Title: Magnetism, Skyrmions and Superconductivity in MoirÃ© Lattices

Speakers: Ashvin Vishwanath

Series: Colloquium

Date: April 28, 2021 - 2:00 PM

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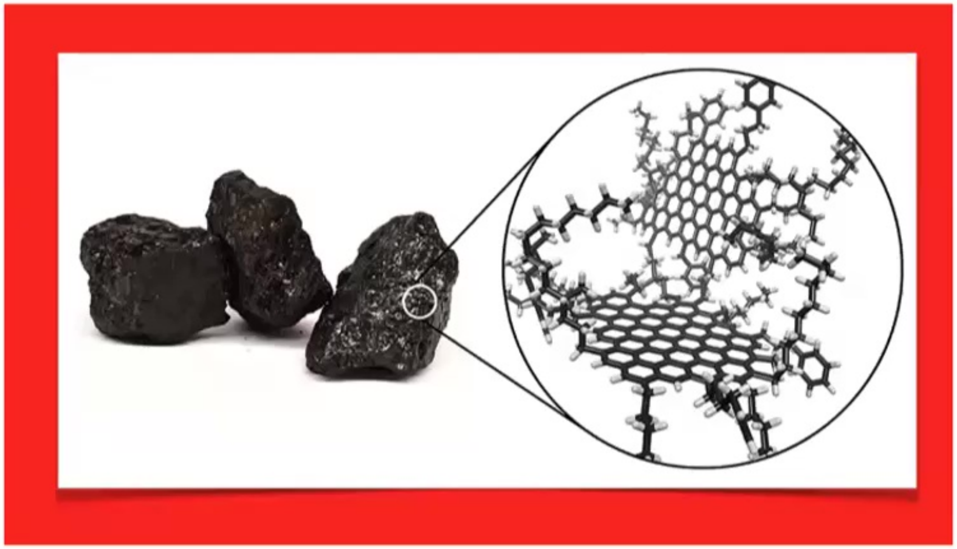
Abstract: The remarkable properties of electrons moving through crystalline lattices continue to surprise us. Recently, electrons in artificial moirÃ© lattices have emerged as an extraordinary new platform. The simplest such moirÃ© material consists of a pair of graphene sheets twisted relative to one another. At a "magic" angle of about 1 degree, a variety of phenomena, including strong-coupling superconductivity, is observed. In this talk, I will review this rapidly moving field and describe our theoretical ideas that invoke the geometry of quantum states and topological textures like skyrmions. Finally, I will explain how these insights indicate a promising new family of moirÃ© materials, twisted trilayer graphene, which is currently under active experimental study.



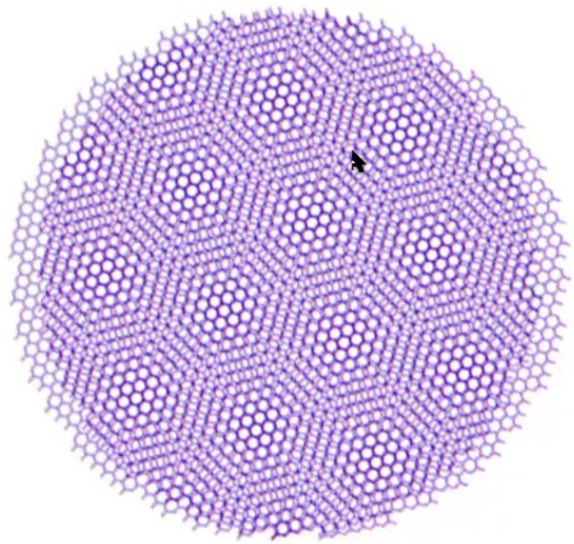
Magnetism, Skyrmions and Superconductivity in Moiré Lattices

Ashvin Vishwanath
Harvard University

Graphene's Electrons in Moiré lattice

Electrons

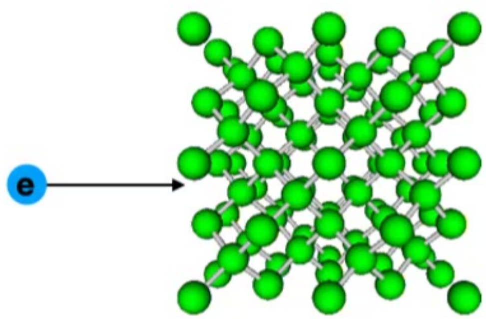
\+ Moire lattice

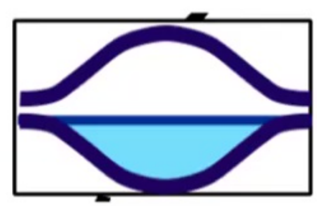


Electronic States in a Crystal

Metals

Insulators





Crystal => Artificial Vacuum for the electrons

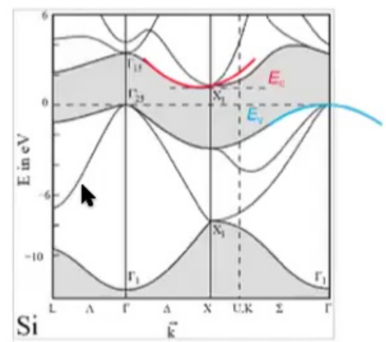
Crystals - Artificial Vacuum for Electrons

Vacuum Tubes <1960s

Transistor

“A sudden gasp filled the room when he flicked on an oscillator circuit, and it emitted a shrill tone <u>instantaneously</u>, with no <u>warmup delay</u> whatsoever.”

Demonstration of the Transistor 1948
From - Crystal Fire

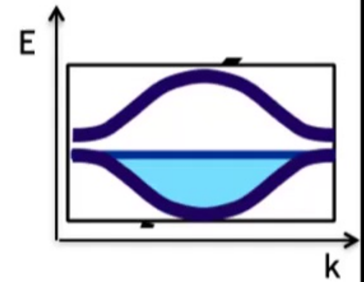


Modify properties of the electron
Effective mass, electrons+holes etc.

Qualitatively new effects?

- Semi-classical theory of electrons in a crystal

$$\dot{x} = \nabla_k \mathcal{E}(k) \;\; + \dot{k} \times \tilde{B}$$
$$\dot{k} = -\nabla_r \mathcal{V}(r) + e\dot{x} \times B$$

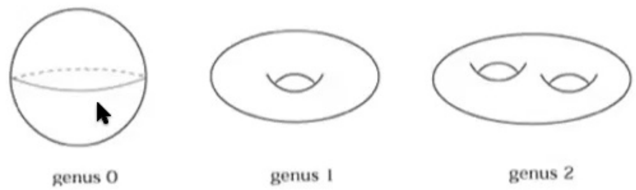


- Symmetry restored in a crystal – Berry Flux $\tilde{B}$ leads to an anomalous velocity.

- Berry Flux is related to the Berry's phase acquired by states in the band. "Quantum Geometry" of bands.

Topology and Geometry

- Topology: Robust aspects of shapes



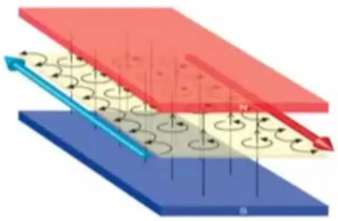
Topology of Surfaces:

Genus = # of holes

$$\oint K\,dS = 4\pi(1-g)$$

Gauss Formula

"Remarkable Theorem"

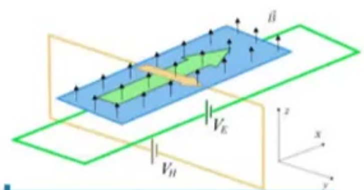


Integrate Berry Curvature

$$\oint \tilde{B}\, d^2k = 2\pi n$$

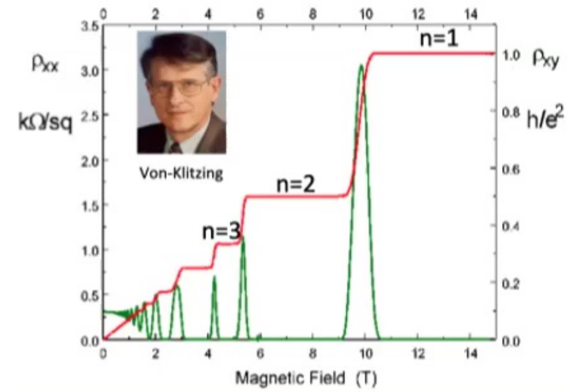
# of Edge States
= Hall
Conductance

Quantized Hall effect in Insulators



Electrons in 2D in a magnetic field.

$$\rho_{xy} = \frac{h}{e^2}\frac{1}{n}$$

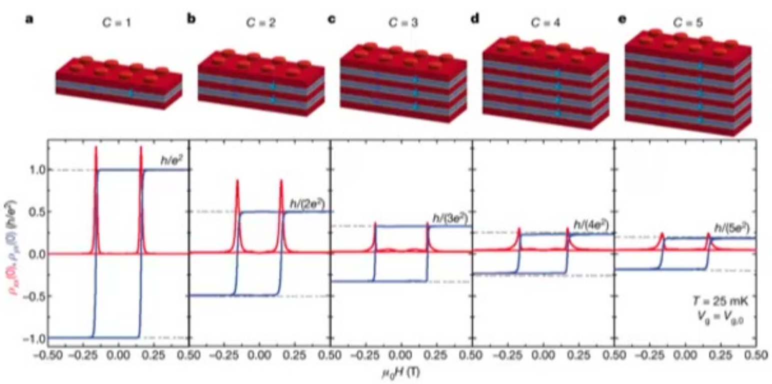


- Integer Quantum Hall States - (1980)
  - Different Integers `n' - different phases.
  - topological distinction.
  - Accurate to 1 part in 10^9!

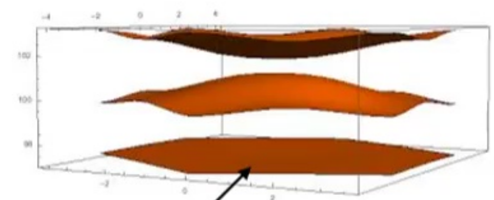
Quantized Hall effect without Magnetic Fields

Quantized Hall Conductance in a Two-Dimensional Periodic Potential

D. J. Thouless, M. Kohmoto,[a] M. P. Nightingale, and M. den Nijs
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 30 April 1982)



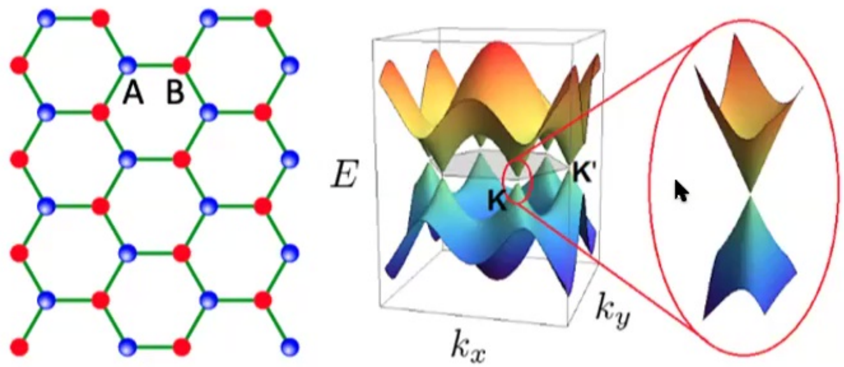
(Bi,Sb)$_{2-x}$Cr$_x$Te$_3$ Zhao et al. Nature 2020



Bands with Chern Number = C

Qualitatively new effects in band structures

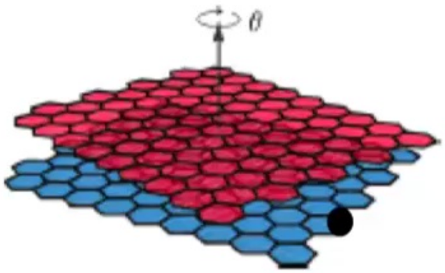
Graphene band structure



Electrons governed by 2+1D *massless* Dirac equation!

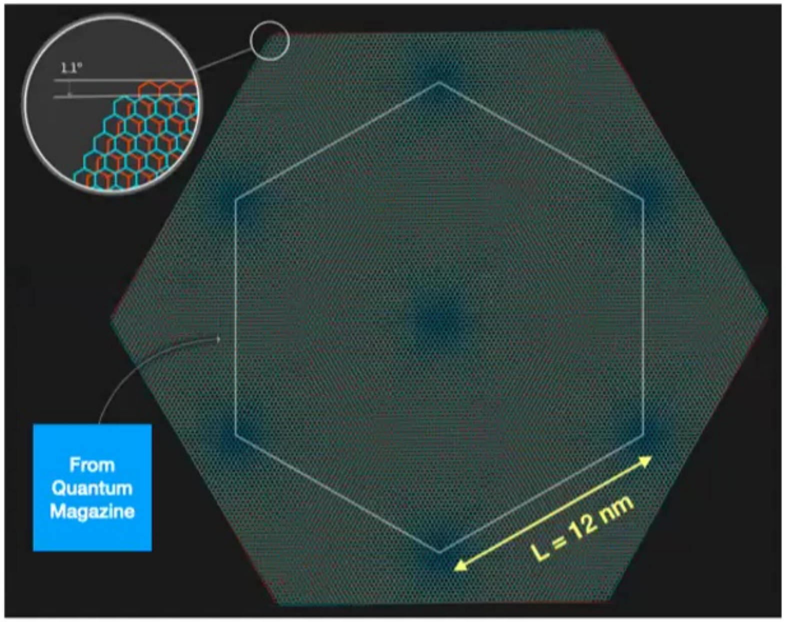
$$\Psi = \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} \qquad H = v_F \hat{\alpha} \cdot p$$

MAGIC ANGLE GRAPHENE



MAGIC ANGLE ~1.1°:
Tunneling time =
Lattice Moire
time

$\theta \sim 1/60$ radians $\quad L \sim a/\theta$



Continuum model

- Larger unit cell→ smaller BZone
- Bistrizer-Macdonald (BM) model (2011)

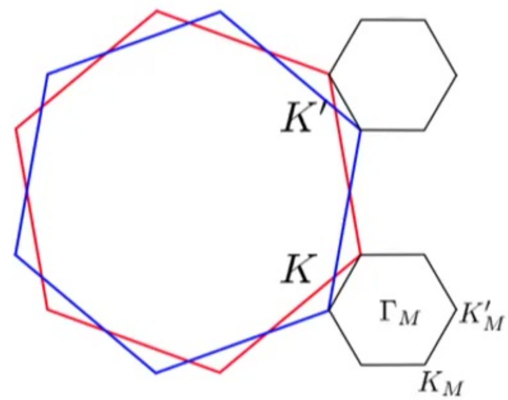
$$\mathcal{H}_K = \begin{pmatrix} -iv_F \boldsymbol{\sigma}_{\theta/2} \cdot \nabla & T(\boldsymbol{r}) \\ T^\dagger(\boldsymbol{r}) & -iv_F \boldsymbol{\sigma}_{-\theta/2} \cdot \nabla \end{pmatrix}_{12},$$

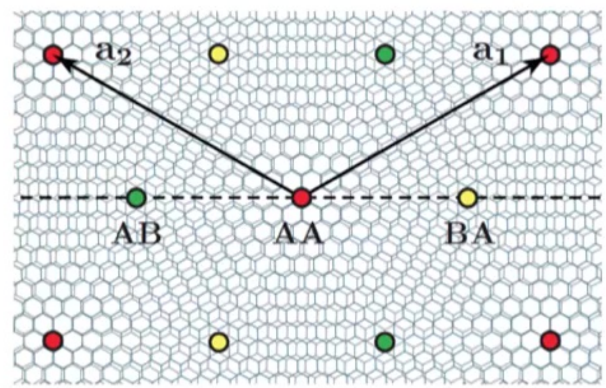
- Moire “potential”

$$T(\boldsymbol{r}) = \begin{pmatrix} w_0 U_0(\boldsymbol{r}) & w_1 U(\boldsymbol{r}) \\ w_1 U^*(-\boldsymbol{r}) & w_0 U_0(\boldsymbol{r}) \end{pmatrix}_{AB}$$

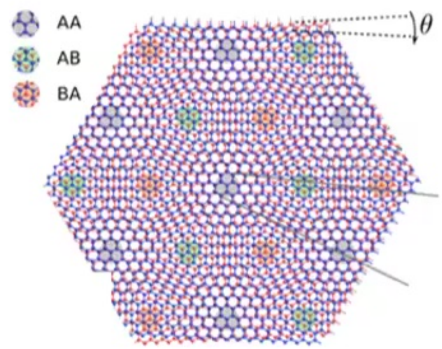
- Lattice relaxation: AB stacking favored to AA stacking (Carr *et al*. 2019, Nam, Koshino 2017)

$$\implies w_0/w_1 \approx 0.7$$

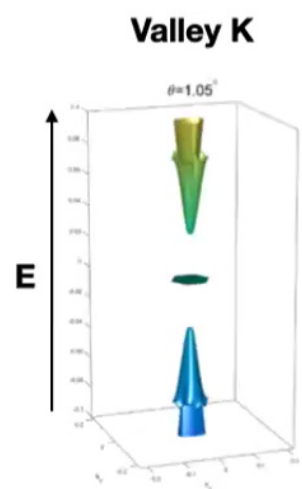


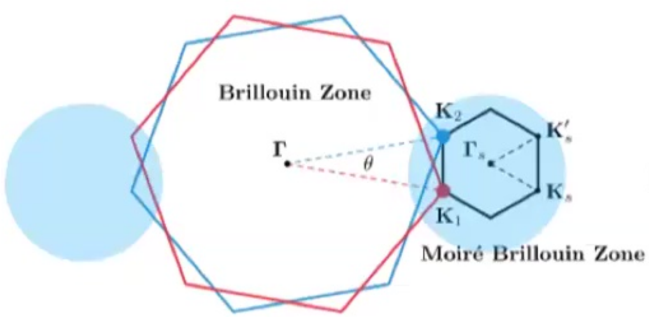


MAGIC ANGLE GRAPHENE

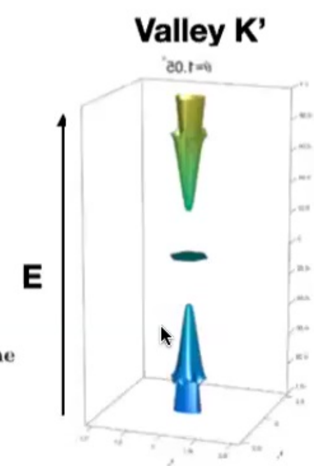


$$T(\mathbf{r}) = \begin{array}{c} \begin{array}{cc} \text{A} & \text{B} \end{array} \\ \begin{pmatrix} w_0 U_0(\mathbf{r}) & w_1 U_1(\mathbf{r}) \\ w_1 U^*(-\mathbf{r}) & w_0 U_0(\mathbf{r}) \end{pmatrix} \end{array} \begin{array}{c} \text{A'} \\ \text{B'} \end{array}$$

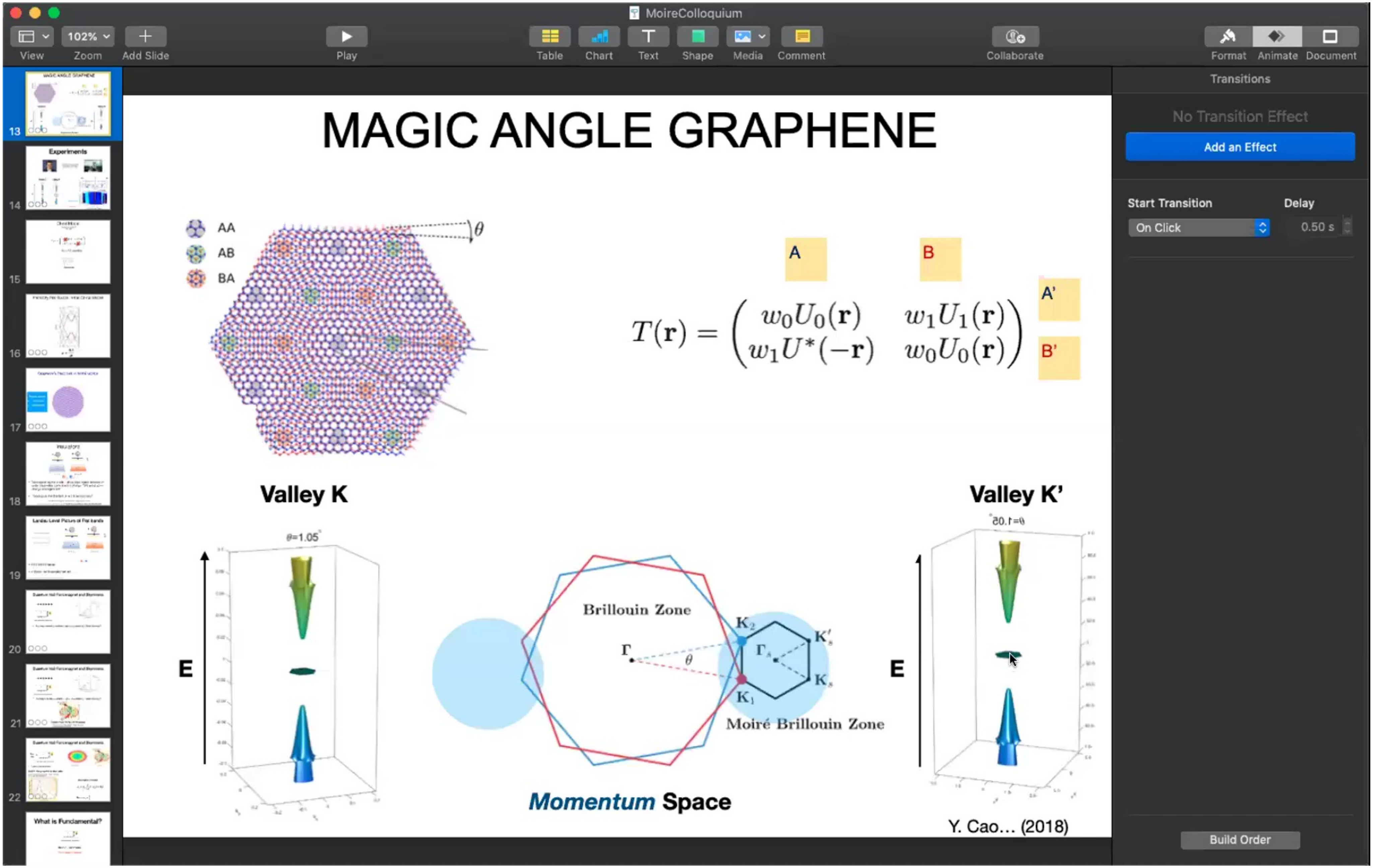


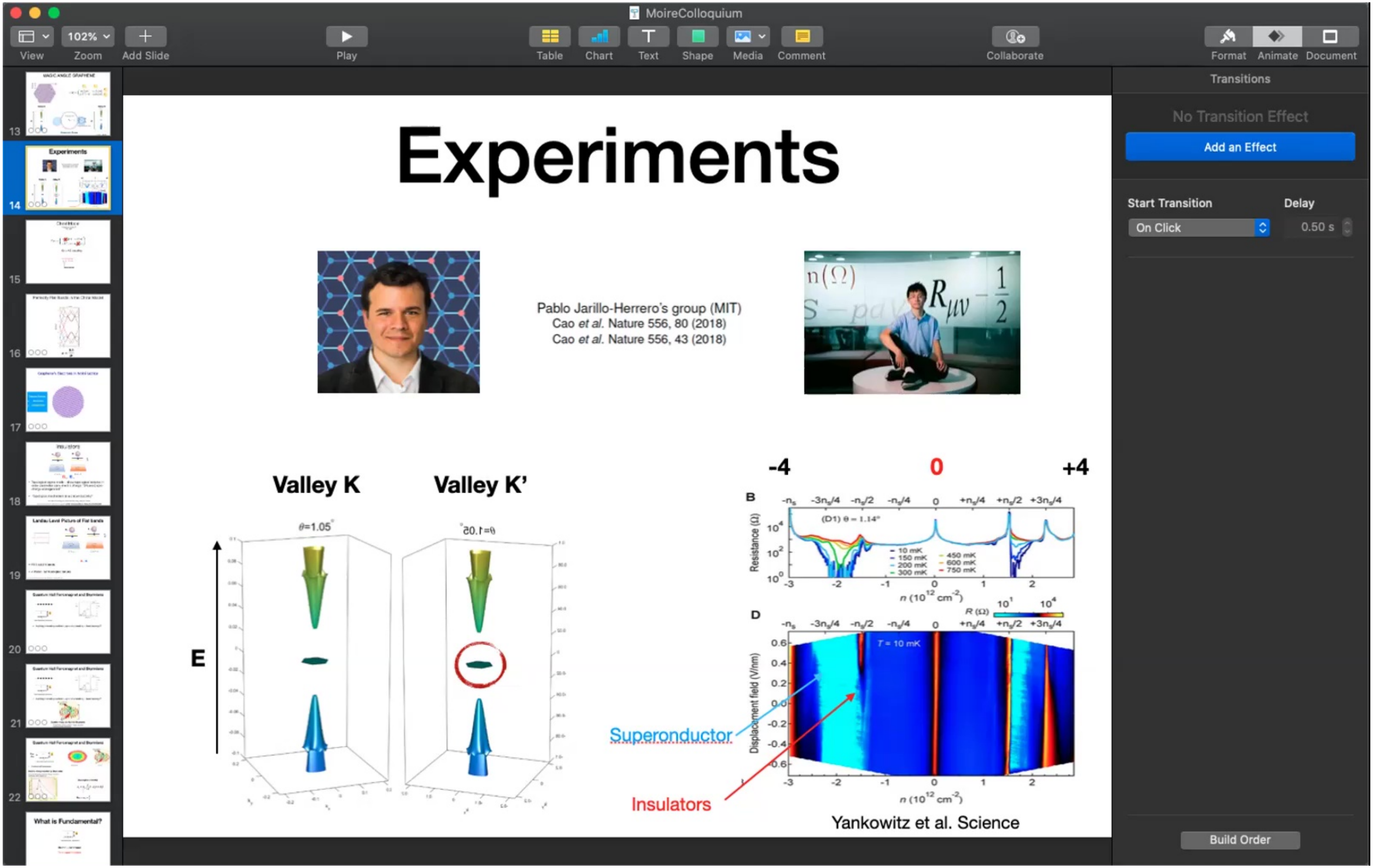


Momentum **Space**



Y. Cao… (2018)


MoireColloquium
MAGIC ANGLE GRAPHENE
AA
AB
BA
θ
A
B
A'
B'
$T(\mathbf{r}) = \begin{pmatrix} w_0 U_0(\mathbf{r}) & w_1 U_1(\mathbf{r}) \\ w_1 U^*(-\mathbf{r}) & w_0 U_0(\mathbf{r}) \end{pmatrix}$
Valley K
Valley K'
θ=1.05°
E
Brillouin Zone
Moiré Brillouin Zone
Momentum Space
Y. Cao… (2018)
Transitions
No Transition Effect
Add an Effect
Start Transition
Delay
On Click
0.50 s
Build Order


MoireColloquium
Experiments
Pablo Jarillo-Herrero's group (MIT)
Cao et al. Nature 556, 80 (2018)
Cao et al. Nature 556, 43 (2018)
Valley K
Valley K'
E
-4
0
+4
Superonductor
Insulators
Yankowitz et al. Science
Transitions
No Transition Effect
Add an Effect
Start Transition
Delay
On Click
0.50 s
Build Order

Chiral Model

Tarnopolski, Kruchkov, AV
PRL 2019

$$T(\boldsymbol{r}) = \begin{pmatrix} \cancel{w_0 U_0(\boldsymbol{r})} & w_1 U(\boldsymbol{r}) \\ w_1 U^*(-\boldsymbol{r}) & \cancel{w_0 U_0(\boldsymbol{r})} \end{pmatrix}$$

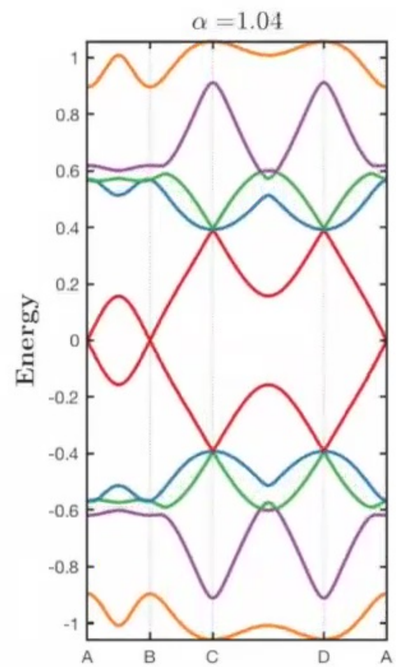
Only AB coupling

Chiral Symmetry

$$\{\sigma_z \otimes 1, \mathcal{H}\} = 0$$

sublattice

Perfectly Flat Bands in the Chiral Model



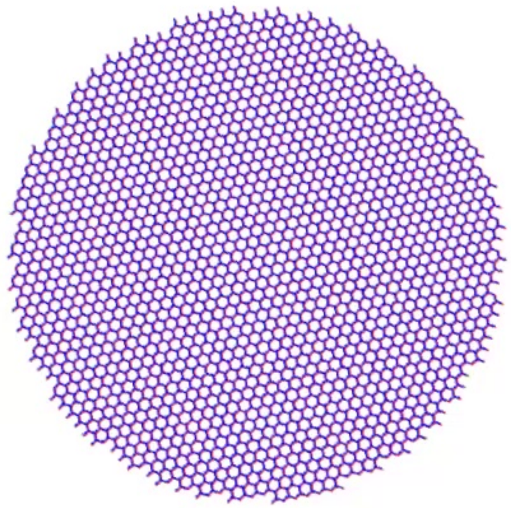
$$\alpha = \frac{0.6}{\theta^o}$$

Graphene's Electrons in Moiré lattice

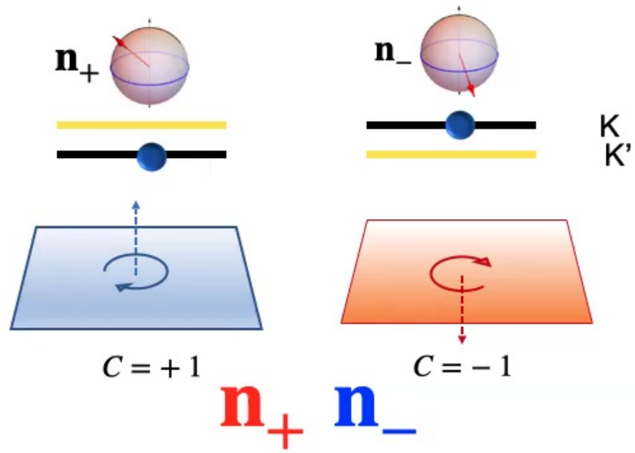
Graphene Electrons

\+ Moire lattice

\+ INTERACTIONS



Insulators



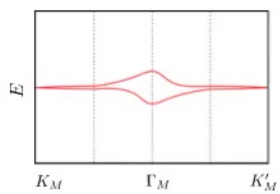
- Topological sigma model - show topological textures in order parameter carry electric charge. "(Psuedo) spin-charge entanglement"

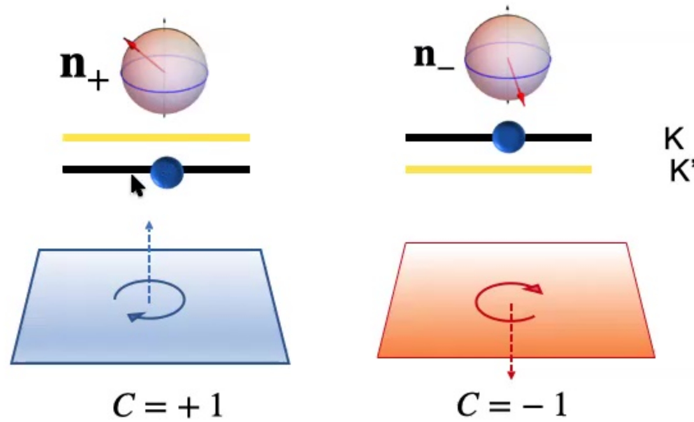
- Topological mechanism of superconductivity?

also: Abanov and Wiegman, Grover & Senthil, Wang, Wang. C…Assad.

Here microscopic theory *with* Coulomb repulsion. **Khalaf, Chatterjee, Bultnick, Zaletel, AV arXiv:2004.00638**

Landau Level Picture of Flat bands



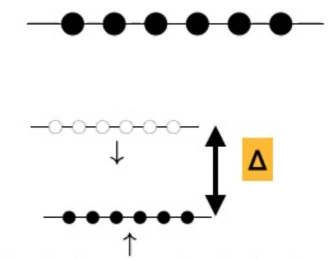


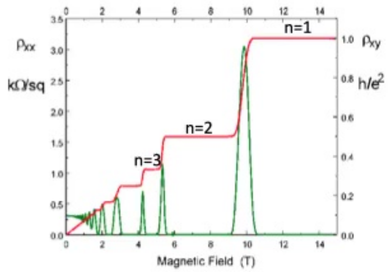
$\mathbf{n}_+$ $\mathbf{n}_-$

- Fill 2 out of 4 bands.
- σ Model - but topological features.

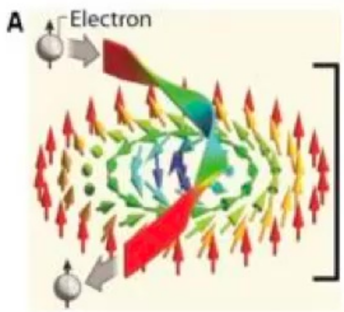
San Jose et al PRL (2012), Tarnopolsky *et al*, PRL (2019), J. Liu *et al*, PRB (2019)

Quantum Hall Ferromagnet and Skyrmions





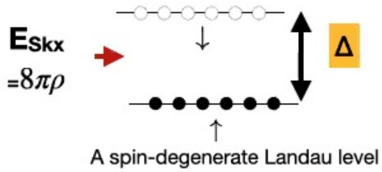
- Anything interesting combining symmetry breaking + band topology?

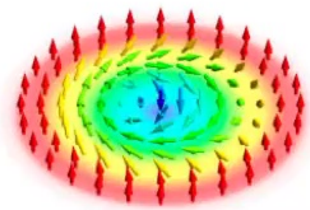


Electric charge carried by *Skyrmions*.

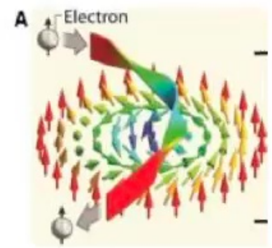
Theory: Sondhi, Karlhede, Kivelson, Rezayi; Lee & Kane
Experiments: NMR - Barrett et al.

Quantum Hall Ferromagnet and Skyrmions





Schütte&Garst



A. Rosch

- Quantum Hall Ferromagnet

Electric charge carried by *Skyrmions*.

Theory: Sondhi, Karlhede, Kivelson, Rezayi; Lee & Kane
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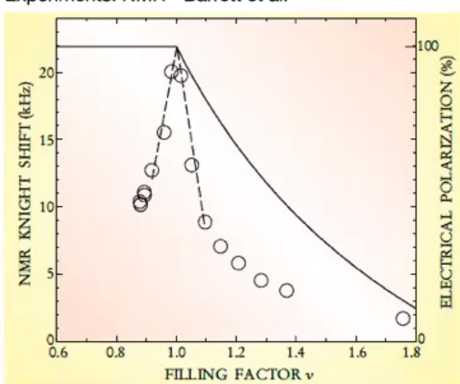


[*topological* σ-model]

$$\rho_c = \underset{1}{\sigma_{xy}} \frac{e}{4\pi} \hat{n} \cdot \partial_x \hat{n} \times \partial_y \hat{n}$$

$$\mathbf{E_{Skx}} = 8\pi\rho_s = \frac{\Delta}{2}$$

What is Fundamental?

Electron -> ferromagnet

Ferromagnet -> electron

Tony Skyrme

A UNIFIED FIELD THEORY OF MESONS AND BARYONS

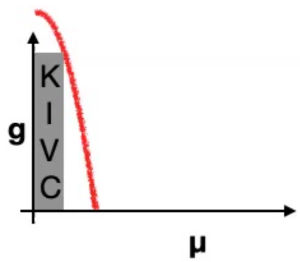
T. H. R. SKYRME †
A.E.R.E., Harwell, England

Nuclear Physics **31** (1962) 556—569;

† Now at Department of Mathematics, University of Malaya, Pantai Valley, Kuala Lumpur, Malaya.

We are indebted to Mr. A. J. Leggatt for carrying out the calculations reported in sect. **3**, while a vacation student at A.E.R.E.

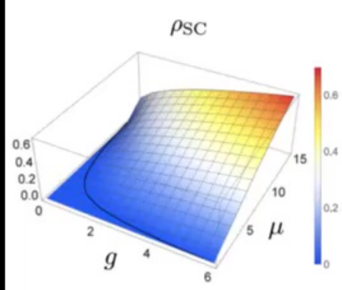
Phase Diagram & Stiffness

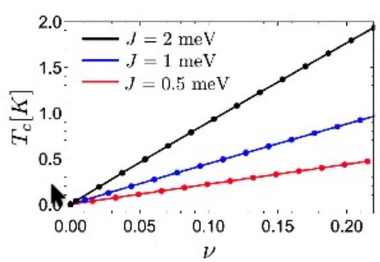


Sigma model -
ORDERED- Insulator
DISORDERED - Superconductor

Solve using large-N CP_N

$$\mathcal{L} = \frac{\Lambda}{g}|(\partial_\mu - i a_\mu) z|^2 + \mu \frac{b}{\pi}$$

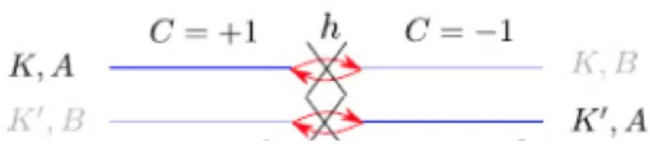


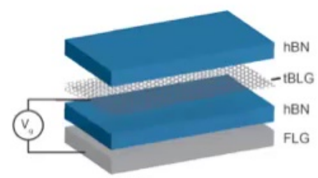


EK, Chatterjee, Bultinck, Zaletel, Vishwanath arXiv:2004.00638

Essential Ingredients for Superconductivity?

- $C_2\mathcal{T}$ symmetry helps superconductivity in this setup
- Sublattice potential *suppresses* the coupling J





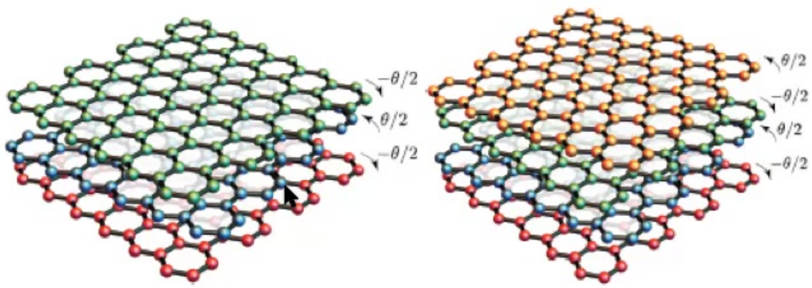
- Twisted bilayer graphene aligned on hBN → no superconductivity (Sharpe et al. Science 19, Serlin et al. Science 20)

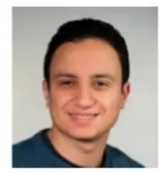
- Relatively *few* Moire materials apart from magic angle graphene with this symmetry.

New platforms for Superconductivity?

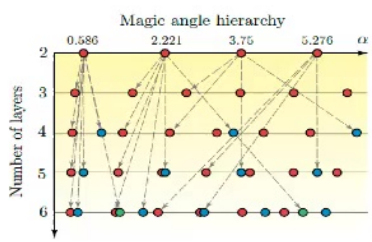
- Other systems with C2 symmetry

Alternating twist sandwich





Eslam Khalaf

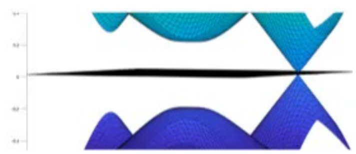


$\sqrt{2}$

$\varphi = \dfrac{1+\sqrt{5}}{2}$

Larger magic angles!

Magic angle = $\sqrt{2}\,1.1^o \sim 1.55^o$



Flat band+Dirac

Carr et al. stability `19

Khalaf, Kruchkov, Tarnopolsky, AV, 1901.10485

Matthias' Rules for Superconductivity

Bernd Matthias (1918-1980)

1. high symmetry is good, cubic symmetry is the best
2. high density of electronic states is good
3. stay away from oxygen
4. stay away from magnetism
5. stay away from insulators
6. stay away from theorists.

Matthias' Rules for Superconductivity

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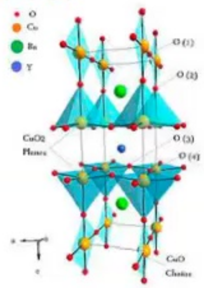
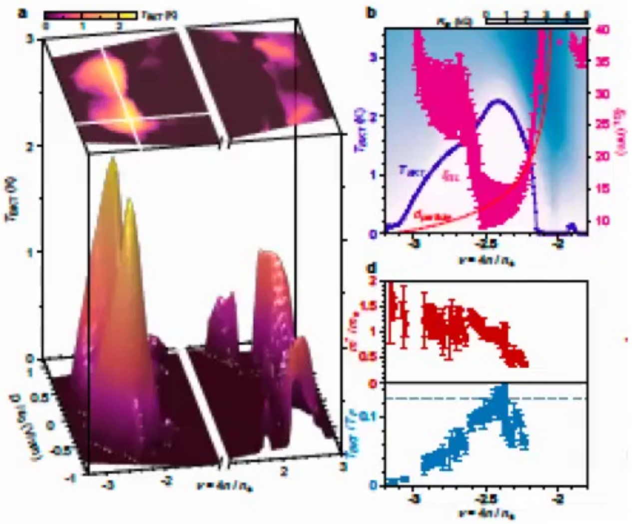
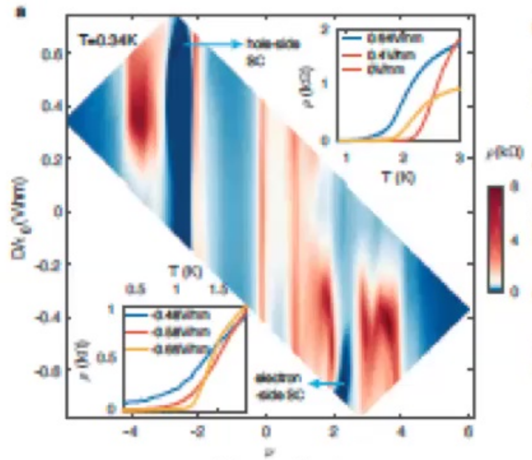


Alternating twist trilayer -EXPT

Strong coupling superconductivity
Tuning by displacement field.





Hao et al.

Park et al.

Tunable Phase Boundaries and Ultra-Strong Coupling Superconductivity in Mirror Symmetric Magic-Angle Trilayer Graphene

Jeong Min Park,[1,*] Yuan Cao,[1,*,†] Kenji Watanabe,[2] Takashi Taniguchi,[2] and Pablo Jarillo-Herrero[1,†]

Electric field tunable unconventional superconductivity in alternating twist magic-angle trilayer graphene

Zeyu Hao[1†], A. M. Zimmerman[1†], Patrick Ledwith[1], Eslam Khalaf[1], Danial Haie Najafabadi[1], Kenji Watanabe[2], Takashi Taniguchi[3], Ashvin Vishwanath[1] & Philip Kim[1*]

Conclusions & Future Directions

- Skyrmions gives a natural mechanism for superconductivity in 2-3 layer graphene.
    - A soluble strong coupling theory - not local DOS related.
    - associated with nu=2
    - Connection to C_2T symmetry, accounts for robust Sc platforms.
    - Predicts new platforms.
- Future Directions
    - measure collective modes to find J, ρ_p, λ.. Quantitative relation between normal state and predictions of skyrmions Sc.
    - We want to incorporate fermions into the theory (coexisting fermions + Skx).
    - Connection to weak coupling theories?
    - Distinct superconductors without flavor polarization?

Lecture Notes: **https://scholar.harvard.edu/avishwanath/teaching**

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