Title: Internally engineered Majorana modes in twisted bilayer graphene

Speakers: Jason Alicea

Series: Quantum Matter

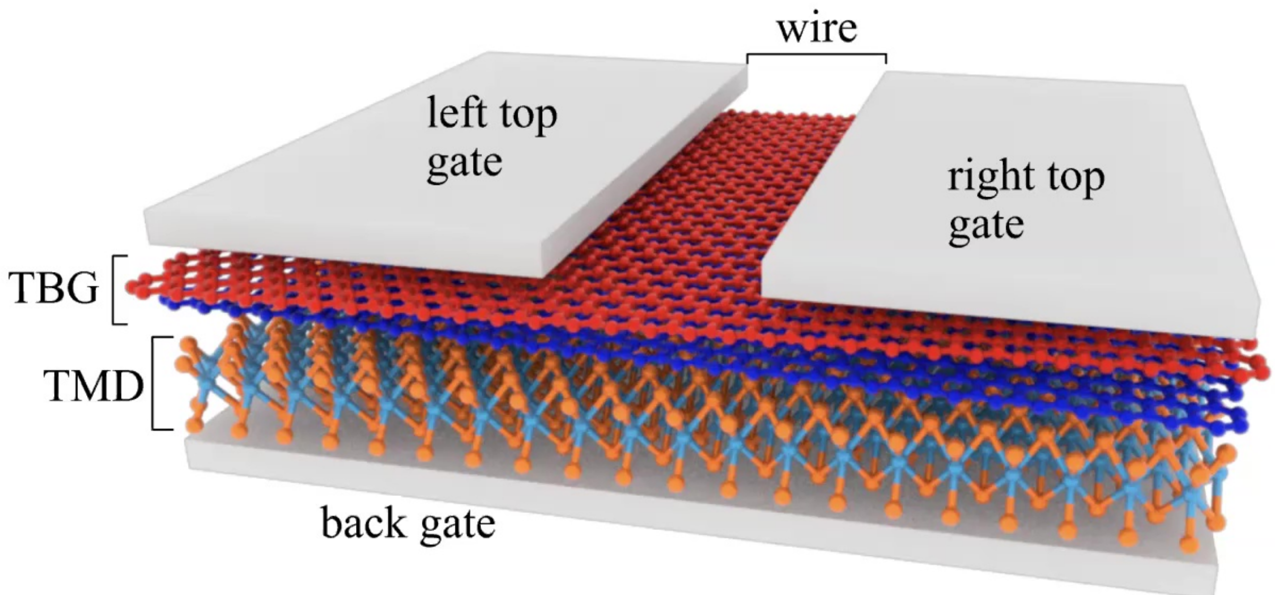
Date: September 27, 2021 - 12:00 PM

URL: https://pirsa.org/21090017

Abstract: Twisted bilayer graphene (TBG) realizes an exquisitely tunable, strongly interacting system featuring superconductivity and various correlated insulating states. In this talk I will introduce gate-defined wires in TBG as an enticing platform for Majorana-based fault-tolerant qubits. Our proposal notably relies on "internally" generated superconductivity in TBG - as opposed to "external" superconducting proximity effects commonly employed in Majorana devices - and may operate even at zero magnetic field. I will also describe how electrical measurements of gate-defined wires can reveal the nature of correlated insulators and shed light on the Cooper-pairing mechanism in TBG.

Zoom Link: https://pitp.zoom.us/meeting/register/tJcqc-ihqzMvHdW-YBm7mYd_XP9Amhypv5vO

Internally engineered Majorana modes in twisted bilayer graphene



Jason Alicea
Caltech, IQIM, & Walter Burke Institute

Acknowledgments

Alex Thomson

Ina Sorensen

Stevan Nadj-Perge

Gate-defined wires in twisted bilayer graphene: from electrical detection of inter-valley coherence to internally engineered Majorana modes

Alex Thomson,[1,2,3,*] Ina Sorensen,[1,2,*] Stevan Nadj-Perge,[2,4] and Jason Alicea[1,2,3]

arXiv:2105.02891

Topological quantum computation overview

Non-Abelian anyons

Locally indistinguishable ground states → **Inherently fault-tolerant qubits!**

$$|000\rangle, |001\rangle, \ldots$$

Anyons carry exotic **zero-energy modes**

Alexei Kitaev

Non-Abelian anyons

Anyons carry exotic **zero-energy modes**

Locally indistinguishable ground states → **Inherently fault-tolerant qubits!**

$$|000\rangle, |001\rangle, \ldots$$

Non-Abelian statistics → **Inherently fault-tolerant gates!**

$$\psi_i \to U_{ij}\psi_j$$

Alexei Kitaev

Non-Abelian anyons

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$$|000\rangle, |001\rangle, \ldots$$

Non-Abelian statistics → **Inherently fault-tolerant gates!**

$$\psi_i \to U_{ij}\psi_j$$


Alexei Kitaev

How to build the hardware?

Spinless 1D superconductors

$$\gamma = \gamma^\dagger \qquad \gamma^2 = 1 \qquad \{\gamma_1, \gamma_2\} = 0 \qquad [\gamma, H] = 0$$

$$f = (\gamma_1 + i\gamma_2)/2$$

$|\text{even}\rangle$ $|\text{odd}\rangle$

Locally indistinguishable ground states

Spinless 1D superconductors

(Kitaev 2001)

$$\gamma = \gamma^\dagger \qquad \gamma^2 = 1 \qquad \{\gamma_1, \gamma_2\} = 0 \qquad [\gamma, H] = 0$$

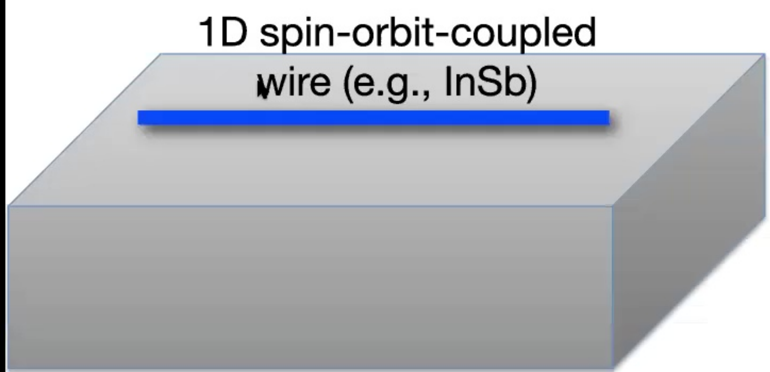
$$f = (\gamma_1 + i\gamma_2)/2$$

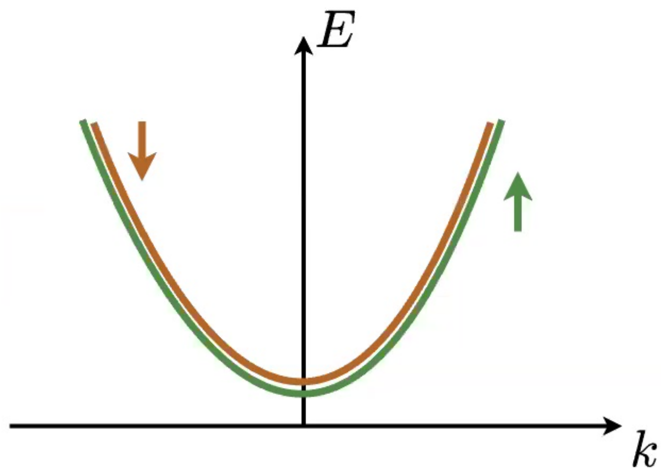
$|\text{even}\rangle$ $|\text{odd}\rangle$

Locally indistinguishable ground states

But…electrons carry spin, and nearly superconductors display **spin-singlet** Cooper pairing

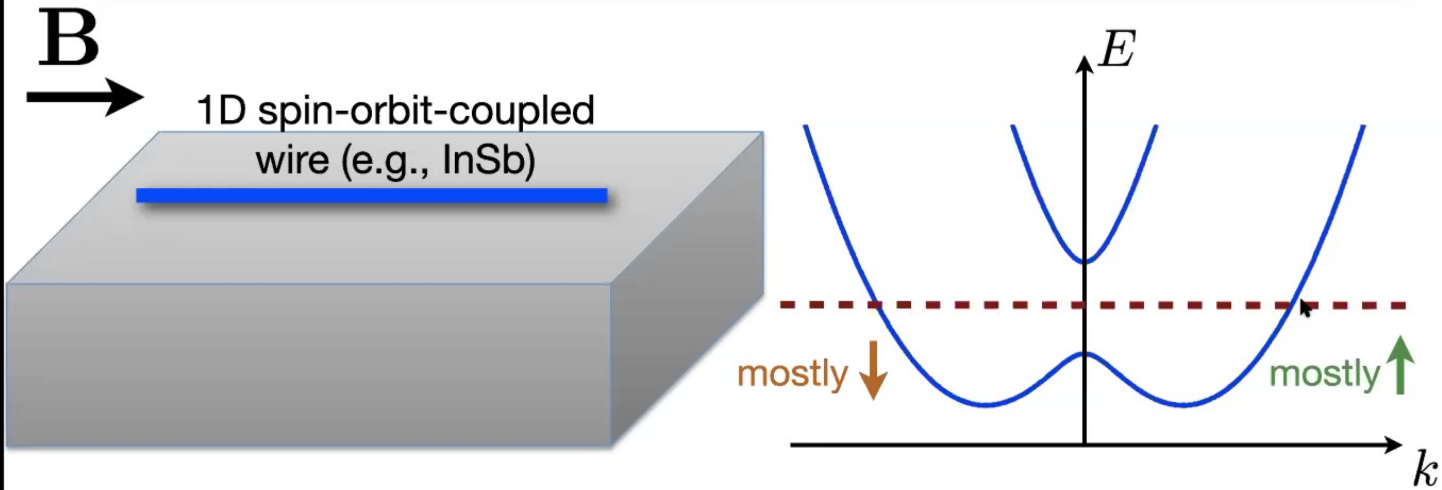
Engineered Majorana platforms





Lutchyn, Sau, Das Sarma PRL 2010; Oreg, Refael, von Oppen PRL 2010

Engineered Majorana platforms



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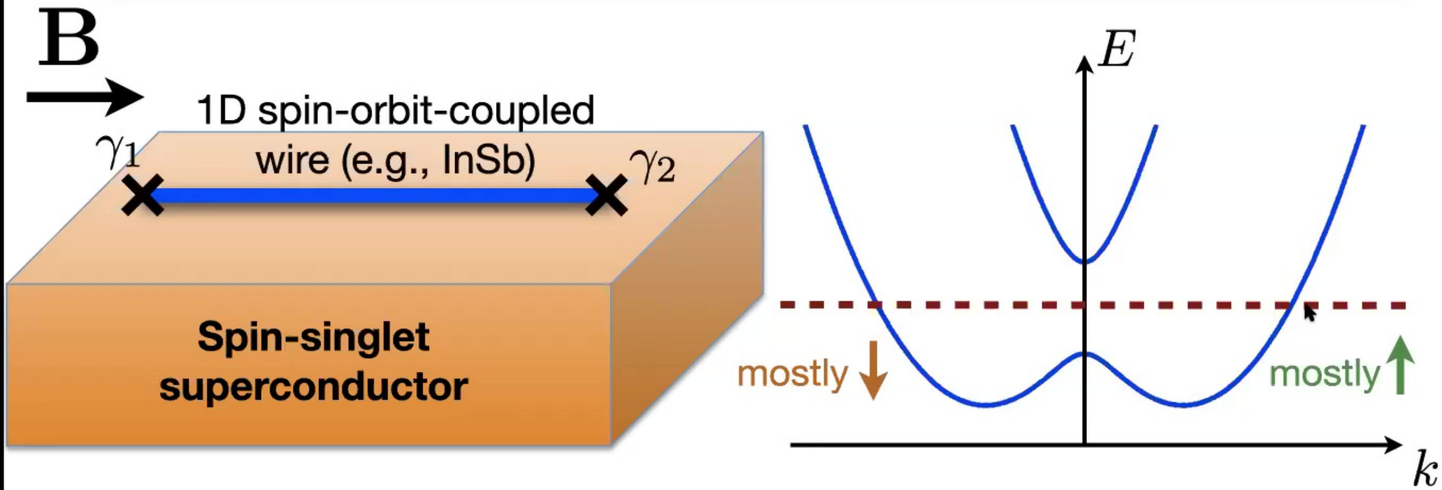
Engineered Majorana platforms



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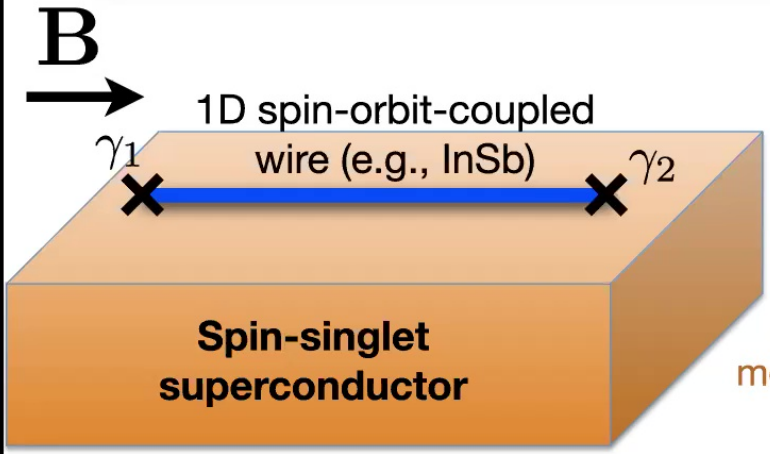
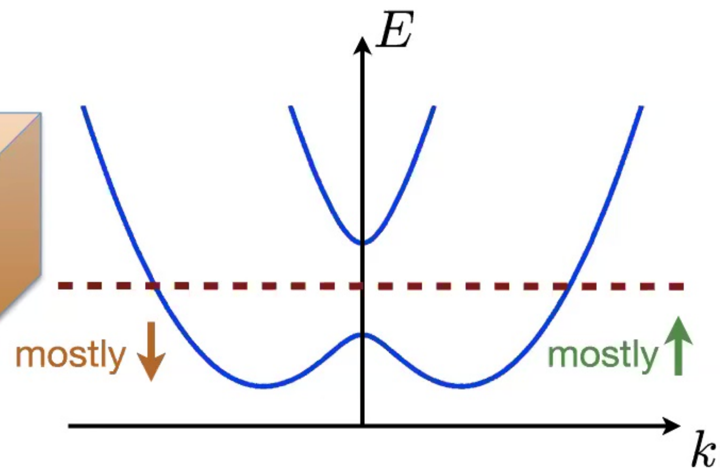
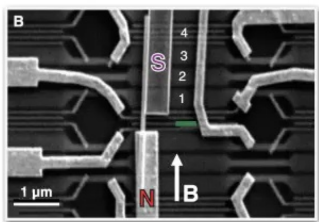
Engineered Majorana platforms

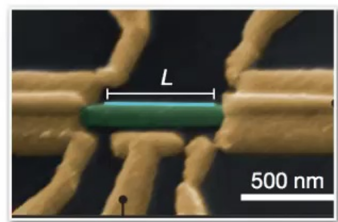




Many experiments followed…



Mourik et al. Science **336**, 1003 (2012)



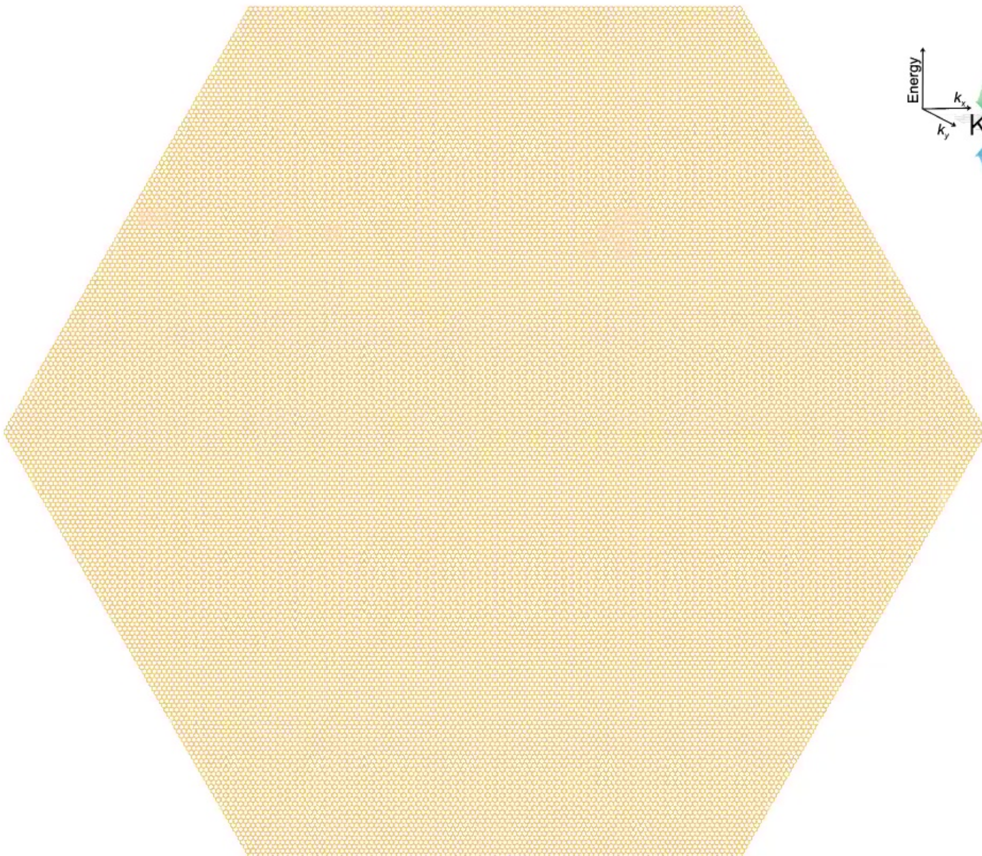
Albrecht et al. Nature **531**, 206 (2016)

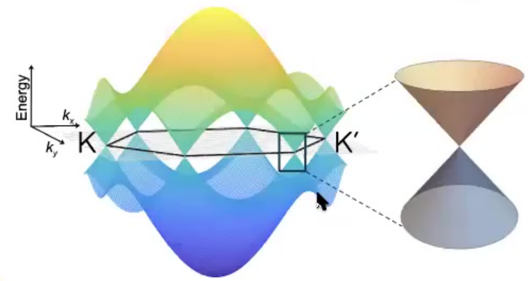
…but Majorana debate continues

Lutchyn, Sau, Das Sarma PRL 2010; Oreg, Refael, von Oppen PRL 2010

Twisted bilayer graphene

Twisted bilayer graphene





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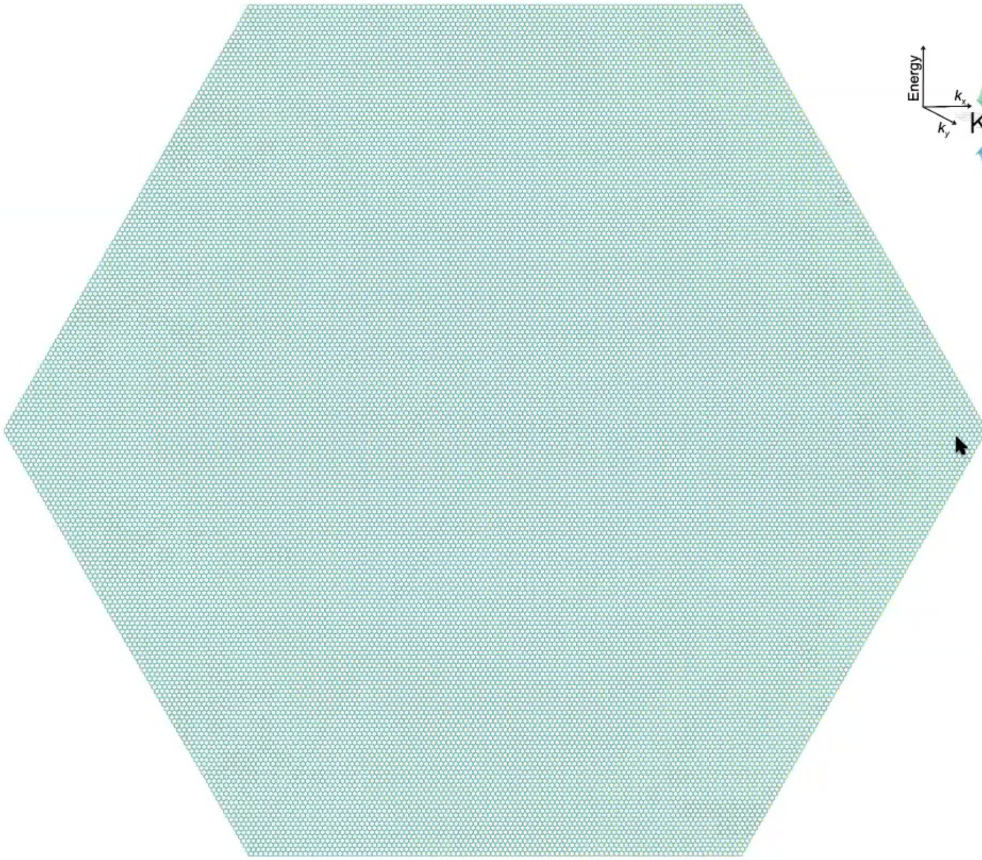
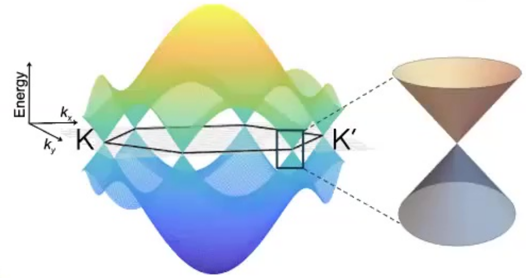
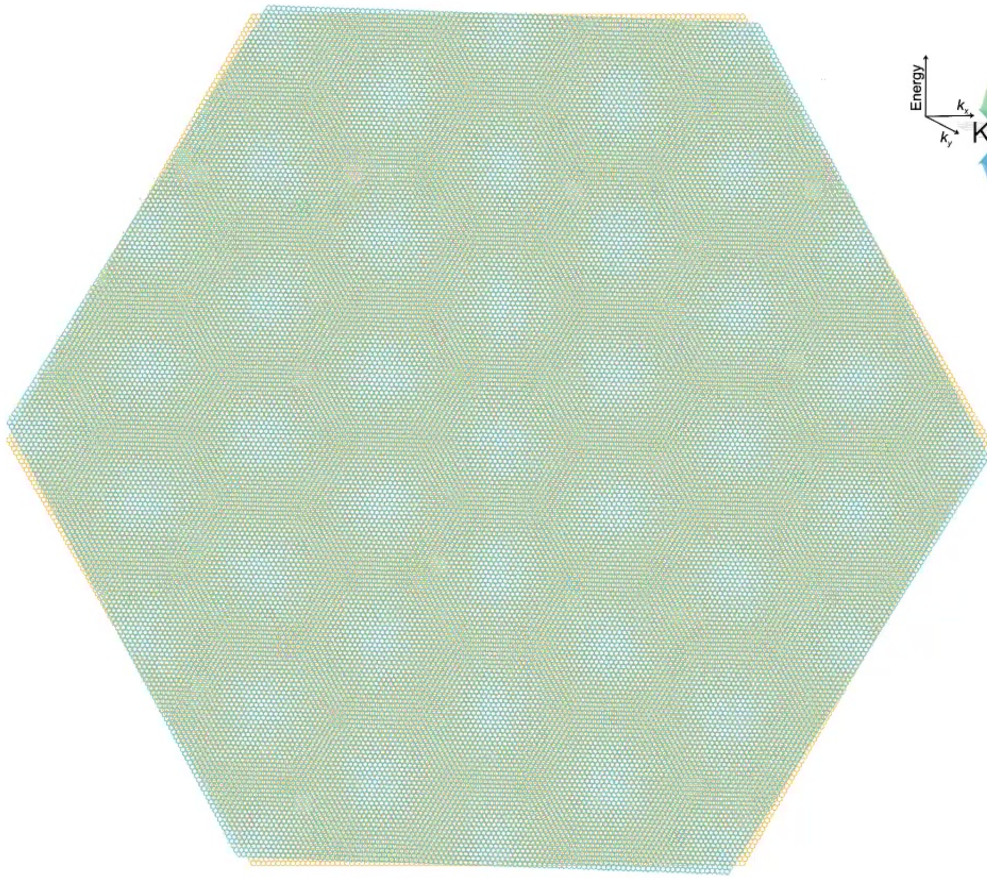
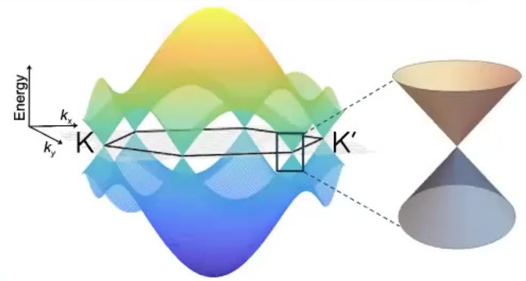


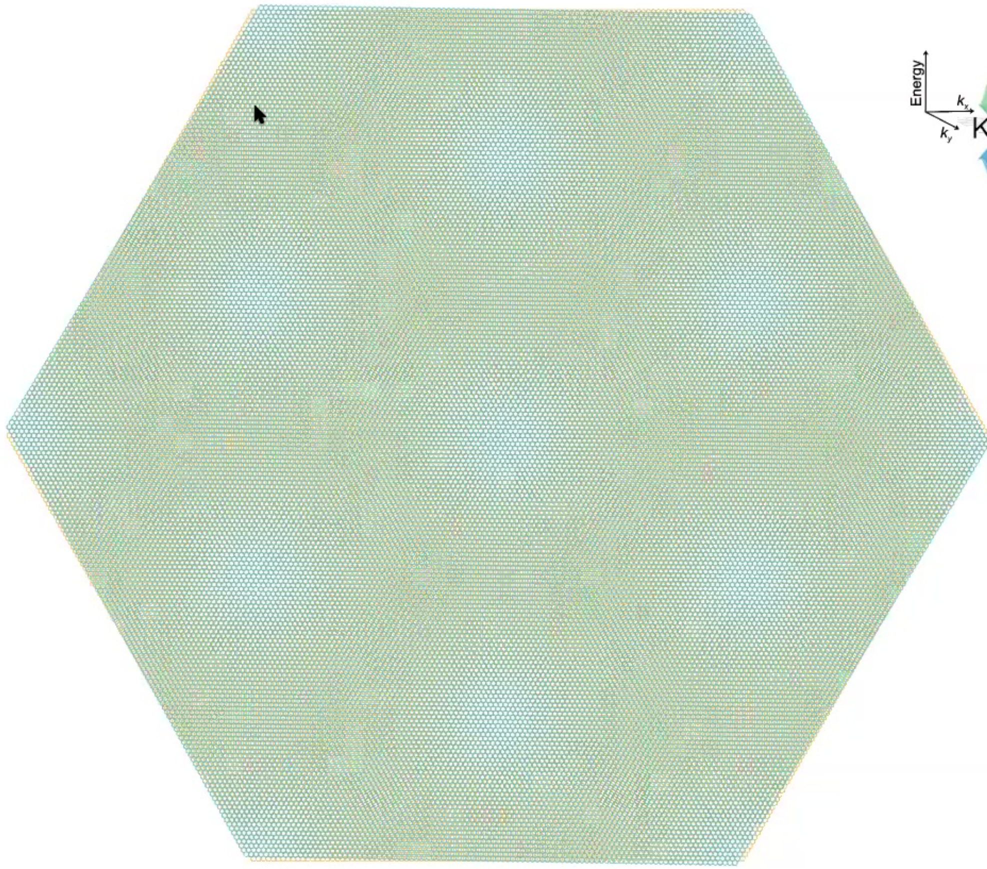


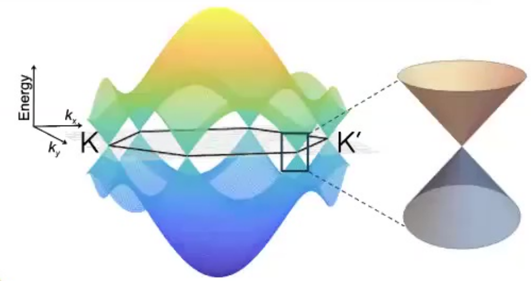
Twisted bilayer graphene



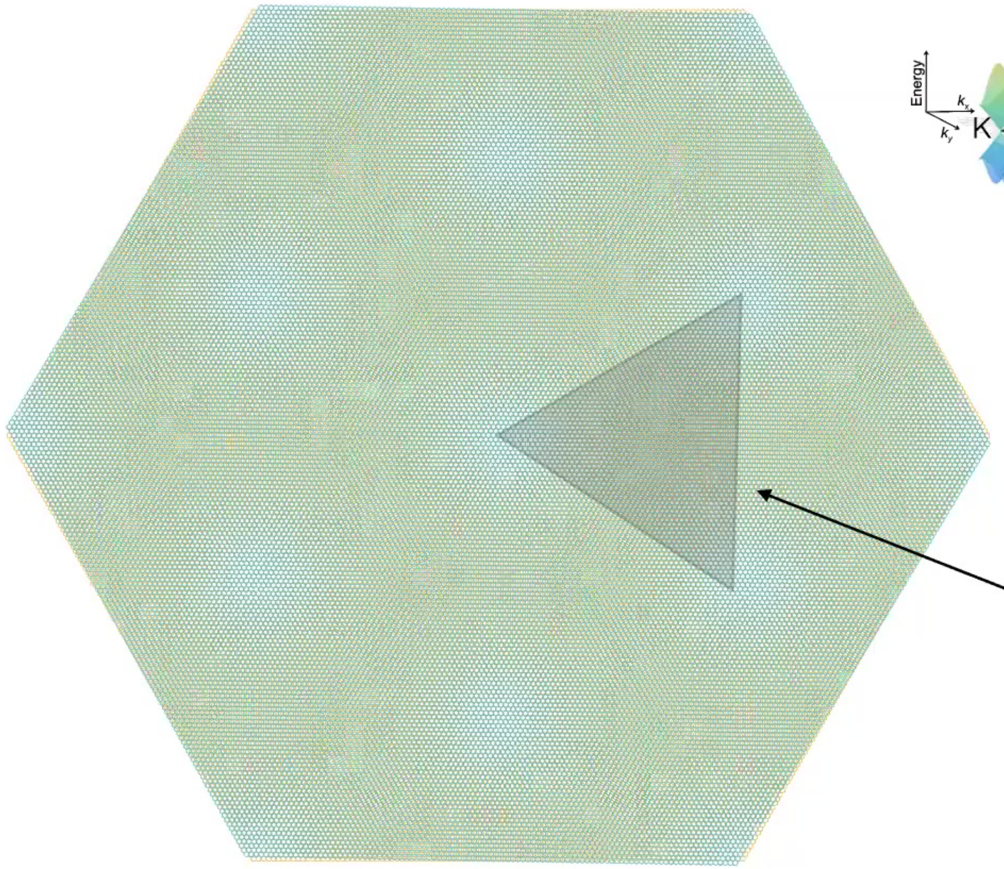


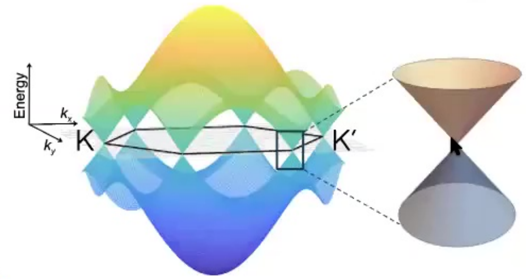
Twisted bilayer graphene





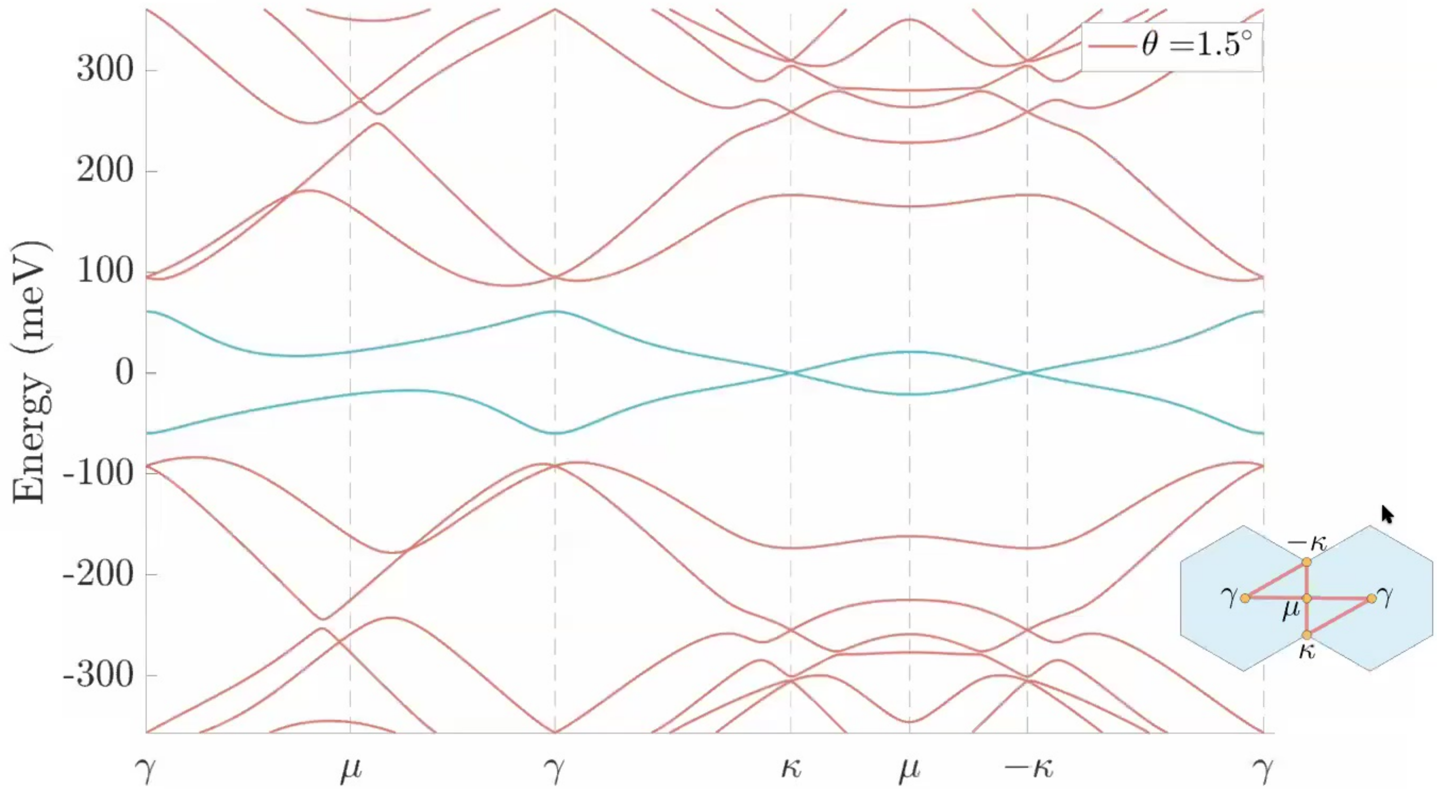
Twisted bilayer graphene





Moire unit cell for
1 degree twist angle.
~10nm in size with
1000's of atoms!

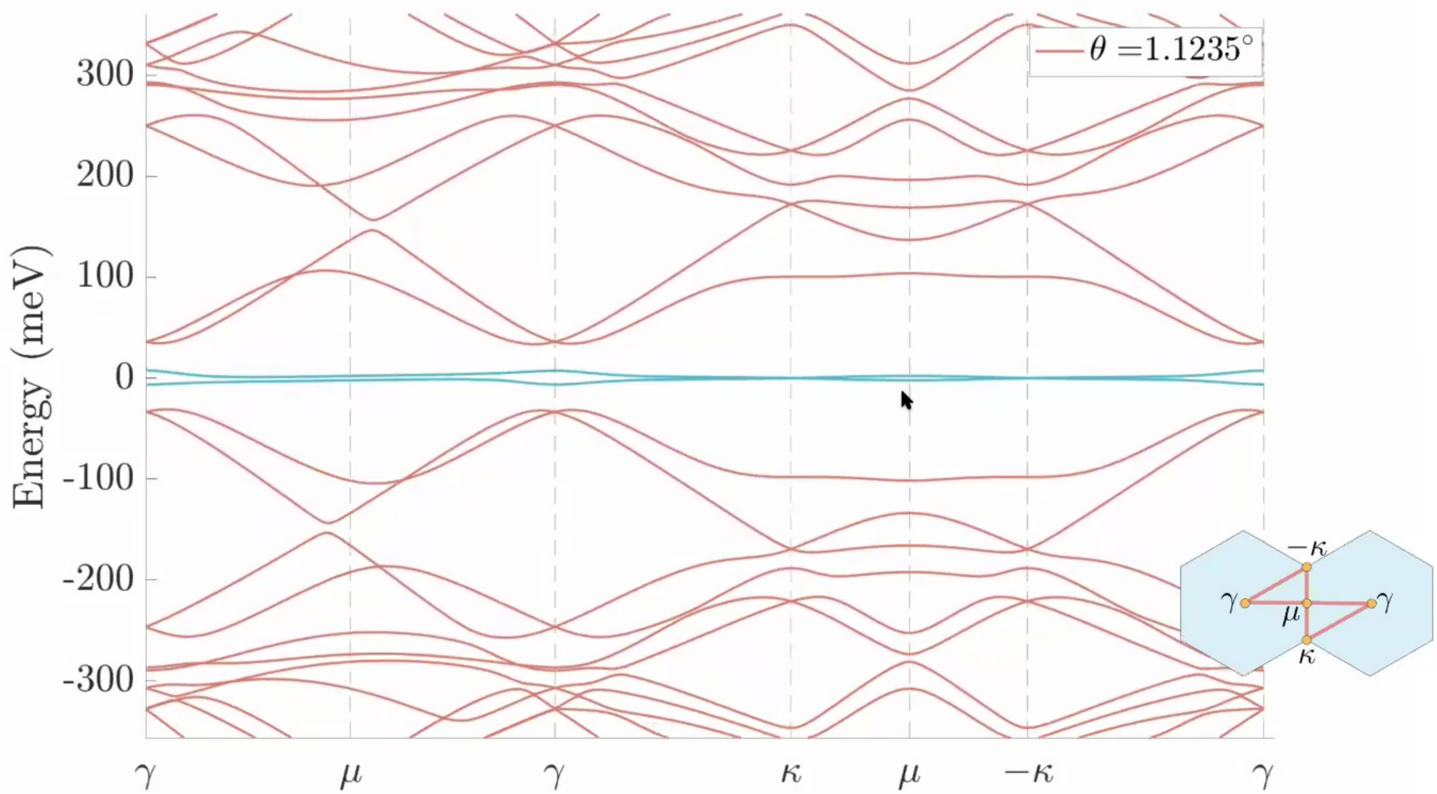
“Magic angle” band structure



Bistritzer & MacDonald PNAS (2011)

Band structures/movie courtesy of Alex Thomson.

“Magic angle” band structure



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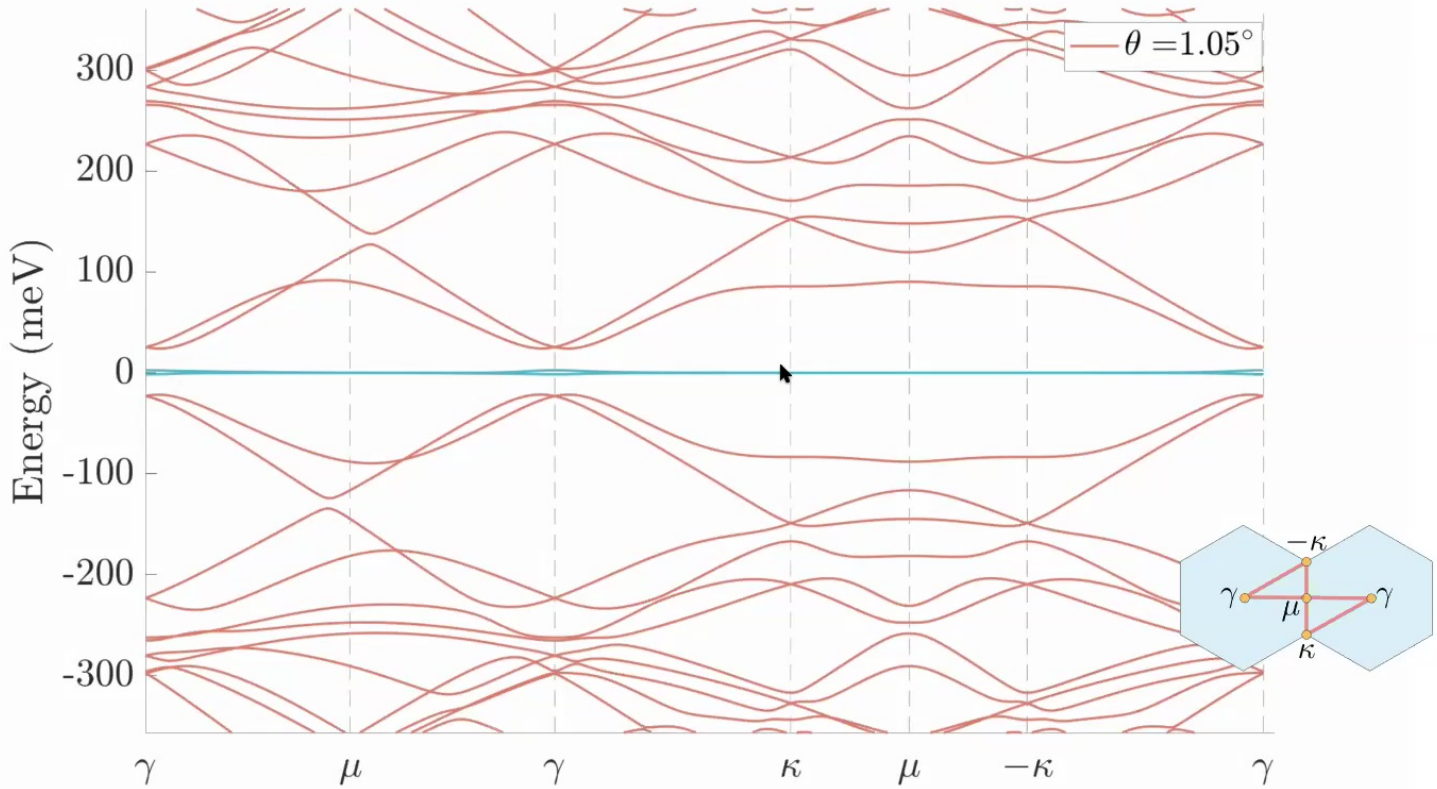

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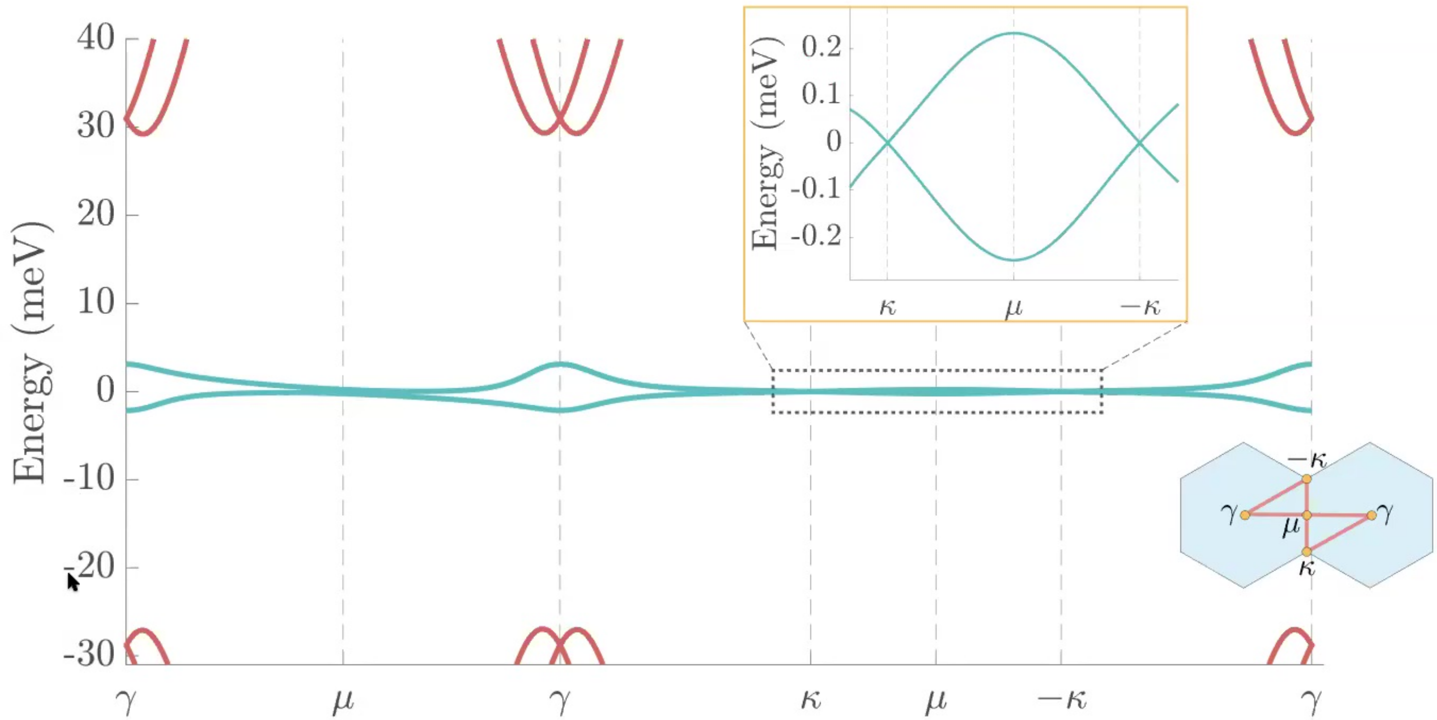

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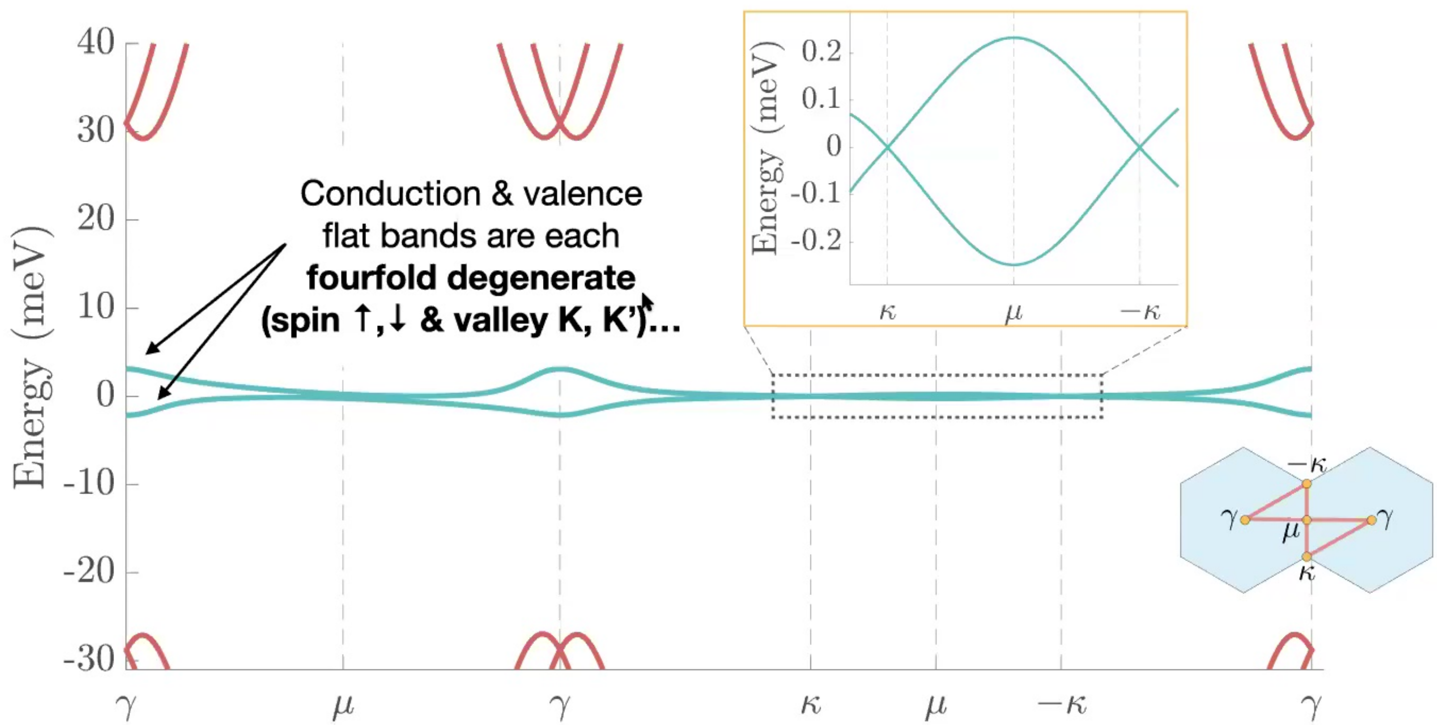

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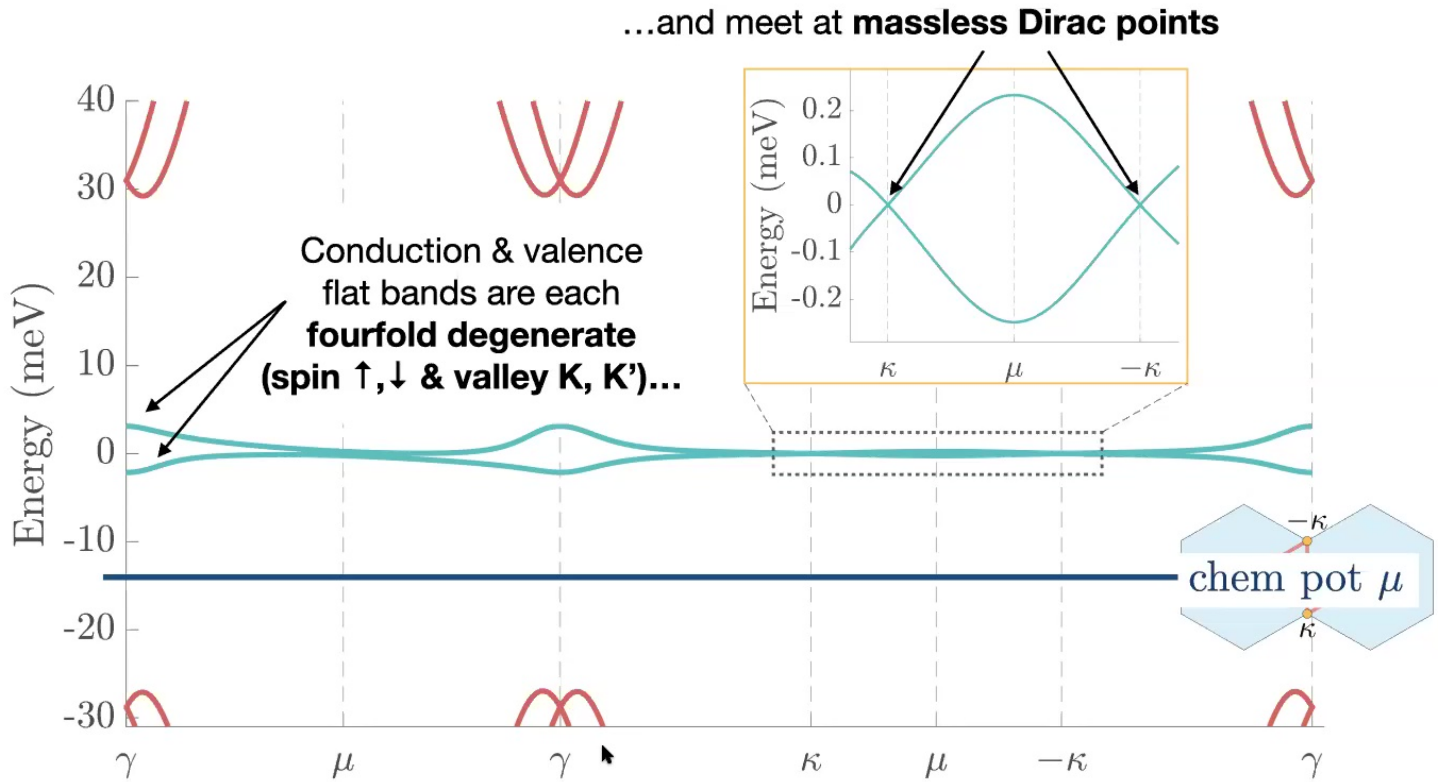


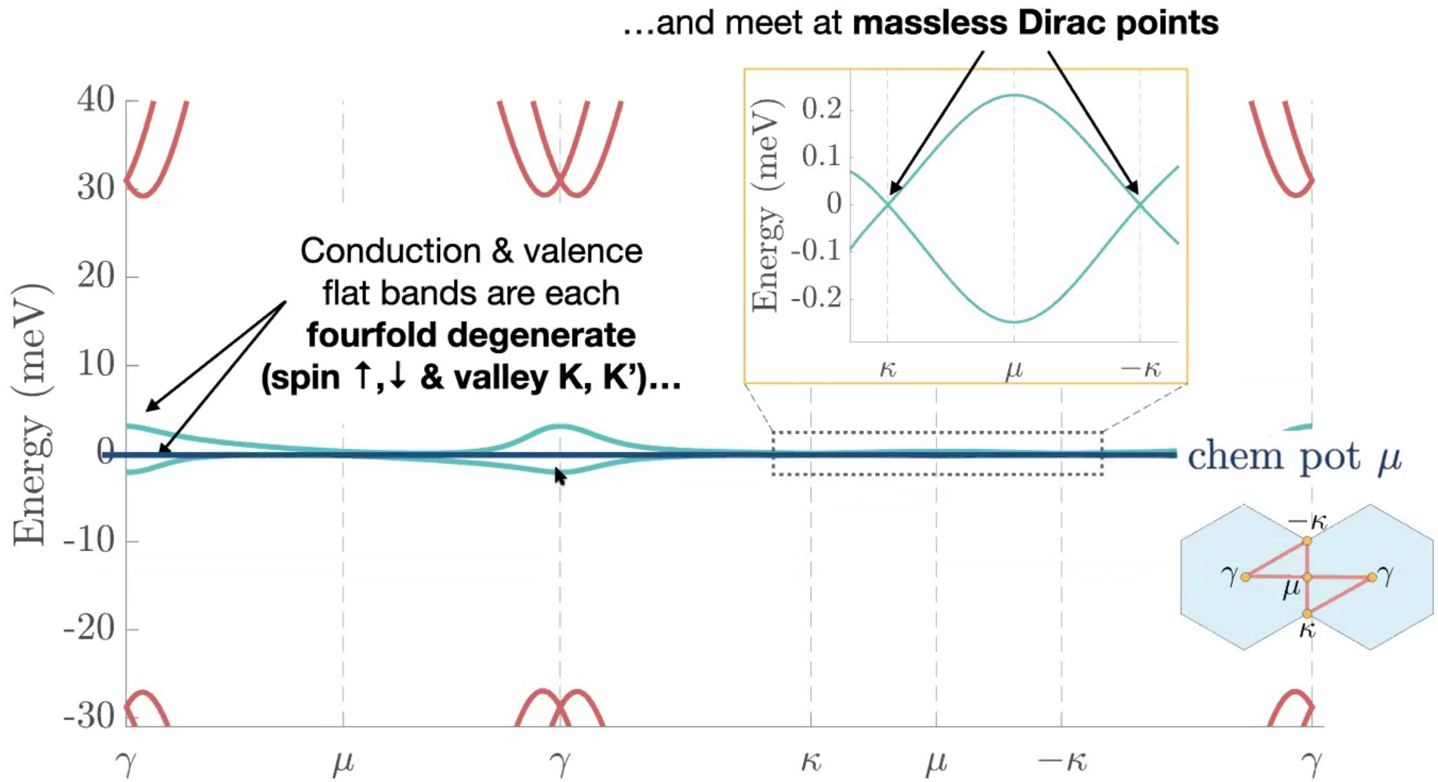
Band insulator

Bistritzer & MacDonald PNAS (2011)

Band structures/movie courtesy of Alex Thomson.

Jason Alicea

“Magic angle” band structure



Band insulator → metal → semimetal

Bistritzer & MacDonald PNAS (2011)

Band structures/movie courtesy of Alex Thomson.

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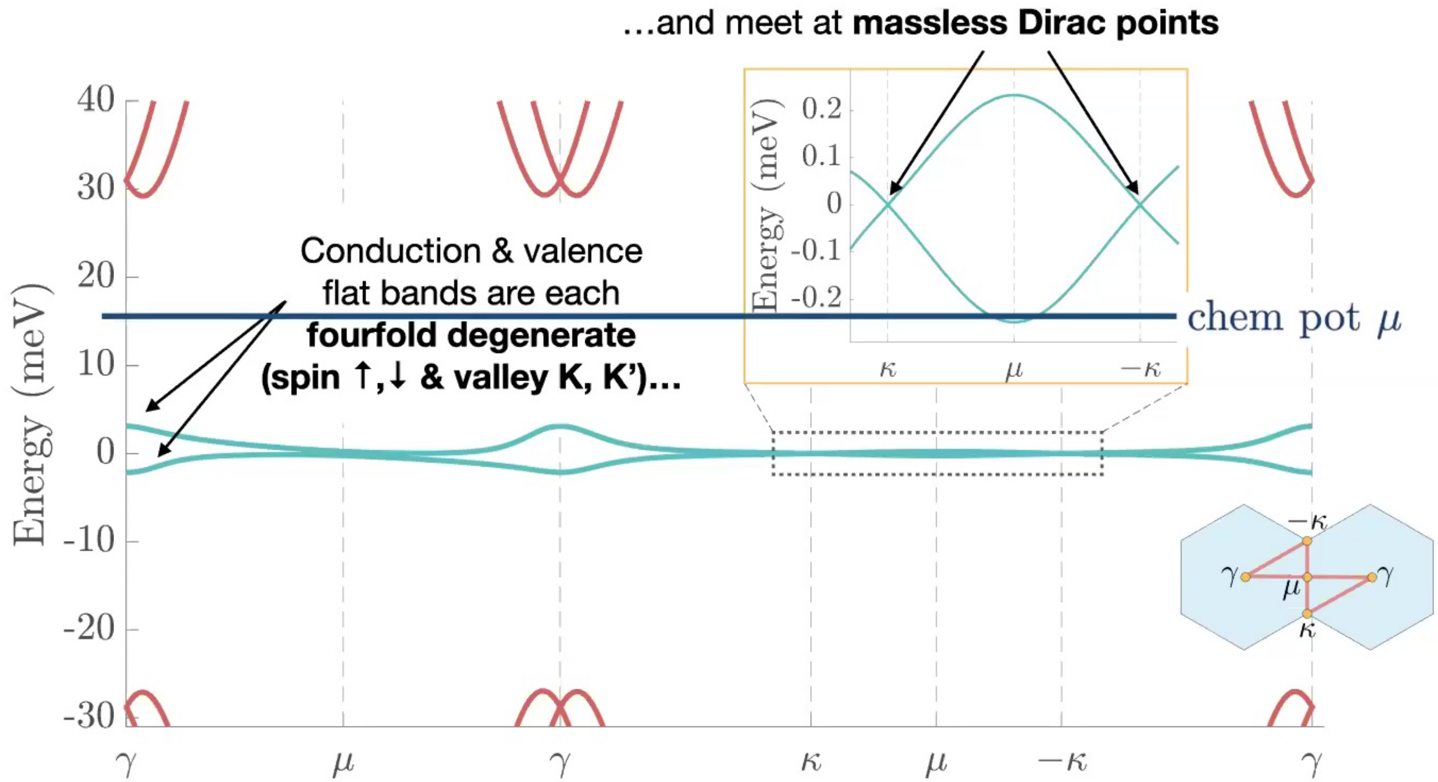
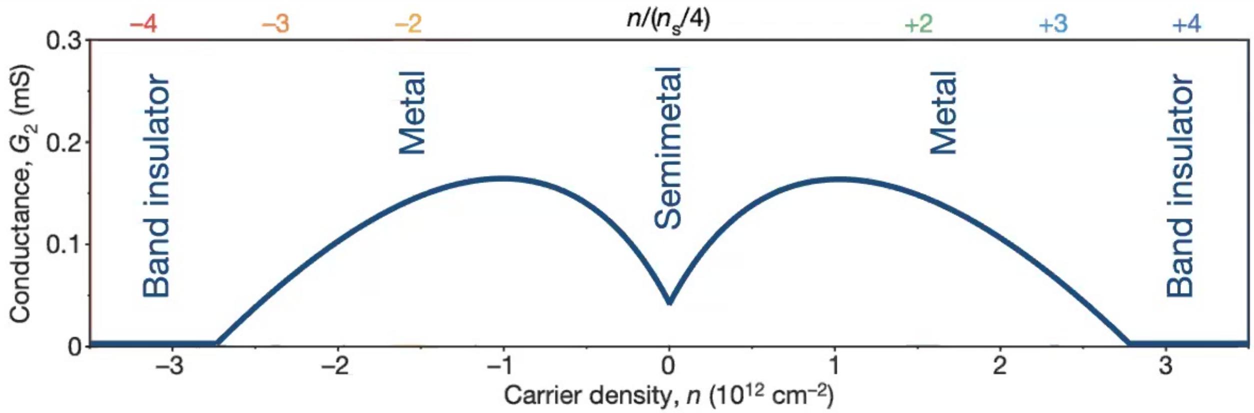


Band insulator → metal → semimetal → metal → band insulator

Bistritzer & MacDonald PNAS (2011)

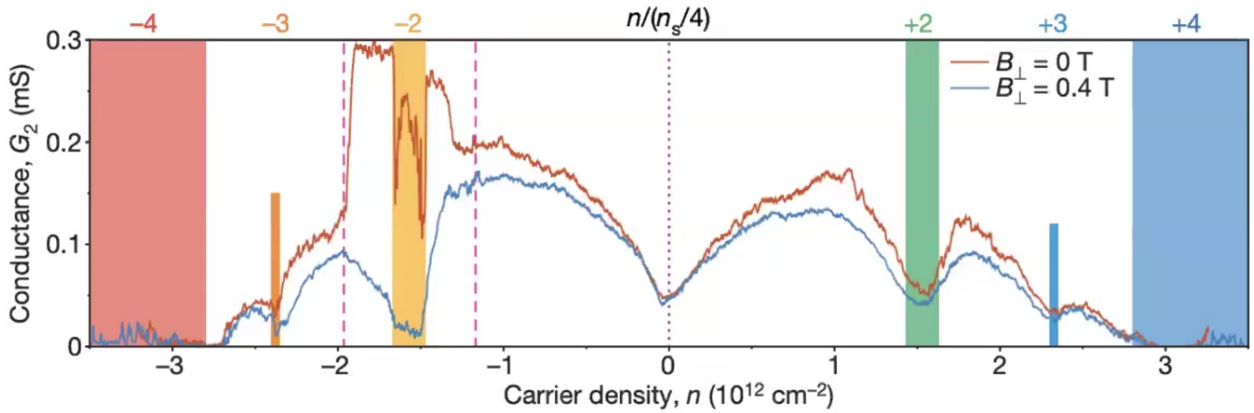
Band structures/movie courtesy of Alex Thomson.

Magic-angle TBG experiments



Cao et al., Nature (2018)

Magic-angle TBG experiments



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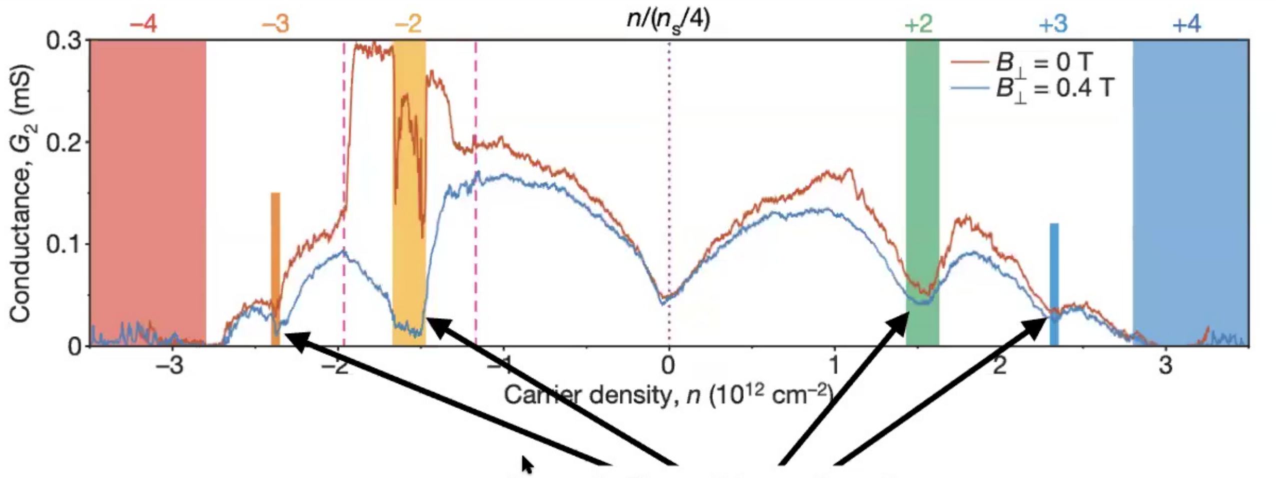
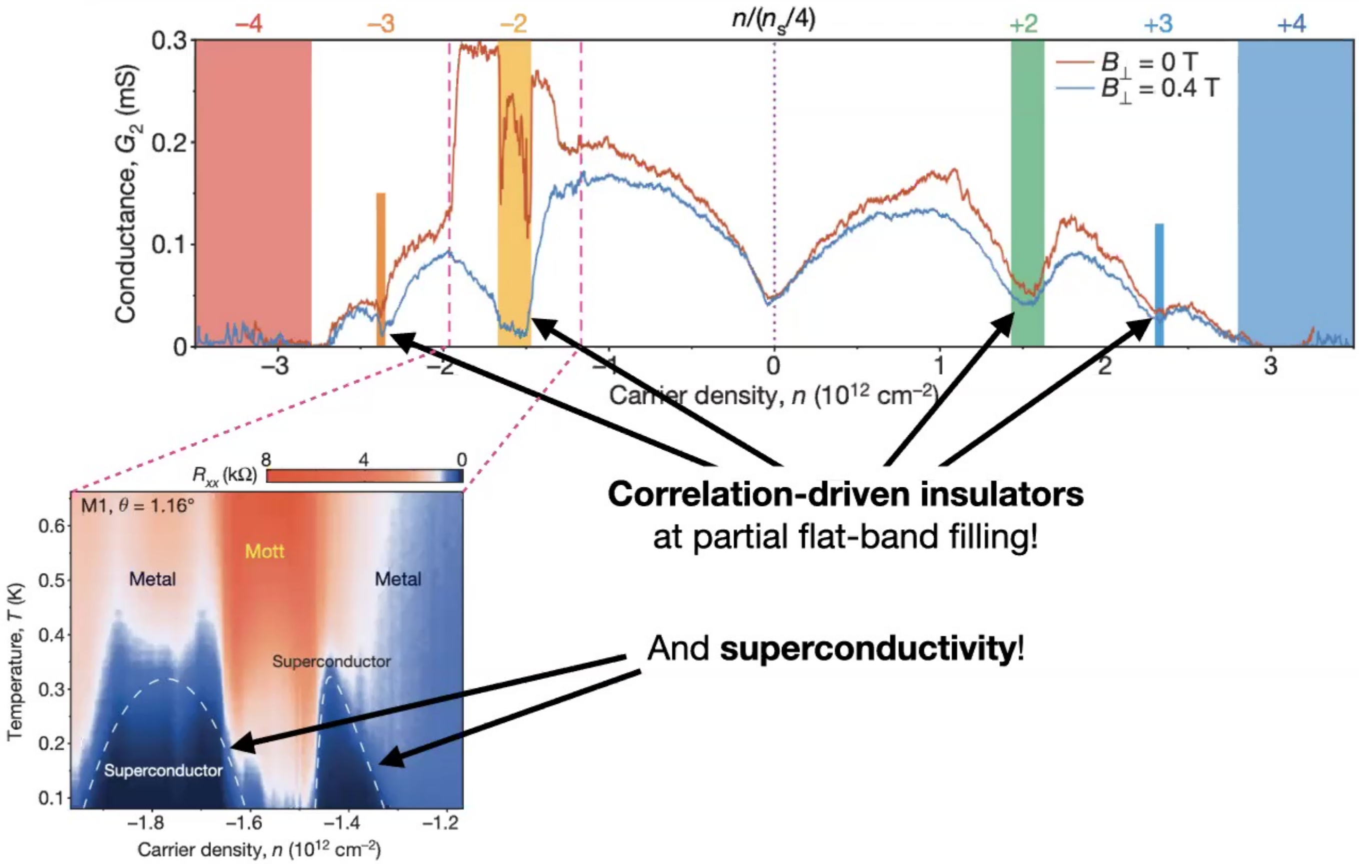


Correlation-driven insulators
at partial flat-band filling!

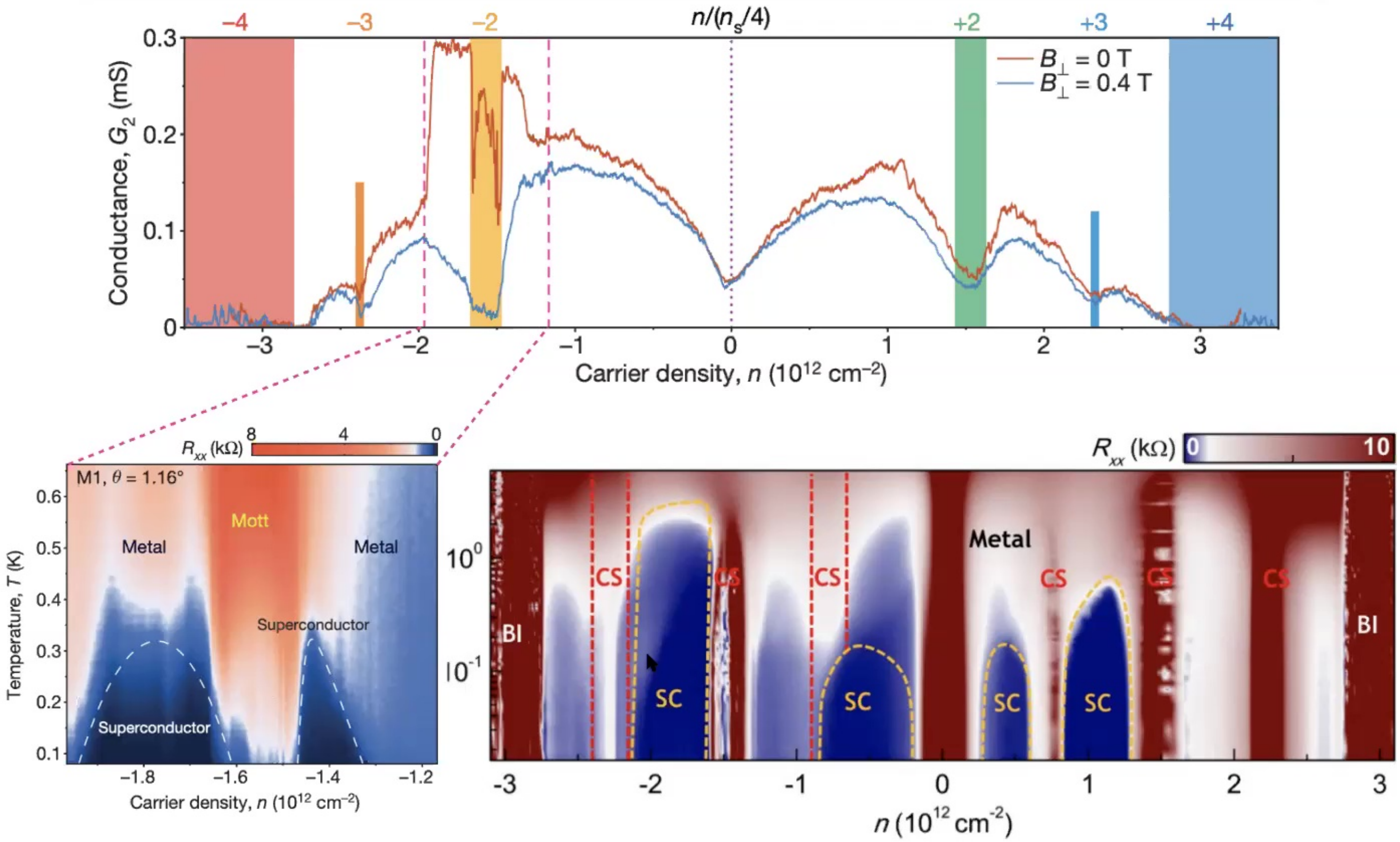
Cao et al., Nature (2018)

Magic-angle TBG experiments



Cao et al., Nature (2018)

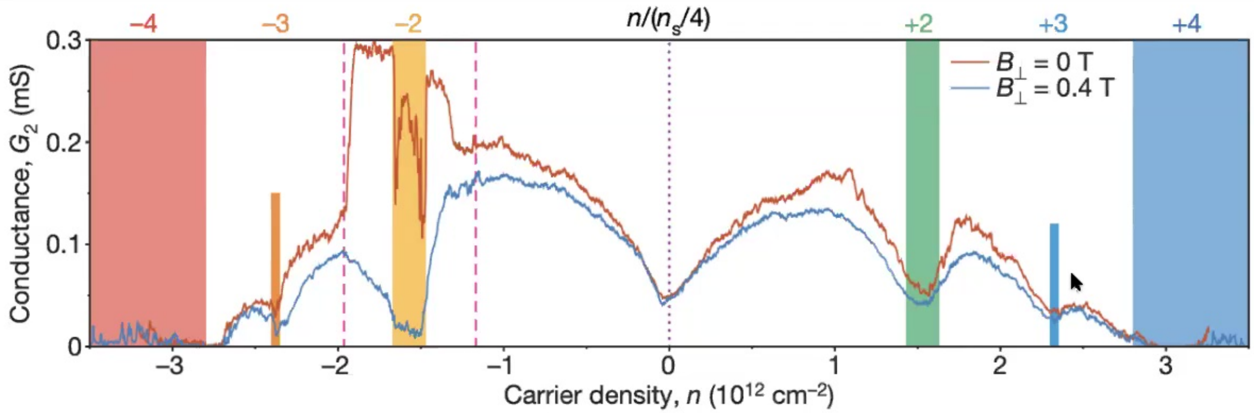
Magic-angle TBG experiments



Cao et al., Nature (2018)

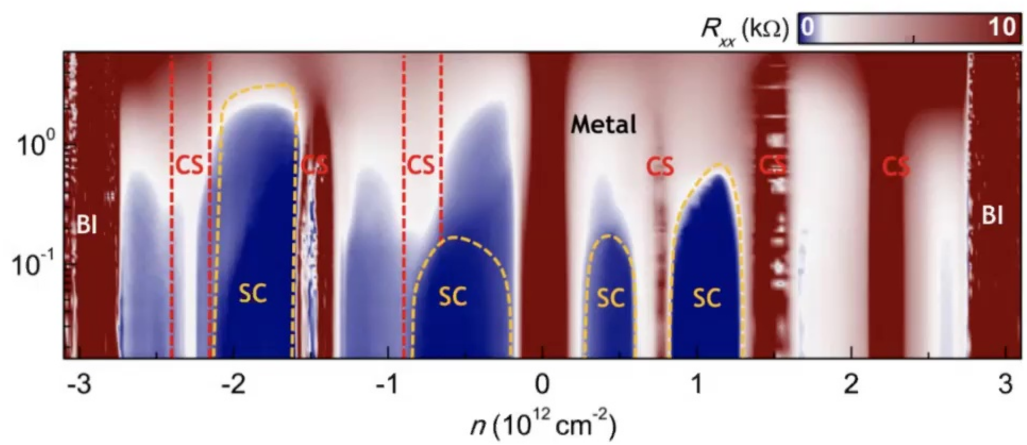
Lu et al., Nature (2019)

Magic-angle TBG experiments



Can readily gate tune between band insulators, metals, various correlated insulators & superconductors!

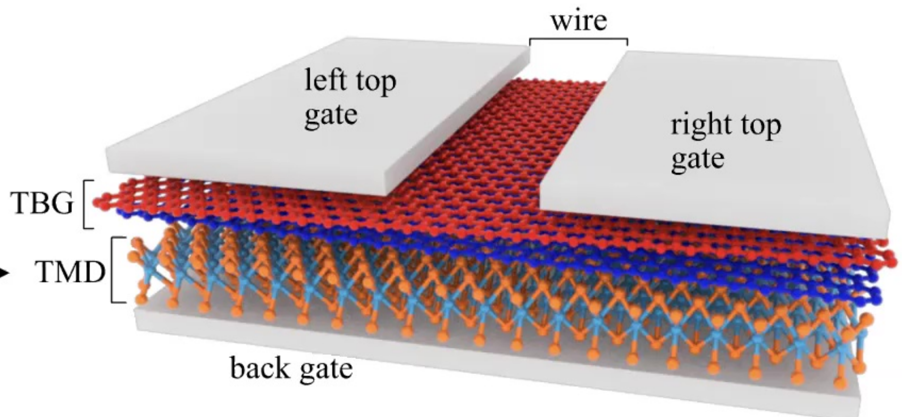
Can we exploit this richness & tunability for novel quantum devices, e.g., Majorana zero mode platforms?



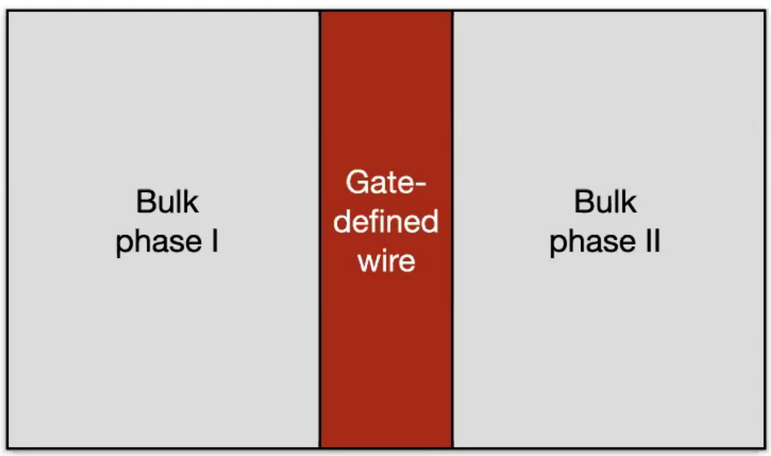
Cao et al., Nature (2018)

Lu et al., Nature (2019)

The big picture



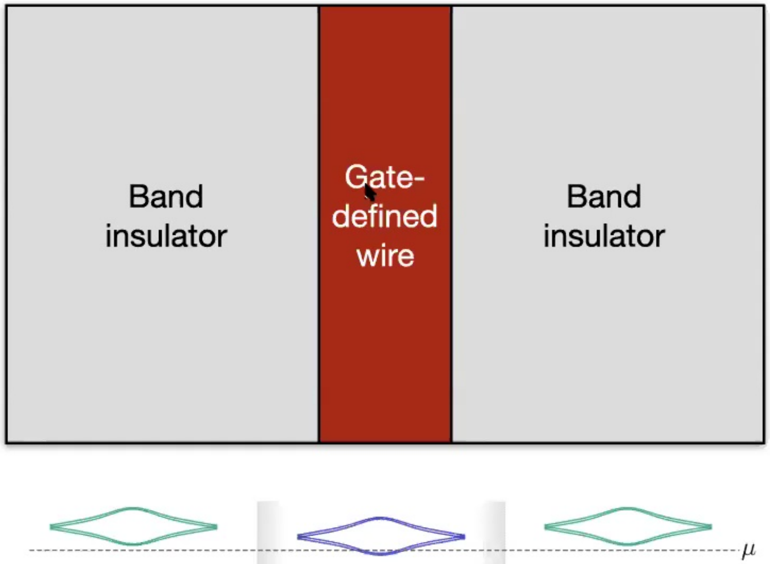
Ignore for now →

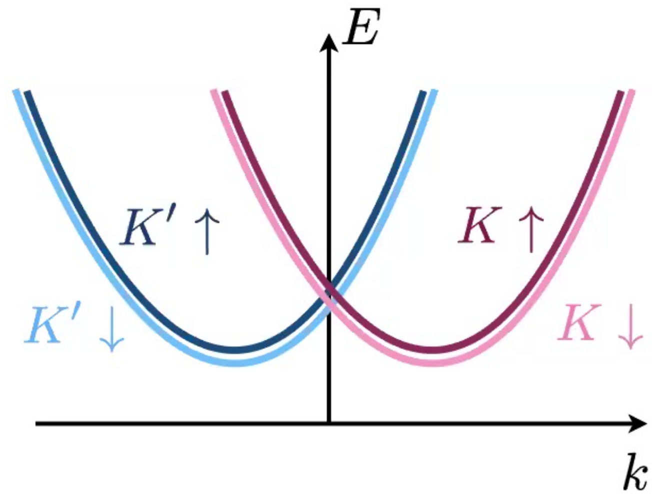


Wire inherits properties of adjacent bulk phases via **"internal" proximity effects**

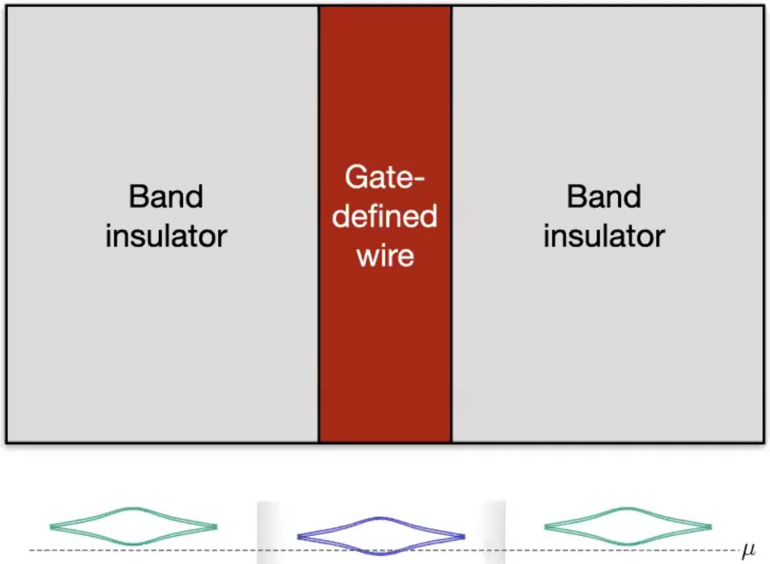
Will exploit for **electrical probes of symmetry-breaking order** and **Majorana engineering**

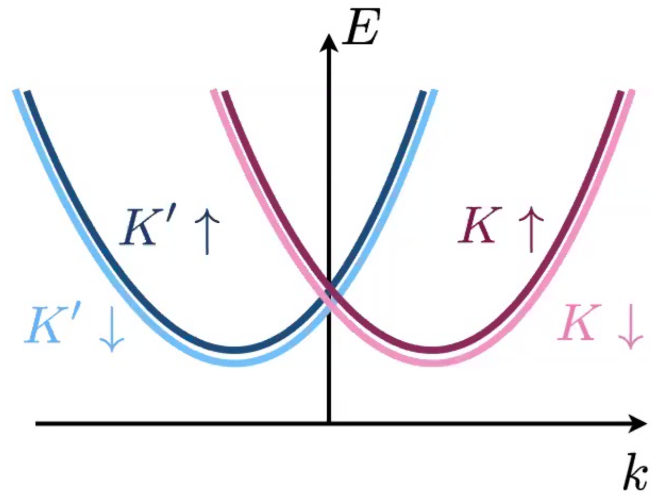
Trivial wire





Trivial wire





Challenge for Majorana engineering:
"Spinless" regime requires removing spin **and** valley degeneracy

Superconductivity in metallic twisted bilayer graphene stabilized by WSe_2

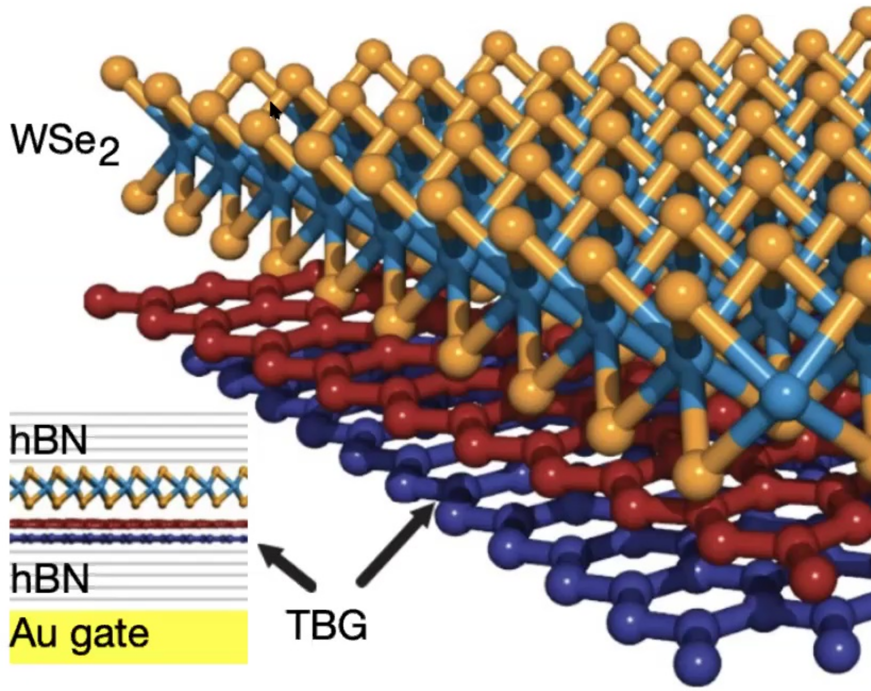
https://doi.org/10.1038/s41586-020-2473-8

Received: 31 January 2020

Accepted: 21 May 2020

Harpreet Singh Arora[1,2,8], Robert Polski[1,2,8], Yiran Zhang[1,2,3,8], Alex Thomson[2,3,4], Youngjoon Choi[1,2,3], Hyunjin Kim[1,2,3], Zhong Lin[5], Ilham Zaky Wilson[5], Xiaodong Xu[5,6], Jiun-Haw Chu[5], Kenji Watanabe[7], Takashi Taniguchi[7], Jason Alicea[2,3,4] & Stevan Nadj-Perge[1,2] ✉

Consistent with previous studies, **imparts meV-scale spin-orbit coupling to TBG** (Landau level spectrum, weak anti-localization)



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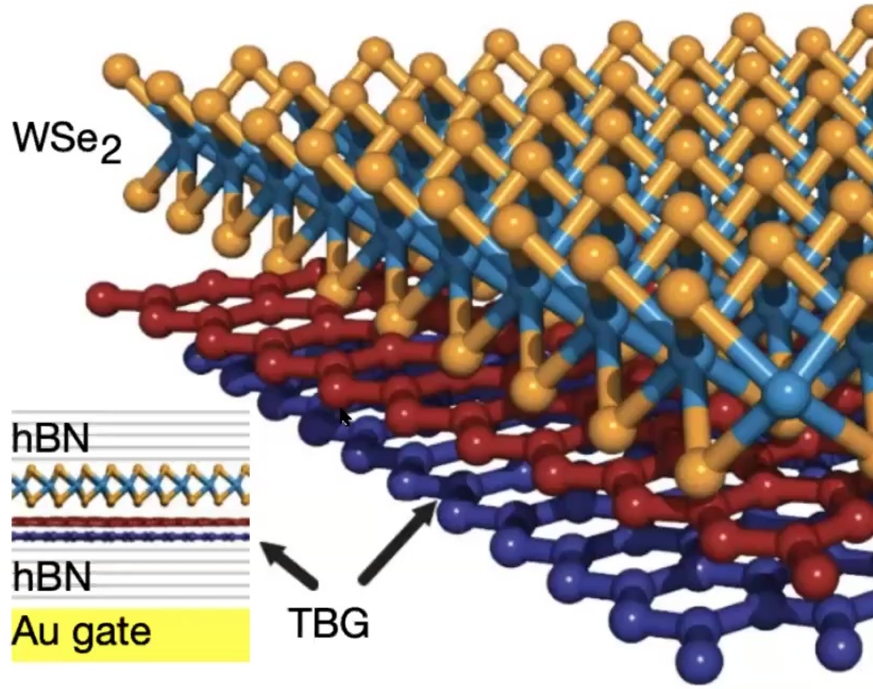

But does the rich phase diagram of “pure” TBG persist?

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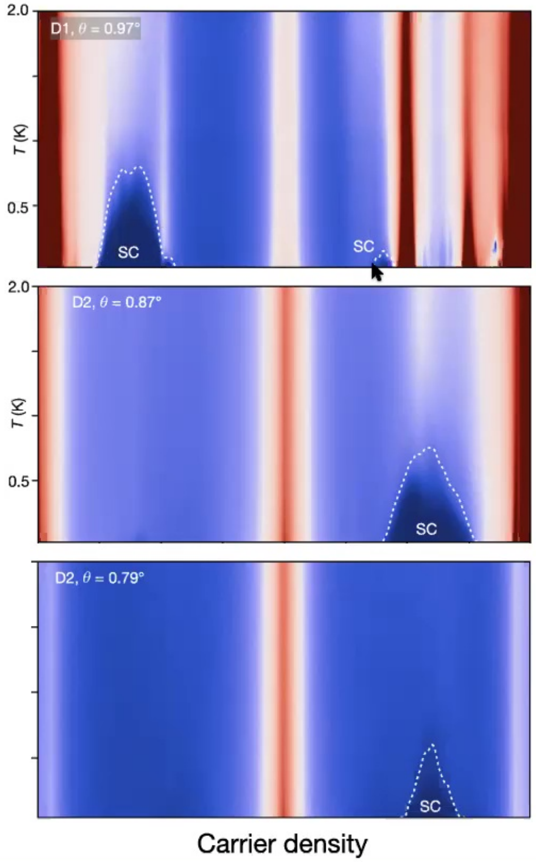

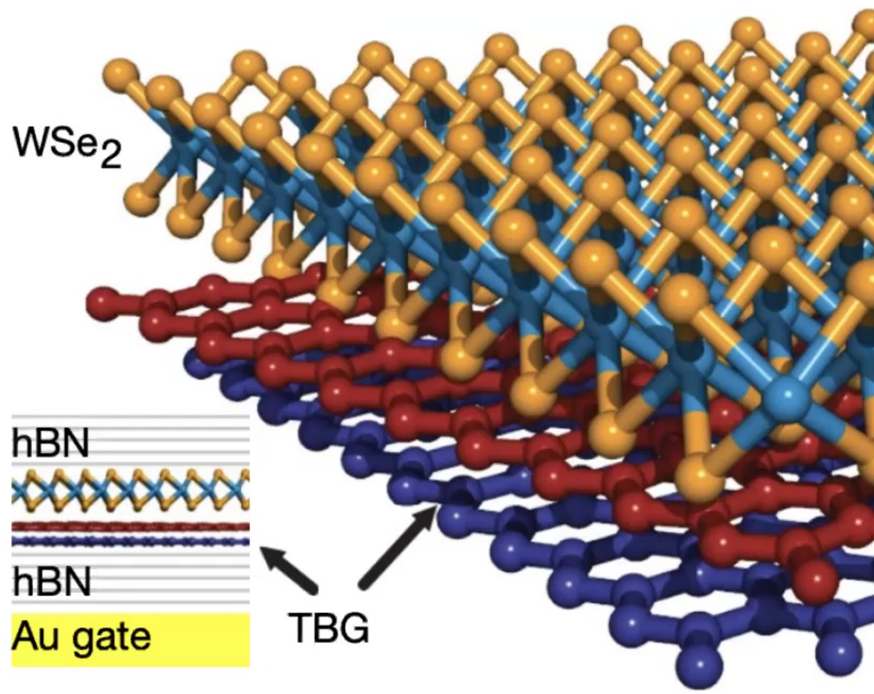

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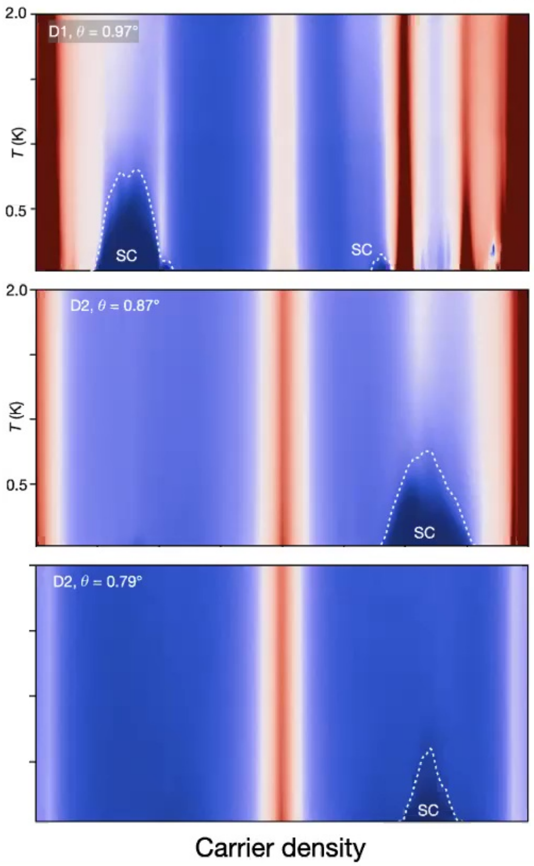

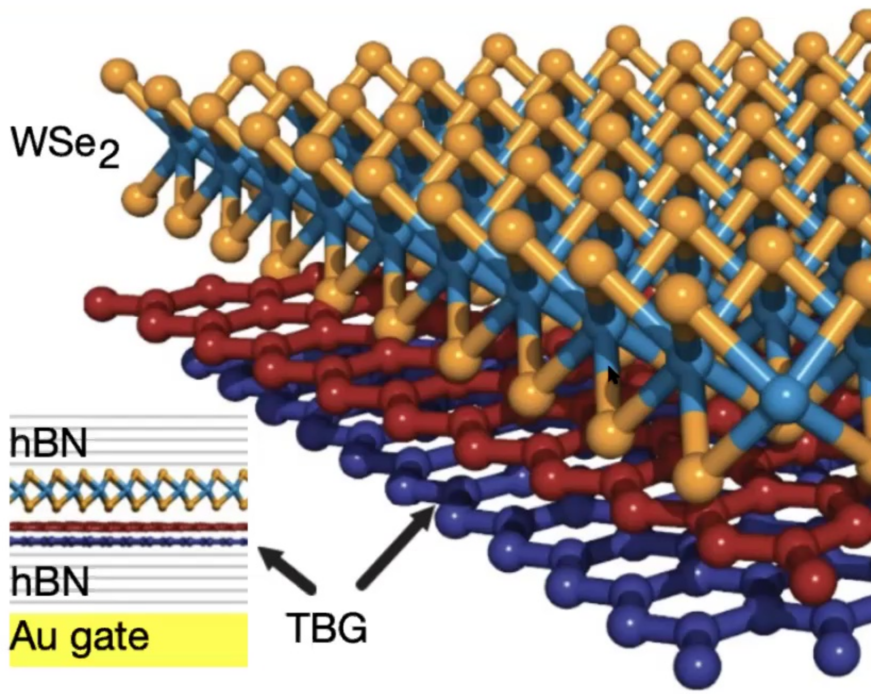

TBG superconductivity no only survives but **thrives** with spin-orbit coupling!

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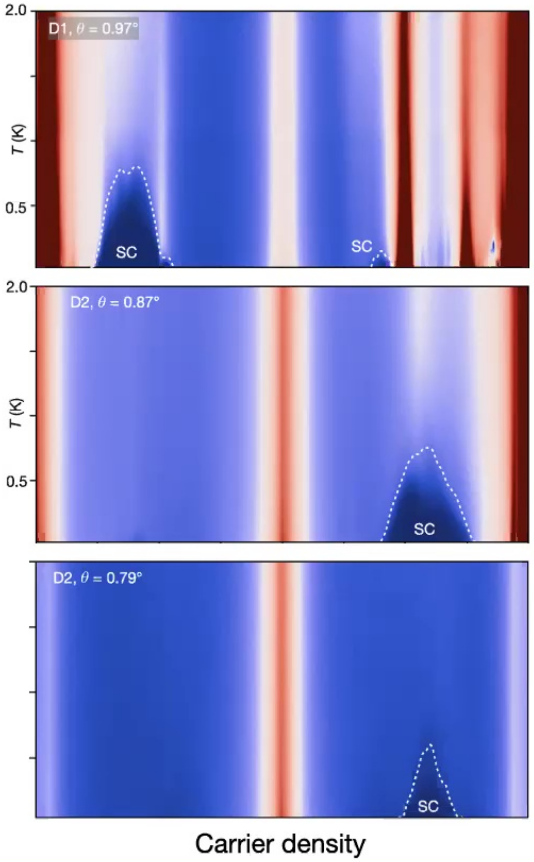
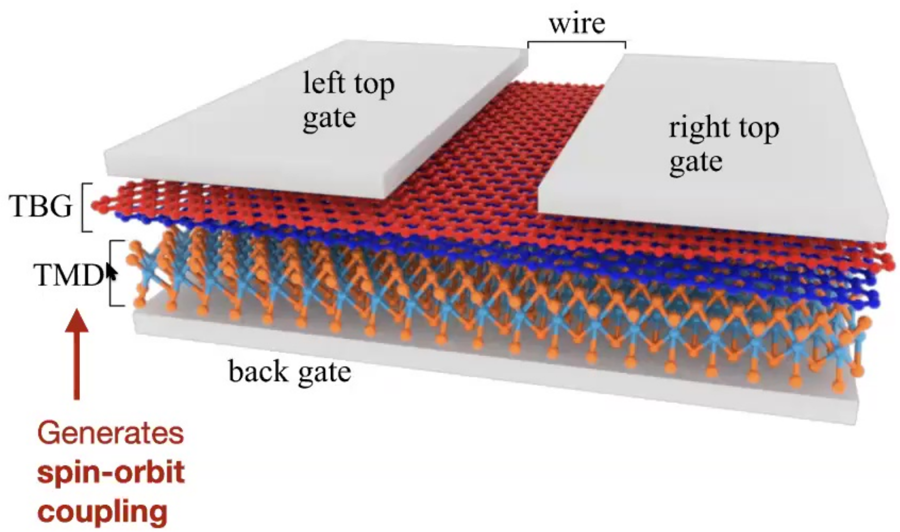
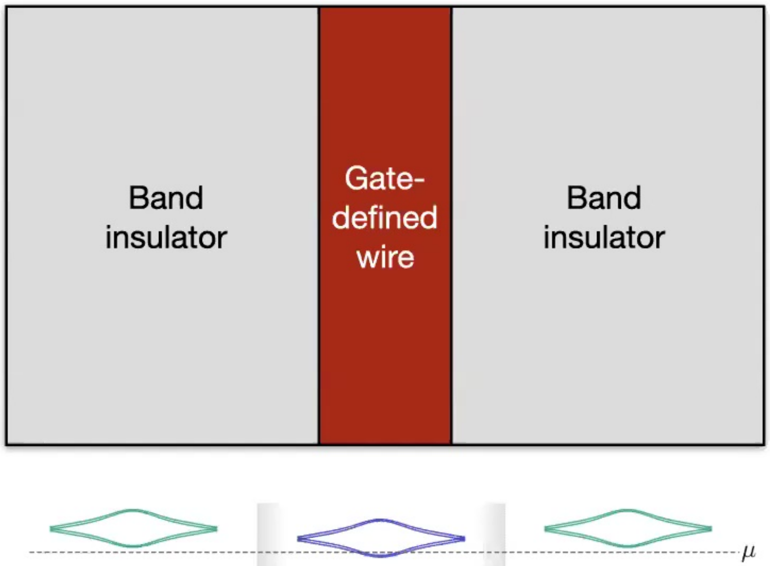
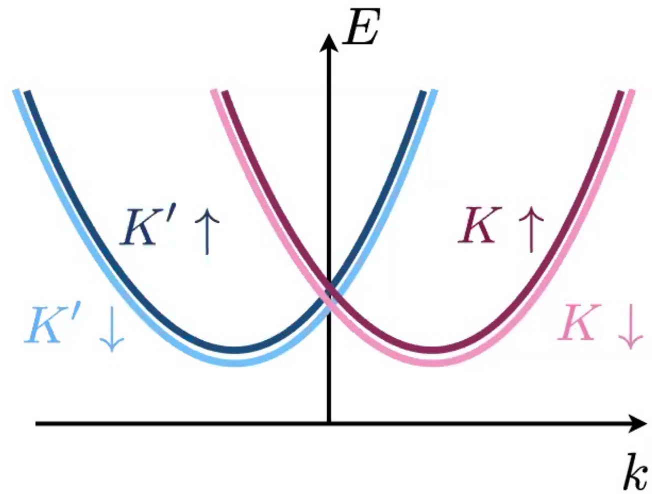




Trivial wire with spin-orbit coupling





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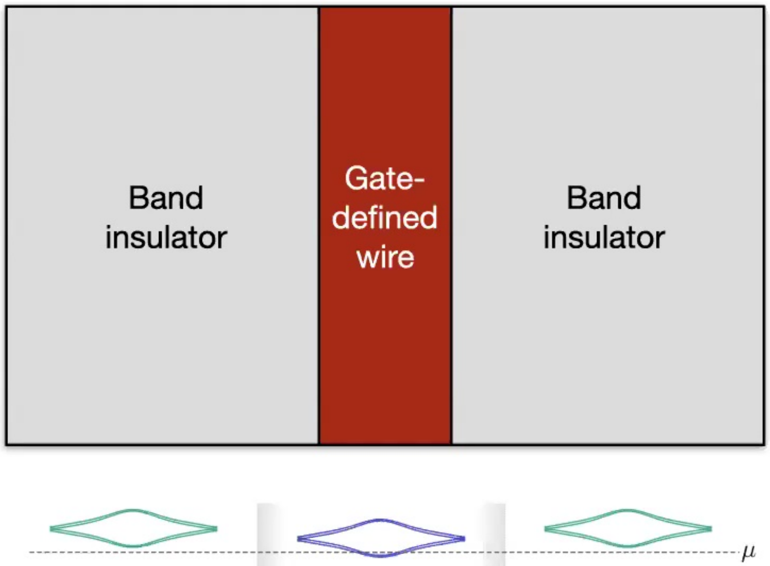
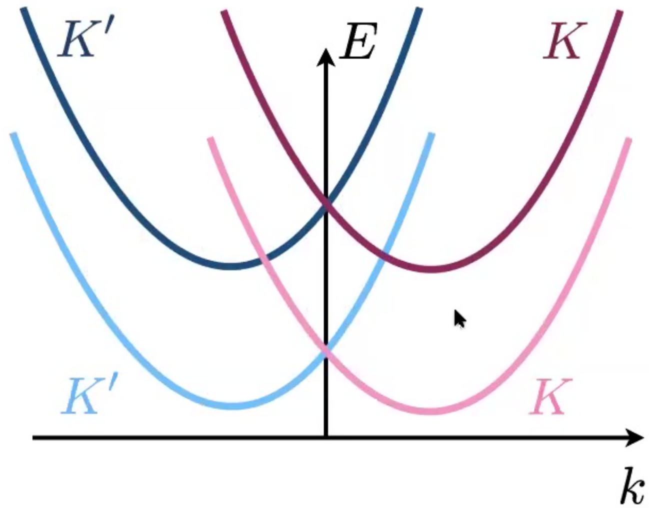
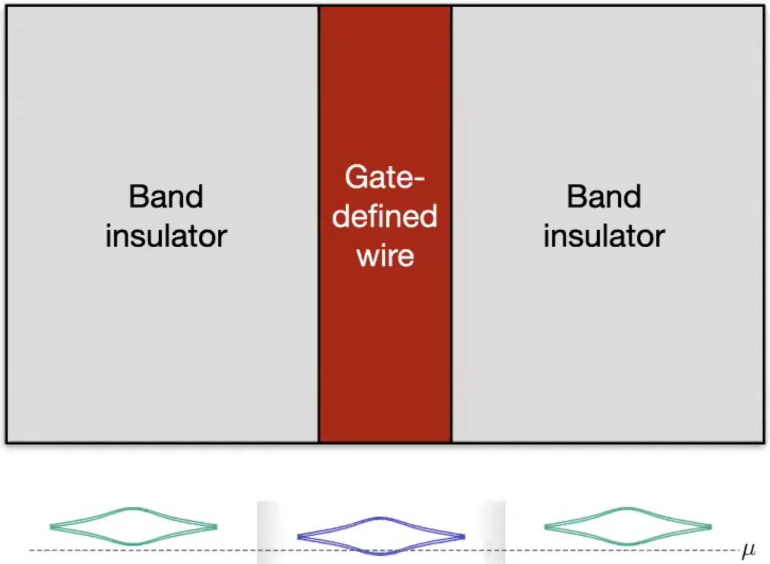
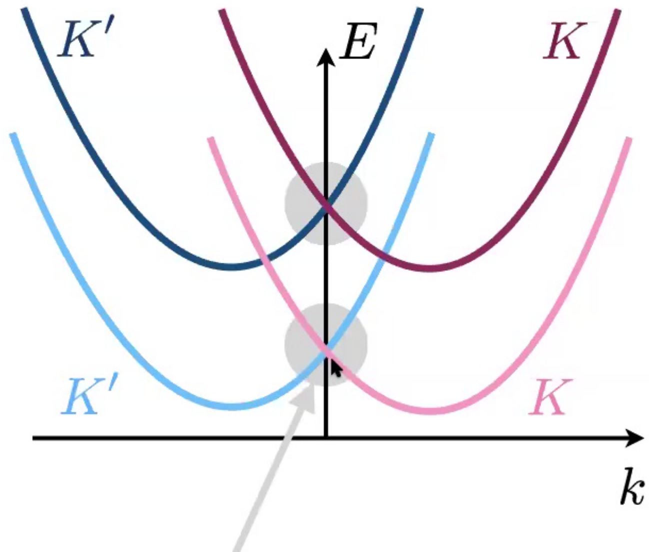




Trivial wire with spin-orbit coupling





Want to lift these crossings!
Requires **large momentum transfer/ultra-short-scale modulations**. Not trivial…

"Inter-valley coherent" correlated insulators

PHYSICAL REVIEW X **10**, 031034 (2020)

Ground State and Hidden Symmetry of Magic-Angle Graphene at Even Integer Filling

Nick Bultinck,[1,†] Eslam Khalaf,[2,†] Shang Liu,[2] Shubhayu Chatterjee,[1] Ashvin Vishwanath,[2] and Michael P. Zaletel[1,*]

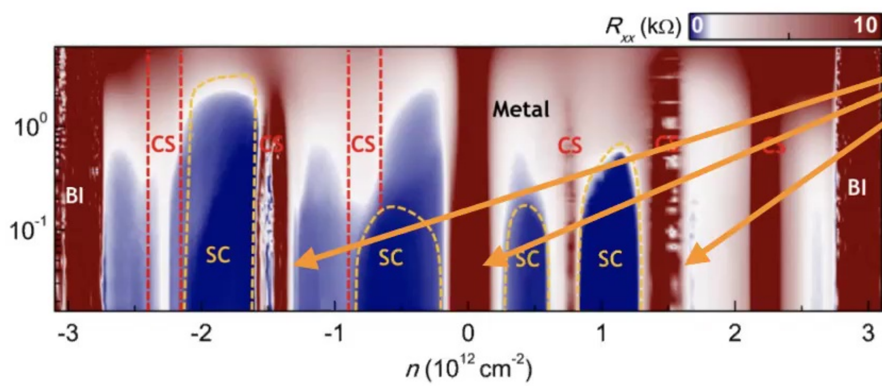
PHYSICAL REVIEW B **102**, 035136 (2020)

Correlated insulating phases of twisted bilayer graphene at commensurate filling fractions: A Hartree-Fock study

Yi Zhang,[1] Kun Jiang,[2,3] Ziqiang Wang,[3] and Fuchun Zhang[1,4]

TBG IV: Exact Insulator Ground States and Phase Diagram of Twisted Bilayer Graphene

Biao Lian,[1] Zhi-Da Song,[1] Nicolas Regnault,[1,2] Dmitri K. Efetov,[3] Ali Yazdani,[1,4] and B. Andrei Bernevig[1]



Predicted to exhibit interaction-driven **spontaneous** inter-valley coherence!

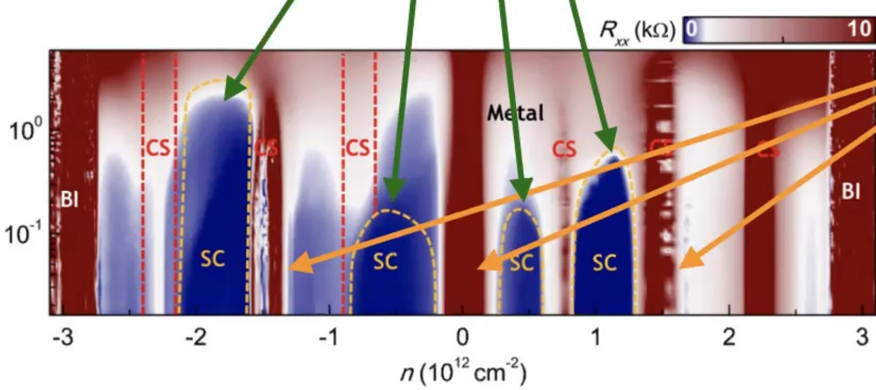
See also Kwan, Wagner, Soejima, Zaletel, Simon, Parameswaran, & Bultinck, arXiv:2105.05857; Wagner, Kwan, Bultinck, Simon, & Parameswaran, arXiv:2109.09749

"Inter-valley coherent" correlated insulators

Charged Skyrmions and Topological Origin of Superconductivity in Magic Angle Graphene

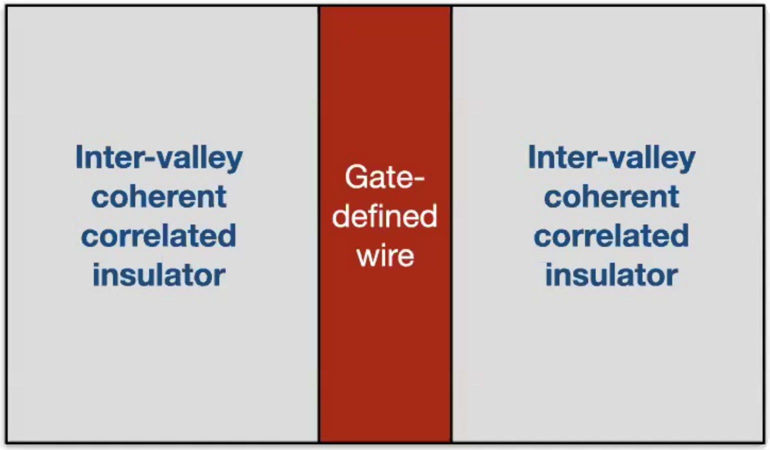
Eslam Khalaf,[1] Shubhayu Chatterjee,[2] Nick Bultinck,[2,3] Michael P. Zaletel,[2] and Ashvin Vishwanath[1,*]

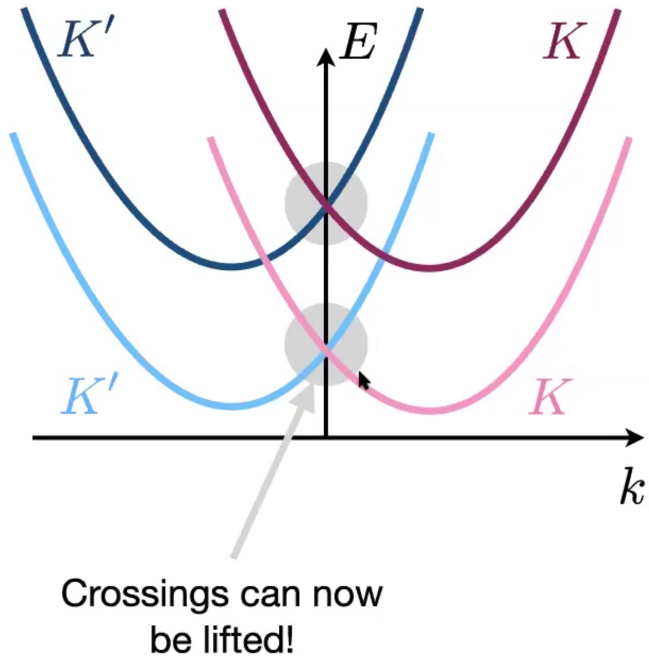
And provides novel route to superconductivity.

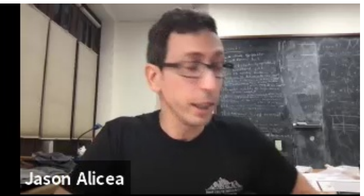


Predicted to exhibit interaction-driven **spontaneous** inter-valley coherence!

Wire with spin-orbit coupling + IVC order







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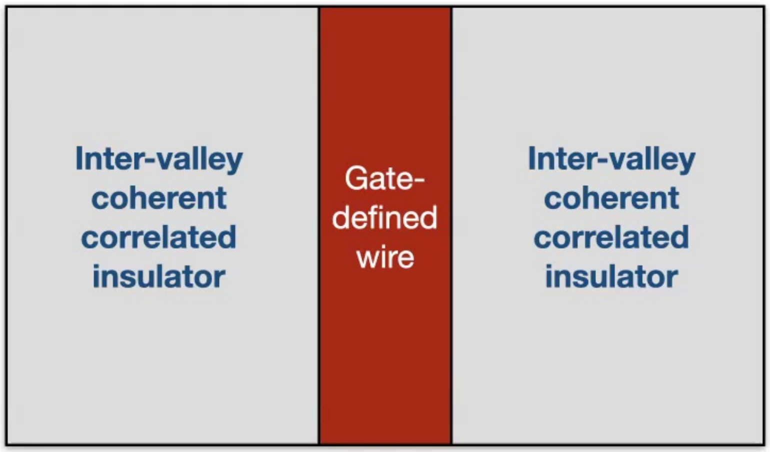
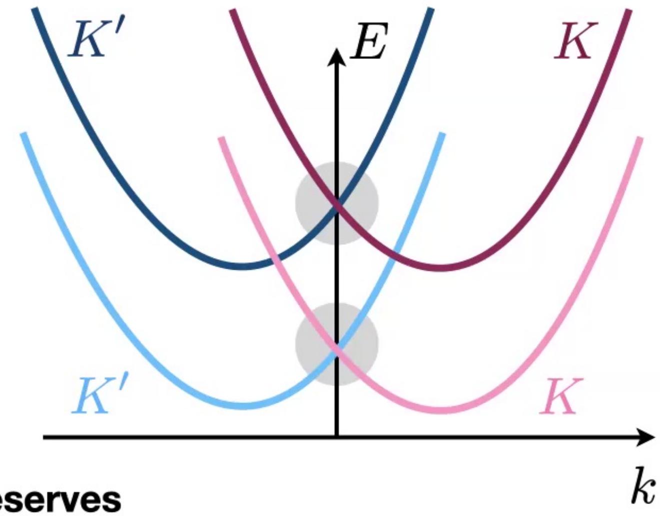
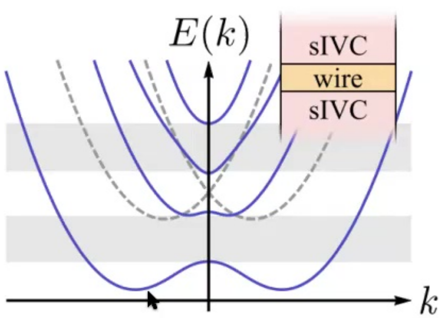
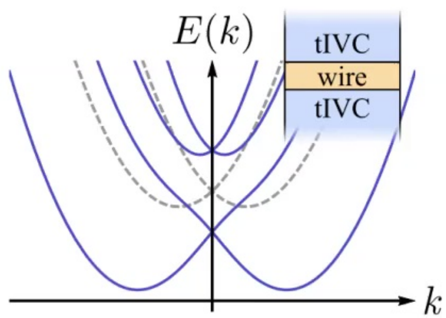




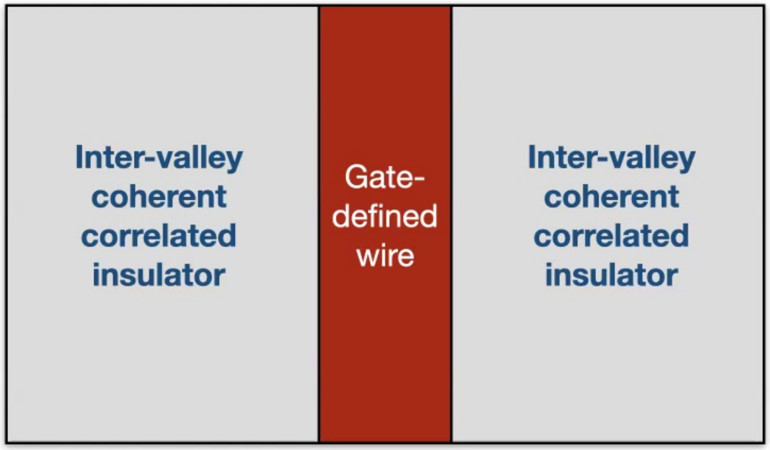
IVC order **breaks** time-reversal symmetry

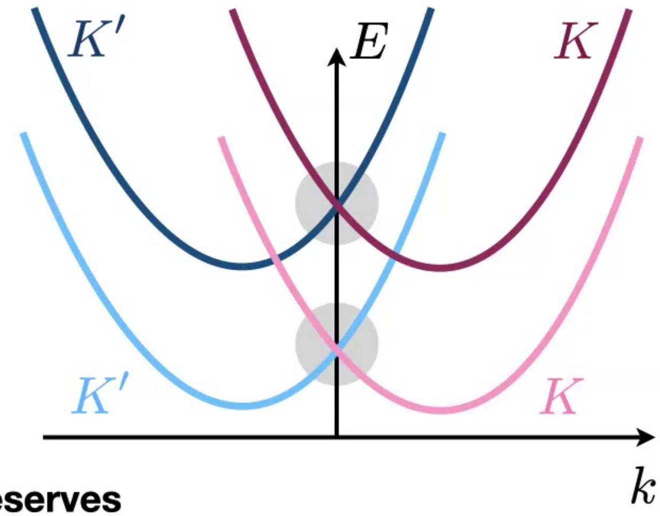


IVC order **preserves** time-reversal symmetry

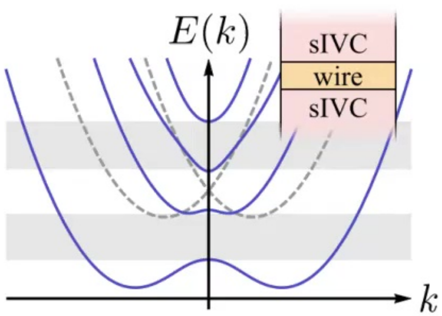


Wire with spin-orbit coupling + IVC order

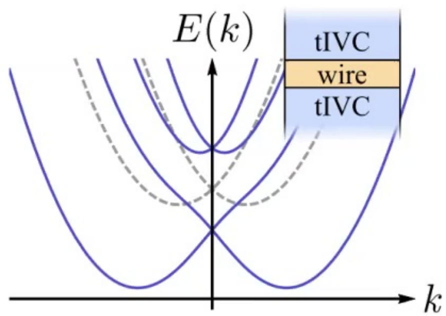


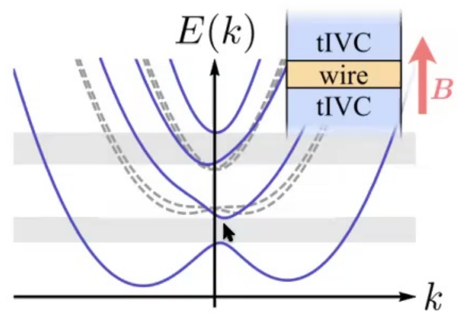


IVC order **breaks** time-reversal symmetry



IVC order **preserves** time-reversal symmetry

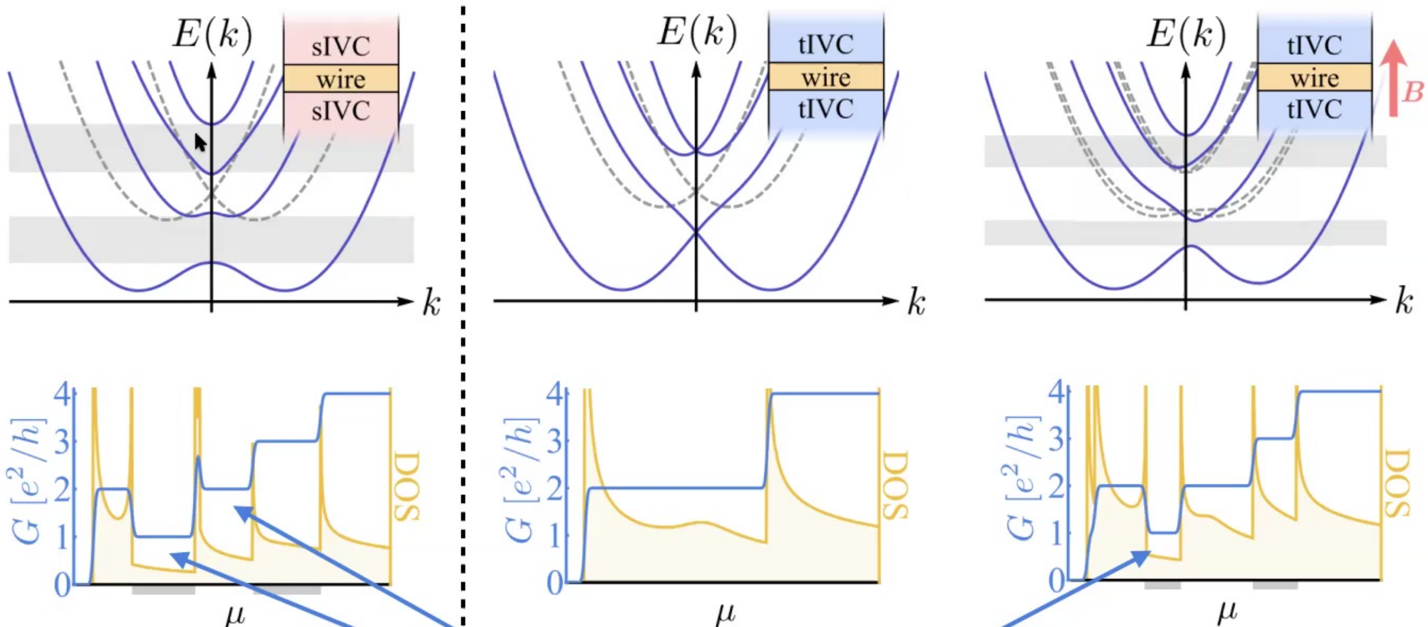




Electrical detection of IVC order

IVC order **breaks** time-reversal symmetry

IVC order **preserves** time-reversal symmetry

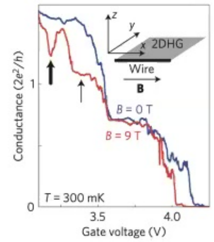


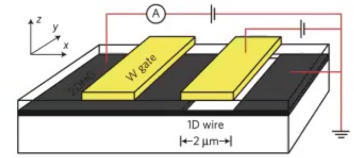
IVC-mediated conductance dips provide large-scale, electrical signature of ultra-short-scale symmetry breaking order!

Electrical detection of IVC order

Observation of a one-dimensional spin-orbit gap in a quantum wire

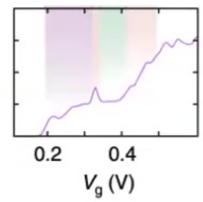
C. H. L. Quay[1,2★†], T. L. Hughes[1†], J. A. Sulpizio[1], L. N. Pfeiffer[2†], K. W. Baldwin[2†], K. W. West[2†], D. Goldhaber-Gordon[1] and R. de Picciotto[2†]

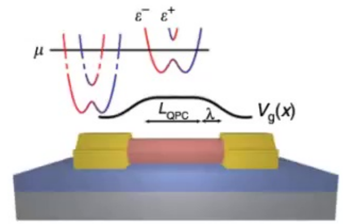


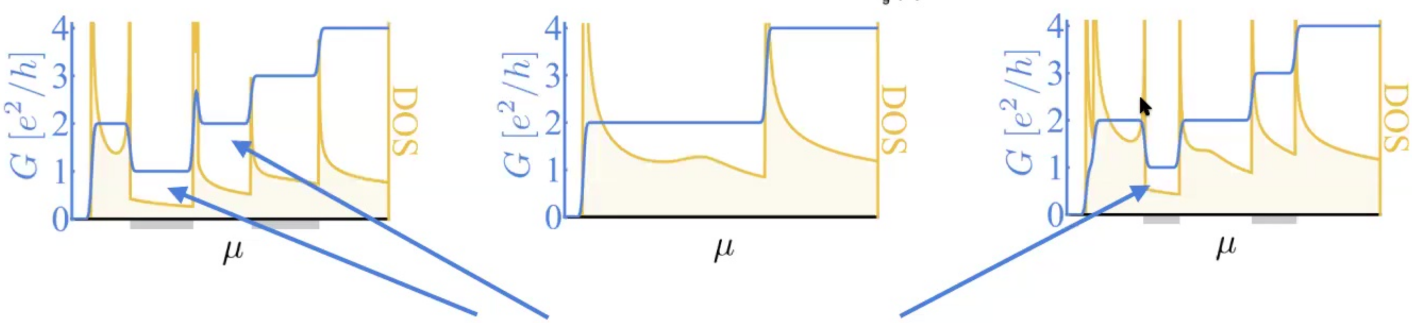


Conductance through a helical state in an Indium antimonide nanowire

J. Kammhuber[1], M.C. Cassidy[1], F. Pei[1], M.P. Nowak[1,2], A. Vuik[1], Ö. Gül[1], D. Car[1,3], S.R. Plissard[4], E.P.A.M. Bakkers[1,3], M. Wimmer[1] & L.P. Kouwenhoven[1]

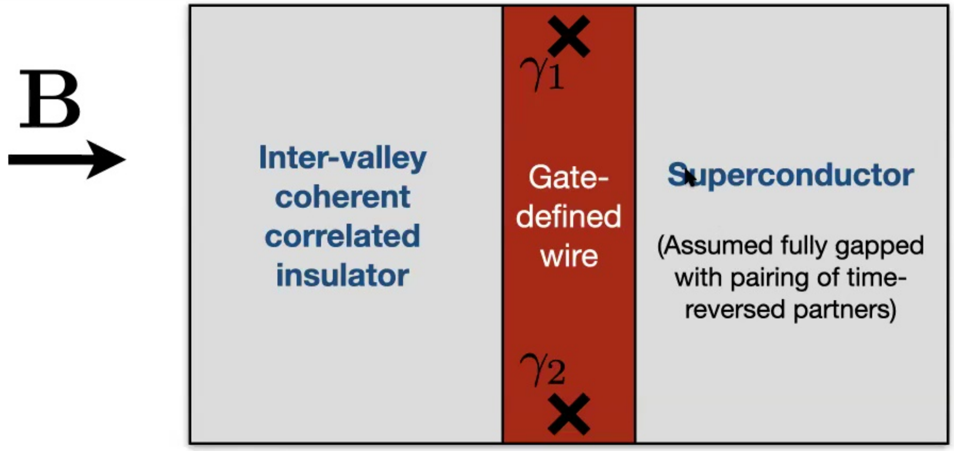




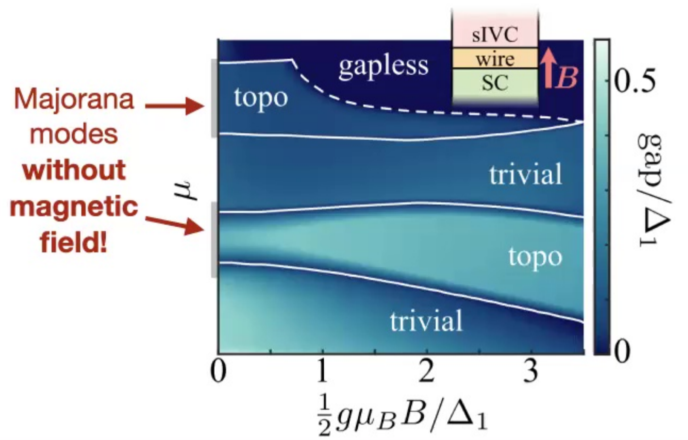


IVC-mediated conductance dips provide large-scale, electrical signature of ultra-short-scale symmetry breaking order!

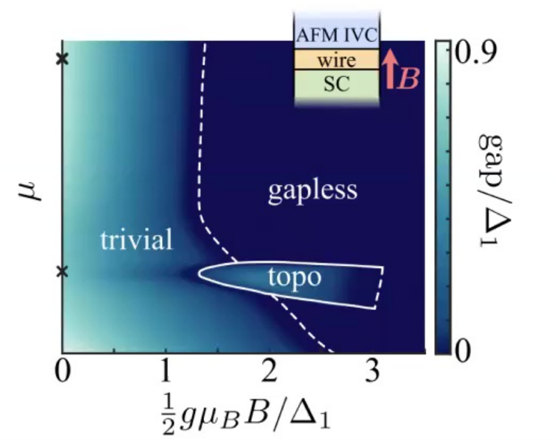
Internally engineered Majorana zero modes



IVC order **breaks** time-reversal symmetry



IVC order **preserves** time-reversal symmetry

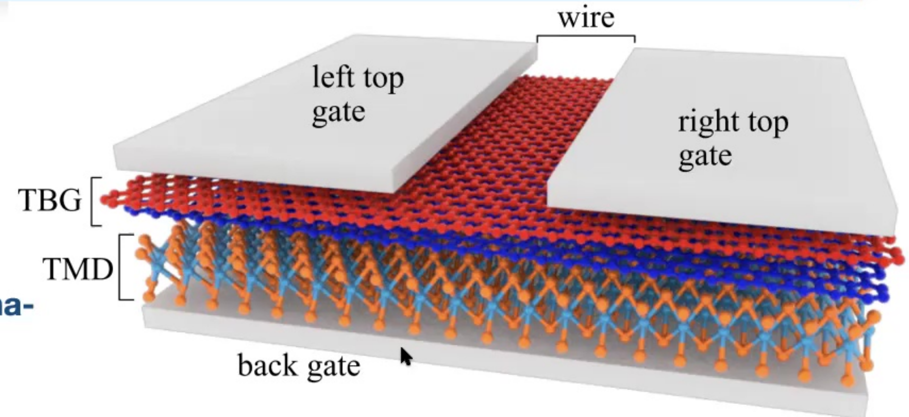


Outlook

Electrical diagnostic of subtle symmetry-breaking order

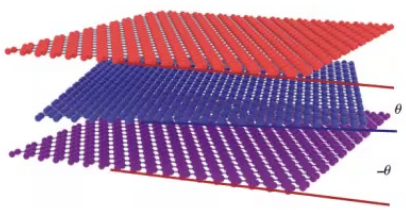
May shed light on the Cooper-pairing mechanism

Promising platform for Majorana-based topological qubits



Virtues for Majorana engineering
Exquisite gate-tunability
Eschews external superconducting proximity effect
Possible operation at zero magnetic field
Real-time control over patterning of phases
Amenable to various transport/local probes
Adaptable to mesoscopic geometries for qubit operation

Challenges
Low critical temperatures
Disorder
Sample-to-sample variation
Relies on IVC order (not yet confirmed)



Extensions to twisted trilayer graphene, other moire materials?

Park et al., Nature (2021); Hao et al., Science (2021)