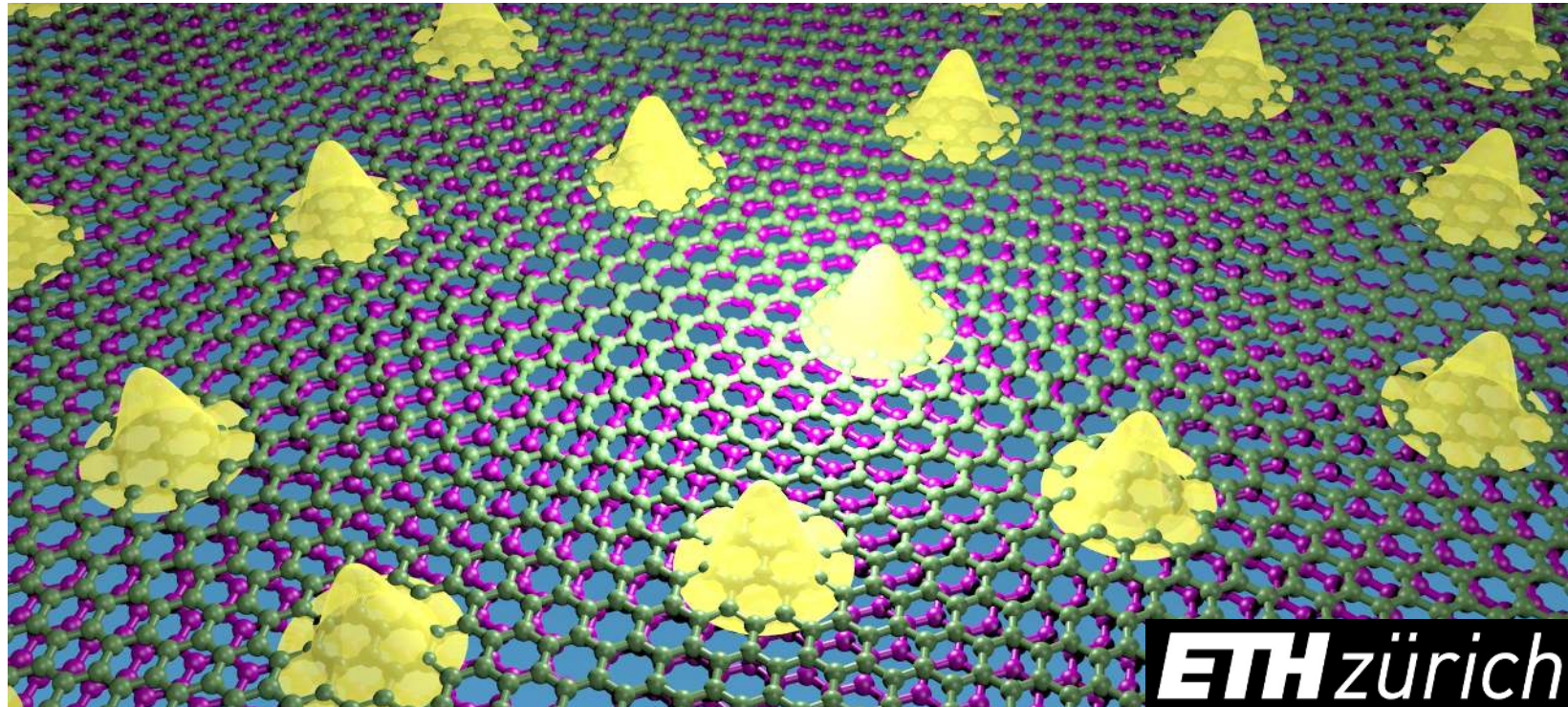


Electrically tunable frustrated lattices and magnetism in twisted bilayer graphene

Jose Lado, ETH Zurich



ETH zürich

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

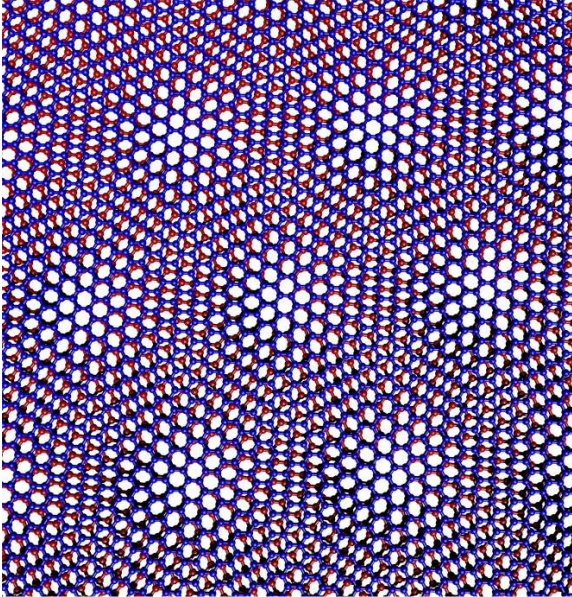
Phys. Rev. Lett. 121, 146801 (2018)



A. Ramires

A story of success, with a twist

Twisted graphene multilayers

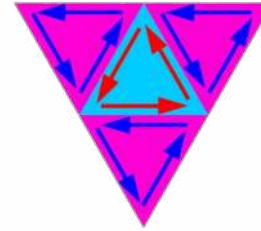


Superconductivity



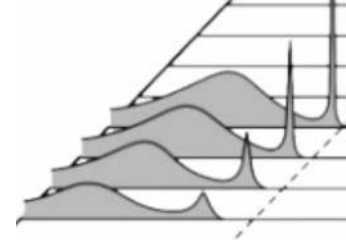
Nature 556, 43–50 (2018)

Topological networks



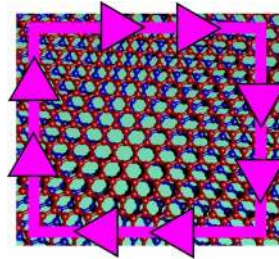
Nano Lett. 18, 11,
6725-6730 (2018)

Strange metals



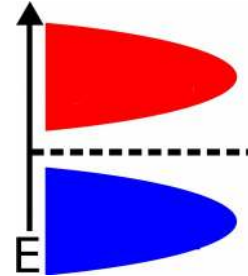
arXiv:1901.03710 (2019)

Anomalous Hall



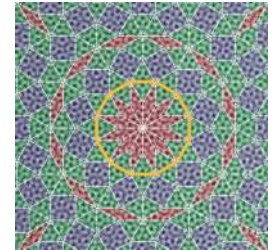
arXiv:1901.03520 (2019)

Correlated insulators



Nature 556, 80–84 (2018)

Quasicrystalline physics



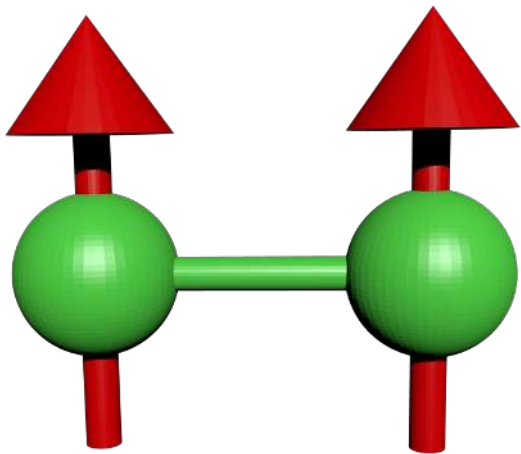
Science 361.6404
782-786 (2018)

Twisted graphene multilayers provide a powerful platform for emergent phenomena

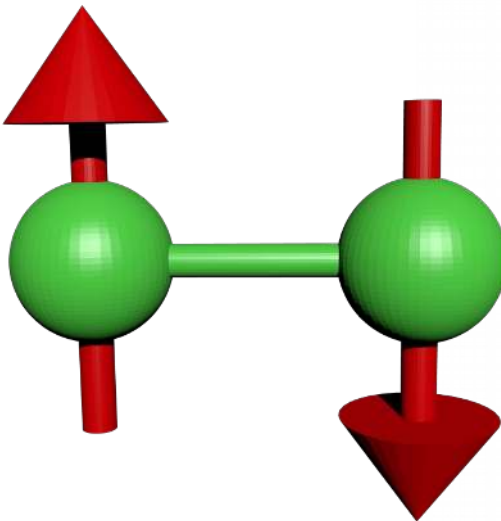
Frustration

A bird's eye view on magnetism

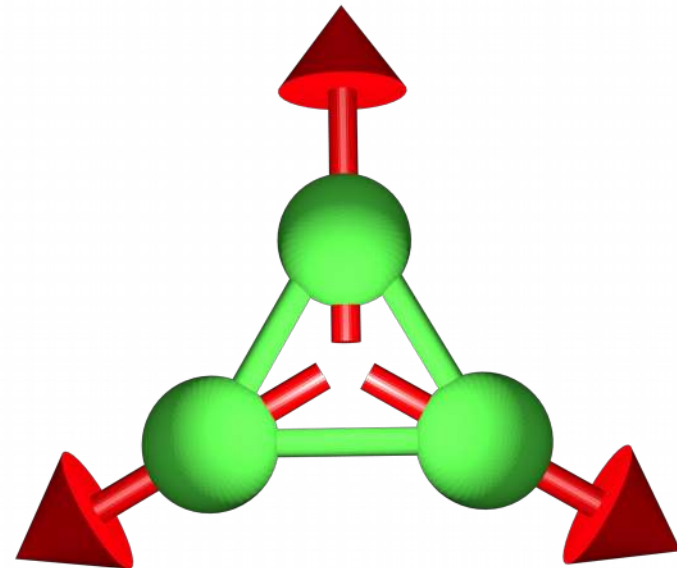
Ferromagnetism



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

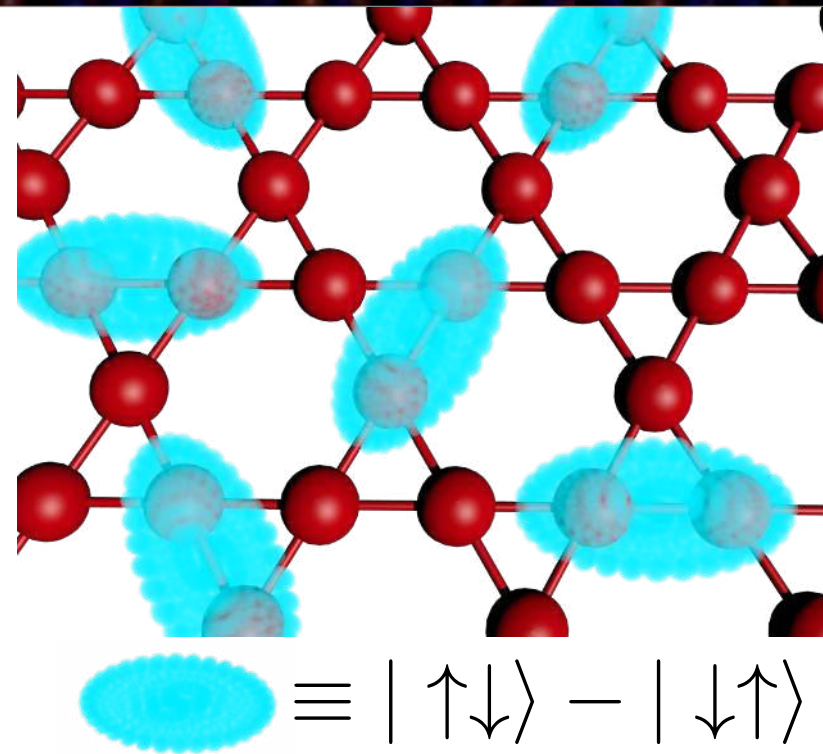
Fractional excitations

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)



Kitaev's honeycomb

Annals of Physics 321.1 (2006)

Kagome Heisenberg

Science 332, 1173-1176 (2011)

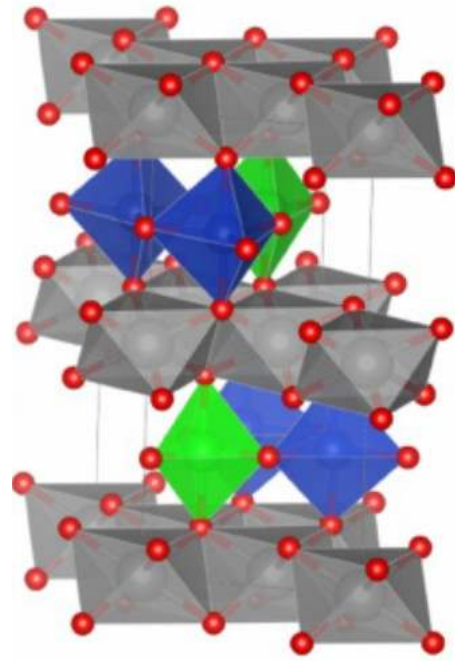
Extended triangular Heisenberg

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

Engineering magnetic materials

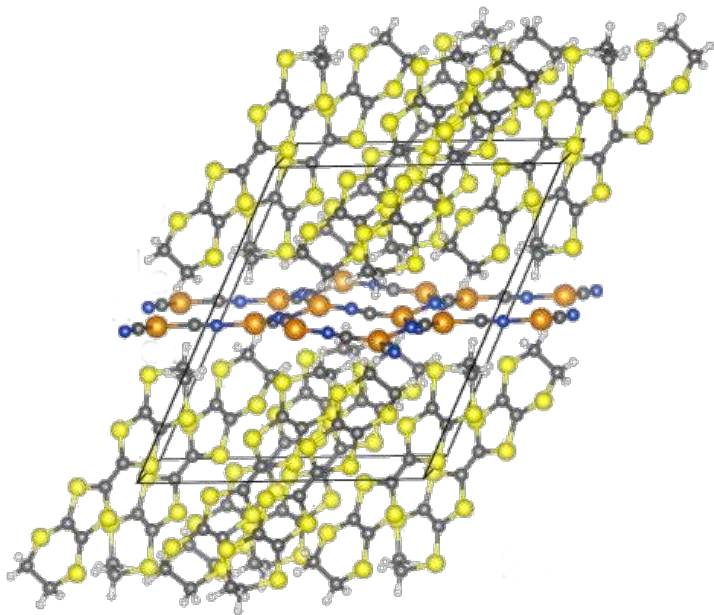
$$\mathcal{H} = \sum_{ij s} t_{ij} c_{i,s}^\dagger c_{j,s} + \sum_i V c_{i,\downarrow}^\dagger c_{j,\downarrow} c_{i,\uparrow}^\dagger c_{i,\uparrow}$$

I A		II A												III A		IV A		V A		VI A		VII A	
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180						
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948						
		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18						
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.630	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80						
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.60	53 I Iodine 126.90	54 Xe Xenon 131.29						
55 Sc Scandium 44.956	56 Ba Barium 137.33	71 Lu Lutetium 174.967	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.84	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.2	83 Bi Bismuth 208.98	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222						
87 Fr Francium 223	88 Ra Radium 226	103 Lr Lawrencium 260	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 266	107 Bh Bohrium 264	108 Hs Hassium 277	109 Mt Meitnerium 268	110 Ds Darmstadtium 271	111 Rg Roentgenium 272	112 Cn Copernicium 285	113 Uut Ununtrium 284	114 Uuq Ununquadium 289	115 Uup Ununpentium 288	116 Uuh Ununhexium 292	117 Uus Ununseptium 294	118 Uuo Ununoctium 294						
89 La Lanthanide 138.91	90 Ce Cerium 140.12	91 Pr Praseodymium 140.91	92 Nd Neodymium 144.24	93 Pm Promethium 145	94 Sm Samarium 150.36	95 Eu Europium 151.96	96 Gd Gadolinium 157.25	97 Tb Terbium 158.93	98 Dy Dysprosium 162.5	99 Ho Holmium 164.93	100 Er Erbium 167.26	101 Tm Thulium 168.93	102 Yb Ytterbium 173.04										
89 Ac Actinide 227	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237	94 Pu Plutonium 244	95 Am Americium 243	96 Cm Curium 247	97 Bk Berkelium 247	98 Cf Californium 251	99 Es Einsteinium 252	100 Fm Fermium 257	101 Md Mendelevium 258	102 No Nobelium 259										



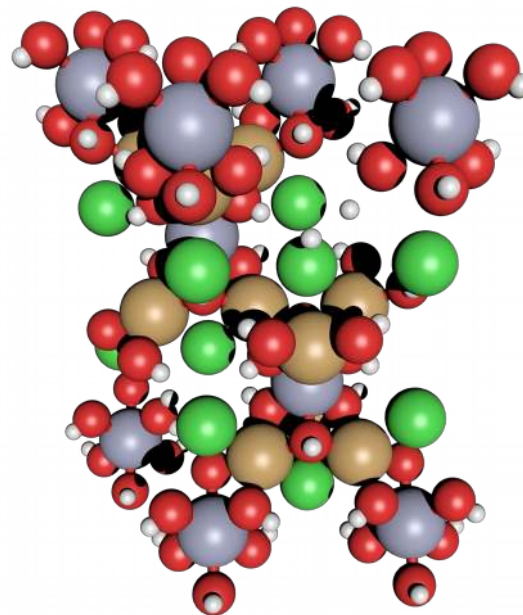
A quest for frustrated quantum magnets

$\kappa\text{-(ET)}_2\text{Cu}_2(\text{CN})_3$ (Triangular)



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

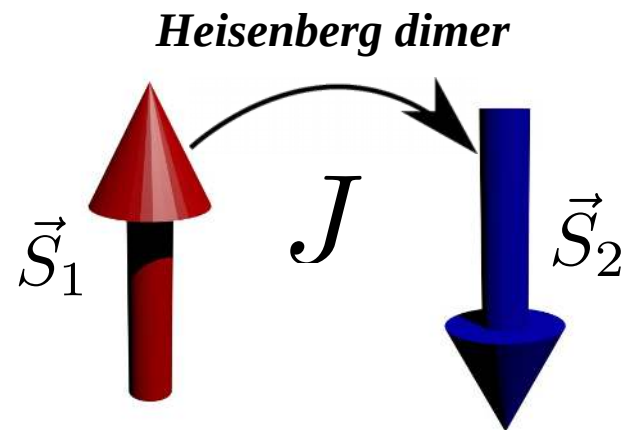
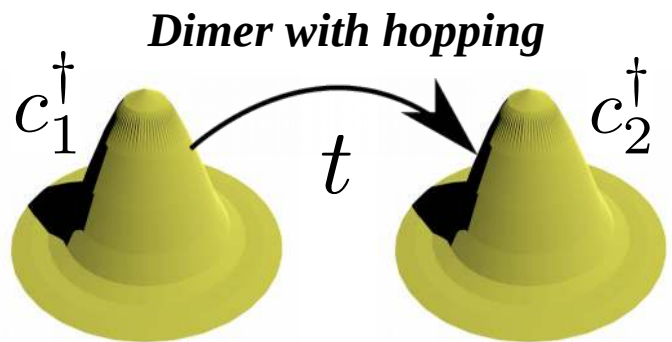
Herbertsmithite (Kagome)



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



Interaction Kinetic energy

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

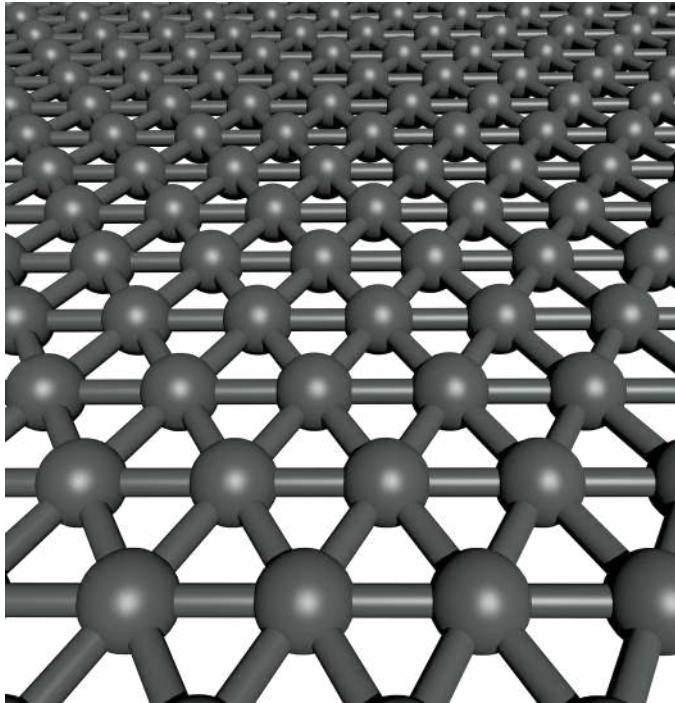
$$U \gg t \quad \downarrow \quad J \propto t^2 / U$$

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

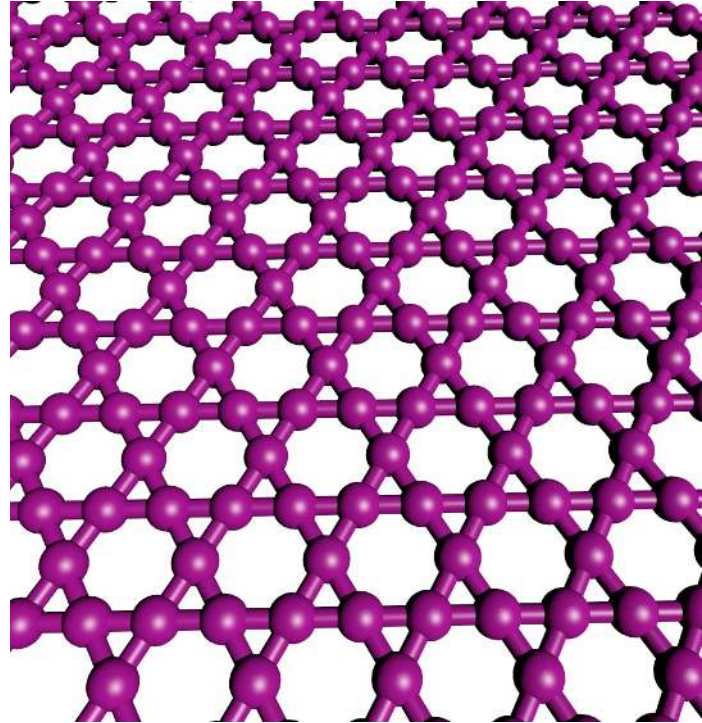
Ground state $|GS\rangle = \frac{1}{\sqrt{2}}(|\uparrow_1 \downarrow_2\rangle - |\downarrow_1 \uparrow_2\rangle)$

Scale up and frustrate

Triangular



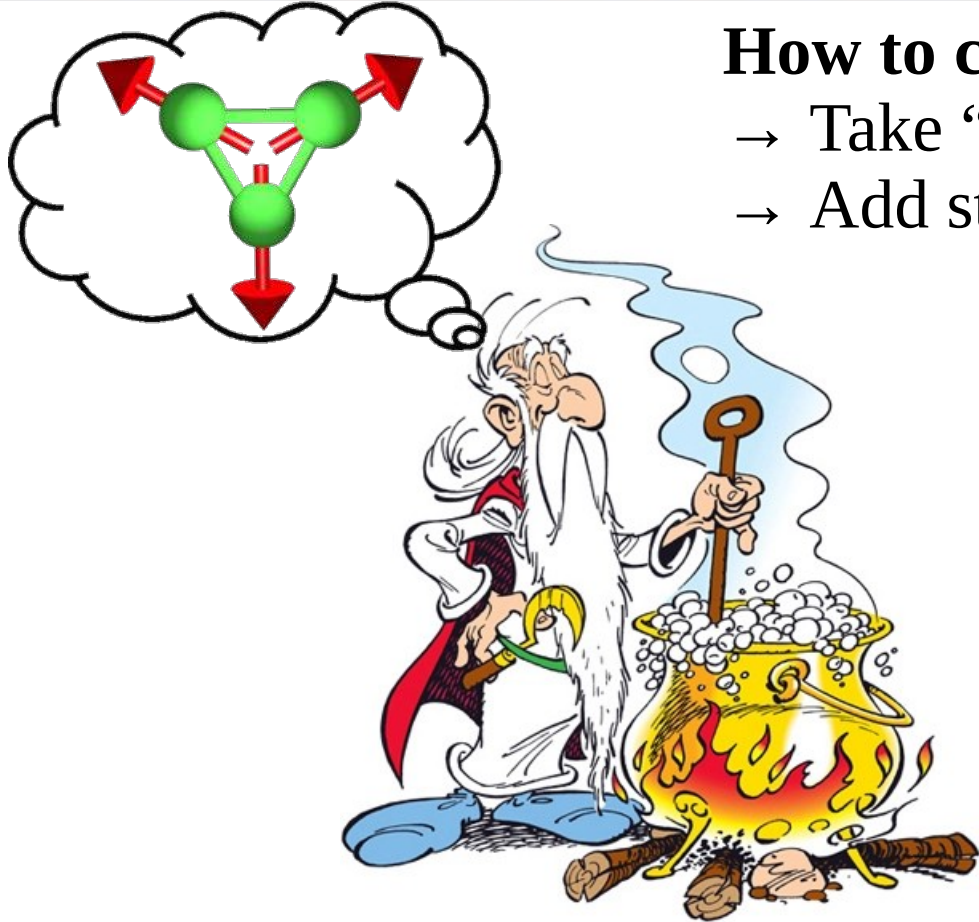
Kagome



A recipe for frustration

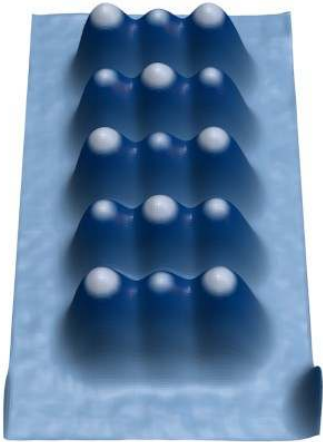
How to create magnetic frustration

- Take “electrons” in a frustrated lattice
- Add strong interactions



Building quantum matter with artificial lattices

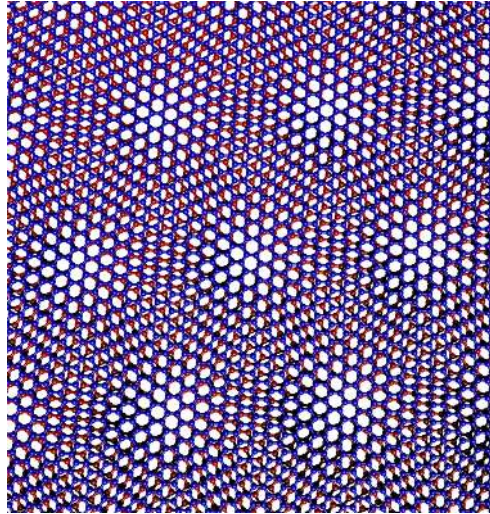
Atomic lattices



$a = 0.5 \text{ nm}$

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

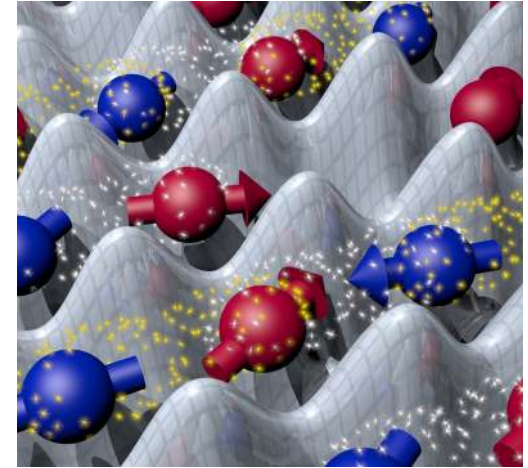
Twisted 2D moire materials



$a = 50 \text{ nm}$

Nature 556, 80–84 (2018)

Cold atoms

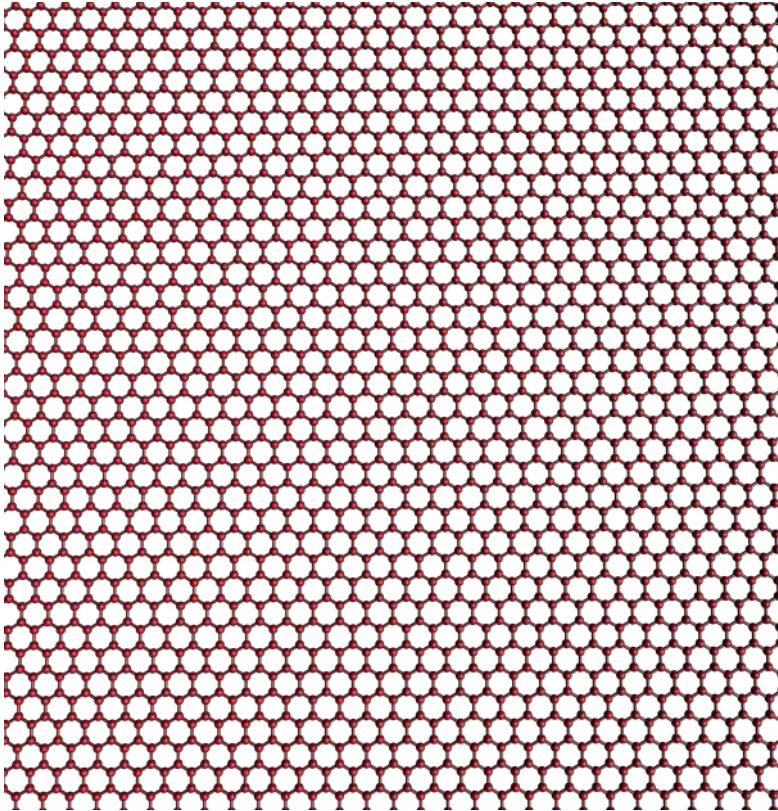


$a = 1000 \text{ nm}$

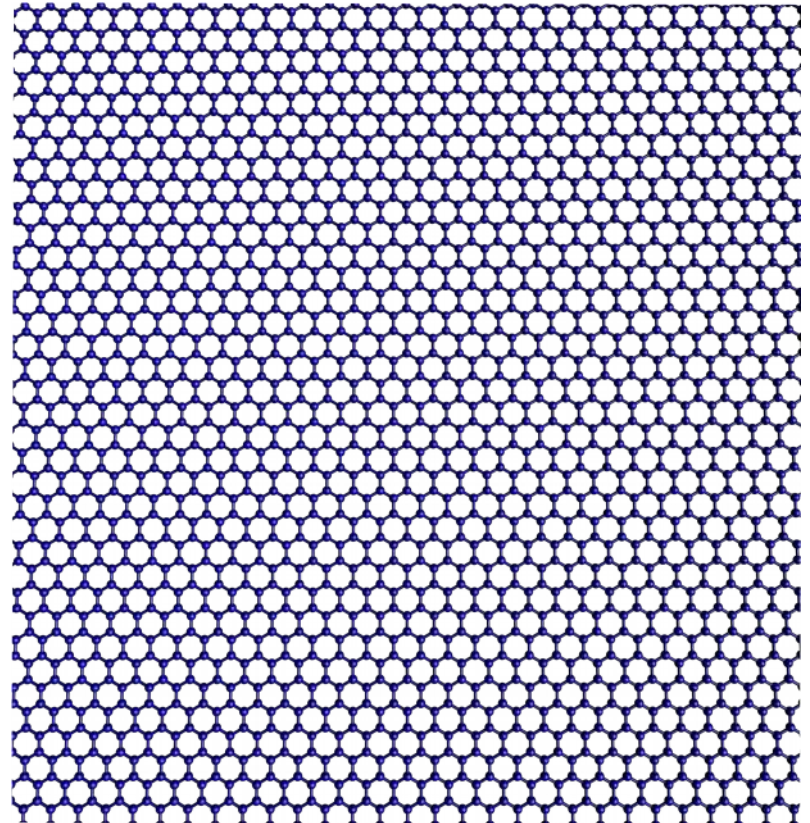
Nature 545.7655 (2017)
Nature 455.7210 (2008)
Phys. Rev. Lett. 111, 185307 (2013)

Moire in twisted bilayer graphene

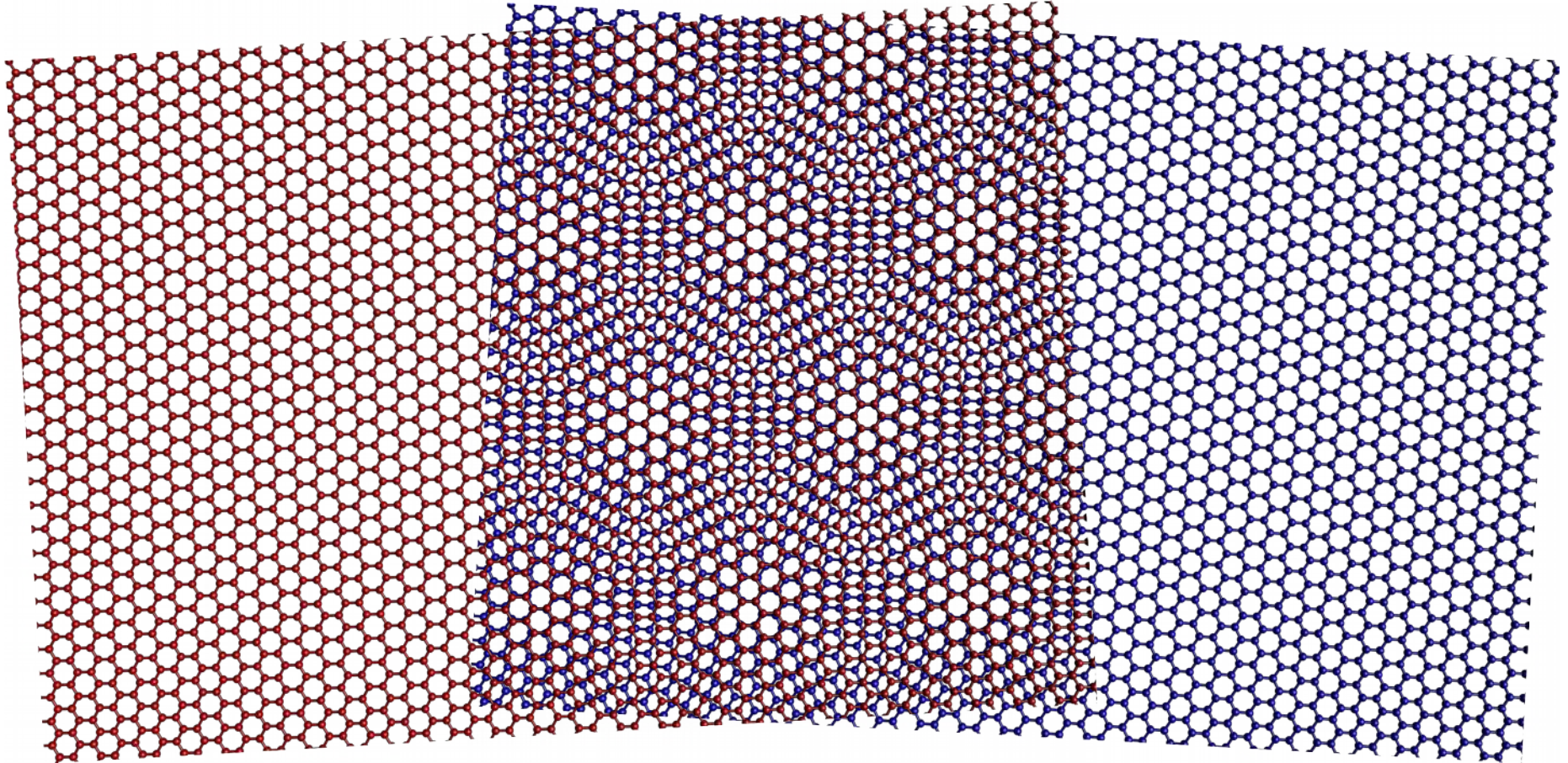
Upper graphene layer



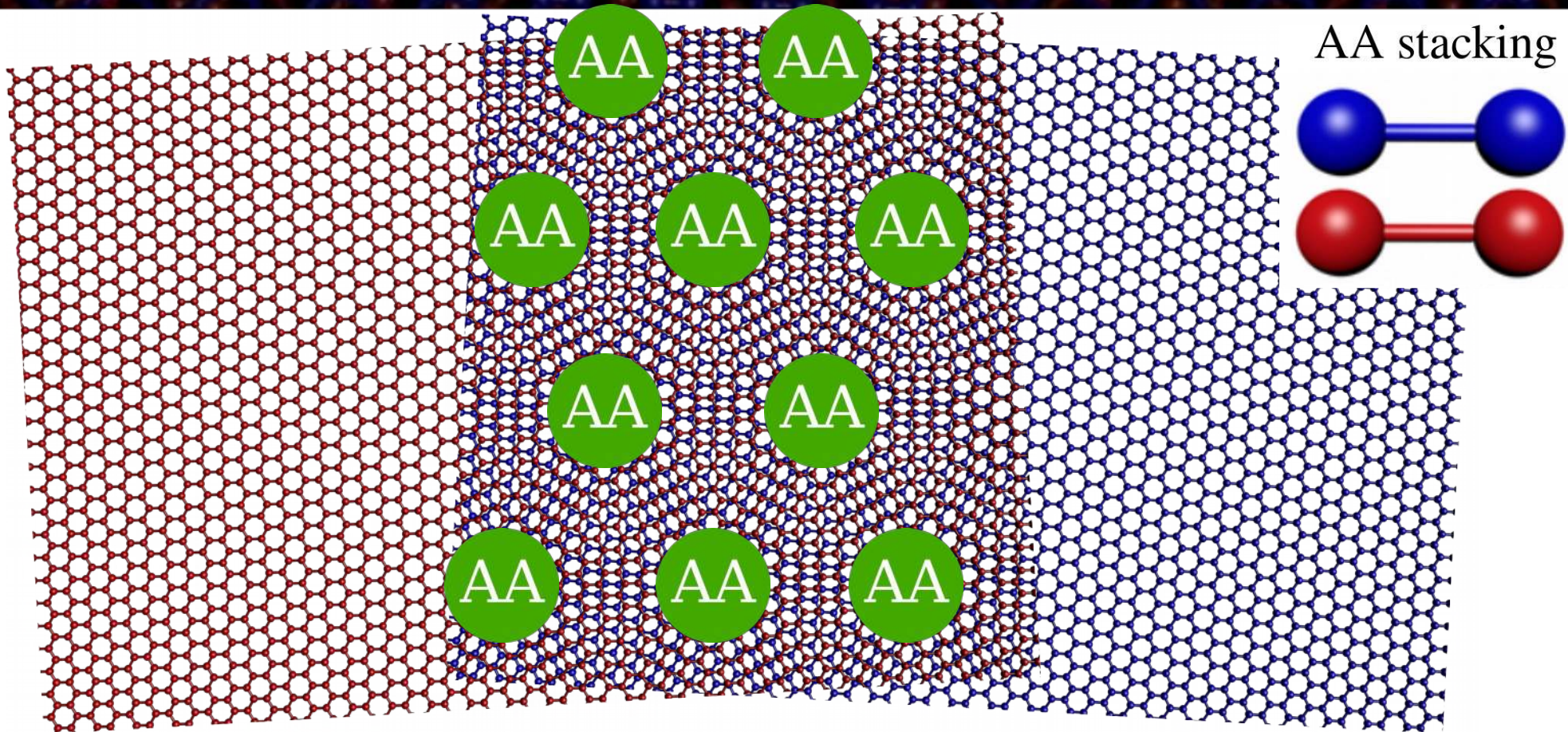
Lower graphene layer



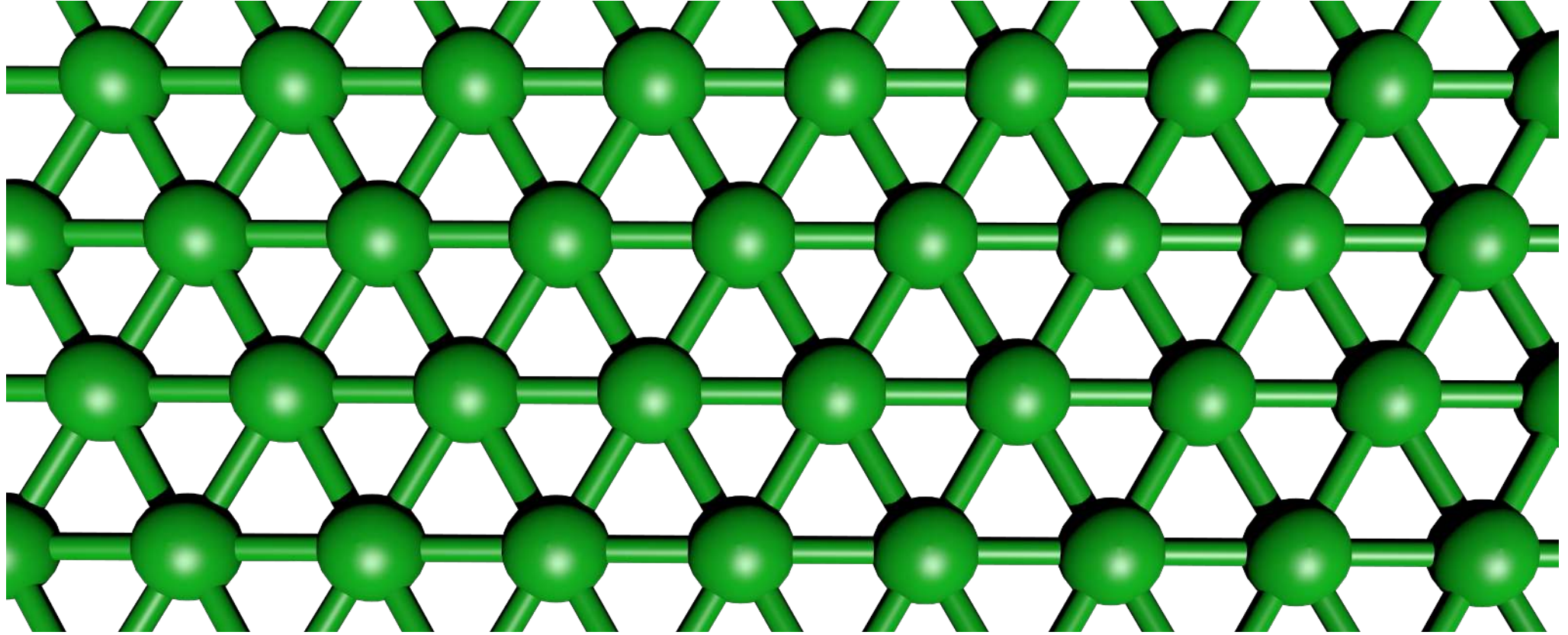
Moire in twisted bilayer graphene

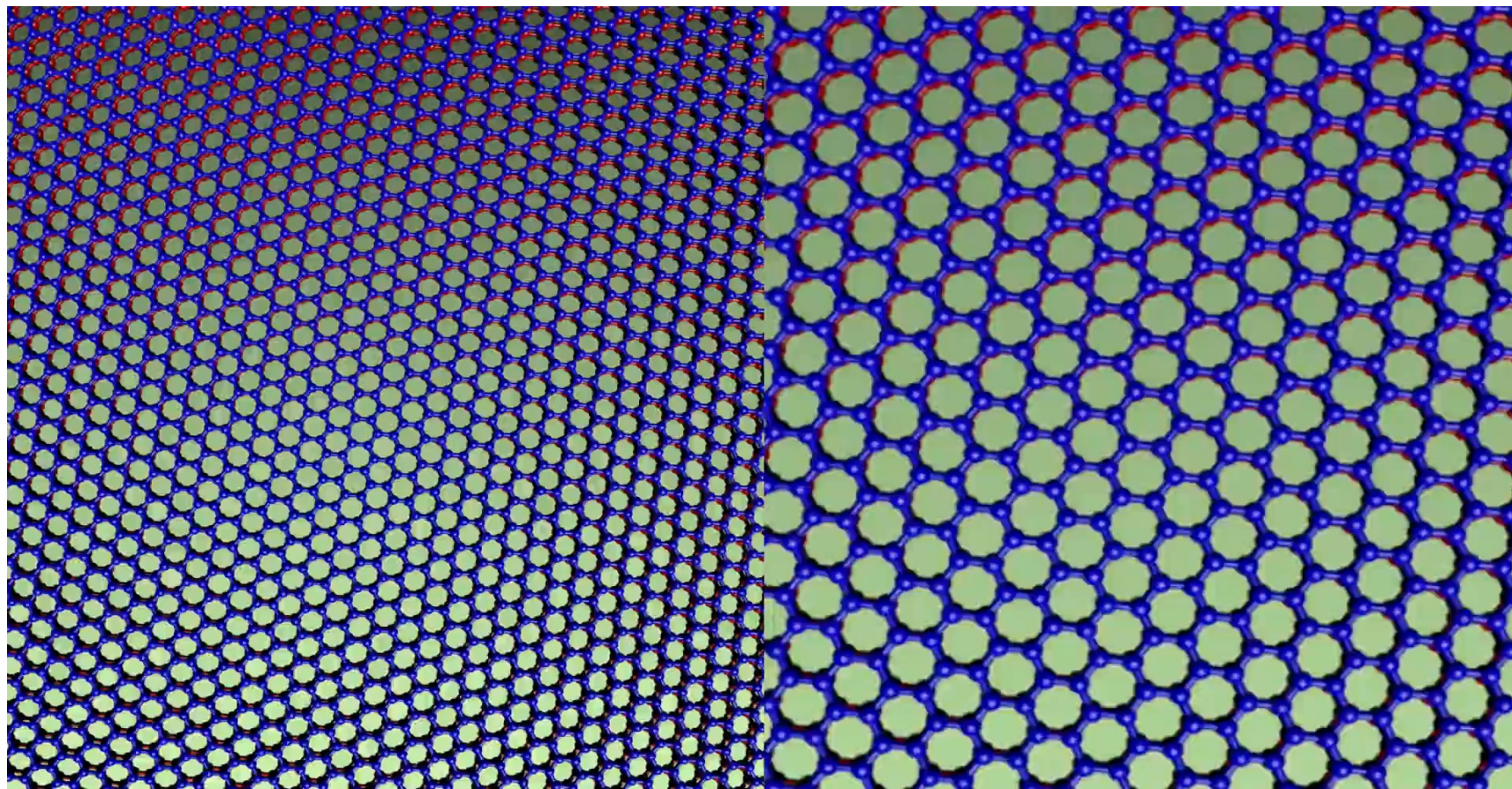
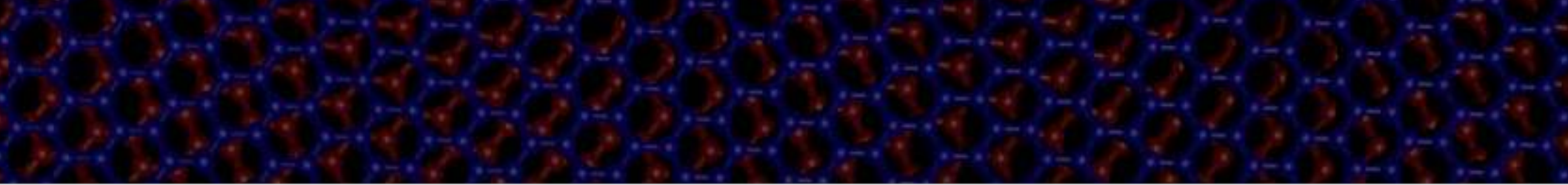


Moire in twisted bilayer graphene

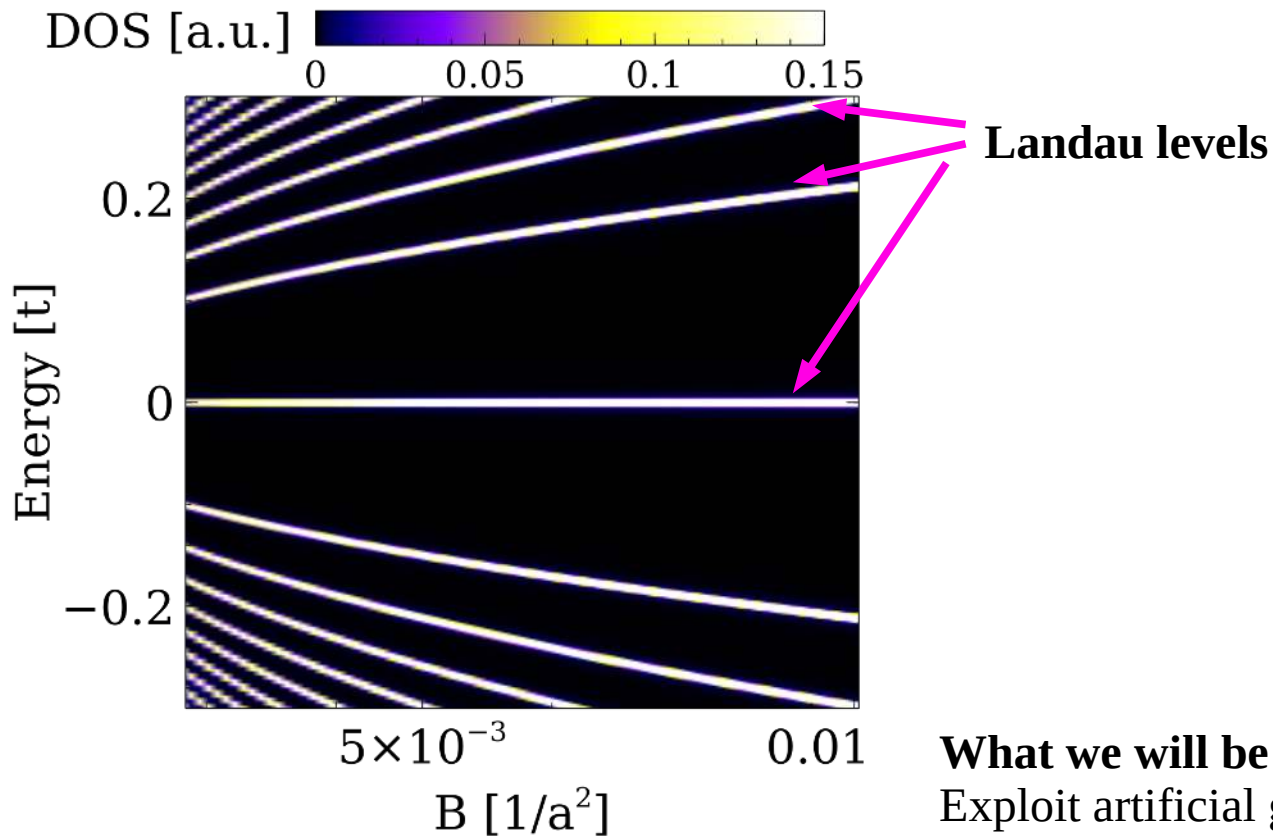


Moire in twisted bilayer graphene

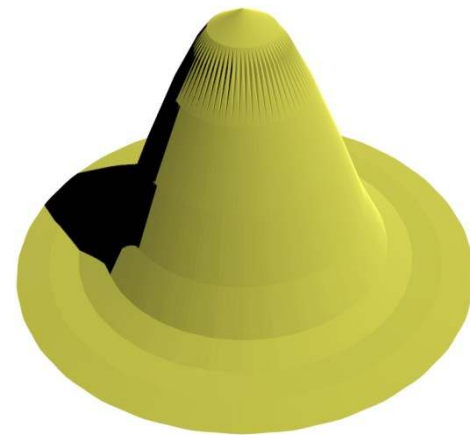




Building localized levels with gauge fields

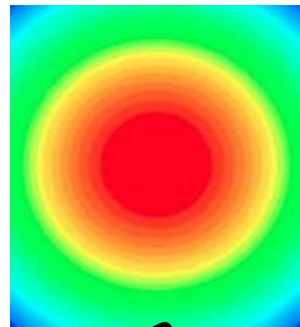


Landau level wavefunction



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

Emergent gauge fields in a nutshell



$$H(\vec{p}, \vec{R})$$

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 $\vec{B} = \vec{\nabla} \times \vec{A}$


$$H(\vec{p} + \vec{A})$$



Non-uniform
strain in graphene

**Non-abelian gauge
field in TBG**

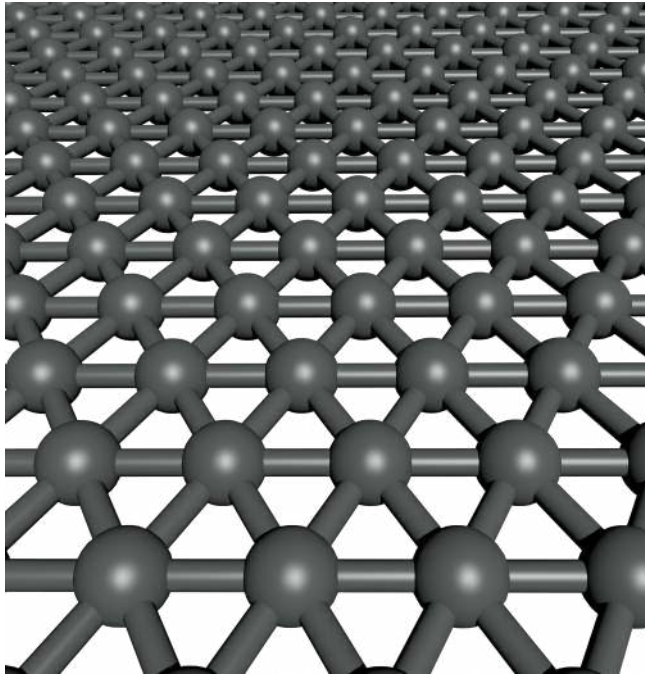
**Electric gauge field
in biased TBG**

Physics Reports 496.4-5 (2010) Phys. Rev. Lett. 108, 216802 (2012) Phys. Rev. Lett. 121, 146801 (2018)

Spatial modulations are a natural source of artificial gauge fields

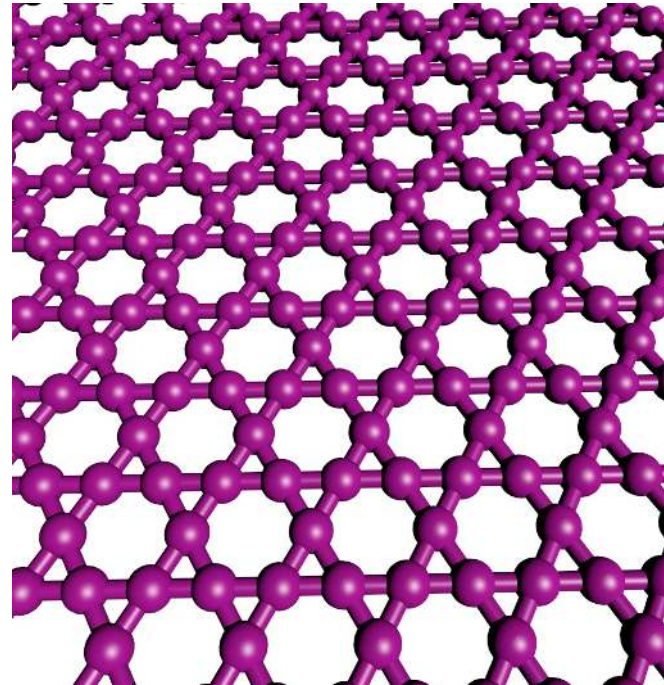
A natural platform for artificial gauge fields

Non-Abelian (elastic) gauge fields



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

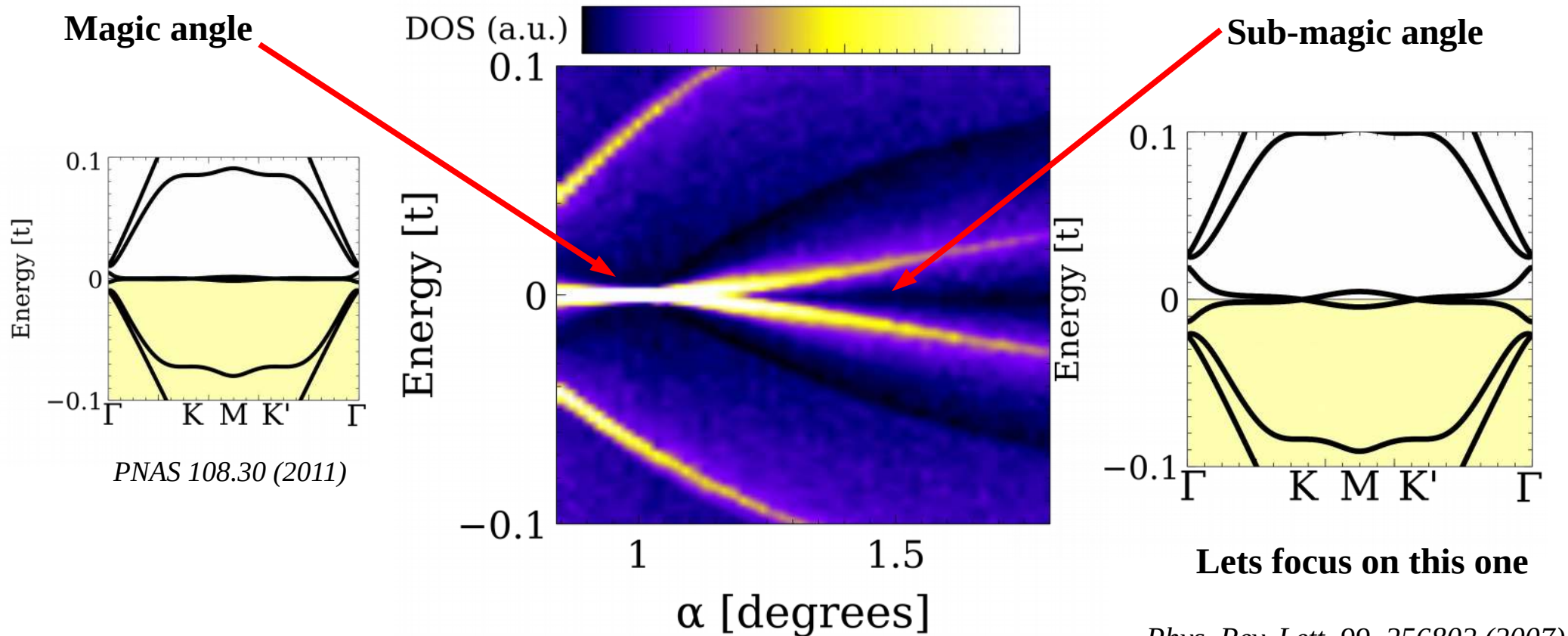
Abelian (electric) gauge fields



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

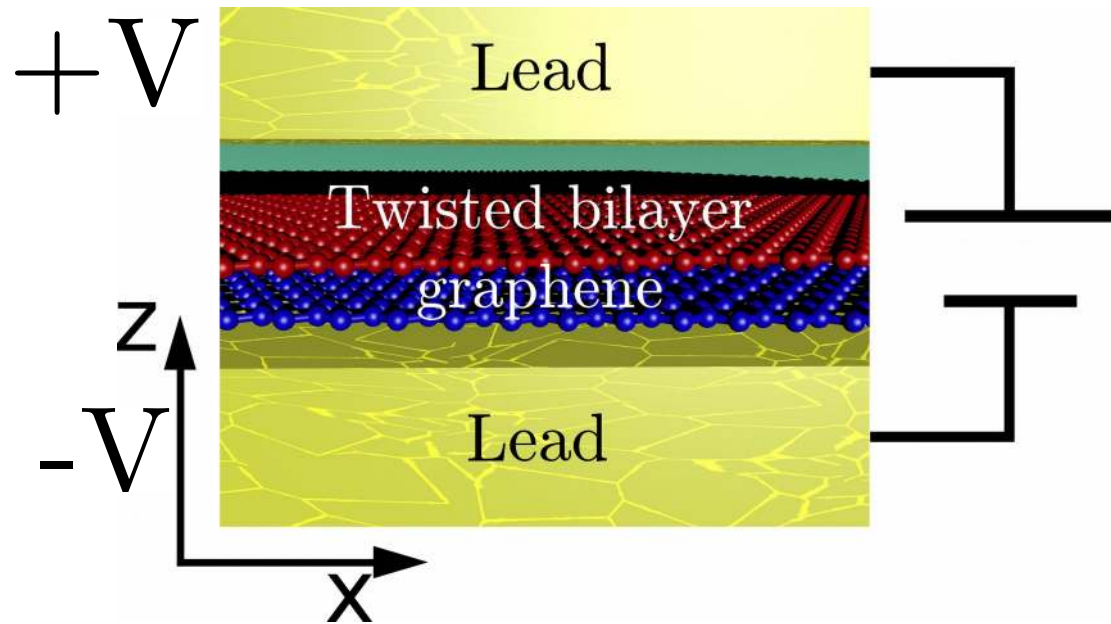
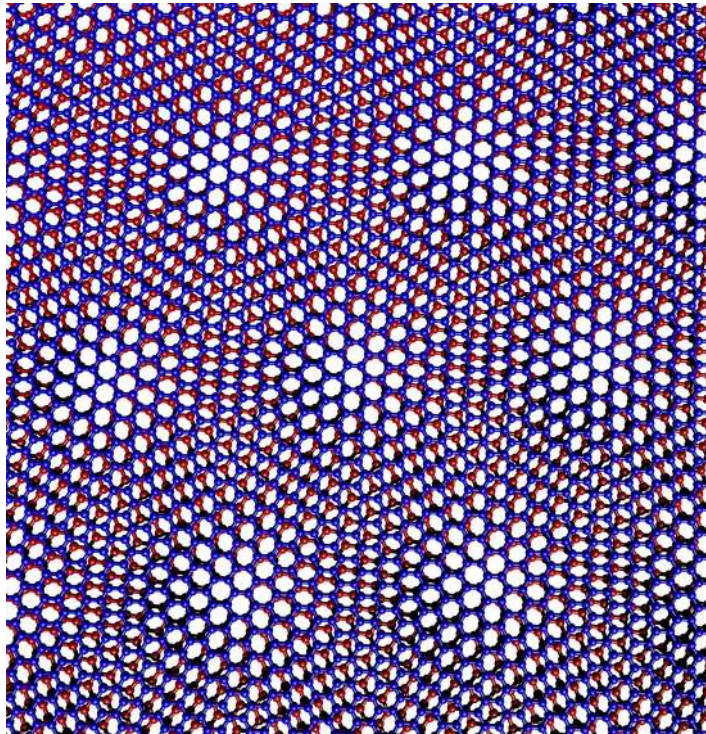
Towards controllable
triangular magnetism

Diving into the magic regime

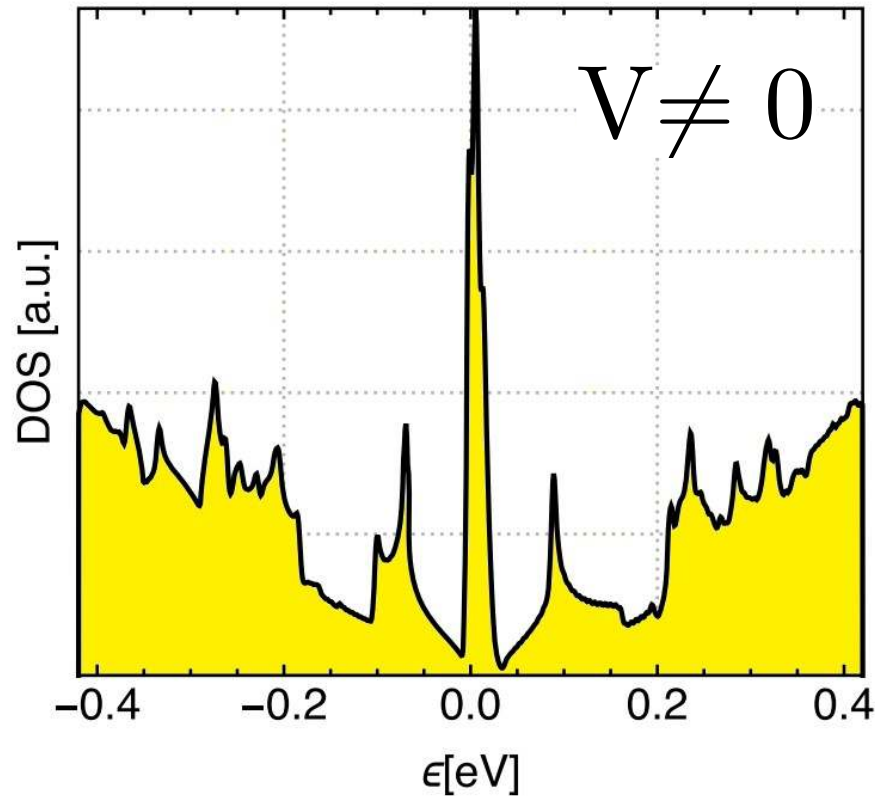
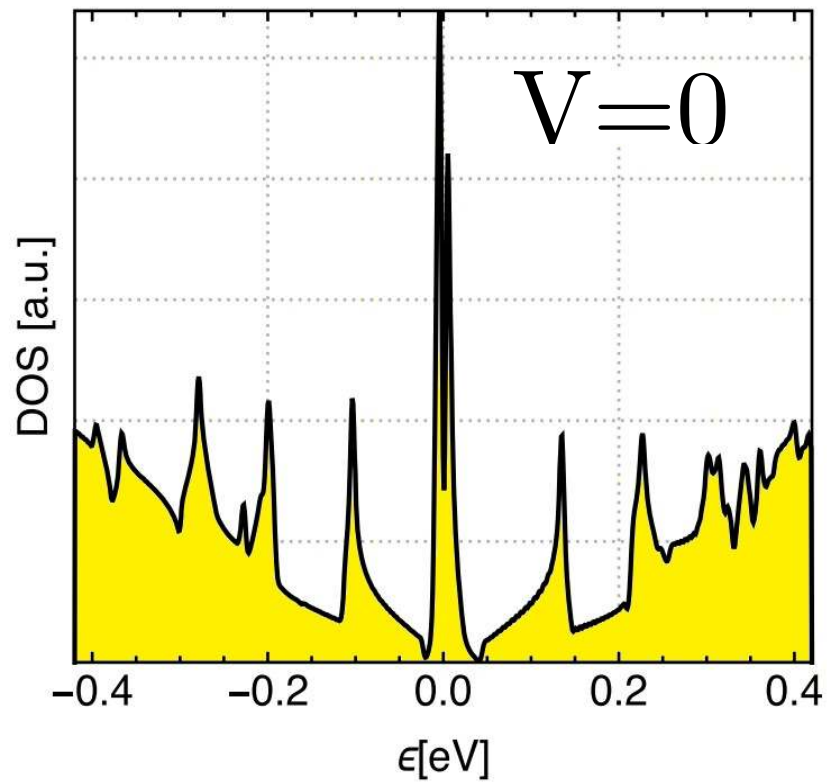


Electrical DOS enhancement for $\alpha = 1.5^\circ$

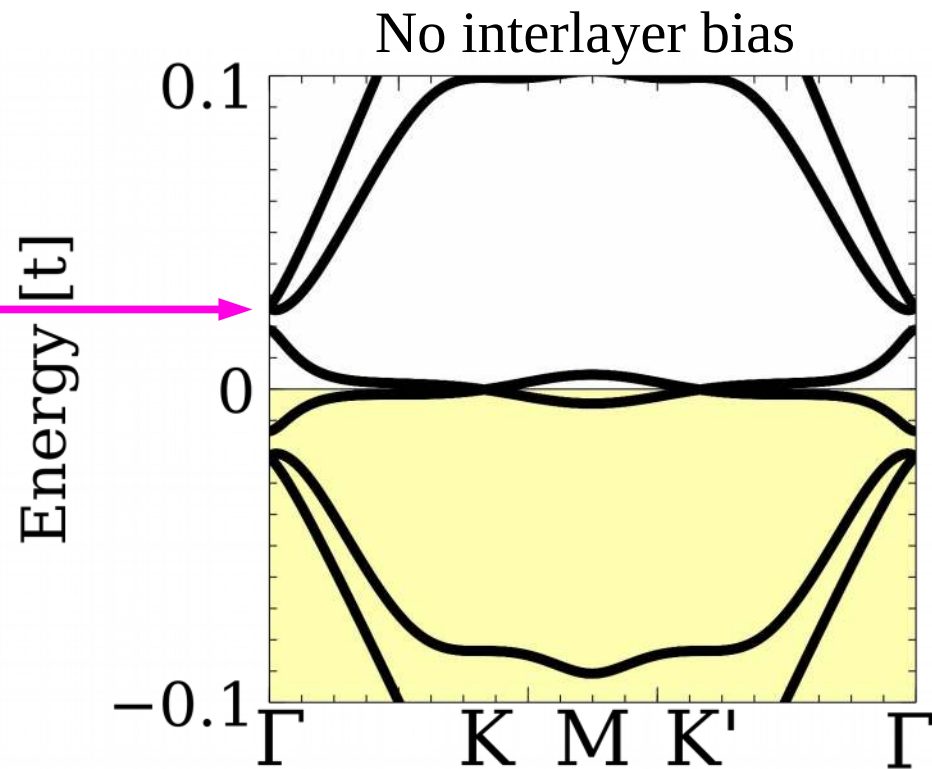
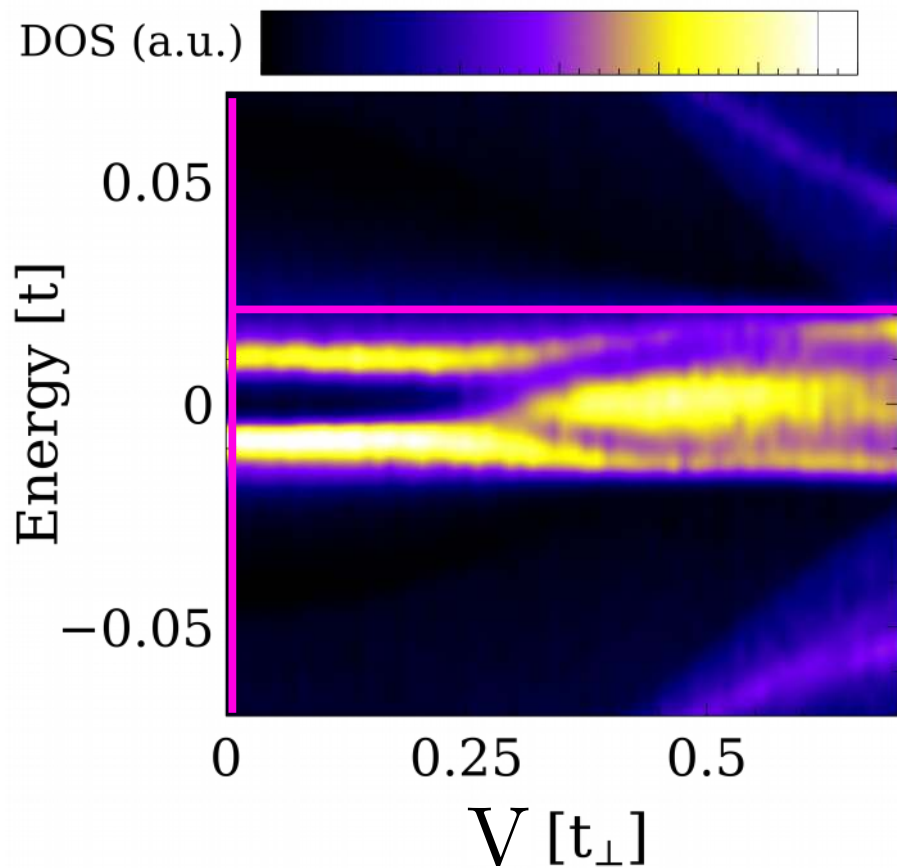
$$\alpha = 1.5^\circ$$



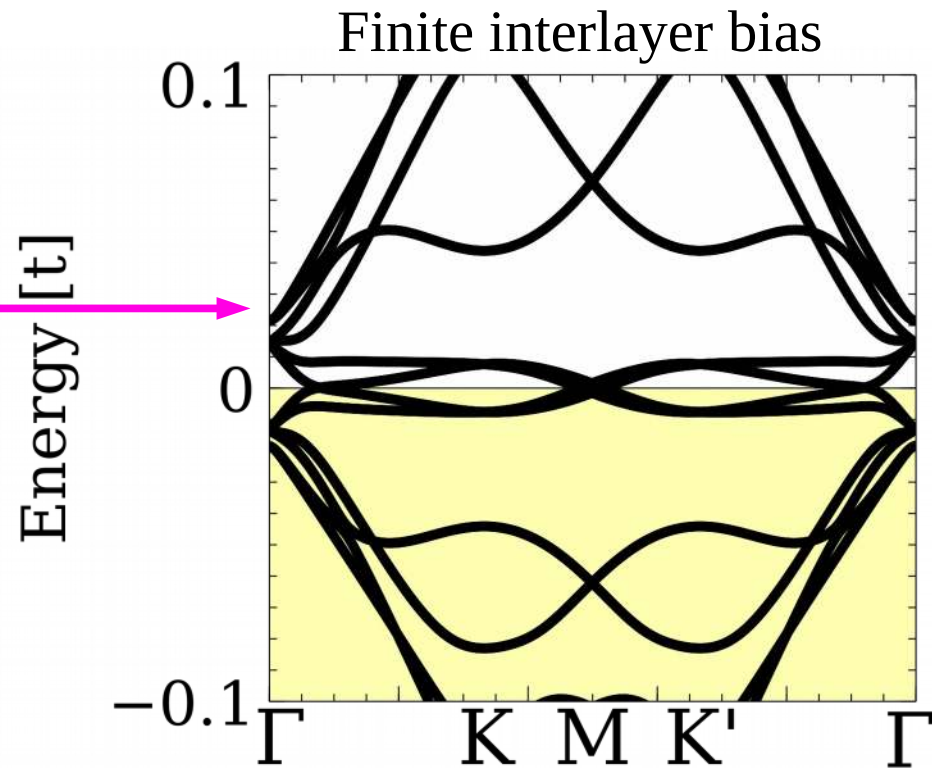
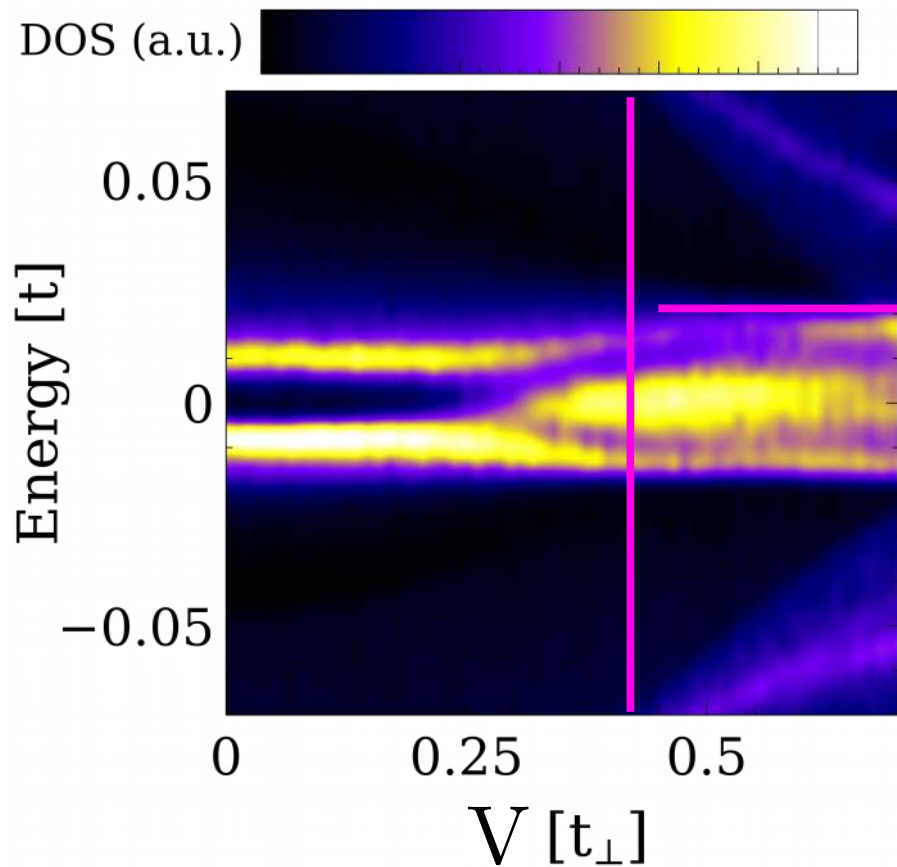
Electric bias in TBG at 1.5 degrees



Enhancing DOS electrically

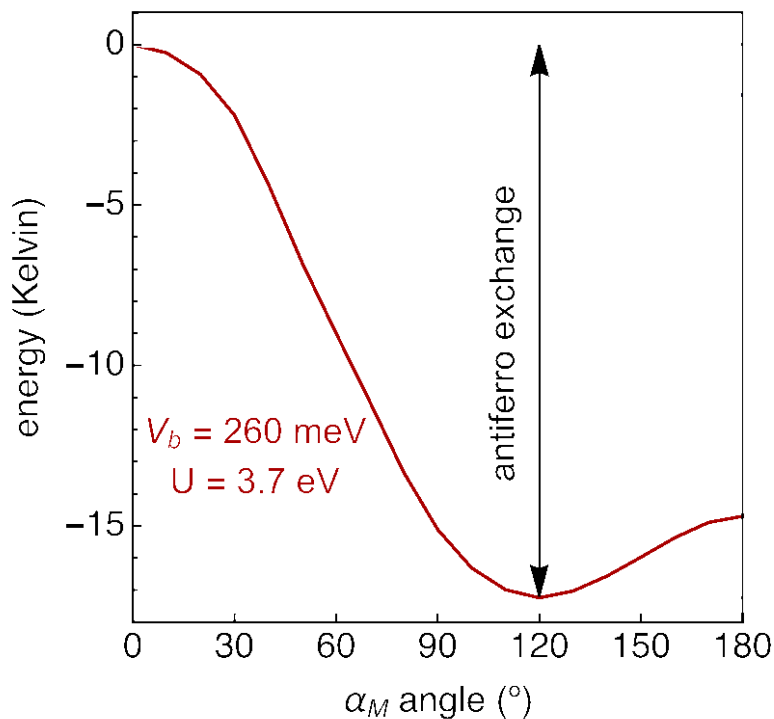


Enhancing DOS electrically



Spiral magnetism in biased TBG

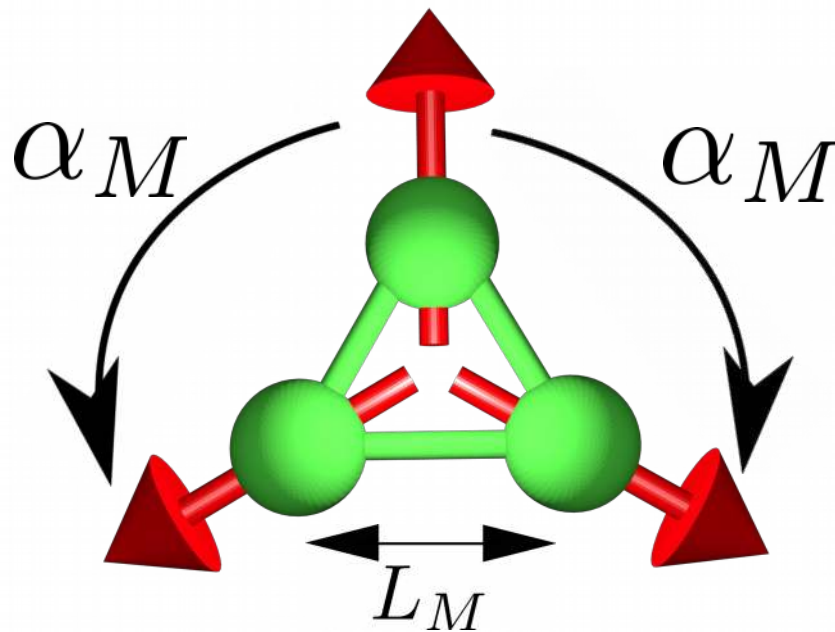
Energy VS spin-spiral angle



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

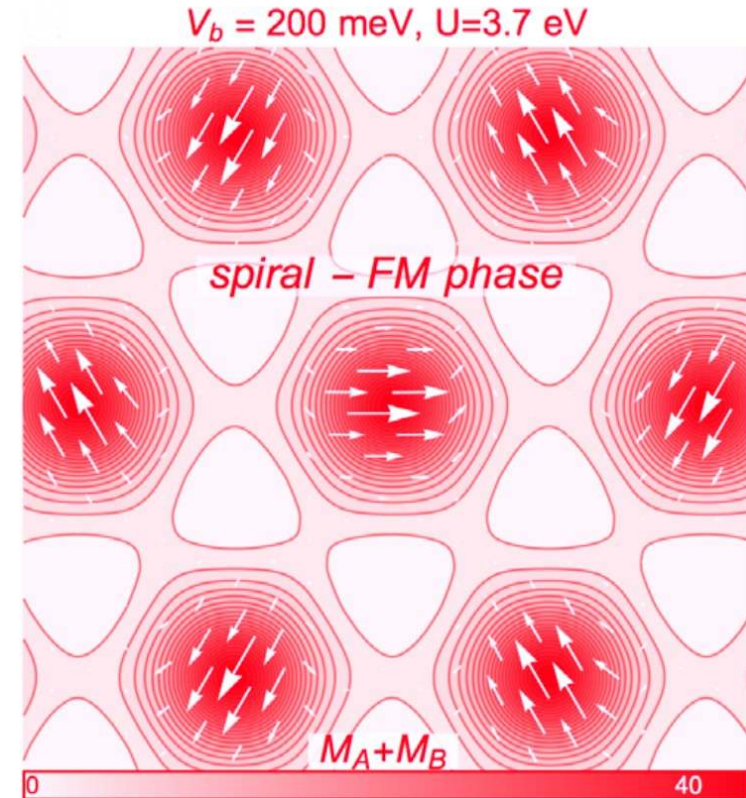
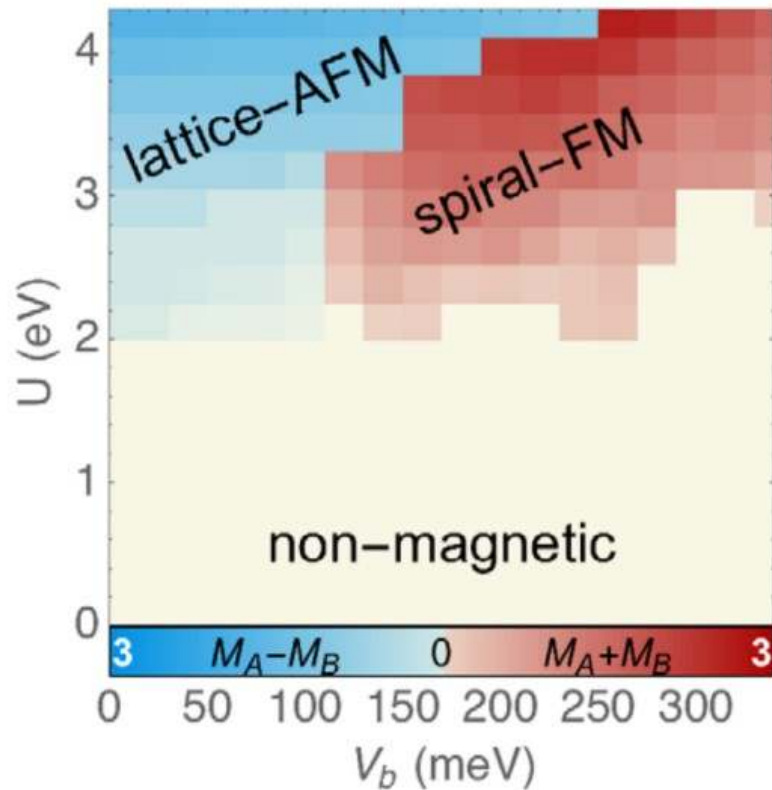
Solving at the mean field level

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



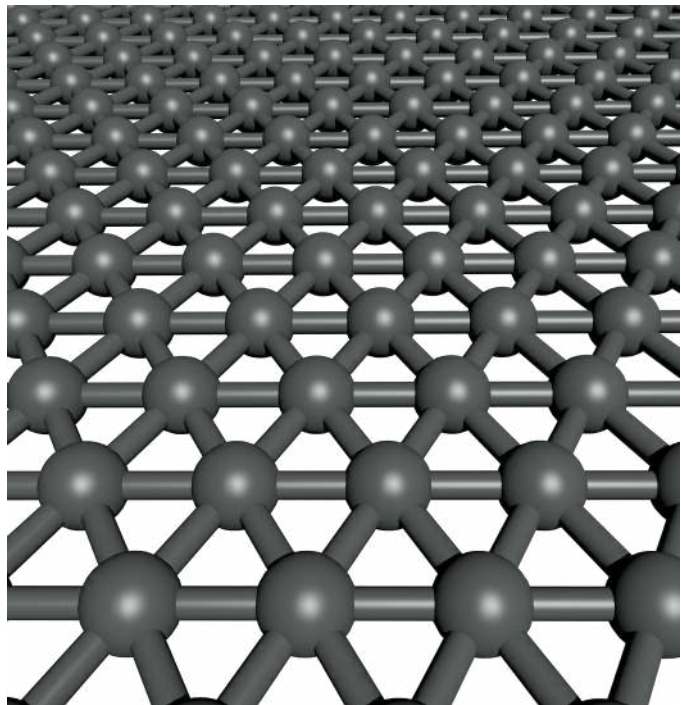
Spin spiral ground state with electric bias

Electrically controlling exchange interactions

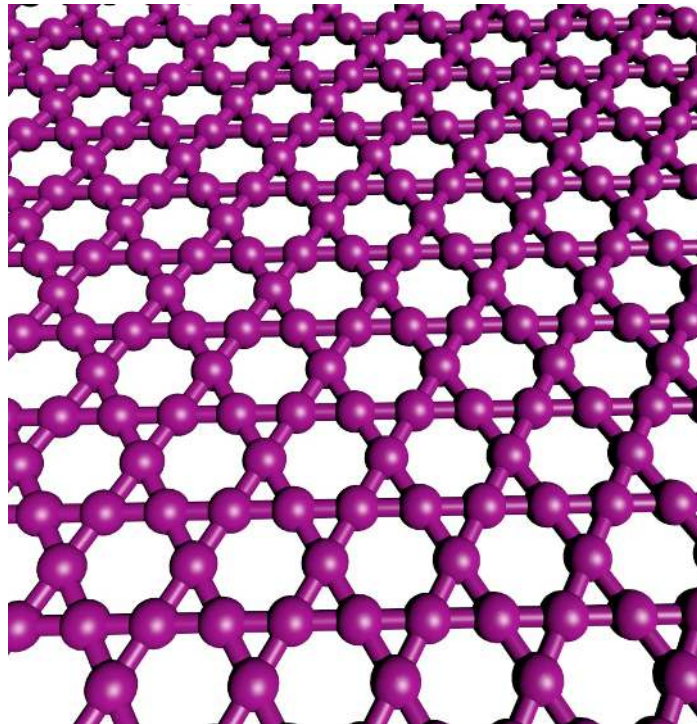


Towards a
Kagome lattice

From triangular to Kagome

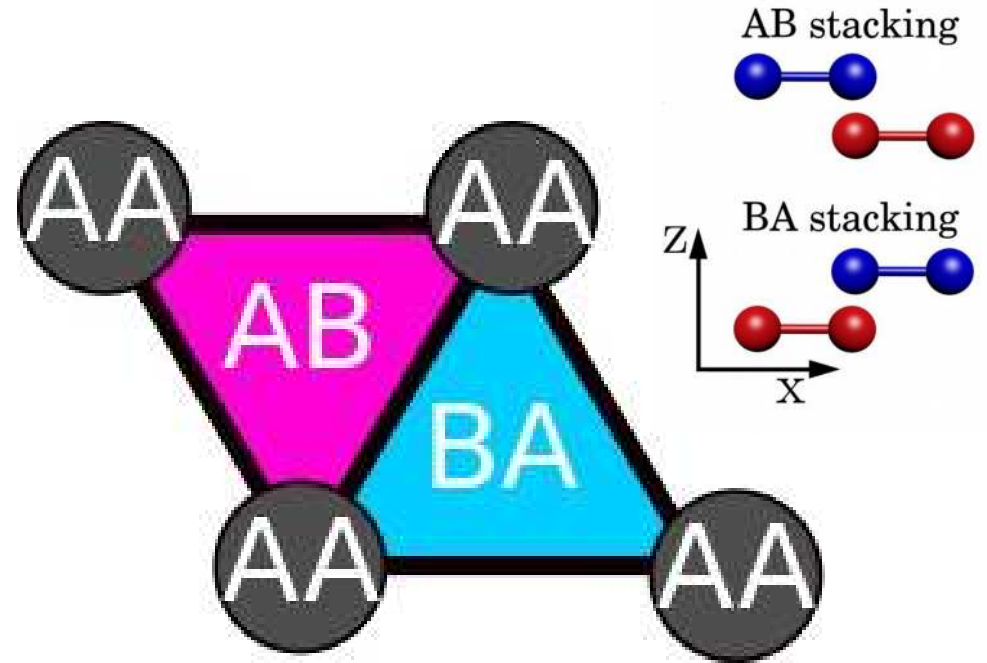
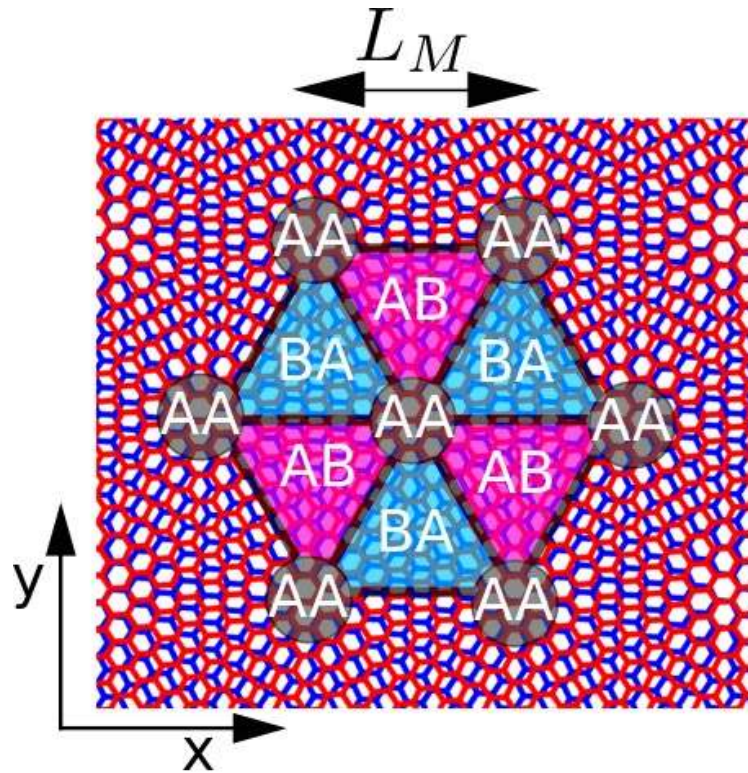


?



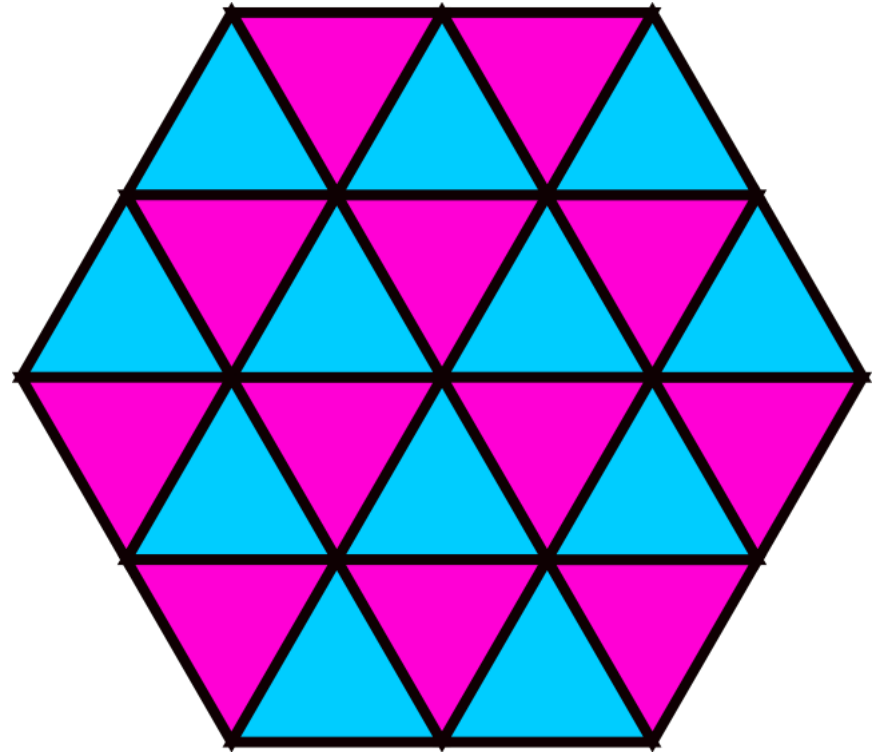
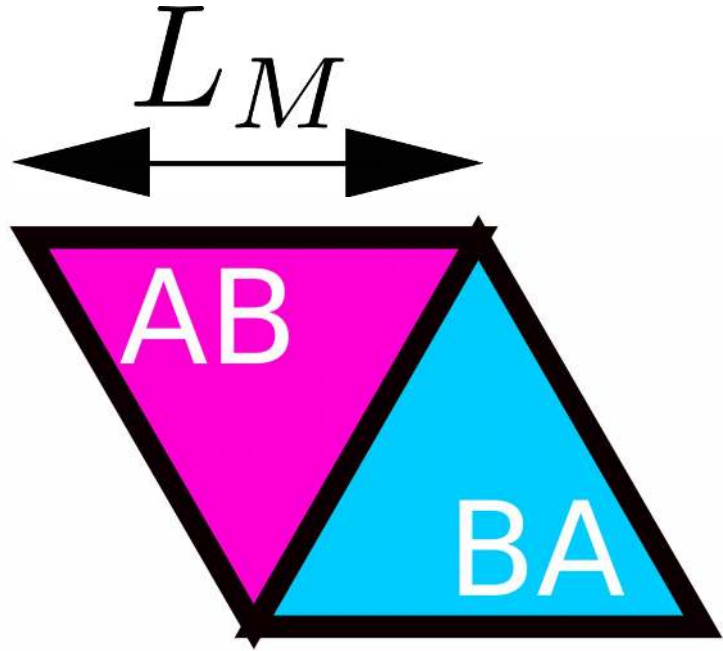
Can we generate additional gauge fields in twisted bilayers?

Towards a possible Kagome lattice

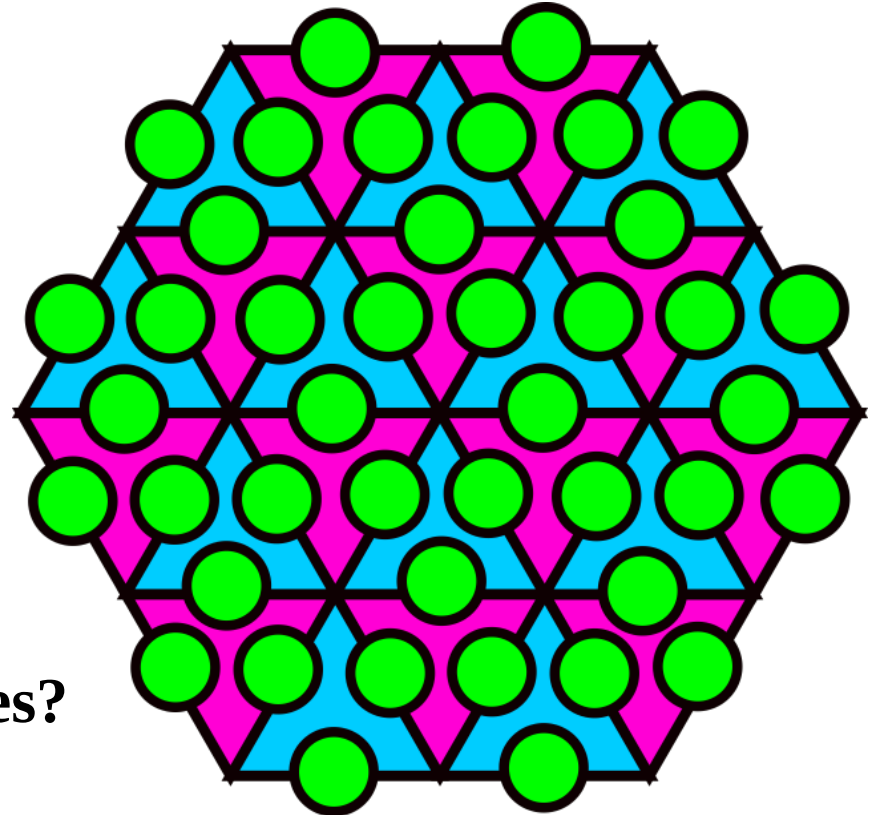
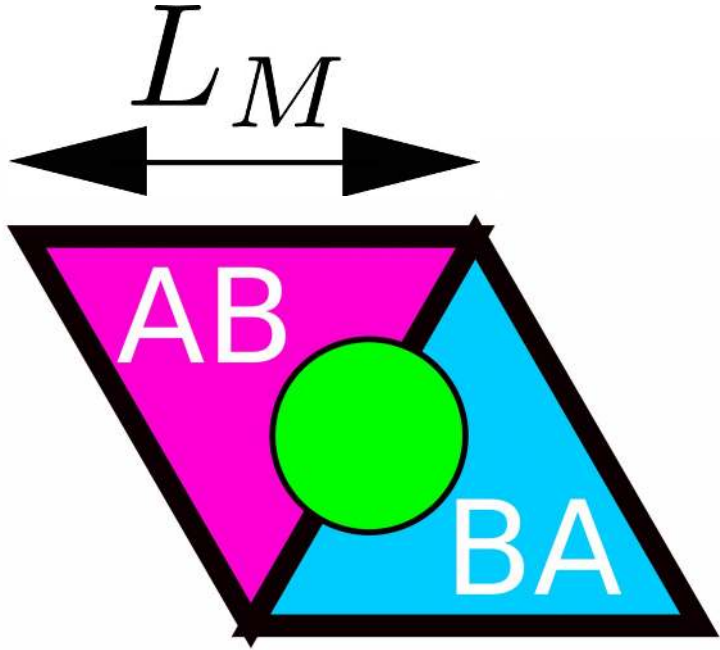


Let us look at the AB/BA structure

The possible Kagome lattice in TBG

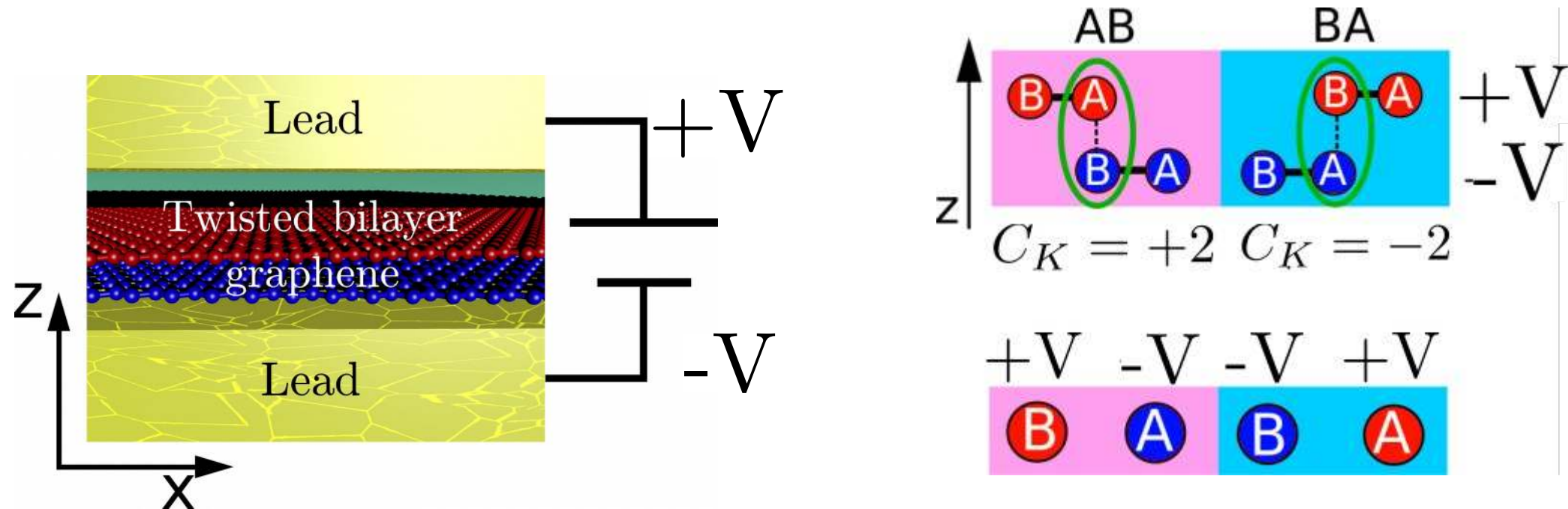


The possible Kagome lattice in TBG



How do we generate such localized modes?

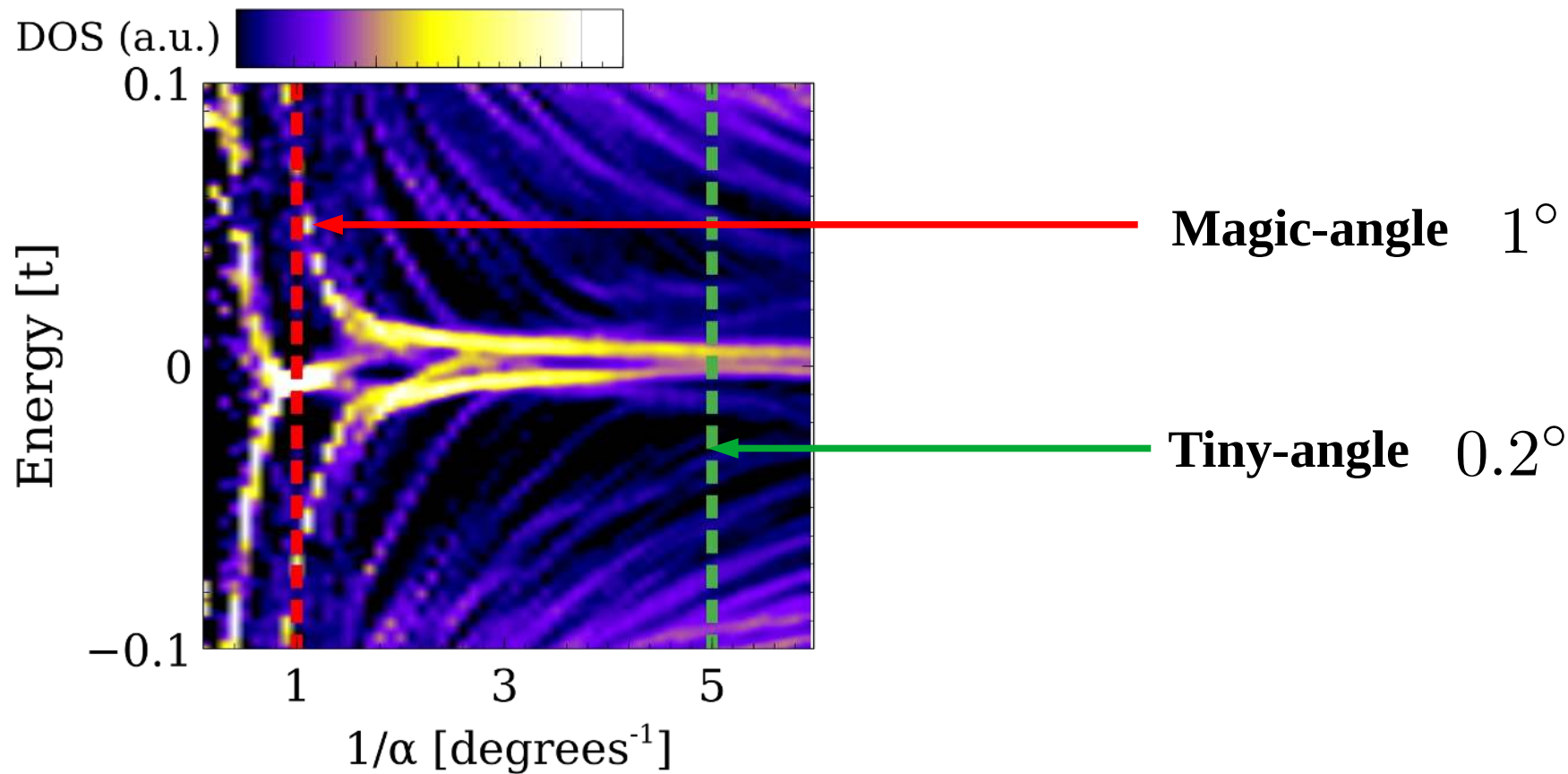
Electric gauge fields in TBG



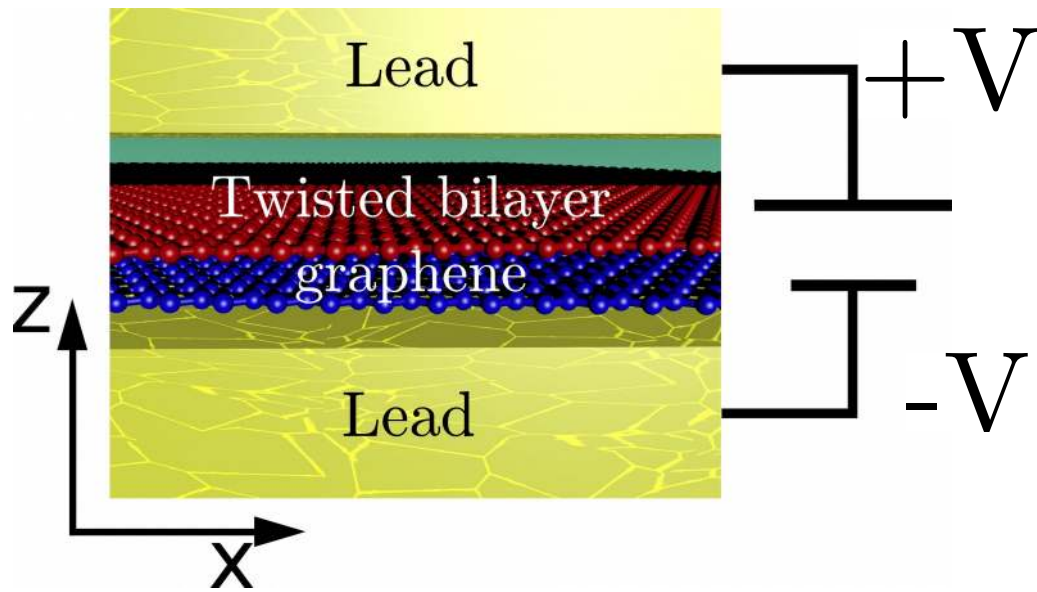
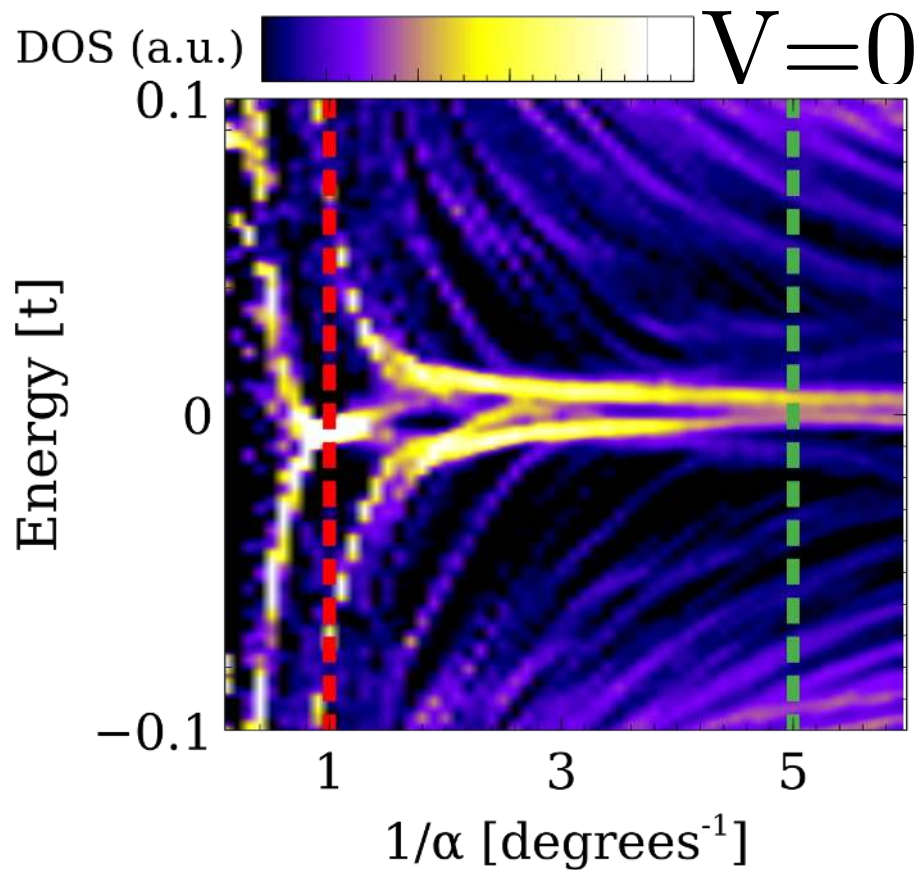
Electrically generated gauge field

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

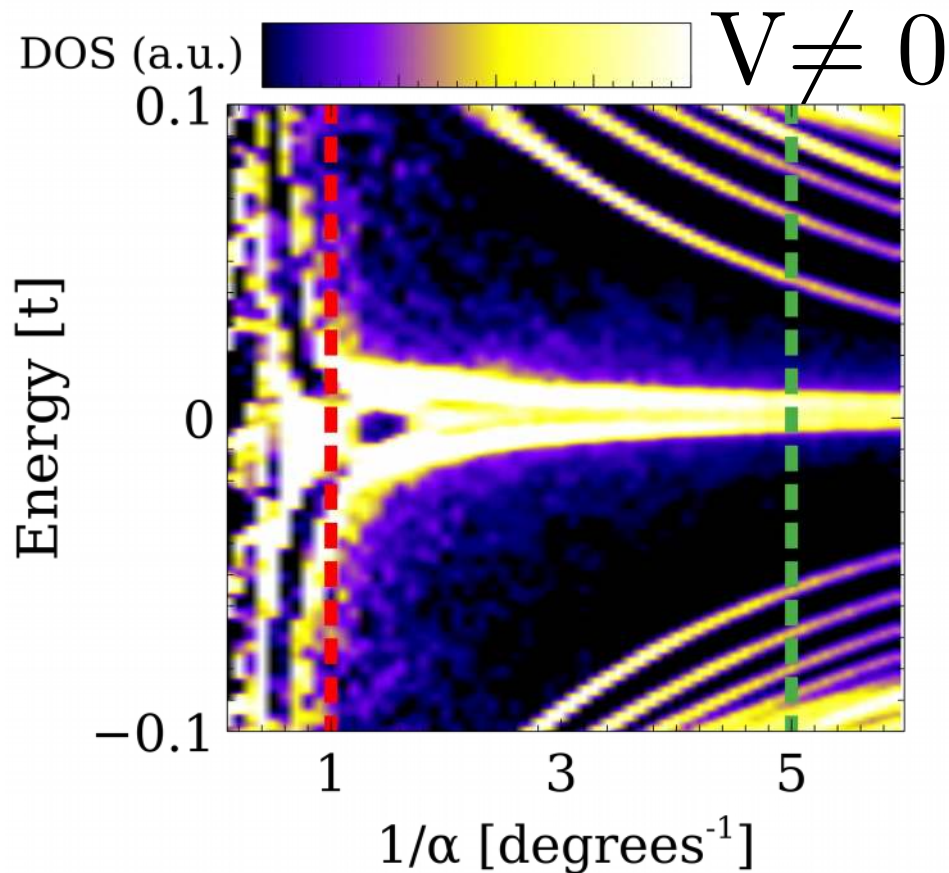
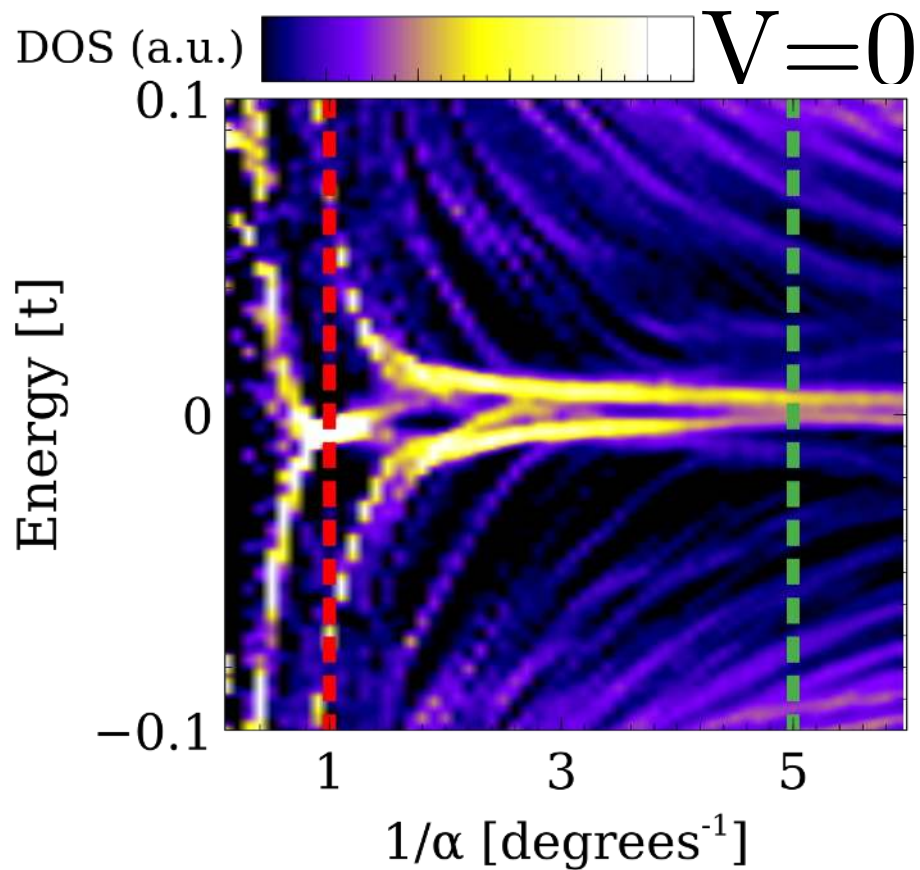
Diving into the tiny-angle regime



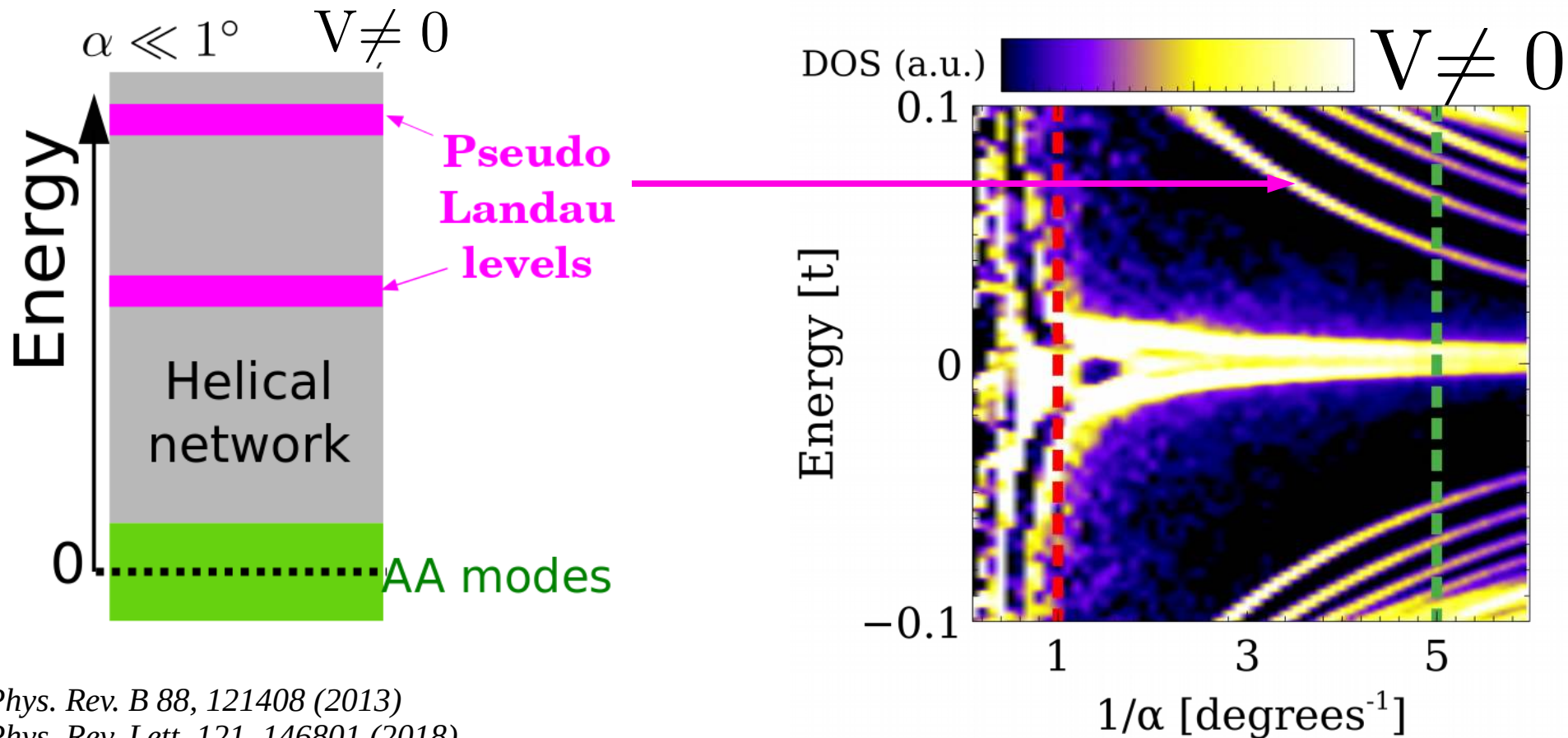
Diving into the biased tiny-angle regime



Diving into the biased tiny-angle regime



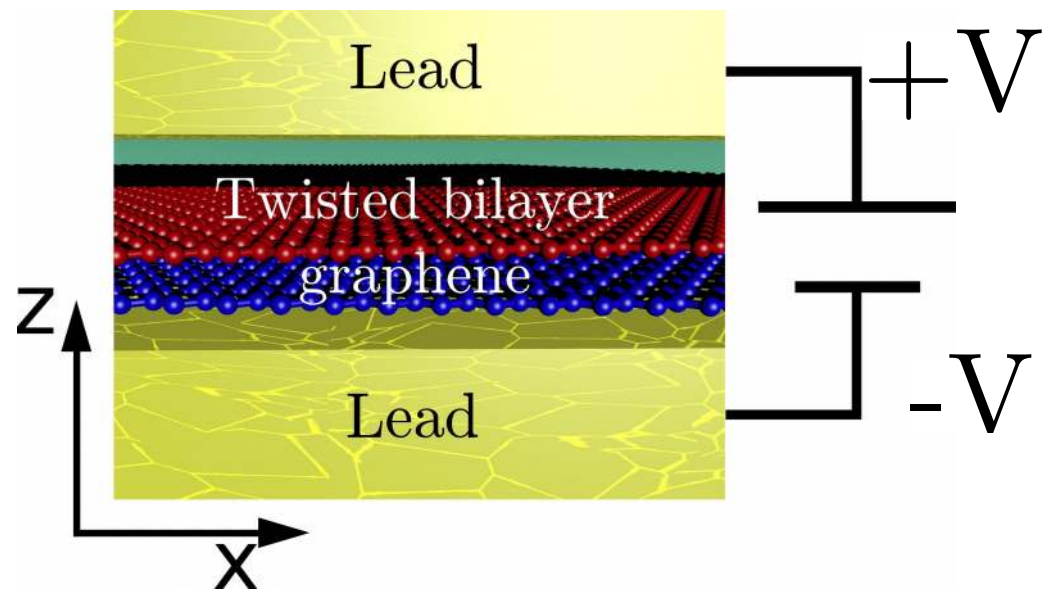
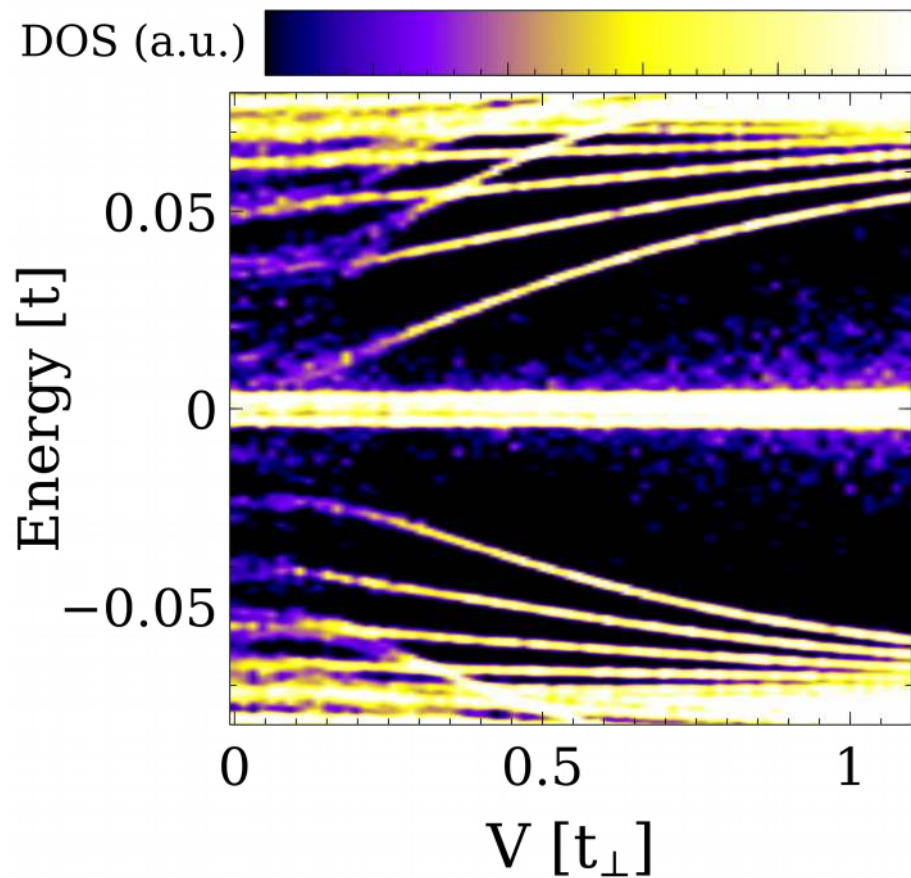
Diving into the biased tiny-angle regime



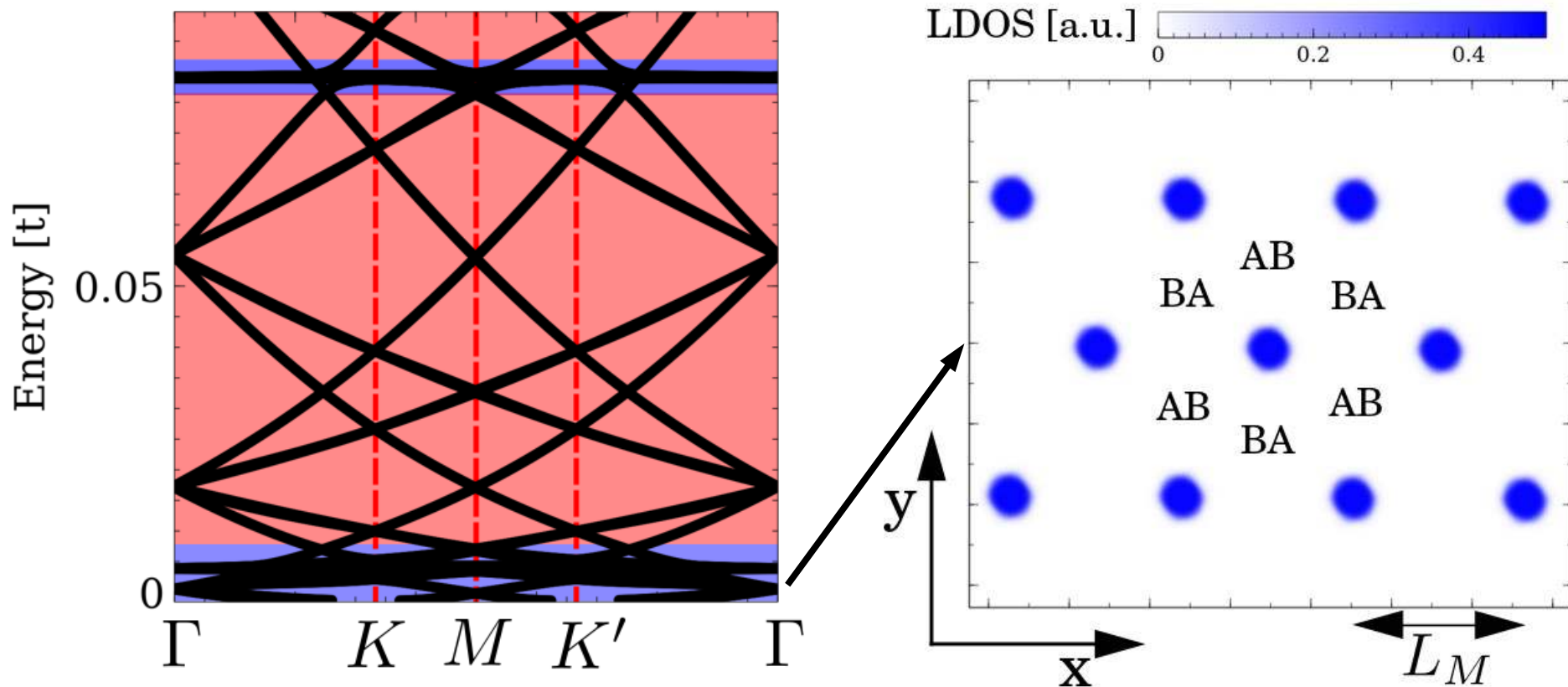
Phys. Rev. B 88, 121408 (2013)

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

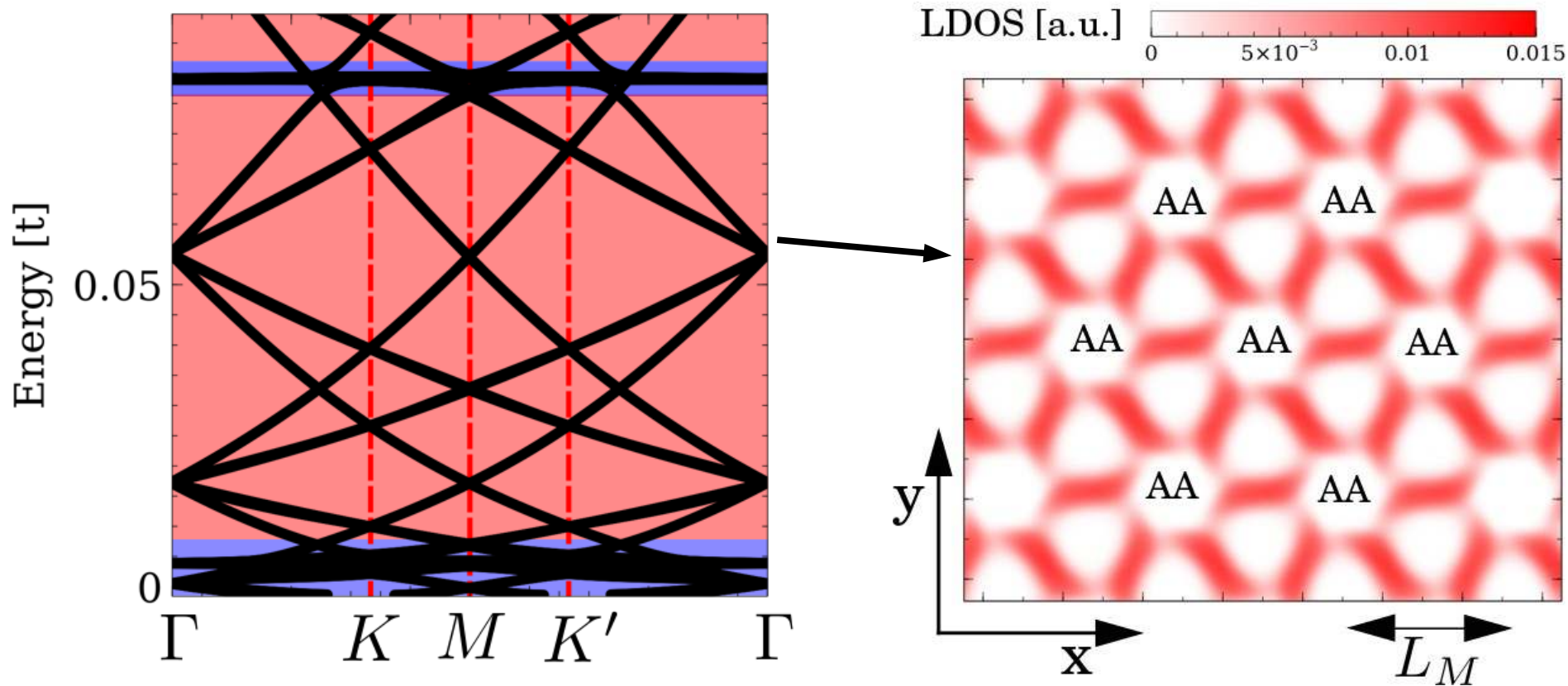
Controlling pseudo Landau levels electrically



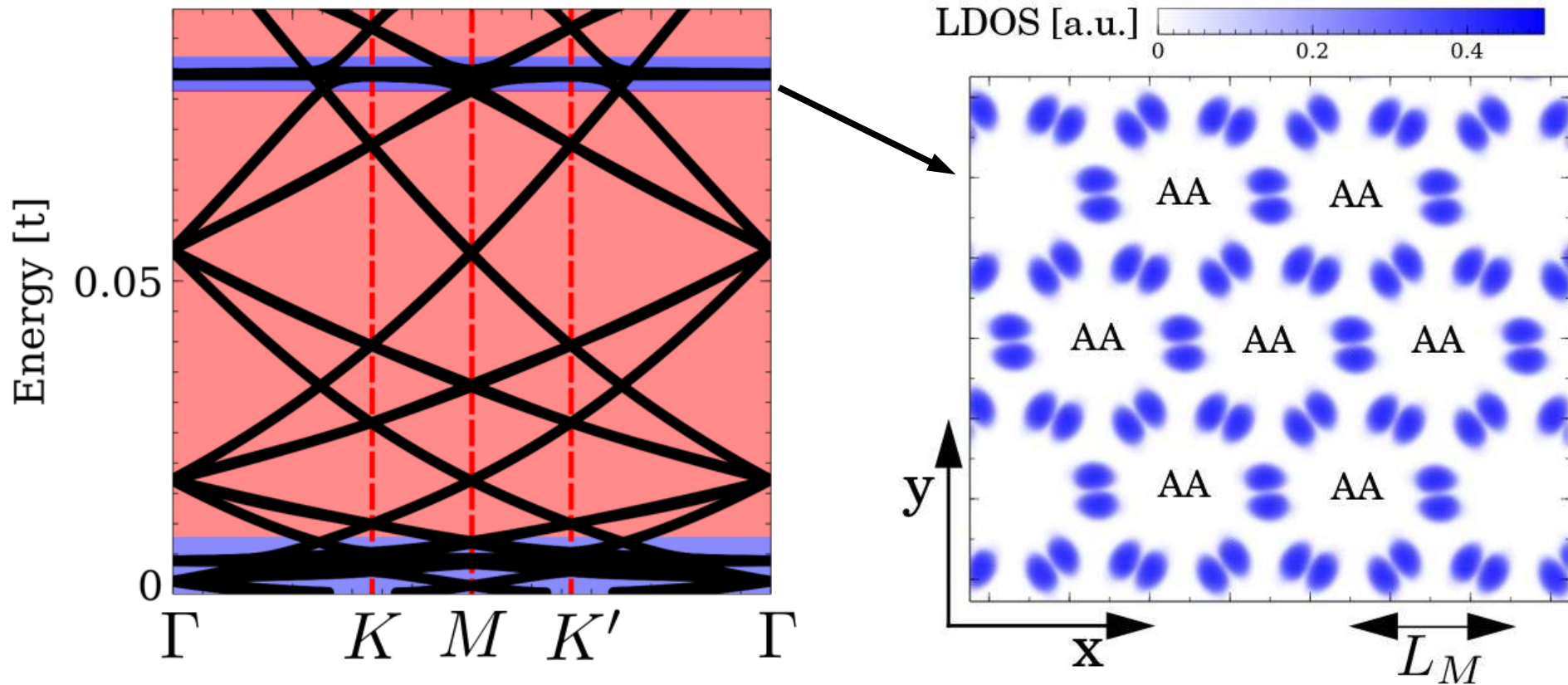
AA modes tiny angle TBG



Helical network in tiny angle TBG

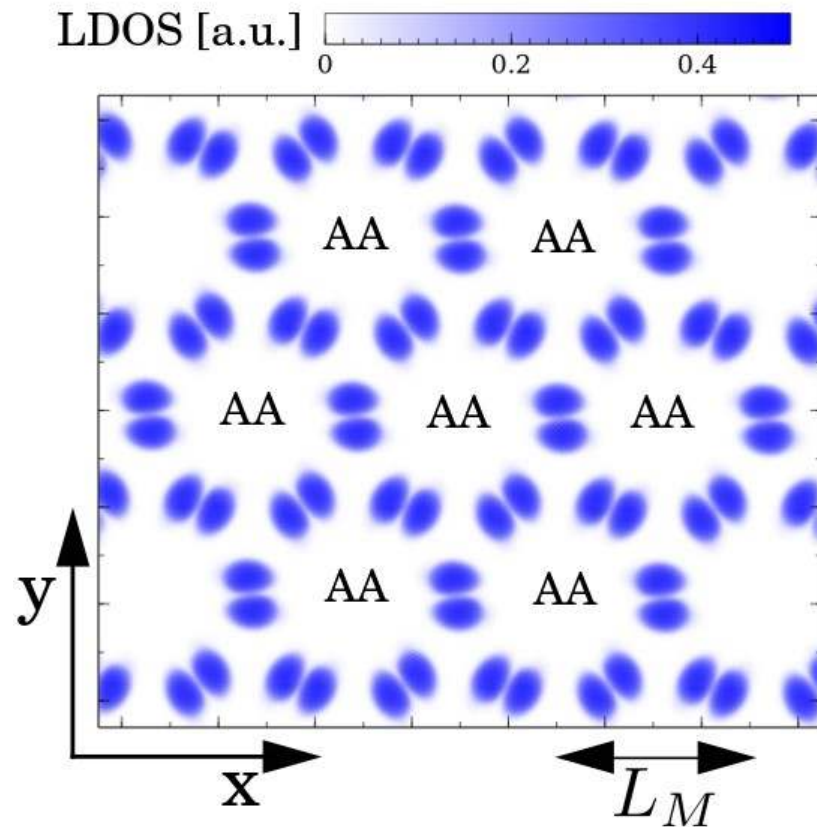
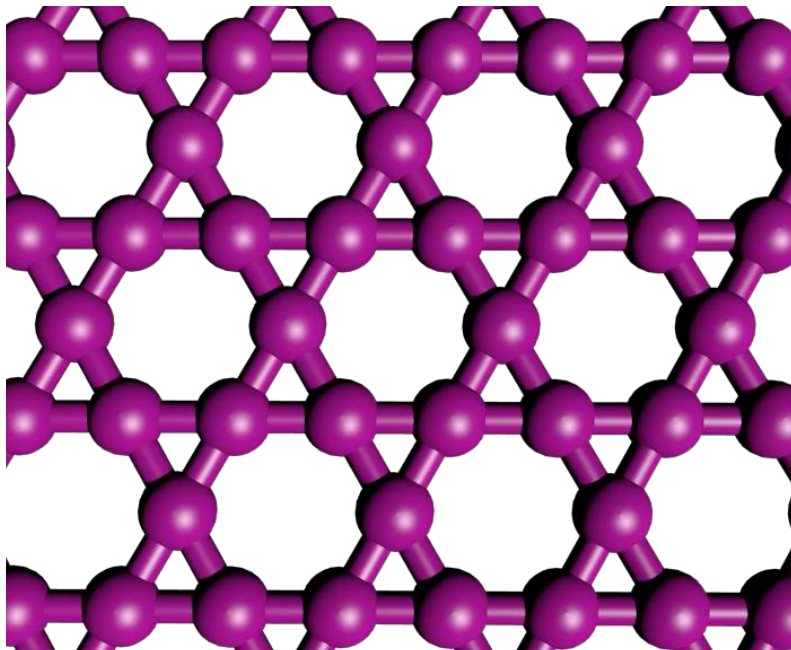


Pseudo Landau level in tiny angle TBG



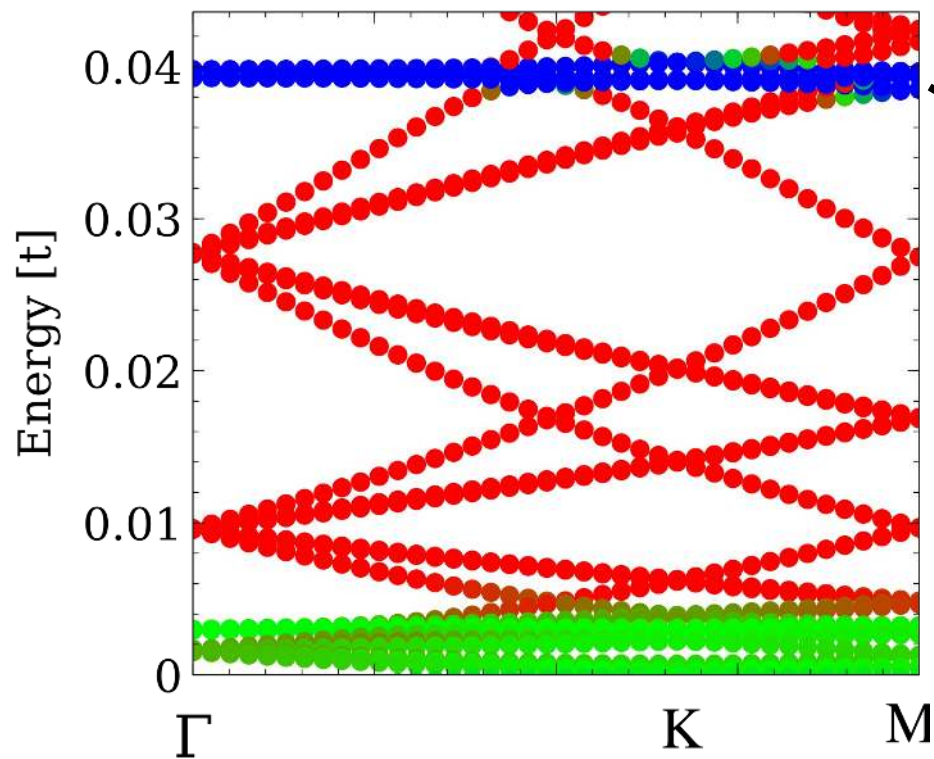
Kagome lattice in TBG

Emergent Kagome lattice

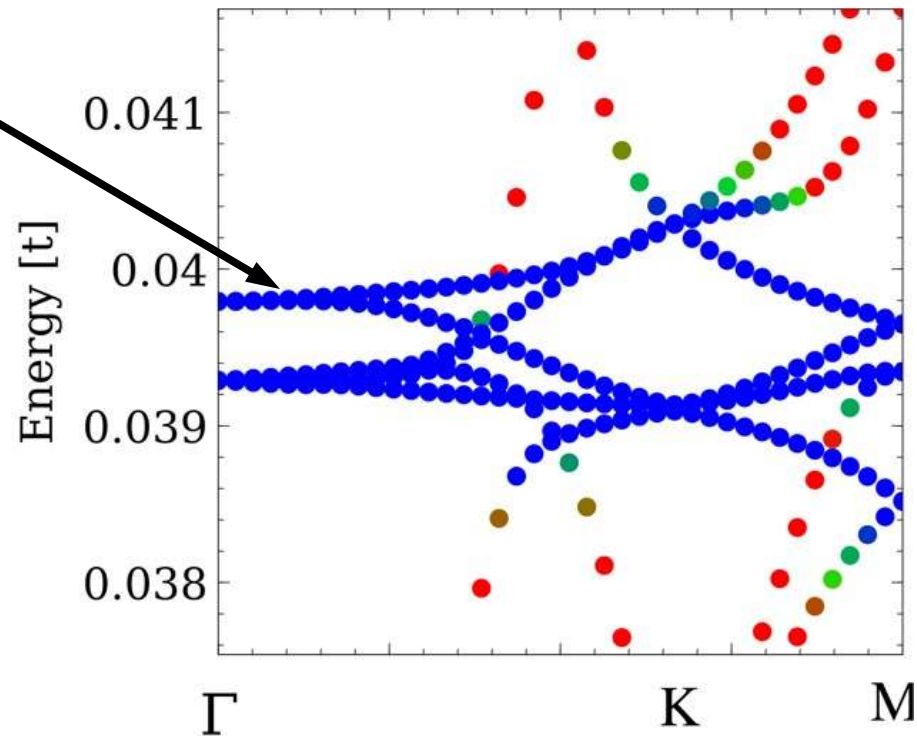


Overlap between pLL

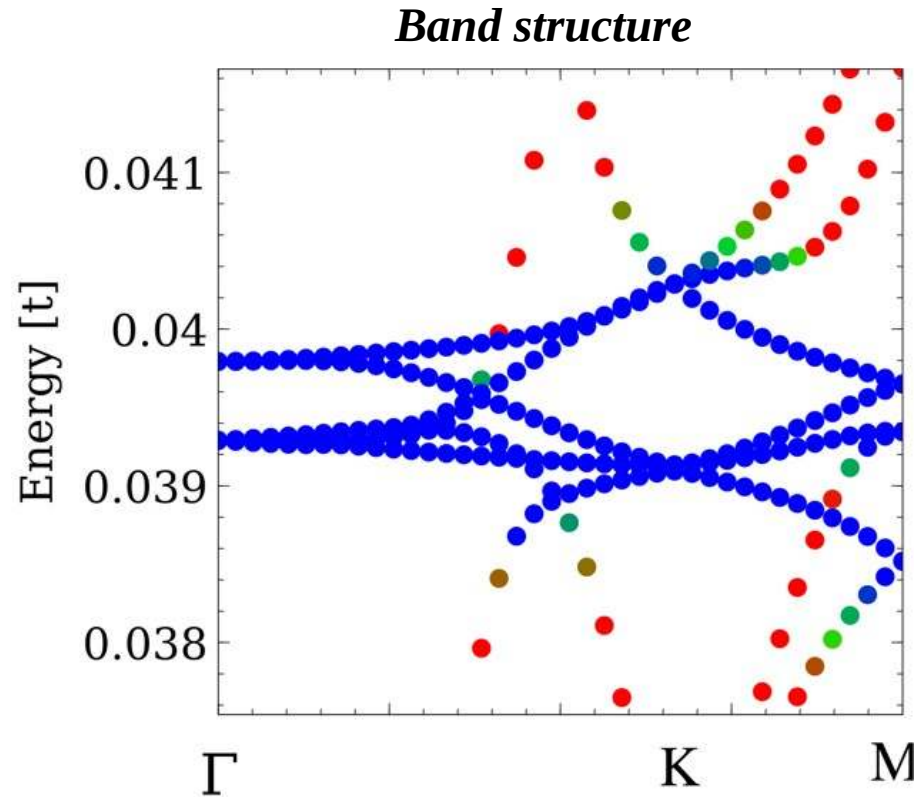
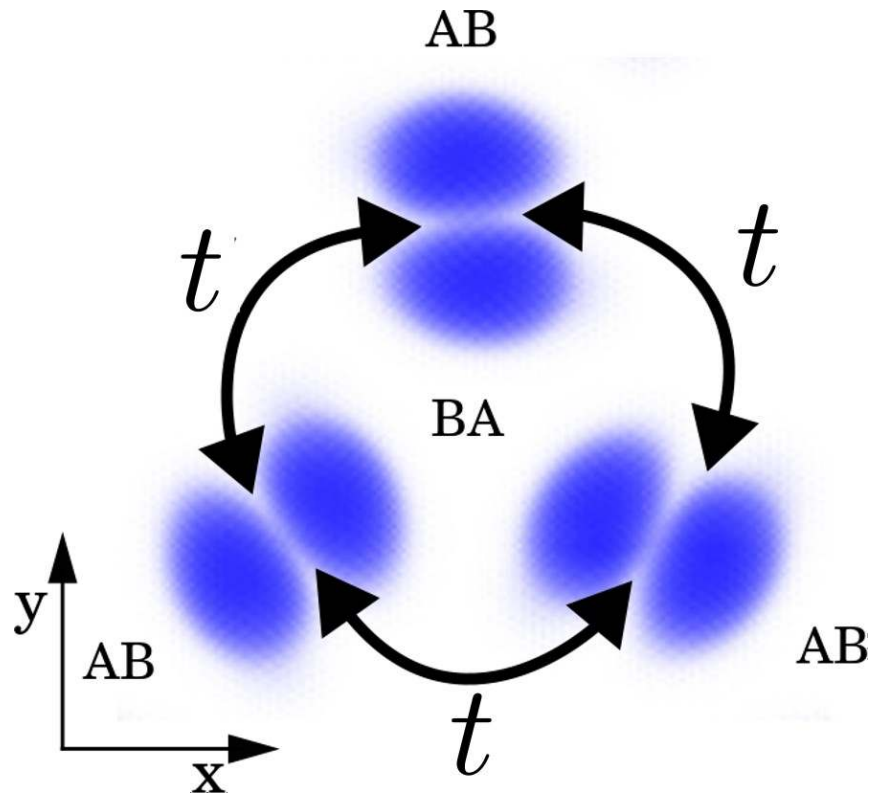
Band structure



Band structure

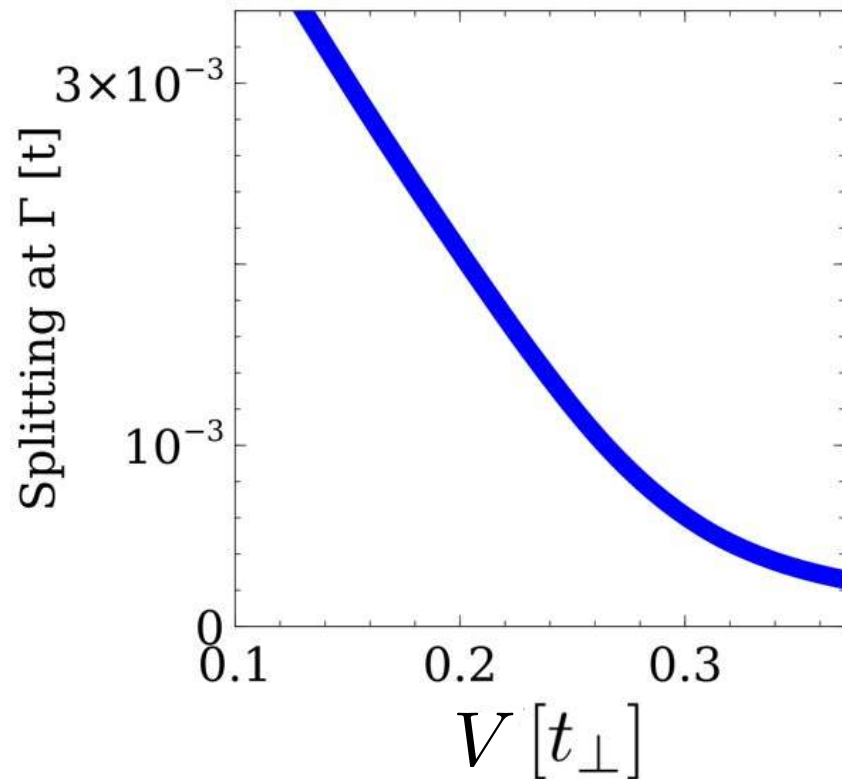


Tailoring the hopping a Kagome lattice

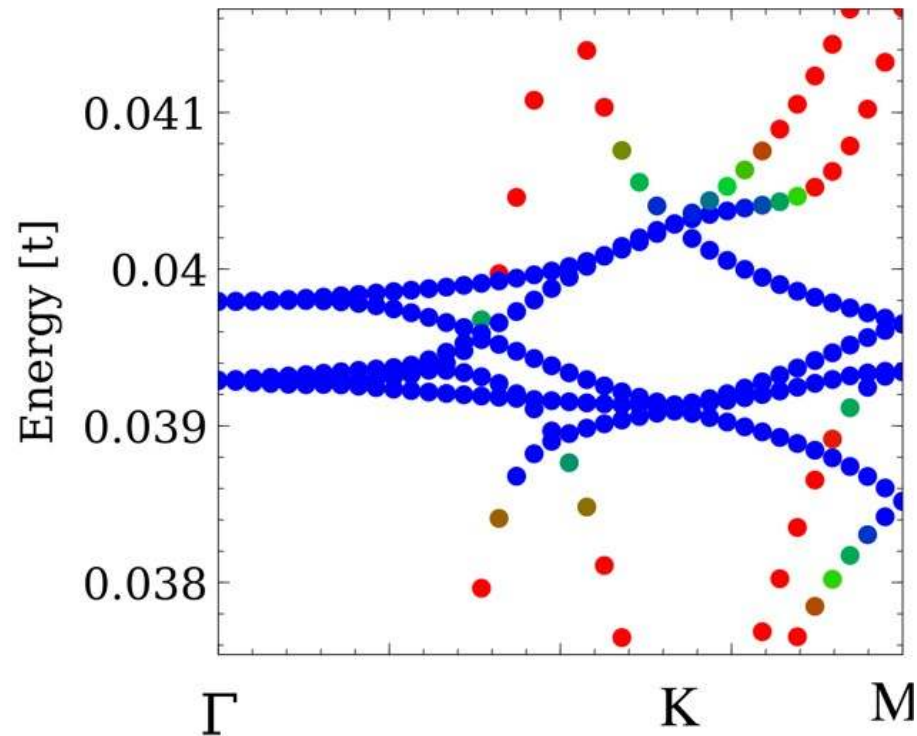


Bias controlled splitting

Splitting VS bias

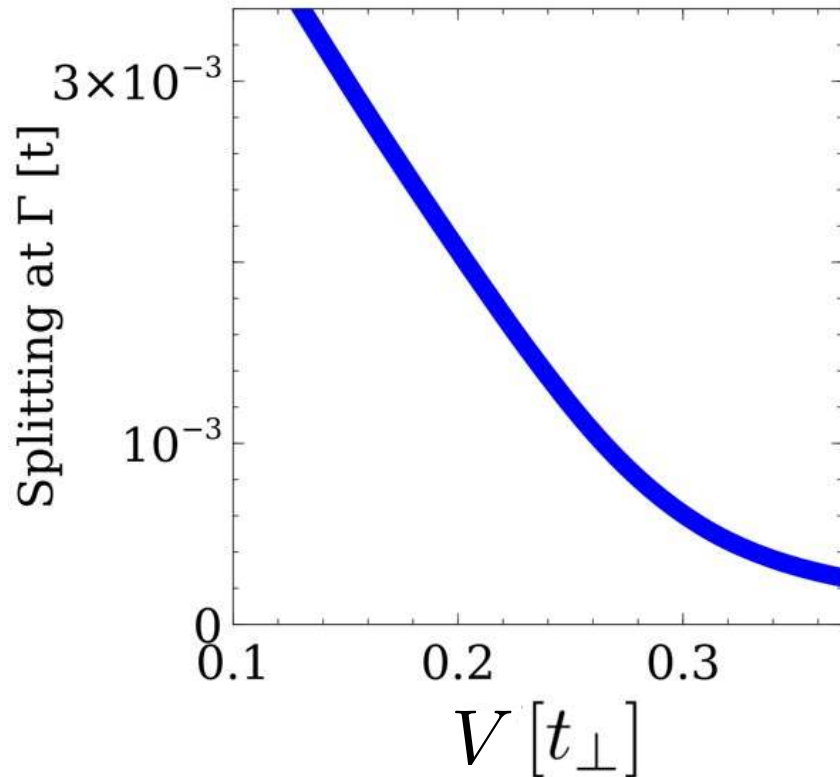


Band structure



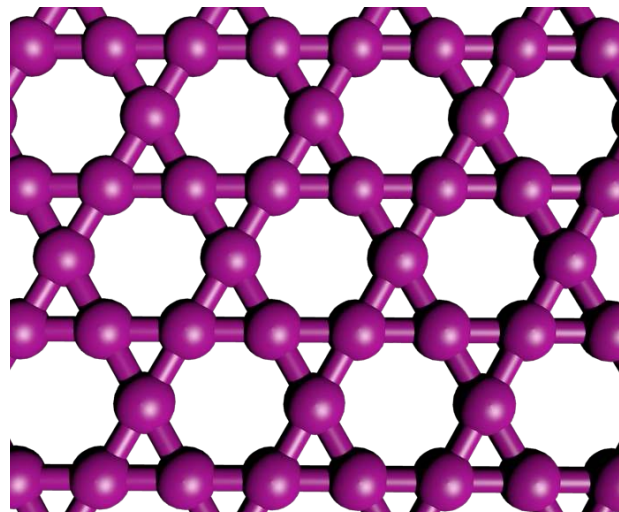
Controllable exchange in a Kagome lattice

Splitting VS bias



Effective Heisenberg model in a Kagome lattice

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

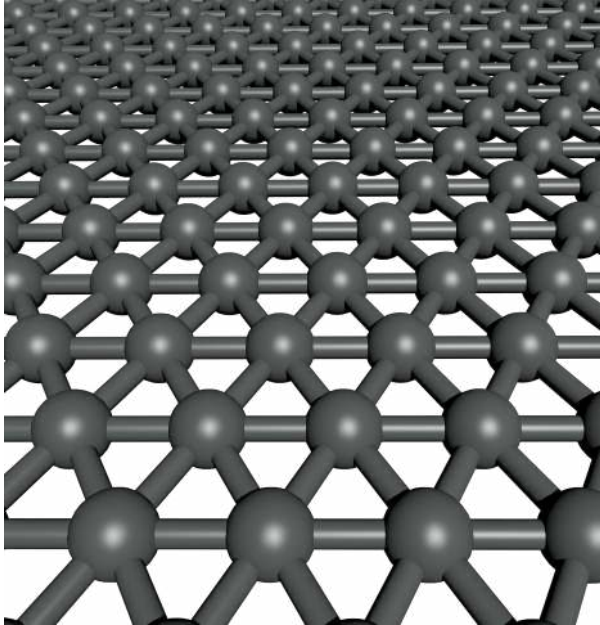


Frustrated superlattices with TBG

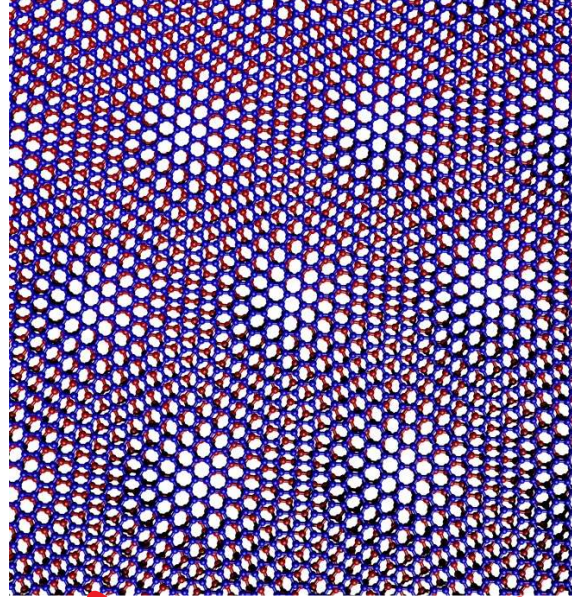
Triangular

1.5 degrees

Tunable exchange



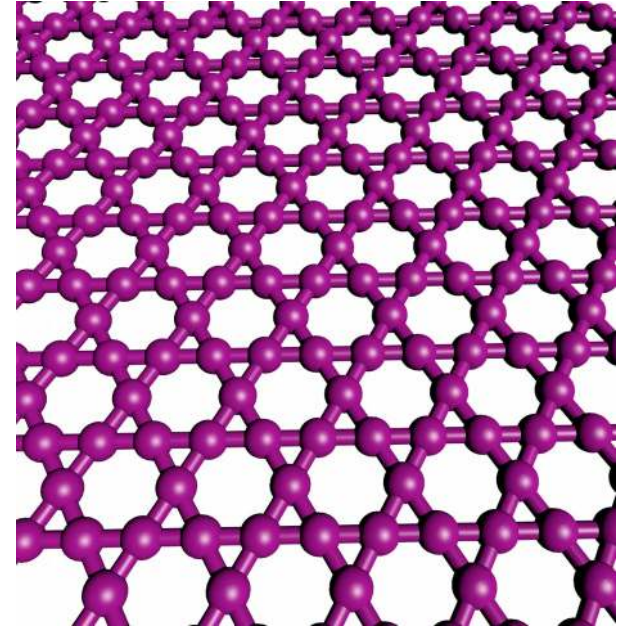
Phys. Rev. Lett. 119, 107201 (2017)



Kagome

0.2 degrees

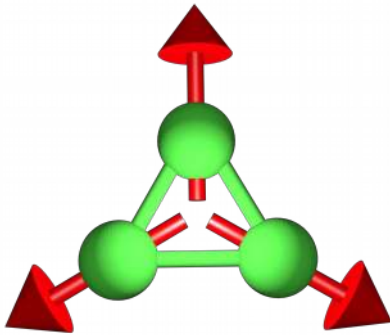
Electric gauge field



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

Take home

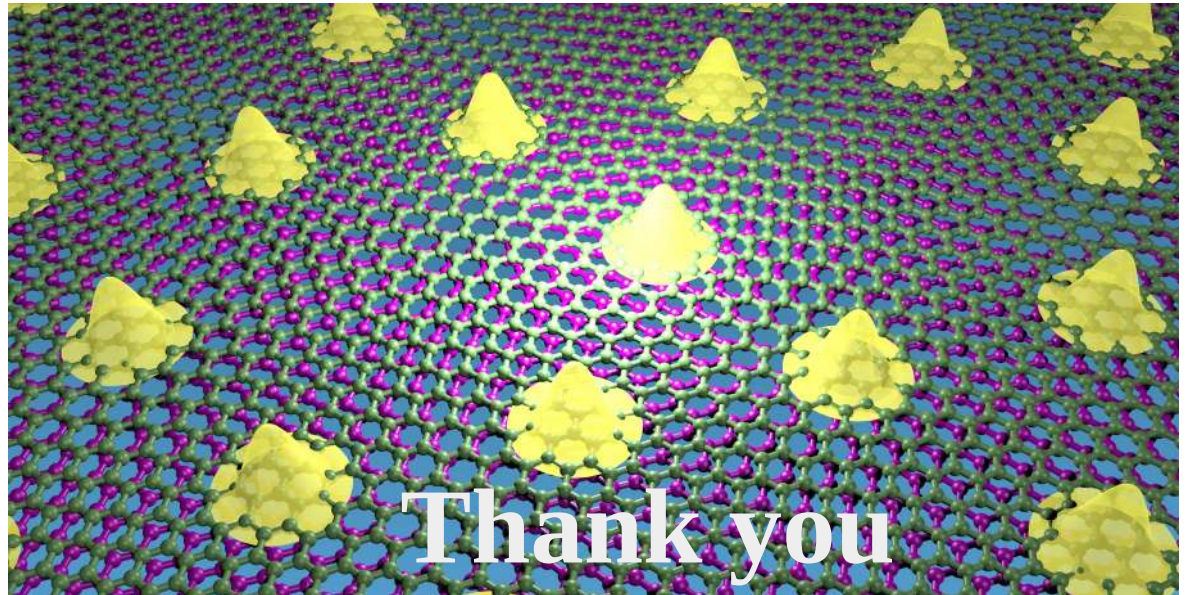
Twisted graphene bilayers provide a venue for frustrated magnetism with electrically controllable interactions



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

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

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Thank you