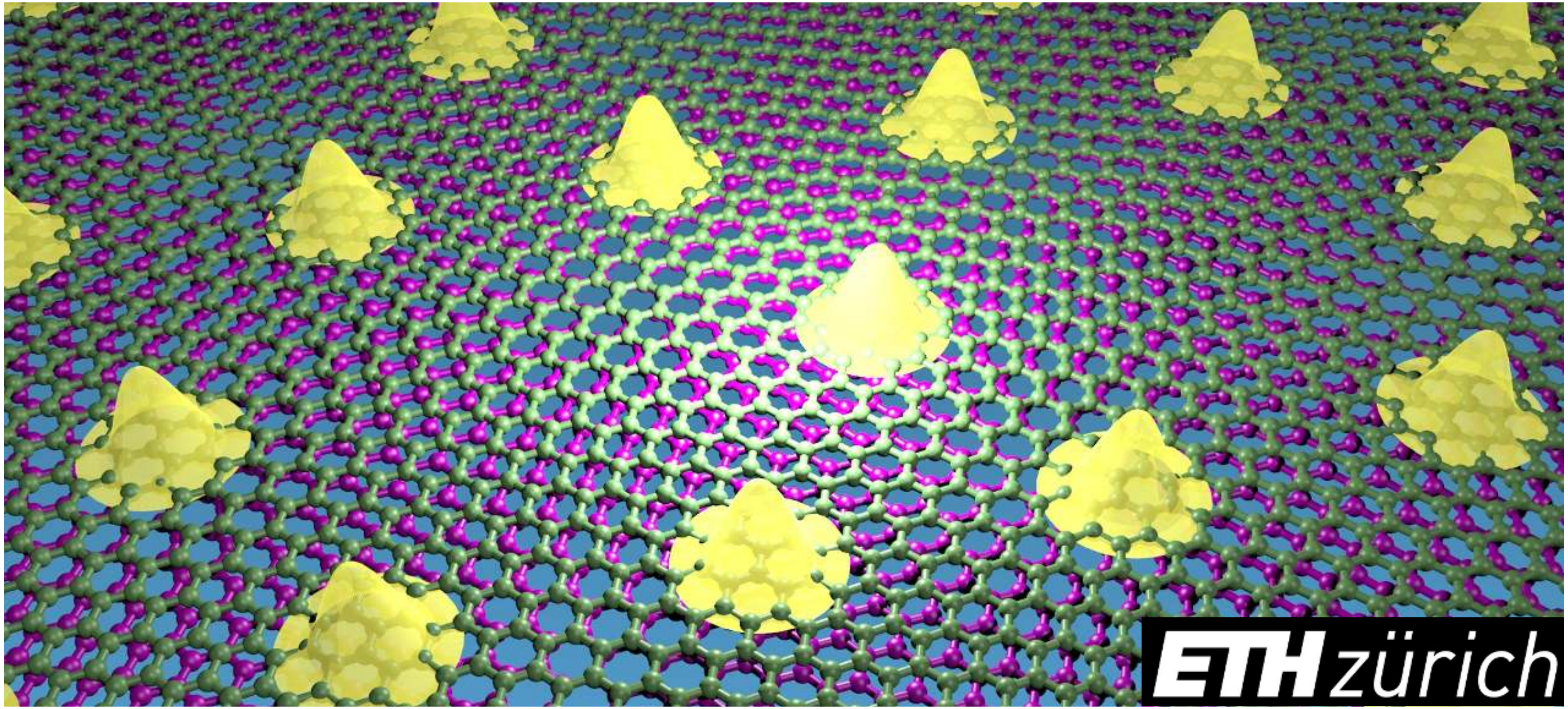
Electrically tunable frustrated lattices and magnetism in twisted bilayer graphene

Jose Lado, ETH Zurich

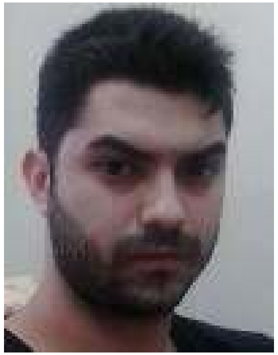


APS March Meeting, 5th March 2019

Behind the scenes

Electrically controllable triangular magnetism

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



L. A. Gonzalez-Arraga

F. Guinea

P. San Jose

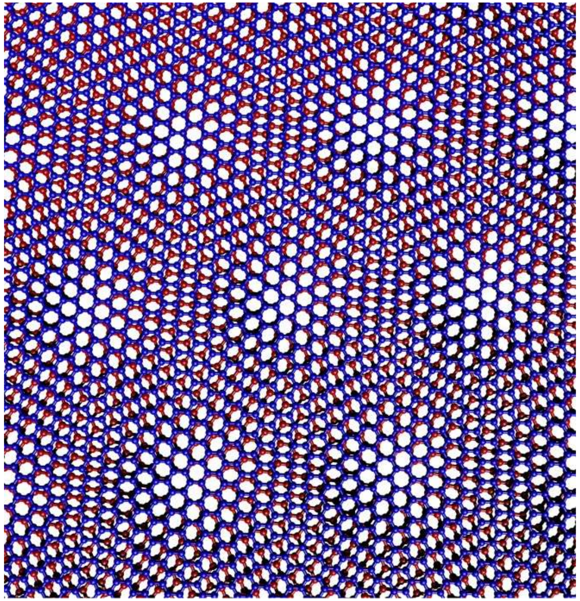
Kagome lattices & electric gauge fields

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

A. Ramires

A story of success, with a twist

Twisted graphene multilayers



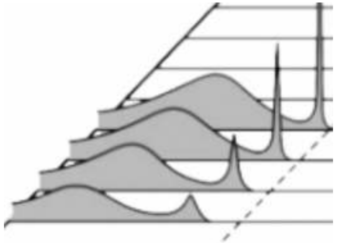
Superconductivity

Nature 556, 43–50 (2018)

Topological networks

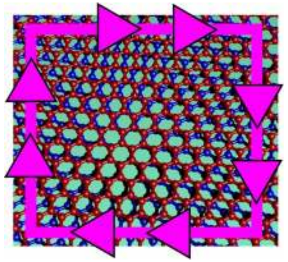
Nano Lett. 18, 11, 6725-6730 (2018)

Strange metals



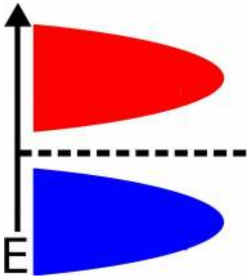
arXiv:1901.03710 (2019)

Anomalous Hall



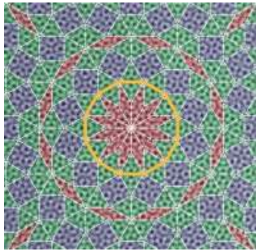
arXiv:1901.03520 (2019)

Correlated insulators



Nature 556, 80–84 (2018)

Quasicrystalline physics



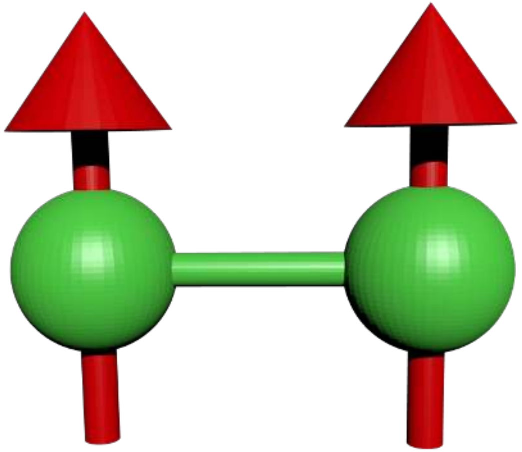
Science 361.6404 782-786 (2018)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

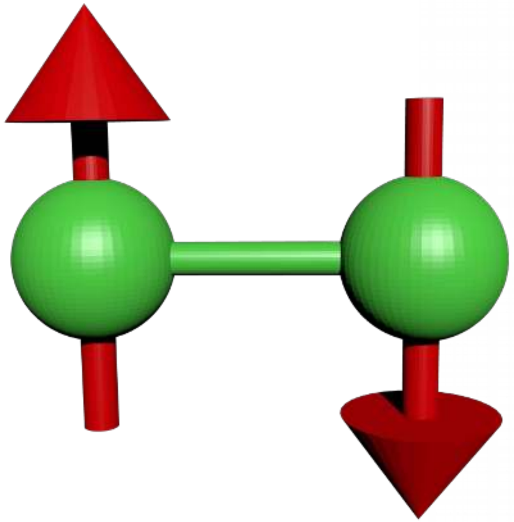
Frustration

A bird’s eye view on magnetism

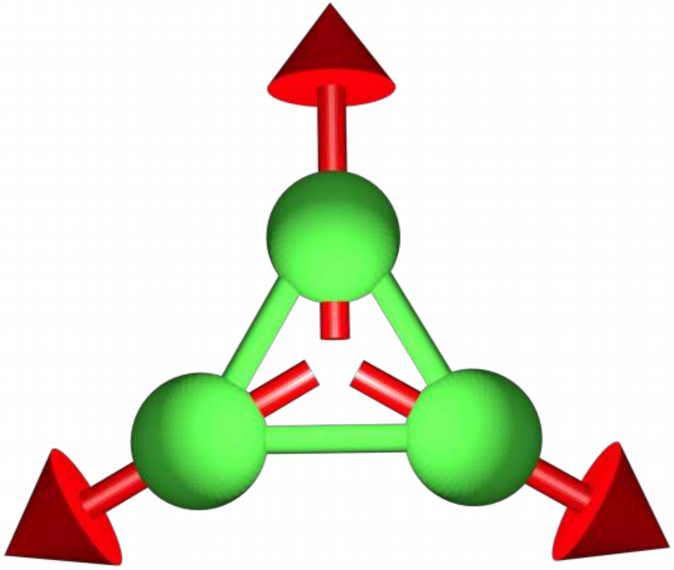
Ferromagnetism



Antiferromagnetism



Frustrated magnetism



Can we control the microscopic properties of a magnet?

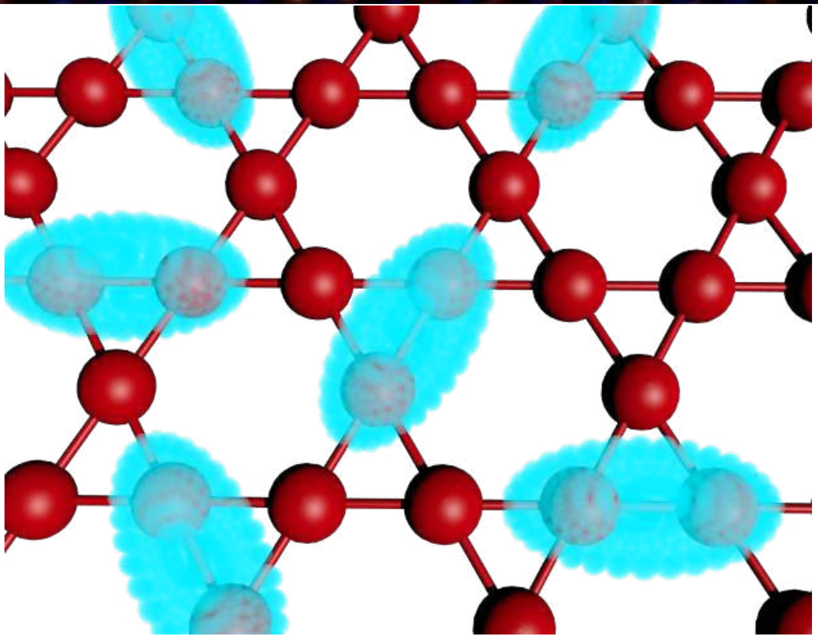
What is the best that can happen?

Quantum spin liquids

No magnetic ordering at T=0
Non-trivial topological properties
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)



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

Kitaev’s honeycomb

Annals of Physics 321.1 (2006)

Kagome Heisenberg

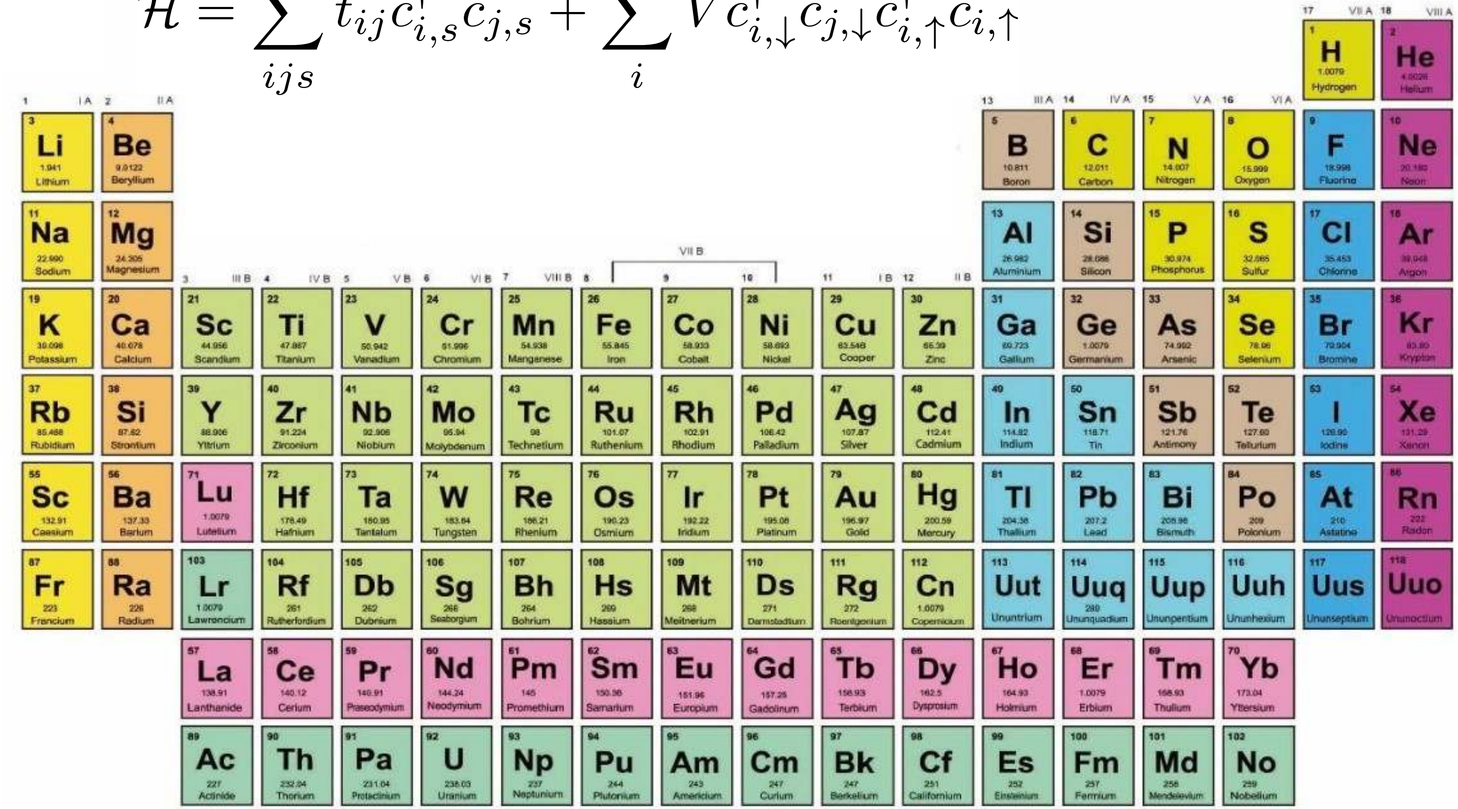
Science 332, 1173-1176 (2011)

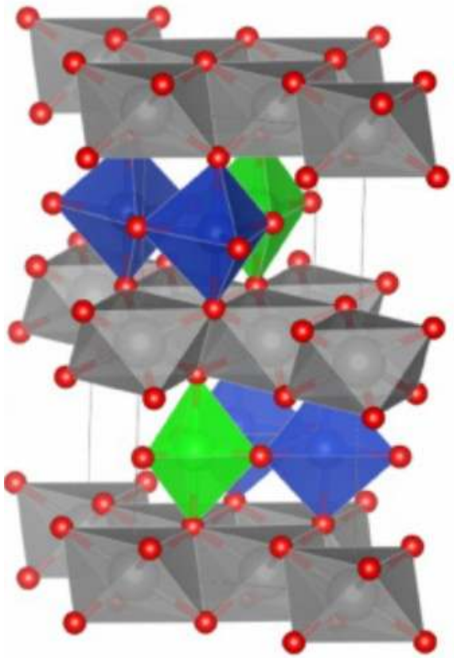
Extended triangular Heisenberg

J. Phys. Soc. Jpn 83, 093707 (2014)

Engineering magnetic materials

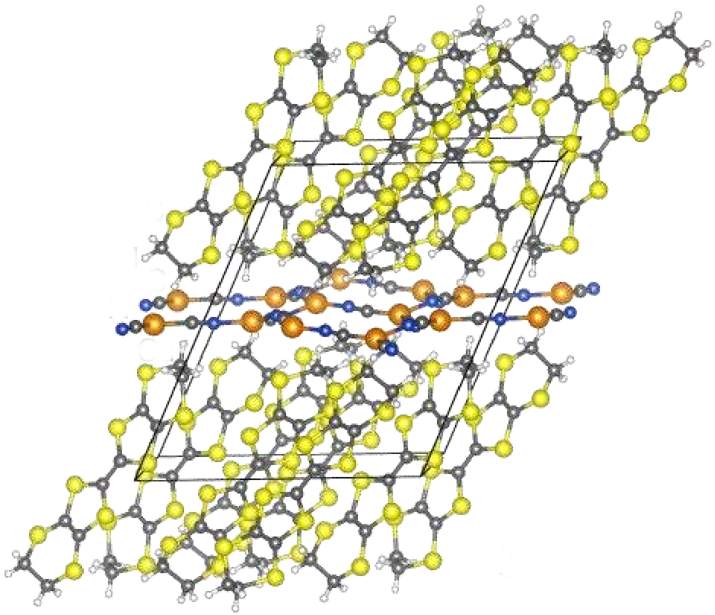
$$\mathcal{H} = \sum_{ijs} t_{ij} c^{\dagger}_{i,s} c_{j,s} + \sum_{i} V c^{\dagger}_{i,\downarrow} c_{j,\downarrow} c^{\dagger}_{i,\uparrow} c_{i,\uparrow}$$





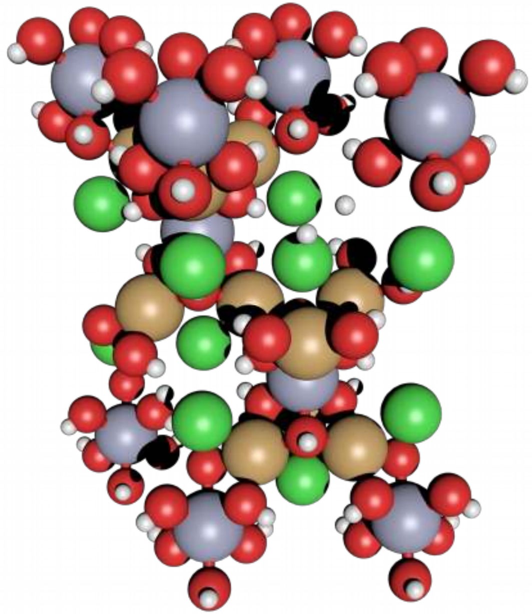
A quest for frustrated quantum magnets

κ-$(ET)_2Cu_2(CN)_3$ (Triangular)



Phys. Rev. Lett. 91, 107001 (2003)
Nat. Phys. 4, 459–462 (2008)
Science 328, 1246–1248 (2010)

Herbertsmithite (Kagome)

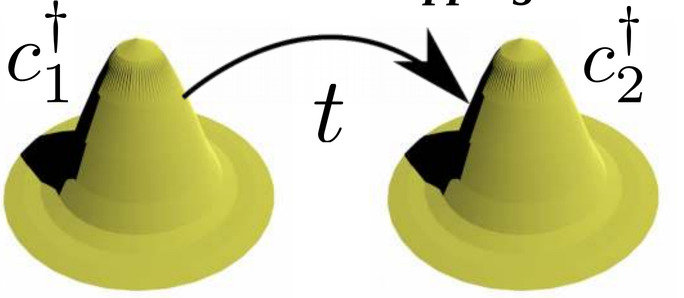


Phys. Rev. Lett. 98, 107204 (2007)
Phys. Rev. Lett. 103, 237201 (2009)
Rev. Mod. Phys. 88, 041002 (2016)

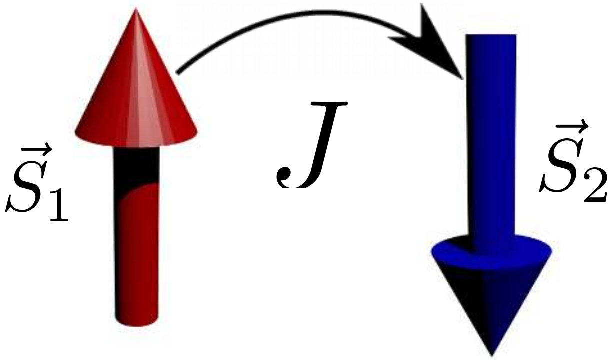
Artificial matter

Building a magnet from scratch

Dimer with hopping



Heisenberg dimer



$$H = \underbrace{U \sum_i n_{i,\uparrow} n_{i,\downarrow}}_{\text{Interaction}} + \underbrace{t \sum_s c_{1,s}^\dagger c_{2,s} + h.c.}_{\text{Kinetic energy}}$$

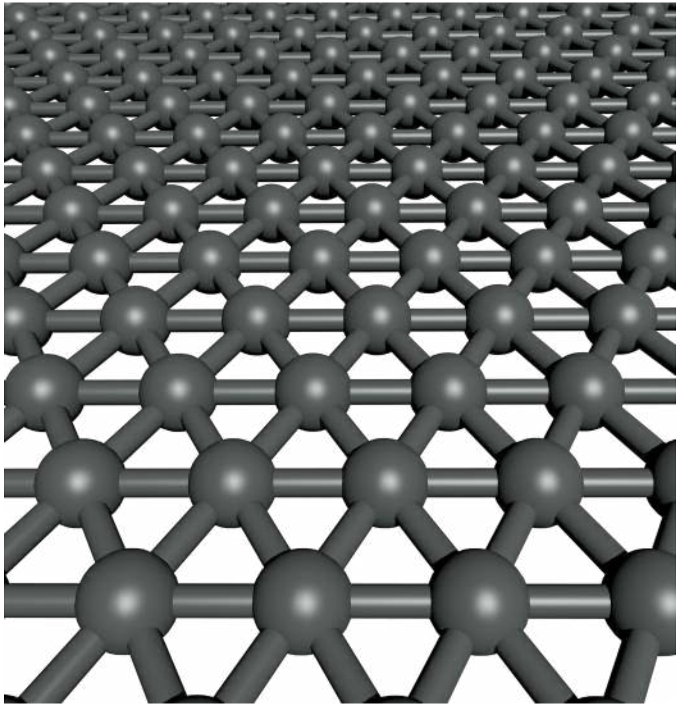
$$U \gg t \quad \Big\downarrow \quad J \propto t^2/U$$

Spin Hamiltonian $\mathcal{H} = J \vec{S}_1 \cdot \vec{S}_2$

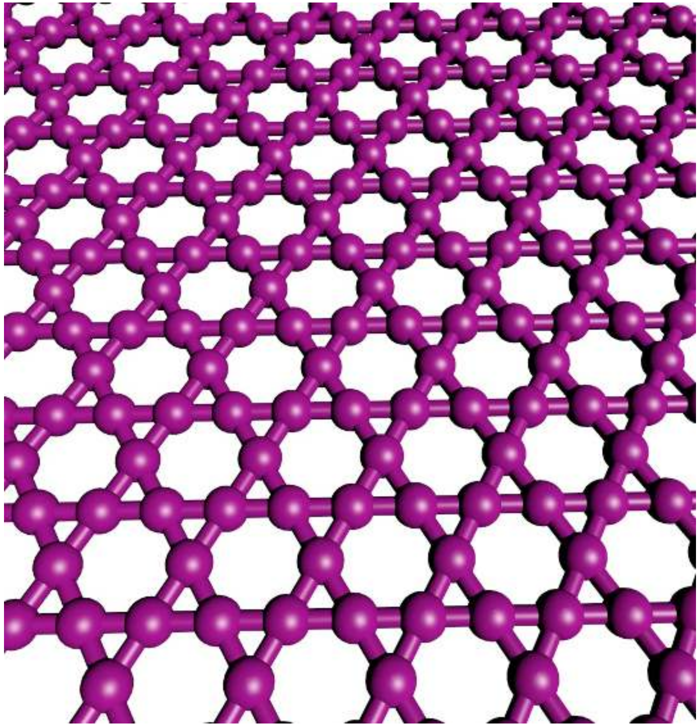
Ground state $|GS\rangle = \frac{1}{\sqrt{2}}(|\uparrow_1\downarrow_2\rangle - |\downarrow_1\uparrow_2\rangle)$

Scale up and frustrate

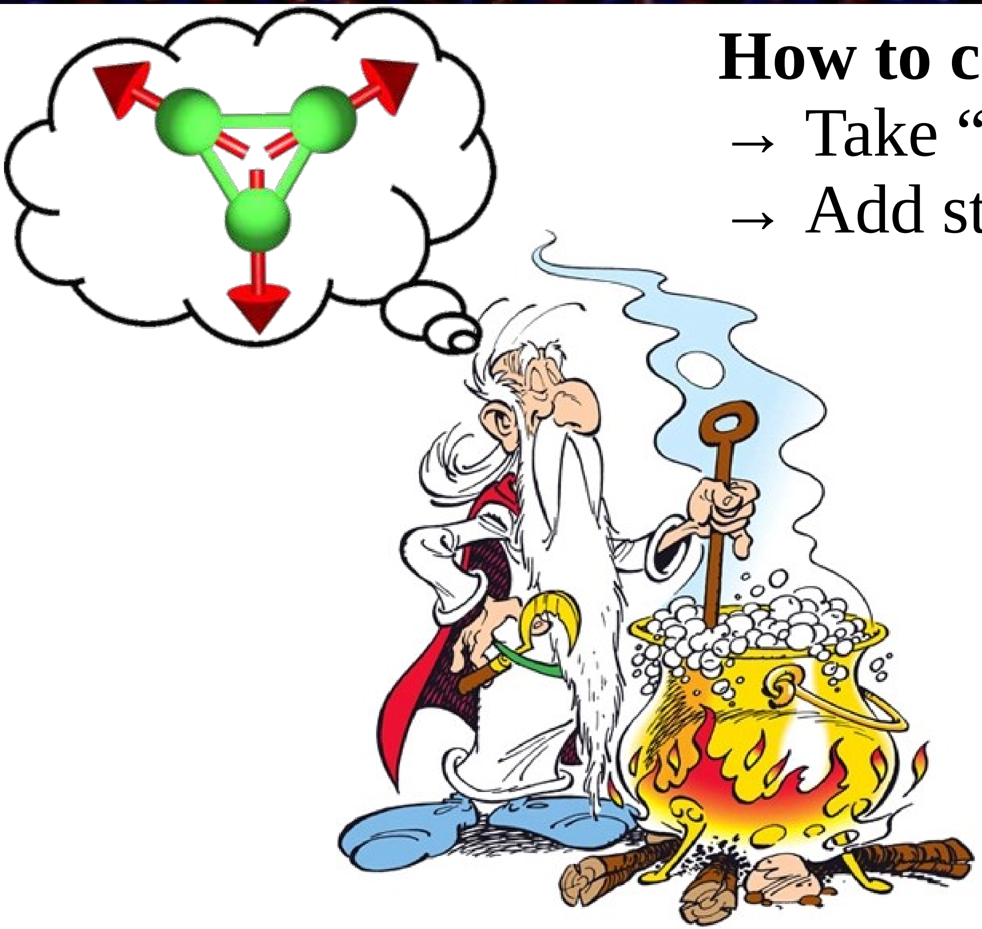
Triangular



Kagome



A recipe for frustration



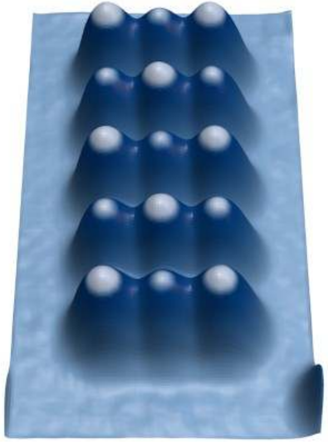
How to create magnetic frustration

→ Take “electrons” in a frustrated lattice

→ Add strong interactions

Building quantum matter with artificial lattices

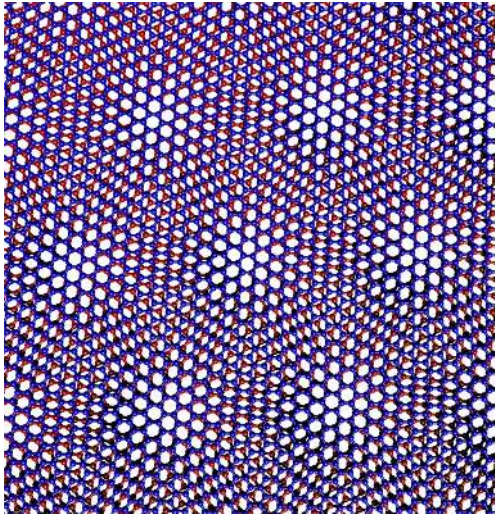
Atomic lattices



a = 0.5 nm

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

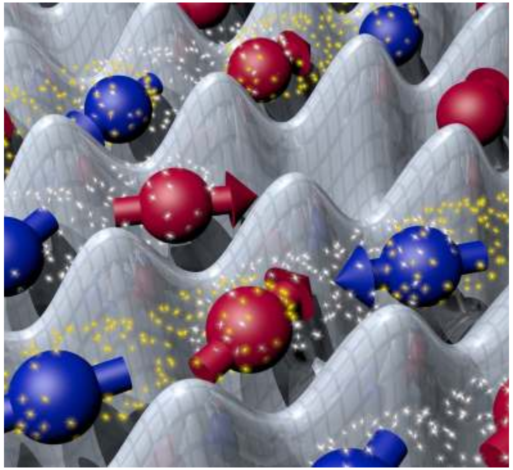
Twisted 2D moire materials



a = 50 nm

Nature 556, 80–84 (2018)

Cold atoms

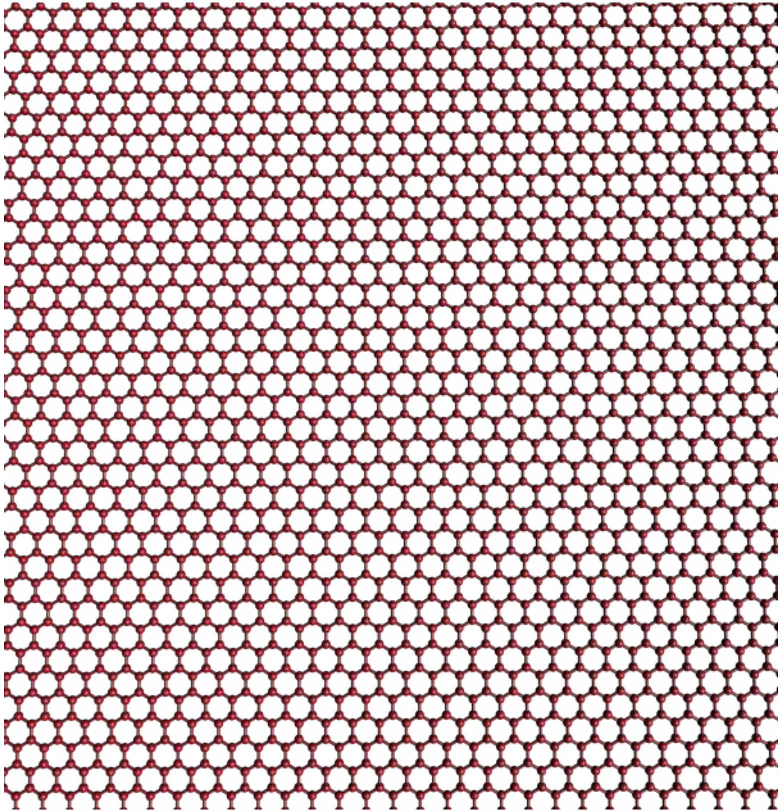


a = 1000 nm

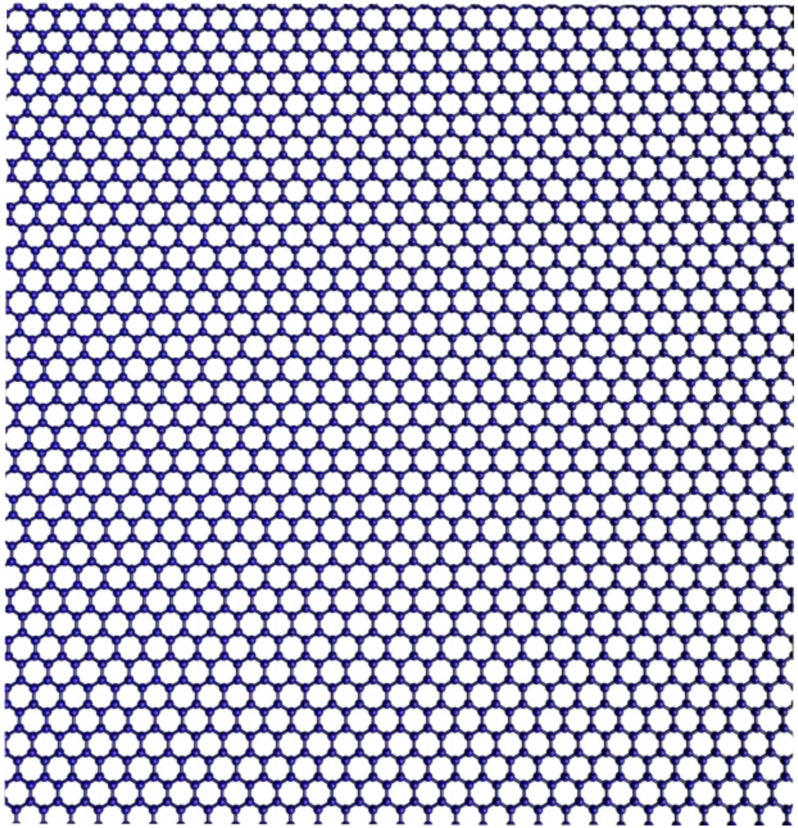
Nature 545.7655 (2017)
Nature 455.7210 (2008)
Phys. Rev. Lett. 111, 185307 (2013)

Moire in twisted bilayer graphene

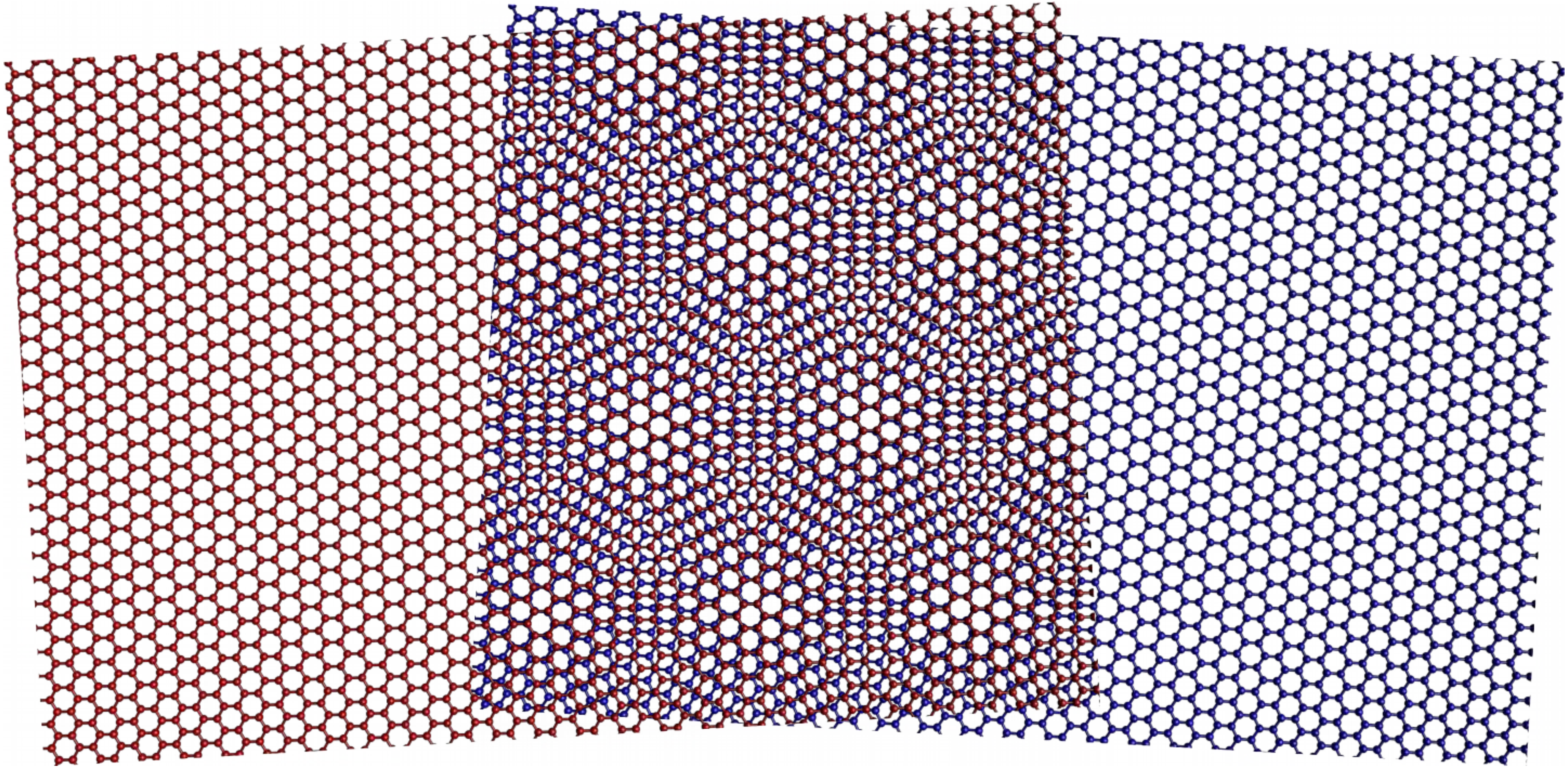
Upper graphene layer



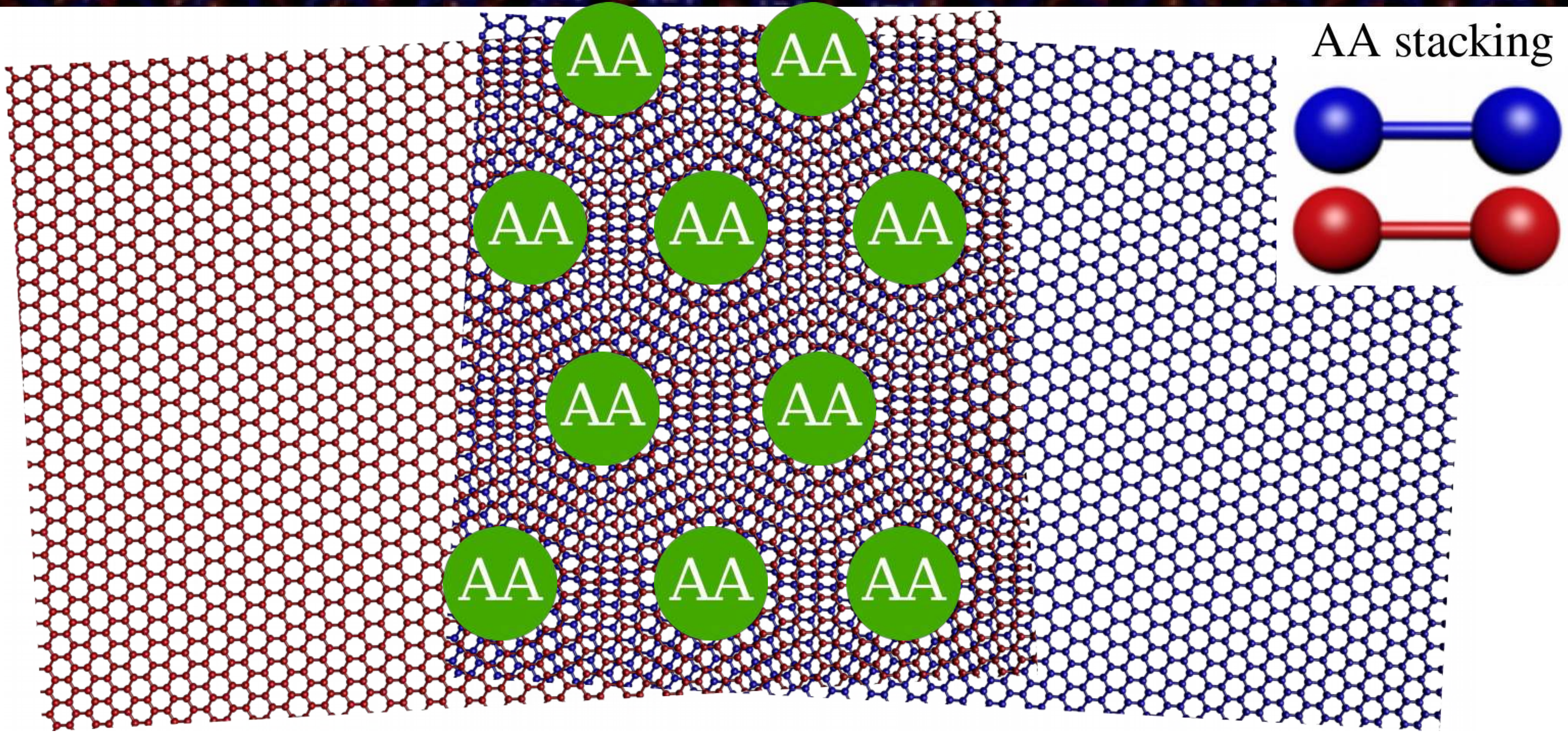
Lower graphene layer



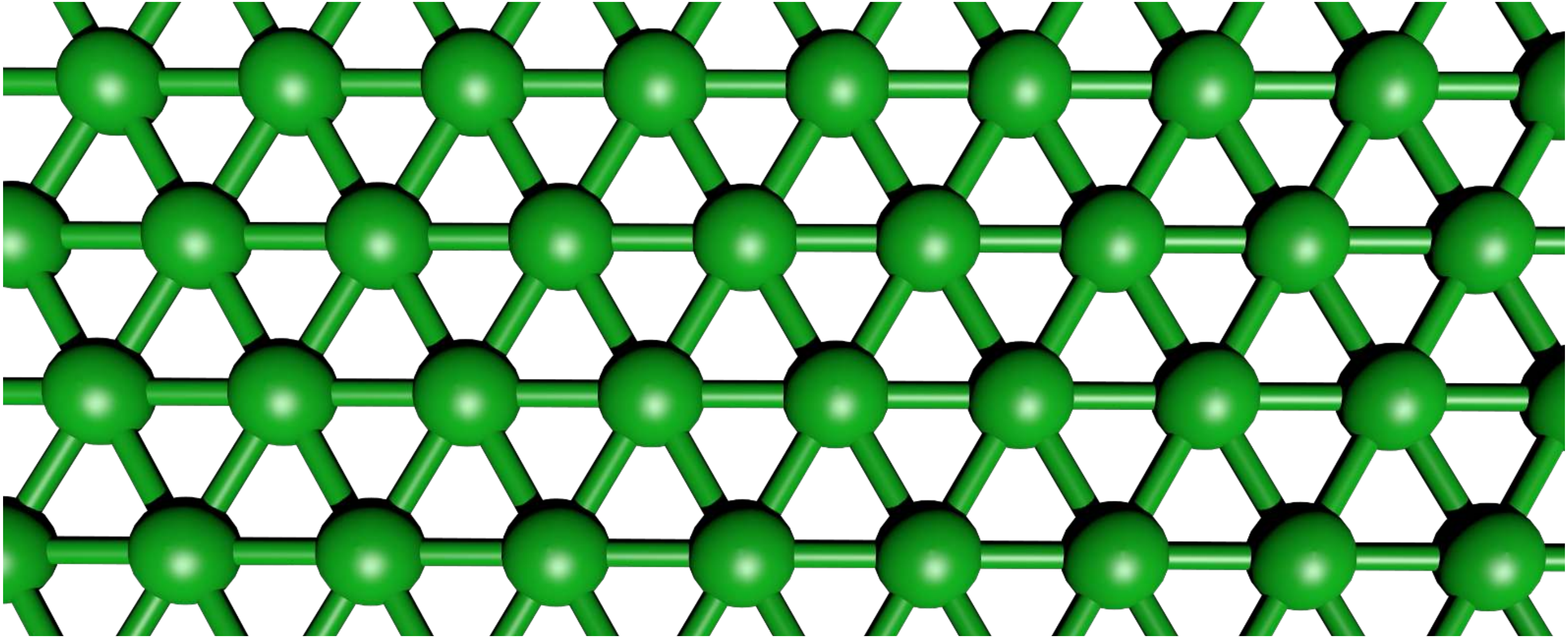
Moire in twisted bilayer graphene

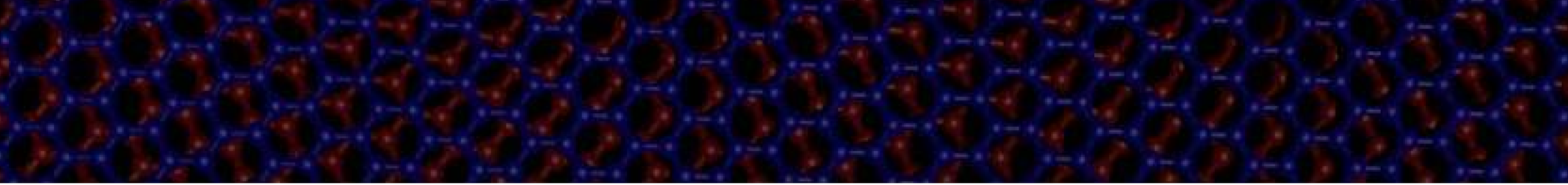


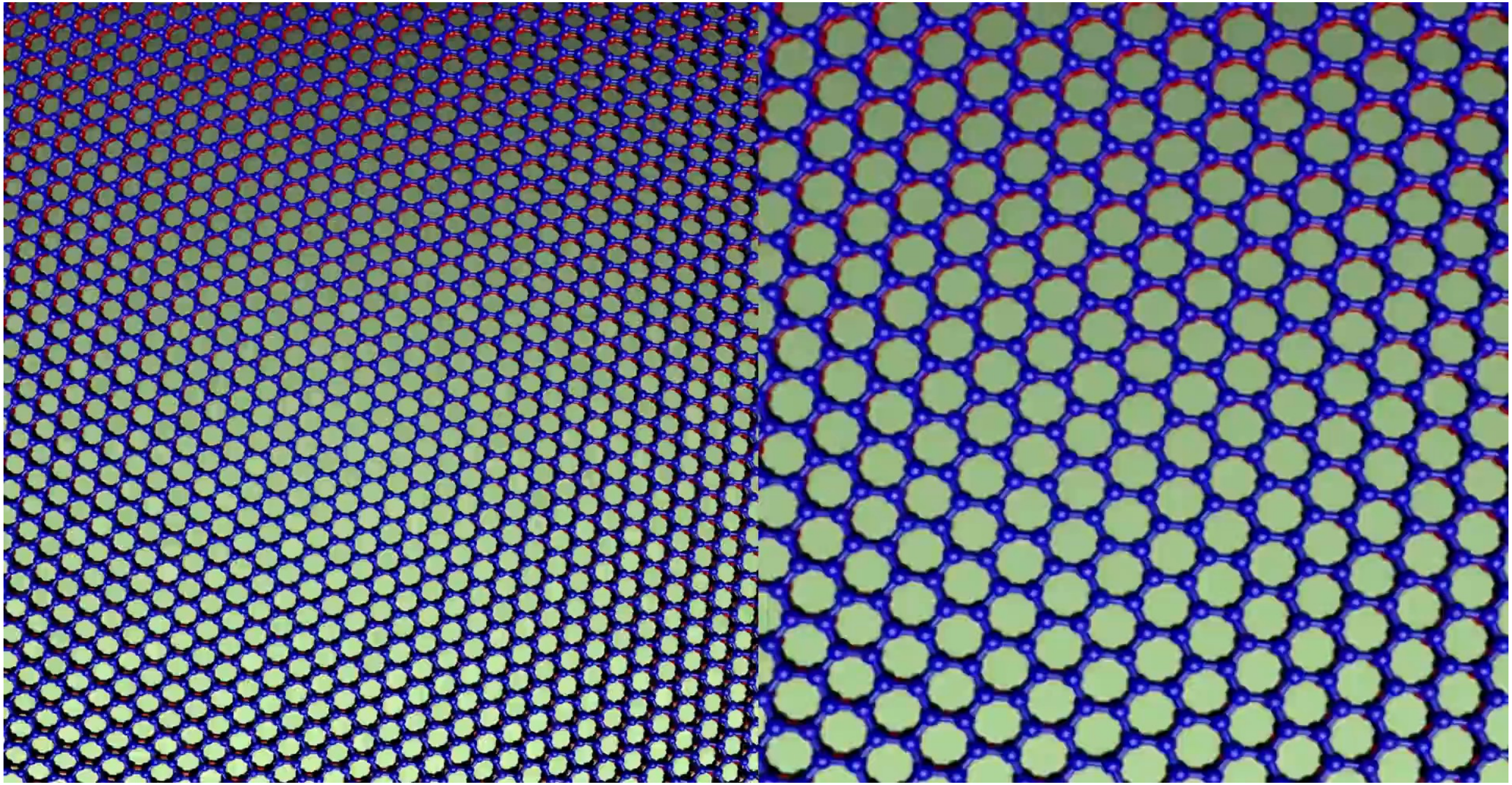
Moire in twisted bilayer graphene



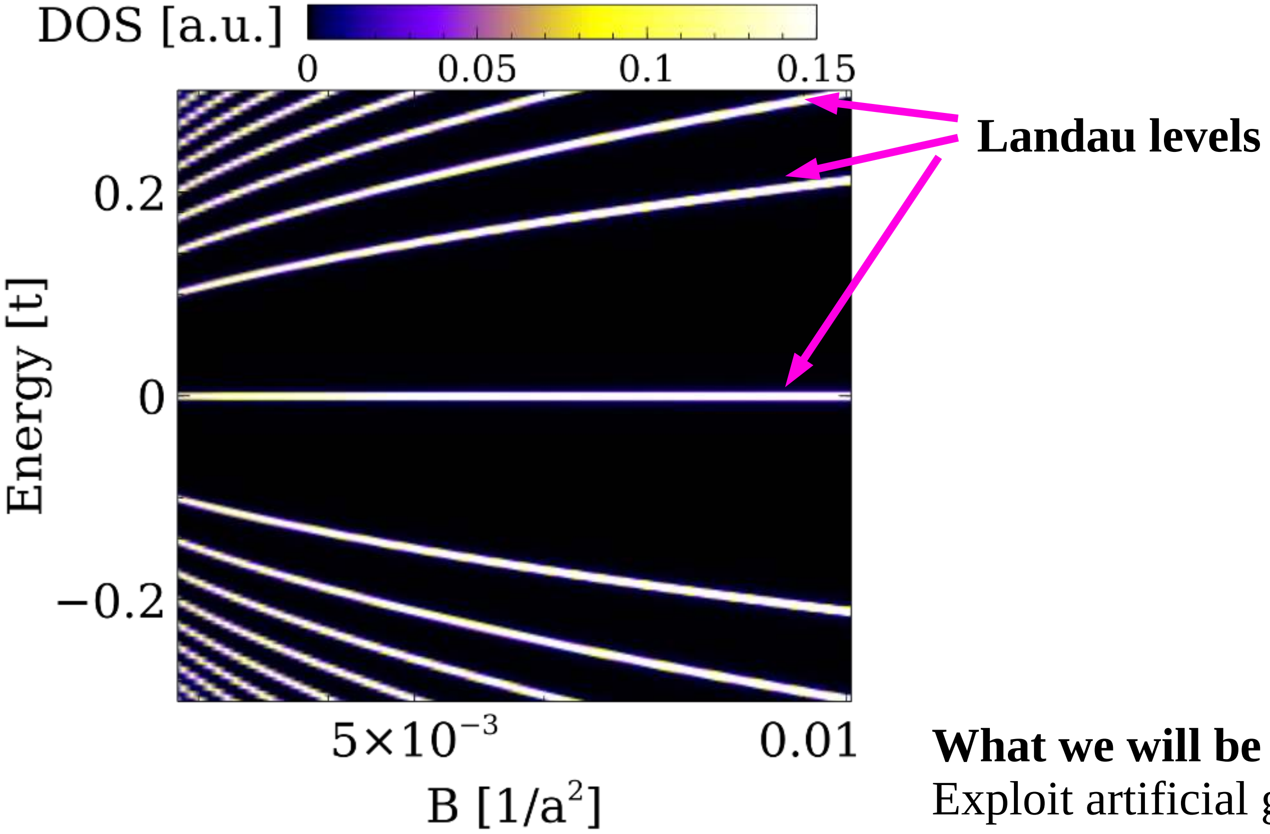
Moire in twisted bilayer graphene



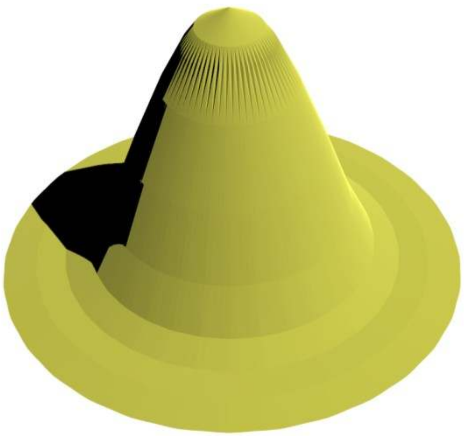




Building localized levels with gauge fields

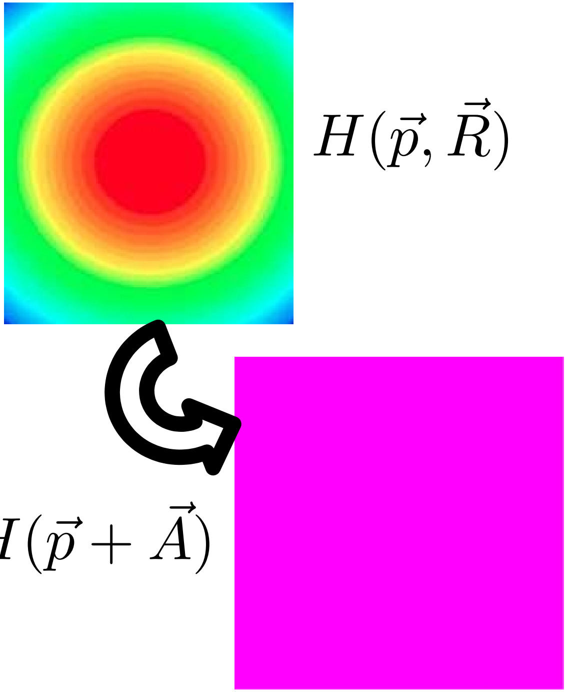


Landau level wavefunction



What we will be doing today:
Exploit artificial gauge fields to create localized modes

Emergent gauge fields in a nutshell



How to derive an artificial gauge field

Spatially modulated Hamiltonian $H = H(\vec{p},\vec{R})$

Taylor expand $H(\vec{p},\vec{R}) \approx H(\vec{p},0) + \vec{\nabla} H \cdot \vec{R}$

Reabsorb in the momentum $H(\vec{p},\vec{R}) \approx H(\vec{p}+\vec{A}(\vec{R}),0)$

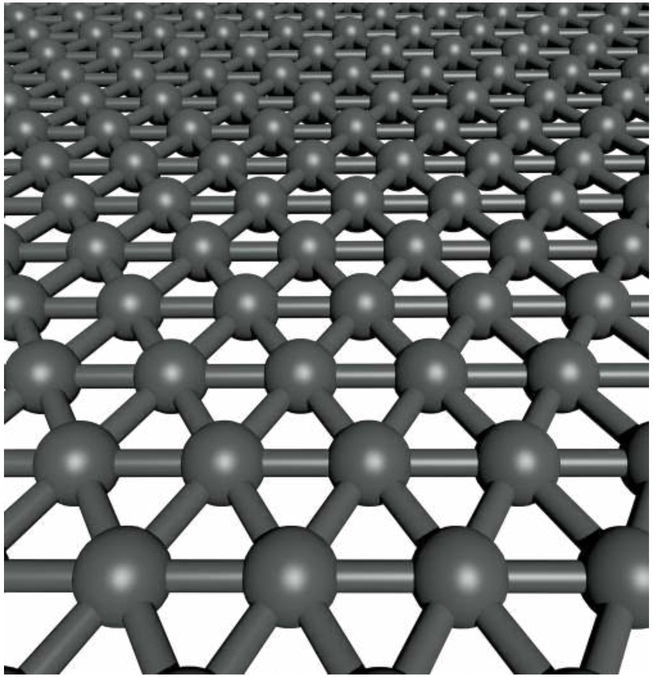
Emergent artificial gauge field $\vec{B} = \vec{\nabla} \times \vec{A}$

Non-uniform strain in graphene	**Non-abelian gauge field in TBG**	**Electric gauge field in biased TBG**
Physics Reports 496.4-5 (2010)	*Phys. Rev. Lett. 108, 216802 (2012)*	*Phys. Rev. Lett. 121, 146801 (2018)*

<u>**Spatial modulations are a natural source of artificial gauge fields**</u>

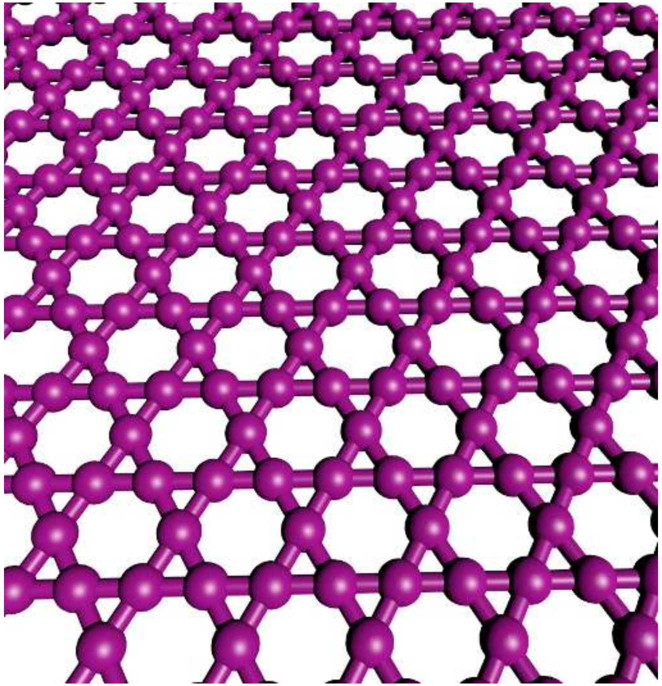
A natural platform for artificial gauge fields

Non-Abelian (elastic) gauge fields



Phys. Rev. Lett. 108, 216802 (2012)

Abelian (electric) gauge fields



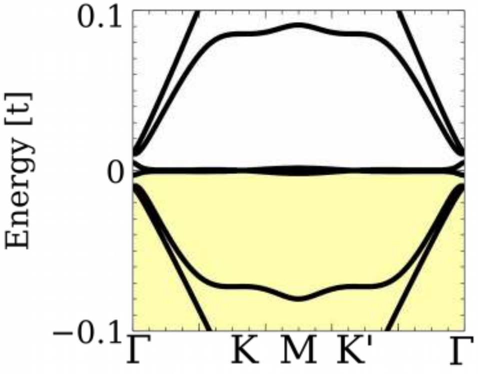
Phys. Rev. Lett. 121, 146801 (2018)

Towards controllable triangular magnetism

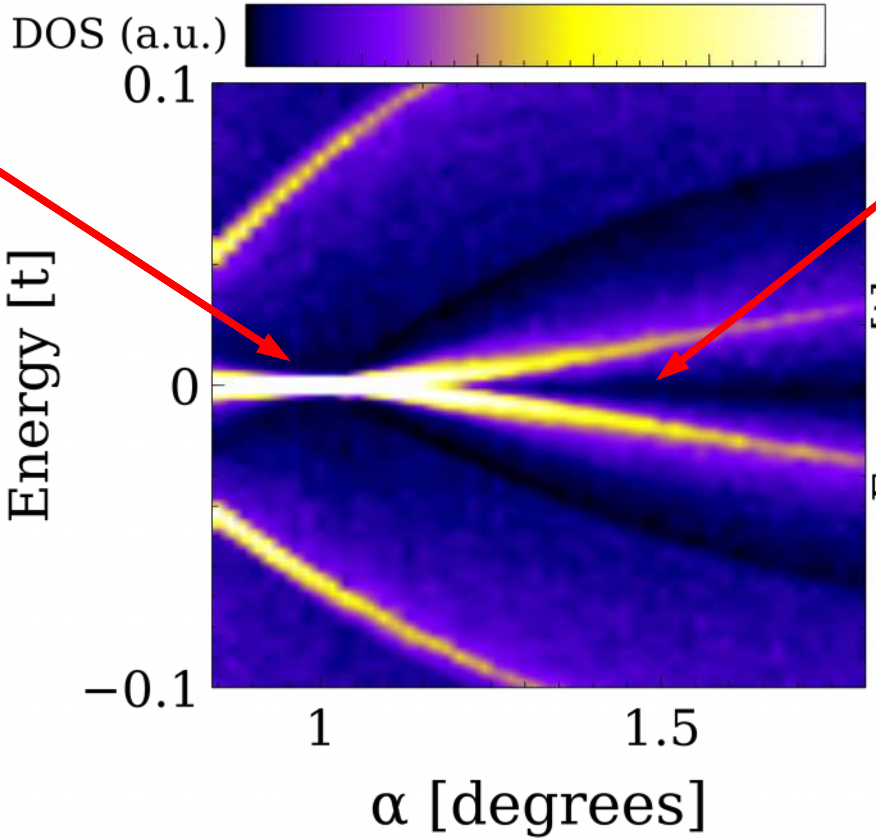
Diving into the magic regime

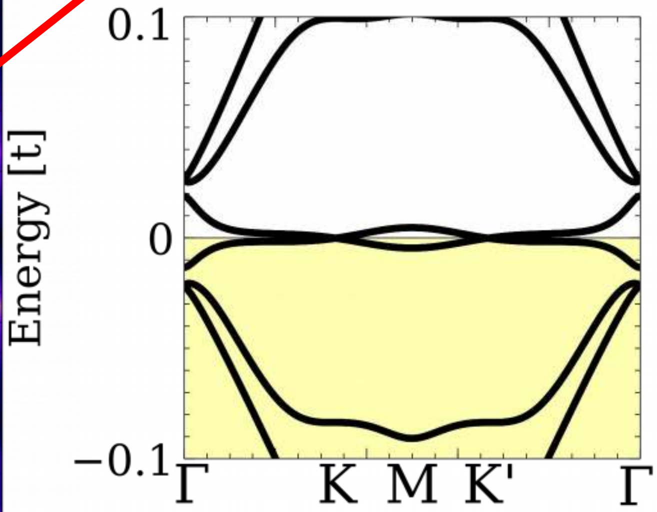
Magic angle

Sub-magic angle



PNAS 108.30 (2011)



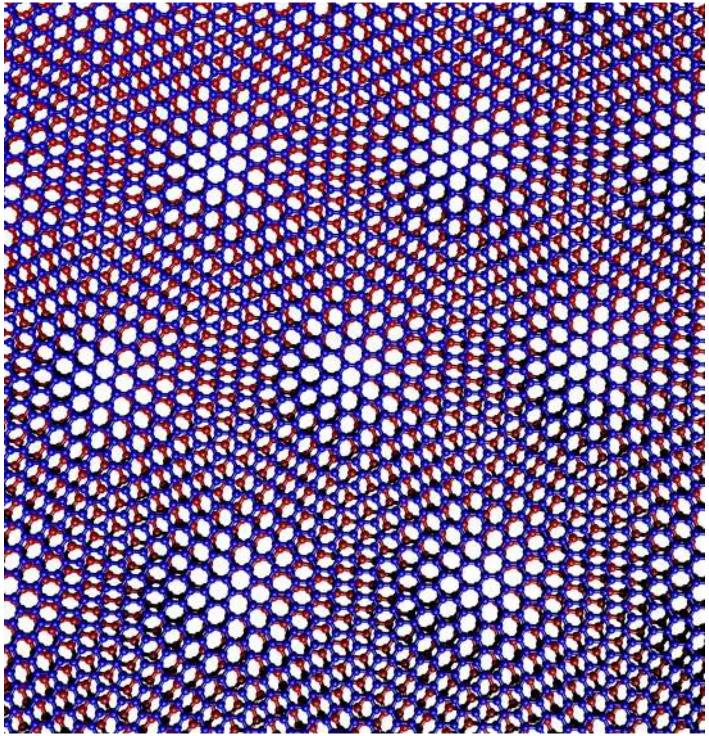


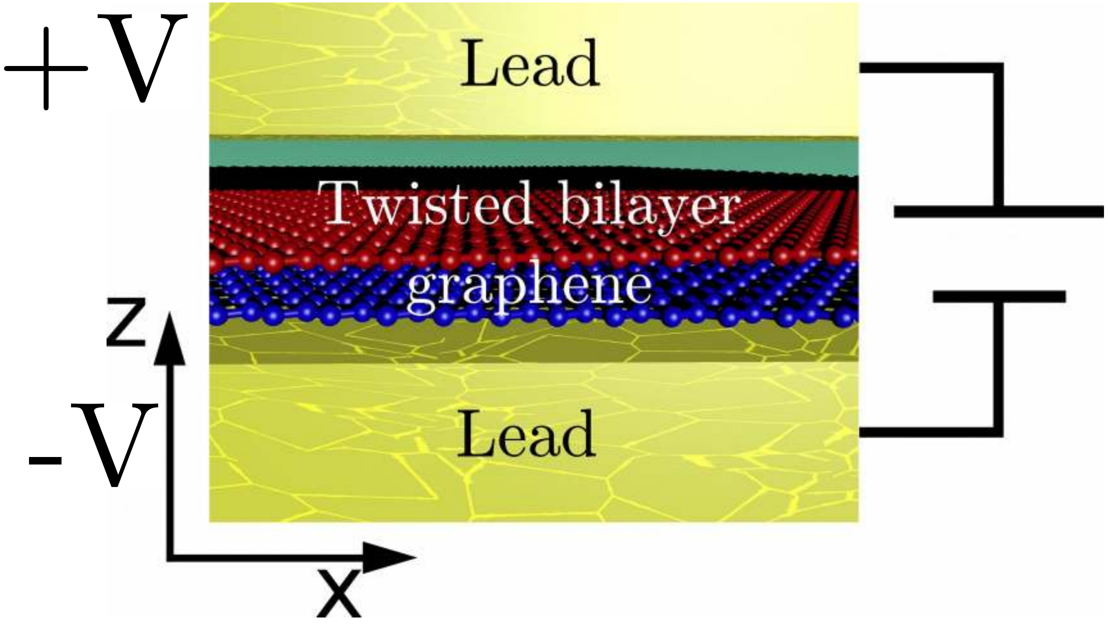
Lets focus on this one

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

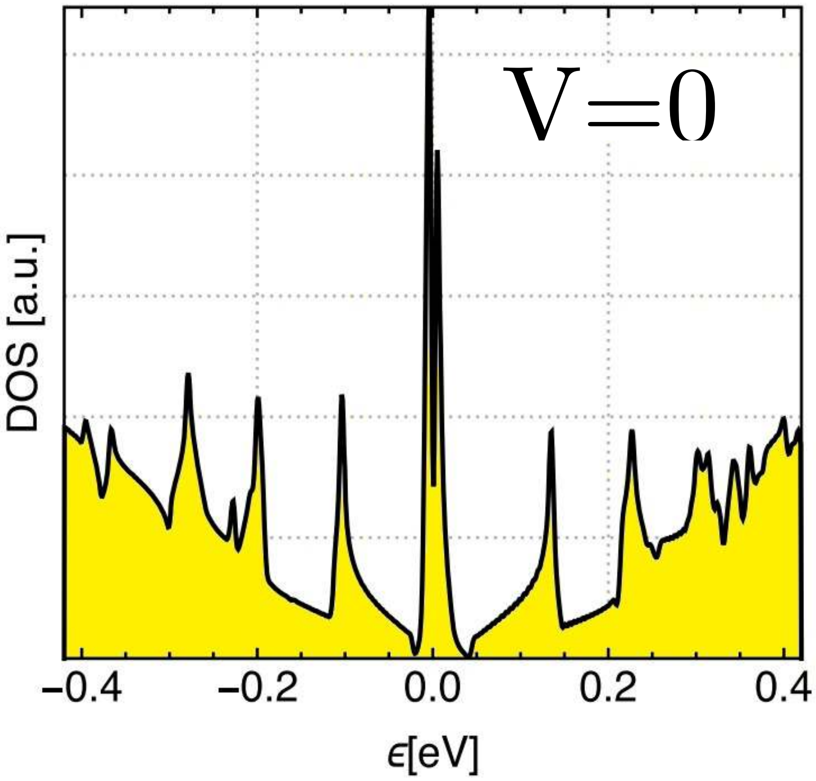
Electrical DOS enhancement for $\alpha = 1.5°$

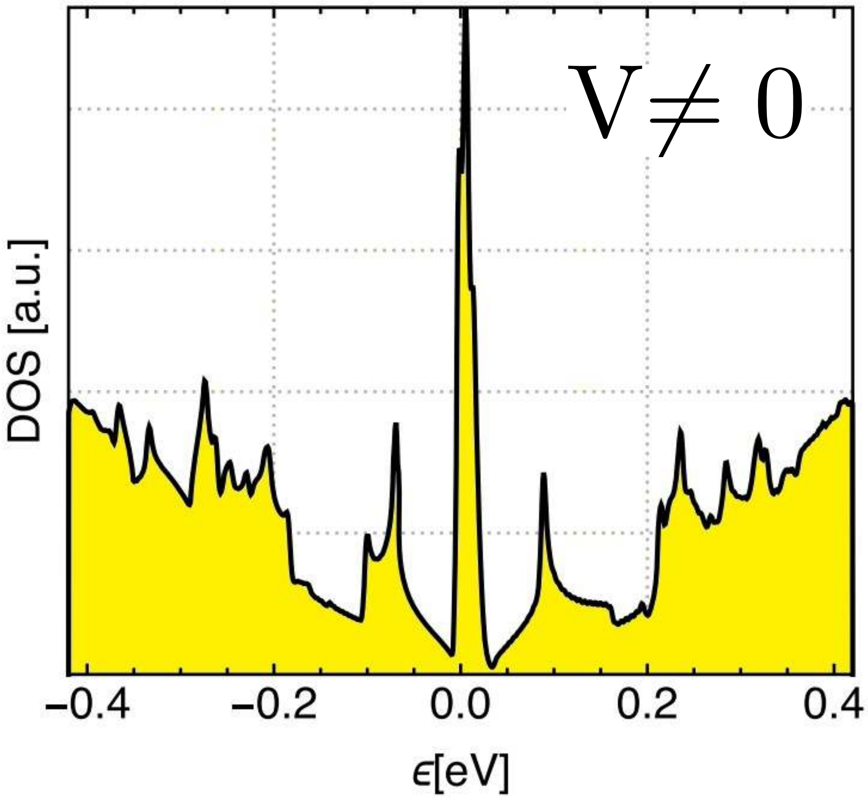
$\alpha = 1.5°$



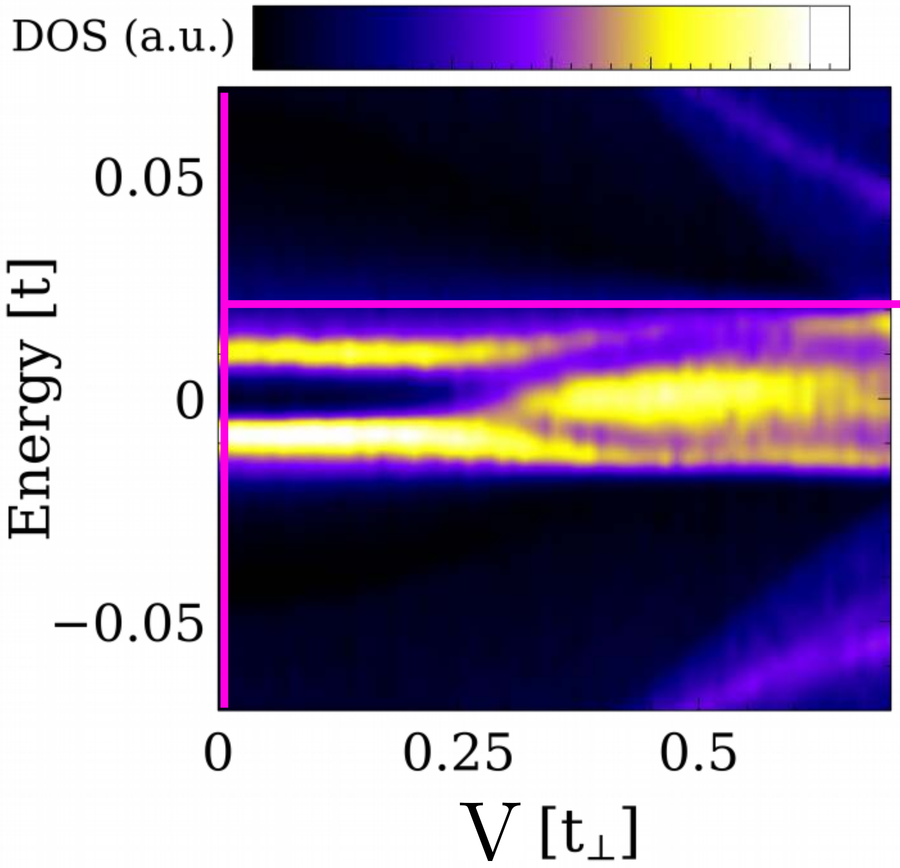


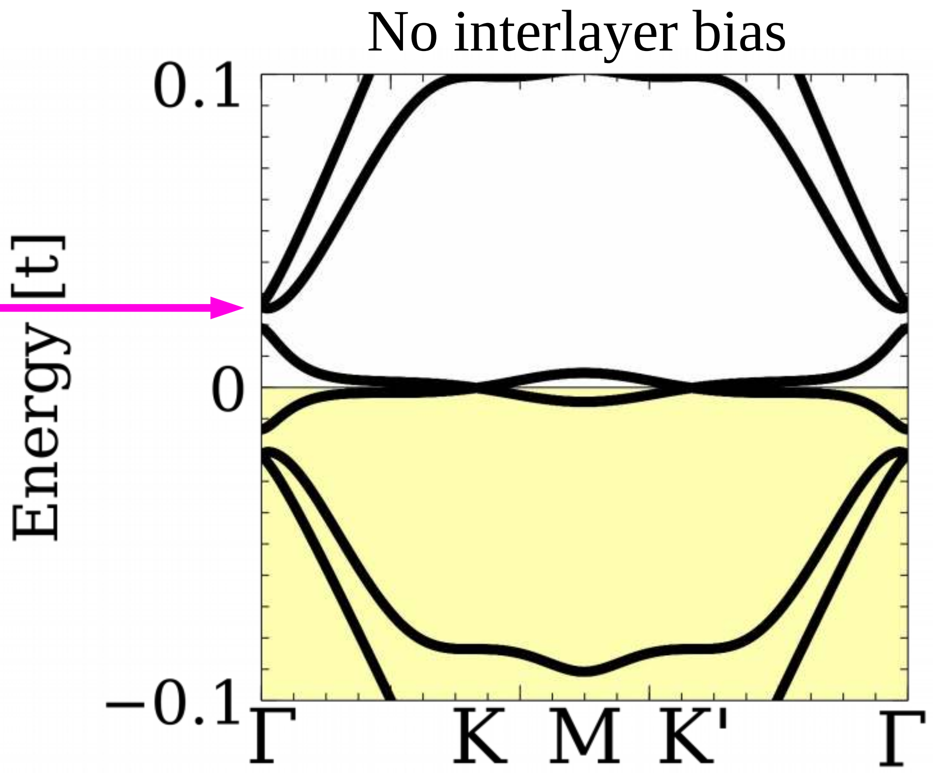
Electric bias in TBG at 1.5 degrees



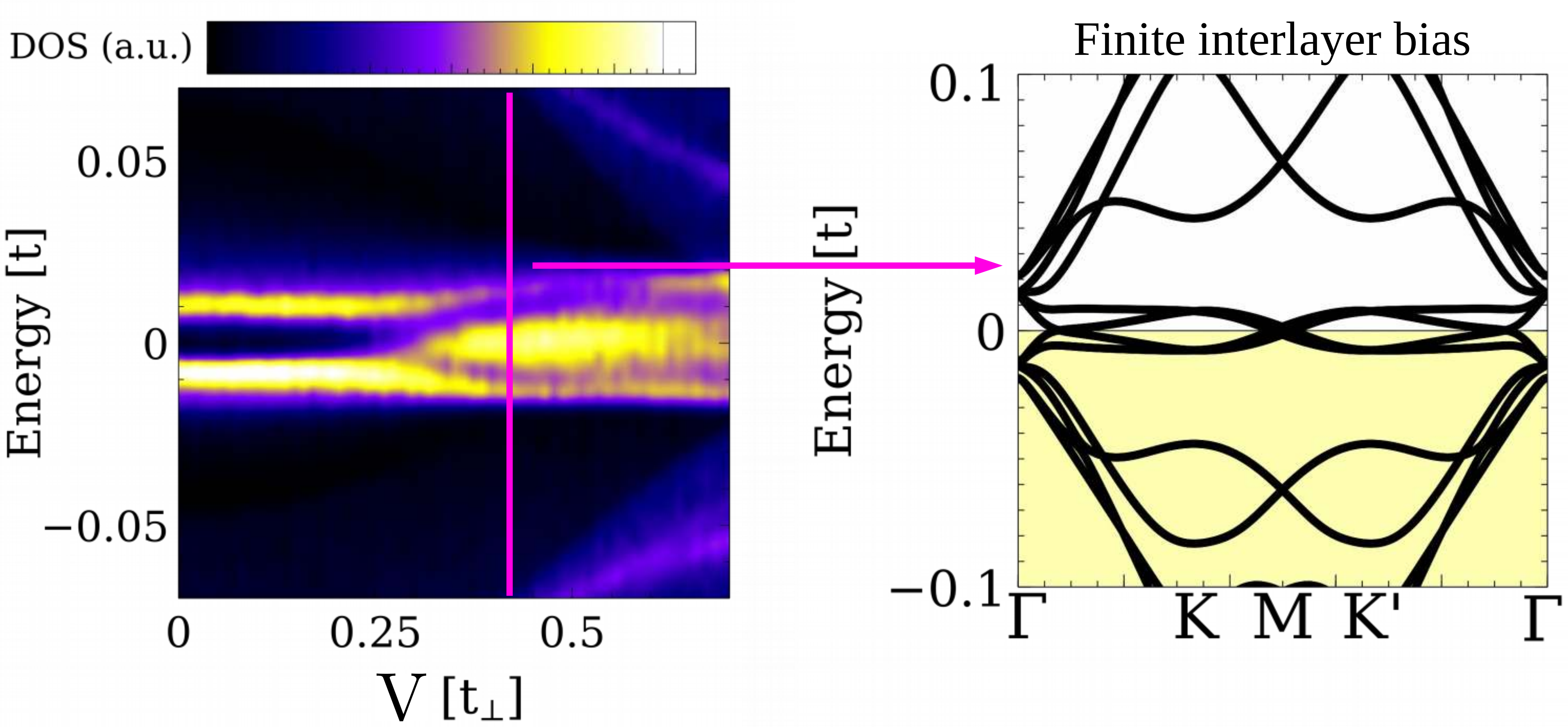


Enhancing DOS electrically



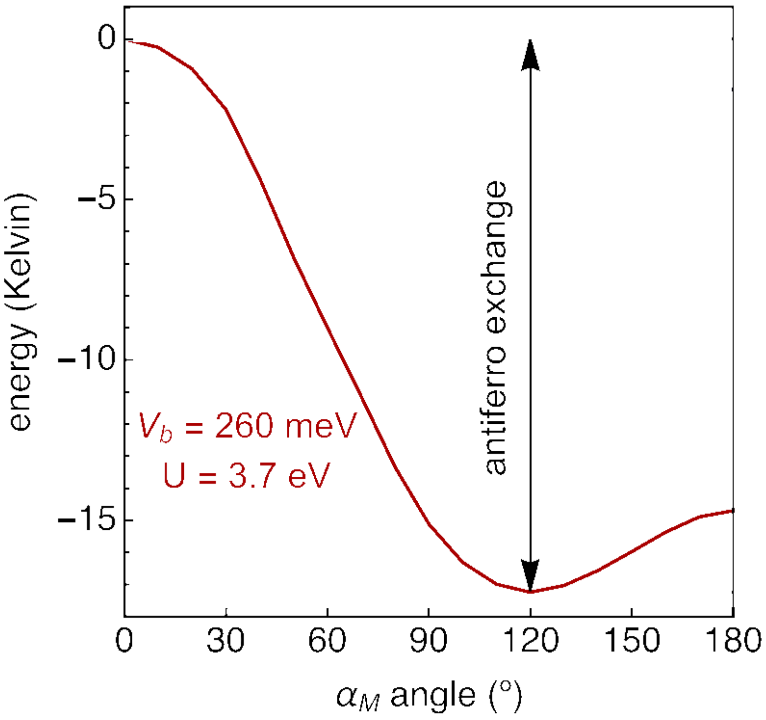


Enhancing DOS electrically



Spiral magnetism in biased TBG

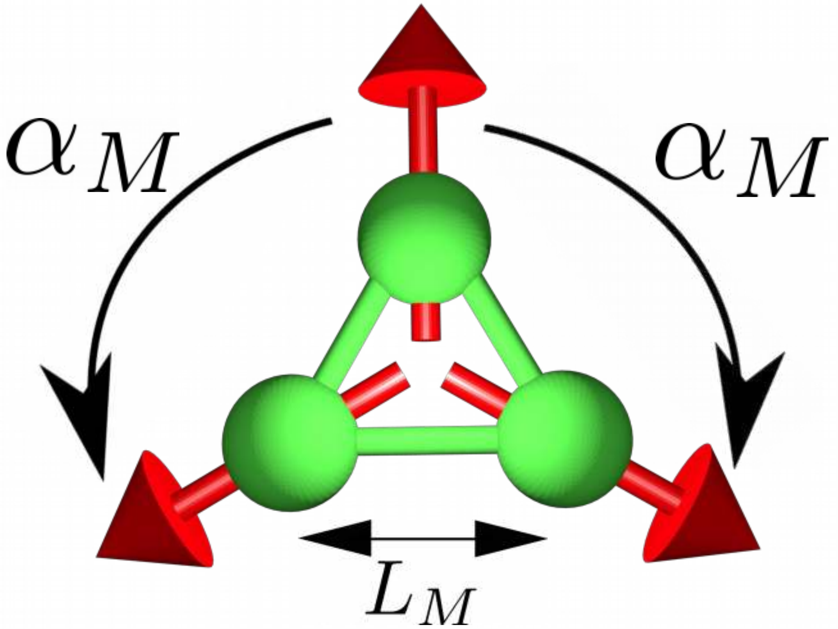
Energy VS spin-spiral angle



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

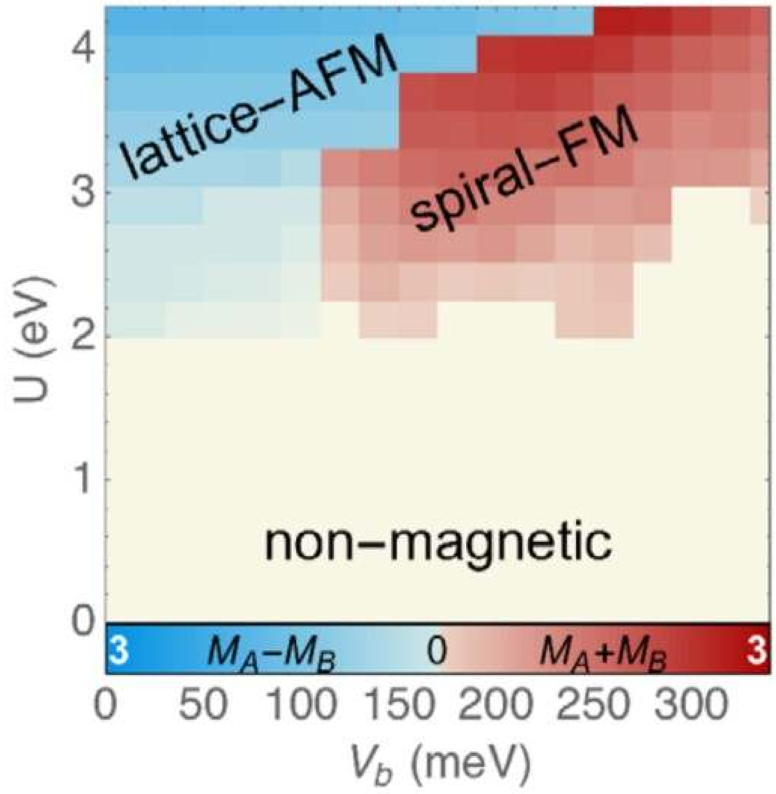
Solving at the mean field level

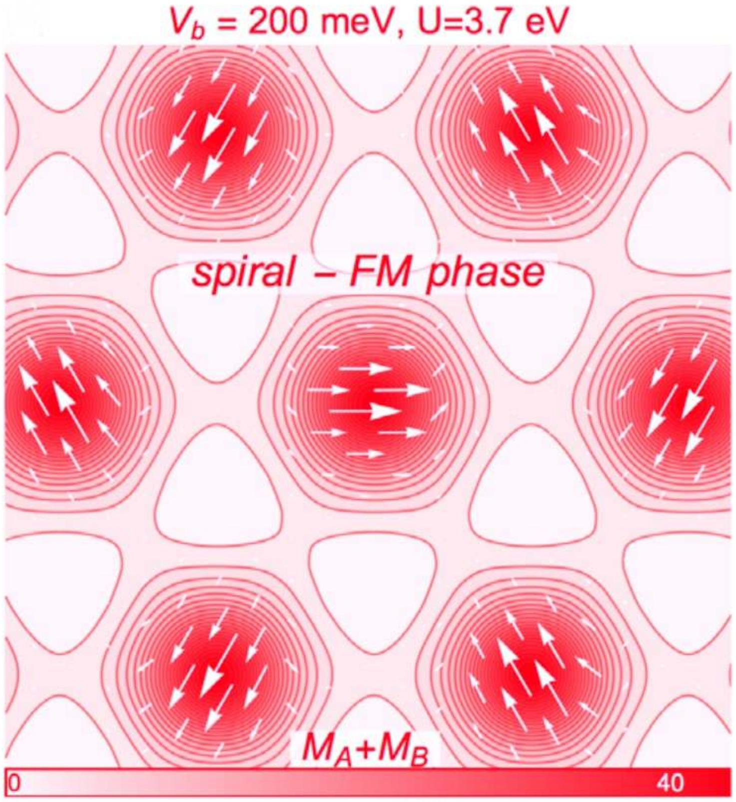
$$H = \sum_{i,j,s} t_{ij} c^{\dagger}_{i,s} c_{j,s} + \sum_i U n_{i,\uparrow} n_{j,\downarrow}$$



Spin spiral ground state with electric bias

Electrically controlling exchange interactions

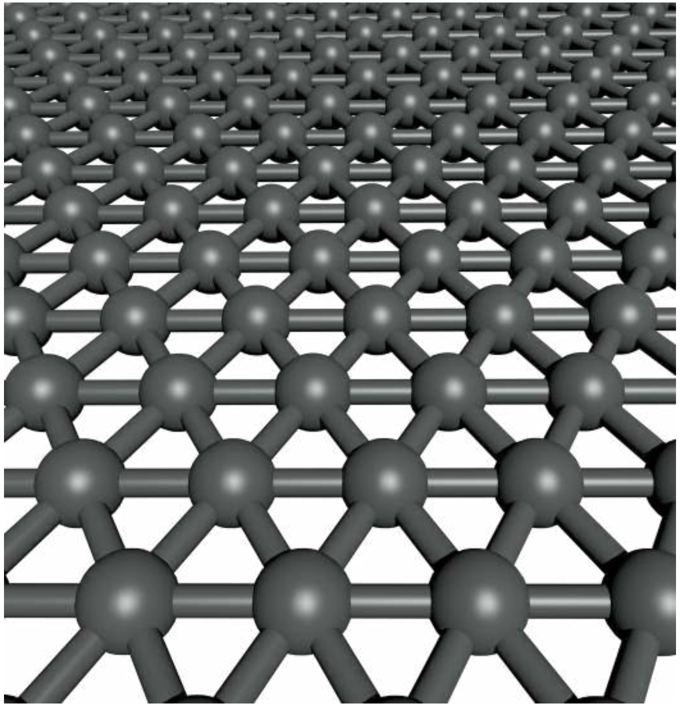




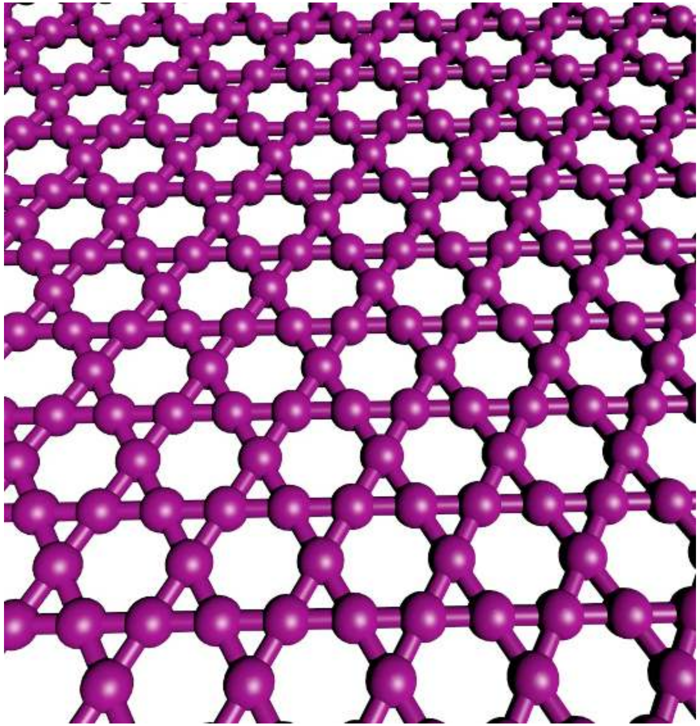
Phys. Rev. Lett. 119, 107201 (2017)

Towards a Kagome lattice

From triangular to Kagome

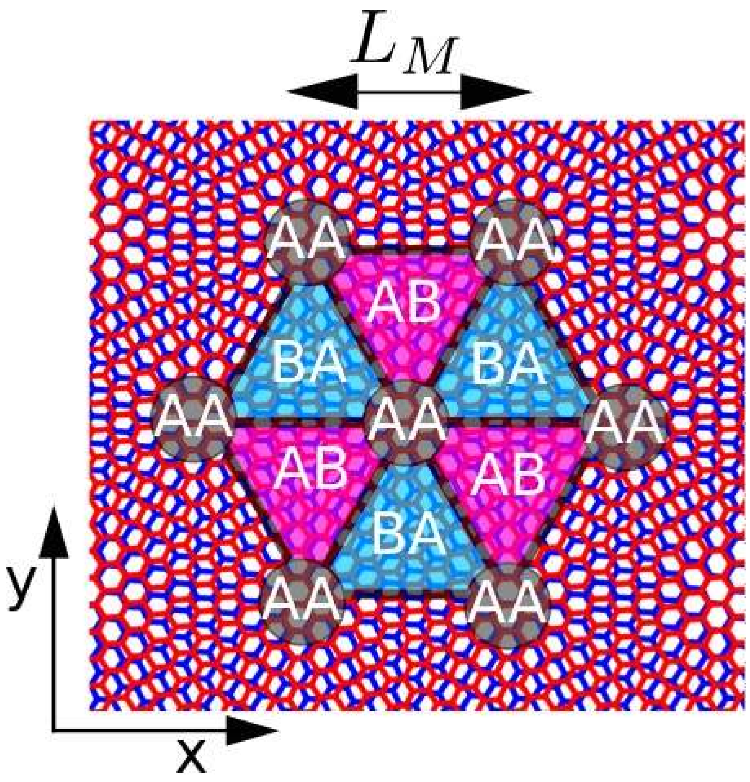


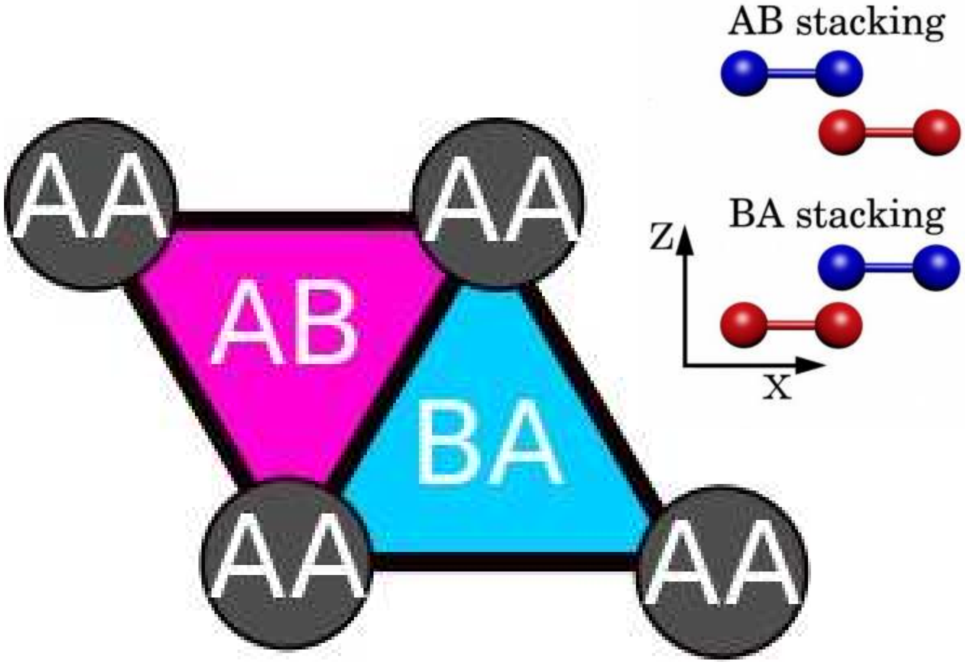
?



Can we generate additional gauge fields in twisted bilayers?

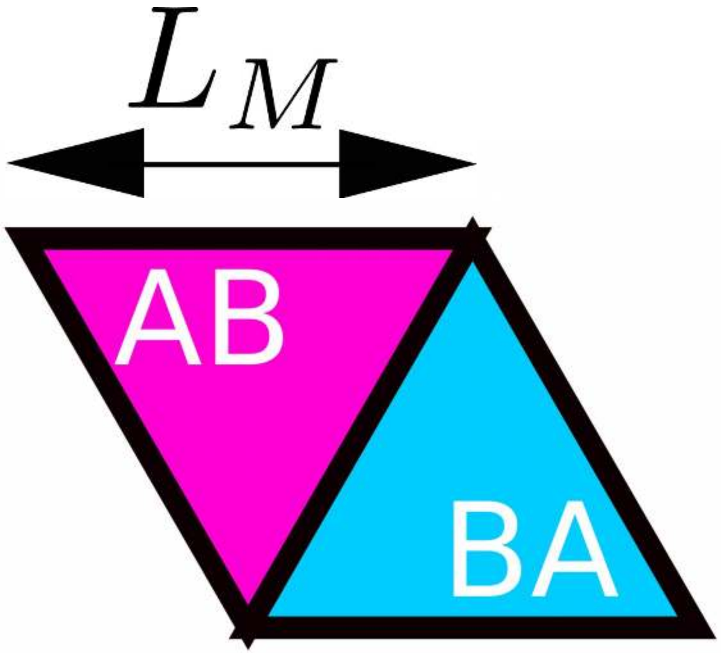
Towards a possible Kagome lattice

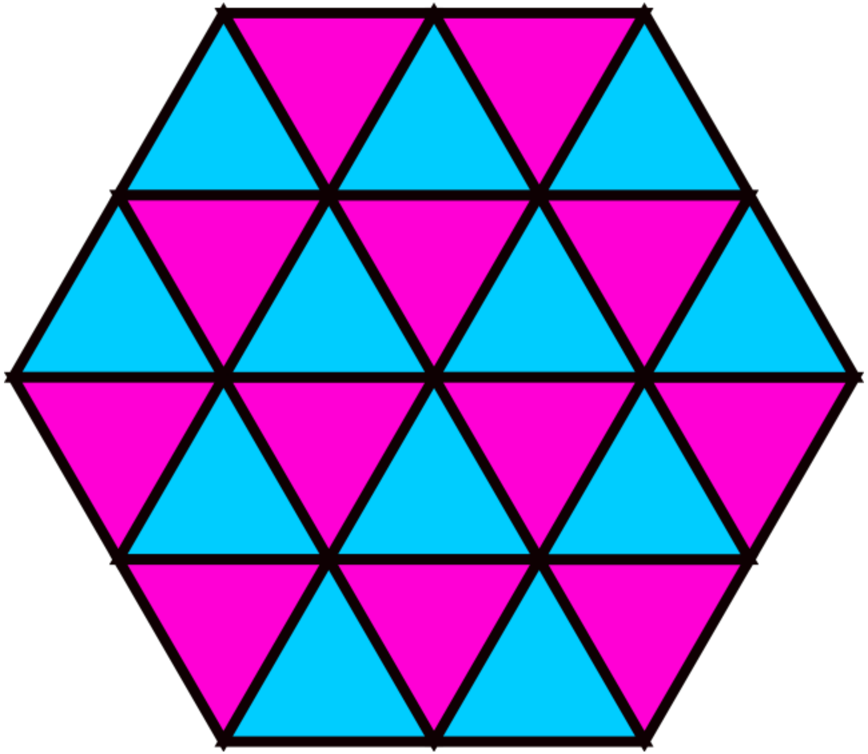




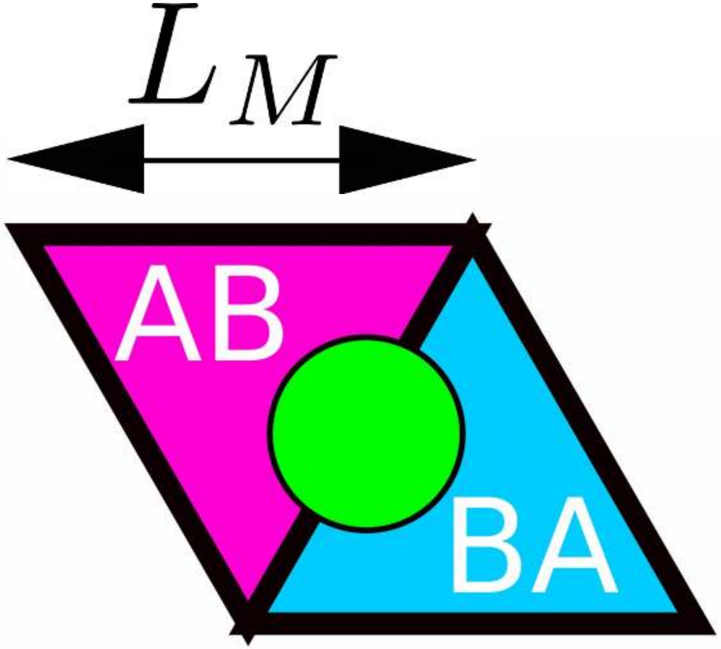
Let us look at the AB/BA structure

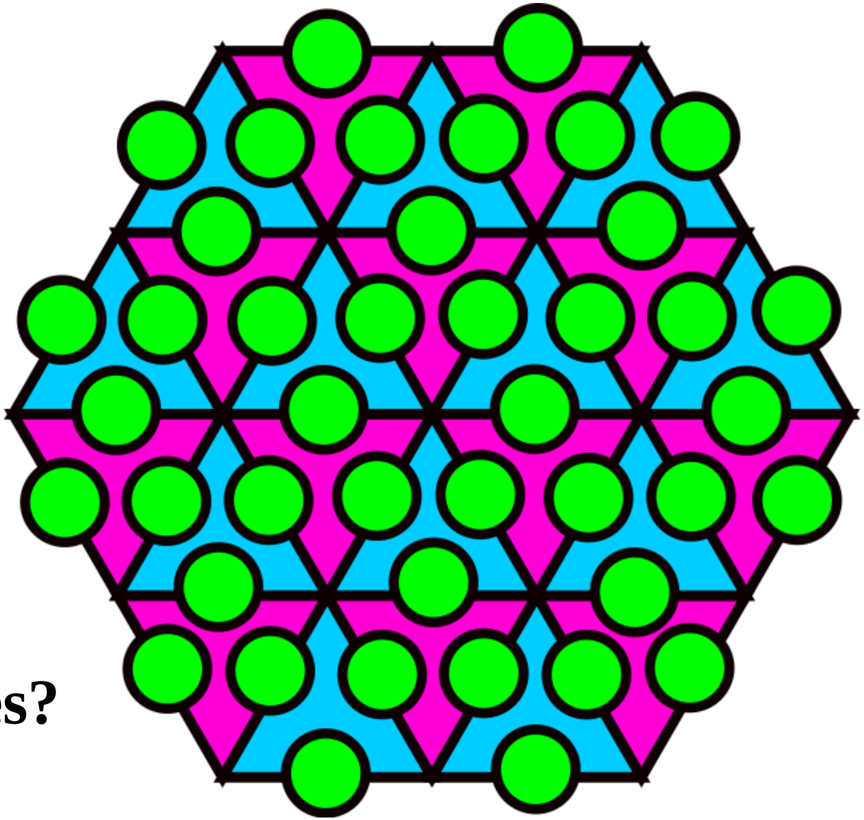
The possible Kagome lattice in TBG





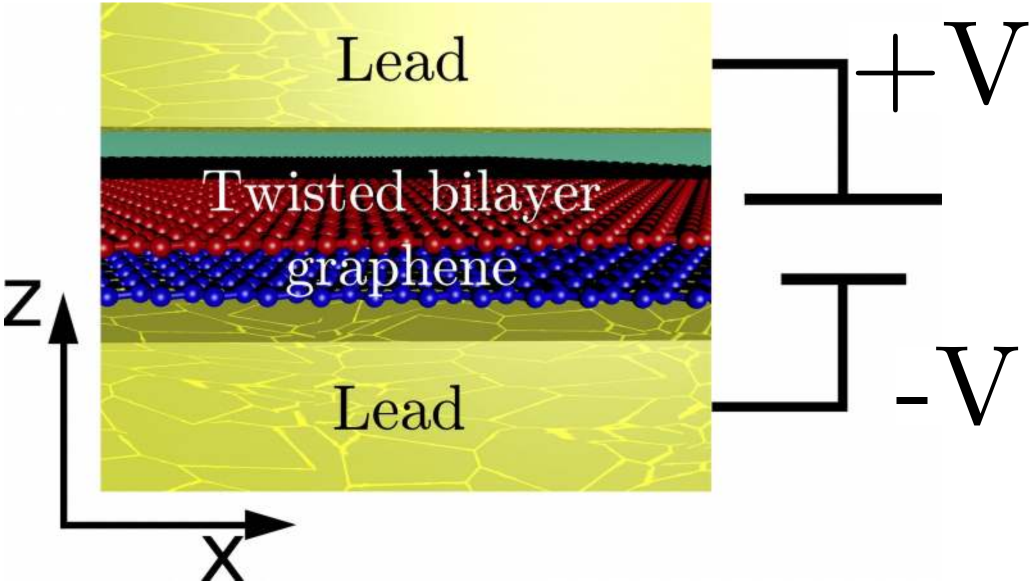
The possible Kagome lattice in TBG

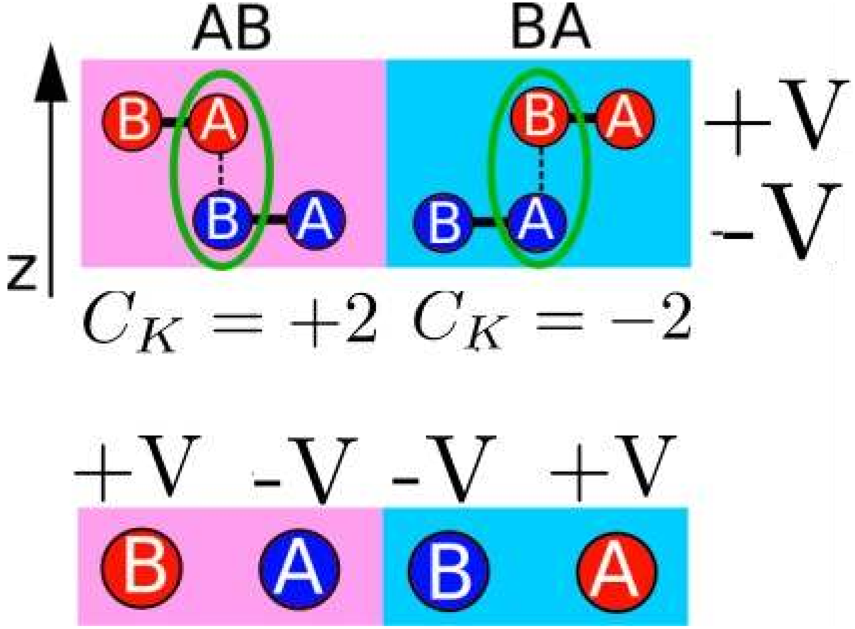




How do we generate such localized modes?

Electric gauge fields in TBG



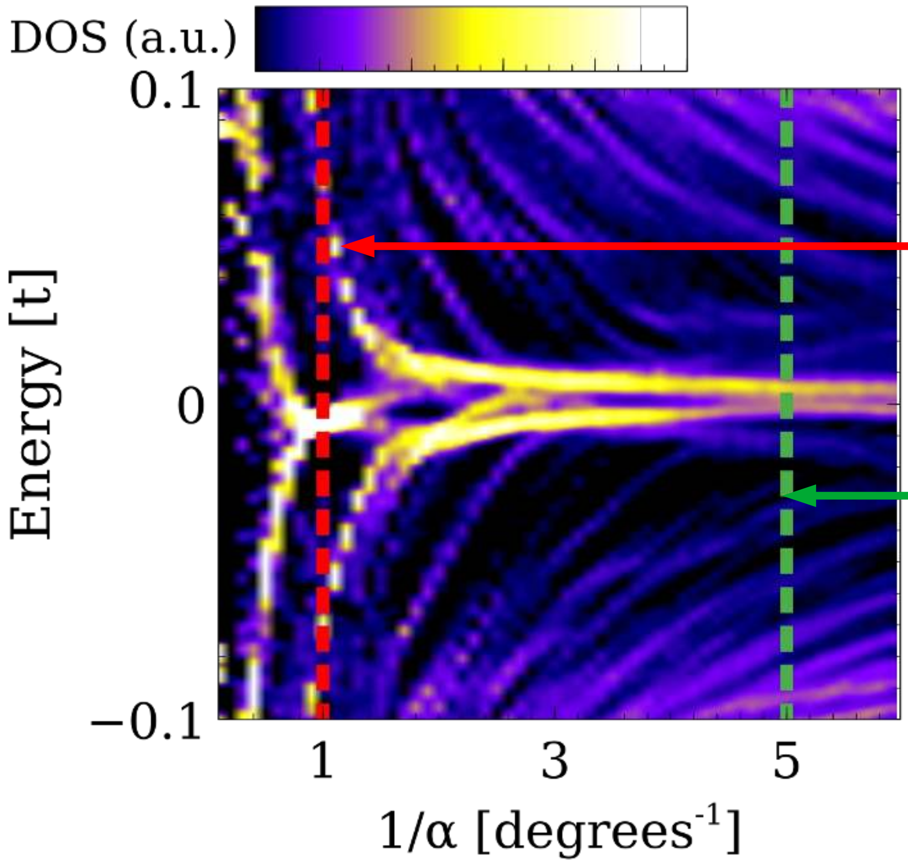


Electrically generated gauge field

$$H(\vec{p}, \vec{R}) \rightarrow H(\vec{p} + \vec{A})$$

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

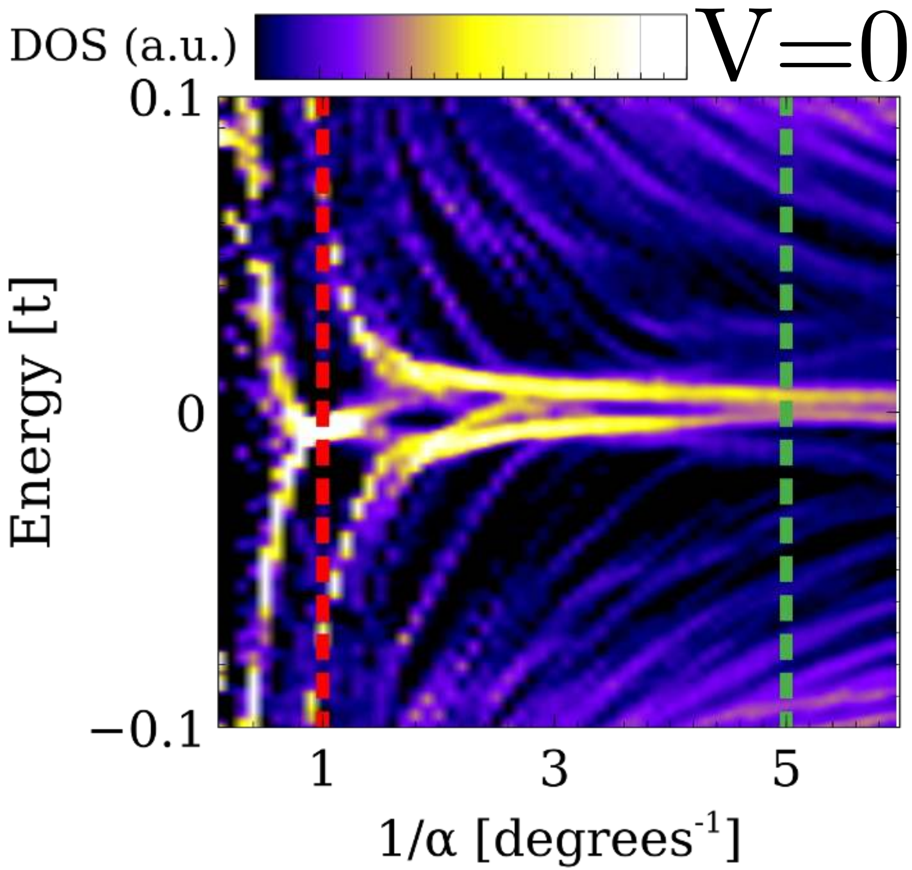
Diving into the tiny-angle regime

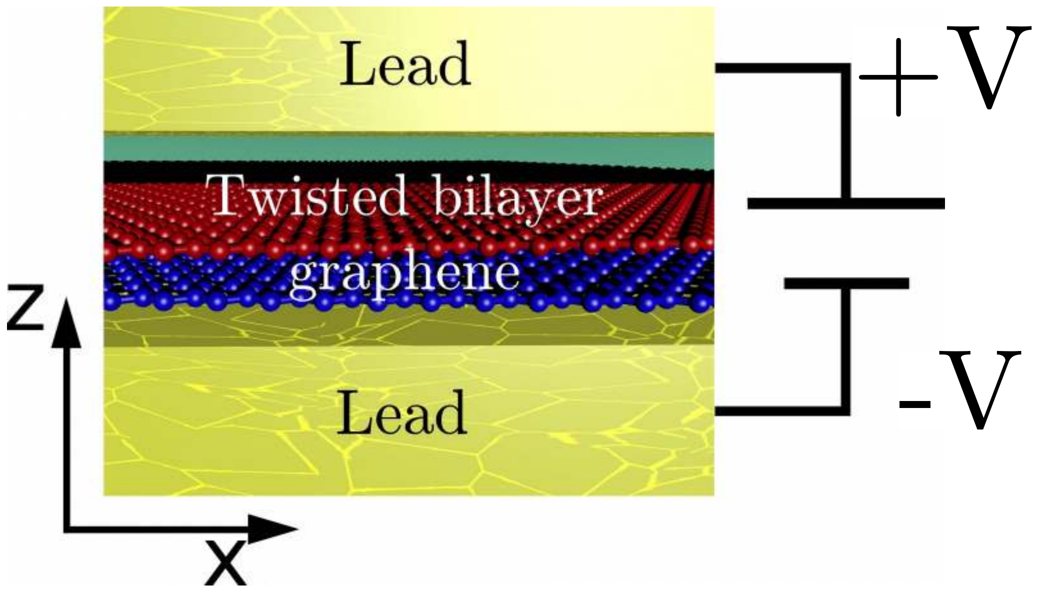


Magic-angle 1°

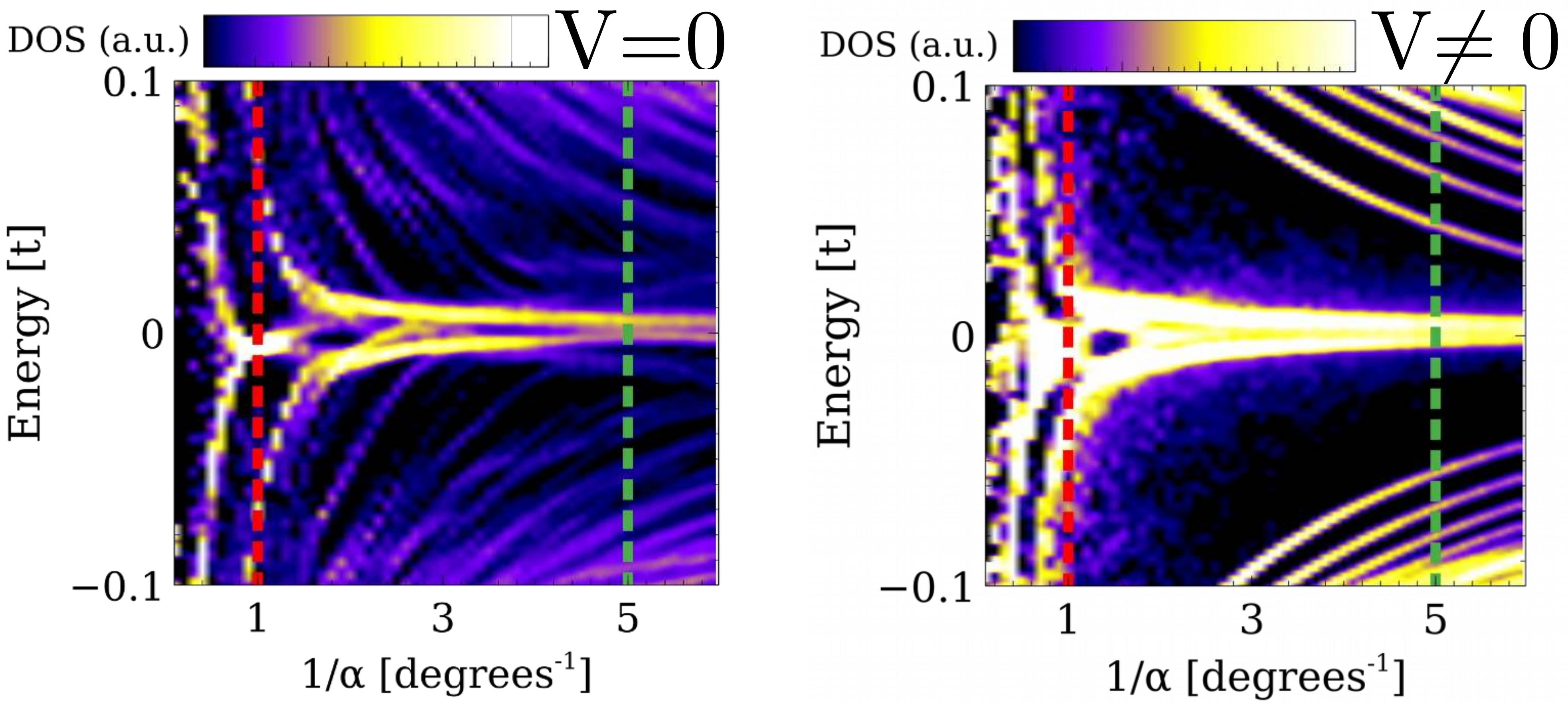
Tiny-angle 0.2°

Diving into the biased tiny-angle regime

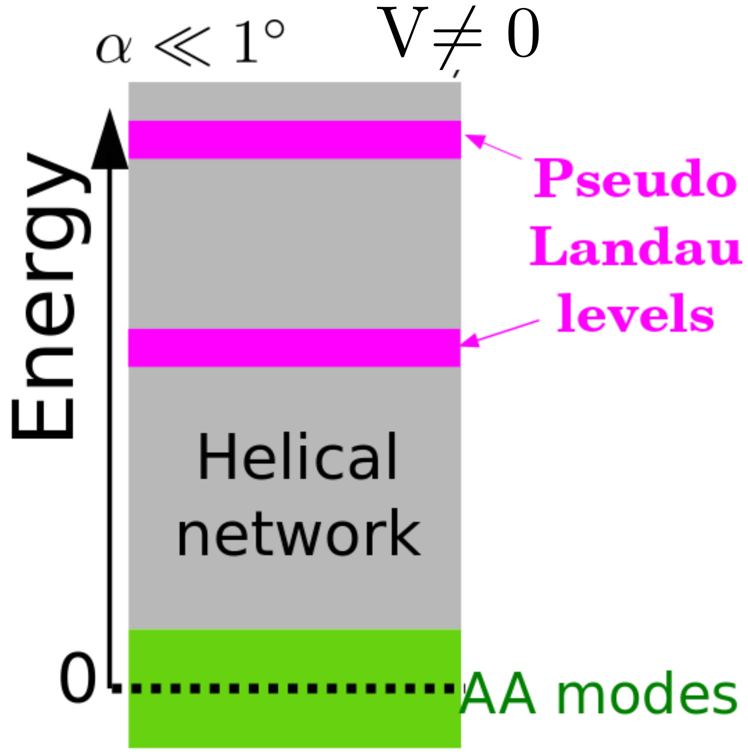


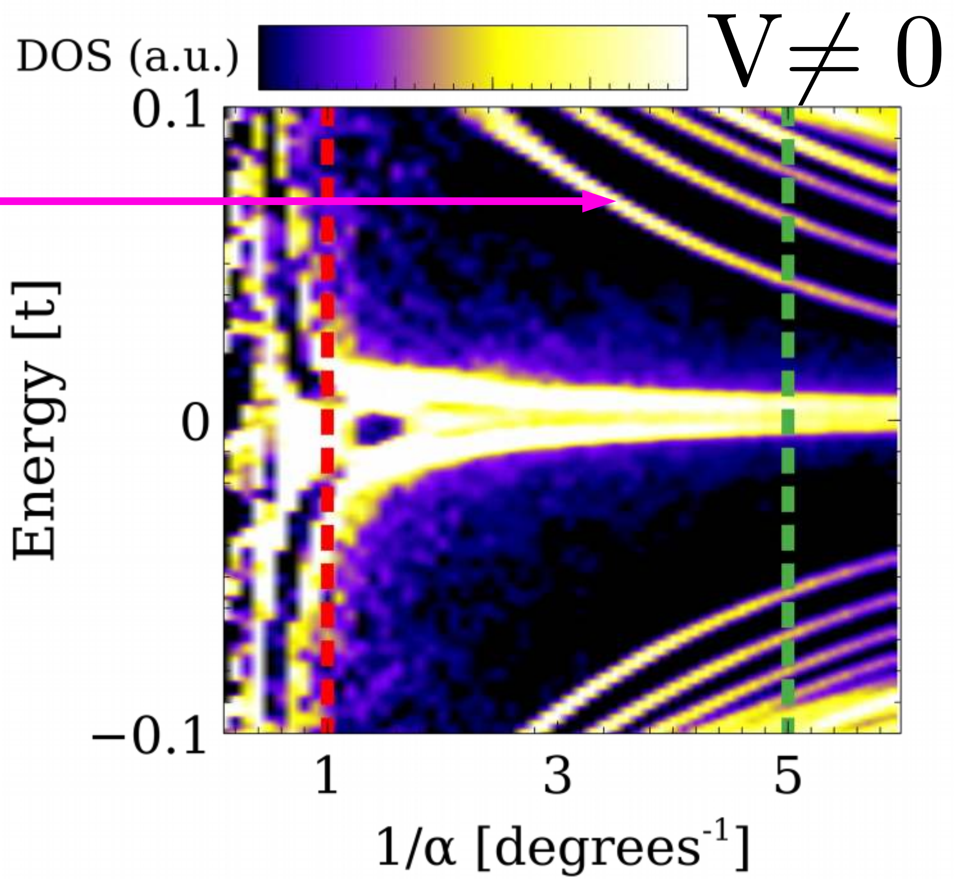


Diving into the biased tiny-angle regime



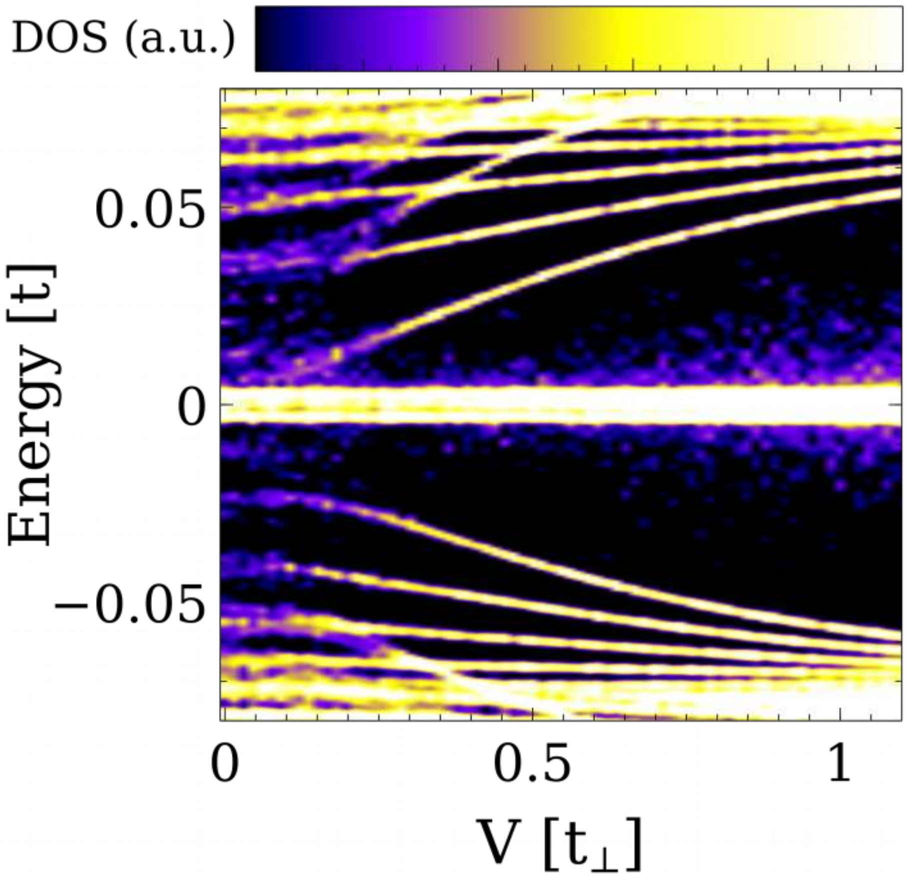
Diving into the biased tiny-angle regime

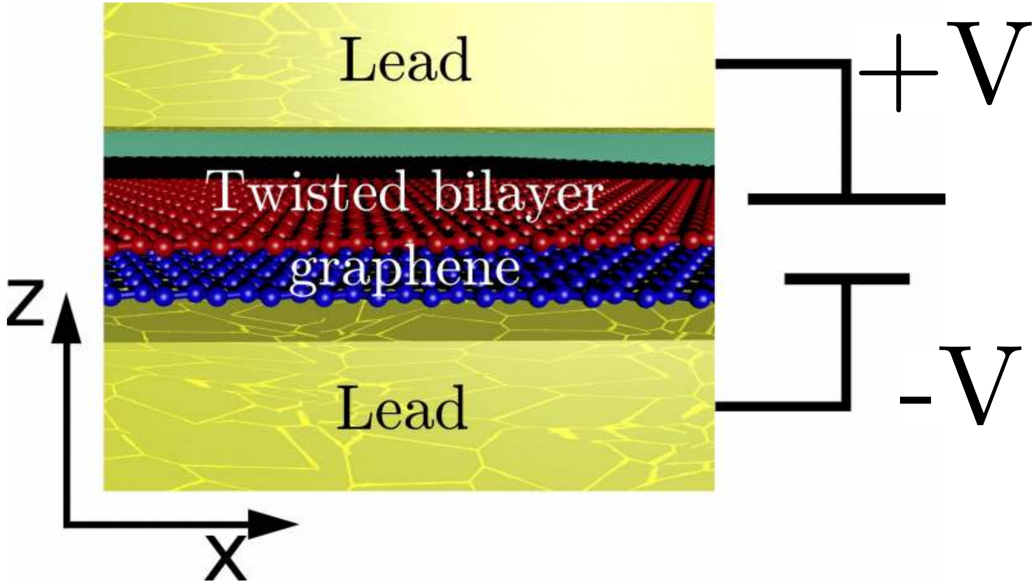




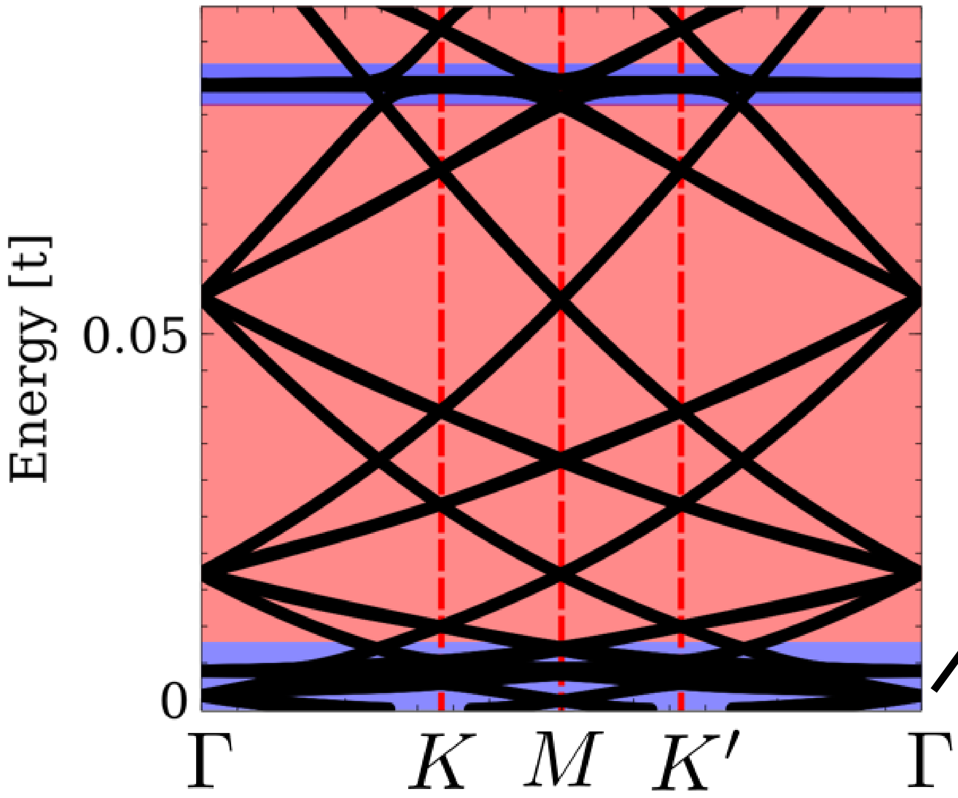
Phys. Rev. B 88, 121408 (2013)
Phys. Rev. Lett. 121, 146801 (2018)

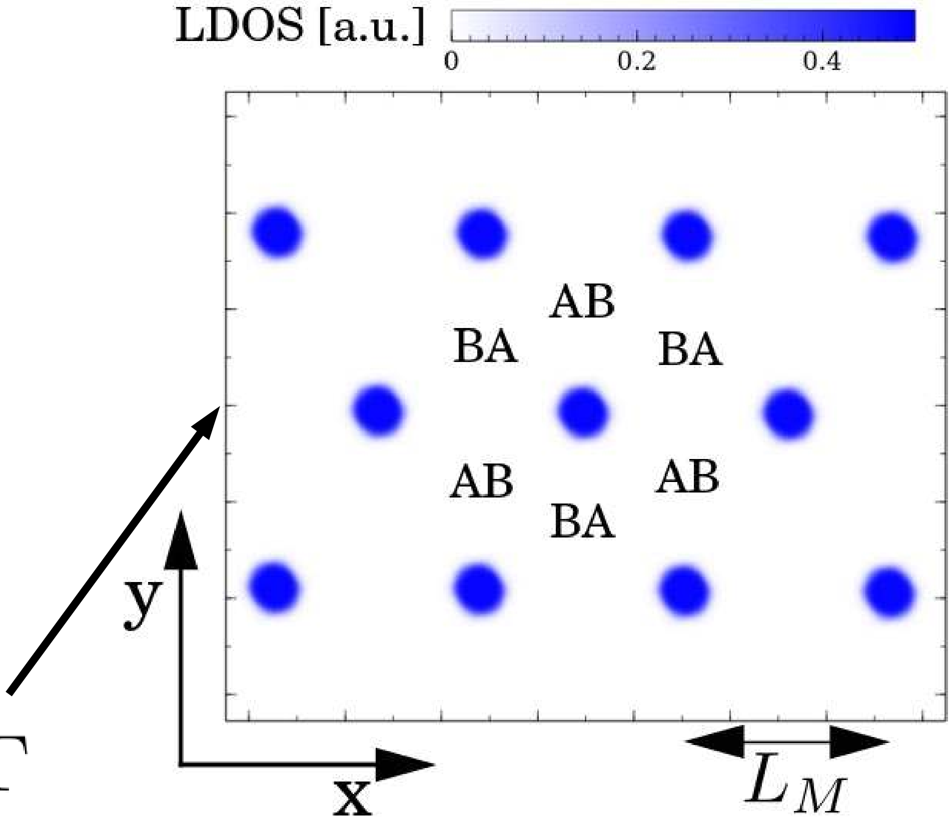
Controlling pseudo Landau levels electrically



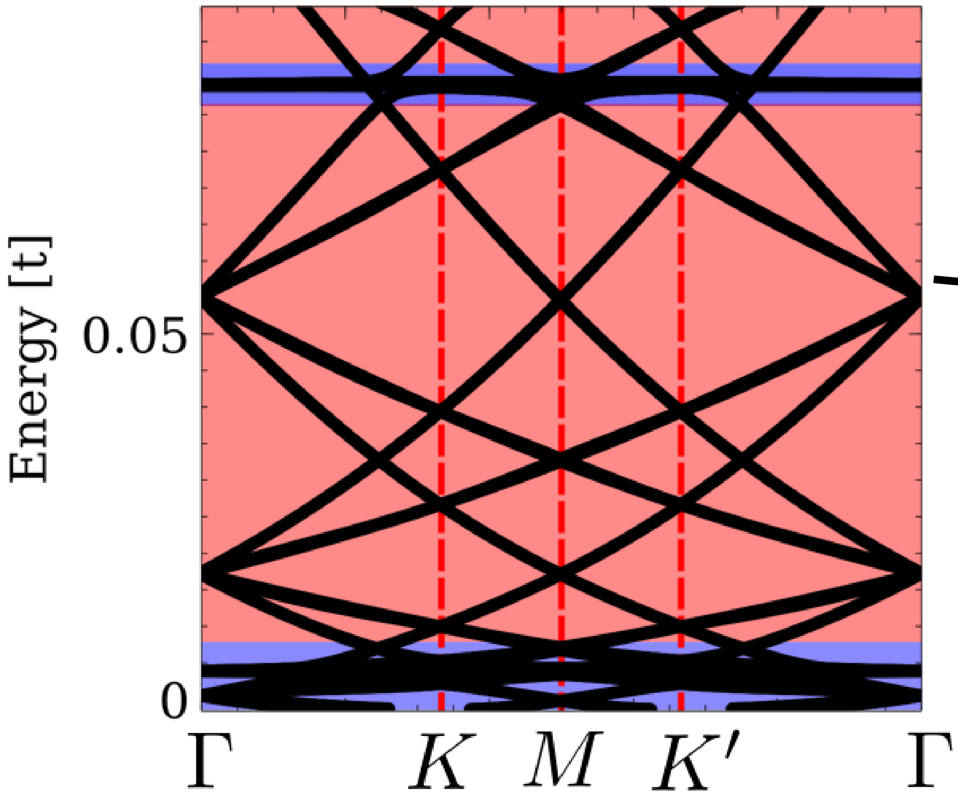


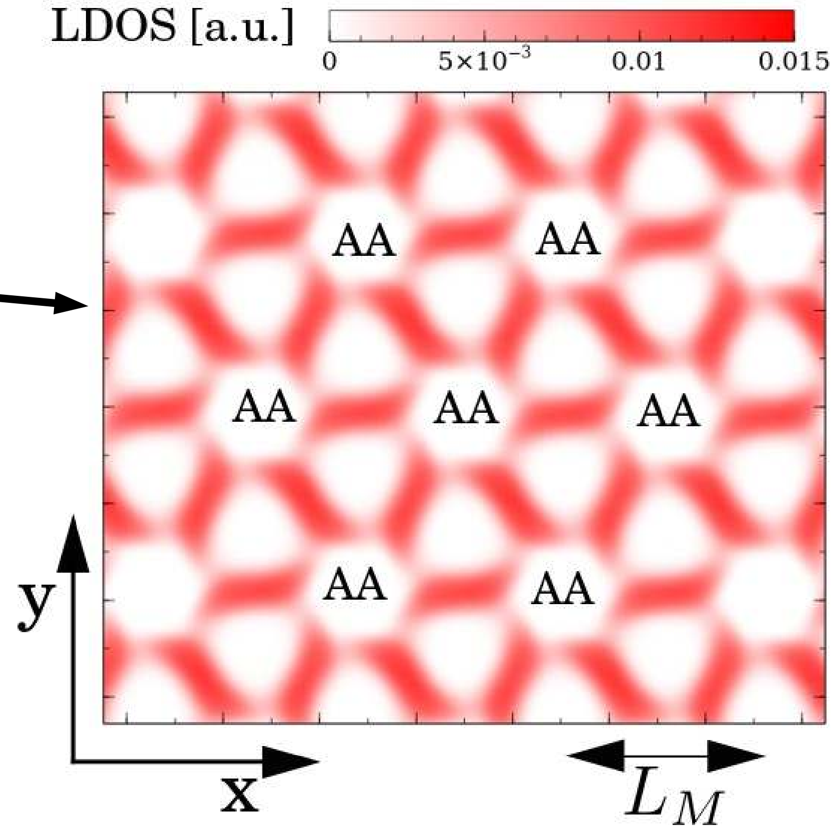
AA modes tiny angle TBG



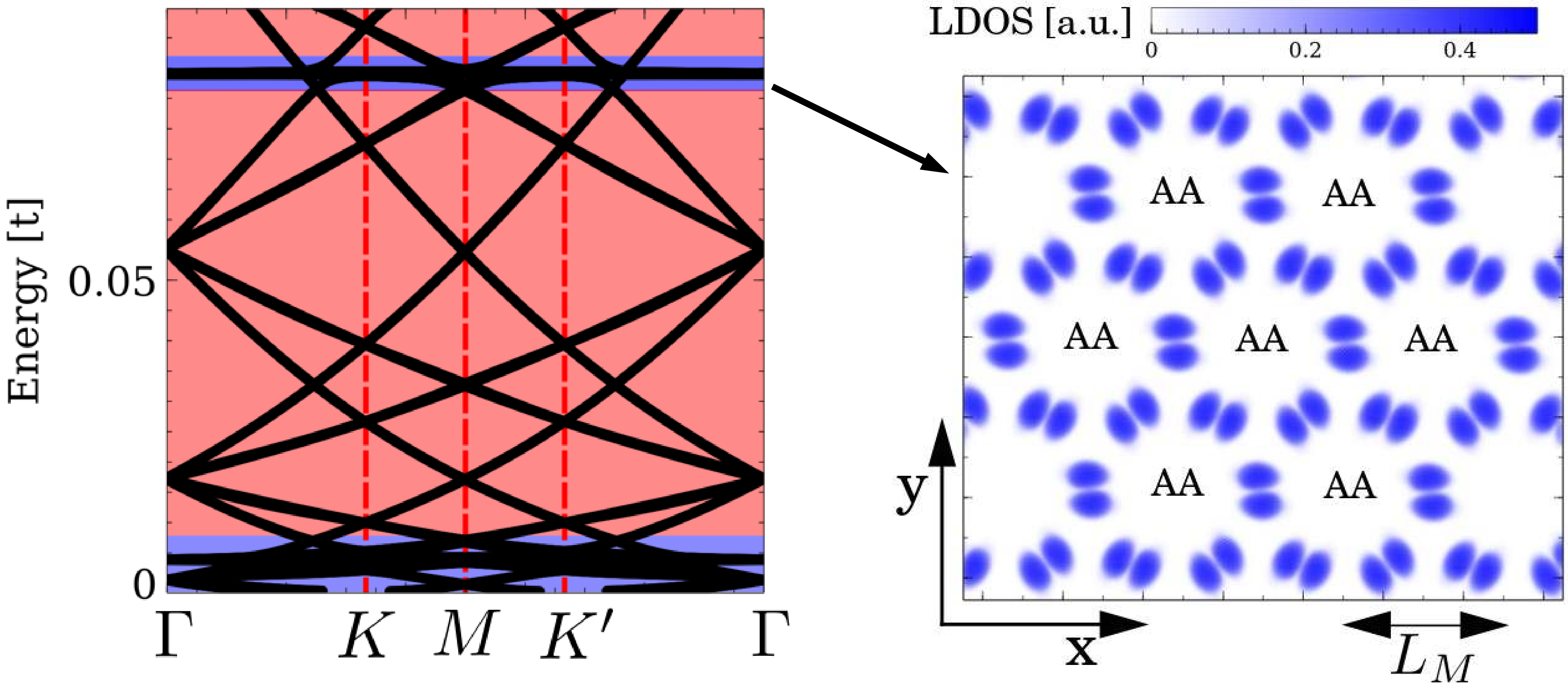


Helical network in tiny angle TBG



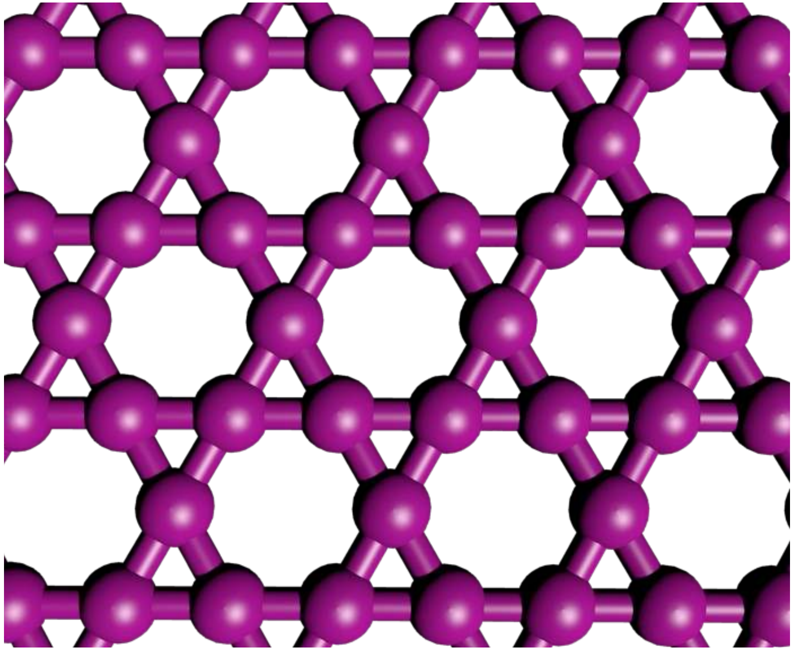


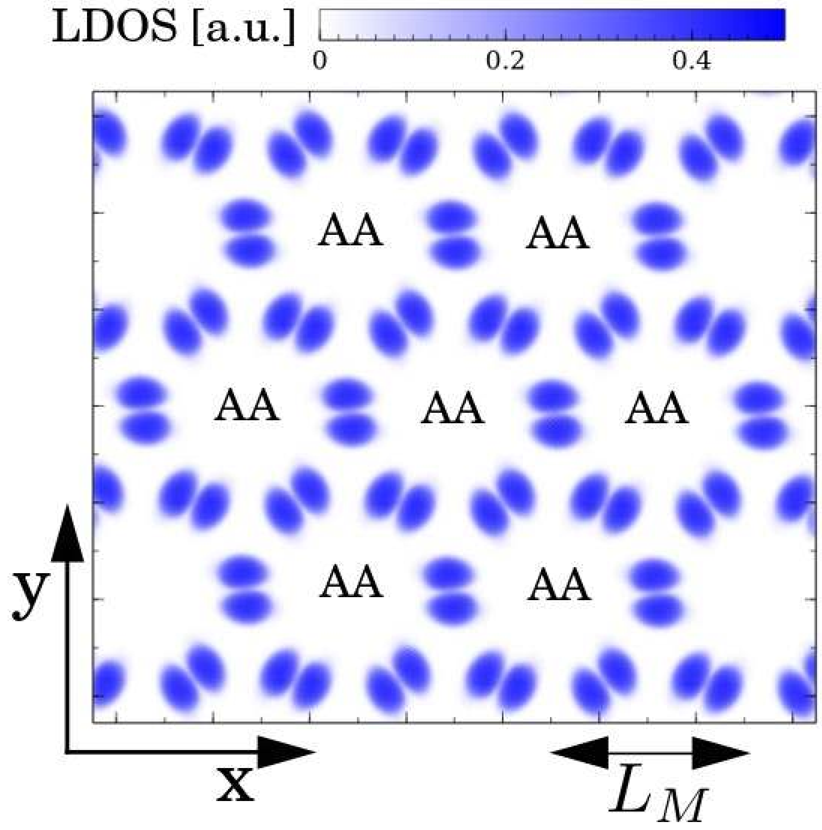
Pseudo Landau level in tiny angle TBG



Kagome lattice in TBG

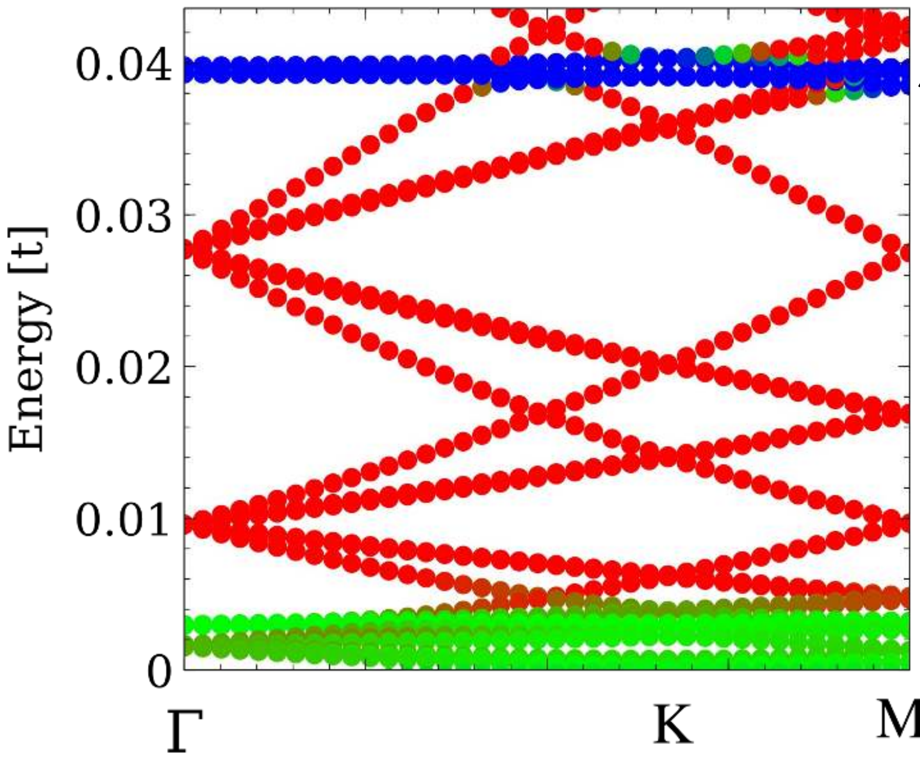
Emergent Kagome lattice



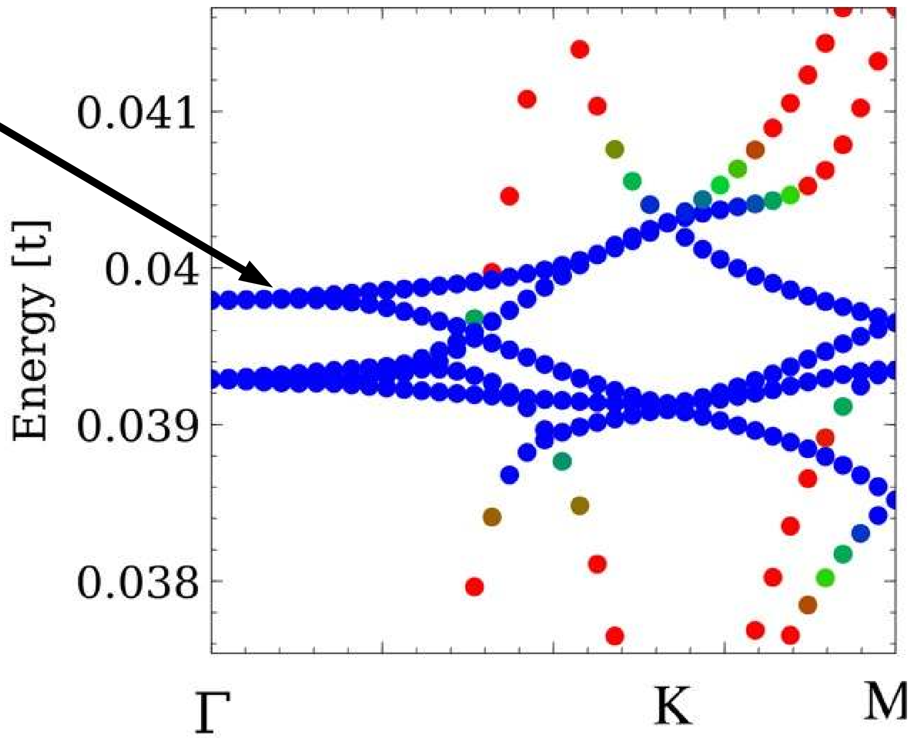


Overlap between pLL

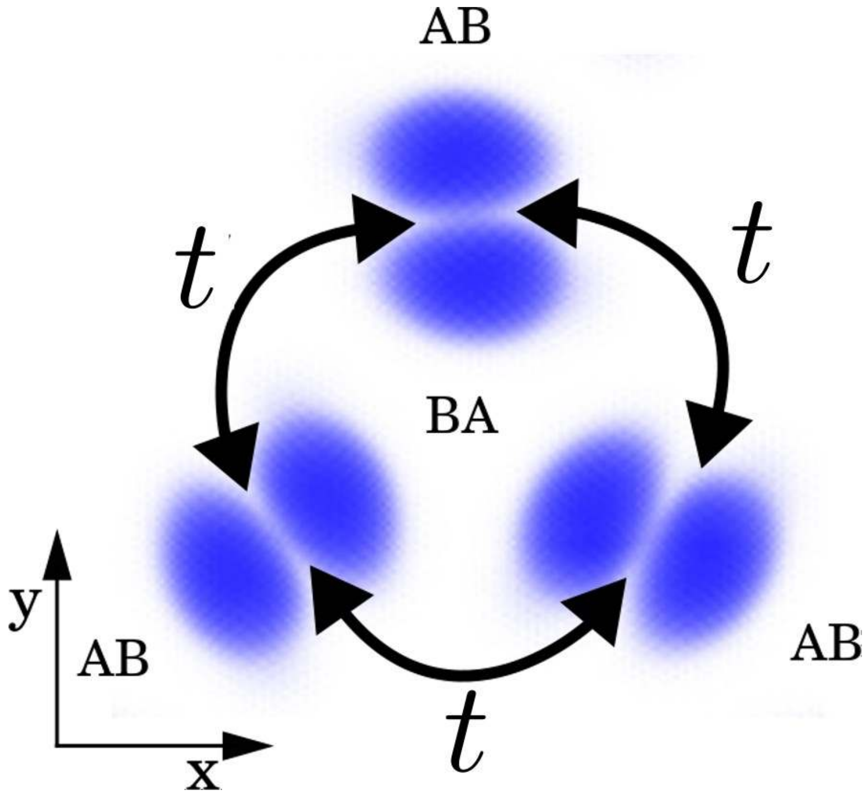
Band structure



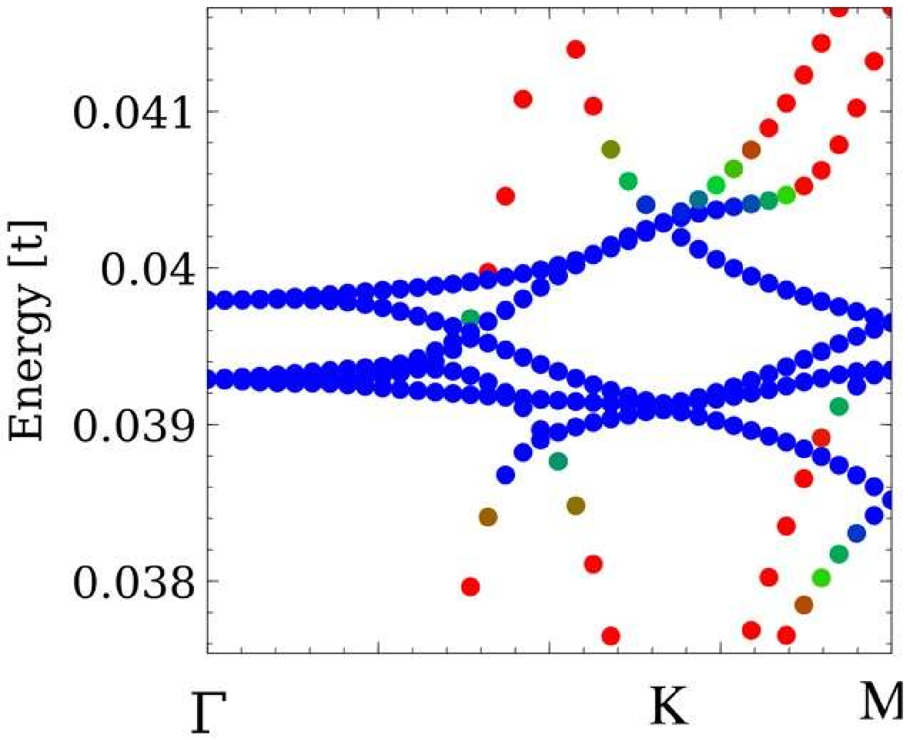
Band structure



Tailoring the hopping a Kagome lattice

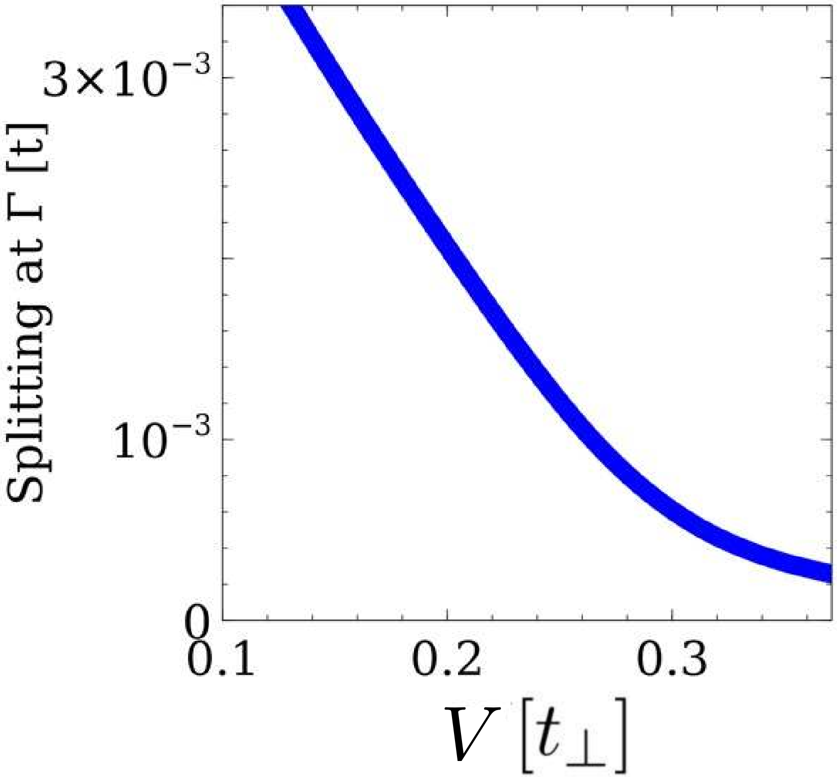


Band structure

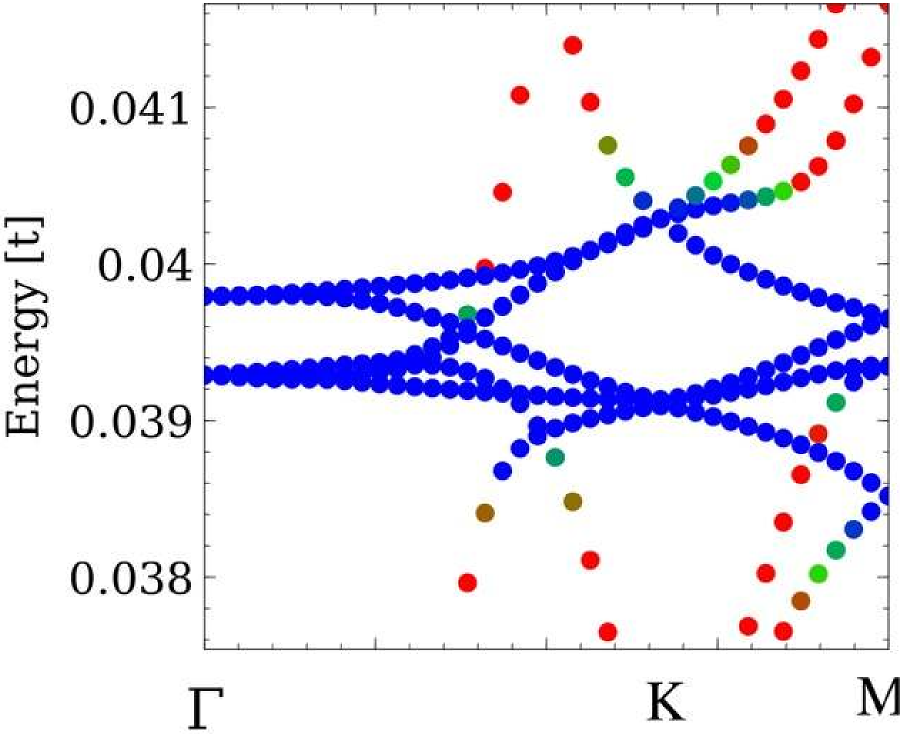


Bias controlled splitting

Splitting VS bias

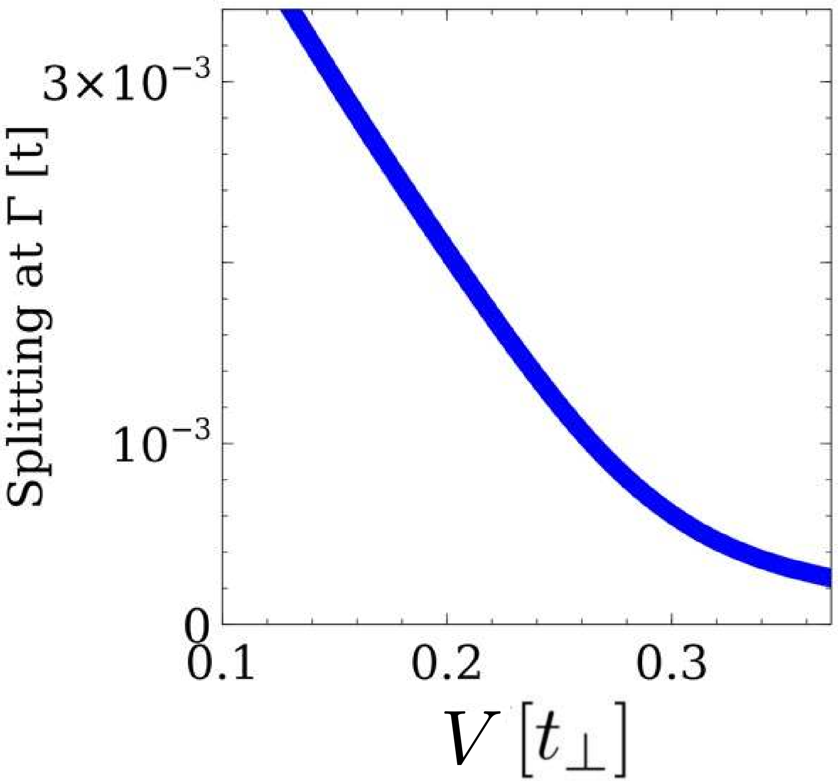


Band structure



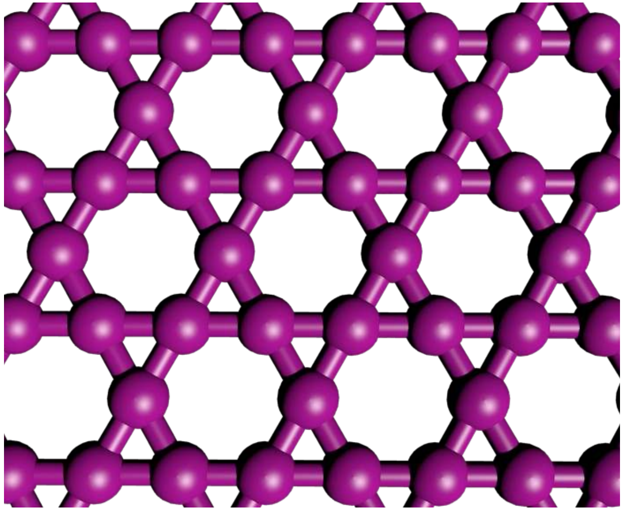
Controllable exchange in a Kagome lattice

Splitting VS bias



Effective Heisenberg model in a Kagome lattice

$$\mathcal{H} = \sum_{ij} J \vec{S}_i \cdot \vec{S}_j \qquad J \propto \frac{t^2}{U}$$

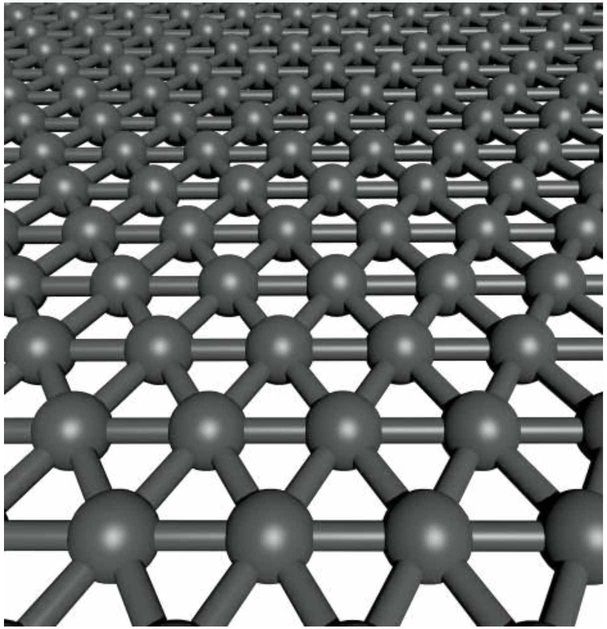


Frustrated superlattices with TBG

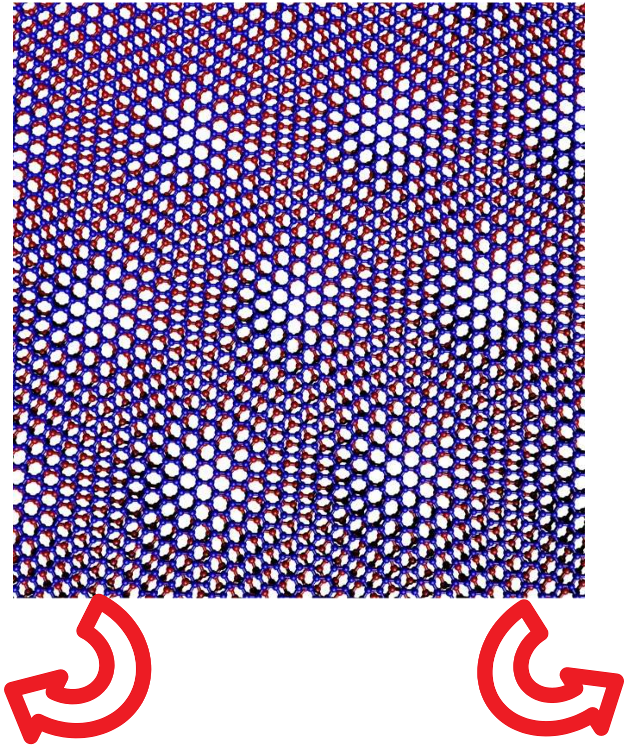
Triangular

1.5 degrees

Tunable exchange



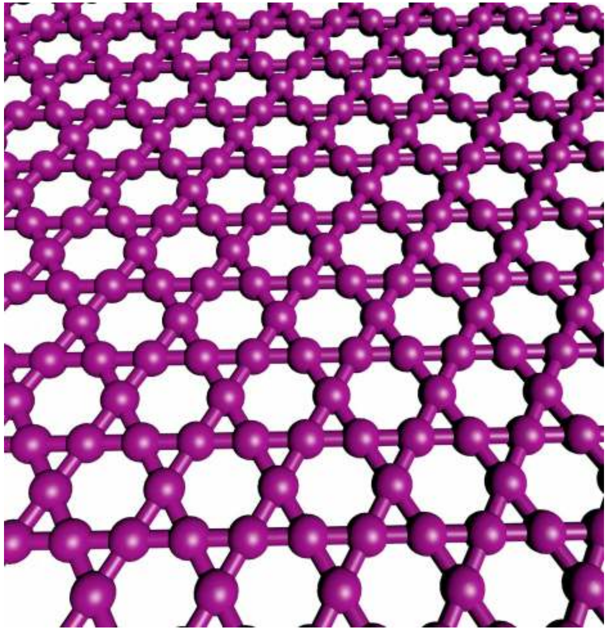
Phys. Rev. Lett. 119, 107201 (2017)



Kagome

0.2 degrees

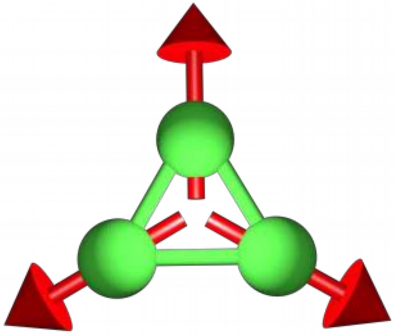
Electric gauge field



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

Take home

Twisted graphene bilayers provide a venue for frustrated magnetism with electrically controllable interactions



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