Title: Warm Superconductors

Date: Oct 10, 2012 02:00 PM

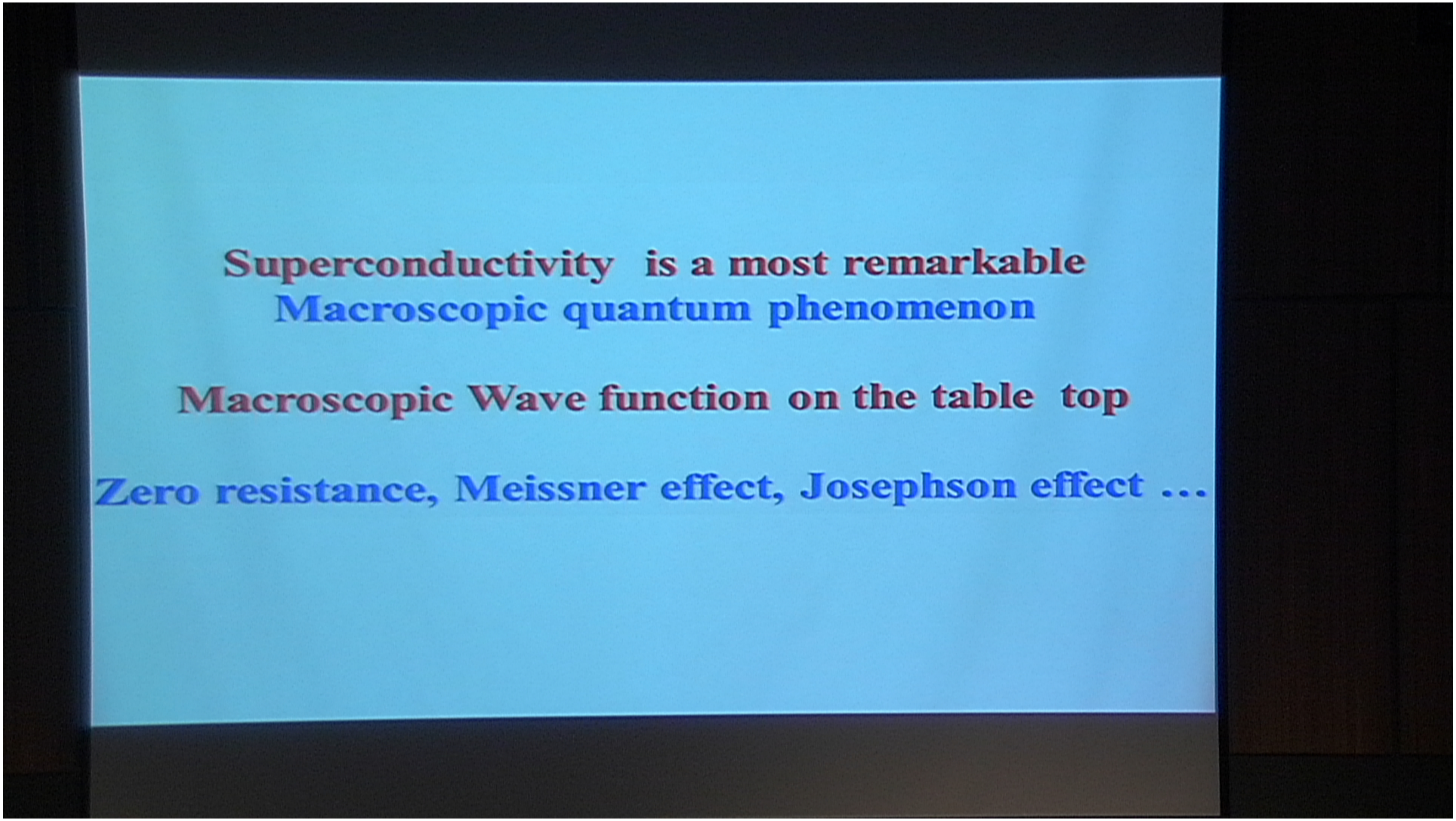
URL: http://pirsa.org/12100059

Abstract:

3rd July 2012

Acknowledgement

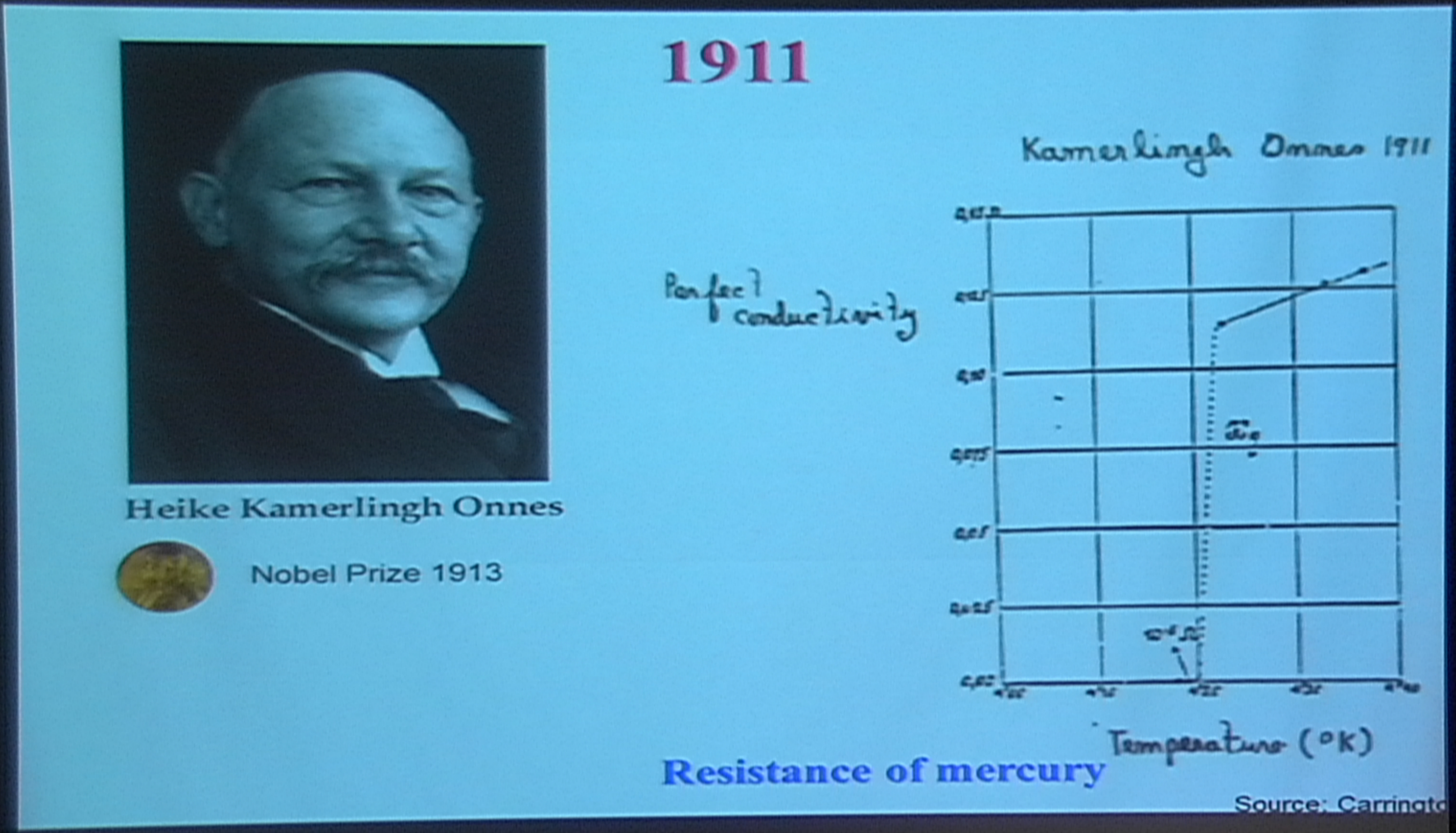
P W Anderson (Princeton)
V Shenoy (IISc, Bangalore)
S Pathak (UC, Santa Cruz)
A Jafari (Shariff)



Superconductivity is a most remarkable
Macroscopic quantum phenomenon

Macroscopic Wave function on the table top

Zero resistance, Meissner effect, Josephson effect …



1911

Heike Kamerlingh Onnes

Nobel Prize 1913

Resistance of mercury

Source: Carringto

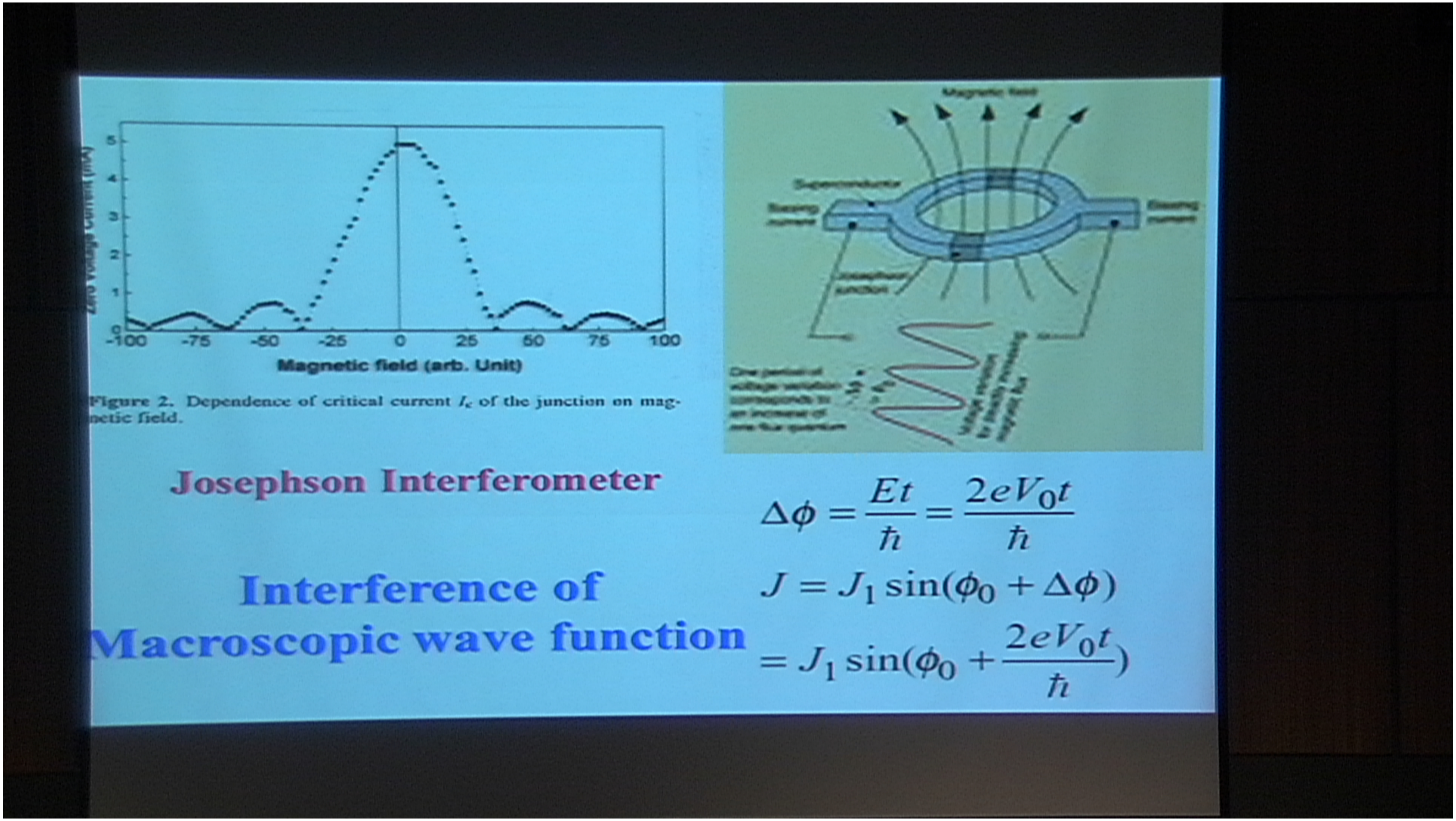


Figure 2. Dependence of critical current I_c of the junction on magnetic field.

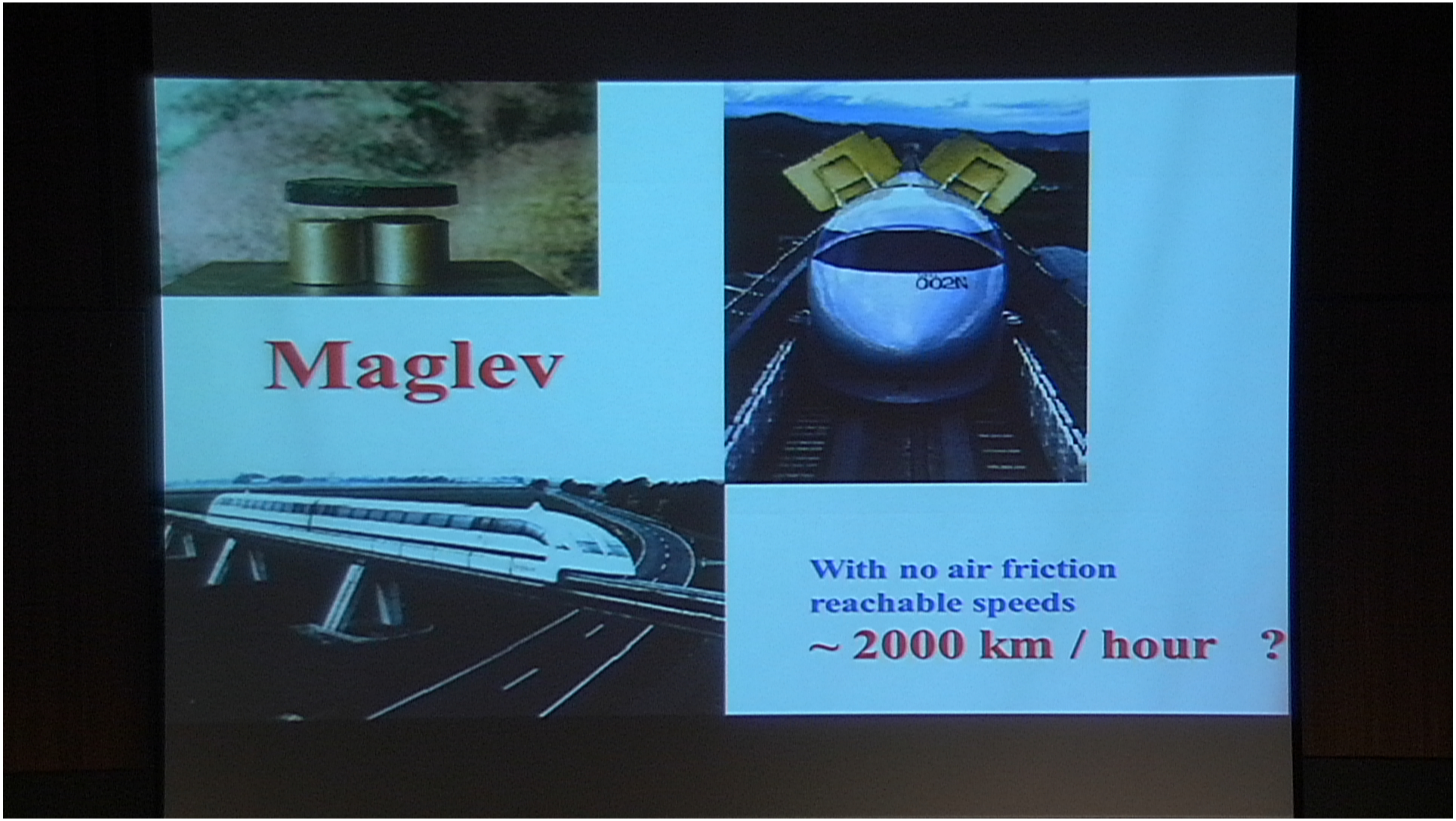
Josephson Interferometer

Interference of Macroscopic wave function

$$\Delta\phi = \frac{Et}{\hbar} = \frac{2eV_0 t}{\hbar}$$

$$J = J_1 \sin(\phi_0 + \Delta\phi)$$

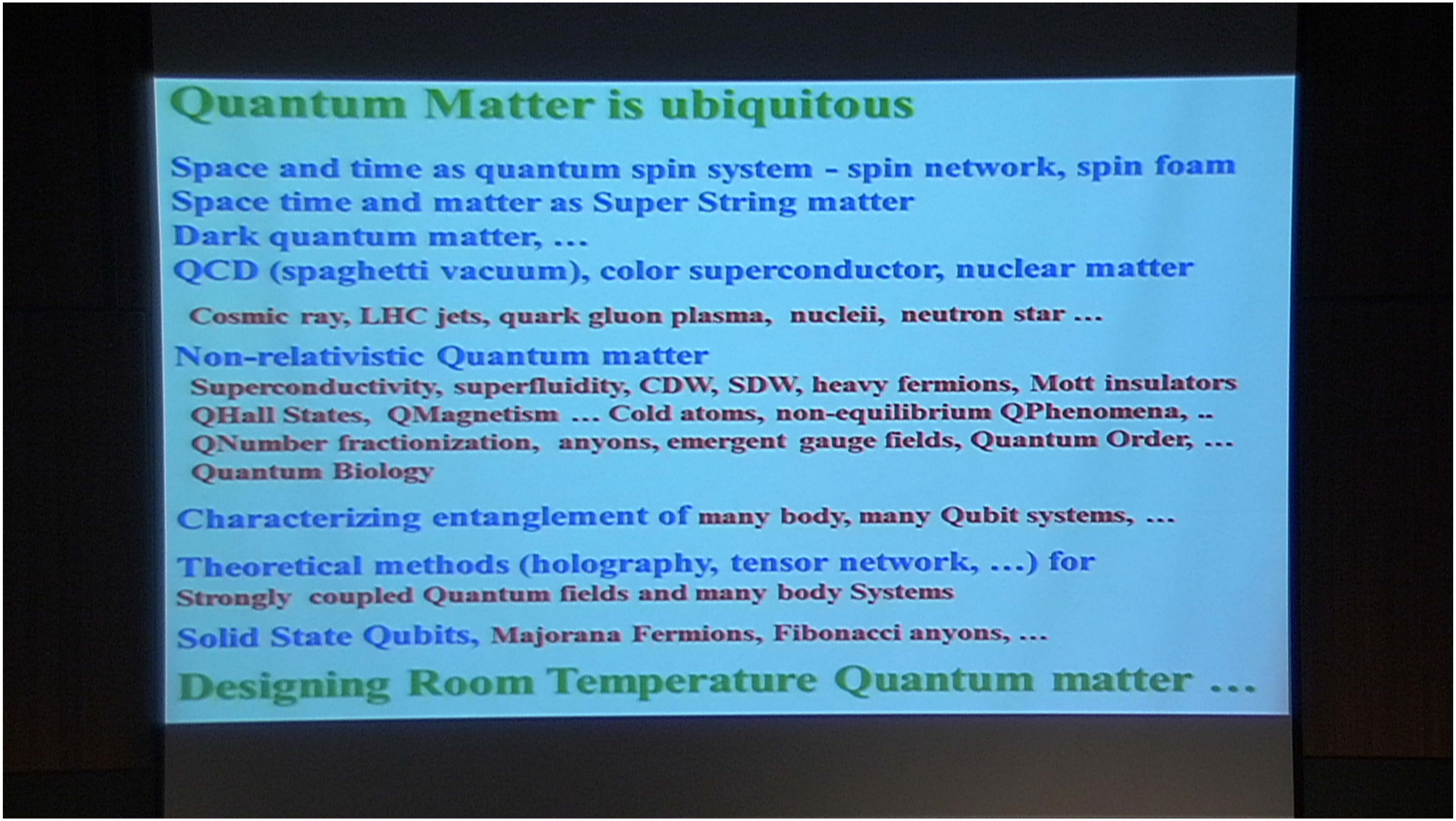
$$= J_1 \sin(\phi_0 + \frac{2eV_0 t}{\hbar})$$



Maglev

With no air friction
reachable speeds

~ 2000 km / hour ?



Quantum Matter is ubiquitous

Space and time as quantum spin system - spin network, spin foam
Space time and matter as Super String matter
Dark quantum matter, ...
QCD (spaghetti vacuum), color superconductor, nuclear matter

Cosmic ray, LHC jets, quark gluon plasma, nucleii, neutron star ...

Non-relativistic Quantum matter
Superconductivity, superfluidity, CDW, SDW, heavy fermions, Mott insulators
QHall States, QMagnetism ... Cold atoms, non-equilibrium QPhenomena, ..
QNumber fractionization, anyons, emergent gauge fields, Quantum Order, ...
Quantum Biology

Characterizing entanglement of many body, many Qubit systems, ...

Theoretical methods (holography, tensor network, ...) for
Strongly coupled Quantum fields and many body Systems

Solid State Qubits, Majorana Fermions, Fibonacci anyons, ...

Designing Room Temperature Quantum matter ...

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Designing Room Temperature Quantum matter ...

Matters of Consequence

BCS theory of (c)old Superconductors has had a
Special and Unifying Role in Physics

It provided key insights for unification of
weak, electromagnetic and strong interactions
in Standard Model of elementary particle physics

Spontaneous symmetry breaking,
Nambu-Jona Lisinio mechanism of mass generation, chiral symmetry breaking
Anderson-Higgs mechanism, Higgs boson ...

Pairing in nucleii, superfluidity in neutron stars, ...

Theory and new physics in Warm Superconductors
Another Special role in Physics ?

Emergent gauge fields, quantum order, topological order,
Novel entanglement structure ...

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Limiting values of

Physical Properties

of Non relativistic matter

Highest density
- melting point
- hardness
- Youngs modulus
- Tc ferromagnetism
- Tc superconductivity
- resistance
- viscosity

Room temperature Qubits

can theory help

ab initio ? not yet

microscopic models
with phenomenological inputs
- yes, to some extent

Basic input

Electric charge	e
Mass of electron	m
Mass of proton	m_p
Atomic numbers	Z
Velocity of light	c
Planck's constant	h

Approaches to High temperature Superconductivity

Theoretical

Little's mechanism

Ginzburg's mechanism

Bipolaron

Pressurized Hydrogen

Doped Mott insulators
& RVB mechanism

Experimental

Cuprates - 32 K to 163 K

Organics - 1 K to 13 K

TM oxides, $Ba_{1-x}K_xBiO_3$, MgB_2 40 K

Nickel borocarbides (TIFR) 24 K

Carbon, fullerene based 40 K

Fe Arsenide 56 K

B.T. Matthias* Rules for Superconductivity

1960's

1) cubic structures
2) avoid oxygen
3) avoid magnetism
4) avoid insulators
5) don't talk to theorists

* An outstanding experimentalist and discoverer
of new families of superconductors, including Nb_3Ge,
a record holder for maximum Tc till 1986,
before high Tc cuprates appeared in the scene

Theory of Lord Kelvin (1902)

According to Rutherford model of atoms,
conduction electrons in metals should get attached back to parent ions
as we lower the temperatures.

**Every metal is likely to become
an insulator at sufficiently low temperatures**

Kammerlingh Onnes went on to prove Lord Kelvin right

He ended up discovering superconductivity in Hg !

Bednorz and Muller (1986) were inspired by

a theory based on Jahn-Teller effect induced bipolaron

Höck, Nickisch, Thomas, Helv. Phys. Acta. 56, 237 (1983)

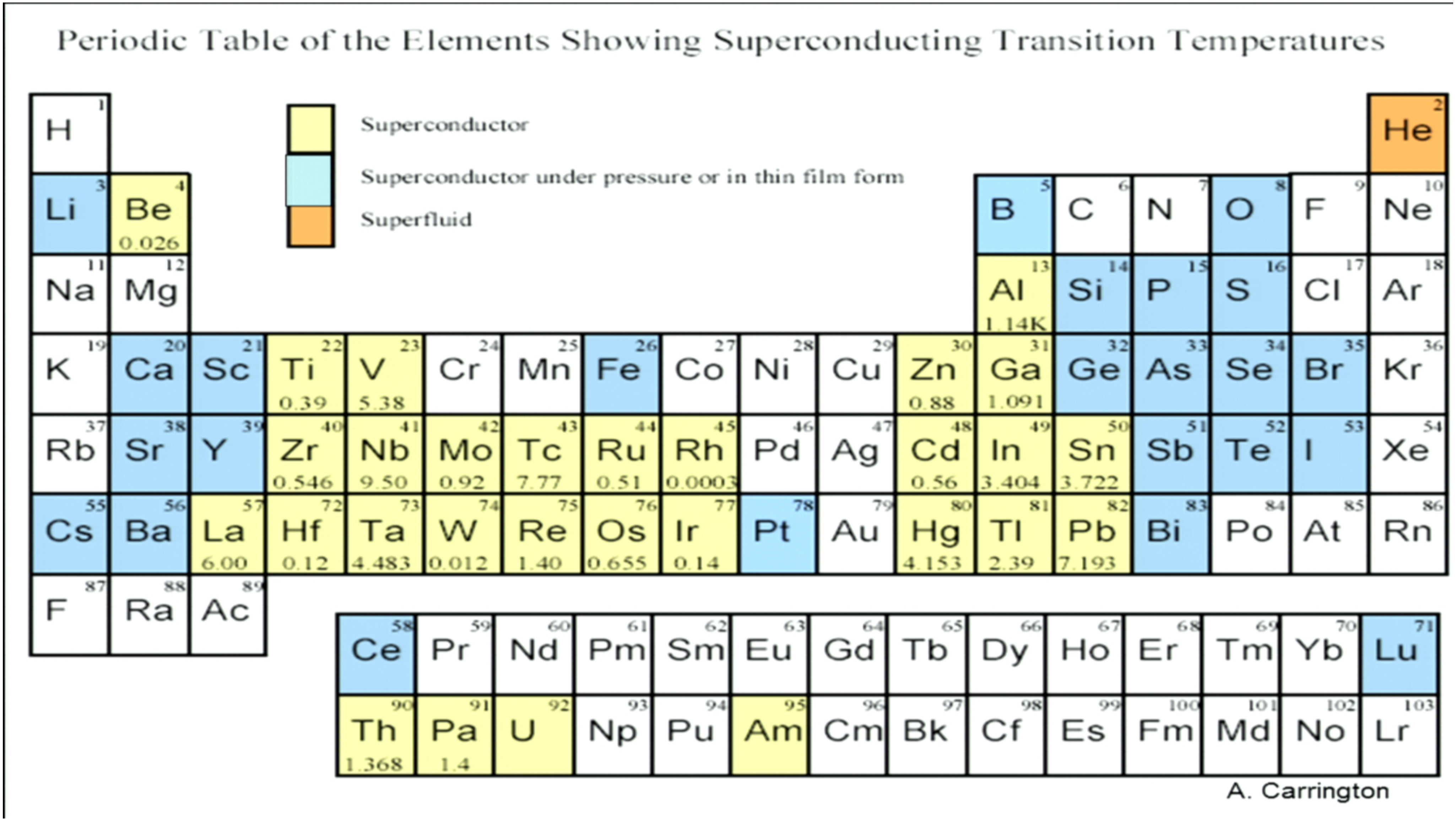
They ended up discovering cuprate superconductors
where there is no Jahn-Teller effect but
an entirely new (RVB) mecehanism
based on electron correlations

Moral of the story (GB)

Listen to theorists

They will put you in some good track

where things might be more interesting than one wanted !



Periodic Table of the Elements Showing Superconducting Transition Temperatures

🟨 Superconductor

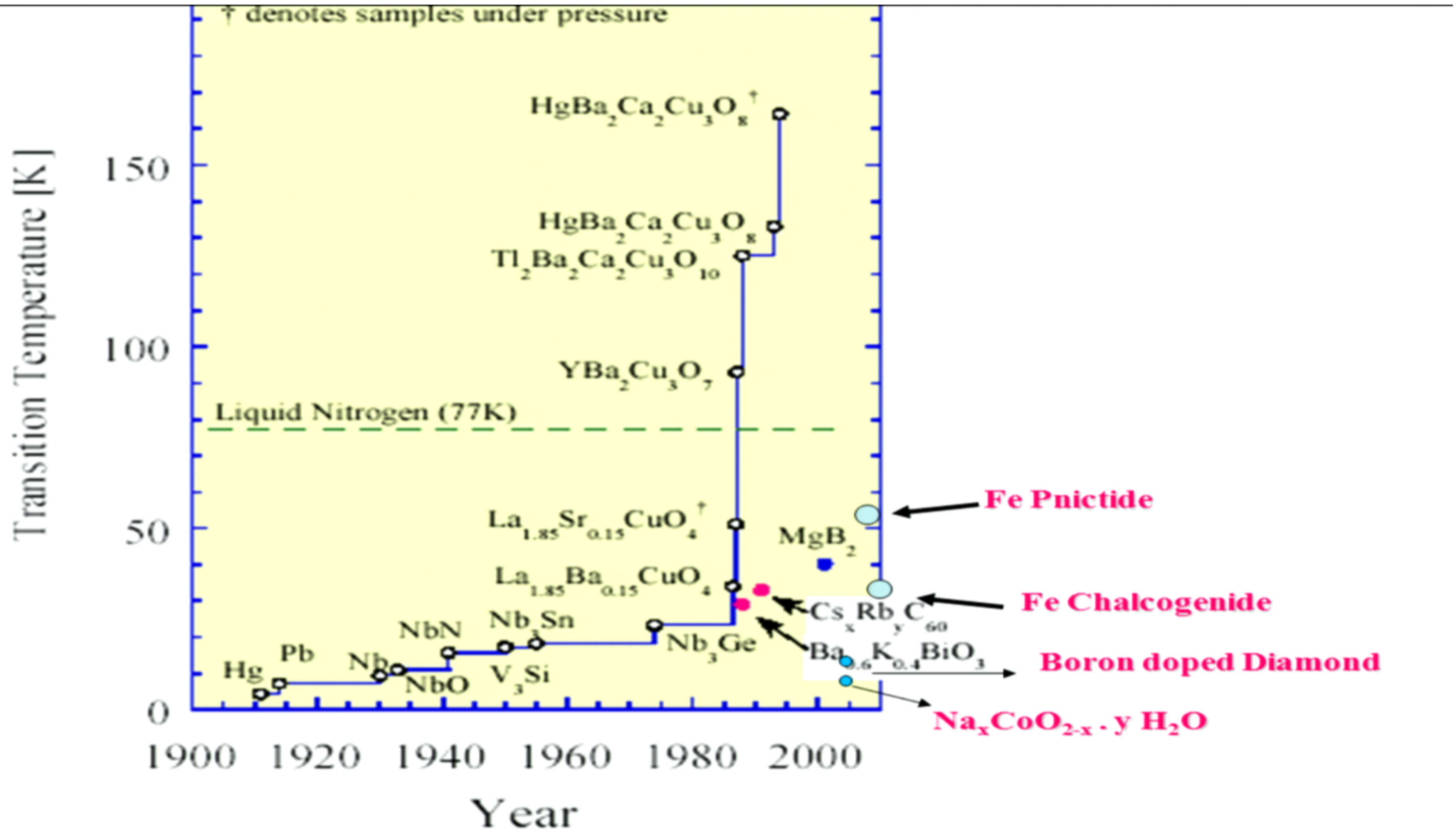
🟦 Superconductor under pressure or in thin film form

🟧 Superfluid

1 H																	🟧 2 He
🟦 3 Li	🟨 4 Be 0.026											🟦 5 B	6 C	7 N	🟦 8 O	9 F	10 Ne
11 Na	12 Mg											🟨 13 Al 1.14K	🟦 14 Si	🟦 15 P	🟦 16 S	17 Cl	18 Ar
19 K	🟦 20 Ca	🟦 21 Sc	🟨 22 Ti 0.39	🟨 23 V 5.38	24 Cr	25 Mn	🟦 26 Fe	27 Co	28 Ni	29 Cu	🟨 30 Zn 0.88	🟨 31 Ga 1.091	🟦 32 Ge	🟦 33 As	🟦 34 Se	🟦 35 Br	36 Kr
37 Rb	🟦 38 Sr	🟦 39 Y	🟨 40 Zr 0.546	🟨 41 Nb 9.50	🟨 42 Mo 0.92	🟨 43 Tc 7.77	🟨 44 Ru 0.51	🟨 45 Rh 0.0003	46 Pd	47 Ag	🟨 48 Cd 0.56	🟨 49 In 3.404	🟨 50 Sn 3.722	🟦 51 Sb	🟦 52 Te	🟦 53 I	54 Xe
🟦 55 Cs	🟦 56 Ba	🟨 57 La 6.00	🟨 72 Hf 0.12	🟨 73 Ta 4.483	🟨 74 W 0.012	🟨 75 Re 1.40	🟨 76 Os 0.655	🟨 77 Ir 0.14	🟦 78 Pt	79 Au	🟨 80 Hg 4.153	🟨 81 Tl 2.39	🟨 82 Pb 7.193	🟦 83 Bi	84 Po	85 At	86 Rn
87 F	88 Ra	89 Ac															

🟦 58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	🟦 71 Lu
🟨 90 Th 1.368	🟨 91 Pa 1.4	🟨 92 U	93 Np	94 Pu	🟨 95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

A. Carrington



Source: Carrington

Superconductivity in Elemental Metals

Hg, Pb, Al, …. Ti, V, Nb, …

Model

Electron gas interacting with a lattice of ions,…, screening
A stable harmonic solid, Fermi liquid
Electron dynamics - Landau quasi particles (electron, hole)
Lattice dynamics – harmonic phonons

Important energy scales are large

Fermi energy ~ 50,000 K, Debye energy ~ 500 K
Deformation potential ~ 10,000 K

Why is Tc always small < 10 K ?

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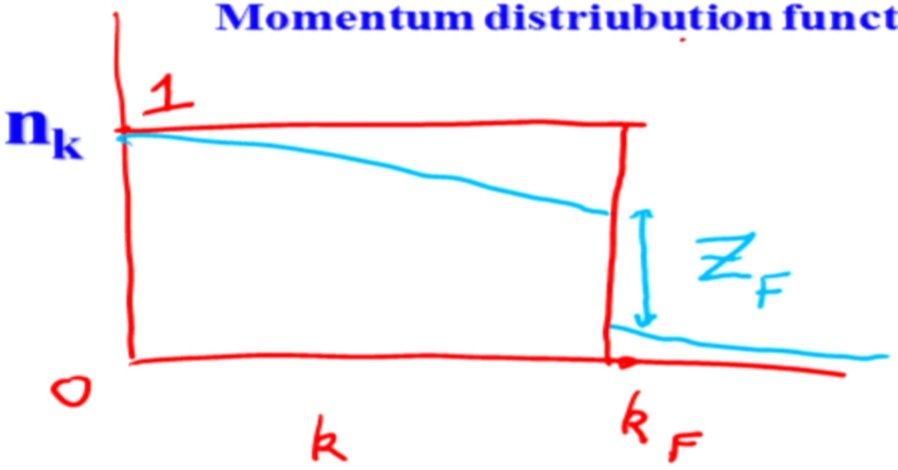
Why is Tc always small < 10 K ?

BCS theory of superconductivity
Needs a reference vacuum/normal state

Fermi liquid metallic state

Superconductivity is a
Minor instability of this vacuum

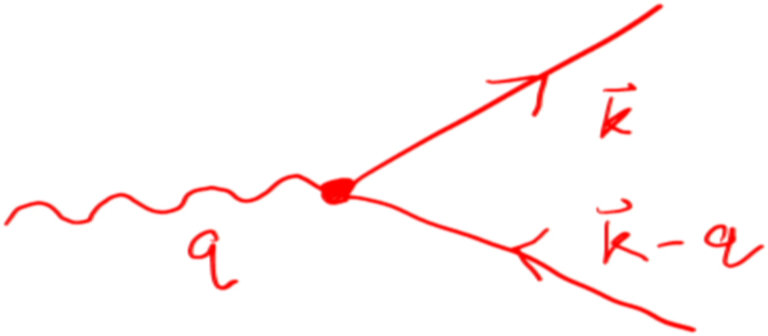

Momentum distriubution function

Z_F **: Wave Function Renormalization Constant**

$$m^* \sim \frac{m_e}{Z_F}$$

Residual interaction between electron and phonon

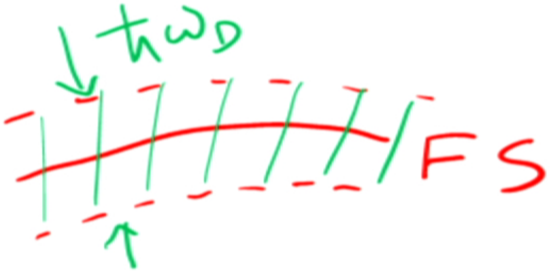
Electron-phonon interaction



Electron-electron attraction Mediated by Phonon

BCS Hamiltonian

$$H = \sum_k \left(\frac{\hbar^2 k^2}{2m} - \mu\right) c^+_{k\sigma} c_{k\sigma} - g \sum{}' c^+_{k\uparrow} c^+_{-k\downarrow} c_{-k'\downarrow} c_{k'\uparrow}$$



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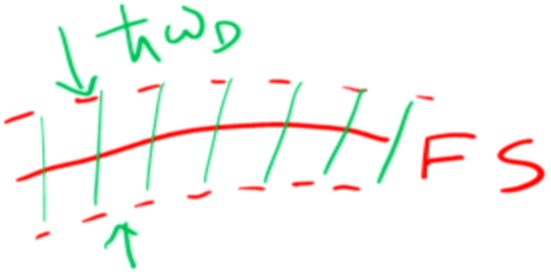

$$k_B T_c = \hbar\omega_D e^{\frac{-1}{\rho \cdot g}}$$

$$\hbar\omega_D \sim \frac{1}{\sqrt{M_N}}$$

Serious constraints from stability point of view -McMillan, Anderson, Cohen

Phonon mediated maximum Tc ~ 30 K

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Phonon mediated maximum Tc ~ 30 K

BCS theory inspired traditional route to new superconductors

$$k_B T_c = \hbar\omega_D e^{\frac{-1}{\rho \cdot g}}$$

Look for

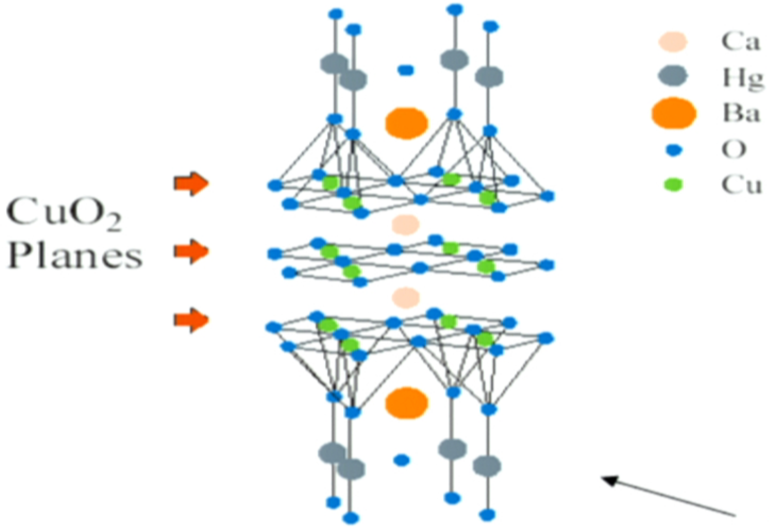
Large Debye energy $\hbar\omega_D$
Large density of states at Fermi level ρ
Large electron phonon coupling constant g

High T_c Superconductivity – Copper Oxides 1986

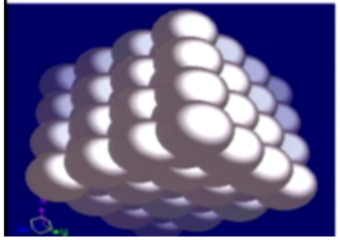
Georg Bednorz

Alex Müller

Nobel Prize 1987



Hg 1223

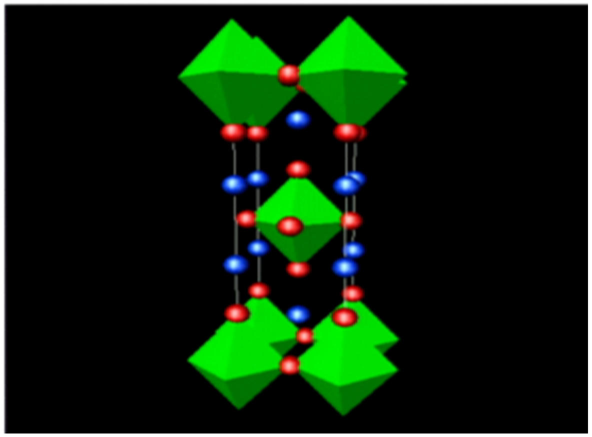


Mercury

Kammerlingh Onnes

Nobe Prize 1913

$La_{1-x}Ba_xCuO_4$ →



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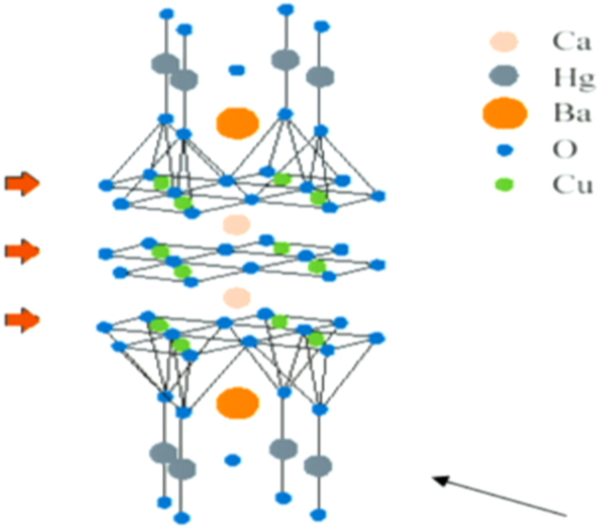
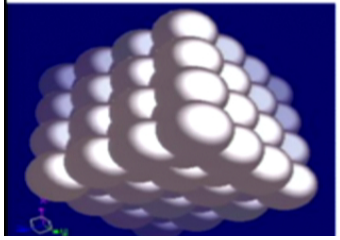


CuO_2 Planes

Hg 1223



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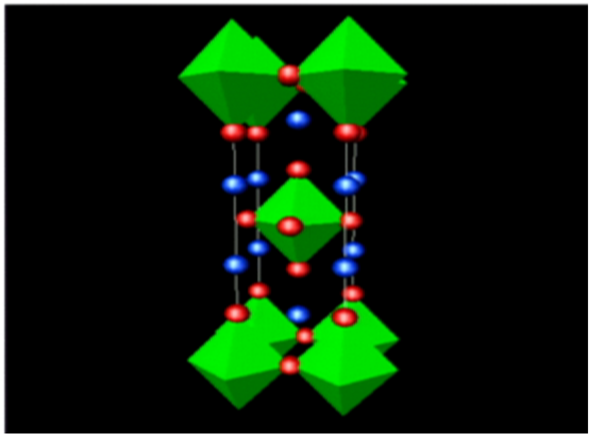
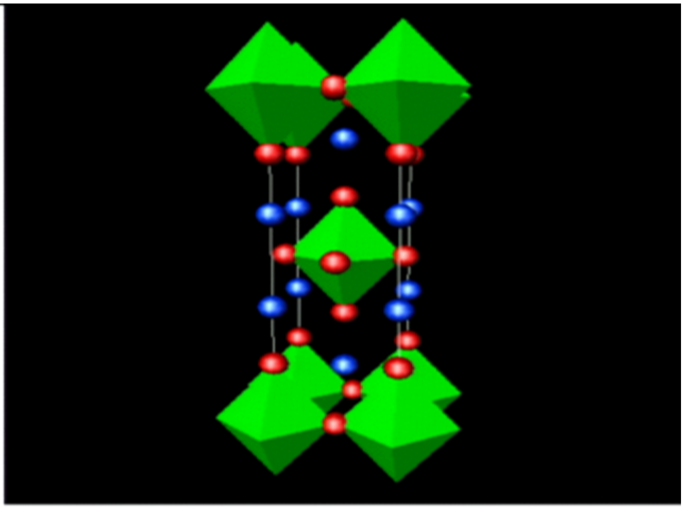
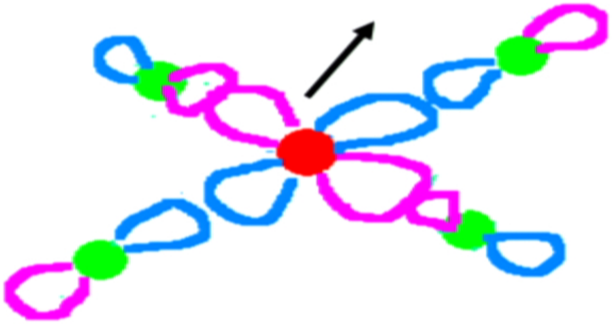


La_2CuO_4





Cu $3d^9$ Ligand

One hole per Cu cell in a molecular orbital of $d_{x^2-y^2}$ symmetry

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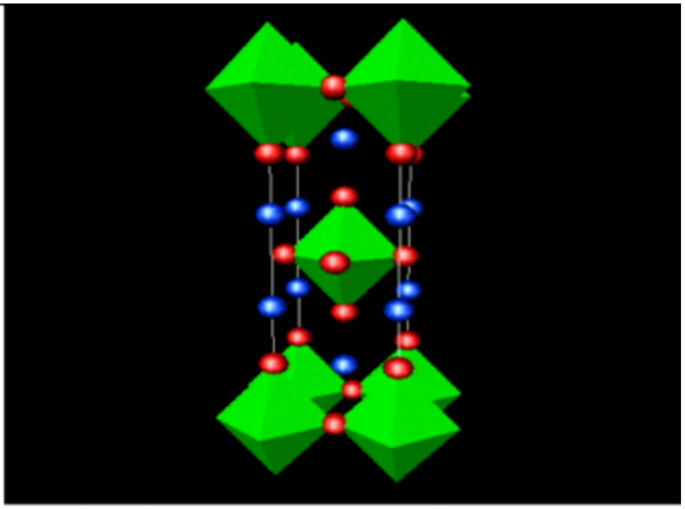

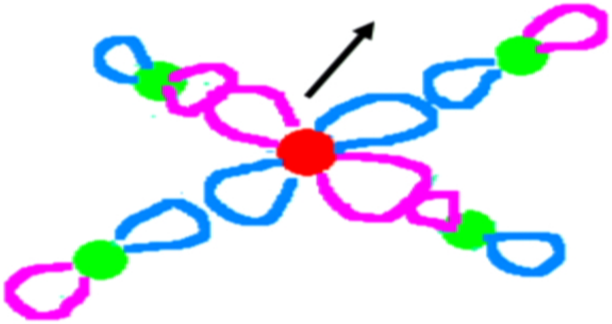

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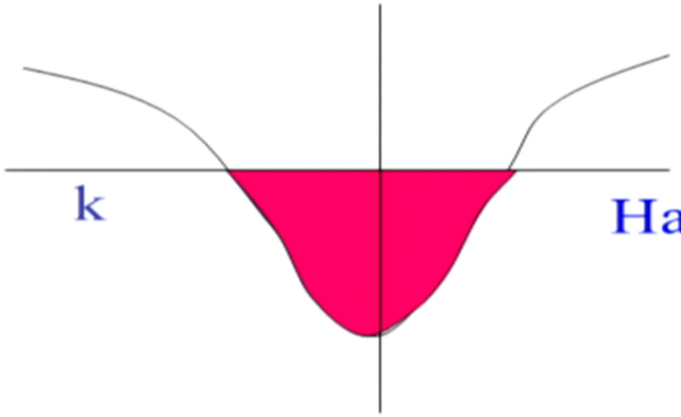
A ray of hope came from Resonating Valence Bond (RVB) theory 1987

Mott insulators
as opposed to fermi liquids
are seats of
High Tc Superconductivity

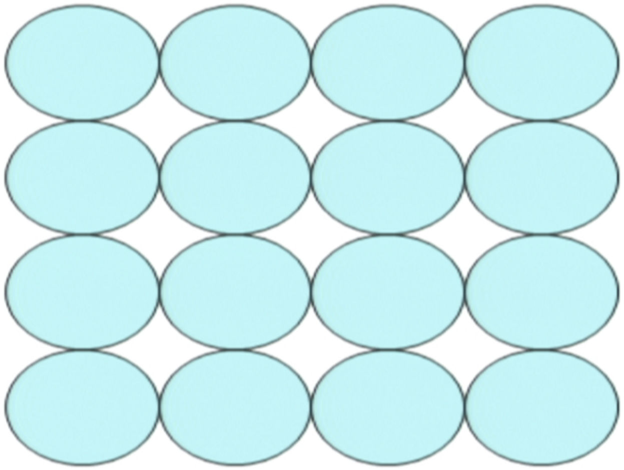
Superexchange
as opposed to exchange of phonon
is the pairing GLUE

A collection of hydrogen atoms forming a hypothetical 3D lattice



Half filled band

1s states of individual hydrogen atoms strongly overlap and form a tight binding half filled band



$a \sim a_B$

It is a metal

described by

Hubbard Model

$$H = -t\sum_{\langle ij\rangle} c^{+}_{i\sigma} c_{j\sigma} + h.c + U\sum n_{i\uparrow} n_{i\downarrow}$$

$$U \ll \underbrace{zt}_{\text{band width}}$$

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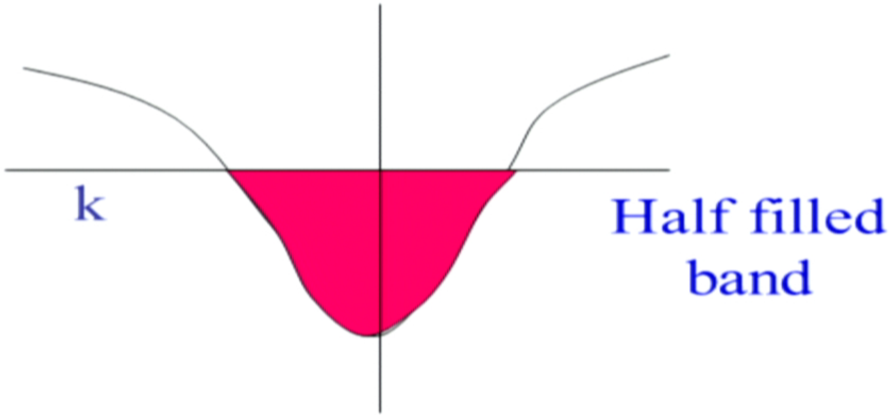

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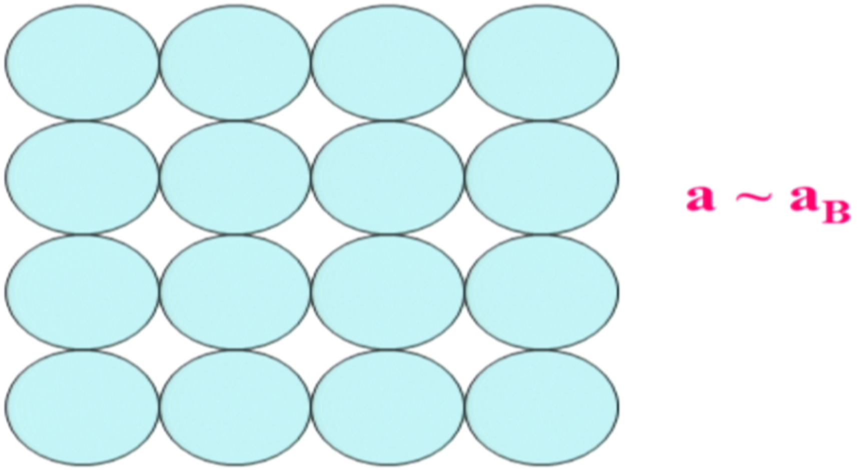

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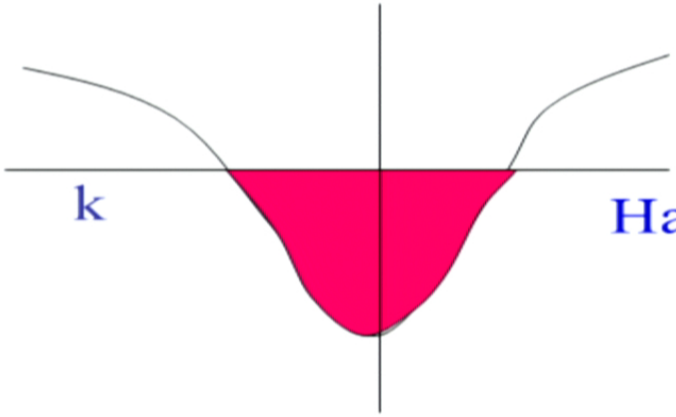

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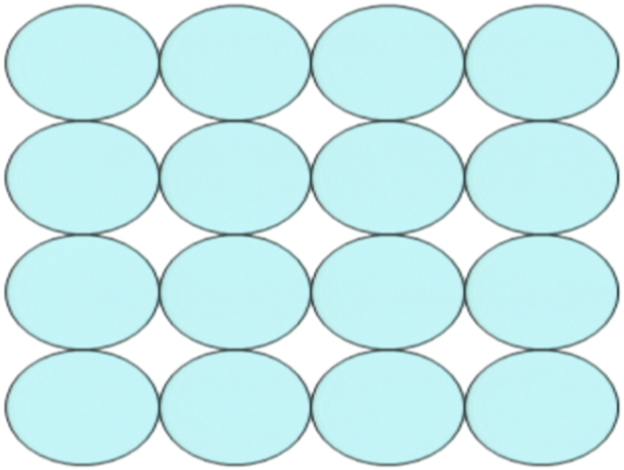

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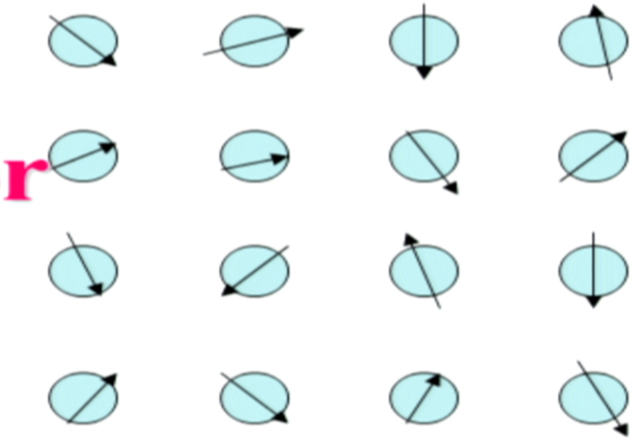
band width

Let us expand the lattice

For $a \gg a_B$

we get a Mott insulator



$a \gg a_B$

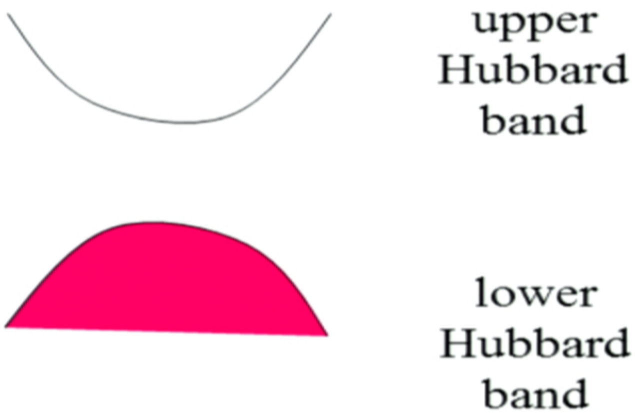
$$H = -t\sum\left(c^{\dagger}_{i\sigma}c_{j\sigma} + h.c\right)$$
$$+ U\sum n_{i\uparrow}n_{i\downarrow}$$

$$U \gg tz$$

Spins are soft degrees of freedom while charges are frozen

A half filled band looses its fermi surface becomes an insulator

Not a Bragg gap but a Correlation gap.



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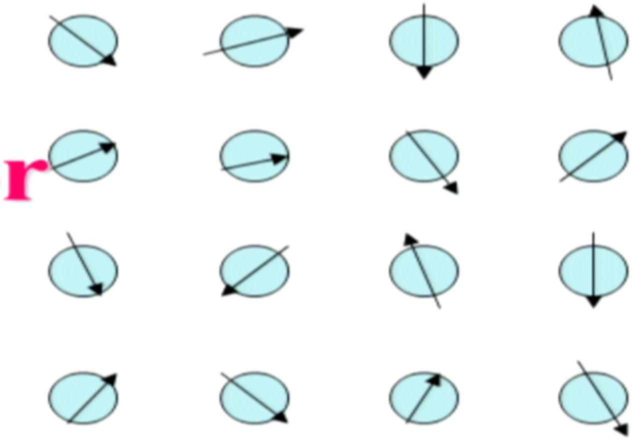

$a \gg a_B$

upper
Hubbard
band

lower
Hubbard
band

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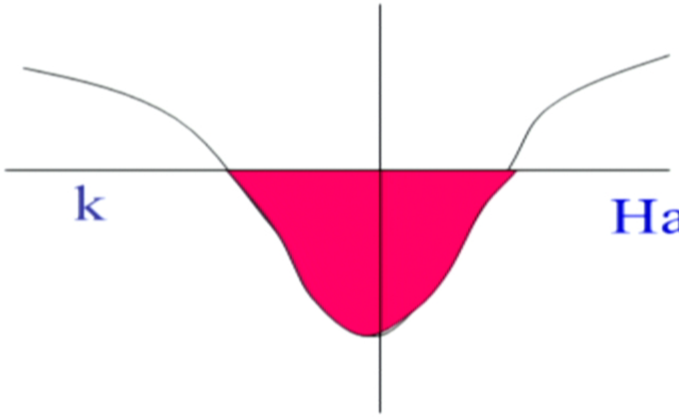

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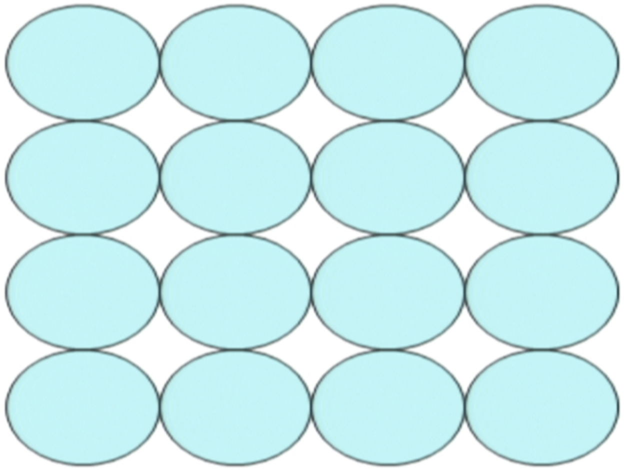

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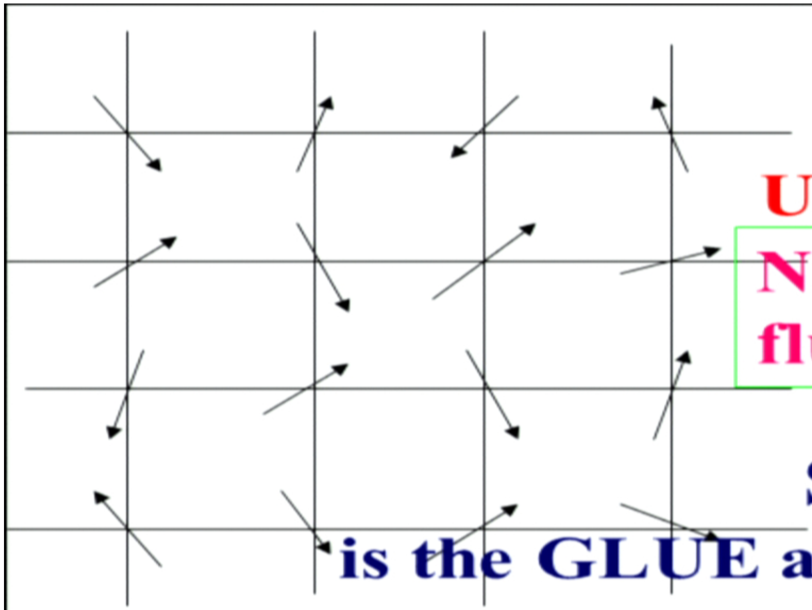
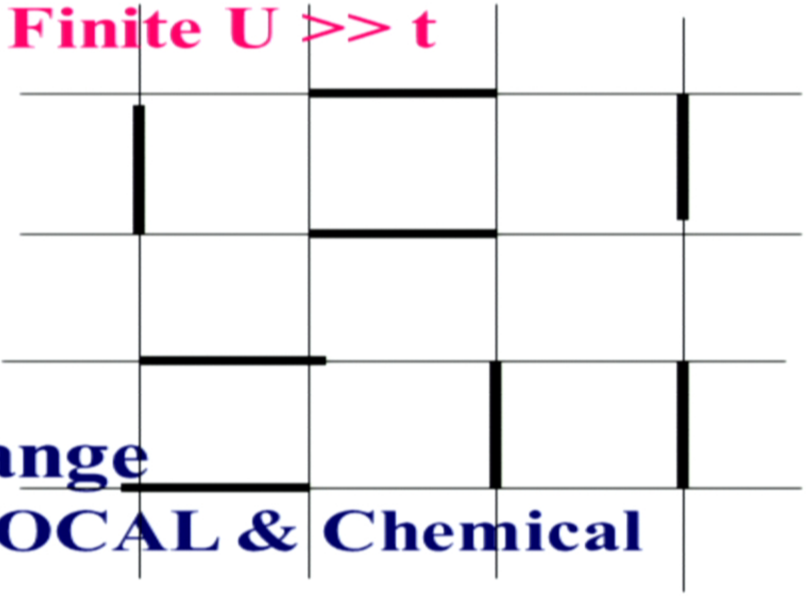


U = infinity

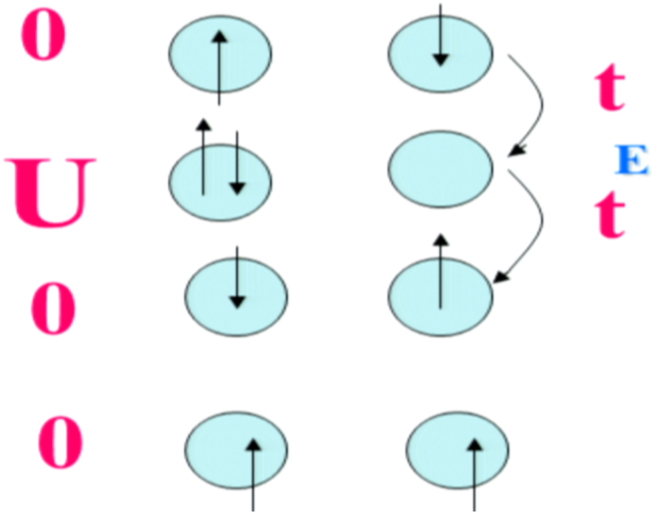
No quantum fluctuations



Finite U >> t

Superexchange

is the GLUE and is very LOCAL & Chemical



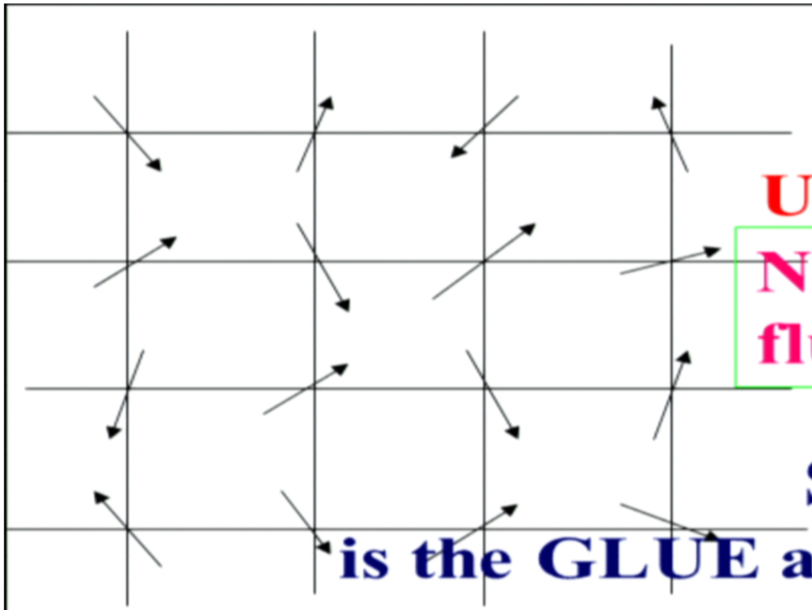
Energy gain = $J = \dfrac{-4t^2}{U}$

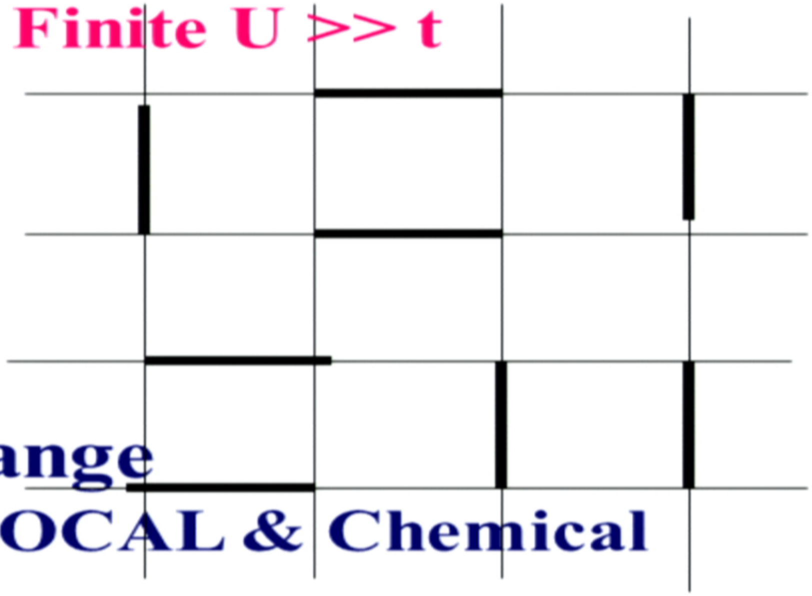
singlet $= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

$$H = J\sum_{\langle ij\rangle}\left(\mathbf{S}_i\cdot\mathbf{S}_j - \tfrac{1}{4}\right)$$

triplet

Energy gain = 0 !





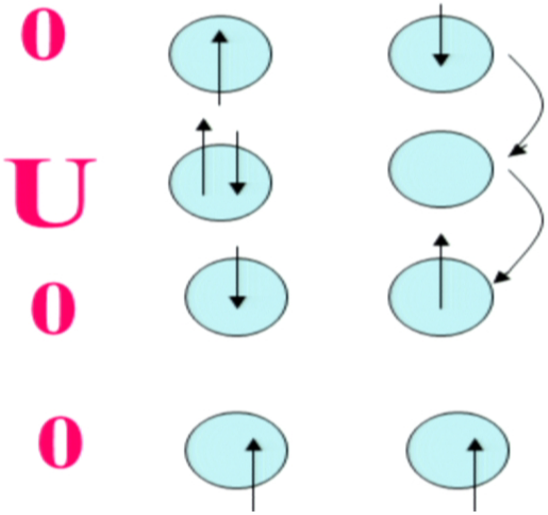
Finite U >> t

U = infinity

No quantum fluctuations

Superexchange

is the GLUE and is very LOCAL & Chemical



t

t

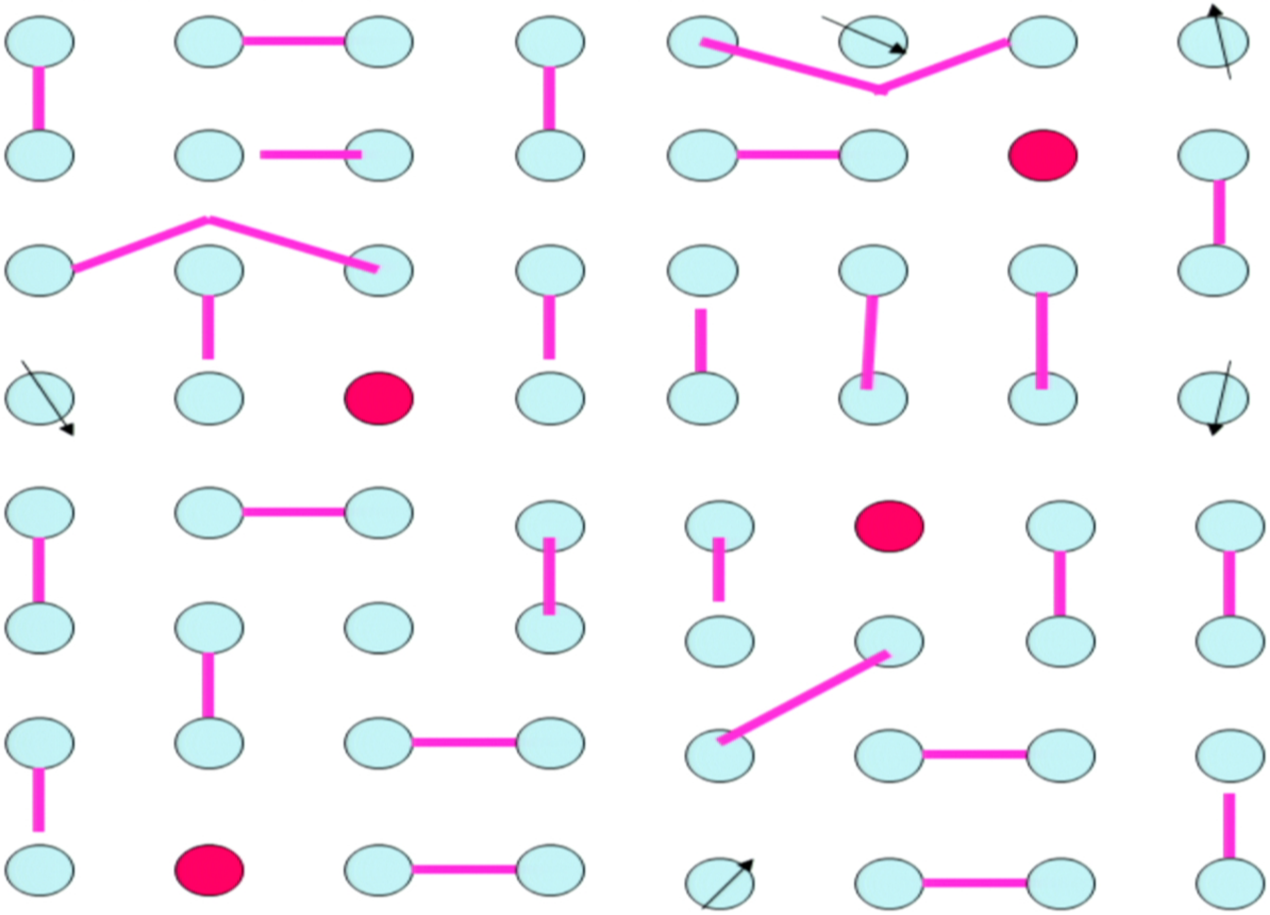
Energy gain = J $= \dfrac{-4t^2}{U}$ $= \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$

singlet

$$H = J\sum_{\langle ij\rangle}\left(\mathbf{S}_i\cdot\mathbf{S}_j - \tfrac{1}{4}\right)$$

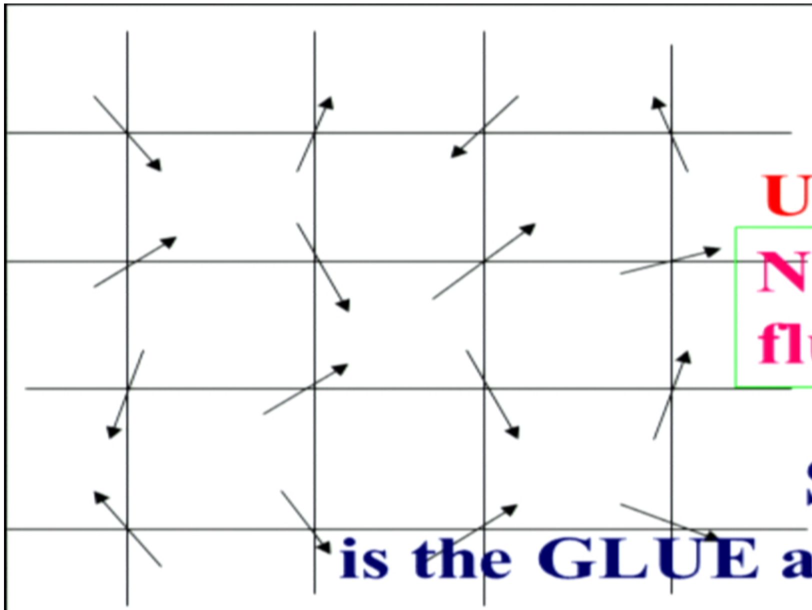
triplet

Energy gain = 0 !



Large positive U
prevents fermi sea formation
and creates local singlets

Nearly all electrons begin to participate in superconductivity



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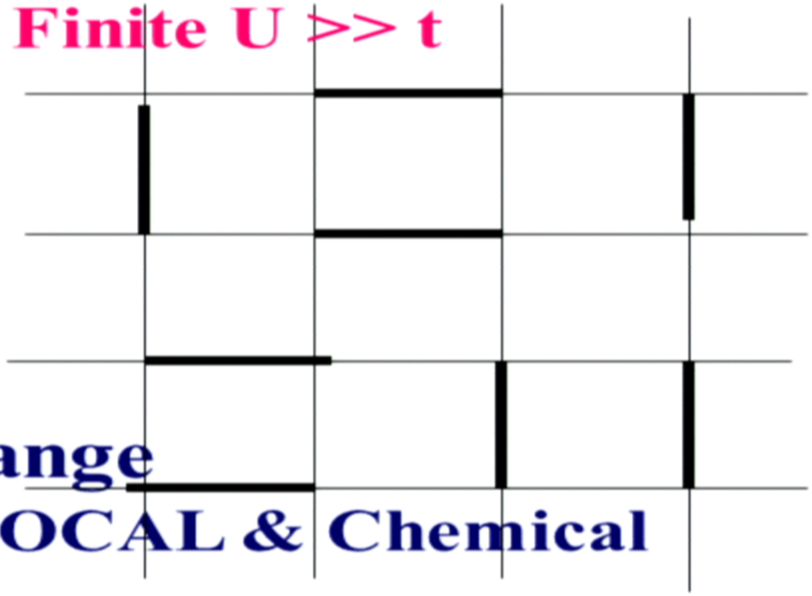

Superexchange

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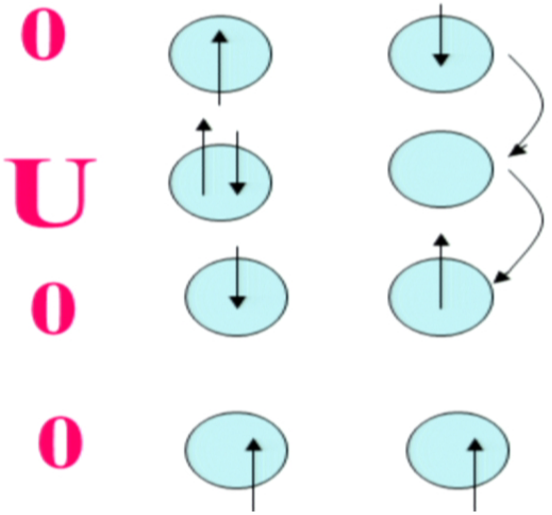

t

t

Energy gain = J = $$-\frac{4t^2}{U}$$

singlet

$$= \tfrac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$$H = J\sum_{\langle ij\rangle}\left(\mathbf{S}_i\cdot\mathbf{S}_j - \tfrac{1}{4}\right)$$

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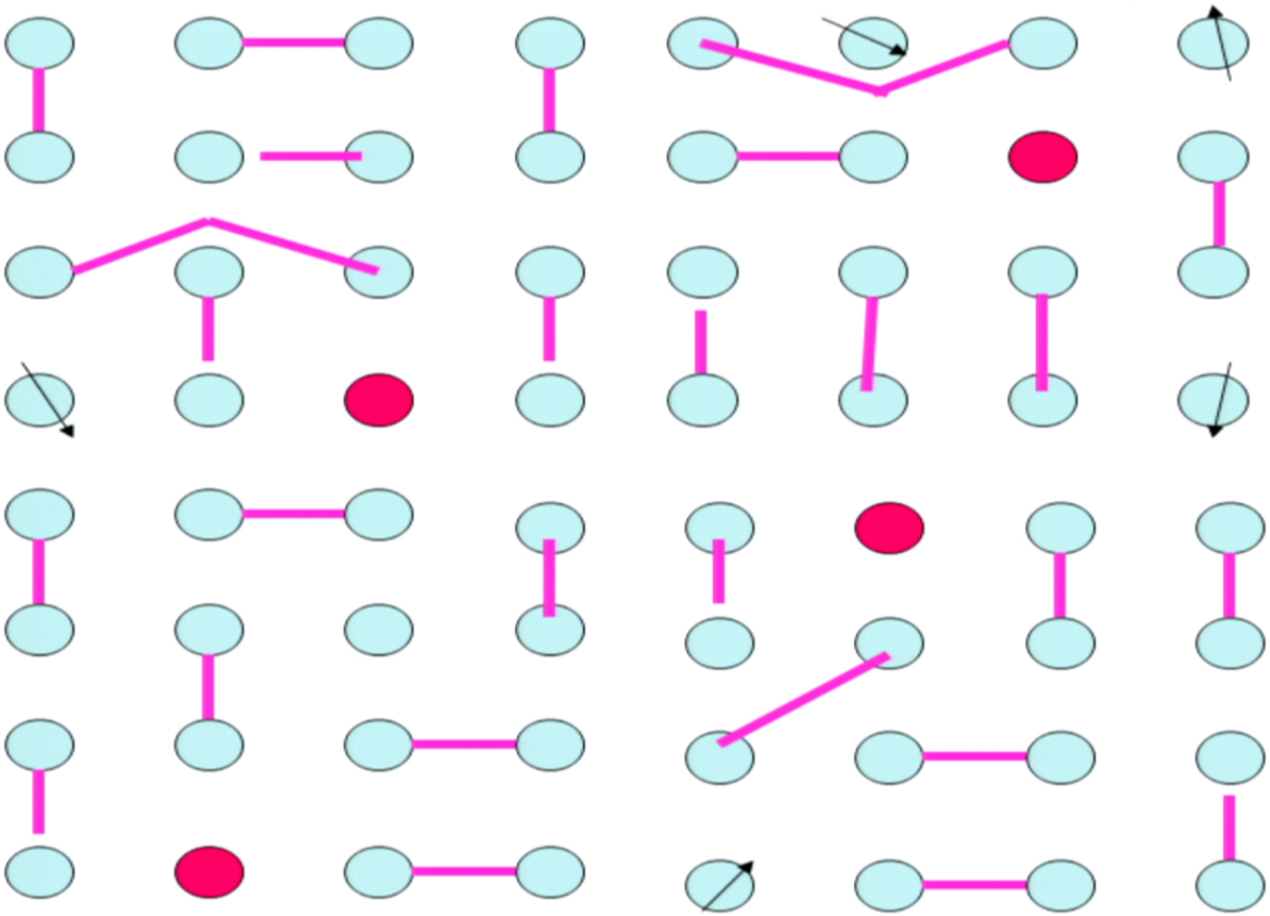

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prevents fermi sea formation
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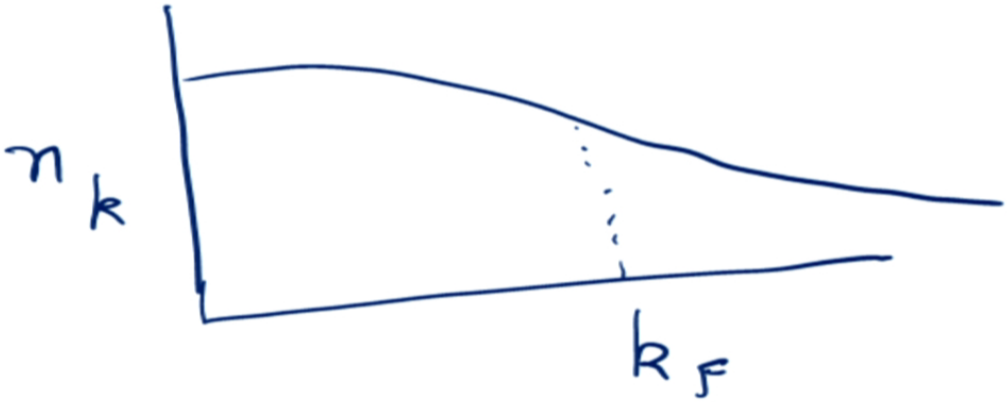
Nearly all electrons begin to participate in superconductivity

Non Fermi liquid metallic state ?



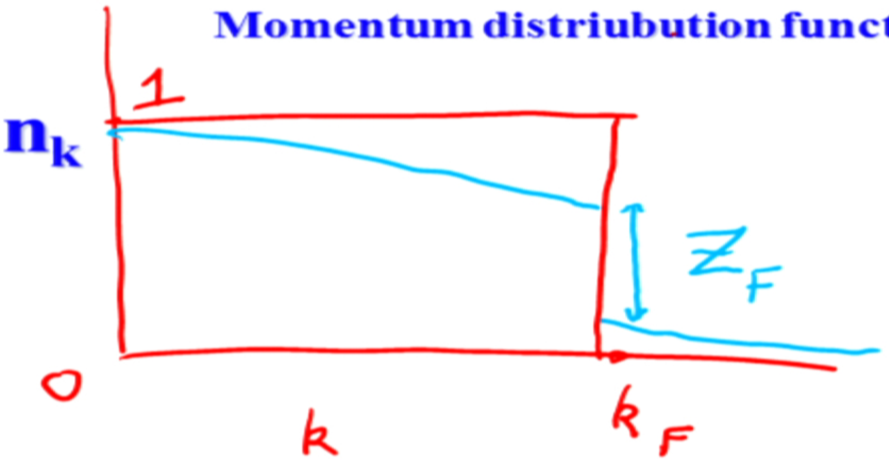
$Z_F = 0$

Luttinger Liquid in 1+1 dim

2+1 dimension?

spin-charge decoupling

Fermi liquid metallic state



Z_F : Wave Function Renormalization Constant

$$m^* \sim \frac{m_e}{Z_F}$$

Message from RVB theory

Mott insulators are seats of high Tc Superconductivity

Superexchange is the GLUE

Fraction of electrons participating in superconductivity

is not $\frac{\hbar\omega_D}{\varepsilon_F}$ **but x**

PW Anderson
GB, Zou, PWA
GB, PWA
PWA, GB, Hsu, Zou
1987-88

Therefore $k_B T_c \sim xt$ **(here t is the hopping parameter)**

Key parameters of RVB theory

t, U, x, lattice structure & Dimensionality

Superexchange J and t

(Magnetism and band formation)

t and U known in known systems inferred from experiments puts Tc already above the scale of room temperature

Graphene is a good example

Cuprates are also failed room temperature Supercondcutors

Impurity band Mott insulator Nitrogen doped Diamond

Cuprate is a failed Room Temperature Superconductor

Intrinsic maximum Tc ~ 250 K

at optimal doping

G. Baskaran, Mod. Phys. Lett., 14 377 (2000)
(and unpublished work)

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Difficulties

1 dimesnion

Fluctuations from low domensionality
Competing orders – Peierls, Spin Peierls Instability

2 dimensions

Competing orders – Valence bond order
AFM, spin stripes
Charge stripes, chirality order
Multiple bands
Jahn Teller effect and polaronic localization

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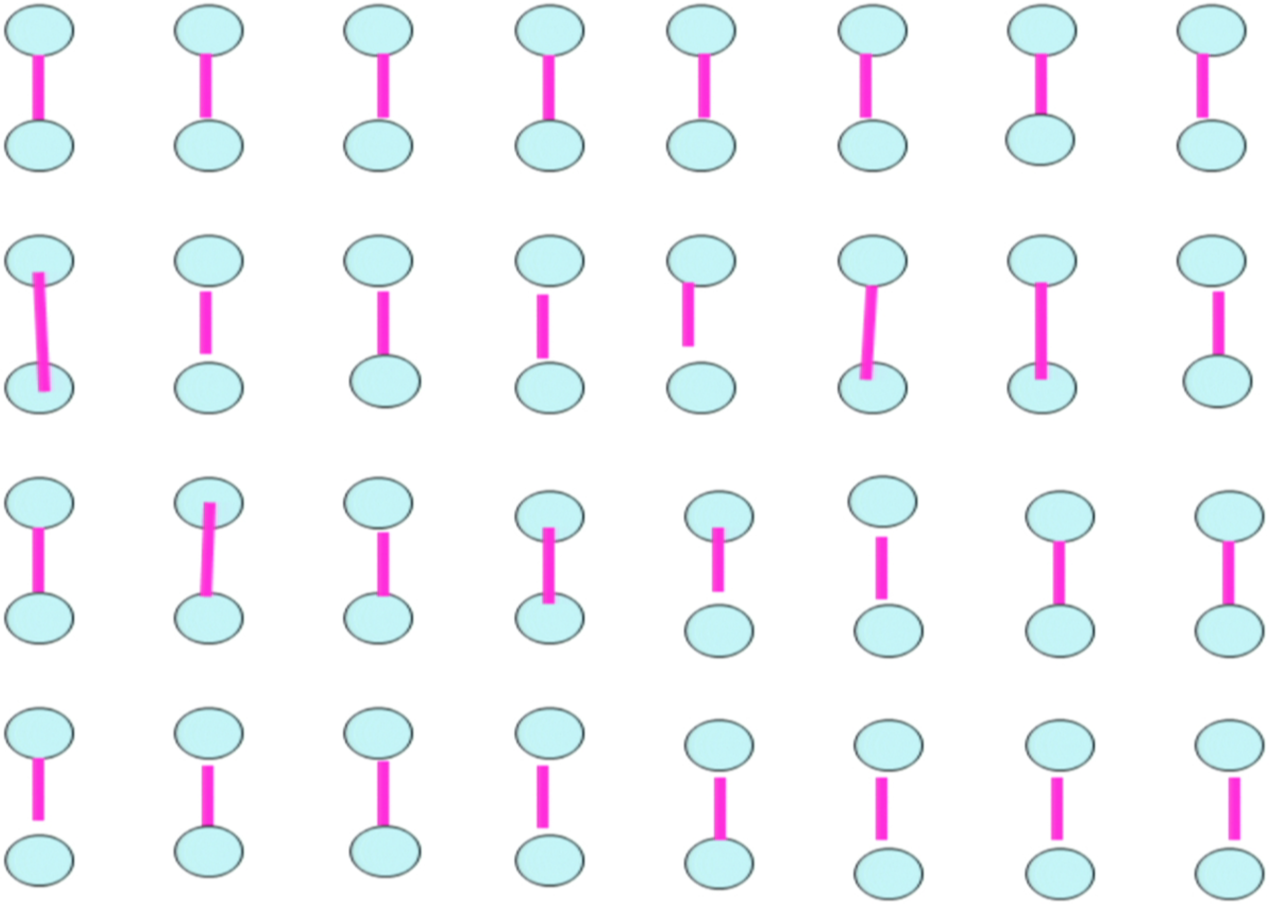


Theory of large U Hubbard model or tJ model

RVB mean field theory, Emergent fermions and superconductivity in undoped and doped Mott insulators (GB, Zou, PWA 1987)

Gauge theory and emergent gauge fields (GB, PWA 1988)

…….. Many significant developments since 1987

BCS vs RVB superconductor and Entanglement hierarchy
(GB, unpublished)

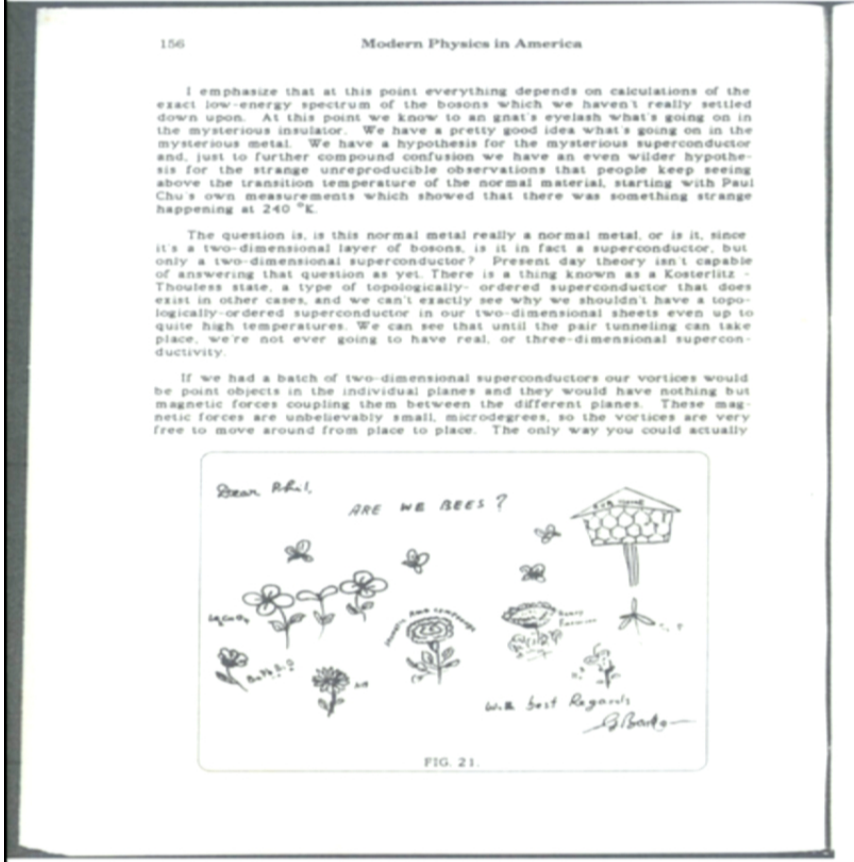
We want to create a
non Fermi liquid metallic state where
Real Space Pairing or singlet formation
is encouraged

However there are competing orders

Is there a clue from nature for another system ?

Yes !

P.W. Anderson,
in AIP Conference Proc. Vol. 169 (1988)



156 Modern Physics in America

I emphasize that at this point everything depends on calculations of the exact low-energy spectrum of the bosons which we haven't really settled down upon. At this point we know to an gnat's eyelash what's going on in the mysterious insulator. We have a pretty good idea what's going on in the mysterious metal. We have a hypothesis for the mysterious superconductor and, just to further compound confusion we have an even wilder hypothesis for the strange unreproducible observations that people keep seeing above the transition temperature of the normal material, starting with Paul Chu's own measurements which showed that there was something strange happening at 240 °K.

The question is, is this normal metal really a normal metal, or is it, since it's a two-dimensional layer of bosons, is it in fact a superconductor, but only a two-dimensional superconductor? Present day theory isn't capable of answering that question as yet. There is a thing known as a Kosterlitz - Thouless state, a type of topologically- ordered superconductor that does exist in other cases, and we can't exactly see why we shouldn't have a topologically-ordered superconductor in our two-dimensional sheets even up to quite high temperatures. We can see that until the pair tunneling can take place, we're not ever going to have real, or three-dimensional superconductivity.

If we had a batch of two-dimensional superconductors our vortices would be point objects in the individual planes and they would have nothing but magnetic forces coupling them between the different planes. These magnetic forces are unbelievably small, microdegrees, so the vortices are very free to move around from place to place. The only way you could actually

Dear Phil,

With best Regards

FIG. 21.

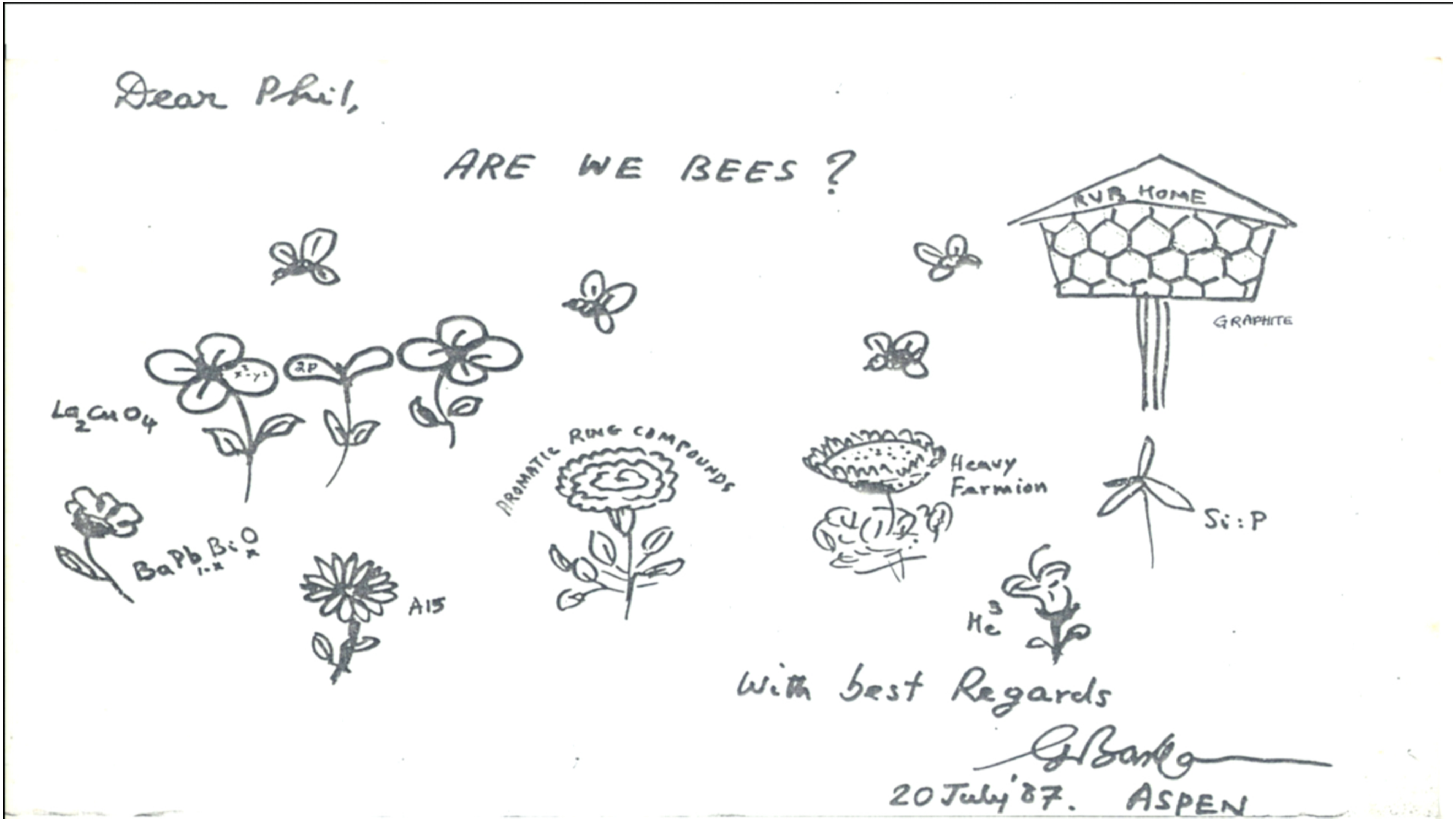
I close with a postcard (Fig.21)

……………………

…… from Aspen. ………

…………

RVB's become a question – and this is the answer. As far as we know, certainly there are B's, but maybe there are some other B's hanging around in a lot of other interesting places



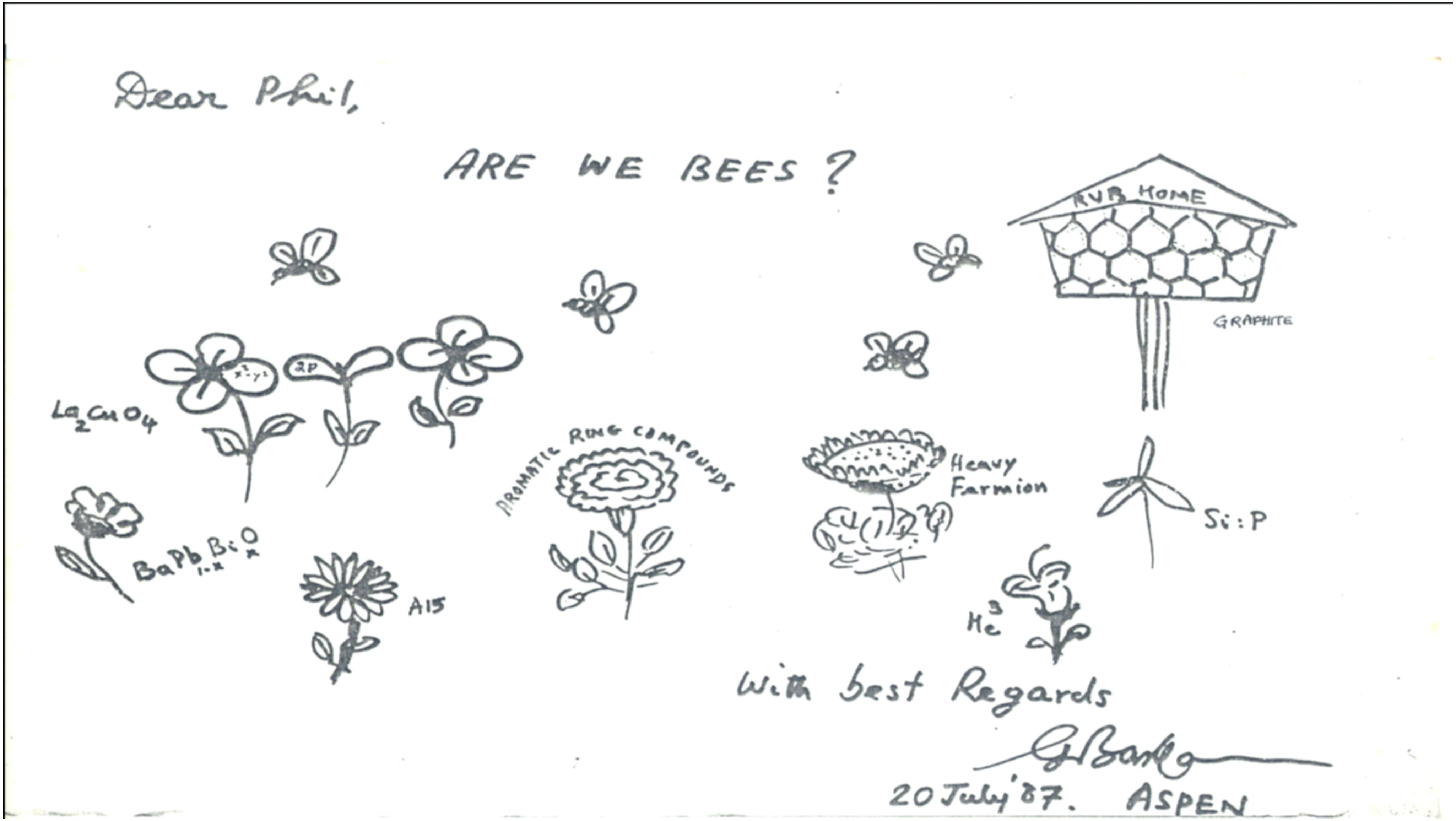
Dear Phil,

ARE WE BEES ?

With best Regards

G Baskaran

20 July '87. ASPEN



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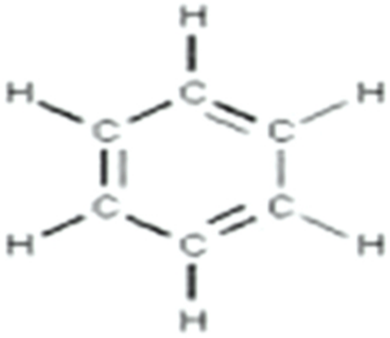
G Bask

20 July '87. ASPEN

Benzene



Resonating valence bond

Resonance of 2 electron bond of valence π electrons

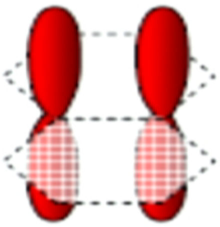
Pauling's Idea of Resonating Valence Bond

Dominance of neutral C^0 configurations and C=C covalent bonds

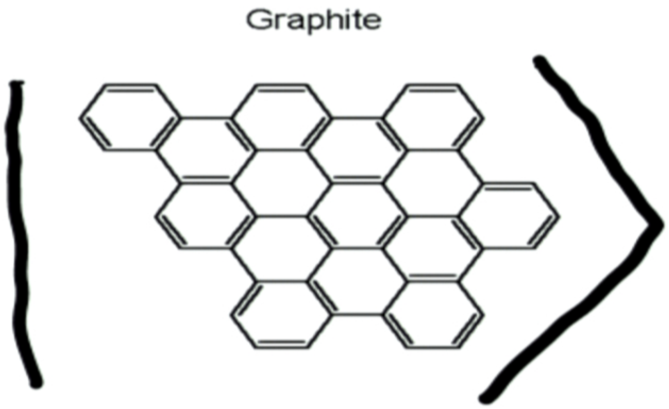
As a first approximation

Freely propagating polar (C^{1+}, C^{1-}) configurations are ignored

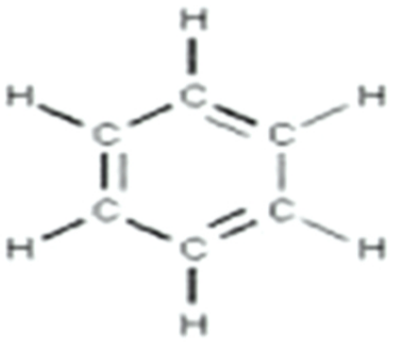
(there by approximating it as a Mott insulator !)

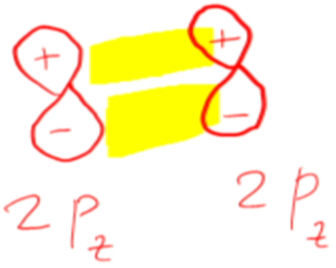


$$|RVB\rangle = \sum$$



Benzene





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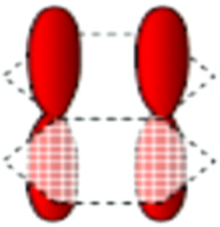

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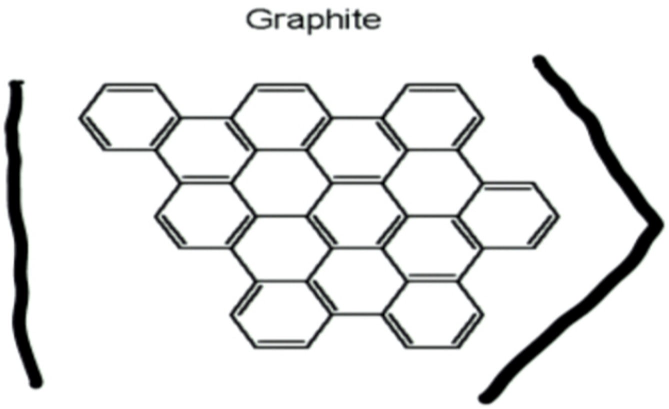
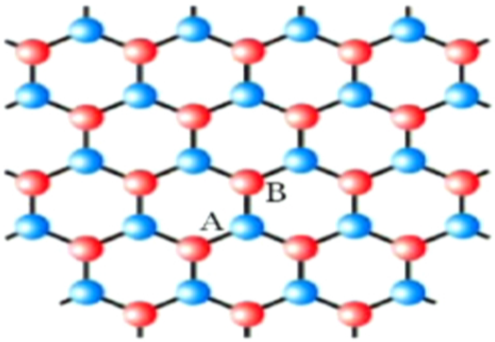
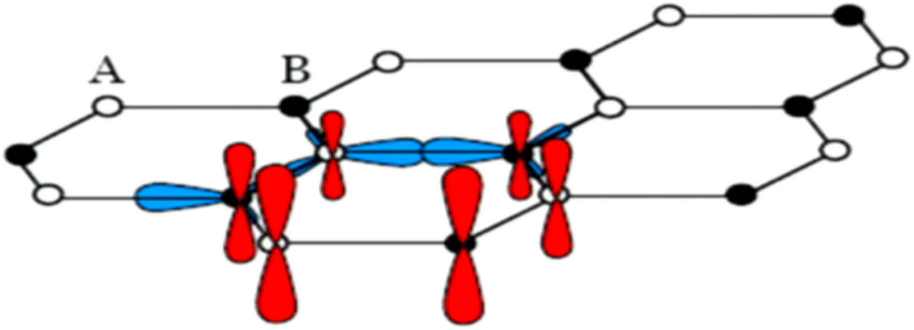
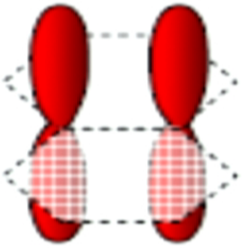




Graphene





- Carbon atom $1s^2 2s^2 2p^2$
- Three in-plan sp^2 covalent bonds with N.Ns
- **One electron per $2p_z$ orbital left for hopping**
- Tight-binding model:

$$H_t = -t \sum_{<i,i>\sigma} (c^+_{i\sigma} c_{j\sigma} + c^+_{j\sigma} c_{i\sigma})$$

Pauling's Idea of Resonating Valence Bond

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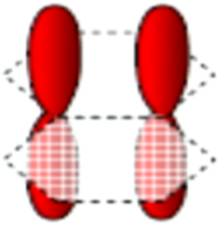

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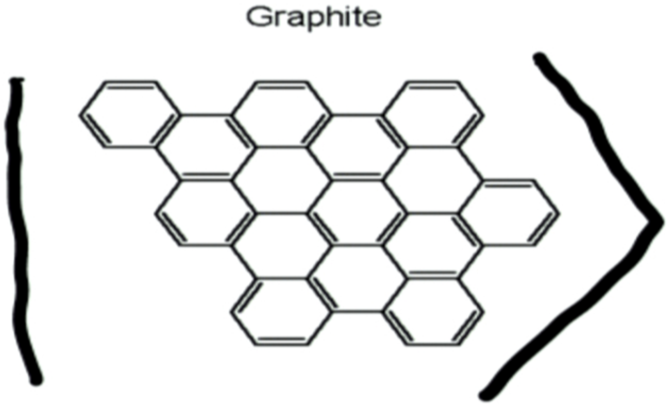

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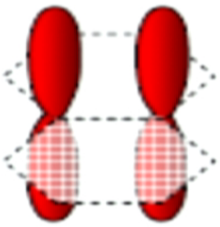

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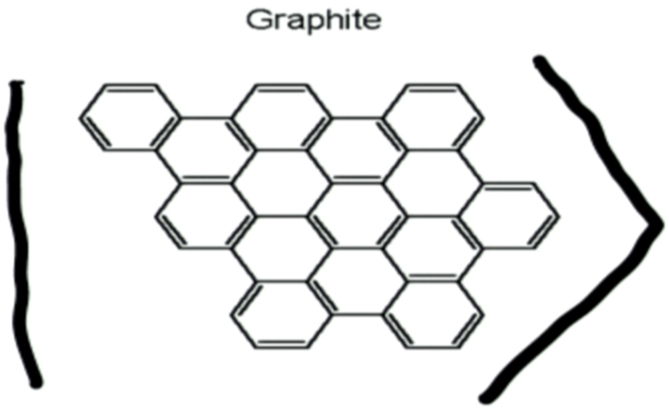

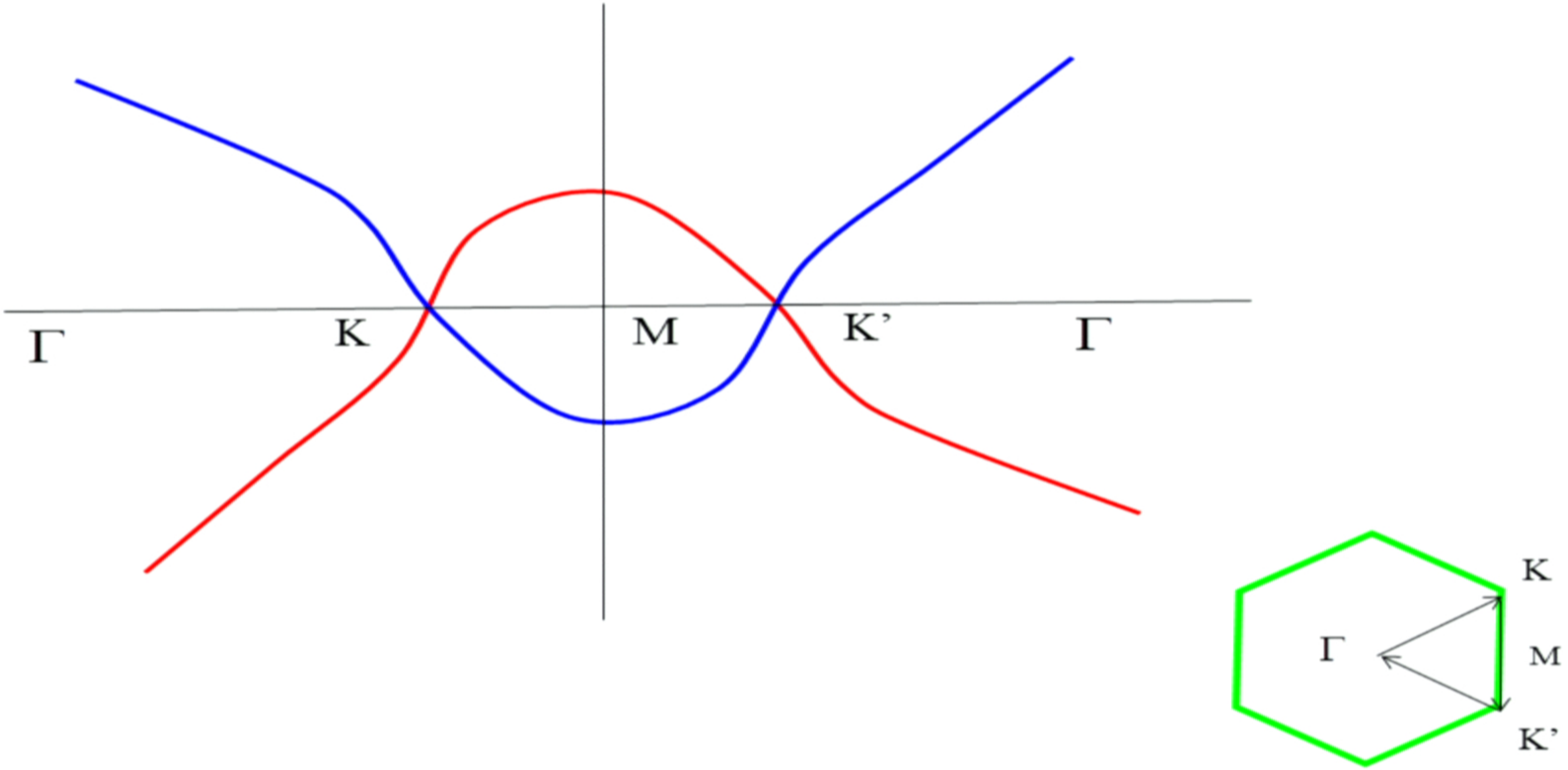
Γ
K
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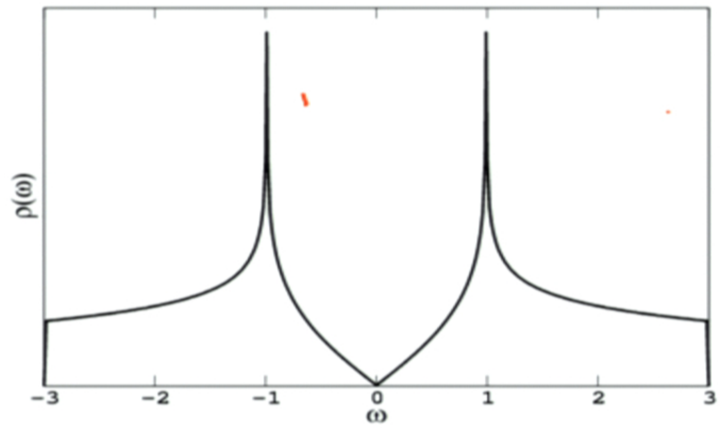
Will J produce Superconductivity in Neutral GRAPHENE ?

As $\rho(\epsilon_F) = 0$ for neutral graphene the available J is below the critical J_c to produce Superconductivity!

GB (2002)



Good!

Graphite & neutral graphene do not superconduct at low T

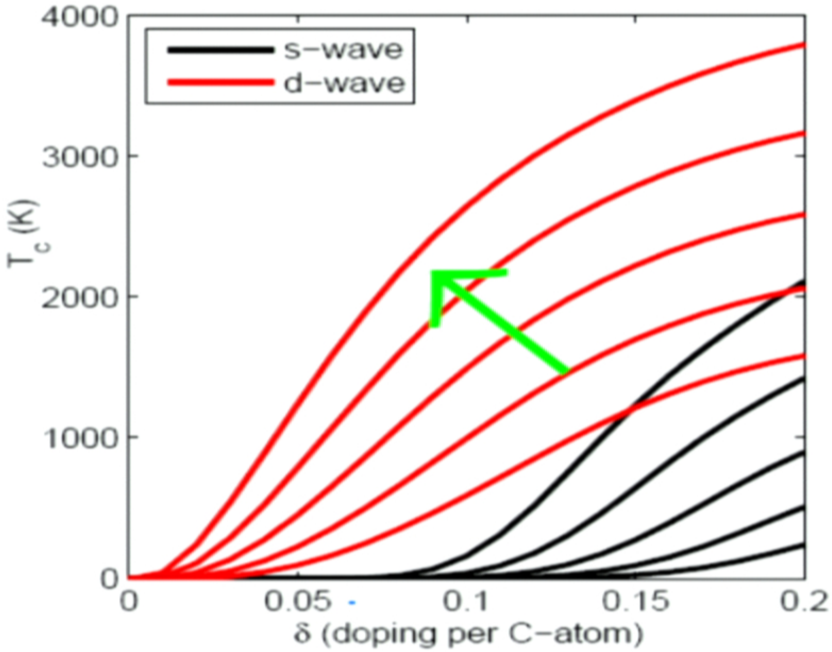
A.M. Black-Schafer and S. Doniach, Phys Rev B 2007

revived the GB (2002) work and performed a careful mean field theory and produced the following phase diagram.

They also found that

d + id order parameter has lower energy.

d + id



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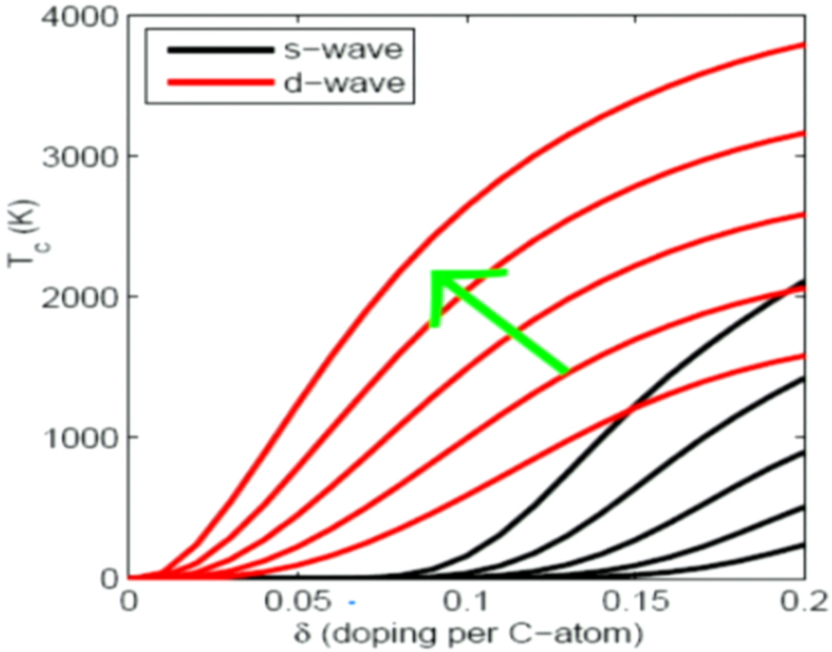
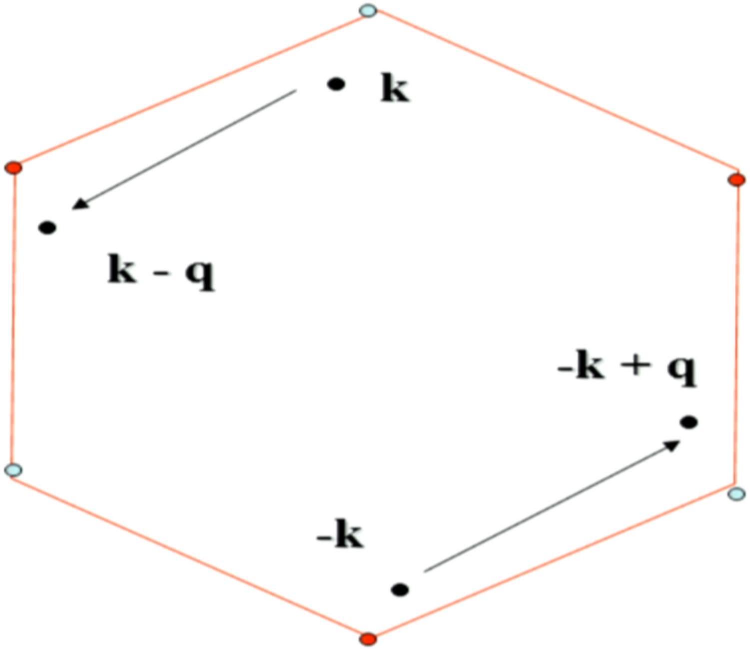
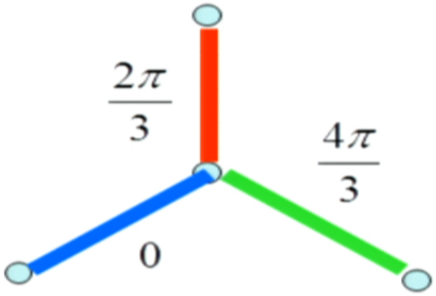


$$\Delta_\alpha = \Delta e^{i\frac{2\pi(\alpha-1)}{3}} \qquad \alpha = 1,2,3$$



Repulsive scattering

d + id



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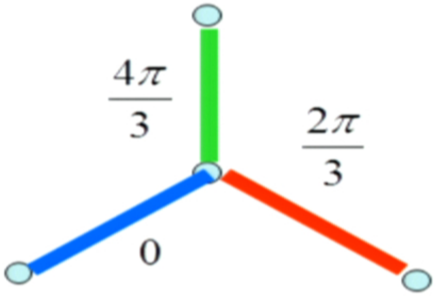

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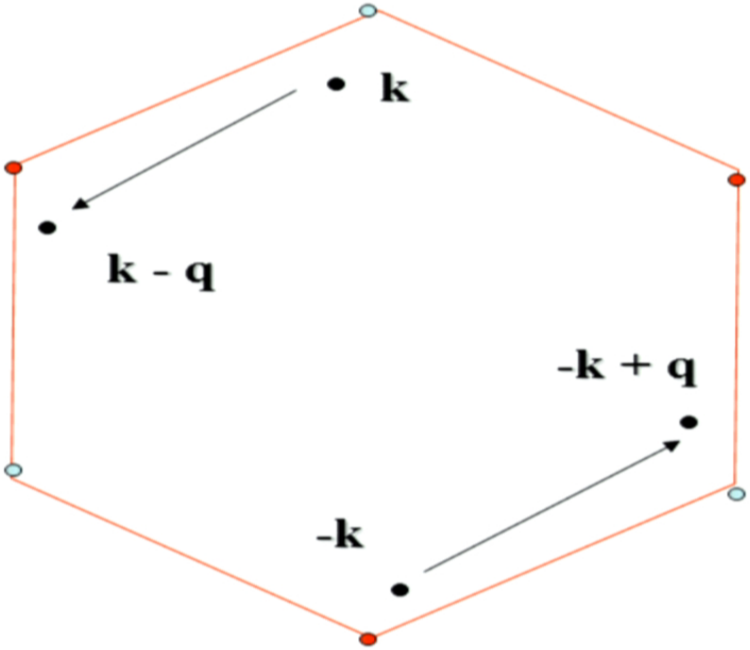

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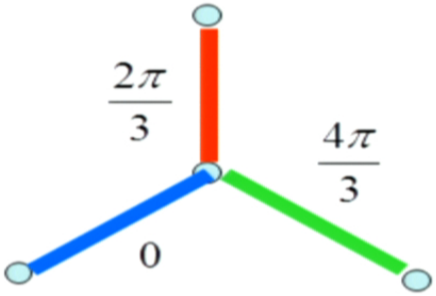

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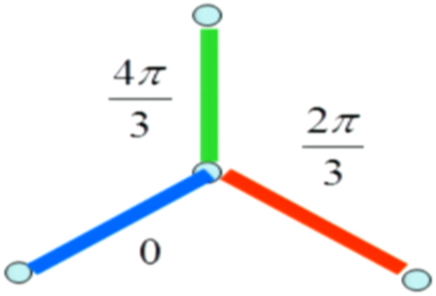


Instead of the model

$$H_{eff} = -t \sum_{<ij>\sigma} (c_{i\sigma}^{+} c_{j\sigma} + c_{j\sigma}^{+} c_{i\sigma}) \quad - J \sum_{\langle ij \rangle} b_{ij}^{+} b_{ij}$$

let us go to the more basic repulsive Hubbard model

$$H = -t \sum_{\langle ij \rangle} C_{i\sigma}^{\dagger} C_{j\sigma} + \mathrm{H.c.} + U \sum n_{i\uparrow} n_{i\downarrow}$$

$$|\Psi\rangle = g^{\mathcal{D}}|BCS\rangle_N$$

$$\mathcal{D} = \sum_i (n_i^a + n_i^b)$$

Two variational parameters: g and Δ

Variational Monte Carlo **13 x 13 sites** **(state of the art)**
(Pathak, Shenoy, GB)

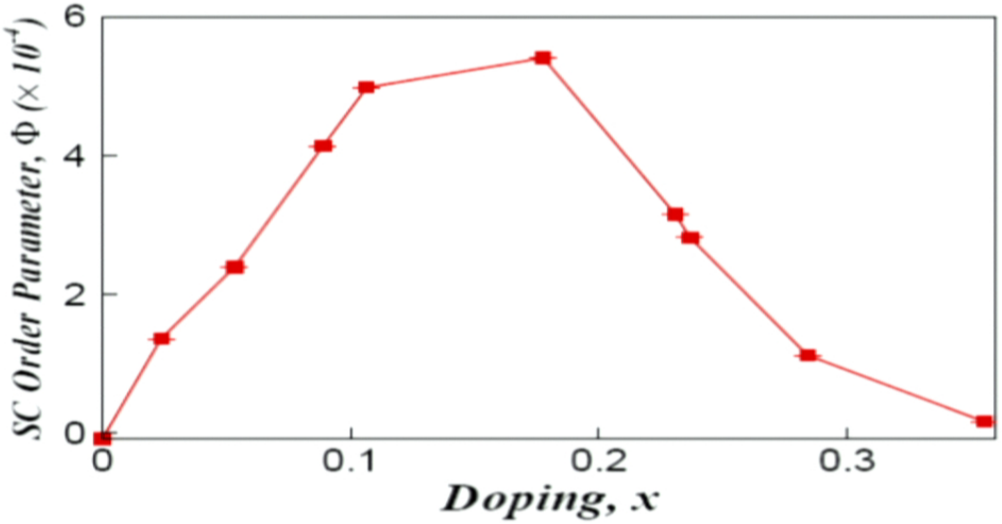
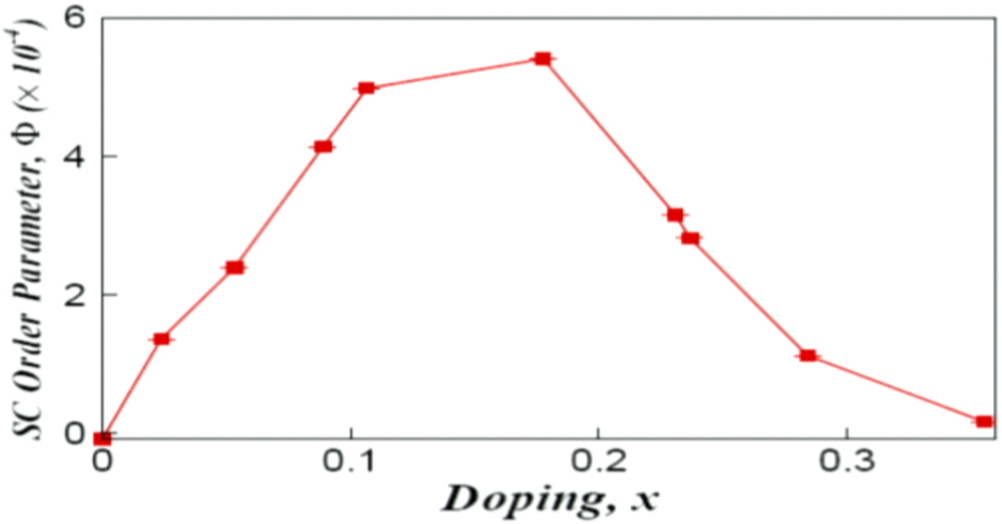


FIG. 1: Doping dependence of superconducting order parameter Φ as obtained from VMC calculation of the Hubbard model on a honeycomb lattice for $U/t = 2.4$.



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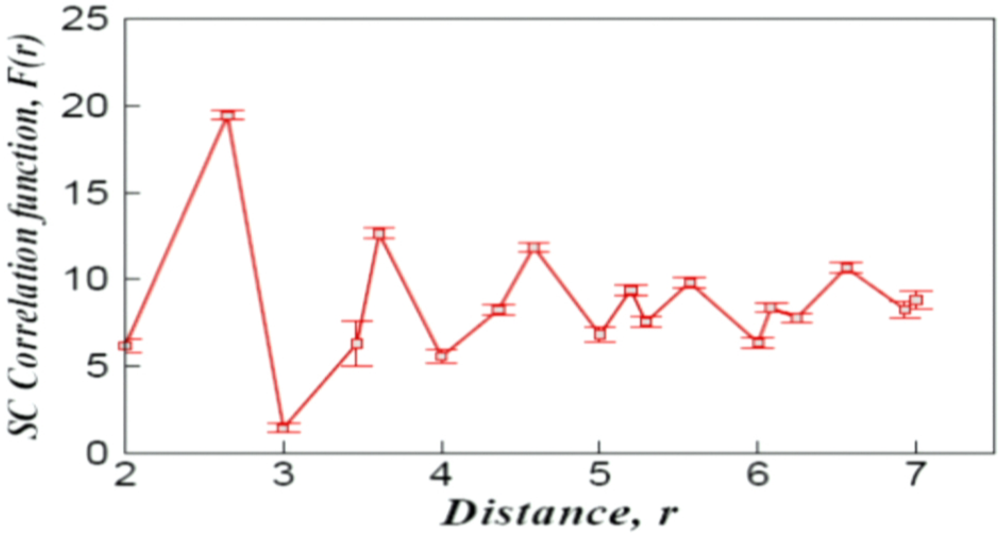

FIG. 2: Dependence of superconducting correlation function $F(r)$ on distance r as obtained from VMC calculation of the Hubbard model on a honeycomb lattice for $U/t = 2.4, x = 0.2$.

In graphene number of C atoms/cm^2 ~ 2 x 10^{15}

Currently available maximum doping ~ 10^{13}/cm^2

To see an appreciable Tc we need 3 to 5 % doping

We need to go to a charge transfer of
5 x 10^{13} to 10^{14} /cm^2

How to dope ?

Intercalation (makes the problem 3 dimensional ...)

Electrical gate doping

Electrochemical (solid electrolyte)

Spraying metal atoms (?)

2 dimensional carbon metals with finite density of states at the fermi level (Hoffmann ... , Cohen ... , Ajayan ...)

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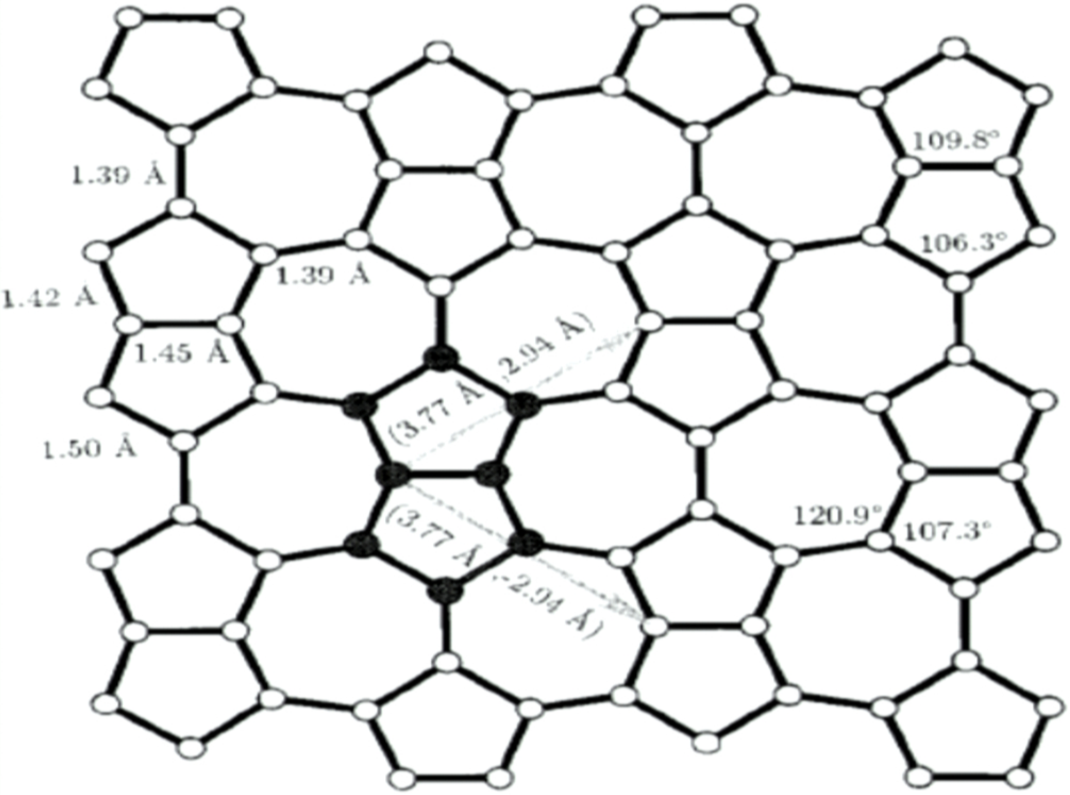
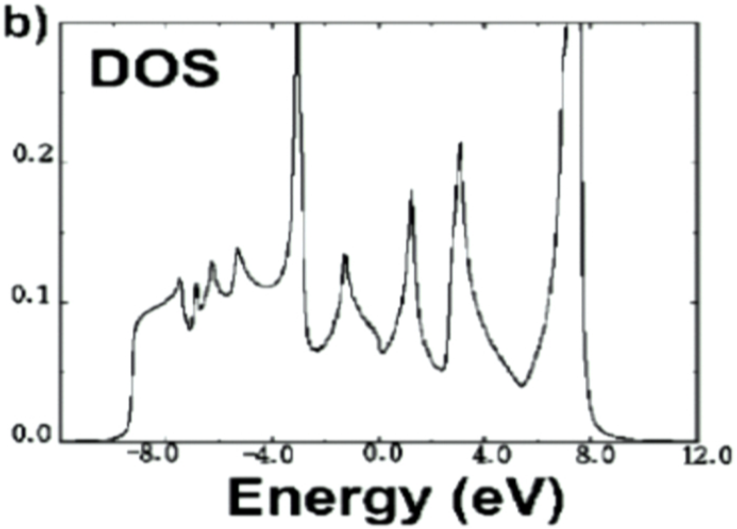
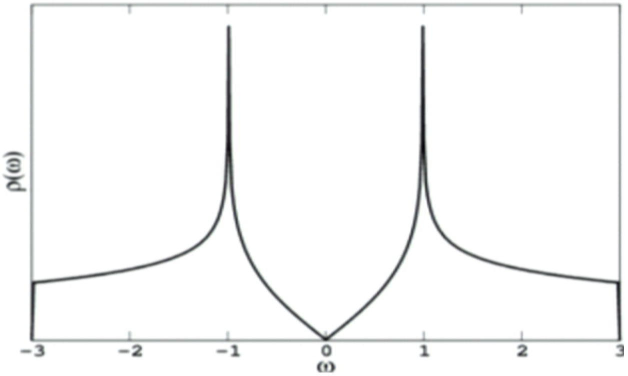
PHYSICAL REVIEW B VOLUME 53, NUMBER 20 15 MAY 1996-II

Prediction of a pure-carbon planar covalent metal

Vincent H. Crespi, Lorin X. Benedict, Marvin L. Cohen, and Steven G. Louie







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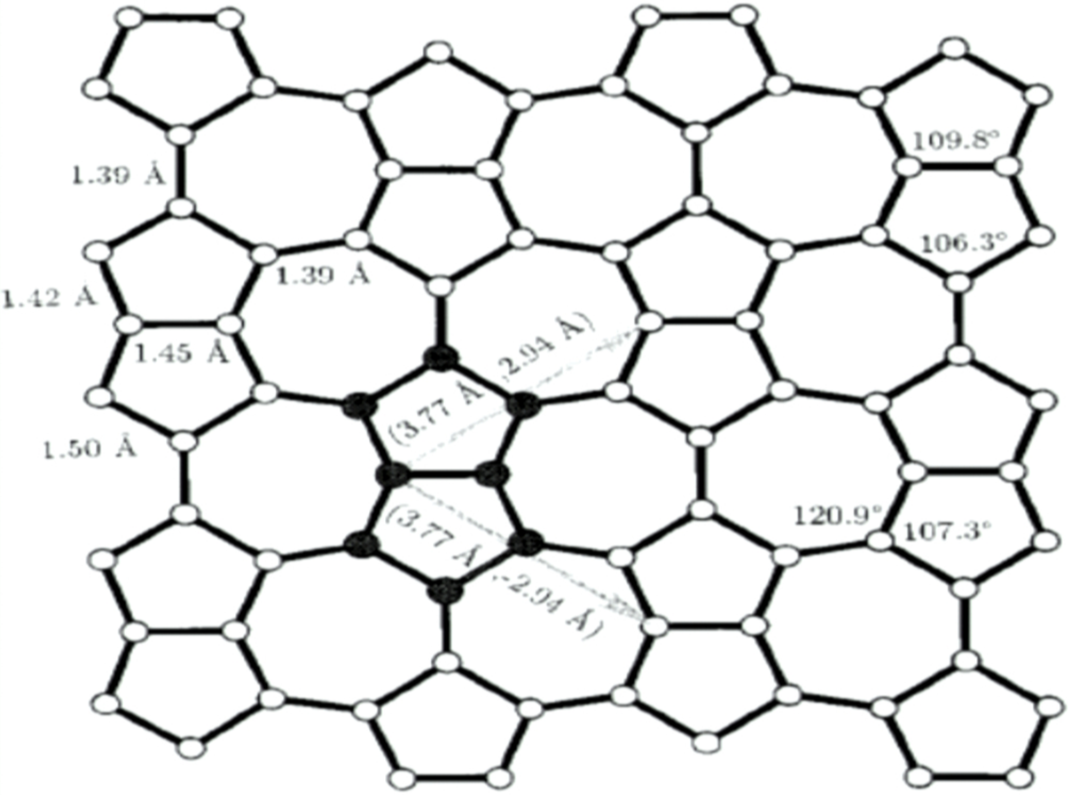

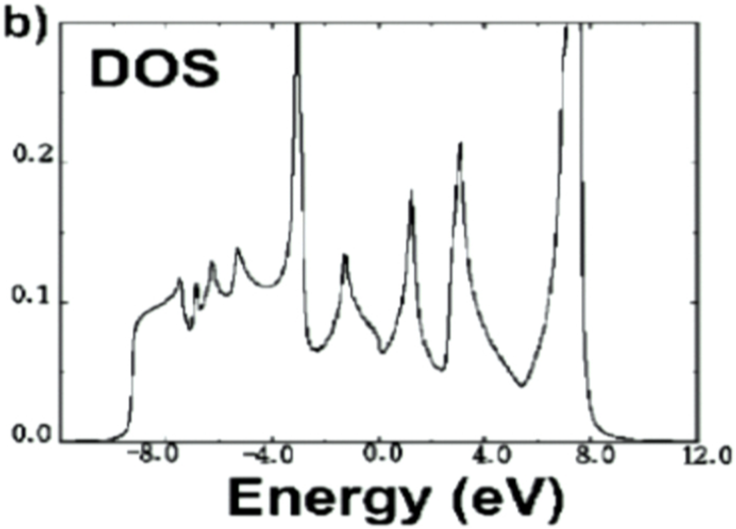

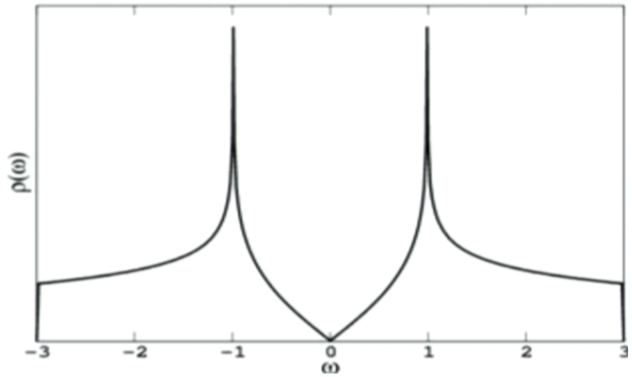

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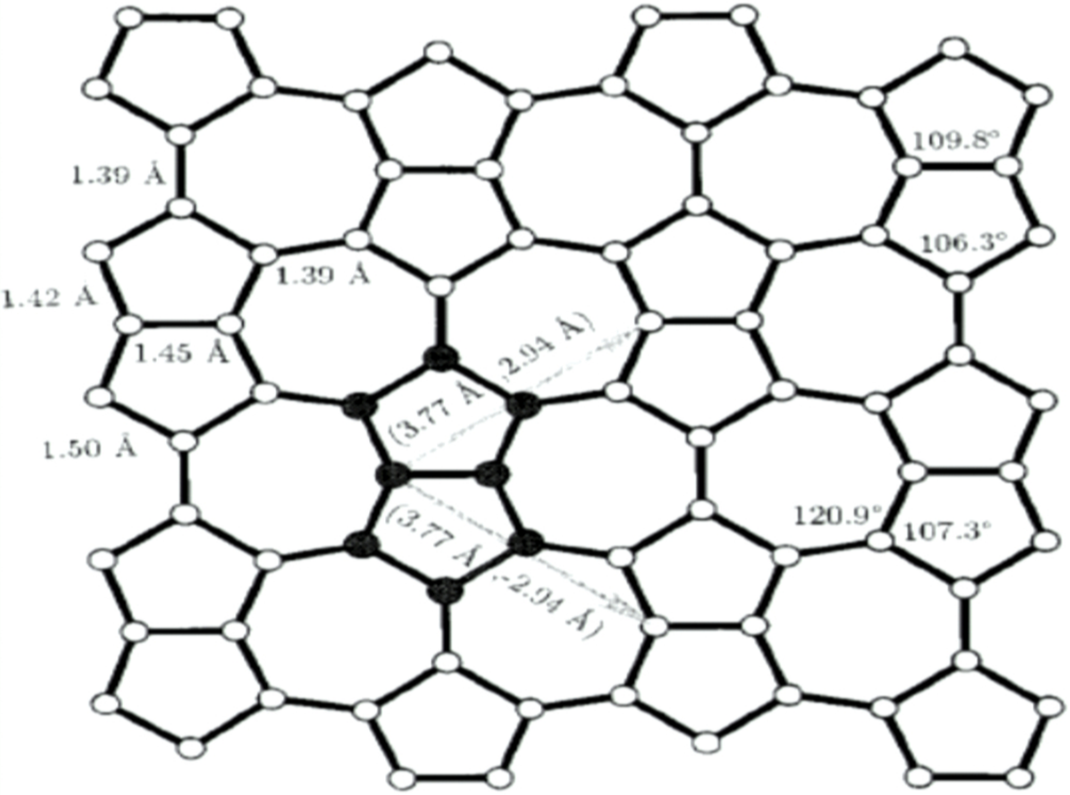

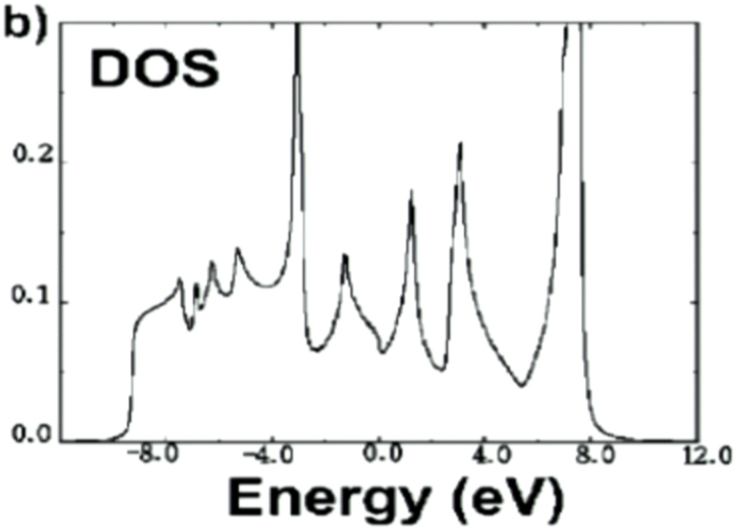

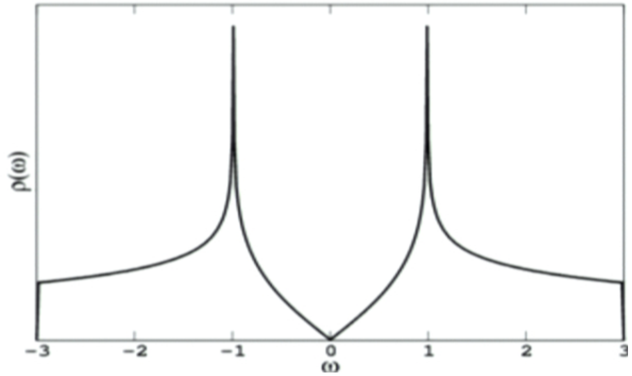

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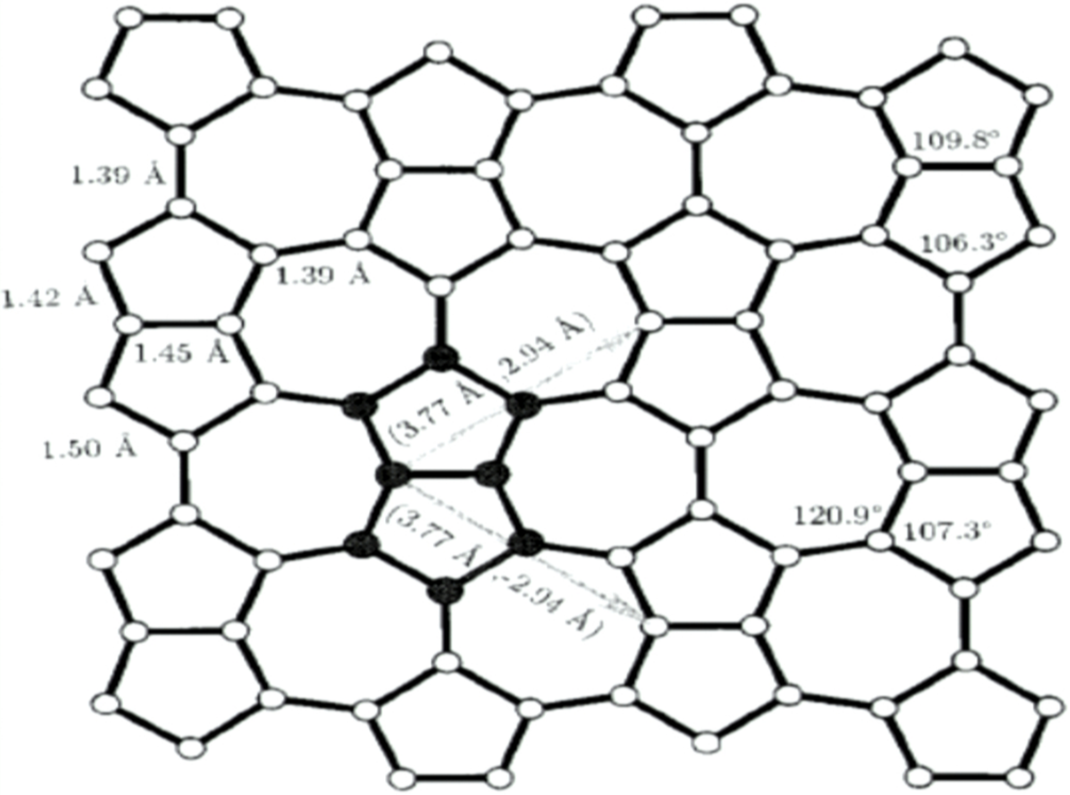

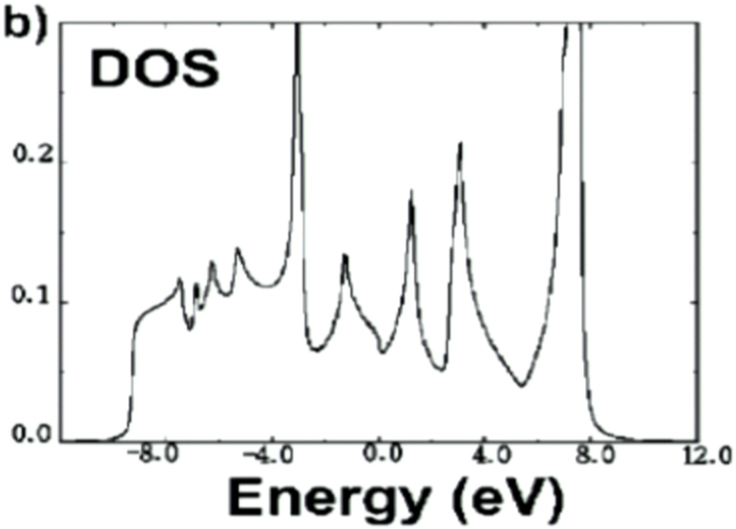

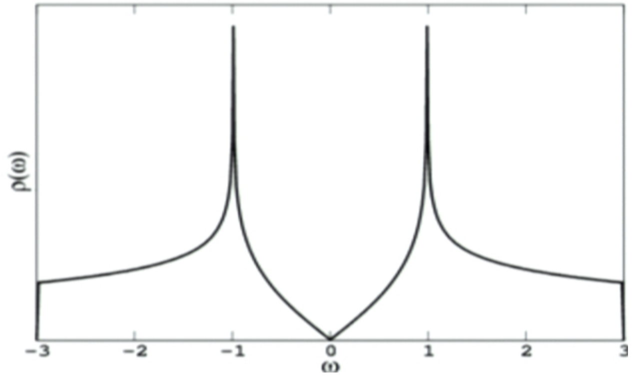

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Can doping graphite trigger room temperature superconductivity ?
Evidence for granular HTSC in water-treated graphite powder

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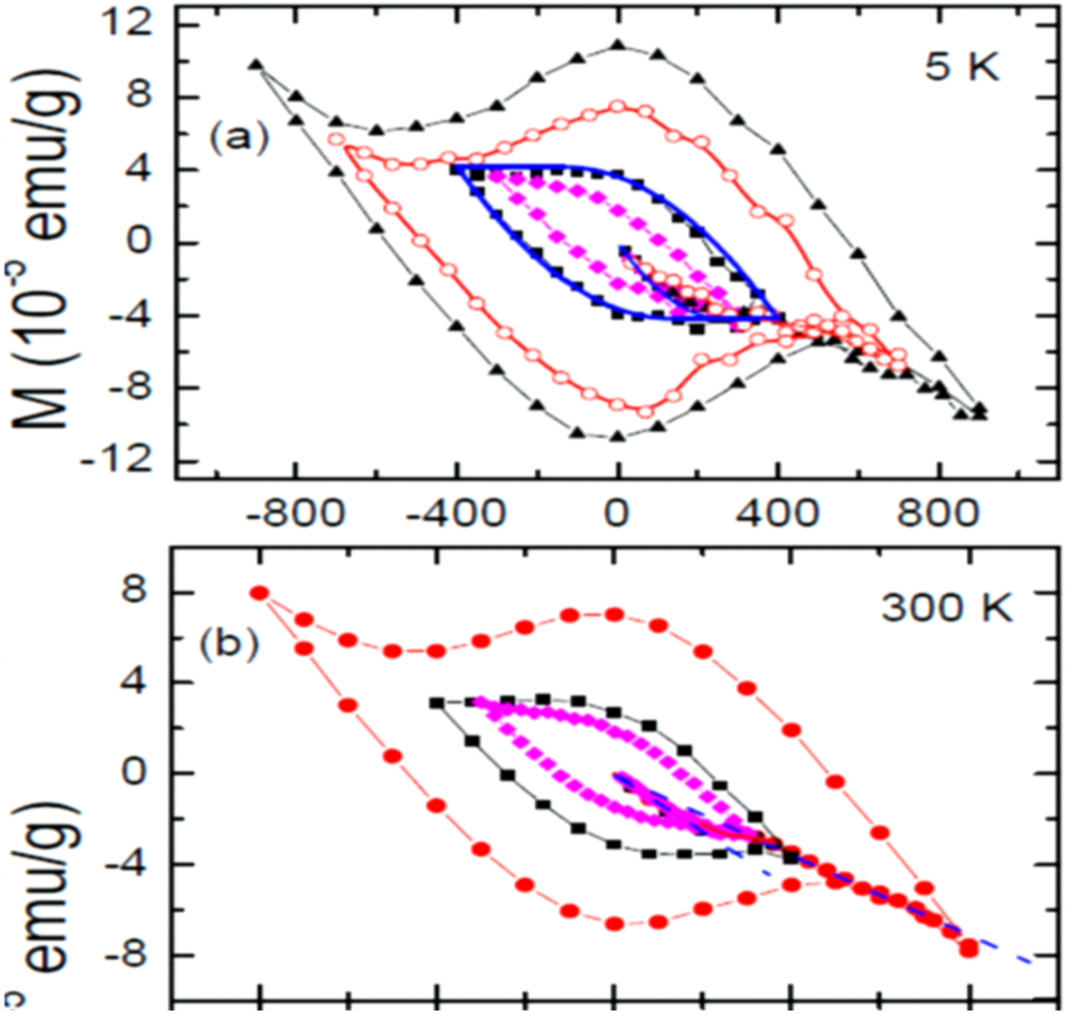
arXiv:1209.1938

http://onlinelibrary.wiley.com/doi/10.1002/adma.201202219/abstract



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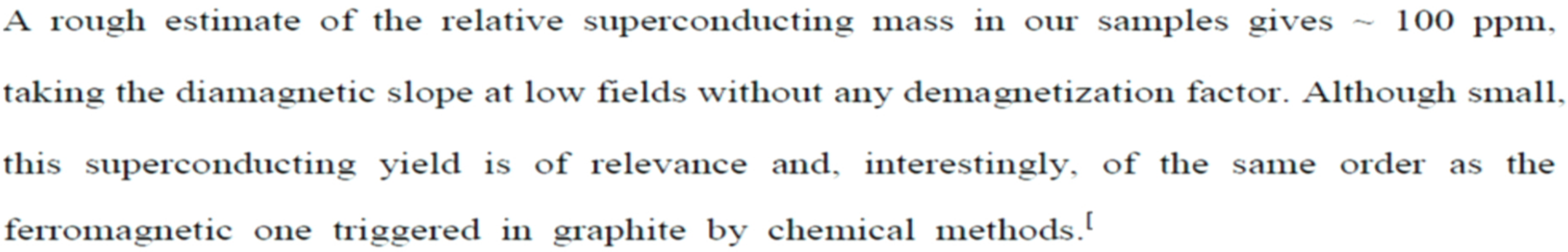

A rough estimate of the relative superconducting mass in our samples gives ~ 100 ppm, taking the diamagnetic slope at low fields without any demagnetization factor. Although small, this superconducting yield is of relevance and, interestingly, of the same order as the ferromagnetic one triggered in graphite by chemical methods.[

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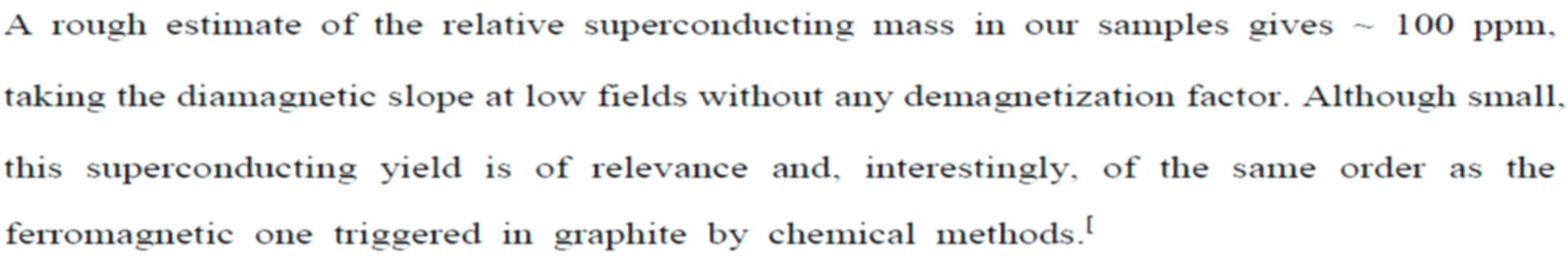

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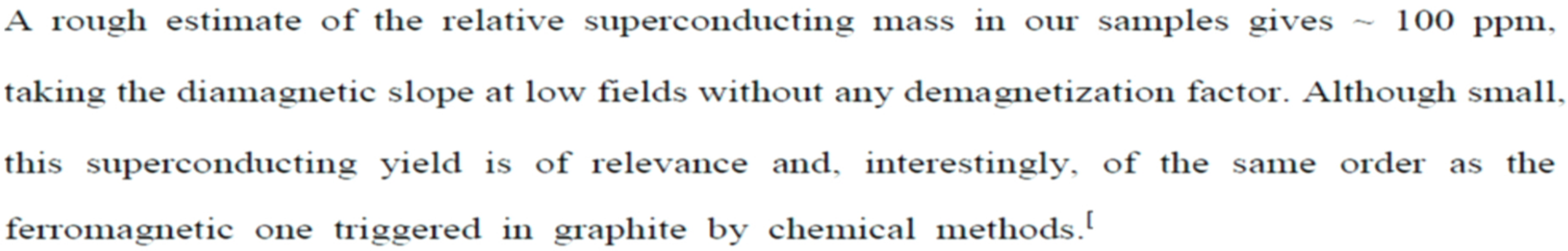

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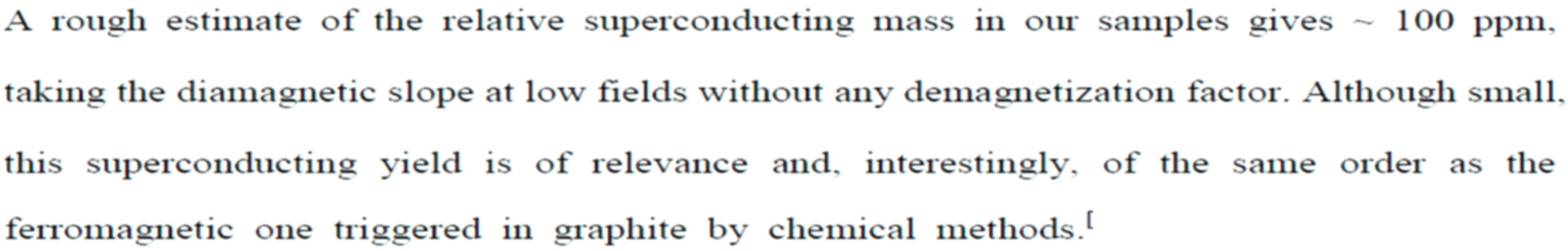

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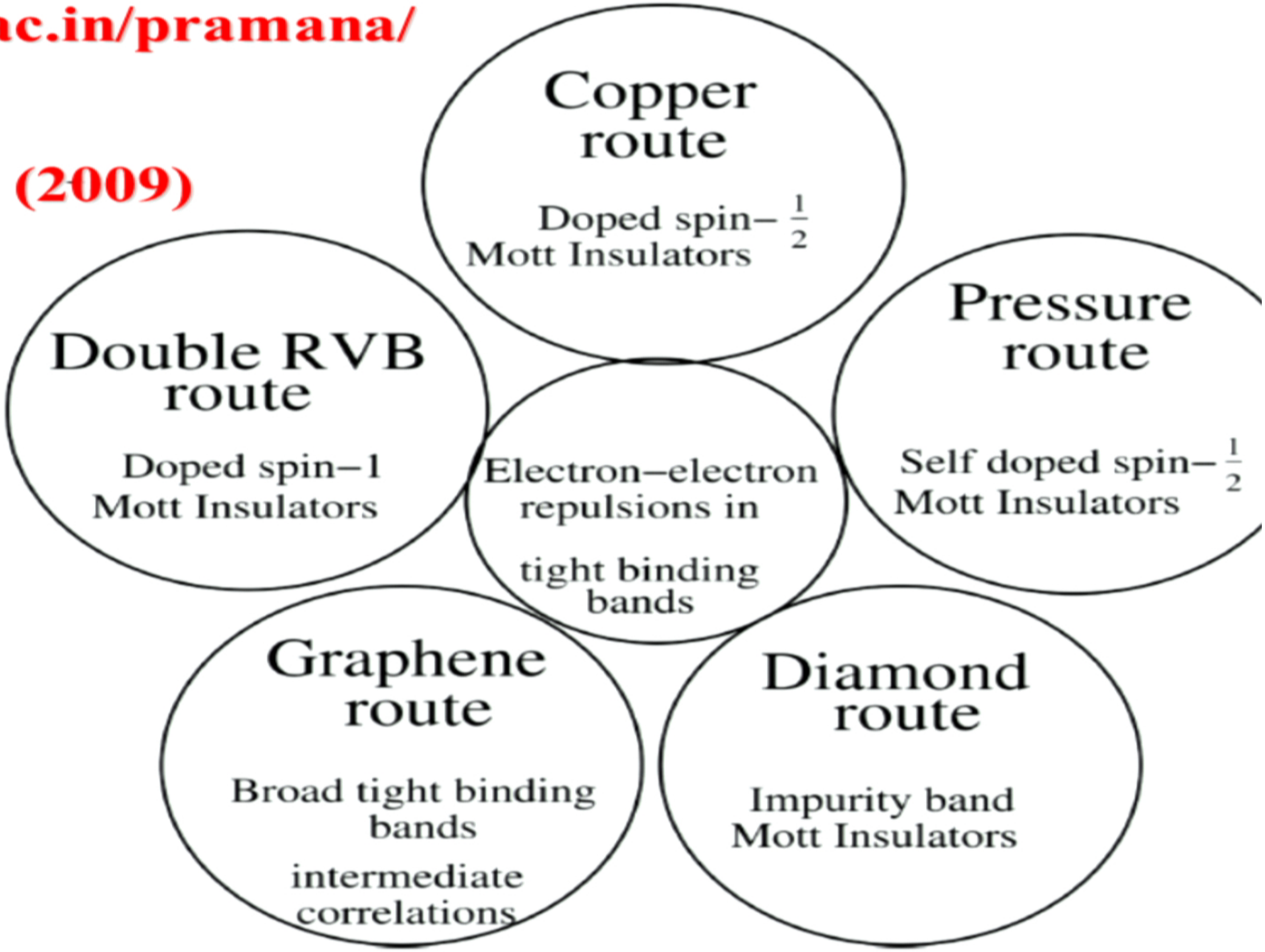
Sahara Desert
10.05.2006 03:58

http://www.ias.ac.in/pramana/

G Baskaran
Pramana 73, 61 (2009)



Copper route

Doped spin$-\frac{1}{2}$
Mott Insulators

Double RVB route

Doped spin-1
Mott Insulators

Pressure route

Self doped spin$-\frac{1}{2}$
Mott Insulators

Electron−electron
repulsions in

tight binding
bands

Graphene route

Broad tight binding
bands

intermediate
correlations

Diamond route

Impurity band
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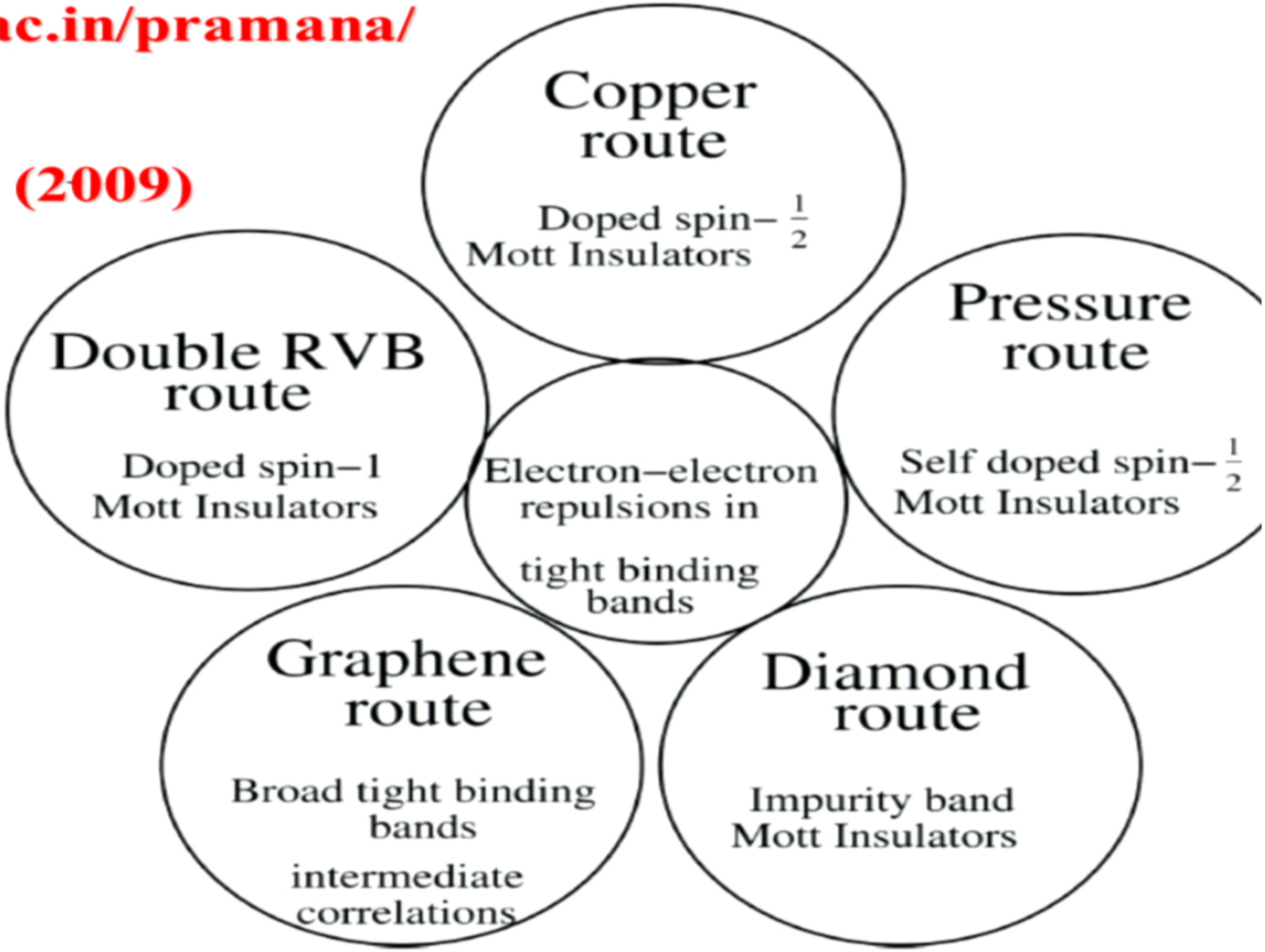

Copper route

Doped spin–$\frac{1}{2}$ Mott Insulators

Double RVB route

Doped spin–1 Mott Insulators

Electron–electron repulsions in tight binding bands

Pressure route

Self doped spin–$\frac{1}{2}$ Mott Insulators

Graphene route

Broad tight binding bands

intermediate correlations

Diamond route

Impurity band Mott Insulators