FUNLAYERS

FUNLAYERS SUMMER SCHOOL at ALBA Synchrotron

An Introduction to (magnetic) 2D materials

Joaquín Fernández-Rossier (INL)

Outline

- Brief intro to Funlayers
- 2D Materials: why all the fuss?
- Magnetic 2D Materials: some key-concepts

FUNLAYERS in a nutshell

1. Title: "**Twinning on Functional Layered Materials for Advanced Applications**"
2. **Call:** HORIZON-WIDERA-2021-ACCESS-03-01: Twinning (Coordination & Support Action)
3. **Partners:** INL as coordinator, ALBA, MPG
4. **Duration**: 3 years, starting on 1/1/2023
5. Budget: close to 1.5M€, 0.9M€ for INL (Less than 30% for research)

5 goals

1. To promote a layered material transnational research environment … to stimulate interdisciplinary research within INL, ALBA-CELLS and MPG
2. To significantly enhance the overall scientific and R&I capacity of INL in layered materials
3. To increase the research excellence of INL, ALBA-CELLS and MPG
4. To extend INL strategic partnerships & strengthen its visibility and reputation among the international research community and other stakeholders
5. To secure a sustainable environment for future collaborations between INL, ALBA-CELLS

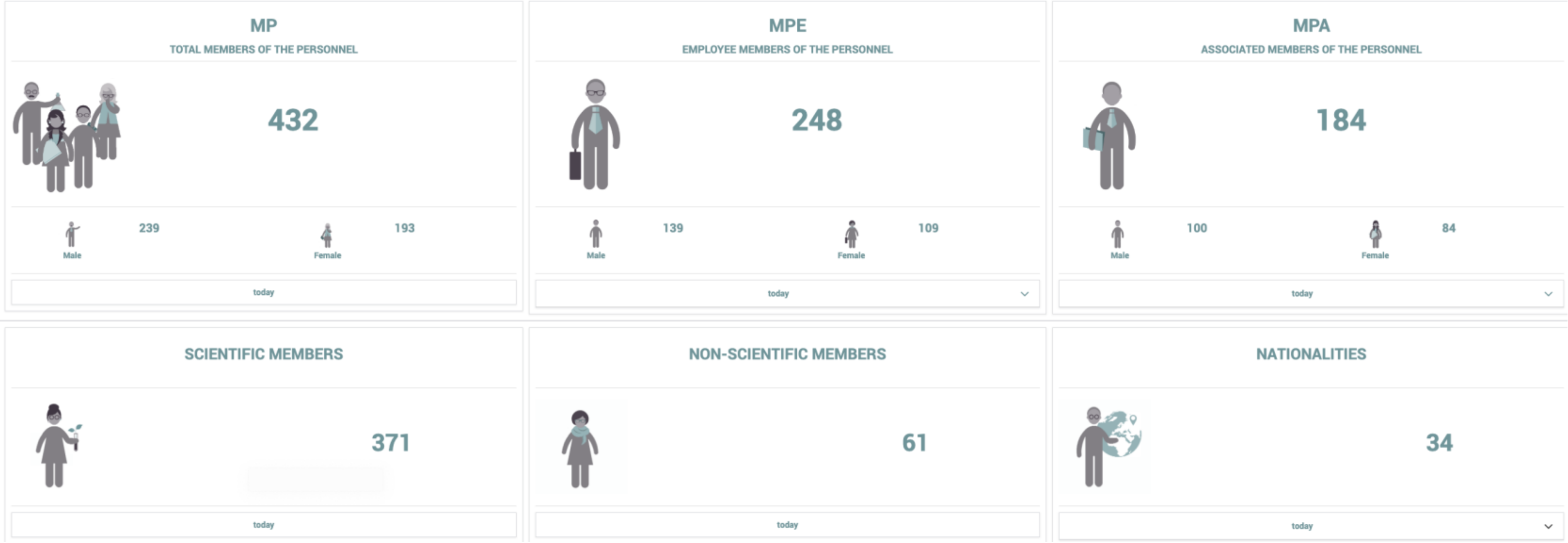
Figure1.2a: The five pillars of the FUNLAYERS proposal that provide the foundation of our mission.

Conference Announcement

https://www.funlayersproject.eu/internationalconference#callforabstracts

INL

- International Organization
- Member States (Spain, Portugal)
- Established in 2008
- INL building: 2010
- Currently: 20 research groups



TQN Group members

As of June 2025

Joaquín
Fernández-Rossier
Group Leader

Nuno Peres
U. Minho Professor
INL MPA

Antonio Costa
U. Minho prof.
INL MPA

Mikhail Vassilevskiy
U. Minho Professor
INL MPA

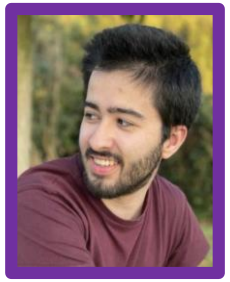
Ricardo Ribeiro
U. Minho Professor
INL MPA

Tatiana Rappoport
FCT researcher
U. Minho
INL MPA

Daniel Santos
FCT researcher
U. Minho
INL MPA

Jan Phillips
Postdoc
INL

Álvaro Buendía
Postdoc
INL



Joao C. Henriques
U. Santiago

Luisa Madail,
U. Aveiro

Marcelo Barreiro
PhD Student
U .Minho

Yelko del Castillo
PhD Student
U .Minho

Pedro Cruz
U. Porto

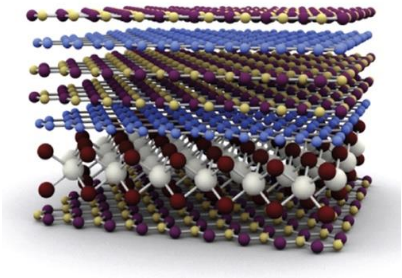
Diogo Cunha
U. Minho

Victor Duarte
Visiting PhD Student

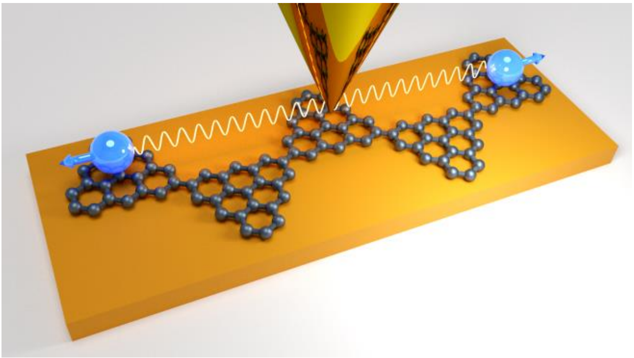
Mar Ferri
U. Alicante

A few words about our research

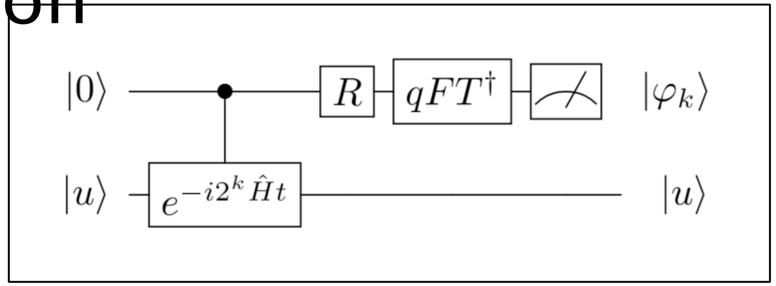
1) Atomically thin artificial layered structures
(Van der Waals heterostructures)



2) Atomically precise surface-spin structures



3) Quantum Computing for quantum simulation



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The discovery of graphene

22 OCTOBER 2004 VOL 306 SCIENCE

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.

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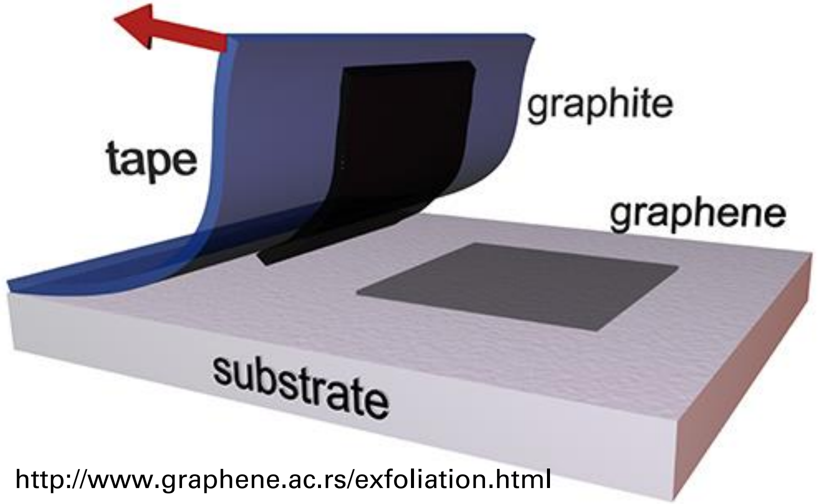
We report the observation of the electric field effect in a naturally occurring two-dimensional (2D) material referred to as few-layer graphene (FLG). Graphene is the name given to a single layer of carbon atoms densely packed into a benzene-ring structure, and is widely used to describe properties of many carbon-based materials, including graphite, large fullerenes, nanotubes, etc. (e.g., carbon nanotubes are usually thought of as graphene sheets rolled up into nanometer-sized cylinders) (5–7). Planar graphene itself has been presumed not to exist in the free state, being unstable with respect to the formation of curved structures such as soot, fullerenes, and nanotubes (5–14).

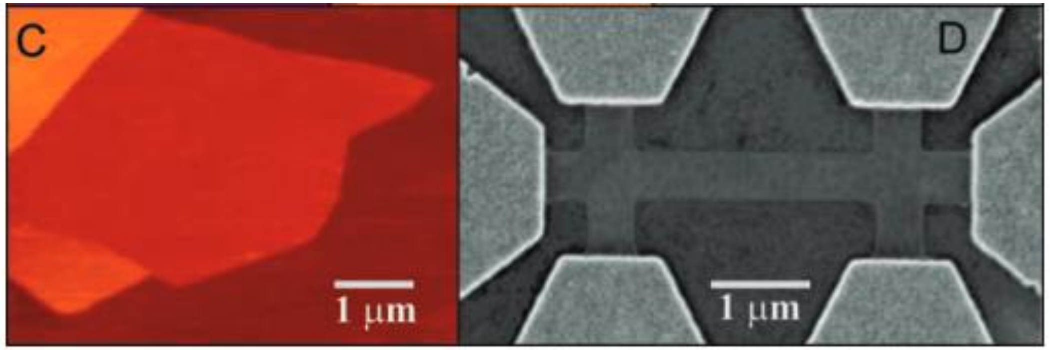
We have been able to prepare graphitic sheets of thicknesses down to a few atomic layers (including single-layer graphene), to fabricate devices from them, and to study their electronic properties. Despite being atomically thin, the films remain of high quality, so that 2D electronic transport is ballistic at submicrometer distances. No

Our graphene films were prepared by mechanical exfoliation (repeated peeling) of small mesas of highly oriented pyrolytic graphite (15). This approach was found to be highly reliable and allowed us to prepare FLG films up to 10 μm in size. Thicker films

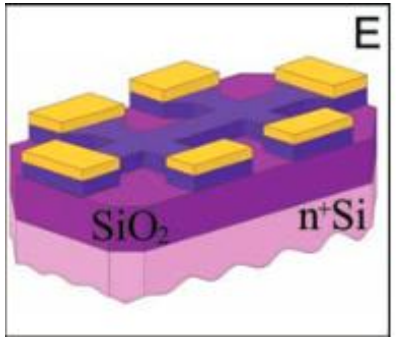
The discovery of graphene



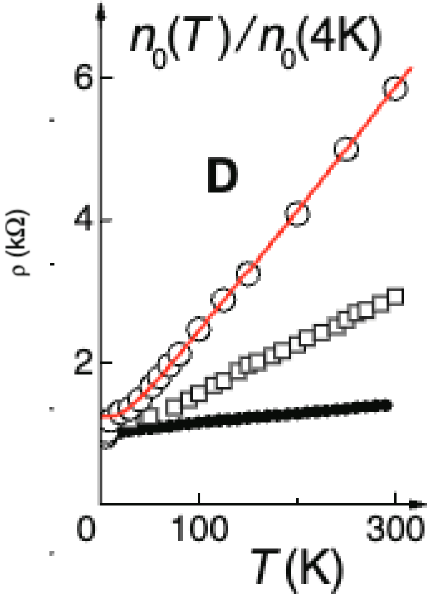
http://www.graphene.ac.rs/exfoliation.html

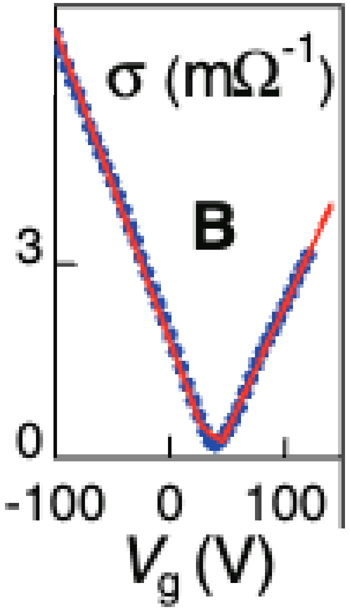


AFM graphene TEM graphene transistor



FL Graphene is metallic





FL Graphene field effect (Transistor effect)

$$\mu = \frac{1}{e}\frac{d\sigma}{dn}$$

The discovery of Quantum Hall effect graphene

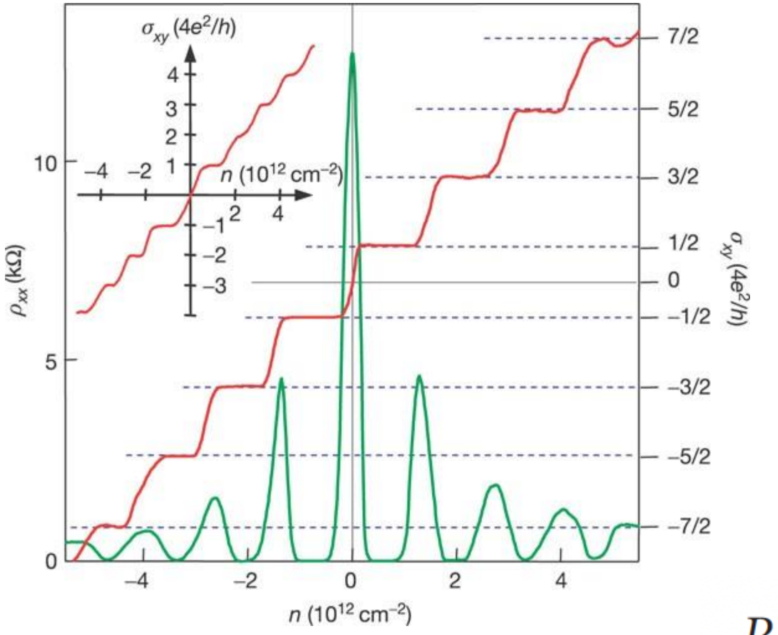
Two papers back-to-back in Nature 2005

Vol 438|10 November 2005|doi:10.1038/nature04233 nature

LETTERS

Two-dimensional gas of massless Dirac fermions in graphene

K. S. Novoselov[1], A. K. Geim[1], S. V. Morozov[2], D. Jiang[1], M. I. Katsnelson[3], I. V. Grigorieva[1], S. V. Dubonos[2] & A. A. Firsov[2]

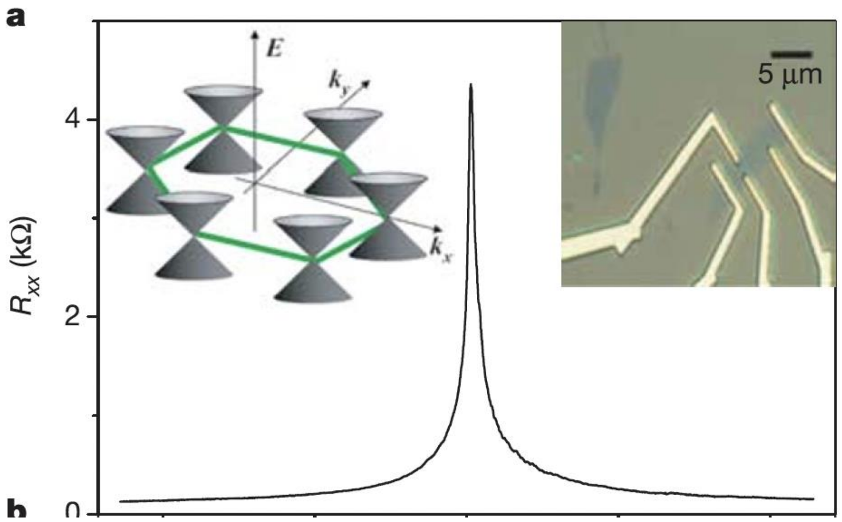


Vol 438|10 November 2005|doi:10.1038/nature04235 nature

LETTERS

Experimental observation of the quantum Hall effect and Berry's phase in graphene

Yuanbo Zhang[1], Yan-Wen Tan[1], Horst L. Stormer[1,2] & Philip Kim[1]



$$R_{xy}^{-1} = \pm g_s(n + 1/2)e^2/h$$

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Impact of graphene papers

1) 2004 paper >81000 citations

2) 2005 papers >16.000, 26.000 citations

3) **2010** Nobel Prize in Physics to Novoselov and Geim (2010)

4) **2012** Graphene Flagship €1 Billion

5) 6 New Research institutes
   (Manchester, Singapore, Aachen, S. Korea, Emirates, USA)

6) 3 New research journals
   (2D Materials (IOP, 2014) , FlatChem (Elsevier,2016), npj 2D materials (Springer Nature, 2017)

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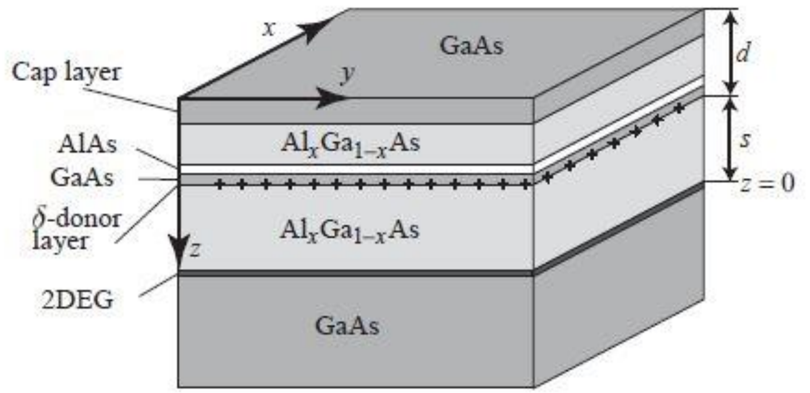
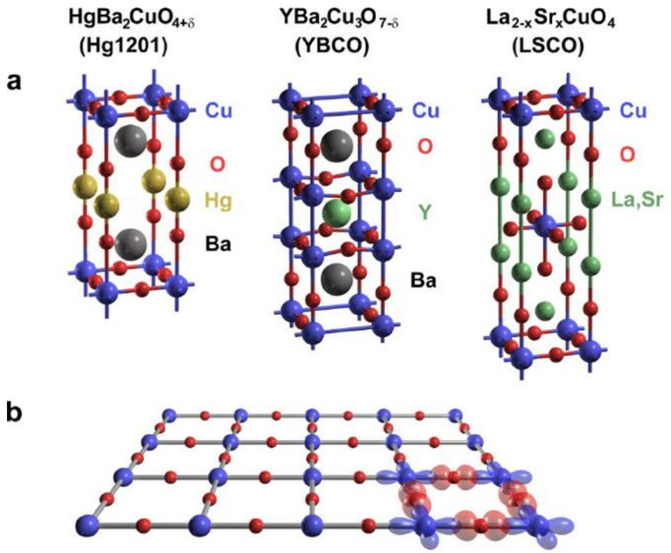
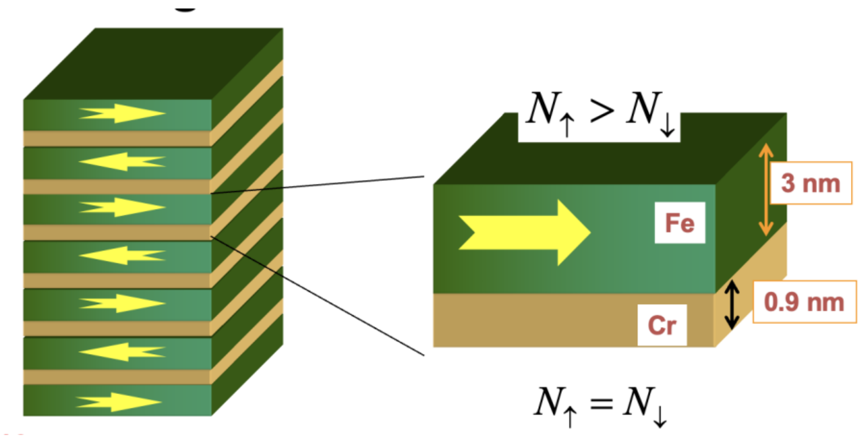
Why all the fuss? (1)

Why so many researchers?

1) **2D physics attracted lots of interest before graphene**:
   1) 197X-199X. Semiconductor Quantum Well lasers (Nobel prize in 2000)
   2) 1981-3 Quantum Hall Effects in 2D electron gas (Nobel prize 1985 and 1998)
   3) 1986 High temperature superconductivity in cuprates (layered materials) (Nobel prize in 1987)
   4) 1987 Giant Magnetoresistance in metallic multilayers (Nobel Prize in 2007)







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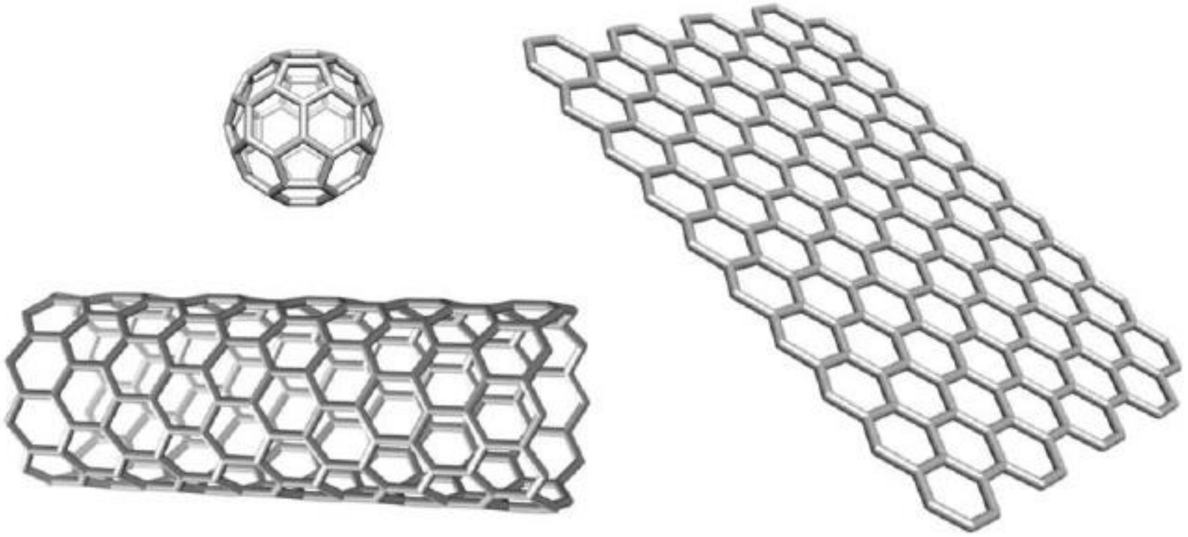
2) **Carbon Nanostructures were important before graphene**:
   1) C60 (Nobel prize 1996)
   2) Carbon Nanotubes



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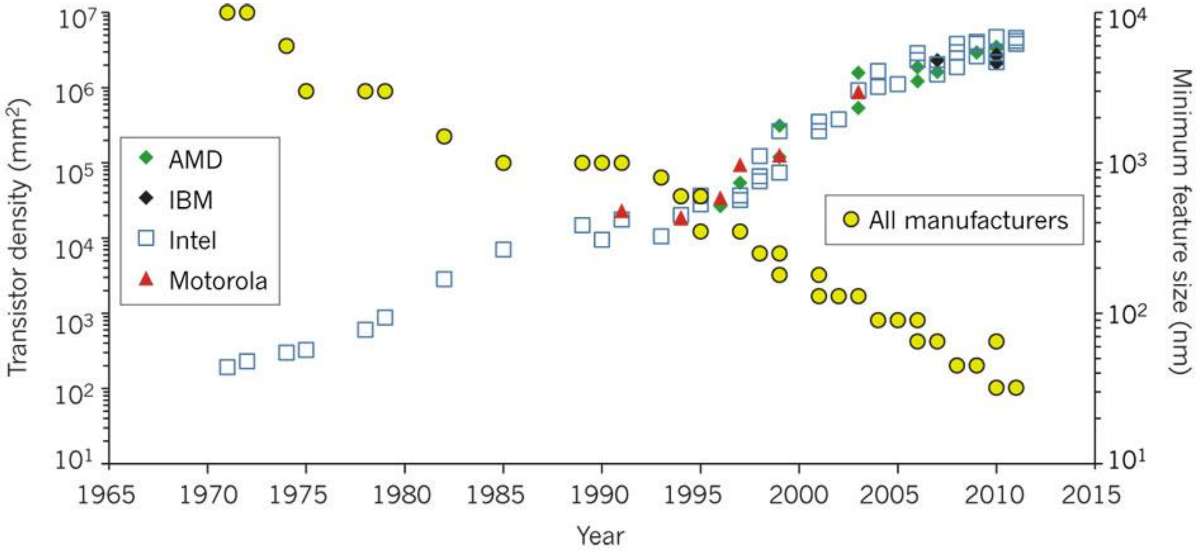

Isabel Ferain, et al
Nature 479, 310–316 (2011)

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4) **Quantum Hall Effect: Low cost high quality electronics**

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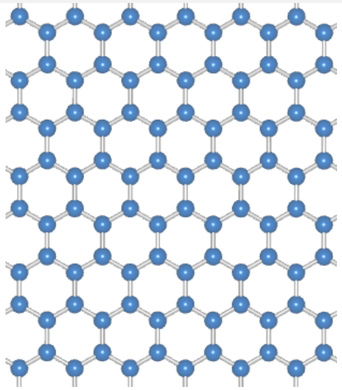
Why all the fuss? (2)

Beyond graphene: more layers, more materials

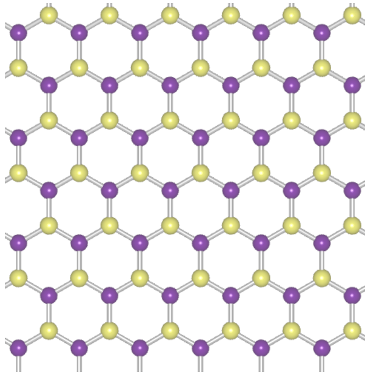
1) **Multilayers**
   1) Graphene bilayer (Electrically controlled band-gap, 2008)
   2) Graphene trilayer

2) **Other 2D Materials obtained by exfoliation of Van der Waals layers**
   1) 2005: H-BN (insulator) (2005)
   2) 2011: MoS_2, direct band-gap semiconductor (2011)
   3) 2012 $NbSe_2$ (2012): superconductor below 3 Kelvin
   4) 2017 CrI_3: ferromagnetic insulator

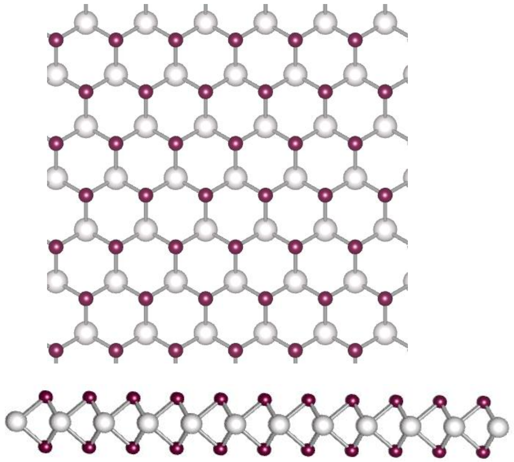
Graphene



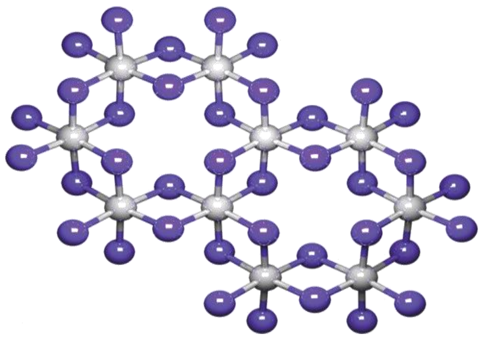
h-BN



MoS_2, WS_2, $MoSe_2$



CrI_3



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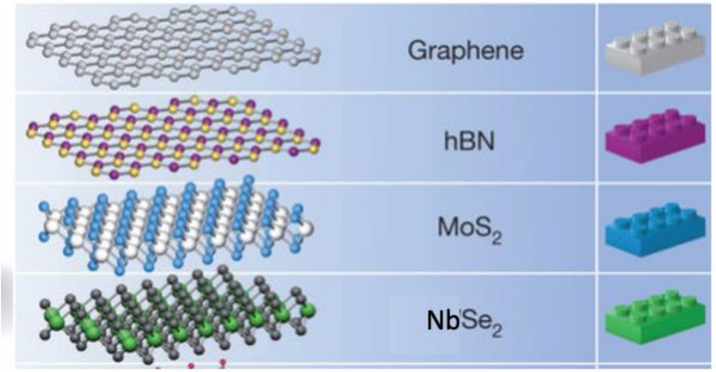

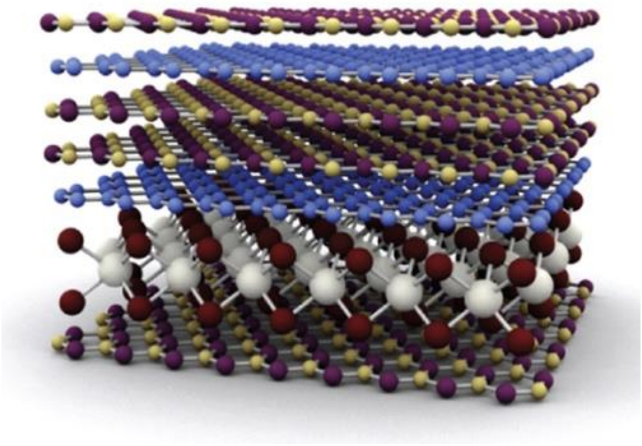

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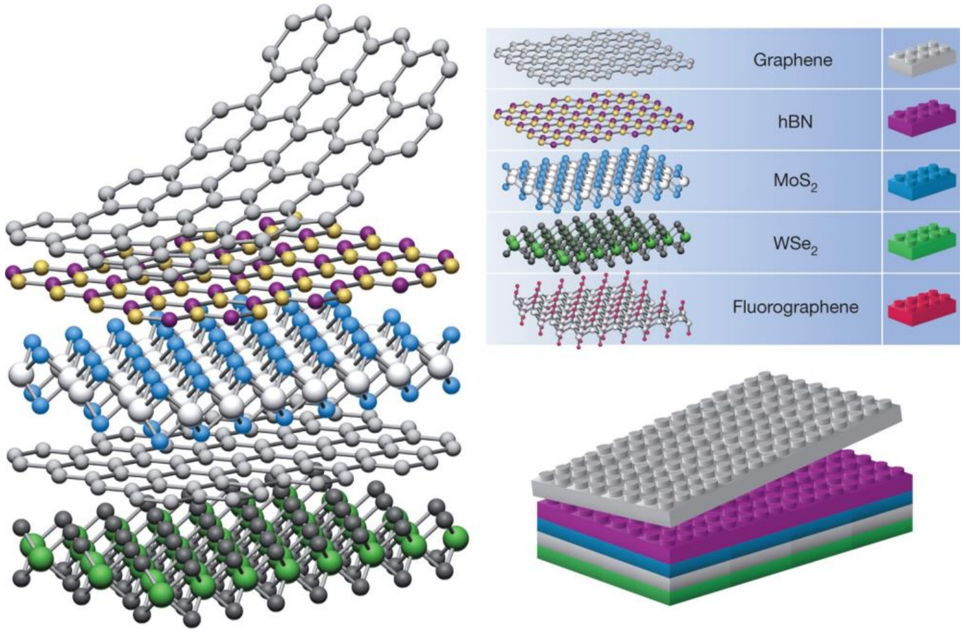
3) **Van der Waals heterostructures (2013)**

A. Geim, I. Grigorieva, Nature, 2013



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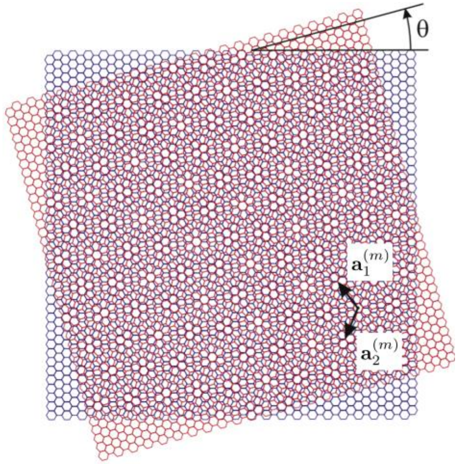
   4) 2017 CrI3: ferromagnetic insulator

3) **Van der Waals heterostructures**

4) **Twisted Bilayers**
   1) 2012: prediction of Magic angle twisted bilayer graphene (MATBG)
   2) 2018: Observation of Mott-insulating and **superconductivity** in MATBG



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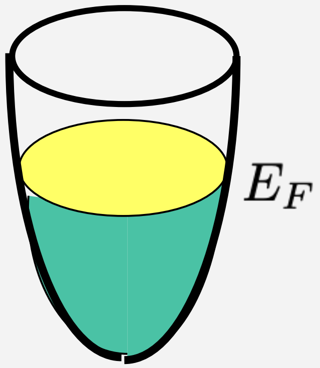
Why all the fuss? (3)

Theory

$D(E_F)$

Density of states at Fermi Energy



Metals

Quantity	Depends on $D(E_F)$?
Electronic heat capacity $C_e \sim \gamma T$	✅ $\gamma \propto D(E_F)$
Pauli susceptibility χ_P	✅ $\chi_P \propto D(E_F)$
Tunneling conductance $G(V)$	✅ $G \propto D(E_F + eV)$
Scattering rate τ^{-1}	✅ Often $\propto D(E_F)$
Stoner criterion $ID(E_F) > 1$	✅ High $D(E_F)$ favors FM
Superconducting T_c	✅ $T_c \sim e^{-1/(VD(E_F))}$

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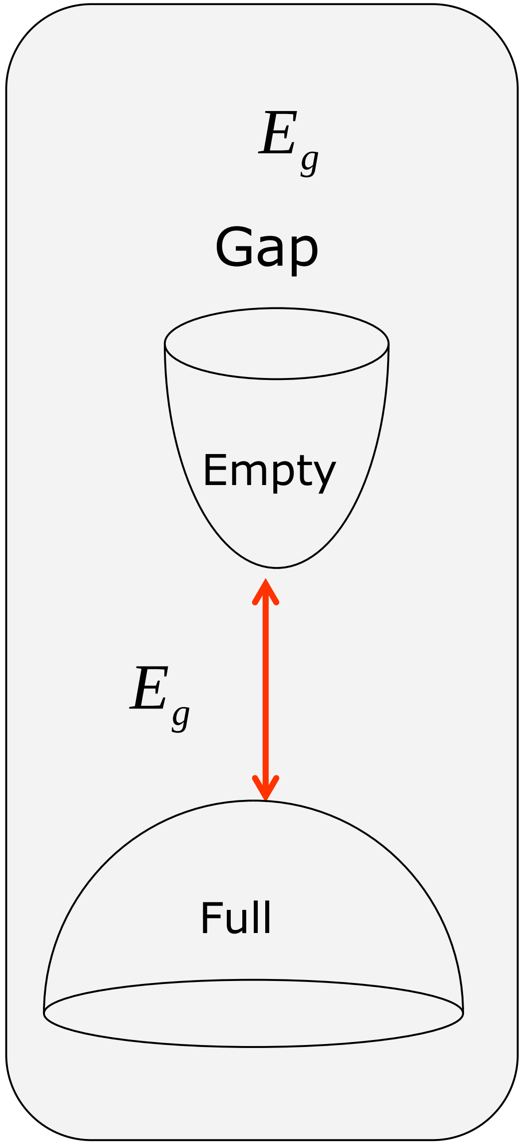
Why all the fuss? (3)

Theory



Quantity	Depends on E_g?
Electrical conductivity σ	✅ $\sigma \sim e^{-E_g/2k_BT}$
Optical absorption edge	✅ Threshold at $\hbar\omega \geq E_g$
Photoluminescence peak	✅ $E_{\mathrm{PL}} \lesssim E_g$
Carrier concentration n, p	✅ $n \sim e^{-E_g/2k_BT}$

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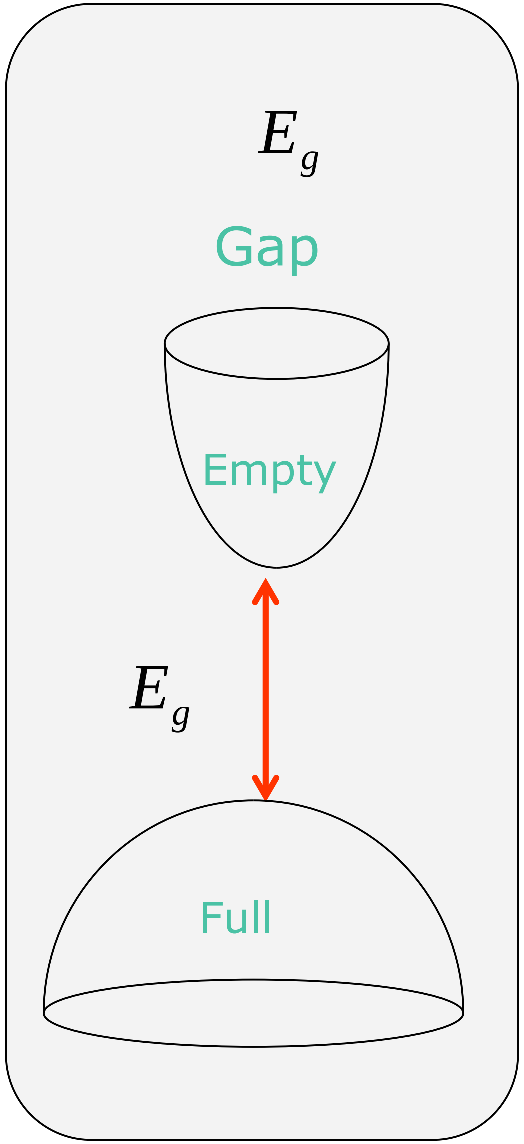
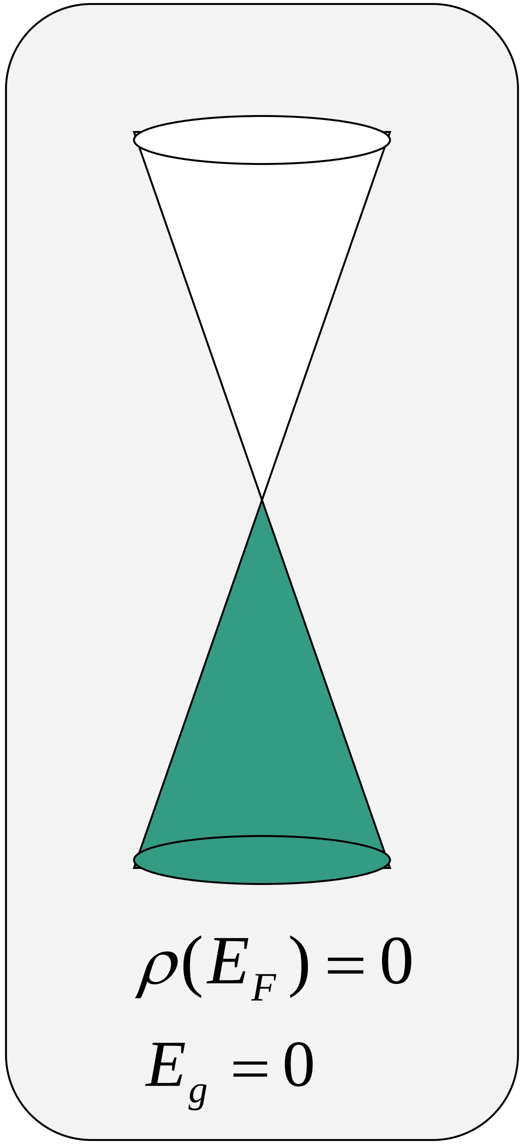
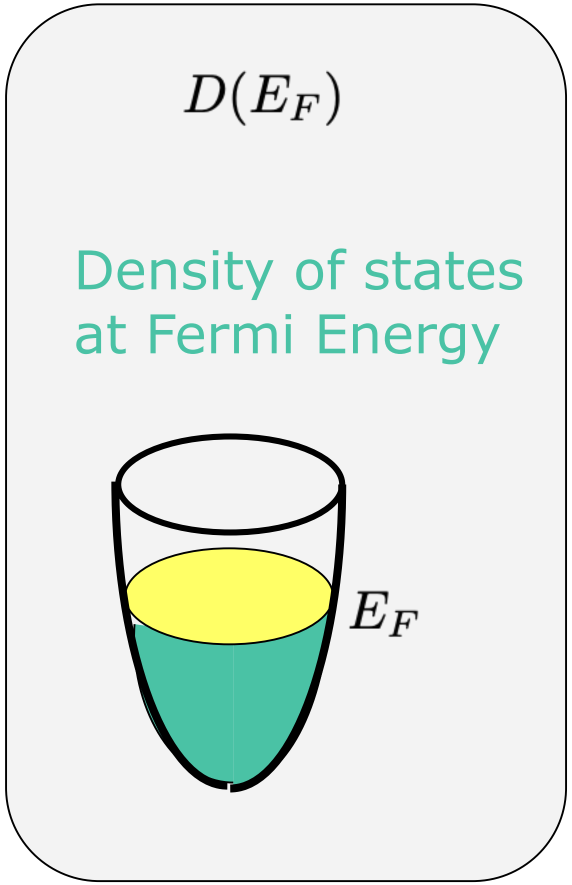
Why all the fuss? (3)

All formulas are "wrong"







Metals

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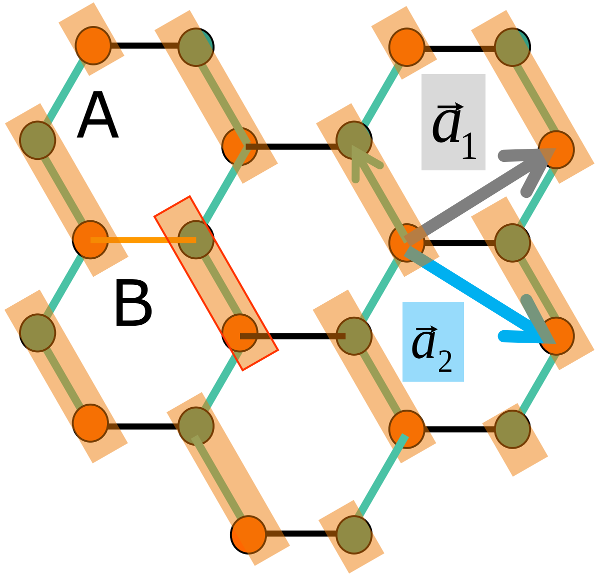
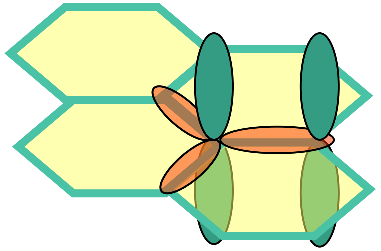
How do we model graphene?

From tight-binding to Dirac Hamiltonian



Honeycomb lattice
2 carbon atoms per unit cell

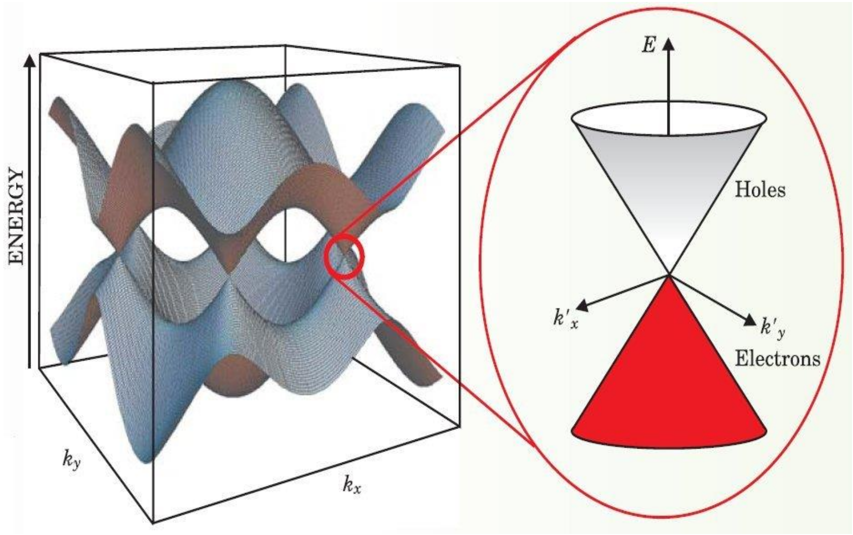


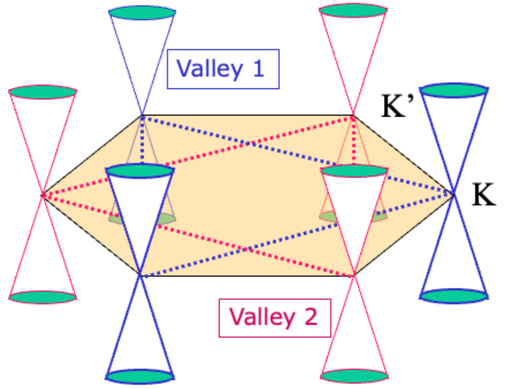
1 Pi orbital per atom
1 electron per Pi orbital

$$H(\vec{k}) = \begin{pmatrix} 0 & h(\vec{k}) \\ h^*(\vec{k}) & 0 \end{pmatrix}$$

Tight-binding model
in honeycomb graph

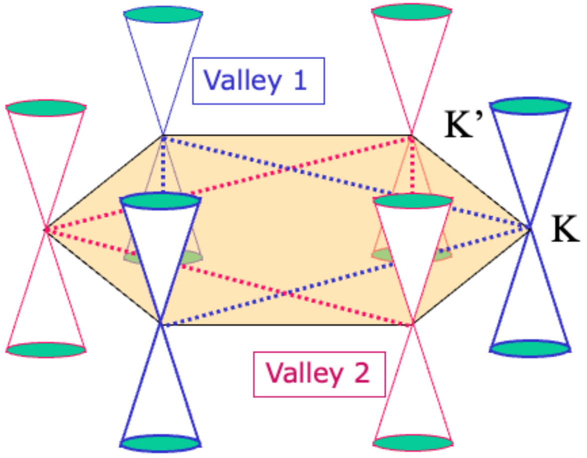
$$h(\vec{k}) = t(1 + e^{i\vec{k}\cdot\vec{a}_1} + e^{i\vec{k}\cdot\vec{a}_2})$$





How do we model graphene?

From tight-binding to Dirac Hamiltonian



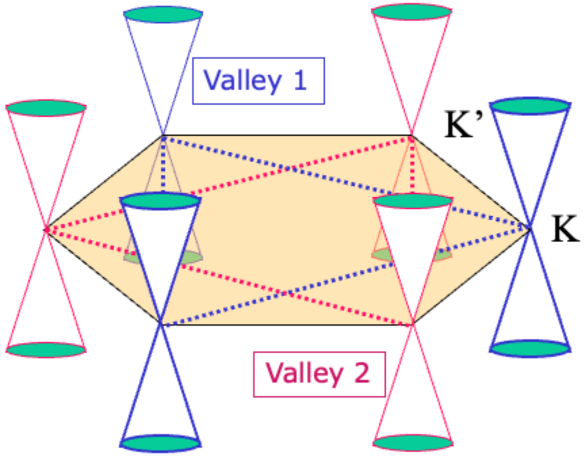
$$H(\vec{k}) = t\left(\mathrm{Re}(h(\vec{k}))\sigma_x + \mathrm{Im}(h(\vec{k}))\sigma_y\right) = \vec{h}\cdot\vec{\sigma}$$

$$h(\vec{k}) = t(1 + e^{i\vec{k}\cdot\vec{a}_1} + e^{i\vec{k}\cdot\vec{a}_2})$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

How do we model graphene?

From tight-binding to Dirac Hamiltonian



$$H(\vec{k}) = t\left(\mathrm{Re}(h(\vec{k}))\sigma_x + \mathrm{Im}(h(\vec{k}))\sigma_y\right) = \vec{h}\cdot\vec{\sigma}$$

$$h(\vec{k}) = t(1 + e^{i\vec{k}\cdot\vec{a}_1} + e^{i\vec{k}\cdot\vec{a}_2})$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$H(\vec{q}) = \hbar v_F\,(q_x\sigma_x \pm q_y\sigma_y)$$

-Linear dispersion
-Shifted Landau Levels
-$\sqrt{B}$

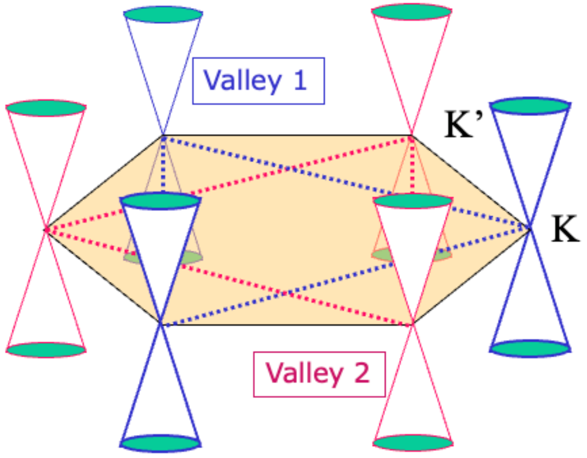
$$R_{xy}^{-1} = \pm g_s(n + 1/2)e^2/h$$

-Quantized minimum "conductivity"

$$\sigma_{\min} \simeq \frac{2e^2}{h}$$

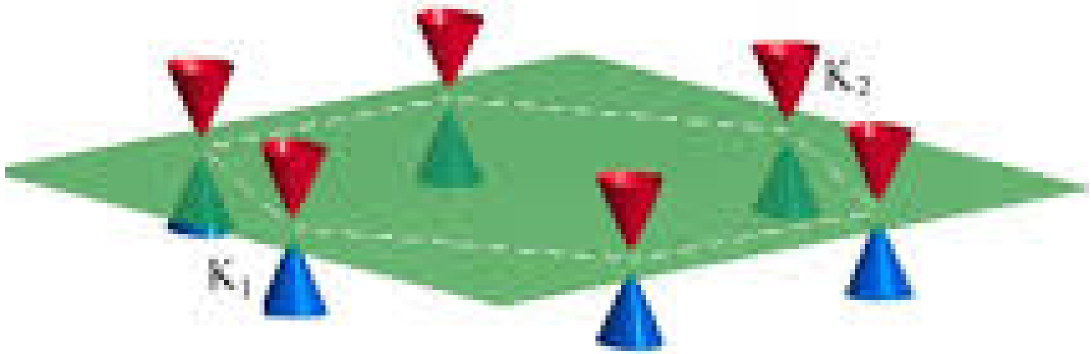
Graphene is "almost topological" (1)

Haldane model (1986)

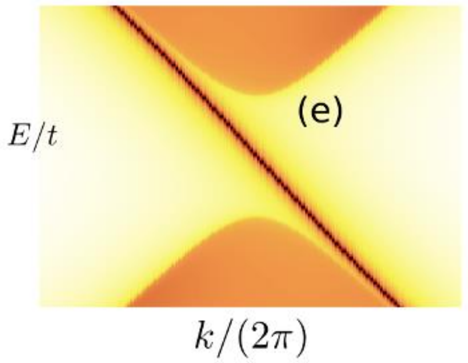


$$H_{\text{Haldane}} = H(\vec{k}) + H_{2nd}$$

-Gap at Dirac cones
-Quantized Hall conductance
(without Landau levels)
-Chiral edge states



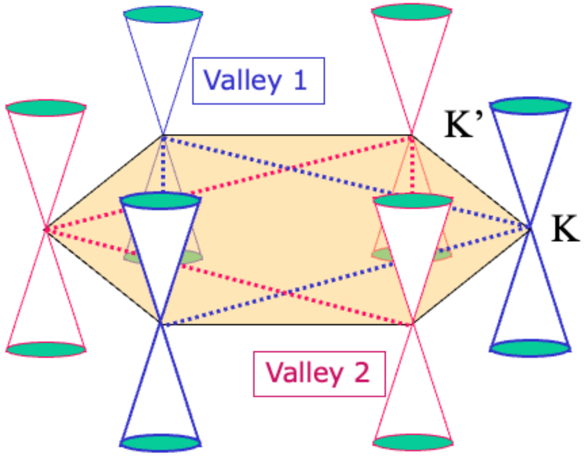
Topological gap



F. D. M. Haldane
Phys. Rev. Lett. 61, 2015 (1988)

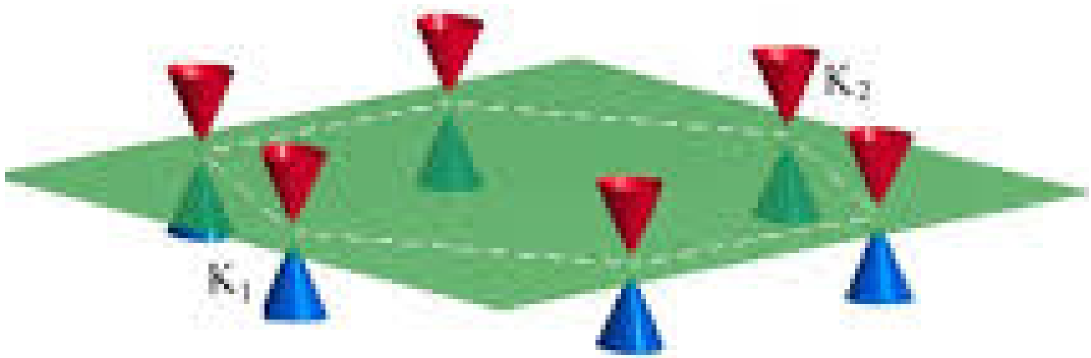
Graphene is topological !!

Kane-Mele model (2005)

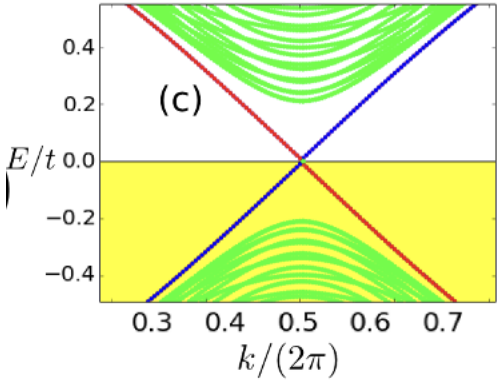


$$H_{\text{Kane-Mele}} = H(\vec{k}) + H_{SOC}$$

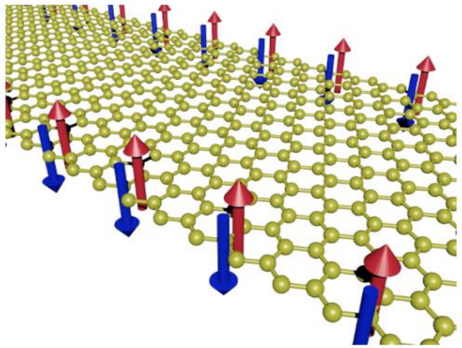
- Graphene + SOC= 2 copies of Haldane
- Gap at Dirac cones
- Quantized Spin Hall conductance
- Spin-filtered Chiral edge states



Topological gap



C. L. Kane and E. J. Mele
Phys. Rev. Lett. 95, 226801 (2005).



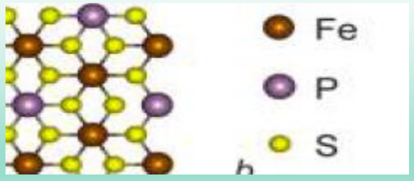
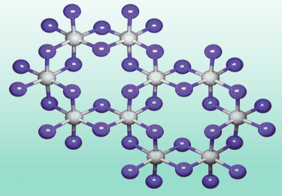
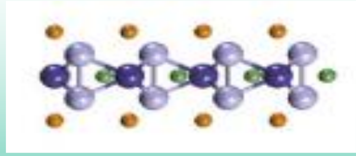
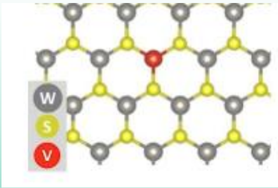
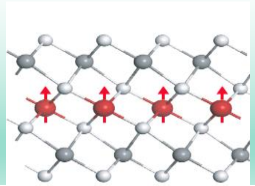
Questions?

Outline

- Brief intro to Funlayers
- 2D Materials: why all the fuss?
- Magnetic 2D Materials: some key-concepts

Time Left?

The rise of magnetic 2D materials

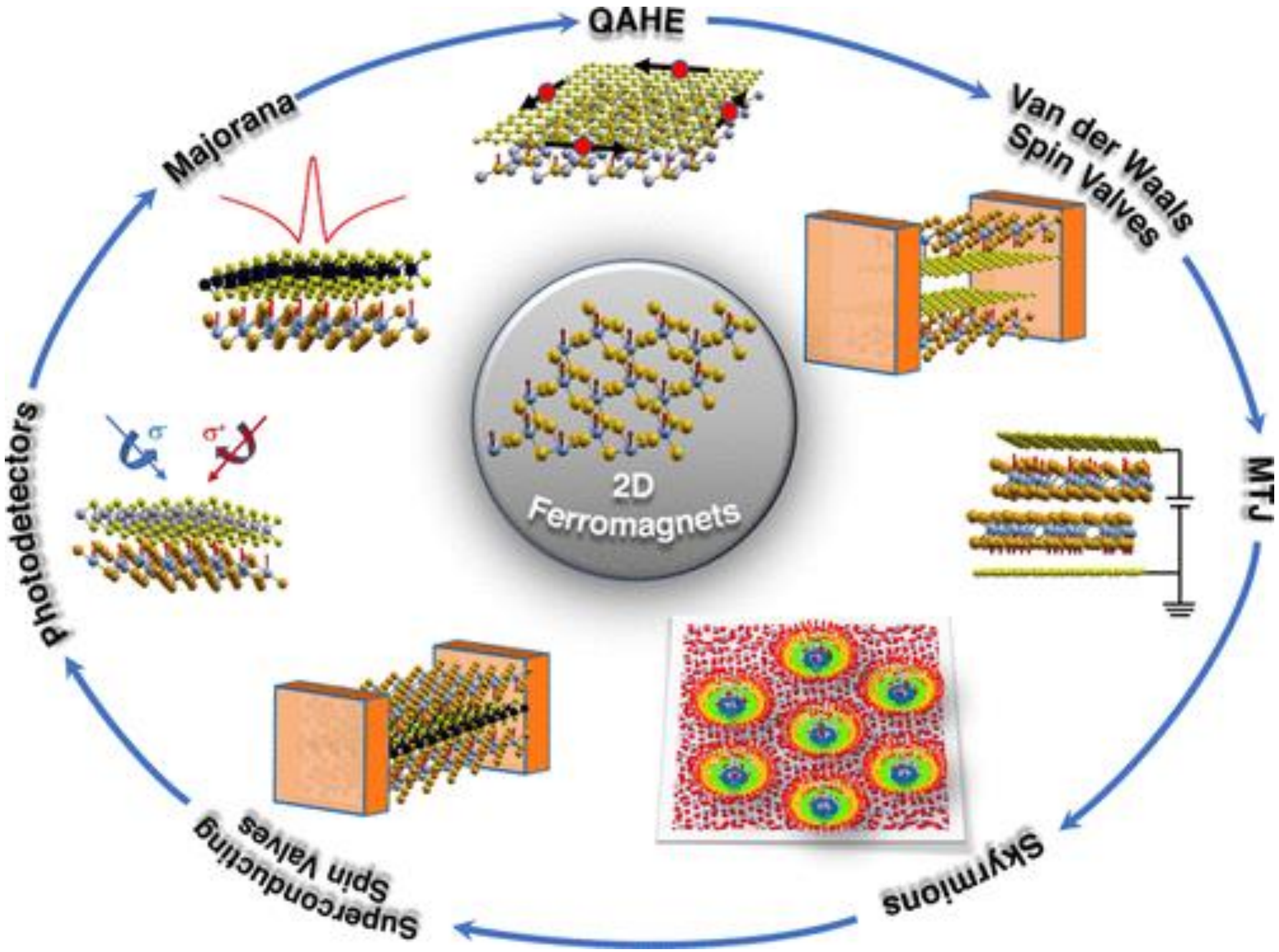
	$FeSP_3$ ($MnSP_3$, $NiSP_3$)	2016 Tc=120 Kelvin ML=1, Bulk	AF Monolayer Insulating
	CrI_3 ($CrBr_3$, $CrCl_3$)	2017 Tc=45 # ML=1,2,..., 20	FM Monolayer Insulating
	Fe_3GeTe_2	2018 Tc=100- RT # ML=1,2,..	FM Monolayer Metal
	$(W_{(1-x)}V_x)S_2$	2020 Tc= RT #ML =1	FM Monolayer Diluted magnetic semiconductor
	$MnBi_2Te_4$	2018 (bulk) 2019 (ML)	FM Monolayer CHERN Insulator

The rise of magnetic 2D materials (2)

CrSBr	2021	Antiferromagnetic	~131 K	Semiconducting
Cobalt Ferrite ($CoFe_2O_4$)	2022	Ferromagnetic	>390 K	Semiconducting
Fe_3GaTe_2	2024	Ferromagnetic	~200 K	Metallic

Why magnetic 2D materials attract so much interest?

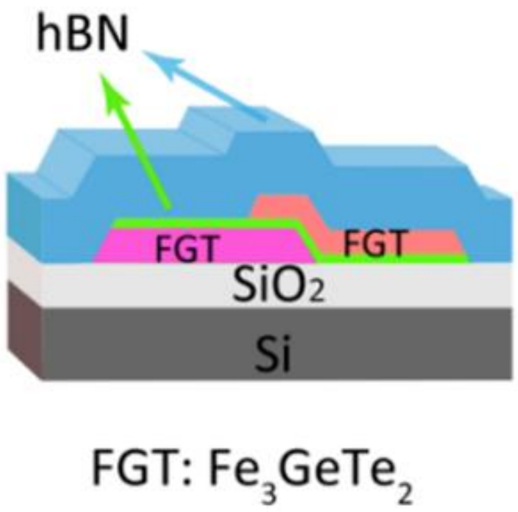
Motivation



D. Soriano, M. Katsnelson, JFR , Nano Letters 20, 9, 6225 ('20)

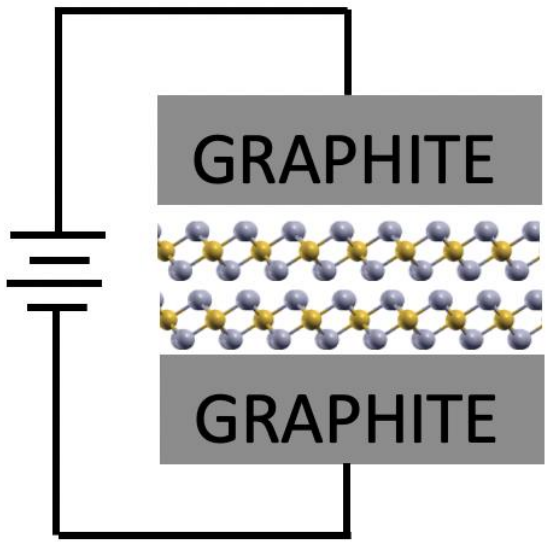
- The promise of Spintronics applications
  - Spin filter MTJ
  - vdW spin valves
- Basic magnetism questions
  - Magnetic order in 2D?
  - Origin of anisotropy?
- New physics in vdW
  - Topological Magnons
  - Majorana
  - Skyrmions

Magnetic 2D crystals: towards spintronics applications
(first steps)



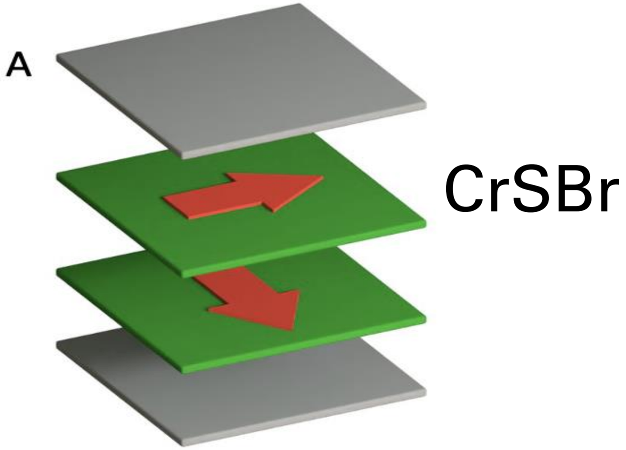
FGT as FM electrode in MTJ.
Very large TMR>160%

Z.Wang, et al. *Nano letters* 18.7 (2018):



Spin-filer Magnetic Tunnel junction (SF-MTJ)
Very large MR>100%

D. R Klein, et al Science 360, 1218 (2018)



Twisted spin-filter SF- MTJ

C. Boix-Constant et al, Nature Materials, 2023

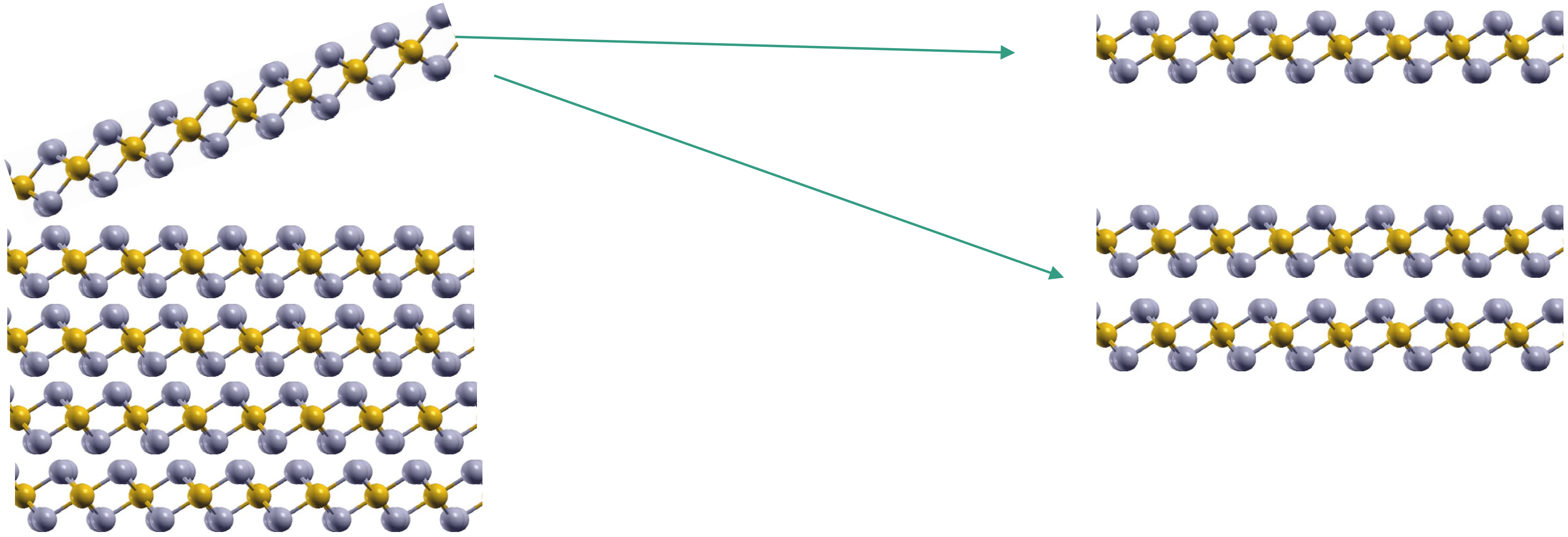
Outline of the rest of the talk

- An intro to CrI_3
- Magnetism and dimensionality: Mermin-Wagner theorem
- Origin of magnetic anisotropy in CrI_3

Common features of Magnetic 2D crystals

- Stand alone crystals
  (as opposed to atomically thin overlayers)

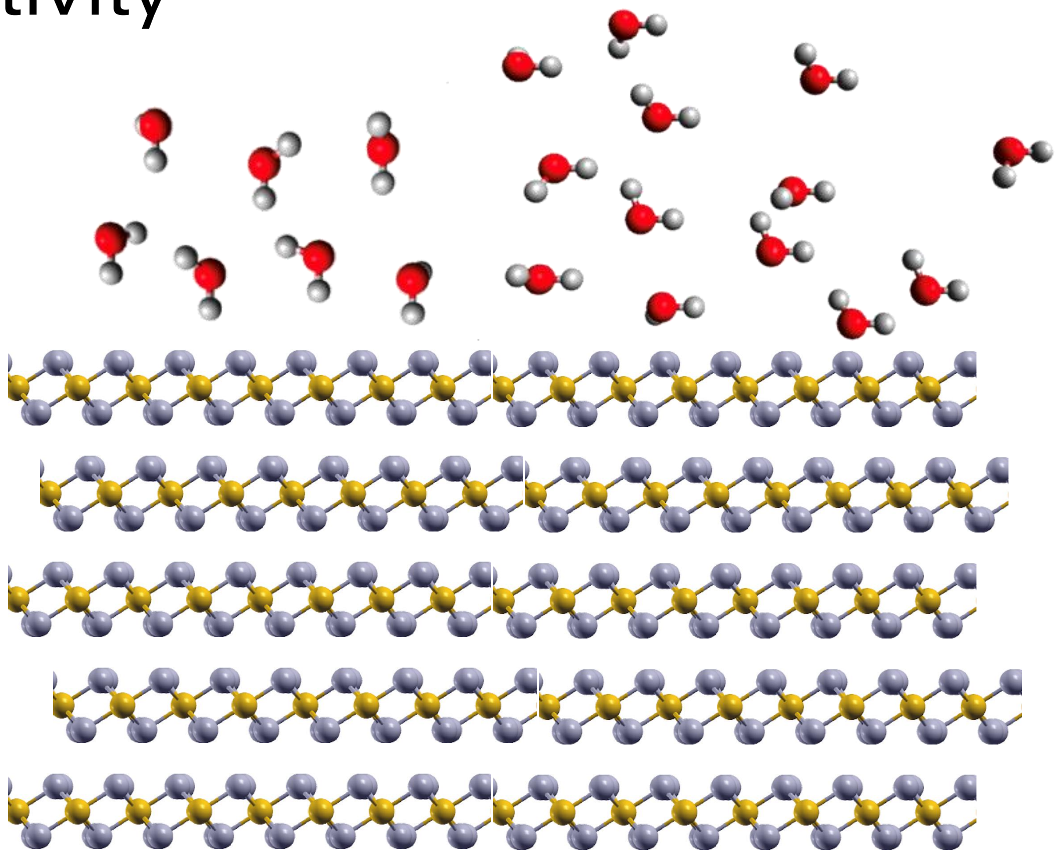
- Van der Waals parent 3D crystals



Why it took so long?

Problems to study magnetically ordered monolayers

1. Chemical reactivity



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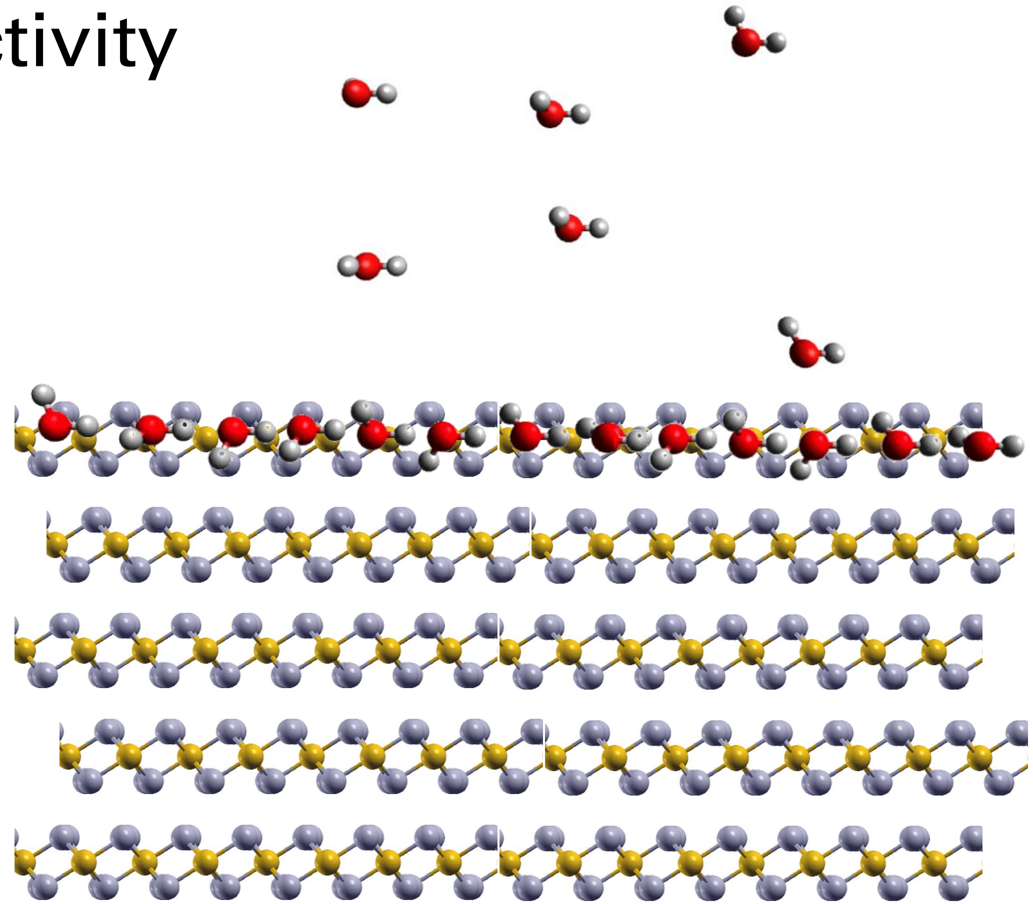

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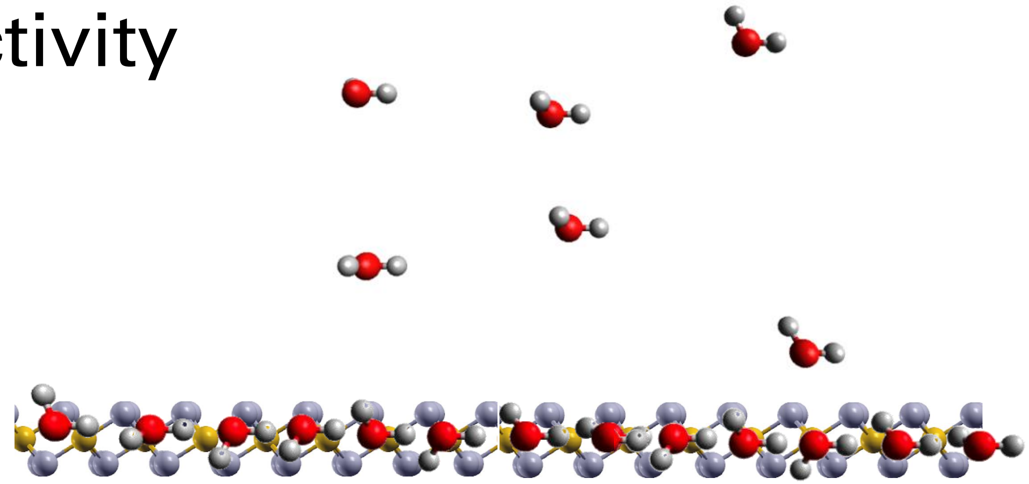

Why it took so long?

Problems to study magnetically ordered monolayers

1. Chemical reactivity
2. Probing magnetism
    1. SQUID

- Squid Sensitivity 10^{-8} emu=10^{12} μ_B
- Magnetic moment per atom= 3 μ_B
- Area per unit cell 5*5 Angstrom=25 A^2
- Area for 10^{12} μ_B =10^{12} *(25/3) A^2=>

L= 3 10^6 A= 300 Micrometers

Typical 2D flake 10 micrometers

Why it took so long?

Problems to study magnetically ordered monolayers

1. Chemical reactivity
2. Probing magnetism
   1. SQUID

- Squid Sensitivity 10^{-8} emu=10^{12} μ_B
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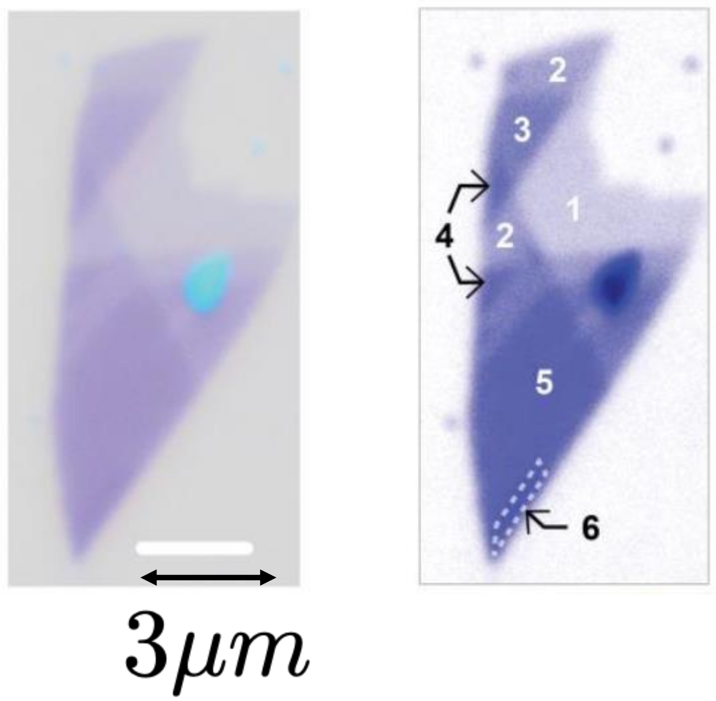
Typical 2D flake 10 micrometers

B. Huang et al. Nature **546**, 270 (2017)



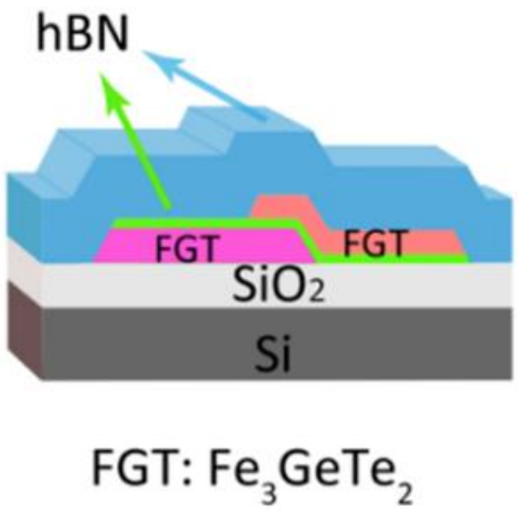
Why it took so long?

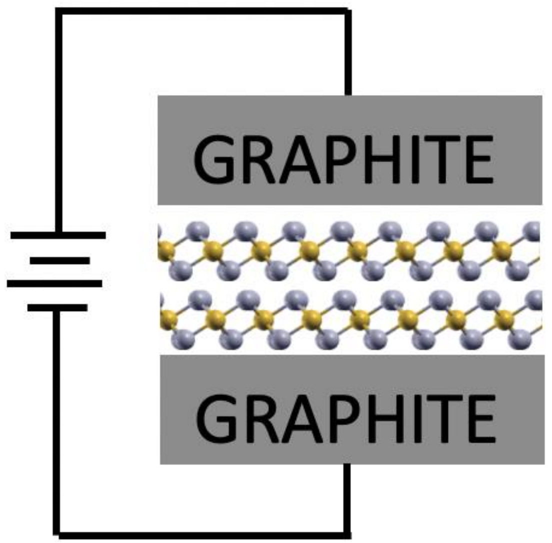
Problems to study magnetically ordered monolayers

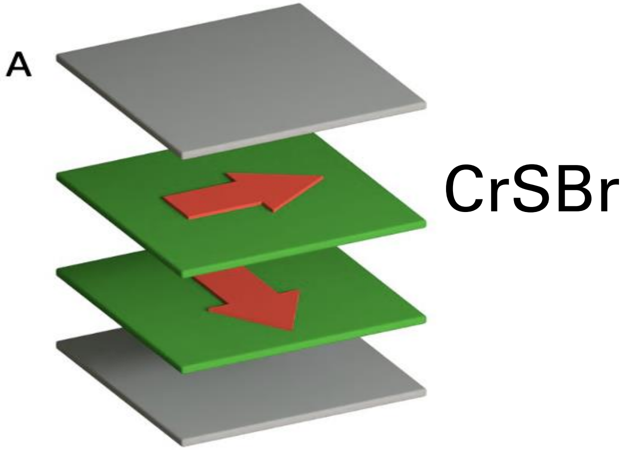
1. Chemical reactivity
2. Probing magnetism
    1. ~~SQUID~~
    2. Optical Kerr effect (detection, but not measurement)
    3. Anomalous Hall effect (only for conductors)
    4. Quantum Sensing (NV magnetometry)
    5. XMCD (monolayers??)

Magnetic 2D crystals: towards spintronics applications

(first steps)







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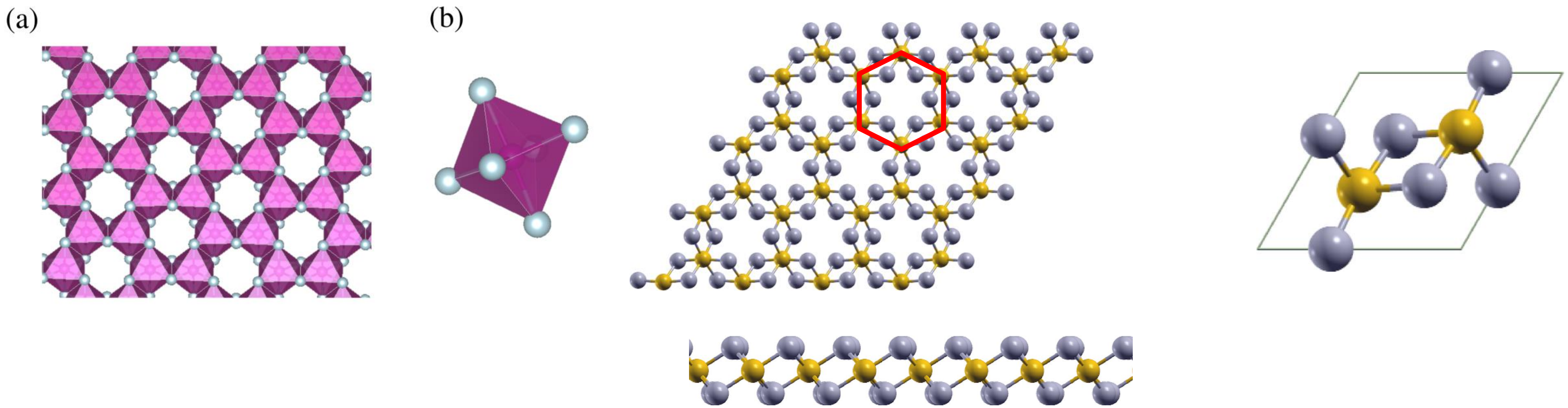
Twisted spin-filter SF- MTJ

C. Boix-Constant et al, Nature Materials, 2023

What is the origin ferromagnetism in CrI3?

Understanding CrI_3

Electronic structure

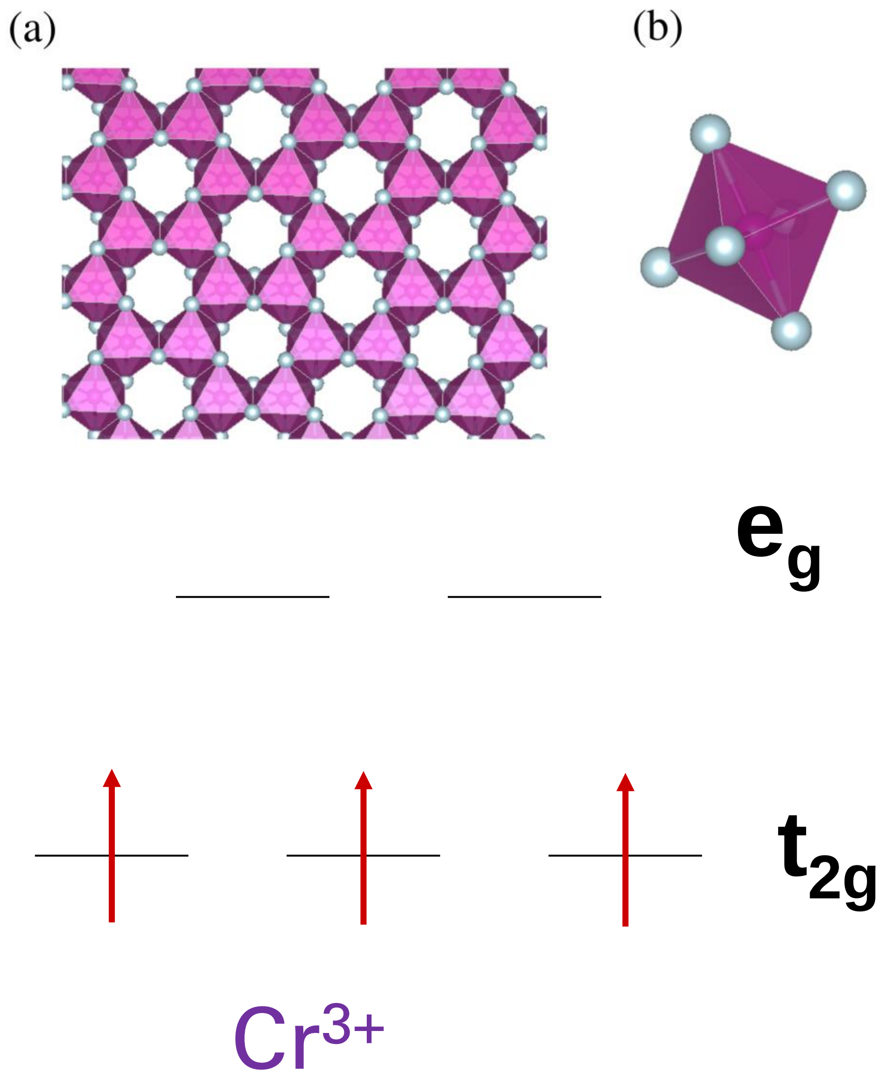


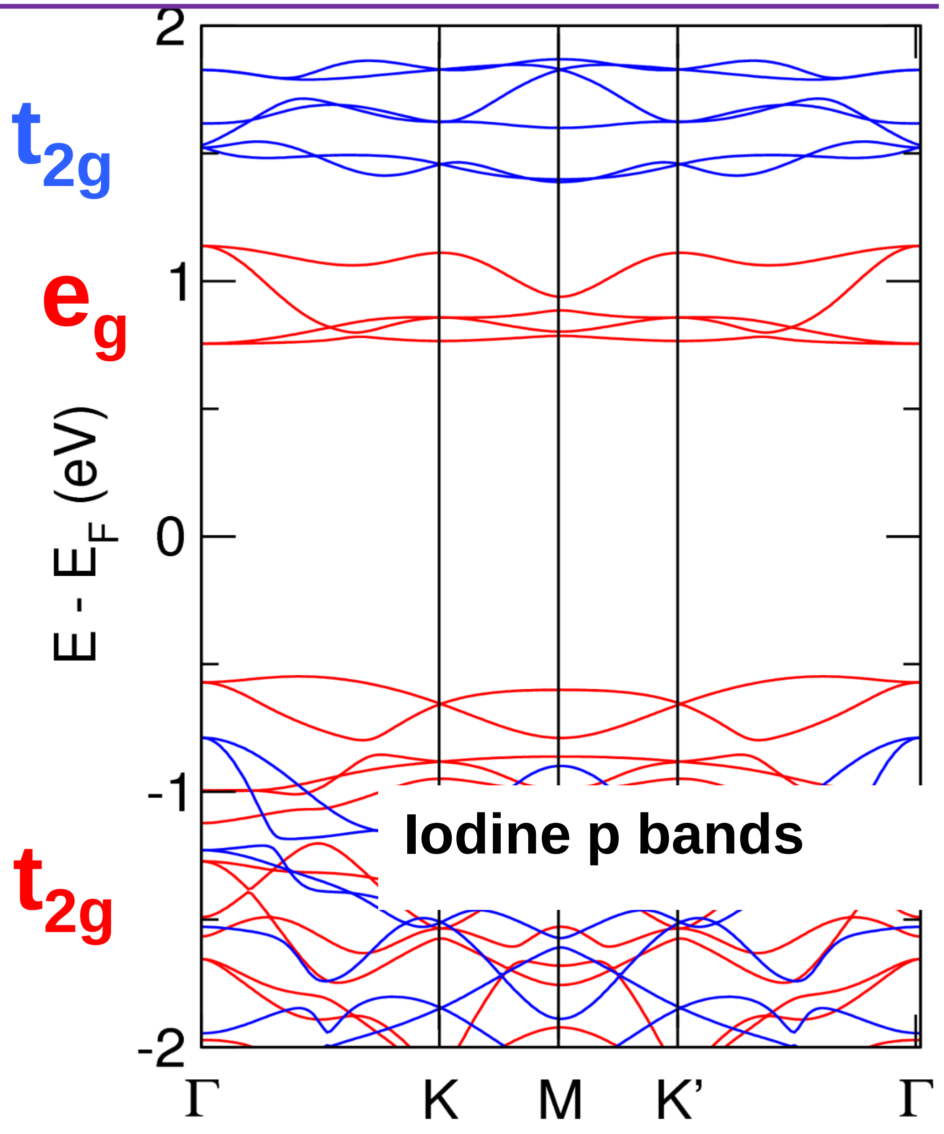
- Cr^{3+} S=3/2
- Cr form a honeycomb lattice
- 2 Cr atoms per unit cell

- Corner sharing octahedra
- Cr –I –Cr pathways forming 90 degrees
- FM interactions

Computing magnons in CrI_3

1st step: DFT calculation



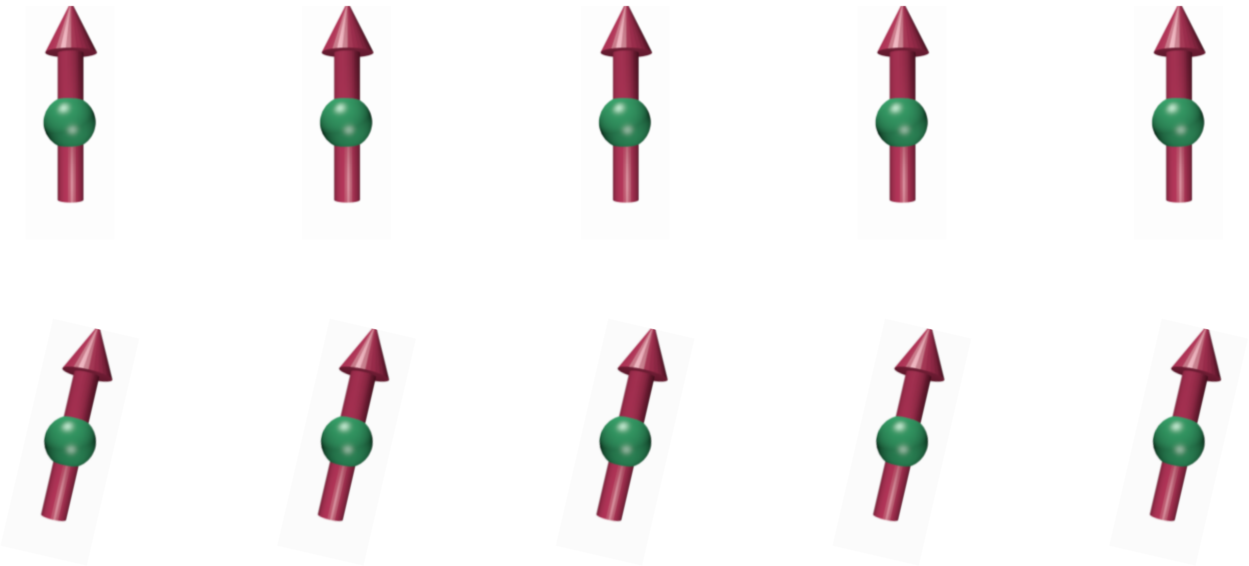


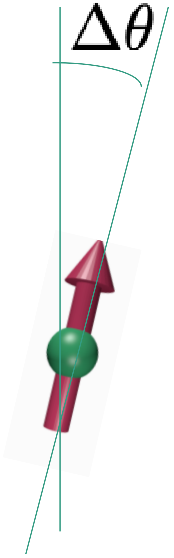
- Mermin Wagner Theorem: long range magnetic order is not possible in 2D:
  - At any finite temperature
  - In the presence of perfect spin rotational invariance (no magnetic anisotropy)
- Poor-man version for MWT : magnon proliferation

Magnons
(a.k.a. spin waves)

The lowest energy “spin excitation”

How can we add/remove 1 unit of spin angular momentum to a crystal?





$$\Delta\theta \propto \frac{1}{N}$$

$$\Delta E = N \left.\frac{dE}{d\theta}\right|_{\text{per atom}} \qquad \Delta\theta = \left.\frac{dE}{d\theta}\right|_{\text{per atom}}$$

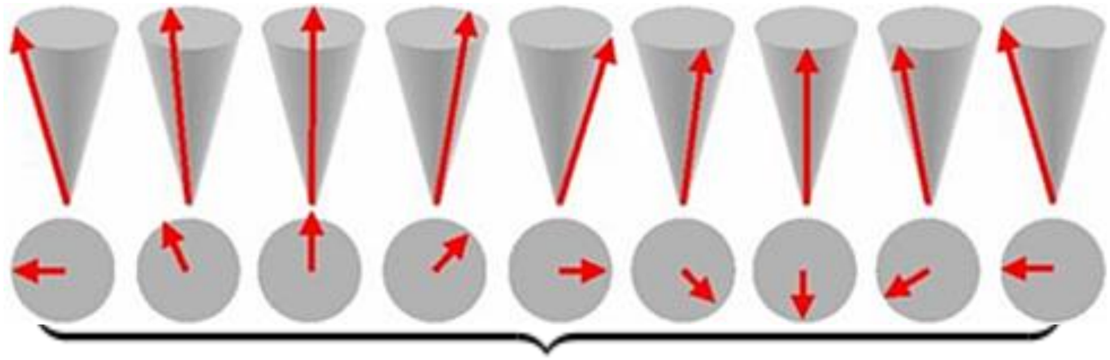
→

1. Magnetic anisotropy energy (less than 3 meV)
2. Zeeman energy (less than 1 meV)

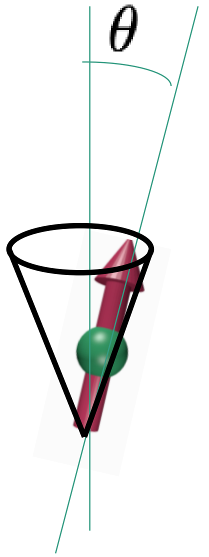
What are magnons

The lowest energy "spin excitation"

How can we add/remove 1 unit of spin angular momentum to a crystal?



$\lambda \qquad q = \frac{2\pi}{\lambda}$



$$\theta = \frac{1}{N}$$

$$\Delta E = \left.\frac{dE}{d\theta}\right|_{\text{per atom}} + \rho q^2$$

$$\rho \propto JzS^2$$

MAE Spin stiffness

What are magnons

The lowest energy “spin excitation”

Magnons, excitations in a (ferro)magnetic crystal.

Properties

- Spin angular momentum $S_z=1$ → Magnons deplete magnetization
- Momentum (q)
- Energy (E) $E_q \simeq \rho q^2 + \Delta_{\mathrm{MAE}} + g\mu_B B_z$
- Hard-core bosons
- Lifetime ⌛

Thermal proliferation of magnons (3D)

$$M = NS - N_{\mathrm{magnon}}$$

$$N_{\mathrm{magnon}} = \sum_q n_B(E_q)$$

$$N_{\mathrm{magnon}} = \sum_q n_B(E_q) = L^d \frac{1}{(2\pi)^d} \int \frac{d^d\vec{q}}{e^{\beta E_q} - 1}$$

Thermal proliferation of magnons (3D)

$$N = \sum_q n_B(E_q) = L^d \frac{1}{(2\pi)^d} \int \frac{d^d\vec{q}}{e^{\beta E_q} - 1}$$

3D

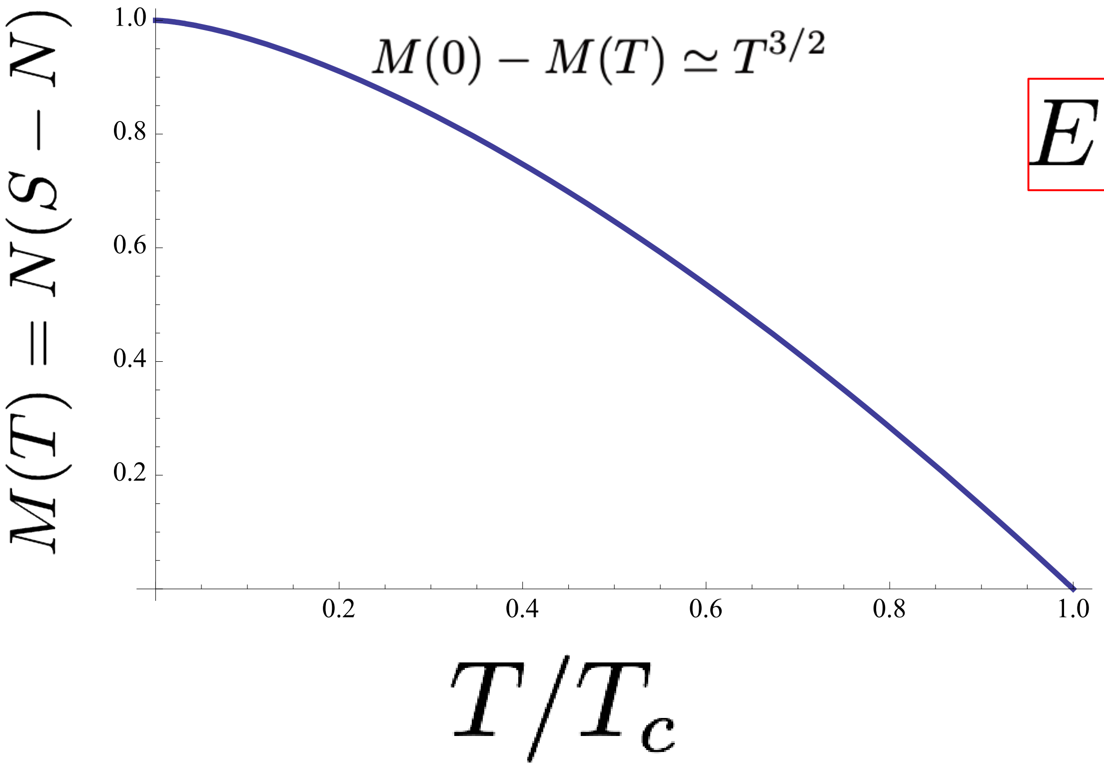
$$E(q) = \rho q^2$$

$$\frac{N}{L^3} \simeq \int_0^{q_c} \frac{q^2 dq}{\beta D q^2} + \int_{q_c}^{q_D} q^2 n_B(E_q) dq = \int_0^{q_D} q^2 n_B(E_q) dq \simeq T^{3/2}$$

Thermal proliferation of magnons (3D)

$$N = \sum_q n_B(E_q) = L^d \frac{1}{(2\pi)^d} \int \frac{d^d\vec{q}}{e^{\beta E_q} - 1}$$

3D



$$E(q) = \rho q^2$$

Thermal proliferation of magnons

$$N_{\mathrm{magnon}} = \sum_q n_B(E_q) = L^d \frac{1}{(2\pi)^d} \int \frac{d^d\vec{q}}{e^{\beta E_q} - 1}$$

2D

$$E(q) = \rho q^2$$

$$\frac{N_{\mathrm{magnon}}}{L^2} \simeq \int_0^{q_c} \frac{qdq}{\beta D q^2} + \int_{q_c}^{q_D} q n_B(E_q) dq = \frac{kT}{D} Log q|_0^{q_c} + \int_{q_c}^{q_D} q^2 n_B(E_q) dq$$

Thermal proliferation of magnons

$$N_{\text{magnon}} = \sum_q n_B(E_q) = L^d \frac{1}{(2\pi)^d} \int \frac{d^d\vec{q}}{e^{\beta E_q} - 1}$$

Infrared
Catastrophe

2D

$$E(q) = \rho q^2$$

$$\frac{N_{\text{magnon}}}{L^2} \simeq \int_0^{q_c} \frac{q dq}{\beta D q^2} + \int_{q_c}^{q_D} q n_B(E_q) dq =$$

$$\frac{kT}{D} Log q|_0^{q_c} + \int_{q_c}^{q_D} q^2 n_B(E_q) dq$$

Thermal proliferation of magnons

$$N_{\text{magnon}} = \sum_q n_B(E_q) = L^d \frac{1}{(2\pi)^d} \int \frac{d^d\vec{q}}{e^{\beta E_q} - 1}$$

$$E = \rho q^2 + \Delta$$

2D **Gap prevents catastrophe**

$$\frac{N}{L^2} \simeq \int_0^{q_c} \frac{q\,dq}{\beta\left(Dq^2 + \Delta\right)} + \int_{q_c}^{q_D} q n_B(E_q) dq =$$

$$kT \log\left(\frac{\Delta + Dq_c^2}{\Delta}\right) + \int_{q_c}^{q_D} q n_B(E_q) dq$$

Magnon gap and spin rotational invariance

Gap in magnon spectrum
=
Breaking spin rotational symmetry
=
Prevents Magnon divergence
=
Makes Ferromagnetic order possible in 2D

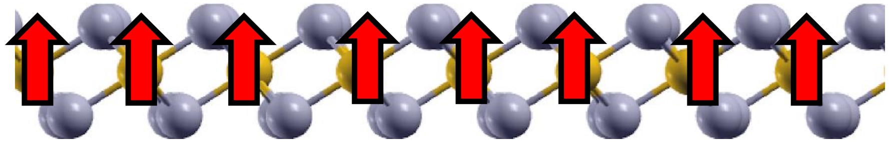
Magnetic Anisotropy is essential in 2D FM

Outline of the rest of the talk

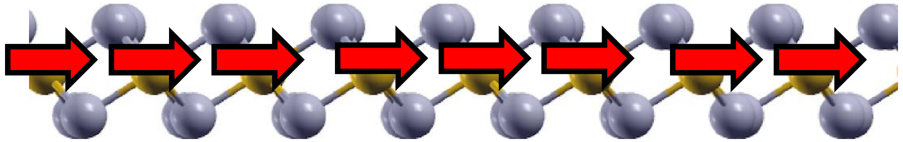
- An intro to CrI_3
- Mermin Wagner theorem
- Origin of magnetic anisotropy in CrI_3
- Topological magnons in CrI_3
- Strong proximity effect in CrI_3/graphene
- Magnon-plasmon coupling in CrI_3/graphene
- CrI_3 nanotubes

What is the origin of magnetic anisotropy in CrI_3?

DFT calculation of MAE



$E_{\perp}$



$E_{||}$

$$\mathcal{E}_{\text{aniso}} = E_{\perp} - E_{||}$$

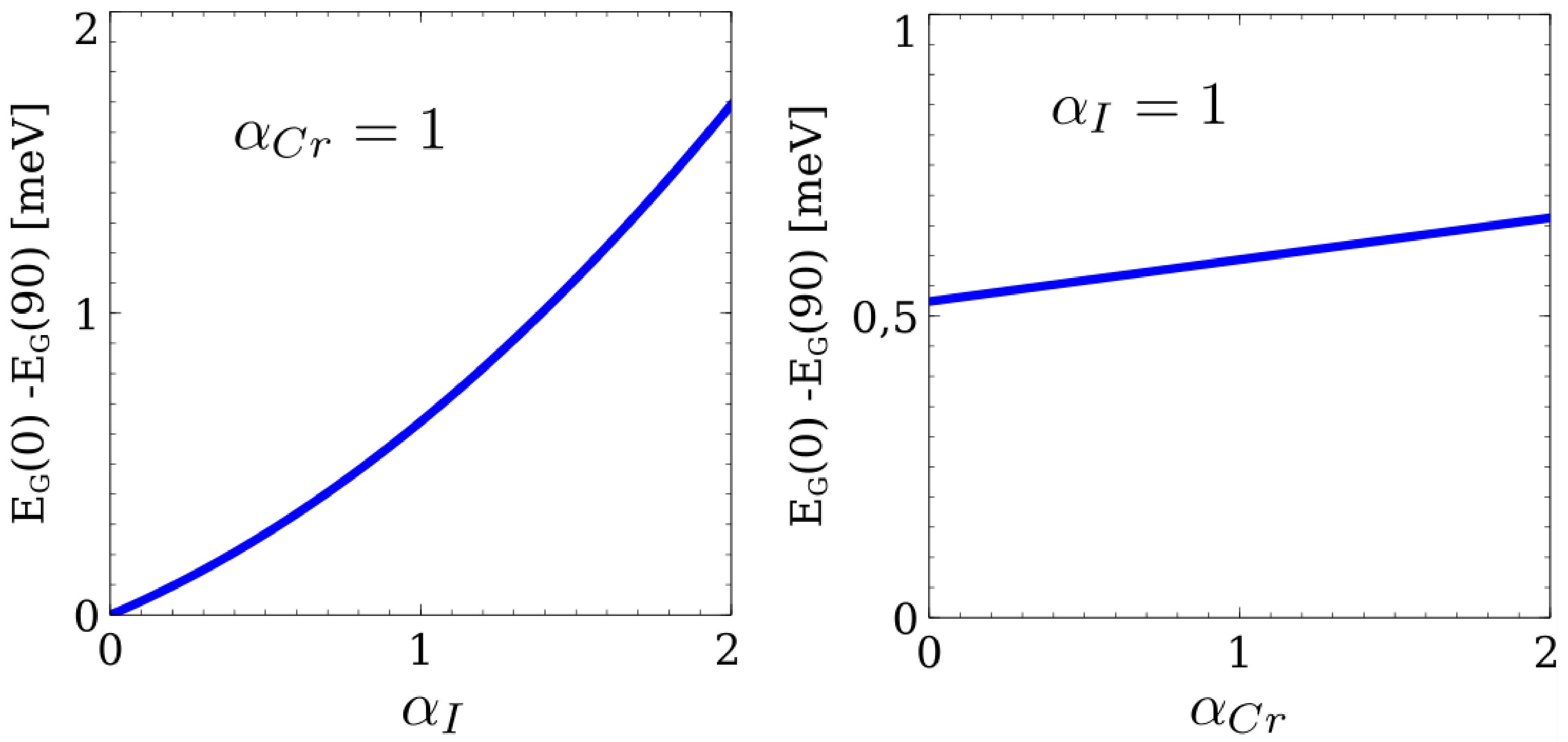
- All electron
- Spin-orbit
- DFT+U
- Elk

J. L. Lado, J. Fernández-Rossier
2D Materials, 2017

Changing independently SOC of I and Cr

We can separately see the effect of the two atoms to magnetic anisotropy

$$\mathcal{H}_{\mathrm{DFT}}(\alpha_I, \alpha_{Cr}) = \mathcal{H}_0 + \alpha_I \mathcal{H}_I^{SOC} + \alpha_{Cr} \mathcal{H}_{Cr}^{SOC}$$



J. L. Lado, J. Fernández-Rossier 2D Materials, 2017

Anisotropy wrap-up:

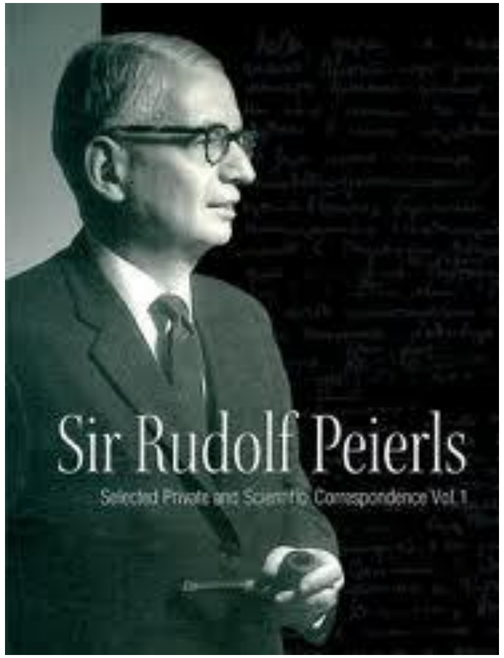
- Spin orbit coupling in Iodine controls **Magnetic Anisotropy** in CrI_3
- Related in part to Curie Temperature trend in CrX_3

  - $T_c(CrI_3)$ > $Tc(CrBr_3)$ > $T_C(CrCl_3)$

Questions?

Time Left?

- Absence of 2D Crystalline order
- Absence of 2D magnetic order

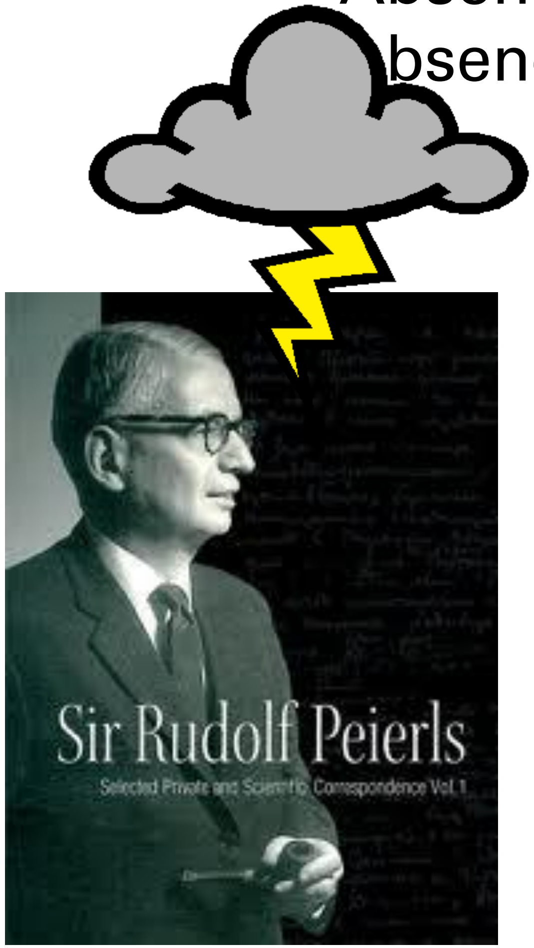


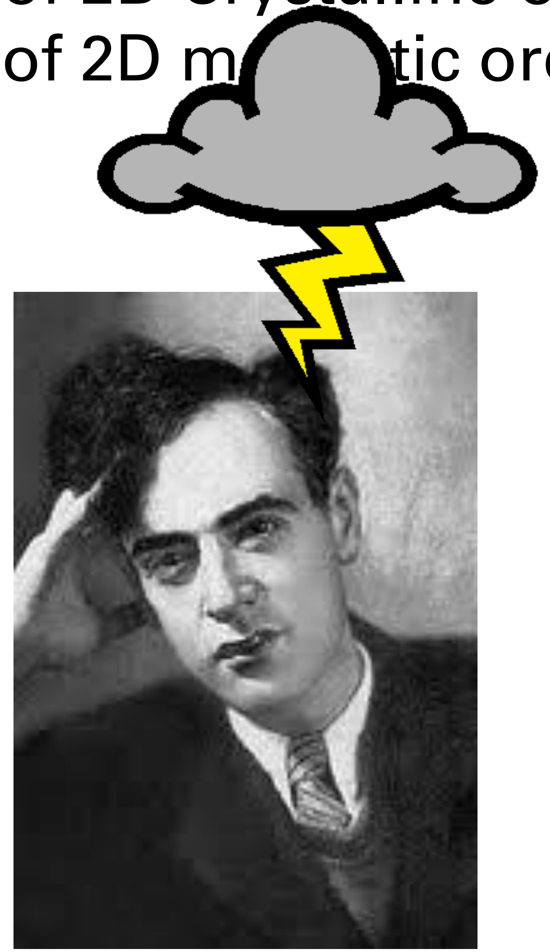
Lev Landau

David Mermin

Joaquin.fernandez-rossier@inl.int

- Absence of 2D Crystalline order
- [illegible]bsence of 2D m[illegible]tic order





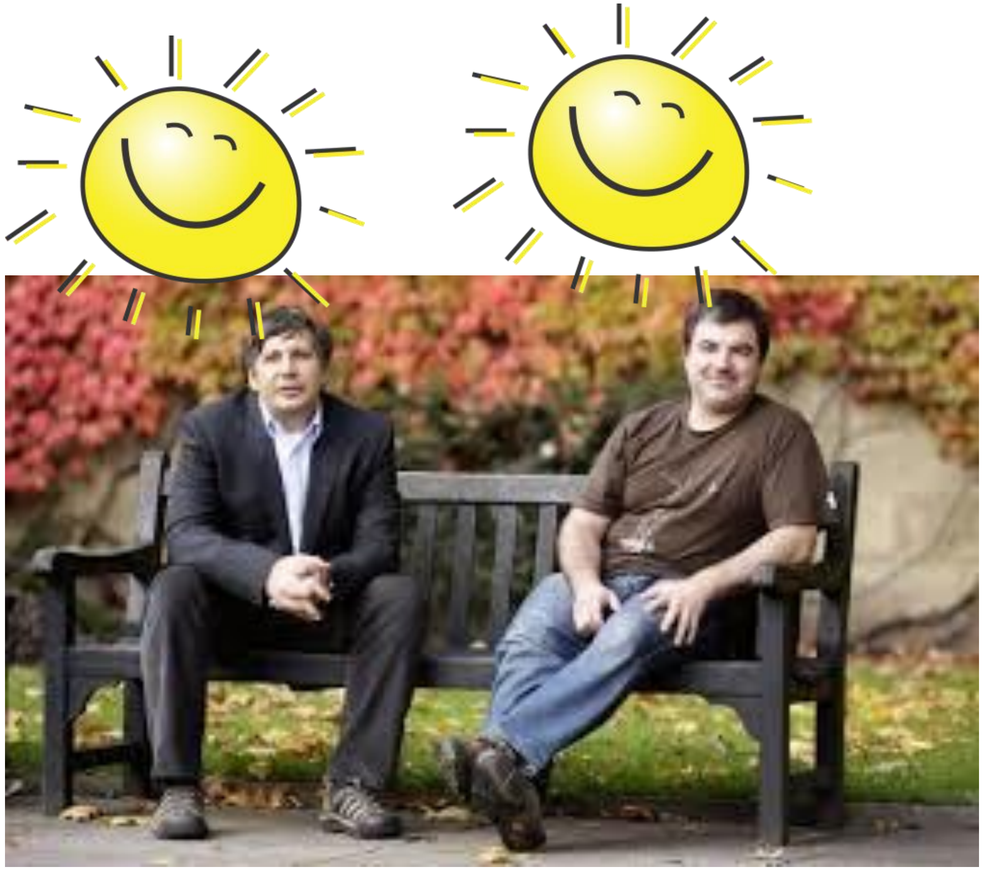
Lev Landau

David Mermin

Experts opinion in 2004

1. Impossible to get 1 atomic plane without MBE (=very expensive machine)
2. “Crystals are made by god, surfaces are made by devil”
   Surface adsorbates and disorder would kill mobility
3. Optical absorption would be negligible
4. Would be fragile

Seeing things differently



Wrap up: Some challenges in the field

Magnetic 2D Materials

1. Room temperature magnetism in 2D layers
2. Observation of topological order
   (useful for Quantum Computing)
3. Can we use 2D materials for neuromorphic computing?
4. Can we design and fabricate materials bottom-up?

Thanks for your attention

FCT Fundação para a Ciência e a Tecnologia
PTDC/FIS-MAC/2045/2021

Swiss National Science Foundation

FUNLAYERS

GOBIERNO DE ESPAÑA