Title: Twisted Bilayer Graphene: Moire' is Different

Date: Dec 05, 2018 11:00 AM

URL: http://pirsa.org/18120017

Abstract: <p>A single layer graphene hides many body effects in the dense viscous
fluid of p-pi electrons, Bilayer graphene, with AA and AB registry, on
the other hand, exposes some of them. A twisted bilayer springs more
surprises. We discuss recently seen superconductivity in twisted bilayer
graphene. Resonating valence bond (RVB) physics contained in the dense
electron fluid in graphene is invoked [1]. RVB fails to produce
superconductivity in neutral graphene, as carrier are absent at the
Fermi level. In a twisted bilayer, interlayer tunneling adds equal
number of electron and hole carriers in Moire superlattice of dominant
AA registry. These carriers use RVB pairing and develop charge -2e and
+2e Cooper pair correlations, in spite of Coulomb repulsions. Resulting
Moire lattice of Cooper pair puddles form a Josephson lattice. Coulomb
blockade makes it a Bosonic Mott insulator. Gate voltage dopes the Bose
Mott insulator and interesting consequences follow.

[1] G. Baskaran, arXiv:1804.00627</p>

Twisted Bilayer Graphene **Moire is Different**

4th November 2018

The Institute of Mathematical Sciences

Chennai, India

G Baskaran

PERIMETER INSTITUTE

Waterloo, Ontario, Canada

Acknowledgement

SERB
Science and Engineering Research Board, DST

Perimeter Institute for Theoretical Physics

Department of
Science & Technology

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

Waterloo, Ontario
Canada

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Research in

Theoretical Physics
Pure Mathematics
Computer Science

~ 60 faculy
100 Ph.D. students
20 PDF's
10 visitors

Junior Research Fellow

Entrance through **JEST** Exam

Autonomous Institute

similar to
IIT's
IISc, Bangalore
TIFR, Bombay

Aided by DAE

Post Doctoral Fellowship
Visiting Research Scholar
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Visiting Professor…

MOU exists between Perimeter Institute and The Institute of Mathematical Sciences


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Uttaranchal
Haryana
New Delhi
Delhi
Rajasthan
Jaipur
Lucknow
Uttar Pradesh
Patna
Bihar
Sikkim
Gangtok
Arunachal Pradesh
Itanagar
Assam
Dispur
Nagaland
Kohima
Manipur
Imphal
Shillong
Meghalaya
Agartala
Tripura
Aizawl
Mizoram
Jharkhand
Ranchi
West Bengal
Kolkata (Calcutta)
Gandhinagar
Gujarat
Bhopal
Madhya Pradesh
Chhattisgarh
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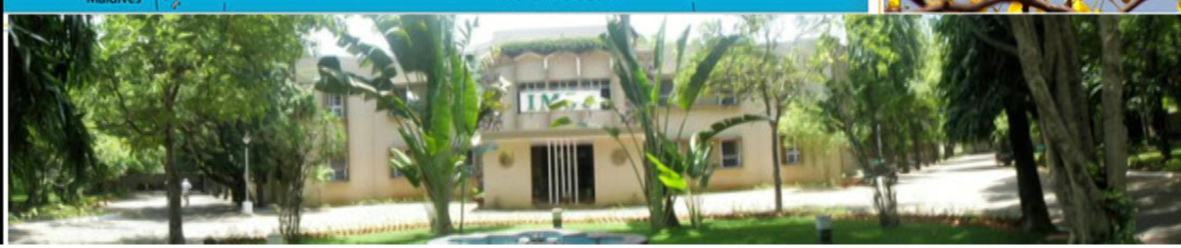
Pondicherry
Tamil Nadu
Kavaratti
Lakshadweep
Kerala
Thiruvananthapuram
Sri Lanka
Colombo
Arabian Sea
Bay of Bengal
Laccadive Sea
Indian Ocean
Maldives
Andaman Islands
Port Blair
Andaman and Nicobar Islands
Andaman Sea
Nicobar Islands



The Whole is more than the sum of its parts
Aristotle

Science, literature, art, .. life … exemplify this

The More part differs from situation to situation

It continues to surprise us & makes emergence exciting …

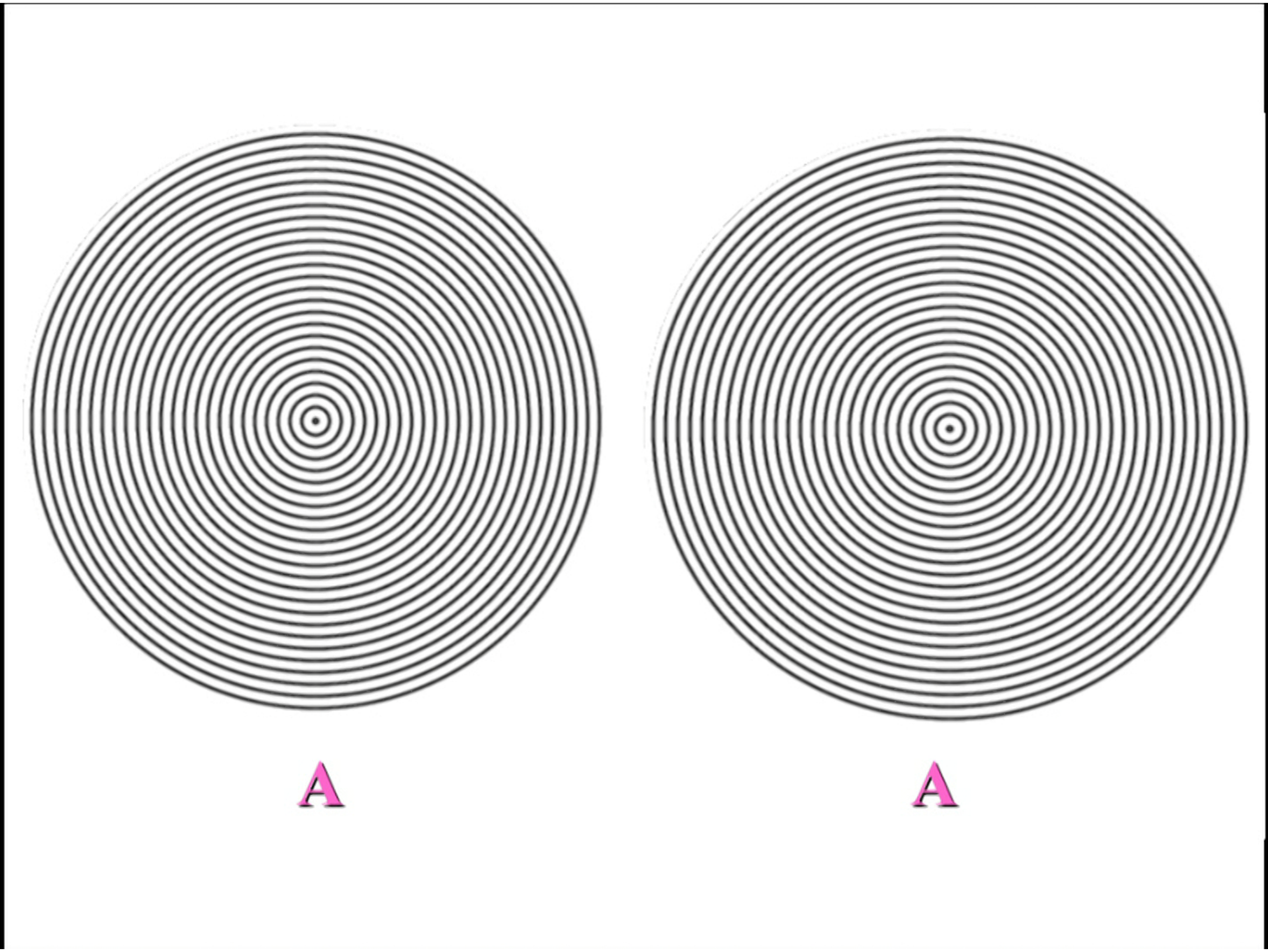
4 August 1972, Volume 177, Number 4047

SCIENCE

More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

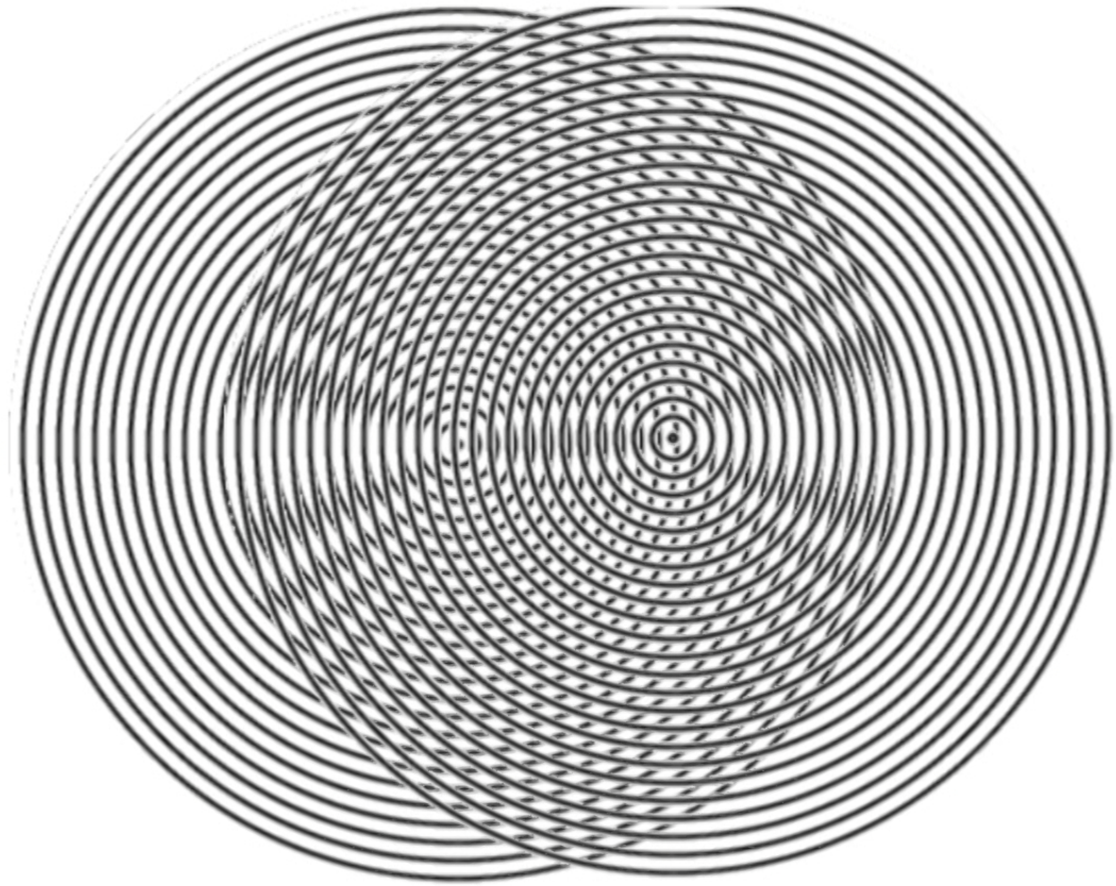
P. W. Anderson

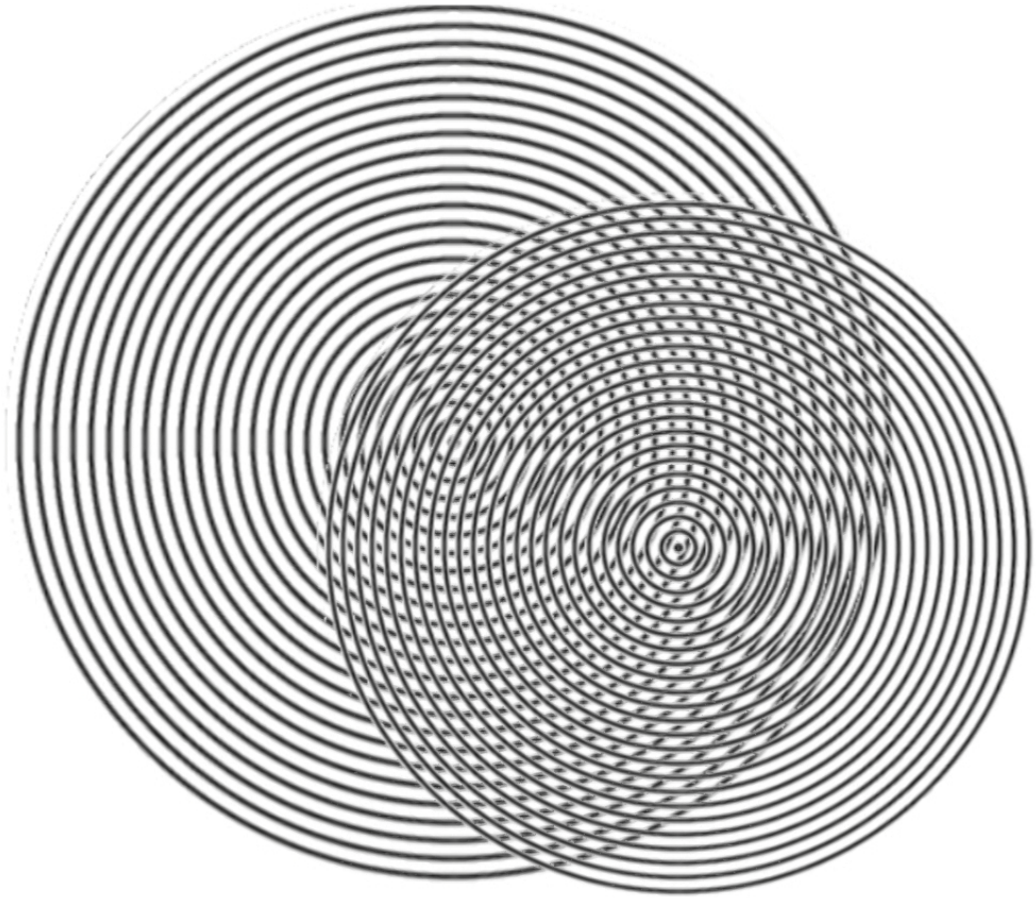

A
A

Complexity and Emergence

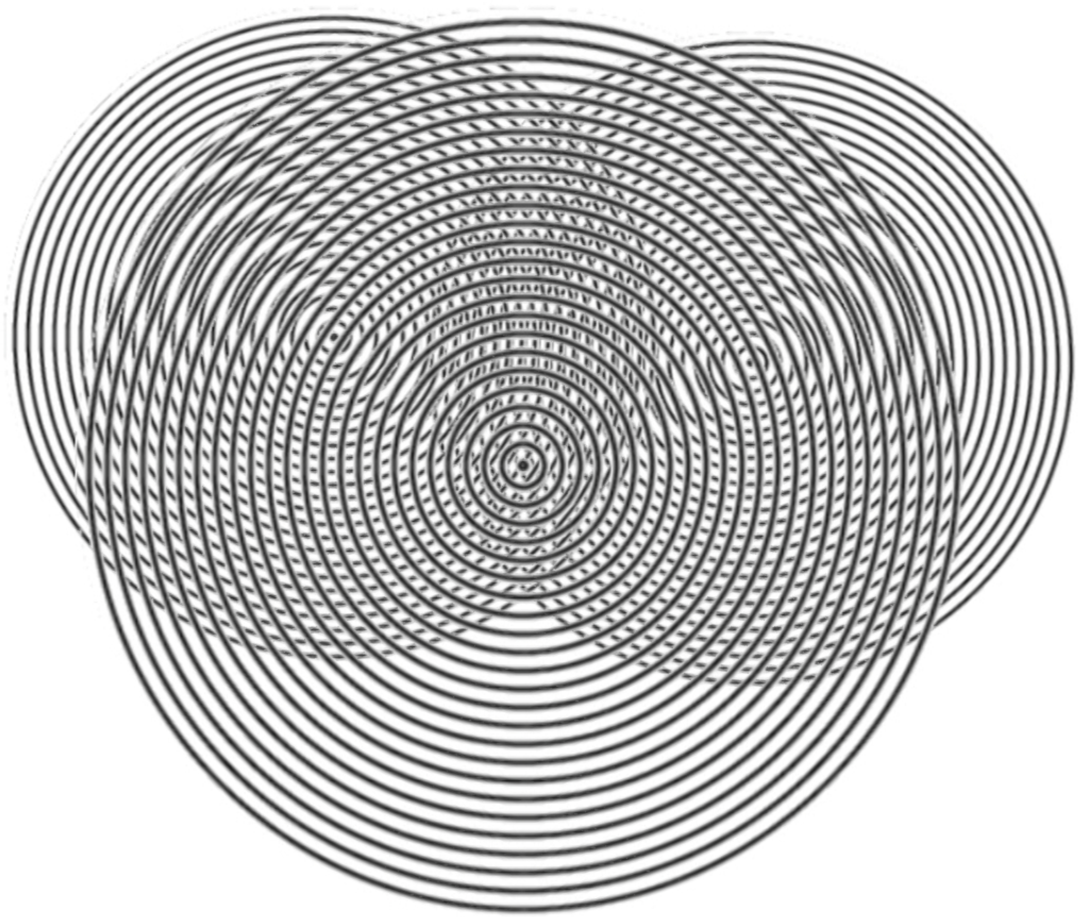
More Than the Sum of the Parts

$$A + A > 2A$$



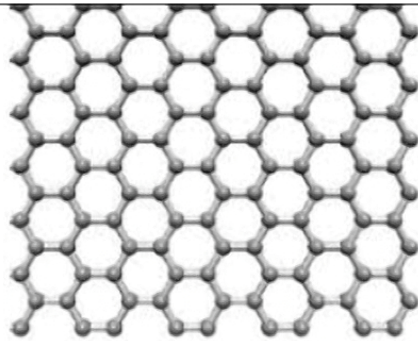


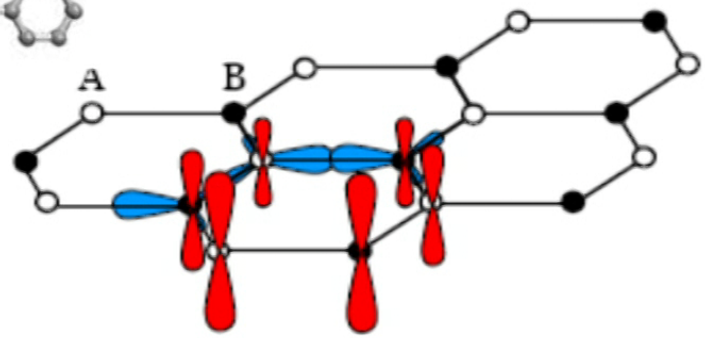
Moire patterns



Kavin

19th April 2018





- σ - bonds in the xy-plane: sp^2 hybridization of the 2s, $2p_x$ and $2p_y$ orbitals
- π - bonds the fourth valence electron ($2p_z$ orbitals) is in a π-orbital with its lobes perpendicular to the plane

Transport properties of graphene are determined by the delocalized π electrons (one per C atom)

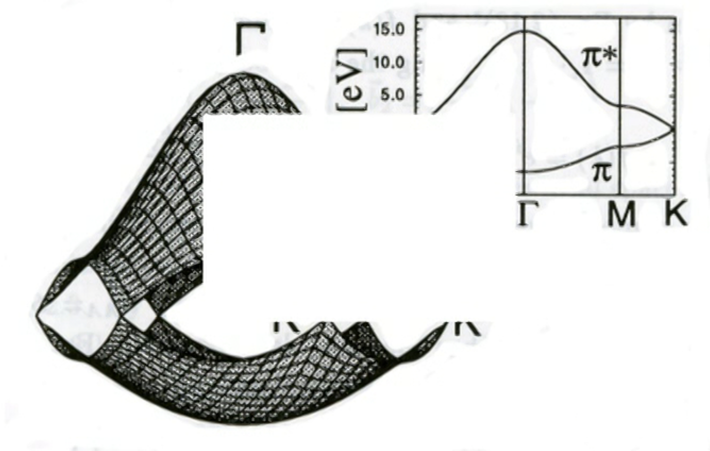
Band structure

- **Tight-binding model; nearest-neighbor interaction**

Wallace, PR 71,622 (1947)

$$E(k_x, k_y) = \pm t\sqrt{1 + 4\cos\left(\frac{\sqrt{3}k_y a}{2}\right)\cos\left(\frac{k_x a}{2}\right) + 4\cos^2\left(\frac{k_x a}{2}\right)}$$

***t* ≈ 2.5 eV overlap integral between nearest neighbors**



Band structure

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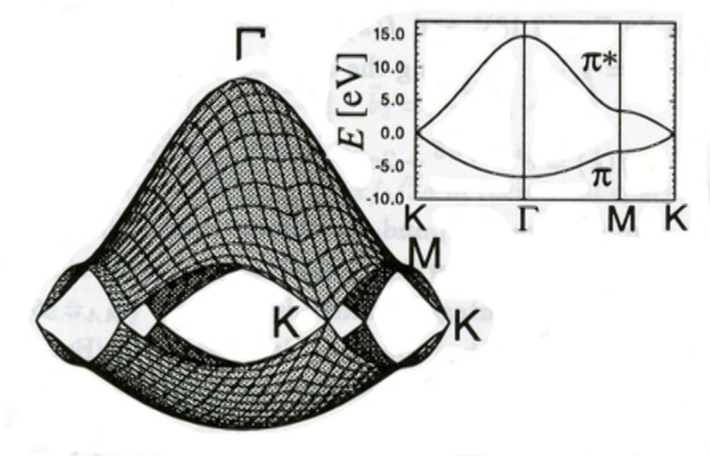
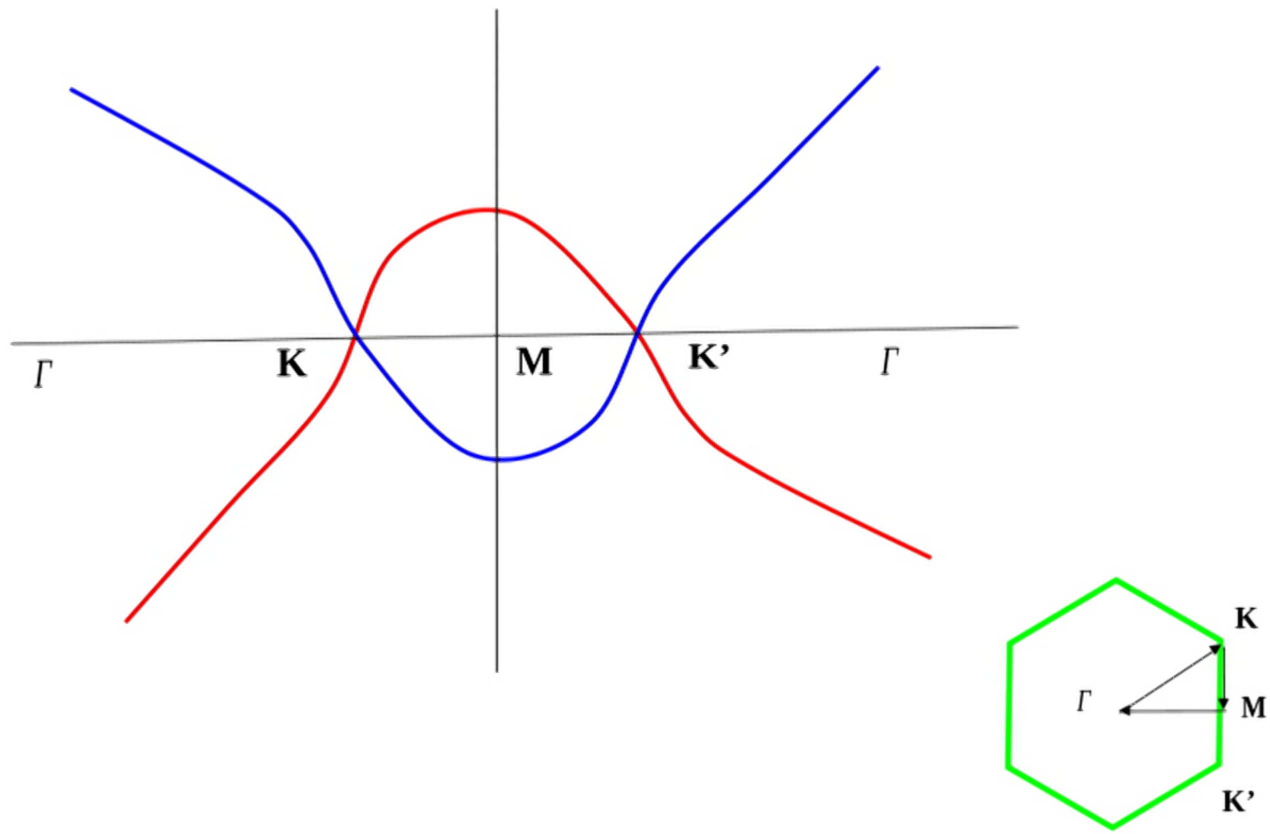
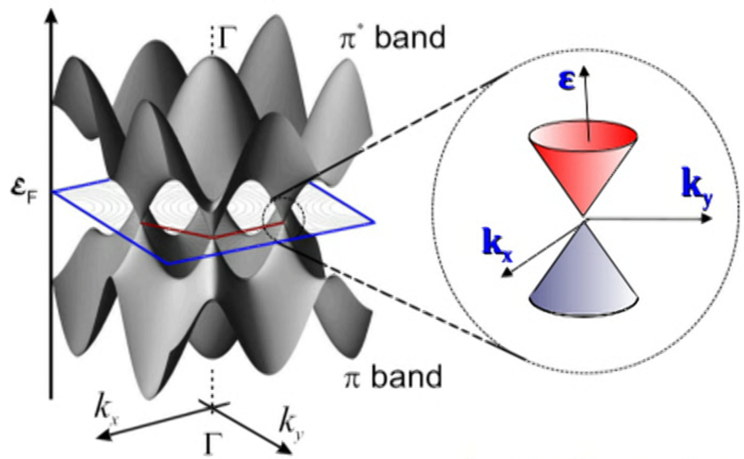
$t \approx 2.5$ eV overlap integral between nearest neighbors



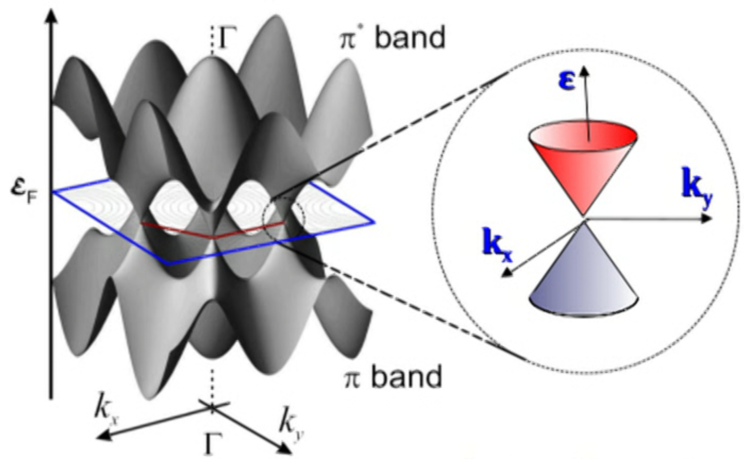

Γ
K
M
K'
Γ
K
Γ
M
K'

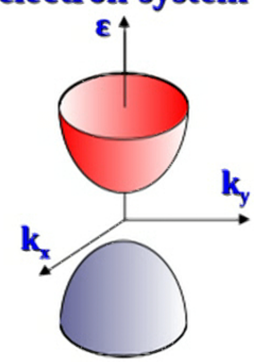
Near the K (K') points



linear dispersion

Near the K (K') points

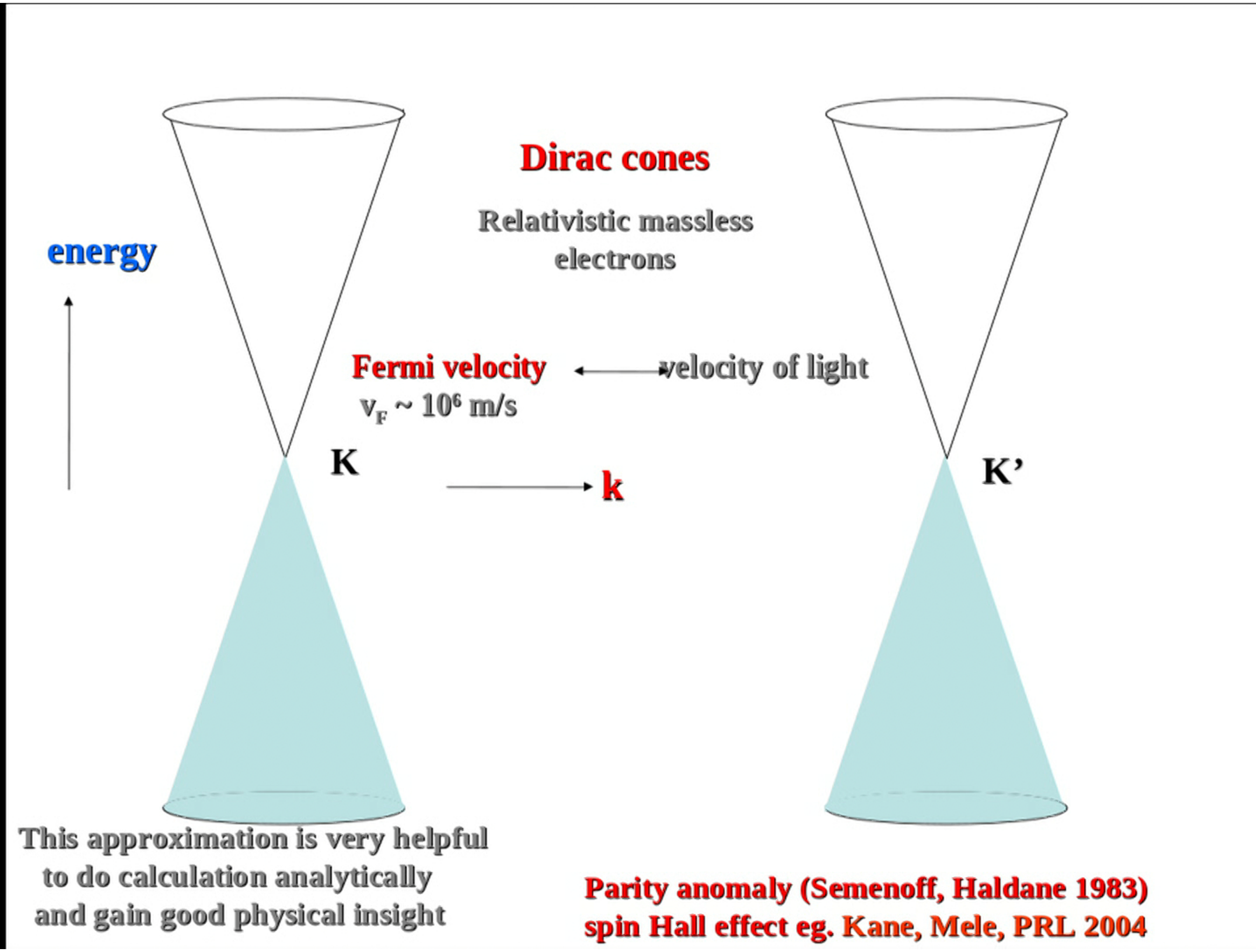




- **In the vicinity of the K (K') points:**

$$\varepsilon(\mathbf{k}) = \pm\left(\frac{3ta_{c-c}}{2}\right)|\mathbf{k}| = \pm\hbar v_F|\mathbf{k}|$$

  - ***k* is measured with respect to the K (K') point**
  - **$v_F \sim 10^6$ m/s → Fermi velocity**


Dirac cones
Relativistic massless electrons
energy
Fermi velocity
$v_F \sim 10^6$ m/s
velocity of light
K
k
K'
This approximation is very helpful to do calculation analytically and gain good physical insight
Parity anomaly (Semenoff, Haldane 1983)
spin Hall effect eg. Kane, Mele, PRL 2004

Massless Dirac fermions

- Unique band structure just described brings profound changes in the electronic properties of the system
- Effective-mass approximation: The Hamiltonian near the K point is

$$H_K(\mathbf{k}) = \frac{3ta_{c-c}}{2}\begin{pmatrix} 0 & k_x - ik_y \\ k_x + ik_y & 0 \end{pmatrix} = \hbar v_F \boldsymbol{\sigma} \cdot \mathbf{k}$$

where s are the 2 × 2 Pauli matrices

- Near the K' point:

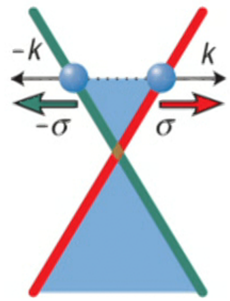
$$H_{\mathbf{K'}}(\mathbf{k}) = -\hbar v_F \boldsymbol{\sigma}^* \mathbf{k}$$

- The Schrödinger equation then transforms into a relativistic Dirac equation with vanishing rest mass

Dirac Weyl Fermions in condensed matter !

Massless Chiral fermions

- The upper and lower components correspond to the quantum-mechanical amplitudes (or 'pseudospin') of finding the particle on one of the two sublattices
- Graphene: 'pseudospin' direction is linked with the 'momentum' of the particles

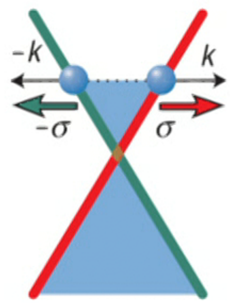


⇒ wavefunctions in the vicinity of K and K' point are 'chiral' (helical fermions) (Geim et al.)

⇒ scattering of particles from k to –k (backscattering) is suppressed (Ando et al.)

Massless Chiral fermions

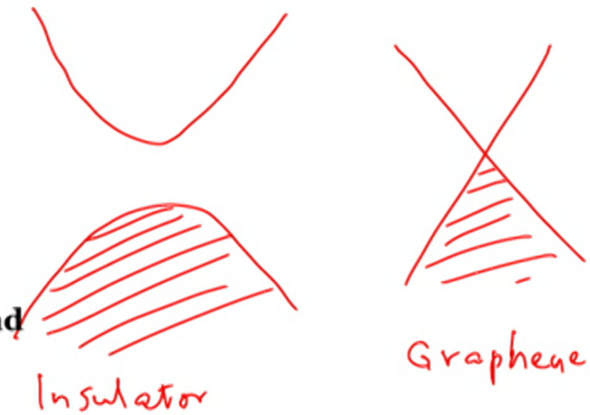
- The upper and lower components correspond to the quantum-mechanical amplitudes (or ‘pseudospin’) of finding the particle on one of the two sublattices
- **Graphene: ‘pseudospin’ direction is linked with the ‘momentum’ of the particles**



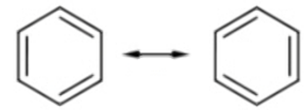
⇒ wavefunctions in the vicinity of K and K’ point are ‘chiral’ (helical fermions) (Geim et al.)

⇒ scattering of particles from k to –k (backscattering) is suppressed (Ando et al.)

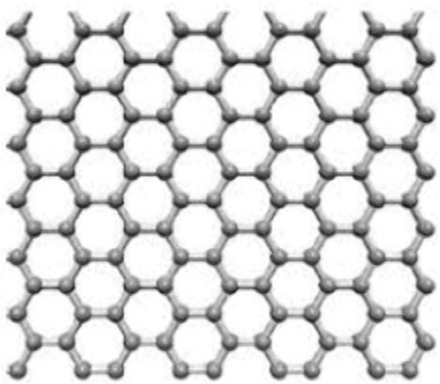
- **Particles have opposite chirality in the K and K’ valleys or in the electron or hole bands**



Diamond



Graphene

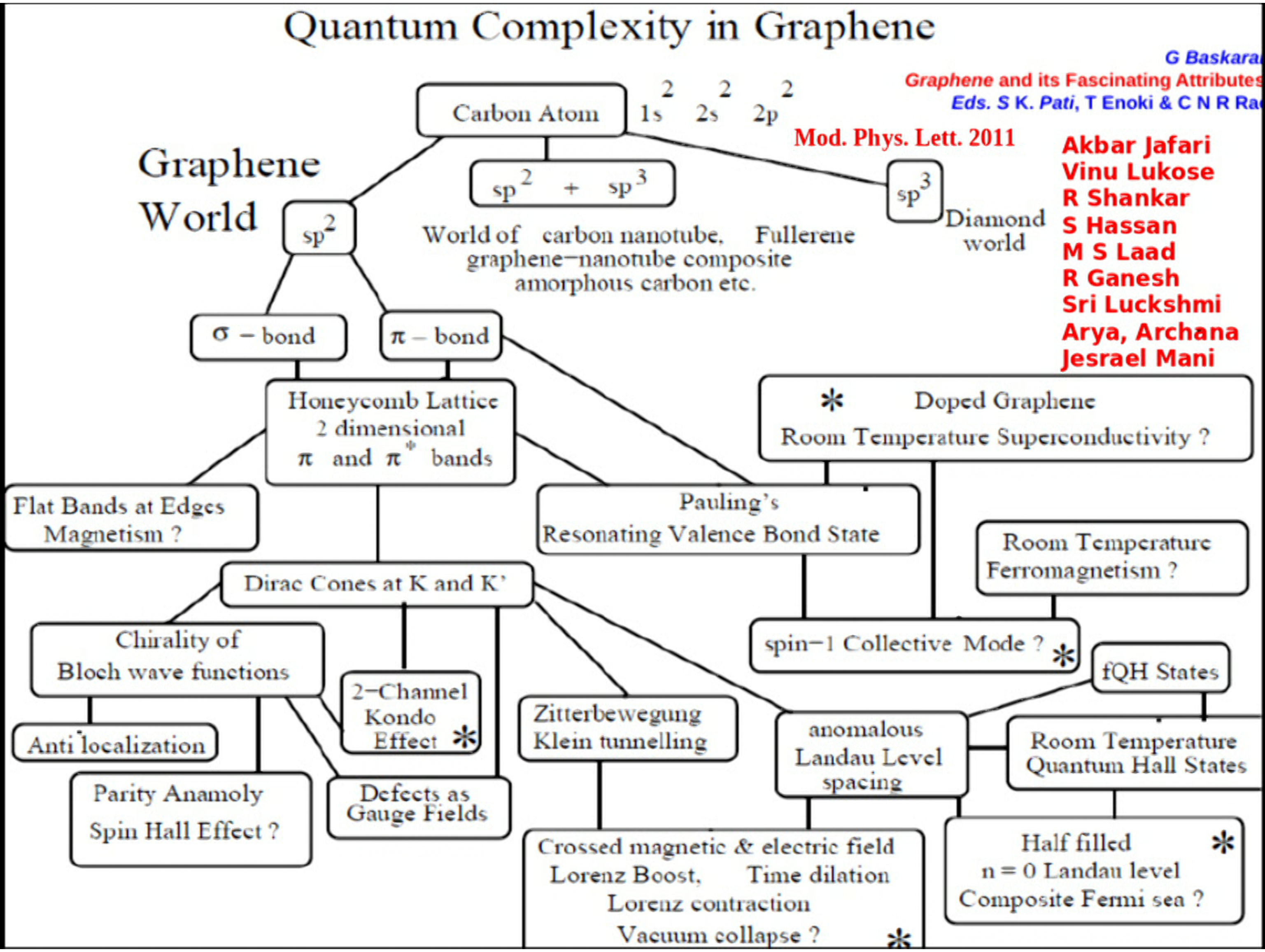


At low energy scales graphene behaves as a Fermi liquid or a Dirac liquid

However, Preformed Cooper pairs or Singlet pairing exist Off shell

This is related to Paulings Resonating Valence Bond Correlations

Graphene is a Sleeping Superconductor

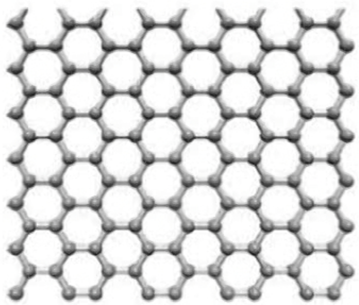


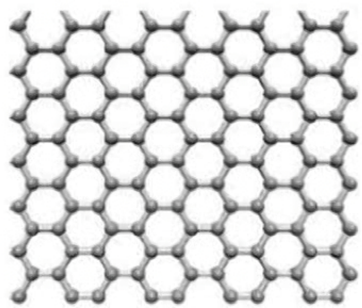
Quantum Complexity in Graphene
G Baskaran
Graphene and its Fascinating Attributes
Eds. S K. Pati, T Enoki & C N R Rao
Mod. Phys. Lett. 2011
Akbar Jafari
Vinu Lukose
R Shankar
S Hassan
M S Laad
R Ganesh
Sri Luckshmi
Arya, Archana
Jesrael Mani
Carbon Atom
$1s^2$ $2s^2$ $2p^2$
Graphene World
sp^2
$sp^2 + sp^3$
World of carbon nanotube, Fullerene graphene–nanotube composite amorphous carbon etc.
sp^3
Diamond world
σ – bond
π – bond
Honeycomb Lattice 2 dimensional π and π* bands
* Doped Graphene Room Temperature Superconductivity ?
Flat Bands at Edges Magnetism ?
Pauling's Resonating Valence Bond State
Room Temperature Ferromagnetism ?
Dirac Cones at K and K'
spin−1 Collective Mode ? *
fQH States
Chirality of Bloch wave functions
2−Channel Kondo Effect *
Zitterbewegung Klein tunnelling
anomalous Landau Level spacing
Room Temperature Quantum Hall States
Anti localization
Parity Anamoly Spin Hall Effect ?
Defects as Gauge Fields
Crossed magnetic & electric field Lorenz Boost, Time dilation Lorenz contraction Vacuum collapse ? *
Half filled * n = 0 Landau level Composite Fermi sea ?

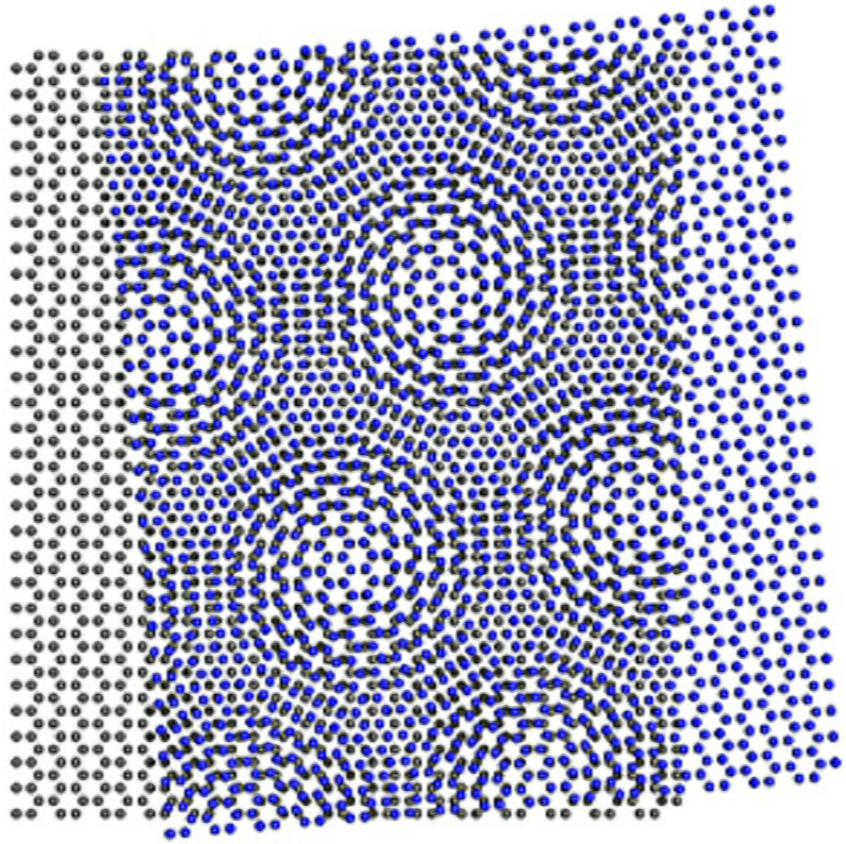
Unconventional superconductivity in magic-angle graphene superlattices

Yuan Cao[1], Valla Fatemi[1], Shiang Fang[2], Kenji Watanabe[3], Takashi Taniguchi[3], Efthimios Kaxiras[2,4] & Pablo Jarillo-Herrero[1]

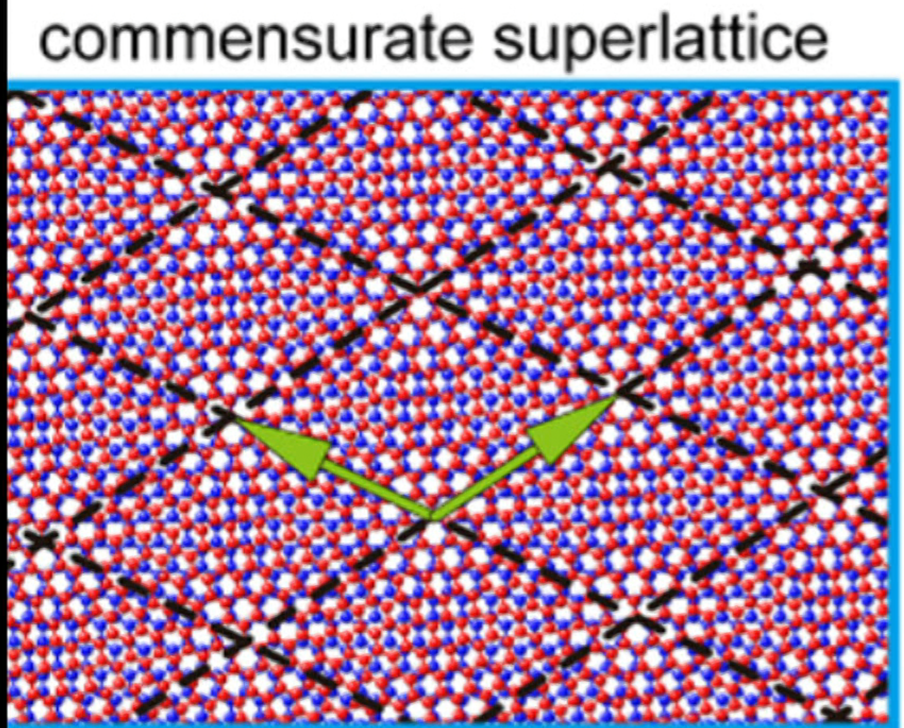
1. Cao, Y. *et al. Nature* http://dx.doi.org/10.1038/nature26160 (2018).
2. Cao, Y. *et al. Nature* http://dx.doi.org/10.1038/nature26154 (2018).

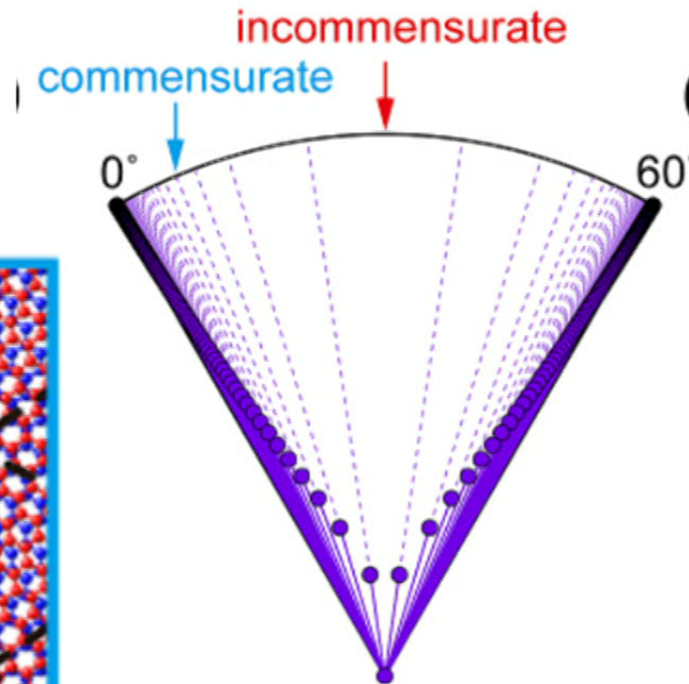


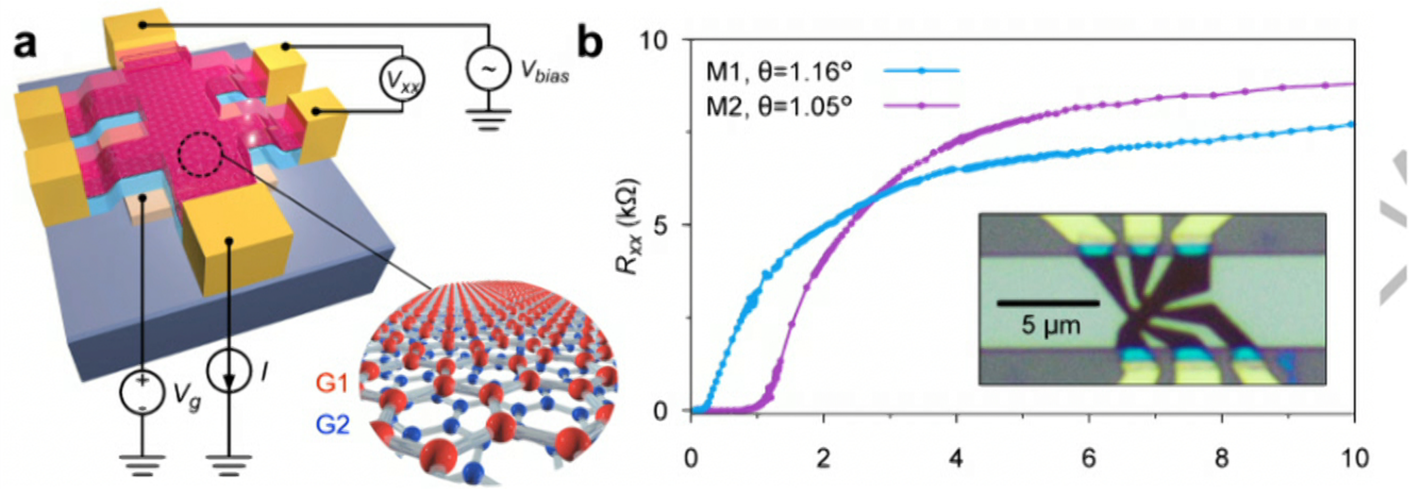


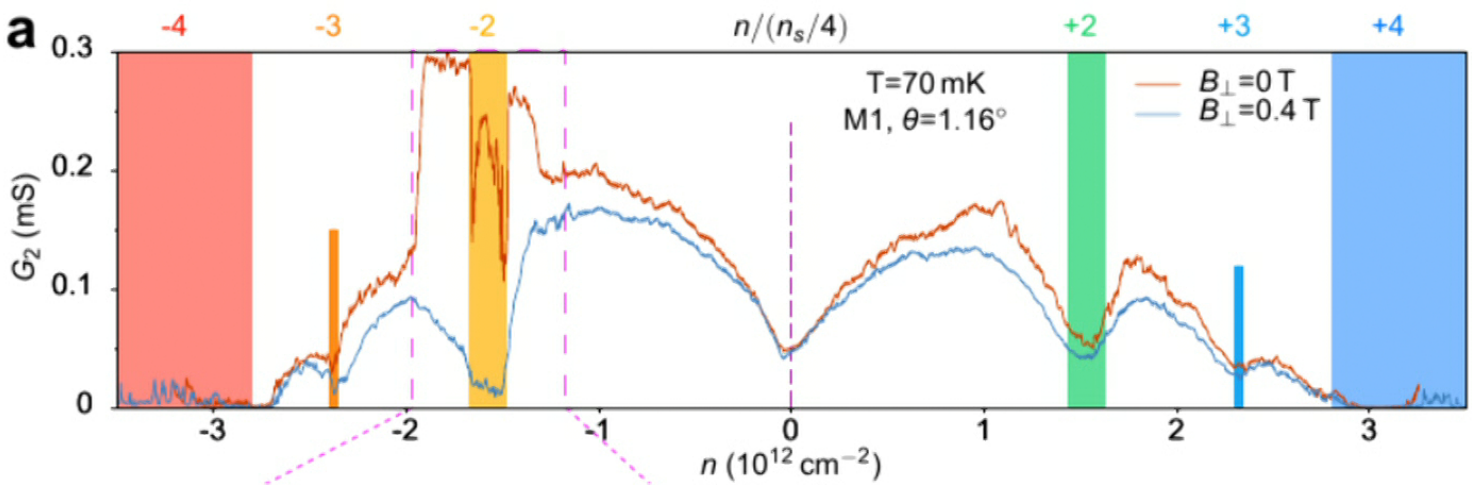


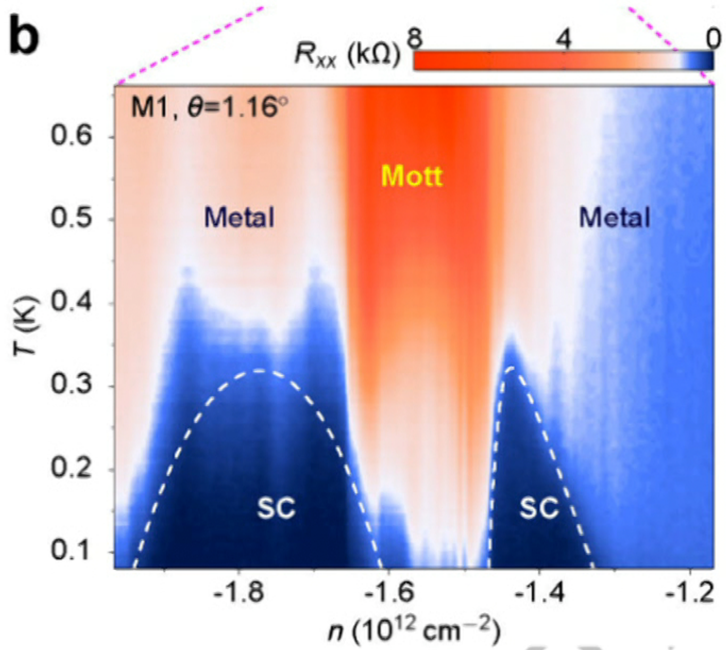
Yao et al., arXiv:1804.05372

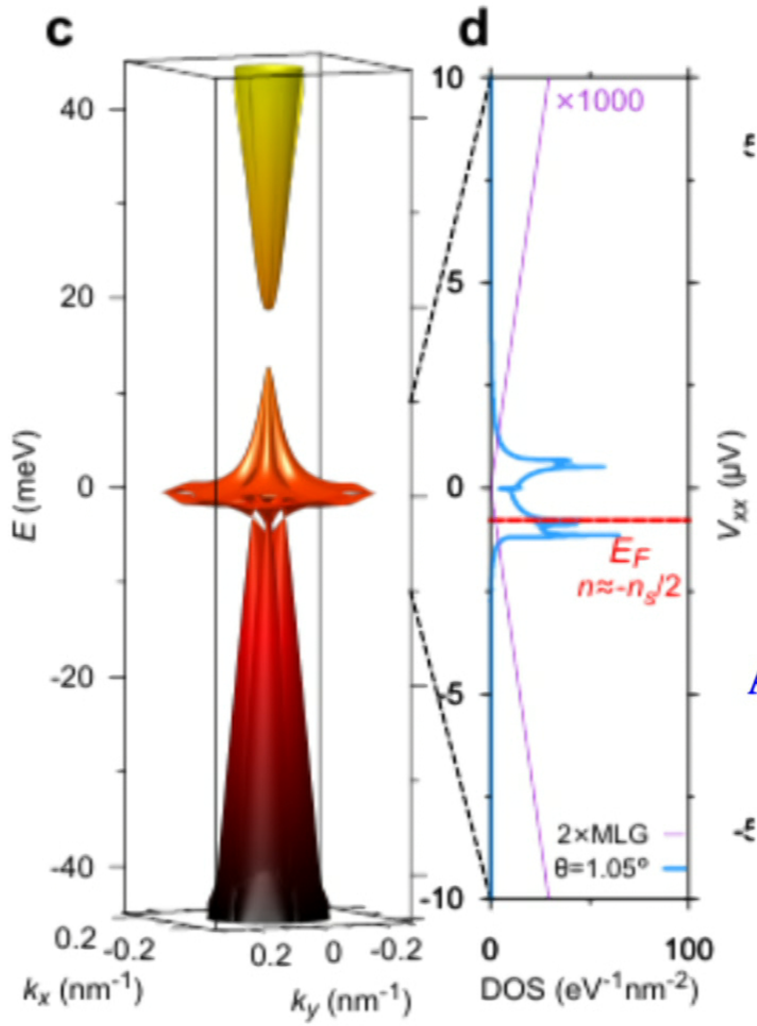


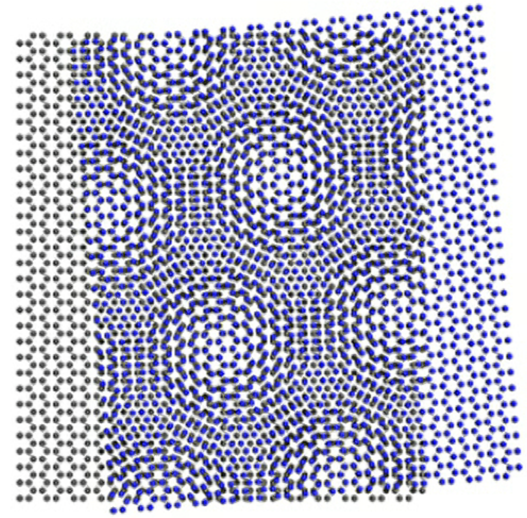



a
V_xx
V_bias
V_g
I
G1
G2
b
M1, θ=1.16°
M2, θ=1.05°
R_xx (kΩ)
5 µm


a
-4
-3
-2
n/(n_s/4)
+2
+3
+4
T=70 mK
M1, θ=1.16°
B⊥=0 T
B⊥=0.4 T
G_2 (mS)
n (10^12 cm^-2)


b
R_{xx} (kΩ)
8
4
0
M1, θ=1.16°
Mott
Metal
Metal
SC
SC
0.6
0.5
0.4
0.3
0.2
0.1
T (K)
-1.8
-1.6
-1.4
-1.2
n (10^{12} cm^{-2})

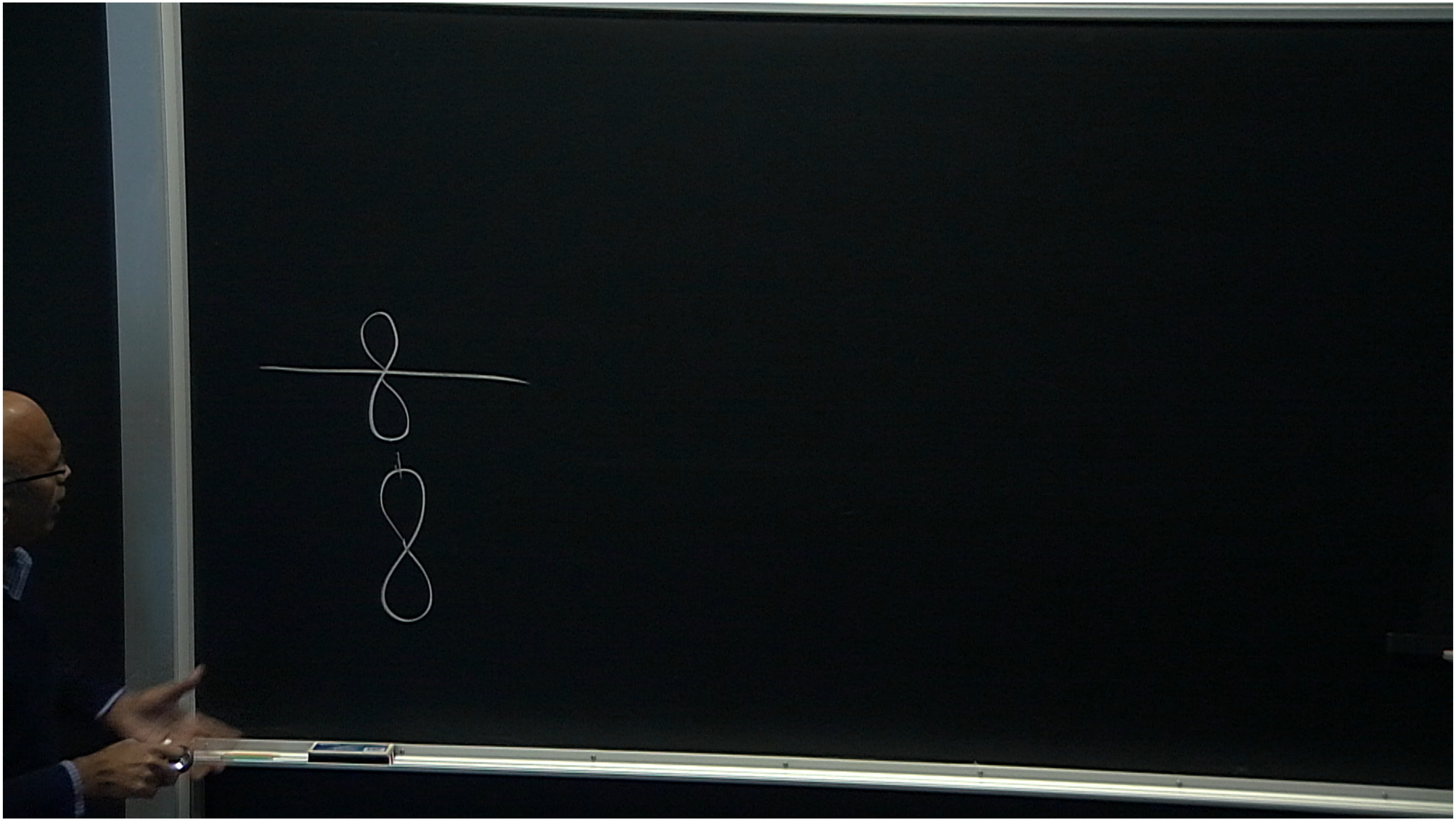


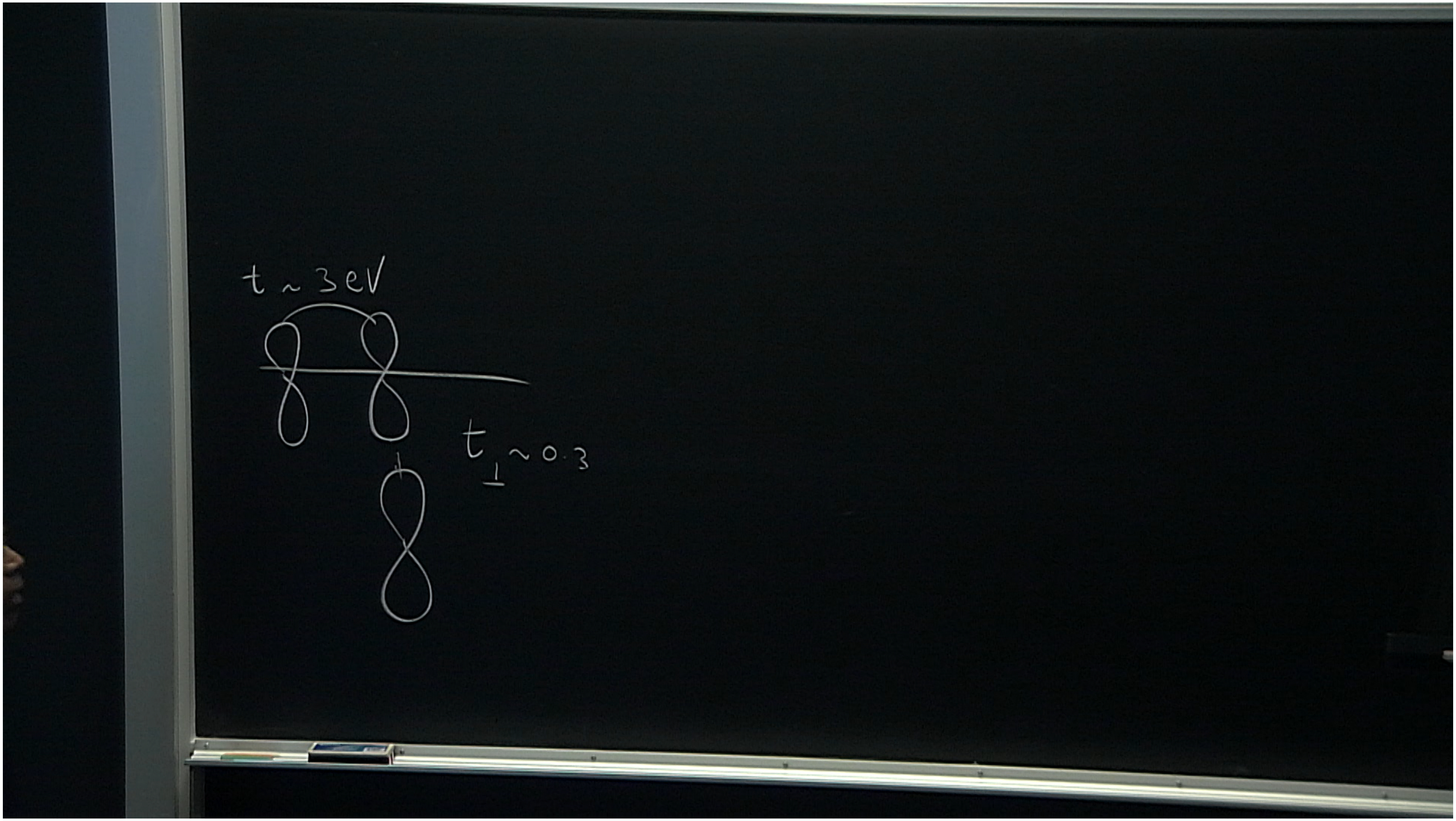


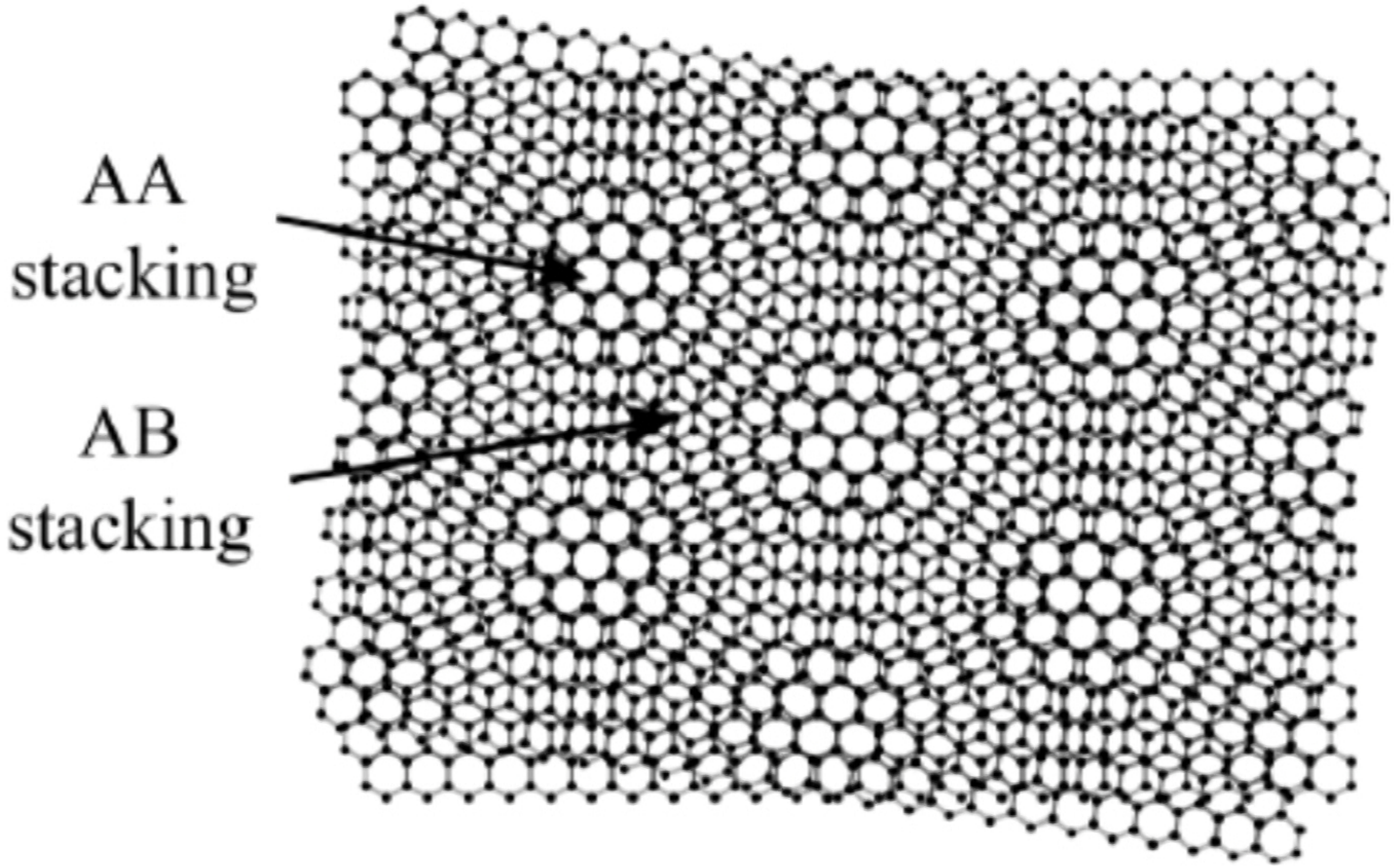
At the magic angle of 1.16 degree number of carbon atoms per unit cell is about 2000

What happens when we put two graphene layers on top of each other ?

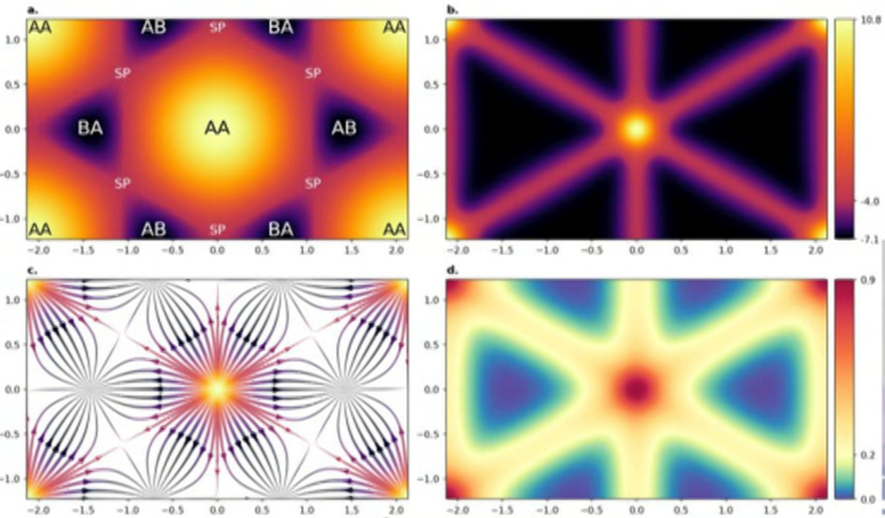
- They communicate via quantum mechanical hopping of electrons between top and bottom 2pz orbitals of C atom that are close to each other
- Interlayer hopping matrix element is ~ 0.3 eV (this is small compared to in plane hopping ~ 3 eV)
- To gain delocalization or tunneling energy carbon atoms of graphene lattices will also relax
- Bloch states of electrons will get modified
- Are there interesting manybody effects ?




t ~ 3eV
t⊥ ~ 0.3

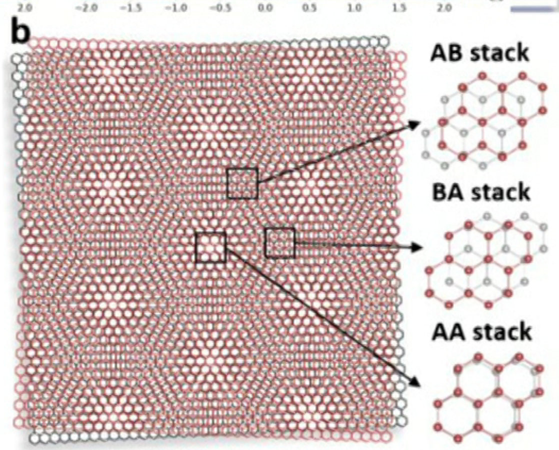

AA
stacking
AB
stacking

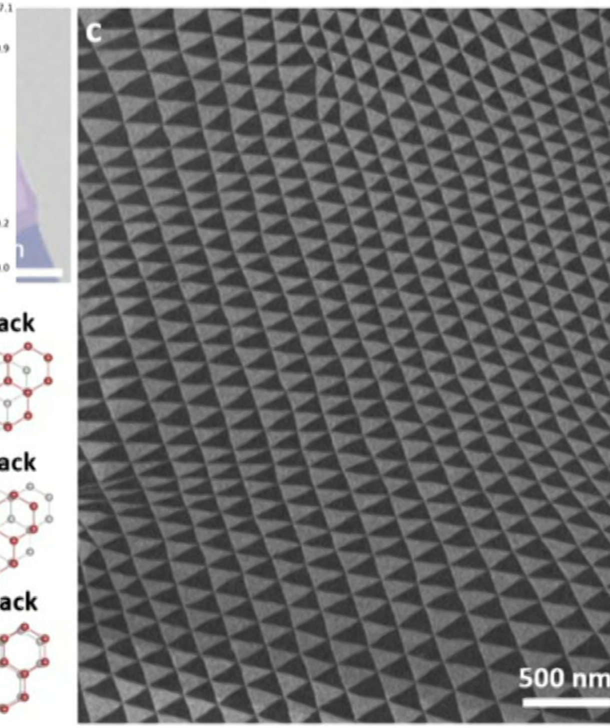
How do atoms of two graphene layers relax ?

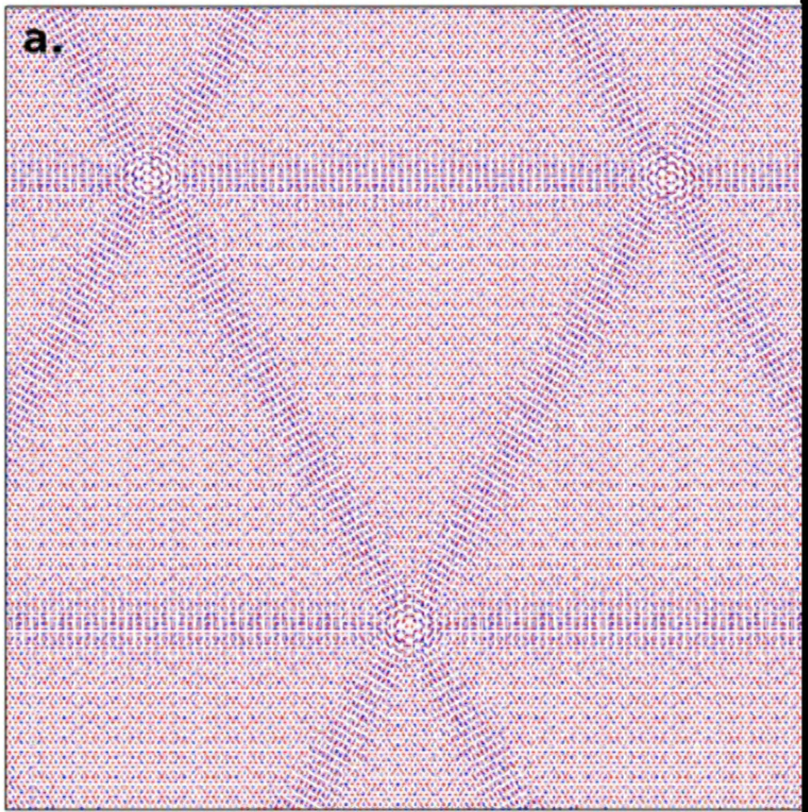


Atomic reconstruction at van der Waals interface in twisted bilayer

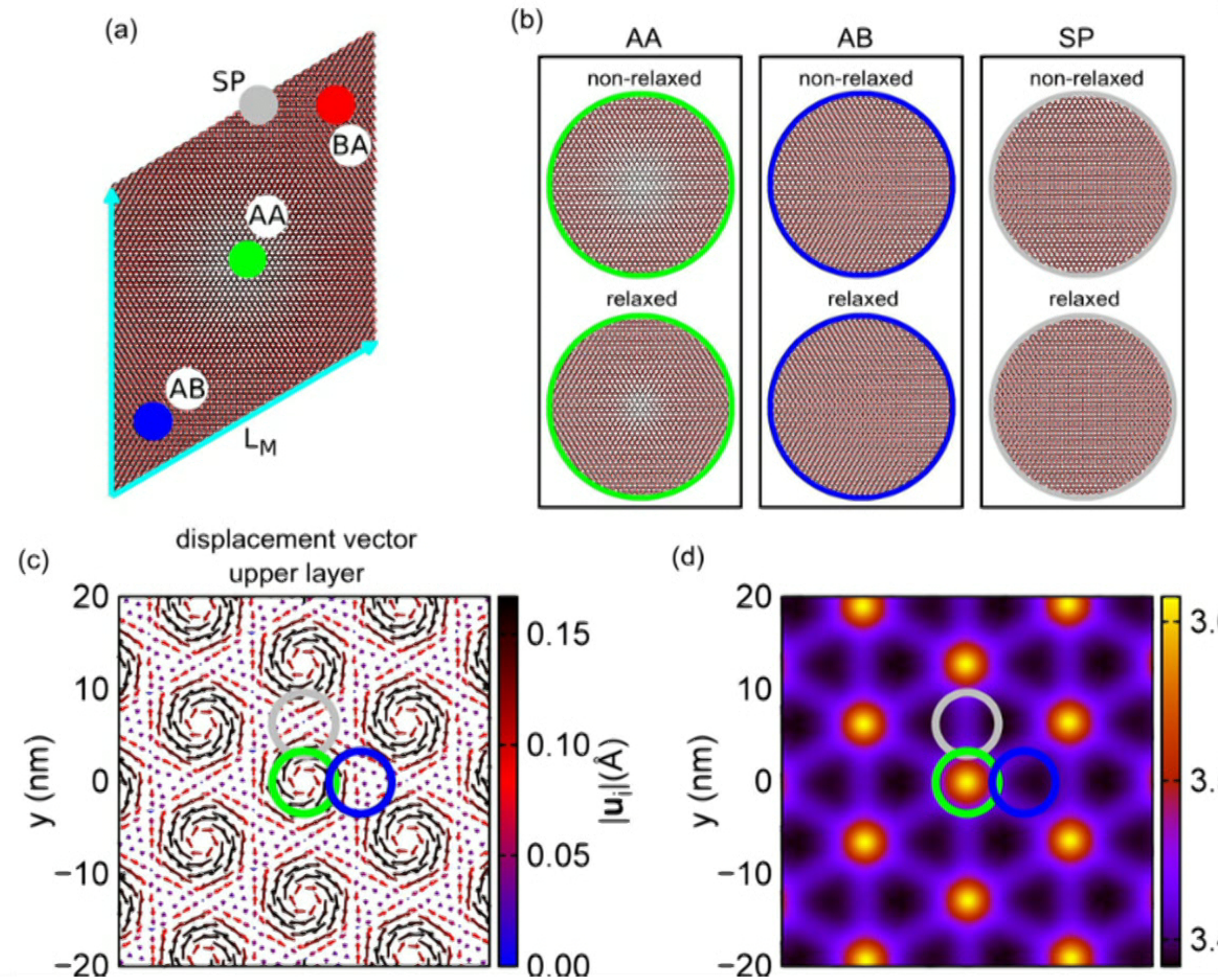
Hyobin Yoo et al.
arXiv:1804.03806
(Phil Kim group)






a.

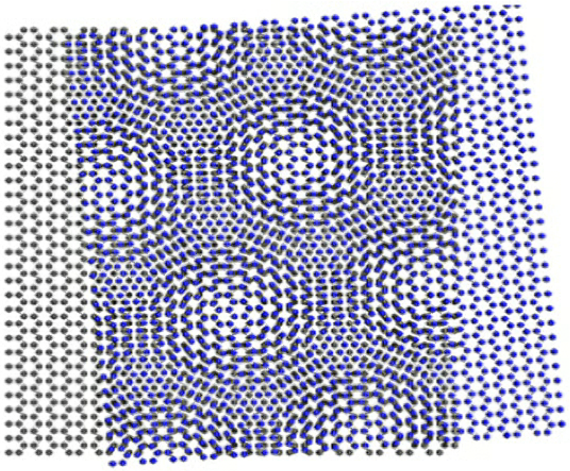
Emergent D 6 symmetry in fully-relaxed magic-angle twisted bilayer graphene
M. Angeli et al., (SISSA group) arXiv:1809.11140



Theory of Emergent Josephson Lattice in Neutral Twisted Bilayer Graphene
(Moiré is Different)

arXiv:1804.00627

G. Baskaran



Resonating Valence Bonds in Graphene

How it affects Twisted Bilayer Graphene ?

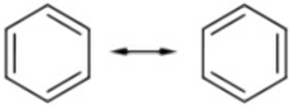
AB stacking as a Mott insulator

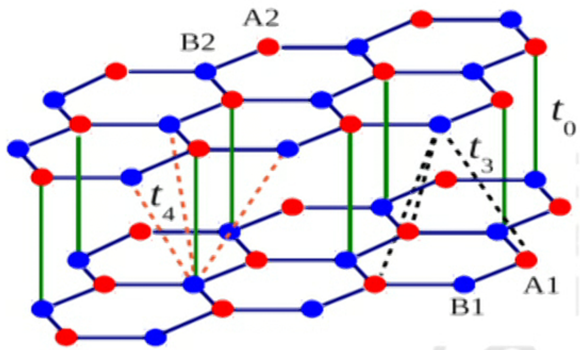
AA stacking, self doping and Cooper pair formation

Triangular lattice Network of Conducting Pathways

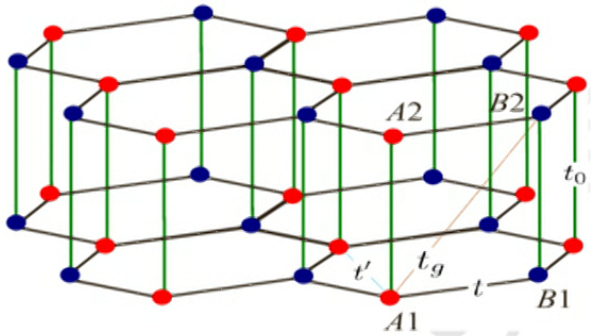
Josephson Tunneling .... Bose Hubbard Model

Doping via gate voltage produces superconductivity

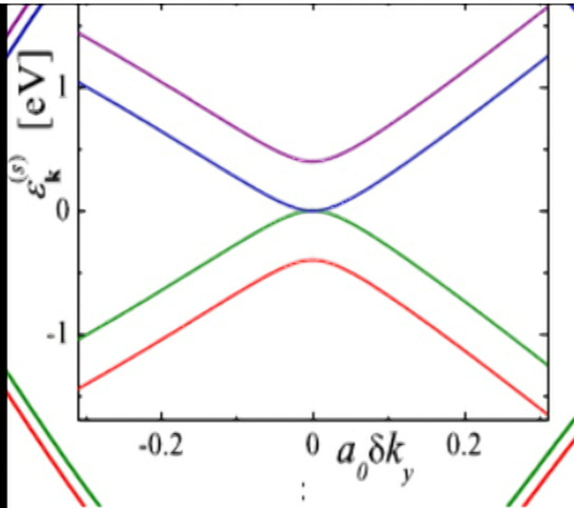




Bernal or AB Stacking



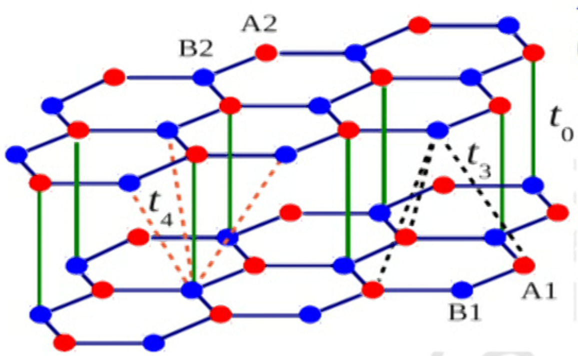
AA Stacking



Consequenes of Electron Electron Interactions

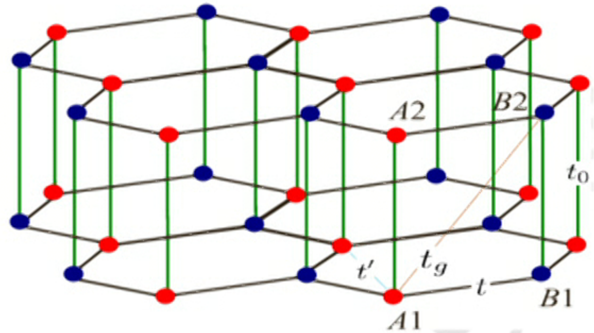
In experiments one sees a many body gap of few meV

Theory predicts long range Antiferromagnetic Order (eg. Fu-Chun Zhang et al.)

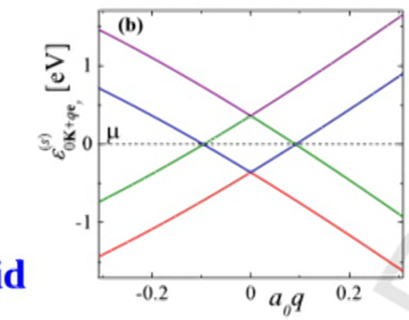


Bernal or AB Stacking

Consequenes of Electron Electron Interactions



No clean experiments available as AA stacking is unstable

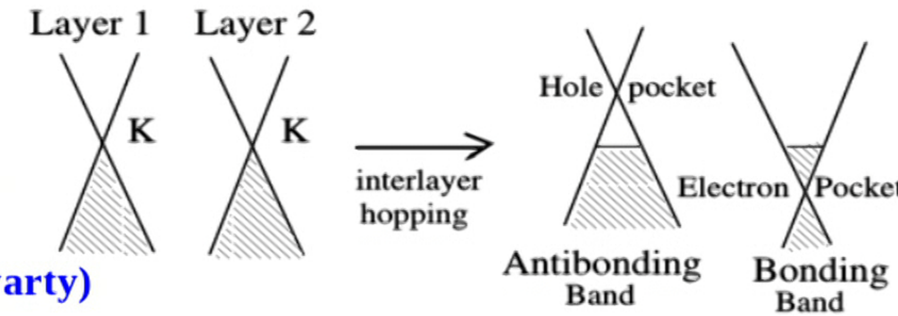


AA Stacking

Theory predicts

Exciton liquid (Levitov et al.)

A Cooper pair Exciton (-2e , +2e) Liquid (G. Baskaran, to be published)



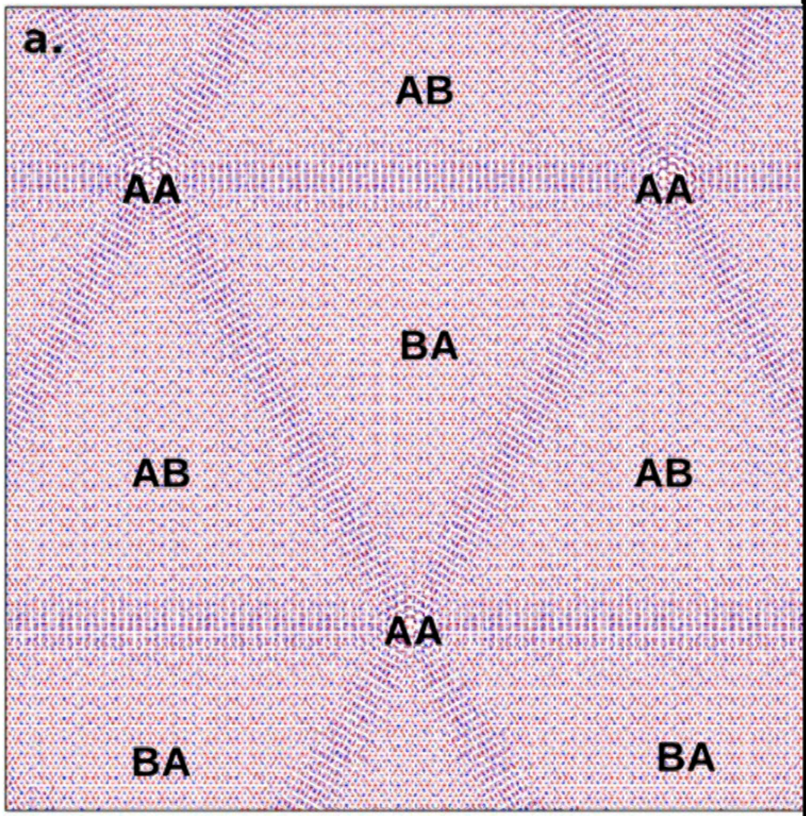
Pair binding in p-pi bonded System including C60 molecule

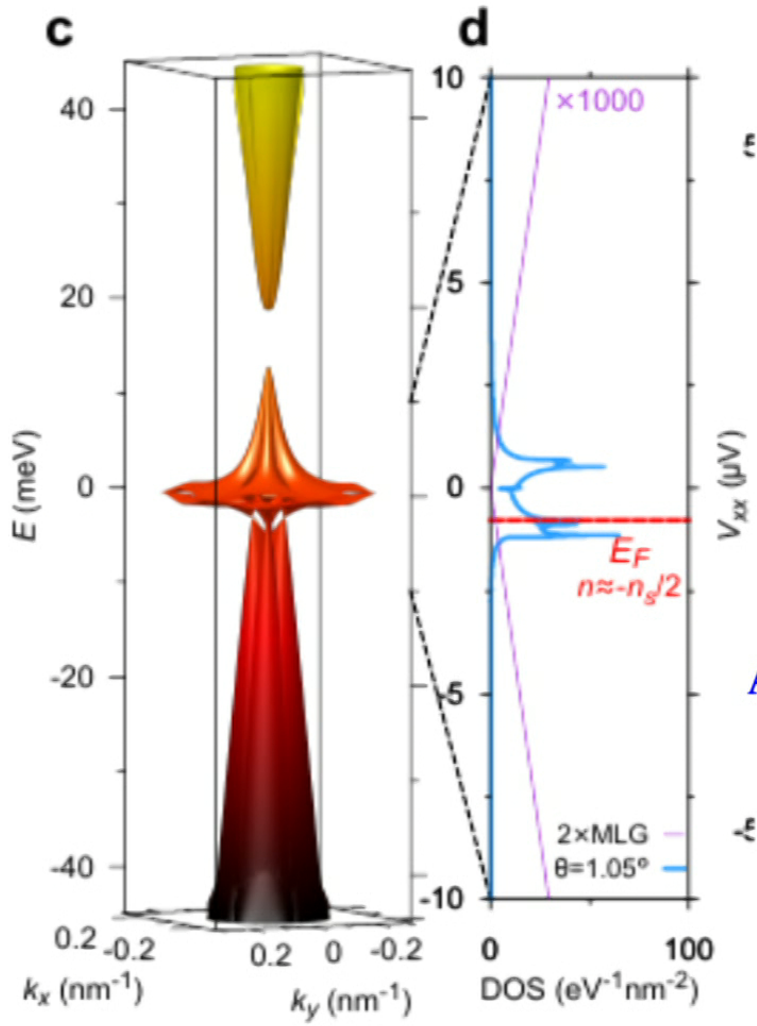
(GB-Tosatti, Kivelson-Chakravarty)

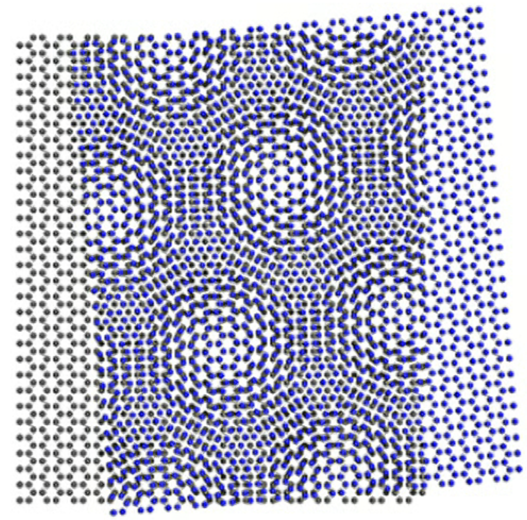
AB and BA
Regions are Mott Insulators

AA region is Metallic

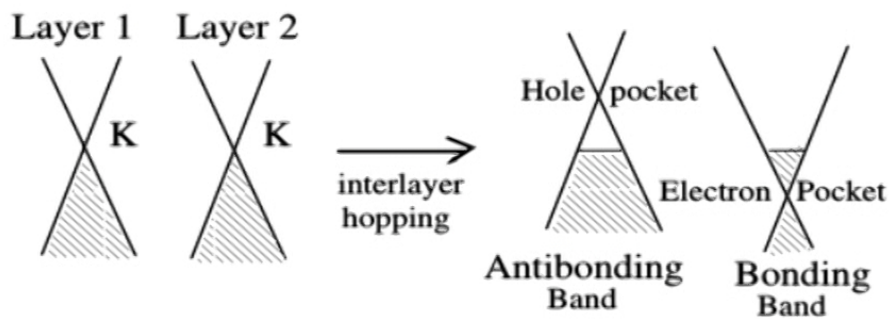
Domain walls are metallic







At the magic angle of 1.16 degree number of carbon atoms per unit cell is about 2000

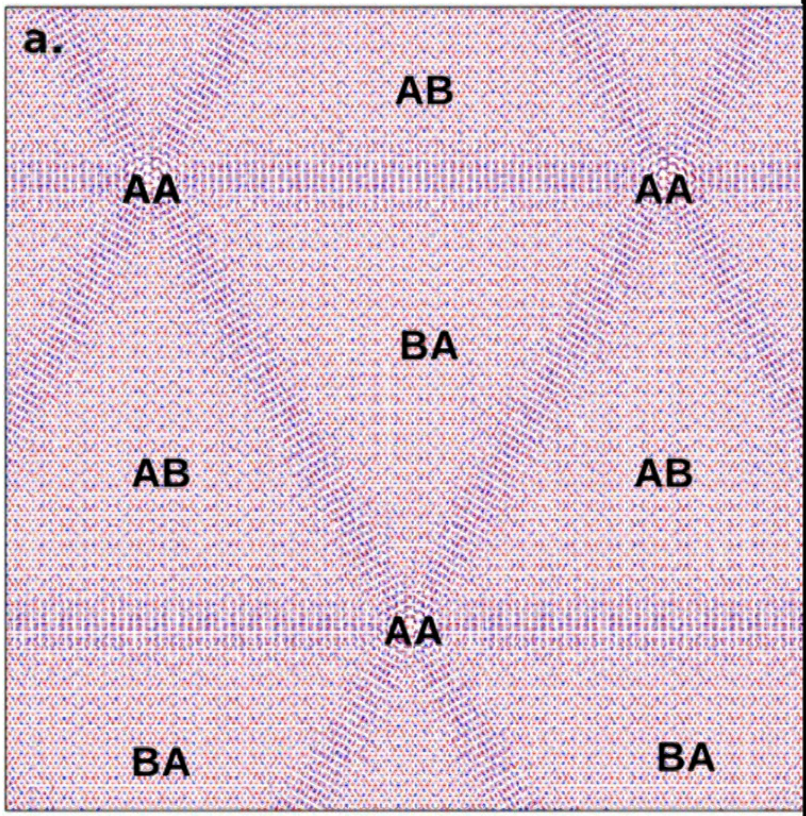


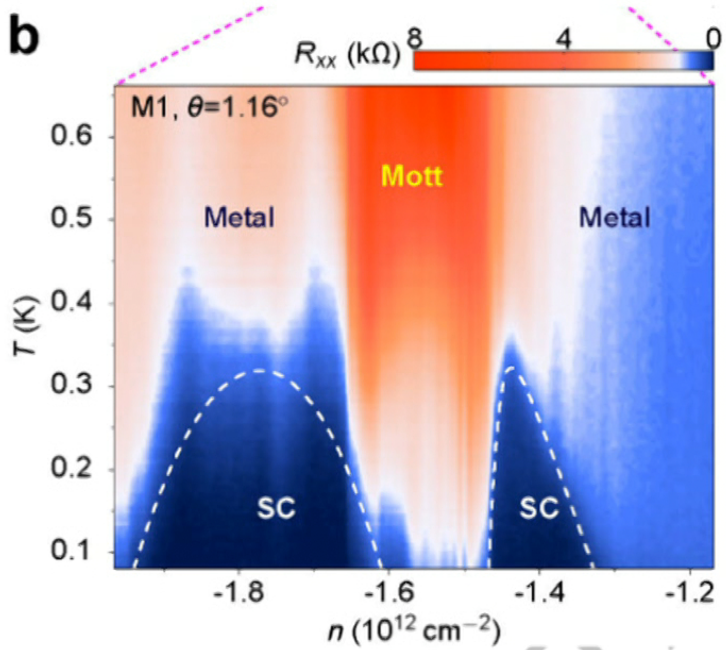
Aerial density of added carriers is $\sim 4 \times 10^{12}/cm^2$. This is very small and is about 0.2 % of density of p_z-electrons $\sim 2 \times 10^{15}$ (or carbon atoms) in neutral graphene layer.

AB and BA
Regions are Mott Insulators

AA region is Metallic

Domain walls are metallic




b
R_{xx} (kΩ) 8 4 0
M1, θ=1.16°
Mott
Metal
Metal
SC
SC
T (K)
0.6
0.5
0.4
0.3
0.2
0.1
-1.8
-1.6
-1.4
-1.2
n (10^12 cm^−2)

Conclusions

Our theory predicts

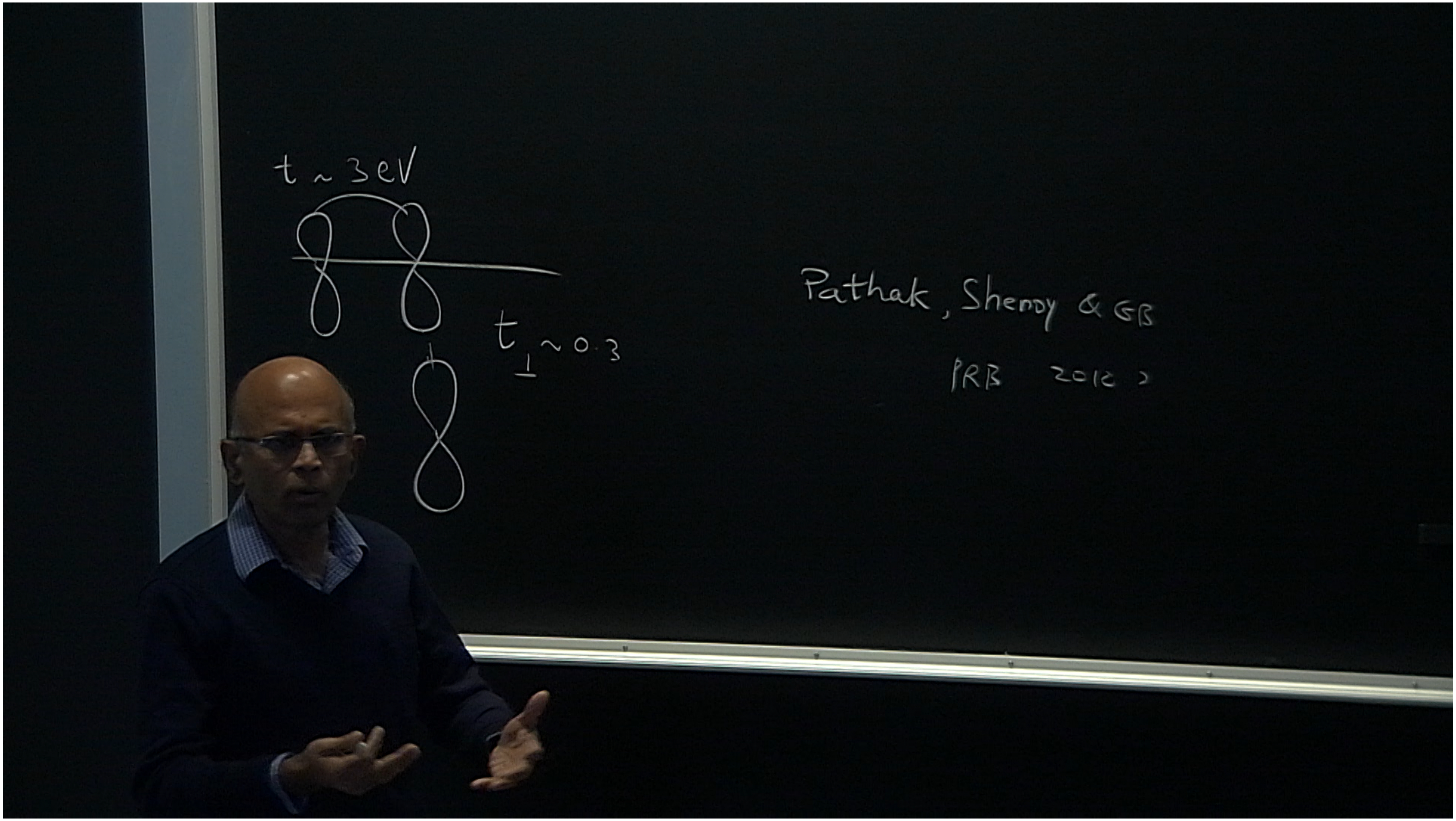
A Cooper pair Exciton (-2e , +2e) Liquid
for untwisted AA Bilayer Graphene

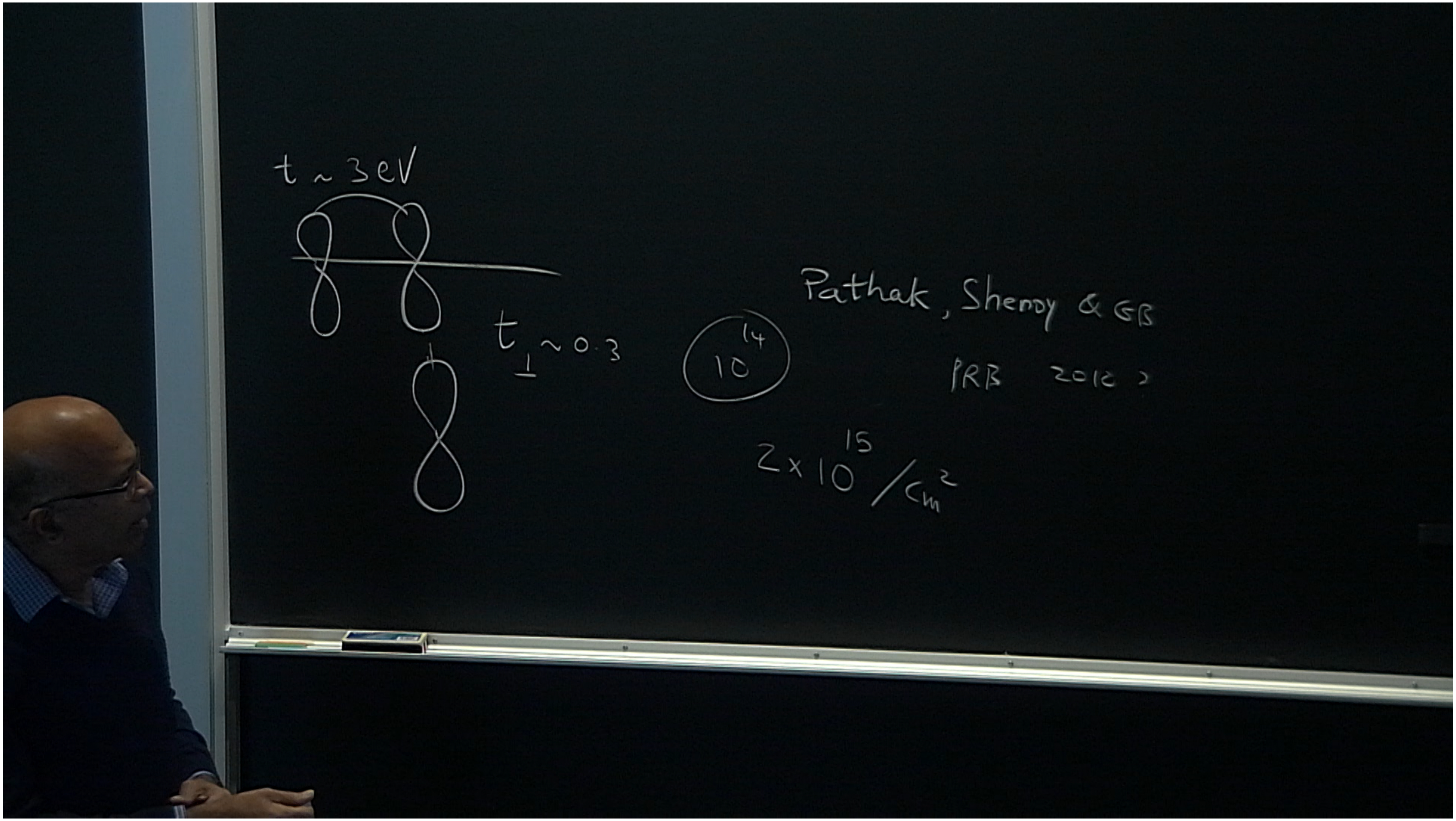
A predominantly Mott insulating lattice of atoms connected
by conducting walls and vortices

Josephson Lattice, a Bose Mott Insulator for TBL graphene
Gate doping induced Bose insulator to Superconductor transtion

Exciton Cooper pair liquid to Superconductor transition
induced by bilayer electric field bias in AA graphene and
TBL grapene.

Presence of shot noise with charge -2e and +2e


t ~ 3eV
t⊥ ~ 0.3
Pathak, Shenoy & GB
PRB 2010


t ~ 3eV
t⊥ ~ 0.3
10^14
Pathak, Shenoy & GB
PRB 2010 ?
2x10^15 /cm^2