The Evolution of the Theory of Electron-Phonon Induced Pairing and its Limits for Superconducting Systems

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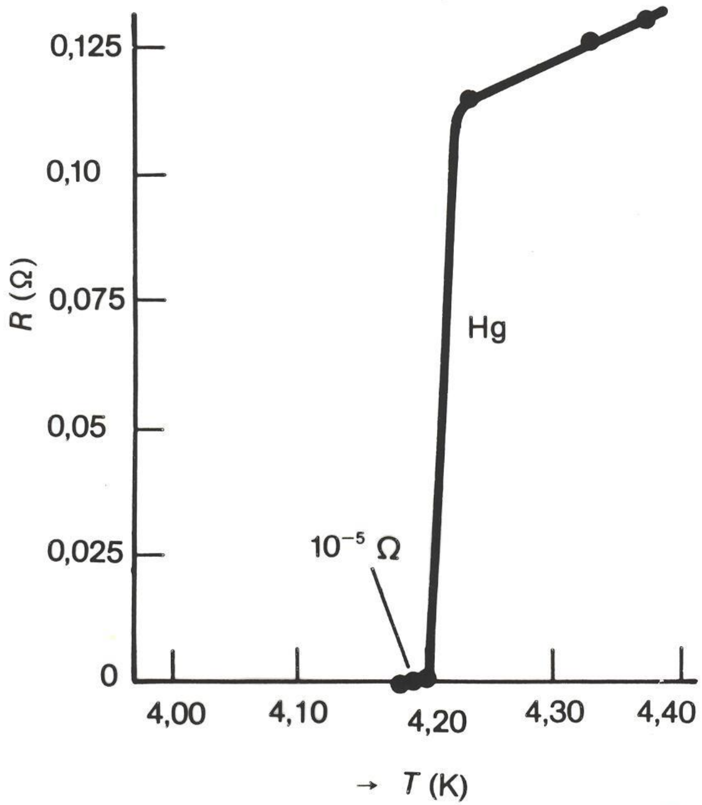
1911

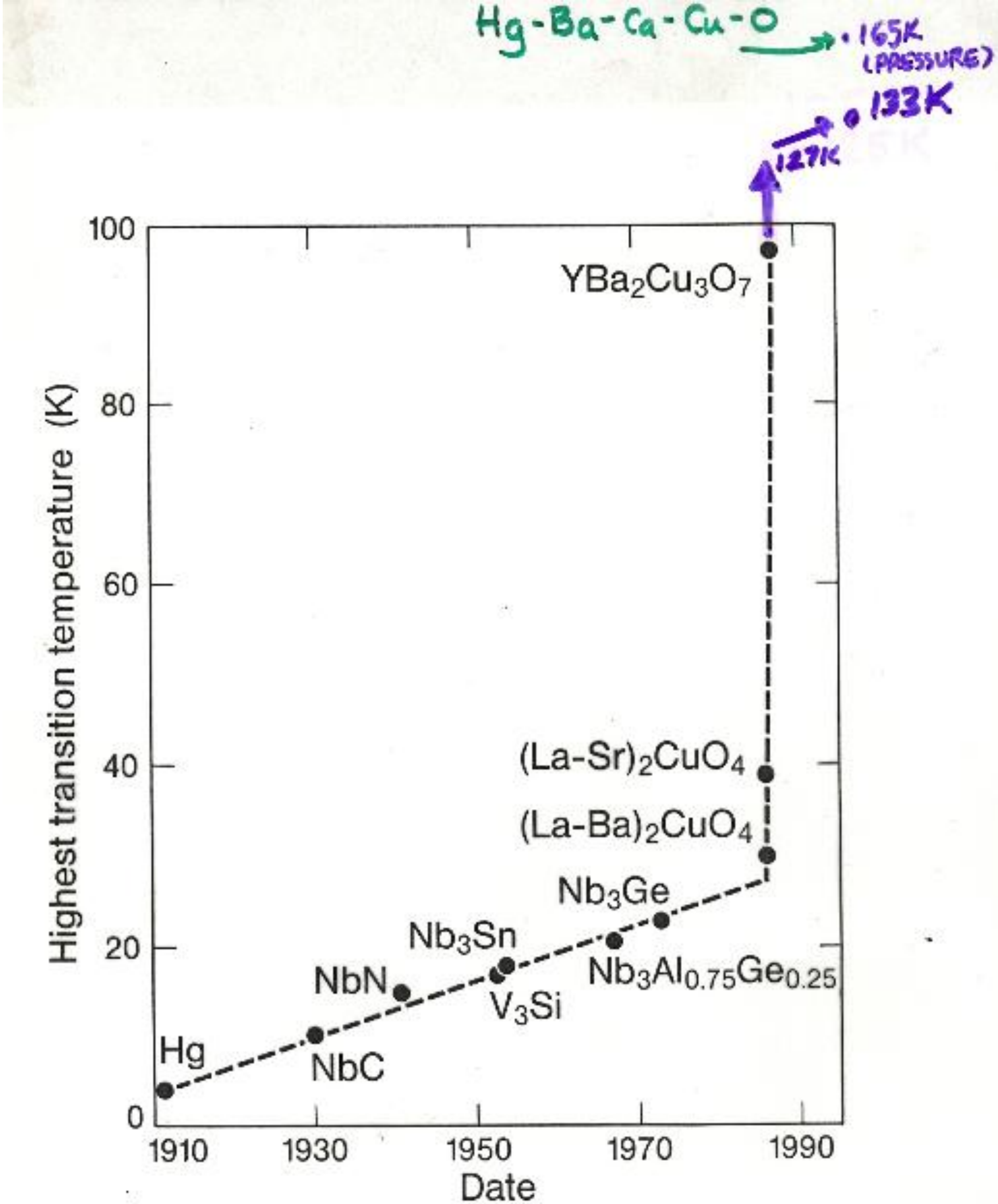
THE FIRST SUPERCONDUCTOR

RESISTANCE



TEMPERATURE

H. KAMERLINGH ONNES


Hg-Ba-Ca-Cu-O
165K (PRESSURE)
133K
127K
100
80
60
40
20
0
Highest transition temperature (K)
$YBa_2Cu_3O_7$
$(La\text{-}Sr)_2CuO_4$
$(La\text{-}Ba)_2CuO_4$
Nb_3Ge
Nb_3Sn
$Nb_3Al_{0.75}Ge_{0.25}$
NbN
V_3Si
Hg
NbC
1910
1930
1950
1970
1990
Date

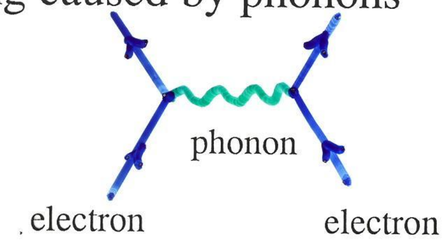
CLASSES OF SUPERCONDUCTORS

CLASS 1: conventional metals, C60, some organics, doped semiconductors, MgB2

CLASS 2: copper oxides, heavy fermion metals, some organics

BCS Theory (1957)

Overlapping pairs
Pairing caused by phonons



BCS Model (1957) $T_C = 1.13\ T_D\ e^{-1/NV}$

$$NV = \lambda - \mu > 0$$

↑ attractive phonon interaction

↑ repulsive Coulomb interaction

Improvements (1960's)

$$\lambda \rightarrow \lambda^* = \frac{\lambda}{1+\lambda} \qquad \mu \rightarrow \mu^* = \frac{\mu}{1 + \mu \ln \frac{E_F}{E_D}}$$

CAN BCS THEORY PREDICT T_c?

$$T_c \propto T_D \, e^{-\frac{1}{NV}} \sim 11K$$

$T_D \sim 300K$, $NV \sim 0.3$

IF "NV" $\rightarrow$ 0.03 $T_c \rightarrow 10^{-12}$

NEED TO KNOW "NV" VERY ACCURATELY

TO PREDICT T_c

DOPED SEMICONDUCTOR

$SrTiO_3$

FIRST SUPERCONDUCTING OXIDE

(COHEN 1963; SCHOOLEY ET AL 1964)

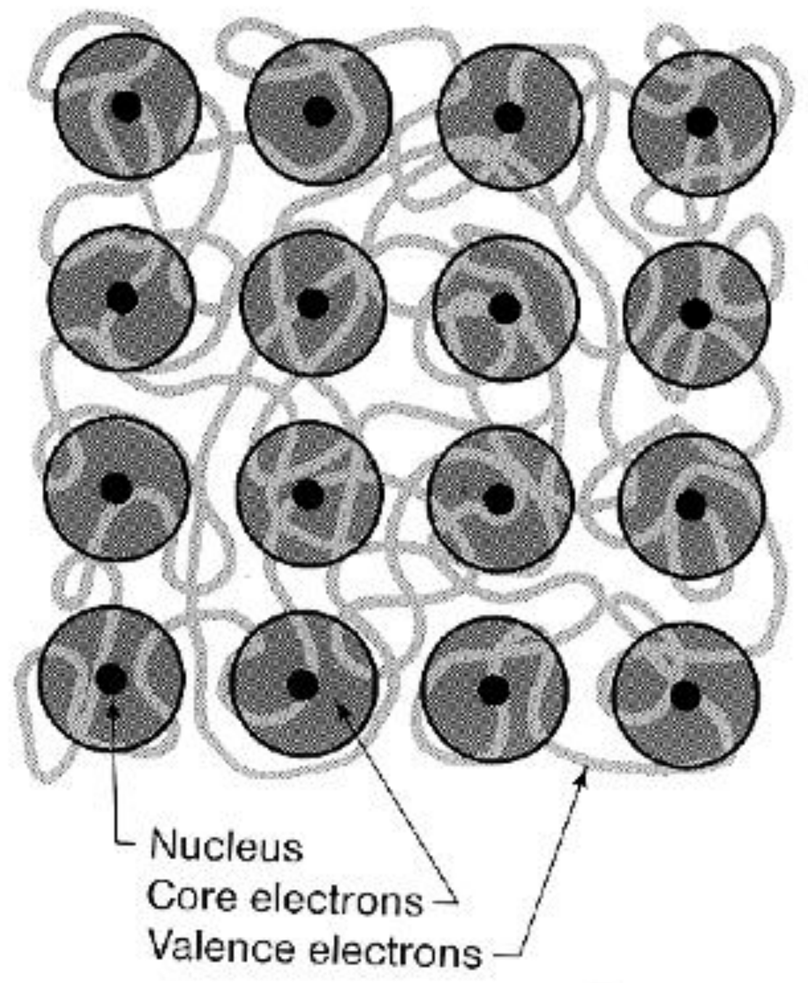
CONCEPTUAL BASIS

ONE CAN ARGUE FOR TWO MODELS OR “MENTAL PICTURES” OF A SOLID:

1. INTERACTING ATOMS MODEL (REDUCTIONISM)
2. ELEMENTARY EXCITATIONS MODEL (EMERGENCE)

Standard Model

Plane Wave Pseudopotential Method [PWPM]

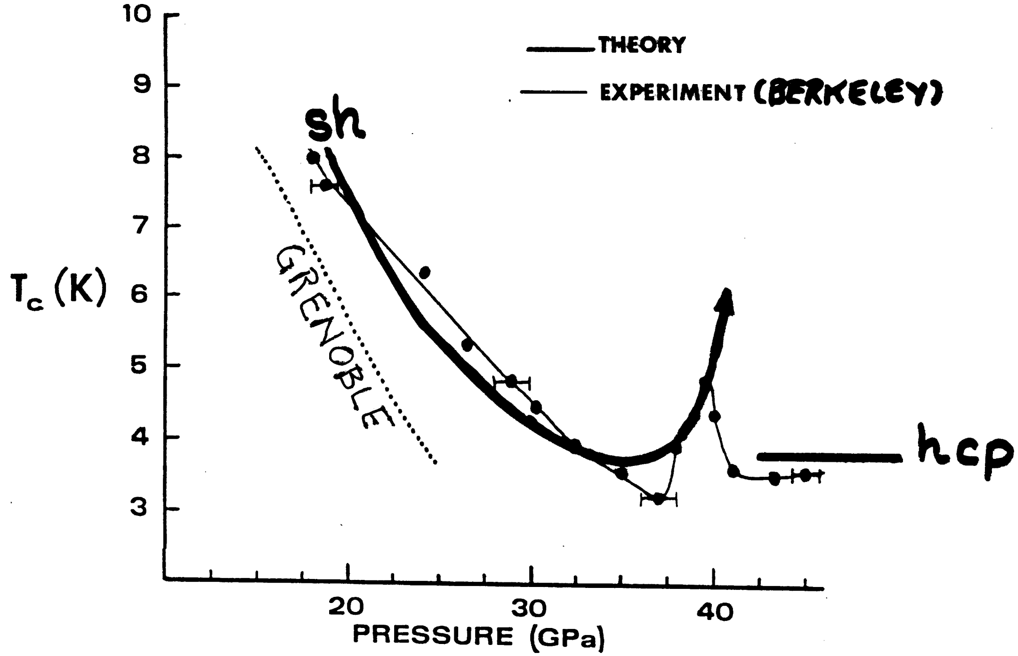


Plane Wave Pseudopotential Method
(Standard Model of Solids)

For a broad class of solids, clusters, and molecules, this method describes ground-state and excited-state properties such as:

- electronic structure
- crystal structure and structural transitions
- structural and mechanical properties
- vibrational properties
- electron-lattice interactions
- superconductivity
- optical properties
- photoemission properties

sh and hcp SILICON T_c (PRESSURE)



THEORY

CHANG, DACOROGNA & COHEN

EXP.

GRENOBLE : MIGNOT, CHOUTEAU & MARTINEZ

BERKELEY : ERSKINE & YU

Calculational Methods

Atomic numbers of Mg and B

⇓

Ab initio pseudopotentials for Mg and B

⇓

Density functional theory
(electronic structures of MgB_2)

⇓

Frozen-phonon method ⇐ Atomic masses of Mg and B
(phonon structure)

⇓

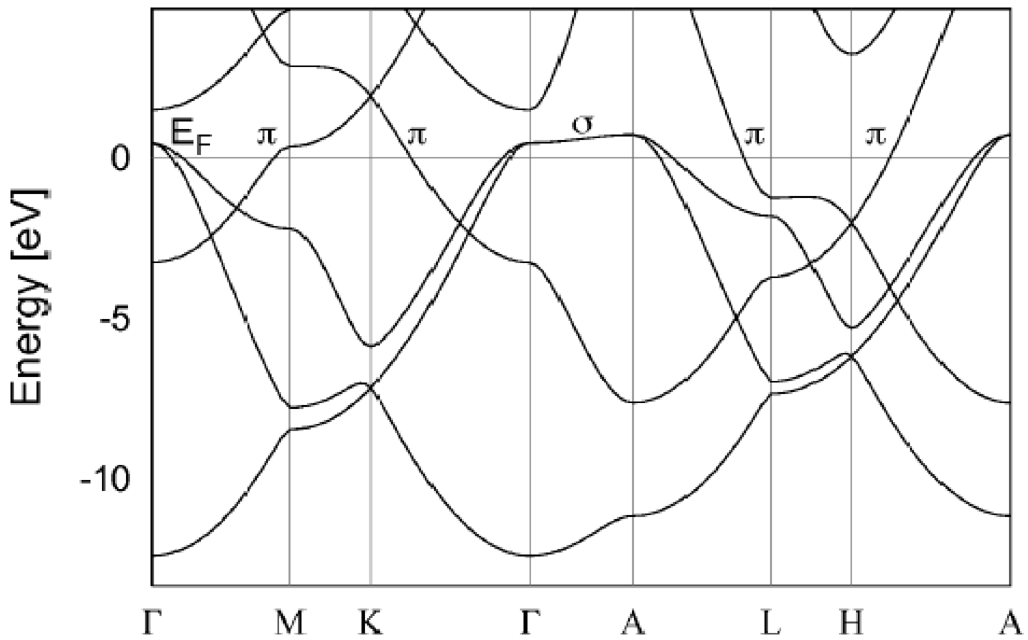
Electron-phonon interactions
(normal-state specific heat)

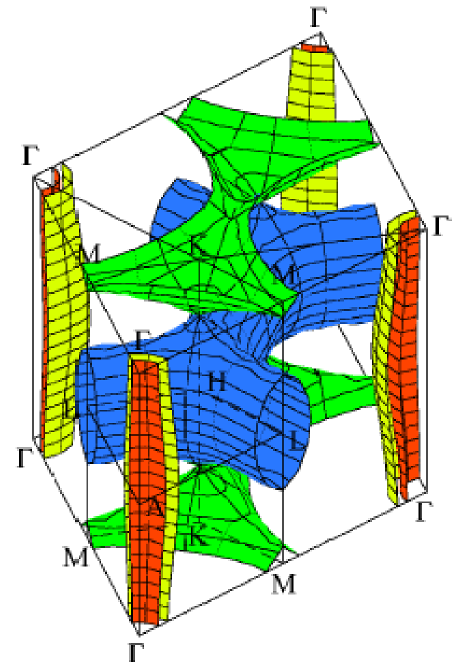
⇓

Eliashberg formalism ⇐ μ^*
(T_c, isotope effect, superconducting gap, specific heat)

Pristine MgB_2: Electronic structures and Fermi surface

- Band structure



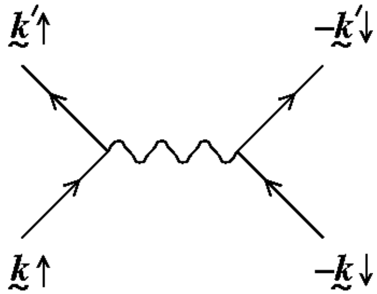


- Fermi surface consists of four sheets:
  two from σ-bonding boron $p_{x,y}$ orbitals
  and two from π-bonding boron p_z orbitals.

Also: An & Pickett, PRL 2001; Kortus, et al, PRL 2001; Liu, et al, PRL 2001
Kong, et al, PRB 2001; ···

Superconductivity in the Eliashberg Formalism

BCS Theory



Electron pairing via phonon exchange

Main ingredient: momentum- and frequency-dependent Eliashberg function

$$\alpha^2 F(\vec{k},\vec{k}',\omega) \equiv N(\varepsilon_F) \sum_j \left| g^j_{\vec{k}\vec{k}'} \right|^2 \delta(\omega - \omega_{j\vec{q}})$$

where $N(\varepsilon_F)$ = density of states per spin at Fermi level

$g_{kk'}$ = electron-phonon matrix element

ω_{jq} = frequency of phonon in jth branch

with q=k'-k

Equivalently:

$$\lambda(\vec{k},\vec{k}',n) \equiv \int_0^\infty d\omega \alpha^2 F(\vec{k},\vec{k}',\omega) \frac{2\omega}{\omega^2 + (2n\pi T)^2}$$

$\lambda = \langle \lambda(k, k', 0) \rangle$

Transition Temperature and Isotope Effect

	harmonic		anharmonic		experiment
	isotropic	anisotropic	isotropic	anisotropic	
T_c	28 K	55 K	19 K	39 K	39 K
α_B	0.42	0.46	0.25	0.32	0.26,0.30
α_{Mg}	0.04	0.02	0.05	0.03	0.02
λ	0.73		0.61		0.58, 0.62
ω_{ph}	62.7 meV		75.9 meV		75.9, 76.9

$\mu^*(\omega_c) = 0.12.$

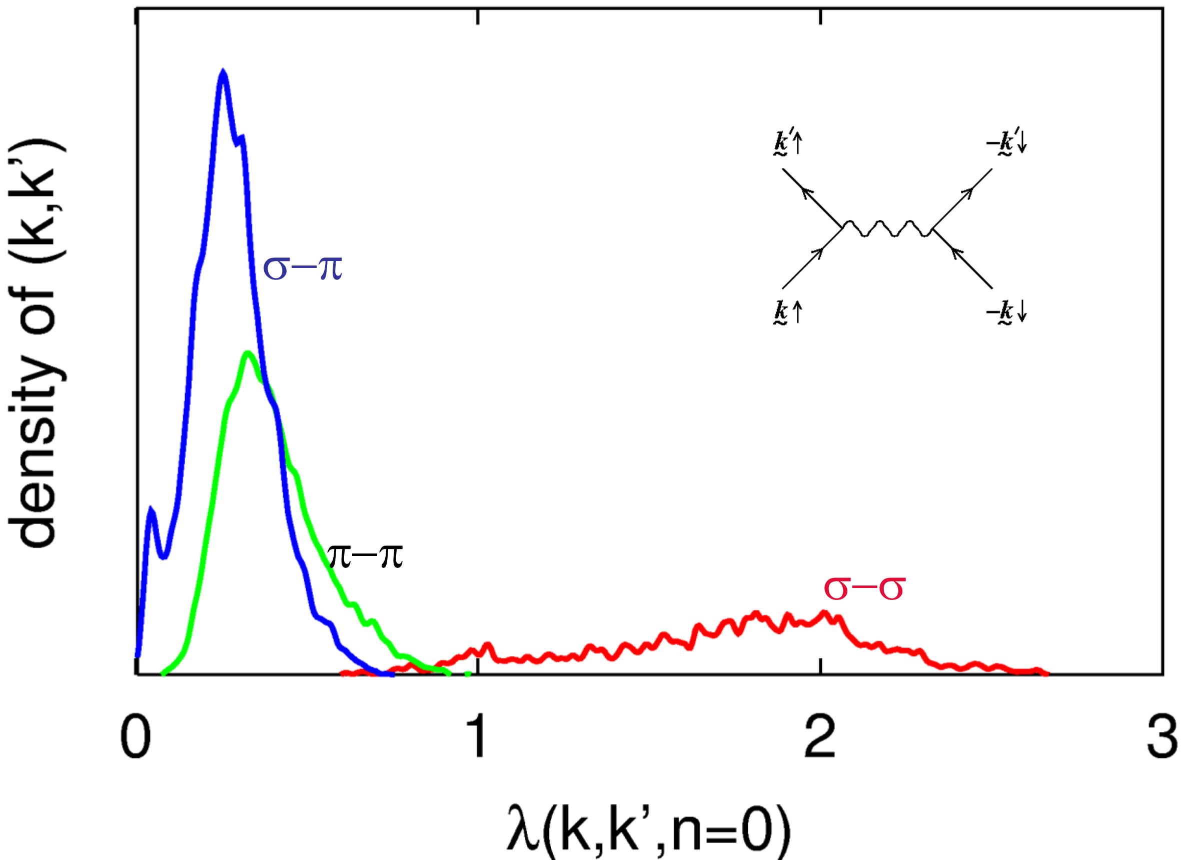
Anharmonicity --> smal

λ : averaged electron-phonon coupling.

ω_{ph} : frequency of the in-plane B–B stretching modes (E_{2g}) at Γ.

For $0.10 \leq \mu^*(\omega_c) \leq 0.14$, 41 K $\geq T_c \geq$ 37K

Distribution of Electron-Phonon Couplings

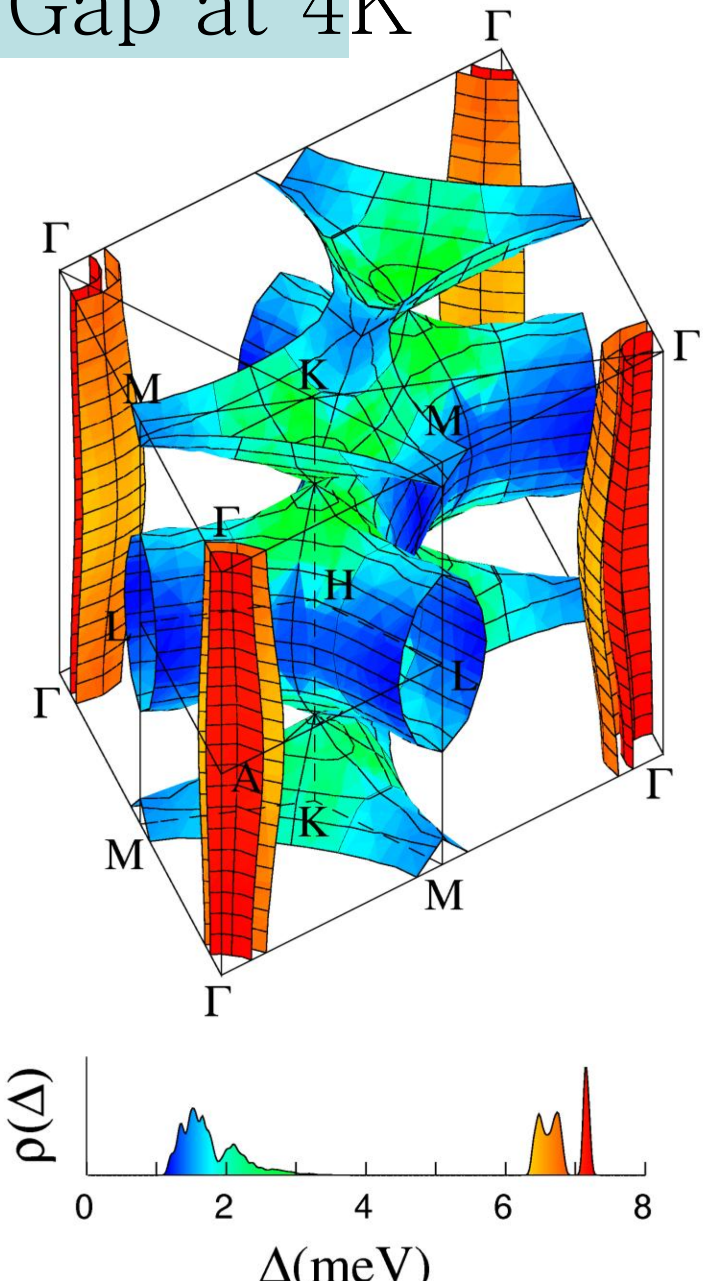


Notes: 1) most metals: $\lambda \sim 0.3 - 0.5$

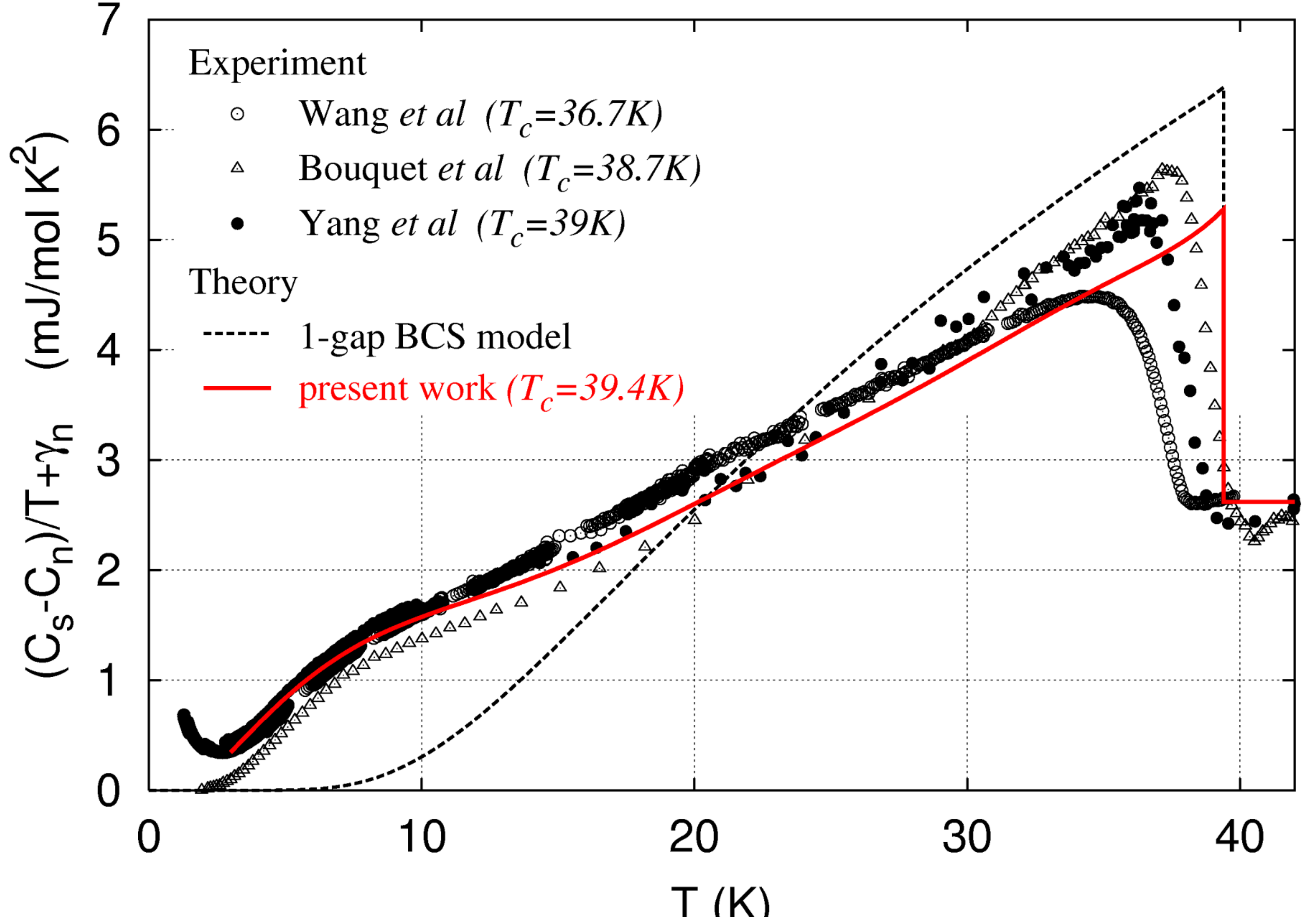
2) MgB_2: **$\langle\lambda\rangle = 0.61$**; specific heat data $\lambda = 0.58, 0.62$

Superconducting Gap at 4K

- Δ(**k**) on Fermi surface at T=4 K
- Large gap on cylindrical σ–sheets
- 2 dominant sets of gap values



Specific Heat of MgB_2



Summary

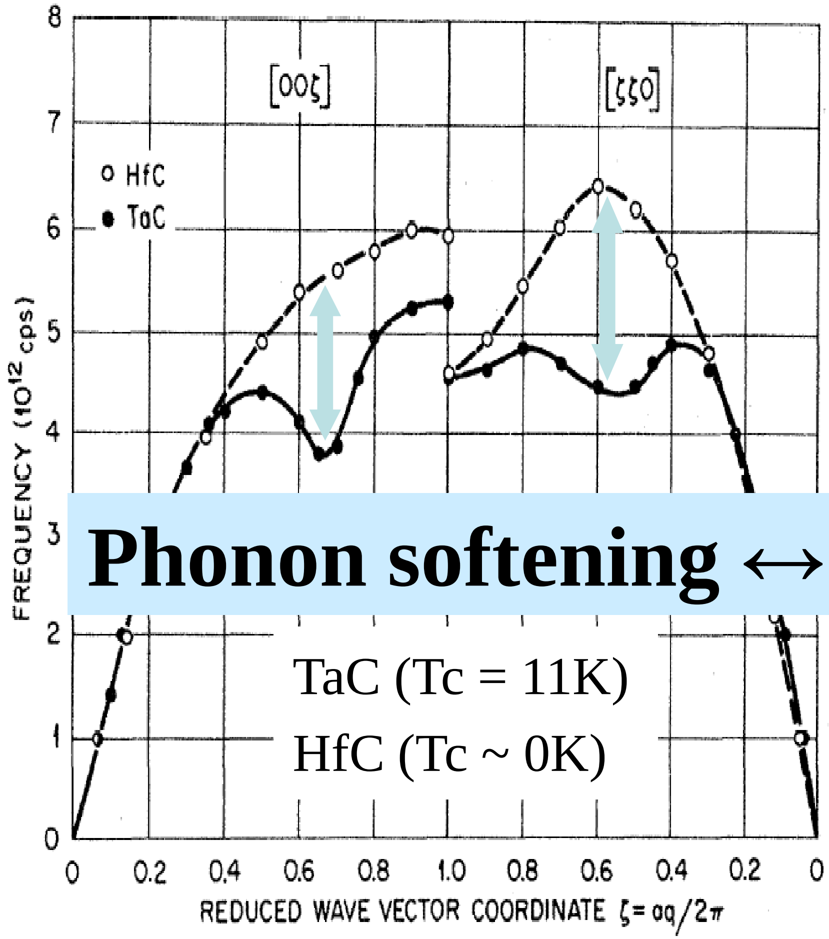
- MgB_2 is a **multi-gap, phonon-mediated** superconductor
- Large electron-phonon coupling of the **σ** boron states responsible for high T_c
- Need to solve the **k-dependent** Eliashberg equations to obtain the correct T_c and other quantities
- First-principles results explained T_c, specific heat, isotope exponents, photoemission, tunneling, and other data
- Theory predicts at least **2 dominant** superconducting gap values at low temperature, and the two-gap feature is robust against pressure, doping and impurity scattering.

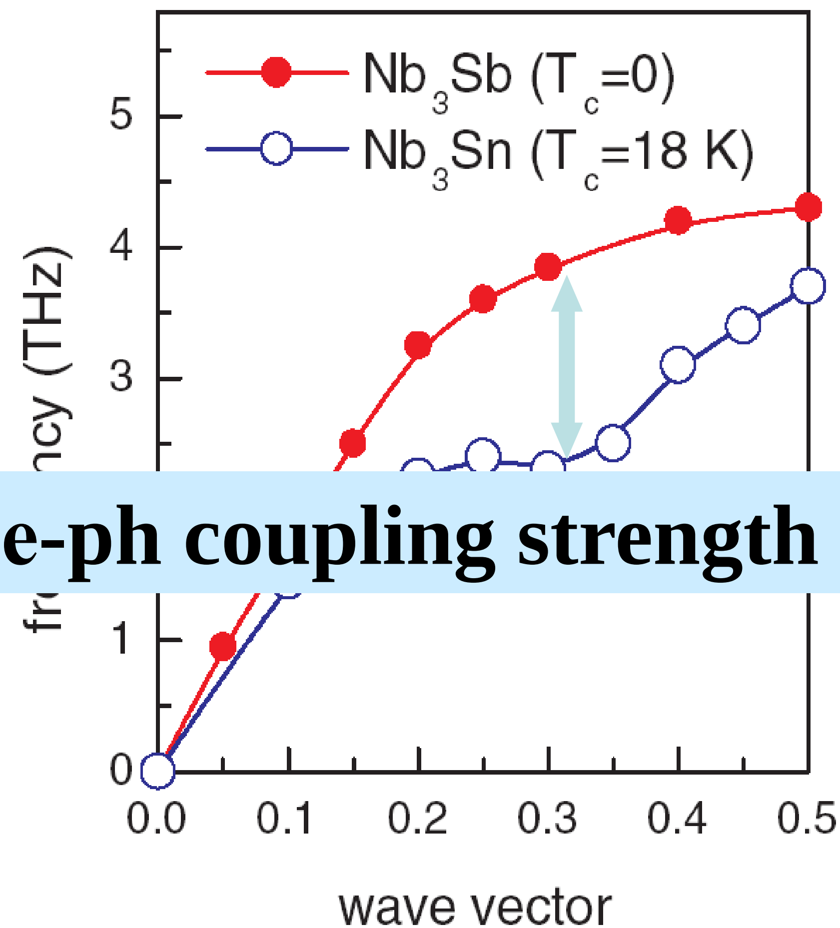
RAISING Tc

WE TRIED TO USE THEORY TO SUGGEST HOW TO INCREASE THE TRANSITION TEMPERATURE OF MAGNESIUM DIBORIDE SIGNIFICANTLY BUT FAILED!

THIS RESULT IS CONSISTENT WITH EXPERIMENTS UP TO NOW.

Phonon softening in superconductors



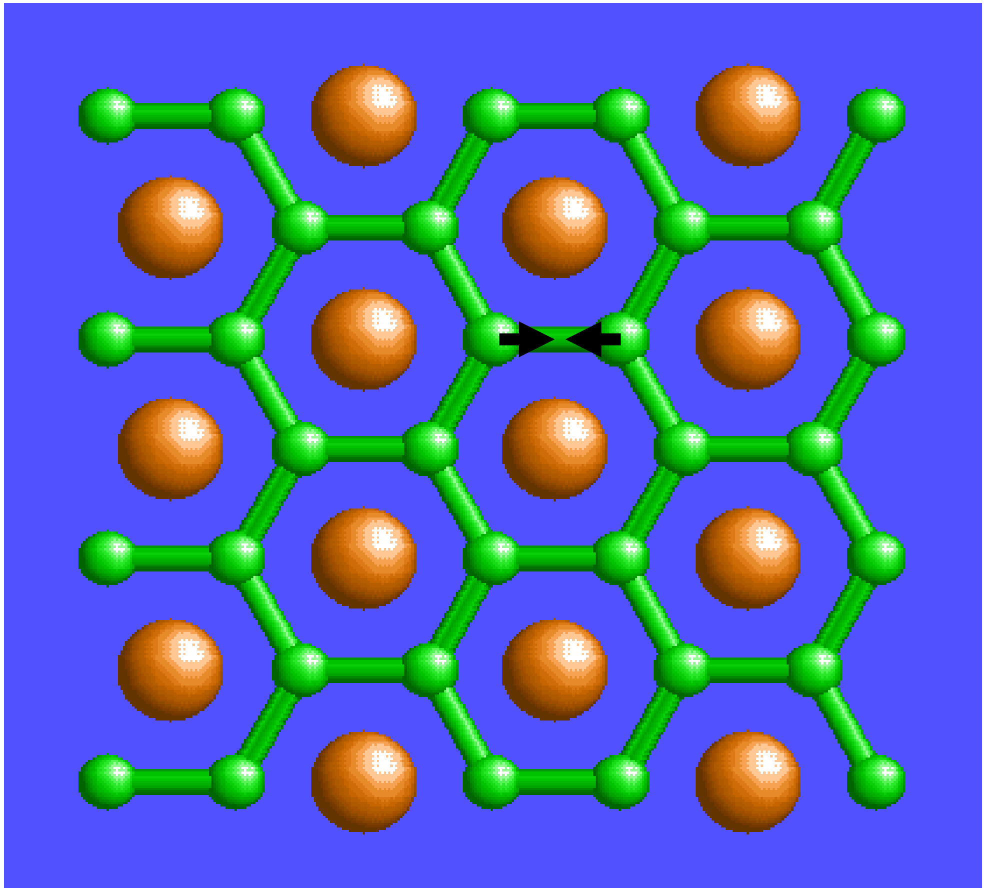


Phonon softening ↔ e-ph coupling strength

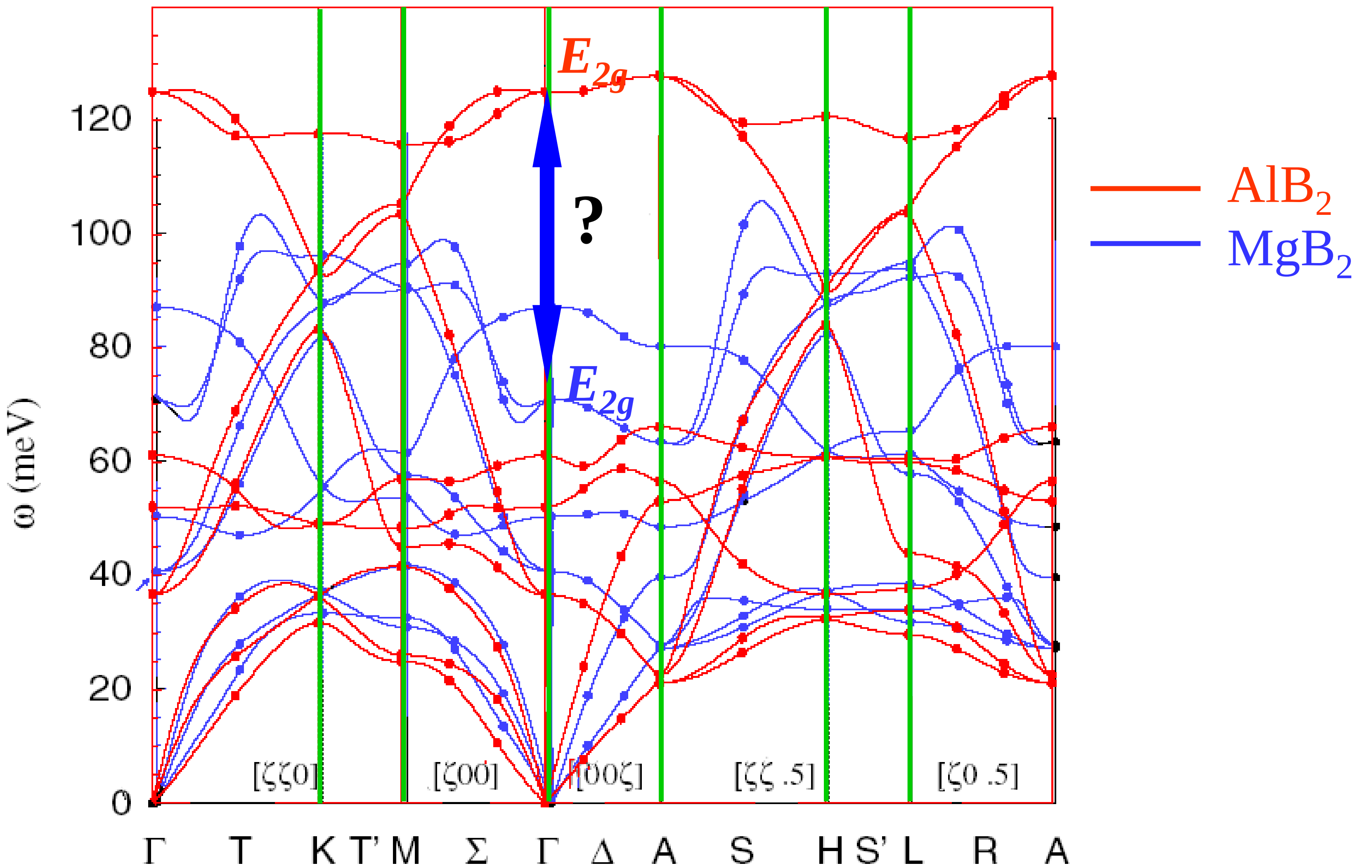
H. G. Smith and W. Glaser, PRL 25, 1611 (1970).

L. Pinstchovius et al., PRL 54, 1260 (1985)
L. Pinstchovius et al. PRB 28, 5866 (1983)
L. Pintschovius, phys. stat. sol. (b) 242, 30 (2005)

E_{2g} phonon in MgB_2 and AlB_2

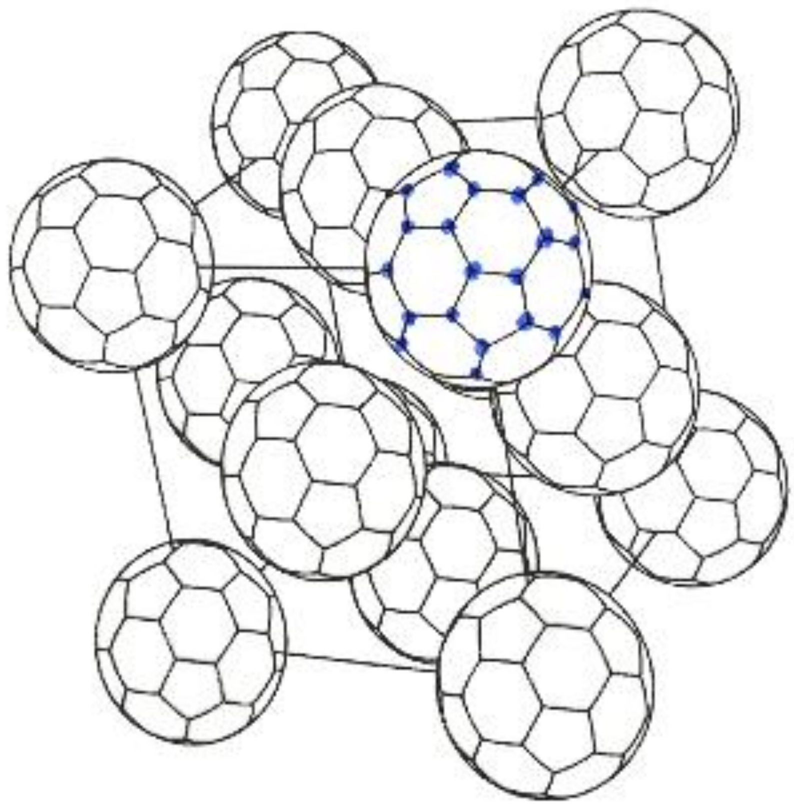


E_{2g} phonon in MgB_2 and AlB_2



K. P. Bohnen, R. Heid, and B. Renker, PRL 86, 5771 (2001).

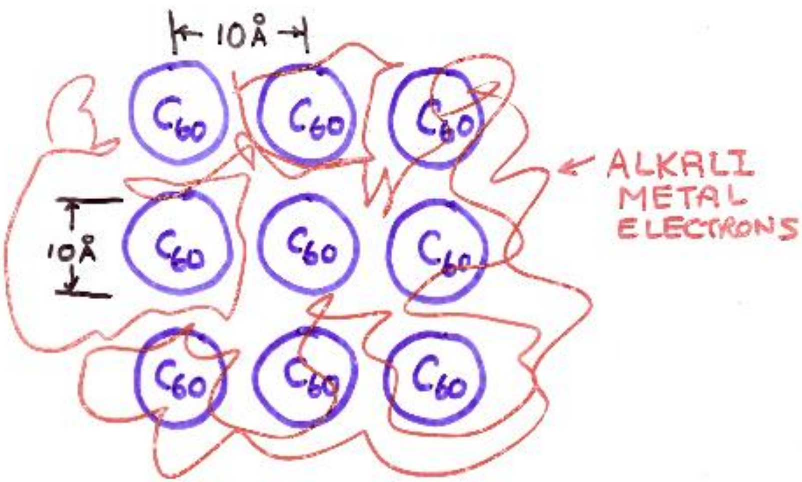
• CARBON ATOMS



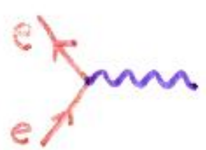
SOLID C_{60}

"STANDARD MODEL"

M_3C_{60} = C_{60}'s + SEA OF ELECTRONS



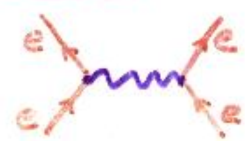
ELECTRON - PHONON SCATTERING



RESISTIVITY

～ PHONONS (MOSTLY INTRABALL)

PAIRING



SUPERCONDUCTIVITY (HEBARD et al 1991)

$$\frac{2\Delta}{k_B T_c} = 3.53 \quad \text{(BCS)}$$

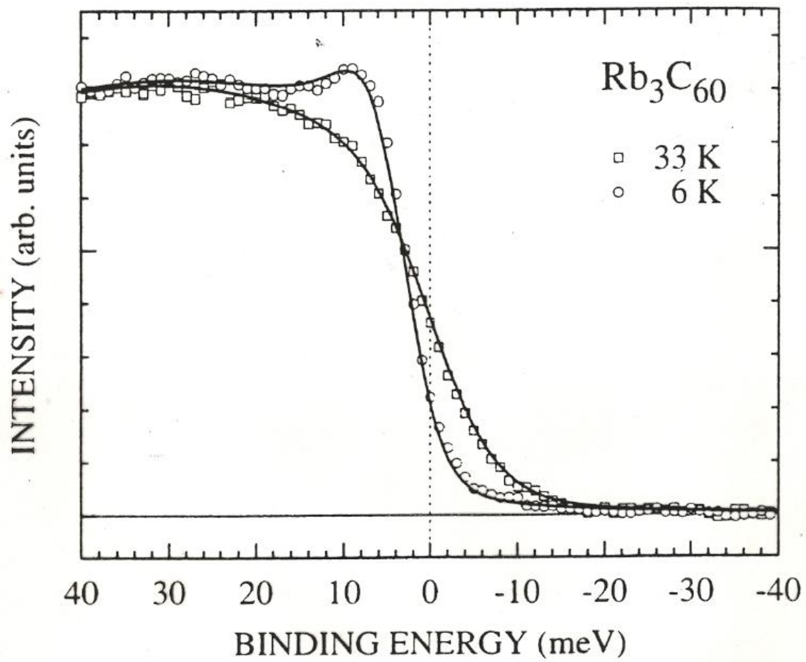


FIG. 4. Photoemission spectra of Rb_3C_{60} at 33 K (squares) and at 6 K (circles). The data are modeled (solid lines) with, respectively, a Fermi-Dirac function at 33 K and a BCS function with a gap $\Delta = 4.4$ meV, broadened by the resolution functions found for the Pt reference.

(SAME FOR K_3C_{60}; $\Delta = 2.9$ meV)

HESPER ET AL

WE FIND THAT FOR C_{60} THAT THE
ELECTRON -PHONON PARAMETER IN BCS $\lambda \sim NV$

THEREFORE TO GET HIGHER Tc's, WE :

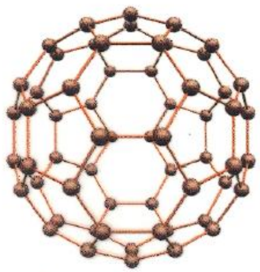
CAN INCREASE "N" WITH CARRIERS BY DOPING OR BAND STRUCTURE [e.g. S. SAITO USING d-ELECTRON EFFECTS]

OR

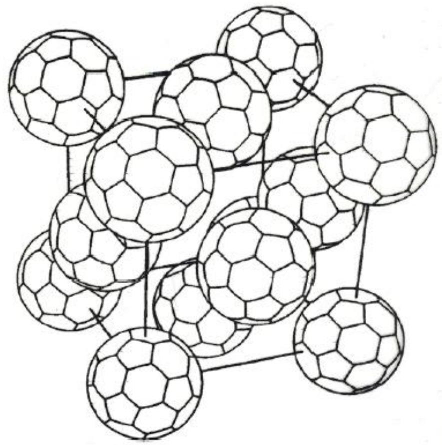
CAN INCREASE "V" BY INCREASING THE "CURVATURE"

GRAPHITE→NANOTUBE→C60→C36→?

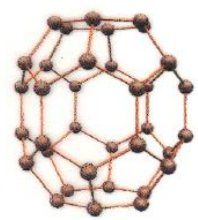
Possible Crystal Structure



C_{60} (I_h)



FCC



C_{36} (D_{6h})

Stacking	Structure
ABAB	hexagonal
ABCABC	rhombohedral

PREDICT

Grossman, Cote, Louie, Cohen, 1998

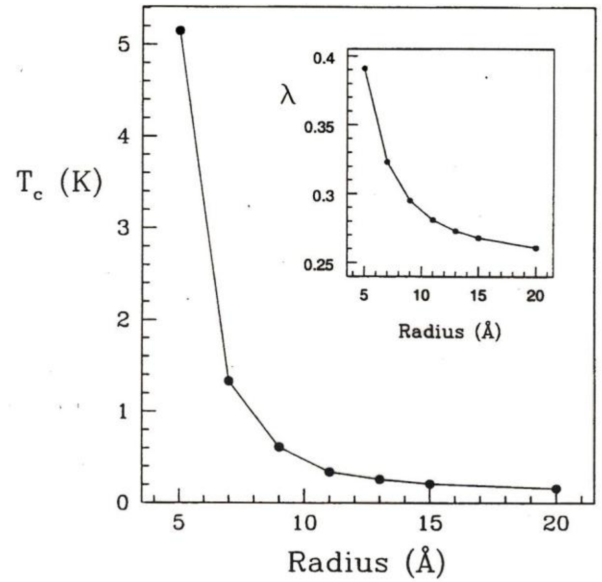
T_c (K doped C_{36} solid) $\approx$ 6 T_c (K doped C_{60} solid)

$\sim$ 100 K

Electron-Phonon Coupling and Superconductivity in Carbon Nanotubes

THEORY:

[L. X. Benedict, V. H. Crespi, S. G. Louie and M. L. Cohen, PRB **52**, 14935 (1995)]



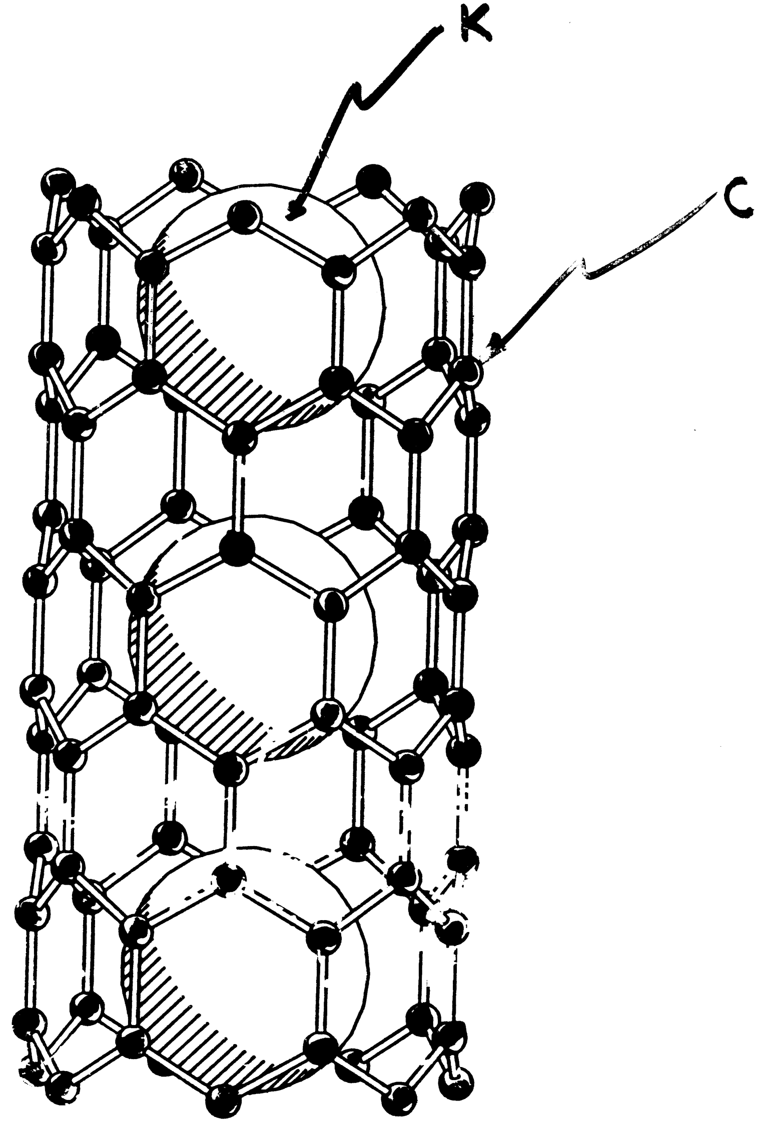
- Large curvature of small diameter tubes leads to enhanced λ.

- Tc can be in the range of 10-20 degrees Kevin for diameter d < 5 A.

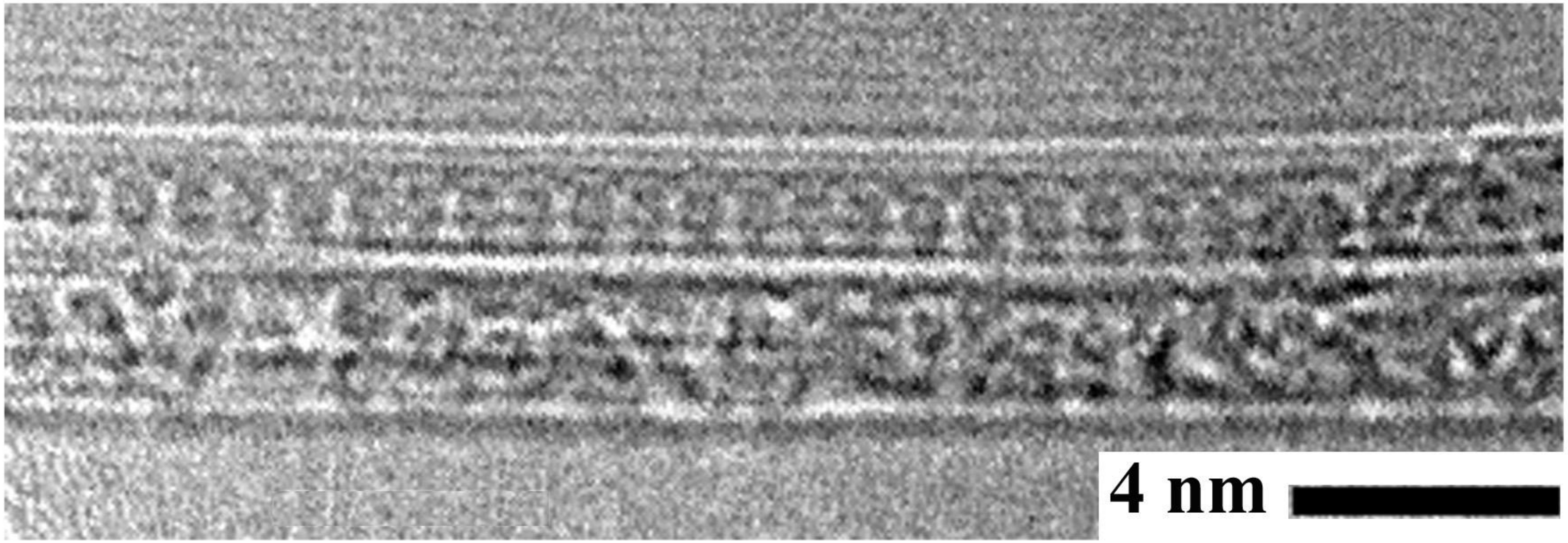
EXP:

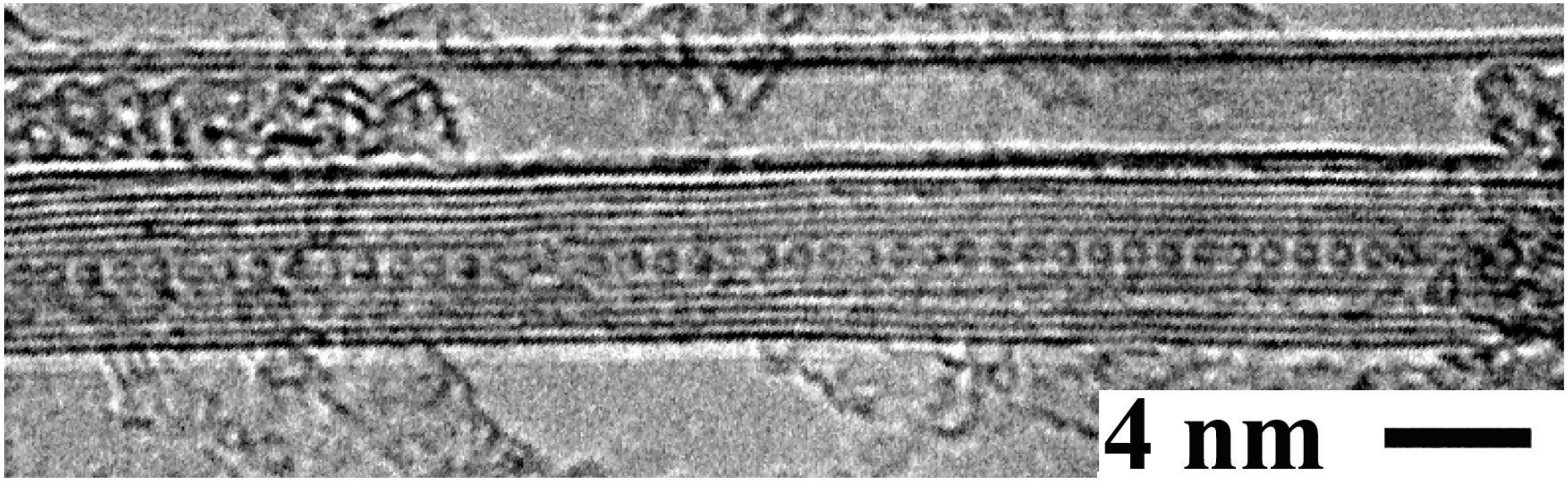
Z.K. TANG et al, Science 292, 2462 (2001)

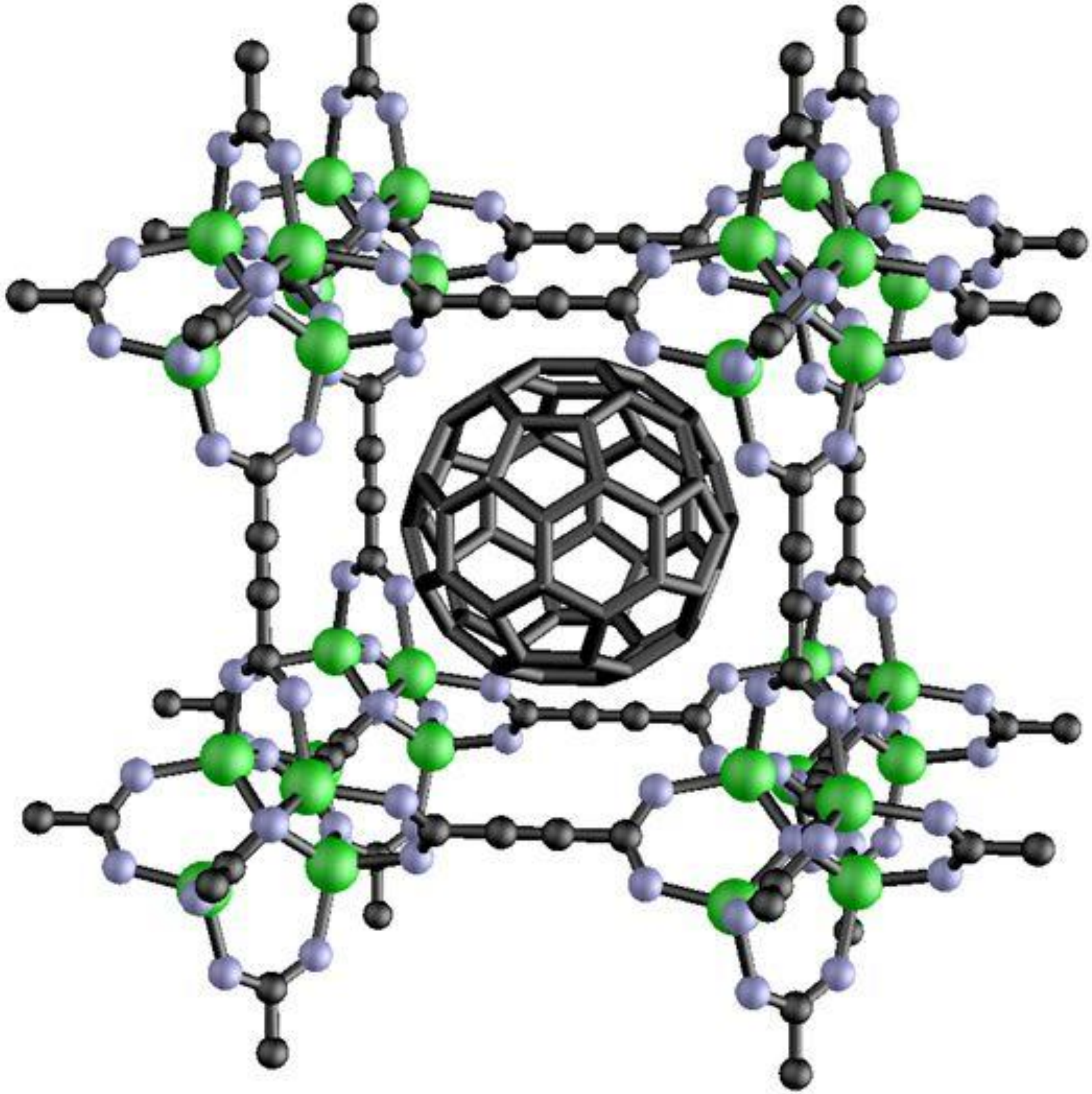
K IN NANOTUBE



BN/C_{60} Peapods







T_c formulas

$$T_c = 1.14\omega_{ph} \exp\left(\frac{-1}{N(0)V}\right)$$ BCS, 1957

$$T_c = \frac{T_D}{1.45} \exp\left(-\frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)}\right)$$ McMillan, 1968

$$T_c = \frac{\langle\omega\rangle_{\log}}{1.20} \exp\left(-\frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)}\right)$$ for $\lambda < 1.5$

Allen and Dynes, 1975

$$T_c = 0.183\sqrt{\lambda\langle\omega^2\rangle}$$ for $\lambda > 10$, $\mu^*=0$

$$\lambda \equiv 2\int_0^{\omega_{\max}} \alpha^2 F(\omega)\omega^{-1} d\omega$$

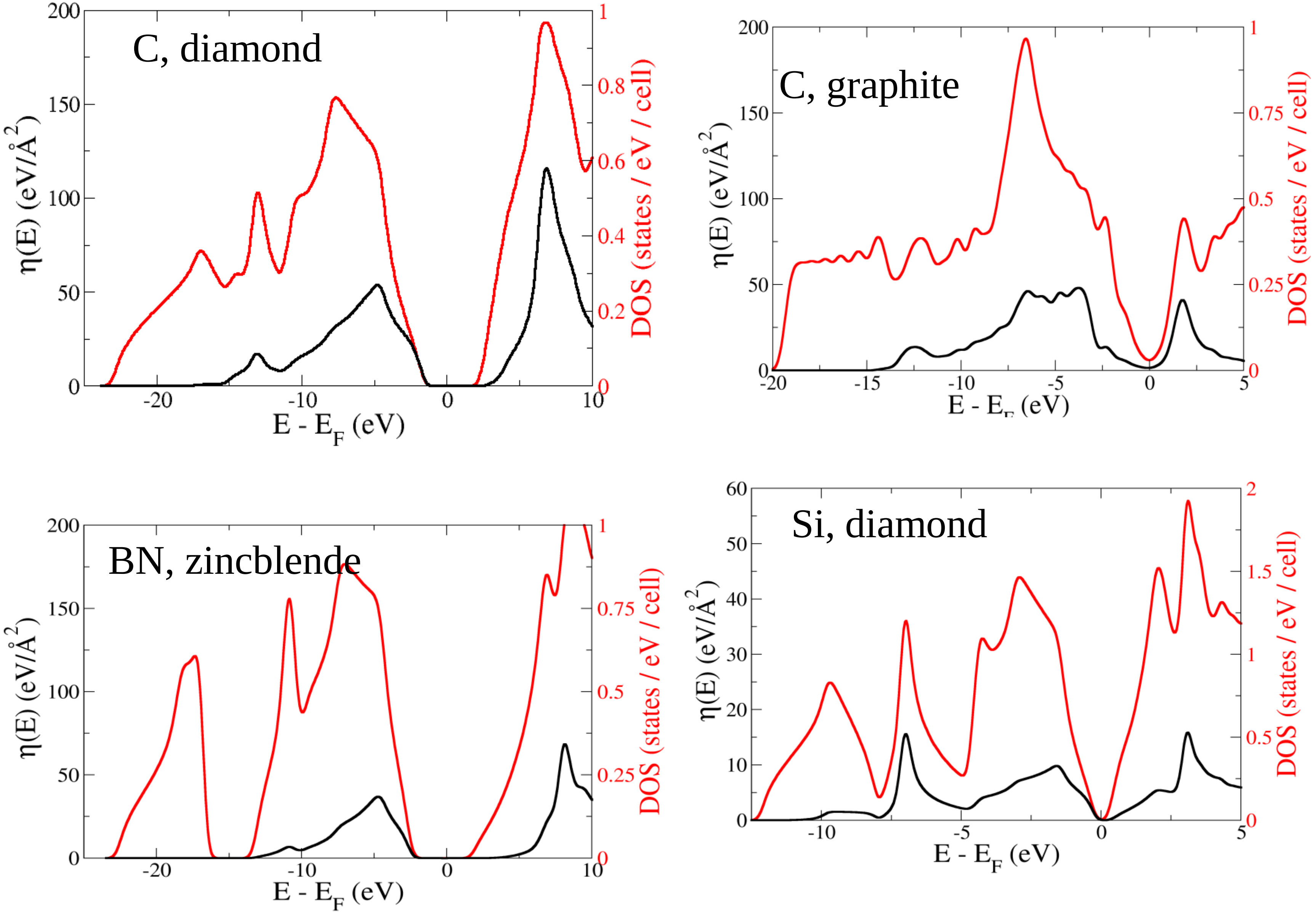
+ anisotropic electrons, anharmonic phonons, etc…

ELECTRON-PHONON COUPLING

$$\lambda \langle \omega^2 \rangle = \sum_i \frac{\eta_i}{M_i}$$

SO λ CAN BE VIEWED AS THE RATIO OF AN ELECTRONIC SPRING CONSTANT η AND A LATTICE SPRING CONSTANT

Numerical results



Values of η

	η (eV/Å^2)	$0.183\sqrt{\lambda\langle\omega^2\rangle}$(K)	EXP
C (diamond)*	54	290	~ 10
C (graphite)*	48	270	?
BN*	36	240	?
Si*	10	82	~10

*at peak of η(E)

Strong coupling limit

$$T_c \leq 0.183\sqrt{\lambda\langle\omega^2\rangle}$$

electron-phonon coupling strength

Or the electronic spring constant /ionic mass

$$\lambda \sim \frac{\Omega_{ph}^2 - \omega_{ph}^2}{\omega_{ph}^2}$$

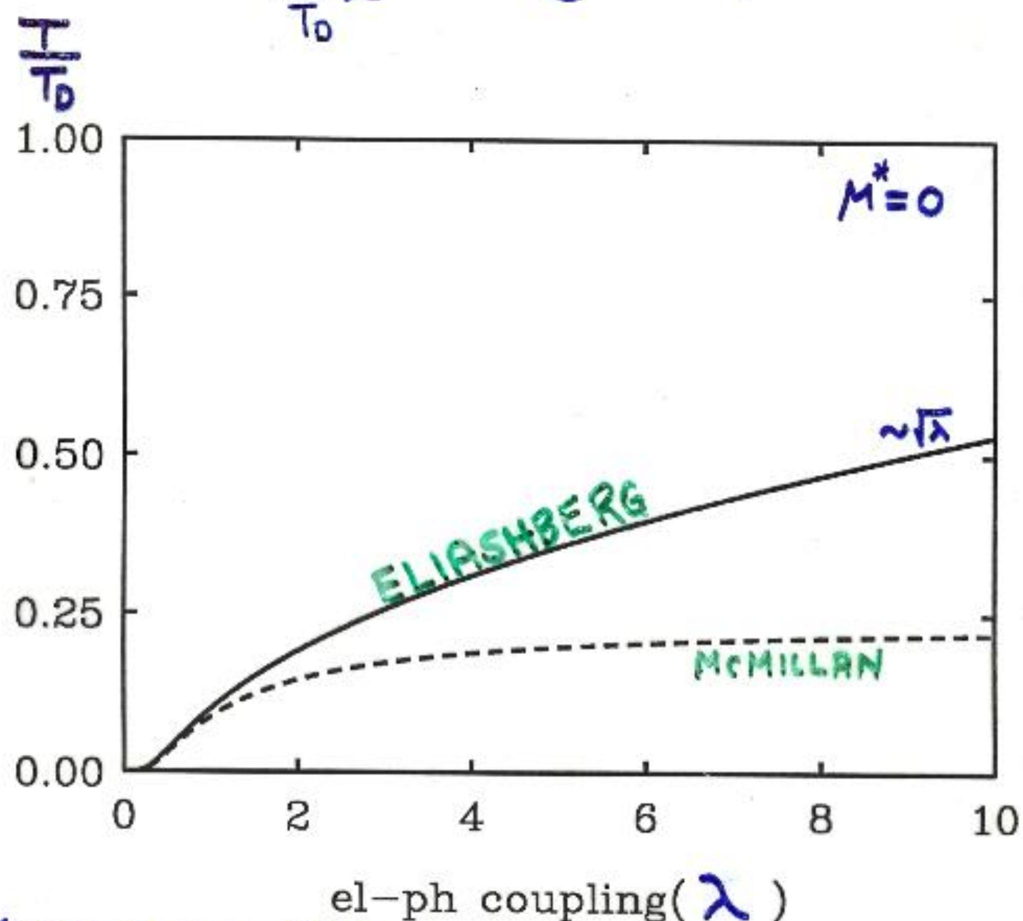
$$\eta / M$$

$$T_c \leq \alpha\sqrt{\Omega_{ph}^2 - \omega_{ph}^2} \leq \alpha\Omega_{ph}$$

stability of bare lattice

McMILLAN 1968

$$\frac{T_c}{T_D} \approx 0.69\, e^{-\frac{1}{\lambda^* - \mu^*}}$$



Kresin-Barbee-Cohen

$$\frac{T_c}{\langle\omega\rangle} = 0.26\left(e^{2/\lambda} - 1\right)^{-1}$$

BEYOND BCS MODEL (FREQUENCY DEPENDENCE)

$\Delta, V, N \ldots$ are $\underset{\sim}{k}$ and ω dependent

$$\Delta(\epsilon) = -\int_{-\infty}^{\infty} \frac{\Delta(\epsilon') K(\epsilon,\epsilon')}{E'} \tanh \beta\frac{E'}{2} \, d\epsilon'$$

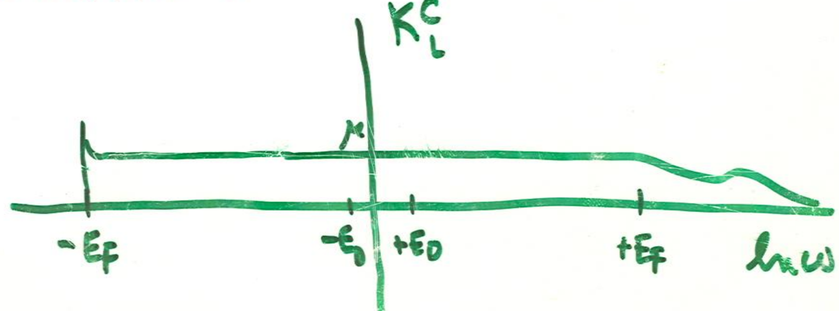
$$K(\epsilon,\epsilon') = \frac{\Omega}{2(2\pi)^2} \frac{m}{\hbar^2 k_F} \int_{q_{min}}^{q_{max}} q \, V(q,\omega) \, dq$$

$$[K] = [NV] = [\lambda] - [\mu]$$

REPULSIVE COULOMB INTERACTION

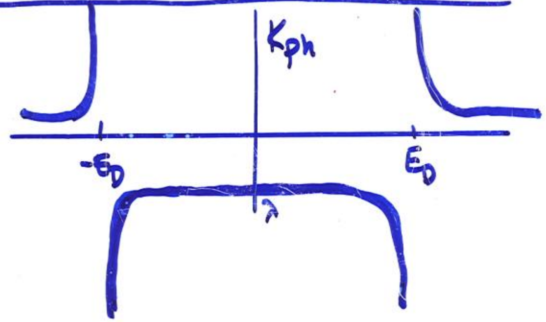
$$K^c = [\mu] \sim \Omega \int q \cdot \frac{4\pi e^2}{\Omega q^2 \epsilon(q,\omega)} dq$$

LINDHARD ϵ

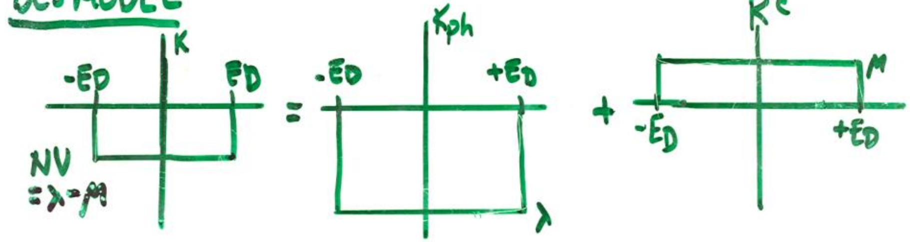


BEYOND BCS MODEL (CONT'D) (FREQUENCY DEPENDENC

ATTRACTIVE PHONON INTERACTION

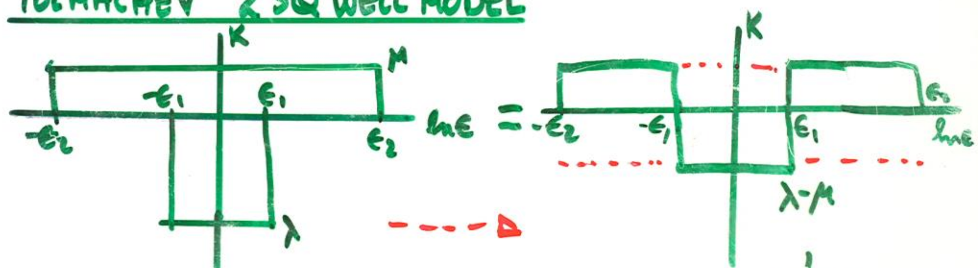


BCS MODEL



NOT APPROPRIATE FOR K^c; GET $T_c \sim T_D e^{-\frac{1}{\lambda-\mu}}$

TOLMACHEV 2 SQ WELL MODEL



$\epsilon_1 \sim E_D$

$\epsilon_2 \sim E_F$

GET $T_c \sim T_D e^{-\frac{1}{\lambda-\mu^*}}$

$$\mu^* = \frac{\mu}{1+\mu \ln \epsilon_2/\epsilon_1}$$

BEYOND BCS MODEL (CONT'D) (FREQUENCY DEPENDENCE)

ISOTOPE EFFECT

BCS MODEL $\quad T_c \sim T_D \underbrace{e^{-\frac{1}{NV}}}_{\text{const}} \sim \frac{1}{\sqrt{M}}$

$$T_c \sim M^{-\alpha} \qquad \alpha = 1/2 \quad \text{BCS MODEL}$$

2 SQ WELL MODEL

$$T_c \sim T_D e^{-\frac{1}{\lambda - \mu^*}}$$

$$\alpha = \frac{1}{2}\left[1 - \left(\frac{\mu^*}{\lambda - \mu^*}\right)^2\right] \Rightarrow \alpha \leq 1/2$$

FOR $\mu^* = \frac{\lambda}{2}$; $\alpha = 0$

WAVEVECTOR DEPENDENCE

TOTAL DIELECTRIC FUNCTION

$\epsilon_T(q, \omega)$ can include electron-electron and electron-phonon effects

e.g. $$V^T_{kk'} = \frac{V_q}{\epsilon_T(q,\omega)} = \frac{4\pi e^2}{\Omega q^2} \frac{1}{\epsilon_e + \epsilon_p}$$

$$\frac{1}{\epsilon_e + \epsilon_p} = \frac{1}{\epsilon_e} - \frac{\epsilon_p}{\epsilon_e(\epsilon_e + \epsilon_p)}$$

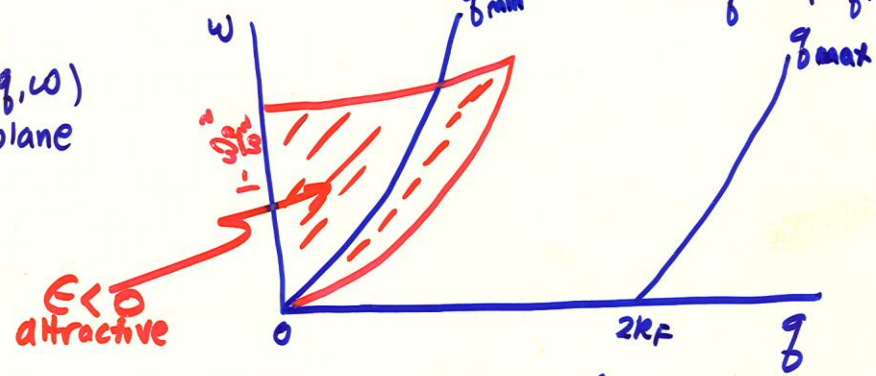
COULOMB (first term) e.g. BARDEEN-PINES (second term)

BEYOND BCS MODEL (WAVEVECTOR AND FREQUENCY DEPENDENCE)

$$K(\omega) \sim \int_{q_{min}}^{q_{max}} q\, V(q,\omega)\, dq$$

$V(q,\omega)$ can be total interaction $= \dfrac{4\pi e^2}{\Omega q^2 \epsilon_T(q,\omega)}$

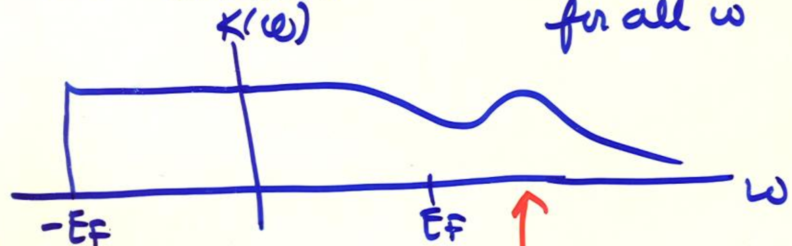
(q,ω) plane



$\hbar\omega = |\epsilon_{\underset{\sim}{k}} - \epsilon_{\underset{\sim}{k}'}|$ energy transfer

$\underset{\sim}{q} = \underset{\sim}{k}' - \underset{\sim}{k}$ "momentum" transfer

FOR $\epsilon_{LINDHARD}$ $K(\omega) > 0$ (repulsive) for all ω



in FEG plasmon exchange is ineffective

HIGH $T_c \Rightarrow$

$T_c \sim E_0 f(\lambda_0)$

WEAK COUPLING

E_0 large

$f(\lambda_0)$ small

(electronic mechanisms)

STRONG COUPLING

E_0 small

$f(\lambda_0)$ large

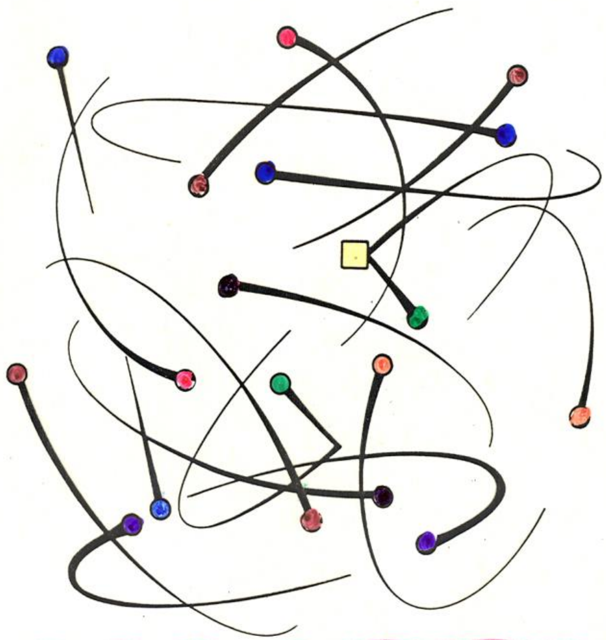
(phonon and low ω mechanisms spin fluctuations)

IMPORTANT TO KNOW (FROM EXPERIMENT) WHICH MODEL APPLIES

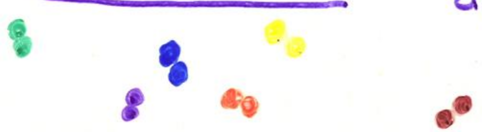
exp: $\frac{2\Delta}{kT_c}$, tunneling, $C_v(T)$ ...

PAIRING

BCS PAIRS: $\frac{d_{PAIR\ MATES}}{d_{PAIRS}} >> 1$



"BOSON" LIKE PAIRS $\frac{d_{PAIR\ MATES}}{d_{PAIRS}} << 1$



FOR Y-Ba-Cu-O

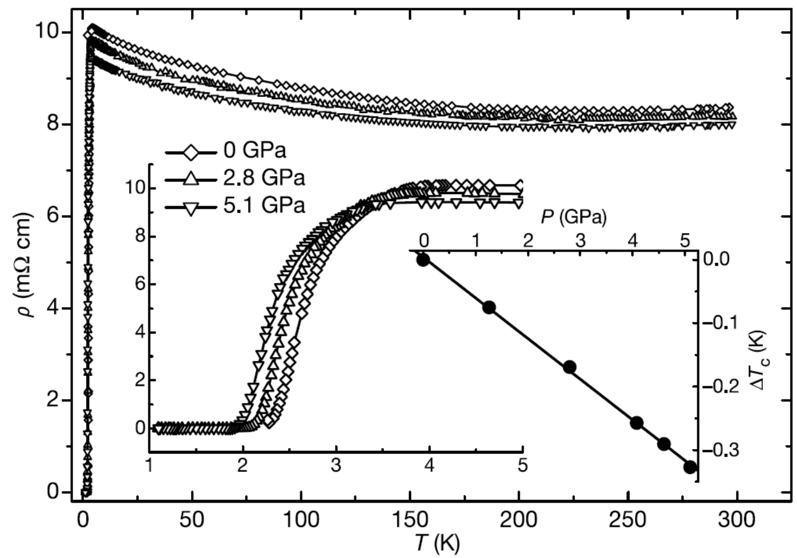
PERHAPS? $\frac{d_{PAIR\ MATES}}{d_{PAIRS}} \sim 1$

Superconductivity in diamond

E. A. Ekimov[1], V. A. Sidorov[1], E. D. Bauer[2], N. N. Mel'nik[3], N. J. Curro[2], J. D. Thompson[2] & S. M. Stishov[1]

[1]*Vereshchagin Institute for High Pressure Physics, Russian Academy of Sciences, 142190 Troitsk, Moscow region, Russia*
[2]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[3]*Lebedev Physics Institute, Russian Academy of Sciences, 117924 Moscow, Russia*

NATURE | VOL 428 | 1 APRIL 2004 | www.nature.com/nature



Quasiparticle dynamics in graphene

AARON BOSTWICK[1], TAISUKE OHTA[1,2], THOMAS SEYLLER[3], KARSTEN HORN[2] AND ELI ROTENBERG[1]*

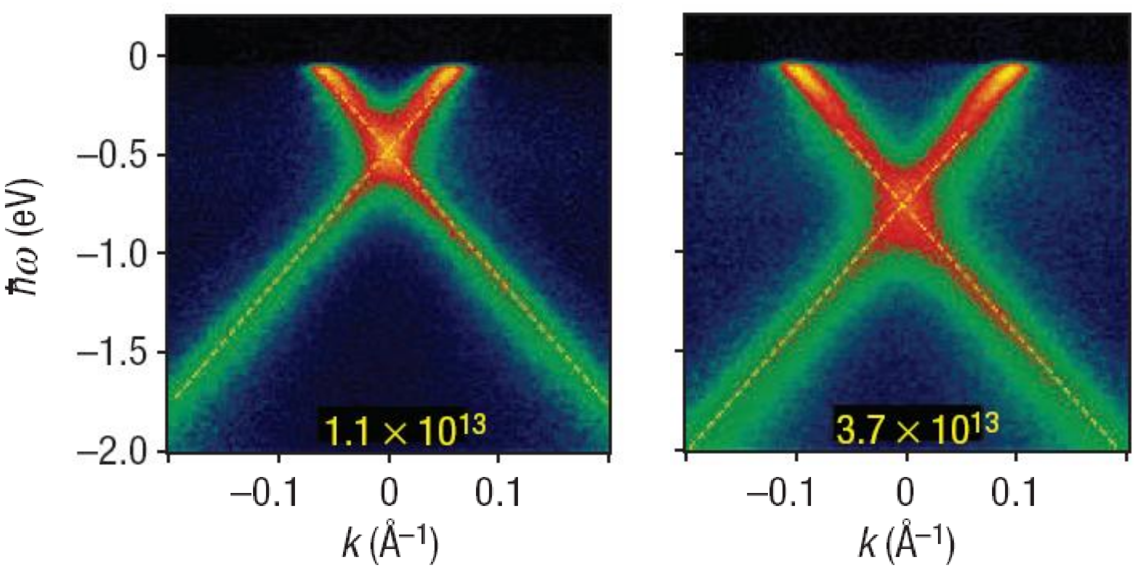
[1] Advanced Light Source, E. O. Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

[2] Department of Molecular Physics, Fritz-Haber-Institut der Max-Planck-Gesellschaft, Faradayweg 4-6, 14195 Berlin, Germany

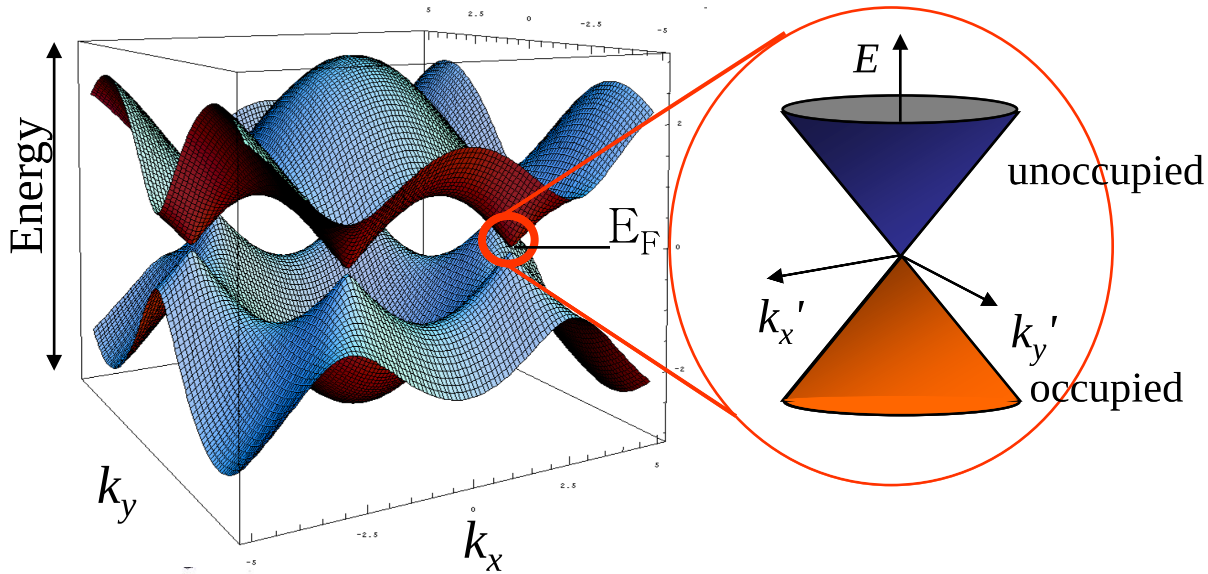
[3] Institut für Physik der Kondensierten Materie, Lehrstuhl für Technische Physik, Universität Erlangen-Nürnberg, Erwin-Rommel-Straße 1, D-91058 Erlangen, Germany

*e-mail: erotenberg@lbl.gov

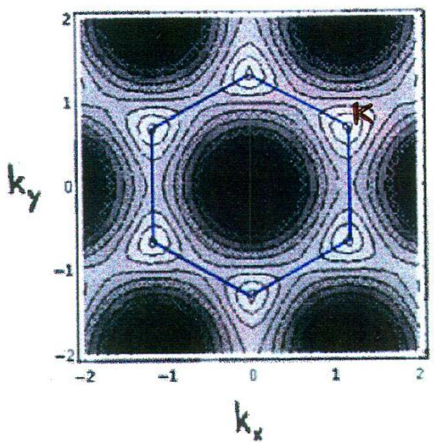
nature physics | VOL 3 | JANUARY 2007 | www.nature.com/naturephysics



Graphene Electronic Structure



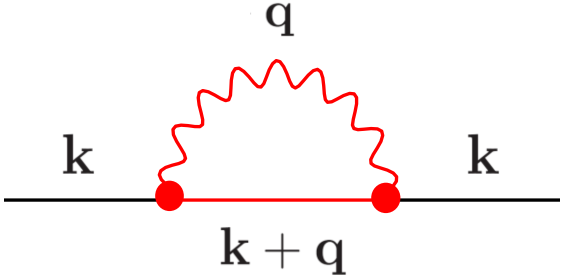
$$E = \hbar v_F |k'|$$



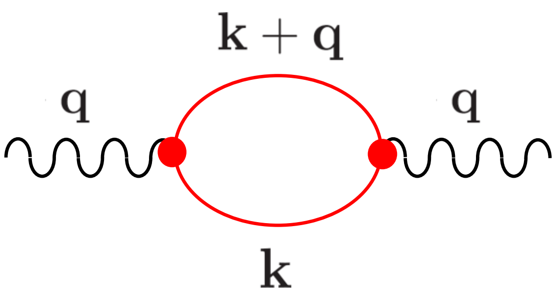
$$E^2 = p^2c^2$$

2D massless Dirac fermion syste

Electron and Phonon Selfenergy



$$\Sigma = i \int \frac{d\,2}{(2\pi)^4}\, |g(1,2)|^2\, D(1-2)\, G(2)$$



$$\Pi = -2\, i \int \frac{d\,1}{(2\pi)^4}\, |g(1,2)|^2\, G(1)\, G(2)$$

Wannier Representation

$$g_{mn}^{\nu}(\mathbf{k},\mathbf{q}) = \langle m\mathbf{k}+\mathbf{q}|\, \Delta V_{\mathbf{q}\nu} |n\mathbf{k}\rangle$$

$$|n\mathbf{k}\rangle = \frac{1}{N_\mathrm{e}} \sum_{m\mathbf{R}_\mathrm{e}} e^{i\mathbf{k}\cdot\mathbf{R}_\mathrm{e}}\, U^{\dagger}_{mn,\mathbf{k}}\, |m\mathbf{R}_\mathrm{e}\rangle$$

$$\Delta_{\mathbf{q}\nu} V(\mathbf{r}) = \sum_{\mathbf{R}_\mathrm{p}} \exp(i\mathbf{q}\cdot\mathbf{R}_\mathrm{p}) \sum_{\kappa\alpha} M_{\kappa}^{-\frac{1}{2}}\, e_{\mathbf{q}\nu}(\kappa\alpha)\ \Delta_{\kappa\alpha,\mathbf{R}_\mathrm{p}} V(\mathbf{r})$$

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Wannier Representation

$$\underbrace{g(\mathbf{k},\mathbf{q})}_{\text{Bloch}} = \sum_{\mathbf{R}_\mathrm{e},\mathbf{R}_\mathrm{p}} \mathrm{e}^{i\mathbf{k}\cdot\mathbf{R}_\mathrm{e}}\, \mathrm{e}^{i\mathbf{q}\cdot\mathbf{R}_\mathrm{p}}\, u_{\mathbf{q}}\, U_{\mathbf{k}+\mathbf{q}}\, \underbrace{g(\mathbf{R}_\mathrm{e},\mathbf{R}_\mathrm{p})}_{\text{Wannier}}\, U^{\dagger}_{\mathbf{k}}$$

$$g(\mathbf{k},\mathbf{q}) = \sum_{\mathbf{R}_\mathrm{e},\mathbf{R}_\mathrm{p}} \mathrm{e}^{i\mathbf{k}\cdot\mathbf{R}_\mathrm{e}}\, \mathrm{e}^{i\mathbf{q}\cdot\mathbf{R}_\mathrm{p}}\, u_\mathbf{q}\, U_{\mathbf{k}+\mathbf{q}}\, g(\mathbf{R}_\mathrm{e},\mathbf{R}_\mathrm{p})\, U_\mathbf{k}^\dagger$$

Bloch

Wannier

$$\langle m\mathbf{0}_\mathrm{e}|\, \Delta_{\kappa\alpha,\mathbf{R}_\mathrm{p}} V(\mathbf{r}) |n\mathbf{R}_\mathrm{e}\rangle$$

Wannier Representation

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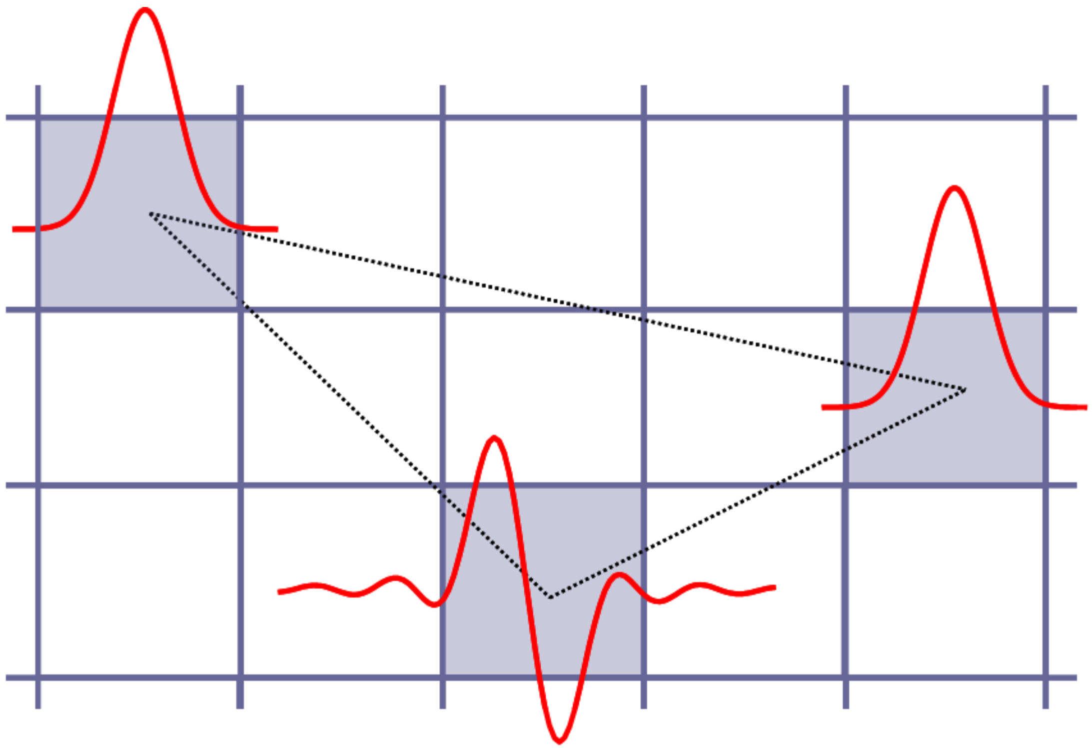

HAROLD WEINSTOCK

JAN 28, 2007

I have proposed that we take steps to videotape the entire workshop. My colleagues are of 2 minds regarding this suggestion: one is that people will keep their best ideas to themselves; the other is that with a recording of our deliberations, there will be unambiguous proof of the genesis of any idea that leads us to the Promised Land. I clearly support the latter view, but I welcome your comments on this issue.

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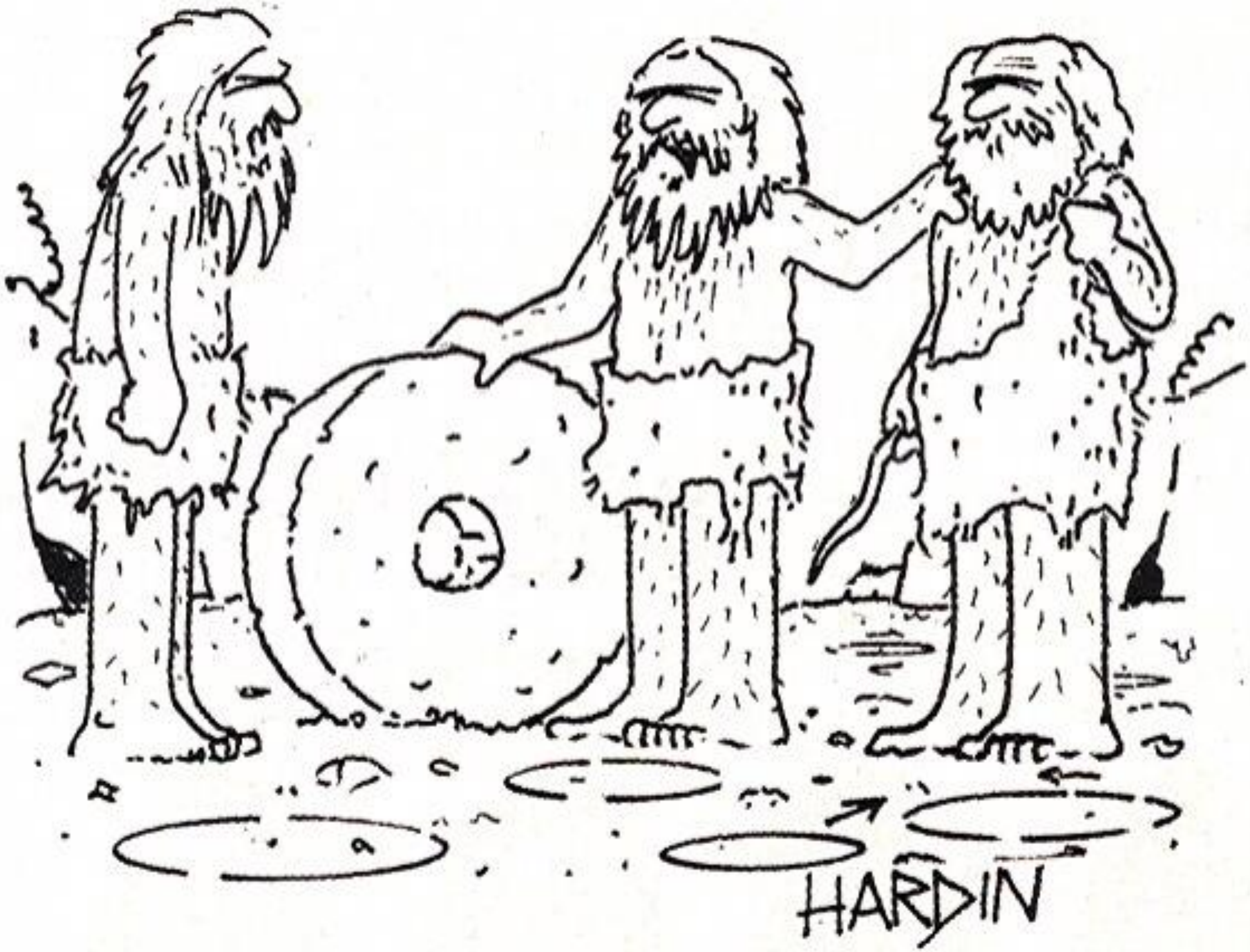
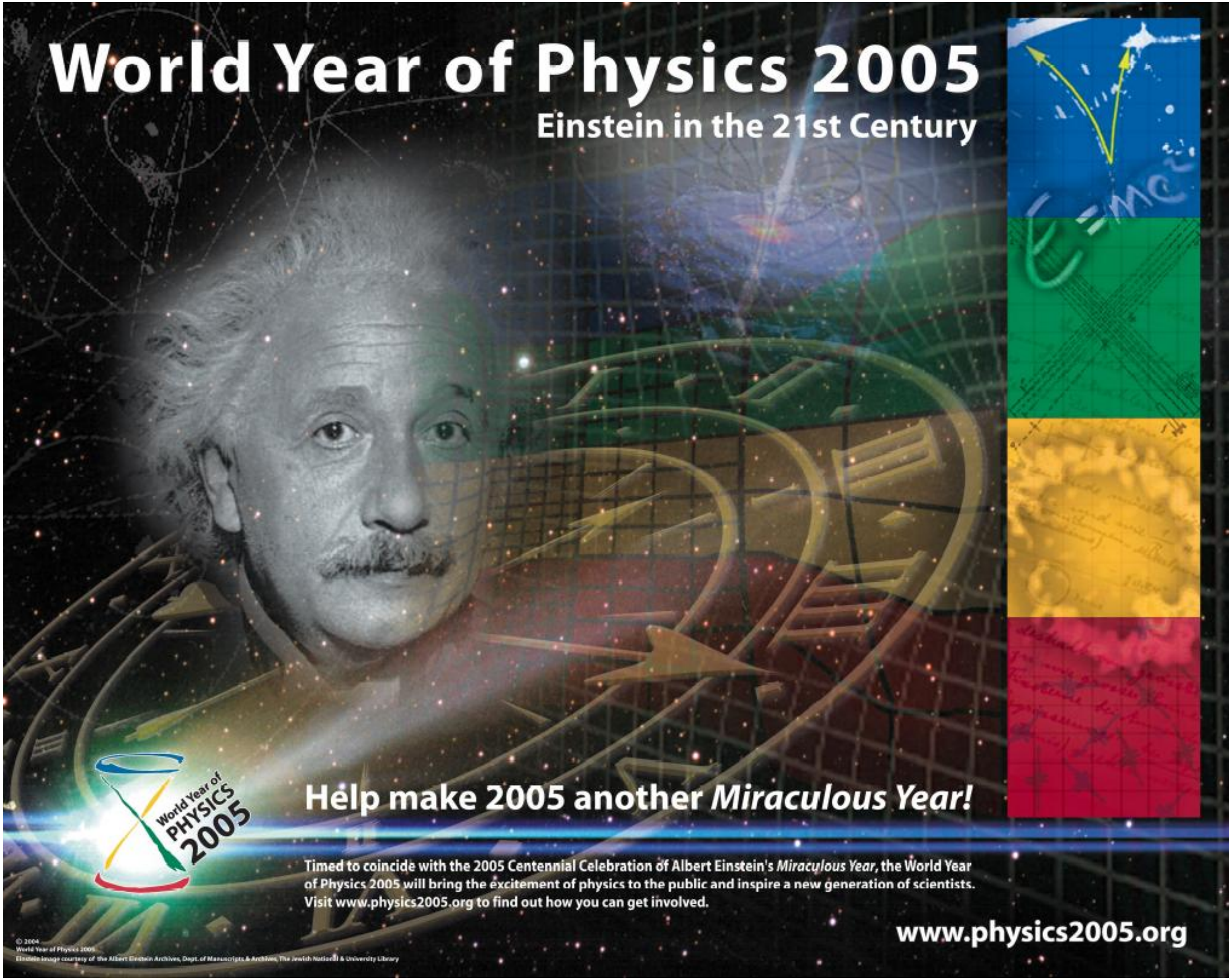
UNLIKE MOSES, I'M GOING IN WITH THEM!



"To be honest, I never would have invented the wheel if not for Urg's groundbreaking theoretical work with the circle."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Einstein in the 21st Century
World Year of PHYSICS 2005
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Einstein’s Thesis Proposals

1. Proposed method for measurement of “c”, using interferometer. Proposed to Prof. Dr. Weber (1900)

(Comment: This was later done by A. A. Michelson who did the experiment and became the first American to be awarded the Nobel Prize [1907])

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REJECTED

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1. Proposed method for measurement of “c”, using interferometer. Proposed to Prof. Dr. Weber.

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（Comment: very important for electronics）

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REJECTED

3. Performed theoretical work on the thermal conductivity of solids. Wrote up as dissertation. Submitted to Prof. Dr. Weber.

（Comment: again important for electronics and heat applications)

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REJECTED (written on wrong kind of paper?)

4. Performed theoretical work on extension of intermolecular forces from liquids to gases. Wrote up as dissertation. Presented to Prof. Dr. Kleiner.

(Comment: a fundamental theory of how matter behaves)

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REJECTED

5. Proposed investigation on electrodynamics of moving bodies. Proposed to Prof. Dr. Kleiner.

(Comment: this later led to Einstein’s famous equation)


A is for apple.
B is for ball.
C is for car.
D is for dog.
E = mc²

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6. Performed theoretical work on measuring the molecular dimensions of sugar molecules. Wrote up as dissertation. Submitted to Profs. Kleiner and Burkhardt.

(Comment: important to prove the existence of atoms and molecules)

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REJECTED (too short, 17 pages)

7. Added one sentence and resubmitted theoretical work on measuring the molecular dimensions of sugar molecules. Submitted to Profs. Kleiner and Burkhardt.

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   ACCEPTED (1905) !

ALBERT EINSTEIN

"The most valuable tool of the theoretical physicist is his wastebasket."

THE END