2D Magnets and Novel Spintronic Devices

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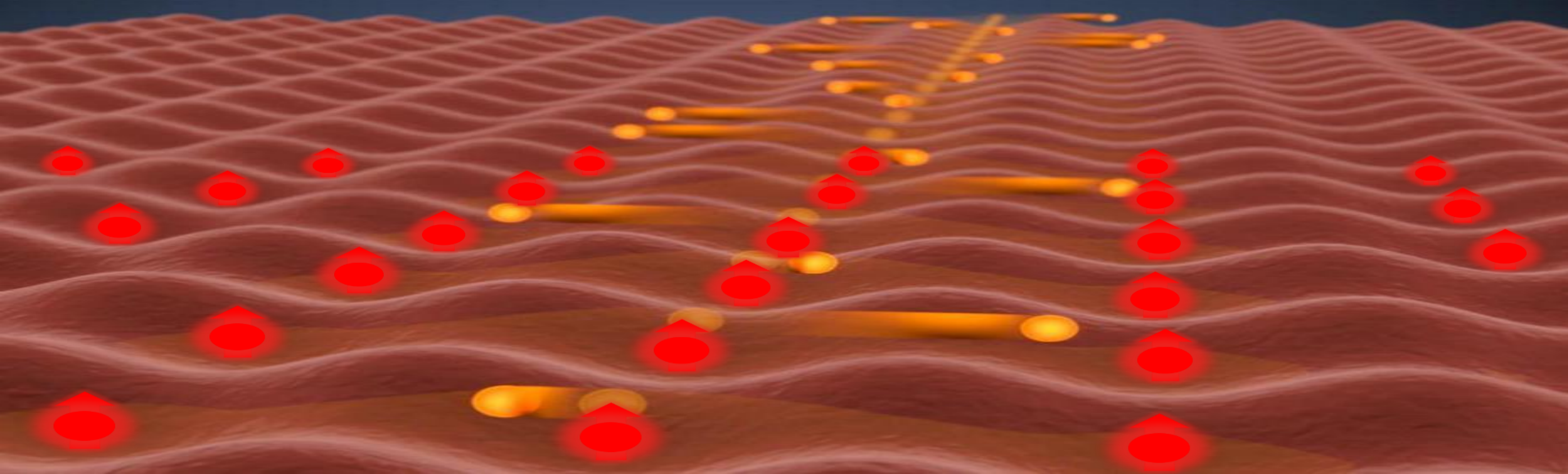


Outline

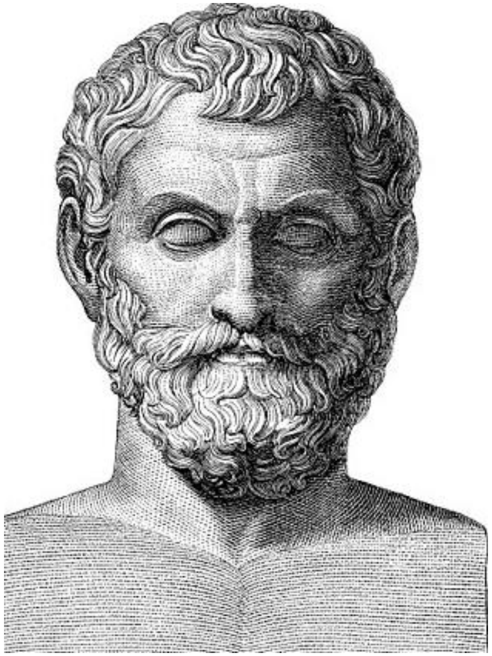
- Background
- Discovery of 2D magnet (ferromagnet)
- Making 2D antiferromagnets promising for spintronics
- Antiferromagnet – ferromagnet mutual conversion
- Outlook

1. Gong, et al. *Nature (2017)*
2. Gong, et al. *Science* (2019)
3. Gong, et al. *PNAS* (2018)
4. Gong, et al. *Nat. Comm.* (2019)
5. A couple of unpublished work…

Lodestone – magic "attraction"

The earliest record on magnets

nationalmaglab.org



Thales of Miletus

(~600 BC)

Magnetism: old? vibrant!

Animal navigation

disney.com

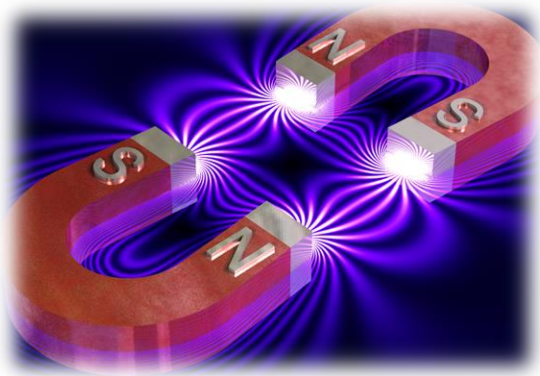
Biologically inspired navigation

- Olfactory
- **Electromagnetic**
- **Magnetosensory**
- Optical

Applications of magnets

Energy harvesting

electronicsb2b.com



slideshare.net

Brain science

legacyneuro.com

Vehicles

(motors, sensors, actuators)

gm.com

Data storage

freepik.com

Synchrotron

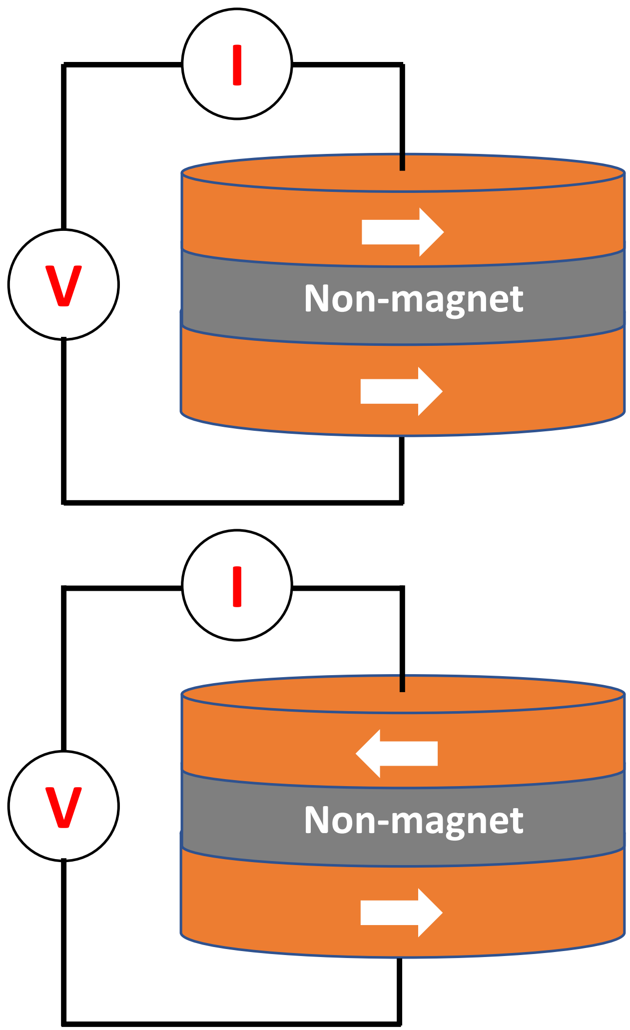
lbl.gov

Magnetic memory

Magnetic tunnel junction

Low resistance

High resistance

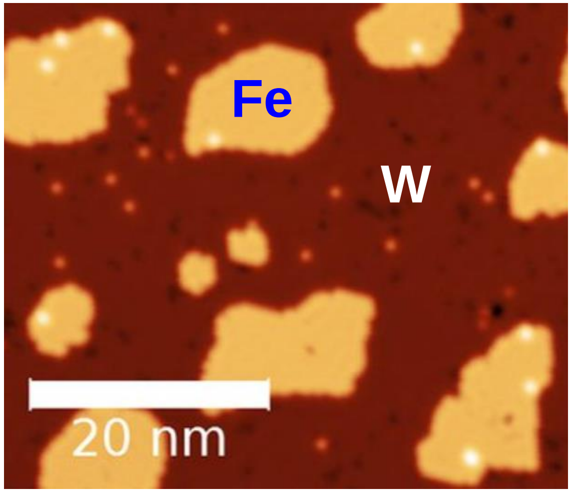


Thinner is better:

- Lower energy consumption
- Less heat
- Higher-density integration

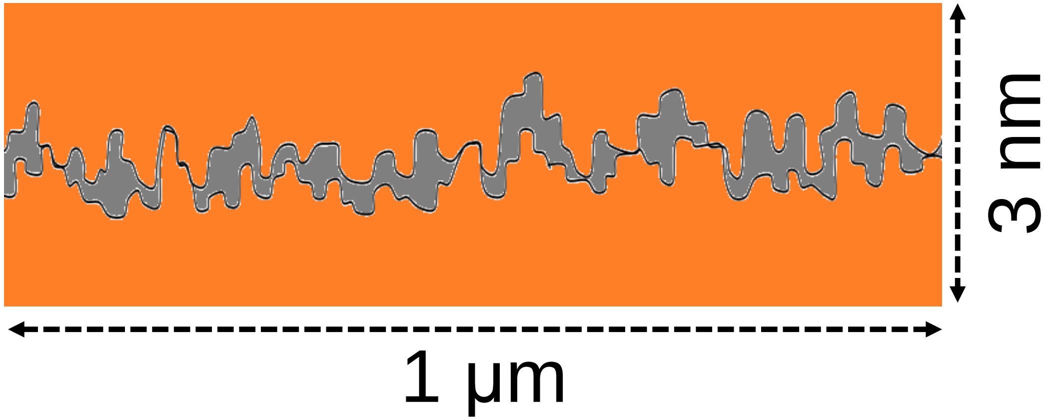
Can we reach "atomic thinness"?

Monolayer Fe on W



Coffey, Sci. Rep. (2015)

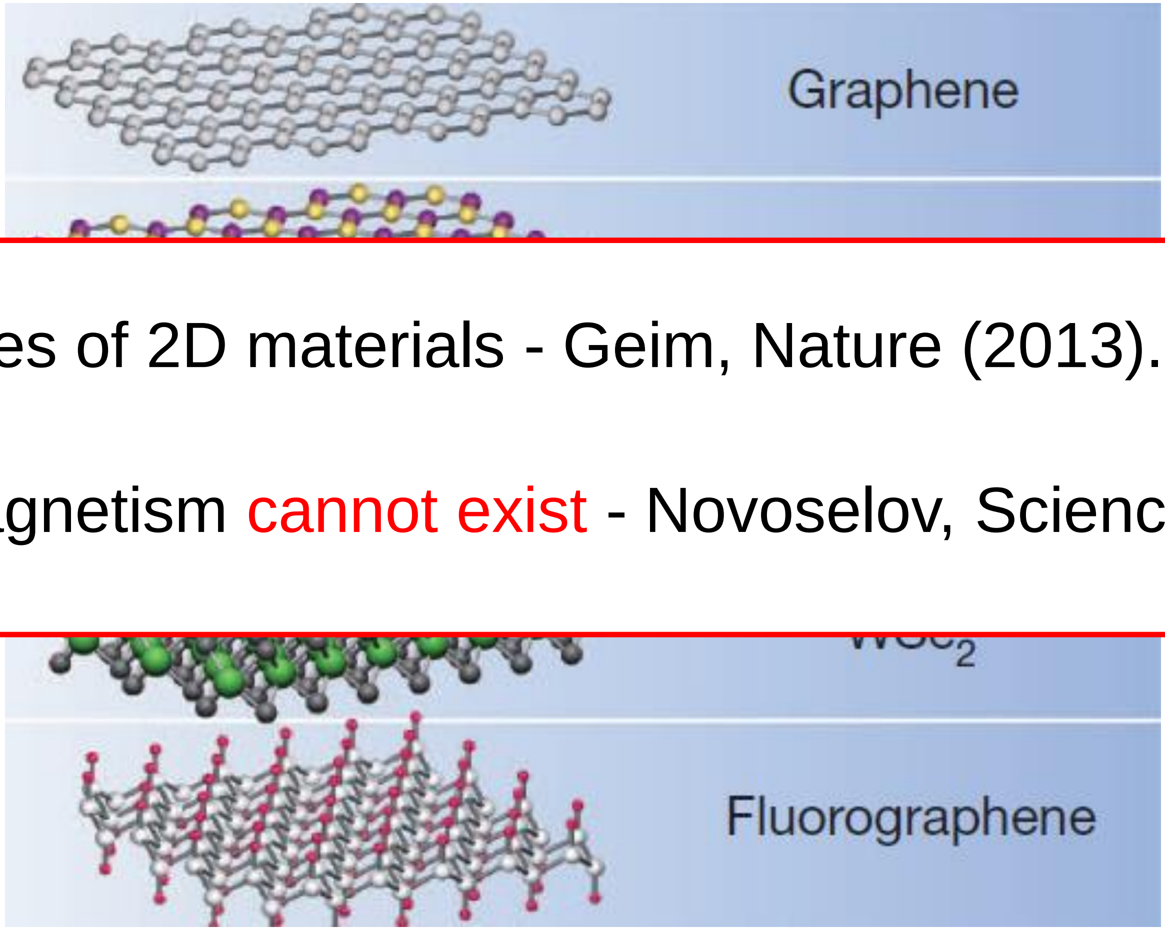
"Rough" tunnel junction



Cannot reach reproducibility and scalability.

2D materials, but not magnetic

Large-size, atomically-thin, single-crystalline

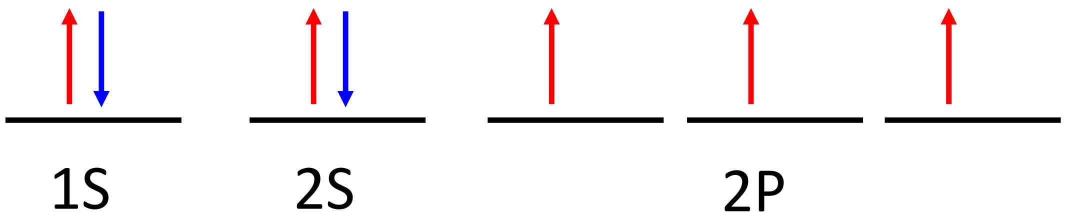


- 40 types of 2D materials - Geim, Nature (2013).
- 2D magnetism cannot exist - Novoselov, Science (2016).

What is magnetism?

Hund's rule

Nitrogen:



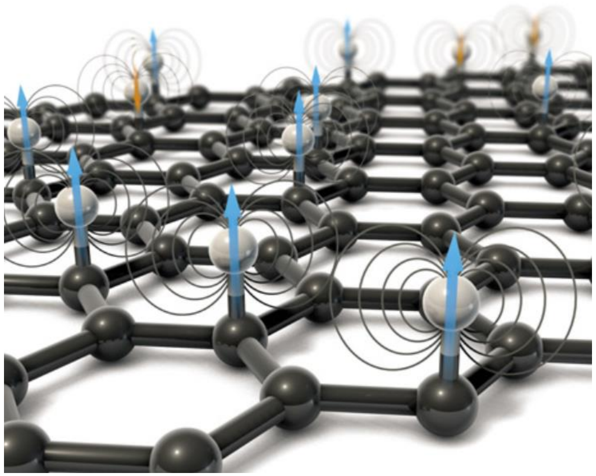
Electron spins

Ferromagnetism:

parallel alignment of unpaired electron spins.

Past efforts in induced 2D magnetism

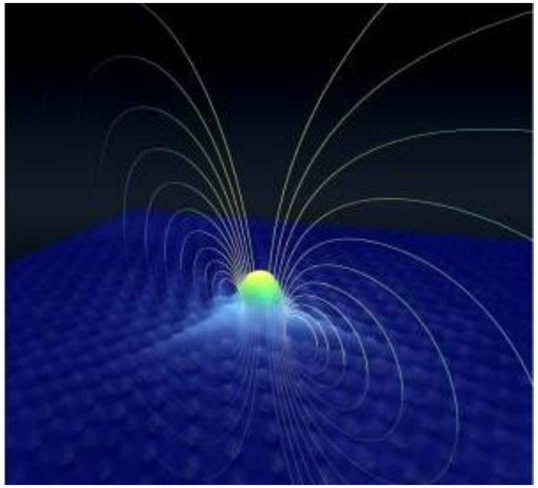
Decorated 2D materials



Hollen, *et al.* Science (2016)

Add "something"

Defective 2D materials



Ugeda, *et al.* Phys. Rev. Lett. (2010)

Take away "something"

Challenge: how to align the randomly created electron spins?

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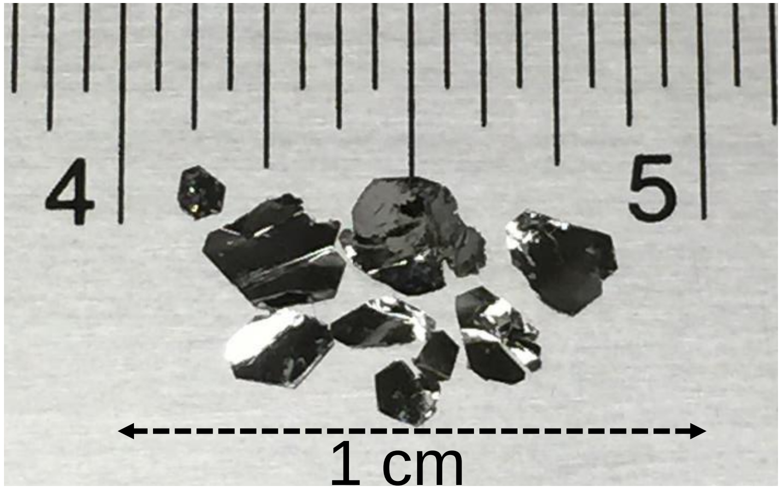
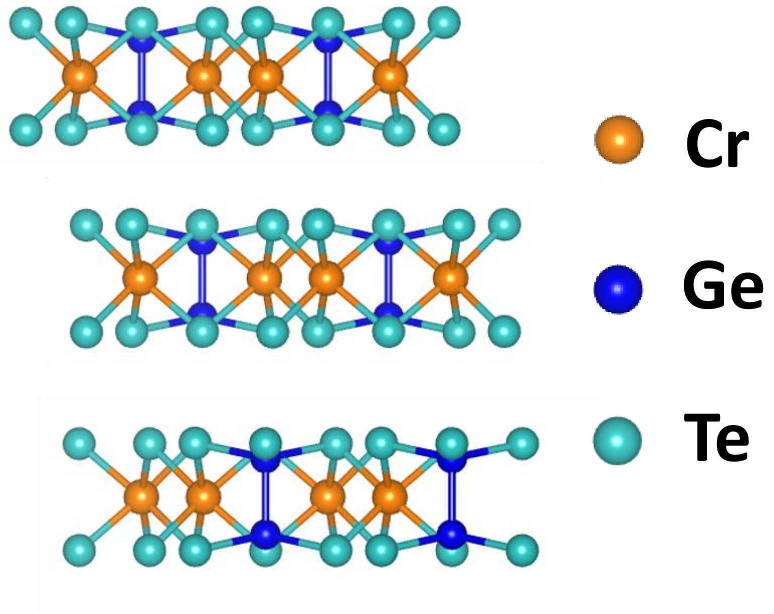
The first observed 2D magnet

$Cr_2Ge_2Te_6$ (CGT)

Image of bulk crystals



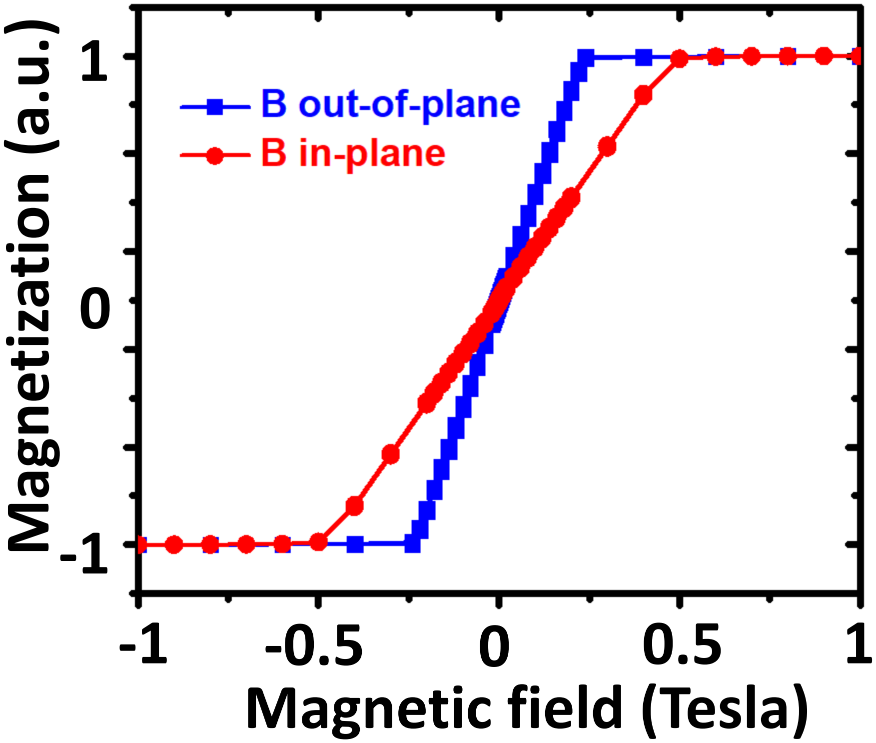
Side view



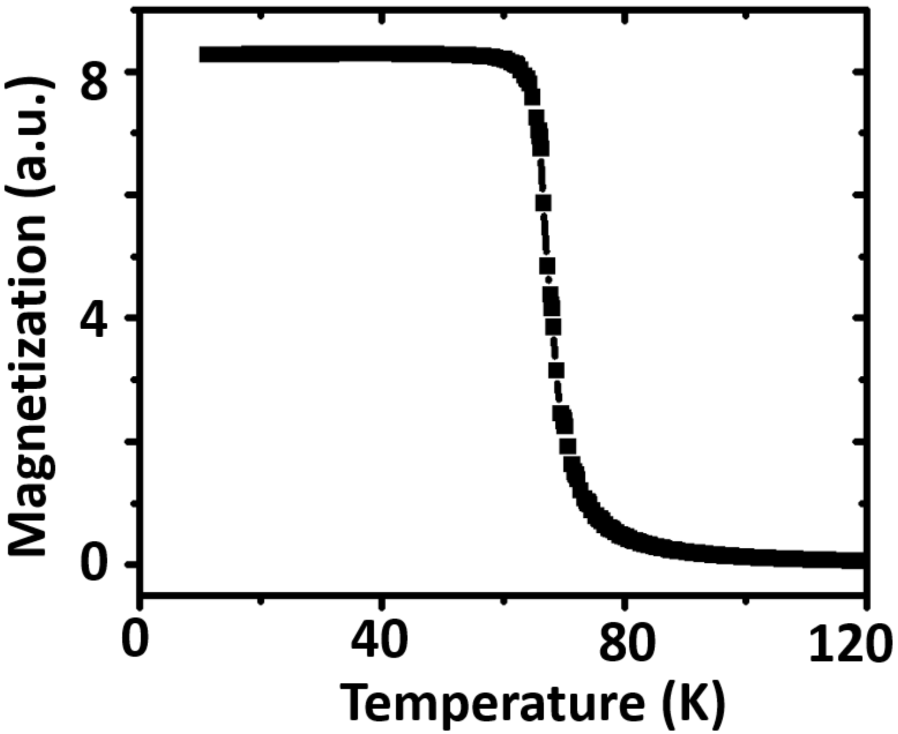
Gong, *et al. Nature* (2017)

Magnetic properties of bulk CGT

Magnetic hysteresis

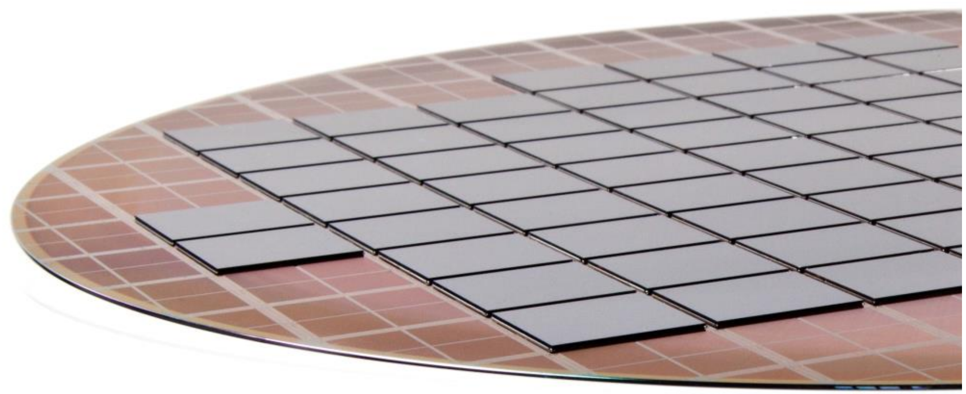


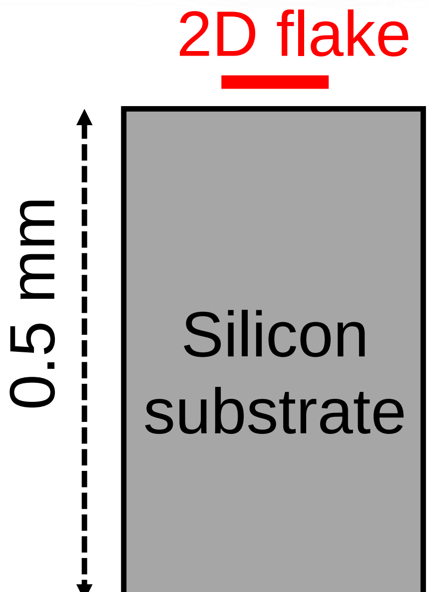
Tc: 65 K



Bulk CGT is a ferromagnet with 65 K T_C.

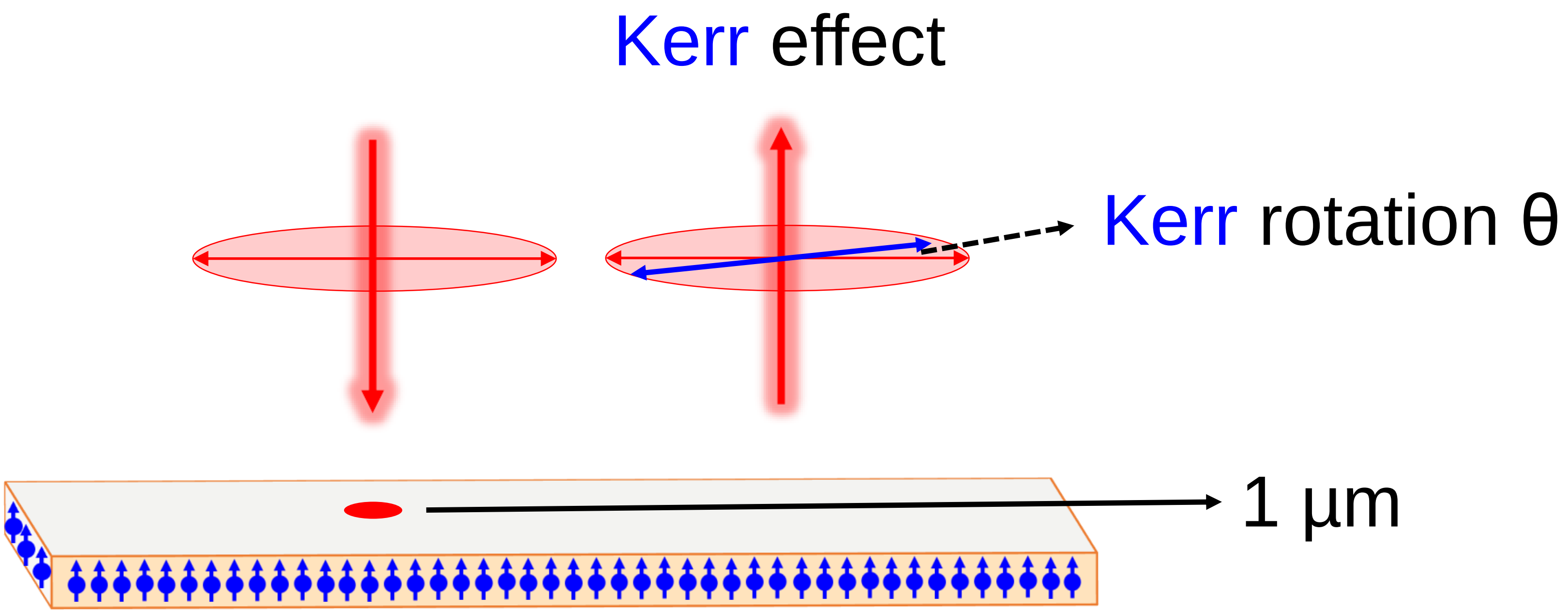
How to measure 2D magnets?





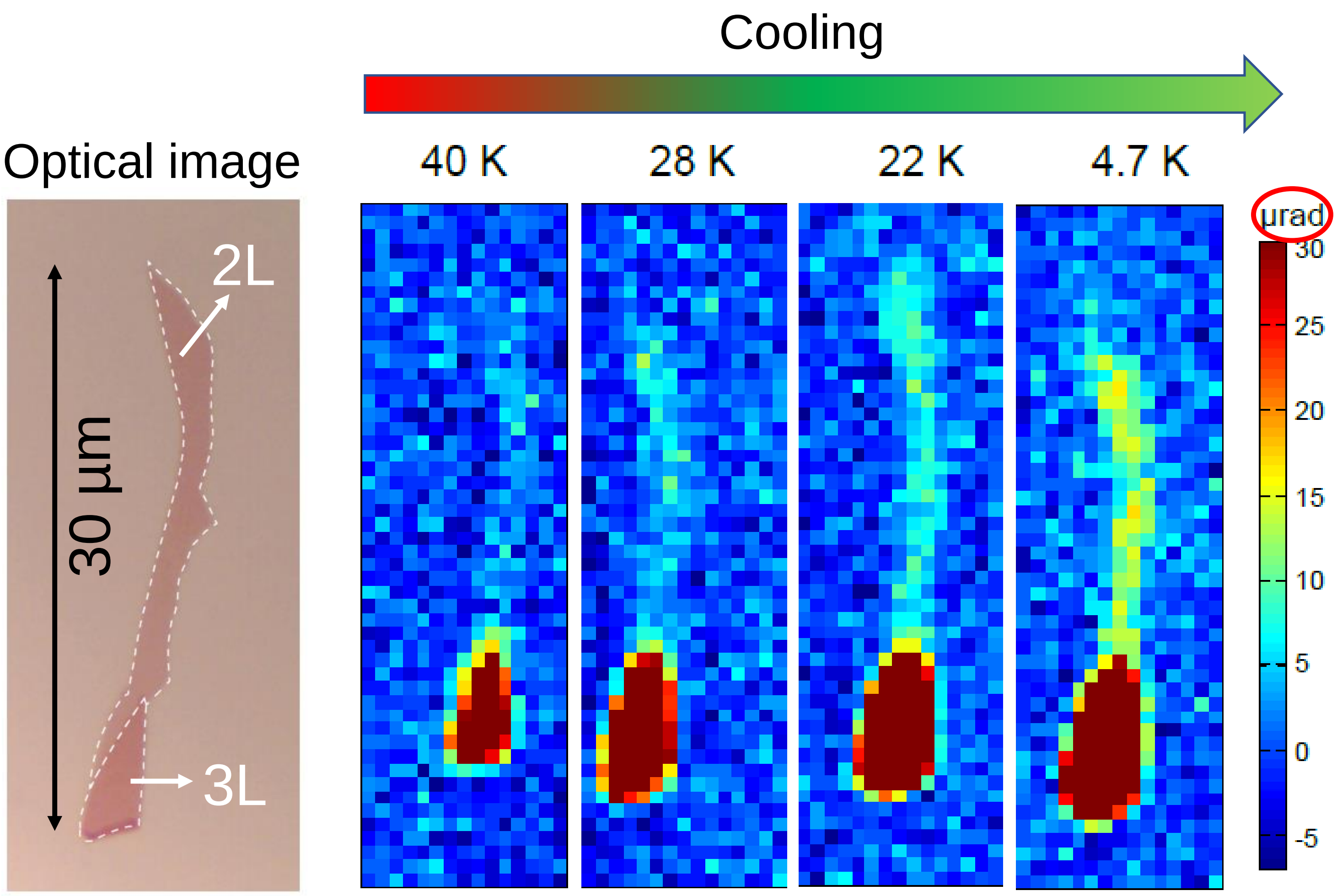
Conventional characterization techniques do not work for 2D flakes.

Magneto-optic Kerr effect (MOKE)



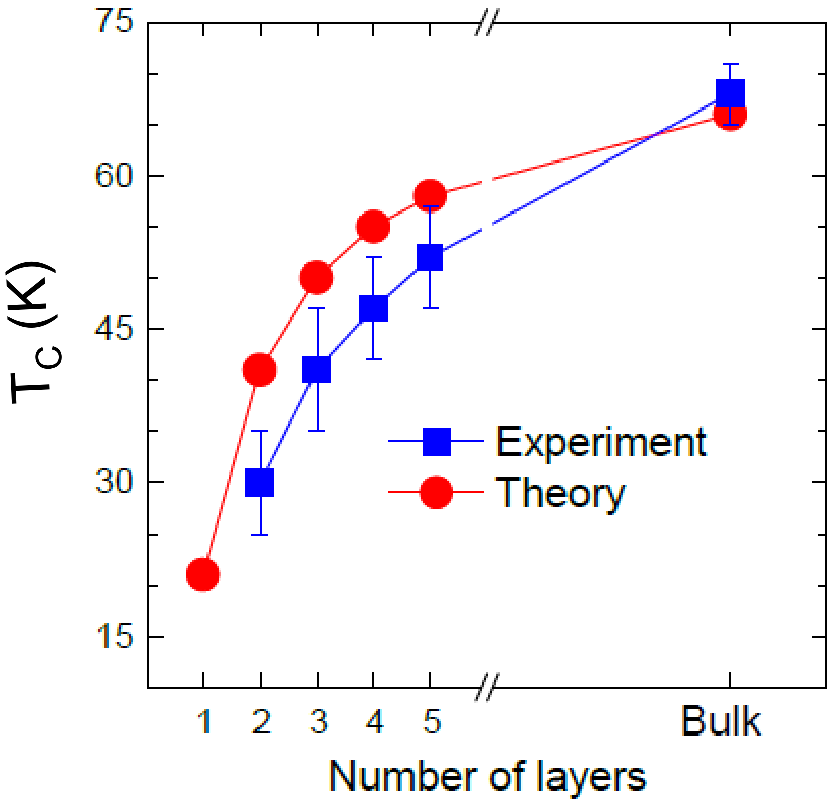
Detect magnetism from atomically-thin, µm-size specimen unambiguously.

Observation of ferromagnetism in 2D CGT



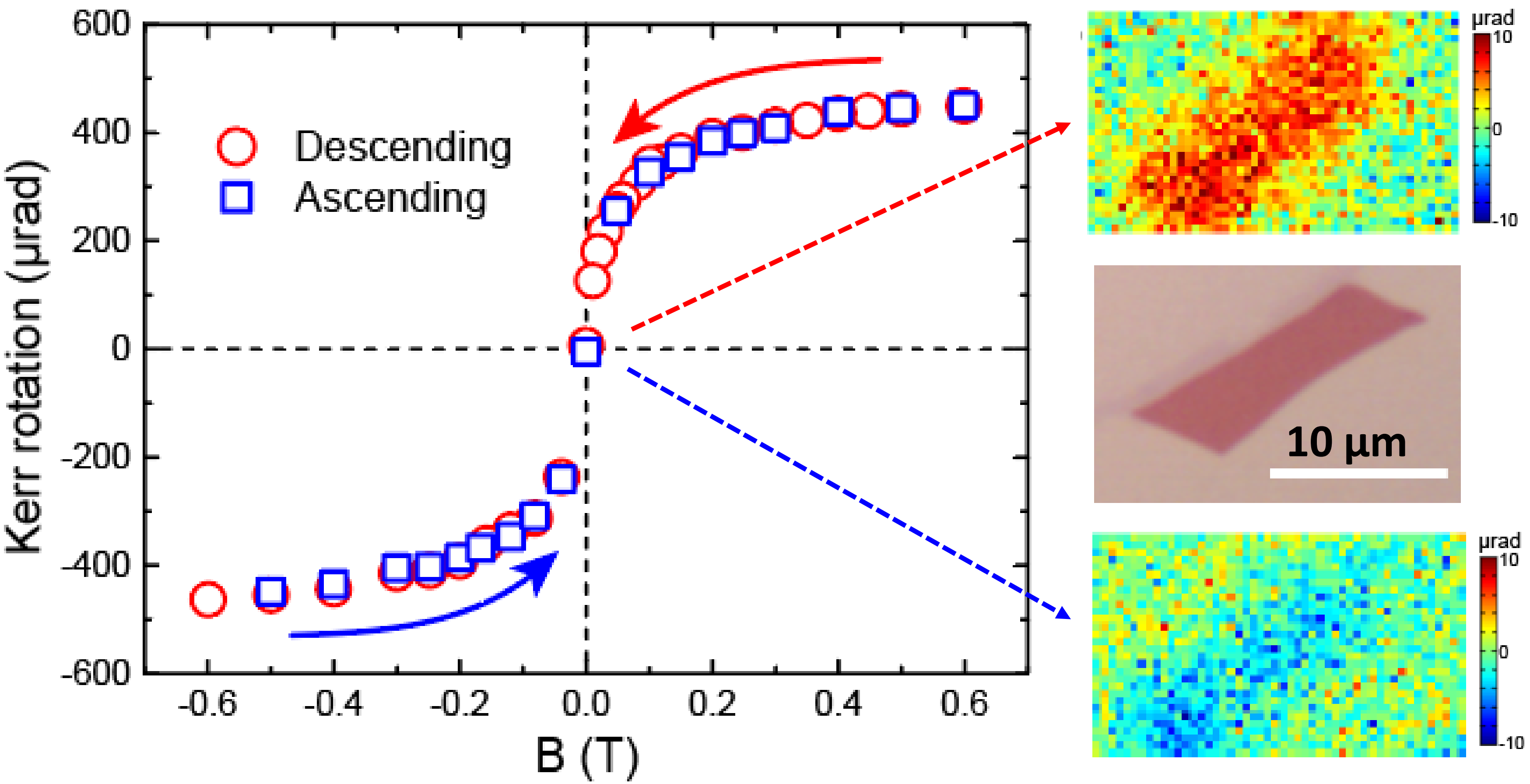
Ferromagnetism emerges in 2D CGT while cooled.

Thinner sample, lower T_C



Nature of 2D: strong thermal effect

Ferromagnetic hysteresis of 2D CGT



Non-zero remanant signal confirmed “ferromagnetism”!

Metal | Semiconductor | Magnet

Graphene | MoS_2 | $Cr_2Ge_2Te_6$, CrI_3

2004, 2005

Novoselov, Science (2004)
Zhang, Nature (2005)

2010

Mak, Phys. Rev. Lett. (2010)
Splendiani, Nano Lett. (2010)

2017

Gong, Nature (2017)
Huang, Nature (2017)

nature
Magnetism in flatland

PHYSICS TODAY
Ferromagnetism found in two-dimensional materials

nature nanotechnology
2D magnetism gets hot

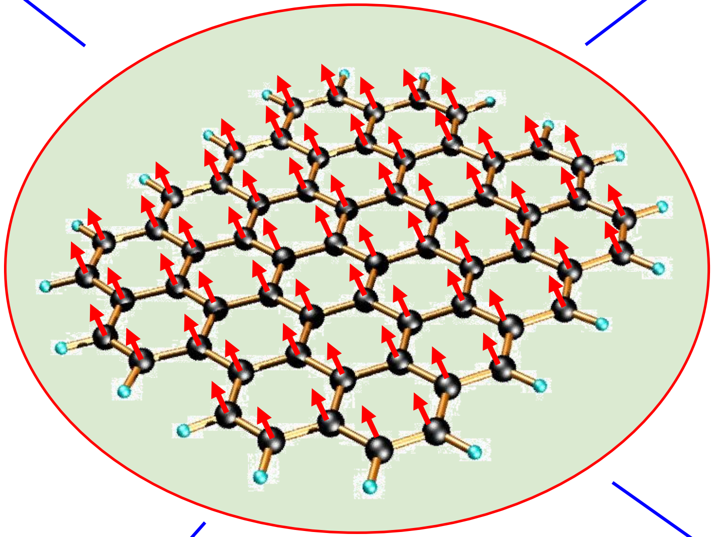
AIR FORCE RESEARCH LABORATORY
2018 MURI

The rise of 2D magnetism

New 2D magnets

High temperature 2D magnets

Large-scale growth



Spintronic devices

Electrical control

Hybrid materials

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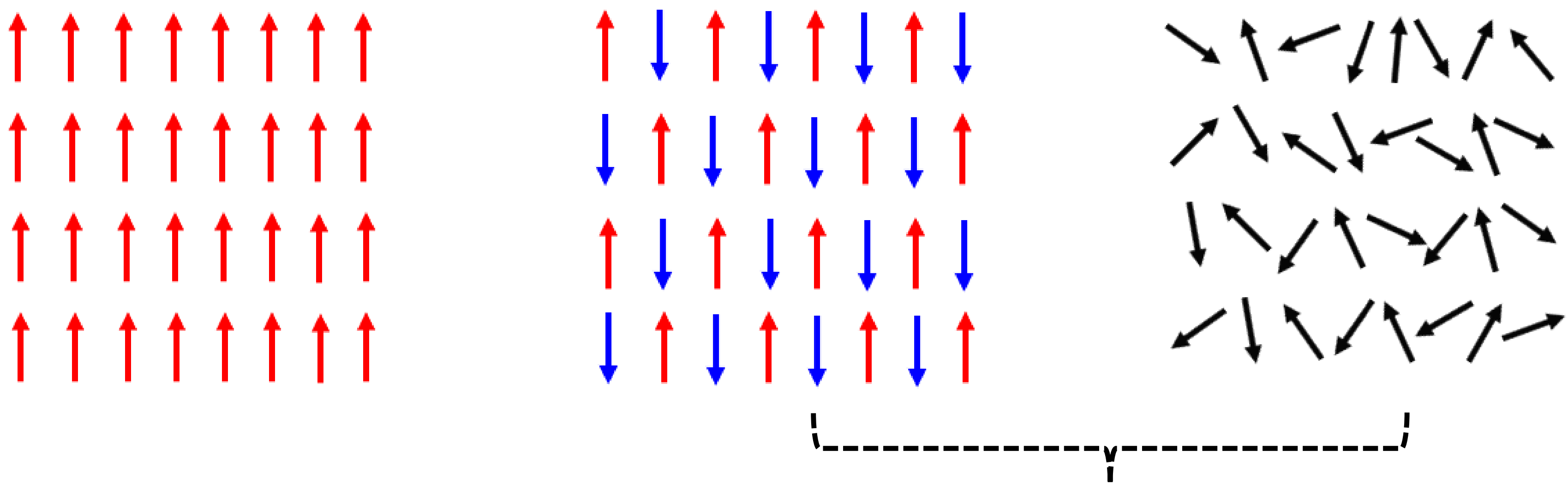
Magnet family

Ferro-magnet | Anti-ferro-magnet | Non-magnet



Zero magnetization

Antiferromagnets are extremely interesting from the theoretical viewpoint, but do not seem to have any applications.
- Louis Néel (1970)

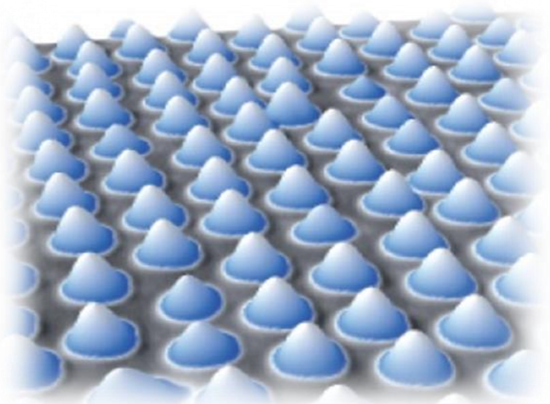
Antiferromagnetic spintronics

1. Abundant

	ferromagnets	antiferromagnets
Chalcogenides	$Cr_2Ge_2Te_6$, $Cr_2Si_2Te_6$, Fe_3GeTe_2, VSe_2, $MnSe^*$	$Fe_2P_2S_6$, $Fe_2P_2Se_6$, $Mn_2P_2S_6$, $Mn_2P_2Se_6$, $Ni_2P_2S_6$, $Ni_2P_2Se_6$, $CuCrP_2Se_6$,* $CdFeP_2S_6$, $AgVP_2S_6$, $AgCrP_2S_6$, $Fe_2Ag_5Sb_{13}Se_{24}$, $CrSe_2$, $Ni_3Cr_2P_2S_9$
Halides	CrI_3,* $CrBr_3$, GdI_2	$CrCl_3$, $FeCl_2$, $FeBr_2$, FeI_2, $MnBr_2$, $CoCl_2$, $CoBr_2$, $NiCl_2$, VCl_2, VBr_2, VI_2, $FeCl_3$, $FeBr_3$, $CrTe_3$, CrOCl, CrOBr, CrSBr

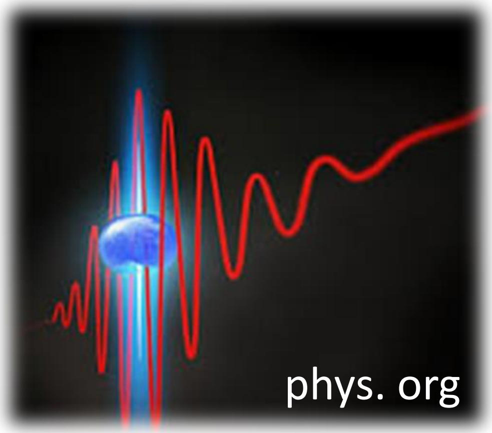
Gong, *et al. Science* (2019)

2. No cross-talk between bits



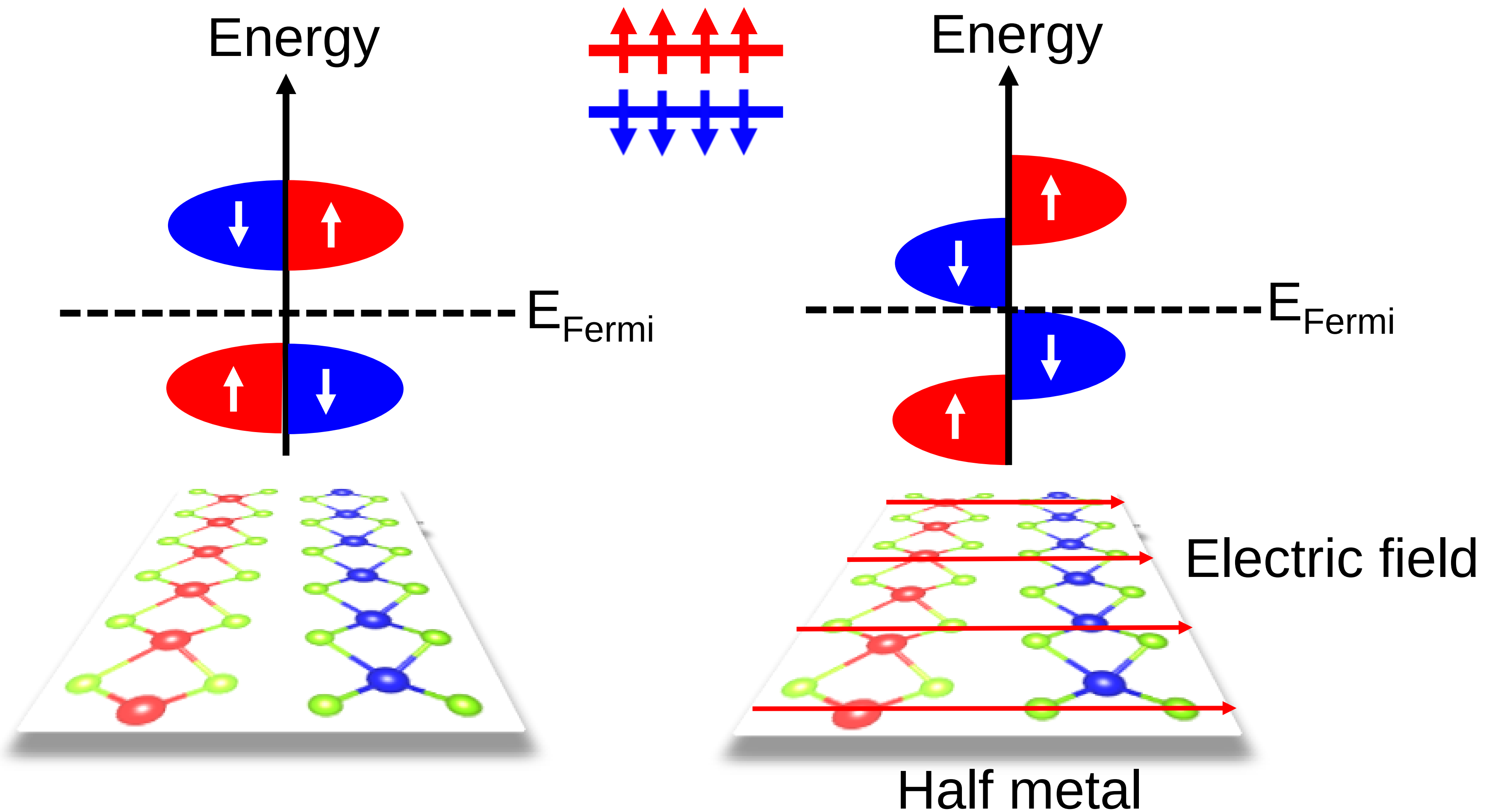
phys. org

3. Fast (>10^{12} Hz)



2018 MURI

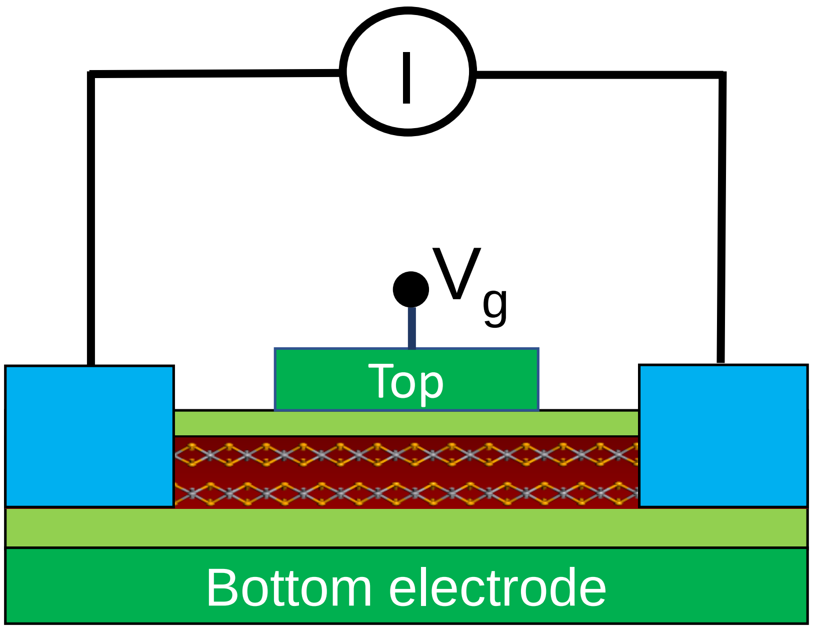
High efficiency spin transistor

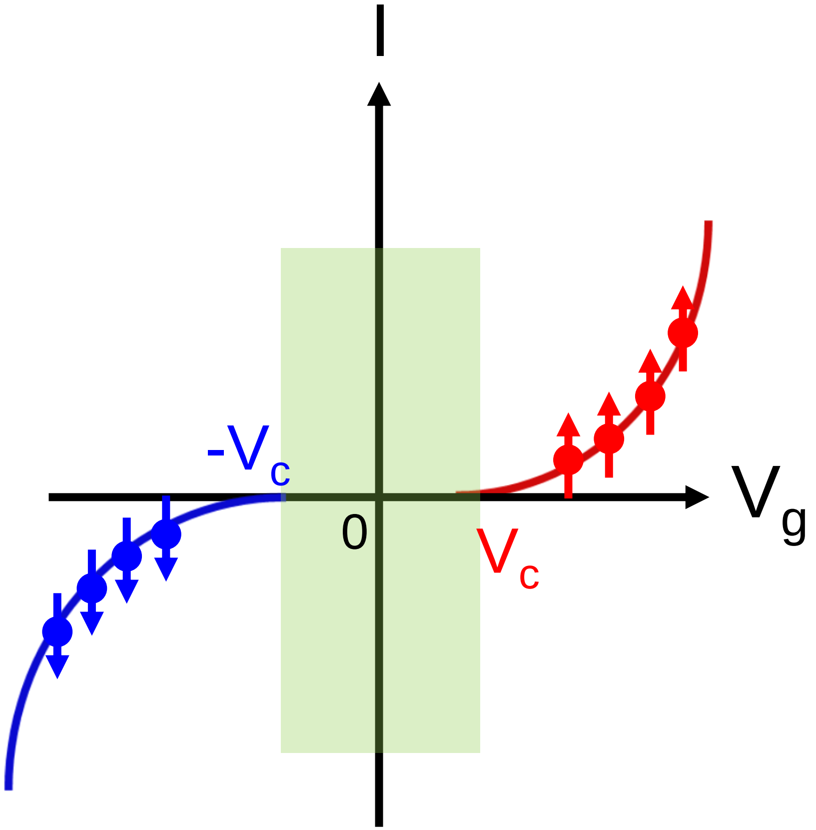


Conduction electrons are 100% spin-polarized!

Gong, *et al. Proc. Natl. Acad. Sci.* (2018)

High efficiency spin transistor





Voltage can:

- Switch ON/OFF the spin transistor
- Reverse the spin polarization

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Large-size, atomically-thin, single-crystalline magnetic flatlands

Biosensors

disney.com

- Lightweight
- Flexible
- Transparent
- Scalable

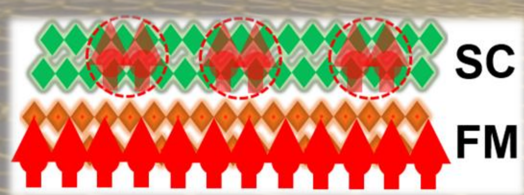
Space craft

nasa.gov

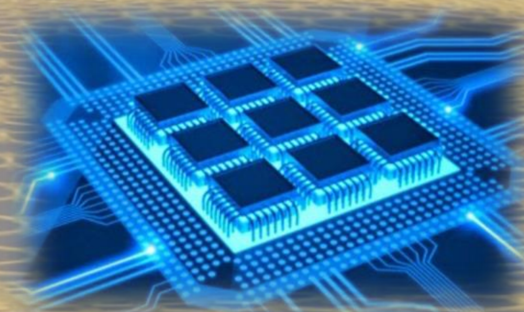
Flexible electronics

ieee.org

Quantum computing



Optical communications



photonics.com

The age of 2D magnets has come

Library of van der Waals magnets

Ferro-magnet | Anti-ferro-magnet | Multi-ferroics

Chalcogenides	$Cr_2Ge_2Te_6$, $Cr_2Si_2Te_6$, Fe_3GeTe_2, VSe_2^*, $MnSe_x^*$	$Fe_2P_2S_6$, $Fe_2P_2Se_6$, $Mn_2P_2S_6$, $Mn_2P_2Se_6$, $Ni_2P_2S_6$, $Ni_2P_2Se_6$, $CuCrP_2Se_6^*$, $CdFeP_2S_6$, $AgVP_2S_6$, $AgCrP_2S_6$, $CrSe_2$, $Ni_3Cr_2P_2S_9$, $MnBi_2Te_4^*$, $MnBi_2Se_4^*$	$CuCrP_2S_6$
Halides	CrI_3^*, $CrBr_3$, GdI_2	$CrCl_3$, $FeCl_2$, $FeBr_2$, FeI_2, $MnBr_2$, $CoCl_2$, $CoBr_2$, $NiCl_2$, VCl_2, VBr_2, VI_2, $FeCl_3$, $FeBr_3$, $CrTe_3$, CrOCl, CrOBr, CrSBr, $MnCl_2^*$, VCl_3^*, VBr_3^*	$CuCl_2$, $CuBr_2$, $NiBr_2$, NiI_2, CoI_2, MnI_2 α-$RuCl_3$
Others	VS_2, SnP_3, InP_3, GeP_3, GaSe, MoN_2	MnX_3 (X= F, Cl, Br, I), $C_{12}Mn_2$, $TiSe_{1.8}$, FeX_2 (X= Cl, Br, I), MnSSe, $TiCl_3$, VCl_3	SnO, GeS, GeSe, SnS, SnSe, GeTeCl

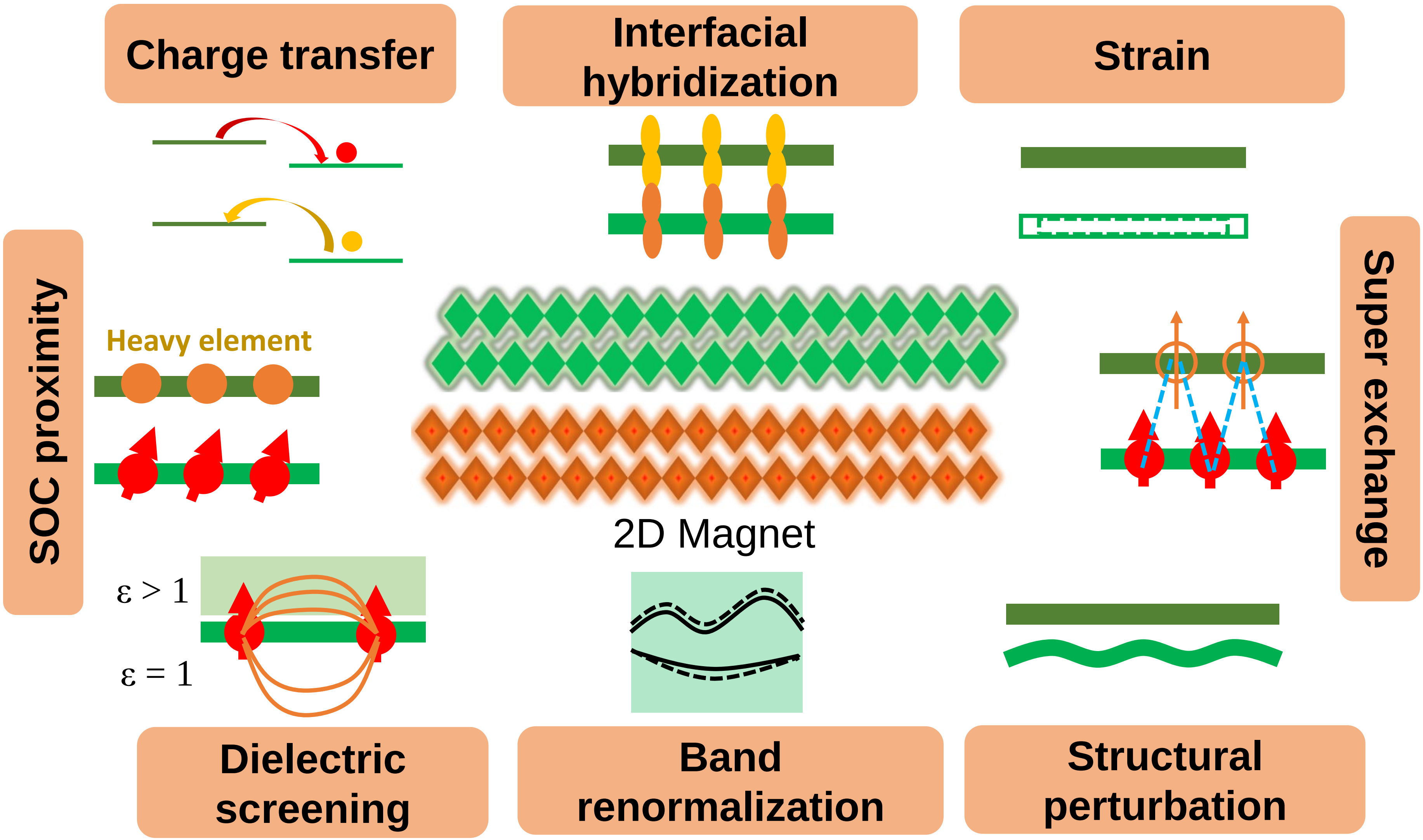
Ferro-magnet | Half metals | Multi-ferroics

Theoretically predicted, experimentally not yet

Spin-liquid

Gong, *et al. Science* (2019)

Future of 2D magnets: interfacial engineering



Gong, *et al. Science* (2019)

Gong, *et al.* Nature Communications (2019)