Team 2 Xuchen Cao, Alejandro Cárdenas-Avendaño & Patrick Carzon

# **ILLINOIS**

Mostly based on: Xu & Balents, Phys. Rev. Lett. **121**, 087001

> 22.11.2019 PHYS 596



## Goals of this Talk

Intro

Graphene

Model

Conclusions

Citation Evaluation



## Goals of this Talk

Conclusions

Citation Evaluation

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Intro

Model



Twisted Bilayer graphene experimentally showed a very interesting behaviour



## Goals of this Talk

An effective model was proposed to explain it

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Twisted Bilayer graphene experimentally showed a very interesting behaviour

## Evolution of superconducting transitions over time



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## Evolution of superconducting transitions over time



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Intro





Intro



Normalized carrier density (cm<sup>-2</sup>) 10<sup>11</sup> 10<sup>12</sup> 10<sup>13</sup> 10<sup>2</sup> FeSe(1L)/STO 14 ه ک Critical temperature,  $T_{\rm c}$  (K) / 61 i  $A_{3}C_{60}$  $(\times 10^{8})$ 1 8H01 10<sup>1</sup> BEDT 🛋 11 NbSe<sub>2</sub> 01 <sup>40</sup>K (×10<sup>8</sup>) Na<sub>x</sub>CoO<sub>2</sub> U<sub>6</sub>Fe 10-1 \* UPd<sub>2</sub>Al<sub>3</sub> TMTSF\_ Magic-angle TBG  $URu_2Si_2$ \* UBe<sub>13</sub> °,7F SrTiO<sub>3</sub> EDLT \*UPt LAO/STO 10-1 10<sup>-2</sup>- $10^{2}$ 1<sup>00</sup> 1<sup>03</sup> 10<sup>1</sup>

> Model Conclusions **Citation Evaluation**

Intro

Graphene

## How "strong" is a superconductor



- \* Heavy-fermion superconductors
- Cuprates
- Iron pnictides
- Conventional superconductors ♦
- BEC in atoms
- Two-dimensional materials
- Organic superconductors
- NbSe<sub>2</sub> •  $A_{3}C_{60}$
- $\triangle$  Na<sub>x</sub>CoO<sub>2</sub>  $\blacksquare$  CaC<sub>6</sub>
- Magic-angle TBG



## Strange Materials: Mott insulator

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## Strange Materials: Mott insulator

but are insulators when measured

Conclusions



#### Materials that conduct electricity under conventional band theories (CBTs)

## Strange Materials: Mott insulator

- but are insulators when measured
- transfer integral of electrons (t) between neighboring atoms (z)

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#### Materials that conduct electricity under conventional band theories (CBTs)

Energy gap understood as competition between coulomb potential (U) and

Eqap=U-2zt

## Strange Materials: Mott insulator

- but are insulators when measured
- transfer integral of electrons (t) between neighboring atoms (z)

Model

Simplest **Mott insulator** is the Hubbard model

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Intro



#### Materials that conduct electricity under conventional band theories (CBTs)

Energy gap understood as competition between coulomb potential (U) and

#### Eqap=U-2zt

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- A model to describe interacting fermions where
  - They can only move between lattice sites
  - Interactions only happen at the lattice sites

Model



- A model to describe interacting fermions where
  - They can only move between lattice sites 0
  - Interactions only happen at the lattice sites 0

Model







- A model to describe interacting fermions where
  - They can only move between lattice sites 0
  - Interactions only happen at the lattice sites 0

$$H = -t \sum_{\langle ij \rangle} \left[ c^{\dagger}_{i\alpha} c_{j\alpha} + \frac{1}{\langle ij \rangle} \right]$$

Intro

Giamarchi (2017)









- A model to describe interacting fermions where
  - They can only move between lattice sites 0
  - Interactions only happen at the lattice sites  $\bigcirc$



Intro



- A model to describe interacting fermions where
  - They can only move between lattice sites 0
  - Interactions only happen at the lattice sites  $\bigcirc$



Intro



## The Graphene direct and reciprocal structure



Intro

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Geim and MacDonald (2007)







## The Graphene direct and reciprocal structure



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Geim and MacDonald (2007)

![](_page_20_Picture_10.jpeg)

![](_page_20_Picture_11.jpeg)

![](_page_20_Picture_12.jpeg)

![](_page_21_Figure_2.jpeg)

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![](_page_21_Picture_8.jpeg)

## An interesting twist on graphene

![](_page_21_Picture_10.jpeg)

![](_page_22_Figure_2.jpeg)

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![](_page_22_Picture_8.jpeg)

## An interesting twist on graphene

![](_page_22_Picture_10.jpeg)

![](_page_23_Figure_2.jpeg)

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![](_page_23_Picture_8.jpeg)

## An interesting twist on graphene

![](_page_23_Figure_10.jpeg)

Physics Today (2018)

![](_page_23_Picture_12.jpeg)

### Magic angles give interesting phases

![](_page_24_Figure_2.jpeg)

![](_page_24_Picture_3.jpeg)

RESISTANCE ( $k\Omega$ )

### Magic angles give interesting phases

0

#### Twisted Graphene

![](_page_25_Figure_3.jpeg)

![](_page_25_Picture_4.jpeg)

RESISTANCE ( $k\Omega$ )

### Magic angles give interesting phases

0

#### **Twisted Graphene**<sup>8</sup>

![](_page_26_Figure_3.jpeg)

![](_page_26_Picture_4.jpeg)

![](_page_26_Figure_5.jpeg)

Credits: Holger Motzkau

![](_page_26_Picture_7.jpeg)

### Band Structure of Bilayer Graphene

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![](_page_27_Picture_8.jpeg)

### Band Structure of Bilayer Graphene

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Citation Evaluation

![](_page_28_Picture_8.jpeg)

## Band Structure of Bilayer Graphene

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 $\mathcal{H} = \begin{pmatrix} h_k(\frac{\theta}{2}) & T_b \\ T_b^{\dagger} & h_{k_b}(-\frac{\theta}{2}) \\ T_{tr}^{\dagger} & 0 \end{pmatrix}$ 

Citation Evaluation

![](_page_29_Picture_8.jpeg)

$$egin{array}{ccc} T_{tr} & T_{tl} & 0 & 0 \ h_{k_{tr}}(-rac{ heta}{2}) & 0 & 0 \ 0 & h_{k_{tl}}(-rac{ heta}{2}) & 0 \end{array}$$

### Band Structure of Bilayer Graphene

 $h_k(\theta) = -vk\left(e^{-\frac{1}{2}}\right)$ 

Intro

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 $\mathcal{H} = egin{pmatrix} h_k(rac{ heta}{2}) & T_b \ T_b^\dagger & h_{k_b}(-rac{ heta}{2}) \ T_{tr}^\dagger & 0 \ T_{tr}^\dagger & 0 \ T_{tr}^\dagger & 0 \ \end{bmatrix}$ 

Citation Evaluation

1

![](_page_30_Picture_9.jpeg)

$$\begin{array}{ccc} T_{tr} & T_{tl} \\ 0 & 0 \\ h_{k_{tr}}(-\frac{\theta}{2}) & 0 \\ 0 & h_{k_{tl}}(-\frac{\theta}{2}) \end{array}$$

$$\begin{pmatrix} 0 & e^{i( heta_k - heta)} \\ -i( heta_k - heta) & 0 \end{pmatrix}$$

## Band Structure of Bilayer Graphene

 $\mathcal{H} = \begin{pmatrix} h_k(\frac{\theta}{2}) & T_b \\ T_b^{\dagger} & h_{k_b}(-\frac{\theta}{2}) \\ T_{tr}^{\dagger} & 0 \\ T_{tr}^{\dagger} & 0 \end{pmatrix}$  $h_k(\theta) = -vk\left(\right.$ 1

Intro

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![](_page_31_Picture_9.jpeg)

$$\begin{array}{ccc} T_{tr} & T_{tl} \\ 0 & 0 \\ h_{k_{tr}}(-\frac{\theta}{2}) & 0 \\ 0 & h_{k_{tl}}(-\frac{\theta}{2}) \end{array}$$

Single layer Hamiltonian

$$egin{array}{ccc} 0 & e^{i( heta_k- heta)} \ -i( heta_k- heta) & 0 \end{array} \end{pmatrix}$$

 $\mathcal{H} = \begin{bmatrix} T_b^{\dagger} \\ T_b^{\dagger} \\ T_{tr}^{\dagger} \end{bmatrix}$ 

## Band Structure of Bilayer Graphene

Twisted angle

 $T_b \ h_{k_b}(-rac{ heta}{2}) \ 0$ 

Conclusions

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1

![](_page_32_Picture_11.jpeg)

$$egin{array}{ccc} T_{tr} & T_{tl} \ 0 & 0 \ h_{k_{tr}}(-rac{ heta}{2}) & 0 \ 0 & h_{k_{tl}}(-rac{ heta}{2}) \end{pmatrix}$$

Single layer Hamiltonian

$$egin{array}{ccc} 0 & e^{i( heta_k- heta)} \ -i( heta_k- heta) & 0 \end{array} \end{pmatrix}$$

### Band Structure of Bilayer Graphene Transfer Amplitudes Twisted angle $T_{tl}$ $T_{tr}$ $h_{k_b}(-rac{ heta}{2}) \ 0$ $h_{k_{tr}}(-\frac{\theta}{2})$ $h_{k_{tl}}$

Conclusions

1

![](_page_33_Picture_11.jpeg)

Single layer Hamiltonian

$$egin{array}{c} 0 & e^{i( heta_k- heta)} \ -i( heta_k- heta) & 0 \end{array} \end{pmatrix}$$

## Twisting creates a flat band

Intro

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Citation Evaluation

![](_page_34_Picture_8.jpeg)

- The bilayer system forms flat bands 0 at the magic angles
- We should now work in a **reduced** 0 ΒZ
- At magic angle **DOS** peaks at the E=0

Graphene

![](_page_35_Picture_10.jpeg)

- The bilayer system forms flat bands  $\bigcirc$ at the magic angles
- We should now work in a **reduced** ΒZ
- At magic angle **DOS** peaks at the E=0

Graphene

![](_page_36_Picture_10.jpeg)

![](_page_36_Figure_11.jpeg)

- The bilayer system forms flat bands 0 at the magic angles
- We should now work in a **reduced** 0 ΒZ
- At magic angle **DOS** peaks at the E=0

Graphene

![](_page_37_Picture_10.jpeg)

- The bilayer system forms flat bands 0 at the magic angles
- We should now work in a **reduced** 0 ΒZ
- At magic angle **DOS** peaks at the E=0

Graphene

Conclusions

![](_page_38_Picture_10.jpeg)

*θ*=3<sup>°</sup> 0.08 0.06 0.04 0.02 E (eV) 0. -0.02 0.04 -0.06 0.08. -0.1 0.2 0.2 -0.1 k, <sup>0</sup> -0.2

Cao. et. al., (2018)

![](_page_38_Picture_21.jpeg)

- The bilayer system forms flat bands 0 at the magic angles
- We should now work in a reduced ΒZ
- At magic angle **DOS** peaks at the E=0

Intro

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![](_page_39_Picture_11.jpeg)

![](_page_39_Figure_12.jpeg)

Cao. et. al., (2018)

![](_page_39_Picture_21.jpeg)

### An effective model to explain flat bands

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![](_page_40_Picture_8.jpeg)

### An effective model to explain flat bands

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![](_page_41_Picture_8.jpeg)

### An effective model to explain flat bands

# valley degrees of freedom in the original problem

<u>Conclusions</u>

![](_page_42_Picture_8.jpeg)

• There is a **SU(4)** flavor structure for fermions, corresponding to the spin and

### An effective model to explain flat bands

- valley degrees of freedom in the original problem
  - approximated by a Hubbard term

Graphene

Model

<u>Conclusions</u>

Citation Evaluation

![](_page_43_Picture_9.jpeg)

• There is a **SU(4)** flavor structure for fermions, corresponding to the spin and

Assume that the hopping term does not mix flavors and Coulomb interaction is

### An effective model to explain flat bands

- valley degrees of freedom in the original problem
  - approximated by a Hubbard term

 $ij\alpha$ 

Intro

Graphene

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Conclusions

Citation Evaluation

![](_page_44_Picture_10.jpeg)

• There is a **SU(4)** flavor structure for fermions, corresponding to the spin and

Assume that the hopping term does not mix flavors and Coulomb interaction is

![](_page_44_Picture_13.jpeg)

## Conclusions

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![](_page_45_Picture_9.jpeg)

## Conclusions

#### **Effective model** for TBG is proposed that explains recently detected Θ superconducting phase

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![](_page_46_Picture_10.jpeg)

## Conclusions

- **Effective model** for TBG is proposed that explains recently detected superconducting phase
- 0 through a **repulsive force**.

Conclusions

Model assumes electrons lie in flat bands that interact with one another

![](_page_47_Picture_13.jpeg)

## Conclusions

- **Effective model** for TBG is proposed that explains recently detected superconducting phase
- Model assumes electrons lie in flat bands that interact with one another  $\bigcirc$ through a **repulsive force**.
- The material's ground state is calculated for various electron densities in the limit of strong repulsive interactions.

Intro

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Conclusions

Citation Evaluation

![](_page_48_Picture_12.jpeg)

- **Effective model** for TBG is proposed that explains recently detected superconducting phase
- Model assumes electrons lie in flat bands that interact with one another through a **repulsive force**.
- The material's ground state is calculated for various electron densities in the limit of strong repulsive interactions.
- Model predicts a Mott insulating state showing unconventional 0 superconductivity, agreeing experiments

![](_page_49_Picture_13.jpeg)

![](_page_50_Picture_1.jpeg)

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![](_page_50_Picture_10.jpeg)

## Our Conclusions

Lack of organization: no headers for the 0 Introduction, Methods, and Conclusion

![](_page_51_Picture_10.jpeg)

# **Our** Conclusions

- Lack of organization: no headers for the 0 Introduction, Methods, and Conclusion
- Lack of justification in use of a coupling as SU(4) 0 symmetry-breaking perturbations

Model

![](_page_52_Picture_14.jpeg)

# **Our** Conclusions

- Lack of organization: no headers for the 0 Introduction, Methods, and Conclusion
- Lack of justification in use of a coupling as SU(4) 0 symmetry-breaking perturbations
- Jargon heavy, not accessible to non-experts 0

Model

![](_page_53_Picture_16.jpeg)

- Lack of organization: no headers for the 0 Introduction, Methods, and Conclusion
- Lack of justification in use of a coupling as SU(4) symmetry-breaking perturbations
- Jargon heavy, not accessible to non-experts 0
- Impact in topological superconductors and strong correlation physics

![](_page_54_Picture_18.jpeg)

- Lack of organization: no headers for the 0 Introduction, Methods, and Conclusion
- Lack of justification in use of a coupling as SU(4) symmetry-breaking perturbations
- Jargon heavy, not accessible to non-experts 0
- Impact in topological superconductors and strong correlation physics
- We recommend it for publication with minor 0 modifications.

![](_page_55_Picture_20.jpeg)

- Lack of organization: no headers for the Introduction, Methods, and Conclusion
- Lack of justification in use of a coupling as SU(4) symmetry-breaking perturbations
- Jargon heavy, not accessible to non-experts
- Impact in topological superconductors and strong correlation physics
- We recommend it for publication with minor 0 modifications.

![](_page_56_Picture_18.jpeg)

![](_page_56_Picture_20.jpeg)

![](_page_56_Picture_21.jpeg)

- 143 citations according to Google Scholar
  - Most cited paper that cites this paper is "Origin of Mott Insulating" Behavior and Superconductivity in Twisted Bilayer Graphene" with 167 citations.

Model

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## Citation Evaluation

![](_page_57_Figure_11.jpeg)

![](_page_57_Picture_12.jpeg)

![](_page_57_Picture_15.jpeg)

![](_page_58_Picture_1.jpeg)

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**Citation Evaluation** 

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![](_page_59_Picture_1.jpeg)

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Graphene

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**Citation Evaluation** 

![](_page_59_Picture_8.jpeg)

Source: https://paperscape.org

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![](_page_60_Picture_3.jpeg)

# AND CRAZY

Thank you!

![](_page_60_Picture_6.jpeg)