Interactions and superconductivity in twisted an un-twisted graphene stacks

UNCONVENTIONAL SUPERCONDUCTORS AND MAGNETS

Workshop May 12th - 14th, 2026
WASEM Monastery, Ingelheim, Germany

ORGANIZERS

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Donostia International Physics Center

EXCELENCIA SEVERO OCHOA

F. Guinea

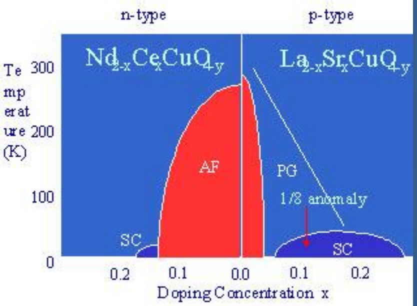
May 14th, 2026

Outline

- Interactions and phase diagram in twisted graphene bilayers
- Superconductivity in graphene stacks.
- Novel features in rhombohedral graphene.

In colaboration with N. R. Walet (U. Manchester), T. Cea, P. Pantaleon, A. Jimeno-Pozo, H. Sainz-Cruz, G. Parra, J. Silva (Imdea). Also V. P. Phong (U. Penn), V. Crépel, L. Fu, L. Levitov (MIT), Y. Oreg, E. Peleg. A. Stern (Weizmann), D. Kaplan (Rutgers), E. Mele (UPenn), A. Bernevig(Princeton, DIPC).

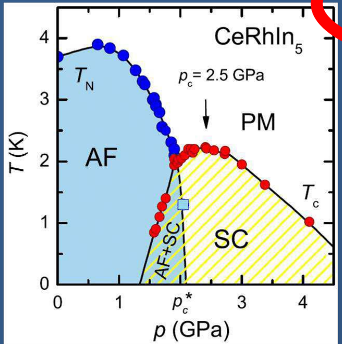
Strongly correlated systems



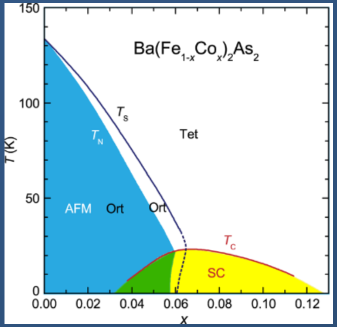
Cuprate superconductors

Pairing due to magnetic fluctuations
Variations of the Hubbard model

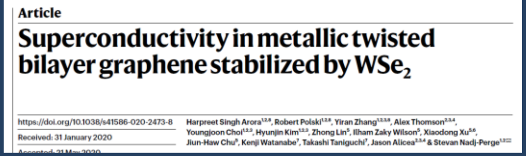
?



Heavy fermion compounds



Pnictides


Article

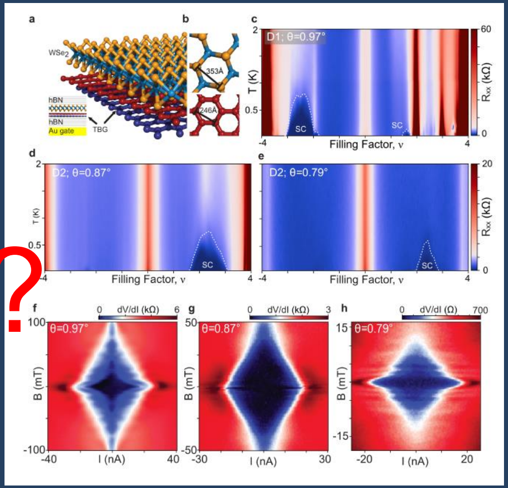
Superconductivity in metallic twisted bilayer graphene stabilized by WSe_2

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

Received: 31 January 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]✉

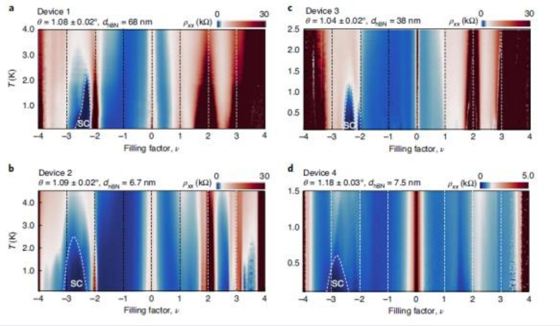
Nature **583**, 579 (2020)




Independent superconductors and correlated insulators in twisted bilayer graphene

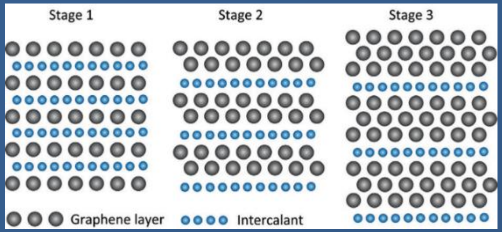
Yu Saito[1], Jingyuan Ge[2], Kenji Watanabe[3], Takashi Taniguchi[3] and Andrea F. Young[2]✉

Nature Phys. **16**, 926 (2020)

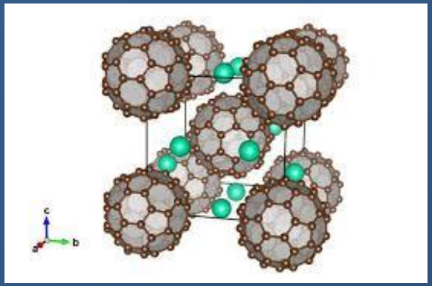


Superconductivity and strongly correlated phases in carbon compunds

Superconductivity



Graphite intercalation compounds, such as C_6Ca, $n \geq 10^{14}\ \mathrm{cm}^{-2}, T_c \sim 1 - 10\mathrm{K}$



Alkali intercalated fullerenes, such as Rb_3C_{60}, $T_c \sim 10 - 40\mathrm{K}$

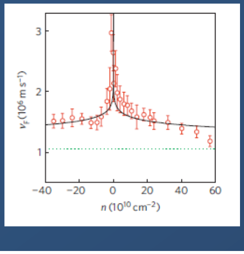
Renormalization of the Fermi velocity

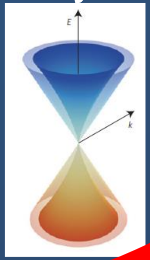
nature physics

LETTERS

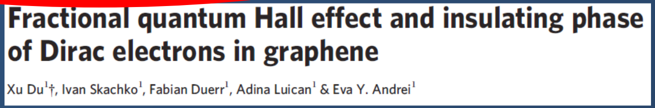
Dirac cones reshaped by interaction effects in suspended graphene

D. C. Elias[1], R. V. Gorbachev[1], A. S. Mayorov[1], S. V. Morozov[2], A. A. Zhukov[3], P. Blake[3], L. A. Ponomarenko[1], I. V. Grigorieva[1], K. S. Novoselov[1], F. Guinea[4]* and A. K. Geim[1,3]





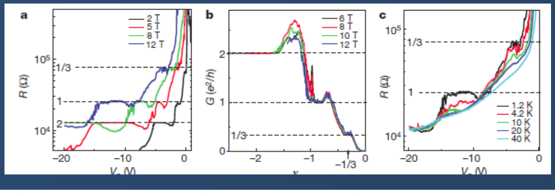
Landau levels

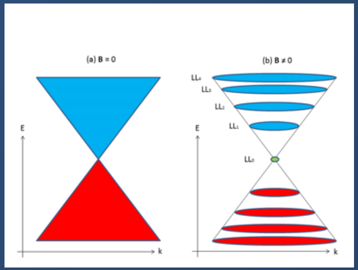


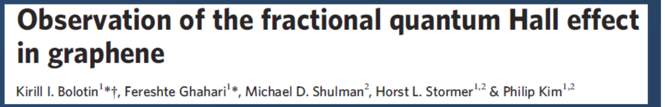
Fractional quantum Hall effect and insulating phase of Dirac electrons in graphene

Xu Du[1]†, Ivan Skachko[1], Fabian Duerr[1], Adina Luican[1] & Eva Y. Andrei[1]

Nature **462**, 192 (2009)



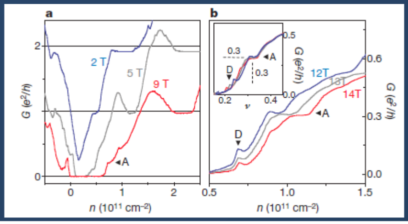




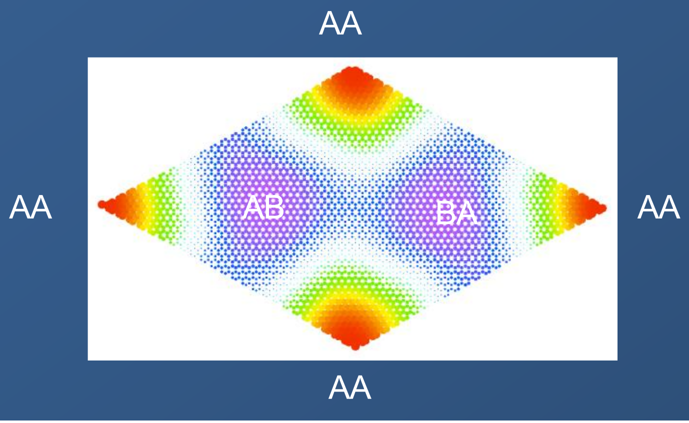
Observation of the fractional quantum Hall effect in graphene

Kirill I. Bolotin[1]*†, Fereshte Ghahari[1]*, Michael D. Shulman[2], Horst L. Stormer[1,2] & Philip Kim[1,2]

Nature **462**, 196 (2009)

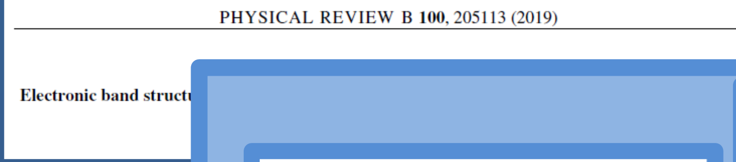


Interactions in twisted bilayer graphene



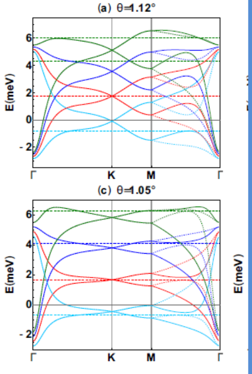
Number of atoms:	$N \approx 10^4$	
Moiré unit length:	$L_M \approx 15\,\mathrm{nm}$	$\sim d\sqrt{N}$
Radius of the charge distribution:	$L_c \quad 5\,\mathrm{nm}$	$\sim d\sqrt{N}$
Coulomb energy:	$E_C \approx \frac{e^2}{\epsilon L_c} \sim 10-50\,\mathrm{meV}$	$\sim \frac{e^2}{\varepsilon d}\frac{1}{\sqrt{N}}$
Intraatomic (Hubbard) repulsion:	$E_{Hubbard} = N \times \frac{U}{N^2} \approx 1\,\mathrm{meV}$	$\sim \frac{e^2}{d} \times \frac{1}{N}$
Electron-phonon coupling, LA:	$g = \frac{D^2}{\lambda + 2\mu} \times \frac{1}{\sqrt{3}L_M^2/2} \approx 1\,\mathrm{meV}$	$\sim \frac{D^2}{\lambda + 2\mu} \times \frac{1}{N}$
Electron-phonon coupling, TA:	$g = \frac{(t\beta)^2}{\mu} \times \frac{1}{\sqrt{3}L_M^2/2} \approx 1\,\mathrm{meV}$	$\sim \frac{(t\beta)^2}{\mu} \times \frac{1}{N}$

Shapes and widths of the bands: theory

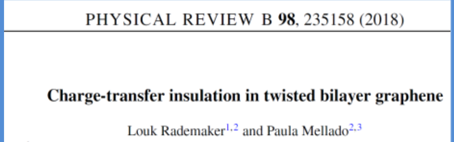


PHYSICAL REVIEW B **100**, 205113 (2019)

Electronic band structu



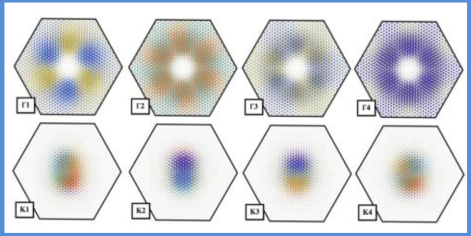
$V_H(AA) - V_$



PHYSICAL REVIEW B **98**, 235158 (2018)

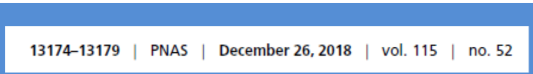
Charge-transfer insulation in twisted bilayer graphene

Louk Rademaker[1,2] and Paula Mellado[2,3]

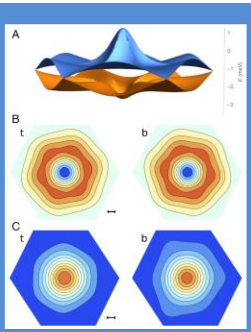


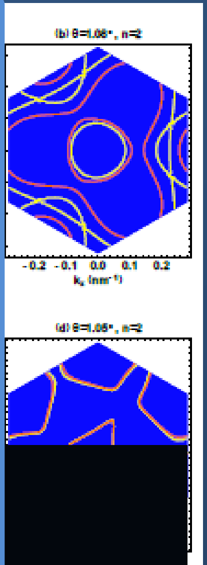
Electrostatic effects, band distortions, and superconductivity in twisted graphene bilayers

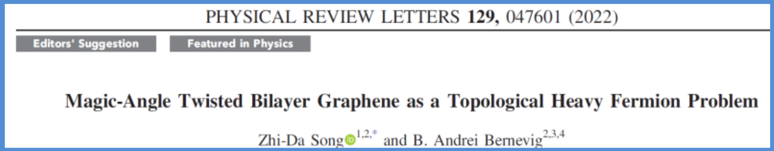
Francisco Guinea[a,b,1,2] and Niels R. Walet[b,1,2]



13174–13179 | PNAS | December 26, 2018 | vol. 115 | no. 52





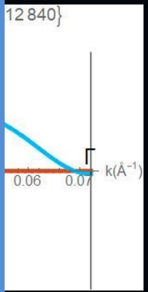


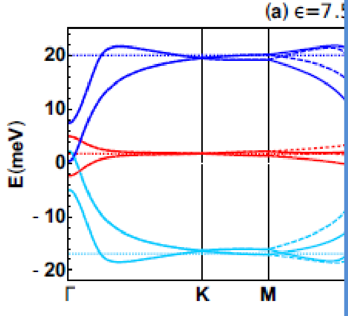
PHYSICAL REVIEW LETTERS **129**, 047601 (2022)

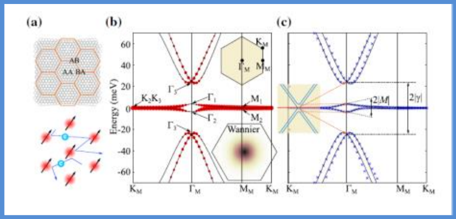
Editors' Suggestion Featured in Physics

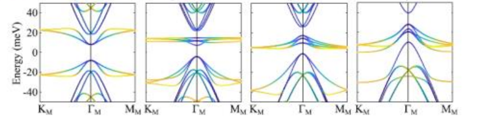
Magic-Angle Twisted Bilayer Graphene as a Topological Heavy Fermion Problem

Zhi-Da Song[1,2,*] and B. Andrei Bernevig[2,3,4]

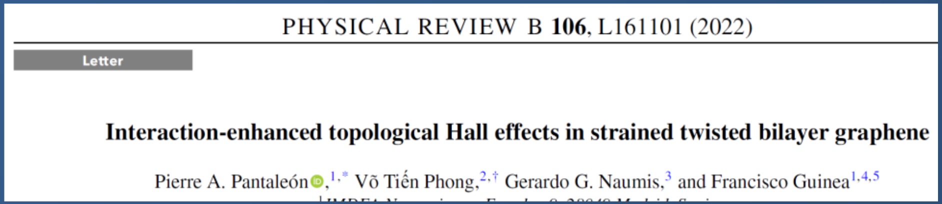








he density of
states at the Fermi energy remains high (pinning of
van Hove singularities).

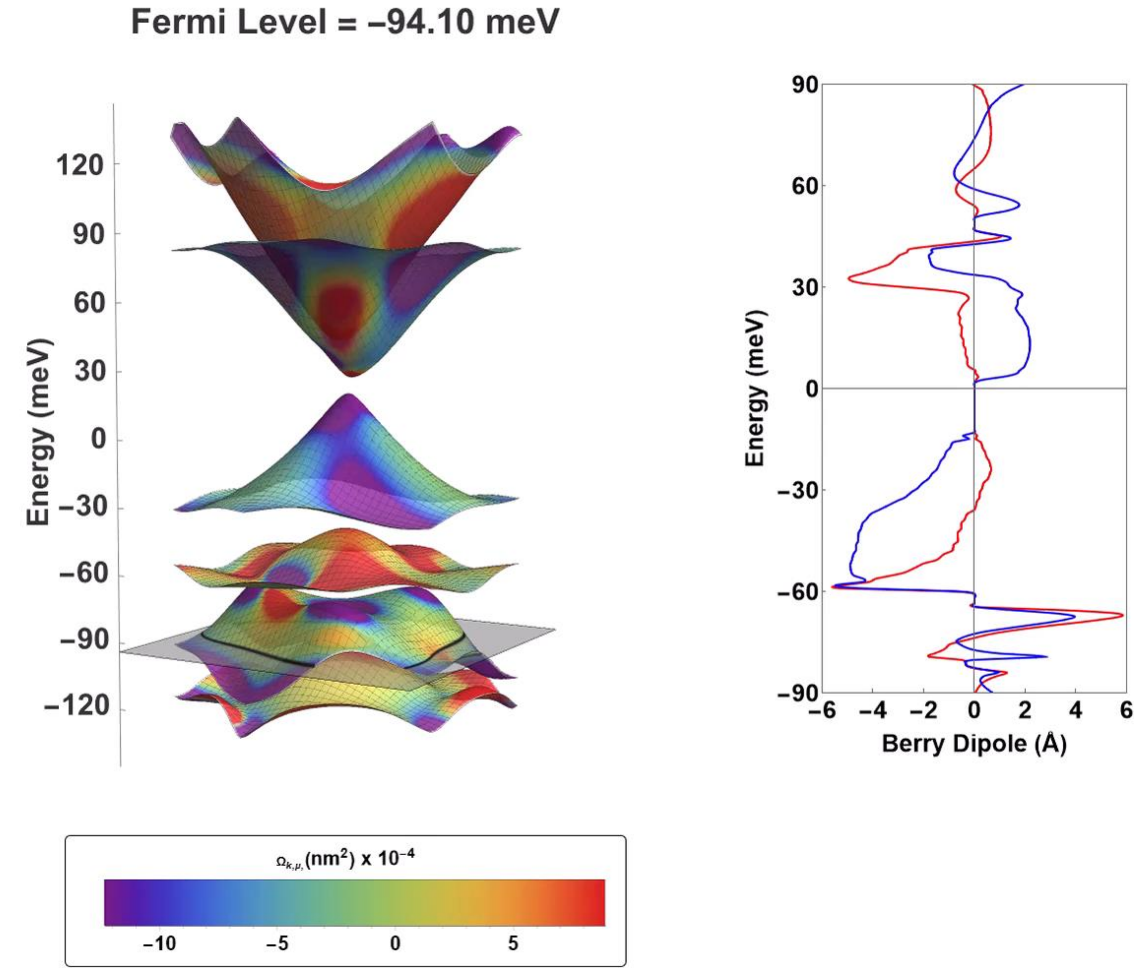


PHYSICAL REVIEW B **106**, L161101 (2022)

Letter

Interaction-enhanced topological Hall effects in strained twisted bilayer graphene

Pierre A. Pantaleón,[1,*] Võ Tiến Phong,[2,†] Gerardo G. Naumis,[3] and Francisco Guinea[1,4,5]



Cascade of phase transitions in twisted bilayer graphene

Article

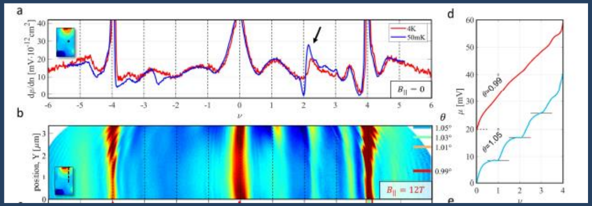
Cascade of phase transitions and Dirac revivals in magic-angle graphene

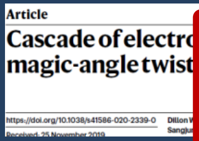
https://doi.org/10.1038/s41586-020-2373-y

Received: 25 November 2019

U. Zondiner[1,5], A. Rozen[1,5], D. Rodan-Legrain[2,5], Y. Cao[2], R. Queiroz[1], T. Taniguchi[3], K. Watanabe[3], Y. Oreg[1], F. von Oppen[4], Ady Stern[1], E. Berg[1], P. Jarillo-Herrero[2] & S. Ilani[1]

Nature **582**, 203 (2020).





Article

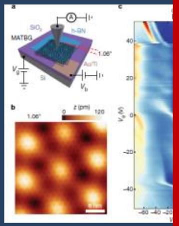
Cascade of electro magic-angle twist

https://doi.org/10.1038/s41586-020-2339-0

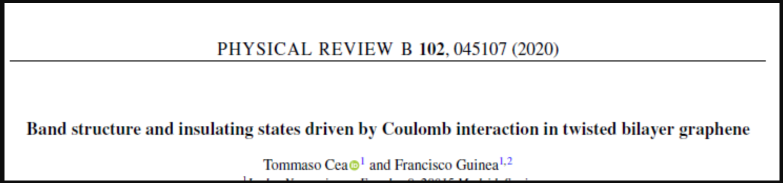
Received: 25 November 2019

Dillon W
Sangjun

Nature **58**



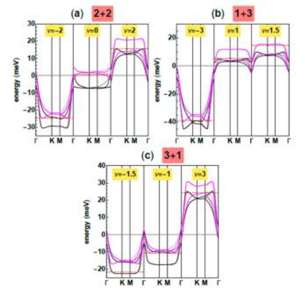
Article



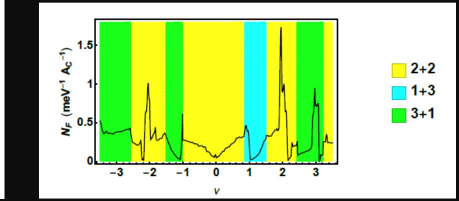
PHYSICAL REVIEW B **102**, 045107 (2020)

Band structure and insulating states driven by Coulomb interaction in twisted bilayer graphene

Tommaso Cea[1] and Francisco Guinea[1,2]



The mean field (HF) cascade



Unconventional sequence of correlated Chern insulators in magic-angle twisted bilayer graphene

Andrew T. Pierce[1*], Yonglong Xie[1,2*‡], Jeong Min Park[2*], Eslam Khalaf[1*], Seung Hwan Lee[1], Yuan Cao[2], Daniel E. Parker[1], Patrick R. Forrester[1], Shaowen Chen[1], Kenji Watanabe[3], Takashi

Chern insulators, van Hove singularities and

Douglas R. Hartree

Vladimir A. Fock

- The long range Coulomb interaction gives a qualitative explanation of the band deformations, and of the broken symmetry phases of twisted bilayer graphene.
- It does not identify details of the broken symmetry phases.

Superconductivity in twisted bilayer graphene. Some theoretical models

Electron-phonon coupling:

F. Wu, E. Hwang, S. Das Sarma, Phys. Rev. B 99, 165112 (2018)
F. Wu, A. H. MacDonald, I. Martin, Phys. Rev. Lett. 121, 257001 (2019)
B. Lian, Z. Wang, B. A. Bernevig, Phys. Rev. Lett. 122, 257002 (2019)

Electron-electron coupling: effect of van Hove singularities:

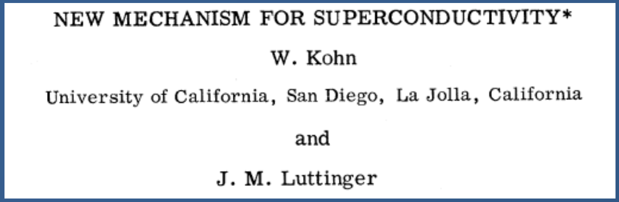
Y. Lin, R. M. Nandkishore, Phys. Rev. B 21, 214521 (2018)

T. Cea, F. G., Proc. Nat. Acad. Sci. **118**, e2107874118 (2021)
V. T. Phong, P. A. Pantaleon, T. Cea, F. G., Phys. Rev. B **104**, L121116 (2022)
T. Cea, P. A. Pantaleon, V. T. Phong, F. G., Phys. Rev. B **105**, 075432 (2022)
A. Jimeno-Pozo, H. Sainz-Cruz, T. Cea, P. Pantaleon, F. G., Phys. Rev. B **107**, L161106 (2023)
H. Sainz-Cruz, P. A. Pantaleon, F. G., Phys. Rev. Lett. **131**, 016003 (2023)
V. T. Phong, H. Sainz-Cruz, E. J. Mele, F. G., arXiv:2307.03031 (2023), Phys. Rev. B, in press
M. Long, A. Jimeno-Pozo, H. Sainz-Cruz, P. A. Pantaleon, F. G., Proc. Nat. Acad. Sci. **121**, e2405259121 (2024)

Electron-electron interactions: diagrammatic methods (Kohn-Luttinger) based on the Coulomb interaction:

T. Cea, F. G., Proc. Nat. Acad. Sci. 118, e2107874118 (2021)
G. Savit, E. Berg, A. Stern, Y. Oreg, Phys. Rev. Lett. 127, 247703 (2022)
V. Kozii, M. P. Zaletel, N. Bultnick, Phys. Rev. B 106, 235157 (2022)

Long range interactions and superconductivity: the Kohn-Luttinger mechanism



NEW MECHANISM FOR SUPERCONDUCTIVITY*

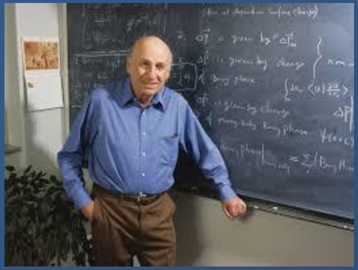
W. Kohn

University of California, San Diego, La Jolla, California

and

J. M. Luttinger

Phys. Rev. Lett. **15**, 524 (1965)



Walter Kohn

Joaquin M. Luttinger

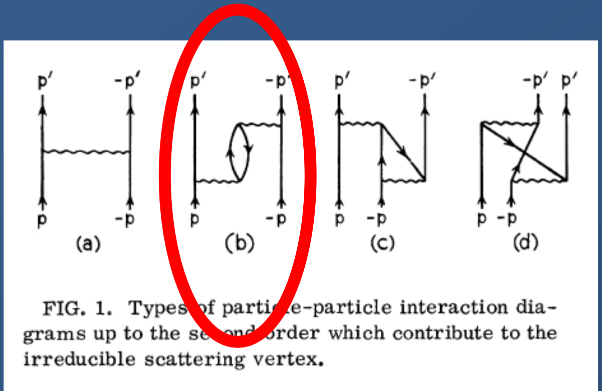
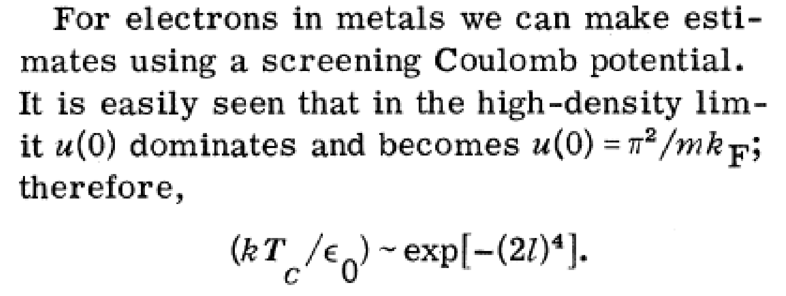


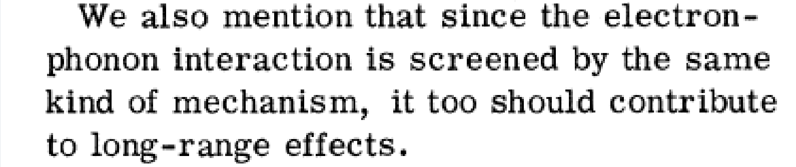
FIG. 1. Types of particle-particle interaction diagrams up to the second order which contribute to the irreducible scattering vertex.

Superconductivity mediated by electron-hole pairs



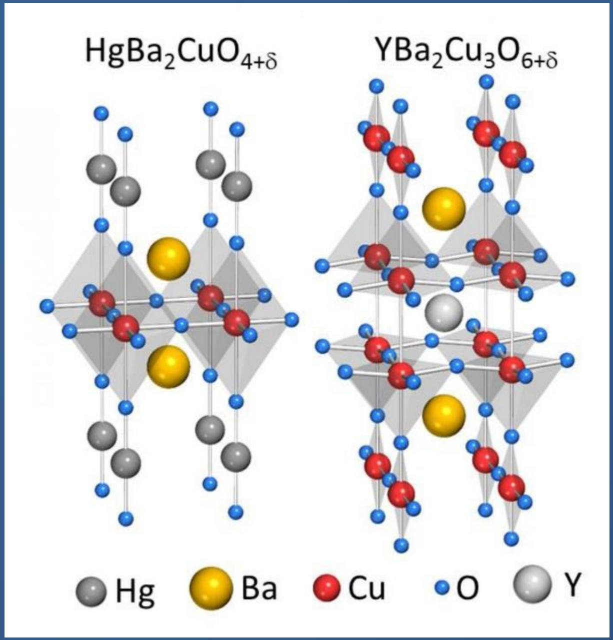
For electrons in metals we can make estimates using a screening Coulomb potential. It is easily seen that in the high-density limit $u(0)$ dominates and becomes $u(0)=\pi^2/mk_{\mathrm{F}}$; therefore,

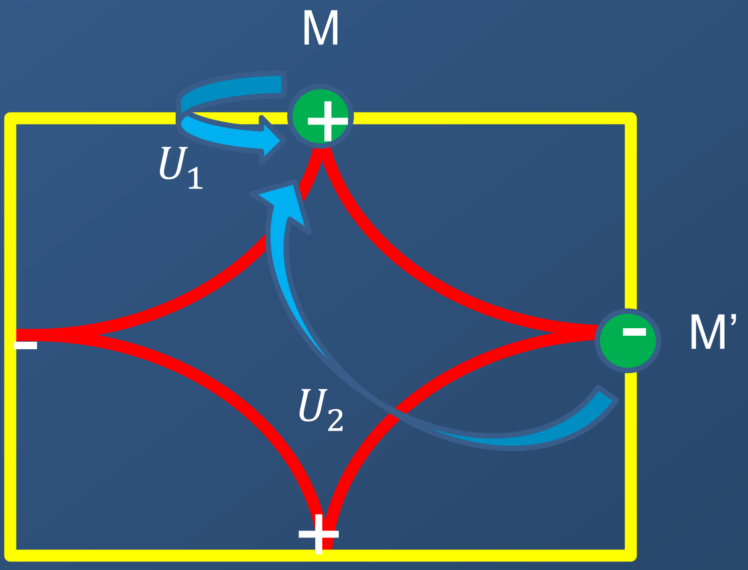
$$(kT_c/\epsilon_0) \sim \exp[-(2l)^4].$$



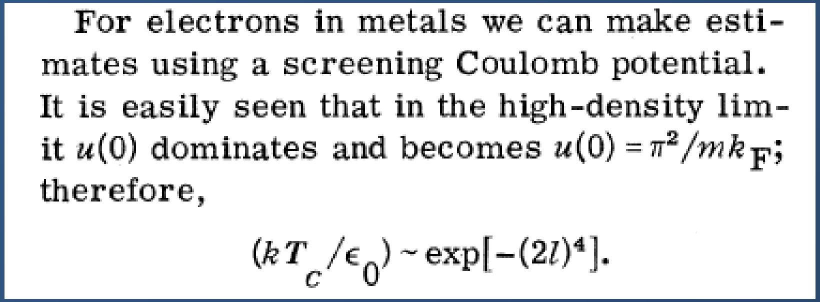
We also mention that since the electron-phonon interaction is screened by the same kind of mechanism, it too should contribute to long-range effects.

d-wave superconductivity in cuprates



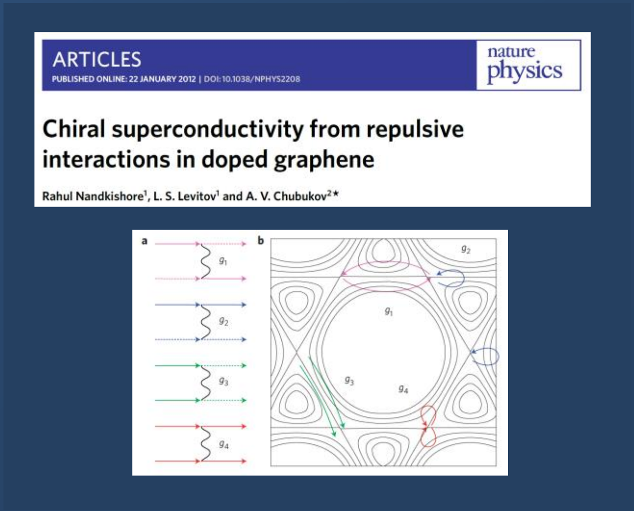


$$U_1, U_2 > 0, U_2 > U_1$$



For electrons in metals we can make estimates using a screening Coulomb potential. It is easily seen that in the high-density limit $u(0)$ dominates and becomes $u(0) = \pi^2/mk_F$; therefore,

$$(kT_c/\epsilon_0) \sim \exp[-(2l)^4].$$



ARTICLES

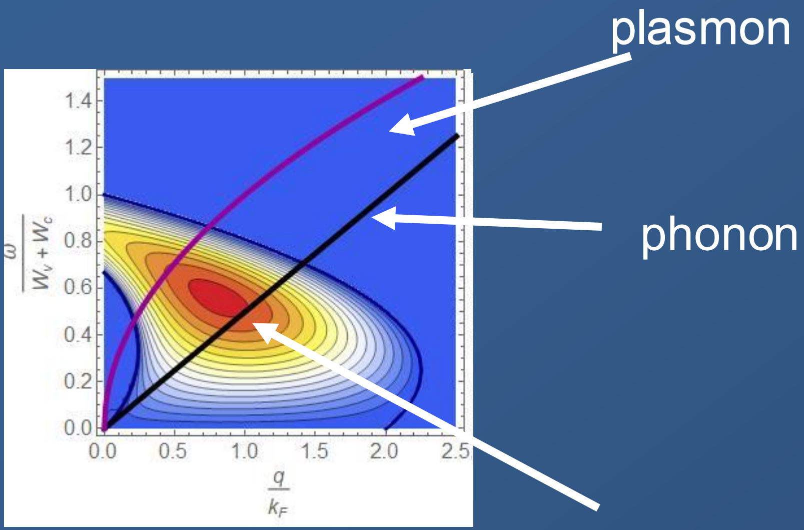
PUBLISHED ONLINE: 22 JANUARY 2012 | DOI: 10.1038/NPHYS2208

nature physics

Chiral superconductivity from repulsive interactions in doped graphene

Rahul Nandkishore[1], L. S. Levitov[1] and A. V. Chubukov[2]*

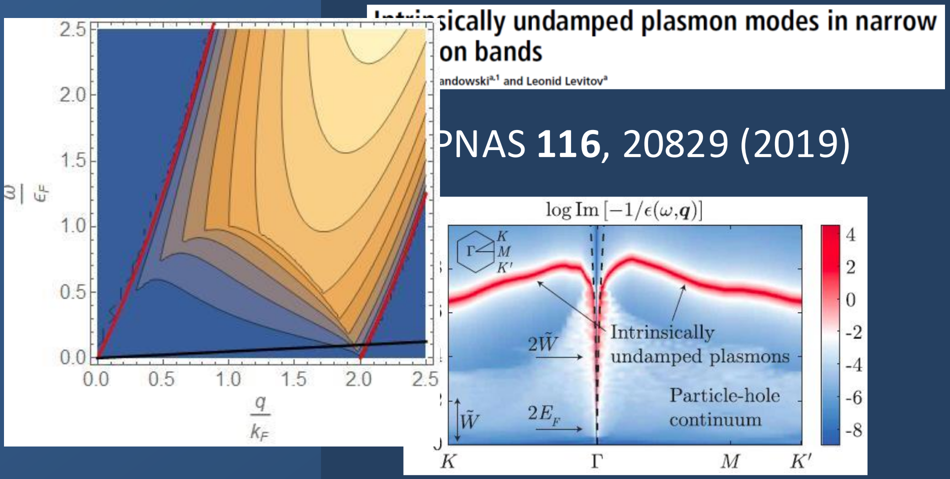
Low energy excitations and charge excitations: Electron-hole pairs, plasmons, and phonons



plasmon

phonon

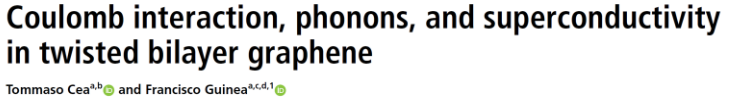
electron-hole pairs



sically undamped plasmon modes in narrow on bands

andowski[a,1] and Leonid Levitov[a]

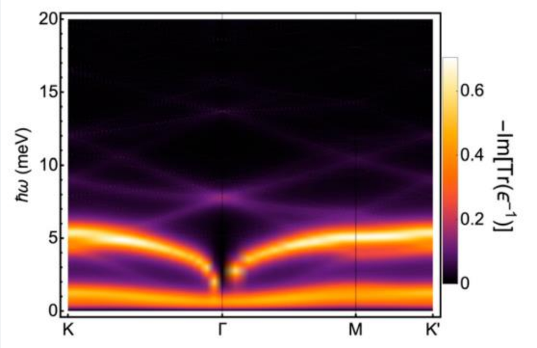
PNAS **116**, 20829 (2019)

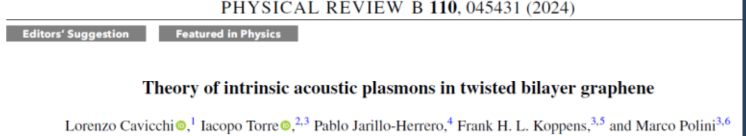


Coulomb interaction, phonons, and superconductivity in twisted bilayer graphene

Tommaso Cea[a,b] and Francisco Guinea[a,c,d,1]

PNAS **118**, e2107874118 (2021)



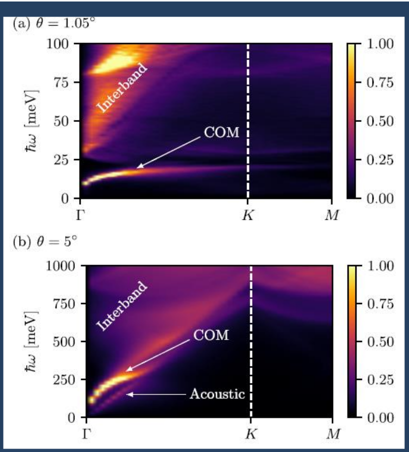


PHYSICAL REVIEW B **110**, 045431 (2024)

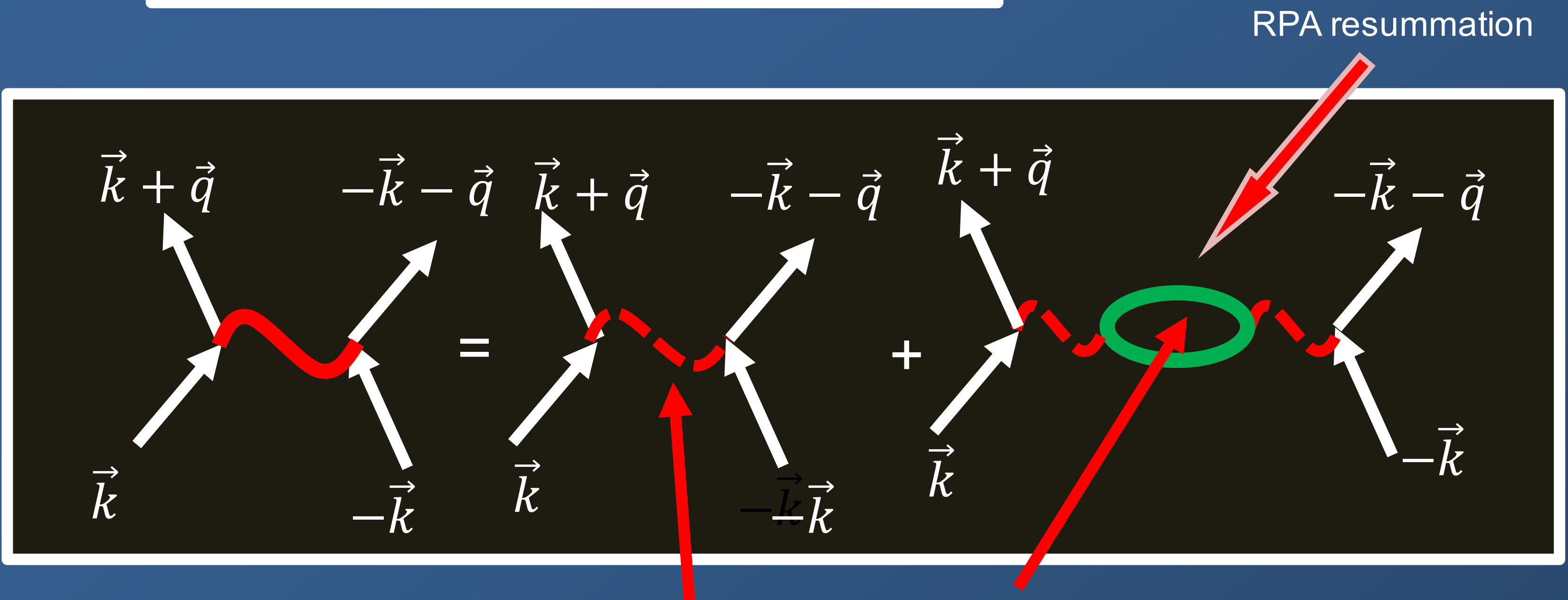
Editors' Suggestion Featured in Physics

Theory of intrinsic acoustic plasmons in twisted bilayer graphene

Lorenzo Cavicchi,[1] Iacopo Torre,[2,3] Pablo Jarillo-Herrero,[4] Frank H. L. Koppens,[3,5] and Marco Polini[3,6]



Repulsive interactions and pairing



RPA resummation

- Longitudinal phonons modify the susceptibility.
- The bare interaction is the repulsive Coulomb coupling

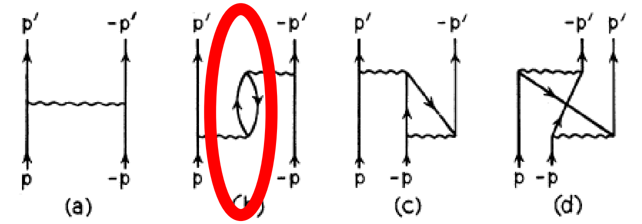
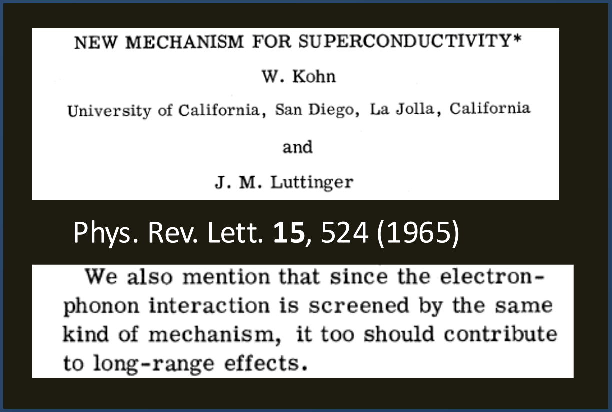


FIG. 1. Types of particle-particle interaction diagrams up to the second order which contribute to the irreducible scattering vertex.



NEW MECHANISM FOR SUPERCONDUCTIVITY*

W. Kohn

University of California, San Diego, La Jolla, California

and

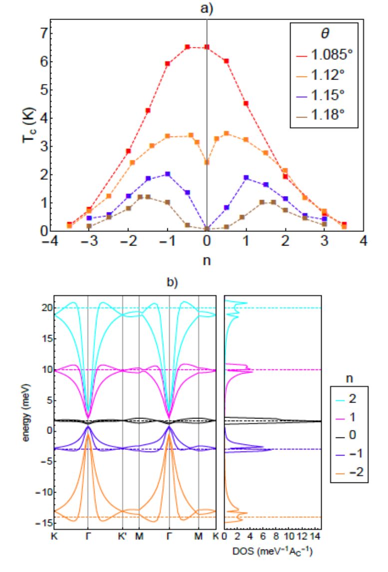
J. M. Luttinger

Phys. Rev. Lett. **15**, 524 (1965)

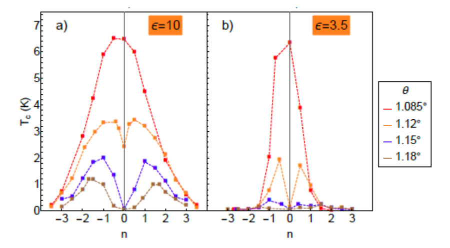
We also mention that since the electron-phonon interaction is screened by the same kind of mechanism, it too should contribute to long-range effects.

Results: critical temperature

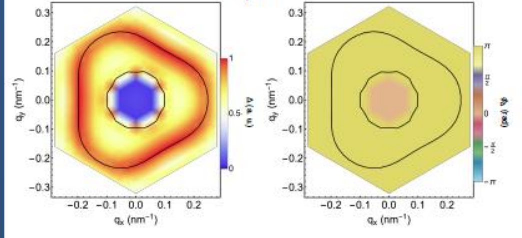
Critical temperatures



Bands, densities of states, magic angle



Dependence on dielectric constant



- Order parameter. Finite gap in each valley
- Consistent with spin singlet/valley triplet or with spin triplet/valley singlet superconductivity.

- The critical temperature is significantly enhanced by the electron-phonon interaction.
- Superconductivity correlates with the density of states at the Fermi level.
- The effect of external screening depends on the strength of the electron-phonon interaction.

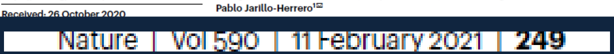
Superconductivity in twisted trilayers

Article

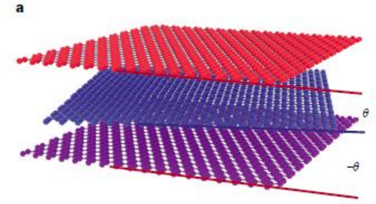
Tunable strongly coupled superconductivity in magic-angle twisted trilayer graphene

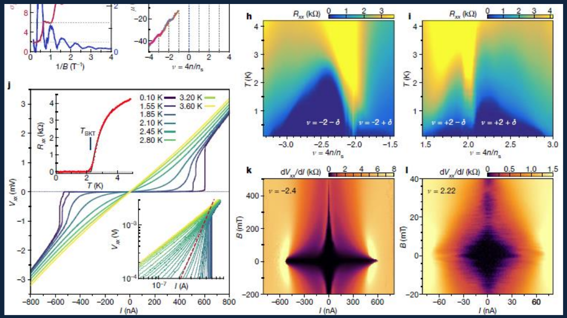
https://doi.org/10.1038/s41586-021-03192-0
Received: 26 October 2020

Jeong Min Park[1,4], Yuan Cao[1,4✉], Kenji Watanabe[2], Takashi Taniguchi[3] & Pablo Jarillo-Herrero[1✉]



Nature | Vol 590 | 11 February 2021 | 249



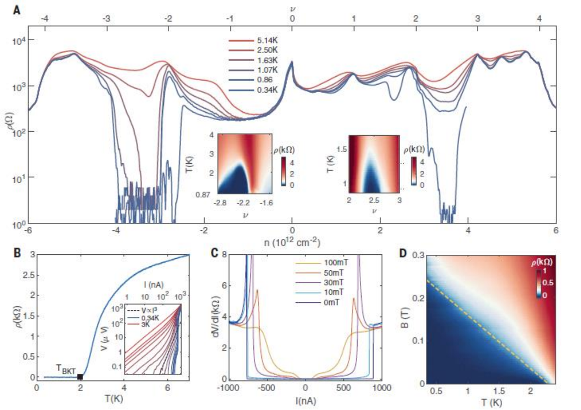


SUPERCONDUCTIVITY

Electric field–tunable 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]†

Hao *et al.*, *Science* **371**, 1133–1138 (2021)   12 March 2021



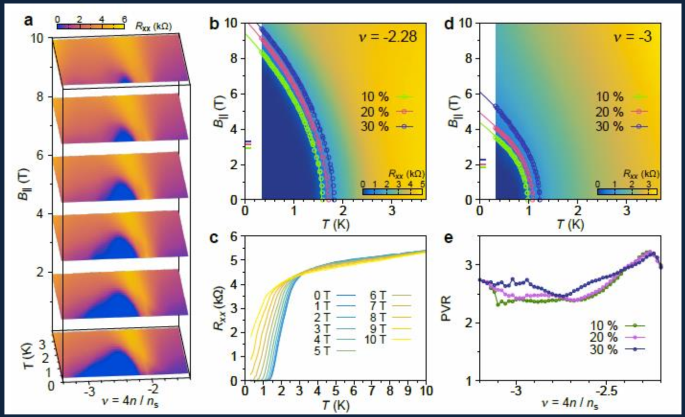
Article

Pauli-limit violation and re-entrant superconductivity in moiré graphene

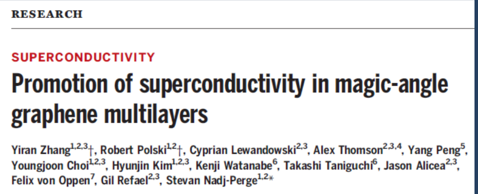
https://doi.org/10.1038/s41586-021-03685-y
Received: 4 March 2021

Yuan Cao[1,4✉], Jeong Min Park[1,4✉], Kenji Watanabe[2], Takashi Taniguchi[3] & Pablo Jarillo-Herrero[1✉]

528 | Nature | Vol 595 | 22 July 2021



Superconductivity in twisted multilayers



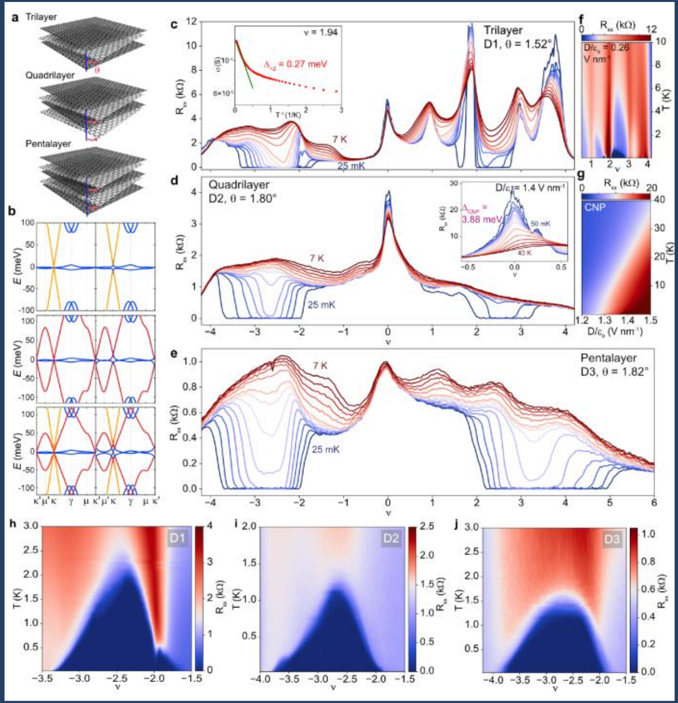
RESEARCH

SUPERCONDUCTIVITY

Promotion of superconductivity in magic-angle graphene multilayers

Yiran Zhang[1,2,3]†, Robert Polski[1,2]†, Cyprian Lewandowski[2,3], Alex Thomson[2,3,4], Yang Peng[5], Youngjoon Choi[1,2,3], Hyunjin Kim[1,2,3], Kenji Watanabe[6], Takashi Taniguchi[6], Jason Alicea[2,3], Felix von Oppen[7], Gil Refael[2,3], Stevan Nadj-Perge[1,2]*

Zhang *et al.*, *Science* **377**, 1538–1543 (2022) 30 September 2022



nature materials

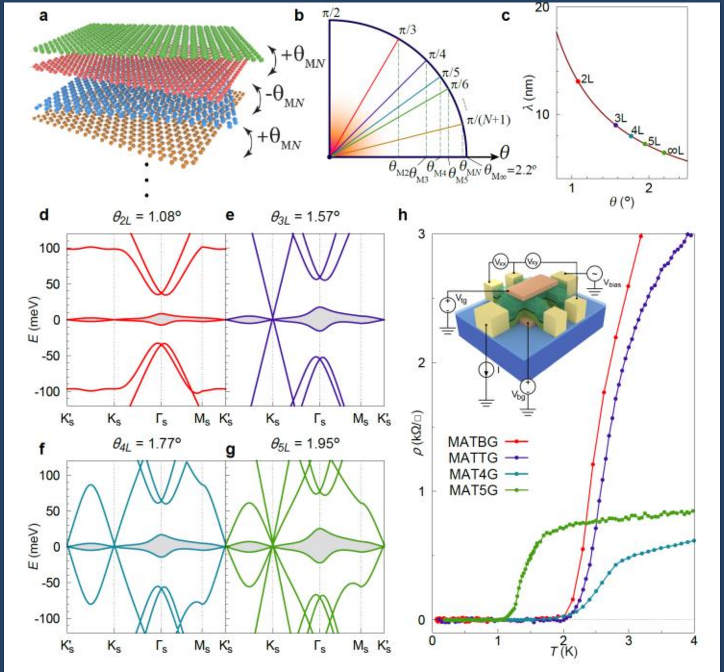
ARTICLES

https://doi.org/10.1038/s41563-022-01287-1

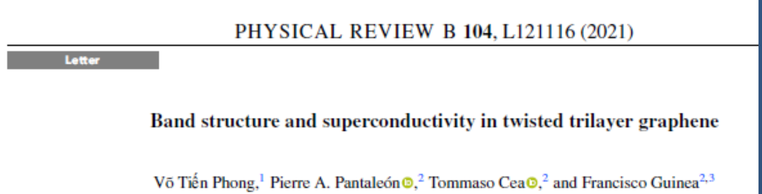
Check for updates

Robust superconductivity in magic-angle multilayer graphene family

Jeong Min Park[1,3]✉, Yuan Cao[1,3], Li-Qiao Xia[1], Shuwen Sun[1], Kenji Watanabe[2], Takashi Taniguchi[2] and Pablo Jarillo-Herrero[1]✉



Superconductivity in twisted trilayers: theory

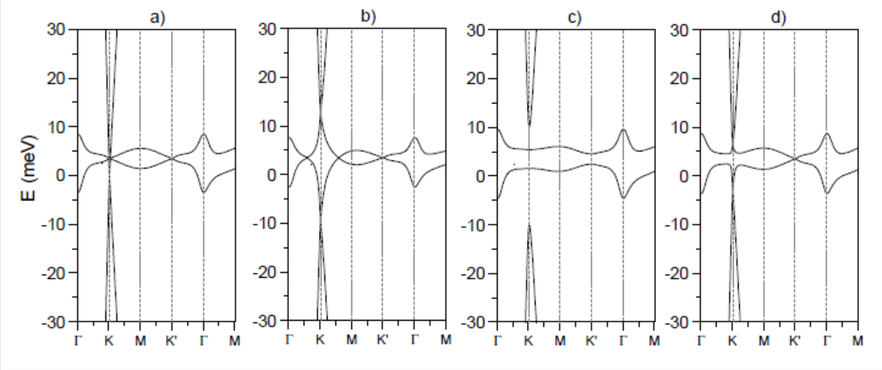


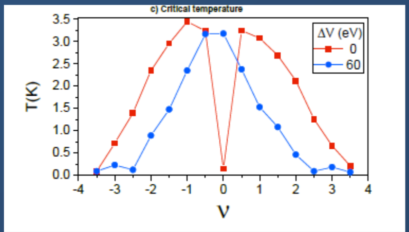
PHYSICAL REVIEW B **104**, L121116 (2021)

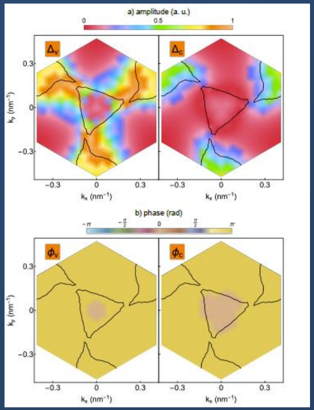
Letter

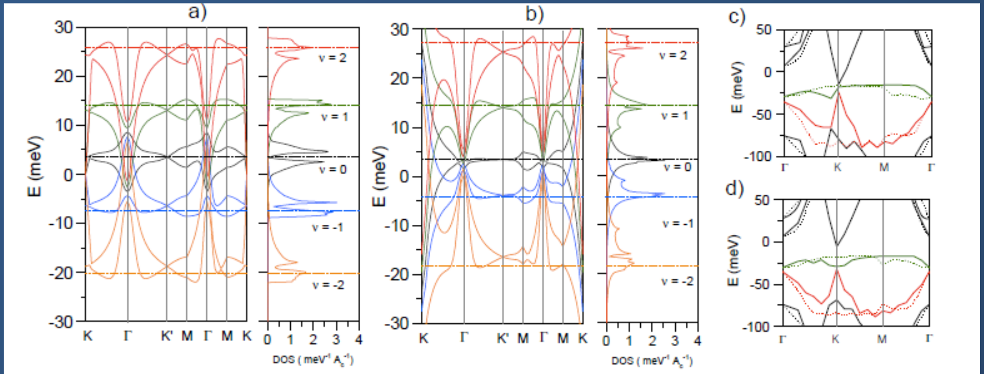
Band structure and superconductivity in twisted trilayer graphene

Võ Tiến Phong,[1] Pierre A. Pantaleón,[2] Tommaso Cea,[2] and Francisco Guinea[2,3]

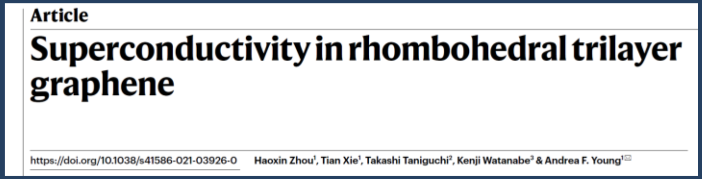








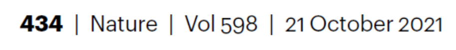
Superconductivity in graphene without a moiré superlattice



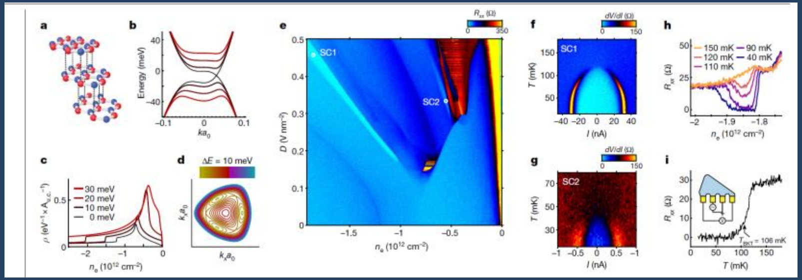
Article

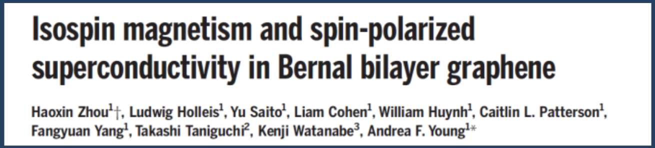
Superconductivity in rhombohedral trilayer graphene

https://doi.org/10.1038/s41586-021-03926-0 Haoxin Zhou[1], Tian Xie[1], Takashi Taniguchi[2], Kenji Watanabe[3] & Andrea F. Young[1]✉



434 | Nature | Vol 598 | 21 October 2021

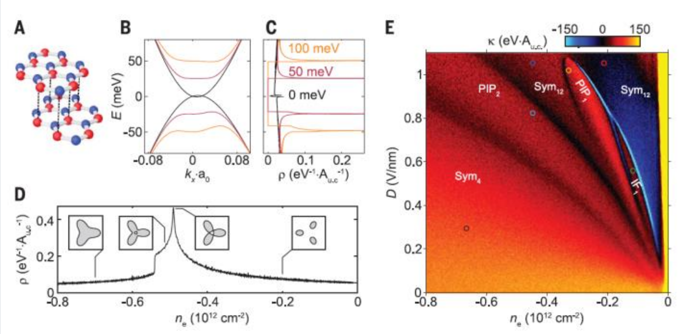


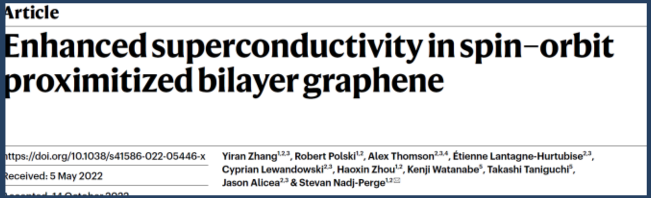


Isospin magnetism and spin-polarized superconductivity in Bernal bilayer graphene

Haoxin Zhou[1]†, Ludwig Holleis[1], Yu Saito[1], Liam Cohen[1], William Huynh[1], Caitlin L. Patterson[1], Fangyuan Yang[1], Takashi Taniguchi[2], Kenji Watanabe[3], Andrea F. Young[1]*

Zhou *et al.*, *Science* **375**, 774–778 (2022) 18 February 2022





Article

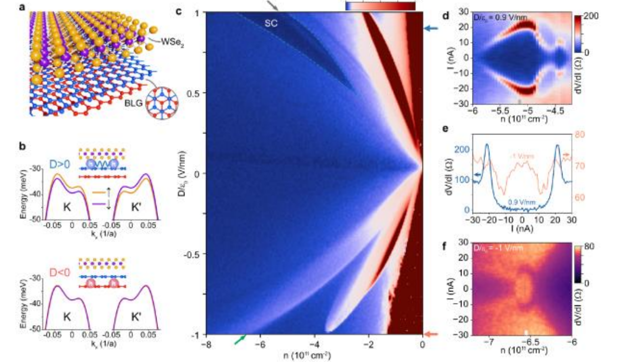
Enhanced superconductivity in spin–orbit proximitized bilayer graphene

ttps://doi.org/10.1038/s41586-022-05446-x

eceived: 5 May 2022

Yiran Zhang[1,2,3], Robert Polski[1,2], Alex Thomson[2,3,4], Étienne Lantagne-Hurtubise[2,3], Cyprian Lewandowski[2,3], Haoxin Zhou[1,2], Kenji Watanabe[5], Takashi Taniguchi[6], Jason Alicea[2,3] & Stevan Nadj-Perge[1,2]✉

268 | Nature | Vol 613 | 12 January 2023



Superconductivity in graphene without a moiré superlattice: theory

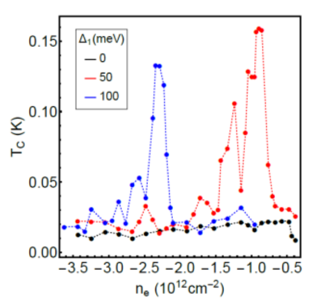
PHYSICAL REVIEW B **105**, 075432 (2022)

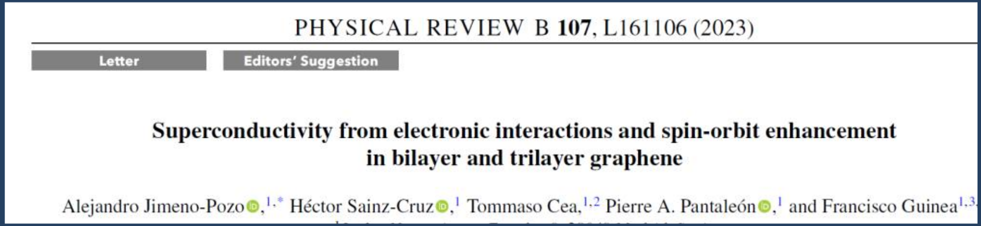
Superconductivity from repulsive interactions in rhombohedral trilayer graphene: A Kohn-Luttinger-like mechanism

Tommaso Cea and Pierre A. Pantaleón
Imdea Nanoscience, Faraday 9, 28015 Madrid, Spain

Võ Tiến Phong
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia PA 19104, USA

Francisco Guinea





PHYSICAL REVIEW B **107**, L161106 (2023)

Letter **Editors' Suggestion**

Superconductivity from electronic interactions and spin-orbit enhancement in bilayer and trilayer graphene

Alejandro Jimeno-Pozo[1,*] Héctor Sainz-Cruz,[1] Tommaso Cea,[1,2] Pierre A. Pantaleón,[1] and Francisco Guinea[1,3]

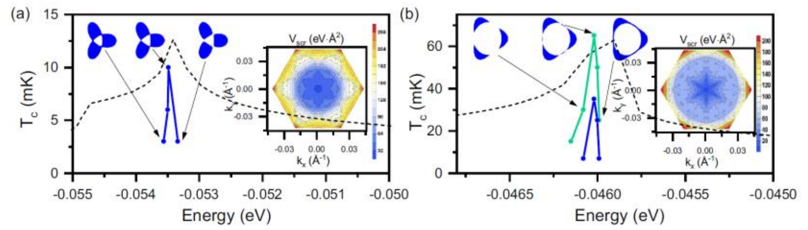


FIG. 2. Superconducting critical temperature due to only the screened long-range Coulomb interaction (blue), and including also the short-range interaction (green), and DOS (a.u., dashed black) versus Fermi energy in (a) BBG with hole doping, near the vHs ($n_e \approx -0.87 \times 10^{12}$ cm^{-2}), we observe a $T_c \approx 10$ mK, and (b) RTG with hole doping, near the vHs ($n_e \approx -0.6 \times 10^{12}$ cm^{-2}), $T_c \approx 33$ mK and it raises to $T_c \approx 65$ mK after including the short-range interaction. The top insets show the shape of the Fermi surfaces, which experience a change in topology at the vHs due to Lifshitz transitions. Right insets: screened Coulomb potential to k_Λ at the energy for which T_c is maximum.

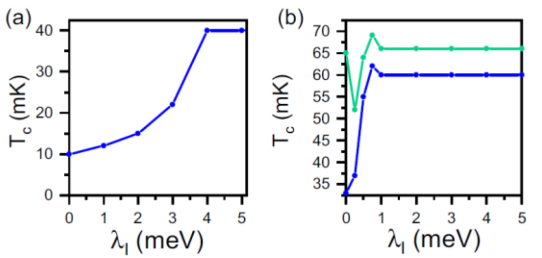
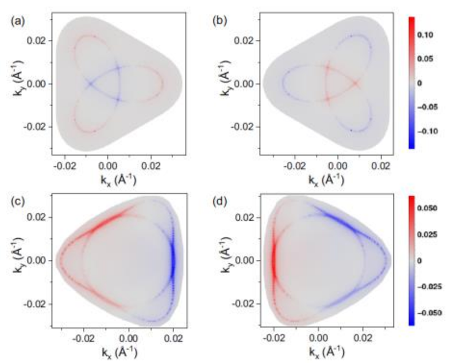
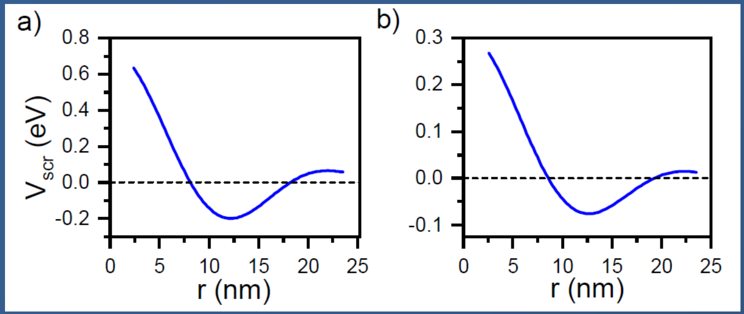
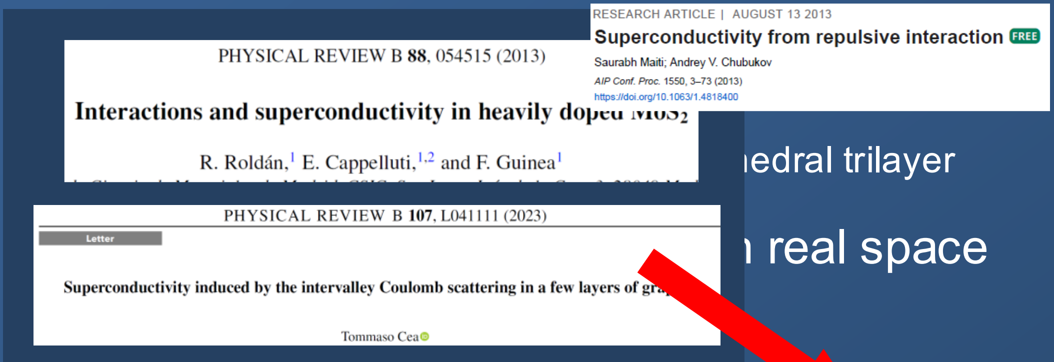


FIG. 3. Ising spin-orbit coupling enhancement of critical temperature in hole-doped (a) BBG, for which T_c augments by a factor of 4 and saturates at $\lambda_I = 4$ meV. (b) RTG, for which T_c due to long-range interactions (blue) augments by a factor of 2 and saturates at $\lambda_I = 1$ meV. In contrast, Ising SOC is detrimental to short-range interactions, so T_c does not increase much when they are included (green).



Superconductivity graphene without a moiré superlattice:effective attraction




RESEARCH ARTICLE | AUGUST 13 2013

Superconductivity from repulsive interaction FREE

Saurabh Maiti; Andrey V. Chubukov

AIP Conf. Proc. 1550, 3–73 (2013)

https://doi.org/10.1063/1.4818400

PHYSICAL REVIEW B **88**, 054515 (2013)

Interactions and superconductivity in heavily doped MoS$_2$

R. Roldán,[1] E. Cappelluti,[1,2] and F. Guinea[1]

PHYSICAL REVIEW B **107**, L041111 (2023)

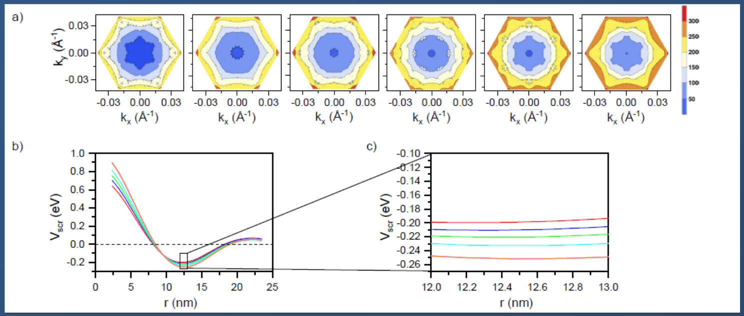
Letter

Superconductivity induced by the intervalley Coulomb scattering in a few layers of gra

Tommaso Cea

ıedral trilayer

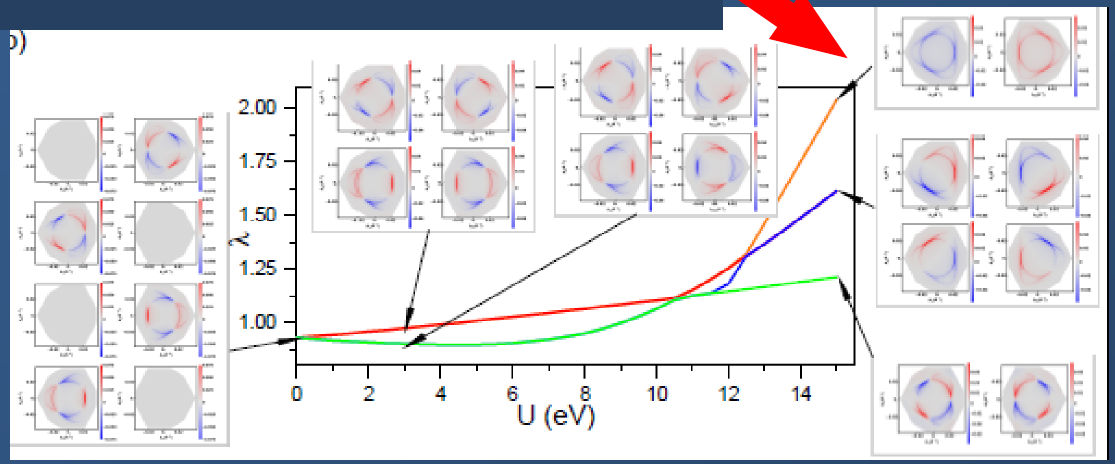
ı real space



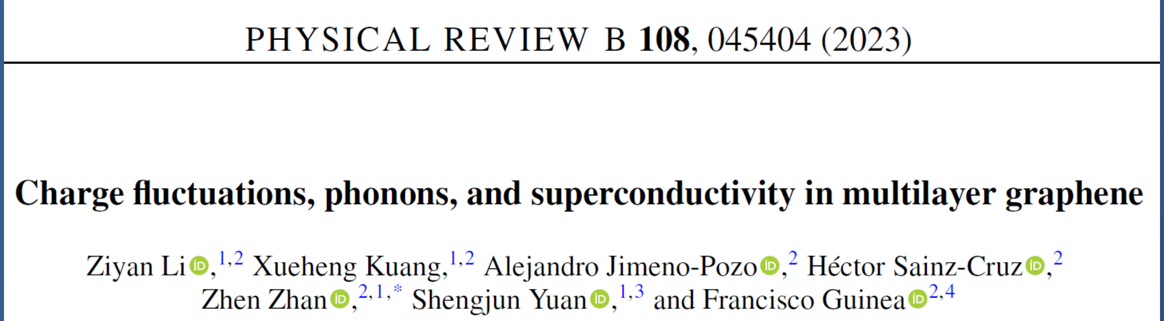
Effect of spin-orbit coupling

$$V_{scr}(\vec{q}) = \frac{V_C(\vec{q})}{1 - V_C(\vec{q})\chi(\vec{q})} \approx \frac{1}{|\chi(\vec{q})|}$$

SOC, due to flavor polarization, lowers screening, and increases both repulsion and attraction



Order parameter and intervalley interactions


PHYSICAL REVIEW B **108**, 045404 (2023)

Charge fluctuations, phonons, and superconductivity in multilayer graphene

Ziyan Li,[1,2] Xueheng Kuang,[1,2] Alejandro Jimeno-Pozo,[2] Héctor Sainz-Cruz,[2]
Zhen Zhan,[2,1,*] Shengjun Yuan,[1,3] and Francisco Guinea[2,4]

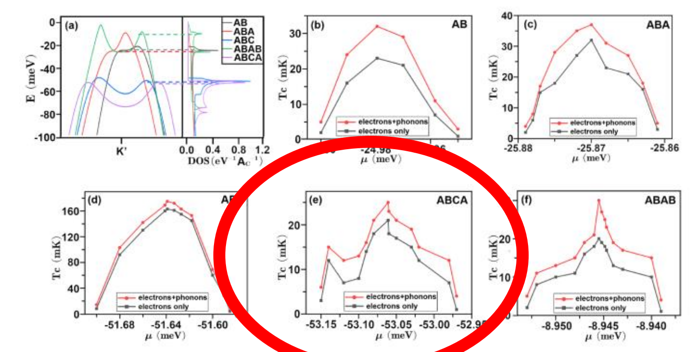


FIG. 4. (a) Band structures and DOS near the CNP in [illegible] superconducting critical temperatures versus Fermi energy near the VHS in five different multilayer graphene stacks, due to electron interactions only or taking into account also the effects of electron-acoustic phonon coupling.

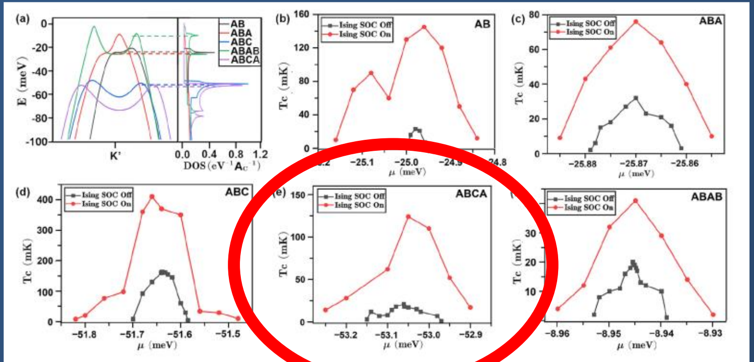


FIG. 5. (a) Bands and DOS near VHS in multilayer graphene, with displacement field $\Delta_1 = 50\,\text{meV}$. (b)–(f) Critical temperature of multilayer graphene with and without Ising SOC, with Fermi energy [illegible]

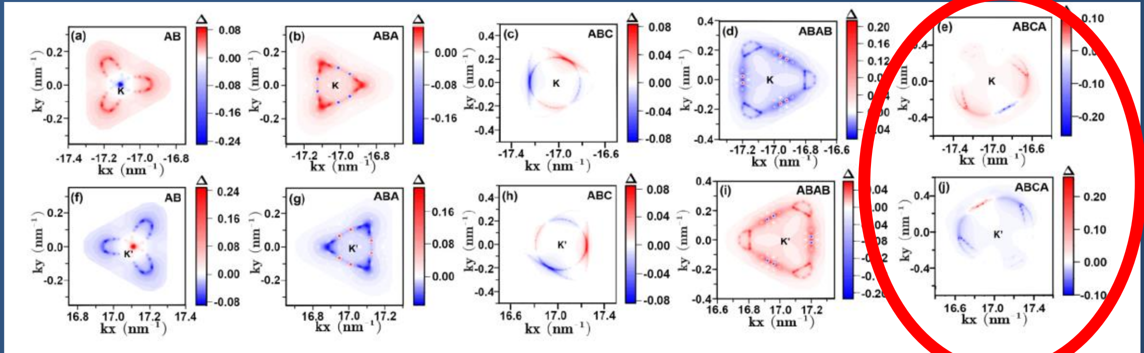


FIG. 6. (a)–(e) Superconducting order parameters near K valley in the first BZ of multilayer graphene with interlayer po[illegible] 50 meV and maximum critical temperatures T_c. (f)–(j) Order parameters near K' valley in the first BZ.

Quarter metal phase

- Lack of Cooper divergence, 1st order transition?
- Does the symmetries change in the superconducting phase?
- Role of trigonal distortion.

Tuning repulsive interactions and superconductivity

nature physics

Article

https://doi.org/10.1038/s41567-026-03243-1

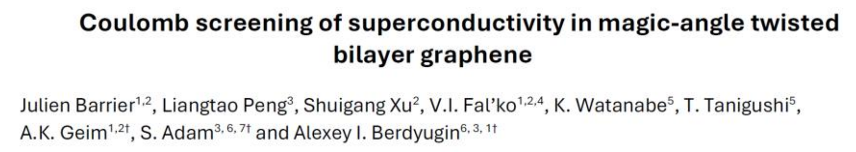
Double-edged role of interactions in superconducting twisted bilayer graphene

Received: 22 December 2024

Accepted: 5 March 2026

Published online: 07 April 2026

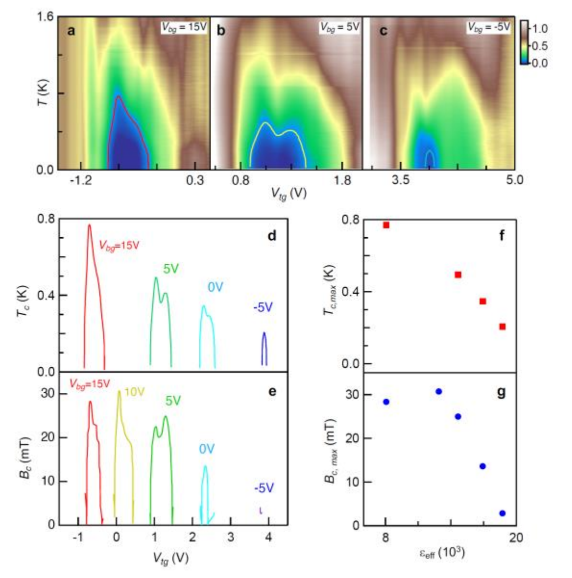
Xueshi Gao[1], Alejandro Jimeno-Pozo[2], Pierre A. Pantaleon[2], Aatmaj Rajesh[1], Emilio Codecido[1,3], Daria L. Sharifi[1], Zheneng Zhang[1], Youwei Liu[1], Kenji Watanabe[4], Takashi Taniguchi[5], Marc W. Bockrath[1], Francisco Guinea[2,6] & Chun Ning Lau[1]

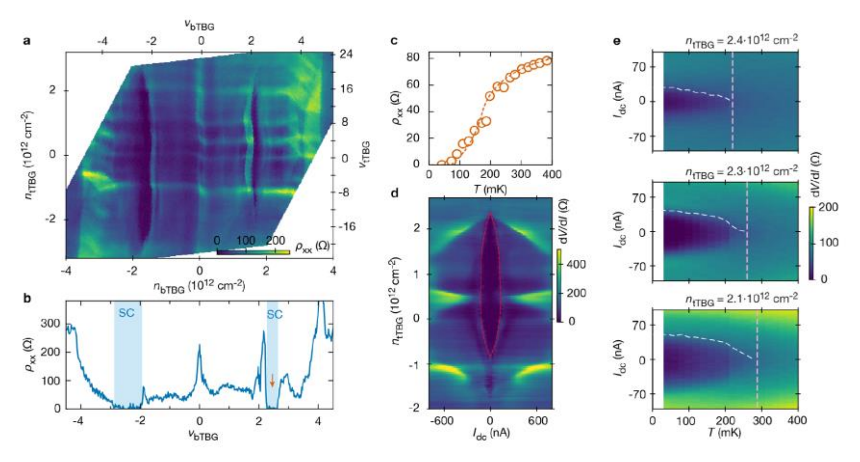


Coulomb screening of superconductivity in magic-angle twisted bilayer graphene

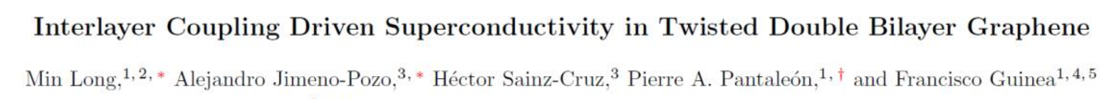
Julien Barrier[1,2], Liangtao Peng[3], Shuigang Xu[2], V.I. Fal'ko[1,2,4], K. Watanabe[5], T. Tanigushi[5], A.K. Geim[1,2†], S. Adam[3,6,7†] and Alexey I. Berdyugin[6,3,1†]

arXiv:2412.01577



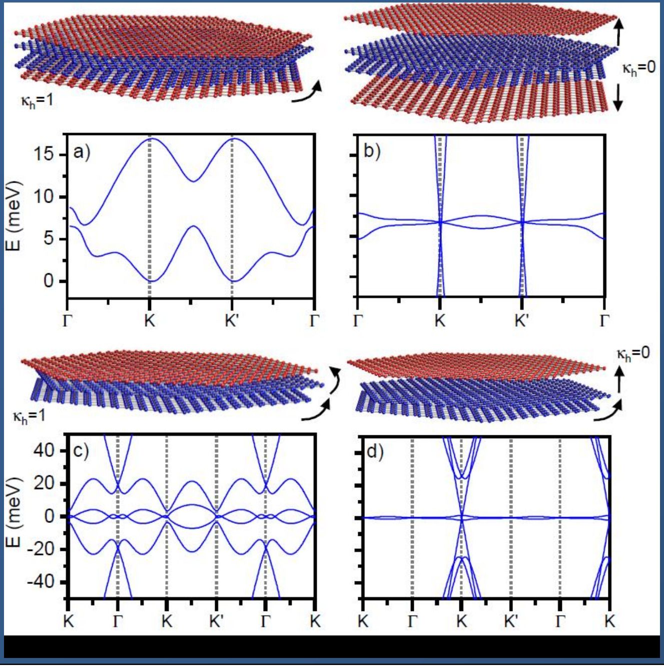


Twisted double bilayer and helical trilayer graphene



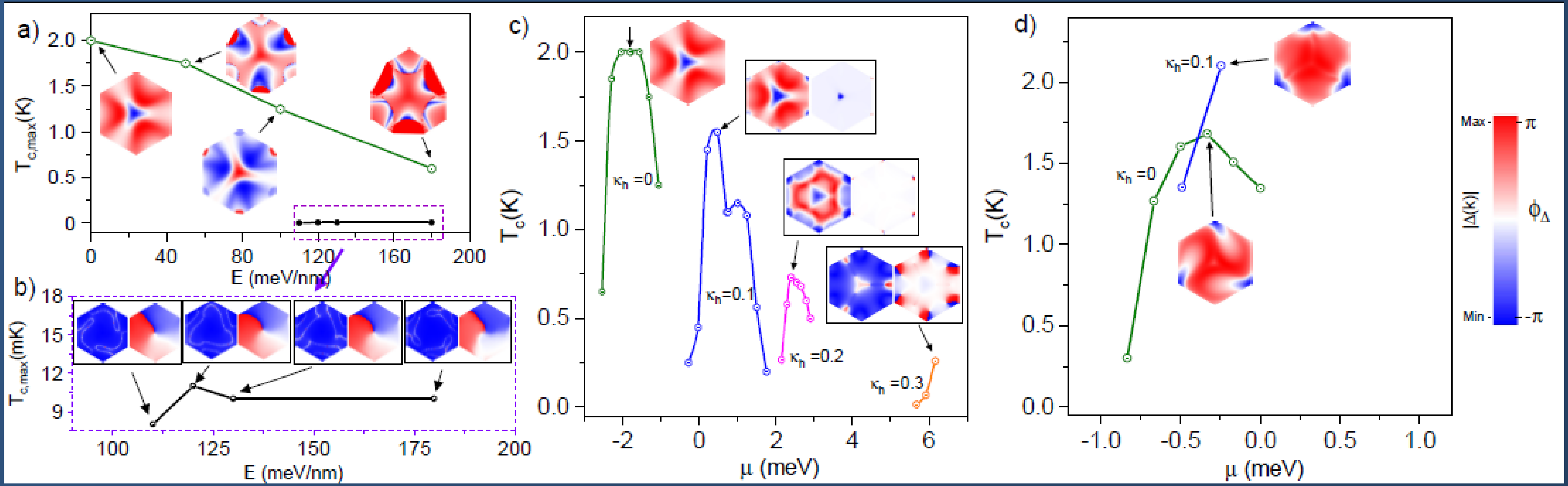
Interlayer Coupling Driven Superconductivity in Twisted Double Bilayer Graphene

Min Long,[1,2,*] Alejandro Jimeno-Pozo,[3,*] Héctor Sainz-Cruz,[3] Pierre A. Pantaleón,[1,†] and Francisco Guinea[1,4,5]



arXiv:2401.09667, PNAS **121** (32) e2405259121 (2024)

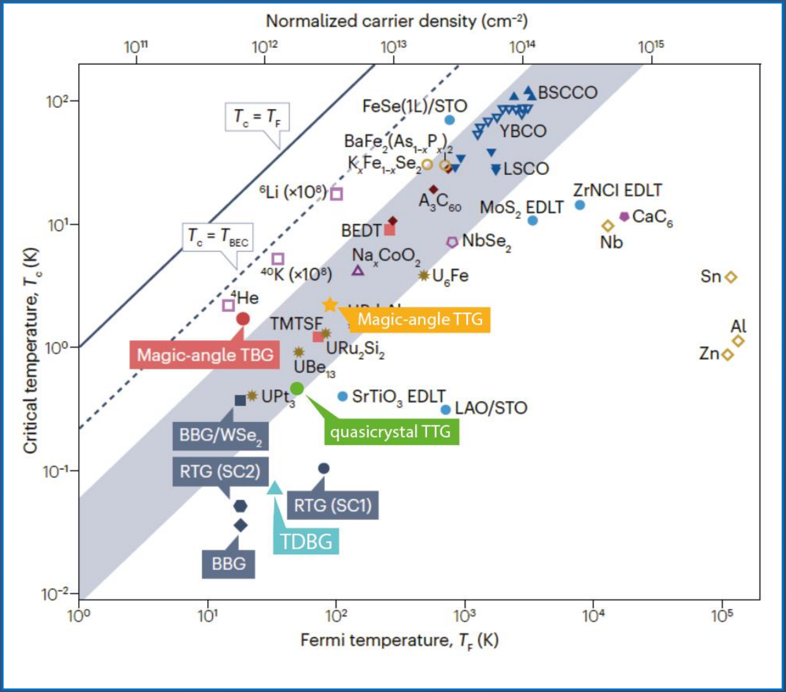
	ee+ph+G	ee+G	ee+ph	ee
TBG	~2K	~10mK	~10mK	< 1mK
TDBG	~10mK	< 1mK	< 1mK	≪ 1mK
hTTG	≪ 1mK	≪ 1mK	??	??

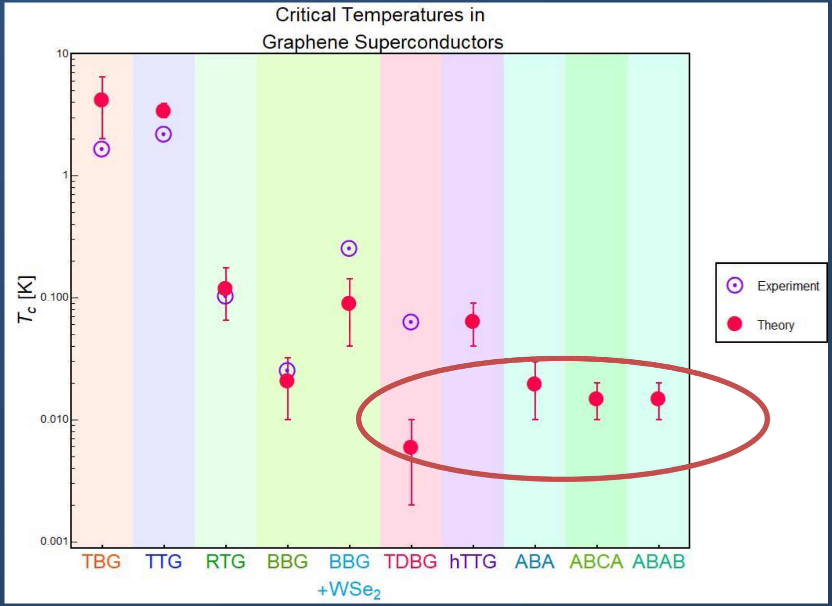


Long range electron-electron interactions and superconductivity in graphene stacks

- Strongest interaction in twisted bilayer graphene
- Few adjustable parameters, $\epsilon \approx 6 - 10$
- Describes well general trends
- Broken symmetry phases not included

Electronic bands								Coulomb potential		Deformation potential and elastic constants		
$a(\text{Å})$	$v_F(eV\text{Å})$	$\gamma_1(eV)$	$\gamma_3(eV)$	$\gamma_4(eV)$	$\Delta'(eV)$	$g_{AA}(eV)$	$g_{AB}(eV)$	$d_G(nm)$	ϵ	$D(eV)$	$\lambda(eV\text{Å}^{-2})$	$\mu(eV\text{Å}^{-2})$
2.46	5.253	0.4	0.32	0.044	0.05	0.797	0.0975	40	10	20	3.25	9.44

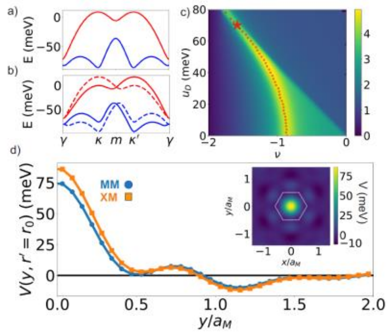




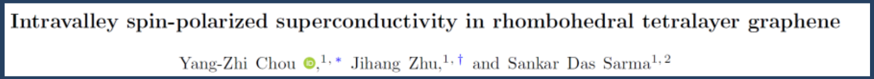
Other recent RPA+KL calculations of superconductivity

Topological superconductivity from repulsive interactions in twisted WSe$_2$

Daniele Guerci,[1,*] Daniel Kaplan,[2,†] Julian Ingham,[3,1] J. H. Pixley,[2,1] and Andrew Millis[3,1]

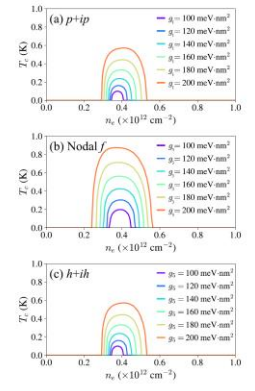


arXiv:2408.16075

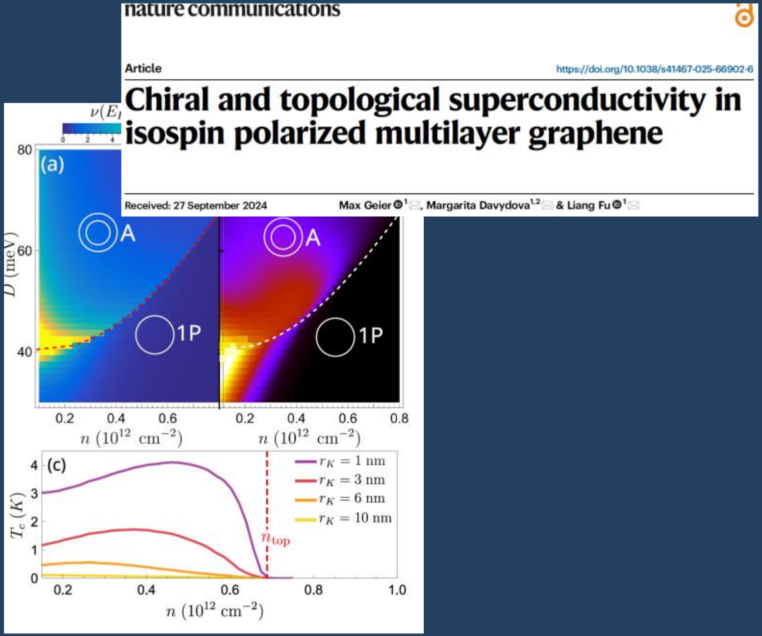


Intravalley spin-polarized superconductivity in rhombohedral tetralayer graphene

Yang-Zhi Chou,[1,*] Jihang Zhu,[1,†] and Sankar Das Sarma[1,2]



Phys. Rev. B **111**,174523 (2025)



nature communications

Article

https://doi.org/10.1038/s41467-025-66902-6

Chiral and topological superconductivity in isospin polarized multilayer graphene

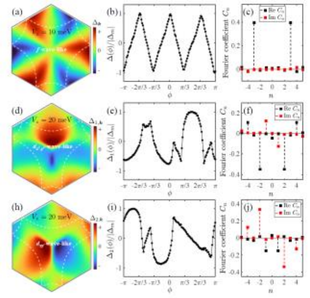
Received: 27 September 2024

Max Geier[1], Margarita Davydova[1,2] & Liang Fu[1]

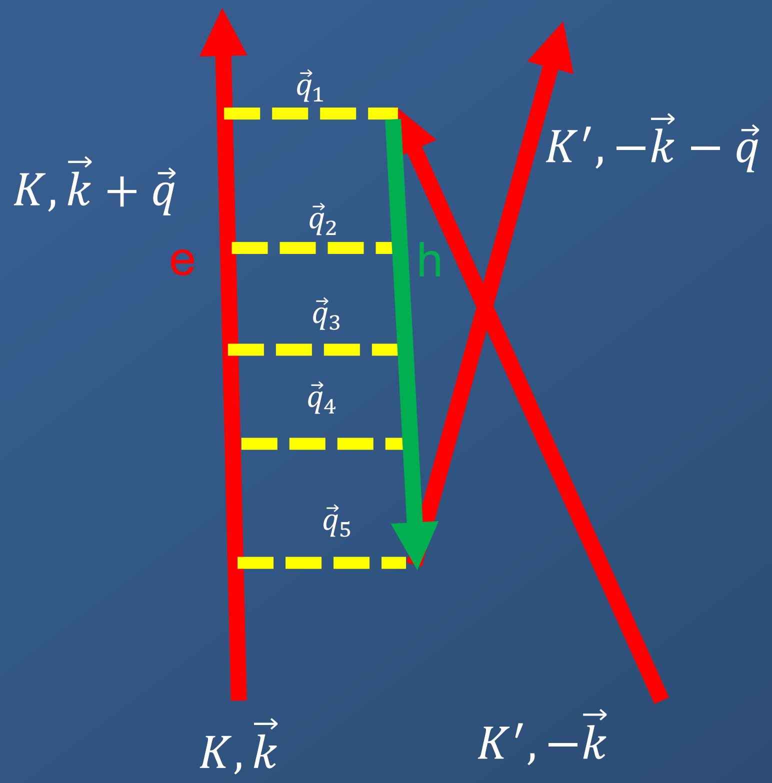
PHYSICAL REVIEW LETTERS **135,** 246002 (2025)

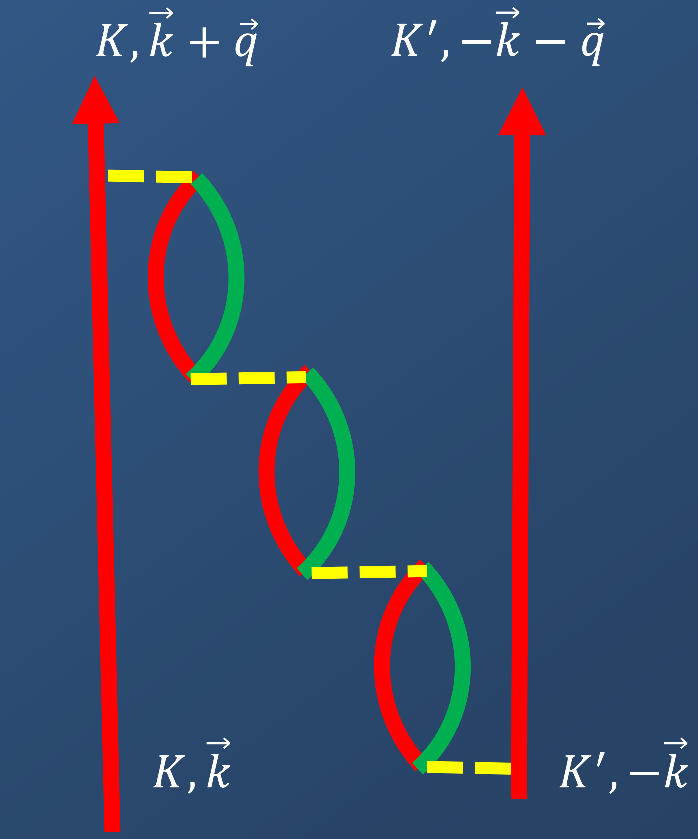
Topological Chiral Superconductivity Mediated by Intervalley Antiferromagnetic Fluctuations in Twisted Bilayer WSe$_2$

Wei Qin,[1,*,†] Wen-Xuan Qiu,[2,*] and Fengcheng Wu[2,‡]



Soft spin and valley modes, broken symmetries





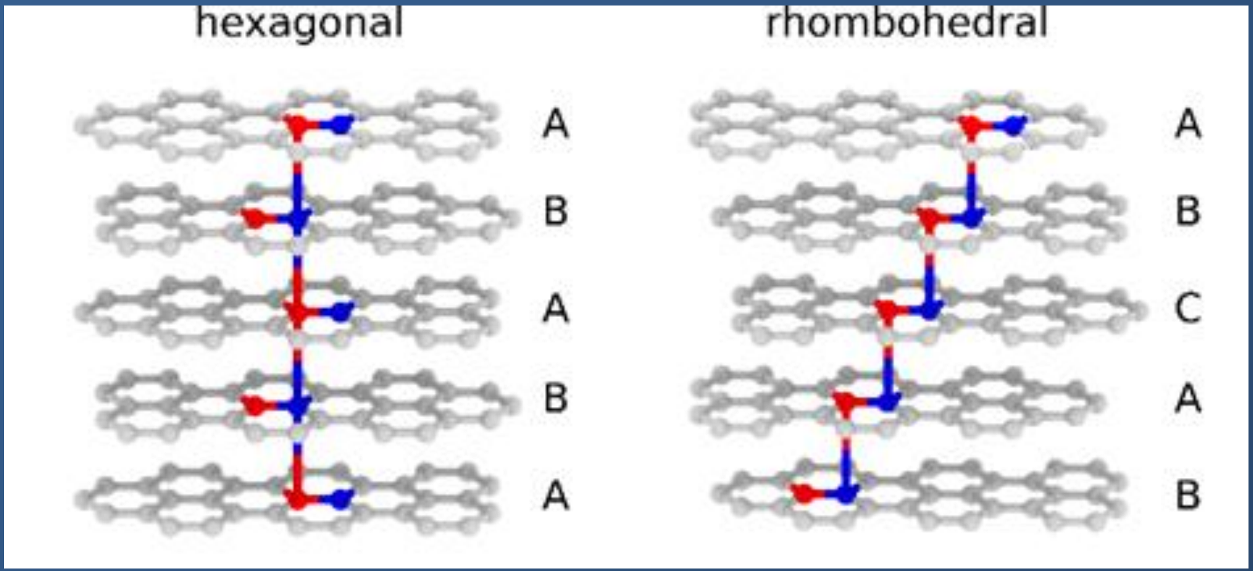
$$V_{\vec G,\vec{G'}}(\vec q,\omega)= V^0_{\vec G,\vec{G'}}(\vec q,\omega)\left(1-\Pi_{\vec G,\vec{G'}}(\vec q,\omega)\right)^{-1}$$

Spin, valley, …, waves

$$V_{\vec G,\vec{G'}}(\vec q,\omega)= V^0_{\vec G,\vec{G'}}(\vec q,\omega)\left(1+\Pi_{\vec G,\vec{G'}}(\vec q,\omega)\right)^{-1}$$

Charge fluctuations

Three dimensional rhombohedral graphite

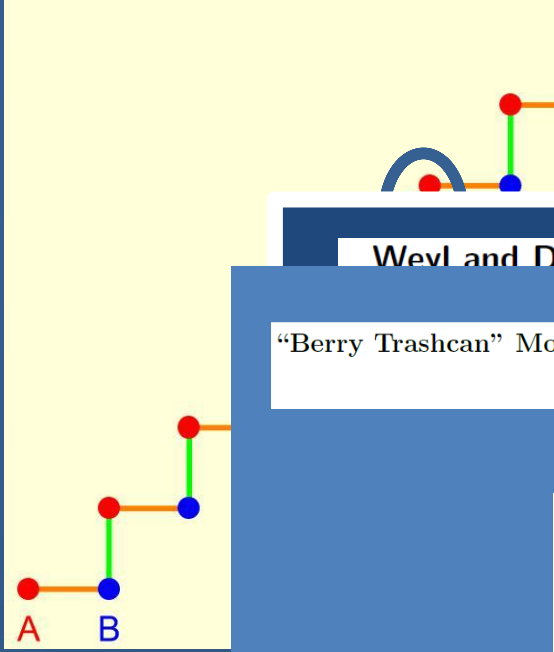


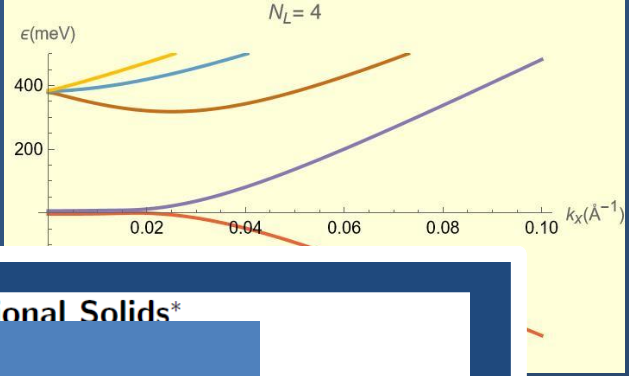
Bernal graphite ABABAB

Rhombohedral graphite ABABAB

About 10% of natural graphite shows rhombohedral stacking (M. Dresselhaus, private communication)

Flat bands in thick rhombohedral multilayers





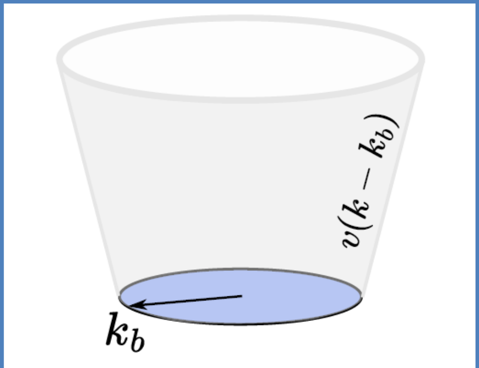
Weyl and Dirac Semimetals in Three Dimensional Solids*

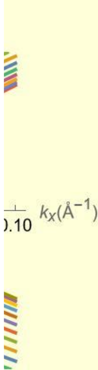
University, Baltimore,

“Berry Trashcan” Model of Interacting Electrons in Rhombohedral Graphene

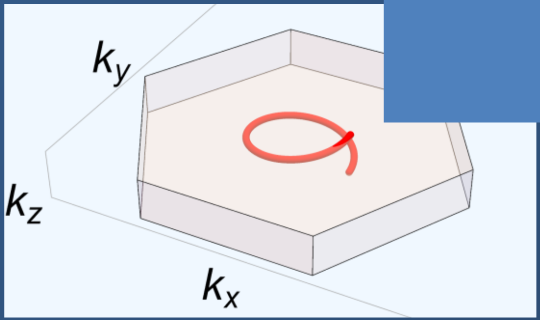
B. Andrei Bernevig[1,2,3] and Yves H. Kwan[4]

arXiv:2503.09692



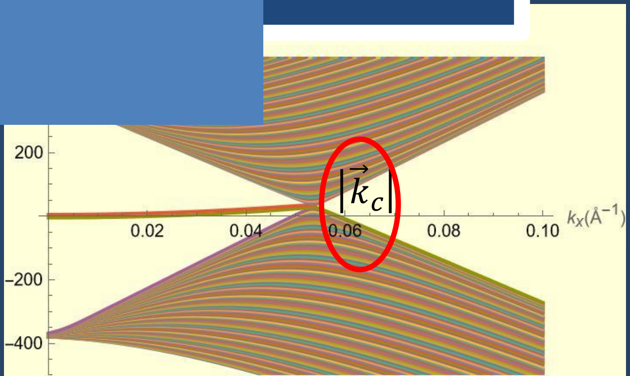


Su-Sc



$$v_F$$

$$\rho_c = \frac{\left|\vec{k}_c\right|^2}{4\pi} \approx 10^{13}\text{cm}^{-2}$$



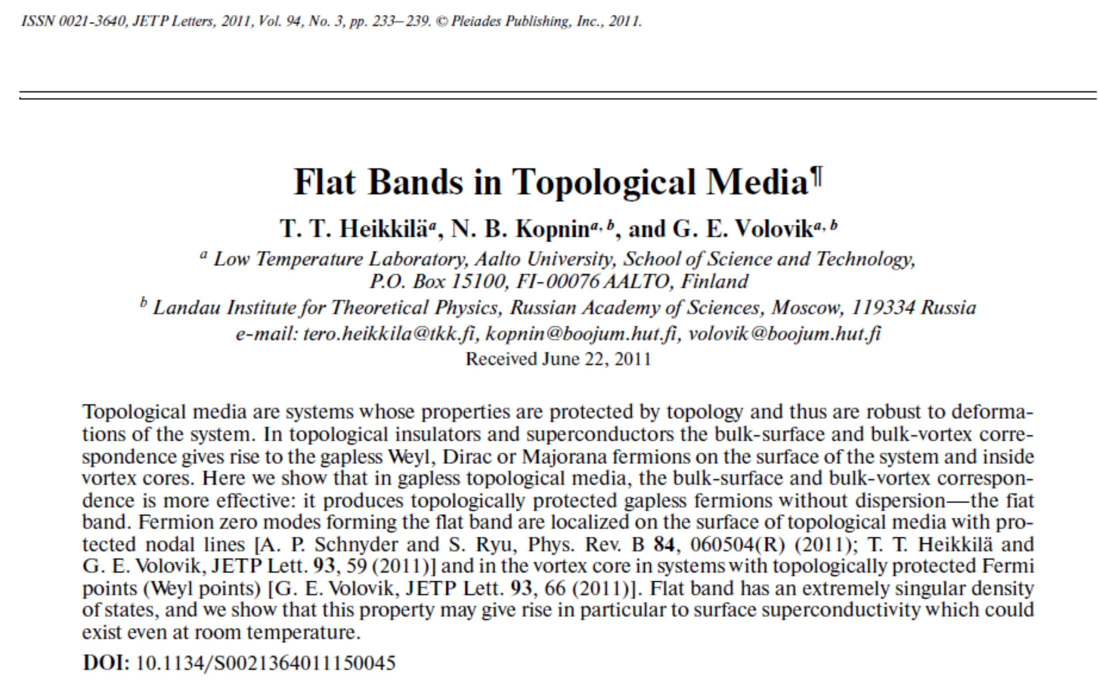
Surface elec

- Metallic bulk:

Finite density of state
the gate is screened w
$l_{TF} \sim \left(e^2 N(E_F)\right)^{-1}$.

- Semiconducting bu

The potential induced
(valence) band down
region and screen the



ISSN 0021-3640, JETP Letters, 2011, Vol. 94, No. 3, pp. 233–239. © Pleiades Publishing, Inc., 2011.

Flat Bands in Topological Media¶

T. T. Heikkilä[a], N. B. Kopnin[a, b], and G. E. Volovik[a, b]

[a] *Low Temperature Laboratory, Aalto University, School of Science and Technology, P.O. Box 15100, FI-00076 AALTO, Finland*

[b] *Landau Institute for Theoretical Physics, Russian Academy of Sciences, Moscow, 119334 Russia*

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Received June 22, 2011

Topological media are systems whose properties are protected by topology and thus are robust to deformations of the system. In topological insulators and superconductors the bulk-surface and bulk-vortex correspondence gives rise to the gapless Weyl, Dirac or Majorana fermions on the surface of the system and inside vortex cores. Here we show that in gapless topological media, the bulk-surface and bulk-vortex correspondence is more effective: it produces topologically protected gapless fermions without dispersion—the flat band. Fermion zero modes forming the flat band are localized on the surface of topological media with protected nodal lines [A. P. Schnyder and S. Ryu, Phys. Rev. B **84**, 060504(R) (2011); T. T. Heikkilä and G. E. Volovik, JETP Lett. **93**, 59 (2011)] and in the vortex core in systems with topologically protected Fermi points (Weyl points) [G. E. Volovik, JETP Lett. **93**, 66 (2011)]. Flat band has an extremely singular density of states, and we show that this property may give rise in particular to surface superconductivity which could exist even at room temperature.

DOI: 10.1134/S0021364011150045

- Rhombohedral graphene:

Vanishing density of sates density of states at the Fermi level, but zero gap.

There is a flat band at the surface, even in the absence of a gate. The band is at the neutrality point (nodal system, drumhead band).

Superconductivity in untwisted tetralayers

Signatures of chiral superconductivity in rhombohedral graphene

https://doi.org/10.1038/s41586-025-09169-7

Received: 1 September 2024

Accepted: 16 May 2025

Tonghang Han[1,6], Zhengguang Lu[1,2,6], Zach Hadjri[1,6], Lihan Shi[1], Zhenghan Wu[1], Wei Xu[1], Yuxuan Yao[1], Armel A. Cotten[3], Omid Sharifi Sedeh[3], Henok Weldeyesus[3], Jixiang Yang[1], Junseok Seo[1], Shenyong Ye[1], Muyang Zhou[1], Haoyang Liu[2], Gang Shi[2], Zhenqi Hua[2], Kenji Watanabe[4], Takashi Taniguchi[5], Peng Xiong[2], Dominik M. Zumbühl[3], Liang Fu[1] & Long Ju[1]✉

Nature **643**, 654 (2025)

4 layers

Superconductivity and quantized anomalous Hall effect in rhombohedral graphene

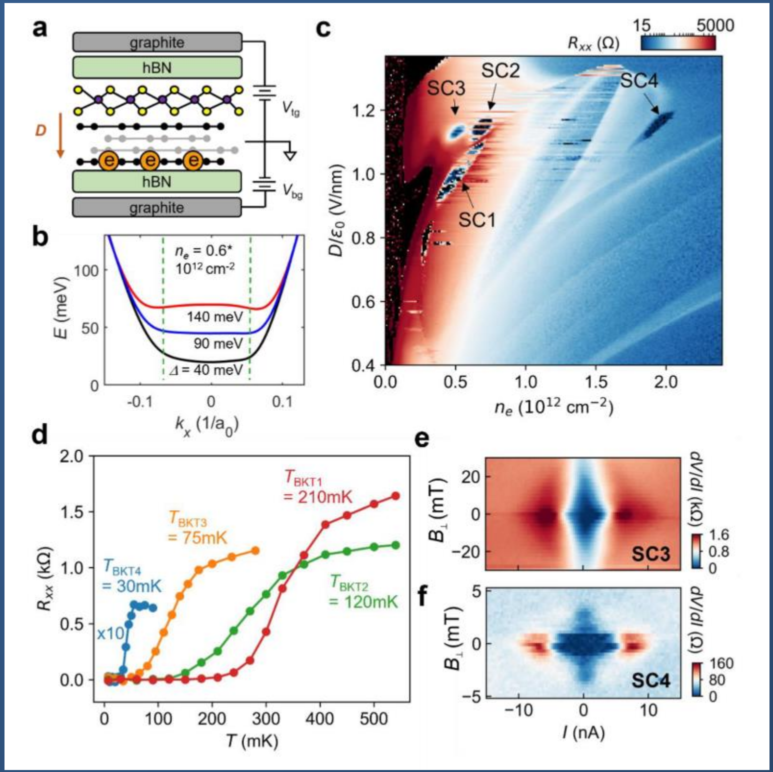
https://doi.org/10.1038/s41586-025-08621-y

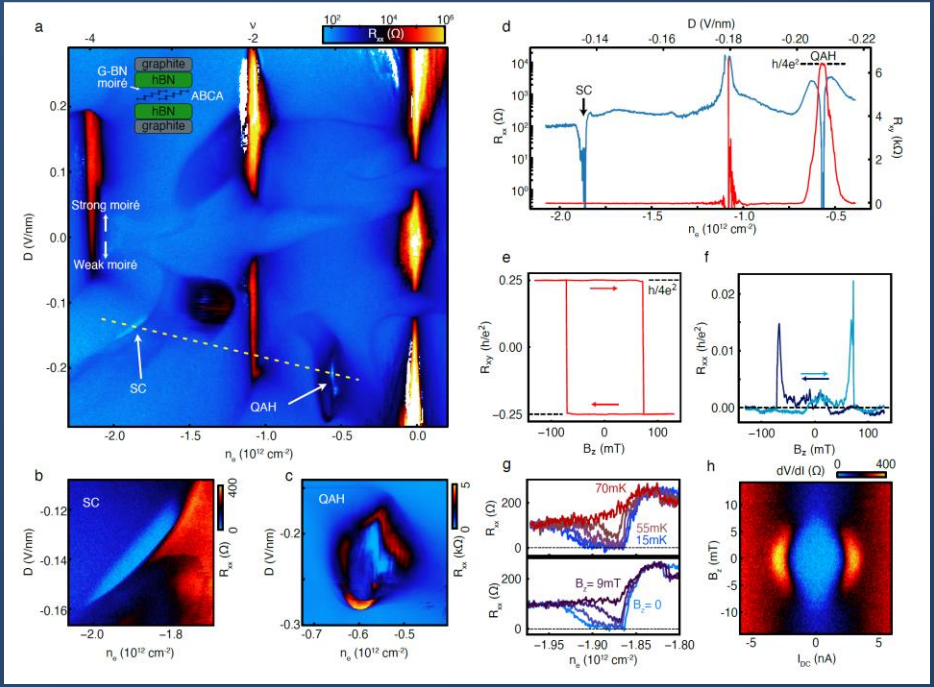
Received: 22 August 2024

Accepted: 9 January 2025

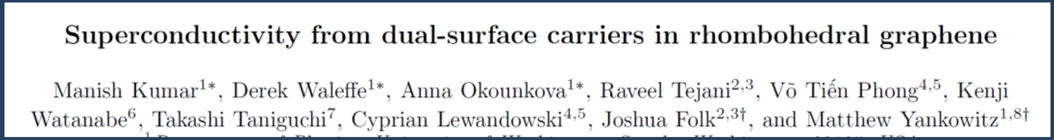
Youngjoon Choi[1,4], Ysun Choi[1,4], Marco Valentini[1,4], Caitlin L. Patterson[1], Ludwig F. W. Holleis[1], Owen I. Sheekey[1], Hari Stoyanov[1], Xiang Cheng[1], Takashi Taniguchi[2], Kenji Watanabe[3] & Andrea F. Young[1]✉

Nature **639**, 342 (2025)





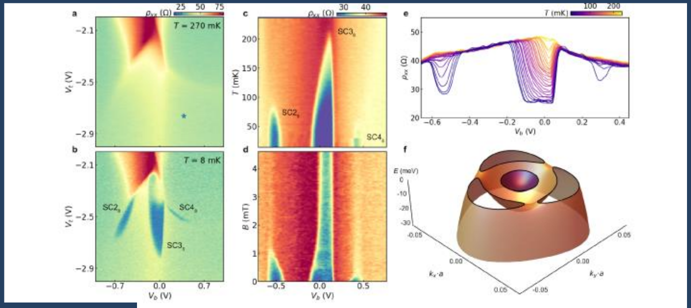
More experiments

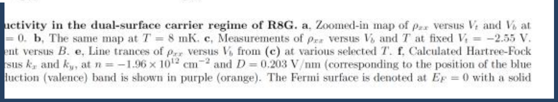


Superconductivity from dual-surface carriers in rhombohedral graphene

Manish Kumar[1*], Derek Waleffe[1*], Anna Okounkova[1*], Raveel Tejani[2,3], Võ Tiến Phong[4,5], Kenji Watanabe[6], Takashi Taniguchi[7], Cyprian Lewandowski[4,5], Joshua Folk[2,3†], and Matthew Yankowitz[1,8†]

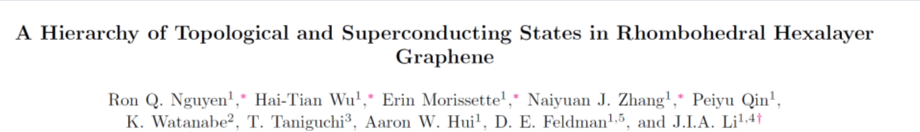
arXiv:2507.18598





uctivity in the dual-surface carrier regime of R8G. a, Zoomed-in map of ρ_{xx} versus V_t and V_b at
= 0. b, The same map at $T = 8$ mK. c, Measurements of ρ_{xx} versus V_b and T at fixed $V_t = -2.55$ V.
ent versus B. e, Line trances of ρ_{xx} versus V_b from (c) at various selected T. f, Calculated Hartree-Fock
rsus k_x and k_y, at $n = -1.96 \times 10^{12}$ cm^{-2} and $D = 0.203$ V/nm (corresponding to the position of the blue
luction (valence) band is shown in purple (orange). The Fermi surface is denoted at $E_F = 0$ with a solid

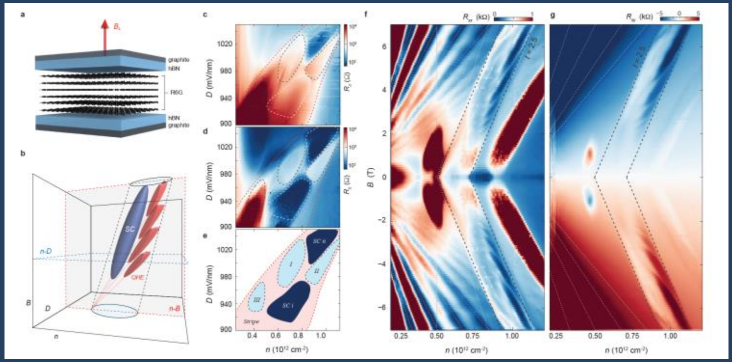
6 layers



A Hierarchy of Topological and Superconducting States in Rhombohedral Hexalayer Graphene

Ron Q. Nguyen[1,*] Hai-Tian Wu[1,*] Erin Morissette[1,*] Naiyuan J. Zhang[1,*] Peiyu Qin[1], K. Watanabe[2], T. Taniguchi[3], Aaron W. Hui[1], D. E. Feldman[1,5], and J.I.A. Li[1,4†]

arXiv:2507.22026



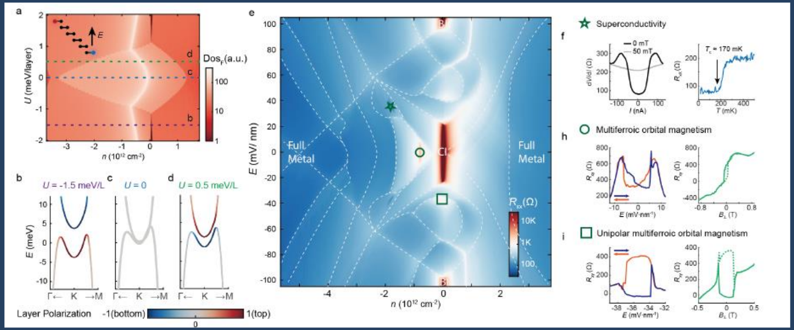
6 layers

Superconductivity and Ferroelectric Orbital Magnetism in Semimetallic Rhombohedral Hexalayer Graphene

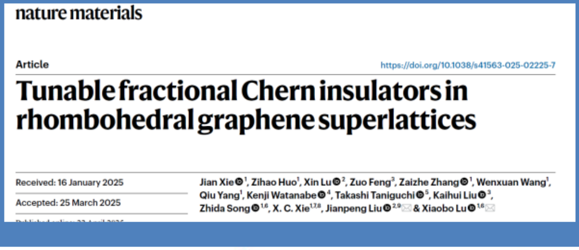
Jinghao Deng[1#], Jiabin Xie[1#], Hongyuan Li[1#], Takashi Taniguchi[2], Kenji Watanabe[3], Jie Shan[4,5], Kin Fai Mak[1,5], Xiaomeng Liu[1]*

arXiv:2508.15909

6 layers



More experiments



nature materials

Article

https://doi.org/10.1038/s41563-025-02225-7

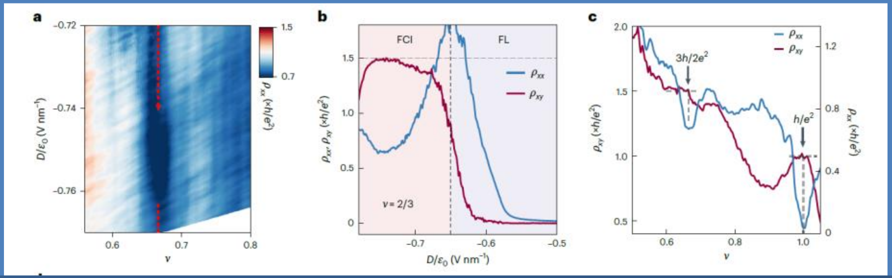
Tunable fractional Chern insulators in rhombohedral graphene superlattices

Received: 16 January 2025

Accepted: 25 March 2025

Jian Xie[1], Zihao Huo[1], Xin Lu[2], Zuo Feng[3], Zaizhe Zhang[1], Wenxuan Wang[1], Qiu Yang[1], Kenji Watanabe[4], Takashi Taniguchi[5], Kaihui Liu[3], Zhida Song[1,6], X. C. Xie[1,7,8], Jianpeng Liu[2,9] ✉ & Xiaobo Lu[1,6] ✉

6 layers



Article

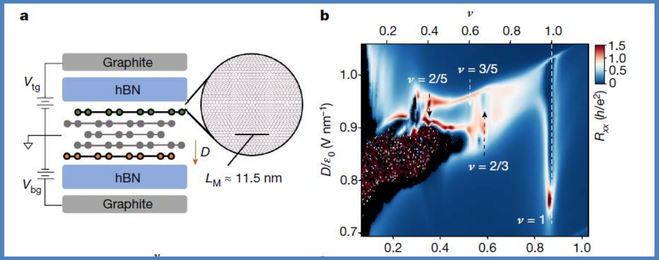
Fractional quantum anomalous Hall effect in multilayer graphene

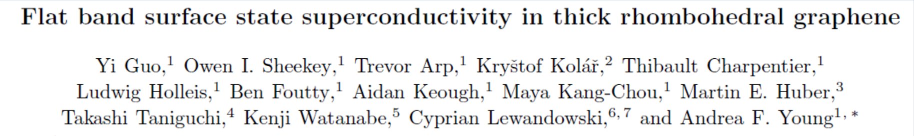
https://doi.org/10.1038/s41586-023-07010-7

Received: 1 October 2023

Zhengguang Lu[1,4], Tonghang Han[1,4], Yuxuan Yao[1,4], Aidan P. Reddy[1], Jixiang Yang[1], Junseok Seo[1], Kenji Watanabe[2], Takashi Taniguchi[3], Liang Fu[1] & Long Ju[1] ✉

5 layers

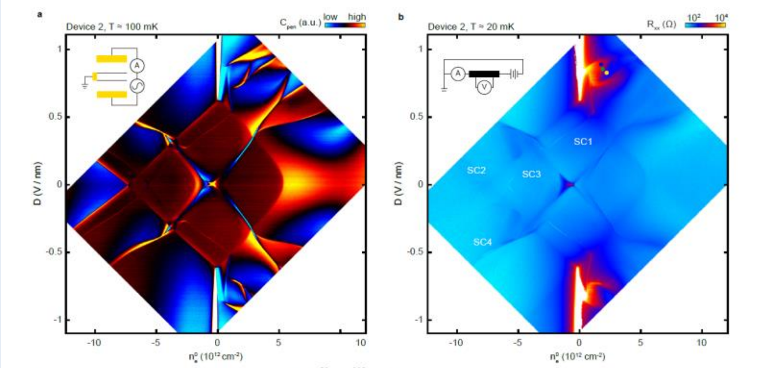




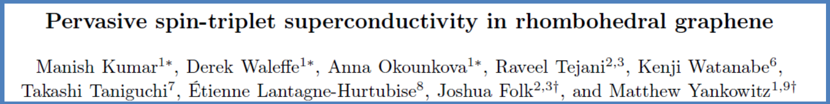
Flat band surface state superconductivity in thick rhombohedral graphene

Yi Guo,[1] Owen I. Sheekey,[1] Trevor Arp,[1] Kryštof Kolář,[2] Thibault Charpentier,[1] Ludwig Holleis,[1] Ben Foutty,[1] Aidan Keough,[1] Maya Kang-Chou,[1] Martin E. Huber,[3] Takashi Taniguchi,[4] Kenji Watanabe,[5] Cyprian Lewandowski,[6,7] and Andrea F. Young[1,*]

arXiv:2511.17423



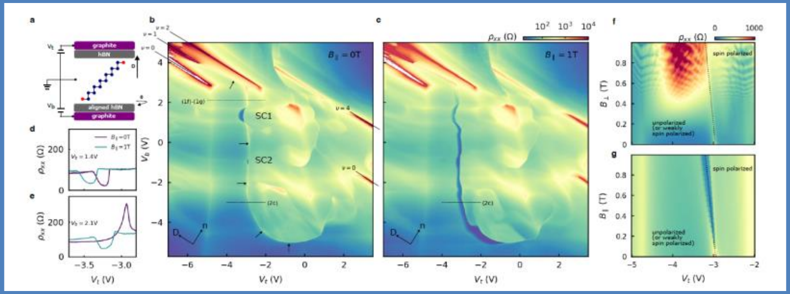
13 layers



Pervasive spin-triplet superconductivity in rhombohedral graphene

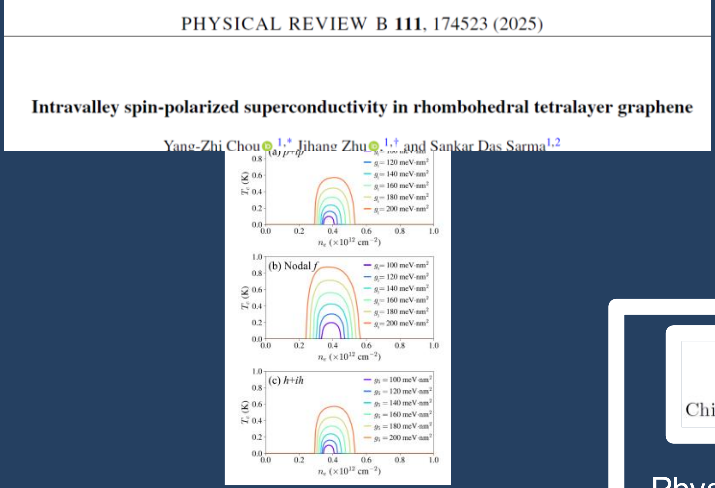
Manish Kumar[1*], Derek Waleffe[1*], Anna Okounkova[1*], Raveel Tejani[2,3], Kenji Watanabe[6], Takashi Taniguchi[7], Étienne Lantagne-Hurtubise[8], Joshua Folk[2,3†], and Matthew Yankowitz[1,9†]

arXiv:2511.16578



7 layers

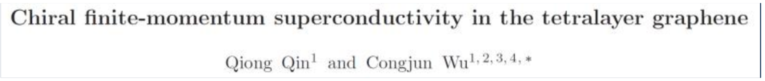
Some calculations in a fully polarized tetralayer



PHYSICAL REVIEW B **111**, 174523 (2025)

Intravalley spin-polarized superconductivity in rhombohedral tetralayer graphene

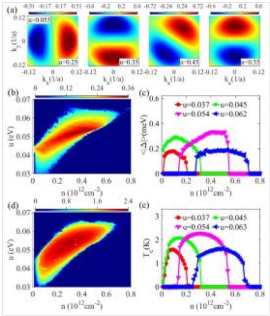
Yang-Zhi Chou[1,*], Jihang Zhu[1,†], and Sankar Das Sarma[1,2]

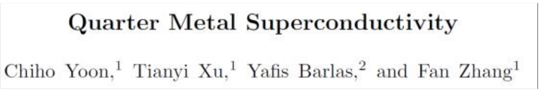


Chiral finite-momentum superconductivity in the tetralayer graphene

Qiong Qin[1] and Congjun Wu[1,2,3,4,*]

arXiv:2412.07145, Chinese Physics Lett., in press

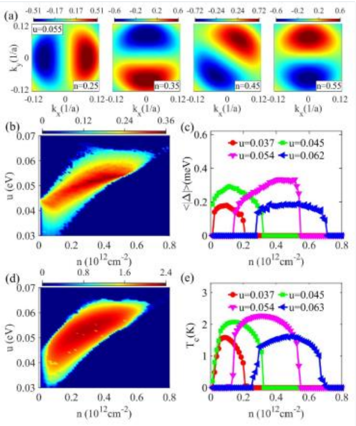




Quarter Metal Superconductivity

Chiho Yoon,[1] Tianyi Xu,[1] Yafis Barlas,[2] and Fan Zhang[1]

Phys. Rev. Lett. 136, 026603 (2026)



nature communications

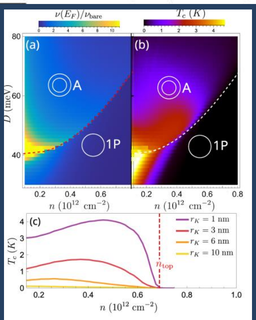
Article

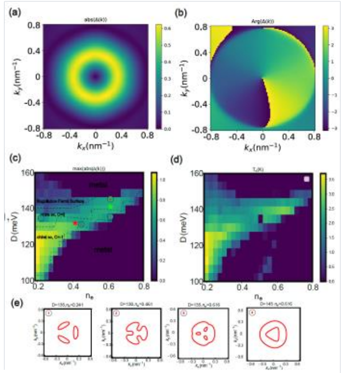
https://doi.org/10.1038/s41467-025-66902-6

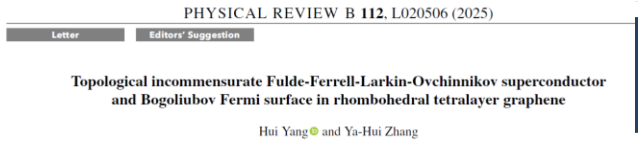
Chiral and topological superconductivity in isospin polarized multilayer graphene

Received: 27 September 2024

Max Geier[1], Margarita Davydova[1,2] & Liang Fu[1]







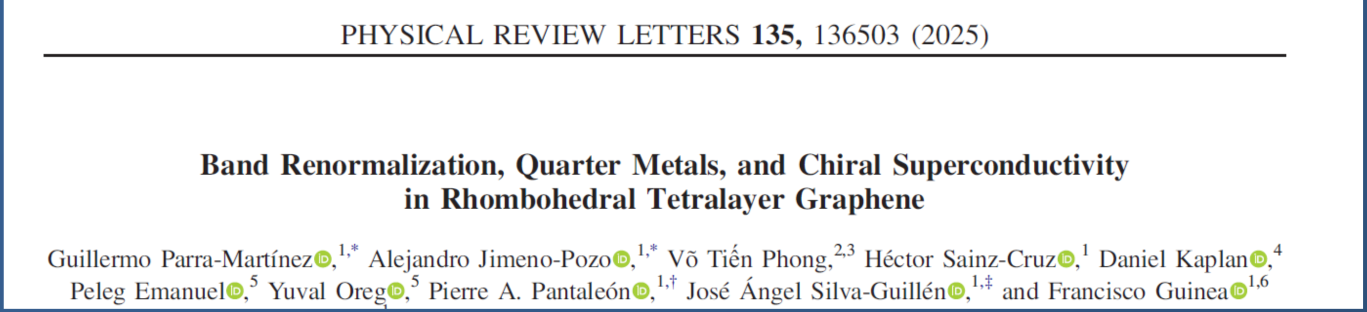
PHYSICAL REVIEW B **112**, L020506 (2025)

Letter

Editors' Suggestion

Topological incommensurate Fulde-Ferrell-Larkin-Ovchinnikov superconductor and Bogoliubov Fermi surface in rhombohedral tetralayer graphene

Hui Yang and Ya-Hui Zhang



PHYSICAL REVIEW LETTERS **135**, 136503 (2025)

Band Renormalization, Quarter Metals, and Chiral Superconductivity in Rhombohedral Tetralayer Graphene

Guillermo Parra-Martínez,[1,*] Alejandro Jimeno-Pozo,[1,*] Võ Tiến Phong,[2,3] Héctor Sainz-Cruz,[1] Daniel Kaplan,[4]
Peleg Emanuel,[5] Yuval Oreg,[5] Pierre A. Pantaleón,[1,†] José Ángel Silva-Guillén,[1,‡] and Francisco Guinea[1,6]

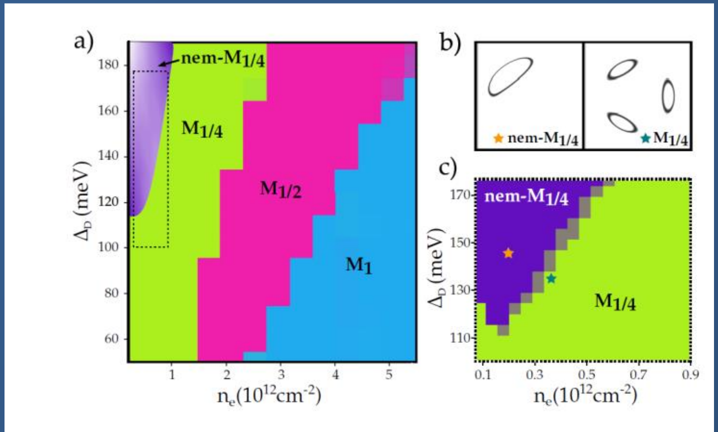


Figure 1. **Hartree-Fock phase diagram.** (a) Self-consistently calculated HF phase diagram, showing $M_{1/4}$, $M_{1/2}$ and M_1 phases as a function of the external displacement field (Δ_D) and electronic density (n_e). The purple region at low densities and high displacement fields highlights schematically where the nem-$M_{1/4}$ is expected to emerge. In (c), we show the calculated phase boundary between $M_{1/4}$ and nem-$M_{1/4}$ in the region indicated by a dashed rectangle in (a). (b) Representative Fermi surfaces at the same point in parameter space indicated by the yellow and blue stars in (c) solutions with and without C_3 symmetry breaking.

- A variety of polarized phases
- Multiple Lifschitz transitions.
- Significant trigonal warping

The HF density of states shows an unphysical dip at the Fermi energy.
The bands are not suited for the calculation of superconductivity.

Superconductivity.
Critical temperature

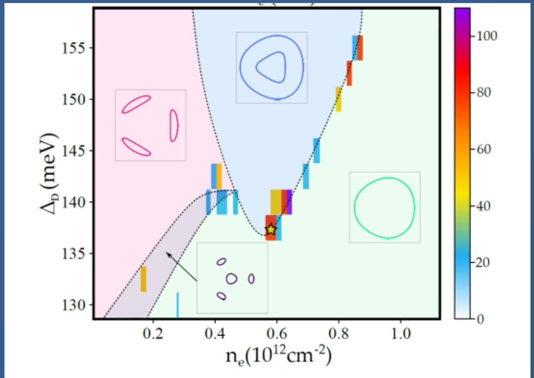


Figure 3. **Superconductivity critical temperature.** Superconducting critical temperature, T_c, as a function of displacement and electron filling in the $\mathrm{M}_{1/4}$ phase. The colored regions indicate different Fermi surface shapes. Black dashed lines mark Lifshitz transitions, between different shapes of the fermi surfaces (see section IV SM [47]). A representative Fermi surface is displayed within each region. The yellow star indicates the parameters used for the calculation of the superconducting order parameter (OP) shown in Fig. 4(a-b).

- Calculations carried out using the RPA screened interaction.
- Trigonal warping suppresses the Cooper instability.
- Narrow slice in phase space where superconductivity appears.

Superconductivity.
Order parameter

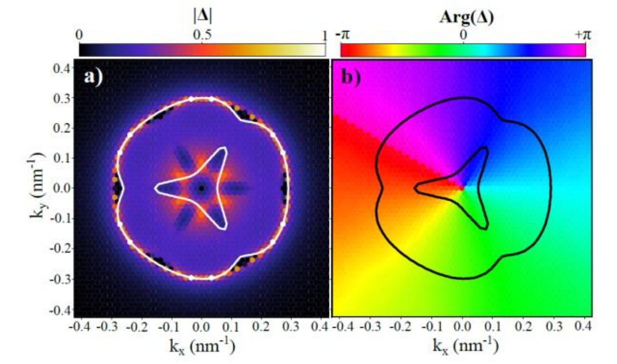
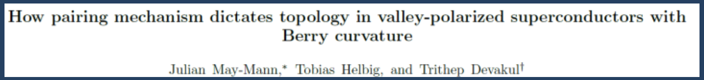


Figure 4. **Superconducting order parameter**. Order parameter of the leading eigenvalue in the screened Hartree-Fock superconductivity calculations. (a) Normalized magnitude of the order parameters and (b) its corresponding phase. The Fermi surface is indicated by solid white and black lines in each panel, respectively. Calculations were made at values $\Delta_D = 137.5$ meV and $n_e = 6.01 \times 10^{11}\mathrm{cm}^{-2}$ with $T_c = 80$ mK, marked in Fig. 3 as a yellow star.

- p-wave superconductivity
- No degeneracy between p_+ and p_- .
- The gap in not pinned to the Fermi surface
- Gapless superconductivity, due to the par breaking effects oftrigonal warping. Similar to s-wave superconductors with magnetic impurities.

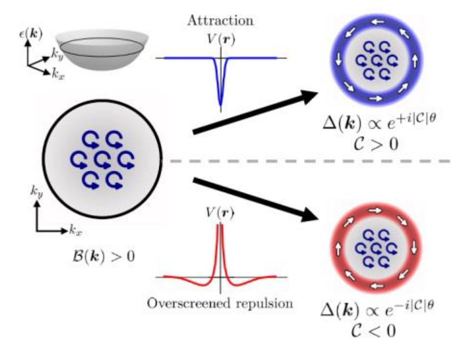
Other works on quarter metal superconductivity

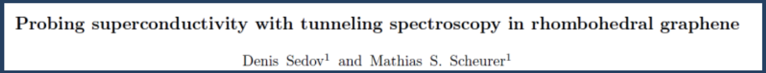


How pairing mechanism dictates topology in valley-polarized superconductors with Berry curvature

Julian May-Mann,* Tobias Helbig, and Trithep Devakul†

arXiv.2503.05697

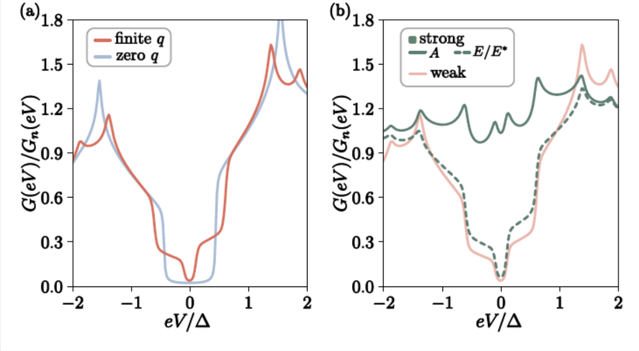


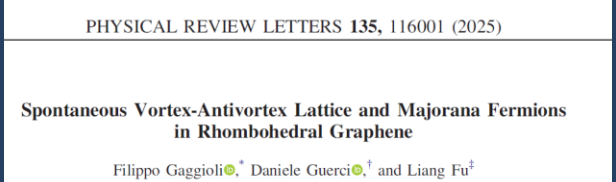


Probing superconductivity with tunneling spectroscopy in rhombohedral graphene

Denis Sedov[1] and Mathias S. Scheurer[1]

arXiv.2503.12650

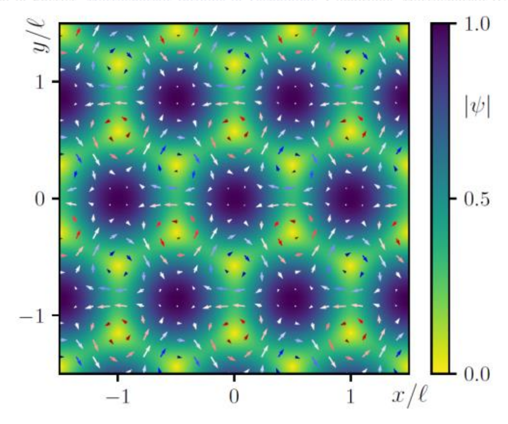


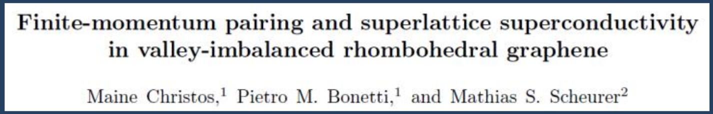


PHYSICAL REVIEW LETTERS **135,** 116001 (2025)

Spontaneous Vortex-Antivortex Lattice and Majorana Fermions in Rhombohedral Graphene

Filippo Gaggioli,* Daniele Guerci,† and Liang Fu‡

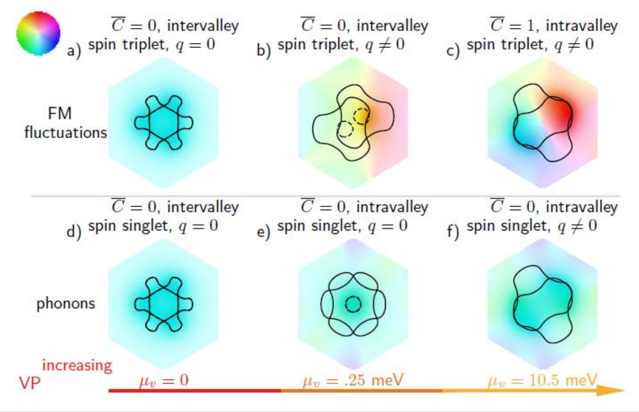




Finite-momentum pairing and superlattice superconductivity in valley-imbalanced rhombohedral graphene

Maine Christos,[1] Pietro M. Bonetti,[1] and Mathias S. Scheurer[2]

arXiv.2503.15471



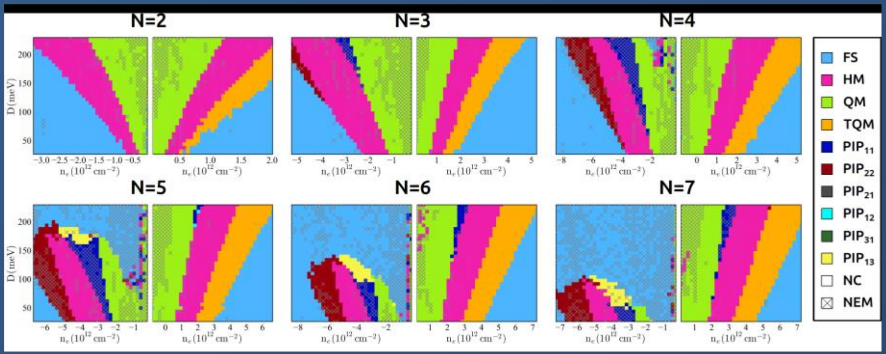
Phase diagrams of rhombohedral multilayers

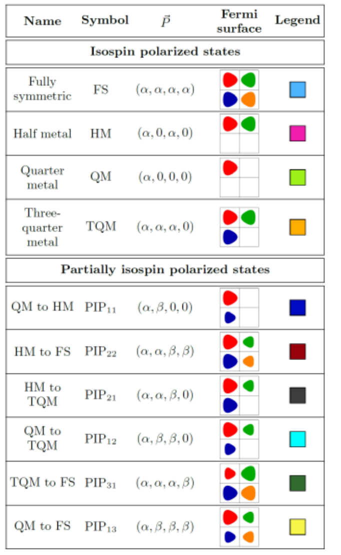

RESEARCH ARTICLE

ADVANCED MATERIALS
www.advmat.de

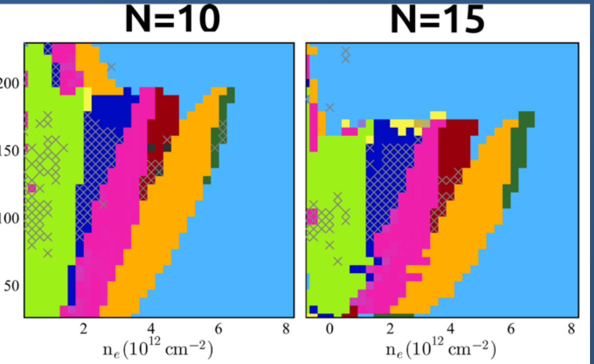
Nematic and Partially Polarized Phases in Rhombohedral Graphene with Varying Number of Layers: An Extensive Hartree–Fock Study

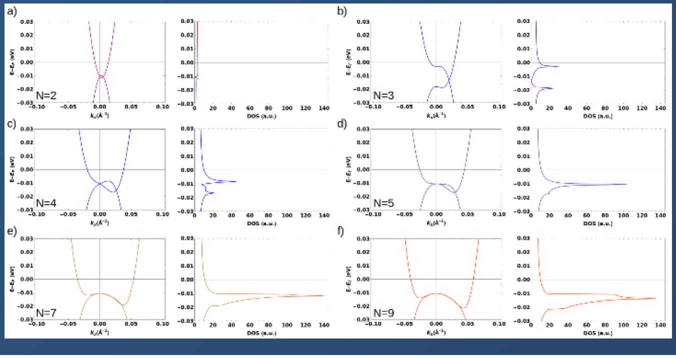
Guillermo Parra-Martínez, Alejandro Jimeno-Pozo, Jose Angel Silva-Guillén, and Francisco Guinea**





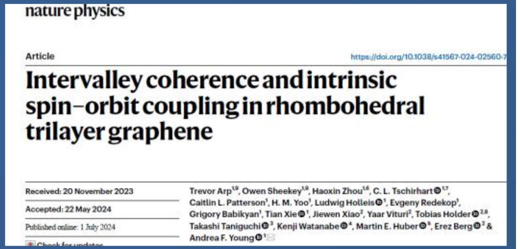
Name	Symbol	$\vec{p}$	Fermi surface	Legend
Isospin polarized states				
Fully symmetric	FS	$(\alpha,\alpha,\alpha,\alpha)$	🔴🟢 🔵🟠	🟦
Half metal	HM	$(\alpha,0,\alpha,0)$	🔴🟢	🟪
Quarter metal	QM	$(\alpha,0,0,0)$	🔴	🟩
Three-quarter metal	TQM	$(\alpha,\alpha,\alpha,0)$	🔴🟢 🔵	🟧
Partially isospin polarized states				
QM to HM	PIP_{11}	$(\alpha,\beta,0,0)$	🔴 🔵	🟦
HM to FS	PIP_{22}	$(\alpha,\alpha,\beta,\beta)$	🔴🟢 🔵🟠	🟥
HM to TQM	PIP_{21}	$(\alpha,\alpha,\beta,0)$	🔴🟢 🔵	⬛
QM to TQM	PIP_{12}	$(\alpha,\beta,\beta,0)$	🔴🟢 🔵	🟦
TQM to FS	PIP_{31}	$(\alpha,\alpha,\alpha,\beta)$	🔴🟢 🔵🟠	🟩
QM to FS	PIP_{13}	$(\alpha,\beta,\beta,\beta)$	🔴🟢 🔵🟠	🟨





- Same succession of unpolarized, half metal, and quarter metal phases in all systems
- Polarized phases stronger on the electron side
- Nematic phases, which break C_3, also possible
- Polarized phases favored by increased band splittings induced by the exchange term
- Trigonal warping leads to three hot spots at the Fermi surface, leading to p-wave SC

“Giant” spin-orbit coupling in rhombohedral graphite


nature physics

Article https://doi.org/10.1038/s41567-024-02560-7

Intervalley coherence and intrinsic spin–orbit coupling in rhombohedral trilayer graphene

Received: 20 November 2023

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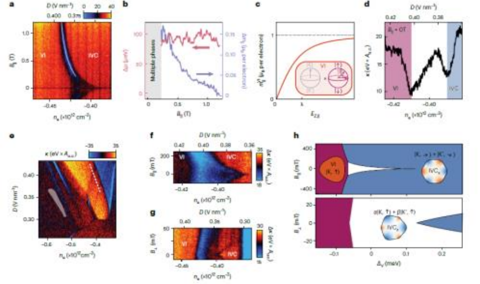
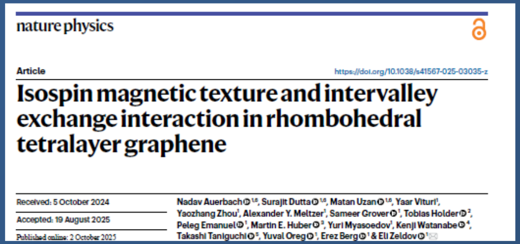
Published online: 1 July 2024

Trevor Arp[1,9], Owen Sheekey[1,9], Haoxin Zhou[1,6], C. L. Tschirhart[1,7], Caitlin L. Patterson[1], H. M. Yoo[1], Ludwig Holleis[1], Evgeny Redekop[1], Grigory Babikyan[1], Tian Xie[1], Jiewen Xiao[2], Yaar Vituri[2], Tobias Holder[2,8], Takashi Taniguchi[3], Kenji Watanabe[4], Martin E. Huber[5], Erez Berg[2] & Andrea F. Young[1]




nature physics

Article https://doi.org/10.1038/s41567-025-03035-z

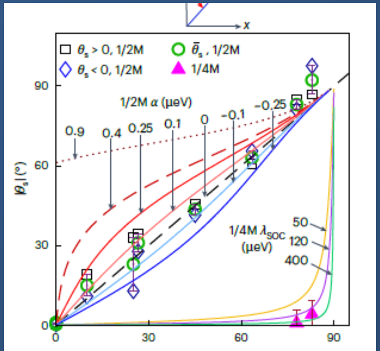
Isospin magnetic texture and intervalley exchange interaction in rhombohedral tetralayer graphene

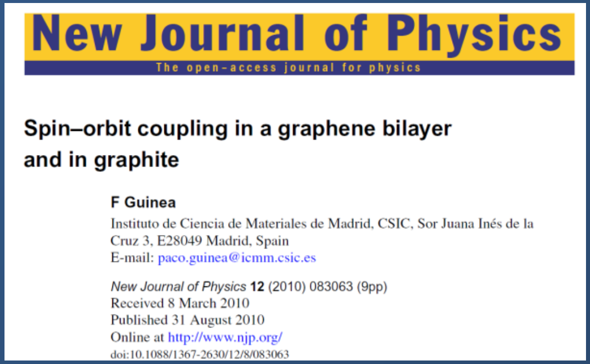
Received: 5 October 2024

Accepted: 19 August 2025

Published online: 2 October 2025

Nadav Auerbach[1,6], Surajit Dutta[1,6], Matan Uzan[1,6], Yaar Vituri[1], Yaozhang Zhou[1], Alexander Y. Meltzer[1], Sameer Grover[1], Tobias Holder[2], Peleg Emanuel[1], Martin E. Huber[3], Yuri Myasoedov[1], Kenji Watanabe[4], Takashi Taniguchi[5], Yuval Oreg[1], Erez Berg[1] & Eli Zeldov[1]




New Journal of Physics
The open-access journal for physics

Spin–orbit coupling in a graphene bilayer and in graphite

F Guinea
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New Journal of Physics **12** (2010) 083063 (9pp)
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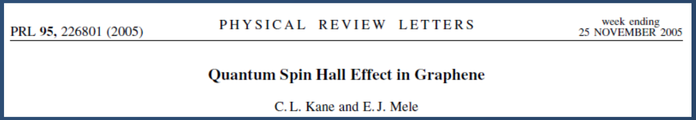
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/8/083063

Spin Orbit Interaction in Graphite
G. Dresselhaus and M. S. Dresselhaus
Physical Review **140**, A401 (1965)


PRL **95**, 226801 (2005) PHYSICAL REVIEW LETTERS week ending 25 NOVEMBER 2005

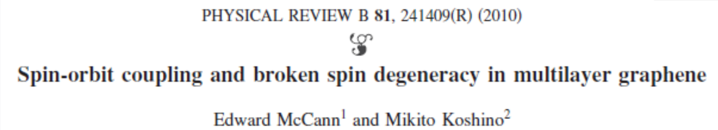
Quantum Spin Hall Effect in Graphene

C. L. Kane and E. J. Mele


PHYSICAL REVIEW B **82**, 245412 (2010)

Tight-binding theory of the spin-orbit coupling in graphene

Sergej Konschuh, Martin Gmitra, and Jaroslav Fabian


PHYSICAL REVIEW B **81**, 241409(R) (2010)

Spin-orbit coupling and broken spin degeneracy in multilayer graphene

Edward McCann[1] and Mikito Koshino[2]


Giant Intrinsic Spin-Orbit Coupling in Bilayer Graphene

Hai-Wen Liu[1], X.C. Xie[1,2], and Qing-feng Sun[1]*

arXiv:1004.0881

Spin-orbit in rhombohedral multilayers

Calculation including all *p* and *s* orbitals in the valence shell
Projection onto the p_z orbitals

In collaboration with A. Stern, G. Parra-Martínez, A. Herando-Pozo, J. Silva

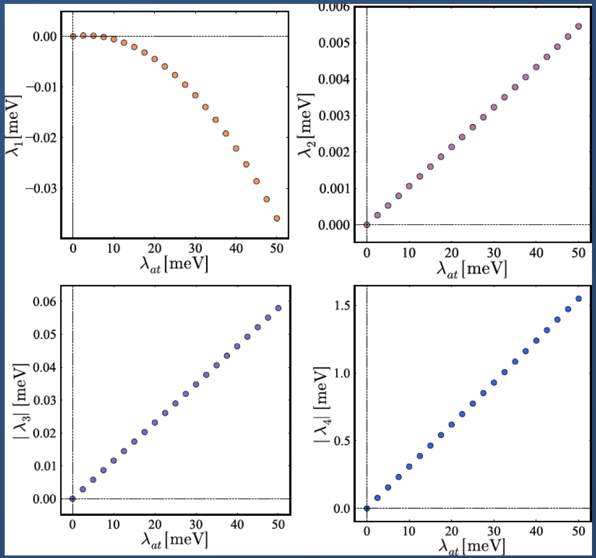
Atomic spin-orbit coupling $\mathcal{H}_{soc}^{at} = \lambda_{at} \sum_n \vec{L}_n \vec{s}_n$

Symmetry allowed terms

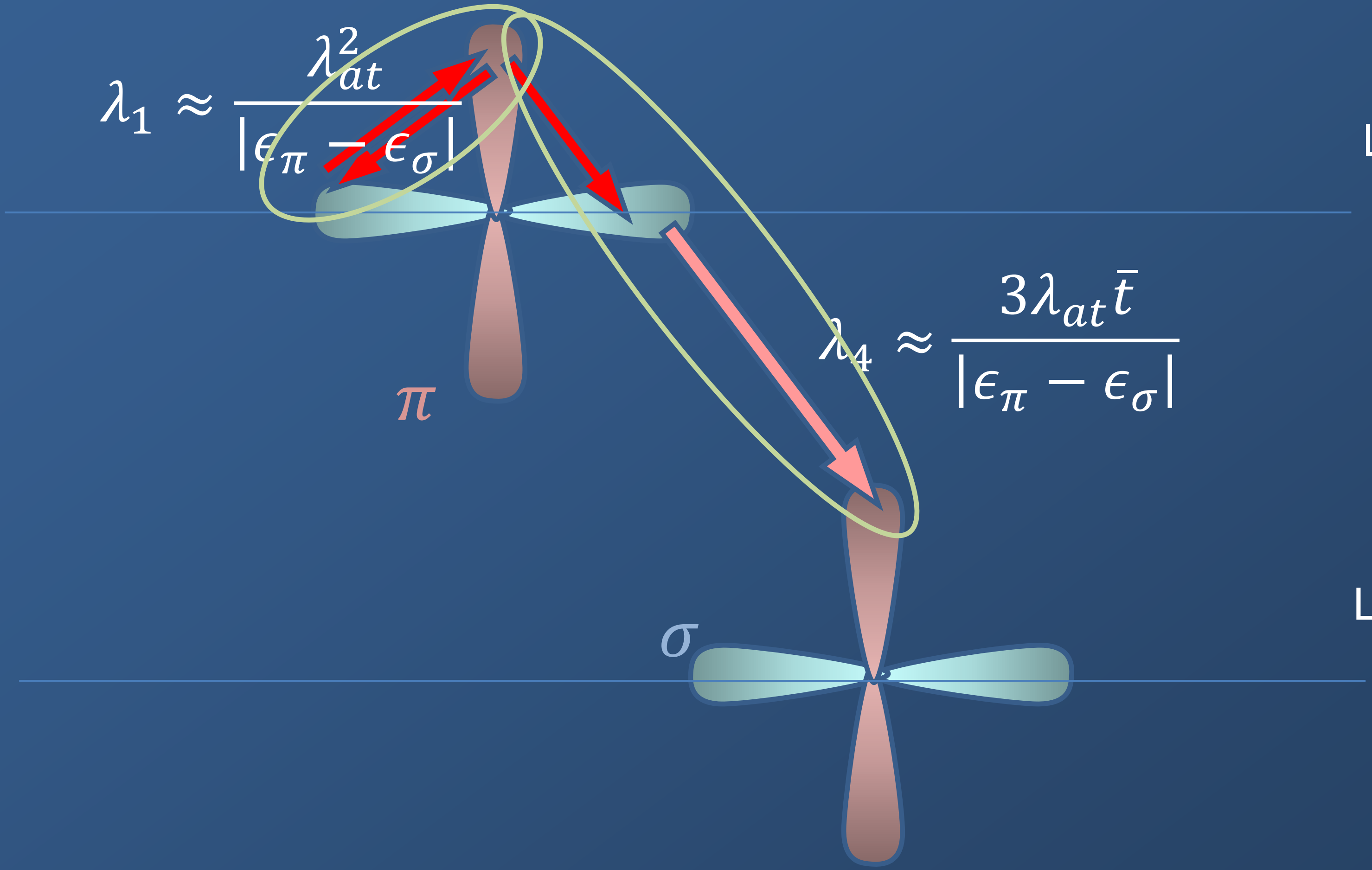
$$\mathcal{H}_{soc} = \sum_{n=1}^{n=N_L} \left[\lambda_1 \tau_z^n \sigma_z^n s_z^n + \lambda_2 (-1)^n \tau_z^n s_z^n + \lambda_3 (-1)^n \left(\sigma_y^n s_x^n - \tau_z^n \sigma_x^n s_y^n\right)\right] + \sum_{n=1}^{n=N_L-1} \lambda_4 \sigma_z^n \left(\mu_y^{n.n+1} s_x^n - \tau_z^n \mu_x^{n.n+1} s_y^n\right)$$

Kane Mele term

Spin flip+interlayer hopping



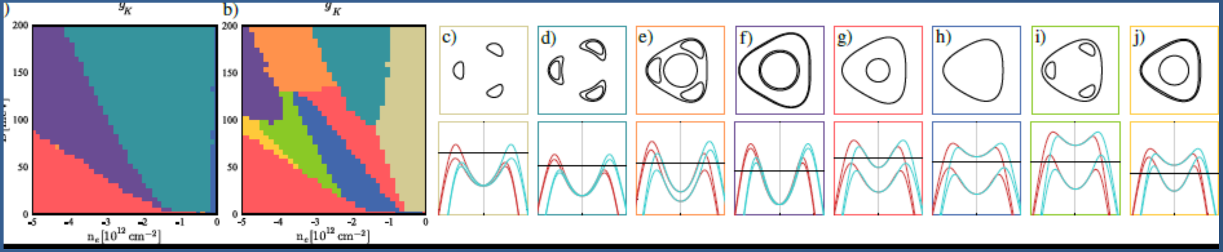
Spin orbit couplings: Kane-Mele, interlayer jump +spin flip



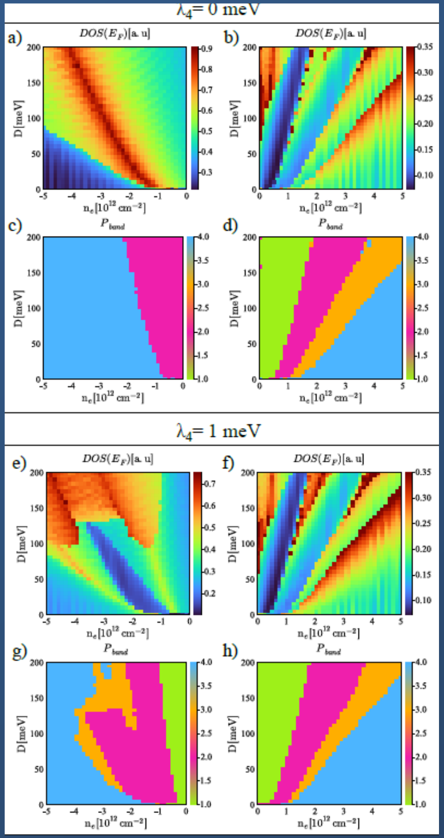
$$\lambda_1 \approx \frac{\lambda_{at}^2}{|\epsilon_\pi - \epsilon_\sigma|}$$

$$\lambda_4 \approx \frac{3\lambda_{at}\bar{t}}{|\epsilon_\pi - \epsilon_\sigma|}$$

Fermi Surface topology, R4G



$\lambda_4 = 0$ $\lambda_4 = 1$ meV



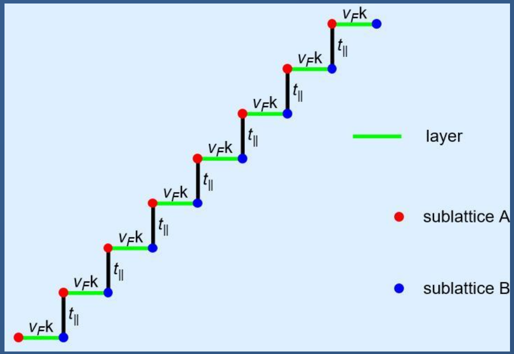
Hartree Fock phase diagram

Rhombohedral graphene. A toy model.

In collaboration with A. Bernevig and Y. Sao

Consider only the flat band of a semiinfinite stack (Berry trashcan approximation),

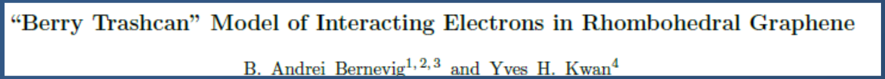
SSH approximation



Tight binding hamiltonian

$$|\vec{k}\rangle = N^{-1/2} \sum_n \left(\frac{v_F k e^{i\phi_k}}{t_{||}} \right)^n |n, A\rangle$$

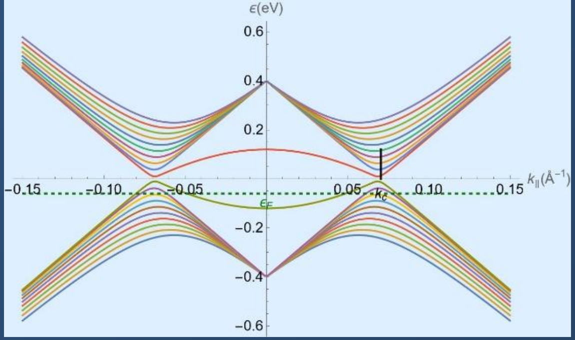
Flat band dispersion



“Berry Trashcan” Model of Interacting Electrons in Rhombohedral Graphene

B. Andrei Bernevig[1,2,3] and Yves H. Kwan[4]

arXiv:2503.09692

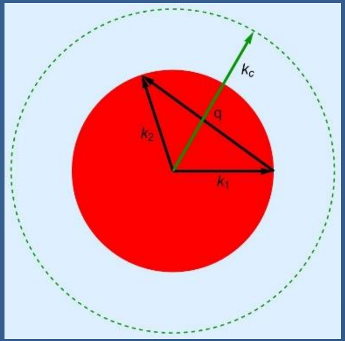


Bands with shift due to displacement field.
Approximate quadratic dispersion.

$$\epsilon_{\vec{k}} = \frac{\vec{k}^2}{2m^*}$$

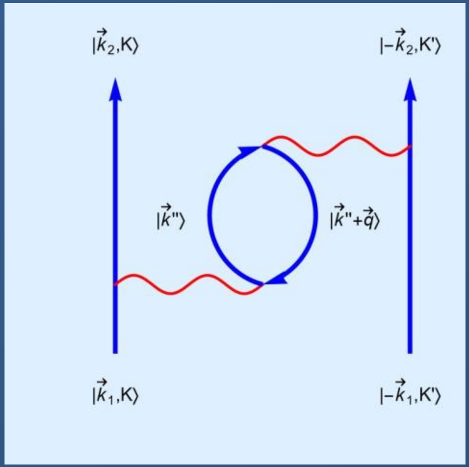
Pairing due to long range interactions (Kohn-Luttinger)

Fermi surface



Radius of the flat band:

$$k_c = \frac{v_F}{t_\parallel}$$



screened potential

$$v_{scr}(q) = \frac{v_0(q)}{1 + n_f v_0(q)\chi_0(q)} \approx \frac{1}{n_f \chi_0(q)}$$

susceptibility

$$\chi_0(q) = \sum_{\vec{k}''} \left|\langle \vec{k}'' | \vec{k}'' + \vec{q} \rangle\right|^2 \frac{n_{\vec{k}''+\vec{q}} - n_{\vec{k}''}}{\epsilon_{\vec{k}''+\vec{q}} - \epsilon_{\vec{k}''}}$$

Linear equation for the gap

$$\Delta_l(T_c) \approx -\log\left(\frac{W}{T_c}\right) \lambda_l \Delta_l(T_c)$$

Gap at zero temperature

$$\Delta_l \approx W e^{-1/|\lambda_l|}$$

See also:

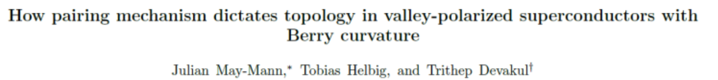
RESEARCH ARTICLE | AUGUST 13 2013

Superconductivity from repulsive interaction FREE

Saurabh Maiti; Andrey V. Chubukov

AIP Conf. Proc. 1550, 3–73 (2013)

https://doi.org/10.1063/1.4818400



How pairing mechanism dictates topology in valley-polarized superconductors with Berry curvature

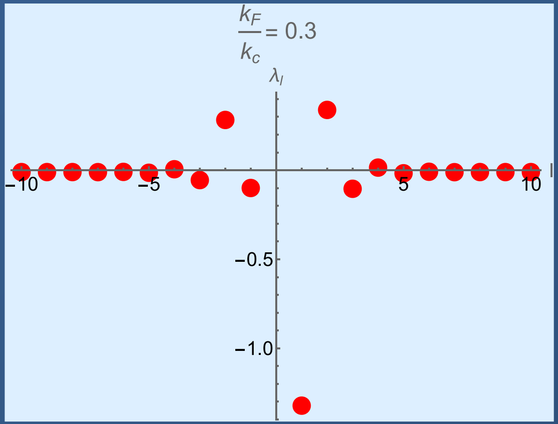
Julian May-Mann,* Tobias Helbig, and Trithep Devakul†

Dimensionless coupling constant

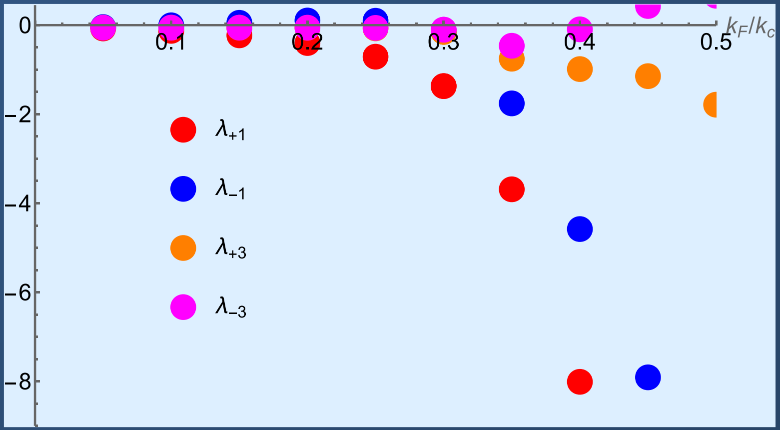
$$\lambda_l = \frac{\rho(\epsilon_F)}{2\pi} \int_0^{2\pi} d\theta\, e^{il\theta} \times \begin{Bmatrix} M_{K,K'}(\vec{k}_1,\vec{k}_2) \\ M_{K,K}(\vec{k}_1,\vec{k}_2) \end{Bmatrix} \times v_{scr}(q) \approx \frac{1}{2\pi} \int_0^{2\pi} d\theta\, e^{il\theta} \times \begin{Bmatrix} M_{K,K'}(\vec{k}_1,\vec{k}_2) \\ M_{K,K}(\vec{k}_1,\vec{k}_2) \end{Bmatrix} \times \frac{\chi_0(0)}{n_f \chi_0(q)}$$

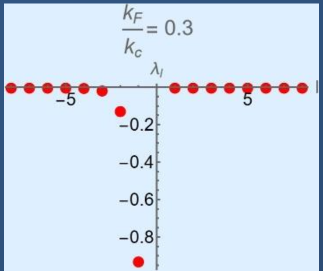
System dependent parameters, e^2, m^*, drop out, only dimensionless form factors remain

Quarter metal. Superconducting coupling constant

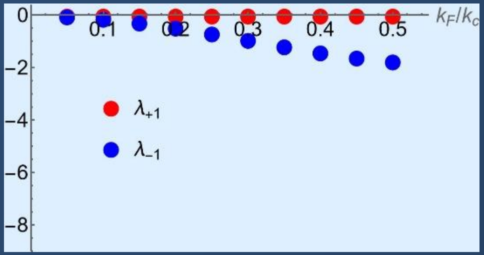


Screened Coulomb interaction

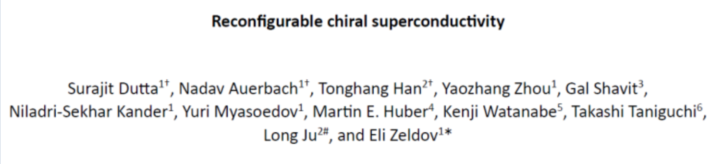




Negative Hubbard U



Domain walls in quarter metals

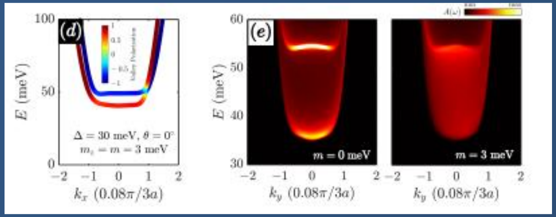


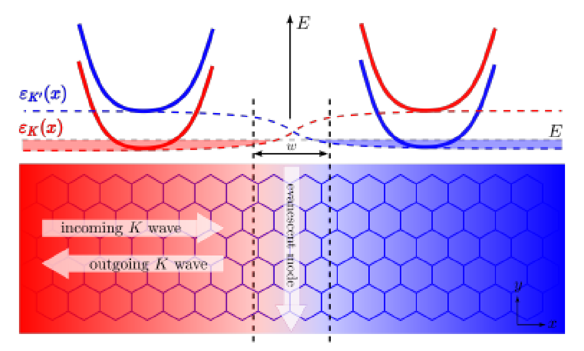
Reconfigurable chiral superconductivity

Surajit Dutta[1†], Nadav Auerbach[1†], Tonghang Han[2†], Yaozhang Zhou[1], Gal Shavit[3], Niladri-Sekhar Kander[1], Yuri Myasoedov[1], Martin E. Huber[4], Kenji Watanabe[5], Takashi Taniguchi[6], Long Ju[2#], and Eli Zeldov[1*]

arXiv:2605.13303

In collaboration with V. T. Phong, E. Mele, E. Prada, P. San-Jose, F. Lobo

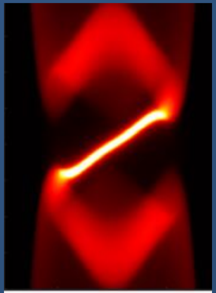


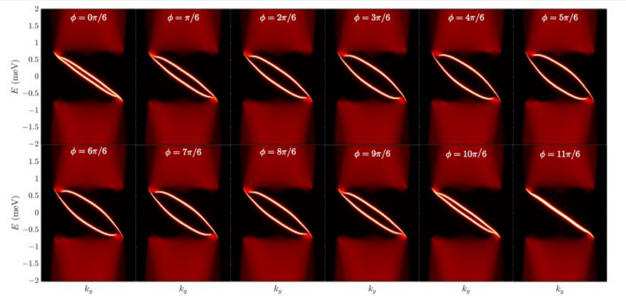


Electronic structure of the domain wall in the normal state.

The transmision vanishes unless:

- The barrier has the armchair orientation.
- There is intervalley coherence at the barrier.

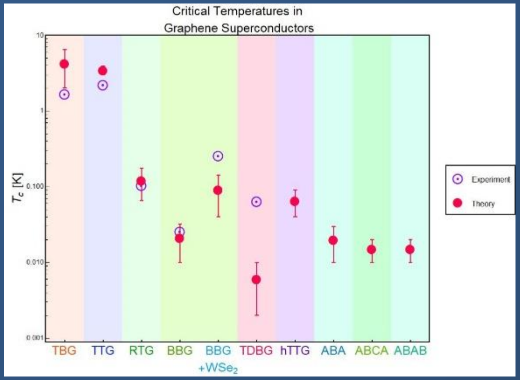




Electronic structure of the domain wall in the superconducting state.

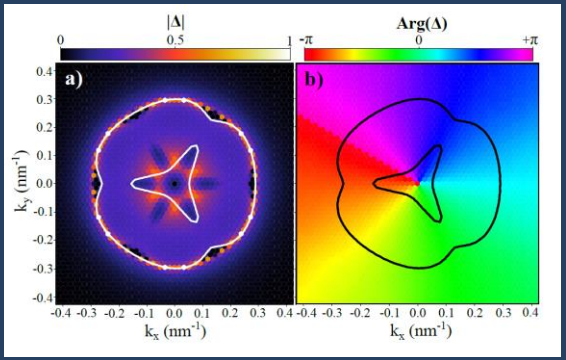
- Topological superconductivity.
- Existence of Majorana states.

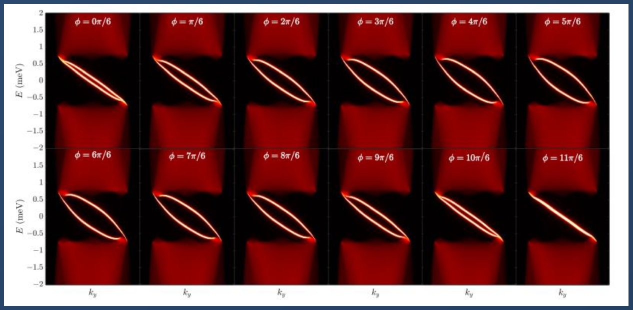
- The long range Coulomb interaction plays a major role inthe electronic properties of graphene stacks.
- The main trends of the superconducting properties are reasonably described using standard parameters,



Electronic bands								Coulomb potential		Deformation potential and elastic constants		
$a(\text{Å})$	$v_F(eV\text{Å})$	$\gamma_1(eV)$	$\gamma_3(eV)$	$\gamma_4(eV)$	$\Delta'(eV)$	$g_{AA}(eV)$	$g_{AB}(eV)$	$d_G(nm)$	ϵ	$D(eV)$	$\lambda(eV\text{Å}^{-2})$	$\mu(eV\text{Å}^{-2})$
2.46	5.253	0.4	0.32	0.044	0.05	0.797	0.0975	40	10	20	3.25	9.44

Rhombohedral graphene stacks show a rich electronic behavior all the way to the 3D limit





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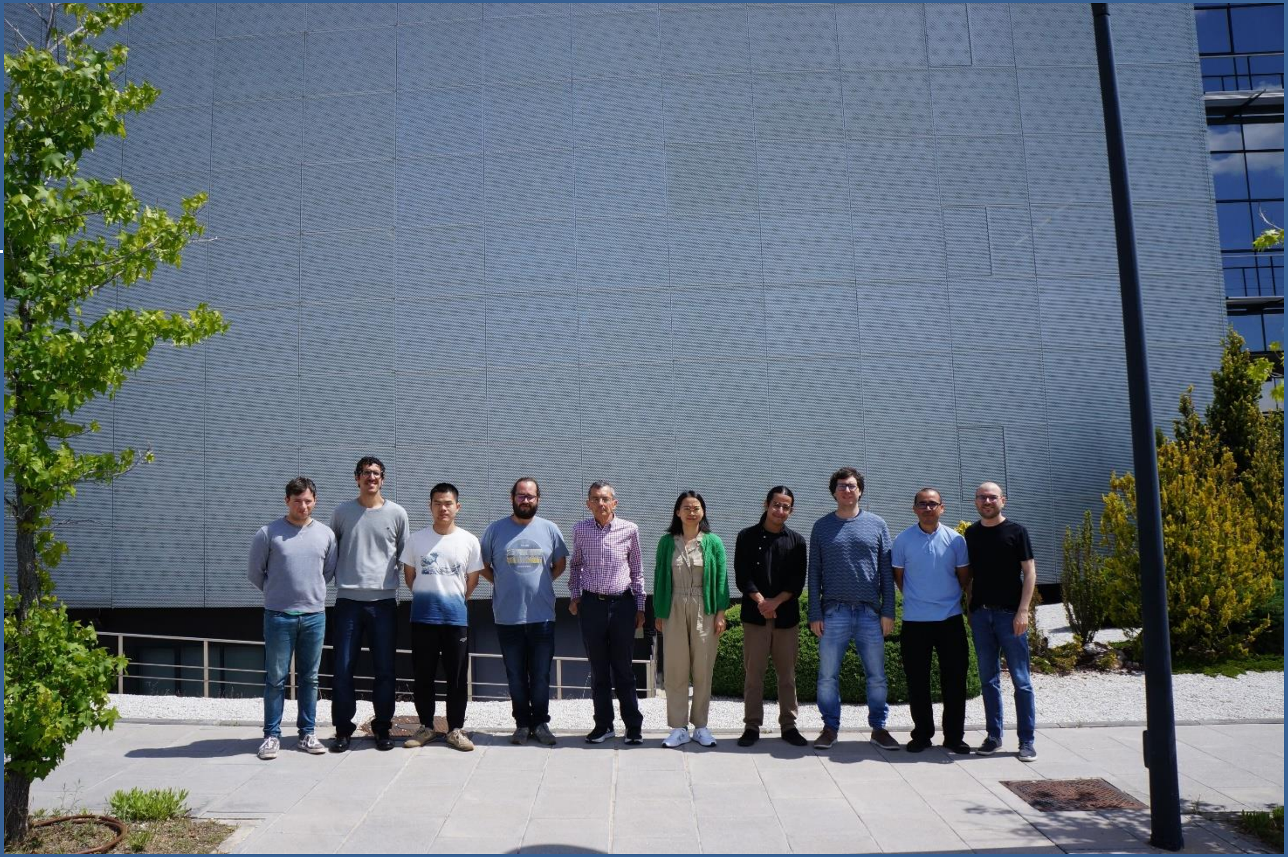

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EXCELENCIA SEVERO OCHOA

- Electronic charge fluctuations describe a pairing mechanism which is not suppressed by repulsive interactions. It is described by few adjustable parameters.
- The role of charge fluctuations is enhanced in systems with complex electronic wavefunctions, like twisted bilayer graphene. The strength of Umklapp processes correlates with the critical temperature.
- f-wave symmetry is a possible order parameter in twisted bilayer graphene.
- Superconductivity in a fully polarized is influenced by trigonal warping, and can be gapless.

Superconducting stiffness: recent results

Superfluid stiffness of magic-angle twisted bilayer graphene

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The physics of superconductivity in magic-angle twisted bilayer graphene

Article

Superfluid stiffness of twisted trilayer graphene superconductors

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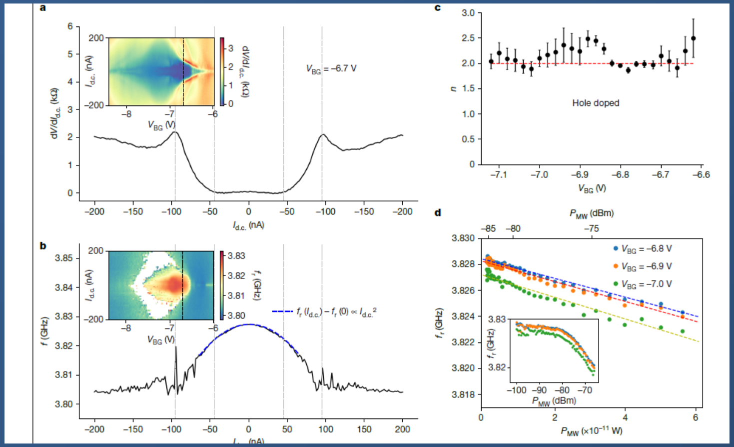
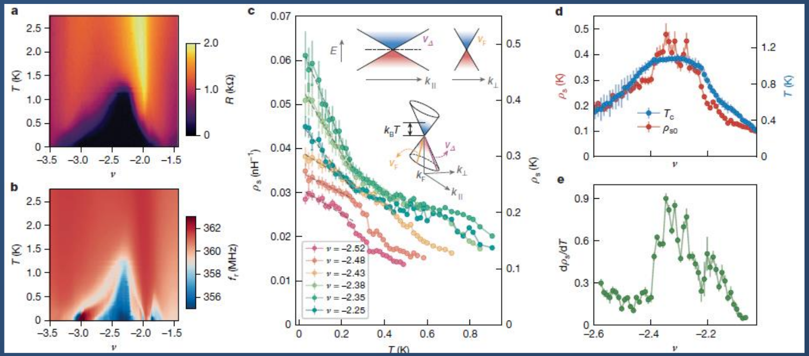
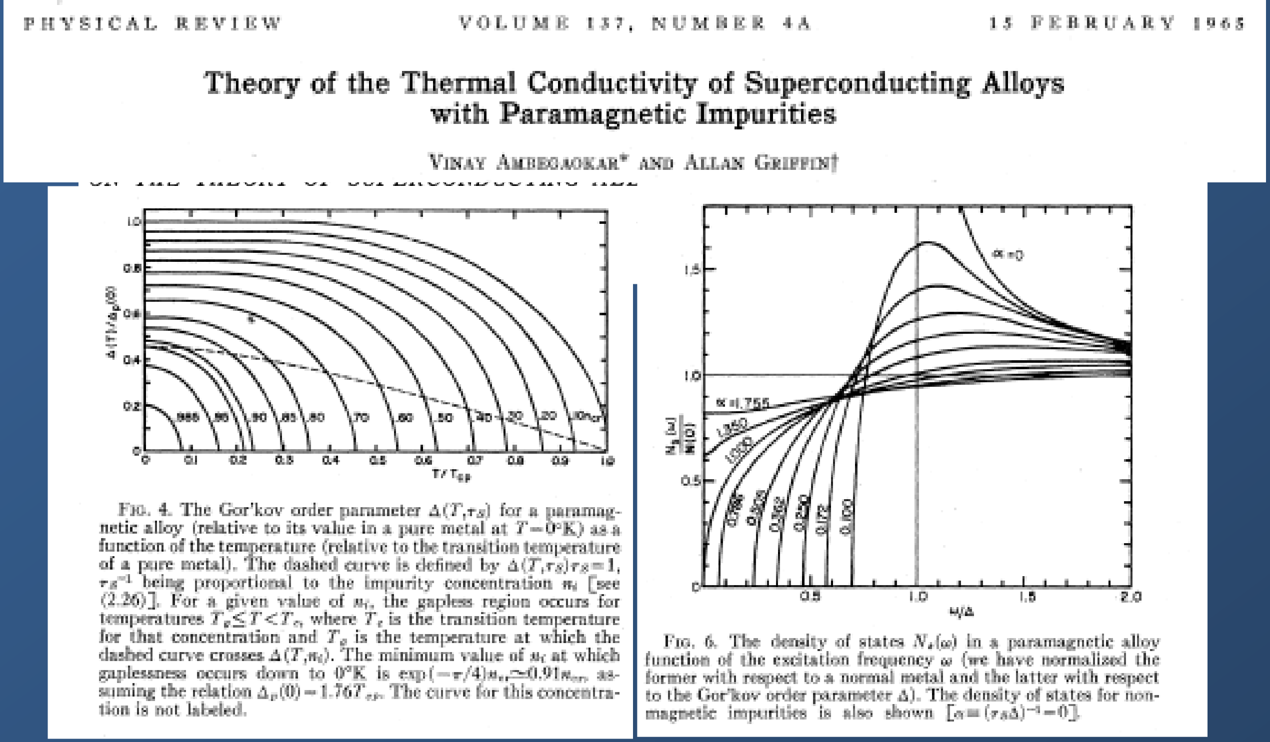




Superconducting stiffness: power law dependence on temperature

Pair breaking due to interlayer scattering

- Pair breaking due to intervalley scattering in a nodeless f-wave superconductor is equivalent to scattering by magnetic impurities in a conventional s-wave superconductor.



PHYSICAL REVIEW VOLUME 137, NUMBER 4A 15 FEBRUARY 1965

Theory of the Thermal Conductivity of Superconducting Alloys with Paramagnetic Impurities

VINAY AMBEGAOKAR* AND ALLAN GRIFFIN†

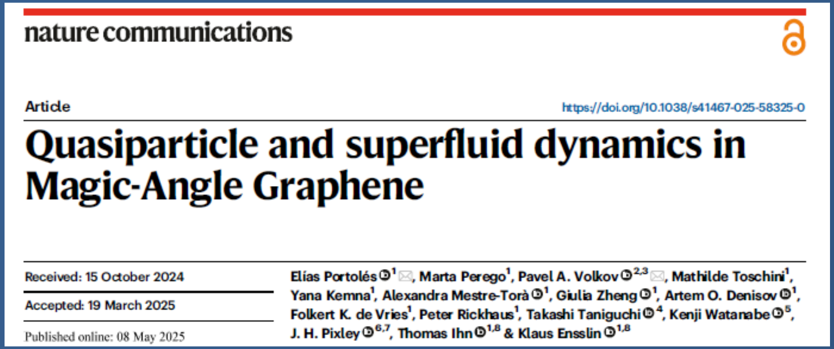
FIG. 4. The Gor'kov order parameter $\Delta(T,\tau_S)$ for a paramagnetic alloy (relative to its value in a pure metal at $T=0$°K) as a function of the temperature (relative to the transition temperature of a pure metal). The dashed curve is defined by $\Delta(T,\tau_S)\tau_S=1$, τ_S^{-1} being proportional to the impurity concentration n_i [see (2.26)]. For a given value of n_i, the gapless region occurs for temperatures $T_g \leq T < T_c$, where T_c is the transition temperature for that concentration and T_g is the temperature at which the dashed curve crosses $\Delta(T,n_i)$. The minimum value of n_i at which gaplessness occurs down to 0°K is $\exp(-\pi/4)n_{cr} \simeq 0.91 n_{cr}$, assuming the relation $\Delta_p(0)=1.76T_{cp}$. The curve for this concentration is not labeled.

FIG. 6. The density of states $N_s(\omega)$ in a paramagnetic alloy function of the excitation frequency ω (we have normalized the former with respect to a normal metal and the latter with respect to the Gor'kov order parameter Δ). The density of states for nonmagnetic impurities is also shown $[\alpha \equiv (\tau_S\Delta)^{-1}=0]$.

- The relevant energy scales are the superconducting gap, Δ, and the scattering time due to intervalley processes, τ_{iv}.
- The superconducting phase is always gapless near the critical temperature.
- The superconductor is gapless at all temperatures if $\Delta(T=0) \leq \hbar/\tau_{iv}$.

Estimates: $\Delta(T=0)$~0.5 meV, $v_F \sim v_F^G/50$, ℓ_{iv}~$50-500$ nm, $\hbar/\tau_{iv}$ ~$0.02-0.2$ meV

Dissipation in TBG Josephson junctions



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Quasiparticle and superfluid dynamics in Magic-Angle Graphene

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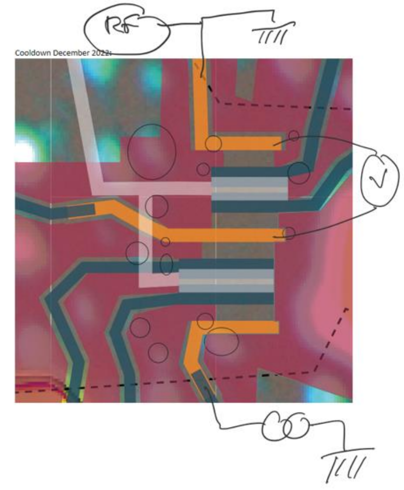
Elías Portolés[1] ✉, Marta Perego[1], Pavel A. Volkov[2,3] ✉, Mathilde Toschini[1], Yana Kemna[1], Alexandra Mestre-Torà[1], Giulia Zheng[1], Artem O. Denisov[1], Folkert K. de Vries[1], Peter Rickhaus[1], Takashi Taniguchi[4], Kenji Watanabe[5], J. H. Pixley[6,7], Thomas Ihn[1,8] & Klaus Ensslin[1,8]



$$I_c \approx 10\, nA$$
$$C = 32\, fF$$
$$R = 2.5\, k\Omega$$
$$\omega_p/2\pi = 4.9\, GHz$$
$$T \approx 10\, mK$$

$$E_J \approx 0.021\, meV$$
$$E_C \approx 0.0025\, meV$$
$$\hbar\omega_p \approx 0.02\, meV$$
$$Q \approx 2.5$$

Quantum effects

$$H = E_C \hat{Q}^2 + E_J \frac{\hat{\phi}^2}{2}$$

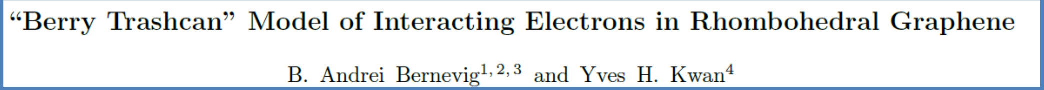
$$[\hat{Q}, \hat{\phi}] = 2i$$

$$\hat{Q} = 2i\partial_\phi$$

$$\psi(\phi) = \frac{2}{\sqrt{\pi}} \left(\frac{2E_C}{E_J}\right)^{1/4} e^{-\frac{1}{4}\sqrt{\frac{E_J}{2E_C}}\phi^2}$$

$$\langle \phi^2 \rangle = \sqrt{\frac{8E_C}{E_J}}$$

$\langle \phi^2 \rangle \approx$0.99



“Berry Trashcan” Model of Interacting Electrons in Rhombohedral Graphene

B. Andrei Bernevig[1,2,3] and Yves H. Kwan[4]

arXiv:2503.09692