Title: Seminar: Quantum matter in Moire materials

Speakers: Pablo Jarillo-Herrero

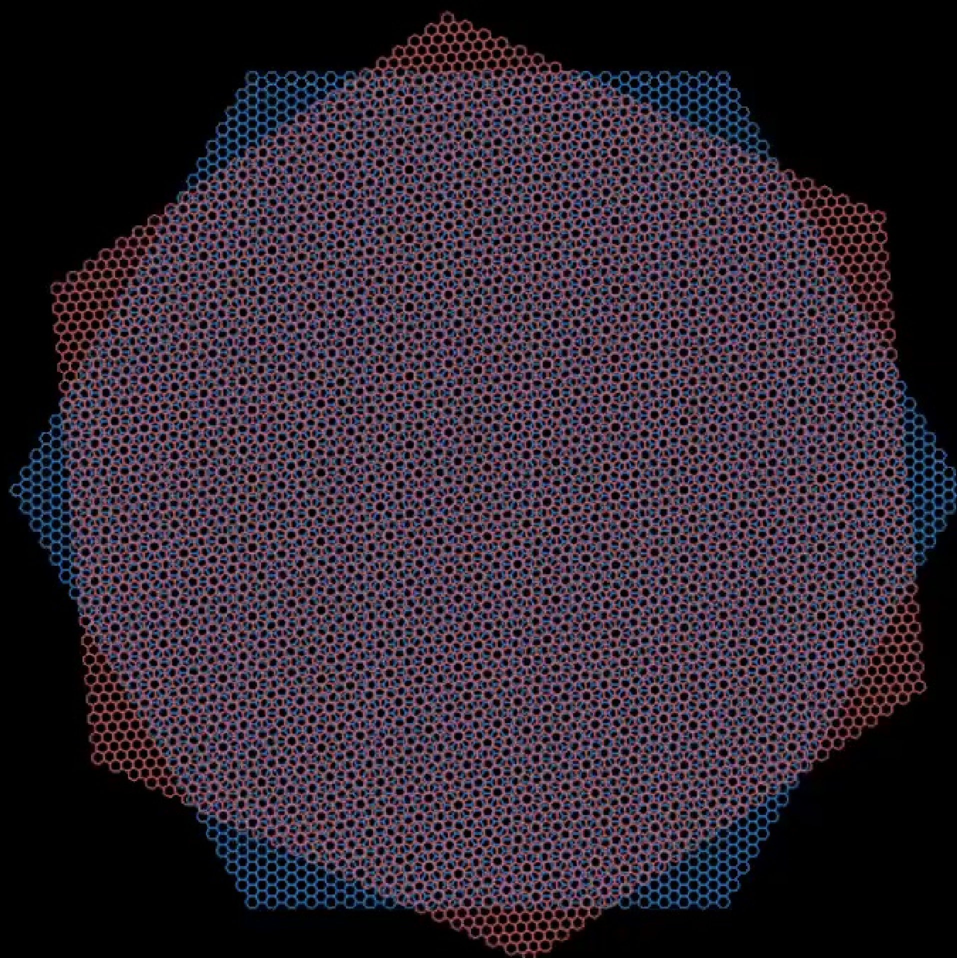
Collection: Online School on Ultra Quantum Matter

Date: August 11, 2020 - 12:40 PM

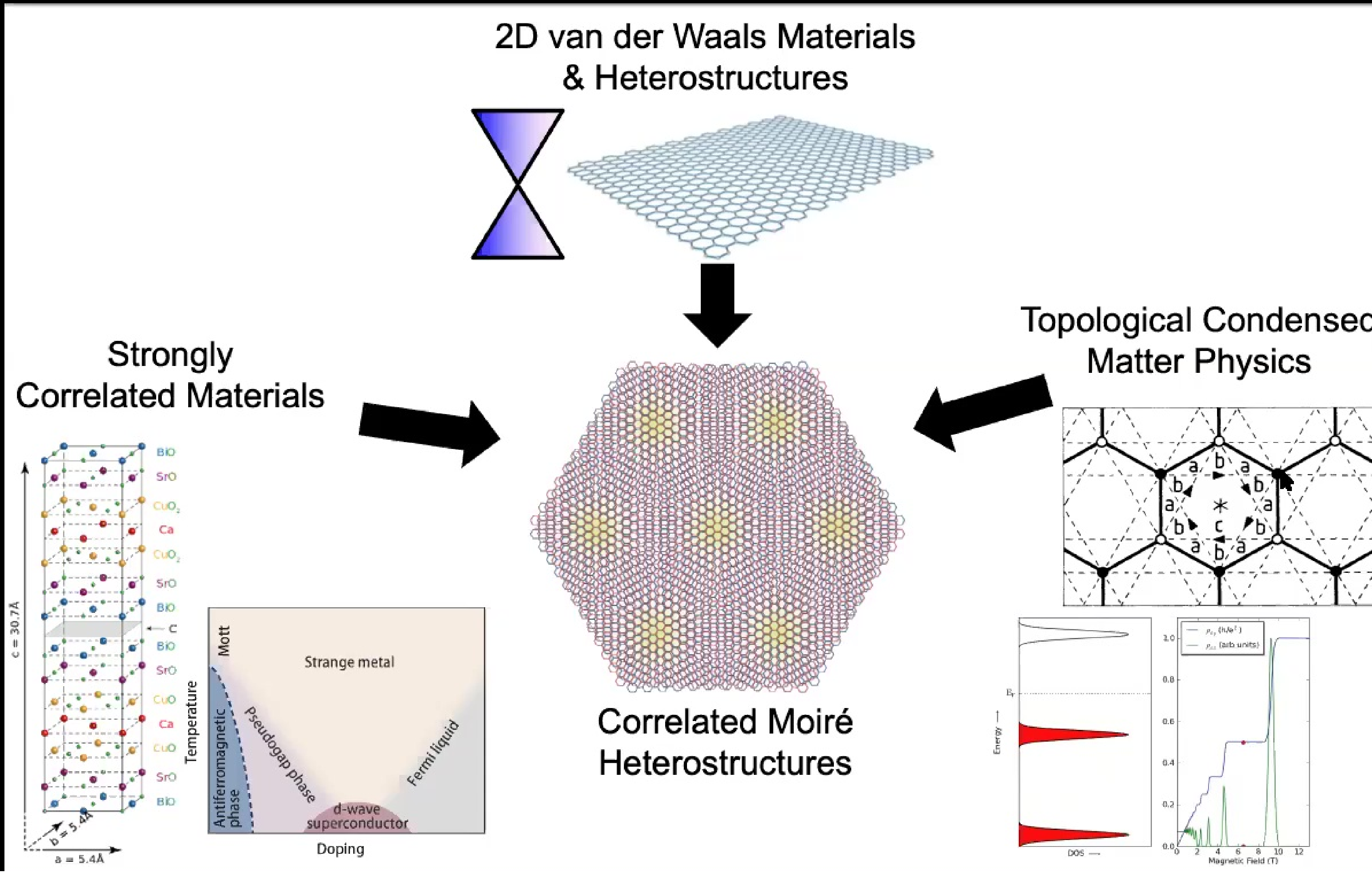
URL: http://pirsa.org/20080019

Competing Orders, Nematicity, and Phase Transitions in Magic-Angle Graphene

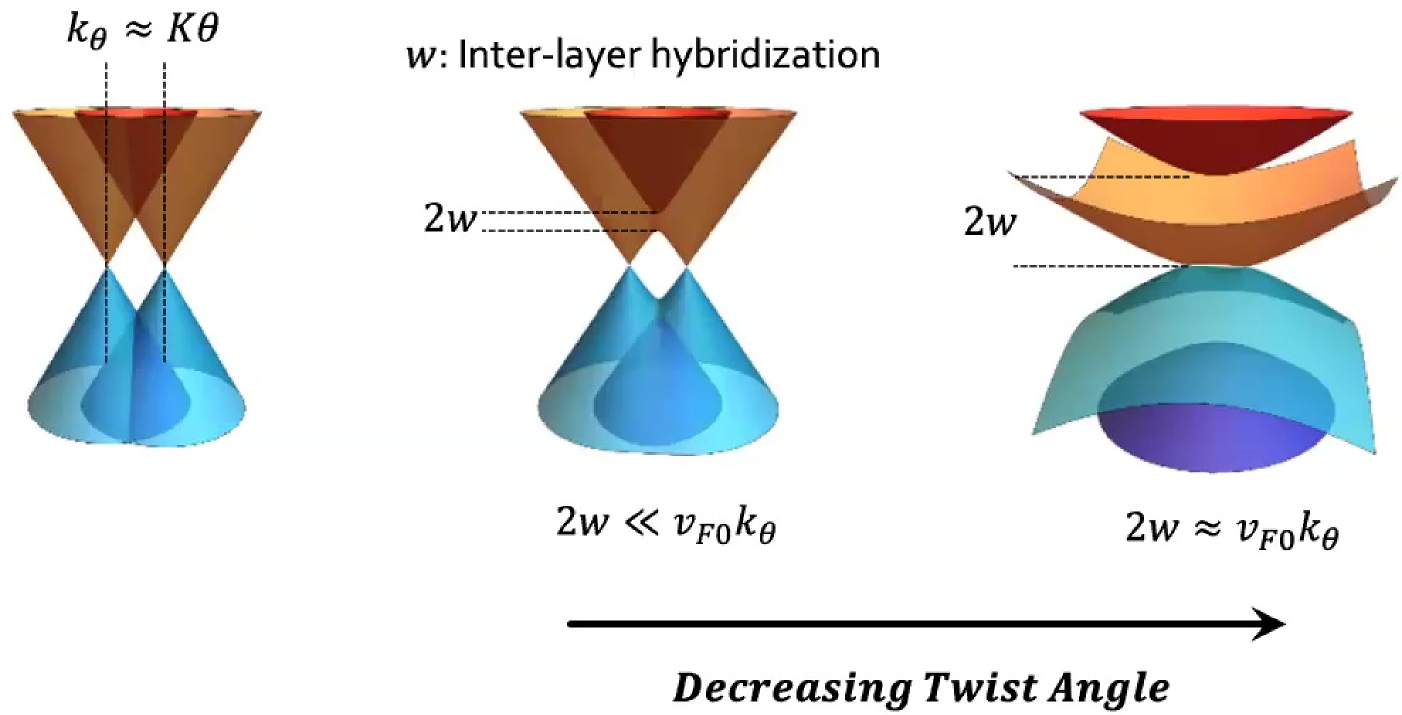
Pablo Jarillo-Herrero



Correlated Moiré Heterostructures -> merging of modern condensed matter communities



Magic-Angle Twisted Bilayer Graphene (MATBG)

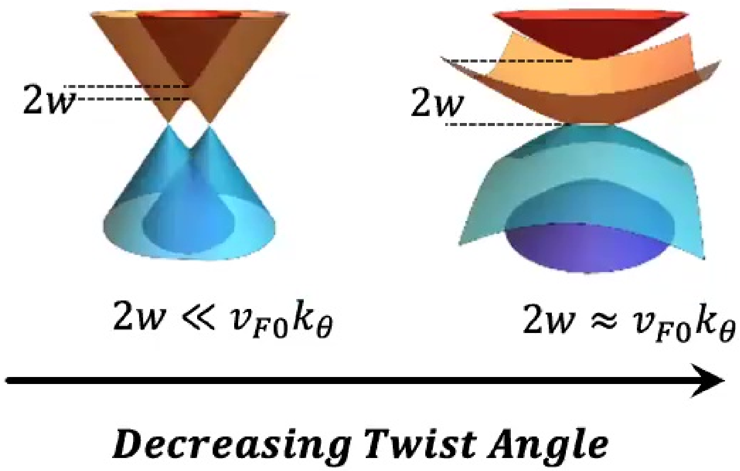


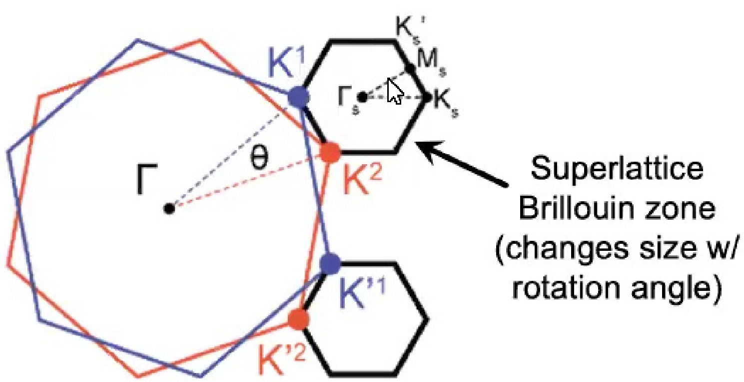
"Flat Band" condition is reached at the "Magic Angle"

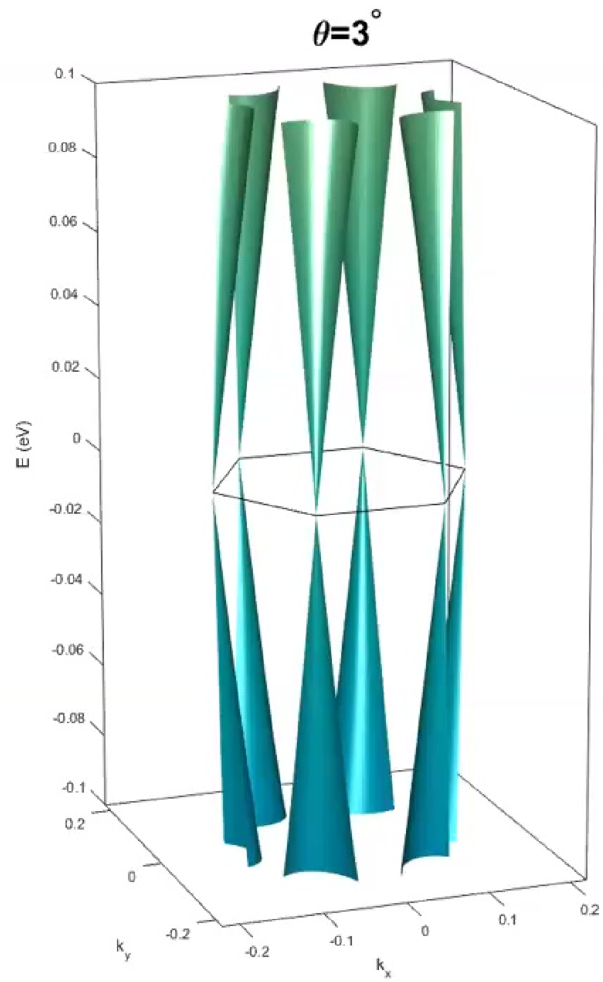
$$\theta_M \approx 1.1°$$

Bistritzer & MacDonald, *PNAS* (2011)
Also: Li *et al. Nature. Phys.* (2010)
Suarez-Morell *et al. PRB* (2010)

Magic-Angle Twisted Bilayer Graphene (MA-TBG)

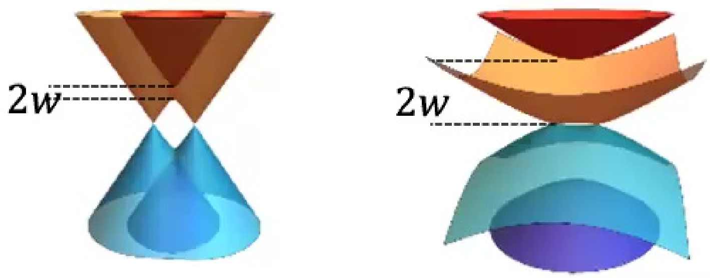






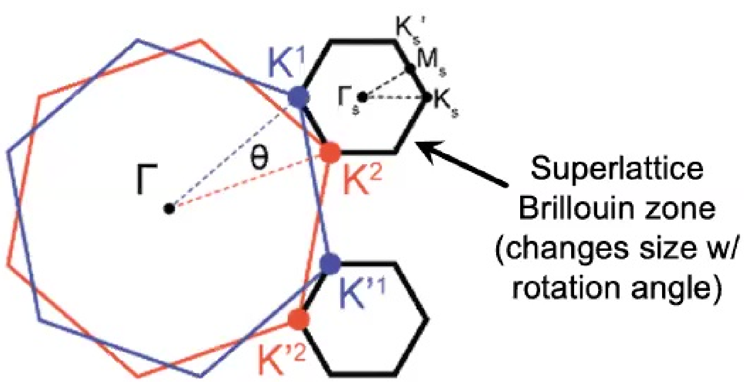
Cao, PJH *et al.* *Nature* **556**, 80 (2018)
Cao, PJH *et al.* *Nature* **556**, 43 (2018)

Magic-Angle Twisted Bilayer Graphene (MA-TBG)

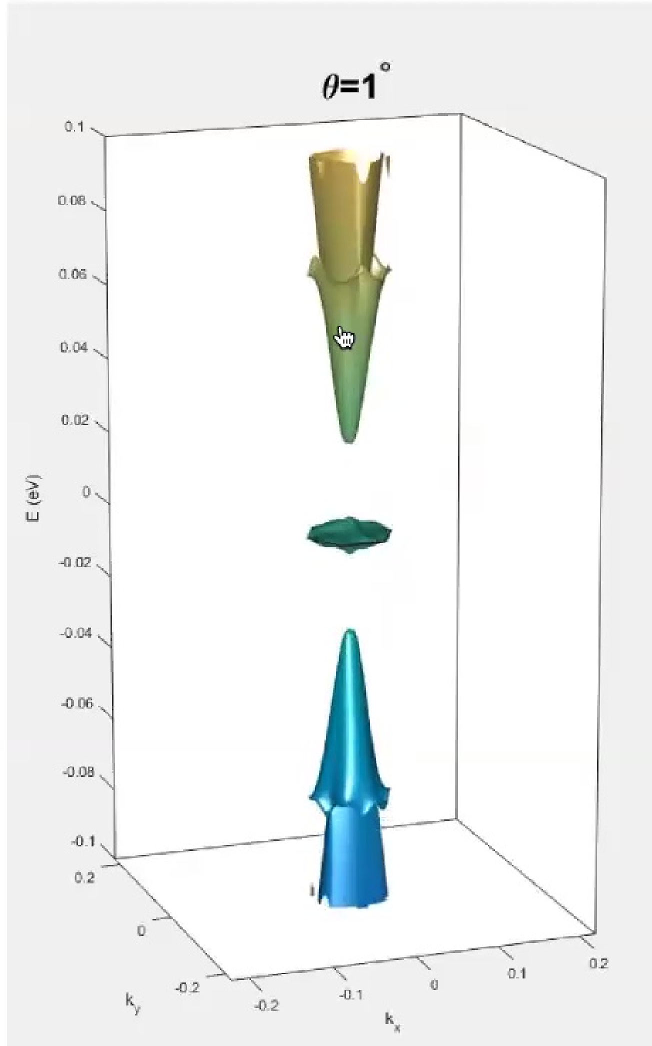


$2w \ll v_{F0} k_\theta$ $2w \approx v_{F0} k_\theta$

Decreasing Twist Angle



Cao, PJH *et al. Nature* **556**, 80 (2018)
Cao, PJH *et al. Nature* **556**, 43 (2018)



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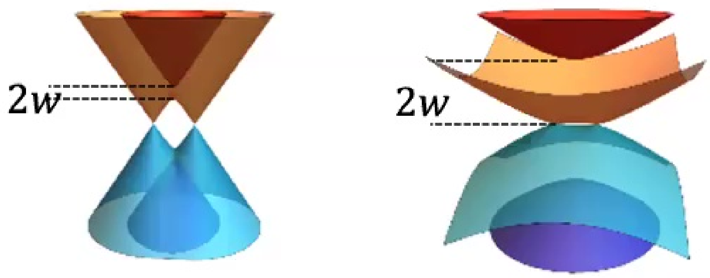

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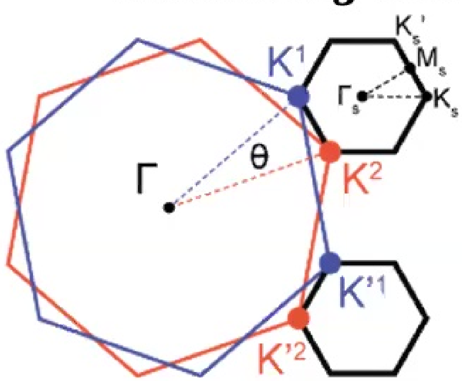
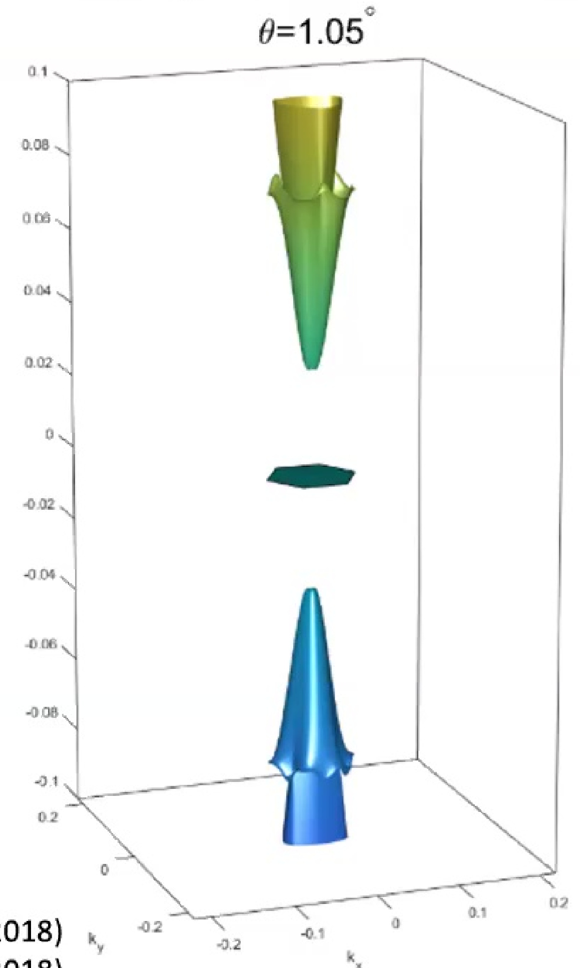


$\theta_M \approx 1.05°$

Including lattice relaxation



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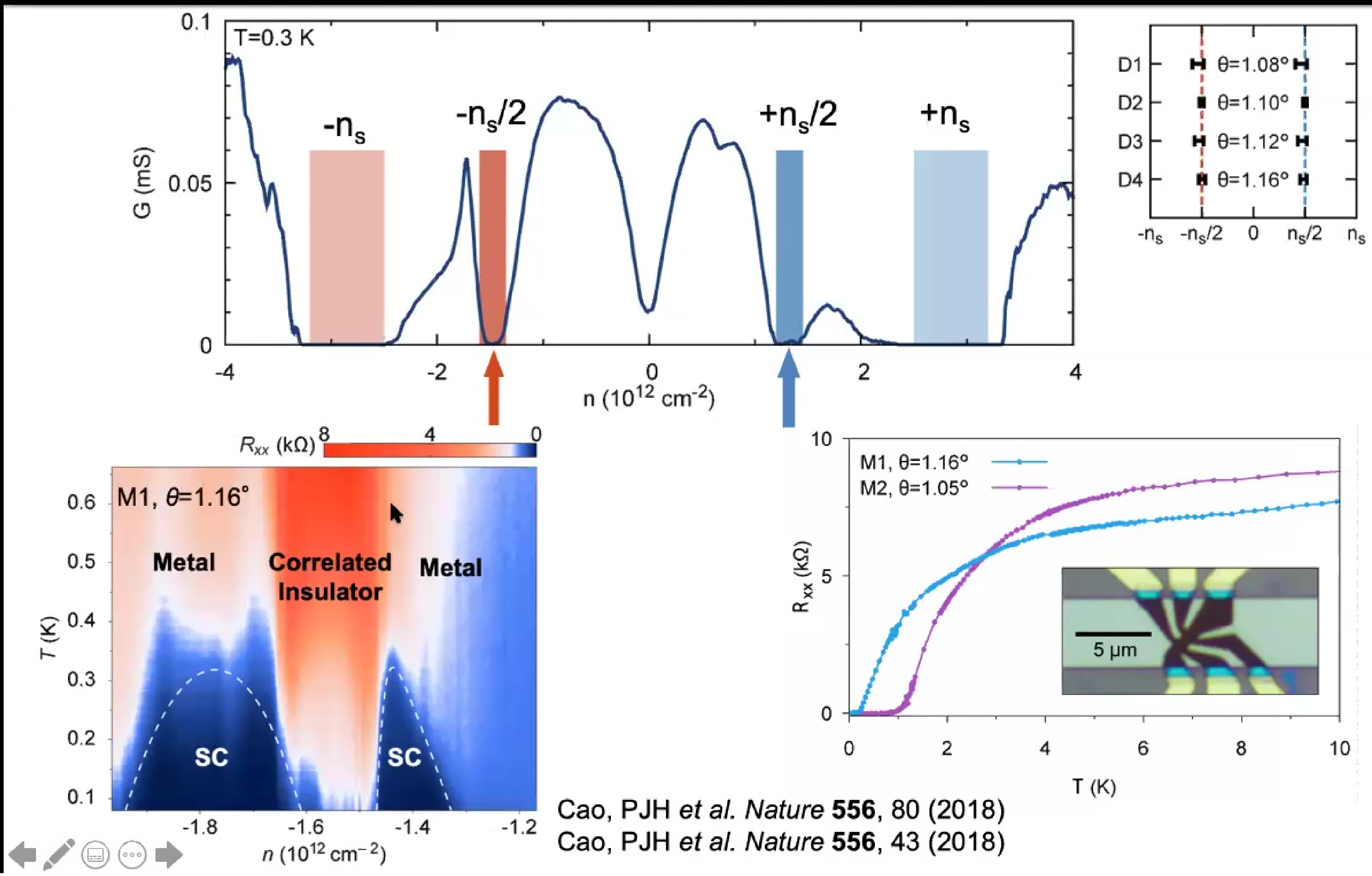
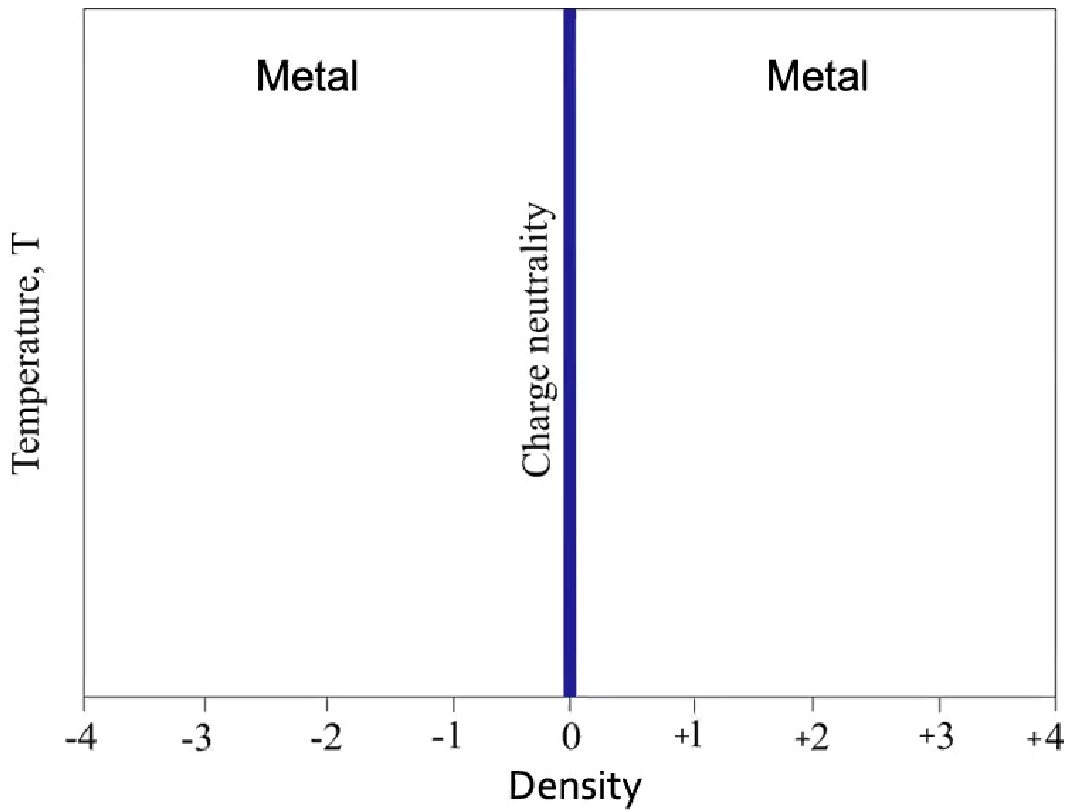
Cao, PJH *et al. Nature* **556**, 80 (2018)
Cao, PJH *et al. Nature* **556**, 43 (2018)

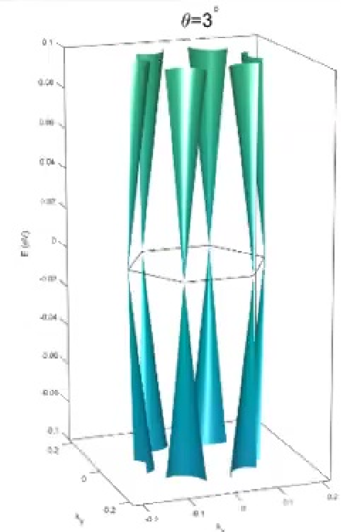
Correlated insulator states & Superconductivity in Magic Angle Graphene



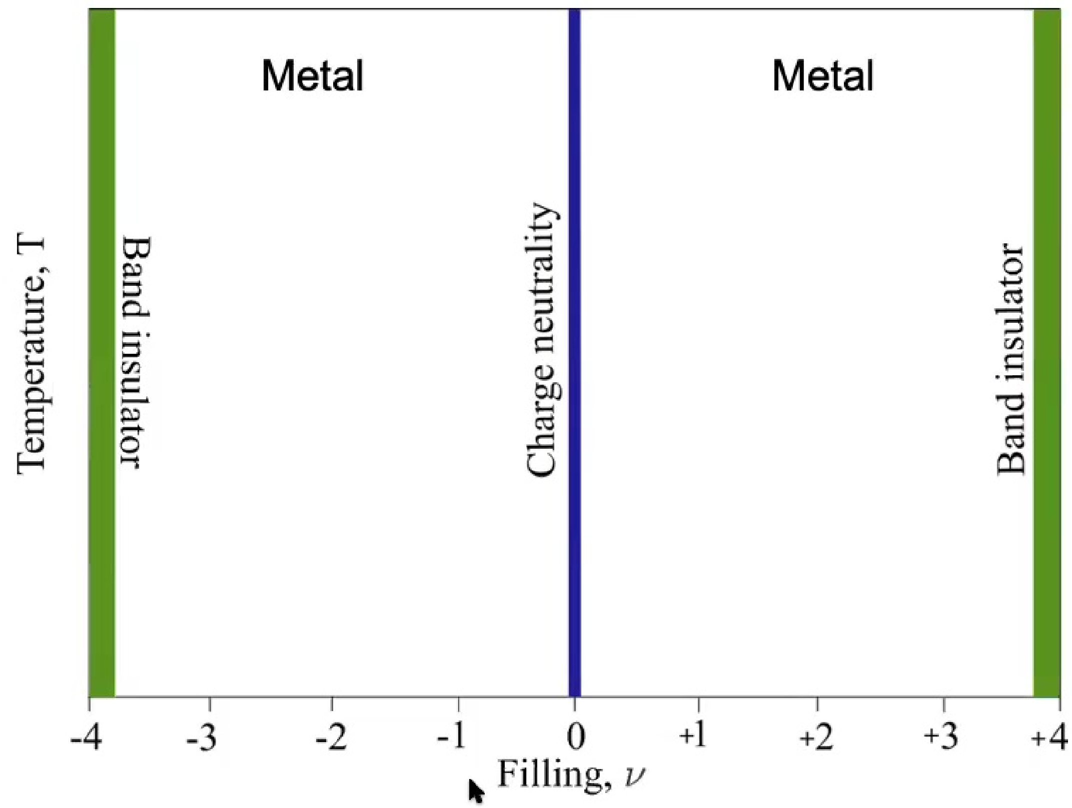
Cao, PJH *et al. Nature* **556**, 80 (2018)
Cao, PJH *et al. Nature* **556**, 43 (2018)

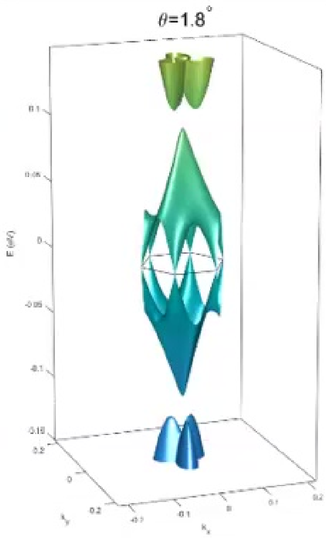
Phase diagram graphene
(also large angle twisted bilayer)





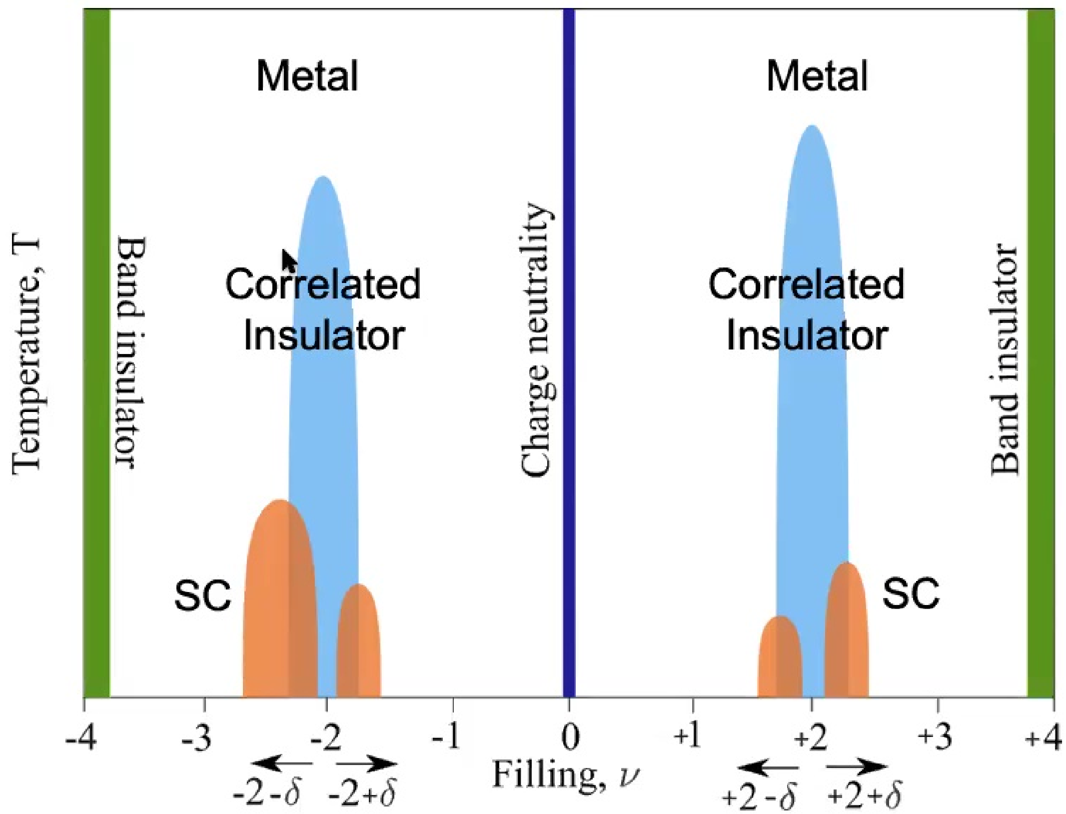
Phase diagram twisted bilayer graphene (small angle)

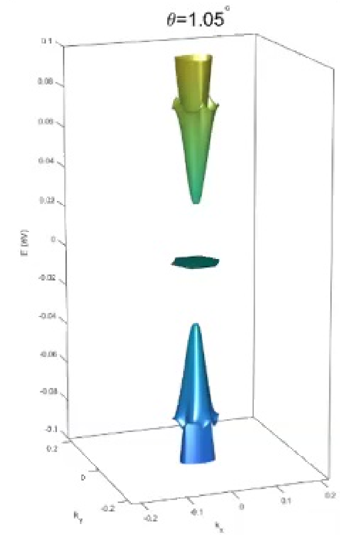




Cao, PJH *et al. Phys. Rev. Lett.* (2016)
Related work: Kim *et al. PNAS* (2017)

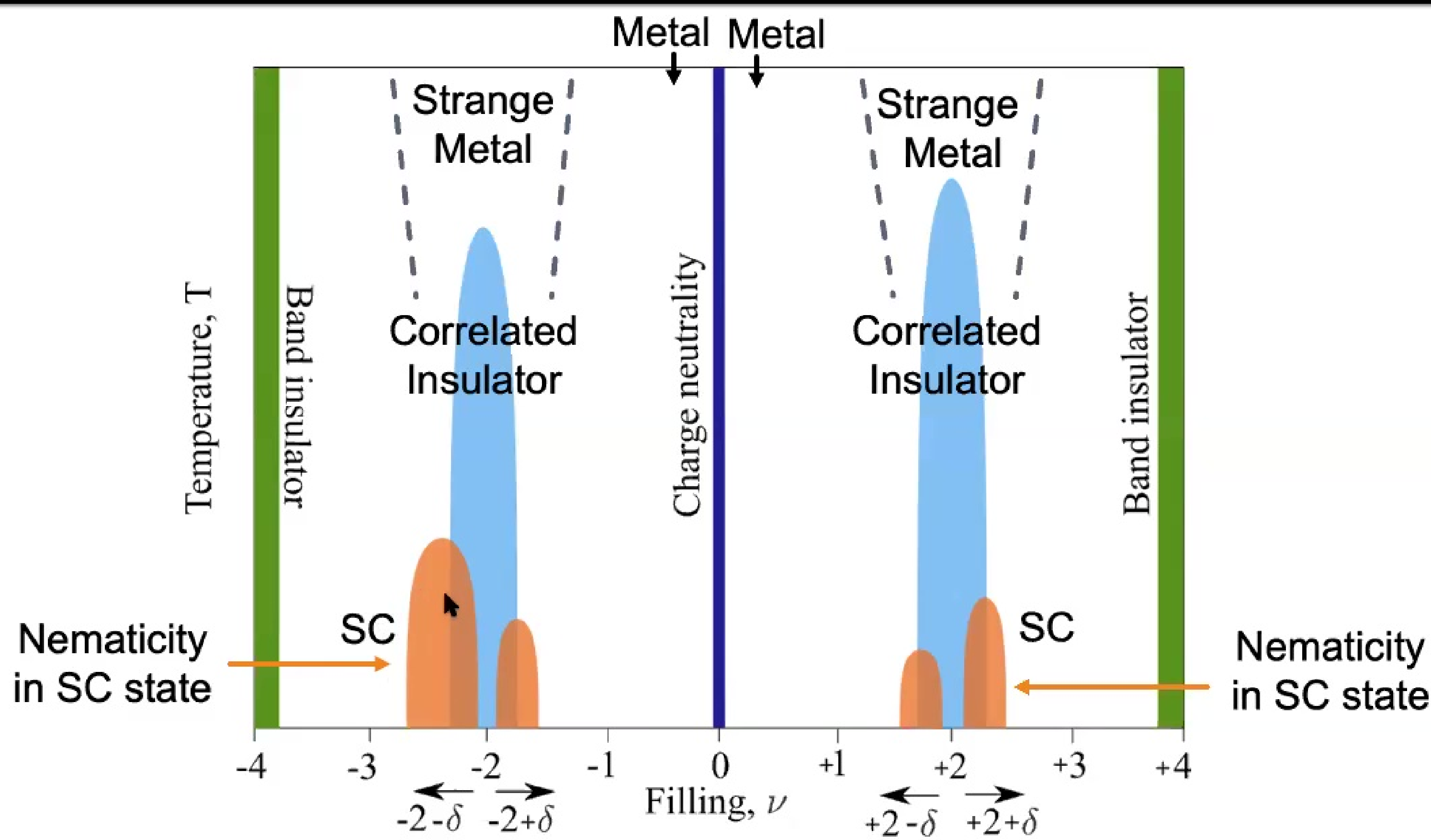
Phase diagram twisted bilayer graphene (magic angle) (schematic, mid 2018)





Cao *et al.* Nature **556**, 43 (2018)
Cao *et al.* Nature **556**, 80 (2018)
Related correlated insulator work on ABC Trilayer graphene on hBN:
Wang group: Chen et al. *Nature Physics* **15**, 237 (2019)

Phase diagram MATBG from Global Transport Measurements (schematic, θ-dependent & evolving fast!)



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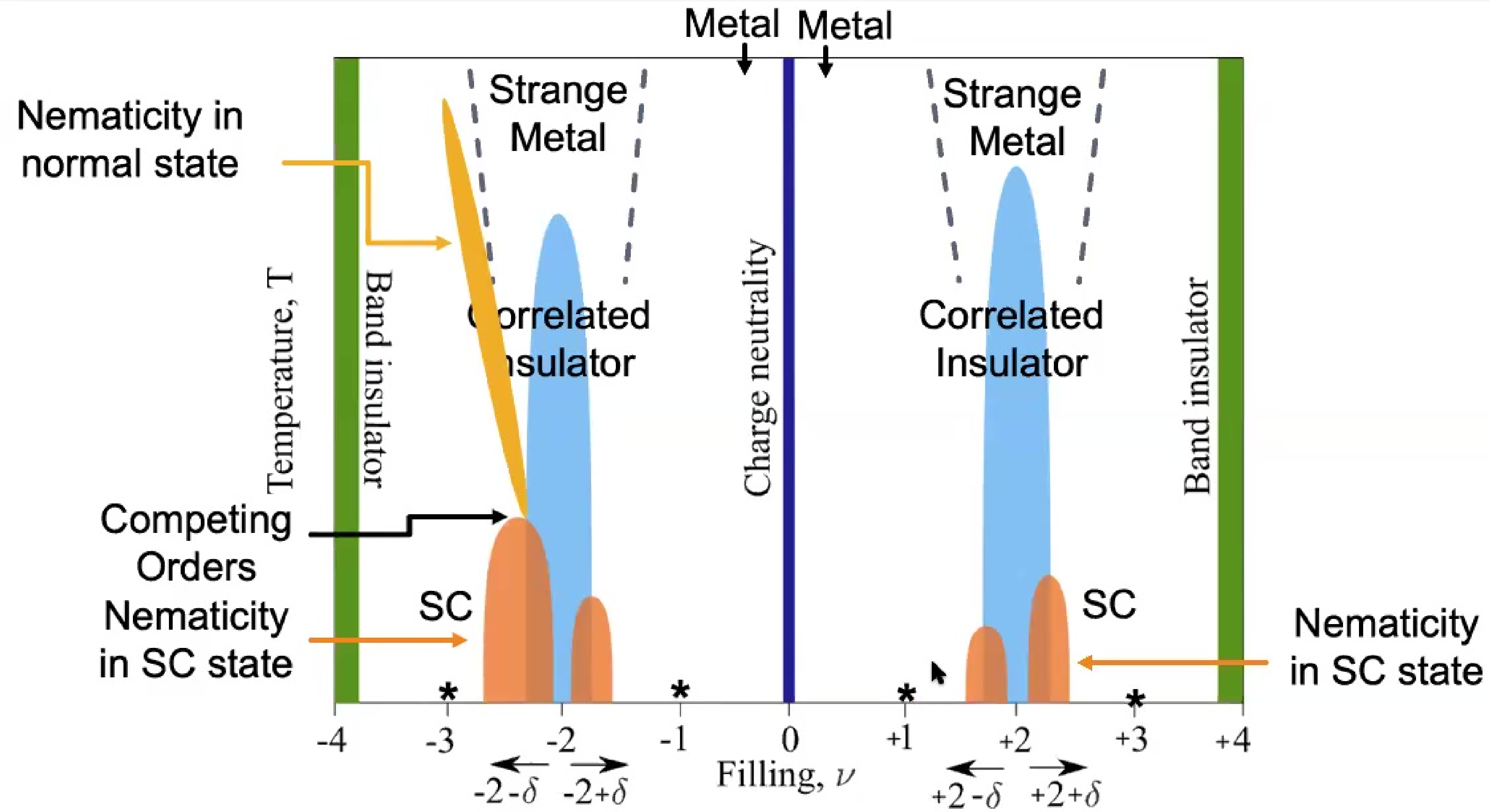


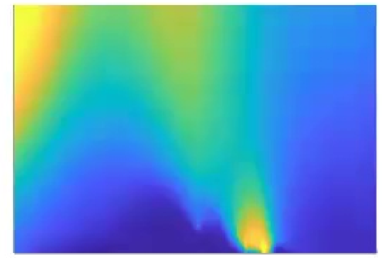
*: Interesting correlated physics also present at fillings ±1 & ±3 !

Cao *et al.* Nature **556**, 43 (2018) & Nature **556**, 80 (2018); Cao *et al.* *PRL* **124**, 076801 (2020)

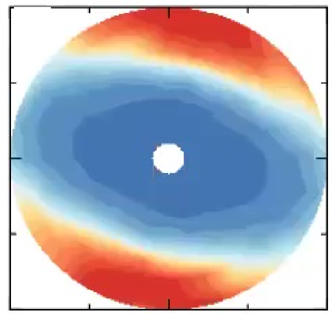
See also: Yankowitz *et al.* Science (2019), Sharpe *et al.* Science (2019), and Lu *et al.* Nature (2019)

Recent STM work: Kerelsky *et al.;* Jiang et al.; Xie et al. Nature (2019), Choi et al. Nat. Phys. (2019)

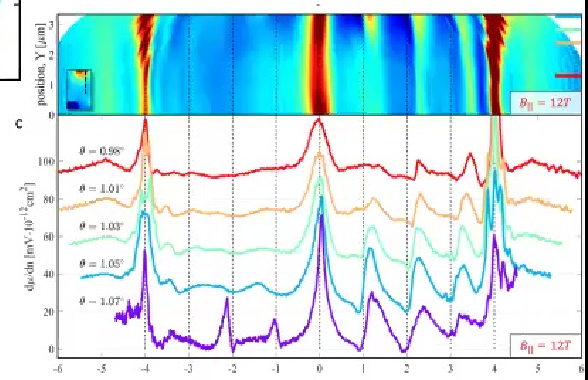
Outline



- Competing orders in MATBG

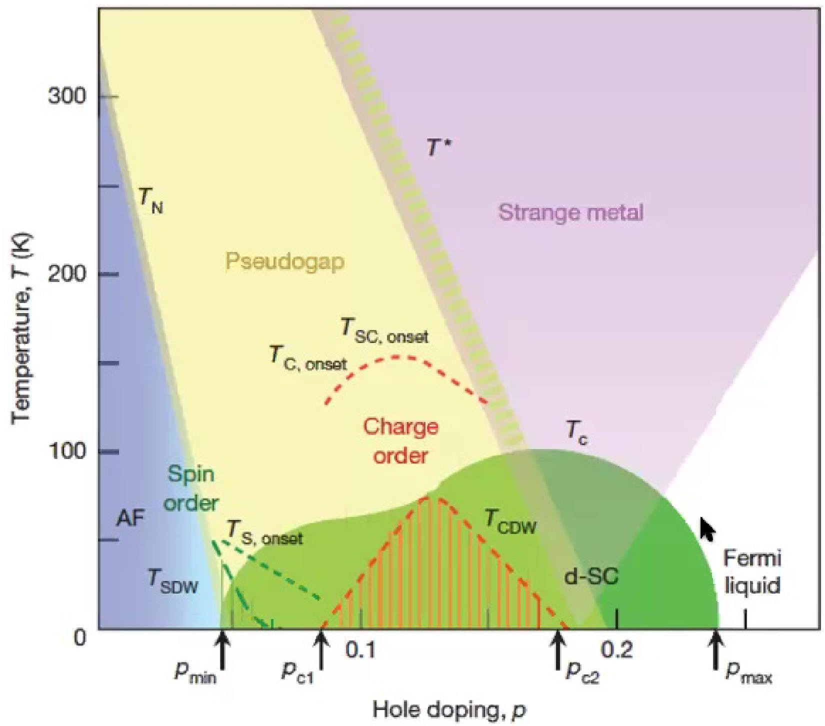


- Nematicity in MATBG



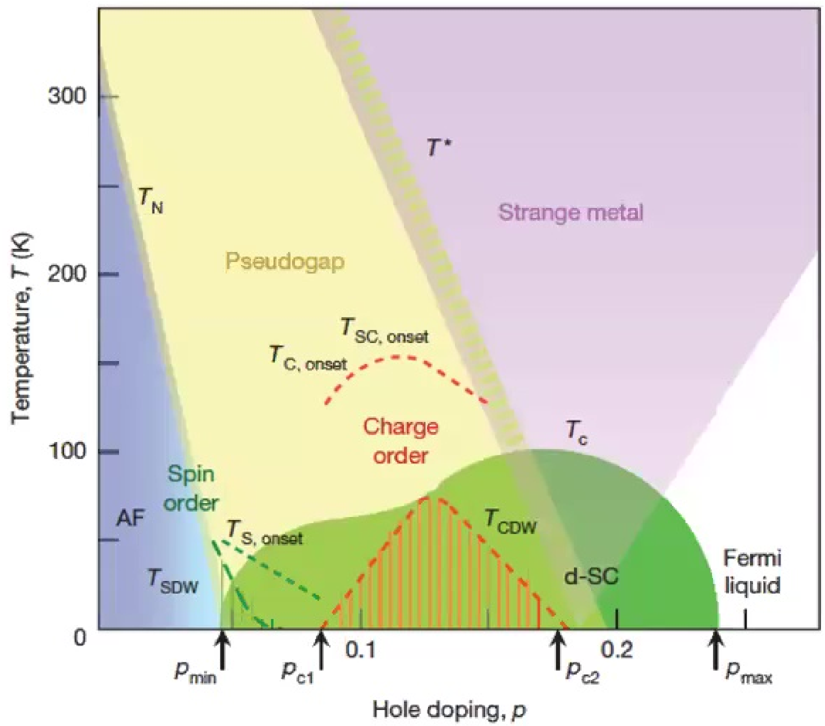
- Compressibility: Cascade of Phase Transitions & Dirac revivals

"Competing/Intertwined" Orders in Cuprates

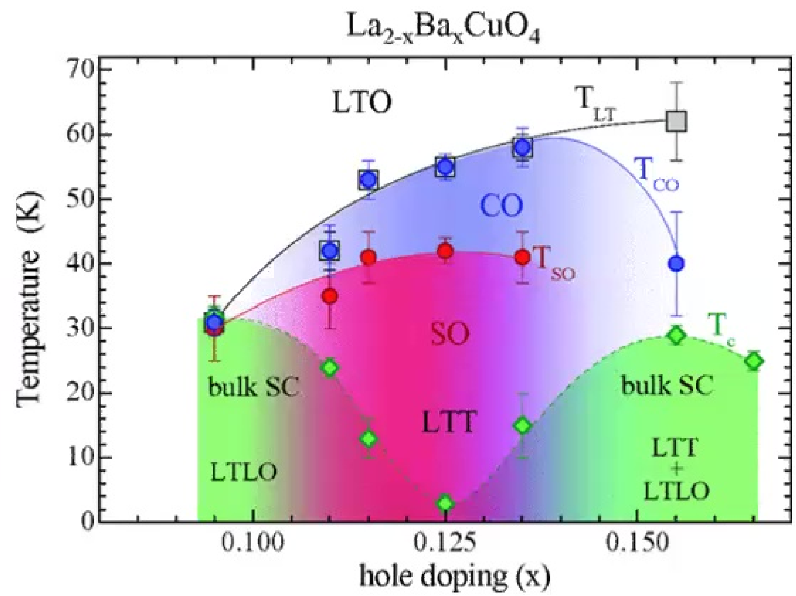


Kaimer *et al.* Nature (2015)

"Competing/Intertwined" Orders in Cuprates



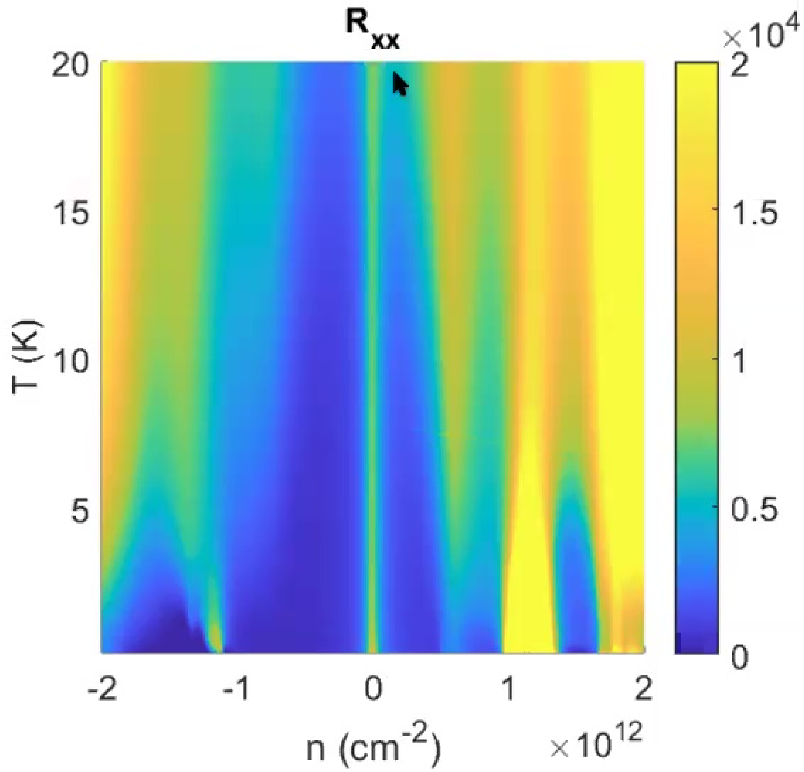
Kaimer *et al.* Nature (2015)



Hucker *et al.* Phys. Rev. B 83, 104506 (2011)

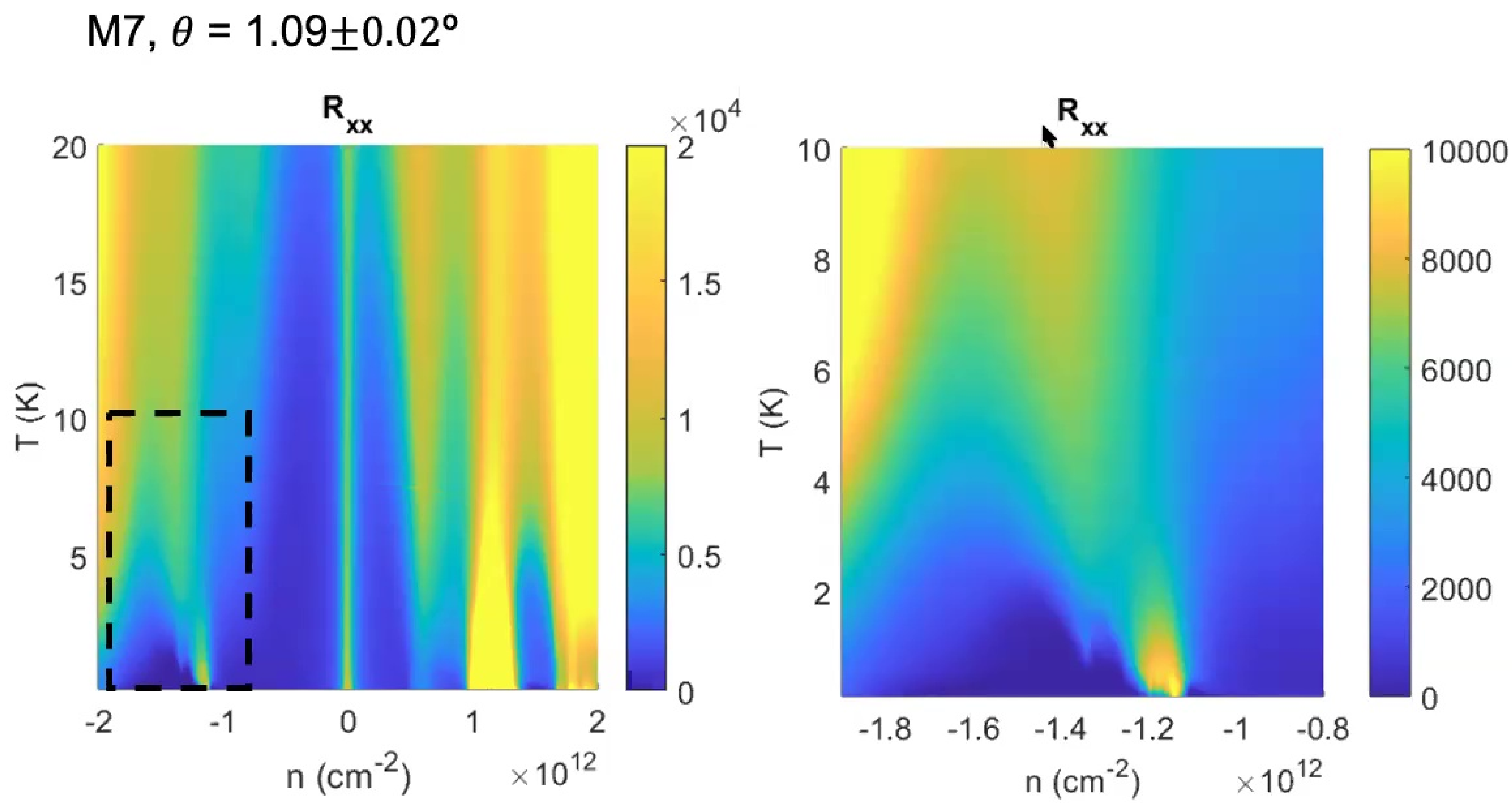
"High-T" Phase diagram MATBG

M7, $\theta = 1.09 \pm 0.02°$



Cao, et al…PJH, arxiv.2004.04148 (2020)

"High-T" Phase diagram MATBG



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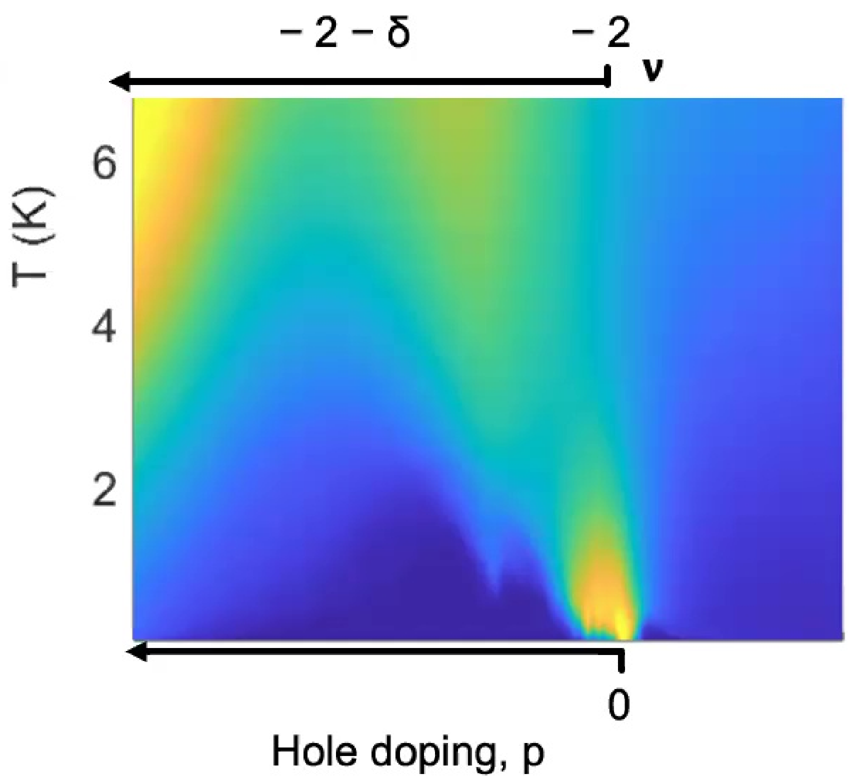
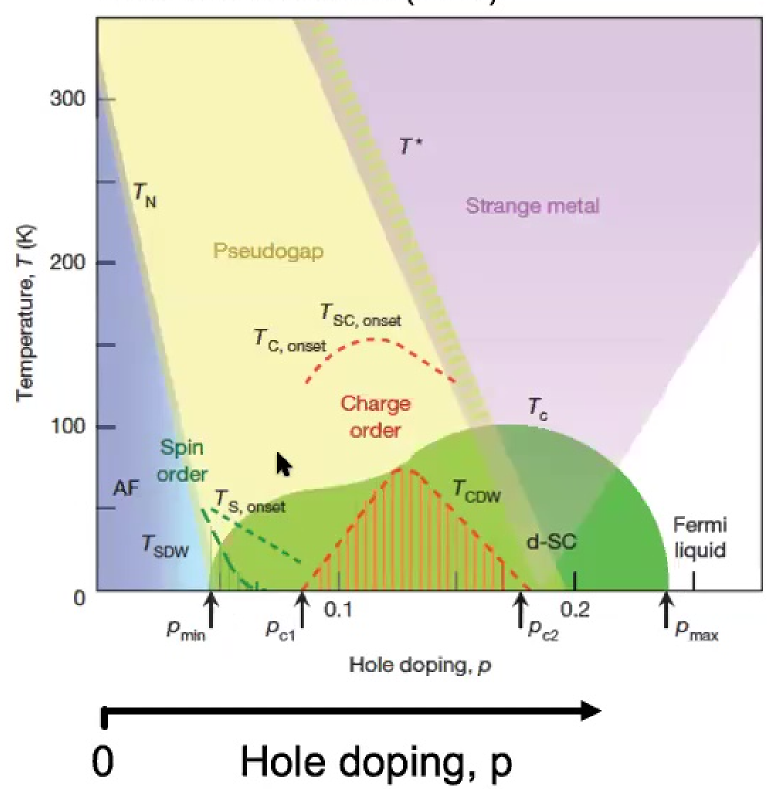
"Competing/Intertwined" Orders in Cuprates

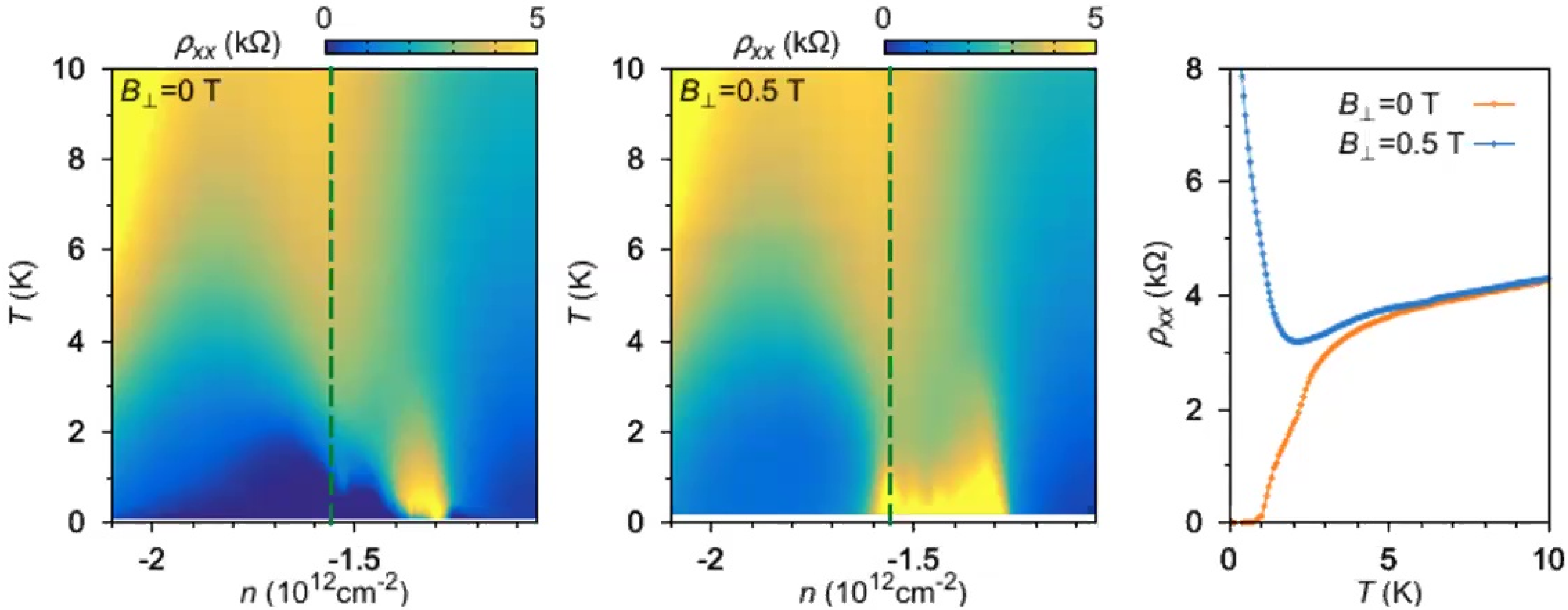


Kaimer *et al.* Nature (2015)



Cao, et al…PJH, arxiv.2004.04148 (2020)

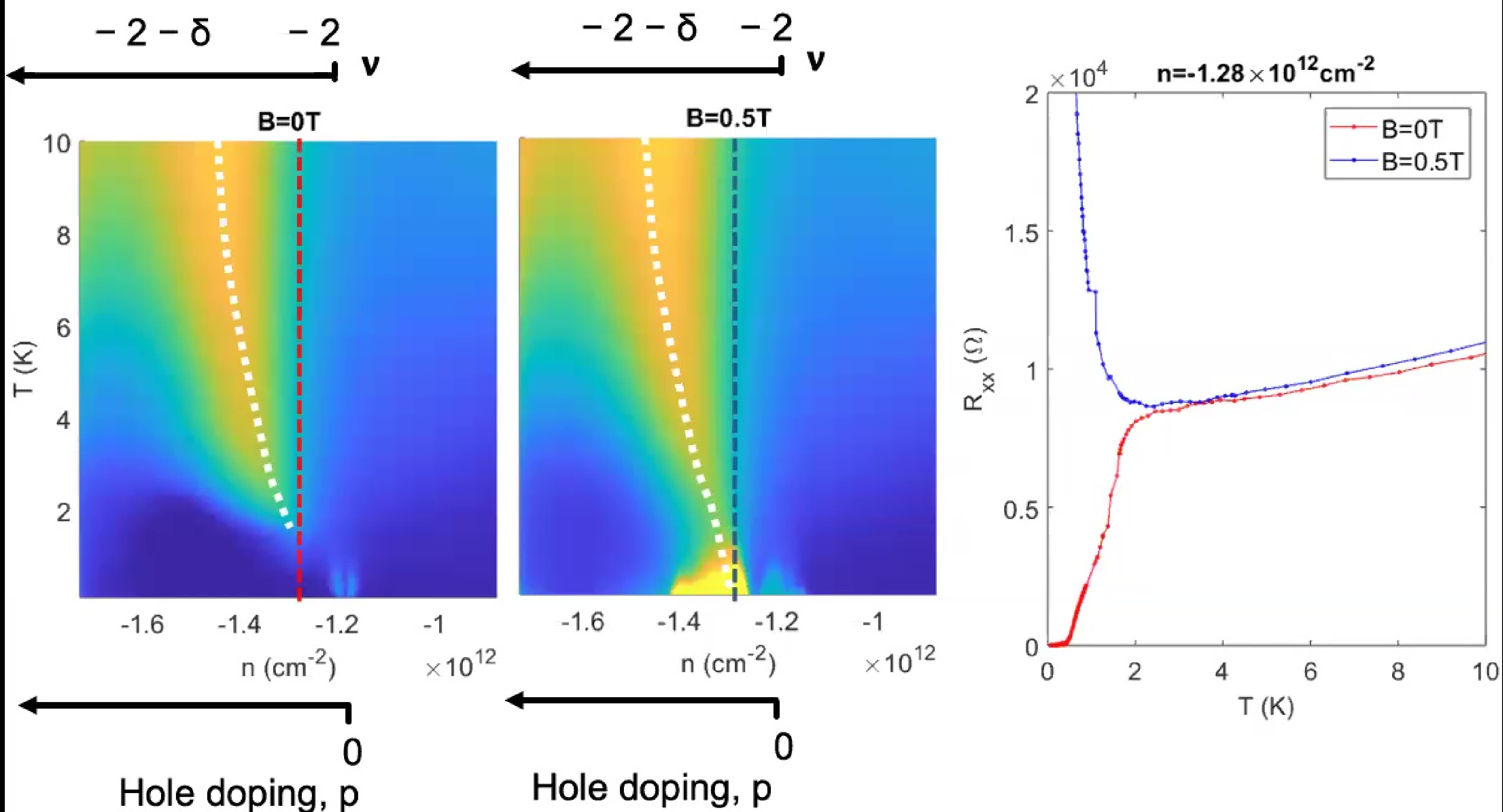
“Competing/Intertwined” Orders in MATBG!



Cao, et al…PJH, arxiv.2004.04148 (2020)

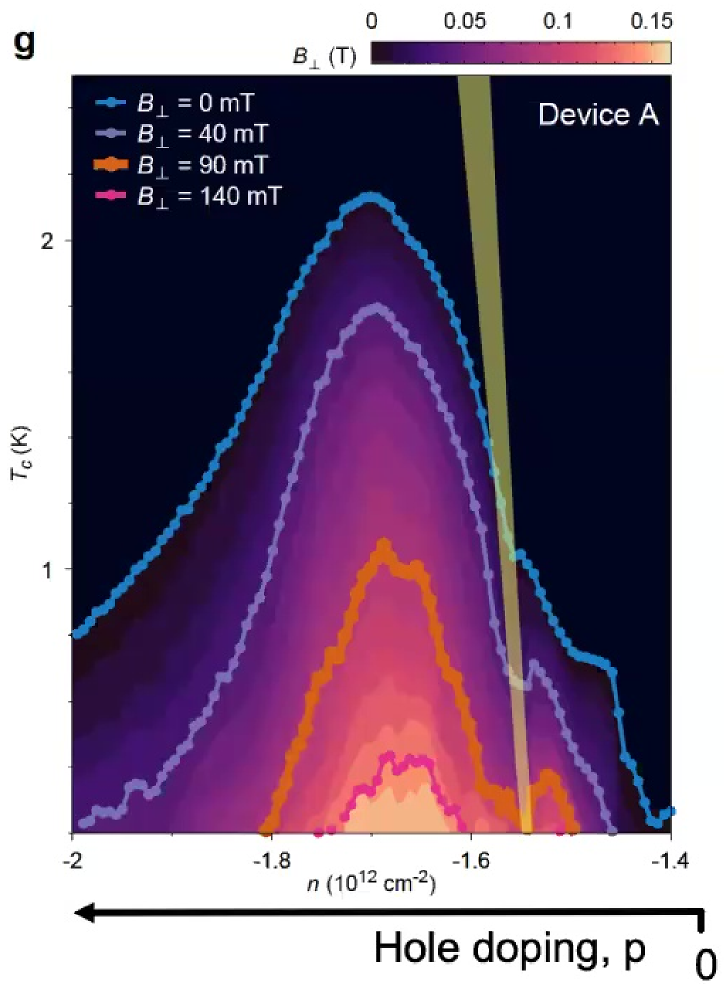
"Competing/Intertwined" Orders in MATBG!

M6, $\theta = 1.07 \pm 0.03°$

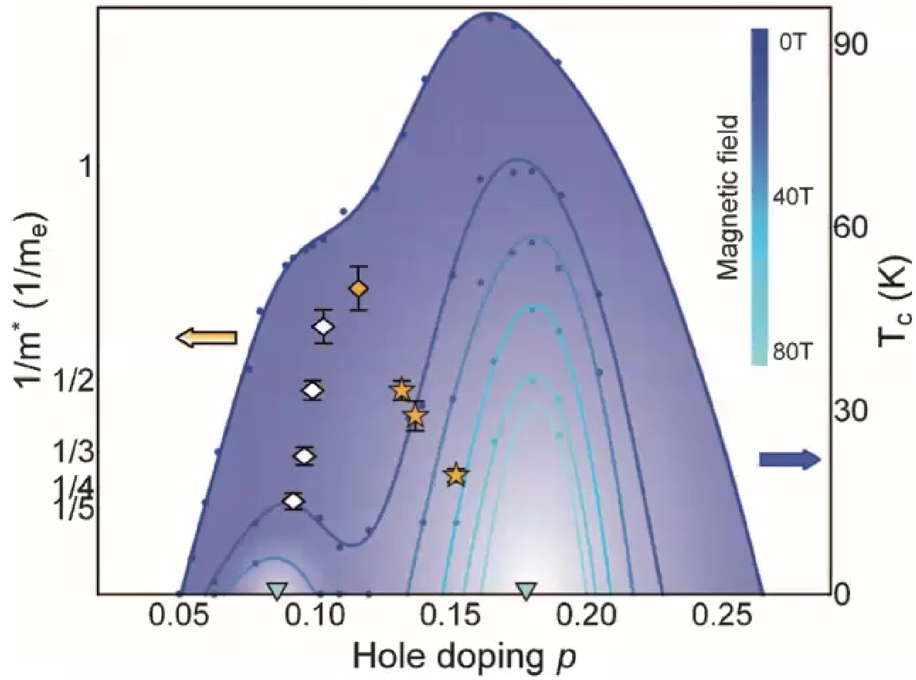


"Competing/Intertwined" Orders in MATBG!

Cao, et al…PJH, arxiv.2004.04148 (2020)



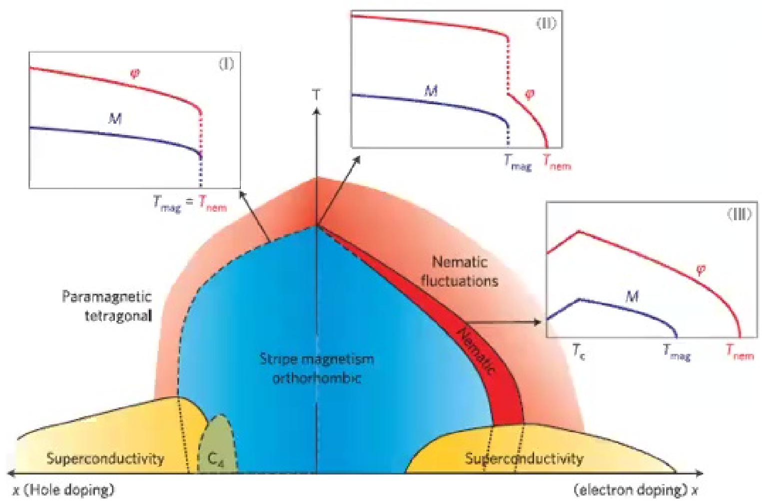
Ramshaw et al. Science **348**, 317 (2015)



Nematicity in correlated materials

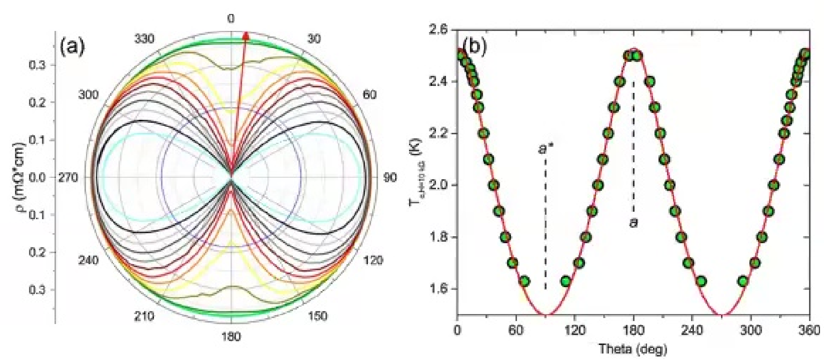
- Nematicity means spontaneous breaking of lattice rotational symmetry of order parameter
- Many families of quantum materials show this: pcnictides, cuprates, heavily-doped topological insulators, etc.
- Nematicity can happen in normal state, in superconducting state, or in both, with different implications in each case.

Nematicity in pnictides



Fernandes *et al.* Nature Phys. (2014)

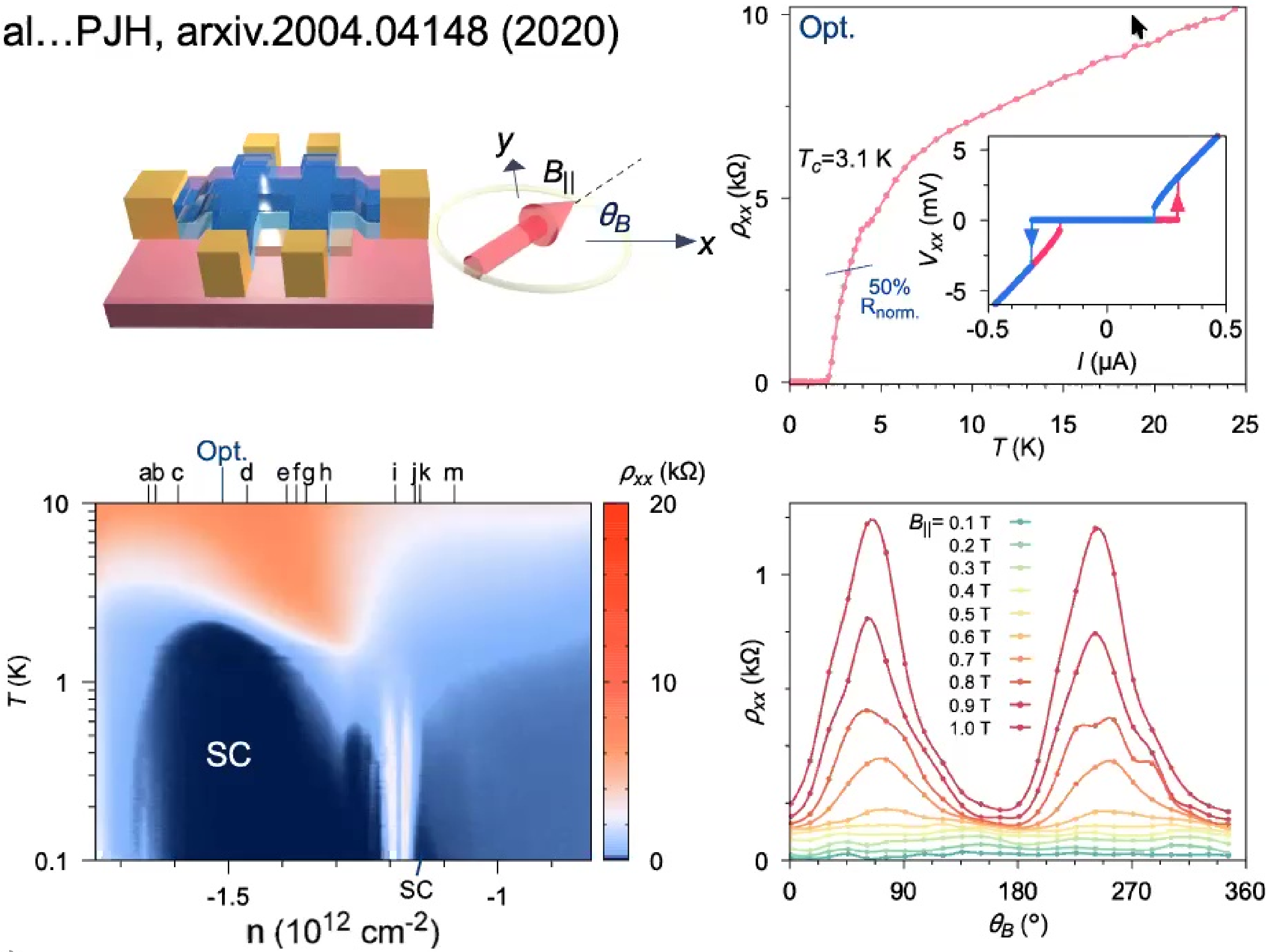
Doped topological insulator Bi2Se3 (Superconducting)



Smylie *et al.*, Scien. Reports (2018)

MABLG: Anisotropic behavior in Hc//

Cao, et al…PJH, arxiv.2004.04148 (2020)



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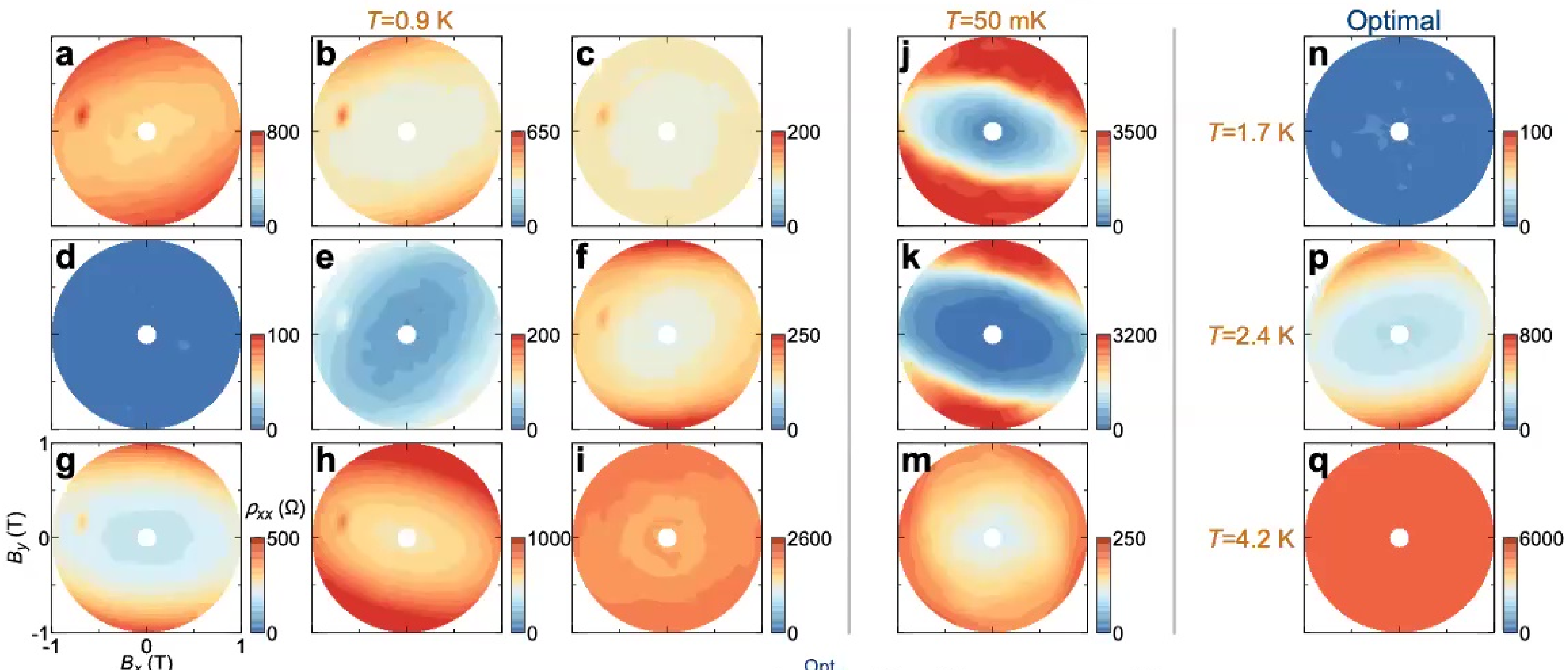
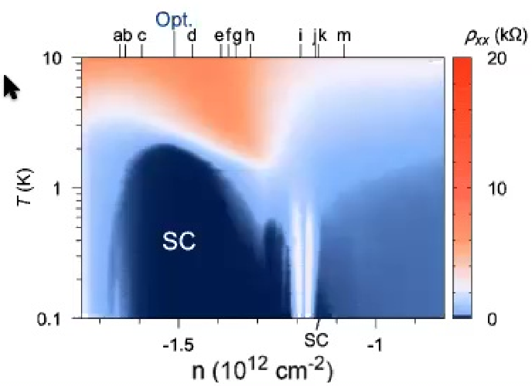
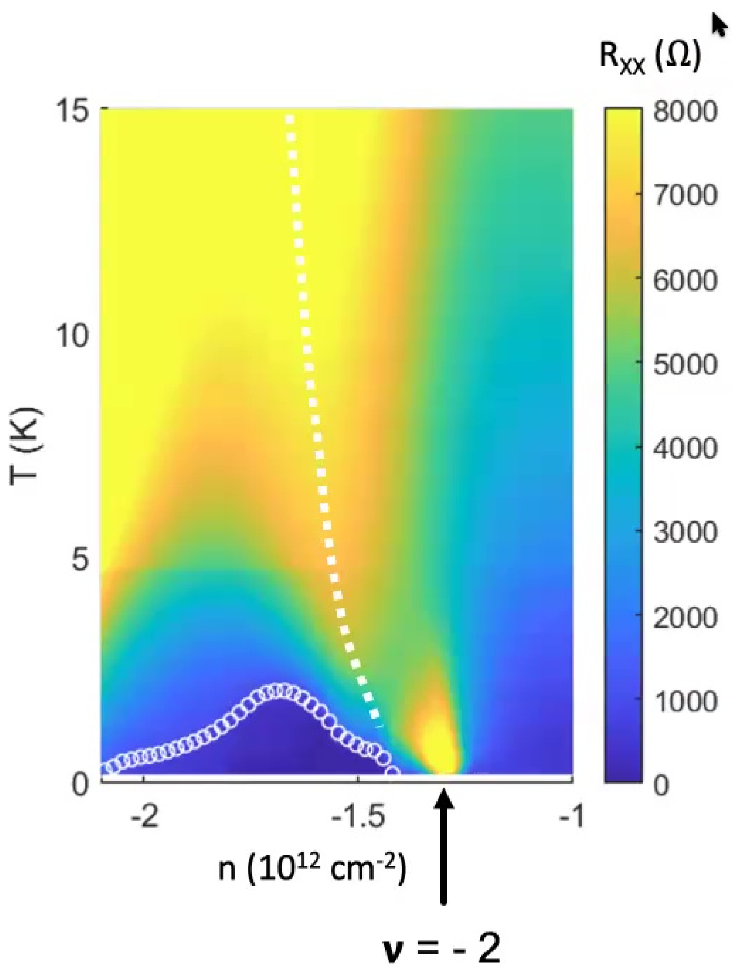


Note ellipse major axis changes direction with density!



What about normal state?



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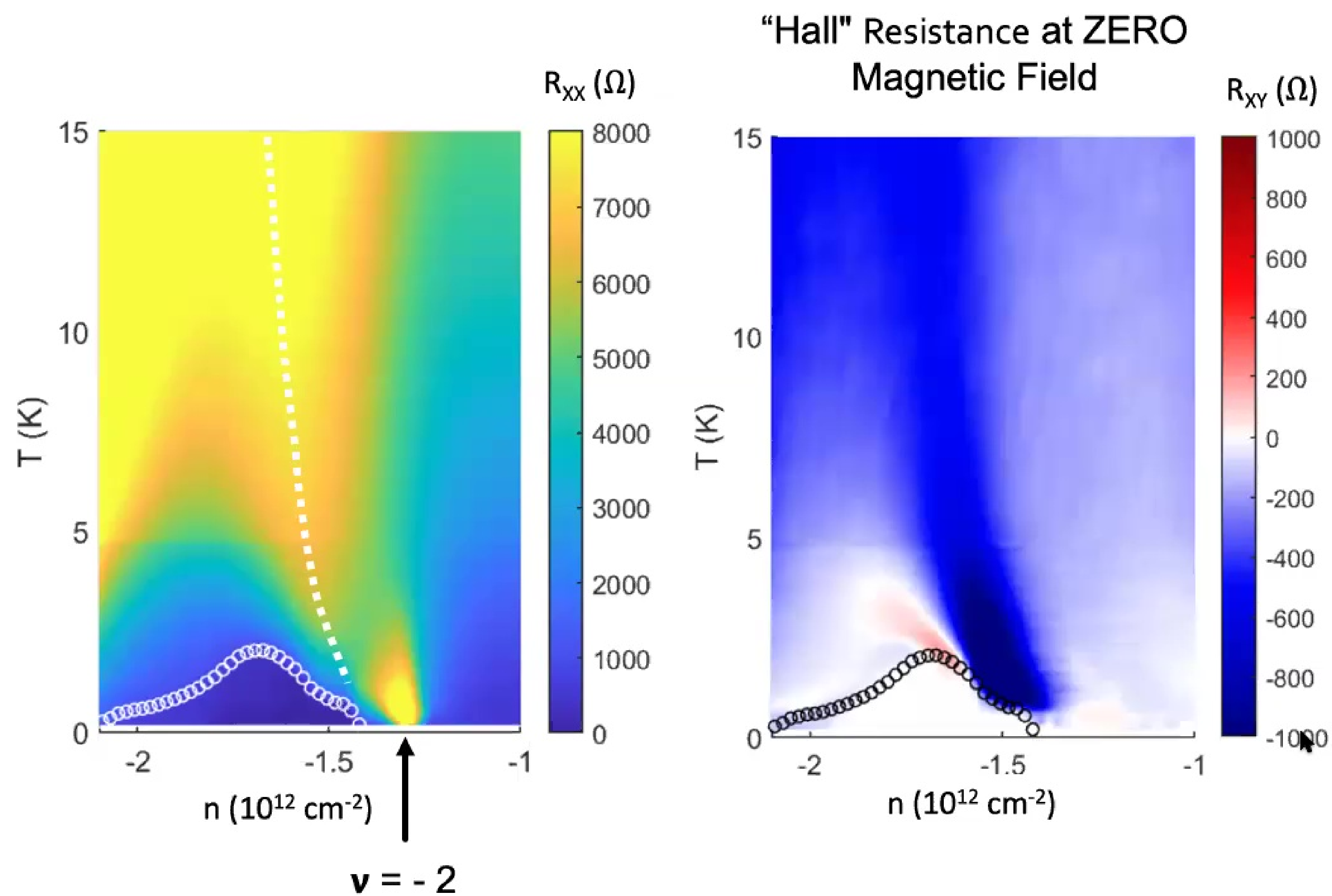
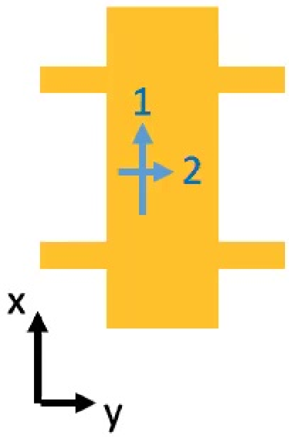


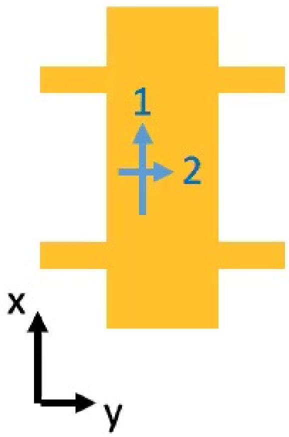
Transverse Resistance for Anisotropic Material

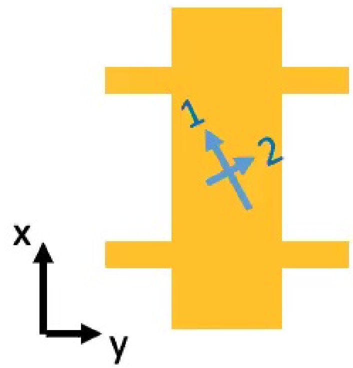
$$\overleftrightarrow{\rho} = \begin{pmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{pmatrix}$$



Transverse Resistance for Anisotropic Material

$$\overleftrightarrow{\rho} = \begin{pmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{pmatrix} \xrightarrow{R = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}} \overleftrightarrow{\rho} = \begin{pmatrix} \rho_1 \cos^2\theta + \rho_2 \sin^2\theta & (\rho_1 - \rho_2)\sin\theta\cos\theta \\ (\rho_1 - \rho_2)\sin\theta\cos\theta & \rho_1 \sin^2\theta + \rho_2 \cos^2\theta \end{pmatrix}$$

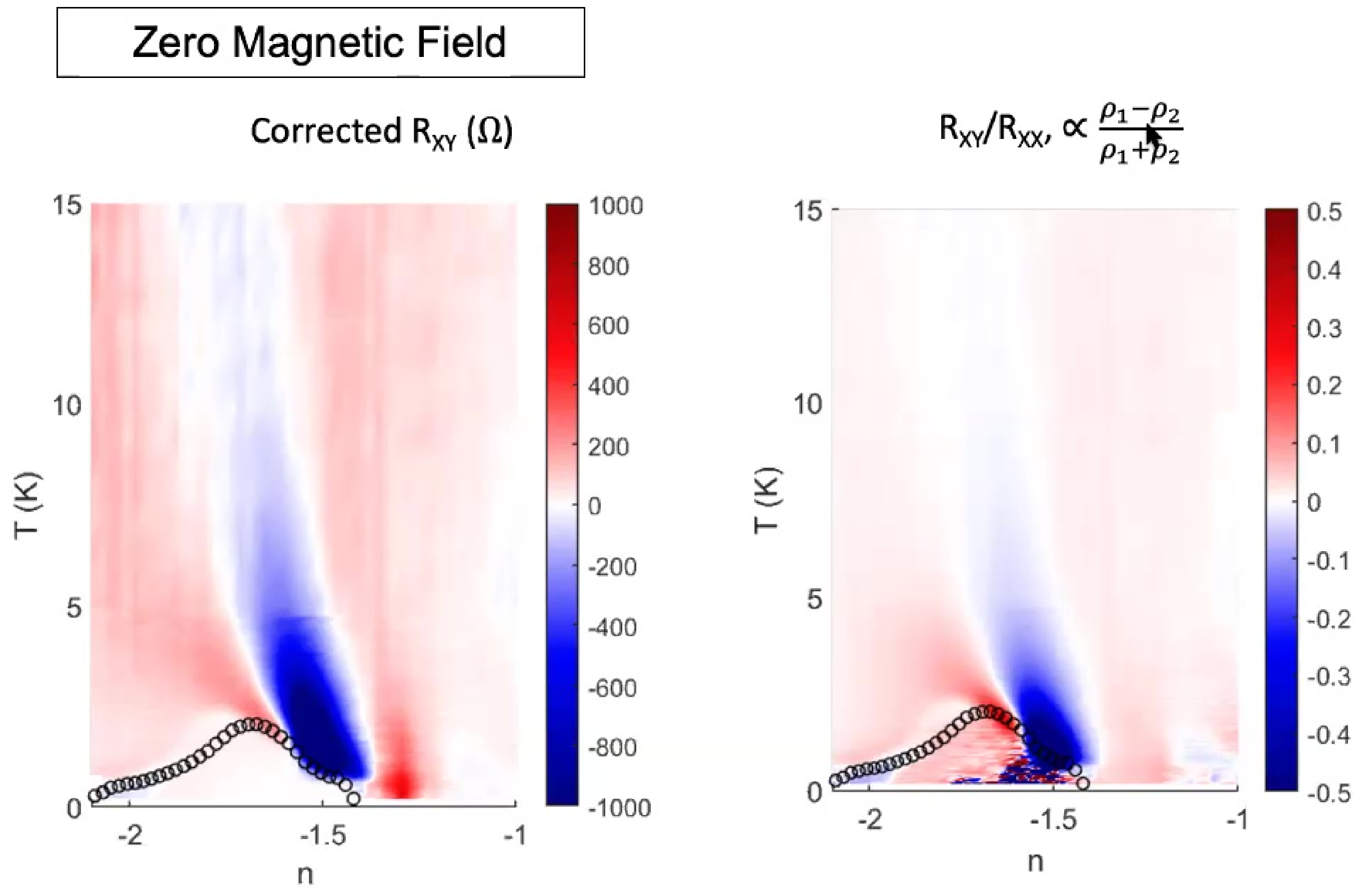




As long as $\sin 2\theta \neq 0$,

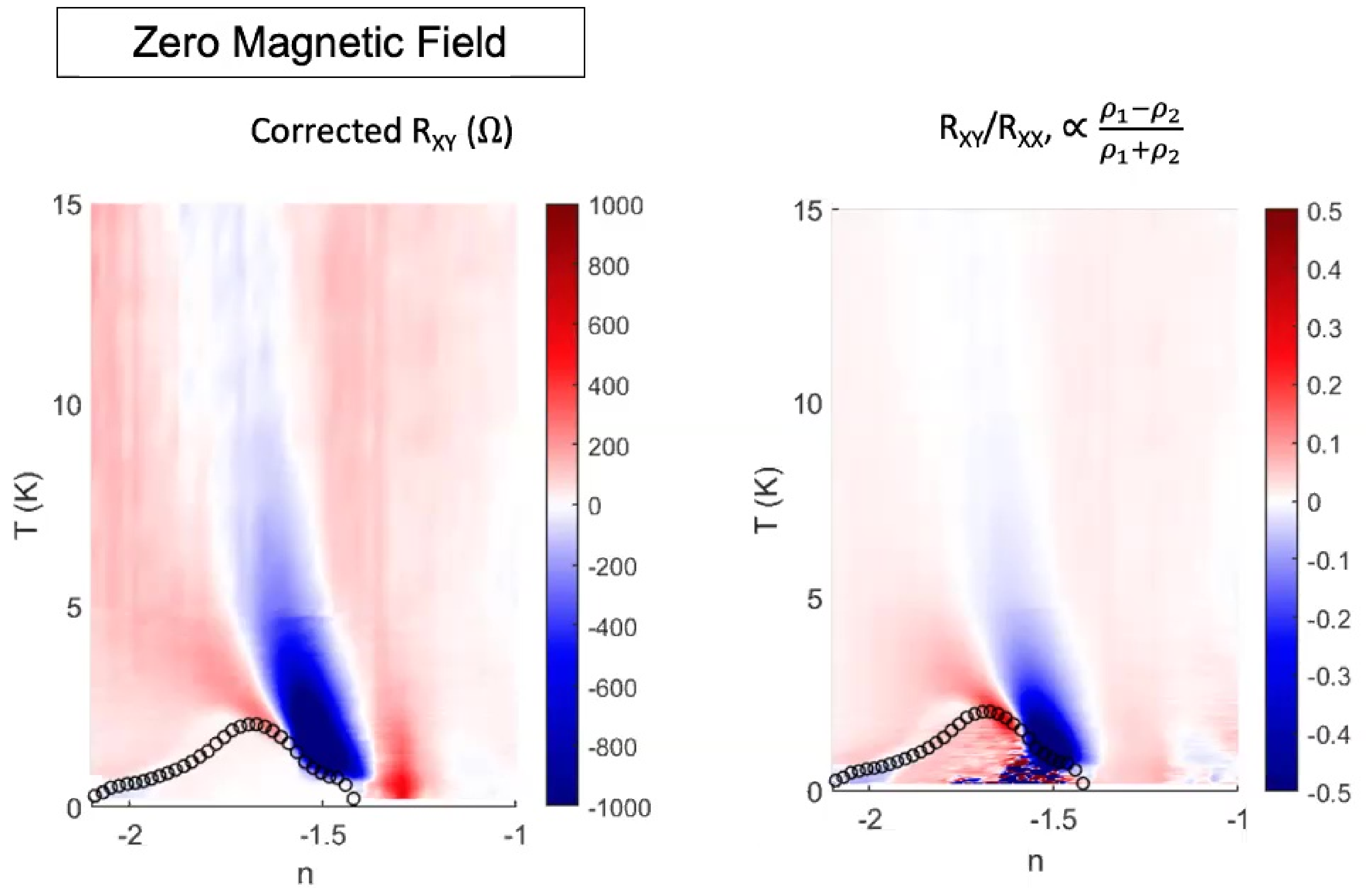
$$\rho_{xy} \propto \rho_1 - \rho_2$$

Normal State Nematicity along "competing order ridge"



Cao, et al…PJH, arxiv.2004.04148 (2020)

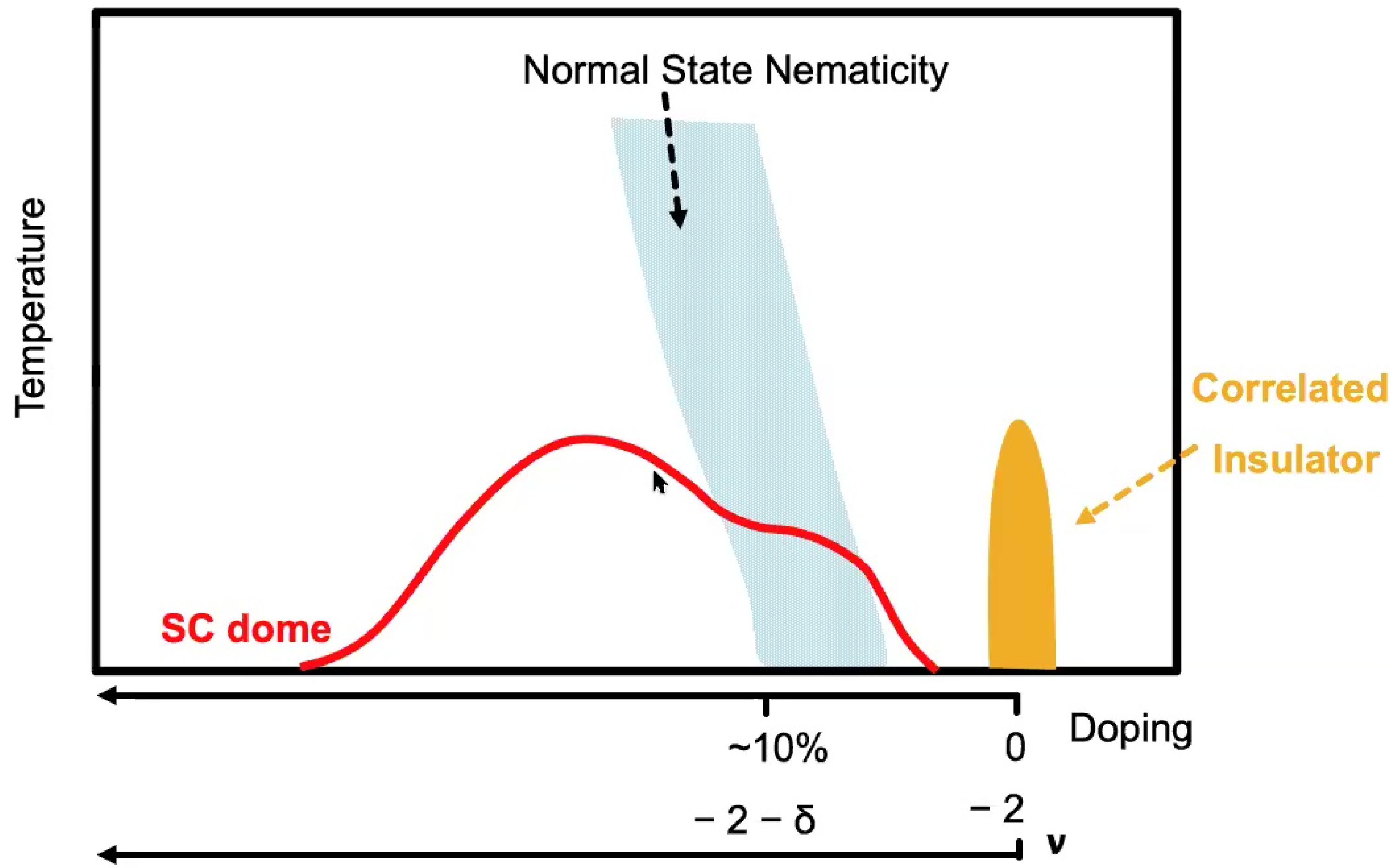
Normal State Nematicity along "competing order ridge"



Cao, et al…PJH, arxiv.2004.04148 (2020)

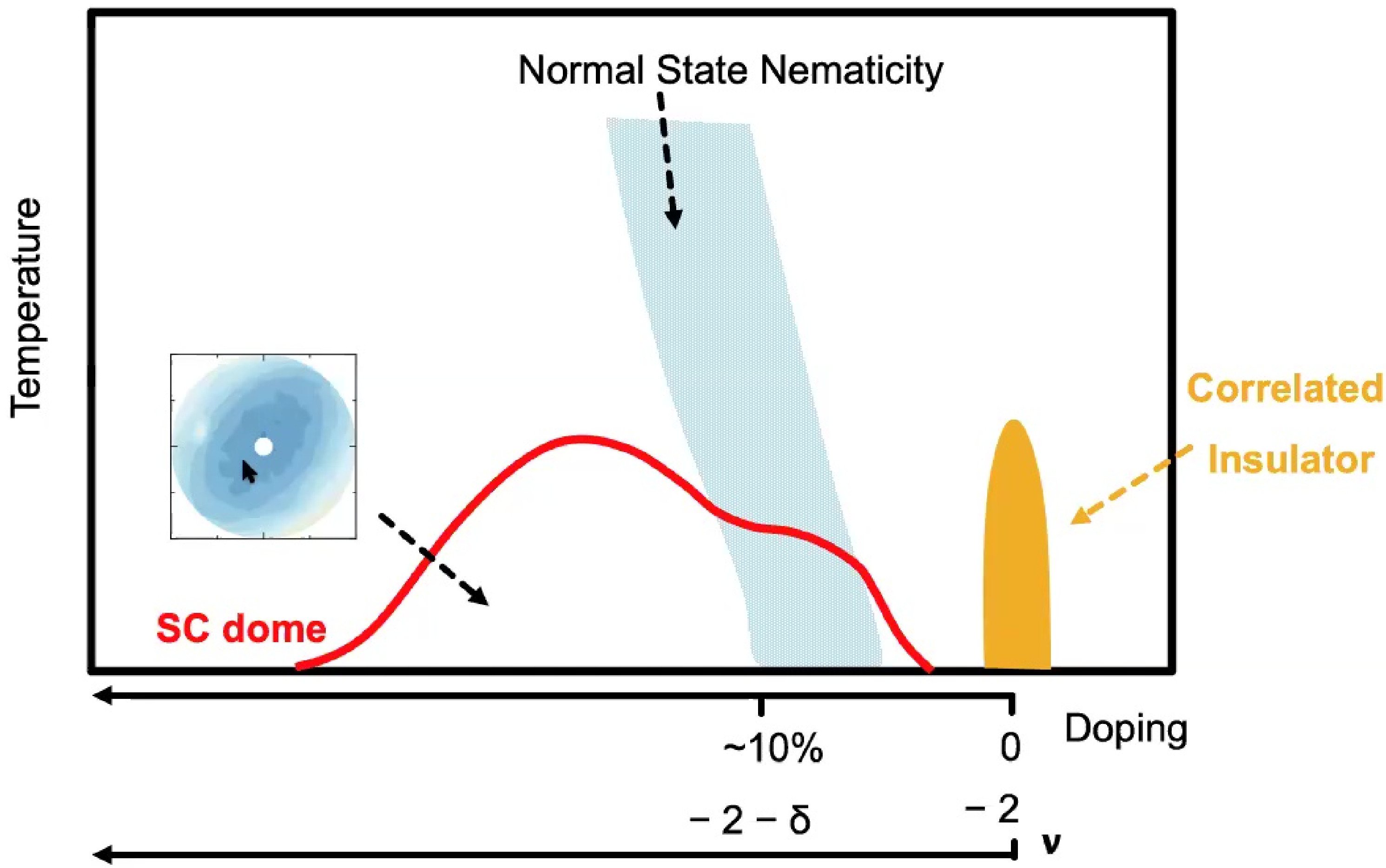
Normal state nematicity evidence seen in recent STM work on MATBG: Kerelsky *et al.*, Jiang et al. Nature (2020), Choi et al. Nature Phys. (2019)

Nematicity and Competing Orders (Schematic)



Cao, et al…PJH, arxiv.2004.04148 (2020)

Nematicity and Competing Orders (Schematic)



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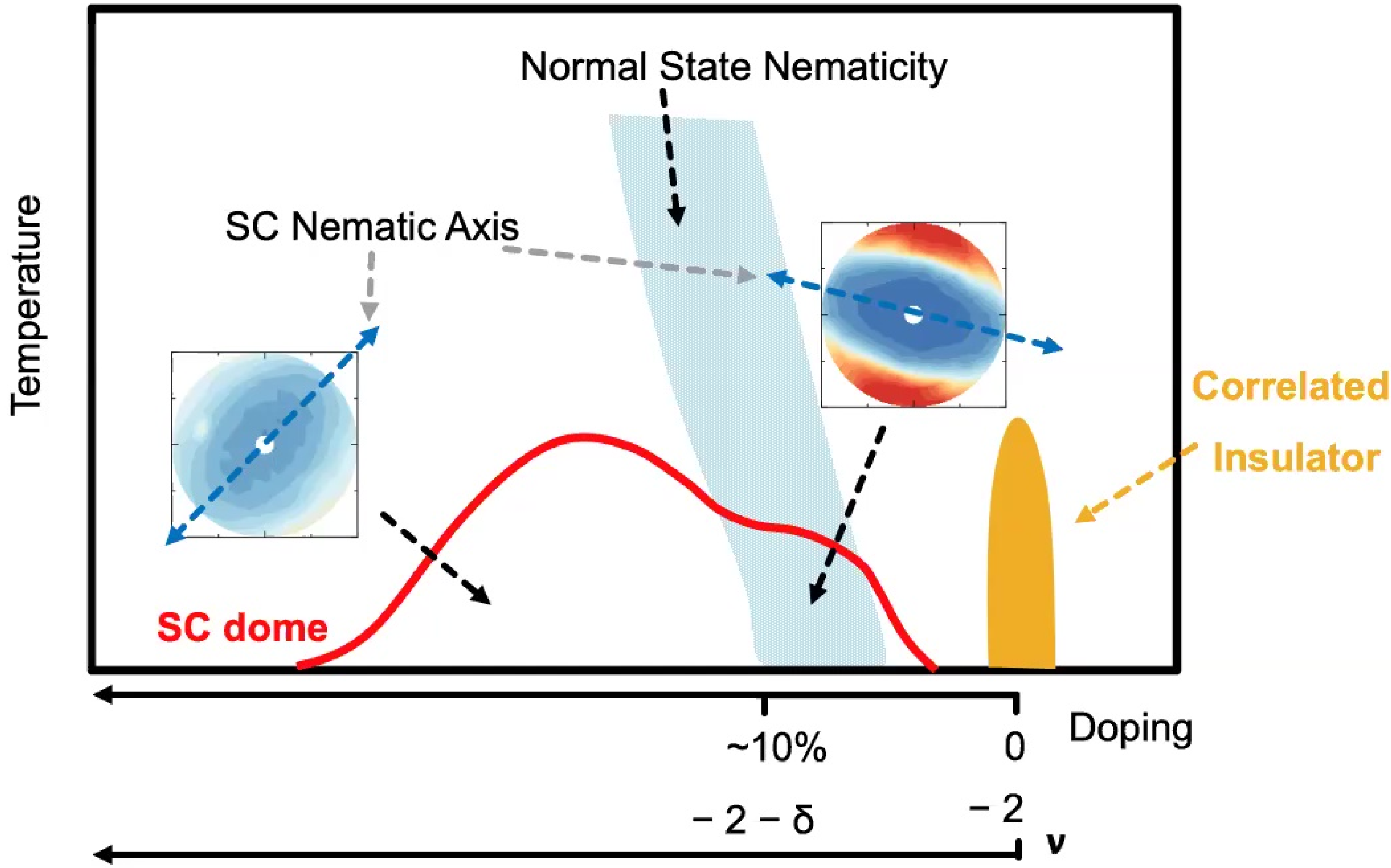
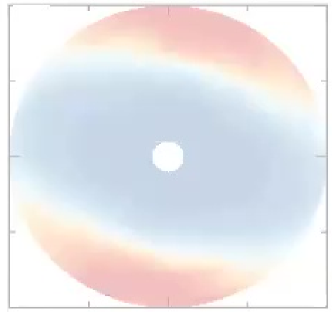


Cao, et al…PJH, arxiv.2004.04148 (2020)

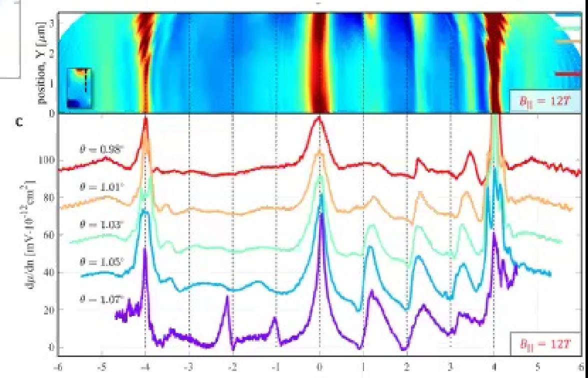
Outline

- Competing orders in MATBG

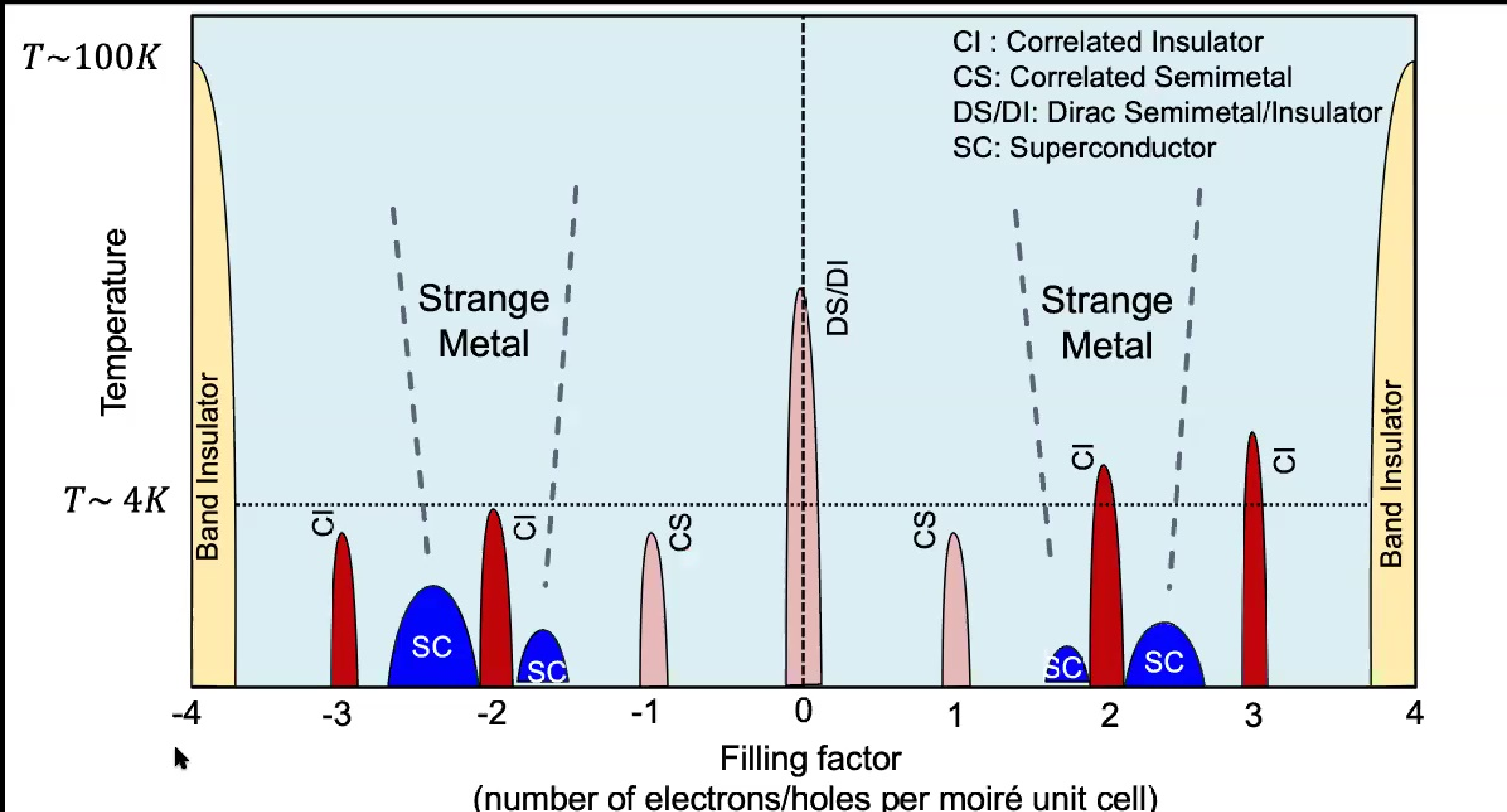


- Nematicity in MATBG

- Compressibility: Cascade of Phase Transitions & Dirac revivals



Phase diagram MATBG from Global Transport Measurements (schematic, θ-dependent & evolving fast!)



Cao *et al.* Nature **556**, 43 (2018) & Nature **556**, 80 (2018); Cao *et al.* *PRL* **124**, 076801 (2020)
See also: Yankowitz *et al.* Science (2019), Sharpe *et al.* Science (2019), and Lu *et al.* Nature (2019)
Recent STM work: Kerelsky *et al.;* Jiang et al.; Xie et al. Nature (2019), Choi et al. Nat. Phys. (2019)

Cascade of Phase Transition and Dirac Revivals in MAG

nature

Article | Published: 11 June 2020

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

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

Nature **582**, 203–208(2020) | Cite this article

Related work:

Cascade of electronic transitions in magic-angle twisted bilayer graphene

Dillon Wong, Kevin P. Nuckolls, Myungchul Oh, Biao Lian, Yonglong Xie, Sangjun Jeon, Kenji Watanabe, Takashi Taniguchi, B. Andrei Bernevig & Ali Yazdani

Nature **582**, 198–202(2020) | Cite this article

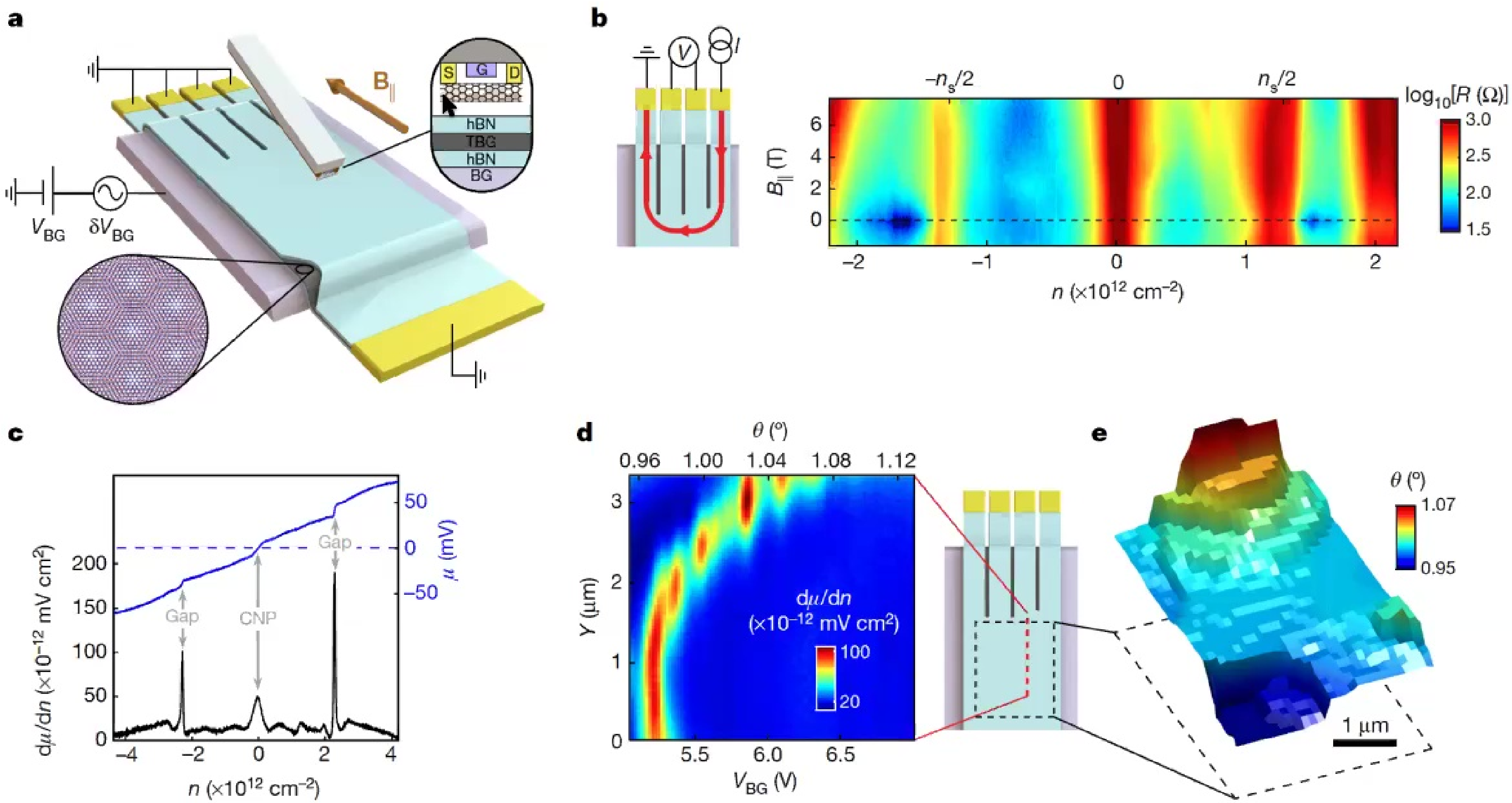
Transport phenomenology and expected compressibility

Electronic compressibility ($dn/d\mu$) is proportional to DOS

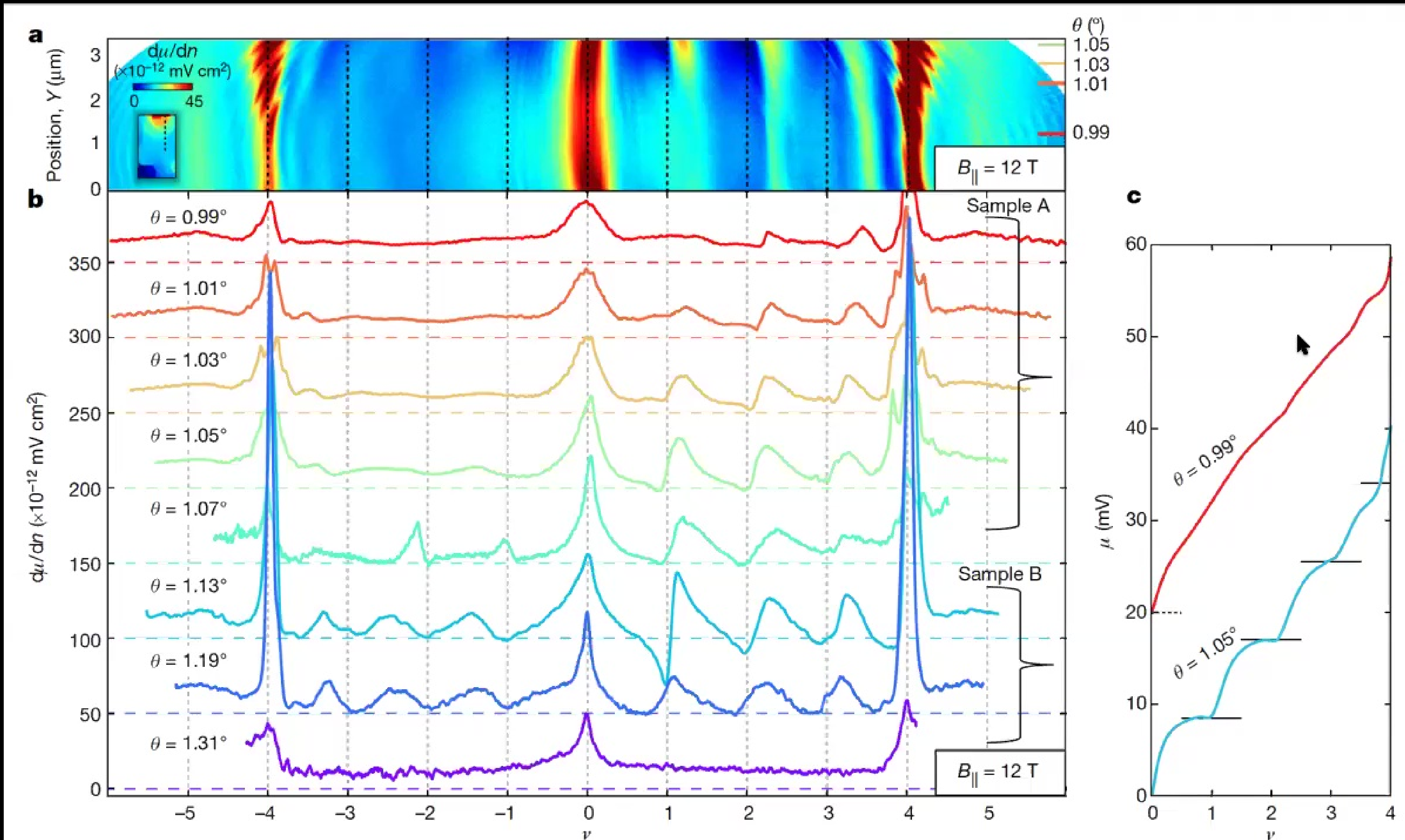
phenomenology	**expected inverse compressibility**
Energy gap	$\frac{d\mu}{dn}$ peak
Dirac like dispersion	$\frac{d\mu}{dn} \propto n^{-\frac{1}{2}}$
Superconductivity	No signal

(Slide adapted from Shahal Ilani)

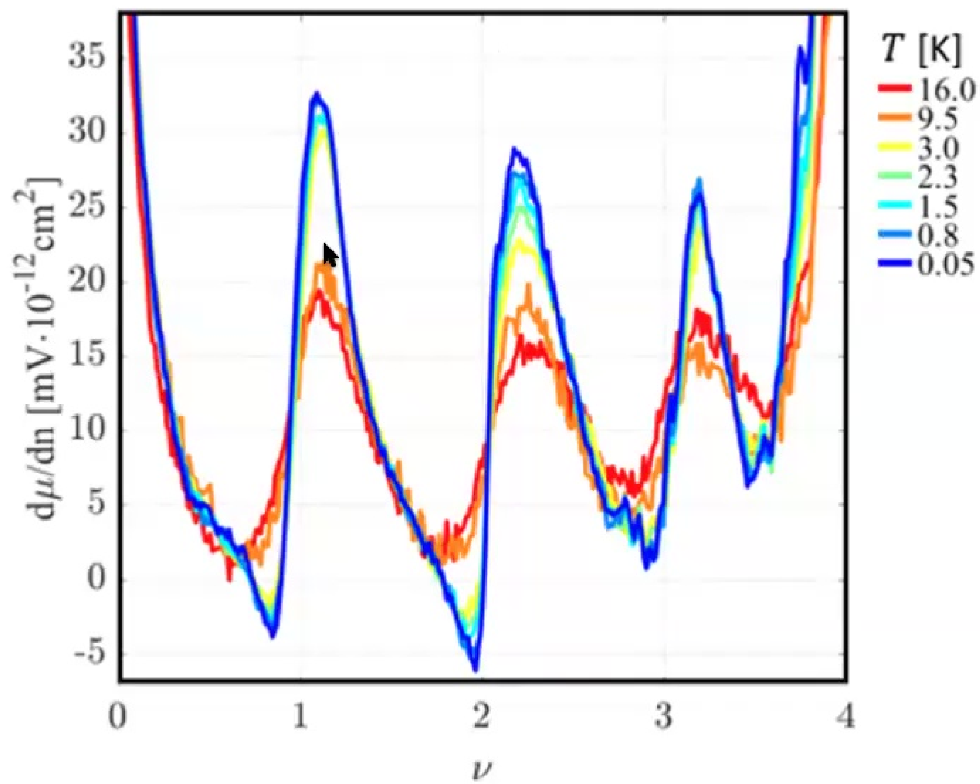
Local Inverse Compressibility Probe: scanning CNT SET



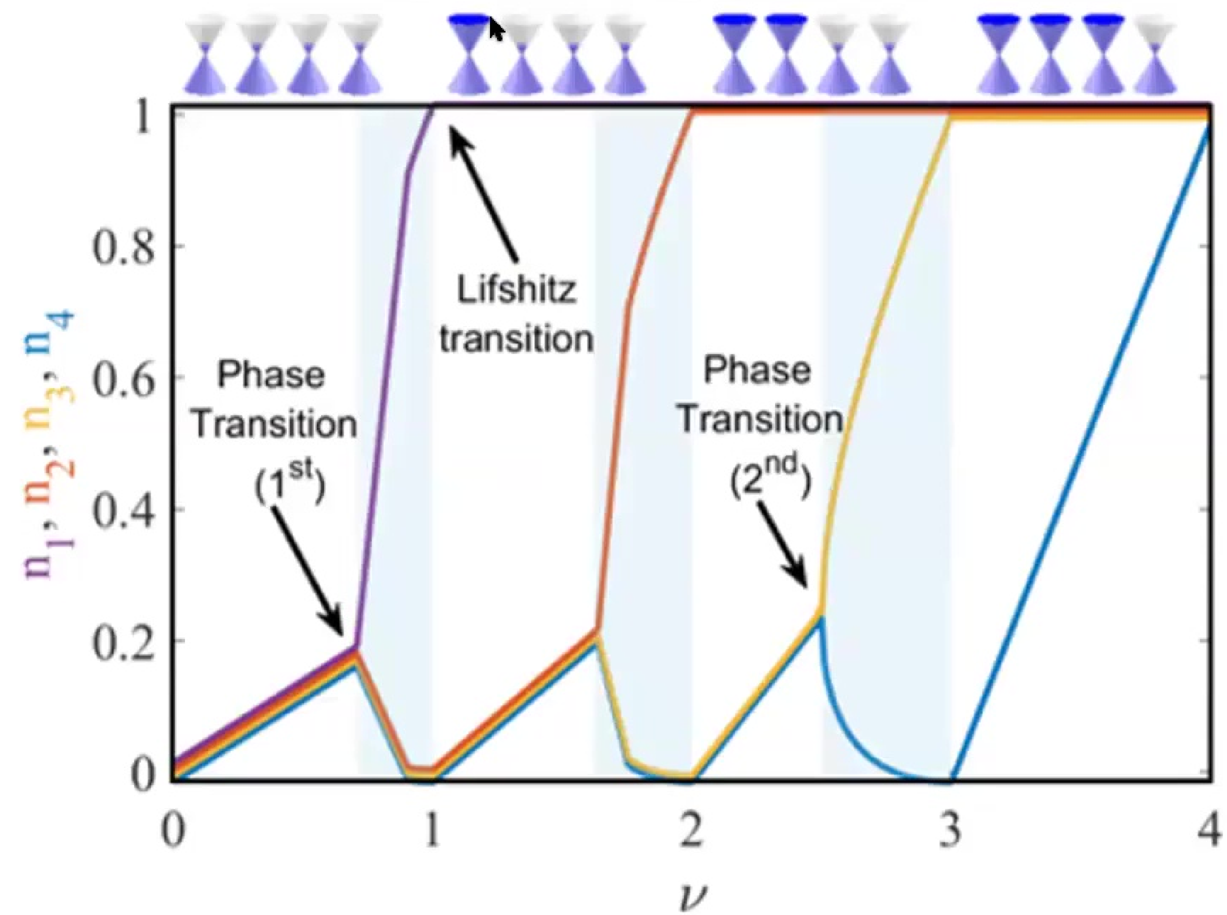
Inverse compressibility asymmetric peaks near each integer!



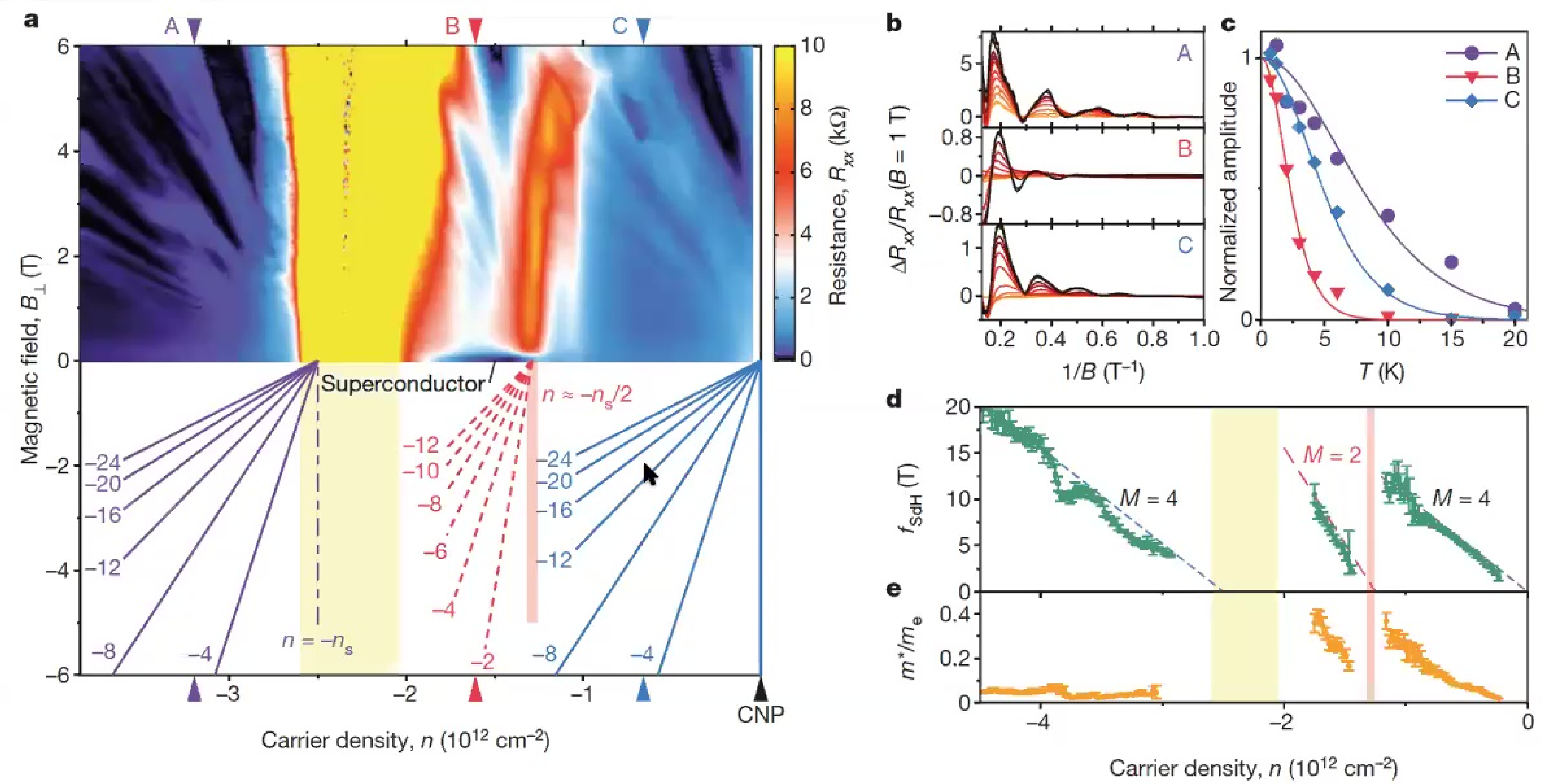
Phase transitions are robust to high temperatures



Model: Cascade of Phase Transitions and Dirac Revivals

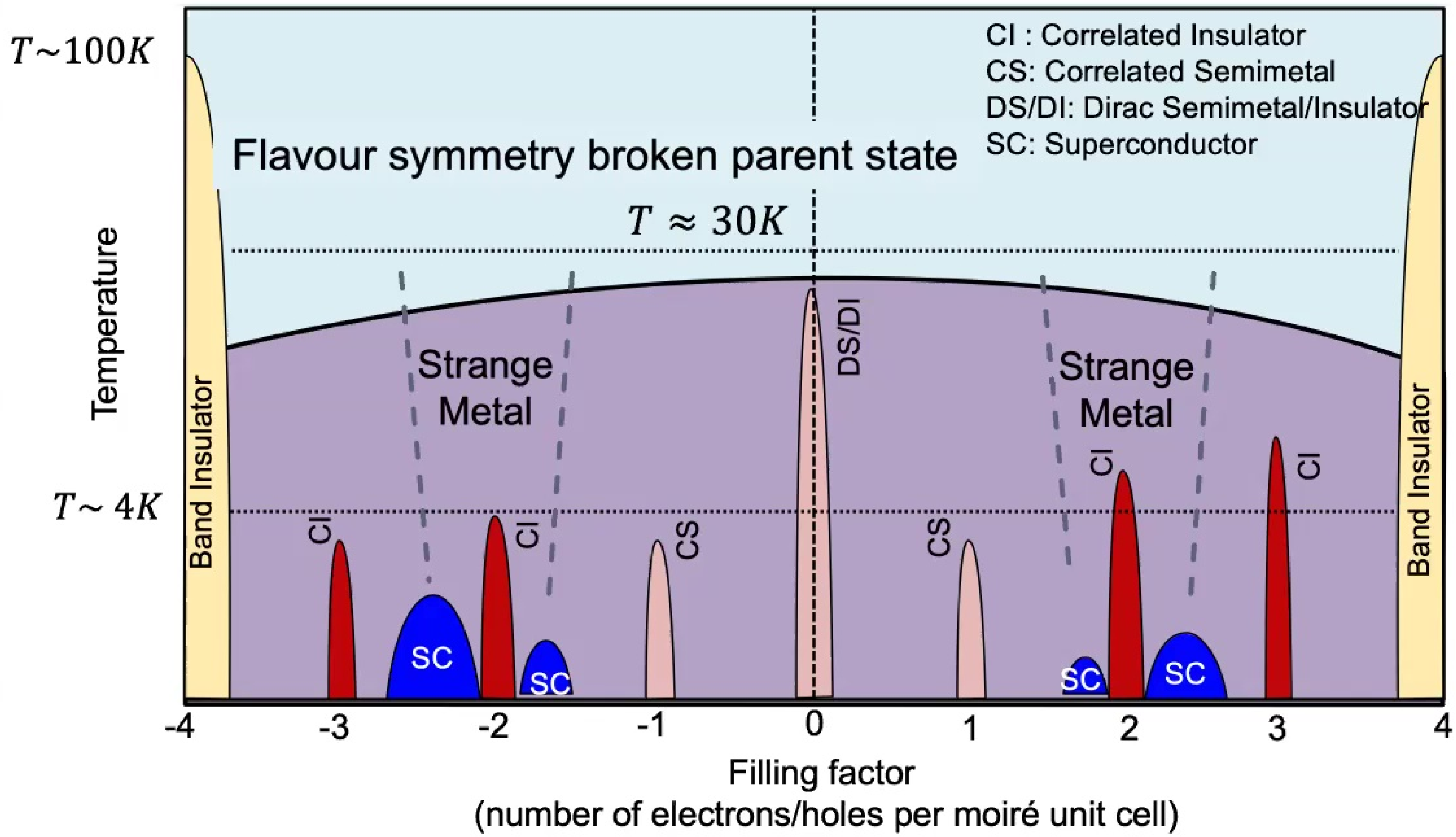


Ground state is very different "before and after" CI states!



Cao et al. Nature **556**, 43 (2018)

New Phase Diagram



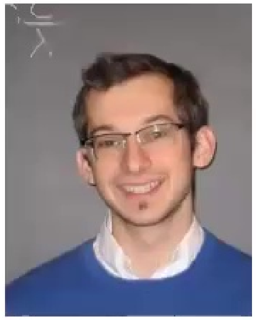
Cao *et al.* Nature **556**, 43 (2018) & Nature **556**, 80 (2018); Cao *et al.* *PRL* **124**, 076801 (2020)
See also: Yankowitz *et al.* Science (2019), Sharpe *et al.* Science (2019), and Lu *et al.* Nature (2019)
Recent STM work: Kerelsky *et al.;* Jiang et al.; Xie et al. Nature (2019), Choi et al. Nat. Phys. (2019)

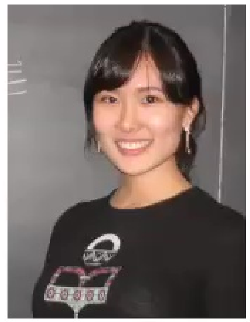
Summary

- Competition between different orders near integer filling factors
- Nematicity in SC and normal state
- Local inverse compressibility measurements indicate cascade of phase transitions and Dirac revivals at each integer filling factor
- Substantial sensitivity of all this to precise twist angle, twist angle (and chemical potential disorder)

Acknowledgements


Yuan Cao


Daniel Rodan-Legrain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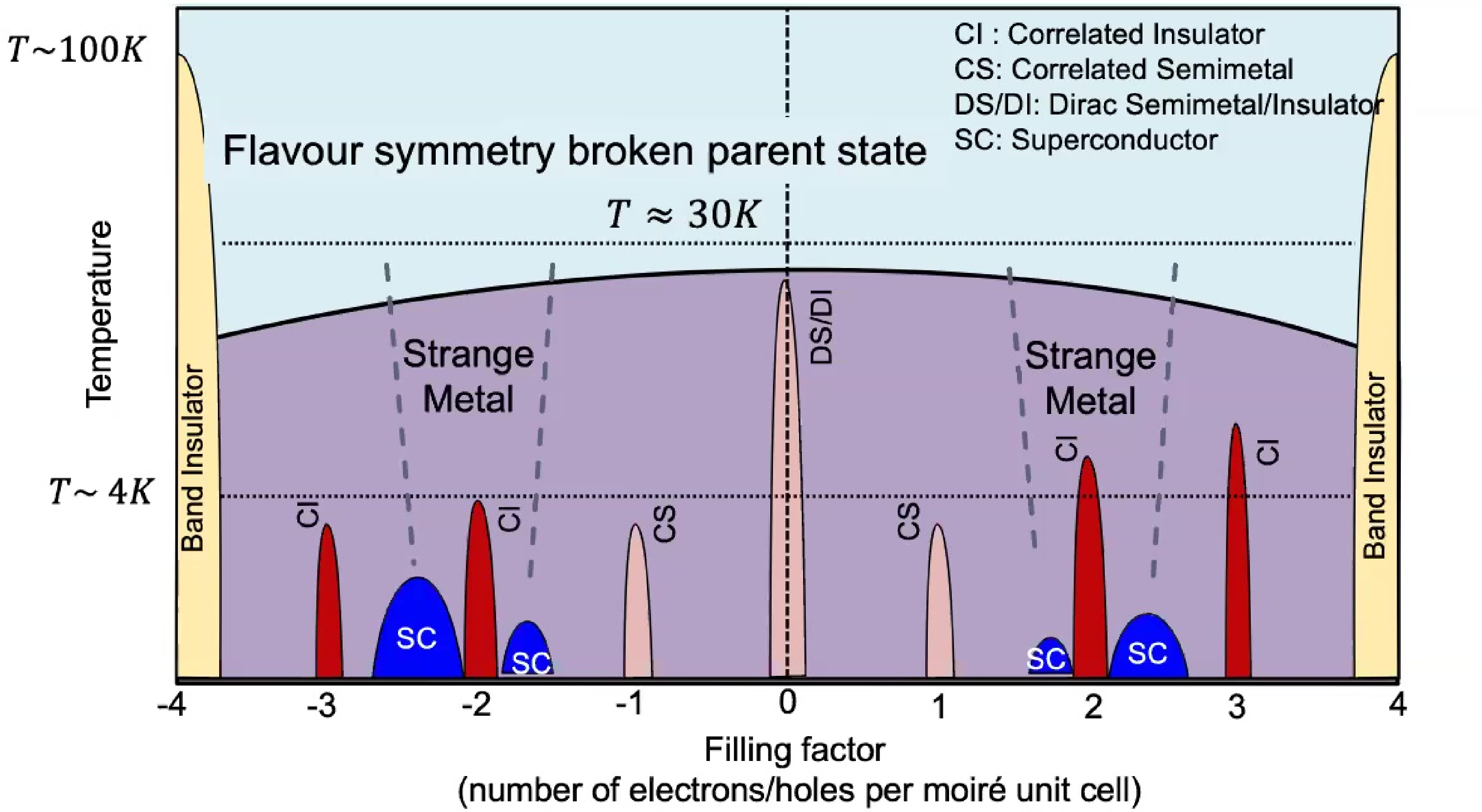
New Phase Diagram



Cao *et al.* Nature **556**, 43 (2018) & Nature **556**, 80 (2018); Cao *et al.* *PRL* **124**, 076801 (2020)
See also: Yankowitz *et al.* Science (2019), Sharpe *et al.* Science (2019), and Lu *et al.* Nature (2019)
Recent STM work: Kerelsky *et al.;* Jiang et al.; Xie et al. Nature (2019), Choi et al. Nat. Phys. (2019)