Artificial quantum matter in twisted van der Waals materials

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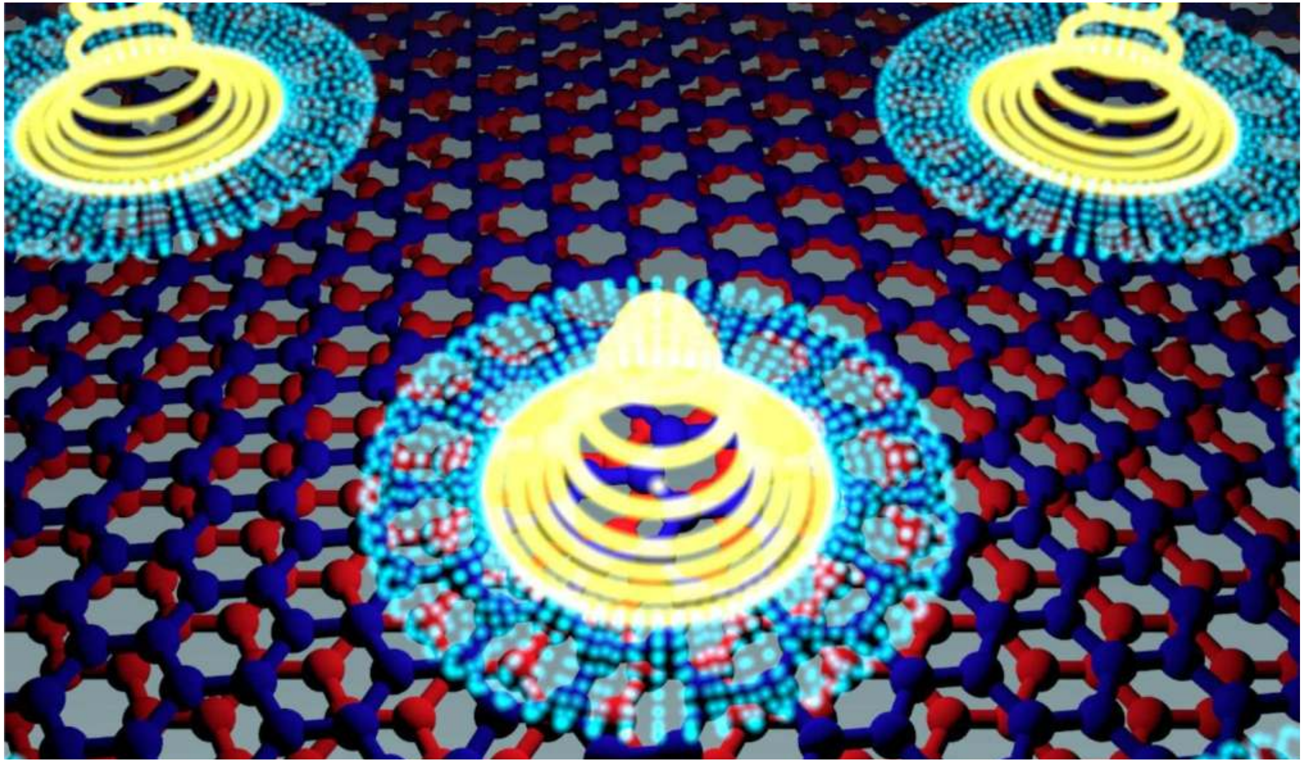


Jyväskylä Physics Colloquium, January 17th 2020

The quantum materials age

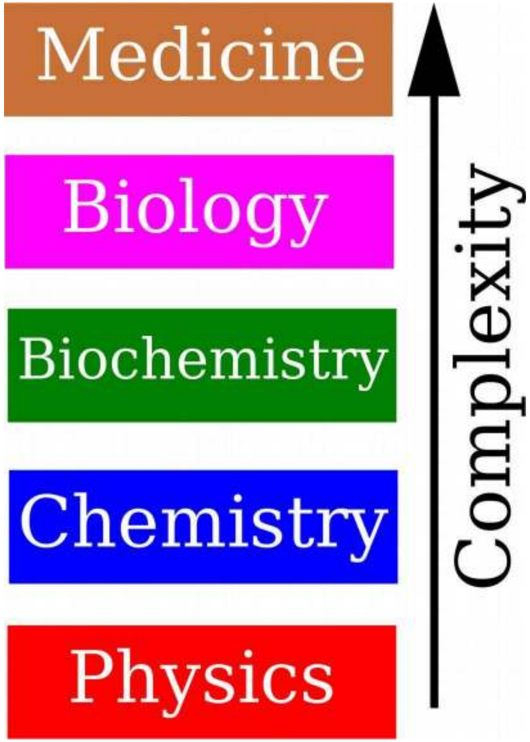
Electronics

Imaging techniques in medicine

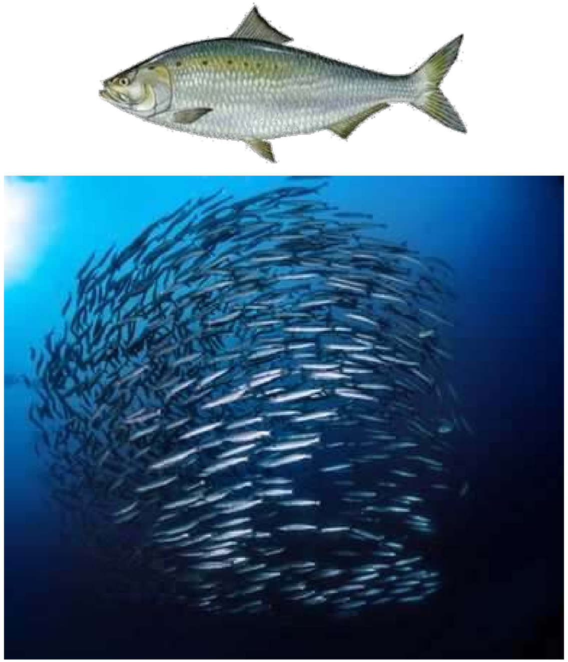
Renewable energy

Materials with exotic properties allow to tackle key technological challenges

Complexity, universality and emergence

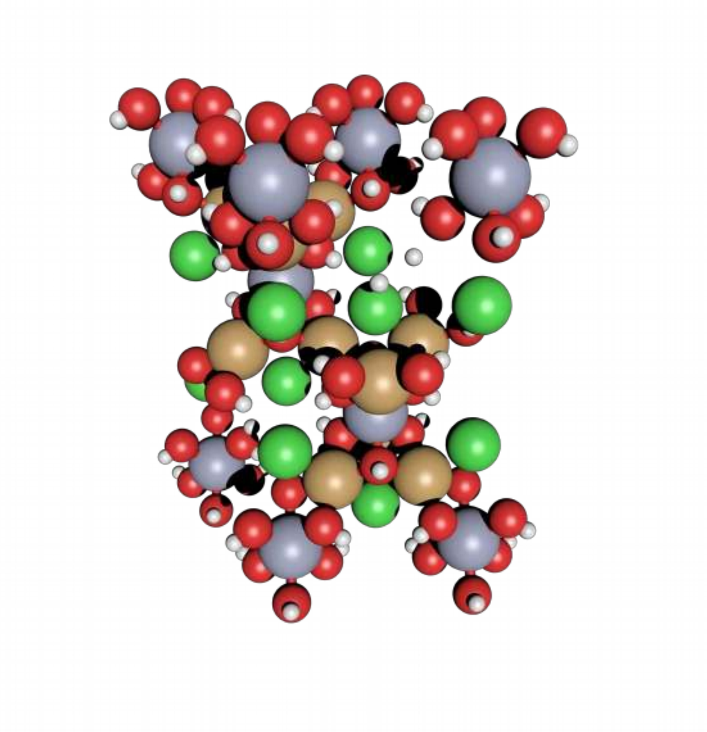


Fish schools



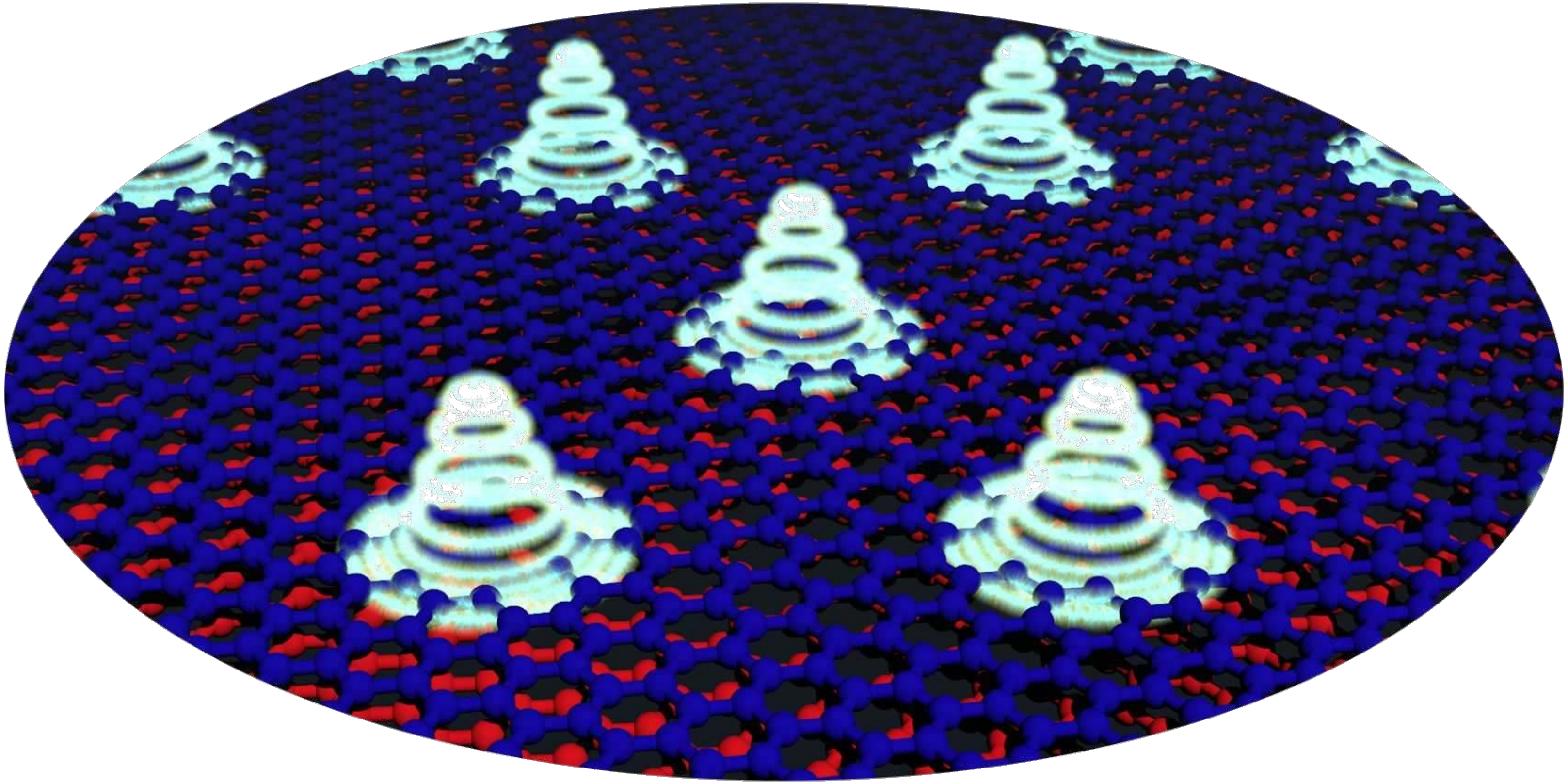
Phys. Rev. Lett. 120, 198101 (2018)

Complex compounds



Complex systems allow to have new phenomena that did not exist before

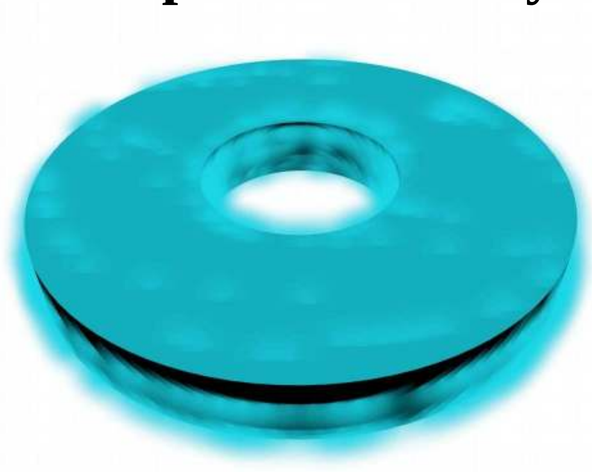
A new universe in each new material



Each material is a new universe for electrons, with laws that change from compound to compound

Macroscopic materials, emergence and fundamental physics

Superconductivity

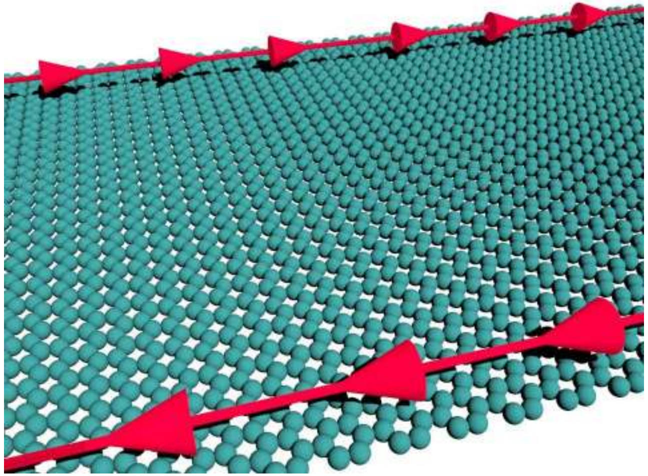


$$\Phi = \frac{h}{2e}$$

Many-body state

<u>Quantization</u> of flux

Quantum Hall effect



$$\sigma_{xy} = \nu \frac{e^2}{h}$$

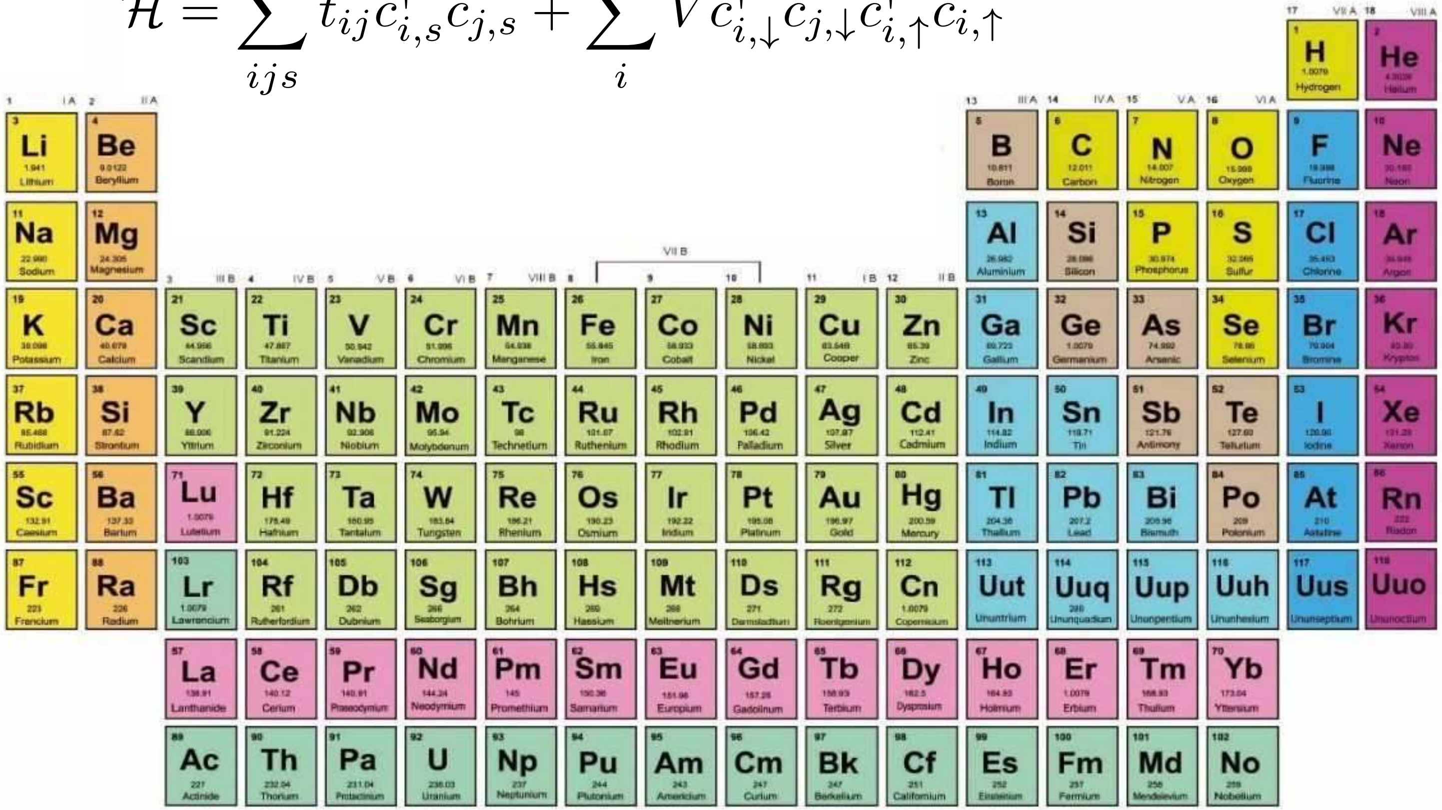
Single-particle state

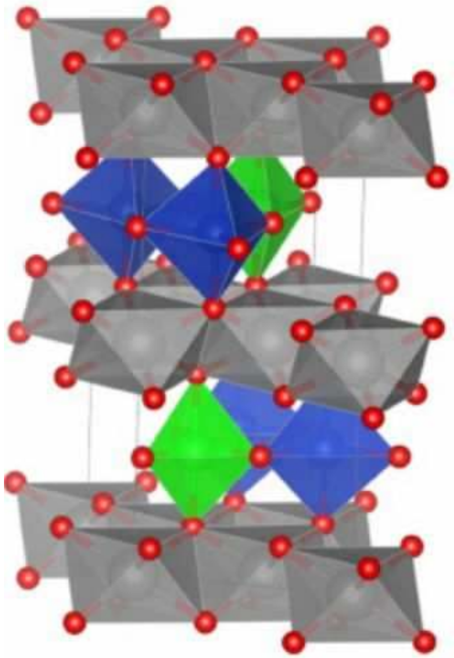
<u>Quantization</u> of conductance

Macroscopic quantum phenomena determine fundamental constants with the highest precision

Engineering quantum materials

$$\mathcal{H} = \sum_{ijs} t_{ij} c^{\dagger}_{i,s} c_{j,s} + \sum_{i} V c^{\dagger}_{i,\downarrow} c_{j,\downarrow} c^{\dagger}_{i,\uparrow} c_{i,\uparrow}$$





Exotic physics in quantum materials

Quantum spin liquids

Unconventional superconductivity

Topological matter

<u>Topological quantum computing</u>

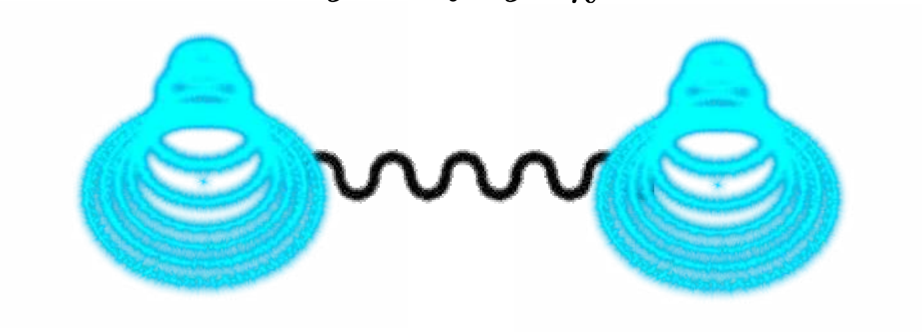
<u>Low consumption electronics</u>

<u>New physics not yet realized in nature (fractional quantum particles)</u>

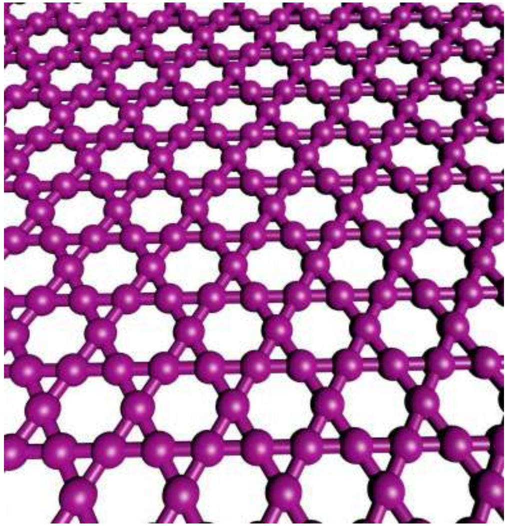
The Achilles' heel of quantum materials engineering

We can hardly control electronic correlations

$$V_{ijkl} c_i^\dagger c_j c_k^\dagger c_l$$

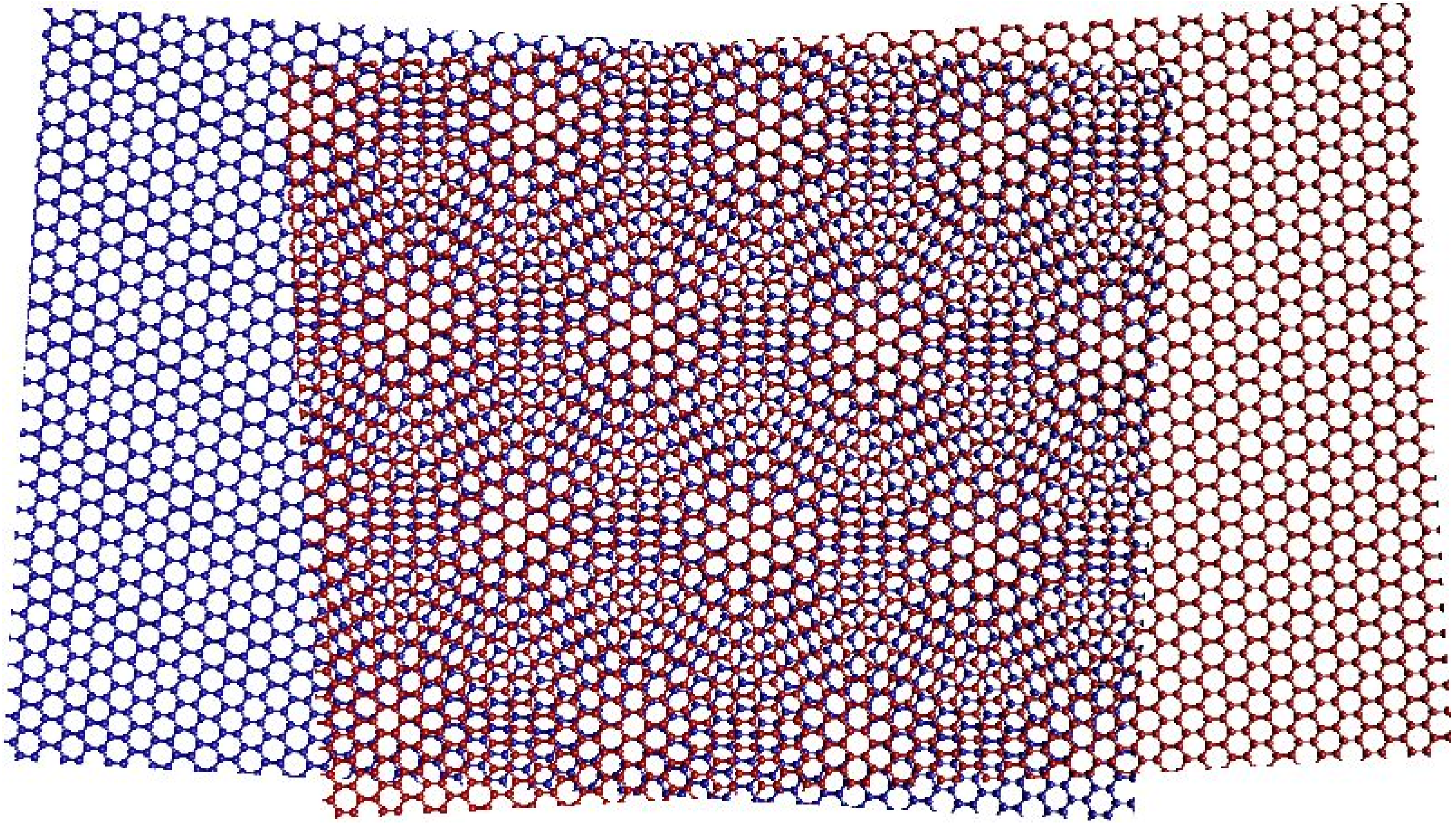


We depend on the microscopic geometry of the material



Can we control interactions and geometry in materials?

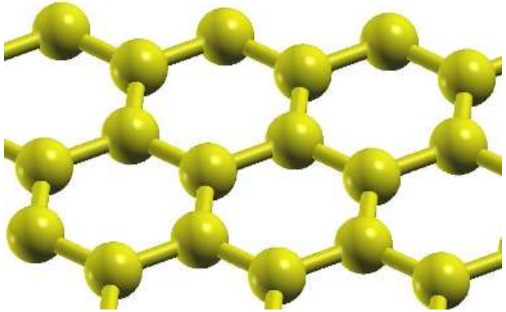
Twisted 2D materials as a platform for artificial quantum matter



The two-dimensional materials world

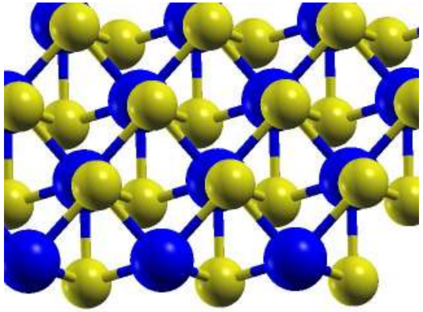
Semimetal

Graphene



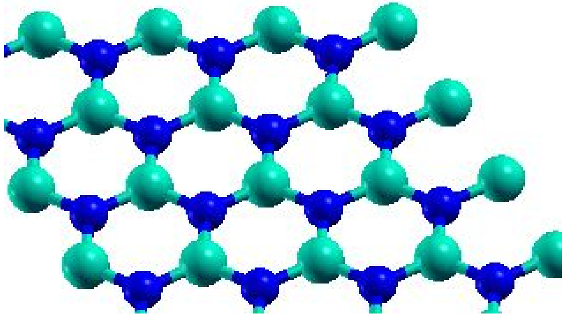
Superconductor

$NbSe_2$



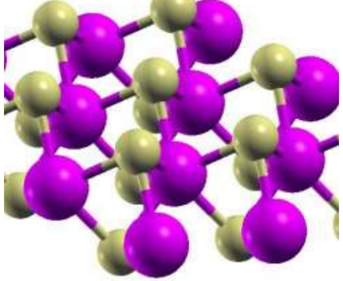
Insulator

BN



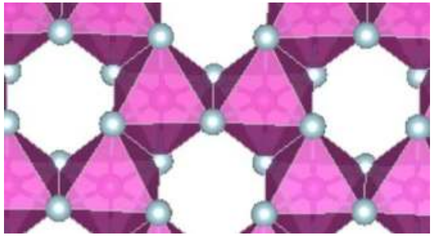
Semiconductor

MoS_2



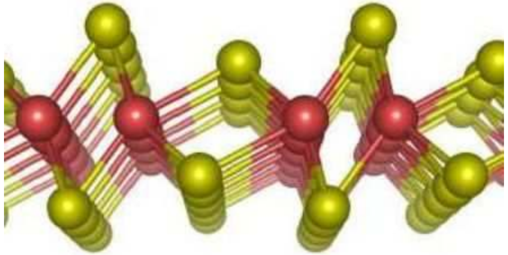
Ferromagnet

CrI_3



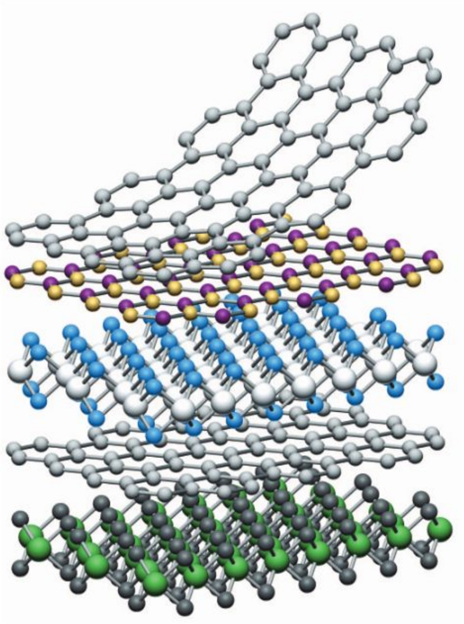
Quantum spin Hall insulator

WTe_2



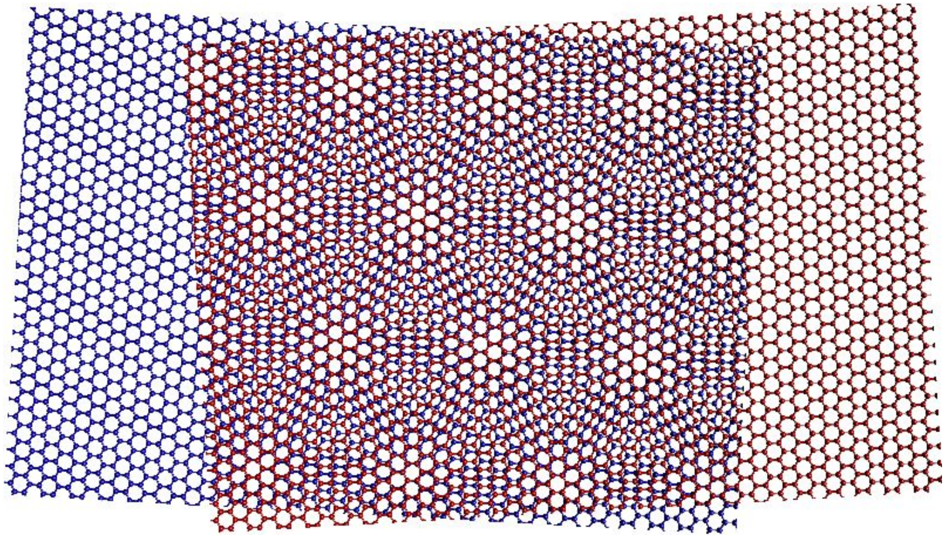
The flexibility of two-dimensional materials

They can be stacked



Nature 499.7459 419. (2013)

They can be rotated

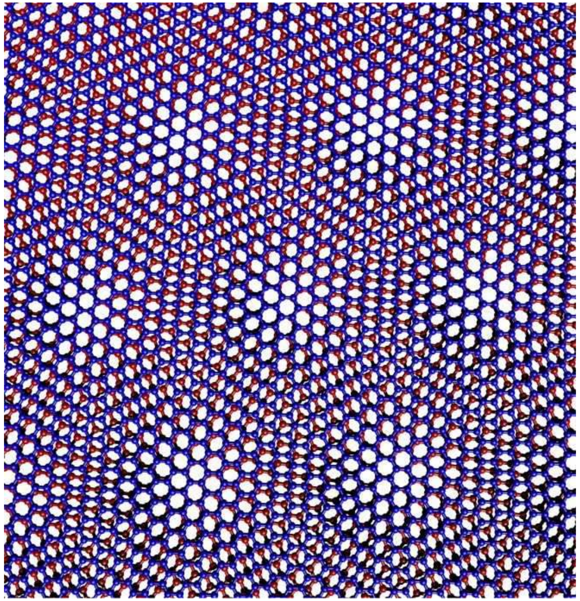


Science 361.6403 690-693. (2018)

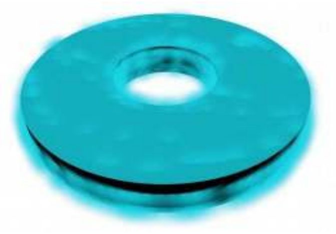
These are unique features of two-dimensional materials

One material, a zoo of electronic phases

Twisted bilayer graphene



Superconductivity

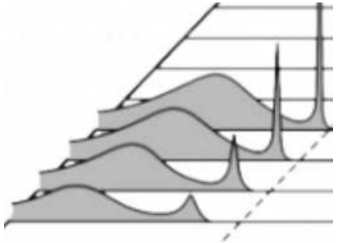


Nature 556, 43–50 (2018)

Topological networks

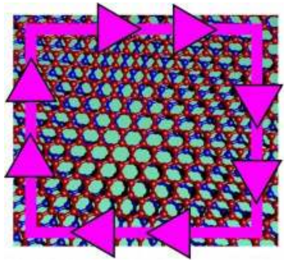
Nano Lett. 18, 11, 6725-6730 (2018)

Strange metals



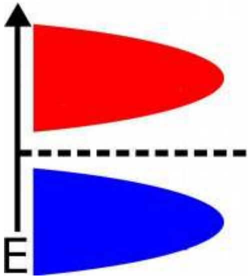
arXiv:1901.03710 (2019)

Chern insulators



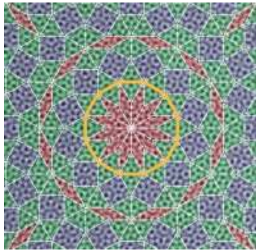
Science 365, 605-608 (2019)

Correlated insulators



Nature 556, 80–84 (2018)

Quasicrystalline physics

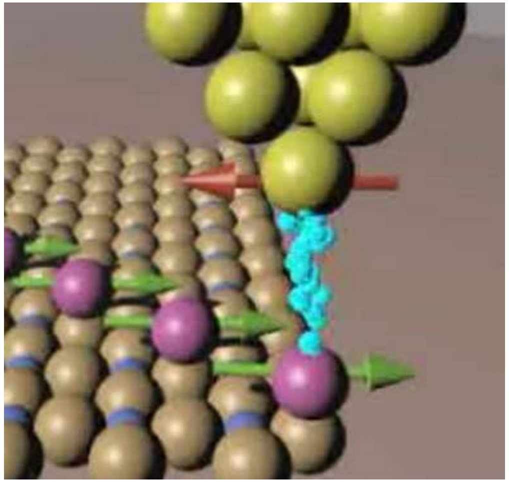


Science 361 782-786 (2018)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

Building quantum matter with artificial lattices

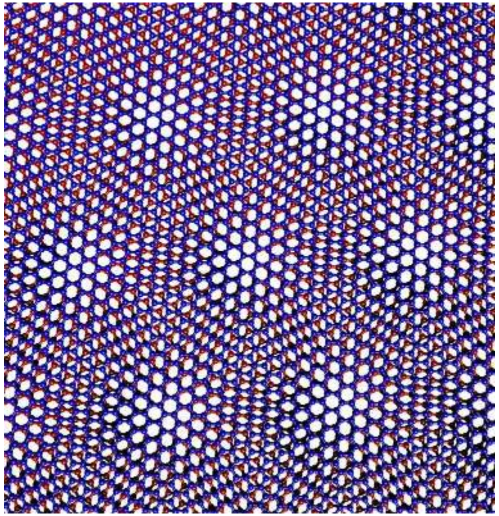
Atomic lattices



a = 0.5 nm

Nature Physics 12 (7), 656 (2016)
Nature Physics 13 (7) 668 (2017)
Science 335 (6065), 196-199 (2012)

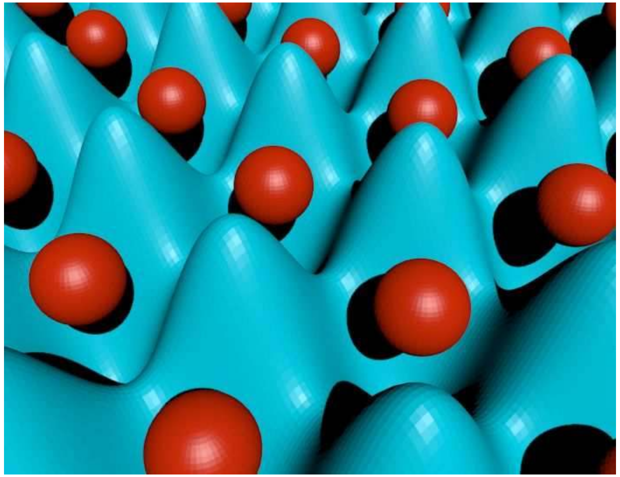
Twisted 2D moire materials



a = 30 nm

Nature 556, 80–84 (2018)
Science 363 (6431) 1059-1064. (2019)

Cold atoms

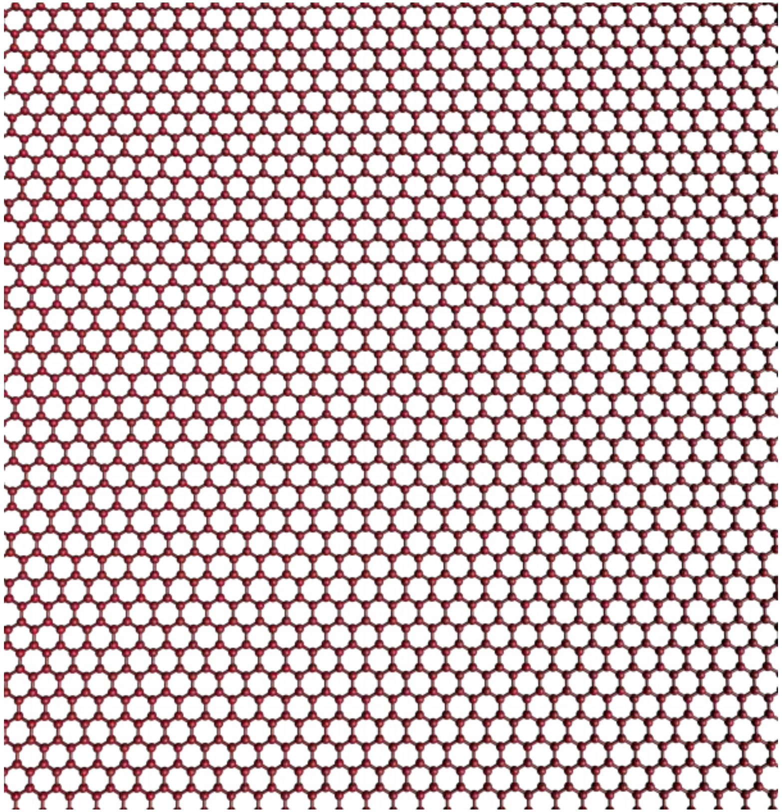


a = 1000 nm

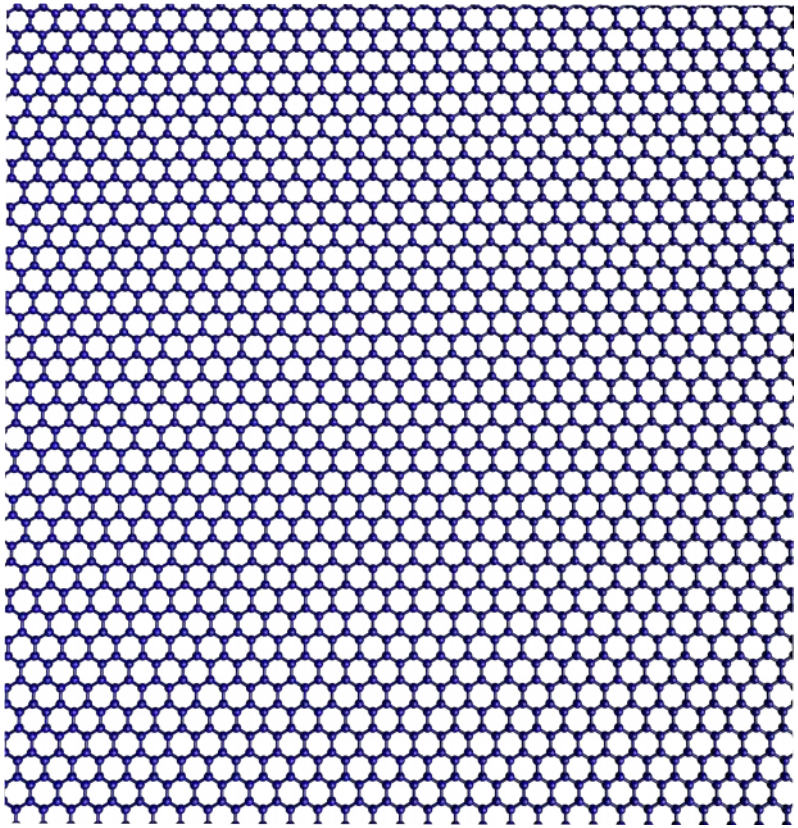
Nature 545.7655 (2017)
Nature 455.7210 (2008)
Phys. Rev. Lett. 111, 185307 (2013)

Moire in twisted bilayer graphene

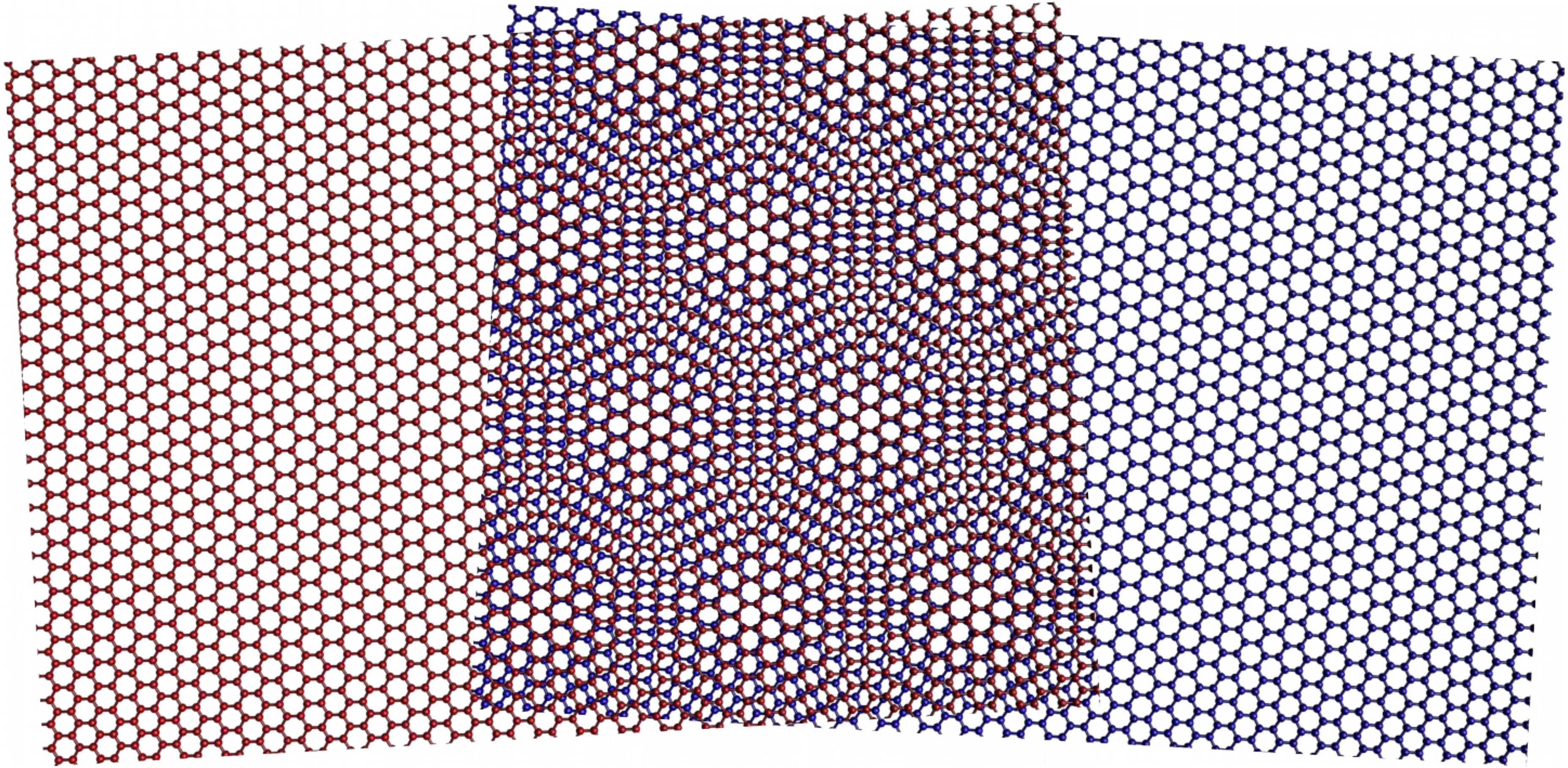
Upper graphene layer



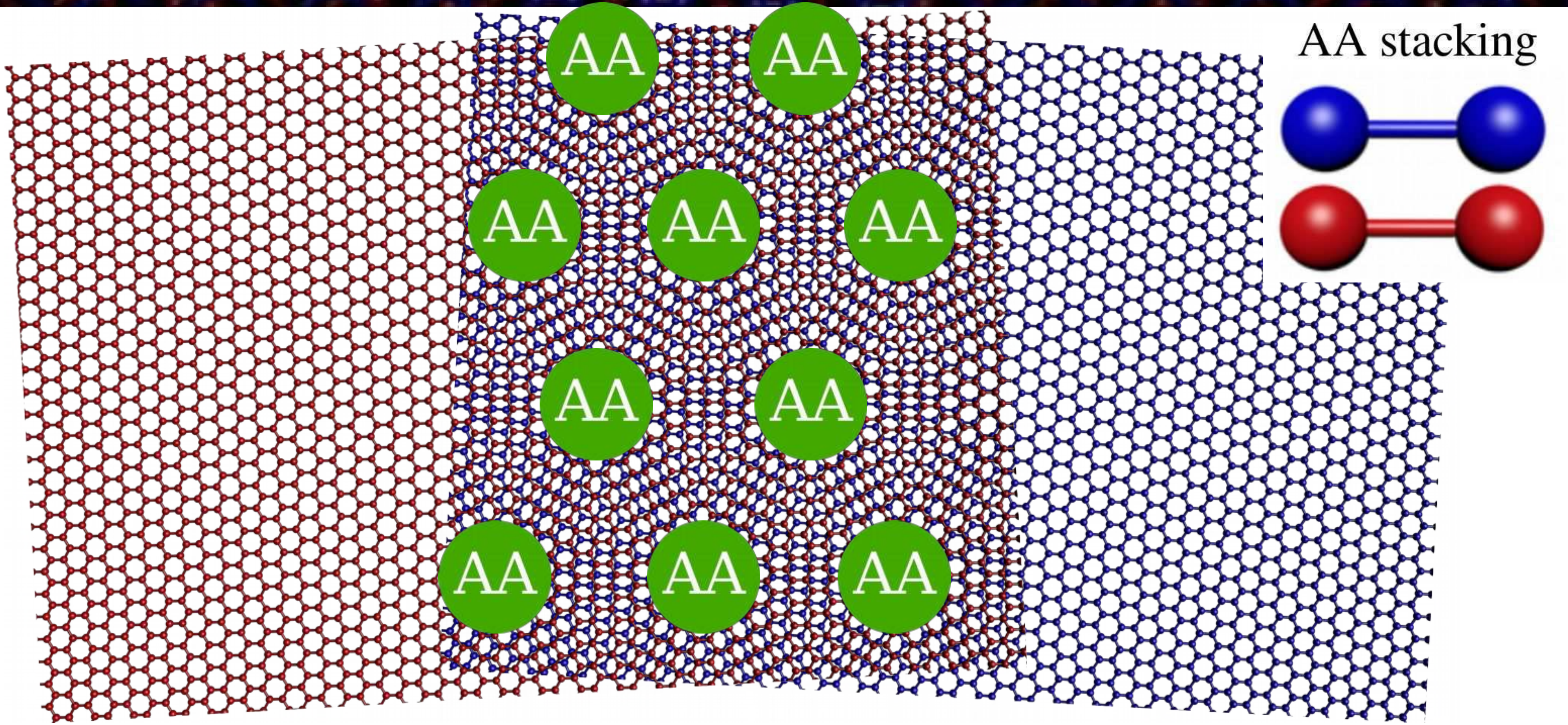
Lower graphene layer



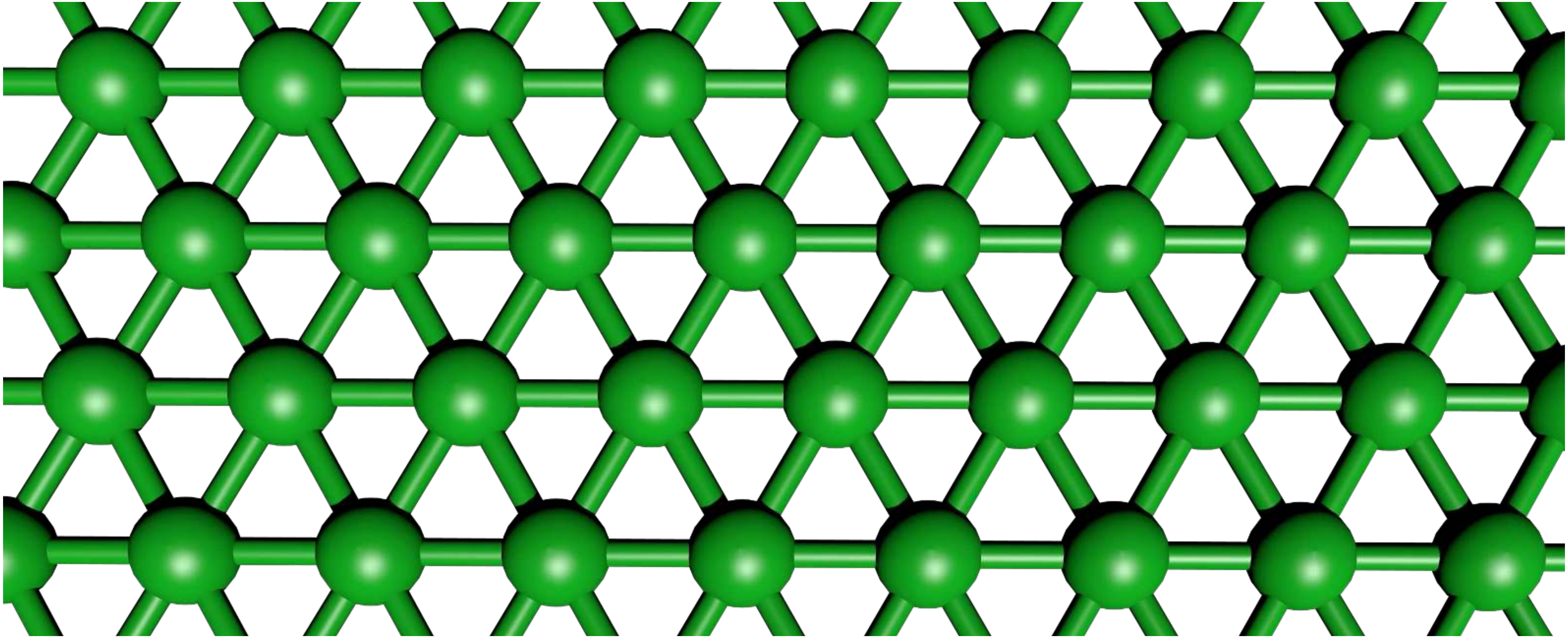
Moire in twisted bilayer graphene

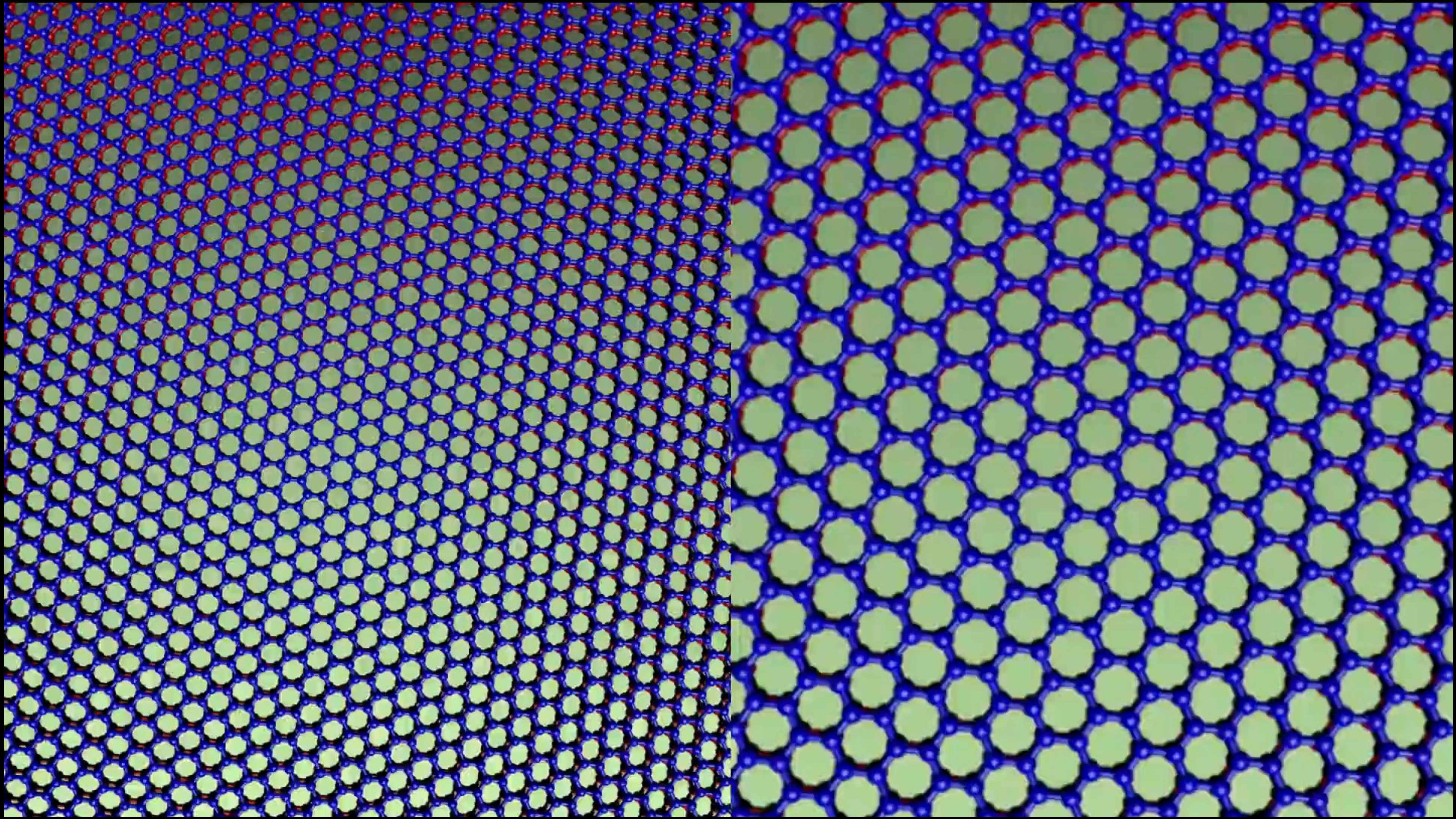


Moire in twisted bilayer graphene



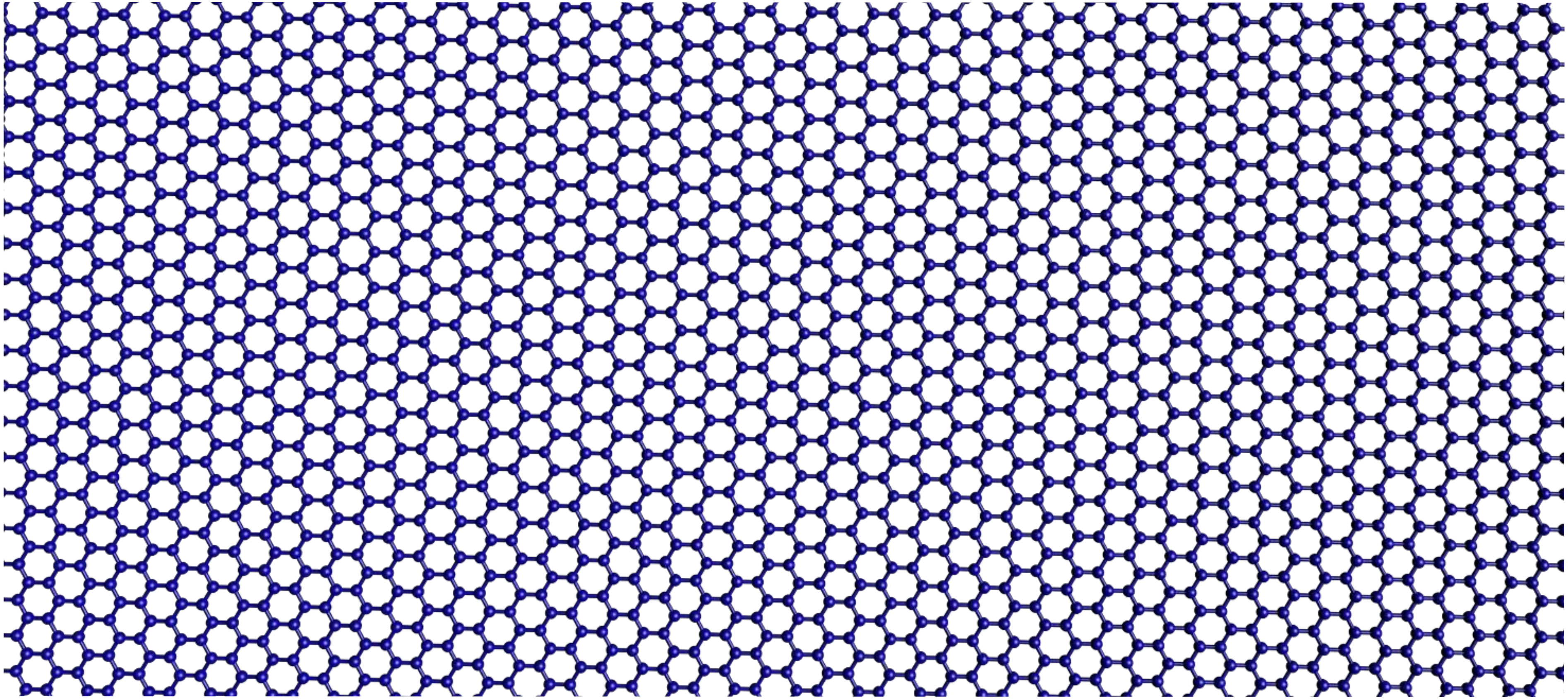
Moire in twisted bilayer graphene





Graphene

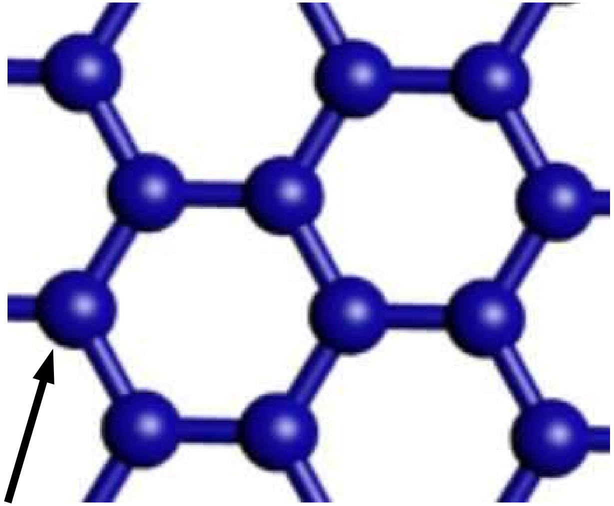
Graphene



Graphene: a honeycomb lattice of carbon atoms

Electrons graphene

Electrons in graphene are described by a periodic Hamiltonian



$$\mathcal{H}(\vec{r}+\vec{R}) = \mathcal{H}(\vec{r})$$

Electronic states are labeled by a crystal momentum

$$\mathcal{H}|k\rangle = E(\vec{k})|k\rangle$$

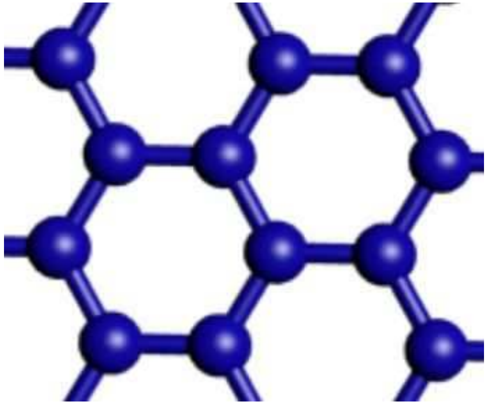
Carbon atom

<u>Electronic dispersion (a.k.a band-structure)</u>

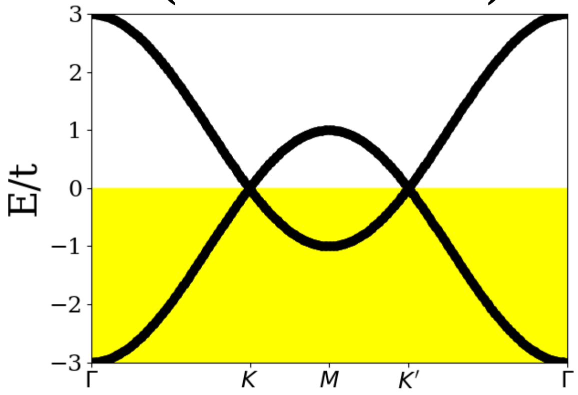
The electronic structure of graphene

Graphene: a honeycomb lattice of carbon atoms

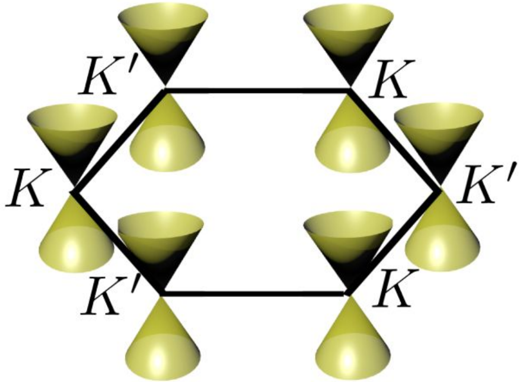
Structure



Energy VS momentum (Band structure)



Momentum space



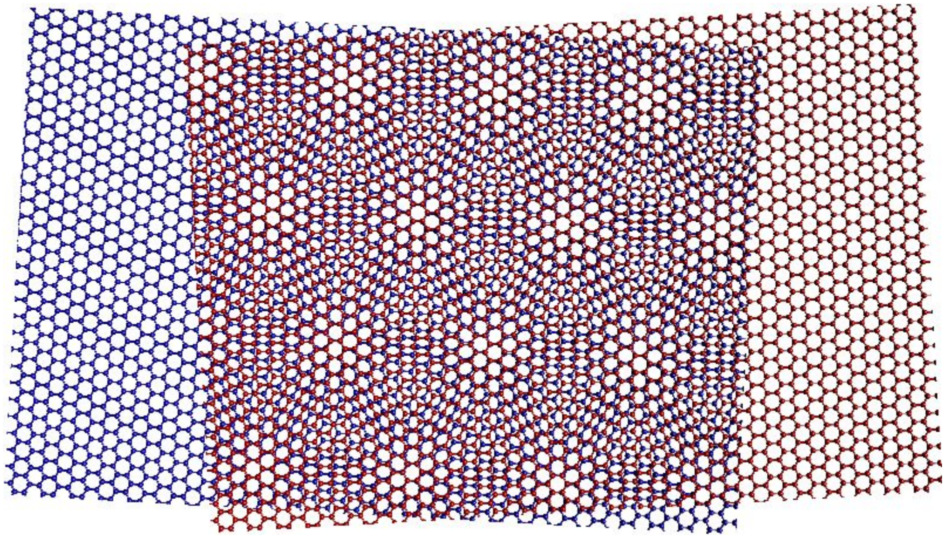
Dirac electrons in graphene

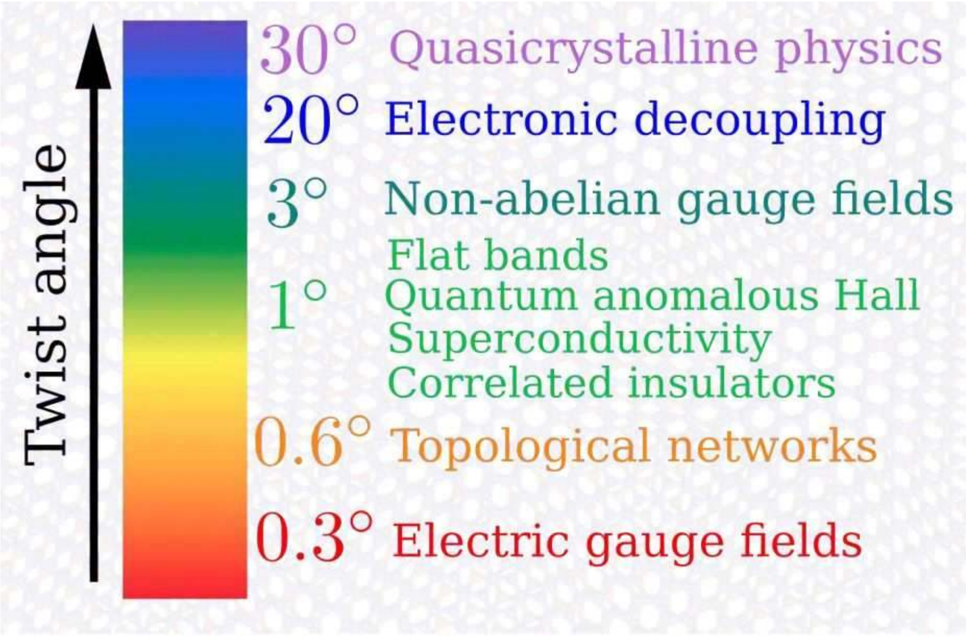
$$H = \begin{pmatrix} 0 & p_x \pm i p_y \\ p_x \mp i p_y & 0 \end{pmatrix}$$

$$H = p_x \sigma_x \pm p_y \sigma_y$$

Interactions in graphene were considered to be unimportant

Twisted bilayer graphene

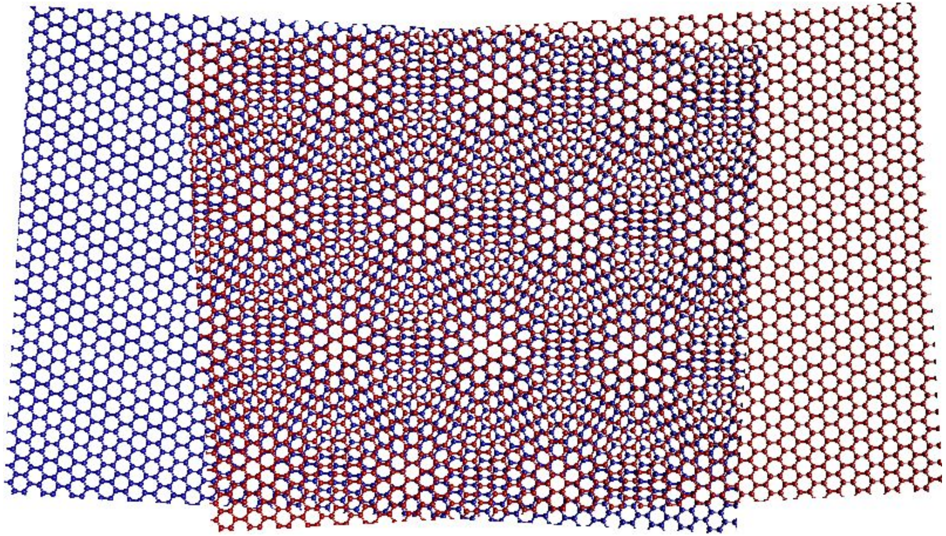




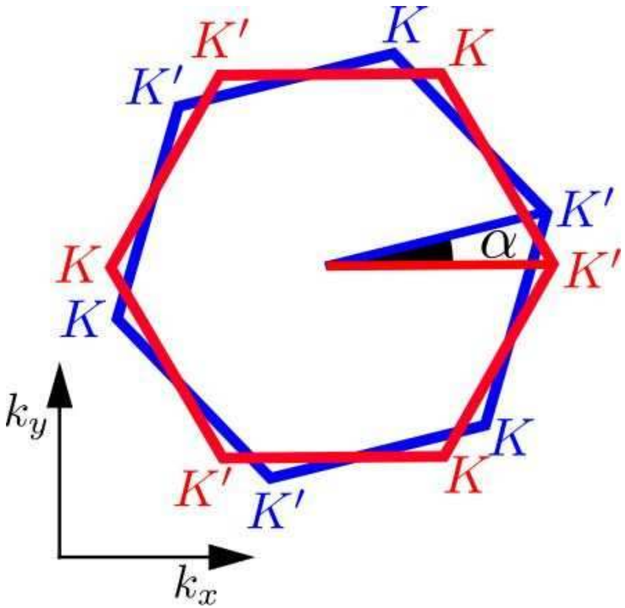
How does the twist angle impact the electronic dispersion?

Twisted bilayer graphene

Real space structure



Momentum space

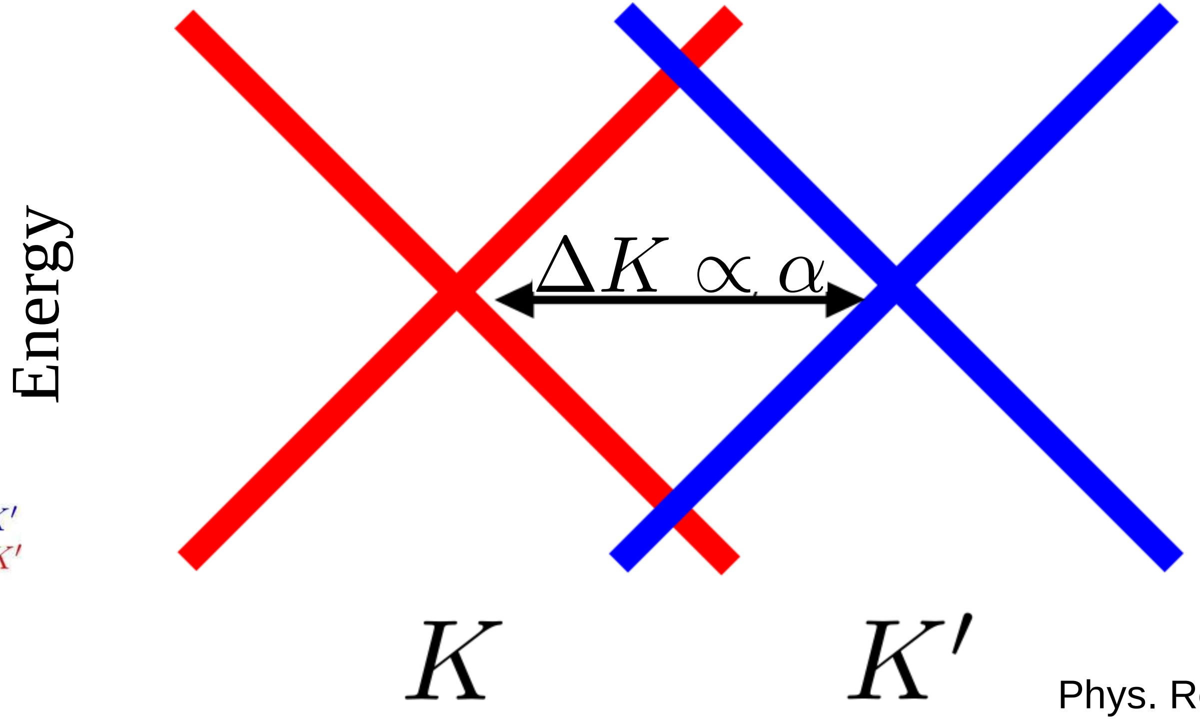


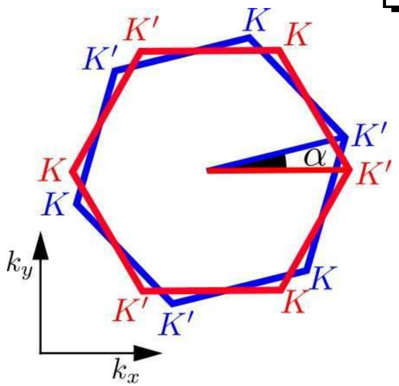
Uncoupled layers

Dirac cone from layer #1

Momentum

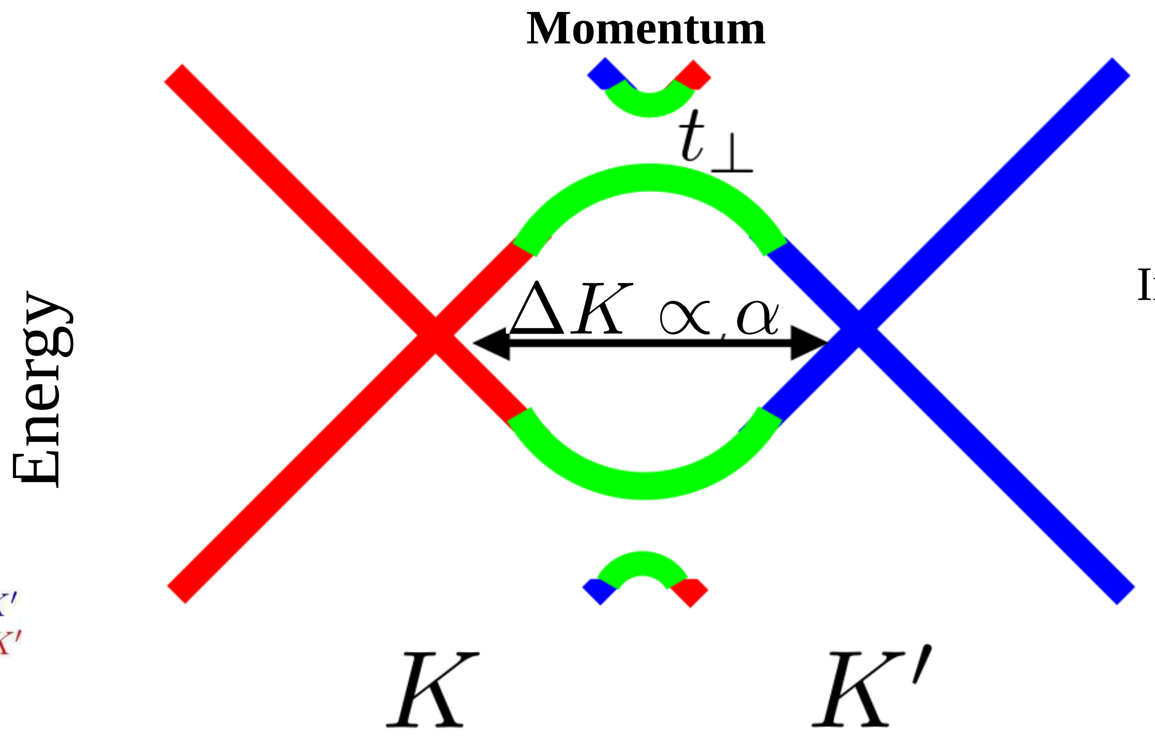
Dirac cone from layer #2

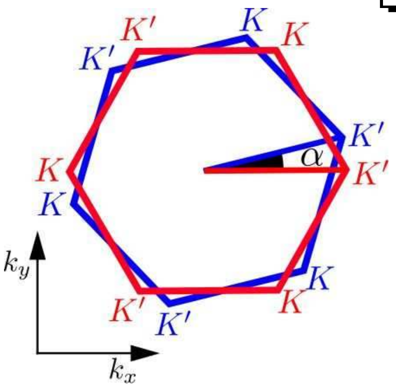




Phys. Rev. Lett. 99, 256802 (2007)

Coupling the layers





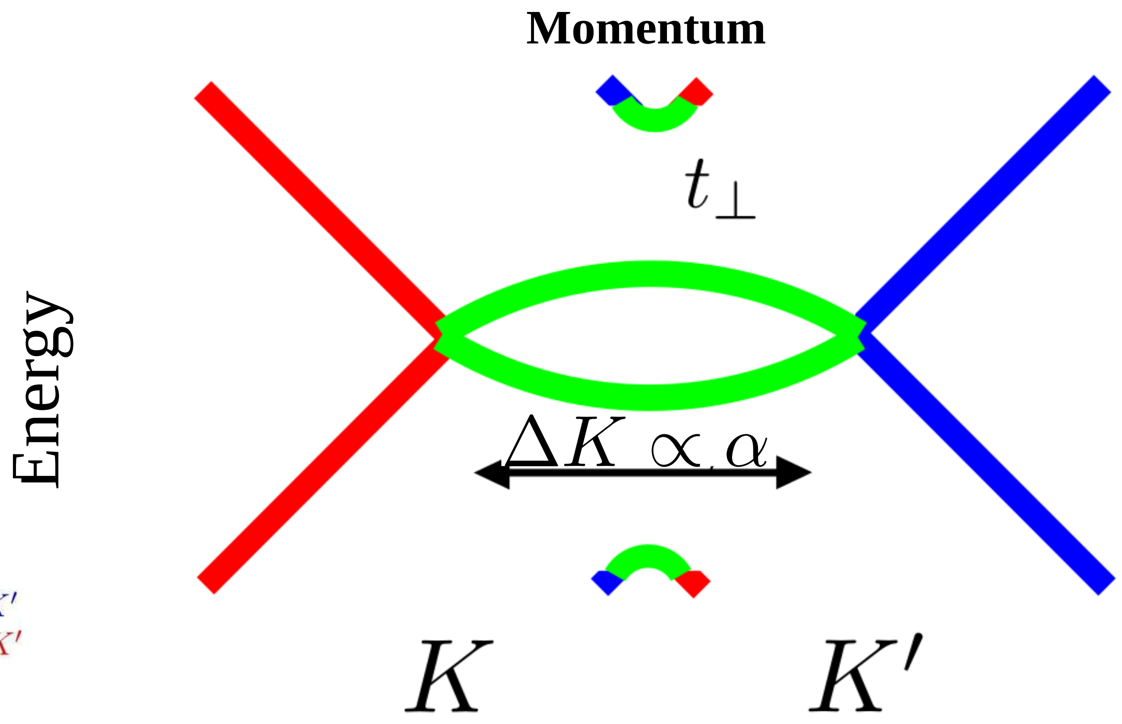
Relevant ratio

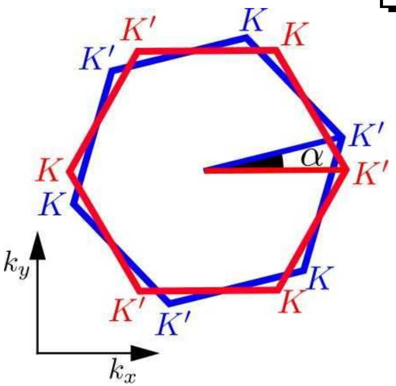
Inter-layer coupling $\qquad \dfrac{t_\perp}{\alpha}$

Twist angle

Phys. Rev. Lett. 99, 256802 (2007)

Coupling the layers





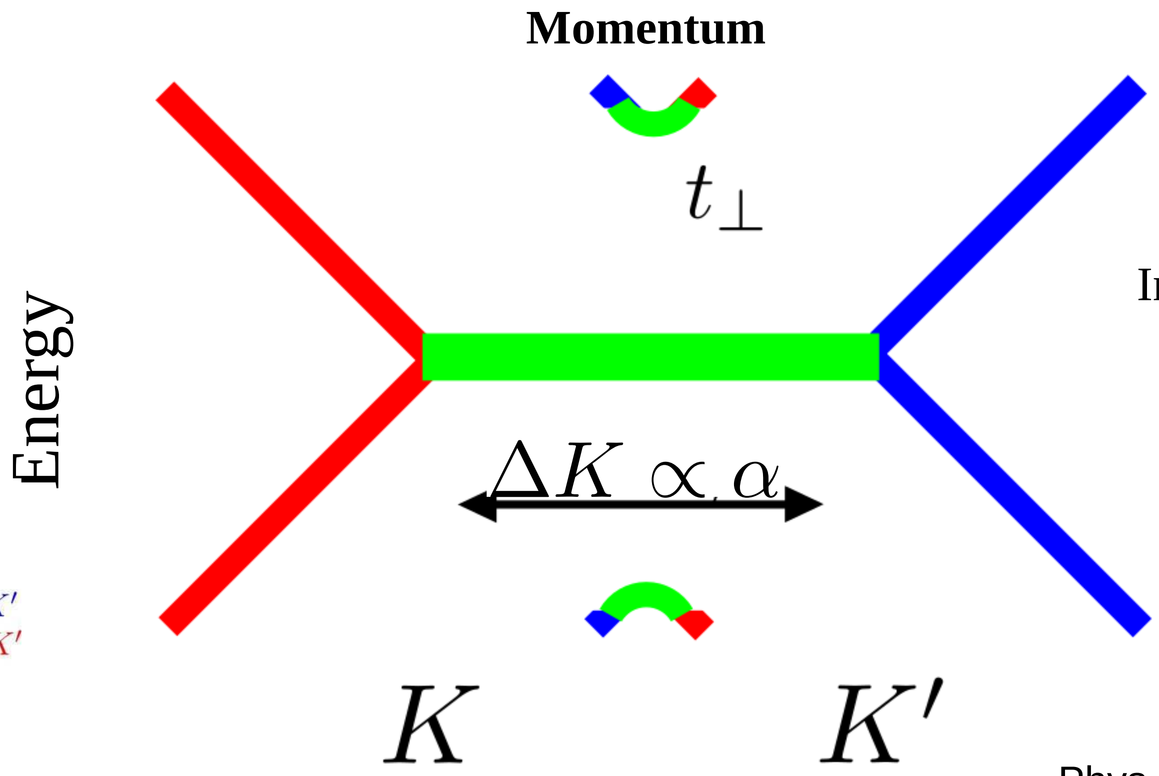
Relevant ratio

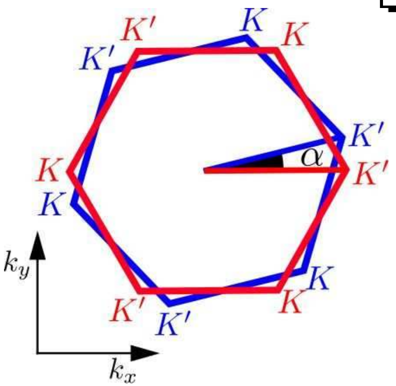
Inter-layer coupling / Twist angle

$$\frac{t_\perp}{\alpha}$$

Phys. Rev. Lett. 99, 256802 (2007)

Coupling the layers





Relevant ratio

Inter-layer coupling

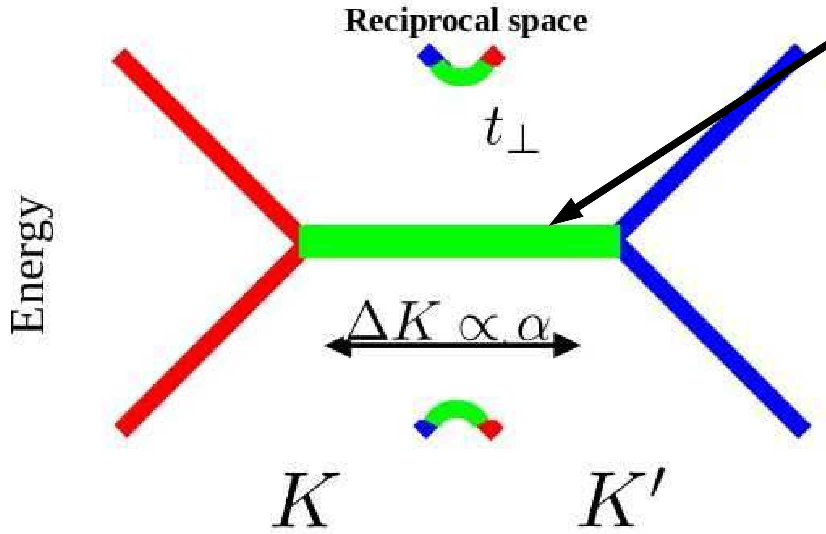
Twist angle

$$\frac{t_\perp}{\alpha}$$

Phys. Rev. Lett. 99, 256802 (2007)

Density of states

Why could such “flat band” be important?



The density of states (DOS):
\# number of states (at the Fermi energy)

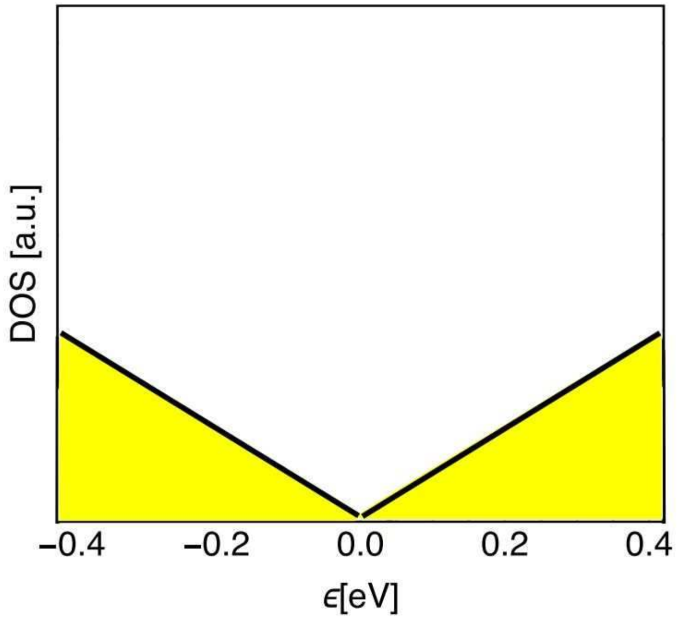
→ ***Flat band means large DOS***

When the DOS is large, electronic interactions take over, and

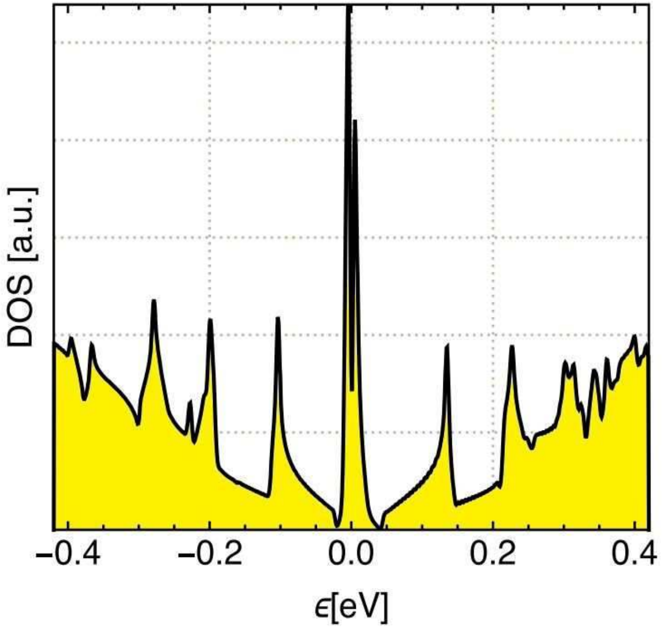
ALL HELL BREAKS LOOSE!!! (but this is what we like)

Controlling the density of states with the twist angle

At large angles



At small angles



The twist between the layers strongly impacts the density of states

Phys. Rev. Lett. 99, 256802 (2007)   Phys. Rev. B 82, 121407(R) (2010)   PNAS 108 (30) 12233-12237 (2011)

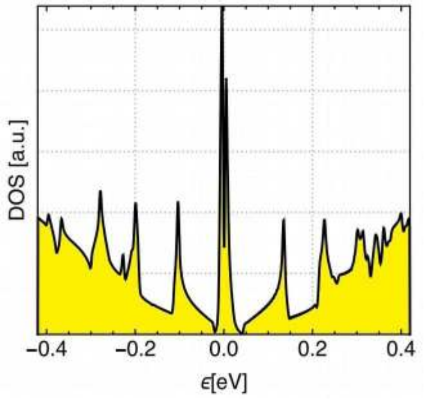
Towards strongly correlated physics

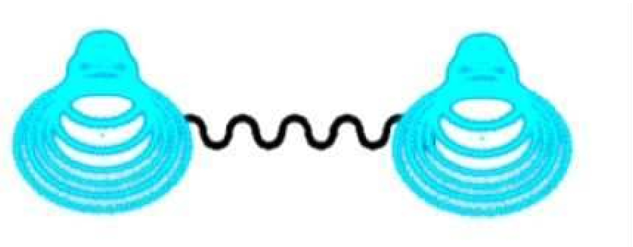
How to get into the strongly correlated regime?

$$|DOS(E_F)V| \gg 1$$

Density of states (DOS) at the Fermi energy

Electronic interaction





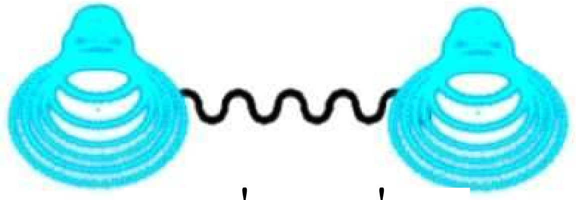
What can happen?

Fractional excitations
Exotic superconductivity, Majorana physics
Macroscopically entangled matter

Flat bands create large DOS, opening up a new strongly correlated universe

Towards strongly correlated physics

$V \equiv$ Electronic interaction

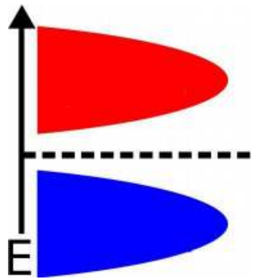


$$V c_i^\dagger c_i c_j^\dagger c_j$$

$V > 0$ **Repulsive interactions**

From electrostatic interactions

Phys. Rev. X 8, 041041 (2018)

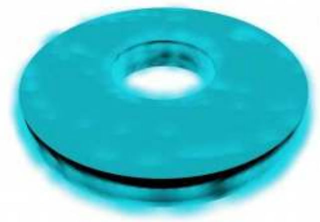


<u>Insulating state</u>

$V < 0$ **Attractive interactions**

From phonons

Phys. Rev. B 98, 220504(R) (2018)



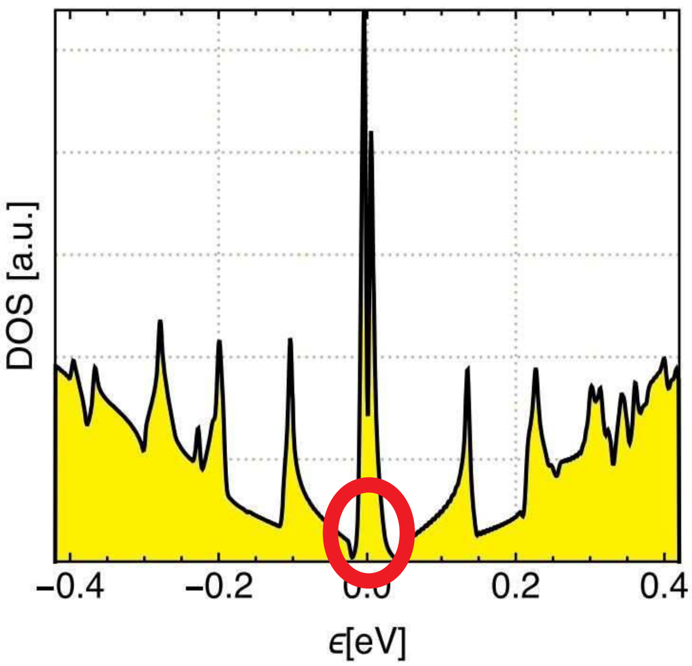
<u>Superconductivity</u>

The two regimes can be explored in the very same sample, changing the filling electrically

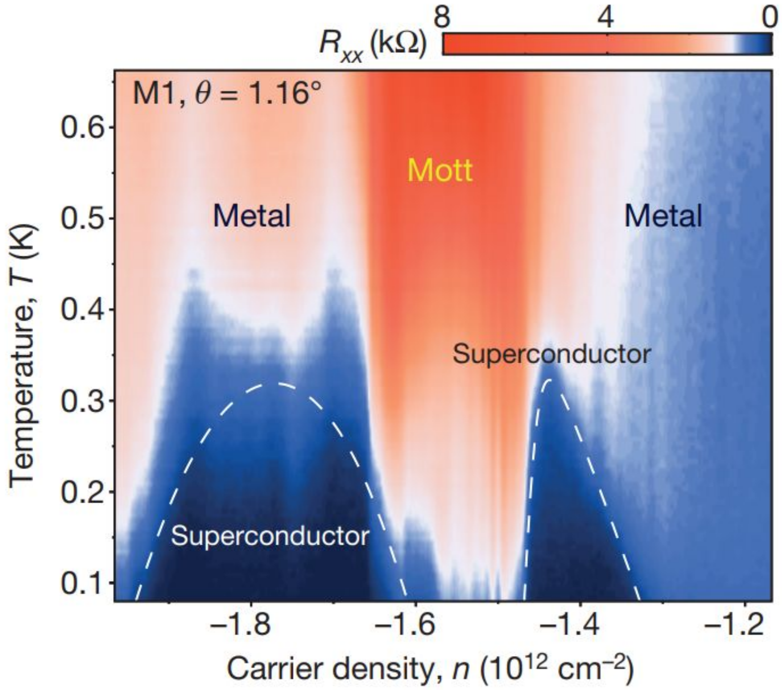
Correlations and superconductivity in twisted bilayer graphene

Correlations and superconductivity in twisted bilayer graphene

Theoretical DOS



Electrical resistance

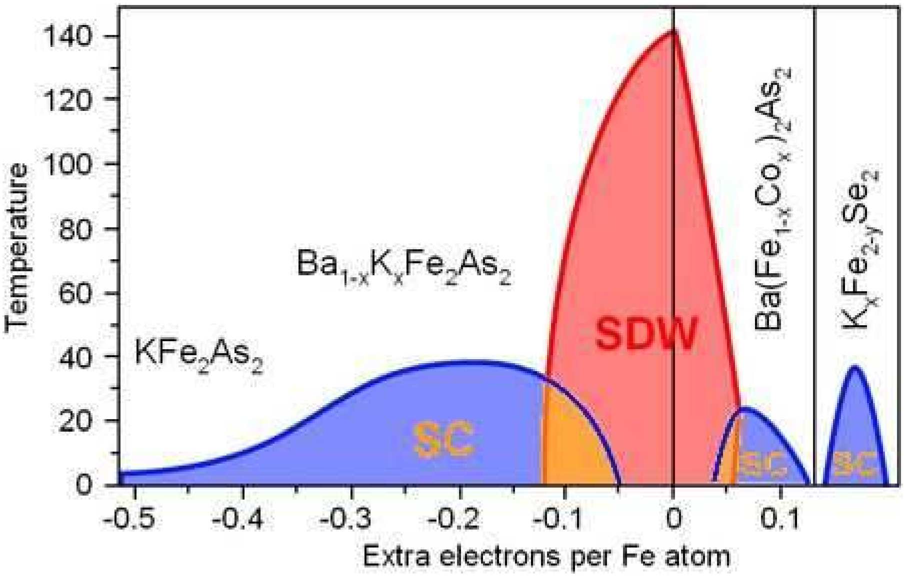


Twisted graphene bilayers at 1.1 degrees show correlations and superconductivity

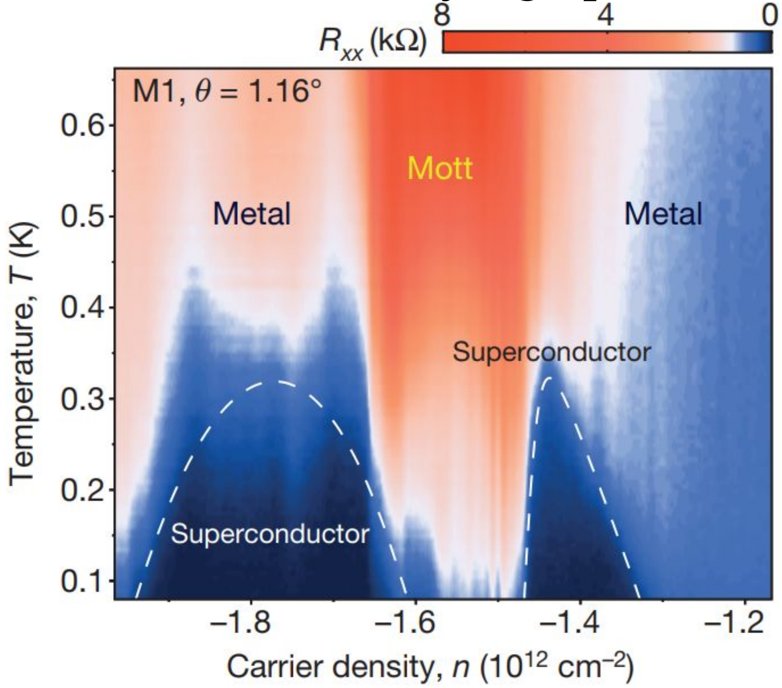
Nature 556, 43–50 (2018) *Nature 556, 80–84 (2018)*

Correlations and superconductivity in twisted bilayer graphene

High temperature superconductors



Twisted bilayer graphene

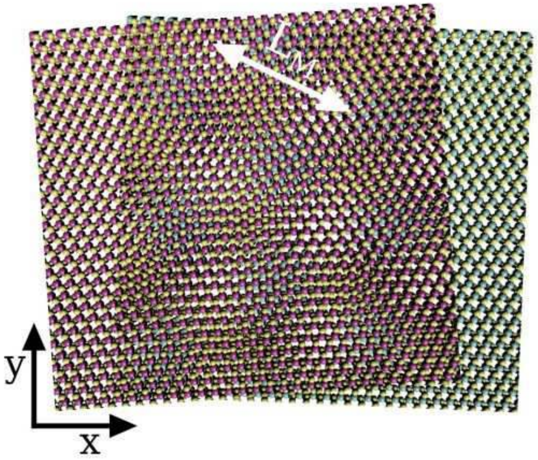


A single graphene sample allows to explore the full correlated phase diagram

The generality of correlated physics in twisted 2D materials

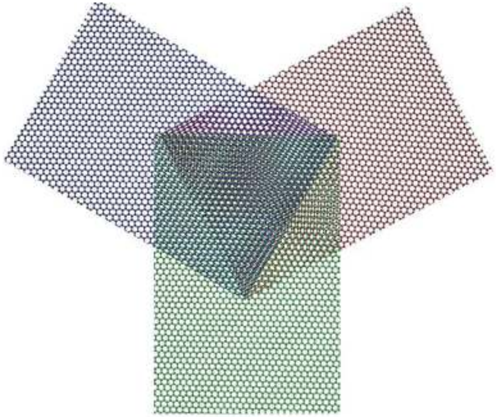
Superconductivity & Correlated behavior found also in

Twisted dichalcogenides



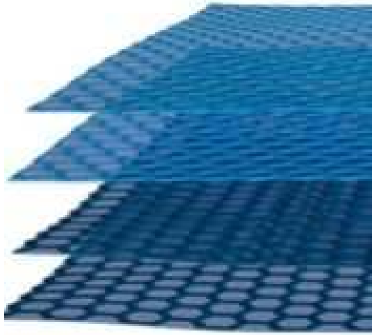
arXiv:1907.03966 (2019)
arXiv:1910.09047 (2019)

Twisted graphene trilayers



arXiv:1912.03375 (2019)

Twisted graphene tetralayers

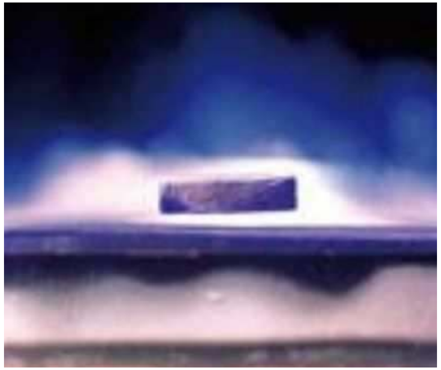


arXiv:1903.08130 (2019)

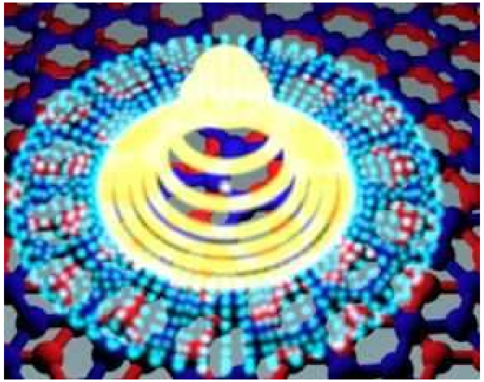
<u>Some of new physics observed were only realized before in rare, heavy or even toxic compounds</u>

The opportunities of twisted van der Waals materials

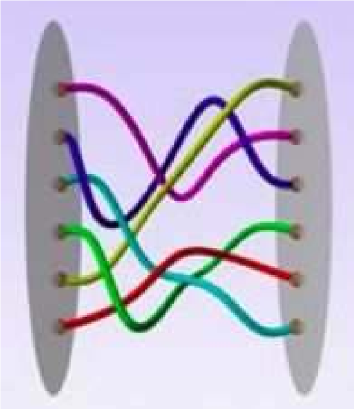
"Unveil" the nature of high T_C superconductivity (?)



Controllable exotic quantum matter (?)



A platform for topological quantum computing (?)



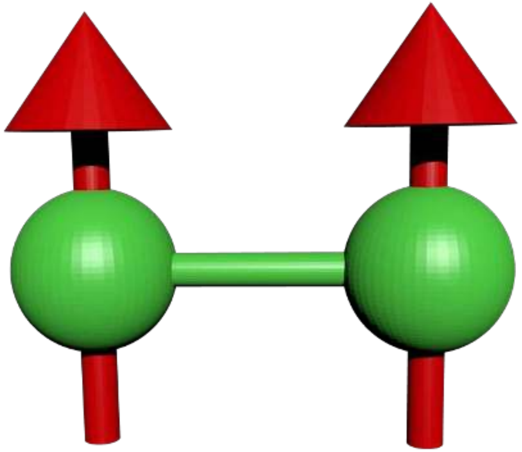
Explore exotic physics with a degree of control unprecedented in any other material

→ *Control of single particle and many-body interactions*
→ *Explore physics that only appear in rare or toxic compounds*

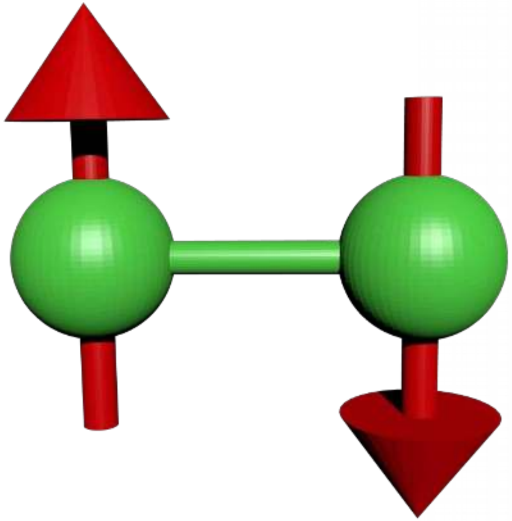
Frustration

A bird’s eye view on magnetism

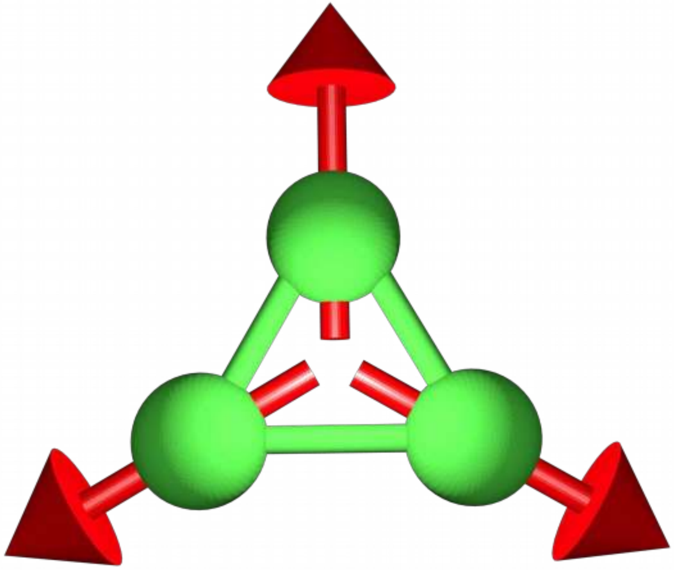
Ferromagnetism



Antiferromagnetism



Frustrated magnetism



Can we control the microscopic properties of a magnet?

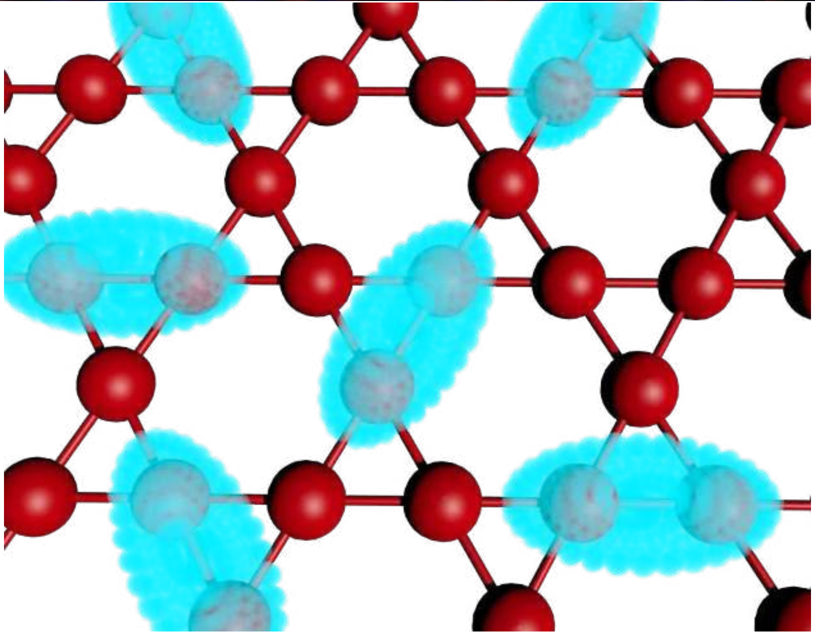
Quantum spin liquids in frustrated magnets

Quantum spin liquids

→ *Fractional excitations*
→ *Macroscopic quantum state*
→ *“Ultra-quantum” matter*

$$\mathcal{H} = \sum_{ij} \vec{S}_i \hat{J}_{ij} \vec{S}_j$$

Rep. Prog. Phys. 80, 016502 (2017)



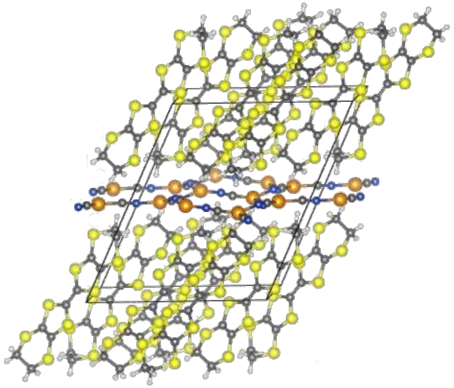
$$\equiv |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

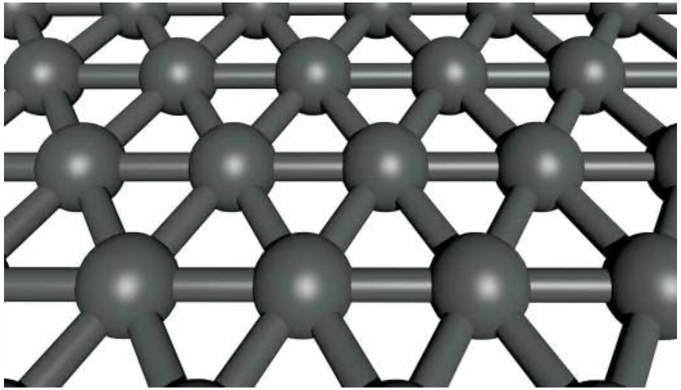
Extended triangular Heisenberg
J. Phys. Soc. Jpn 83, 093707 (2014)

Kagome Heisenberg
Science 332, 1173-1176 (2011)

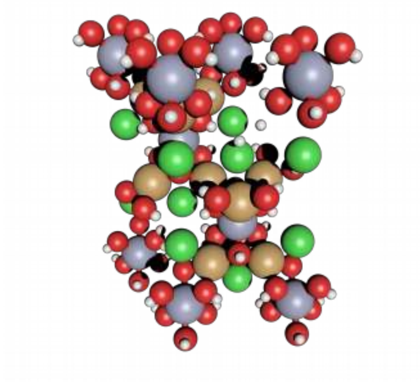
A quest for frustrated quantum magnets

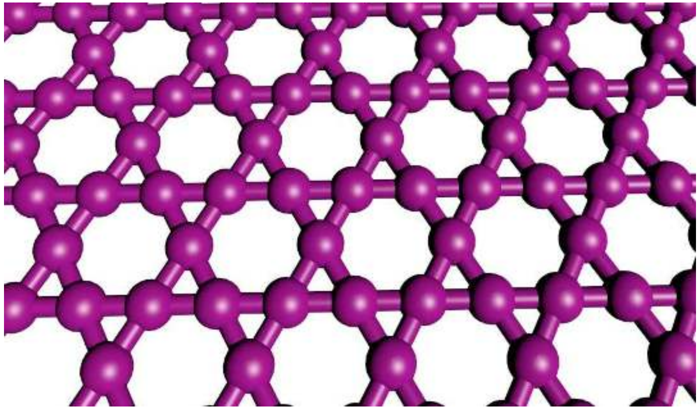
κ-(ET)$_2$Cu$_2$(CN)$_3$ (Triangular)





Herbertsmithite (Kagome)





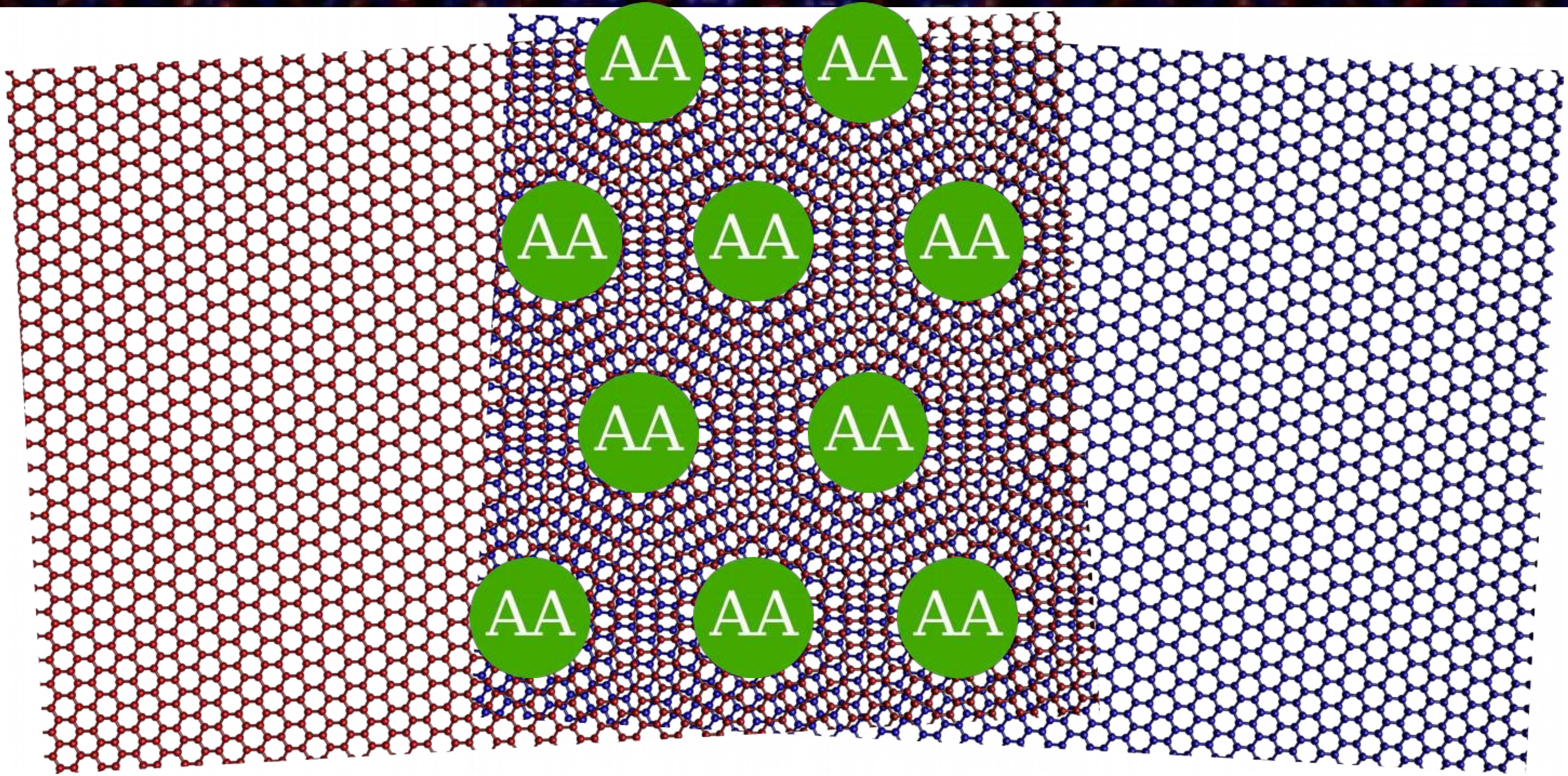
A recipe for frustrated magnets

How to create a frustrated magnet

→ Localize electrons in a frustrated lattice

→ Add strong interactions

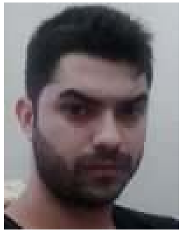
Triangular lattice in twisted bilayer graphene



Twisted 2D materials as a platform for controllable frustrated magnets

Controllable magnetic interactions (1.5°)

Phys. Rev. Lett. 119, 107201 (2017)



Luis Gonzalez

Francisco Guinea

Pablo San-Jose

Tuning topology to quench correlations (0.8°)

Phys. Rev. Lett. 123, 096802 (2019)

Tobias Wolf

Gianni Blatter

Oded Zilberberg

Controllable Kagome lattices (0.3°)

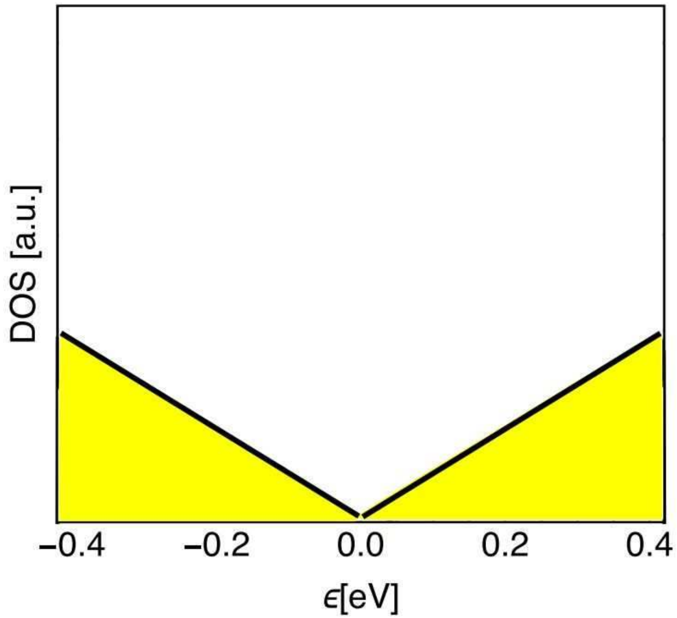
Phys. Rev. Lett. 121, 146801 (2018)

Aline Ramires

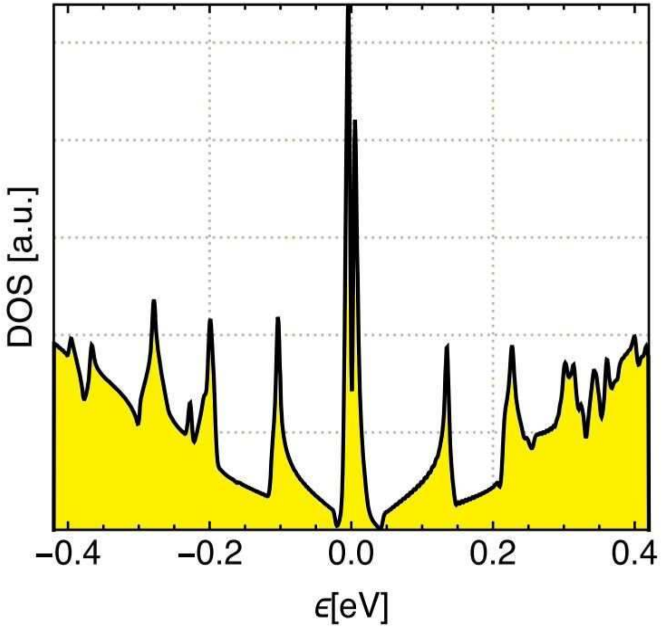
Controllable magnetic interactions in twisted bilayer graphene (1.5°)

Controlling electronic properties with the twist angle

At large angles



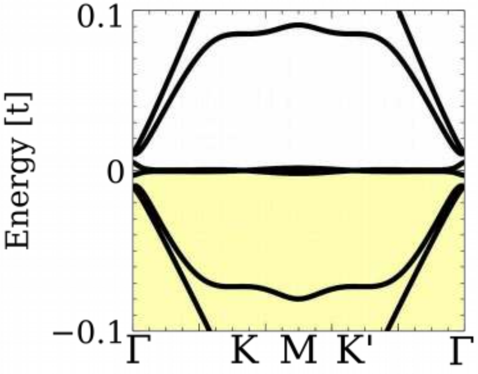
At small angles



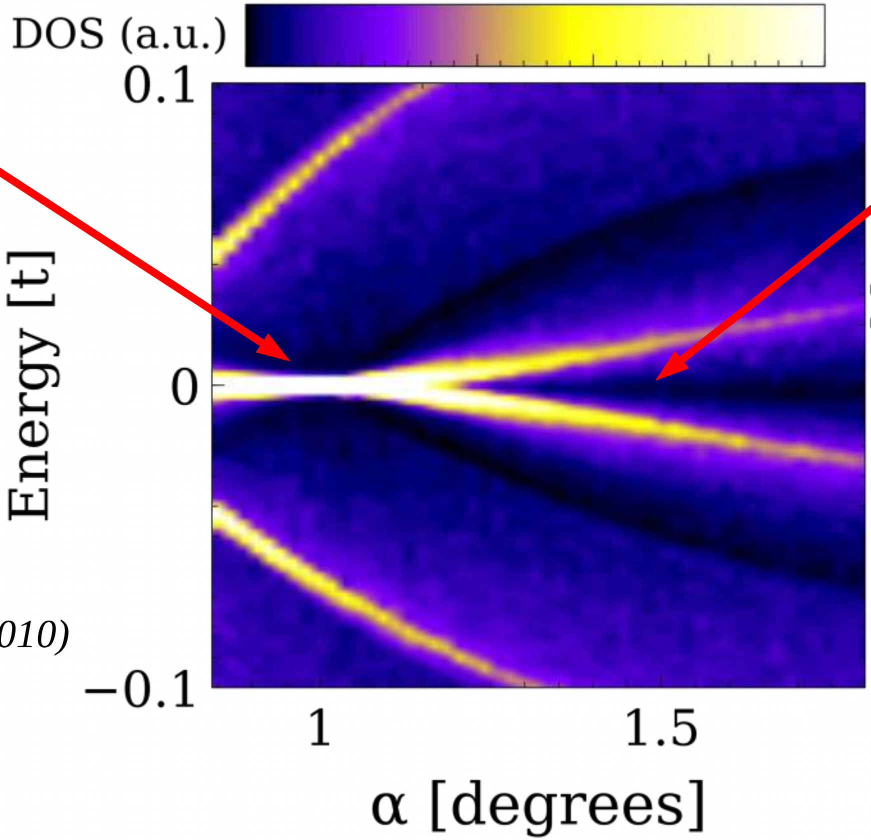
The twist between the layers strongly impacts the density of states

Controlling electronic properties with the twist angle

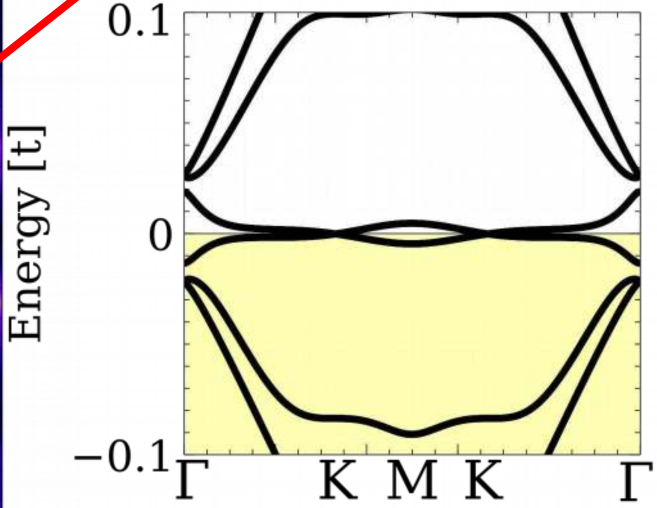
Magic angle



Phys. Rev. B 82, 121407(R) (2010)
PNAS 108.30 (2011)



Sub-magic angle

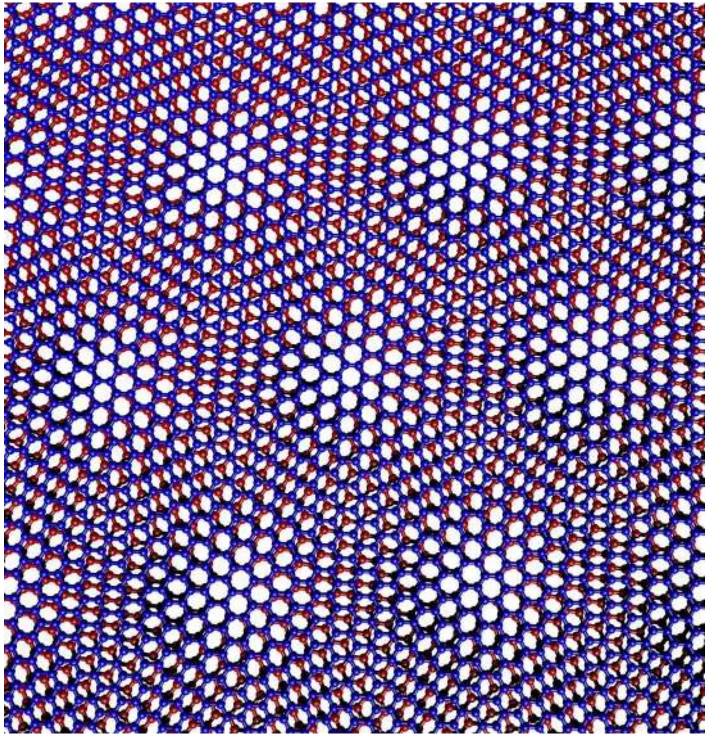


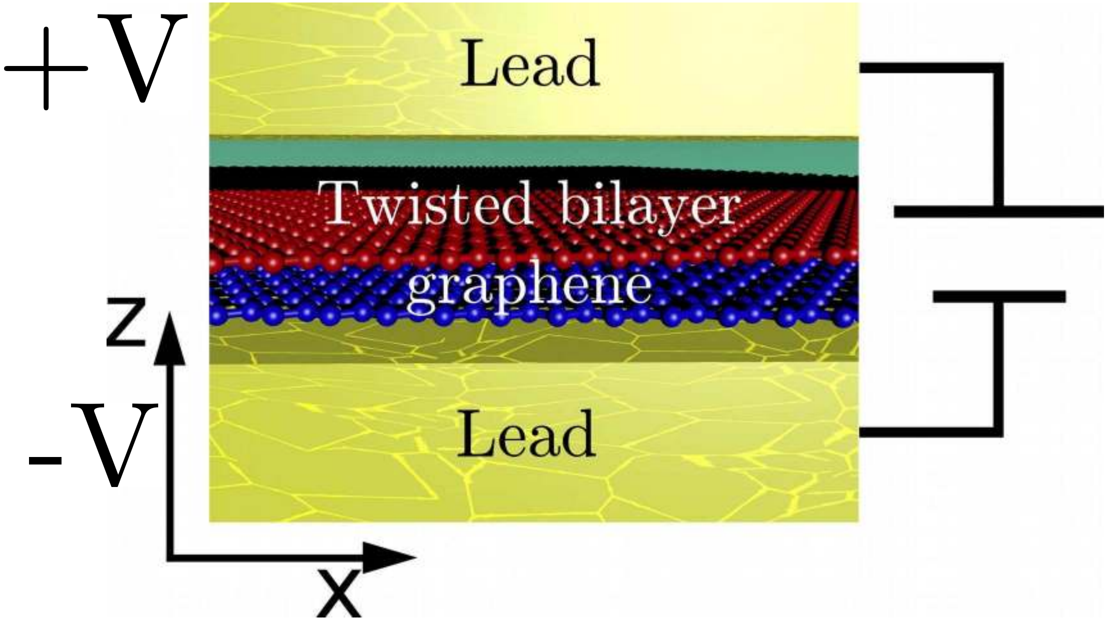
Lets focus on this one

Phys. Rev. Lett. 99, 256802 (2007)

Enhancing DOS electrically at 1.5 degrees

$$\alpha = 1.5^\circ$$

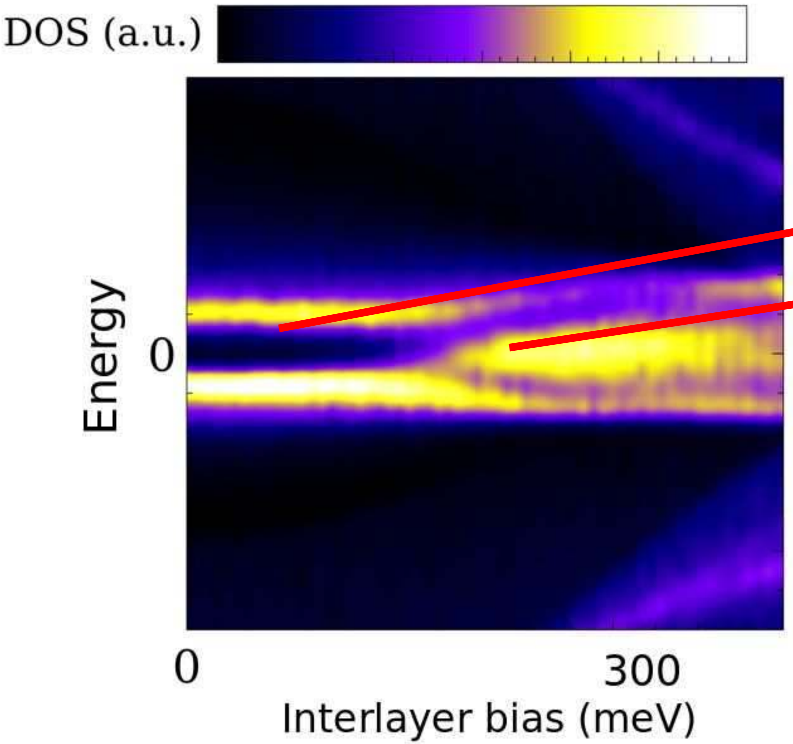


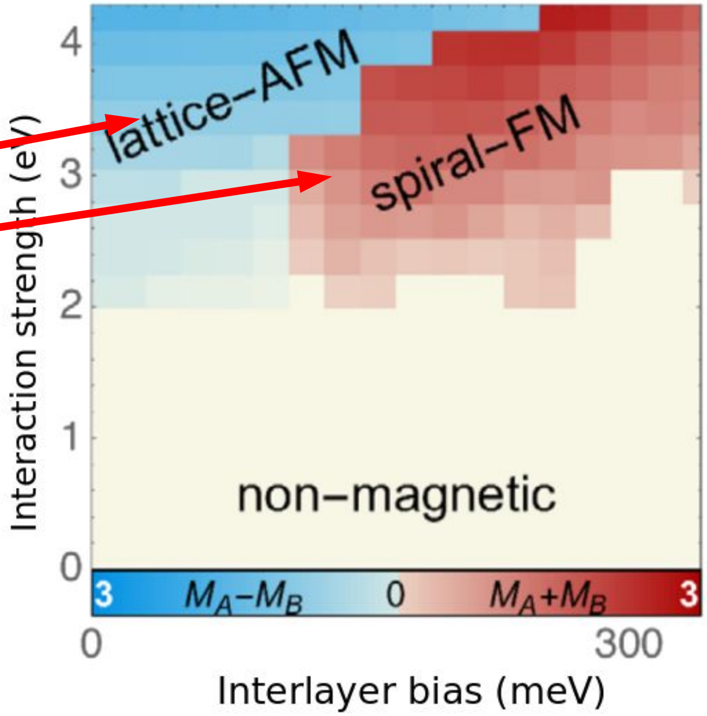


Controlling DOS and magnetism electrically

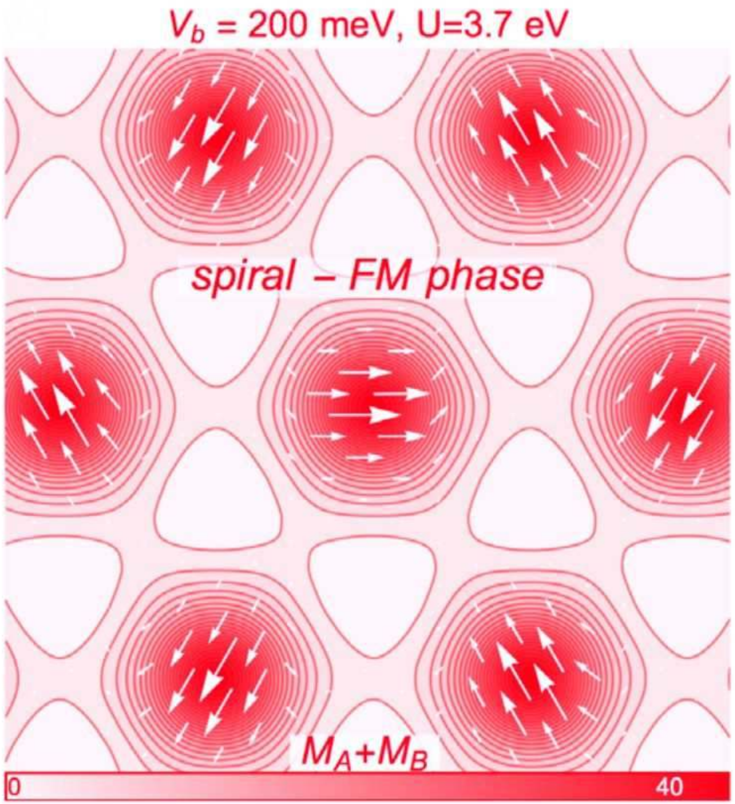
Without interactions

With interactions

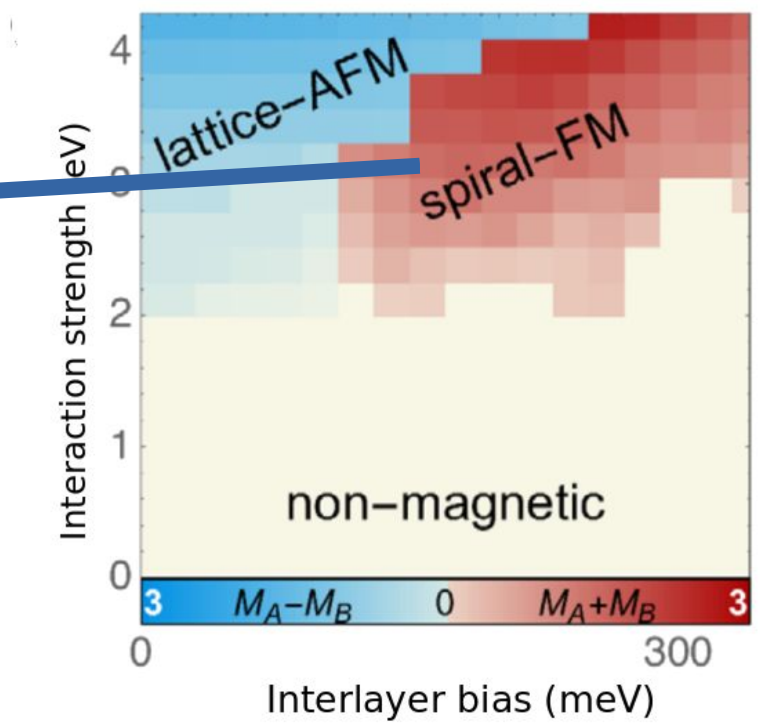




Controlling DOS and magnetism electrically

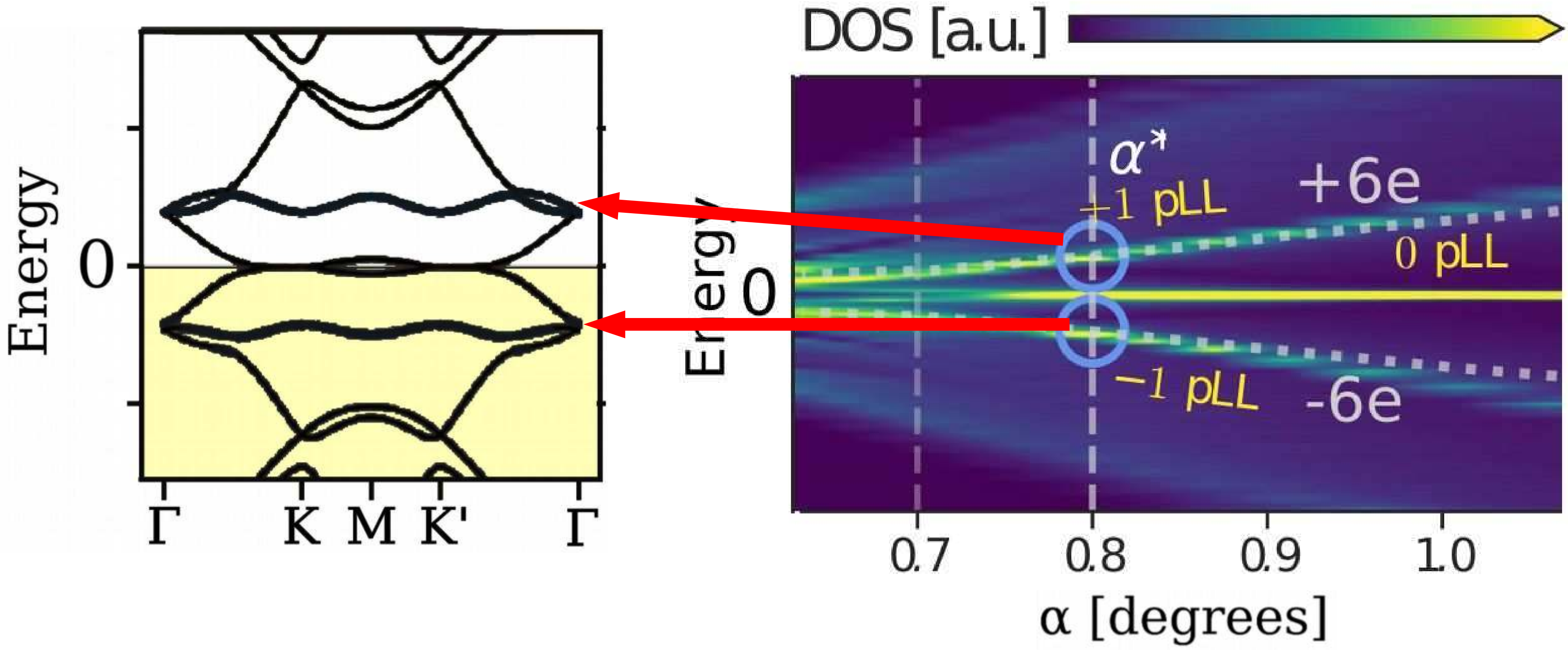


With interactions



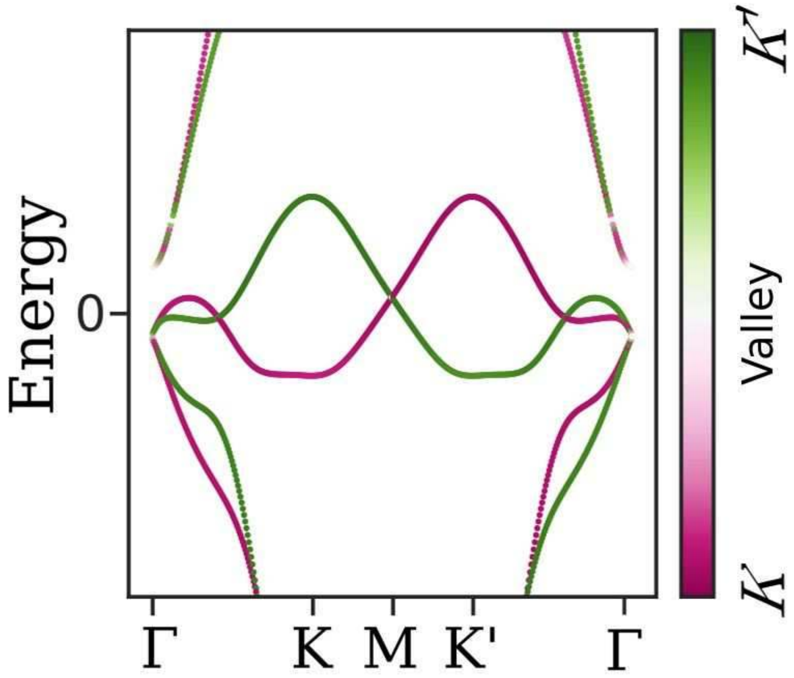
Tuning topology to quench correlations in twisted bilayer graphene (0.8°)

Flat bands above charge neutrality at 0.8 degrees

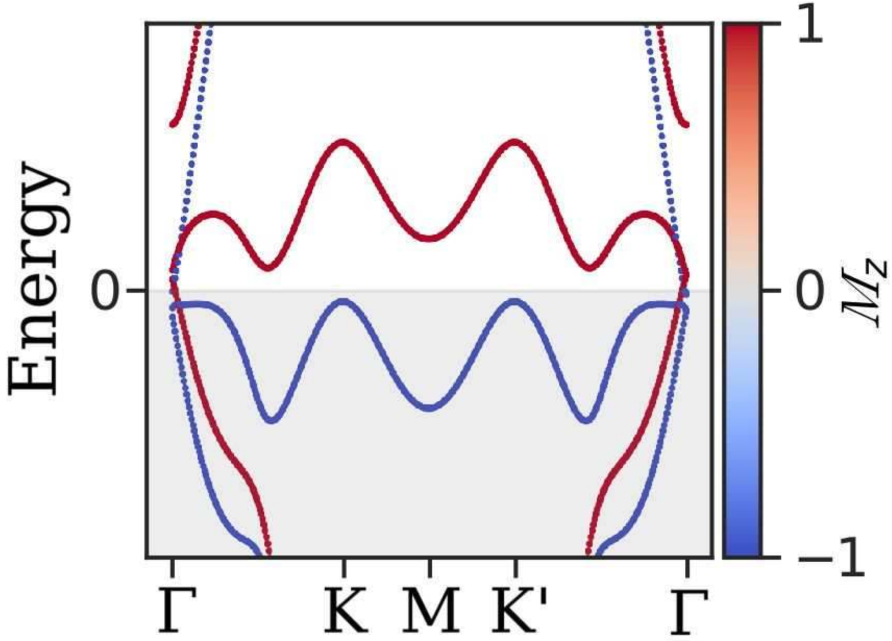


Interlayer bias VS interactions (-6e)

Only interlayer bias (valley topology)

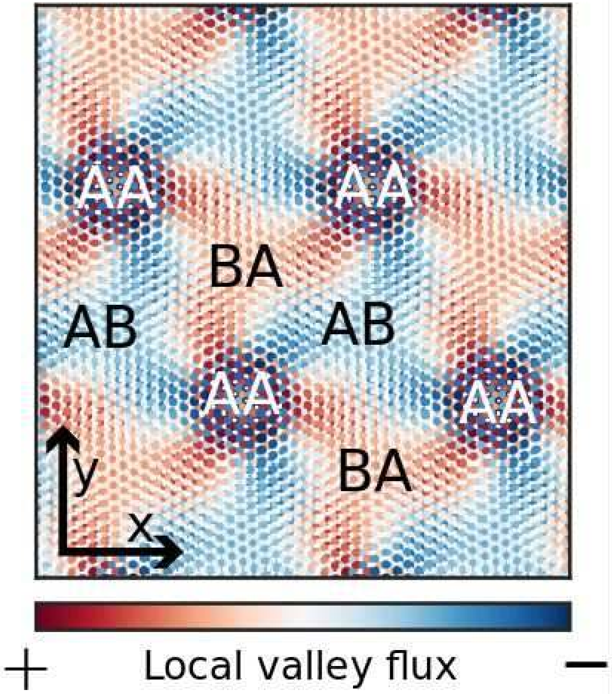


Only interactions (magnetism)



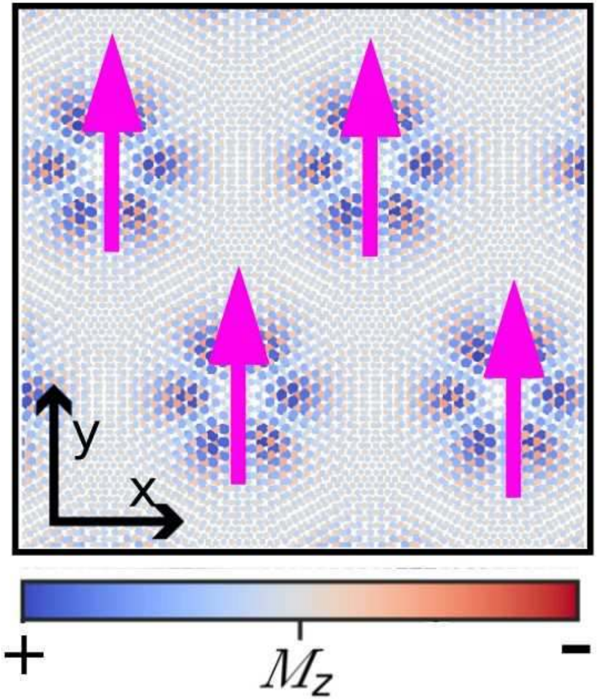
Interlayer bias VS interactions (-6e)

Only interlayer bias (valley topology)



Real space valley Berry flux

Only interactions (magnetism)

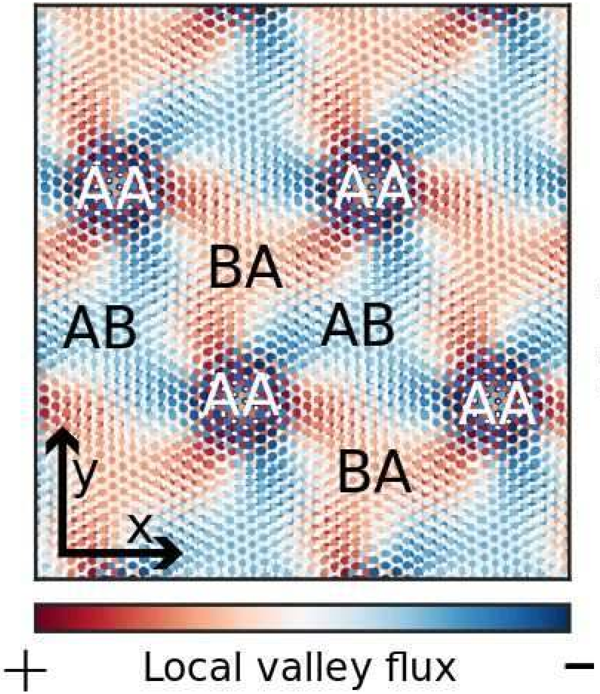


Real space magnetic moment

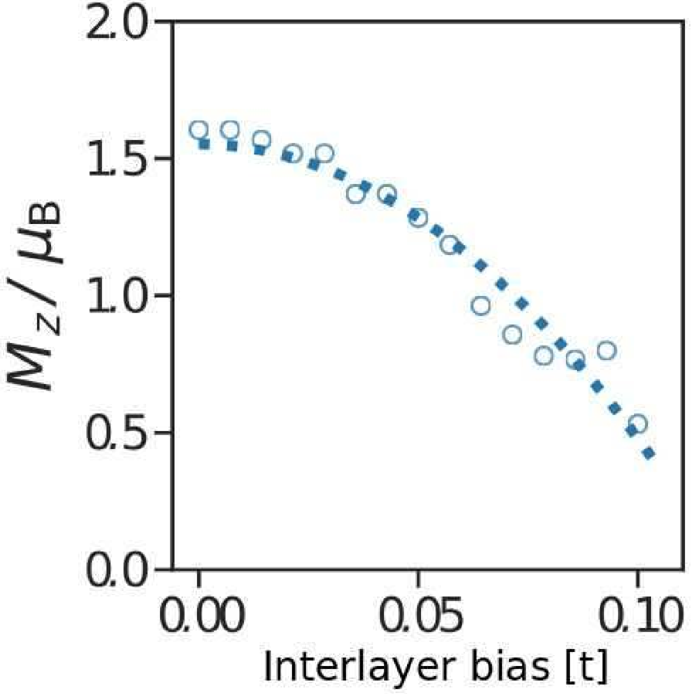
Interlayer bias & interactions (-6e)

Magnetic correlations quenched by the bias-induced valley flux

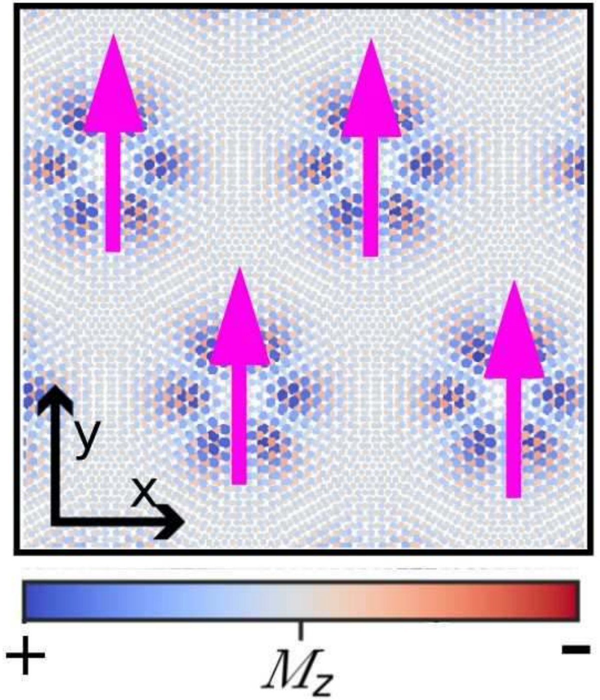
Bias



Bias & interactions

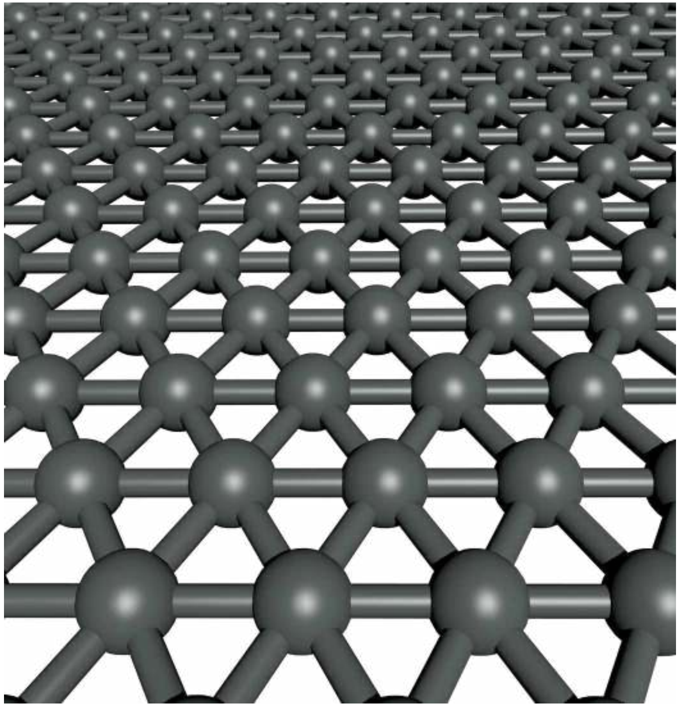


Interactions

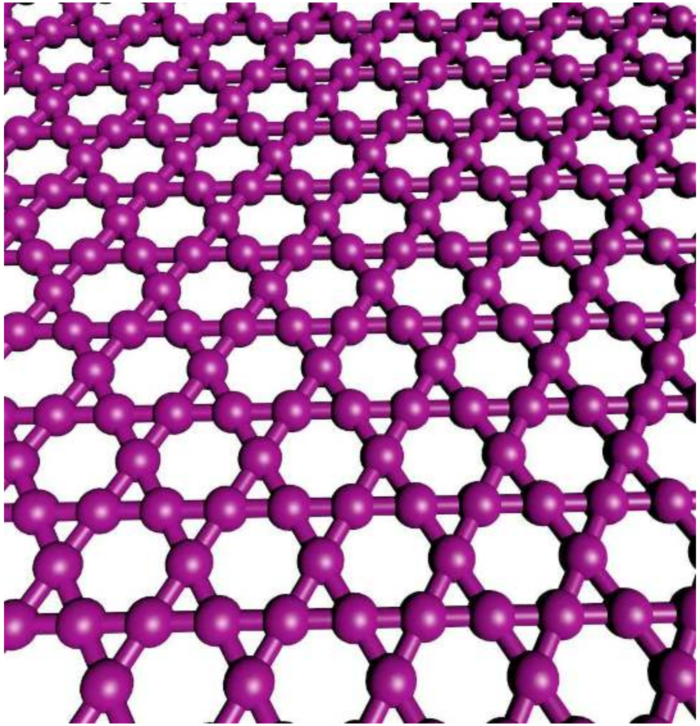


Controllable Kagome lattices in twisted bilayer graphene (0.3°)

From triangular to Kagome

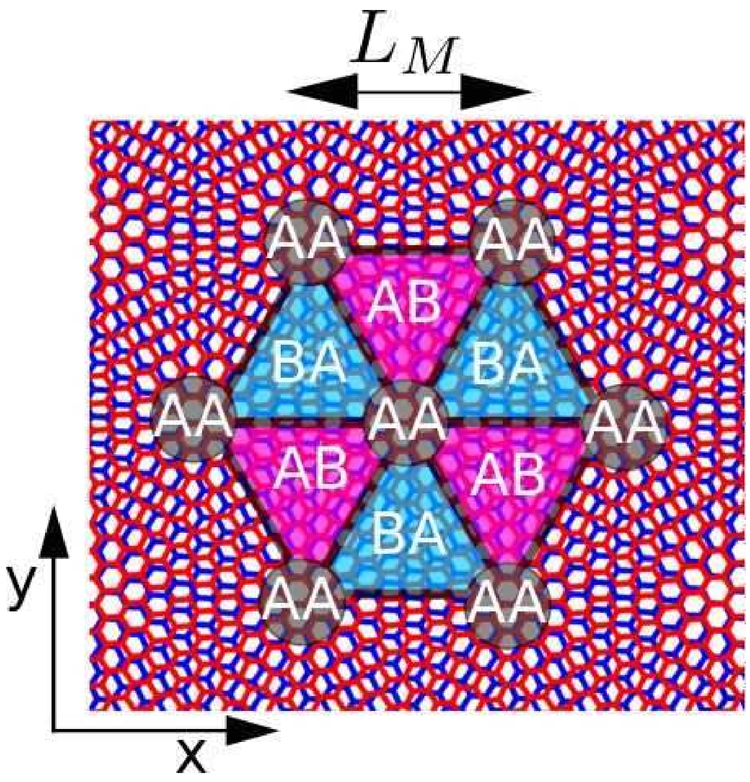


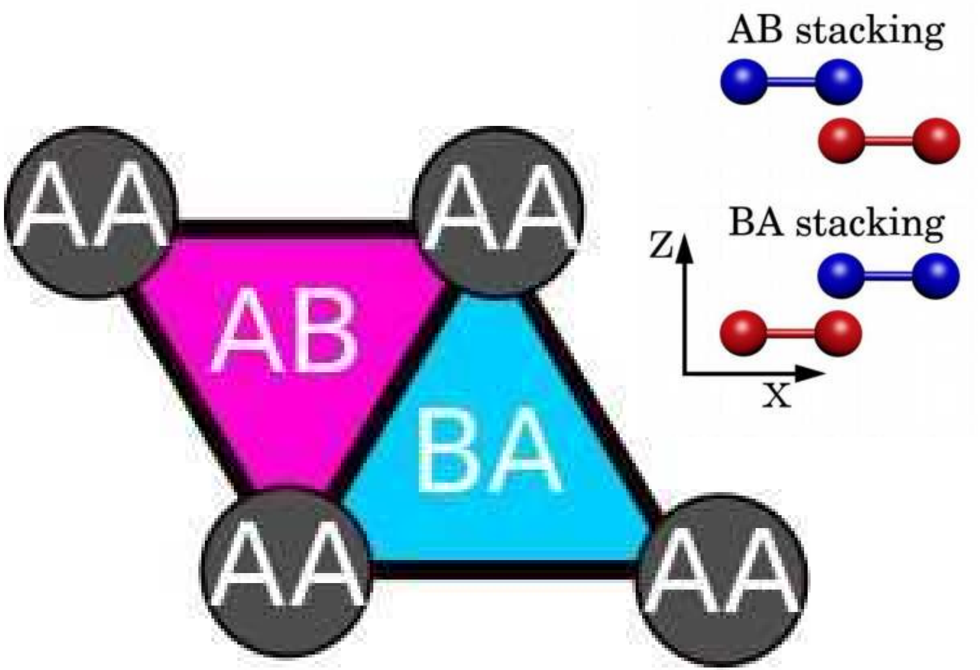
?



How do we generate a Kagome lattice in graphene?

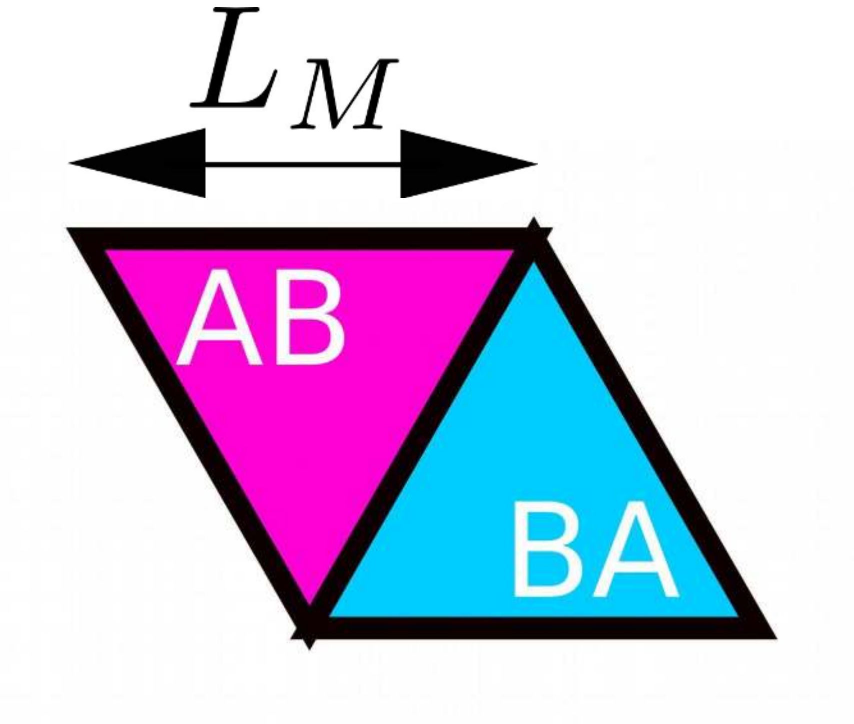
Towards a possible Kagome lattice

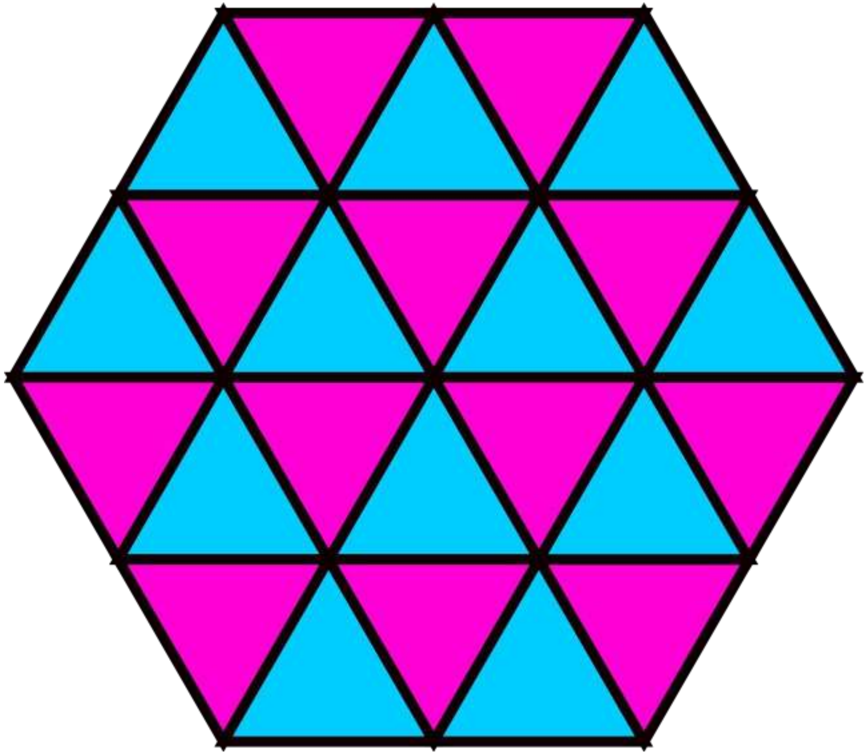




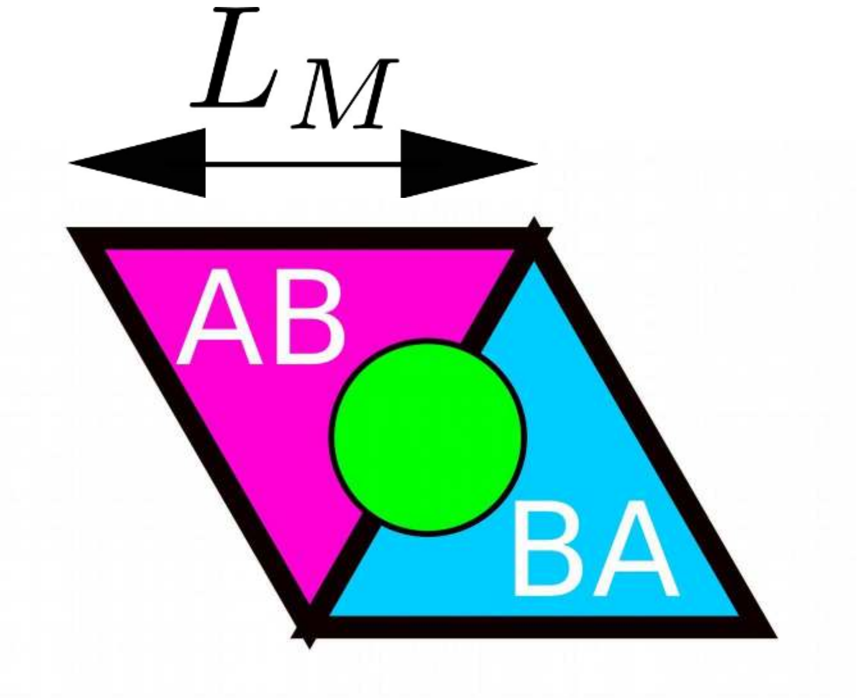
Let us look at the AB/BA structure

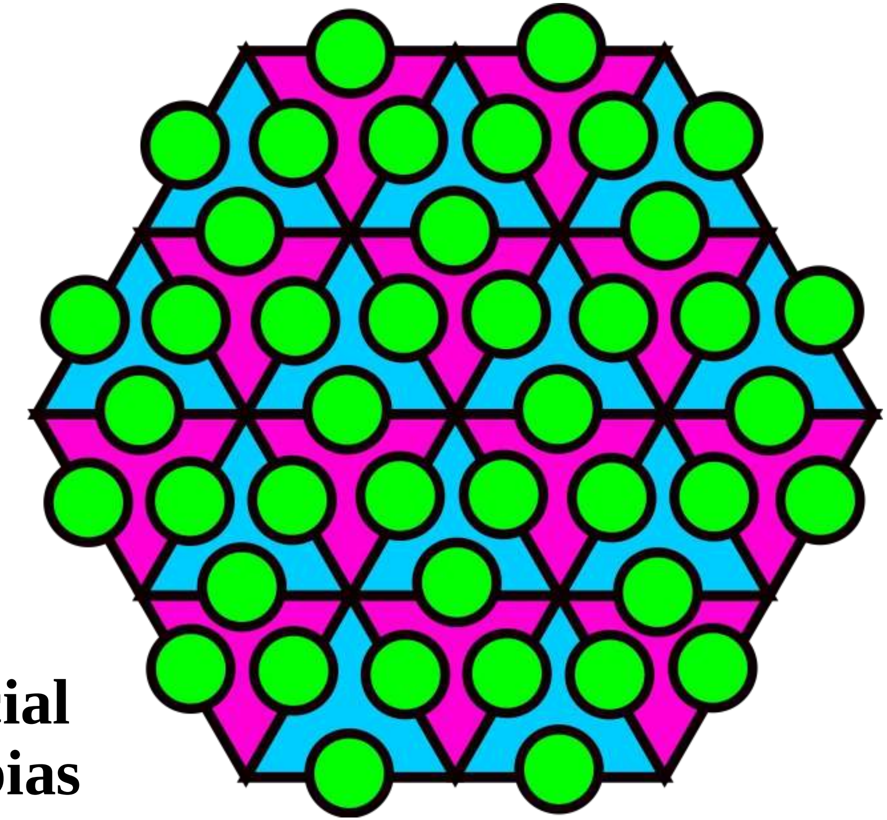
The possible Kagome lattice in TBG





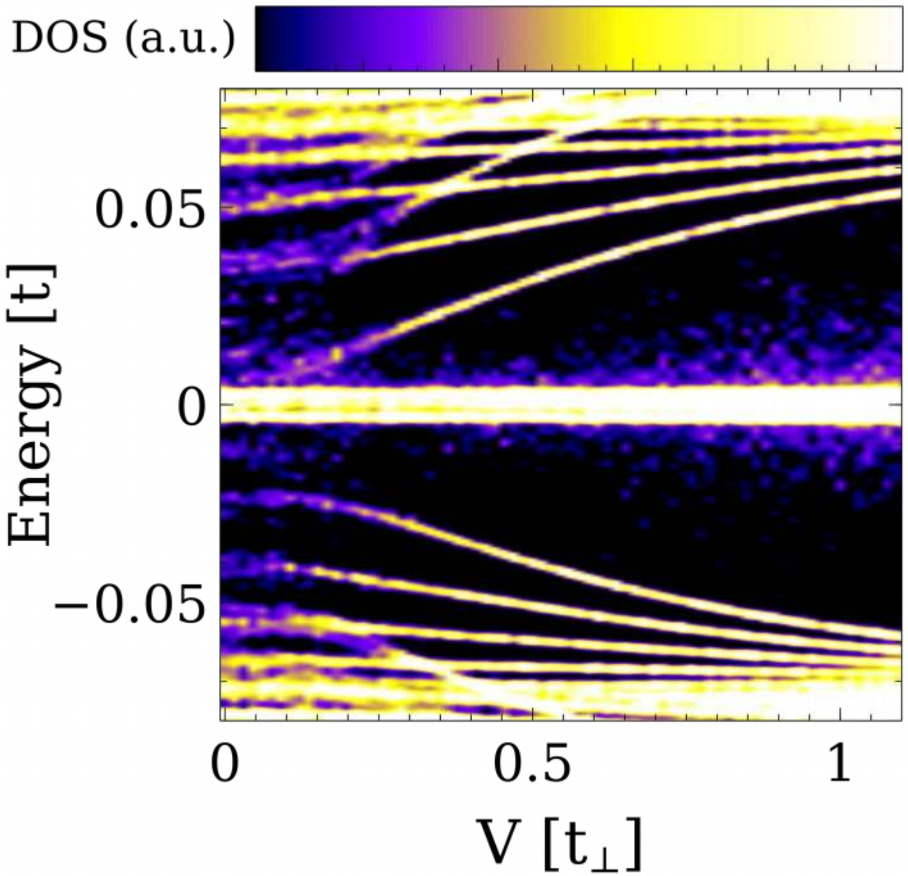
The possible Kagome lattice in TBG

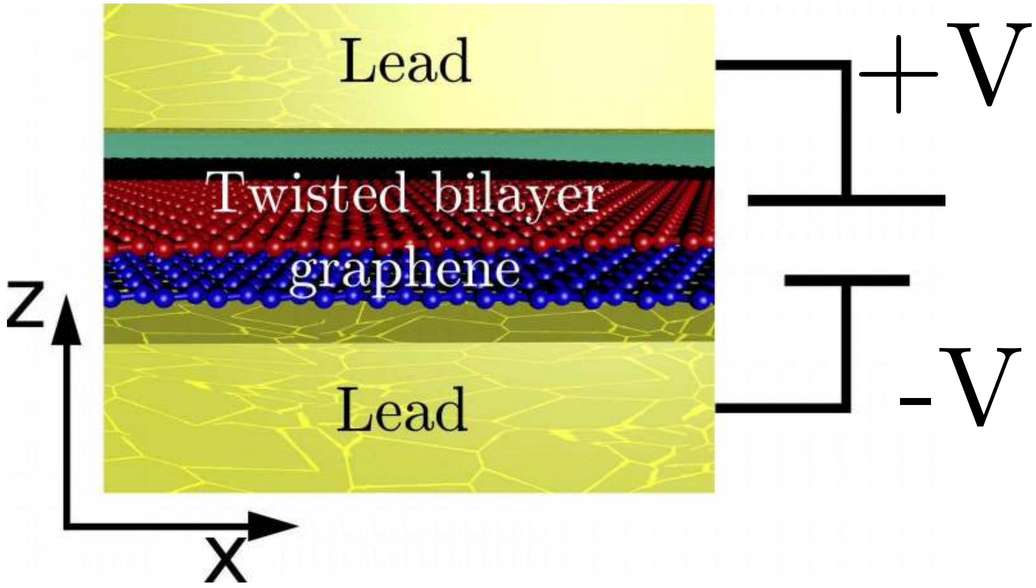




A localized mode is created by an artificial gauge field controlled by an interlayer bias

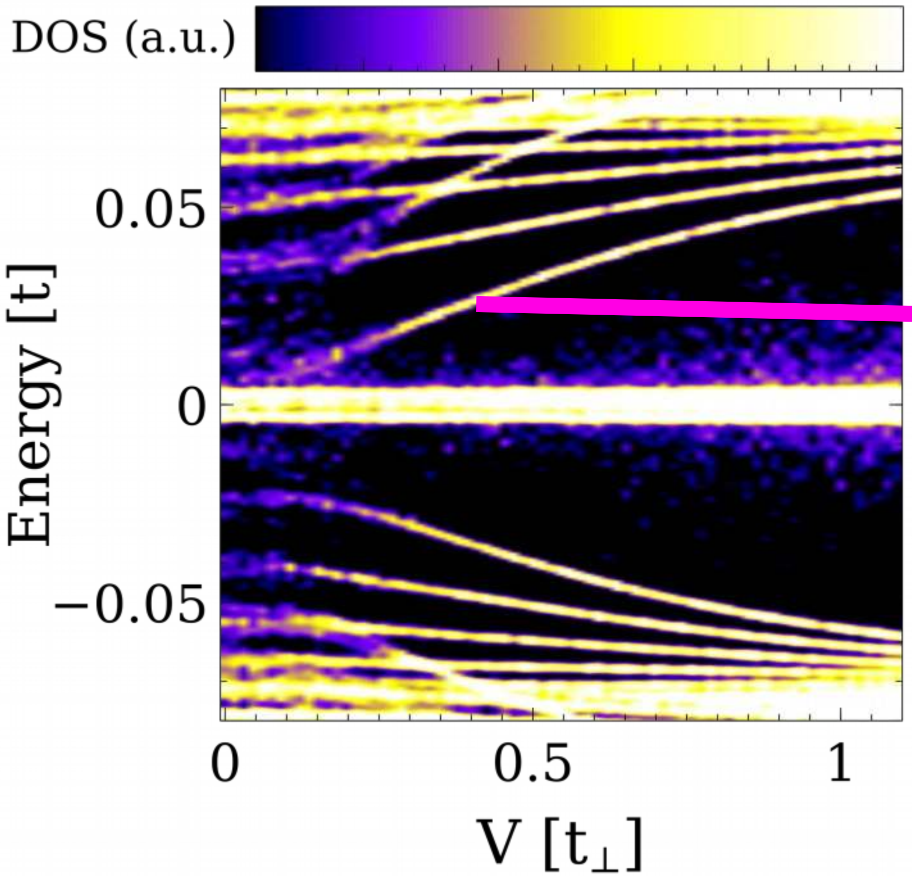
Controlling pseudo Landau levels electrically

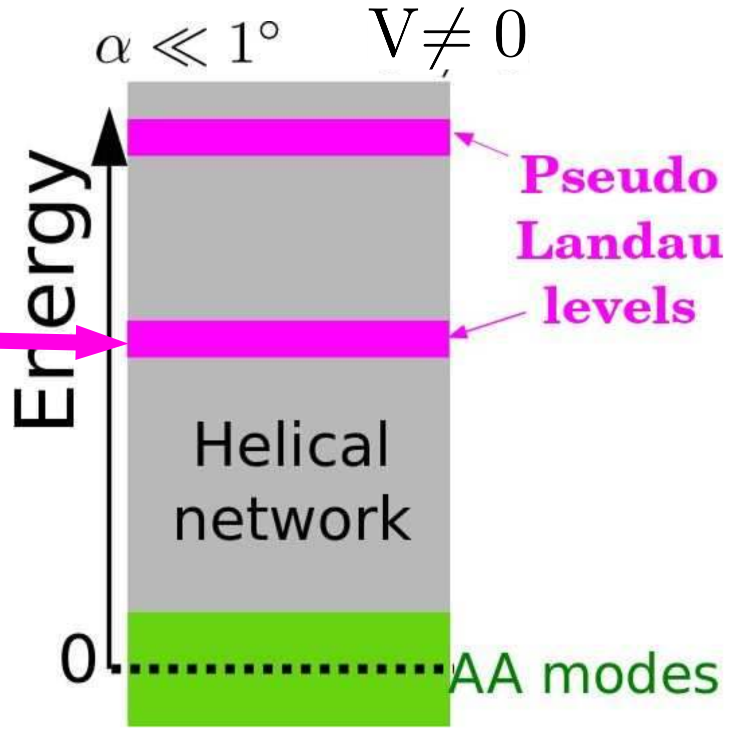




$$B_{eff} \propto V$$

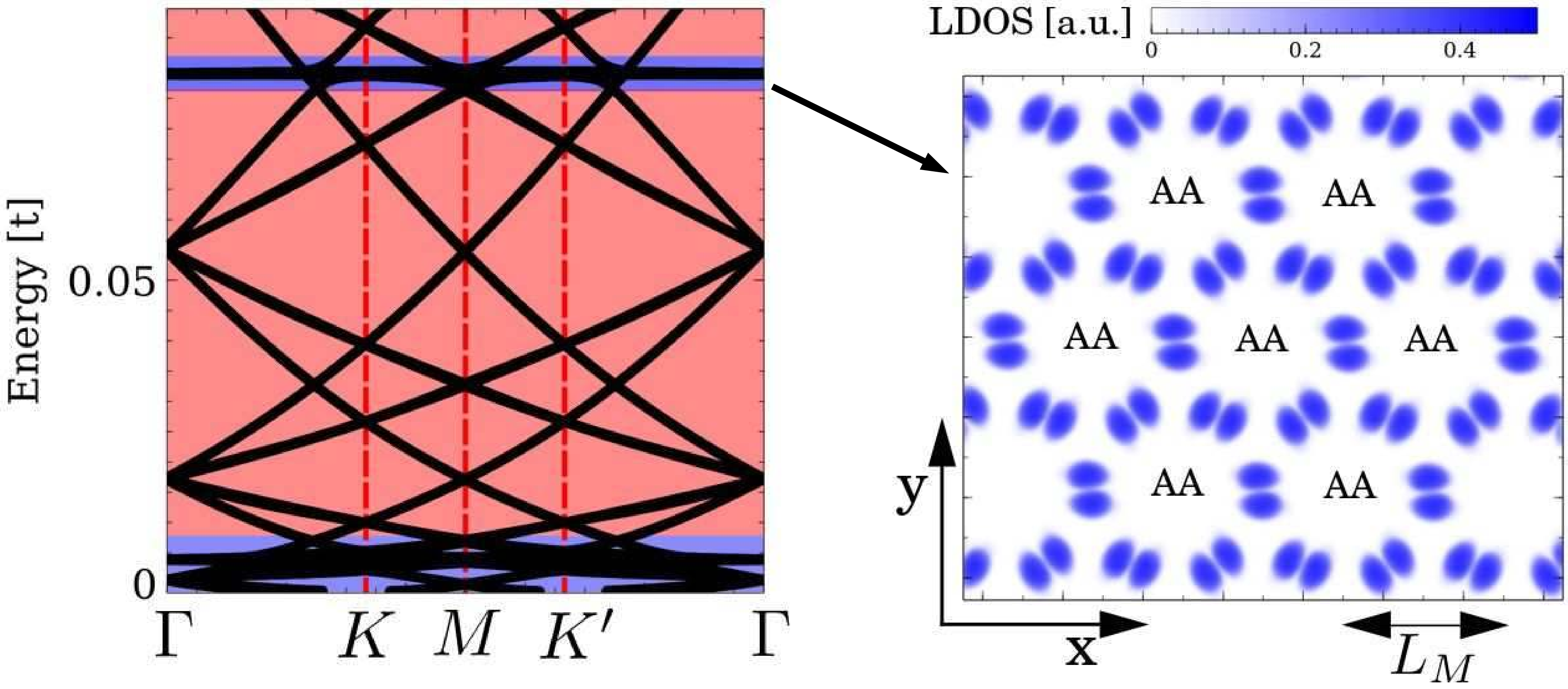
Controlling pseudo Landau levels electrically





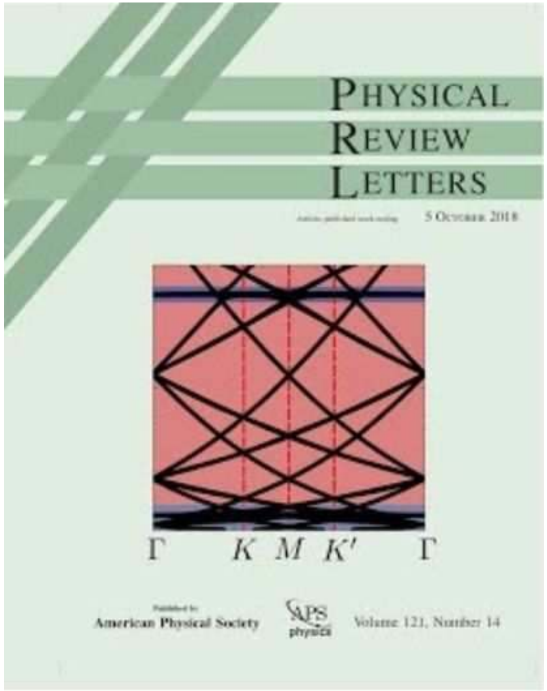
$$B_{eff} \propto V$$

The Kagome lattice in twisted bilayer graphene

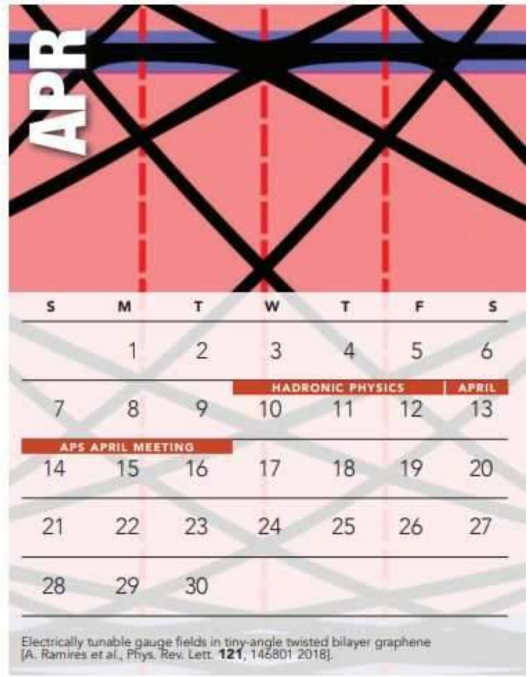


Electrically controllable gauge fields and the American Physical Society

Cover of Physical Review Letters (2018)



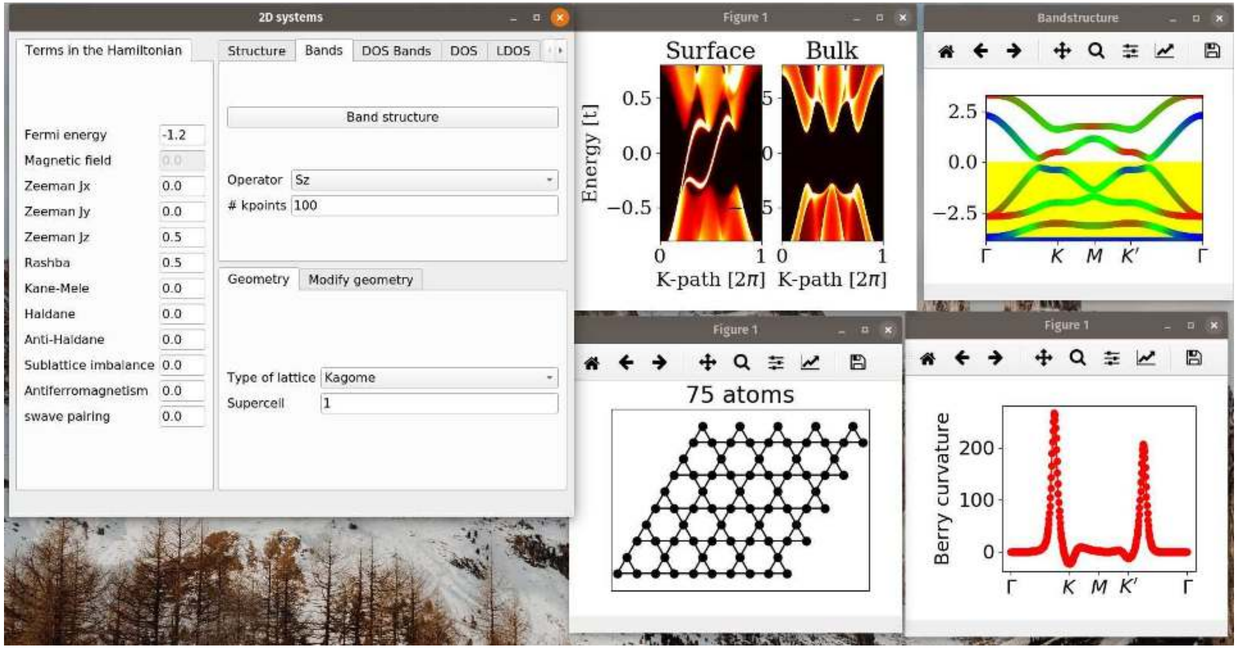
Calendar of the American Physical Society (2019)



Aline Ramires and Jose lado, Phys. Rev. Lett. 121, 146801 (2018)

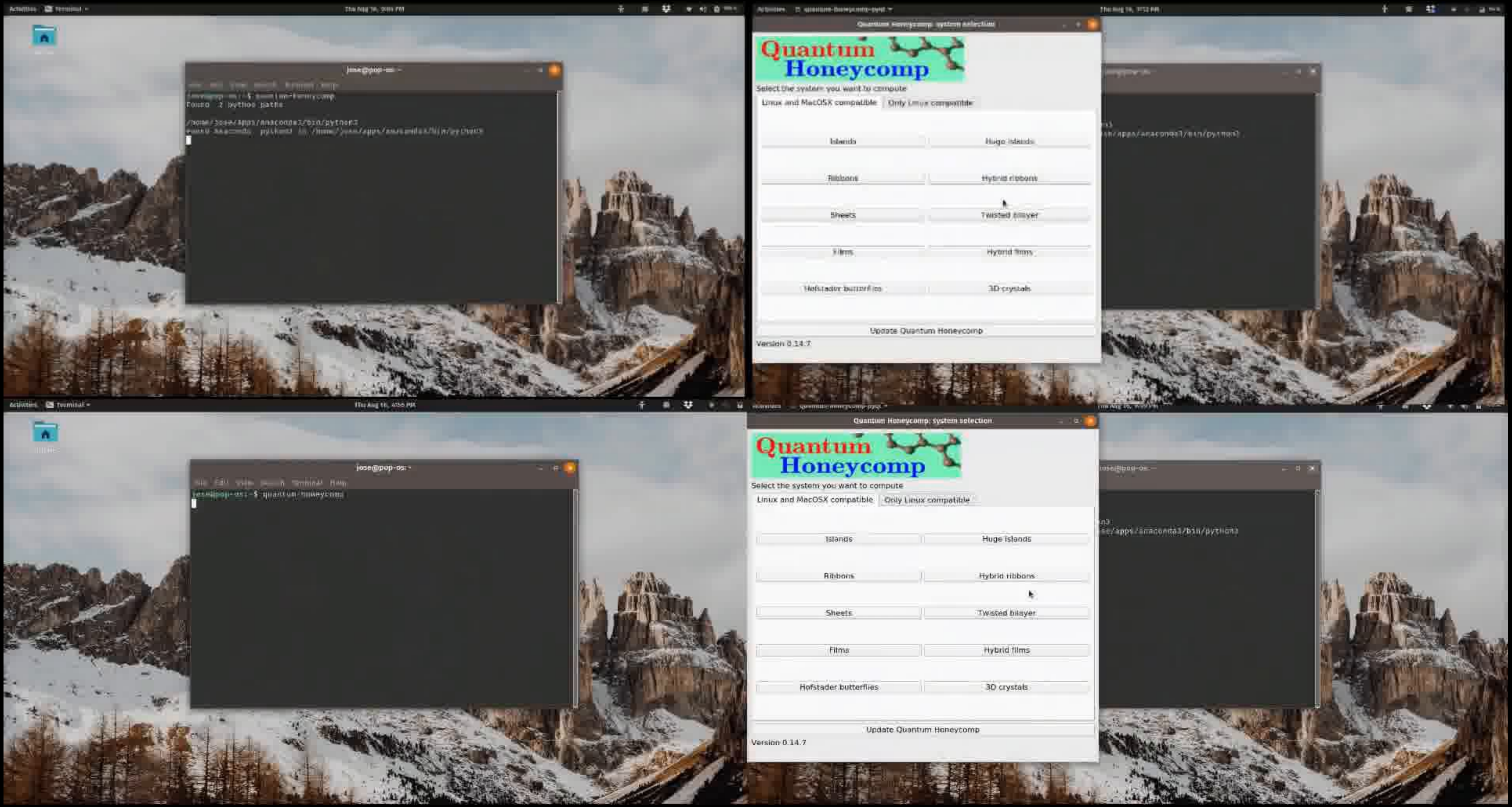
Computing electronic properties

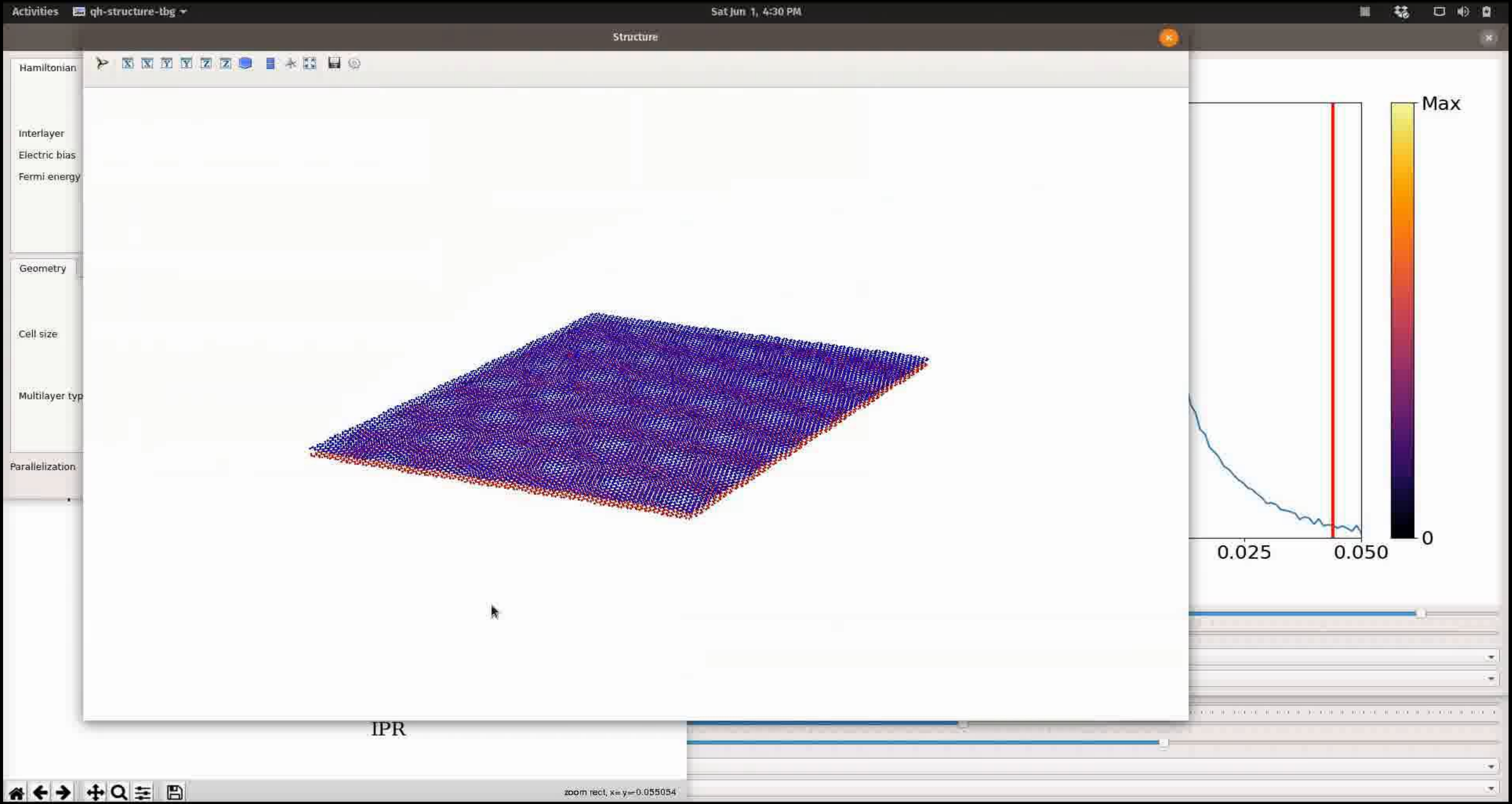
A user interface to compute electronic properties



Quantum Honeycomp: open source interactive interface for tight binding modeling

https://github.com/joselado/quantum-honeycomp


jose@pop-os: ~
jose@pop-os:~$ quantum-honeycomp
Quantum Honeycomp: system selection
Quantum
Honeycomp
Select the system you want to compute
Linux and MacOSX compatible
Only Linux compatible
Islands
Huge islands
Ribbons
Hybrid ribbons
Sheets
Twisted bilayer
Films
Hybrid films
Hofstader butterflies
3D crystals
Update Quantum Honeycomp
Version 0.14.7


Activities
qh-structure-tbg
Sat Jun 1, 4:30 PM
Structure
Hamiltonian
Interlayer
Electric bias
Fermi energy
Geometry
Cell size
Multilayer typ
Parallelization
Max
0
0.025
0.050
IPR
zoom rect, x= y=0.055054

Take home

Twisted van der Waals materials open up a new route to explore exotic quantum states, offering an unprecedented degree of control.