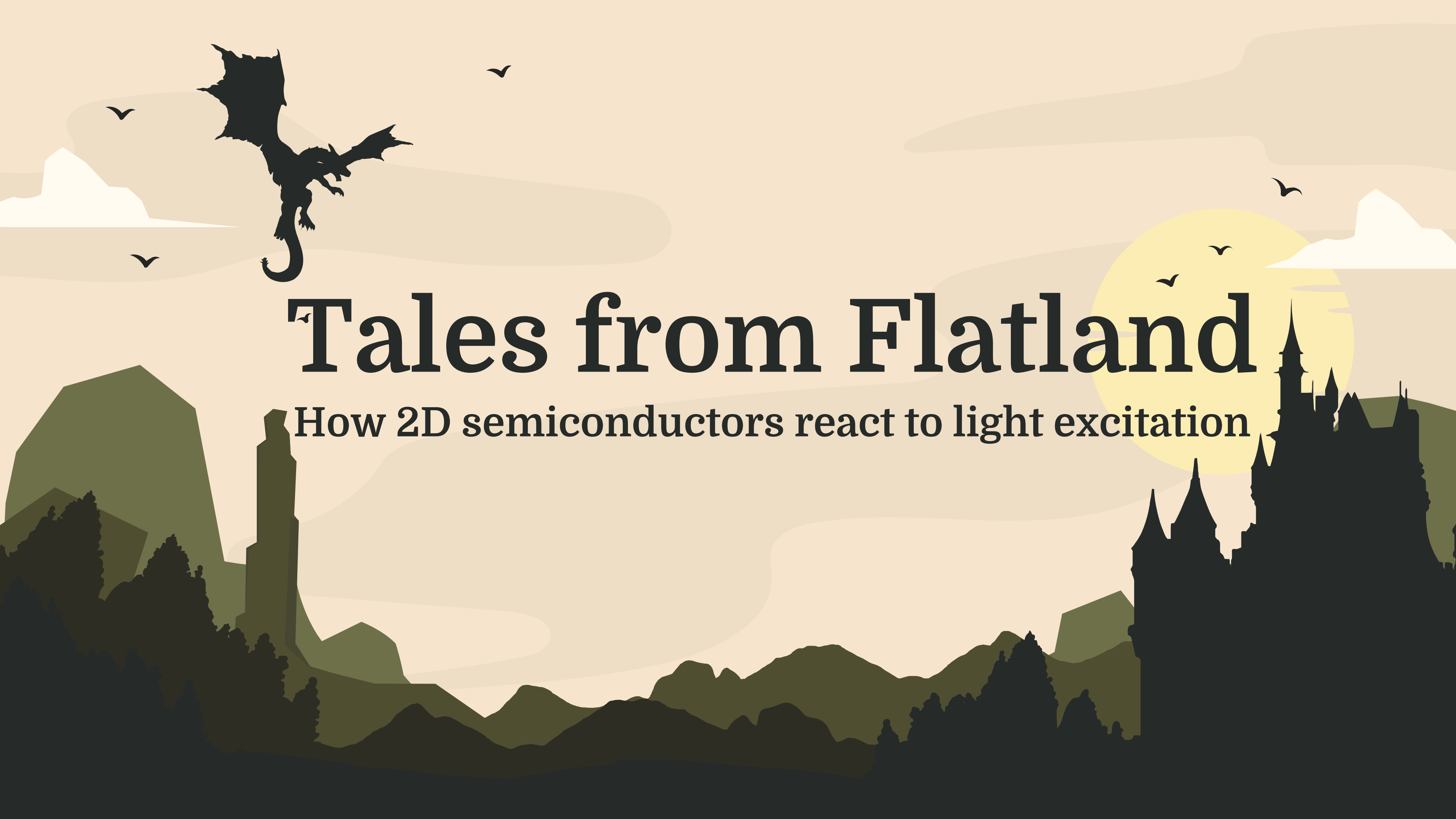


Tales from Flatland

How 2D semiconductors react to light excitation

Table of contents

01

Something about Semiconductors

and their main features

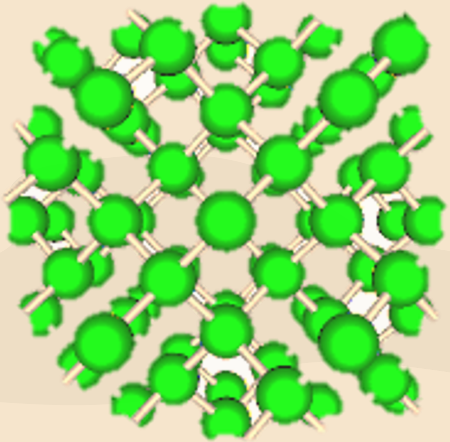
Electrons’ energy levels in solids

- In crystals, electrons feel the periodic potential of surrounding ions

$$H(\vec{r}) = H_0 + U(\vec{r})$$

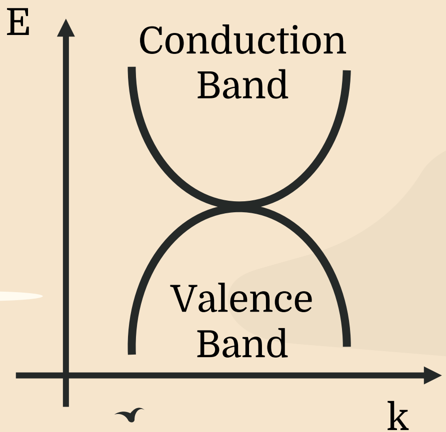
$$\downarrow$$

- This leads continous energy levels that we call «**band**»

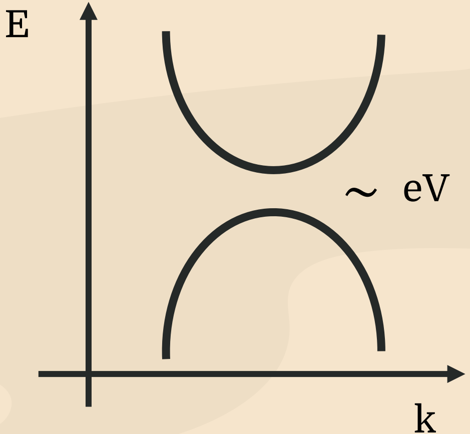


Band Structures

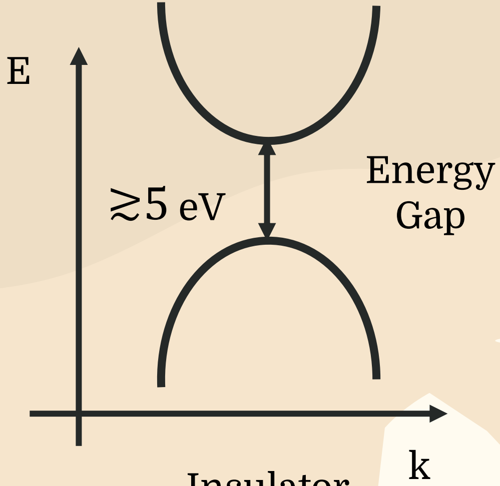
- Depending on the band structure, solids react as:
  - Metal
  - Semiconductor
  - Insulator



Metal



Semiconductor



Insulator

02

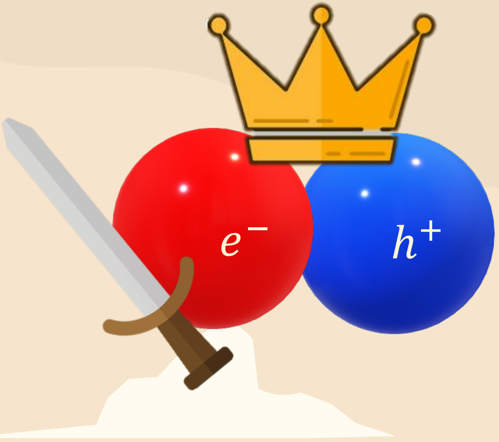
Photoluminescence

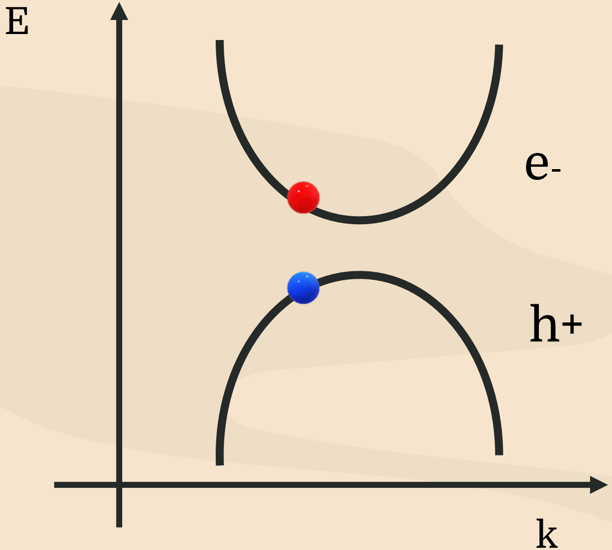
That is, how do we investigate
semiconductors

Excitons in semiconductors

- Excitons are quasi-particles made by an electron in the conduction band and a «hole» in the valence band

- Having opposite charge, they form a bound state due to the Coulomb interaction





Photoluminescence

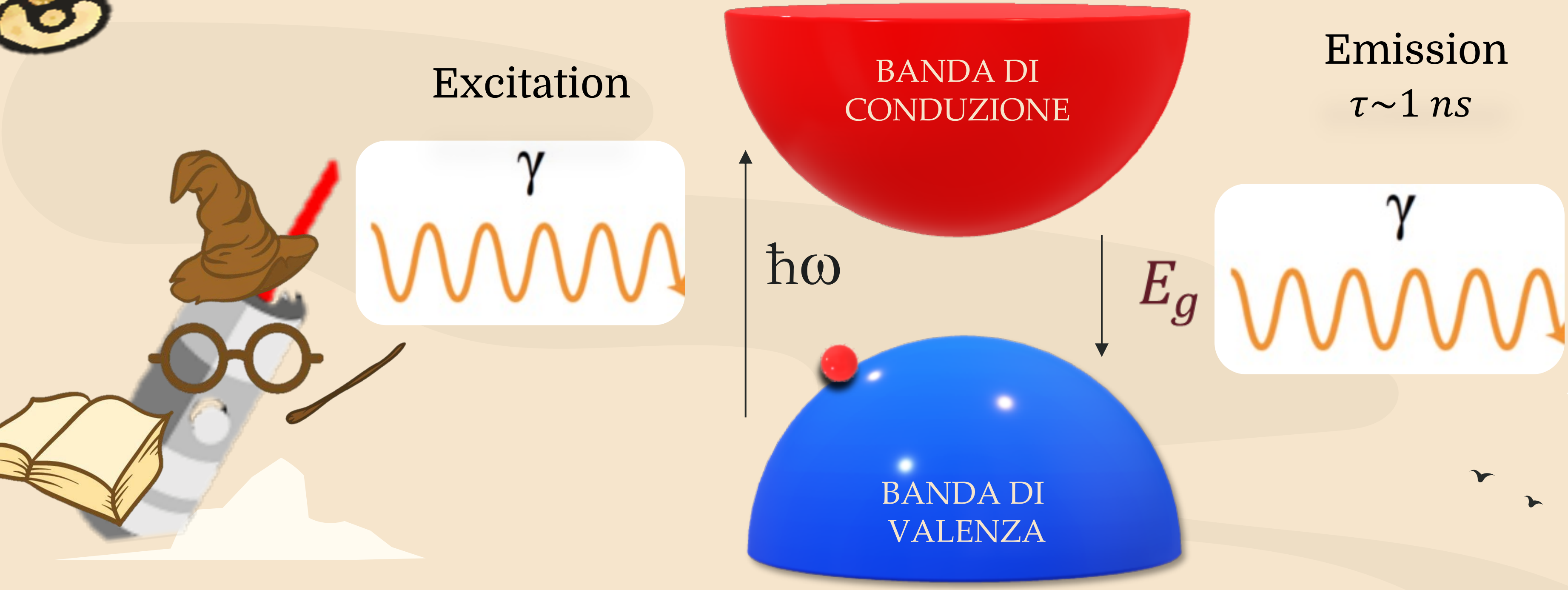
Thermalization

$\tau \sim 10\, fs$

Excitation

Emission

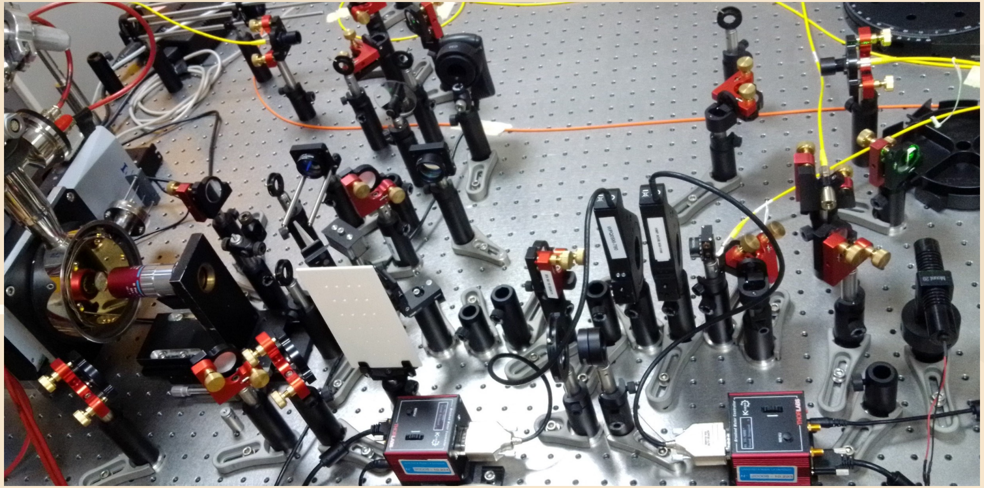
$\tau \sim 1\, ns$

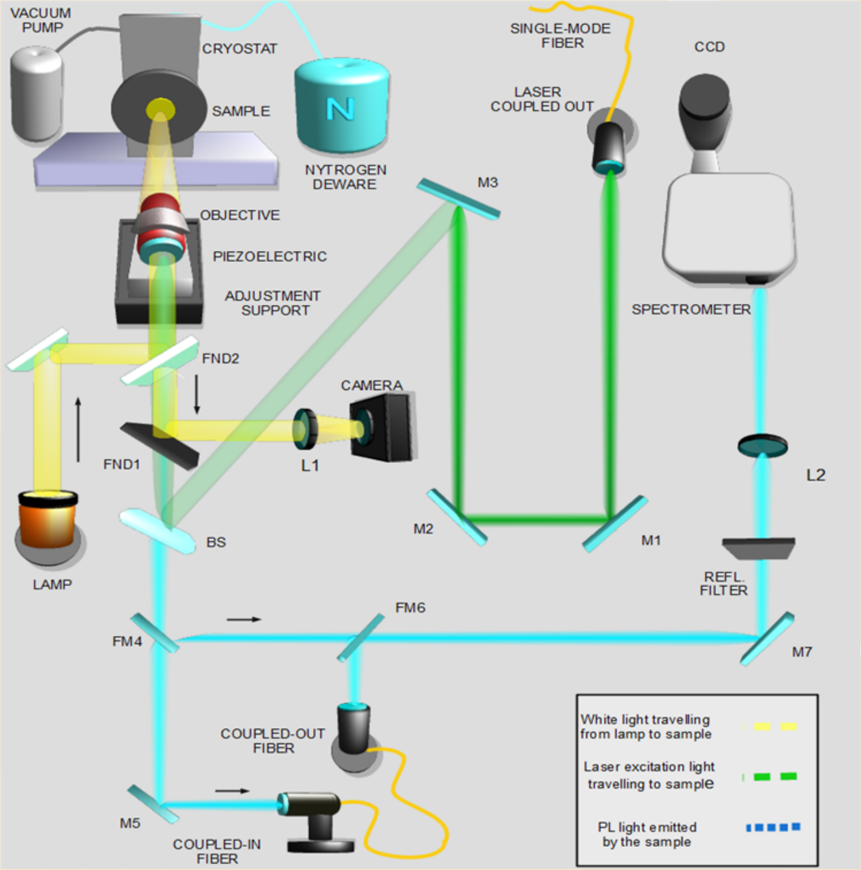


The gate to Flatland

- The Nanophotonics gate to Flatland is a μ-PL experimental setup

- We excite our samples with laser, and collect the emitted signal with CCD cameras





03

2D TMDs

and why they are so intreresting

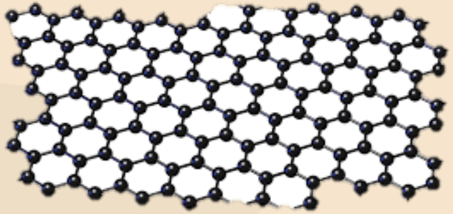
WHY 2D TMDs?

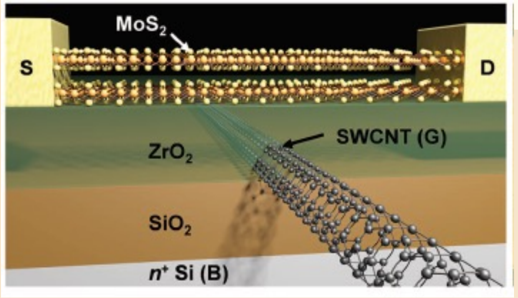
- Semiconductors are the basic brick of our technology
- Silicon is the most used for practical purposes, like microprocessor
- In order to improve the processors' efficiency, we need to increase the transistors' density
- But Silicon presents scaling problem, being not possible to realize devices smaller than 5 nm

↓

We need to look for semiconductors useful on lower length scale

A bit of history





1965

Moore's Law

2004

Discovery of Graphene [1]

2010

First PL observation from ML MoS2 [2]

2016

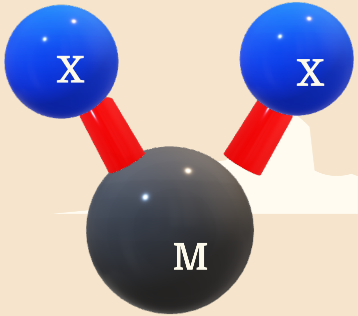
MoS2 based transistor with 1 nm length gate [3]

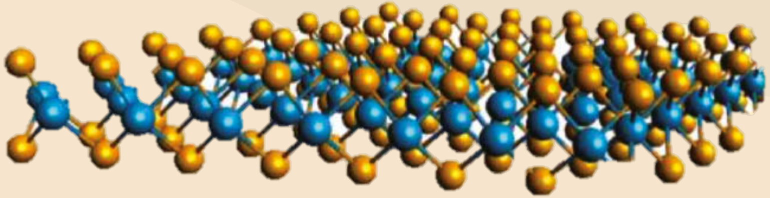
[1] Novoselov, Geim et al. «*Electric field effects in atomically thin carbon films», Science*, 306 (5696), 666-669 (2004)
[2] A. Splendiani, et al. «*Emerging photoluminescence in Monolayer MoS2*» Nano Lett. 10, 1271 (2010).
[3] Desai, et al. «*MoS2 transistor with 1-nanometer gate length* » Science, 354-6308 (2016)

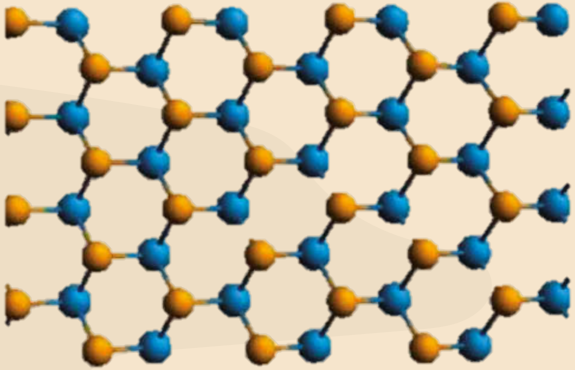
Let's meet TMDs

- Hexagonal structure
- Monolayer made of three atomic sheets
- Direct semiconductors in the monolayer limit [4]

2D TMDs are made of
- 1 Transition Metal M (Mo, W)
- 2 Chalcogens X (Se, S, Te)



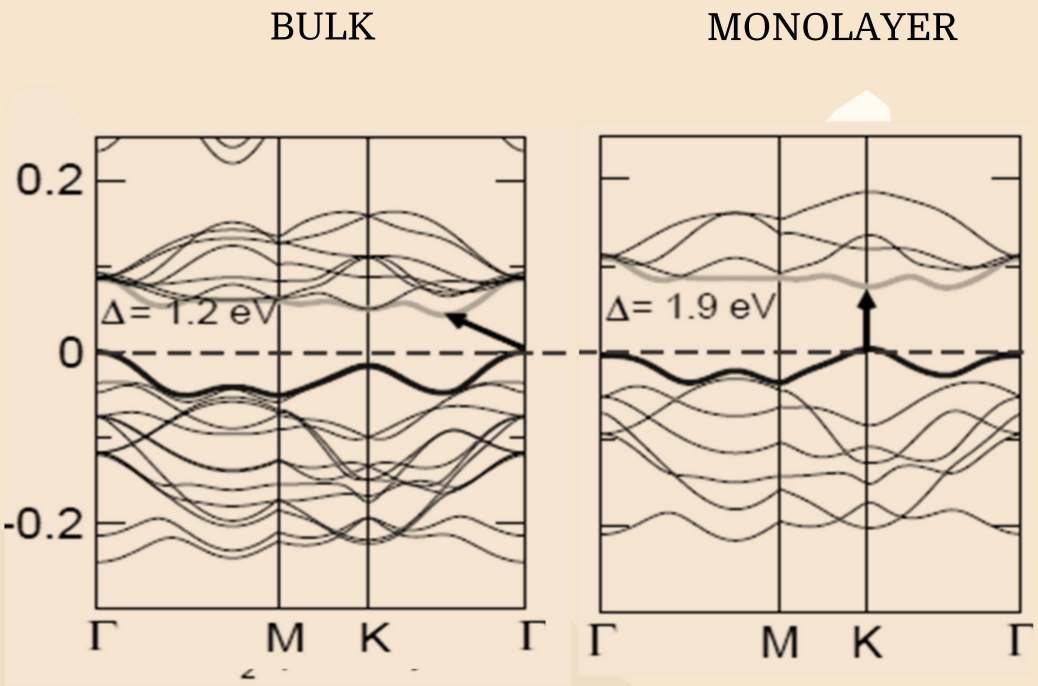




[4] Kuc et al. «*How does quantum confinement influence the electronic structure of transition metal sulphide*» , Phys. Revi. B, (2011)

Indirect to direct transition

- While bulk TMDs are indirect semiconductors, ML TMDs have a direct transition due to different orbitals contributions[5],[6]
- This promotes them as efficient semiconductors, suitable for practical purposes



[5] T. Li and G. Galli. "*Electronic Properties of MoS2 Nanoparticles*" .J.Phys. Chem. 111, 16192 (2007).

[6] A. Cappelluti et al. "*Tight-binding model [...] and multilayer MoS2*" Phys. Rev. B. 88, 075409 (2013).

04

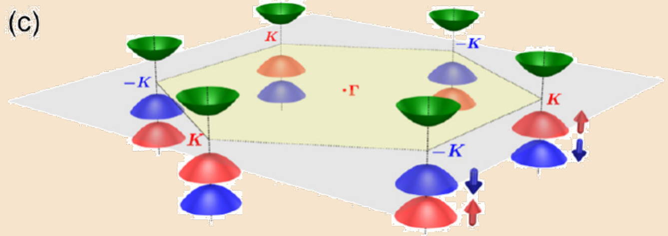
Valley-Hall Effect

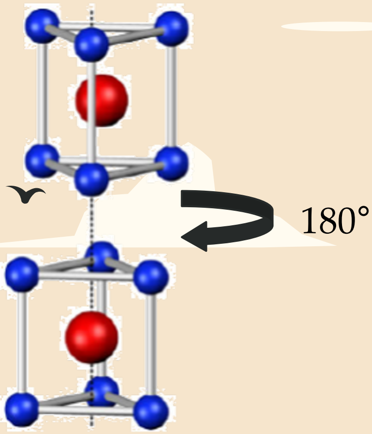
yes, the fanciest part

Valley degree of freedom

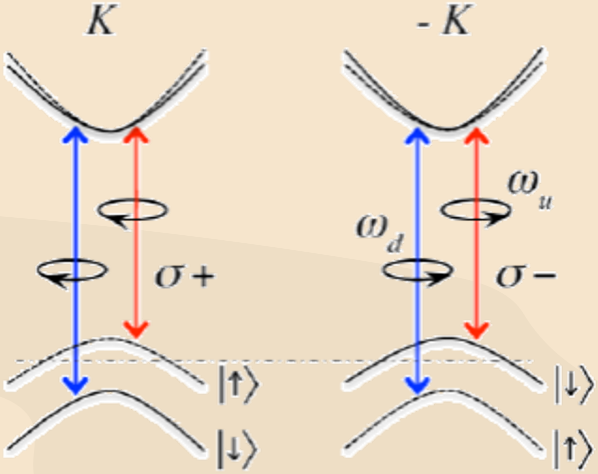
- The band structure presents two «valleys» K, -K with the same energy
- The breaking of rotational symmetry couples each valley with left/right circular polarization
- The strong spin orbit coupling protects the valley degree of freedom (VDF) against relaxation processes

We can use the VDF as a qubit!



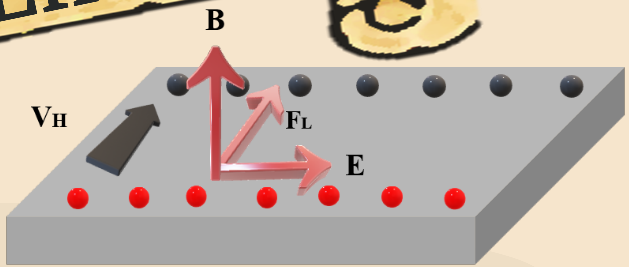


$\Delta_{SO}^{WS2} = 0.4\ \mathrm{eV}$

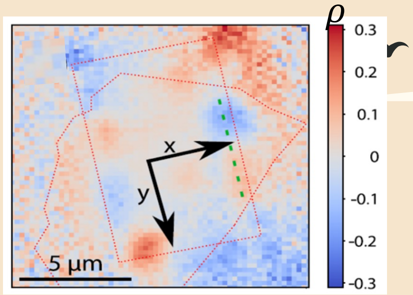


[7] D. Xiao, et al. "*Coupled Spin and Valley Physics in Monolayers of MoS2 and Other.*" PRL. 108, 196802 (2012).
[8] W. Yao, et al. "*Valley-dependent optoelectronics from inversion symmetry breaking.*" Phys. Rev. B 77, 235406 (2008).

Valley Hall Effect



CLASSICAL HALL EFFECT



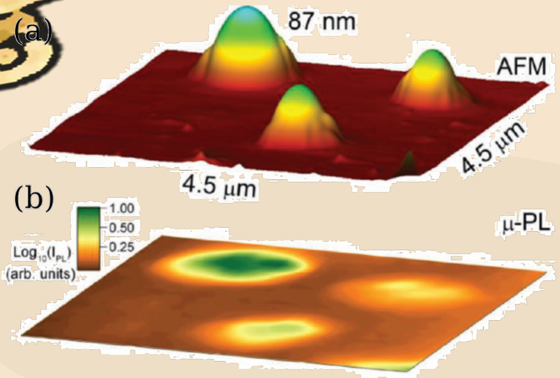
VALLEY-HALL EFFECT

	CLASSICAL HALL EFFECT	VALLEY-HALL EFFECT
CARRIER	CHARGE	VALLEY INDEX
BOOSTER	MAGNETIC FIELD	PSEUDO-MAGNETIC FIELD (STRAIN)
EFFECT	HALL CURRENT	ANOMALOUS VELOCITY [9]
OBSERVABLE	HALL VOLTAGE	CIRCULAR DICHROISM
CONDUCTIVITY	$R_H = \frac{1}{ne}$	$\sigma^H = \frac{e^2}{\hbar}\int_{BZ}\frac{d^2k}{(2\pi)^2} f_0(k)\Omega(k)$ [10]

[9] M-C. Chang et al. "*Berry phase, hyperorbits, and the Hofstadter spectrum:Semiclassical dynamics in magnetic Bloch bands.*" Phys. Rev. B 53, 11 (1996).

[10] D. Xiao et al., «*Valley-Contrasting Physics in Graphene: Magnetic Moment and Topological Transport*" PRL, **99**, 236809 (2007)

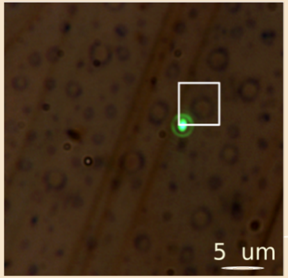
Experimental candies

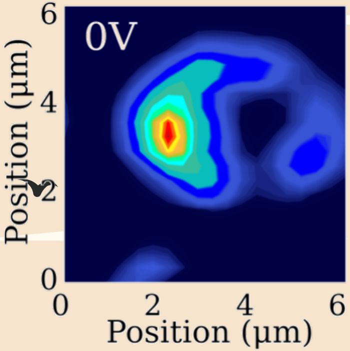


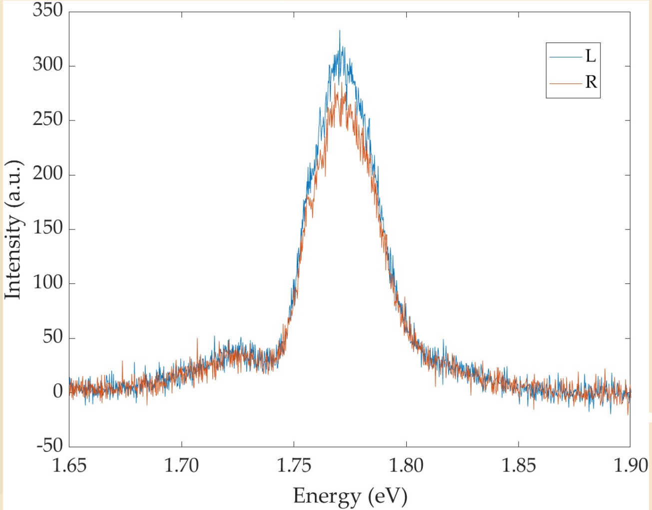
- We create monolayer hydrogenating bulk crystals
- This provides monolayered «domes» with high strain fields
- In the figure it's reported the PL intensity arising from the ML region [11]

- The top-left panel is an optical image of a WS2 dome-patterned region
- The right panel provides a PL map from the white squared dome

- The bottom figure is a typical PL spectrum that exhibits circular dichroism







[11] D. Tedeschi et al. «*Proton-driven patterning of bulk transition metal dichalcogenides.*" arXiv:1803.09825v1 (2018).

Thanks...

...you all for your attention, and the whole Nanophotonics group of Prof. Rinaldo Trotta for the funny adventures that we have in Flatland (...and zero-land)

The End