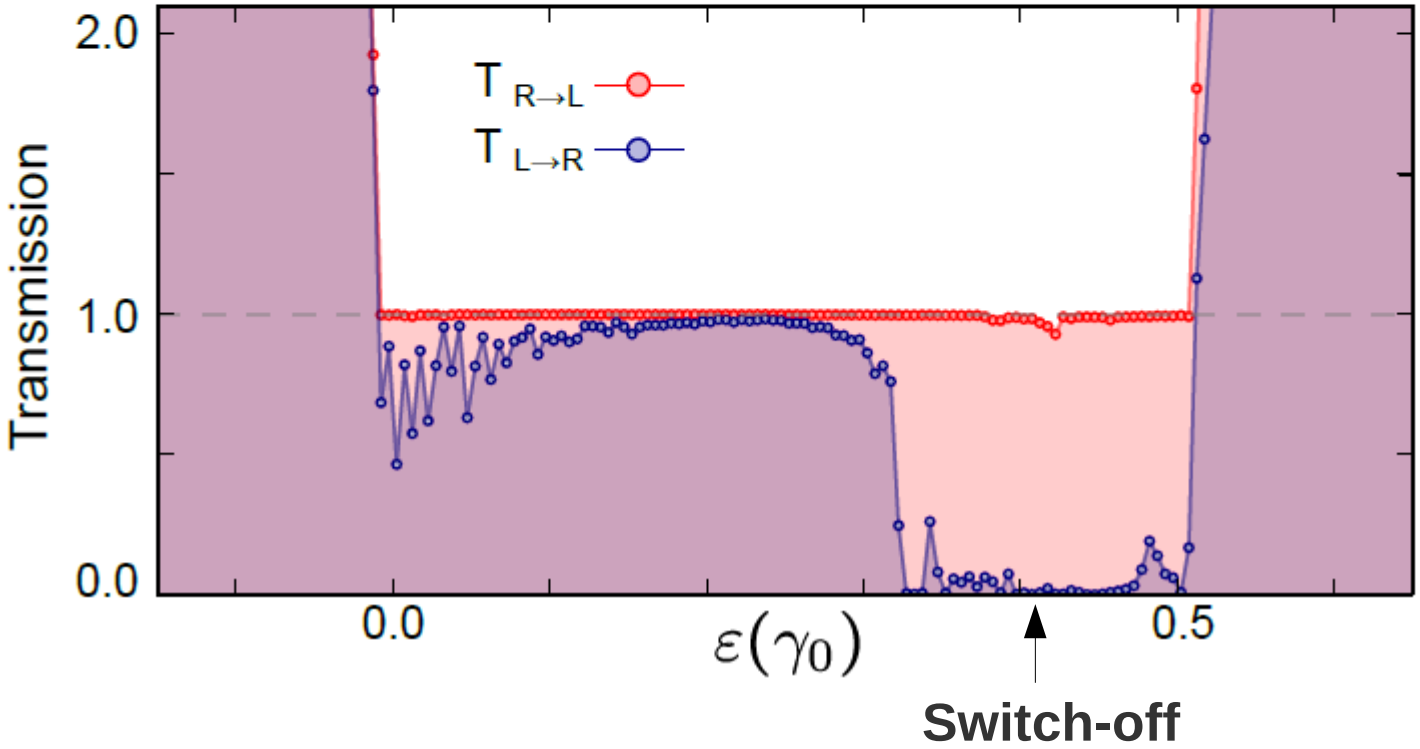
→ **Selective environment (stacking + sublattice polarization of edge states)**

Sublattice polarization of the edge states



One-way charge (and valley) transport





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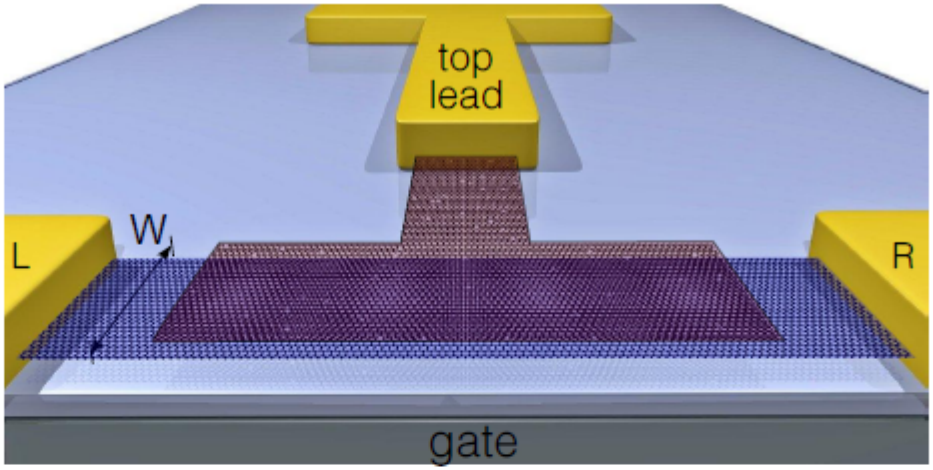
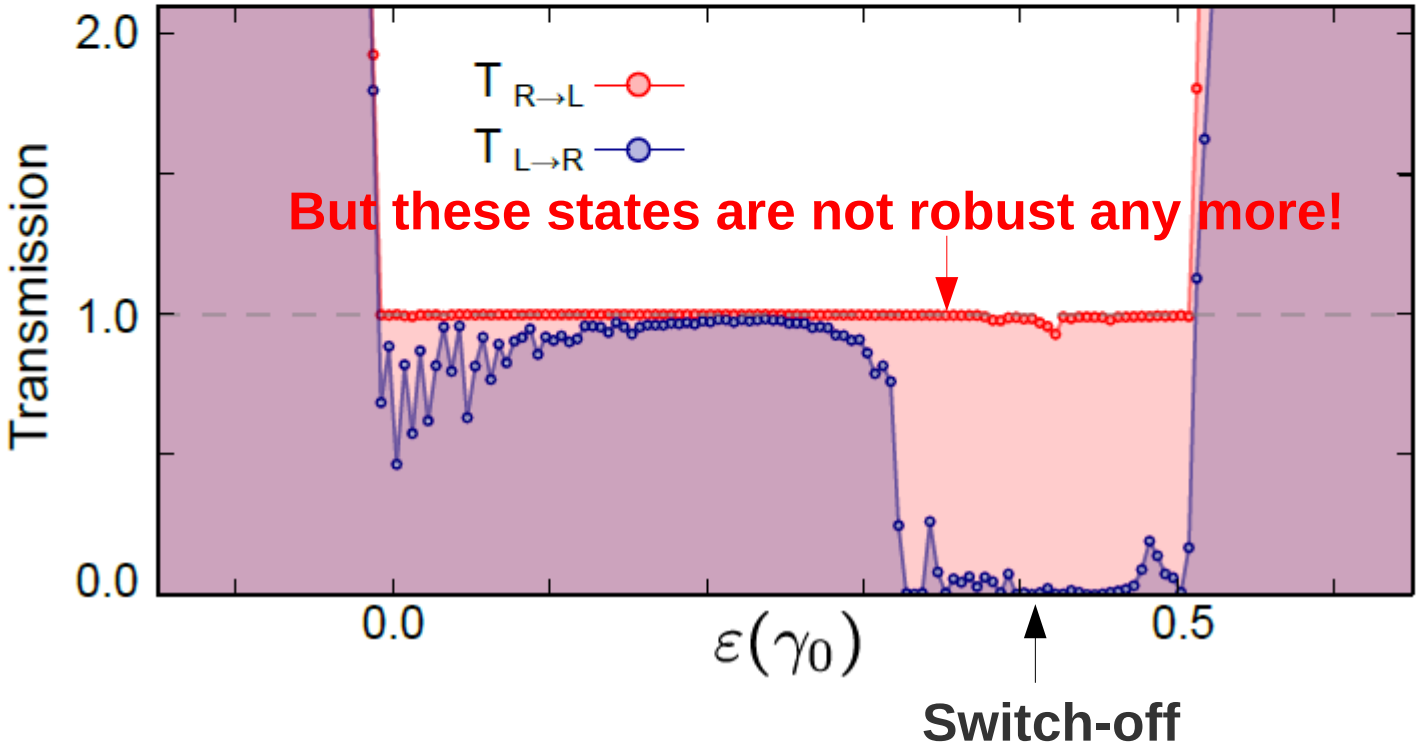


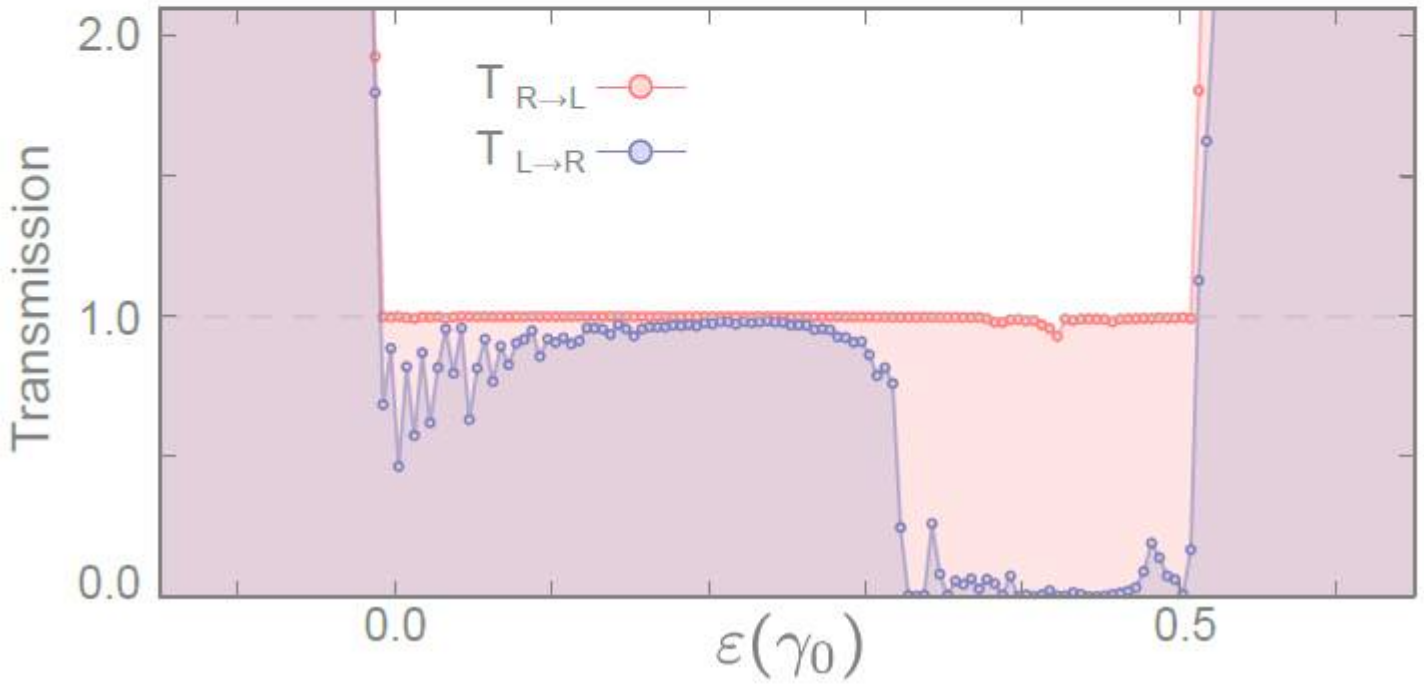


Making it anti-fragile

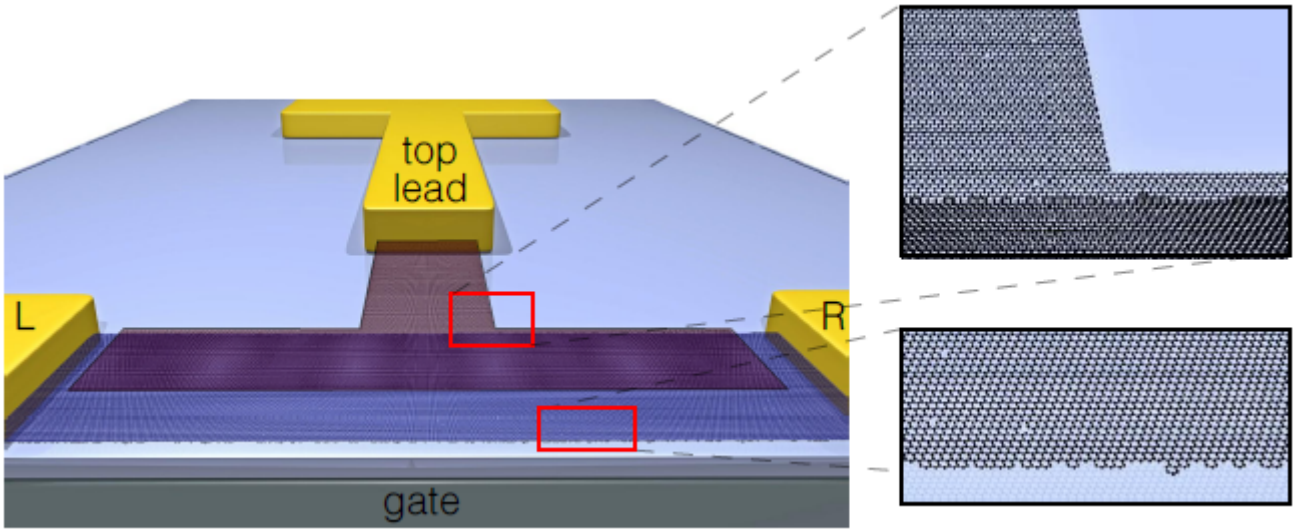
Wish list :

(1) Keep the robustness of the surviving edge states.

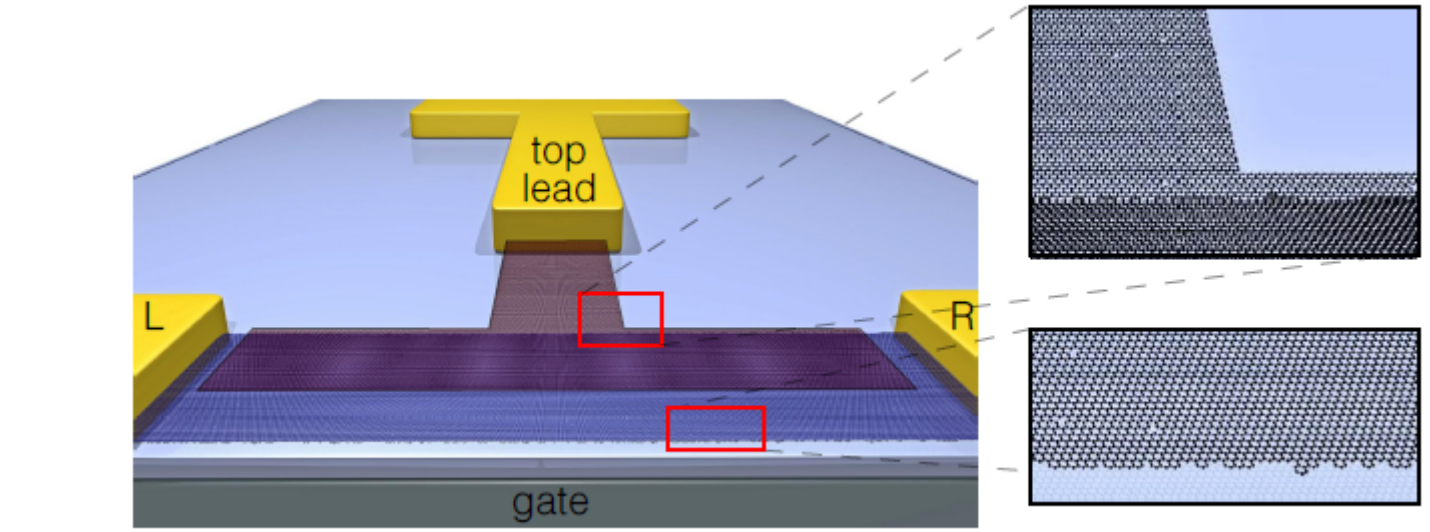
(2) Enhance the switch-off effect
so that it doesn't depend on edge type.

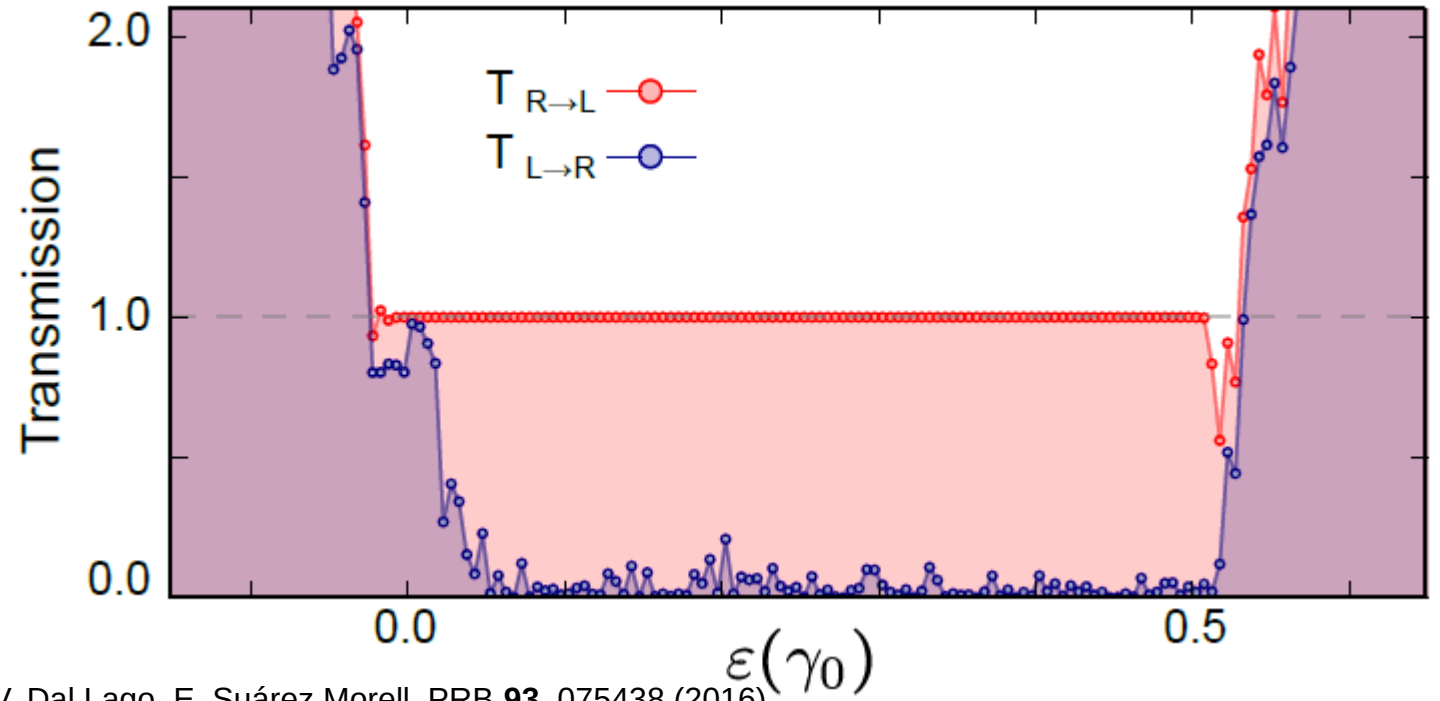


Making it anti-fragile



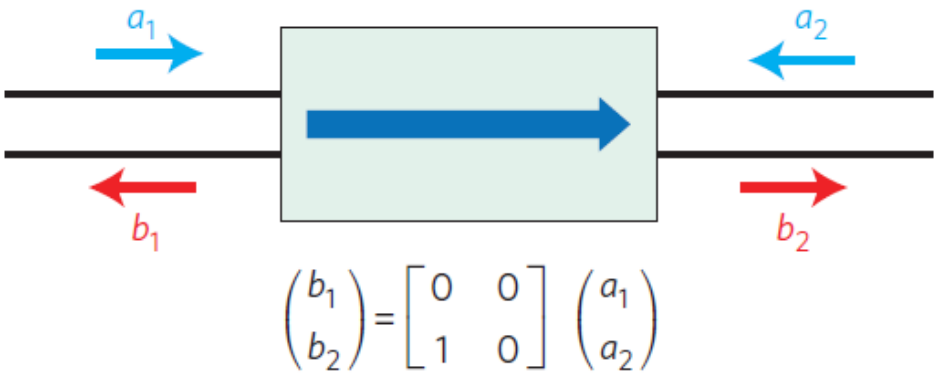
Making it anti-fragile





L. E. F. Foa Torres, V. Dal Lago, E. Suárez Morell, PRB **93**, 075438 (2016)

Isolator



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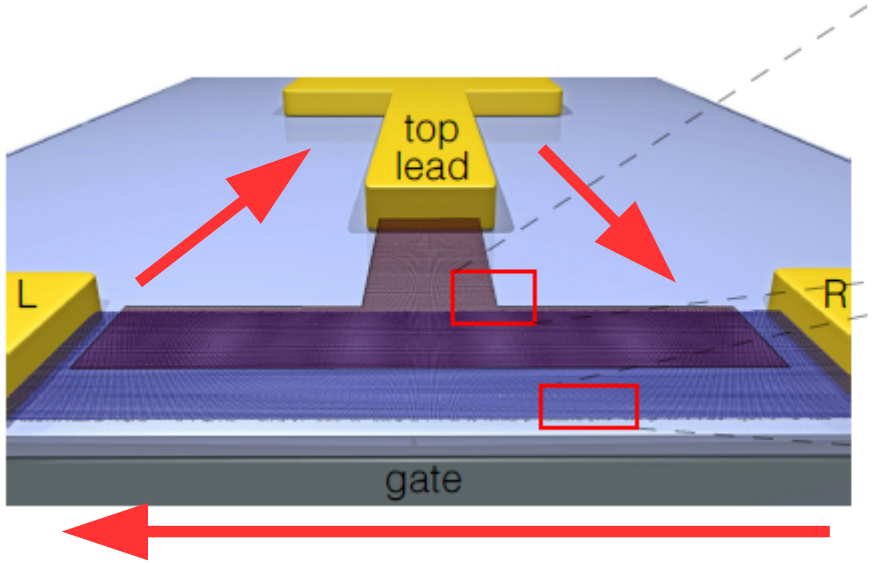
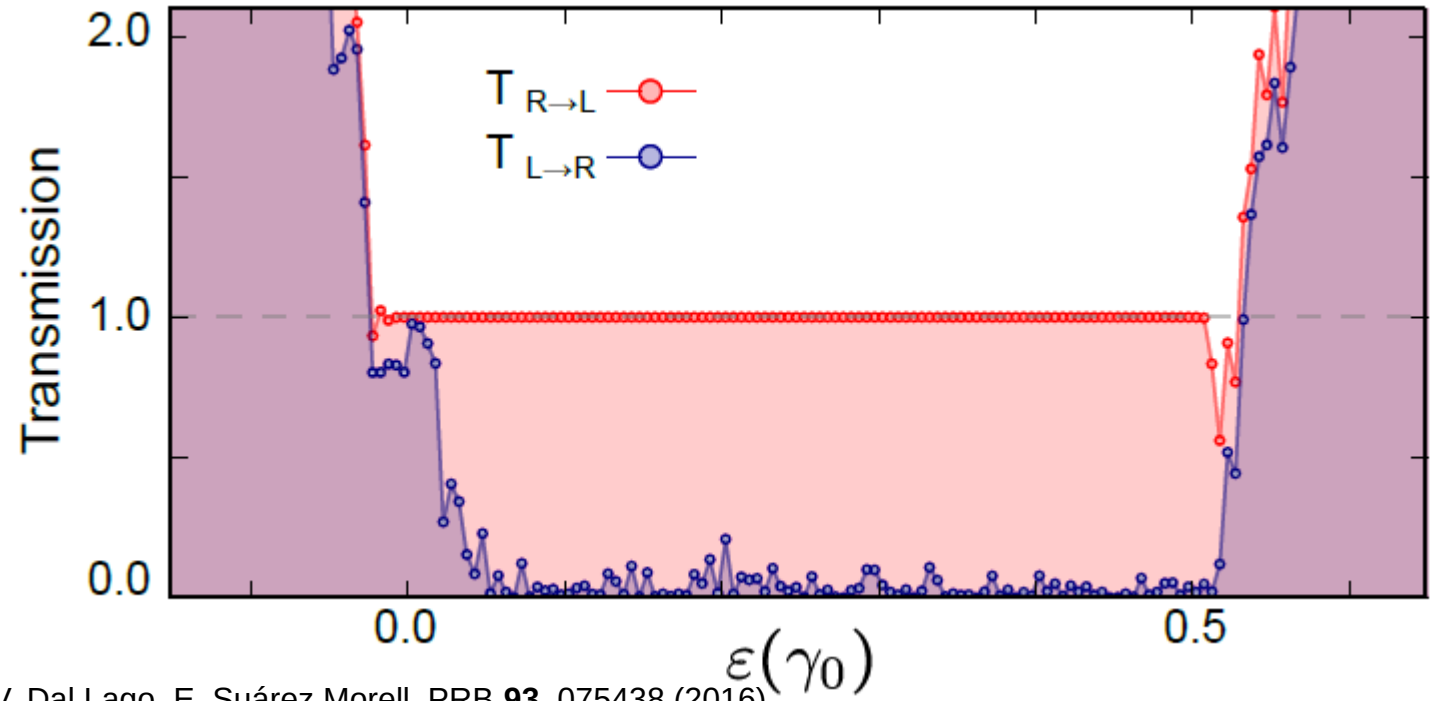
Jalas et al., “What is and what is not an optical isolator”, Nat. Photonics **7**, 579 (2013)

Pump-like effect without time-dependent potential

Circulator / Isolator





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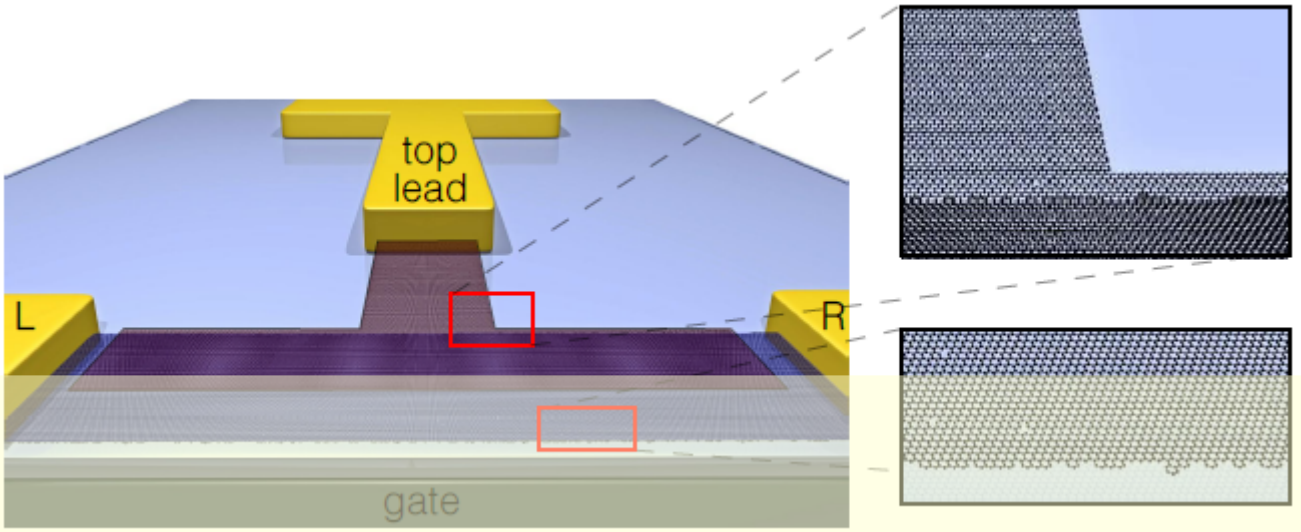
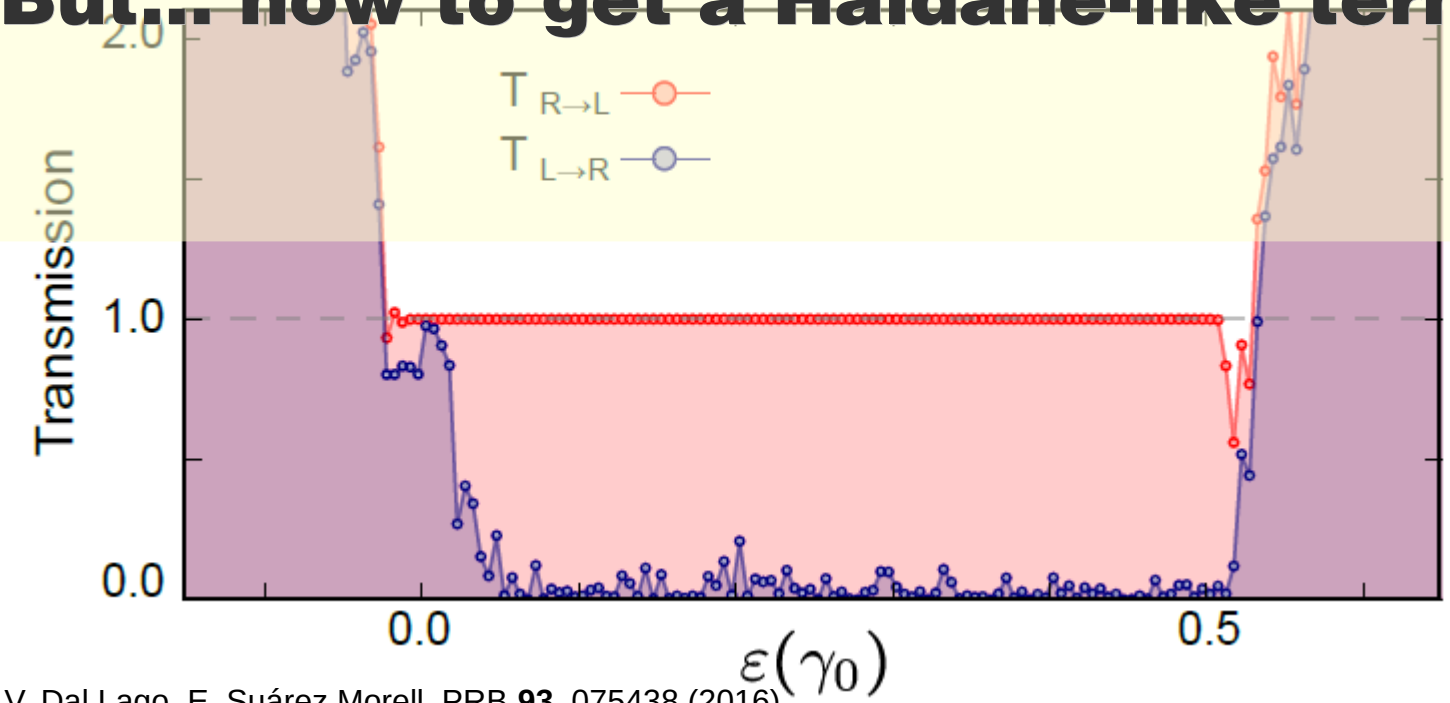
Making it anti-fragile



But... how to get a Haldane-like term?



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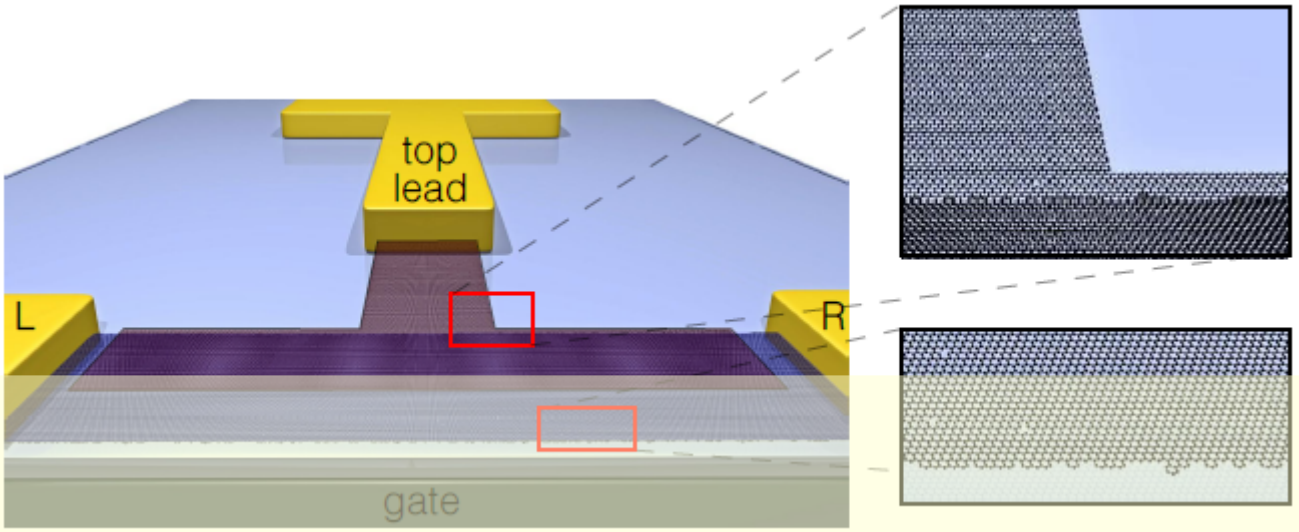
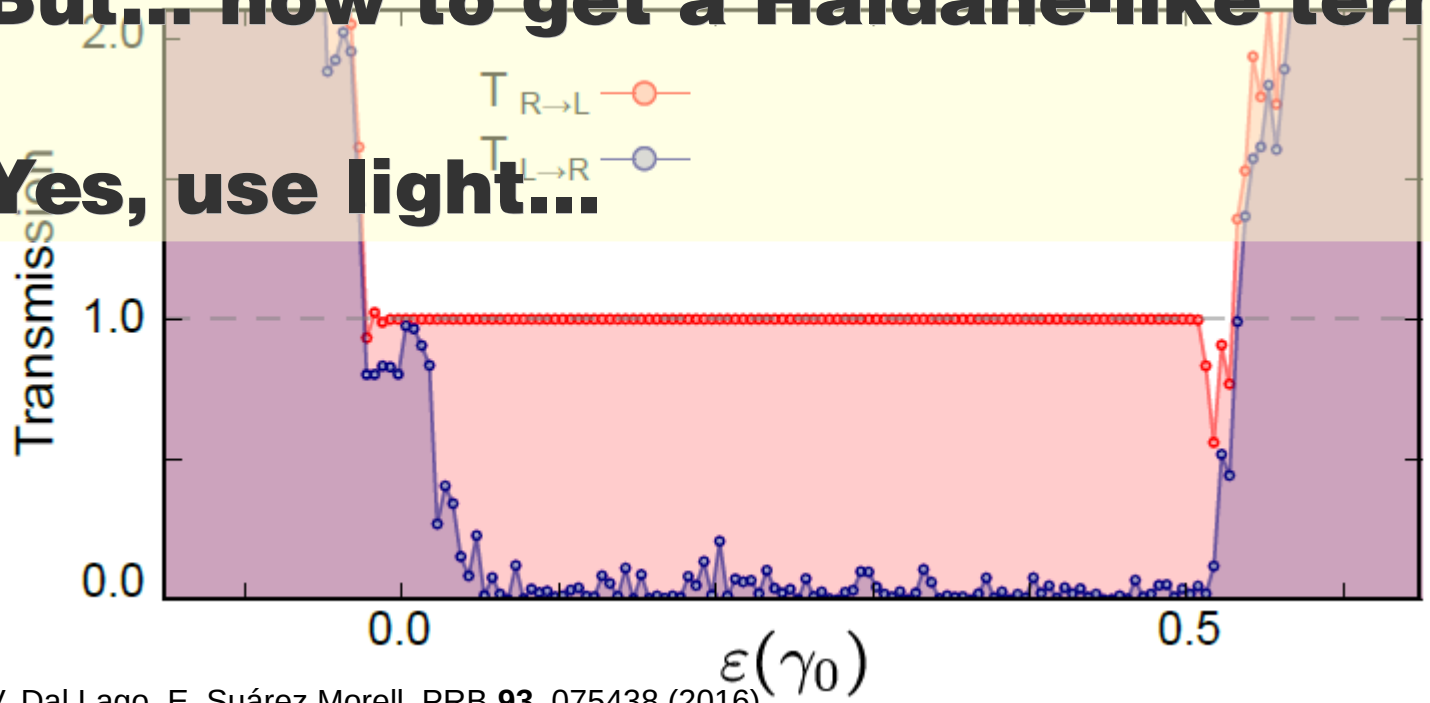
Making it anti-fragile



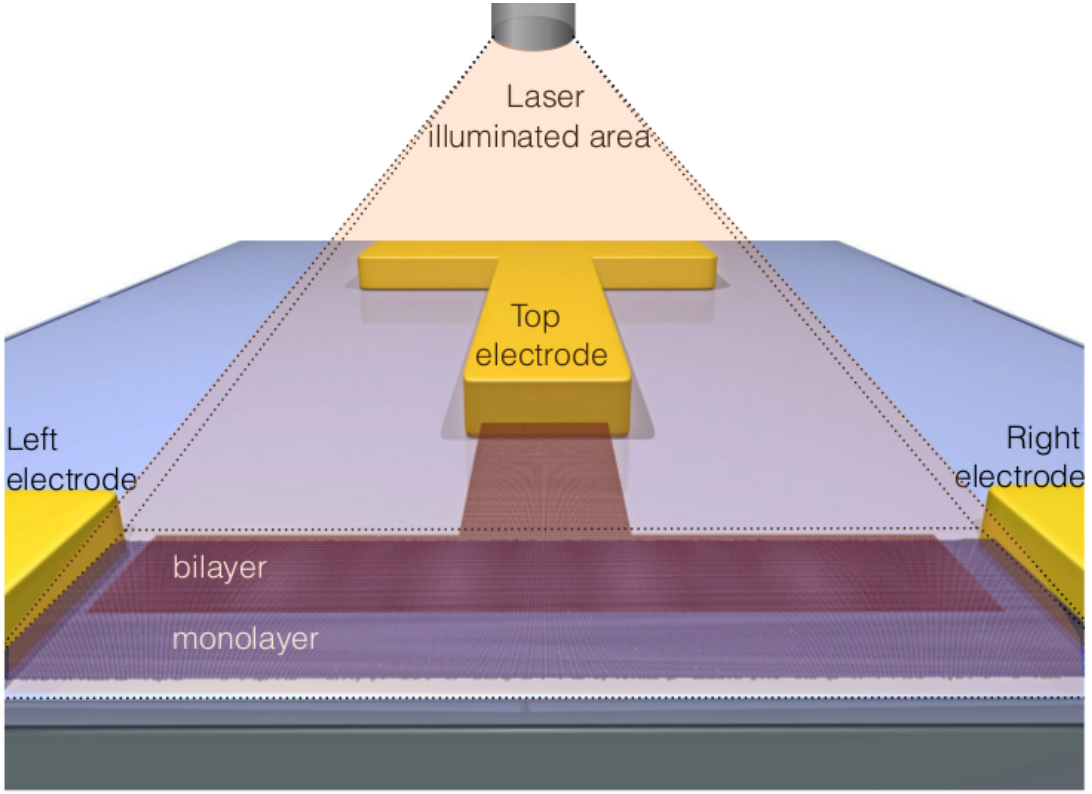
But... how to get a Haldane-like term?

Yes, use light...



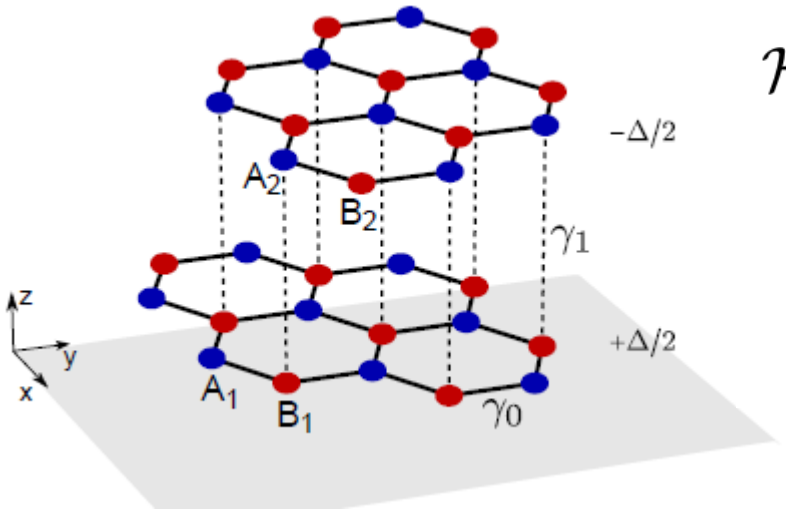
L. E. F. Foa Torres, V. Dal Lago, E. Suárez Morell, PRB **93**, 075438 (2016)

Proof of concept



V. Dal Lago, E. Suárez Morell, and L. E. F. Foa Torres, PRB **96**, 235409 (2018)

The Spin-full case: Bilayer with ISO

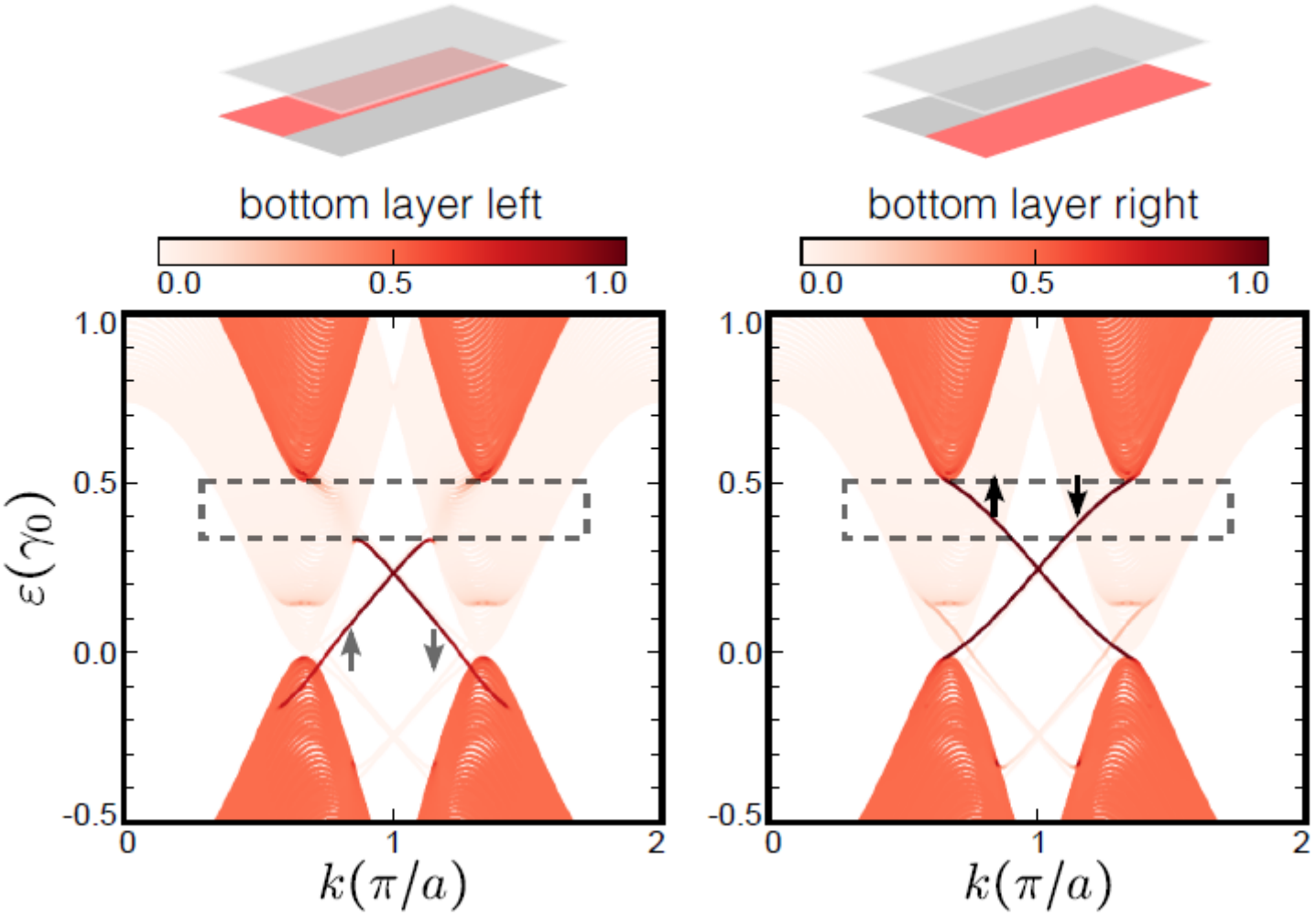


$$\mathcal{H} = \sum_{i,s_z} E_i \, c^{\dagger}_{i,s_z} c_{i,s_z} - \gamma_0 \sum_{\langle i,j\rangle,s_z} c^{\dagger}_{i,s_z} c_{j,s_z}$$

$$- i\gamma_{SO} \sum_{\langle\langle i,j\rangle\rangle,s_z} \nu_{i,j} s_z c^{\dagger}_{i,s_z} c_{j,s_z} + \mathcal{H}_{\perp}$$

Intrinsic spin-orbit term

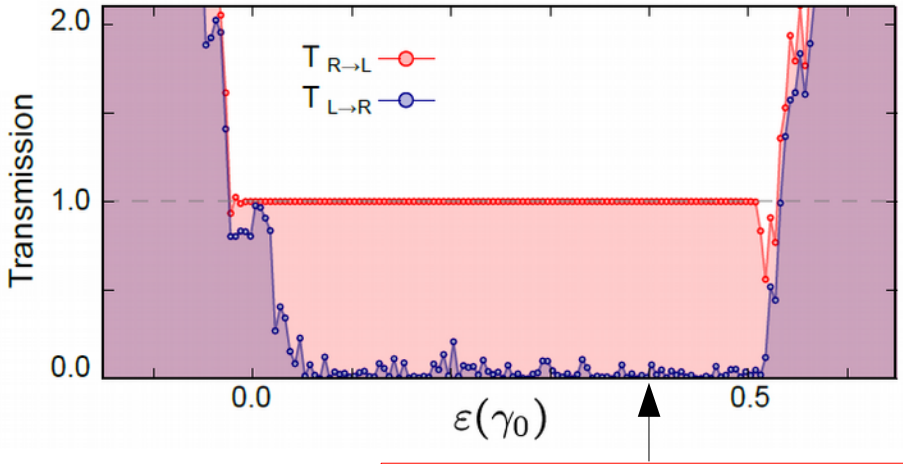
The Spin-full case: Bilayer with ISO



Similar as before but for spin-Hall states.

pure-spin currents

A note directional control: The search of a transistor-like effect in a metal



Switch-off in a device that remains metallic!

Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1]* S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

We describe monocrystalline graphitic films, which are a few atoms thick but are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films are found to be a two-dimensional semimetal with a tiny overlap between valence and conductance bands, and they exhibit a strong ambipolar electric field effect such that electrons and holes in concentrations up to 10^{13} per square centimeter and with room-temperature mobilities of ~10,000 square centimeters per volt-second can be induced by applying gate voltage.

The ability to control electronic properties of a material by externally applied voltage is at the heart of modern electronics. In many

semiconductor industry is nearing the limits of performance improvements for the current technologies dominated by silicon, there is a

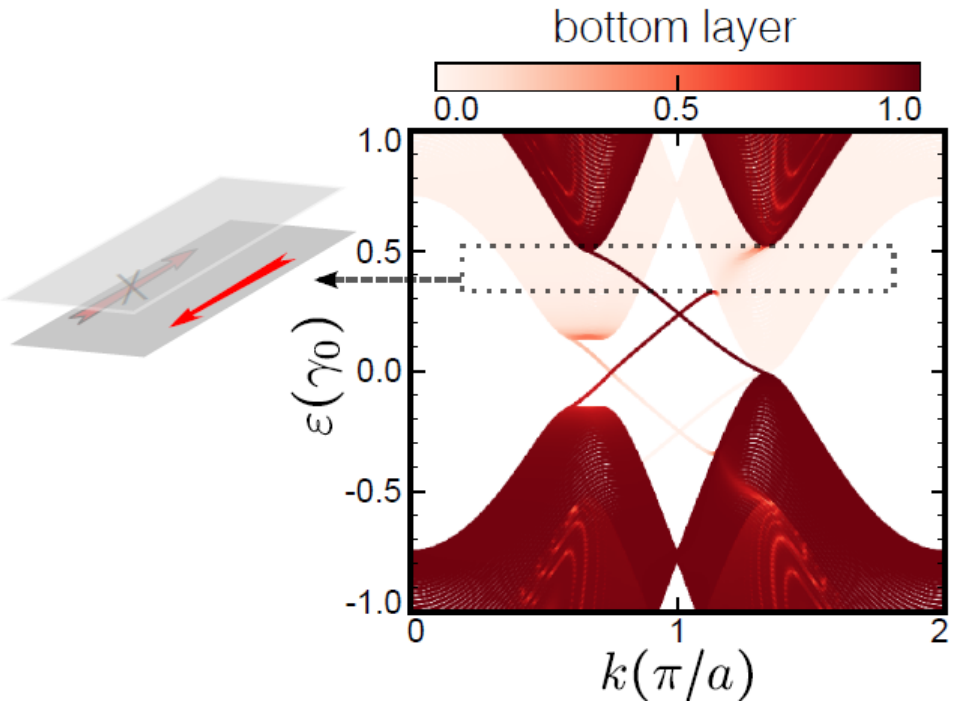
examples of such materials are organic conductors (*1*) and carbon nanotubes (*2*). It has long been tempting to extend the use of the field effect to metals [e.g., to develop all-metallic transistors that could be scaled down to much smaller sizes and would consume less energy and operate at higher frequencies

Conclusions

. **One-way transport built-in the bandstructure (via selective environment).**

. Electrical version of an isolator / circulator.

. **Source of nearly perfect charge/valley/spin polarized currents**.

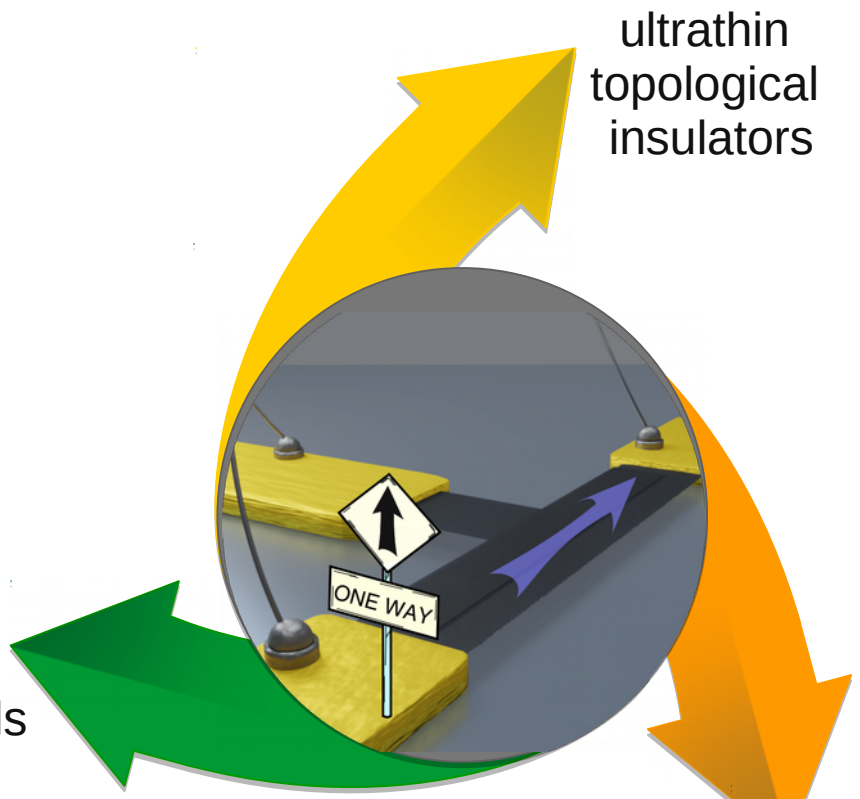


Matías Berdakin

Go and see Poster #139

M. Berdakin, J. E. Barrios Vargas, and L. E. F. Foa Torres, to appear.

Perspectives



ultrathin
topological
insulators

silicene
& other
2D materials

van der Waals
heterostructures

Imagine one-way transport of *energy*.

Layertronics?

Gracias!
Thanks!

Positions available

Send me an email to
luisfoa@gmail.com

Let's chat during the conference.

Gracias!
Thanks!

Note:
This is shortened version of the full presentation.
The full presentation is available at
http://www.foatorres.com