

Title: New physics in flat Moire bands

Speakers: Erez Berg

Date: November 02, 2020 - 12:30 PM

URL: <http://pirsa.org/20110000>

Abstract: Flat bands in Moire superlattices are emerging as a fascinating new playground for correlated electron physics. I will present the results of several studies inspired by these developments. First, I will address the question of whether superconductivity is possible even in the limit of a perfectly flat band. Then, I will discuss transport properties of a spin-polarized superconductor in the limit of zero spin-orbit coupling, where the topological structure of the order parameter space allows for a new dissipation mechanism not known from conventional superconductors. If time allows, I will also discuss the interpretation of new measurements of the electronic compressibility in twisted bilayer graphene, indicating a cascade of symmetry-breaking transitions as a function of the density of carriers in the system. 

References:

<https://arxiv.org/abs/2006.10073>

<https://arxiv.org/abs/1912.08848>

<https://arxiv.org/abs/1912.06150>

# New Physics in Moiré Flat Bands



Erez Berg

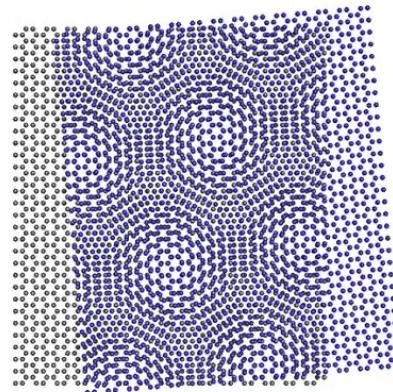
Johannes Hofmann, Debanjan Chowdhury,  
Eyal Cornfeld, Mark Rudner



# Moiré is different

*G. Baskaran*

A new kind of strongly correlated system



**Twisted bilayer graphene** *E. Andrei et al.; Tutuc et al.; Castro Neto et al. (2007); Bistritser, MacDonald (2010); Cao, Harrillo-Jerrero (2018); ...*

**Twisted bilayer on bilayer** *P. Kim et al.; Jarillo-Herrero et al.; Shen, Zhang et al. (2019)*

**Trilayer graphene on HBN** *F. Wang et al.; Goldhaber-Gordon, A. Young et al. (2019)*

**Twisted TMDs** *Pasupathy et al. (2019); Shan et al. (2020)*

# Moiré is different

*G. Baskaran*



**A new kind of strongly correlated system**

- Highly tunable band structure and  $\frac{U}{W}$
- Valley, spin degree of freedom
- Interplay of band topology, superconductivity, and strong correlations
- New probes not easily accessible in bulk materials

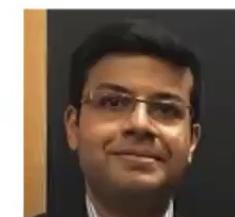
# Outline



- Superconductivity in flat bands
- Order parameter topology and dissipation in a triplet spin-polarized superconductor



*Johannes Hofmann  
(WIS)*



*Debanjan  
Chowdhury(Cornell)*



*J. Hofmann, EB, D. Chowdhury, arXiv:1912.08848*

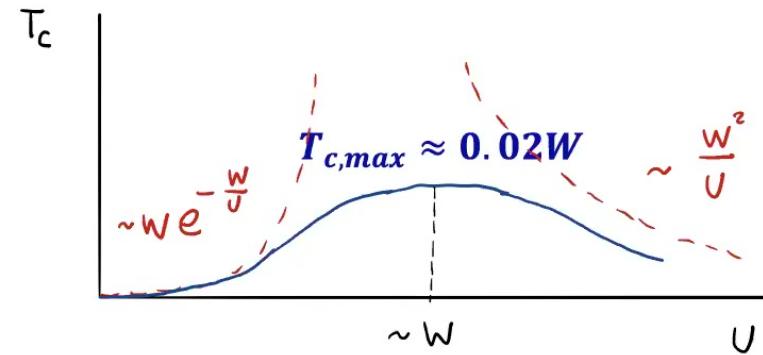
# Superconductivity in flat bands



- Reduced  $\frac{W}{U}$ : increased role of correlations
- $\frac{W}{U} \rightarrow 0$  limit: superconductivity?

Often:  $T_c \rightarrow 0$  since as  $\frac{W}{U} \rightarrow 0$ ,  $T_\theta \rightarrow 0$  *Emery, Kivelson (1995)*

E.g. negative-U Hubbard model:



*Paiva, Scalletar et al. (2004)*

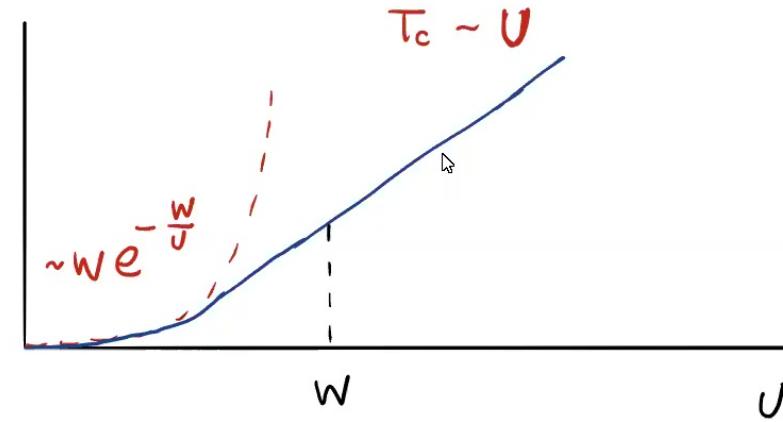
# Superconductivity in flat bands



- If Wannier functions are non-localizable (e.g., topological bands): when  $W \rightarrow 0$ ,  $T_\theta \propto U$ . Then,  $T_c \propto U$

*Volovik (2011); Peotta, Torma (2015); Tovmasyan, Huber et al. (2016); Xie, Bernevig et al. (2019); Park, Kim, Lee (2020)*

- Superconductivity in the limit  $W \rightarrow 0$ ?



# Superconductivity in flat bands

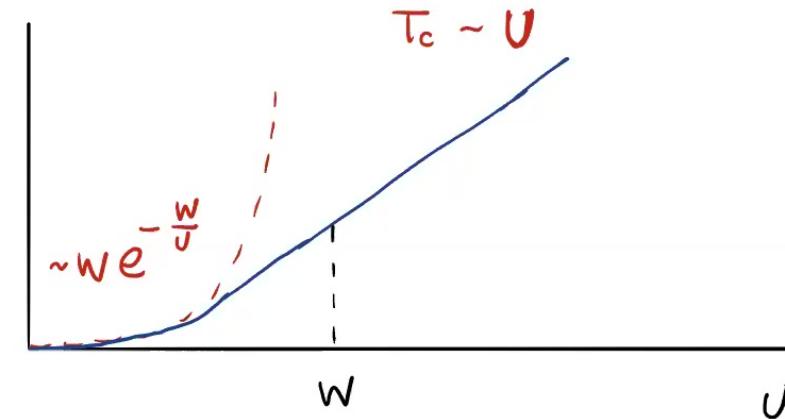


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- Superconductivity in the limit  $W \rightarrow 0$ ?

*Competing states?  
Phase separation?*



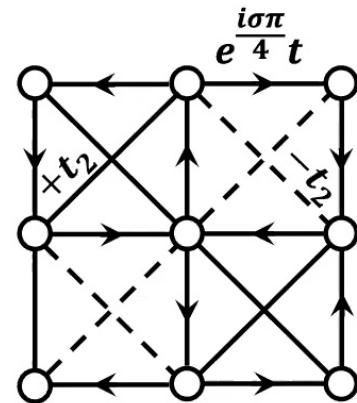


# Explicit model

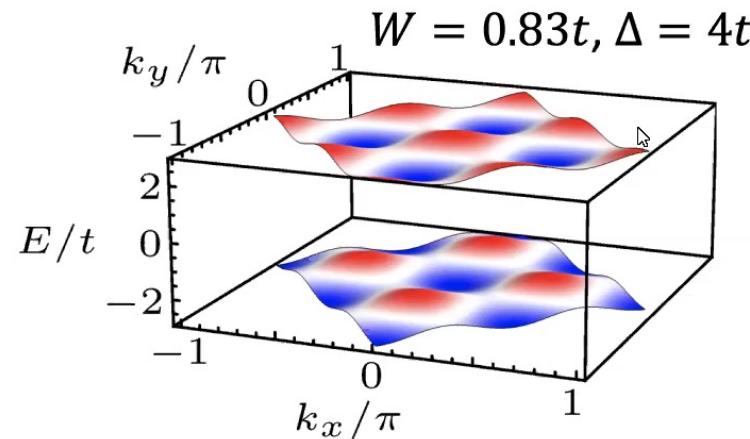
Negative-U Hubbard model with topological bands ( $C = \pm 1$ )

$$H = \sum_{i,j,\sigma} t_{ij}^\sigma c_{i\sigma}^\dagger c_{j\sigma} - |U| \sum_j n_{j\uparrow} n_{j\downarrow}$$

Time reversal symmetry:  $(t_{ij}^\downarrow)^* = t_{ij}^\uparrow$



Neupert et al. (2011)



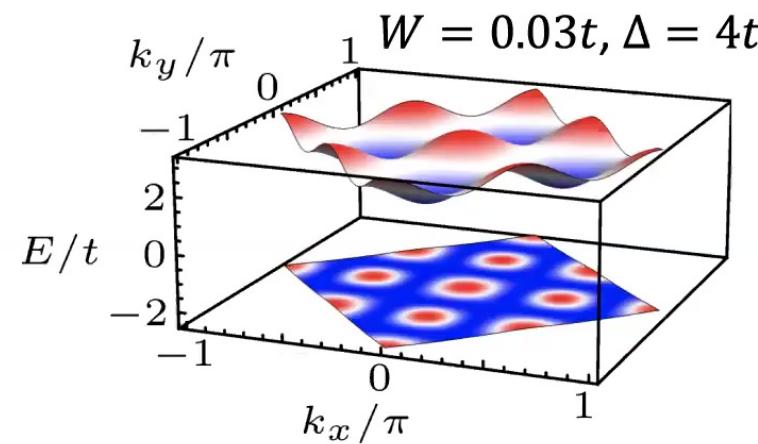
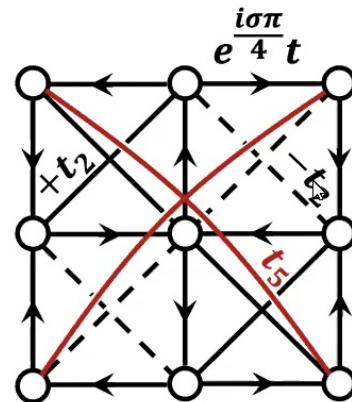


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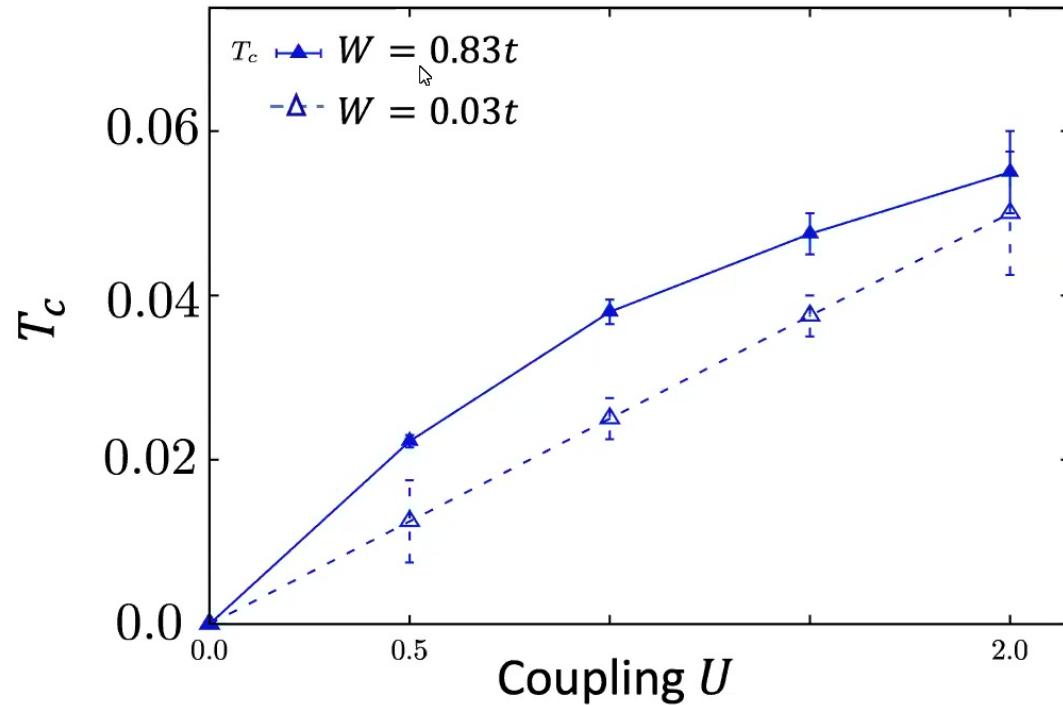
Time reversal symmetry:  $(t_{ij}^\downarrow)^* = t_{ij}^\uparrow$



# QMC results



$T_c$  (from superfluid density  $\rho_s(T_c) = \frac{2}{\pi} T_c$ )

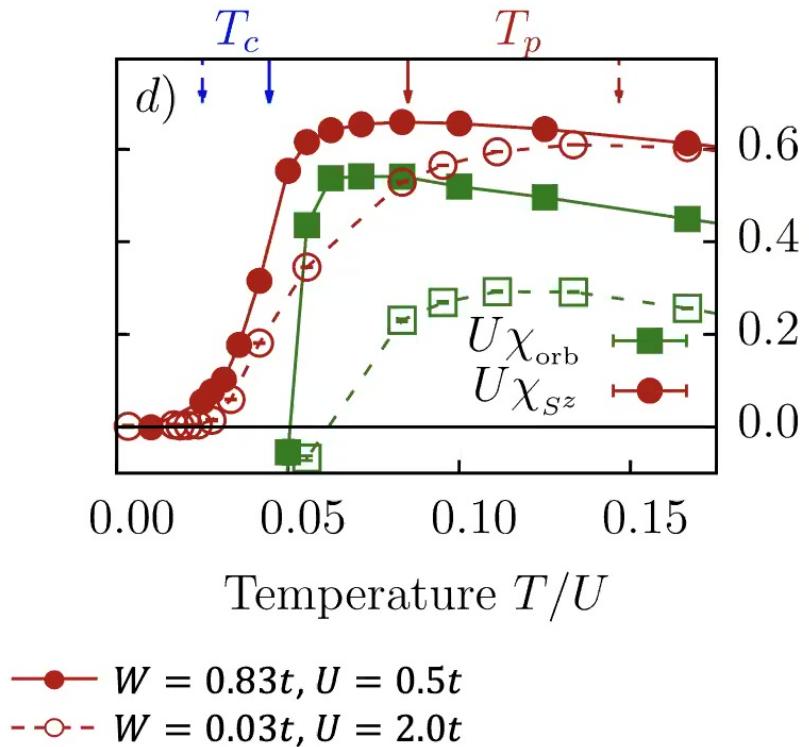


*J. Hofmann, EB, D. Chowdhury, arXiv:1912.08848*

# QMC results

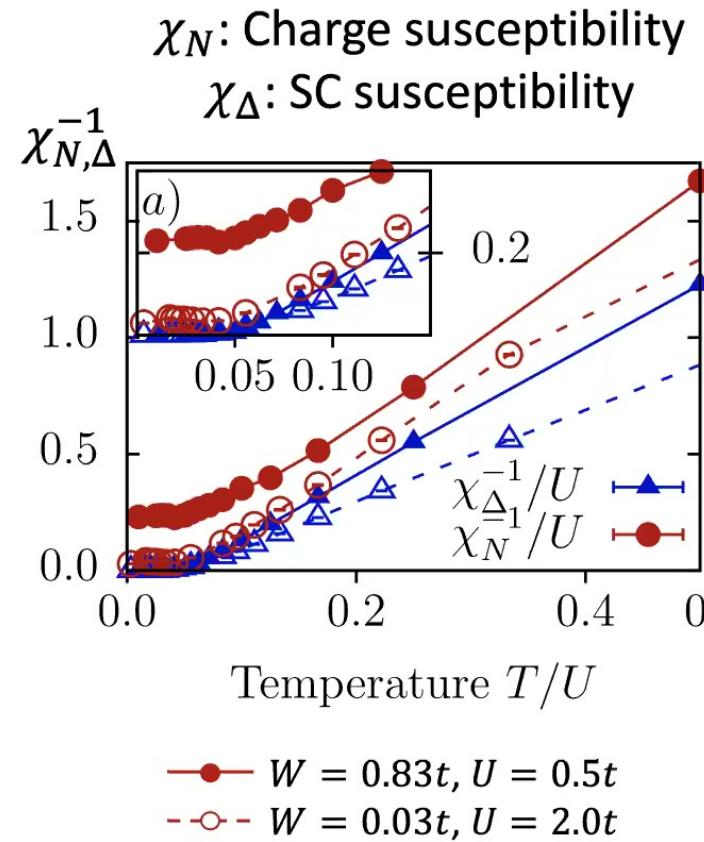


“Pseudogap” above  $T_c$   
(from spin susceptibility)

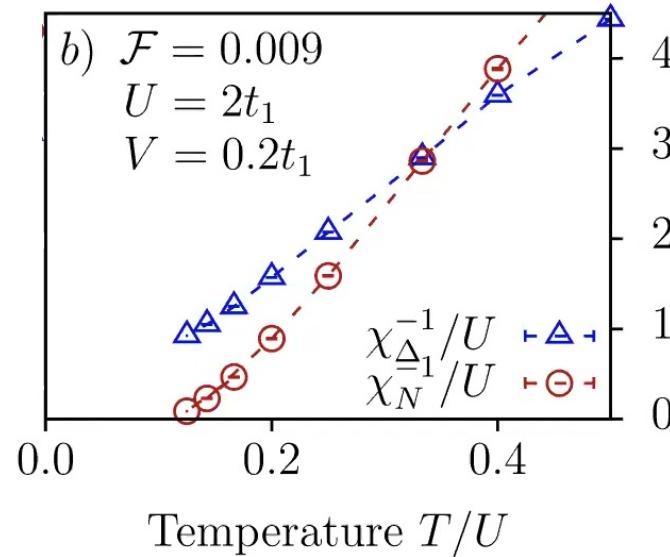


*J. Hofmann, EB, D. Chowdhury, arXiv:1912.08848*

# Phase separation



Small nearest-neighbor attractive interaction  $V$ : Phase separation!



Approximate SU(2) symmetry relating  $\chi_N$  and  $\chi_\Delta$  upon projection to flat band

*Tovmasyan, Huber et al. (2016)*



# Outline



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*Eyal Cornfeld  
(WIS)*



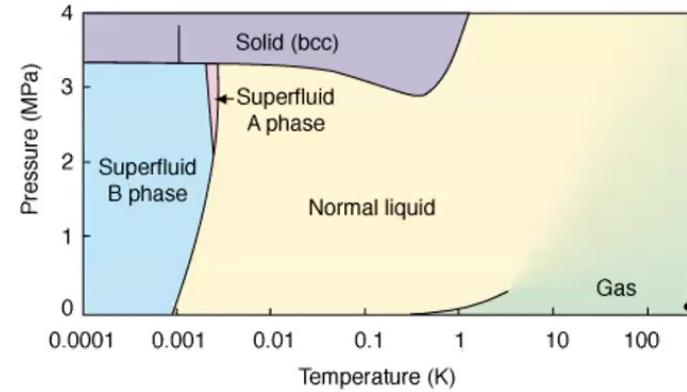
*Mark Rudner  
(Copenhagen)*

*E. Cornfeld, M. Rudner, EB, arXiv:2006.10073*



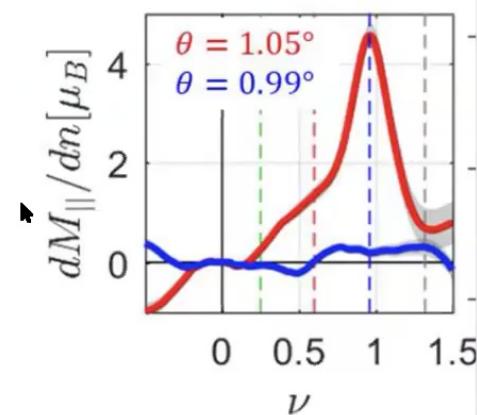
# Triplet superconductivity in TBG?

Solid state analogue  
of superfluid  $^3\text{He}$ ?



Triplet superconductivity:

- Strong electronic correlations ✓
- Nearby ferromagnetism ✓
- Extremely clean



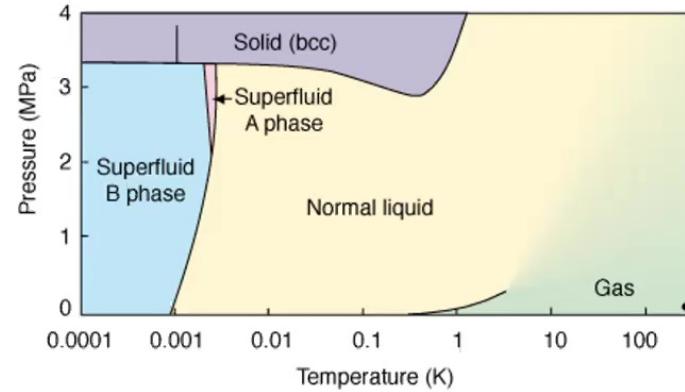
*U. Zondiner, S. Ilani et al.,  
Nature (2020)*



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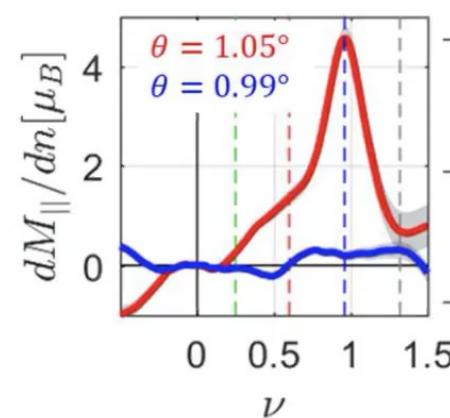
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Very small spin-orbit: SC and magnetism intertwined in interesting way?



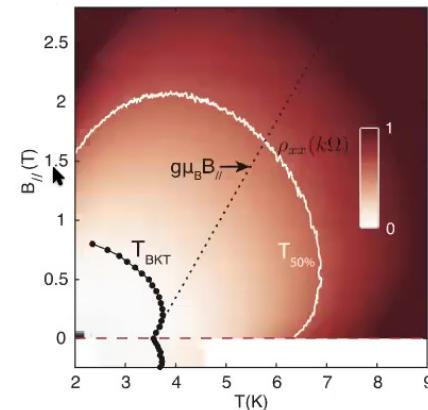
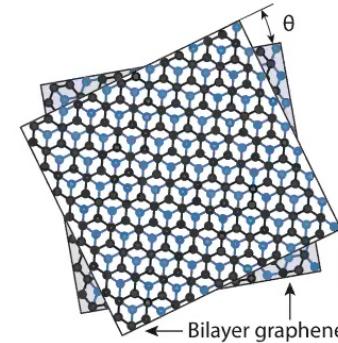
*U. Zondiner, S. Ilani et al.,  
Nature (2020)*

# Twisted double bilayer graphene: a triplet superconductor?



- Bandwidth controlled by a perpendicular electric field  
*Liu, Kim et al.; Cao, Jarillo-Herrero et al.; Shen, Zhang et al. (2020)*
- Correlated insulators observed near integer fillings. At half filling, gap increases linearly with  $|B_{\parallel}|$ : spin ferromagnet
- Onset of resistivity drop (superconductivity?) near half filling:  $T_{onset} \propto |B_{\parallel}|$   
*Triplet?*

*Liu, P. Kim et al. (2020)*



# Order parameter of a spin-polarized superconductor



Order parameter of a spin-triplet SC:

$$\vec{d}_k = \langle c_k^\dagger i\sigma_2 \vec{\sigma} c_{-k}^\dagger \rangle \equiv \vec{d}_{1,k} + i\vec{d}_{2,k}$$

Fully spin polarized SC:  $|\vec{d}_{1,k}| = |\vec{d}_{2,k}|$ ,  $\vec{d}_{1,k} \perp \vec{d}_{2,k}$

Order parameter space:  $SO(3)$   
*(Neglecting spin-orbit coupling)*

$$\begin{aligned}\vec{m} &\propto \vec{d}_1 \times \vec{d}_2 \\ &= \frac{1}{2i} \vec{d}_k \times \vec{d}_k^*\end{aligned}$$
A 3D diagram illustrating the order parameter space  $SO(3)$ . It shows two vectors,  $\vec{d}_1$  (red) and  $\vec{d}_2$  (blue), originating from the same point. A green vector, representing the magnetic moment  $\vec{m}$ , is shown as the cross product of  $\vec{d}_1$  and  $\vec{d}_2$ , pointing vertically upwards. The angle between  $\vec{d}_1$  and  $\vec{d}_2$  is 90 degrees, indicating they are perpendicular to each other.

No finite  $T$  transition in  $d = 2$   
*Mukerjee, Xu, Moore (2006)*





# Topological defects

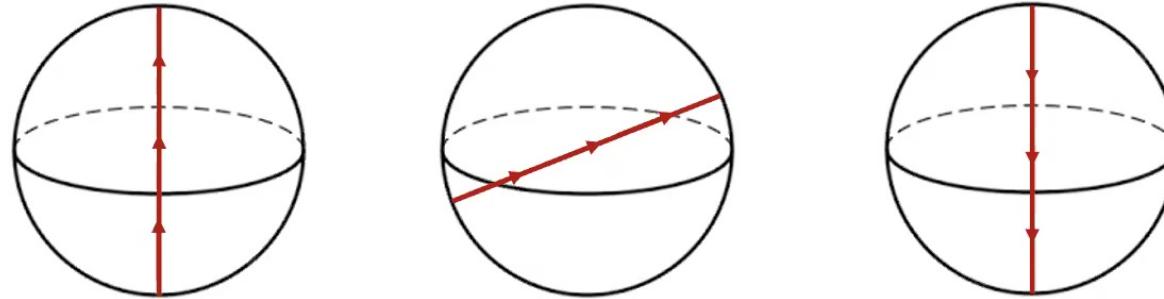
$$\pi_1(SO(3)) = \mathbb{Z}_2$$

$\mathbb{Z}_2$  superconducting vortex

**Direction:** axis of rotation

**Radius:** rotation angle

(antipodal points of radius  $\pi$  identified)



# Consequences for current relaxation

Free energy density (assuming spin rotation invariance):

$$f = \frac{\kappa_d}{2} |\nabla \vec{d}|^2 + \frac{\kappa_m}{8} |\nabla(\vec{d}^* \times \vec{d})|^2$$



Represent order parameter by unitary matrix  $u$ :

$$\vec{d} = \text{Tr}[u(\sigma_1 + i\sigma_2)u^\dagger \vec{\sigma}]$$

*Spin rotation:  $u \rightarrow e^{\frac{i}{2}\vec{\theta} \cdot \vec{\sigma}} u$ , Gauge transformation:  $u \rightarrow ue^{\frac{i}{2}\varphi \sigma_3}$*

Supercurrent carrying state:  $u(\vec{r}) = e^{i\pi n \sigma_3 \frac{x}{L_x}}$

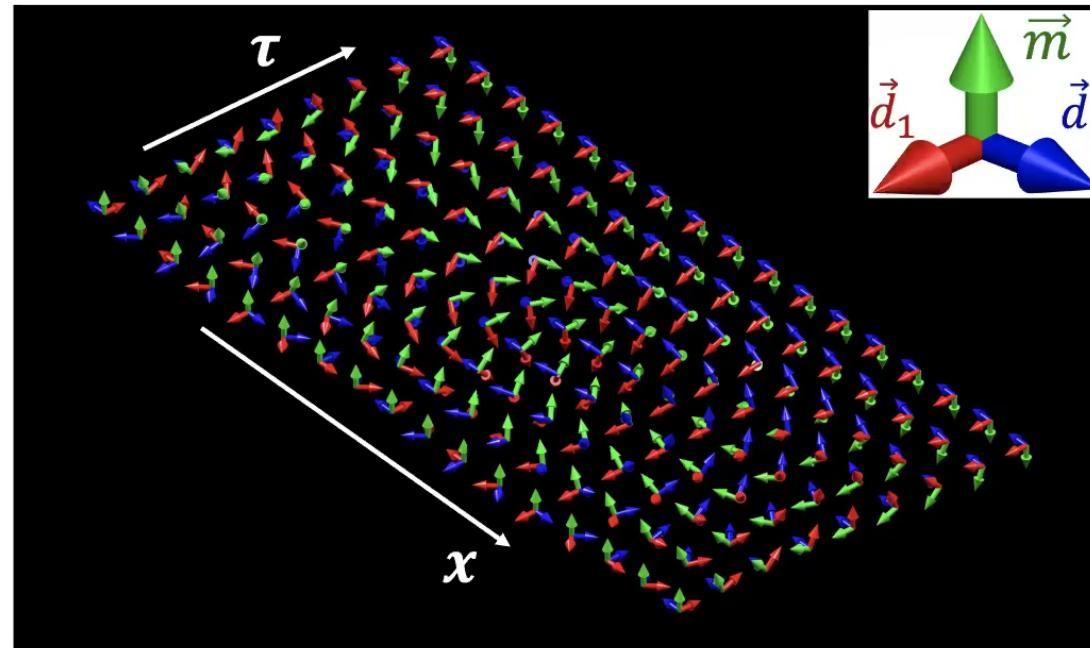


*E. Cornfeld, M. Rudner, EB, arXiv:2006.10073*

# Consequences for current relaxation

Unwinding a phase twist of  $4\pi$ :

$$u(\vec{r}, 0 \leq \tau \leq 1) = e^{i\pi\sigma_3 \frac{x}{L_x}} e^{\frac{i\pi}{2}\sigma_1 \tau} e^{i\pi(n-1)\sigma_3 \frac{x}{L_x}}$$



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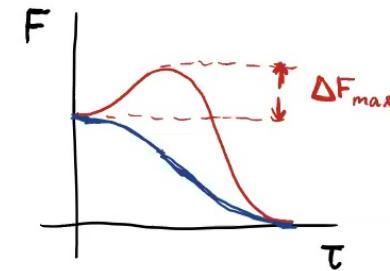
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Path requires mechanism to dissipate magnetization  
(spin bath/coupling to leads)

Energy landscape:

$$\Delta F_{\max} = \begin{cases} 0 & \frac{\kappa_m}{\kappa_d} \leq 2n - 1, \\ \frac{2\pi^2 L_y (\kappa_m - (2n-1)\kappa_d)^2}{L_x (\kappa_m - \kappa_d)} & \frac{\kappa_m}{\kappa_d} > 2n - 1. \end{cases}$$



# Consequences for current relaxation



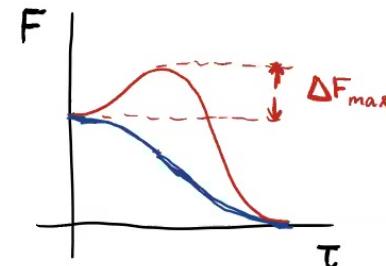
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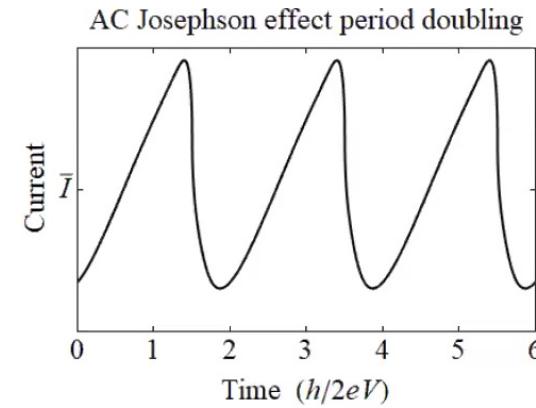
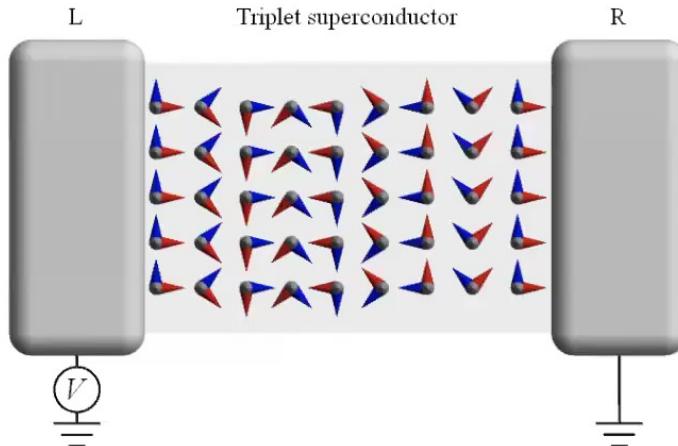


“Critical current density” depends on the system size!

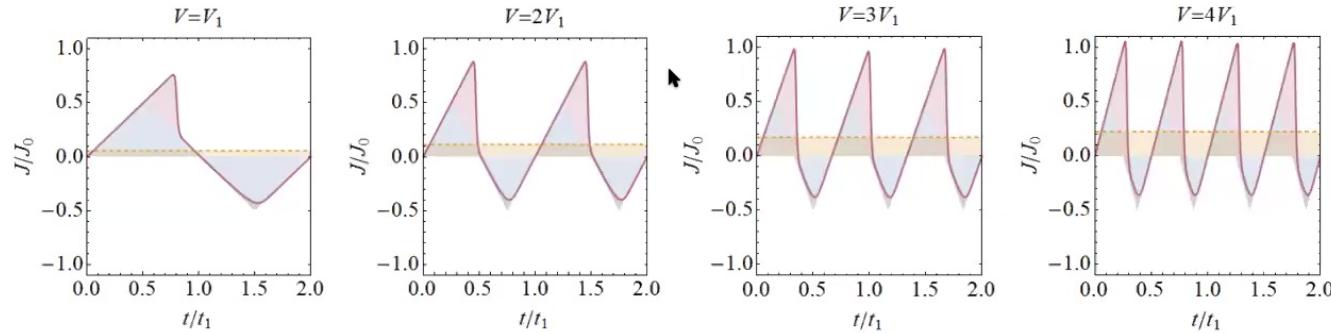
$$J_c \sim \frac{\kappa_d}{L_x} \left( \frac{\kappa_m}{2\kappa_d} + 1 \right)$$



# Double-period Josephson effect

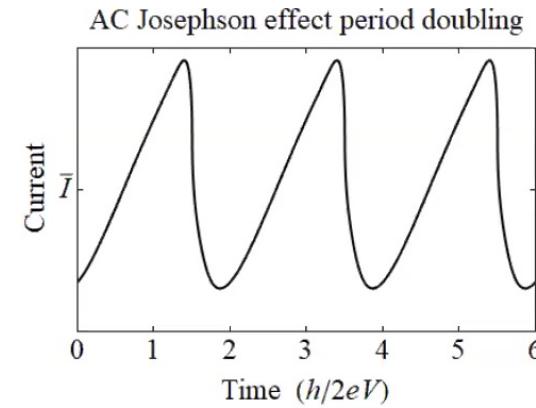
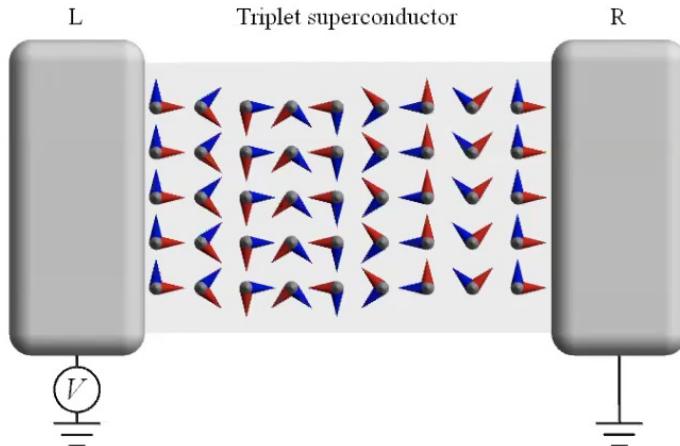


Langevin simulation (assuming coupling to a spin bath)

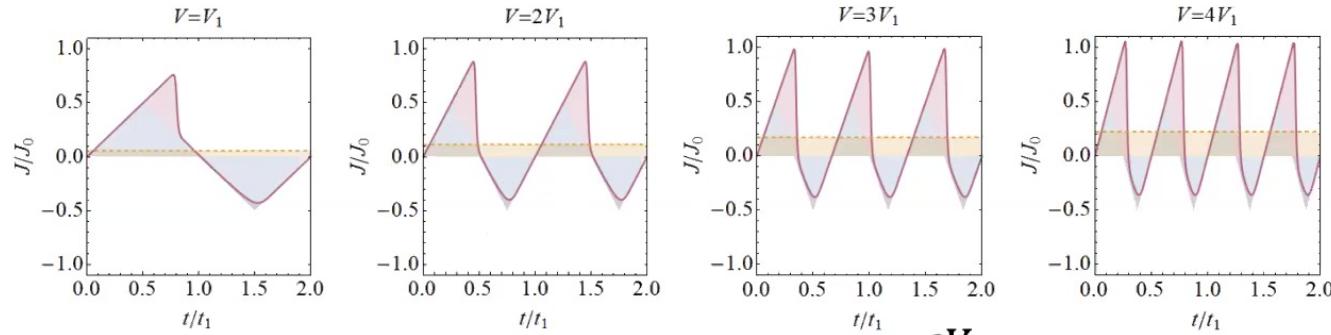


\* *T is low enough such that vortex-antivortex dissociation is suppressed.*

# Double-period Josephson effect



Langevin simulation (assuming coupling to a spin bath)



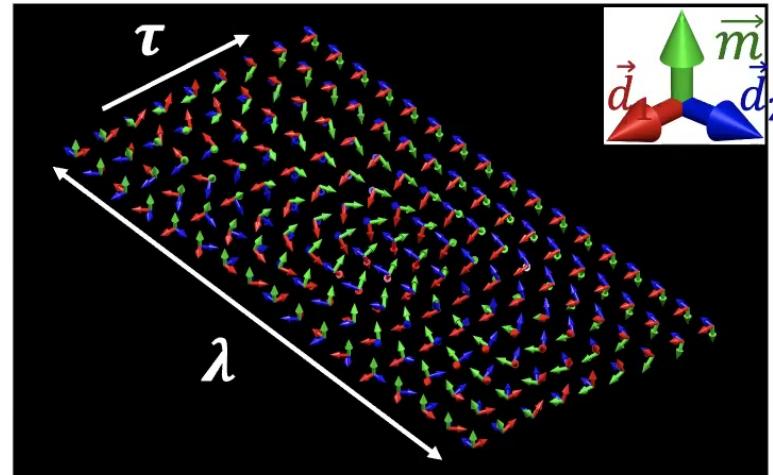
Half the usual Josephson frequency:  $\omega = \frac{eV}{\hbar}$ .  $\bar{J} - J_\epsilon \sim \sqrt{V}$

\* *T is low enough such that vortex-antivortex dissociation is suppressed.*





# In-plane magnetic field



$$\Delta F_{max} \sim \frac{\kappa_d}{\lambda} \left( \frac{\kappa_m}{2\kappa_d} + 1 \right) + \lambda \mu B$$

Minimize over  $\lambda$ :  $\lambda \sim \frac{1}{\sqrt{B}}$

Critical current:  $J_c \sim \sqrt{B}$

*E. Cornfeld, M. Rudner, EB, arXiv:2006.10073*

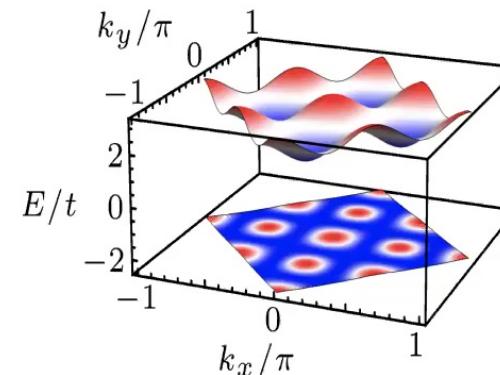


# Summary

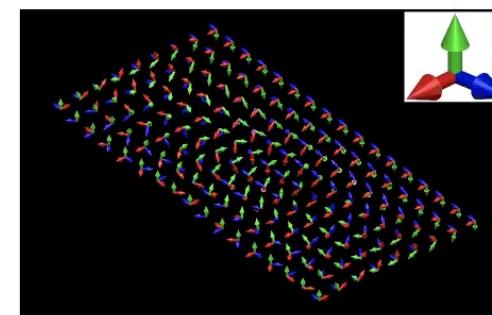
Moiré superlattices are a fascinating new playground for correlated electron physics.

- Theoretically, superconductivity can survive in the limit  $\frac{W}{U} \rightarrow 0$ .

Optimal  $\frac{W}{U}$ ?



- Possible fully spin polarized SC: fragility of supercurrent due to topology of order parameter space, double-period Josephson effect



Thank you!