KITP - MATBG workshop

Moiré Superlattices: Fundamental Physics with a Twist

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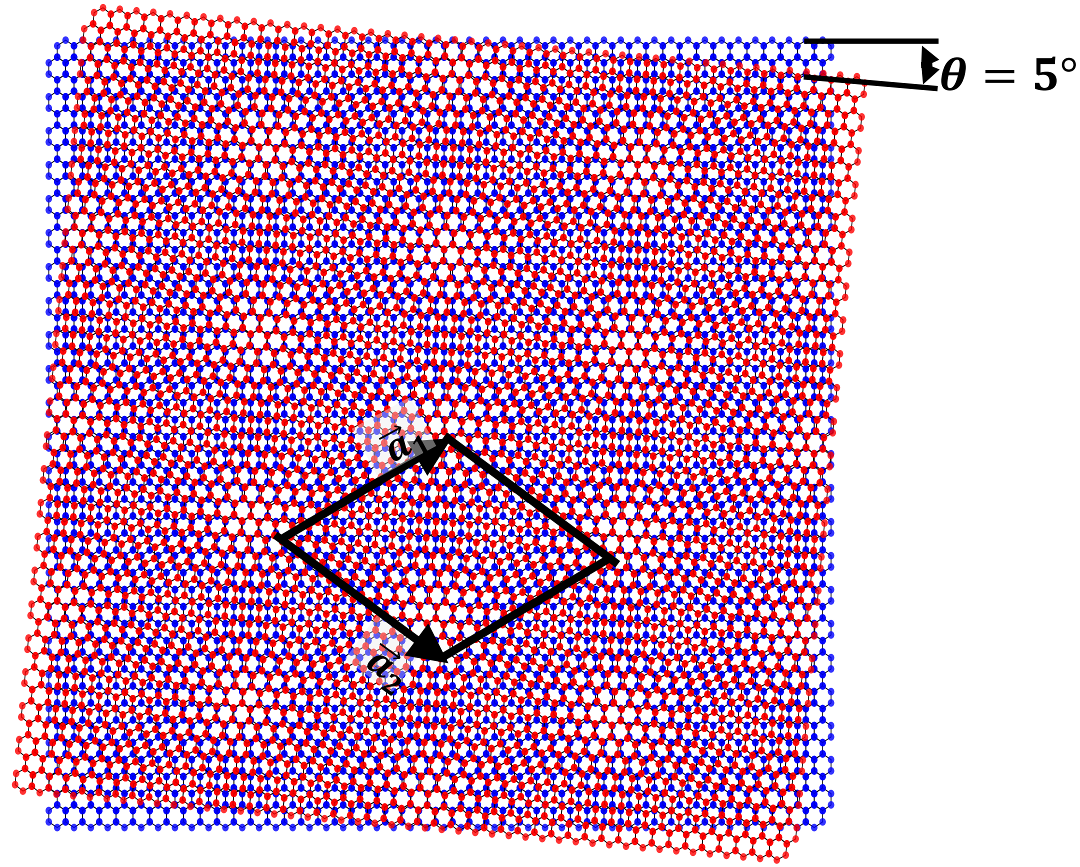
Moiré Superlattices

- Moire Bands
- Cuprates vs. Magic Angle vs. Gr Bilayer FQHE
- What can we measure?
- What can we calculate?

Twisted vdW Heterojunctions

$$\vec{d}(\vec{r}) = \theta \ \hat{z} \times \vec{r}$$

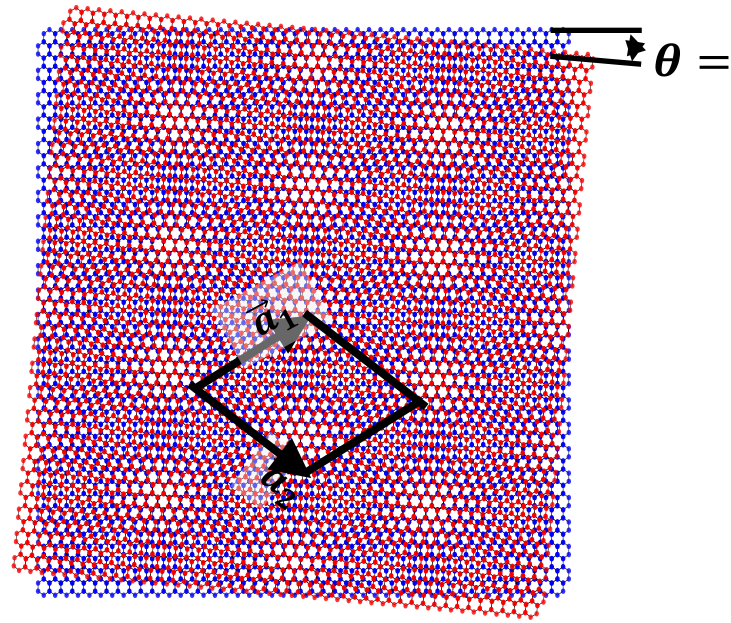
$$\theta(\vec{r}) = \frac{1}{2}\hat{z} \cdot (\vec{\nabla} \times \vec{d}(\vec{r}))$$



Twisted vdW Heterojunctions

$$\mathcal{H}(\vec{d}) = \mathcal{H}(\vec{d} + \vec{a})$$

Superlattice Hamiltonian
for Semiconductors
&
Semimetals Only



Twisted vdW Heterojunctions

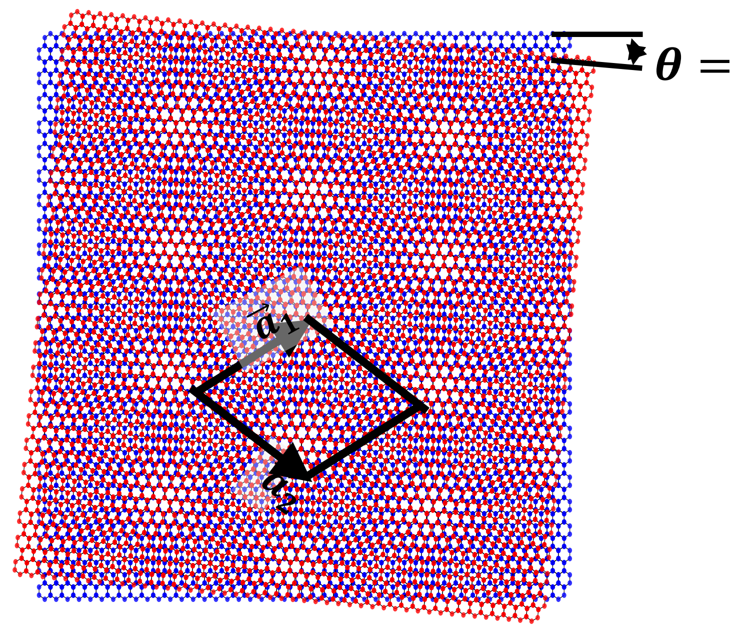
Graphene Multilayers
(1 band/2valleys/2spins)

Group VI TMD Homobilayers
(1 band/ 2 valleys)

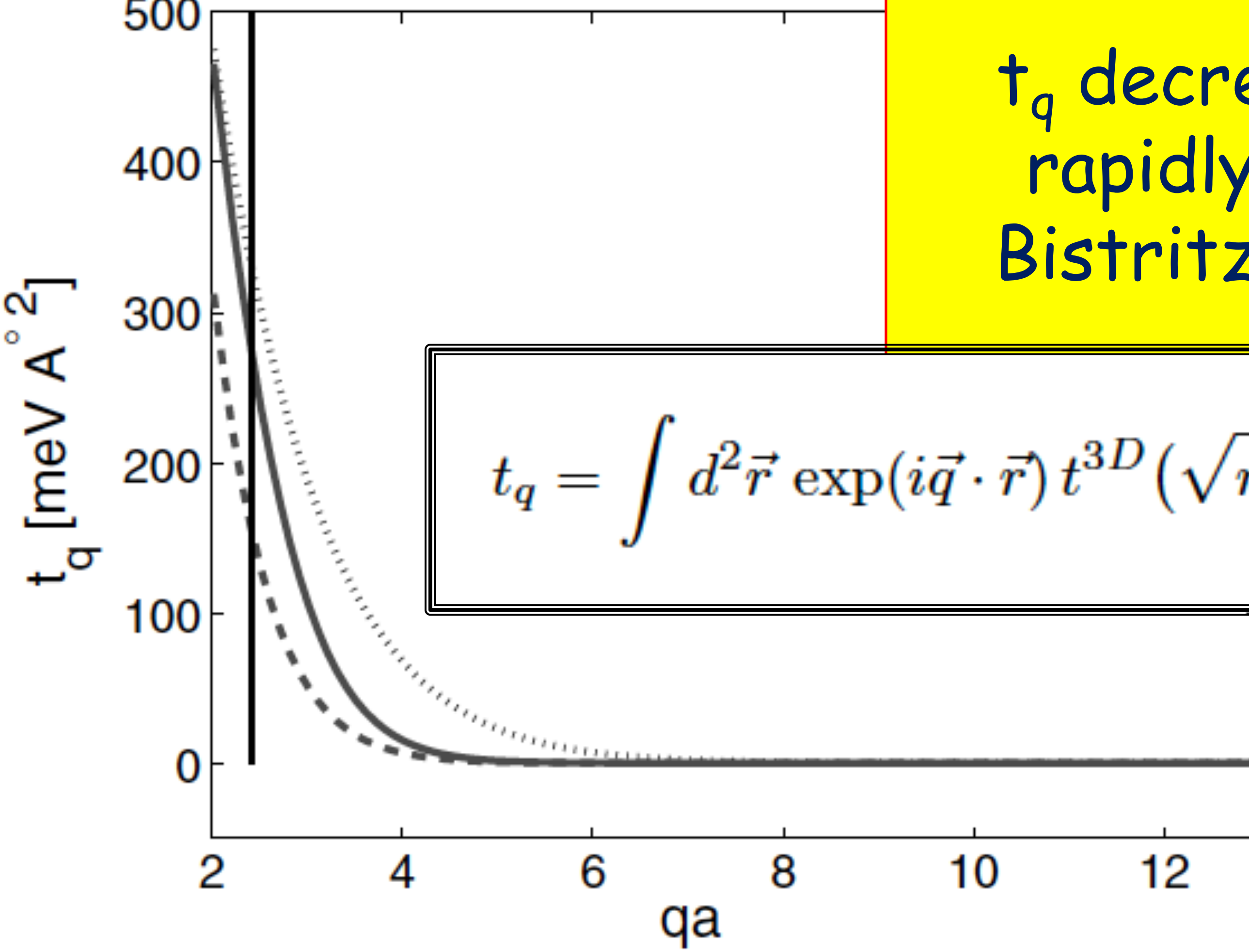
Group VI TMD
Heterobilayers
(2 bands/2valleys)

hBN Barriers
.....

$$\mathcal{H}(\vec{d}) = \mathcal{H}(\vec{d} + \vec{a})$$



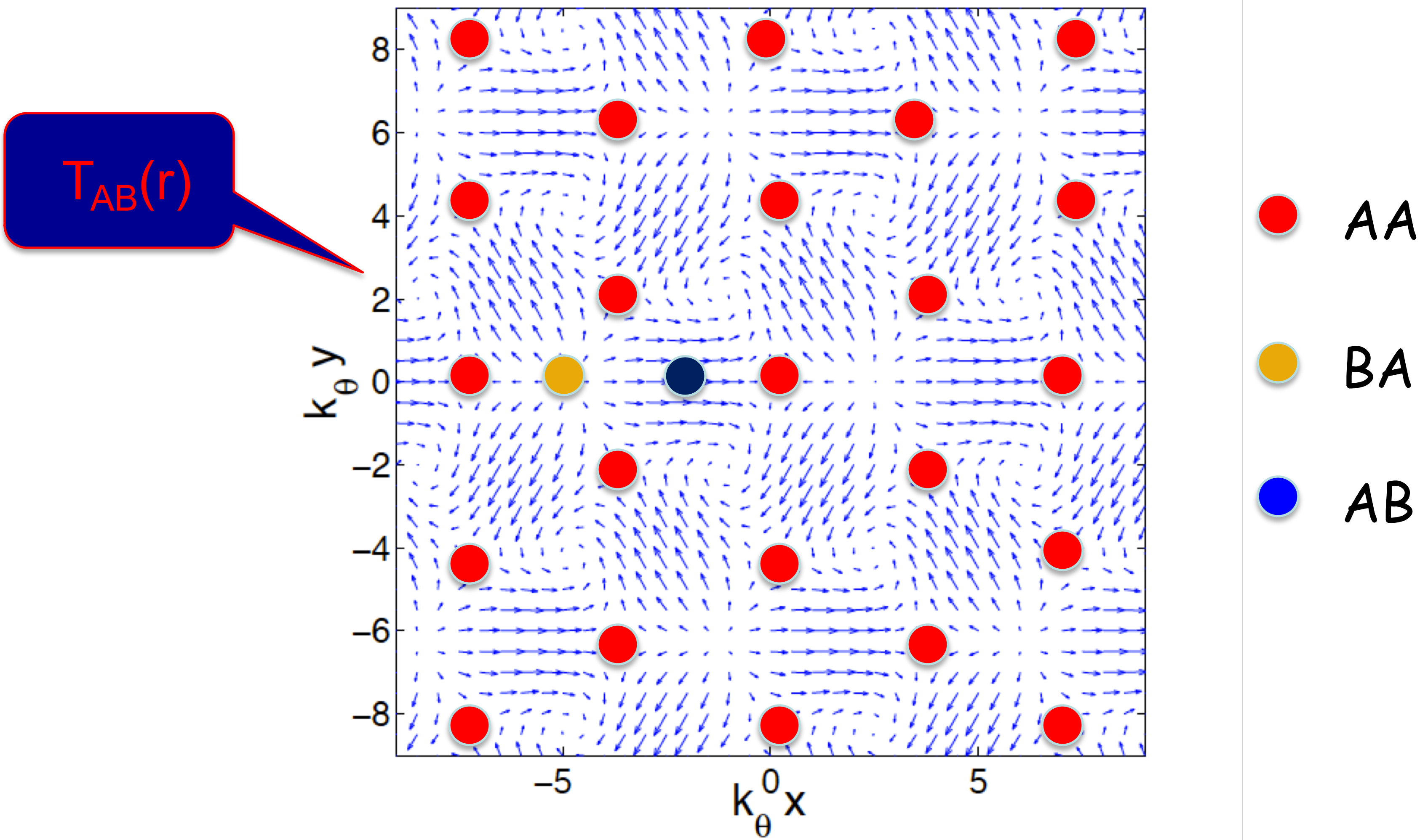
Fourier X-form of π-band interlayer hopping amplitude



t_q decreases very rapidly with q !
Bistritzer PNAS

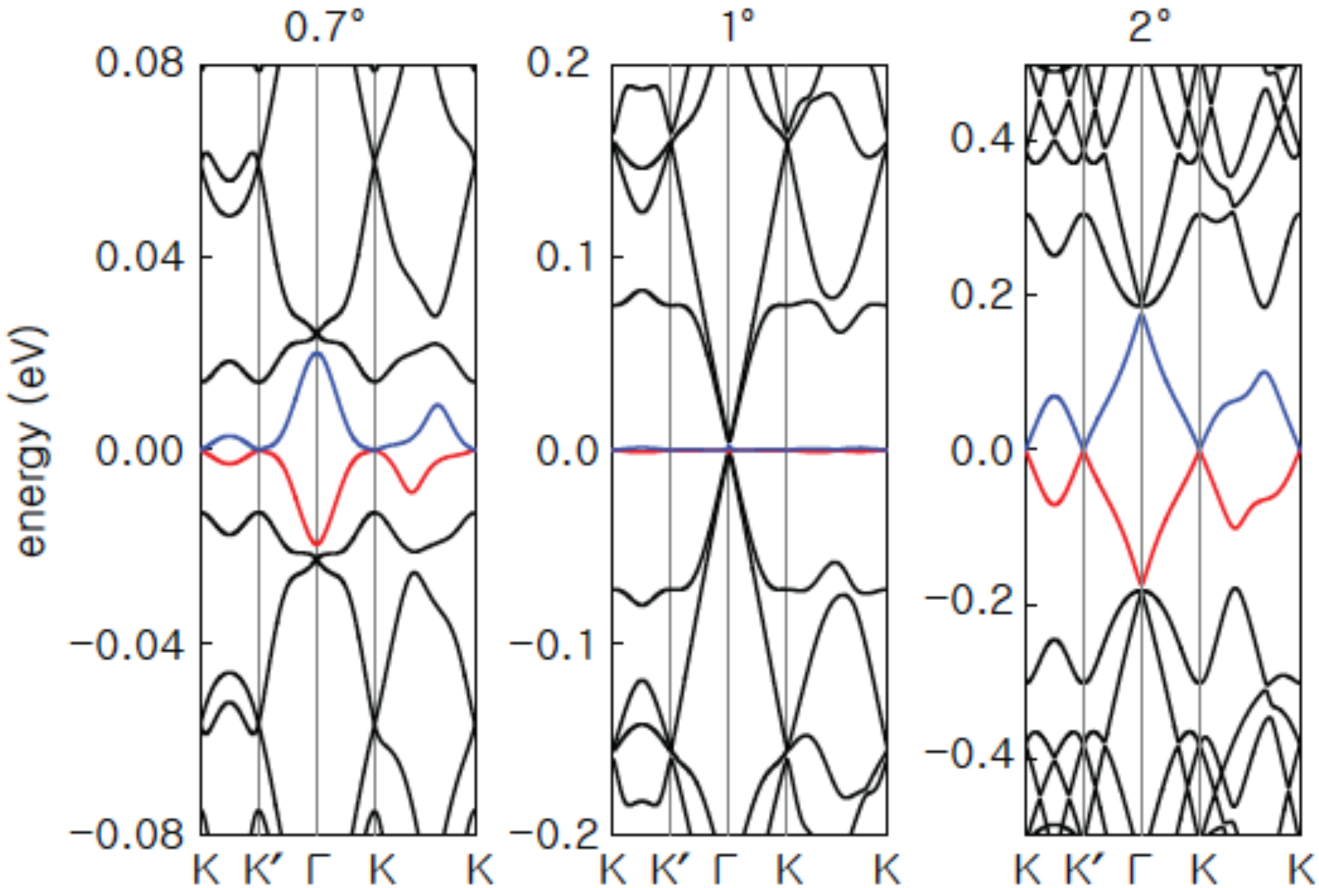
$$t_q = \int d^2\vec{r}\, \exp(i\vec{q}\cdot\vec{r})\, t^{3D}\left(\sqrt{r^2 + d^2}\,\right)$$

Periodic Tunneling Hamiltonian



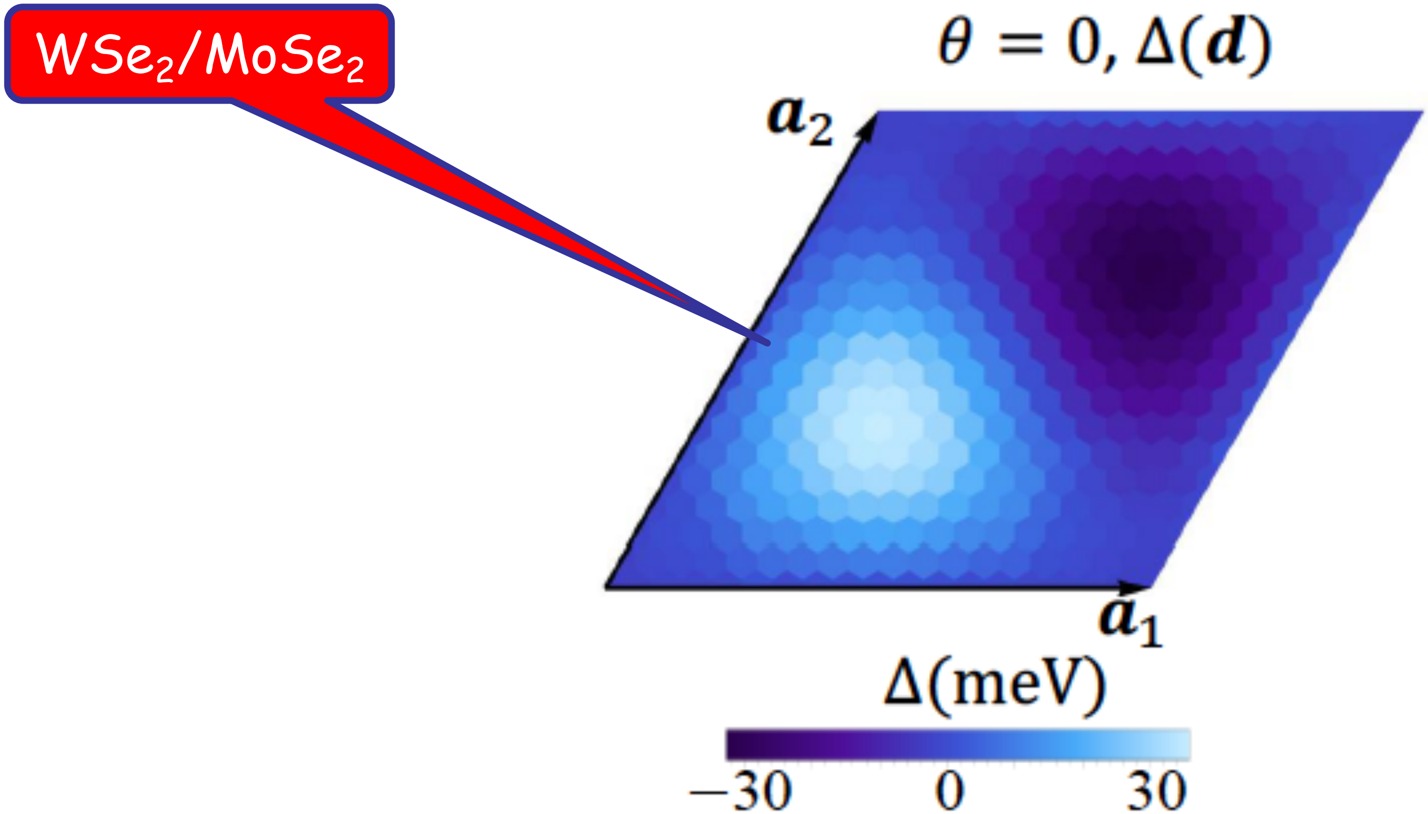
Magic Angles !

$$T^{\alpha\beta}(\mathbf{r}) = w\sum^{3} \exp(-i\mathbf{q}_j \cdot \mathbf{r})T_j^{\alpha\beta}$$



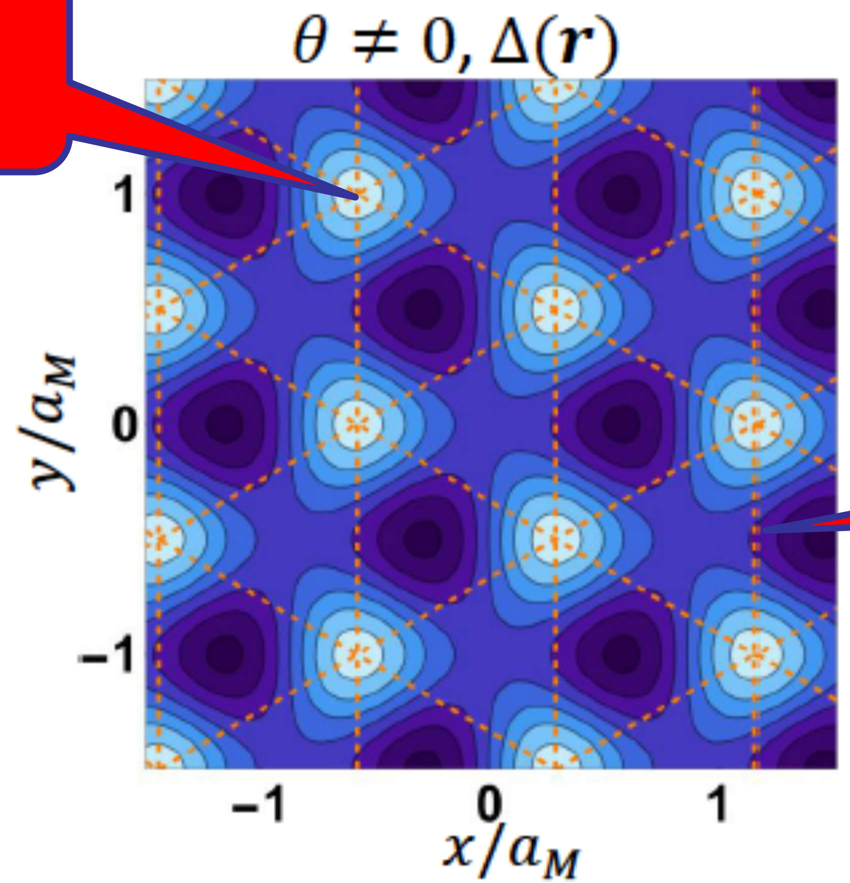
also Morrell *et al.* PRB (2010)

Moiré Bands in 2D Semiconductor Heterobilayers



Wu, Lovorn & AHM
PRL (2018)

Moiré Band Potential

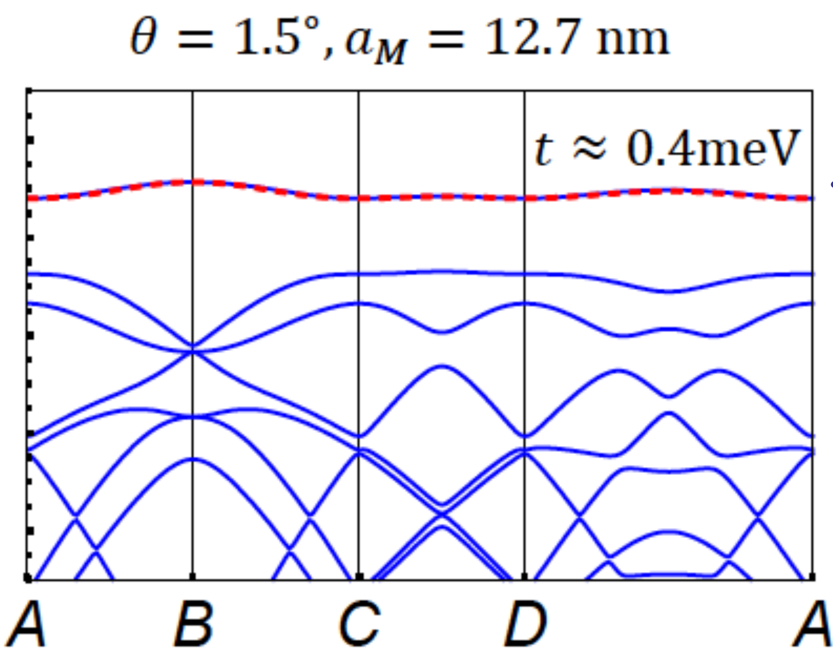


Hole Lattice Sites

$a_M = a/(2\sin(\Theta/2))$

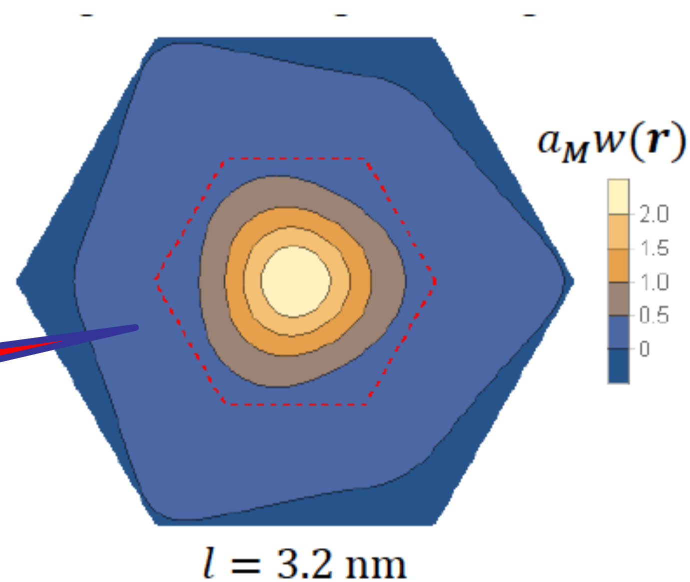
Wu, Lovorn & AHM
PRL (2018)

Moiré Hubbard Bands at 2D Semiconductor Heterojunctions



$WSe_2/MoSe_2$ twisted heterojunction

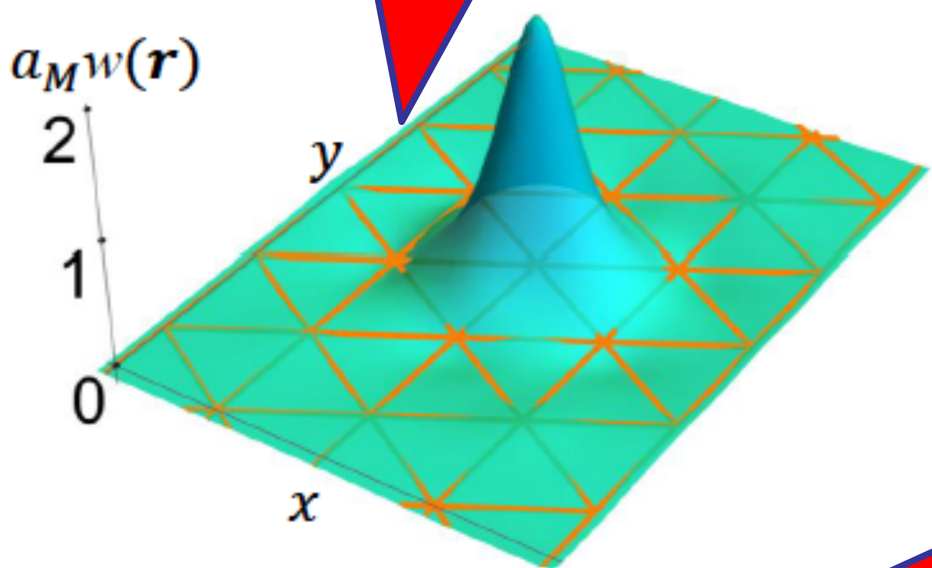
Wannier wavefunction

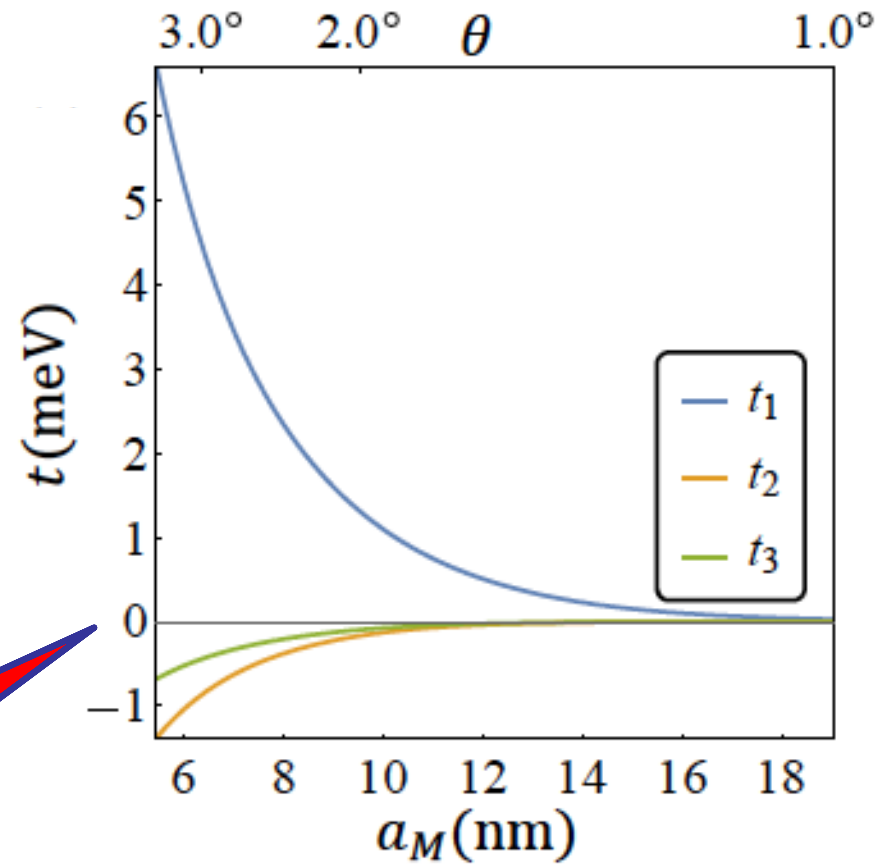


Wu, Lovorn & AHM
PRL (2018)

Tunable Moiré Hubbard Bands
SU(2) Hubbard Model

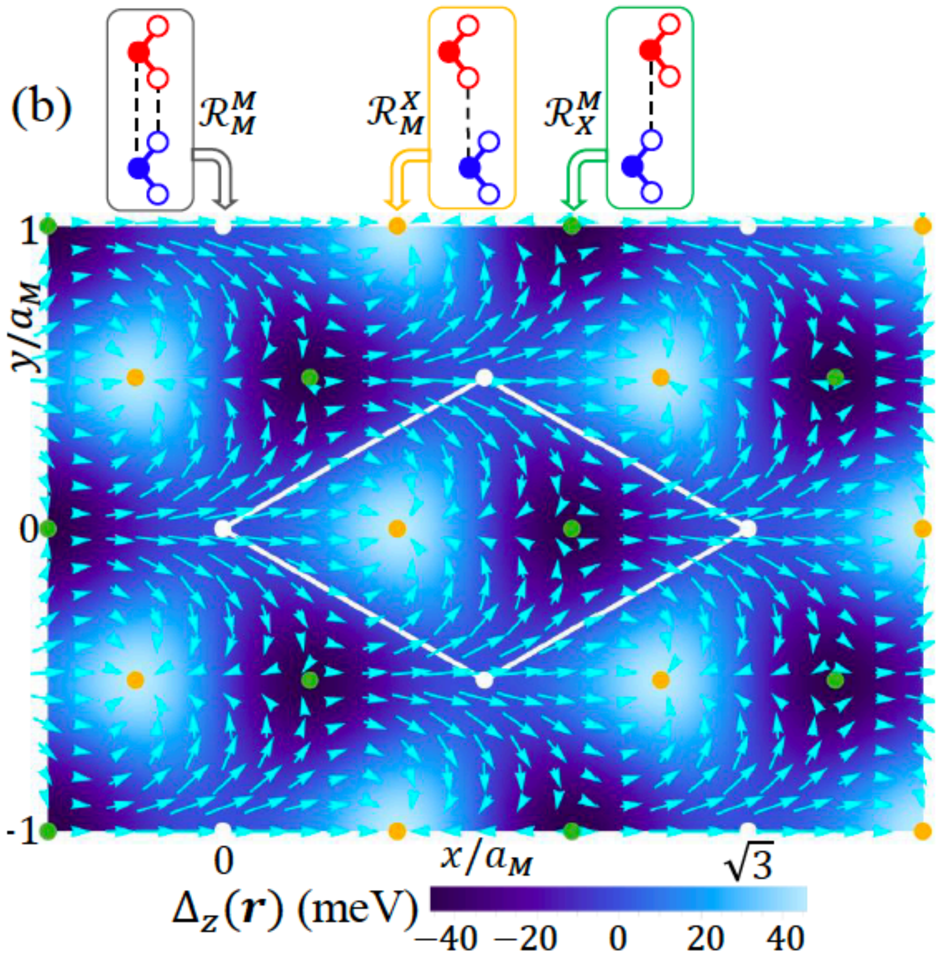
ε U ≈ 300 meV





Spin Liquid for
Θ > 3 degrees

$$\mathcal{H}_{\uparrow} = \begin{pmatrix} -\frac{\hbar^2(\boldsymbol{k}-\boldsymbol{\kappa}_+)^2}{2m^*} + \Delta_{\mathfrak{b}}(\boldsymbol{r}) & \Delta_T(\boldsymbol{r}) \\ \Delta_T^{\dagger}(\boldsymbol{r}) & -\frac{\hbar^2(\boldsymbol{k}-\boldsymbol{\kappa}_-)^2}{2m^*} + \Delta_{\mathfrak{t}}(\boldsymbol{r}) \end{pmatrix}$$

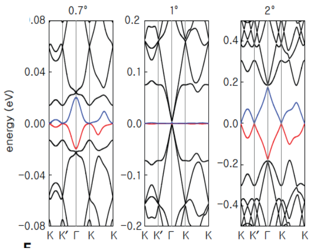


Wu et al.
arXiv:1807.03311

TMD Homobilayer

Magic Angle Bilayer Graphene

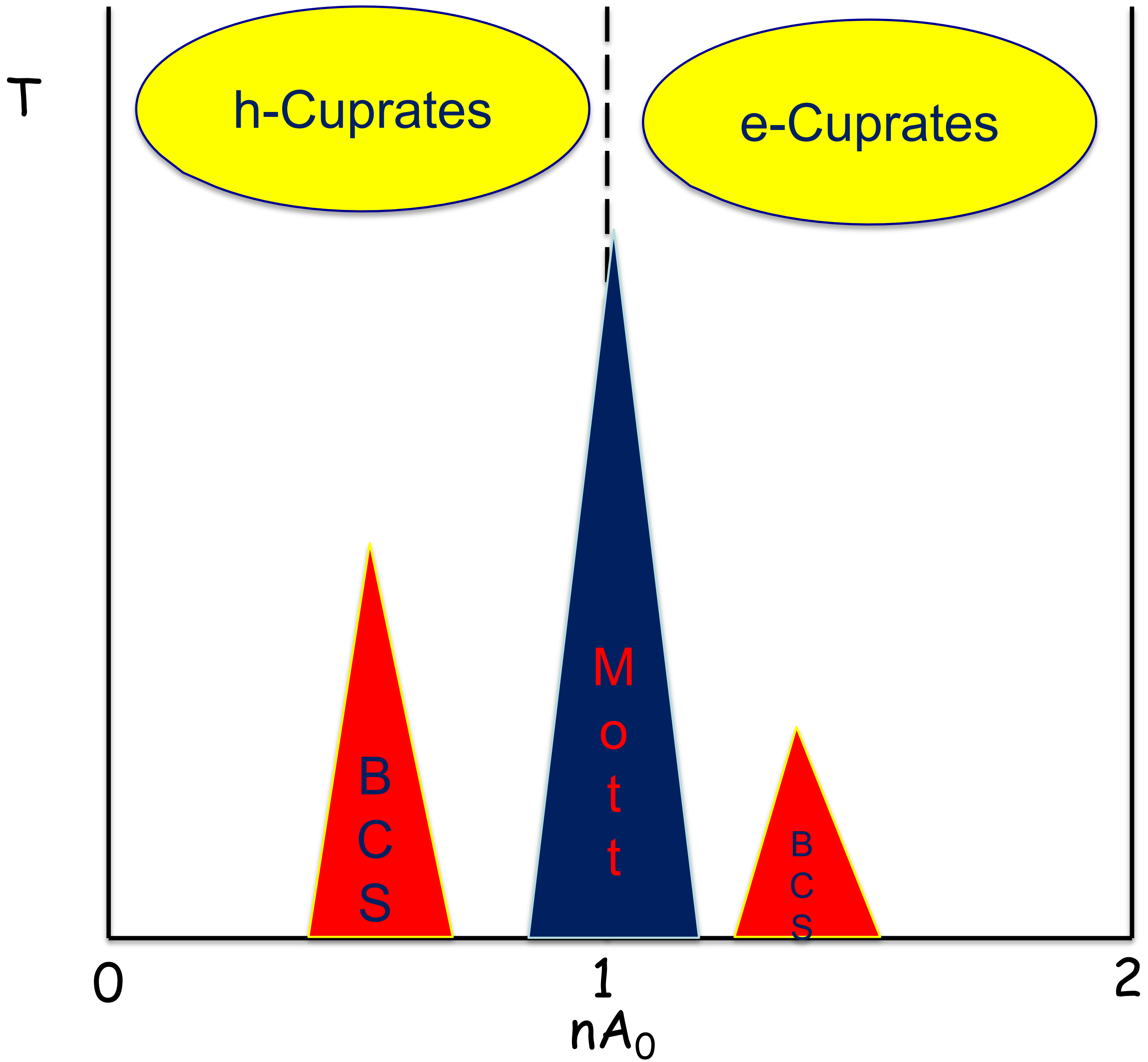
- Moire Bands



- Cuprates vs. Magic Angle vs. Gr Bilayer FQHE

- What can we measure?

- What can we calculate?


T
h-Cuprates
e-Cuprates
BCS
Mott
BCS
0
1
2
nA0

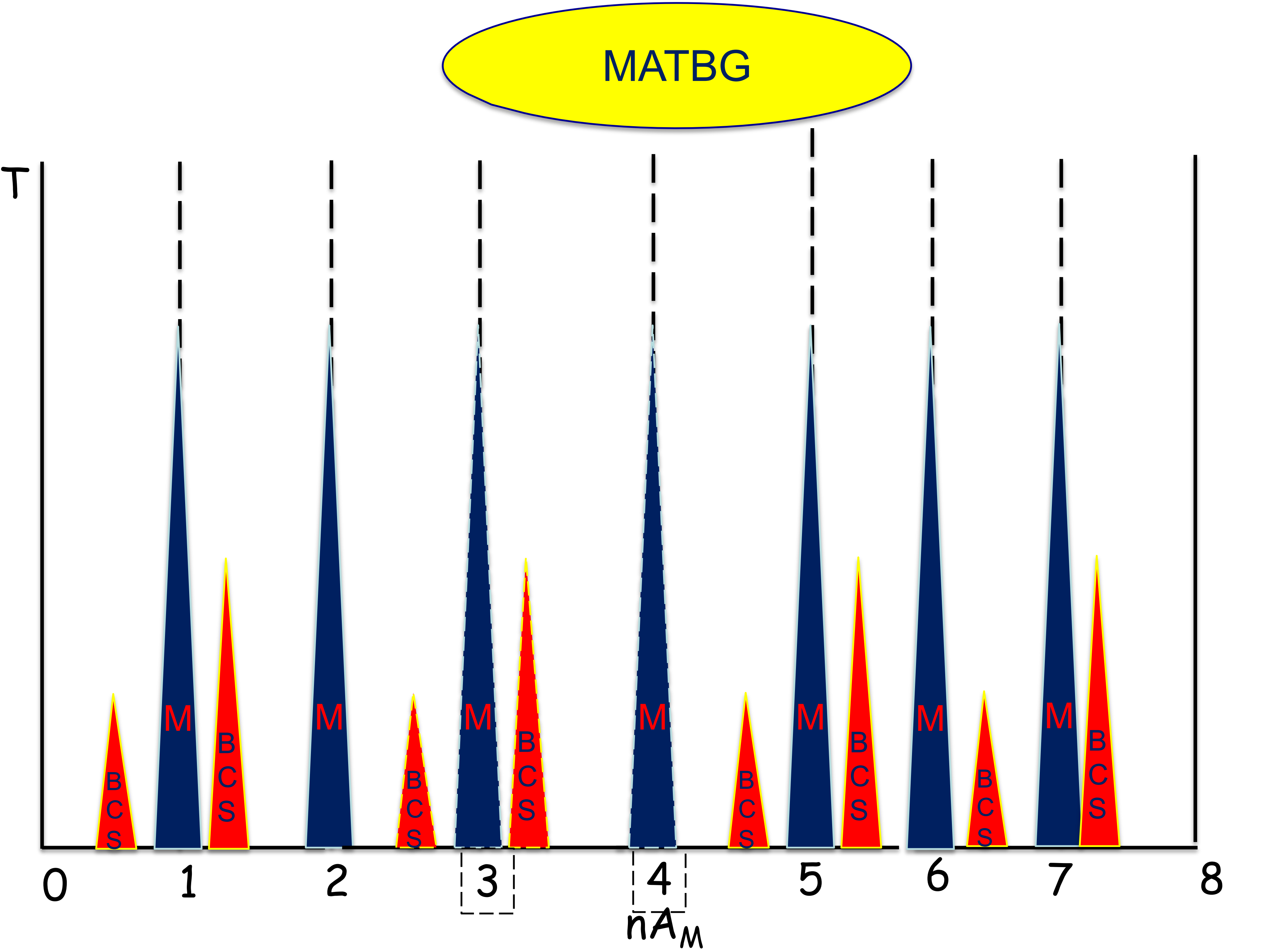
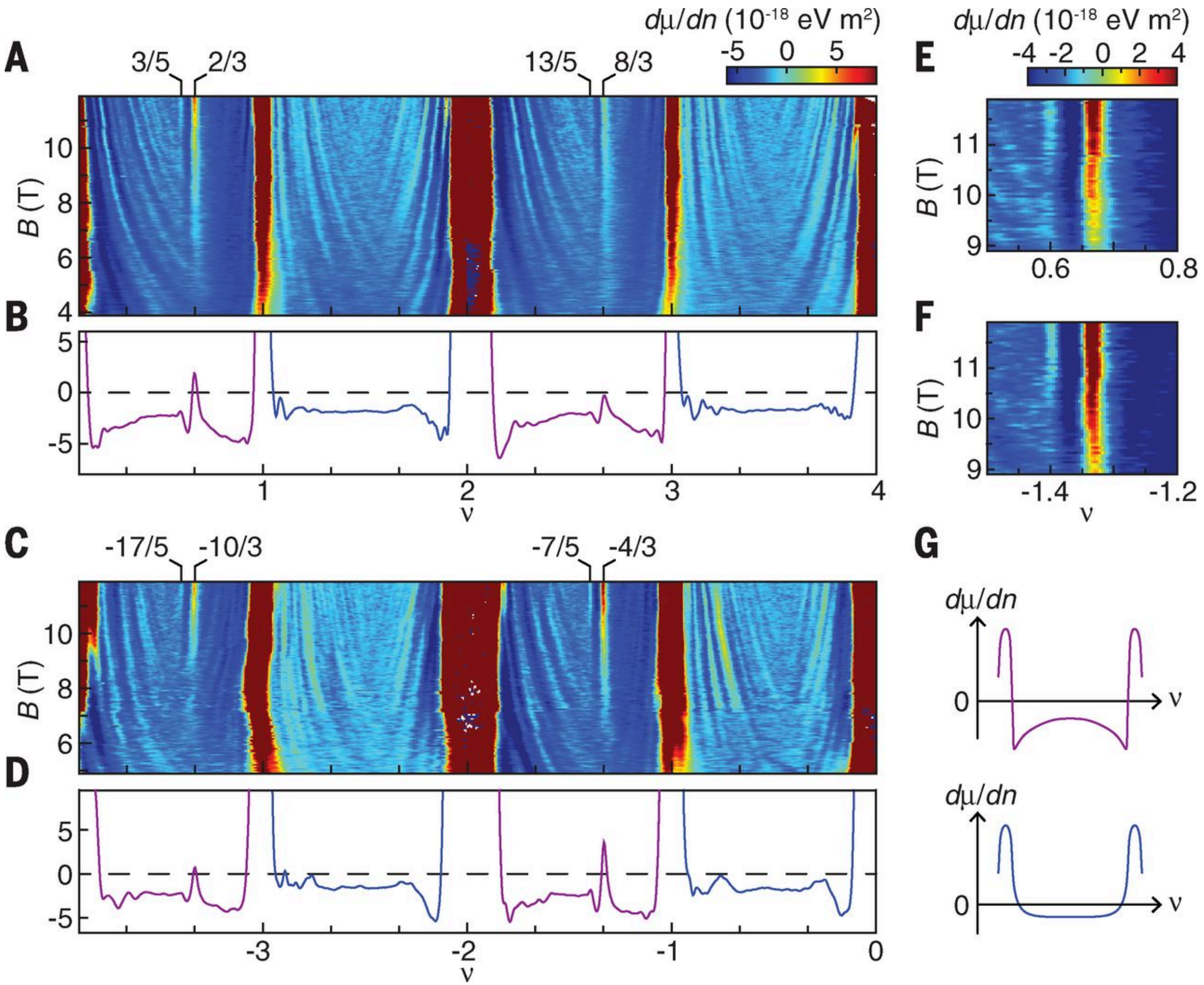

MATBG
T
M
BCS
0
1
2
3
4
5
6
7
8
nA_M

Fig. 2 Fractional quantum Hall states in bilayer graphene.(A and C) Inverse compressibility as a function of filling factor and magnetic field.

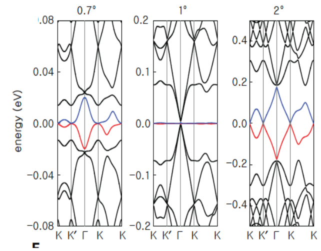


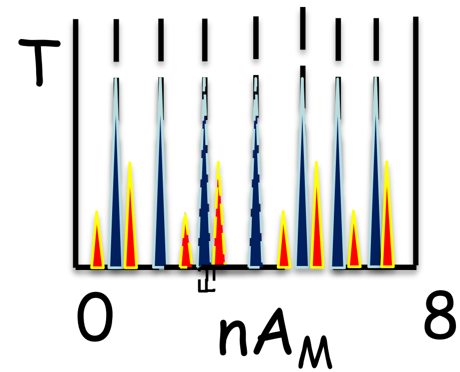
A. Kou et al. Science 2014;345:55-57

Published by AAAS

Moiré Superlattices

- Moire Bands





- Cuprates vs. Magic Angle vs. Gr Bilayer FQHE

- What can we measure?

- What can we calculate?

Isolated 2DEG response

Transport

Gate Response - Compressibility

Infrared, THz, optical properties

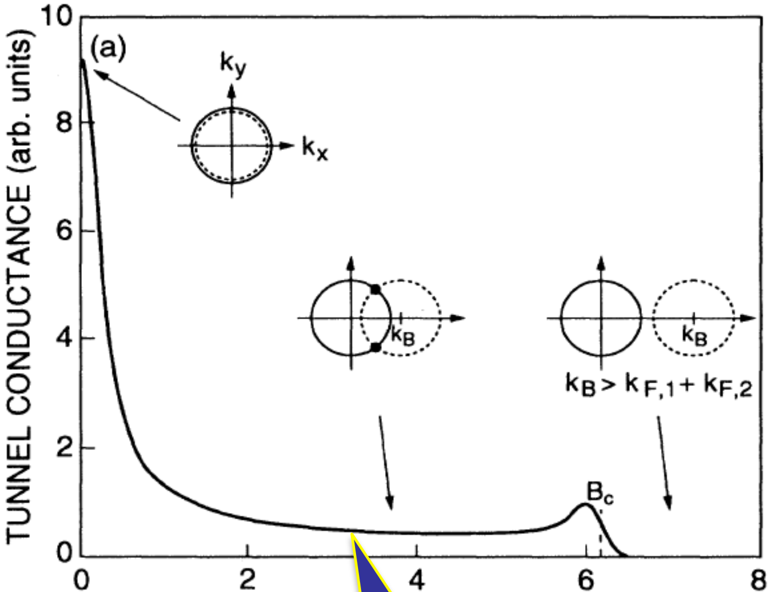
ESR

2D to 2D Tunneling

.....

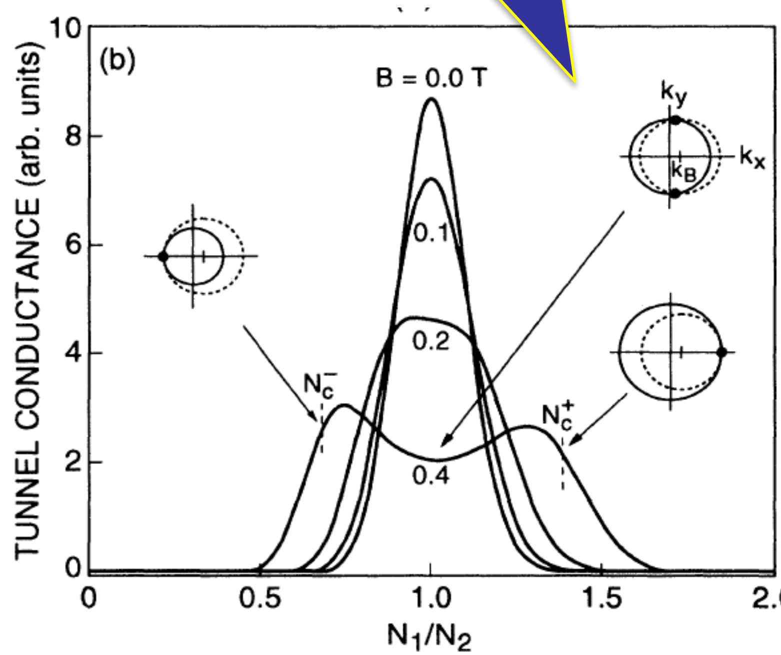
2D to 2D Tunneling

Eisenstein PRB (1991)



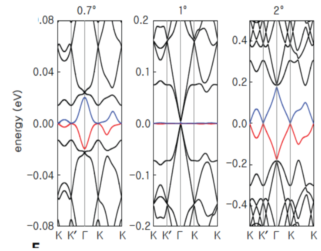
In-Plane Magnetic Field

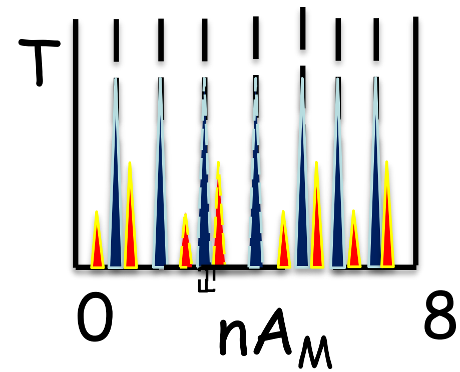
Fermi Surface Area



Moiré Superlattices

- Moire Bands





- Cuprates vs. Magic Angle vs. Gr Bilayer FQHE

- What can we measure?

- What can we calculate?

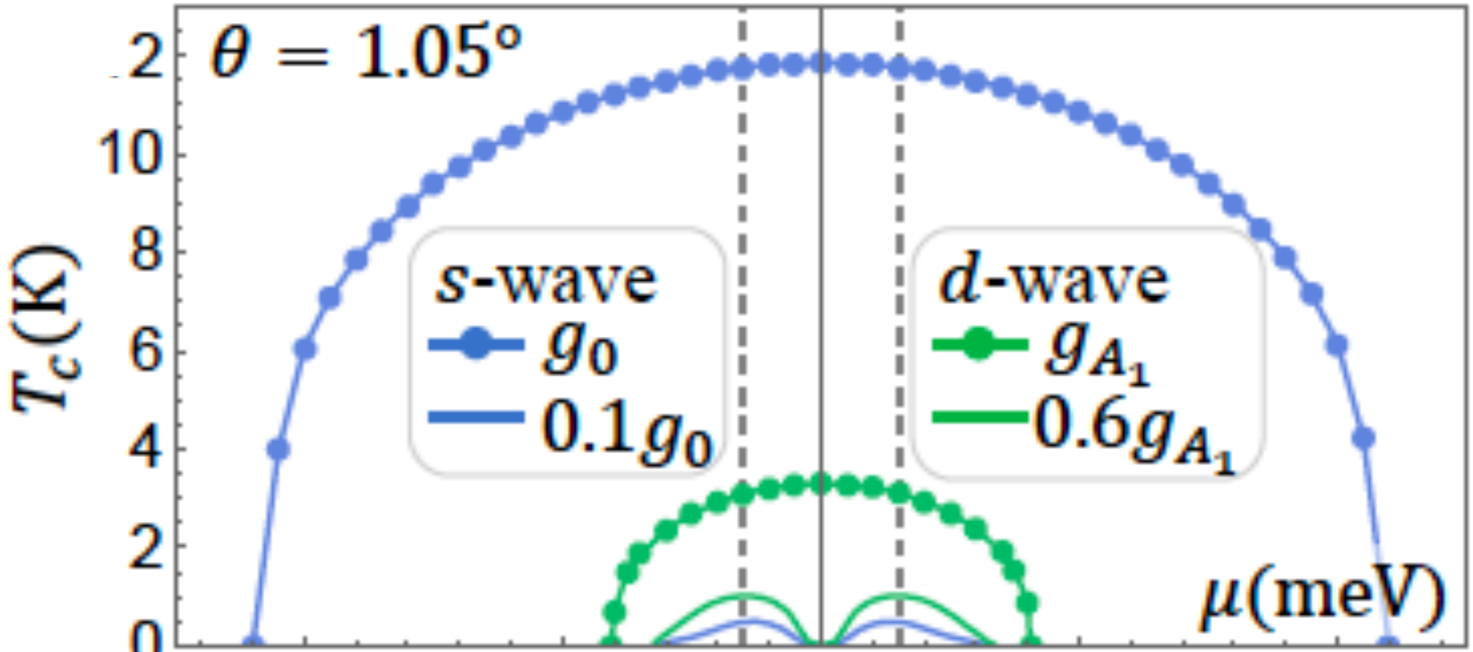
What can we calculate ?

Simplest Models that
Might Explain Superconductivity

Best Lattice Models
(Are the Flat Bands Enough)

Properties of the Insulating State

Phonon-Mediated Superconductivity



- ✓ Superconductivity over a range of angles
- ✓ T_c consistent with experiment
- ✓ Competition with insulating states?

Fengcheng Wu et al. – PRL

What can we calculate ?

Simplest Models that
Might Explain Superconductivity

Best Lattice Models
(Are the Flat Bands Enough)

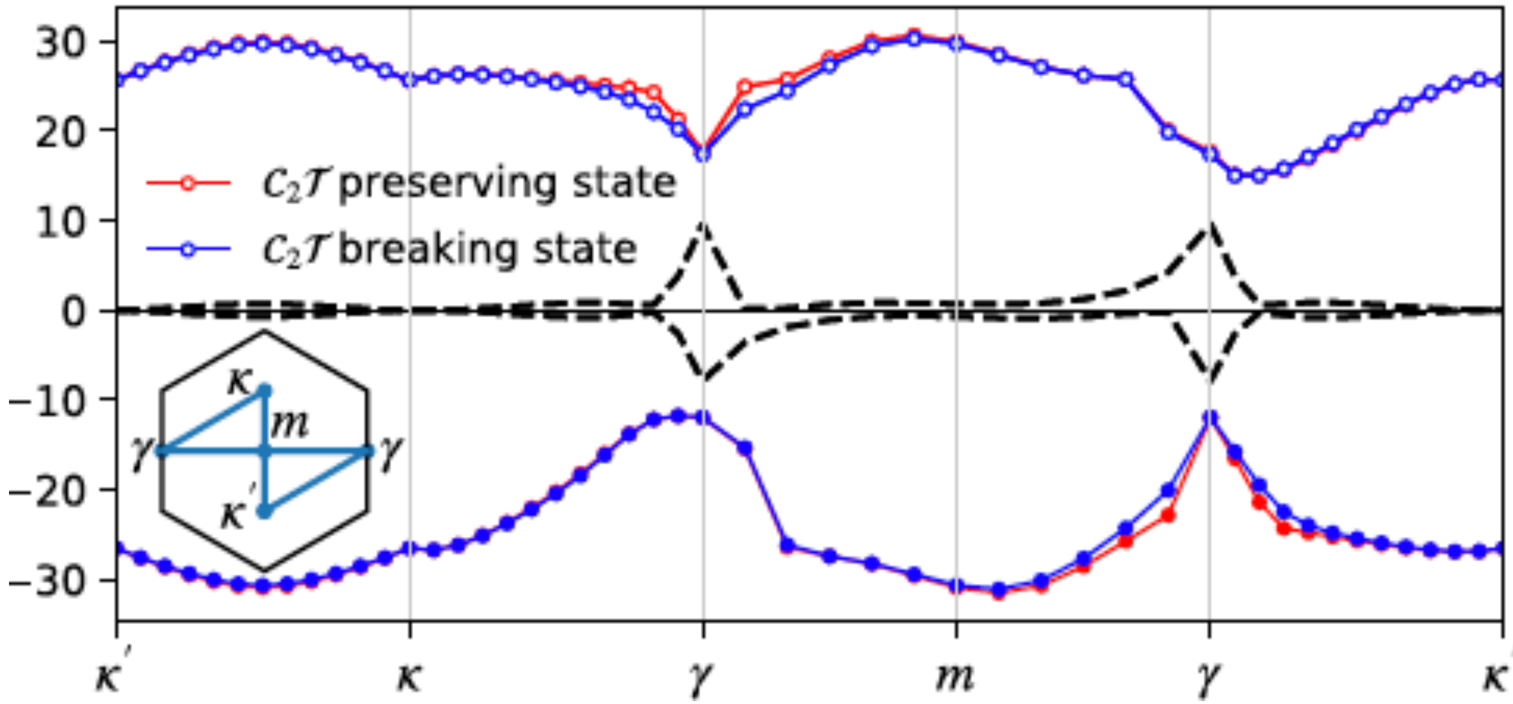
Properties of the Insulating State

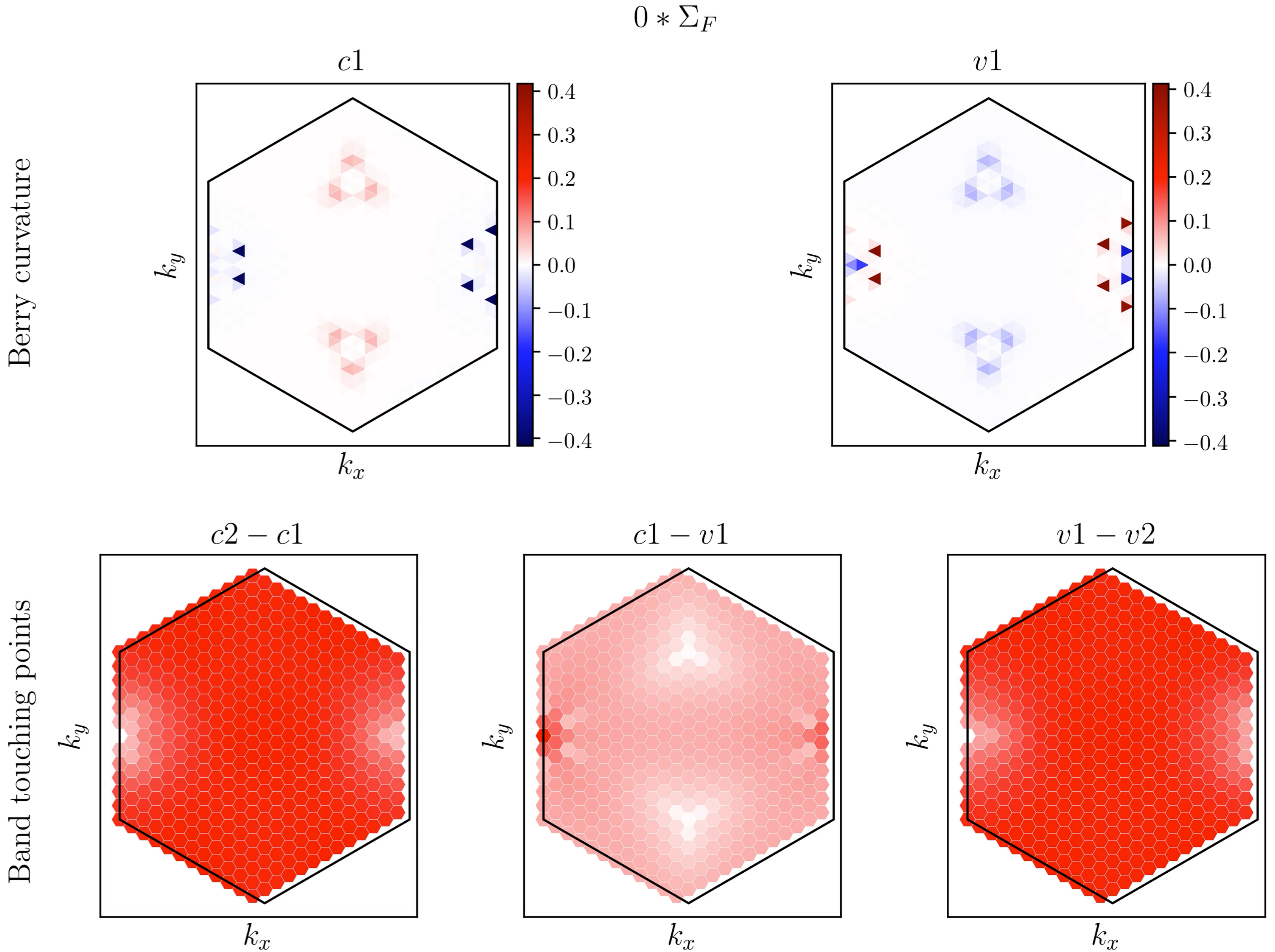
Hartree-Fock for Insulating States

- ε and T_{AA}/T_{AB} = parameters

E(meV)	Intra-layer			Inter-layer			Total
	Hopping	Hartree	Fock	Hopping	Hartree	Fock	
SP	1730	0	-21	-3154	0	-143	-1588
SCHF	2140	0	-34	-3539	0	-183	-1616

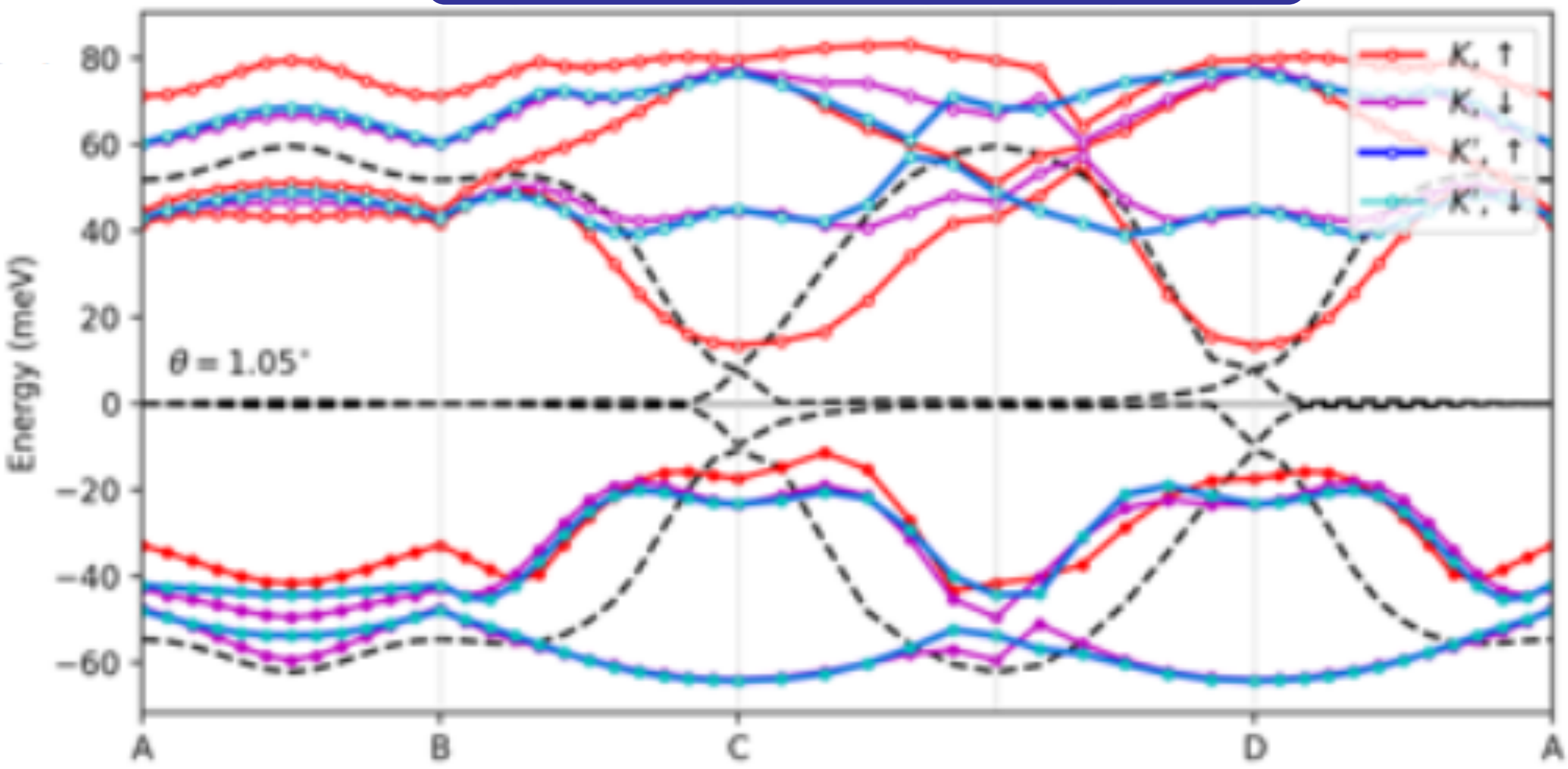
Gaps without Breaking C_2T symmetry




$0 * \Sigma_F$
$c1$
$v1$
Berry curvature
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
k_y
k_x
$c2 - c1$
$c1 - v1$
$v1 - v2$
Band touching points

Broken Flavor Symmetries

K↑ valence band empty n =-1/4

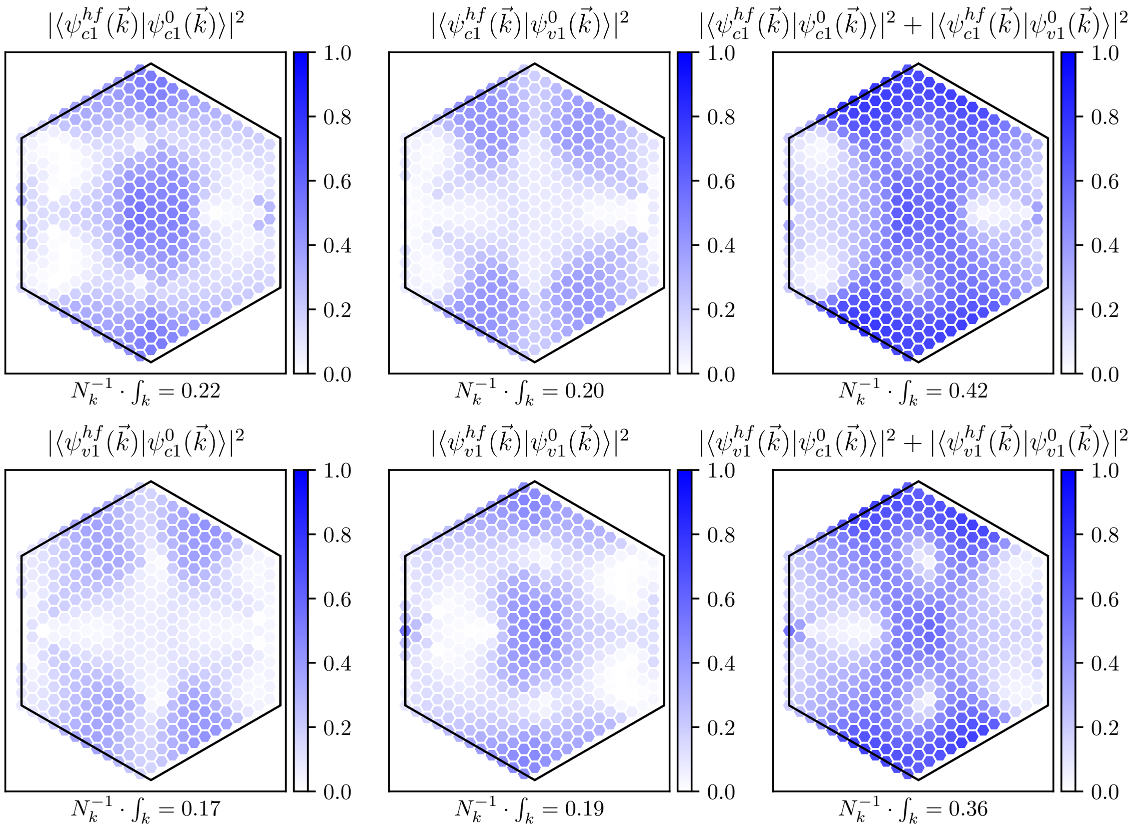


Xie & AHM arXiv:1812.04213

$\epsilon = 5$

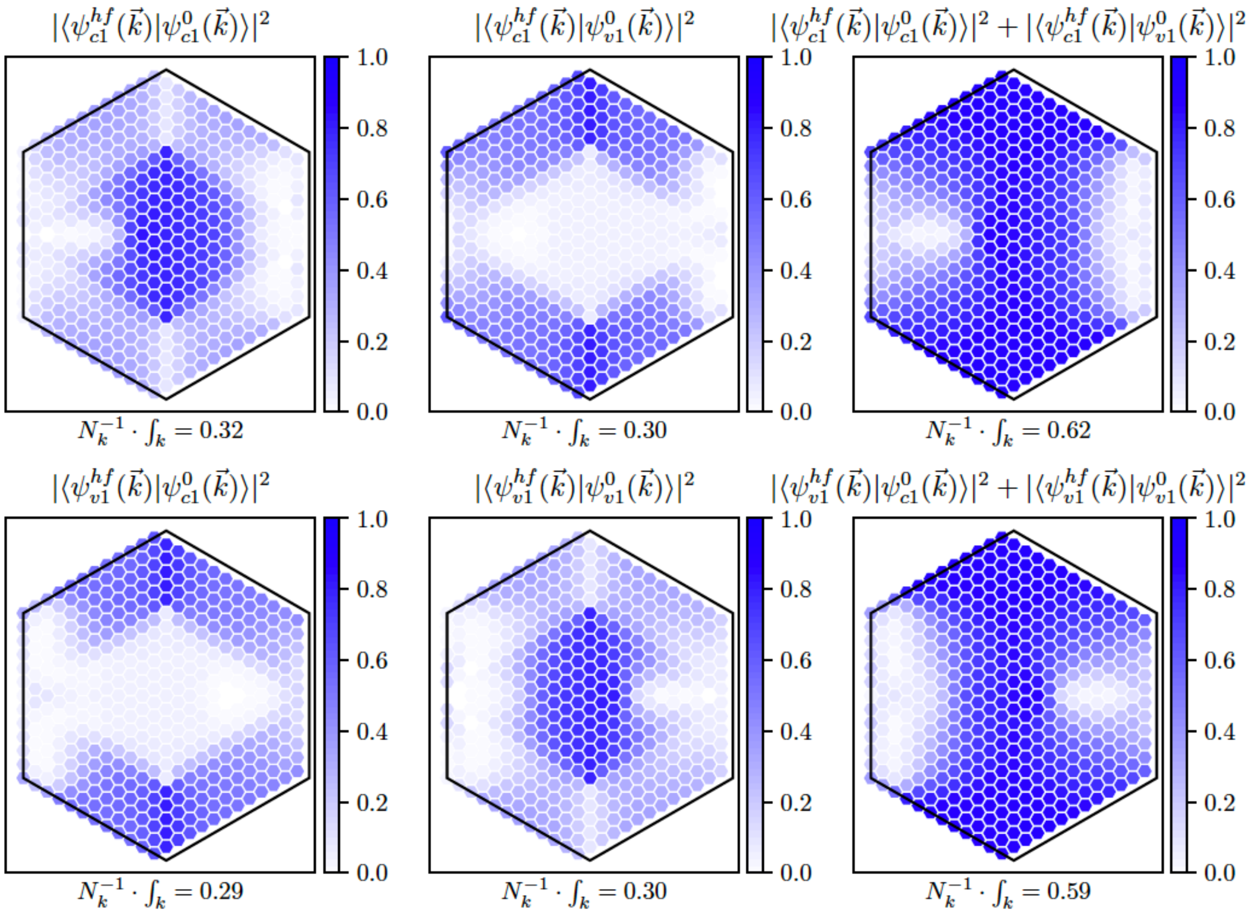
$T_{AA} = T_{AB}$

$E_g(indirect)$	**27.2**
$E_g(\kappa)$	**116.8**



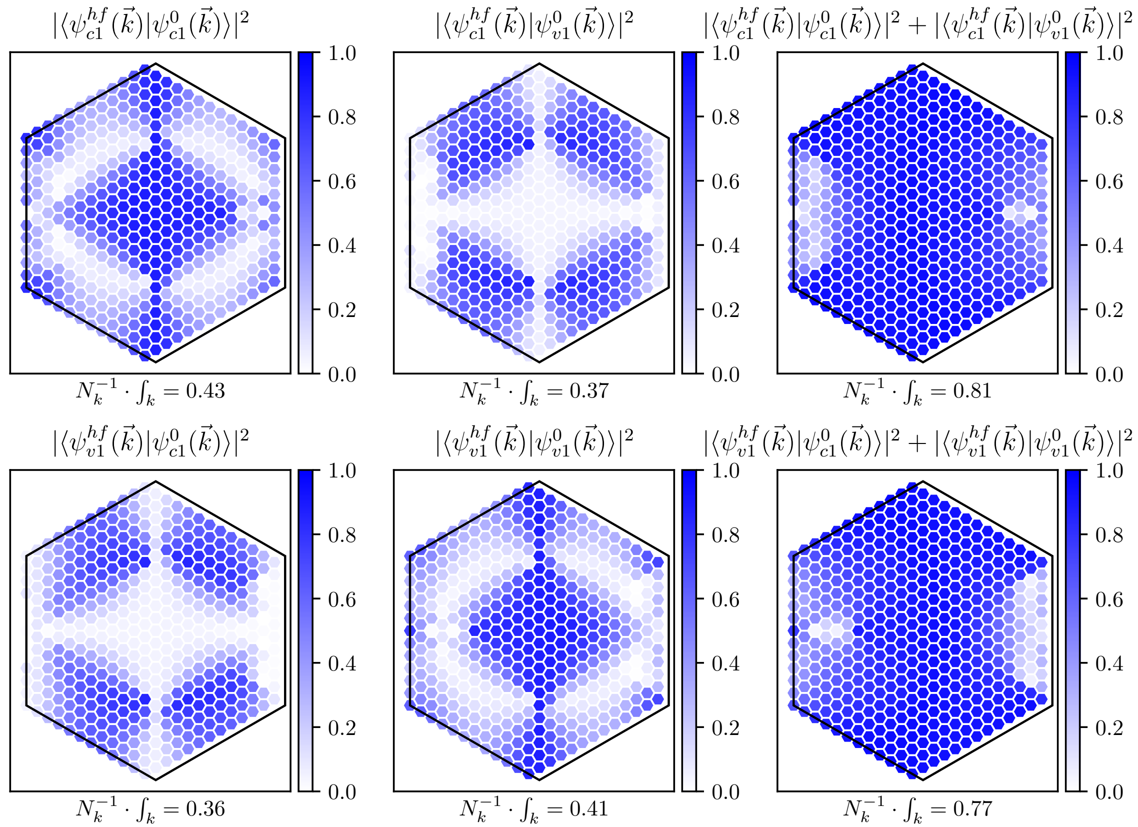
$\epsilon = 5$

$T_{AA} = 0.8\ T_{AB}$



$\epsilon = 7.5$
$T_{AA} = T_{AB}$

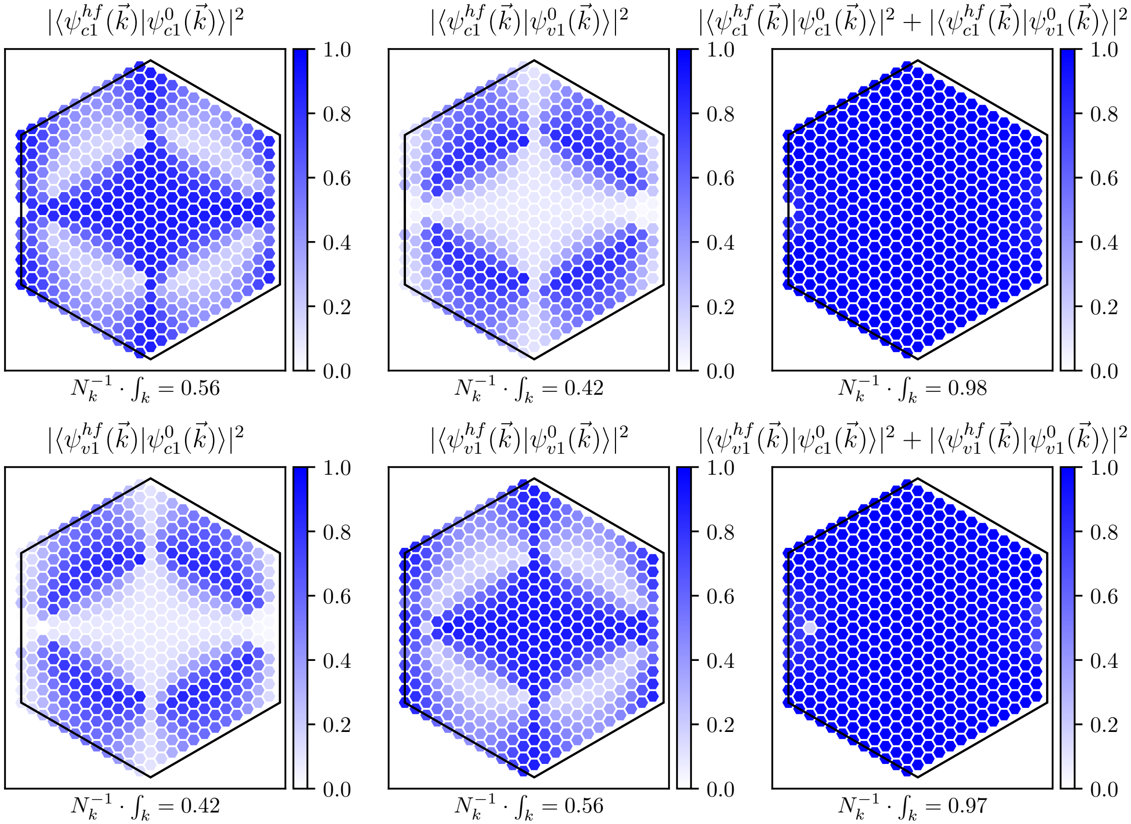
$E_g(indirect)$	**13.4**
$E_g(\kappa)$	**73.5**



$\epsilon = 20.0$

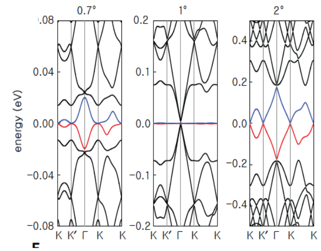
$T_{AA} = T_{AB}$

$E_g(indirect)$	**5.2**
$E_g(\kappa)$	**23.7**

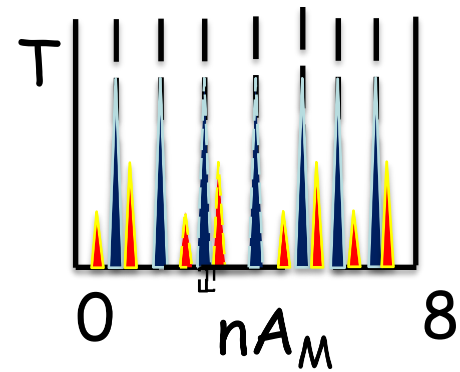


Magic Angle Bilayer Graphene

- Moire Bands



- Cuprates vs. Magic Angle vs. Gr. AB Bilayer FQHE



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