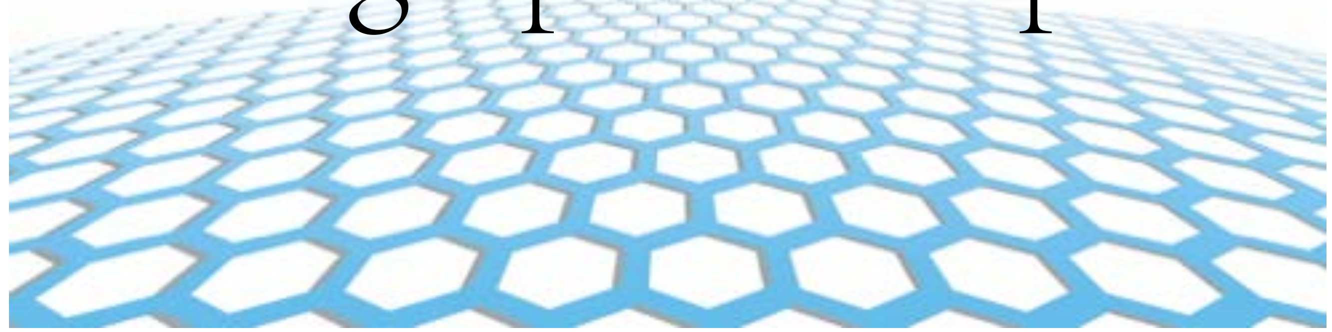
How to make graphene superconducting



Gianni Profeta

Physics Department, University of L'Aquila, Italy

&

Max-Planck Institute of Microstructure Physics, Halle, Germany

Matteo Calandra and Francesco Mauri

IMPMC, University of Paris 6, CNRS, Jussieu , Paris France

Graphene: physical realization of fundamental phenomena in solid-state-physics

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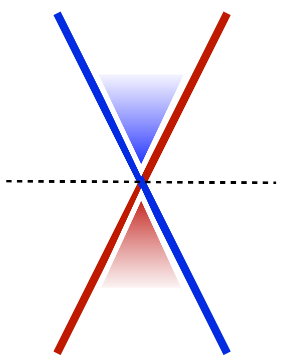

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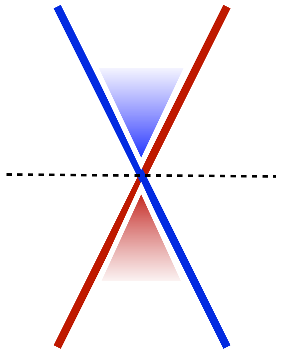

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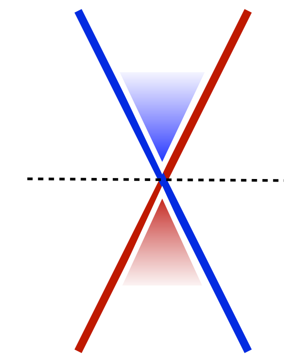

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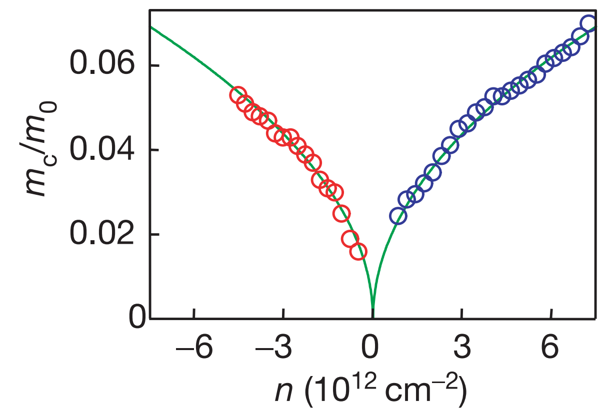

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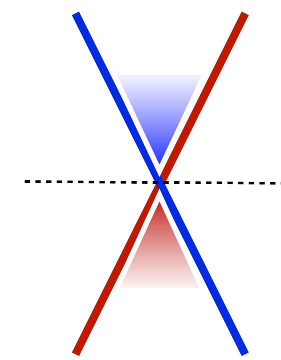

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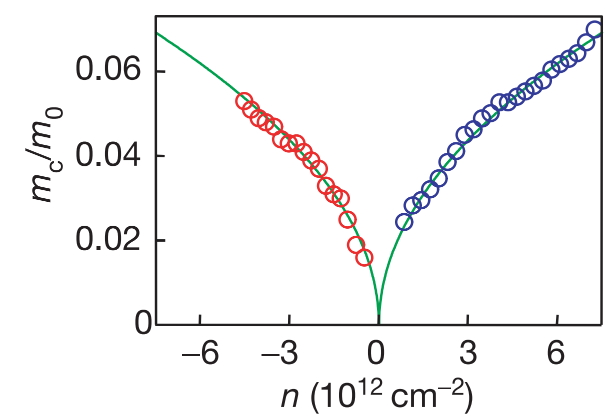

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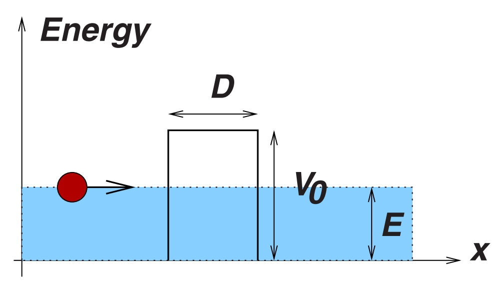

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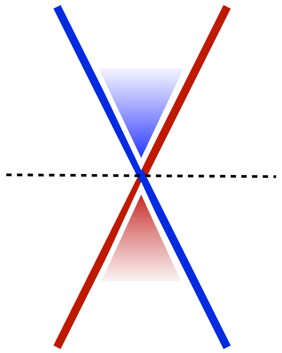

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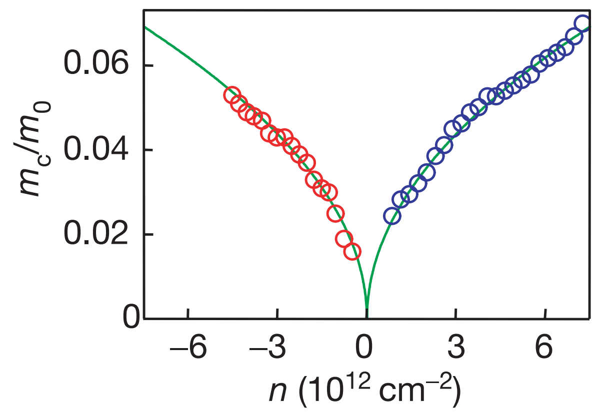

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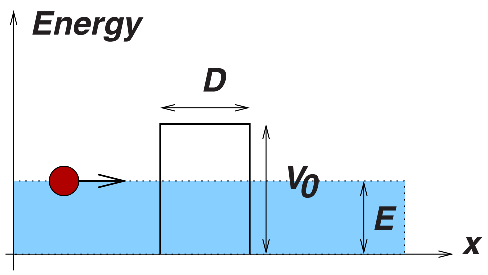

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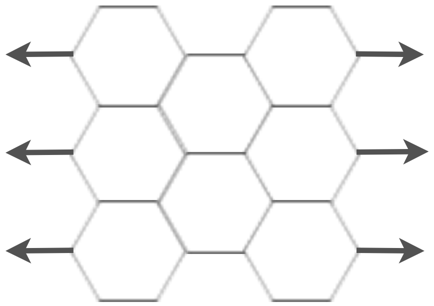

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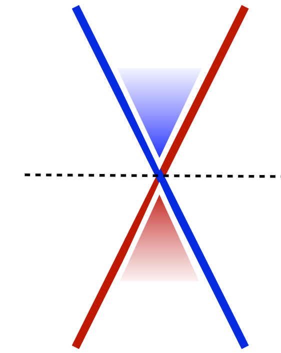

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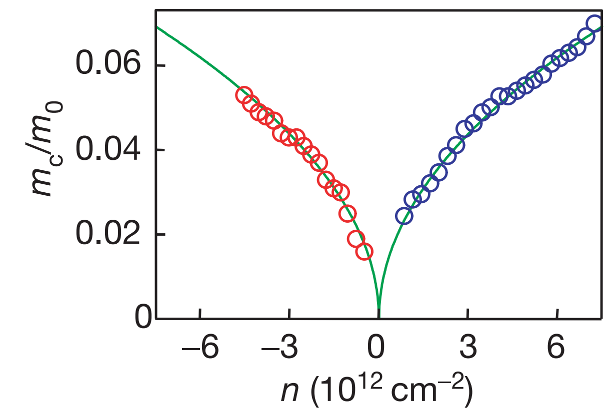

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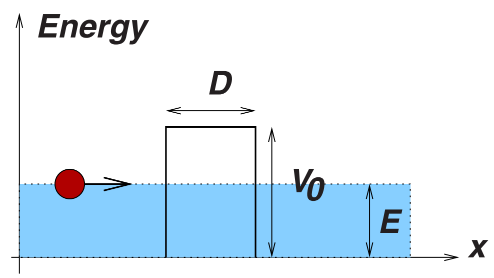

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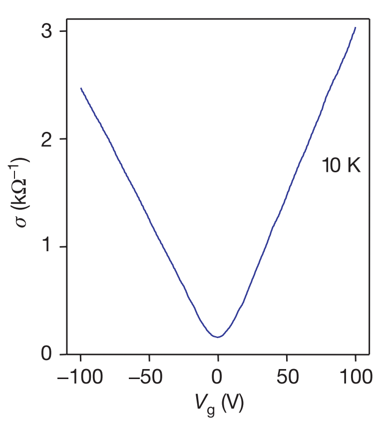
- Ambipolar



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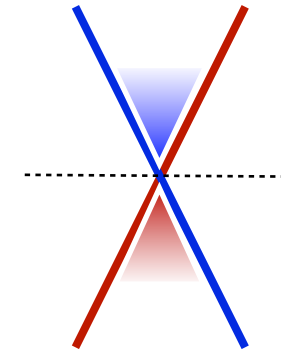

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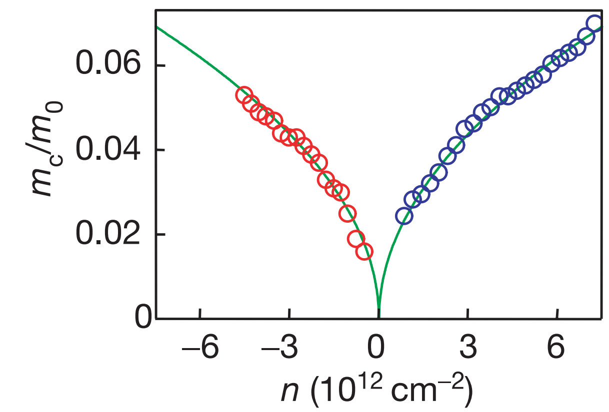

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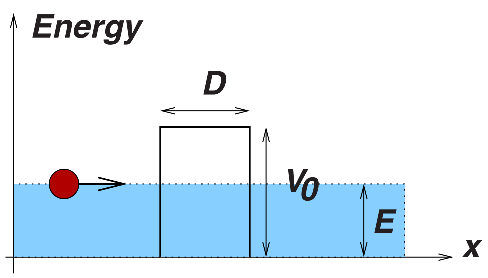

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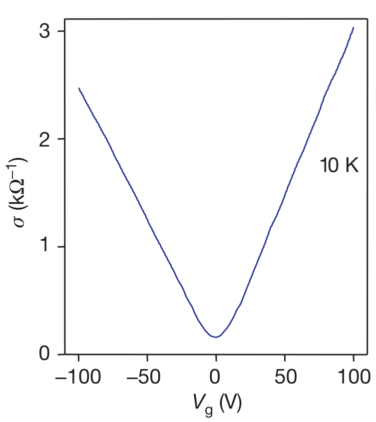

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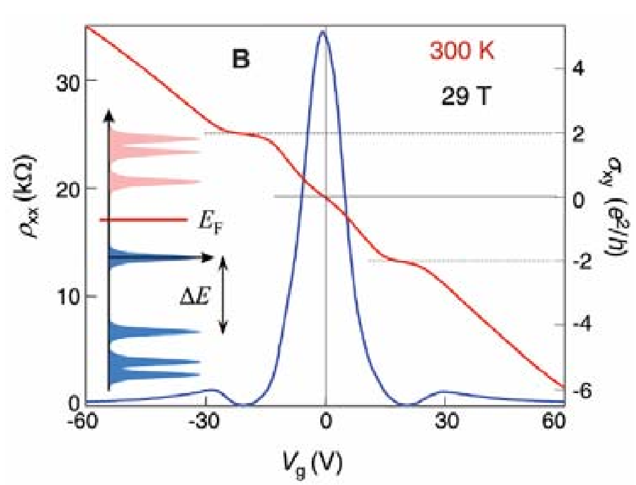

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SUPERCONDUCTIVITY

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Some experimental discoveries

nature Vol 446|1 March 2007|doi:10.1038/nature05555

LETTERS

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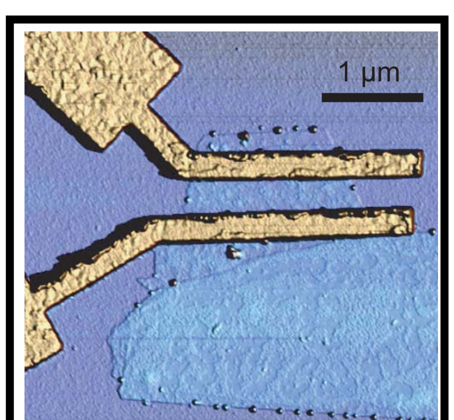
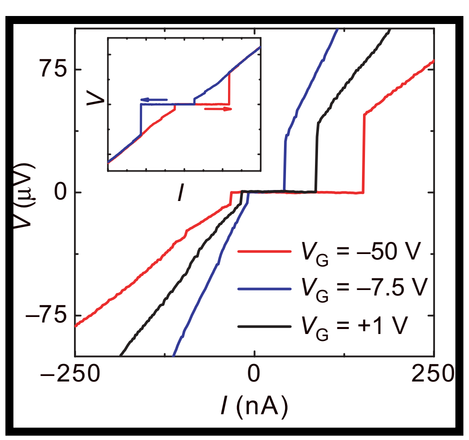
Hubert B. Heersche[1]*, Pablo Jarillo-Herrero[1]*, Jeroen B. Oostinga[1], Lieven M. K. Vandersypen[1] & Alberto F. Morpurgo[1]

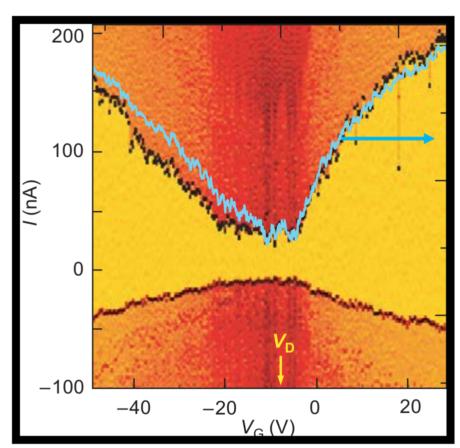
LETTERS PUBLISHED ONLINE: 6 FEBRUARY 2011 | DOI: 10.1038/NPHYS1911 nature physics

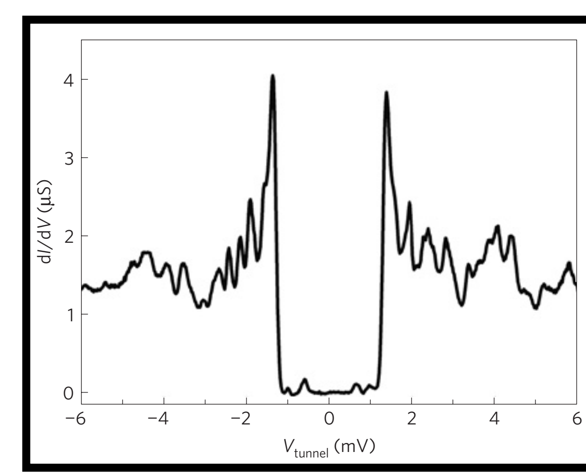
Transport through Andreev bound states in a graphene quantum dot

Travis Dirks, Taylor L. Hughes, Siddhartha Lal†, Bruno Uchoa, Yung-Fu Chen, Cesar Chialvo, Paul M. Goldbart† and Nadya Mason*









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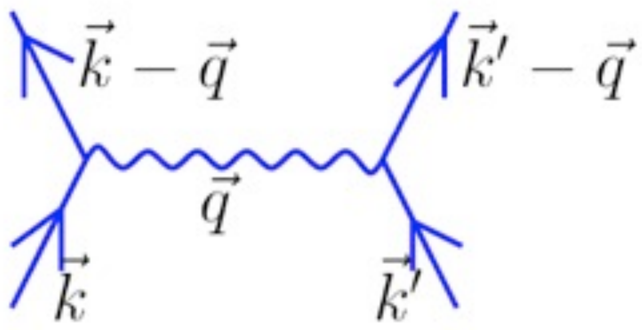

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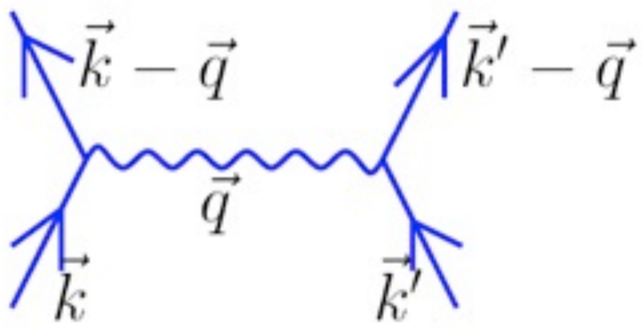

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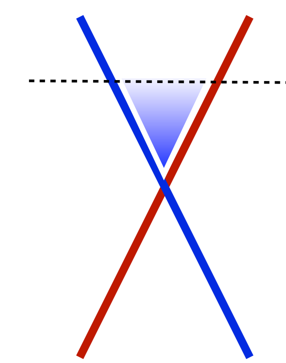

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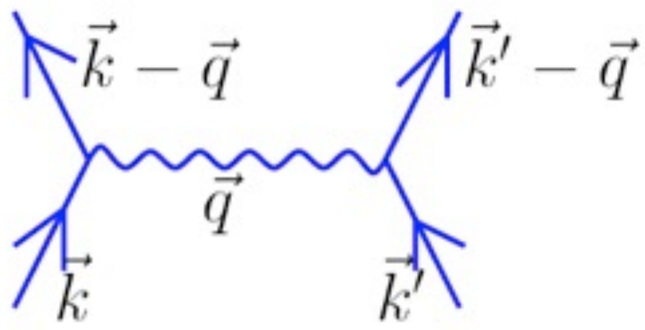

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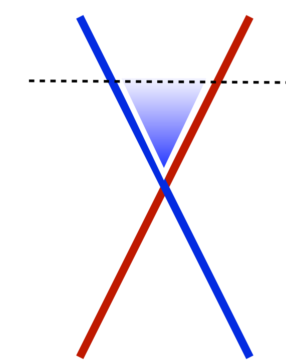

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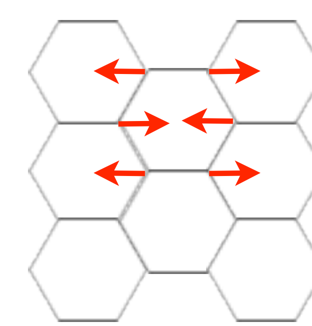

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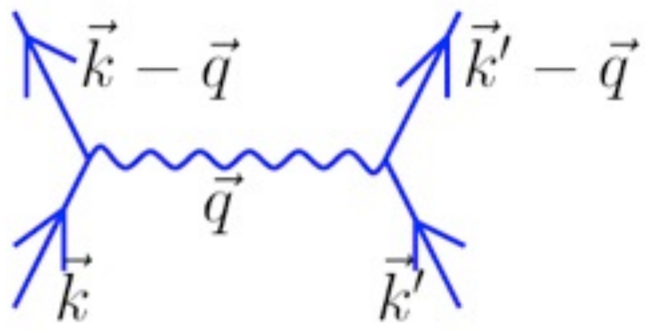

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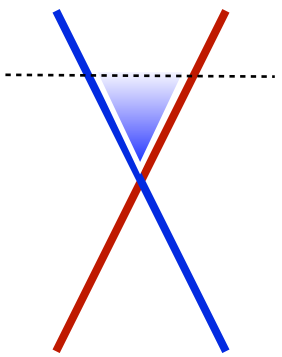

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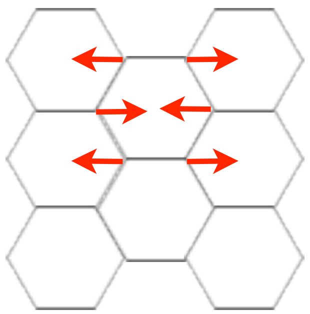
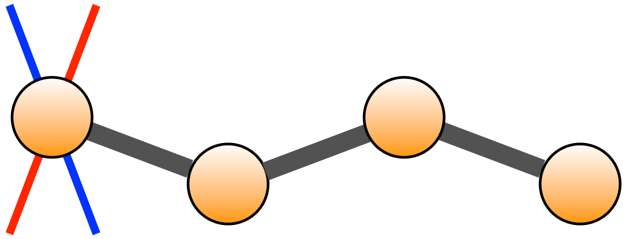


By symmetry out-of-plane modes do not couple with π electrons



Superconductivity in Graphite

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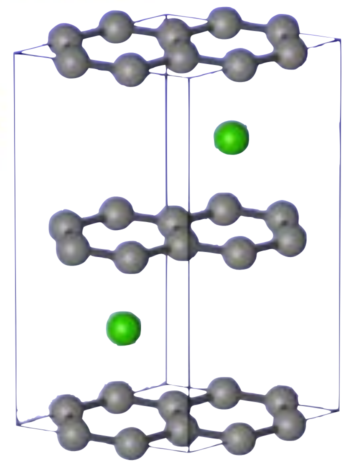

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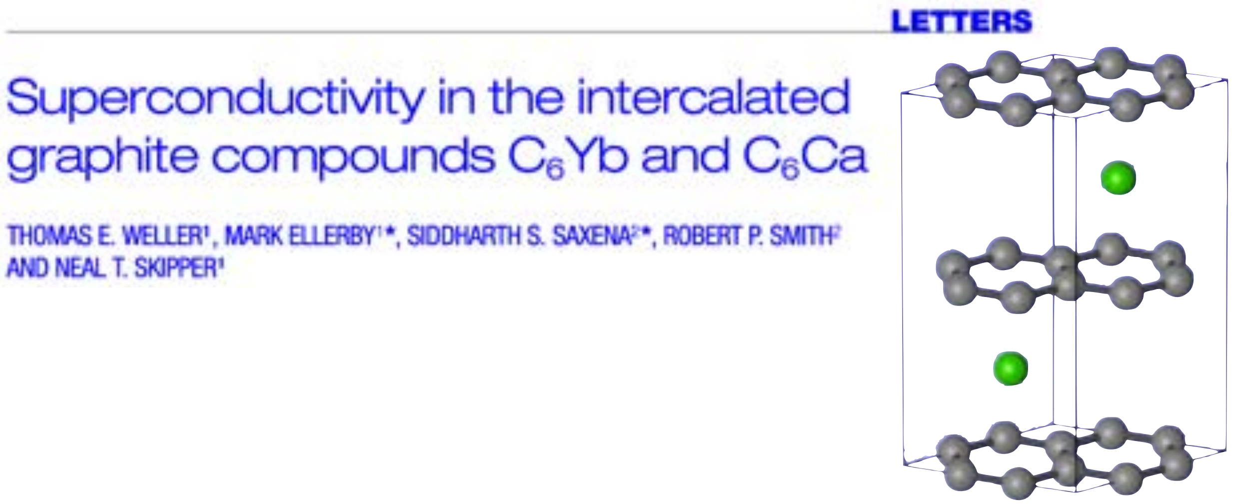
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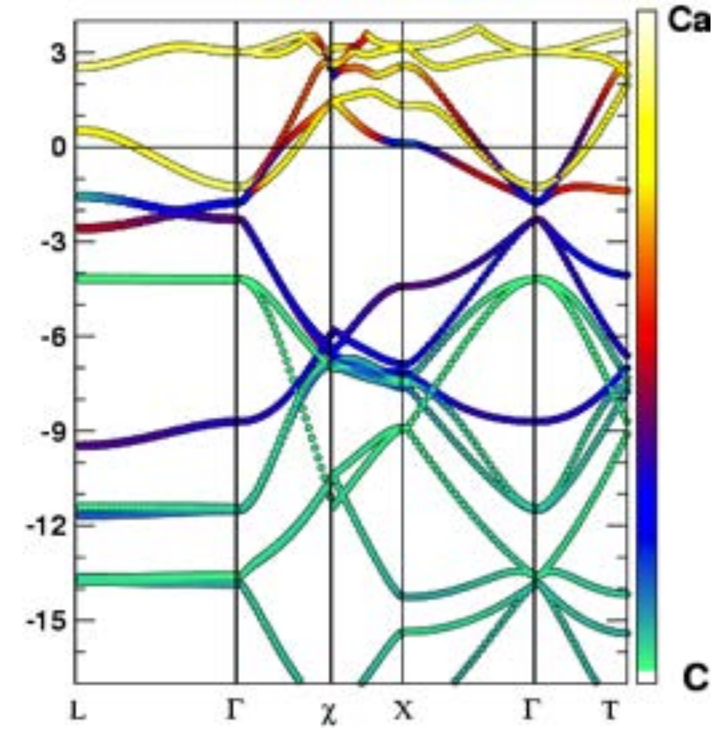

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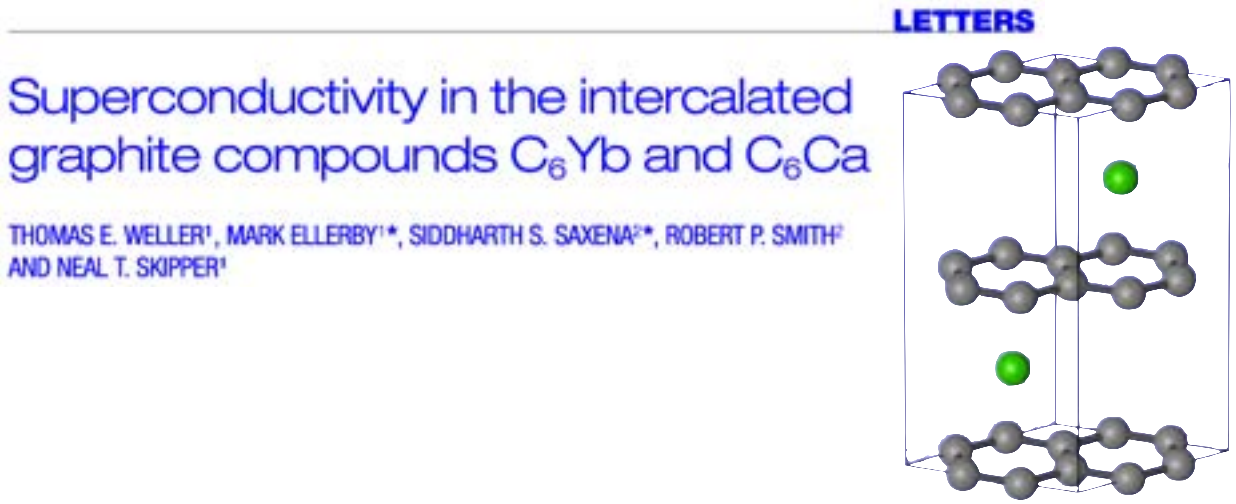
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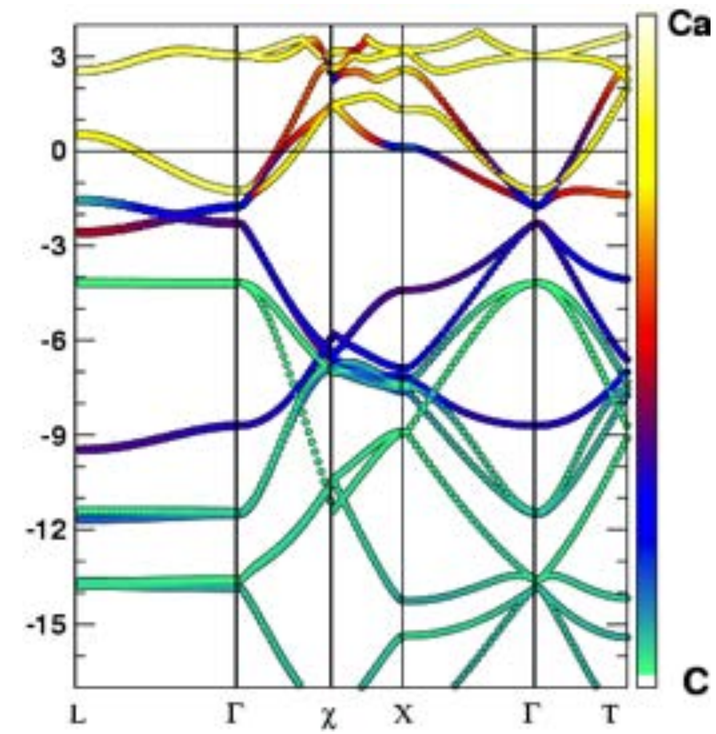

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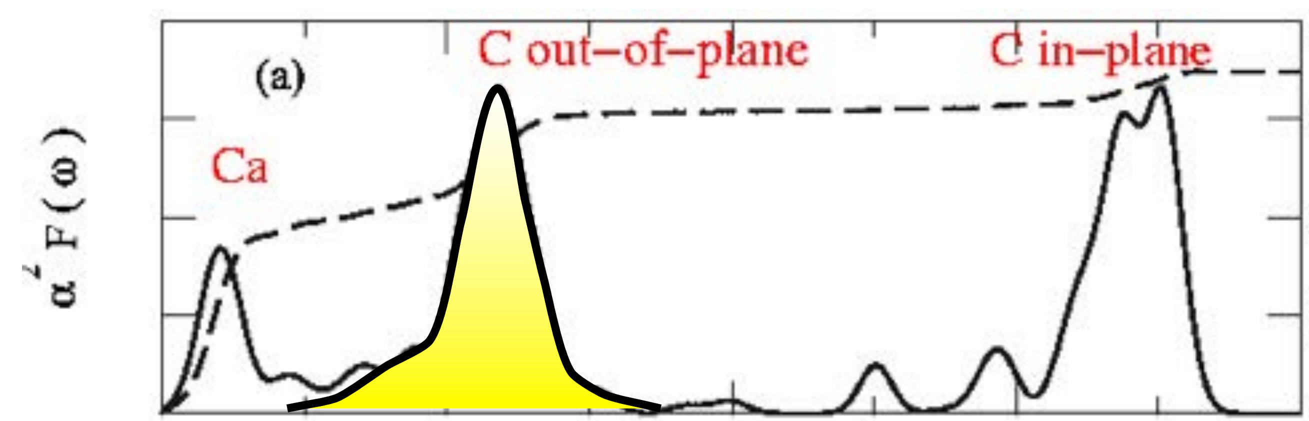

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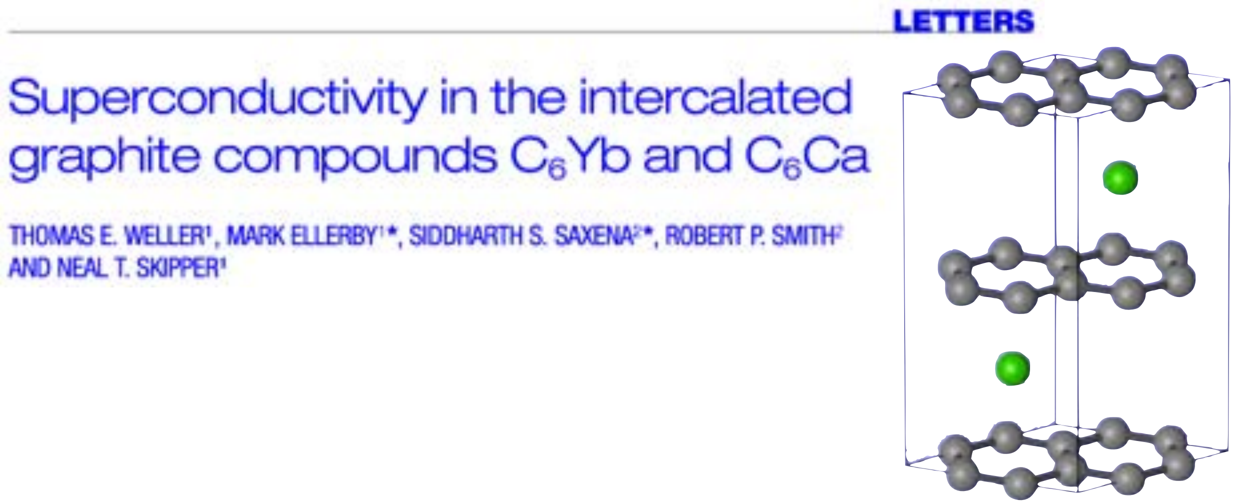
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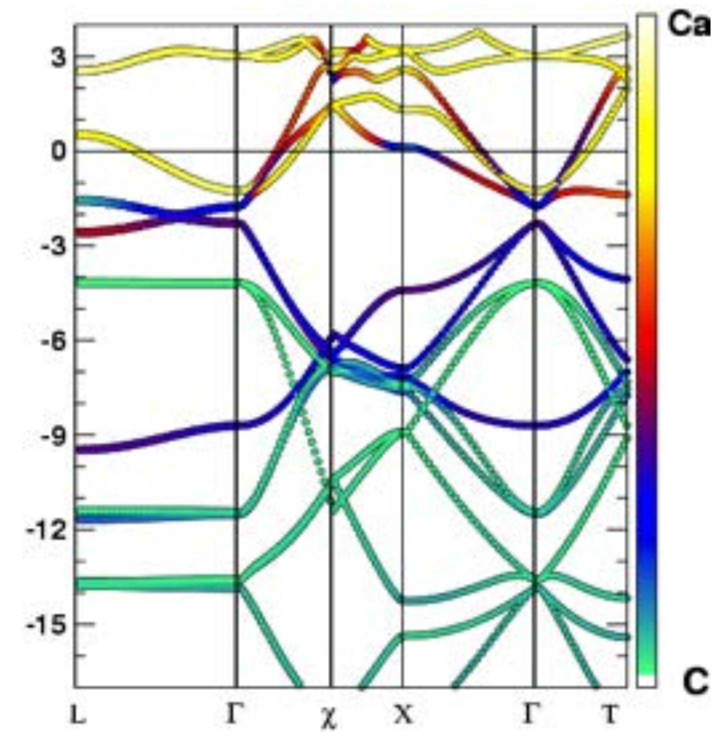

The Cambridge criterion

M. S. Dresselhaus and G. Dresselhaus, Adv. in Phys. (2002)

G. Csanyi et al, Nat. Phys. (2005)

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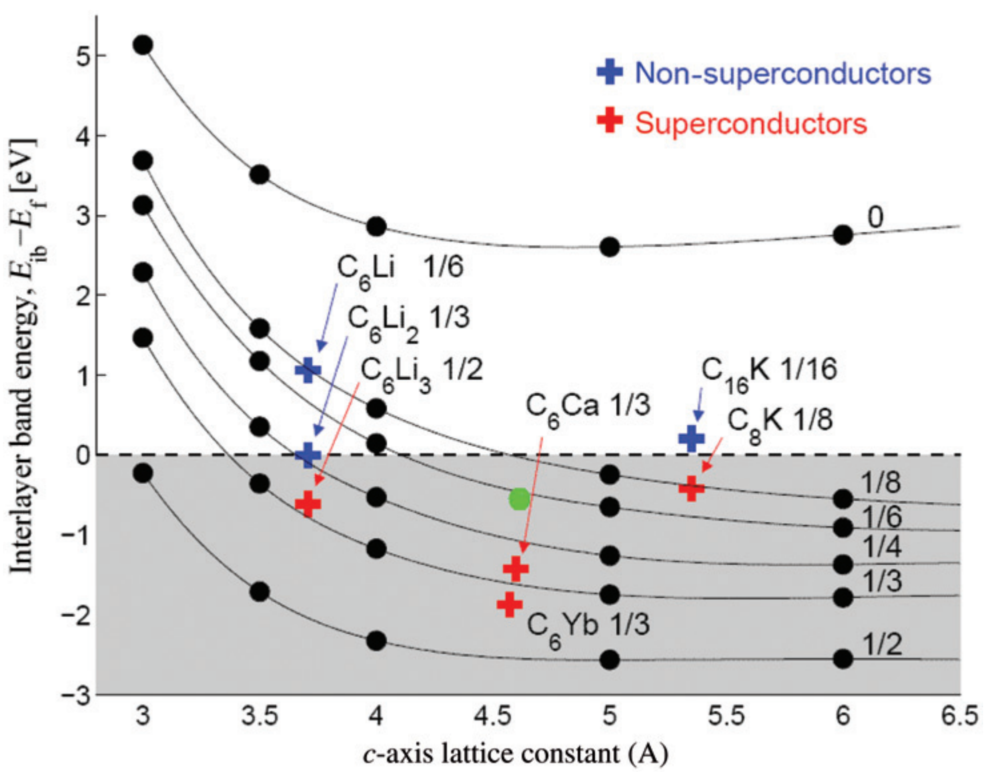

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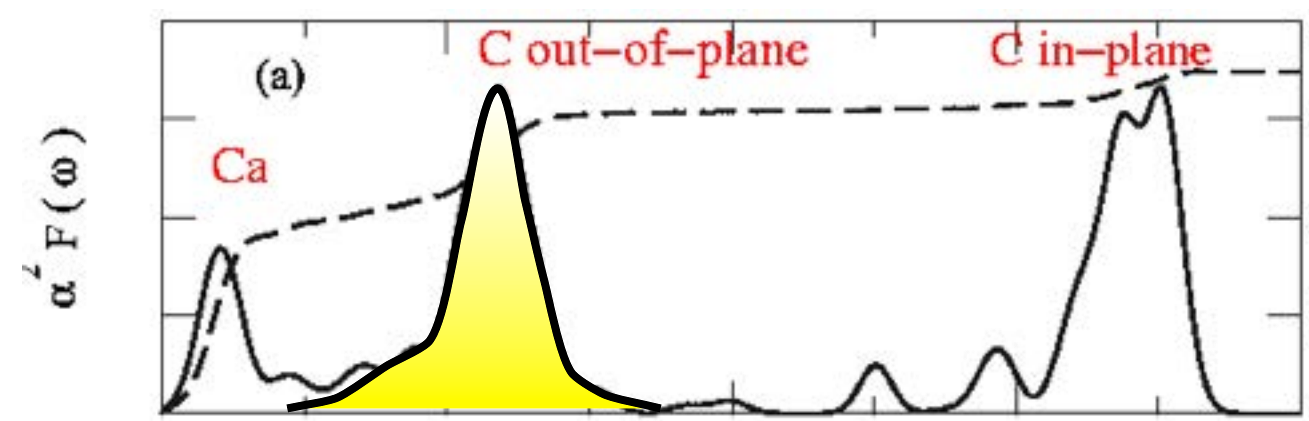

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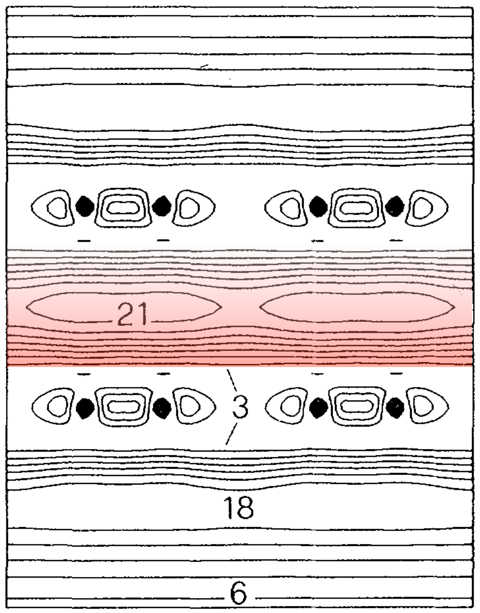

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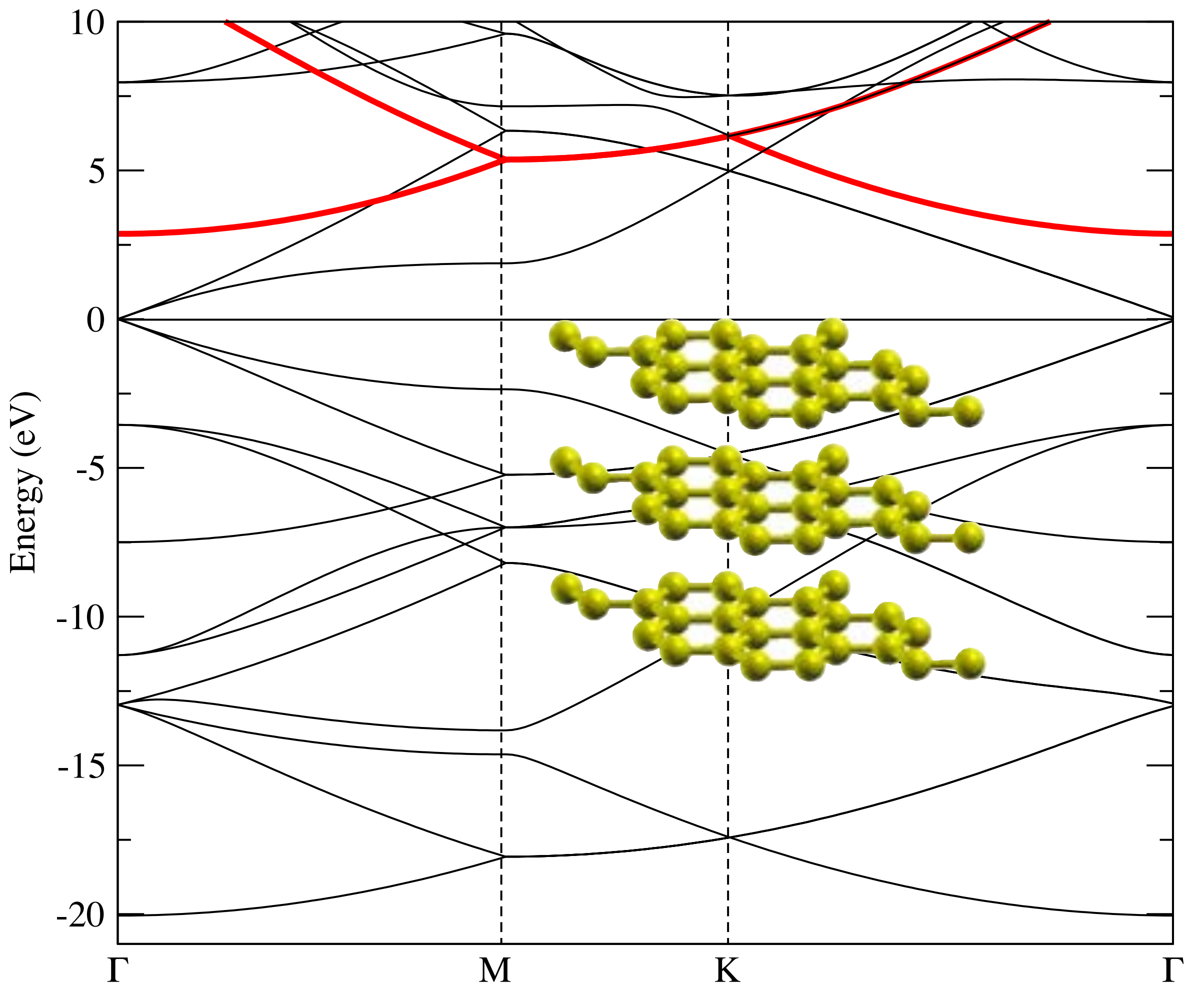

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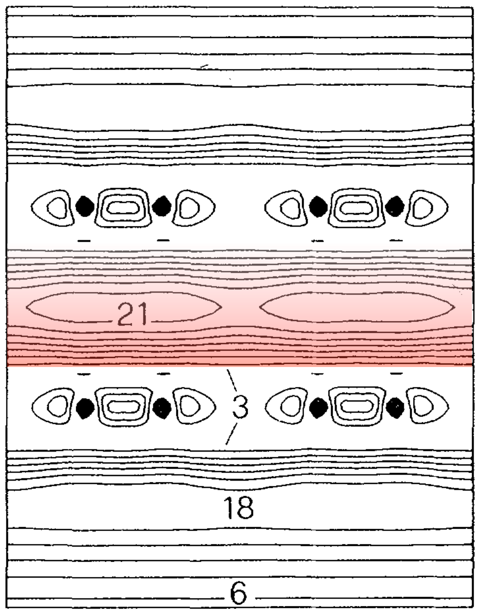

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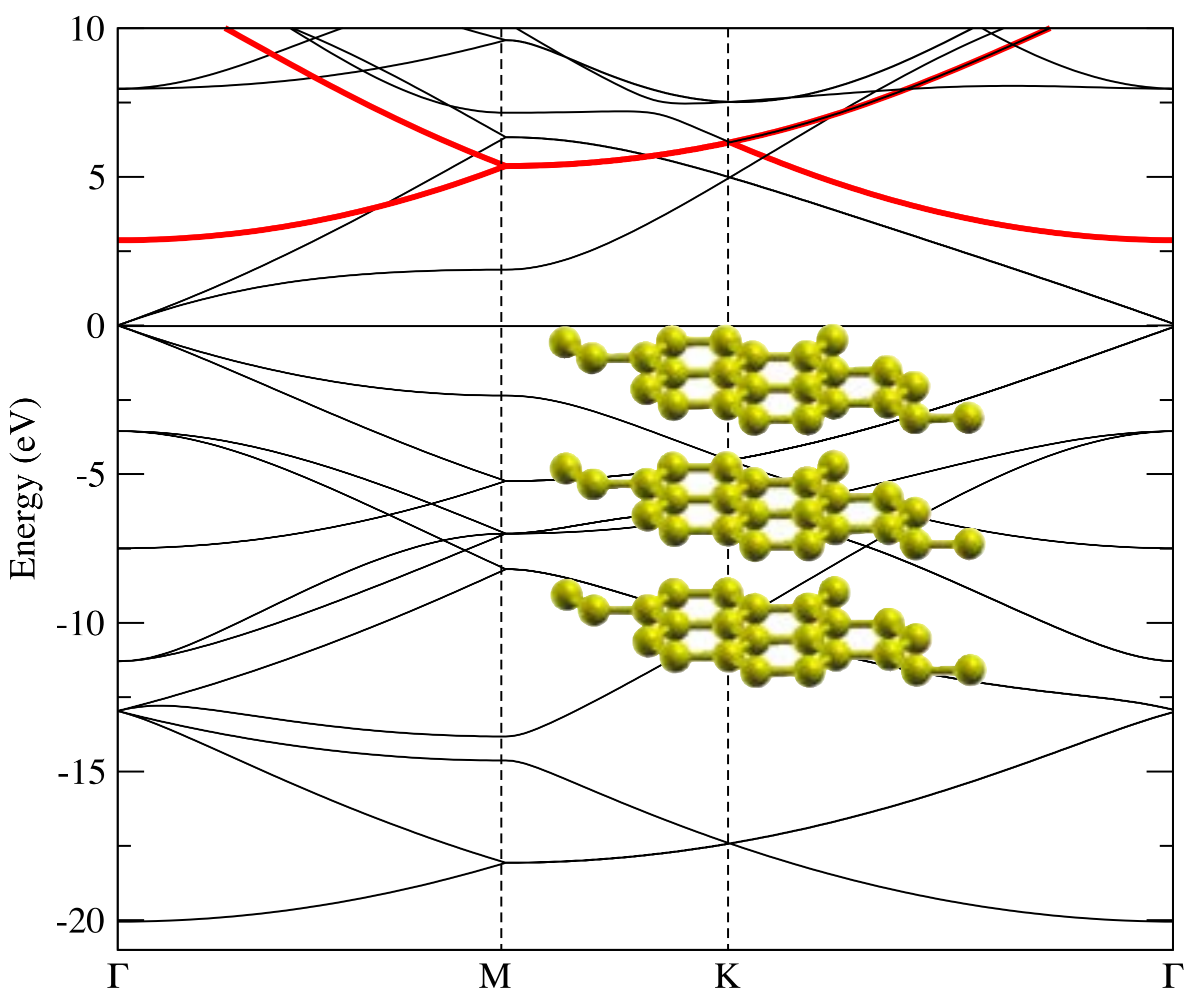
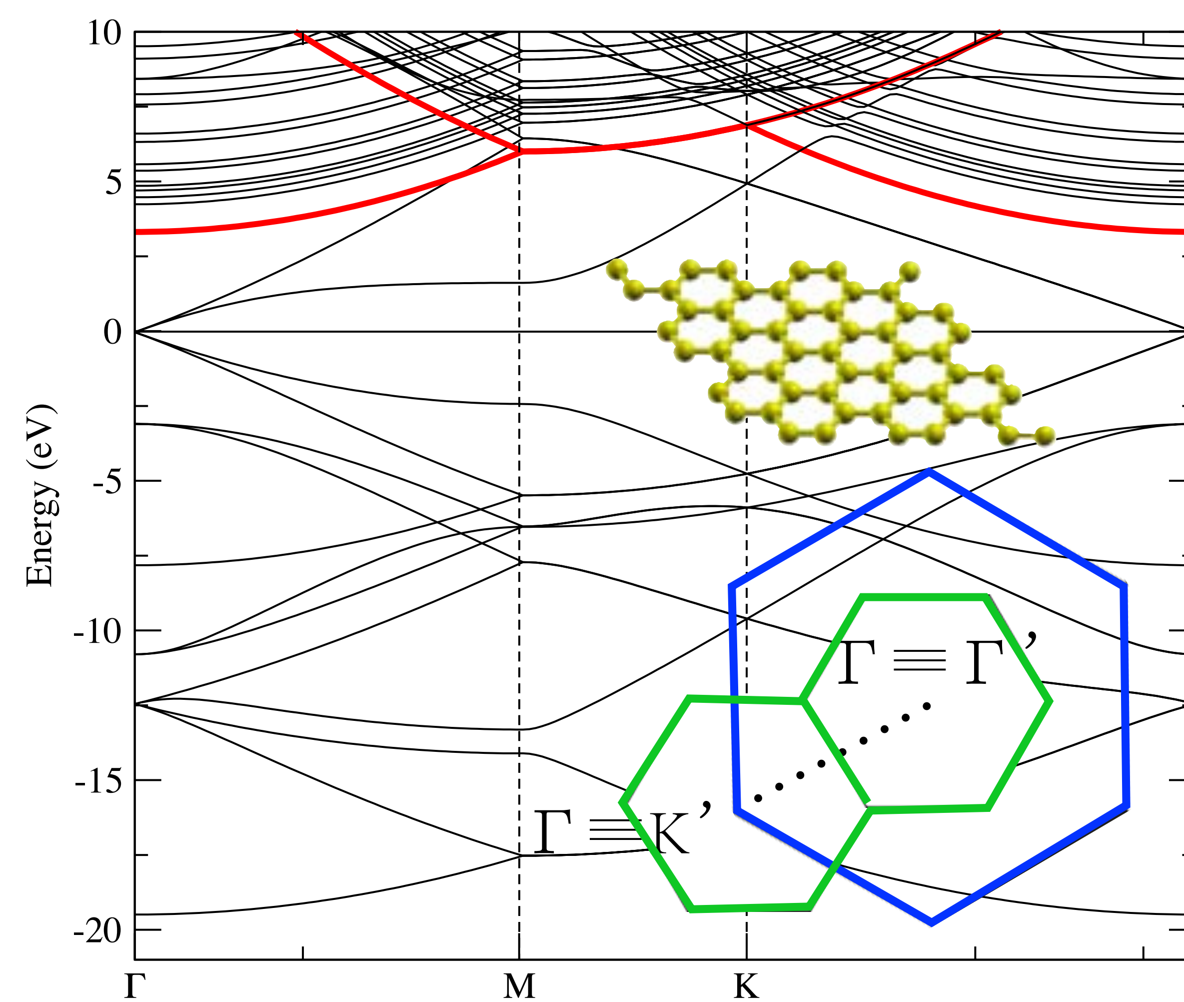
But it exists even in multiwall nanotubes, fullerenes, BN, MgB_2 and………

…….graphene



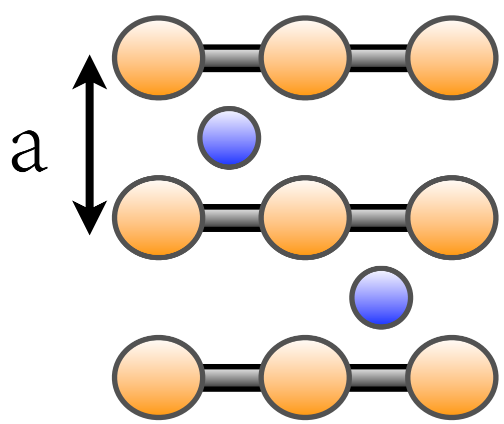


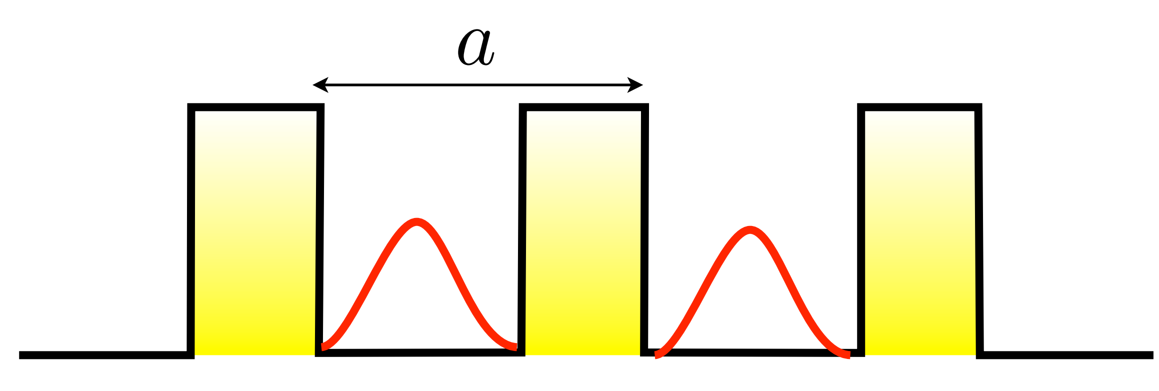
Use the interlayer state: put it at E_F

Interlayer state is a truly 2D free-electron state in xy direction, $\psi(x,y) = e^{i(k_x x + k_y y)}$

However, in the z direction is not exactly "free".

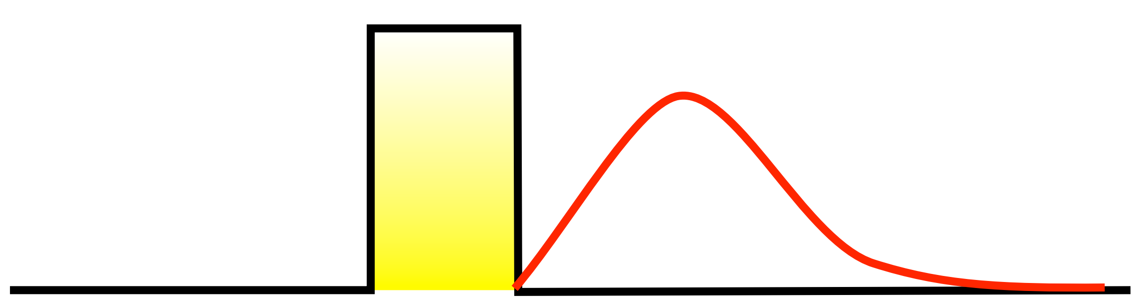
Kronig-Penney model of bulk GIC





$$E_n = n^2 \frac{\hbar^2}{2m} \frac{\pi^2}{a^2}$$

The interlayer state energy decreases removing the quantum confinement along z



$$a \to \infty$$

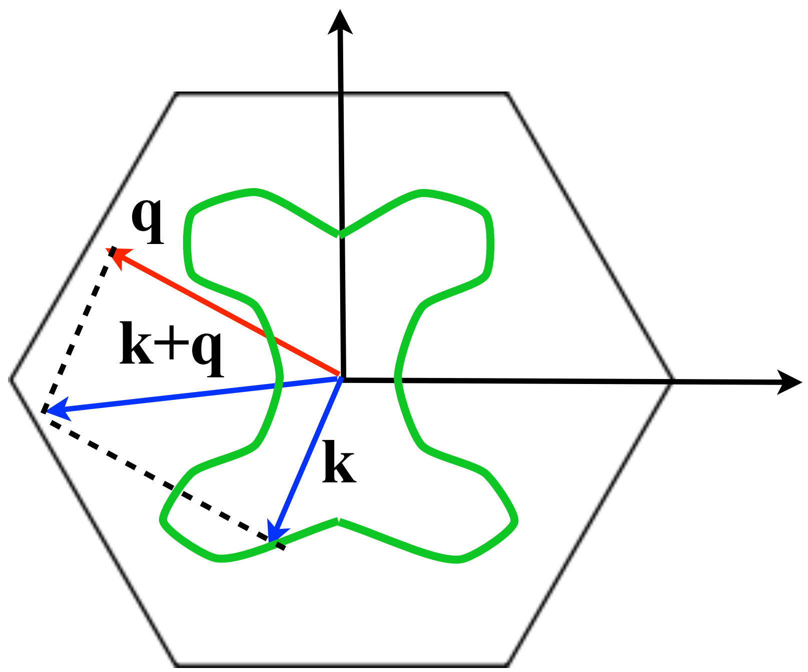
that is Metal adatoms on Graphene

Metal doped Graphene

We performed first-principles Density Functional Theory calculation of structural, electronic, dynamical and superconducting properties of metal adatoms on Graphene

The electron-phonon matrix element

$$g^{\nu}_{nm}(\mathbf{k},\mathbf{k}+\mathbf{q}) \propto \langle \mathbf{k}+\mathbf{q}m | \frac{\delta v_{\mathrm{SCF}}}{\delta \mathbf{u}_{\mathbf{q}s}} | \mathbf{k}n \rangle$$



Phonon linewidth

$$\gamma_{\mathbf{q}\nu} = \frac{4\pi\omega_{\mathbf{q}\nu}}{N_k(T)} \sum_{\mathbf{k},n,m}^{N_k(T)} |g^{\nu}_{nm}(\mathbf{k},\mathbf{k}+\mathbf{q})|^2 \delta(\varepsilon_{\mathbf{k}n})\delta(\varepsilon_{\mathbf{k}+\mathbf{q}m})$$

$$\lambda_{\mathbf{q}\nu} = \frac{\gamma_{\mathbf{q}\nu}}{2\pi\omega^2_{\mathbf{q}\nu}\mathcal{N}_{\mathrm{s}}}$$

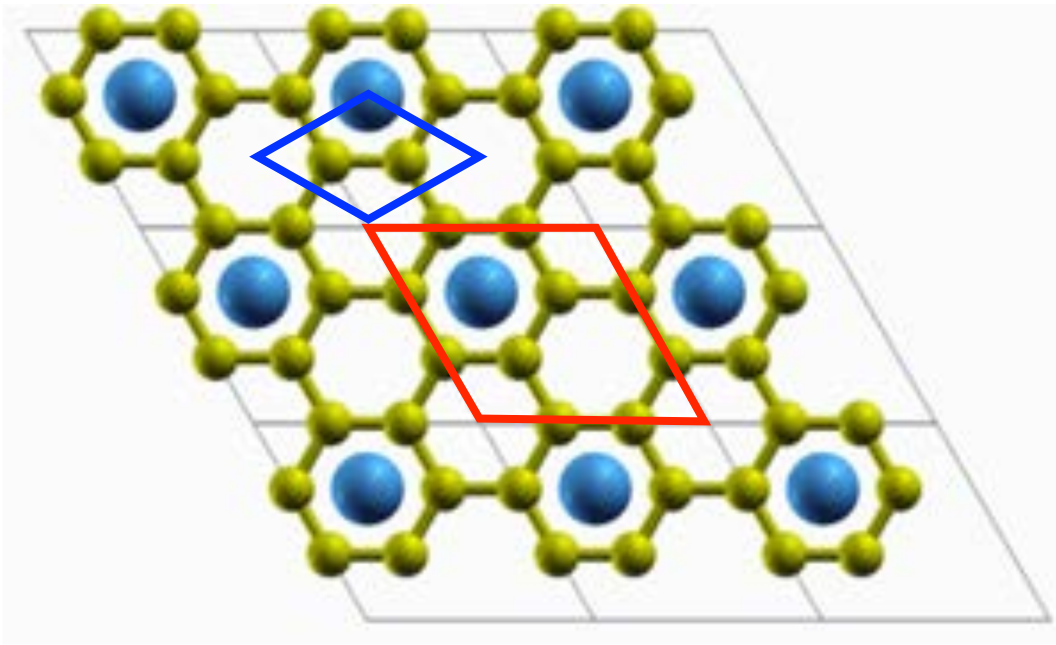
The Eliashberg function

$$\alpha^2 F(\omega) = \frac{1}{2N_q} \sum_{\mathbf{q}\nu} \lambda_{\mathbf{q}\nu}\omega_{\mathbf{q}\nu}\delta(\omega - \omega_{\mathbf{q}\nu})$$

$$T_c = \frac{\omega_{log}}{1.20} exp\{-\frac{1.04(1+\lambda)}{\lambda-\mu^*(1+0.62\lambda)}\}$$

Metal doped Graphene

- Ca is the first choice (CaC_6 has Tc=11.5 K)
- Ca adsorbs in the hollow site at 2.24 Å
- IL at E_F ?



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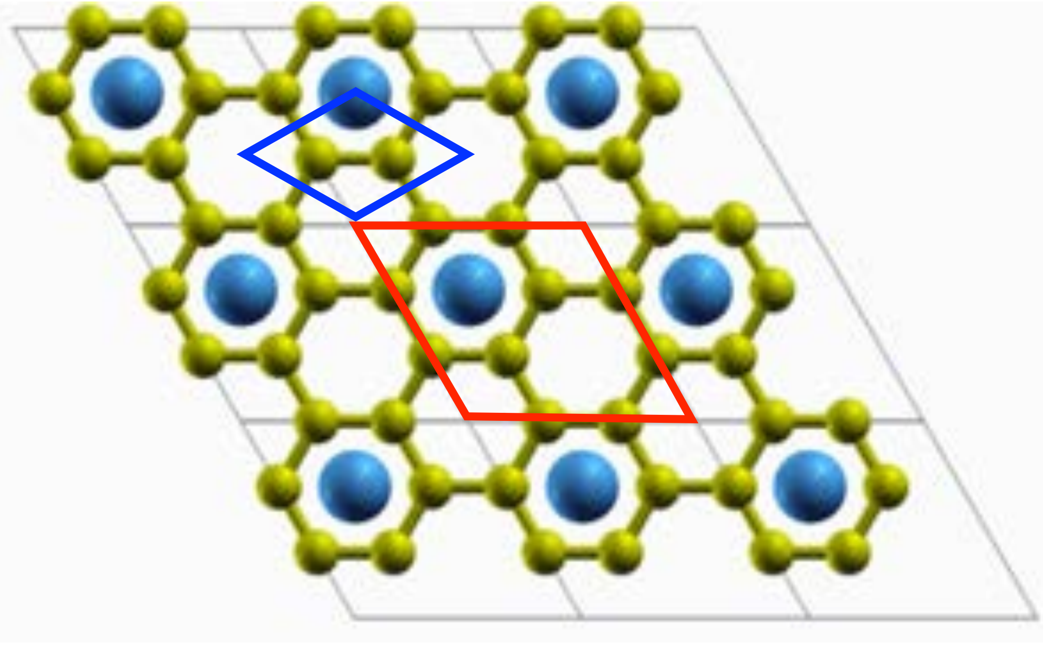
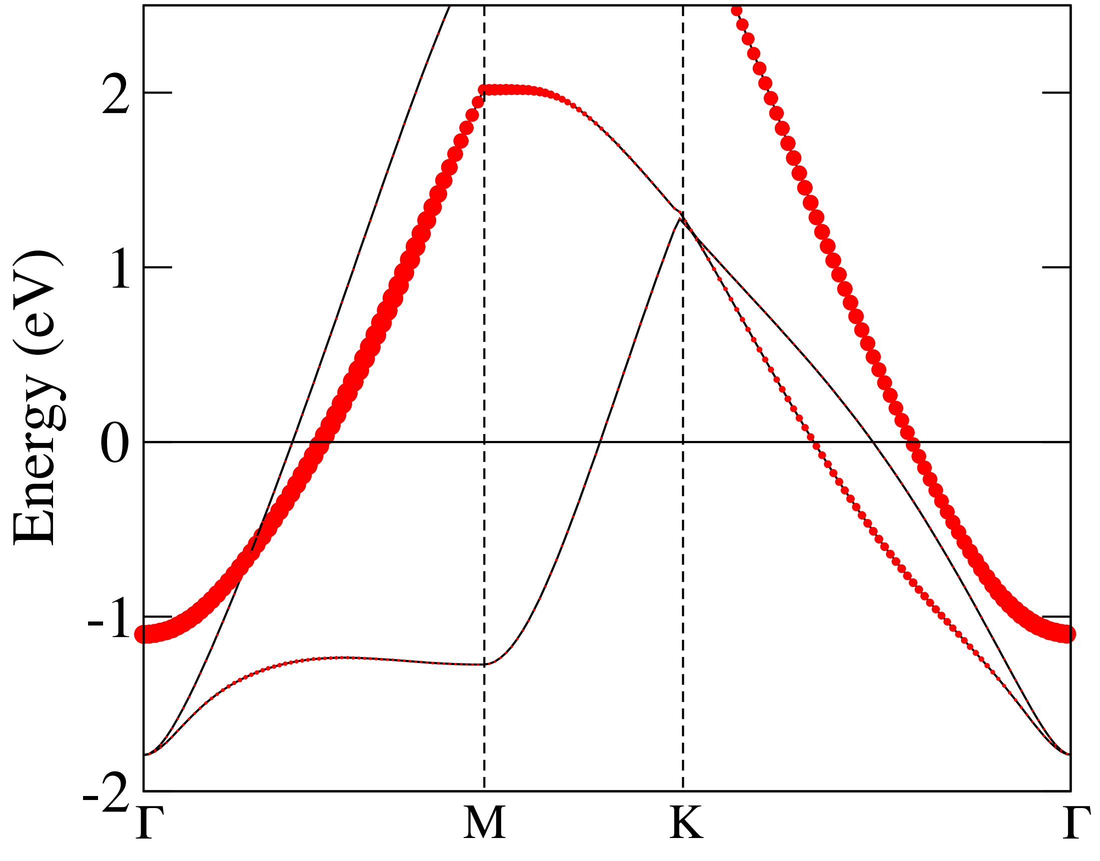
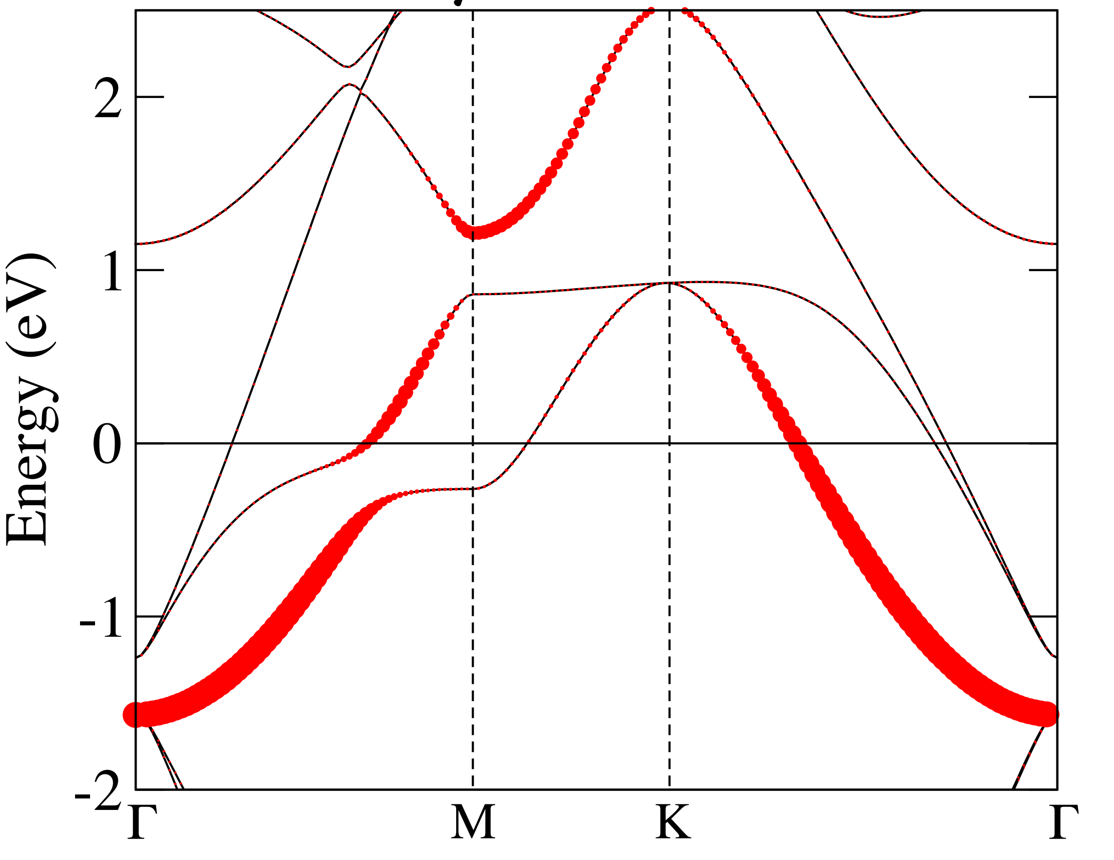


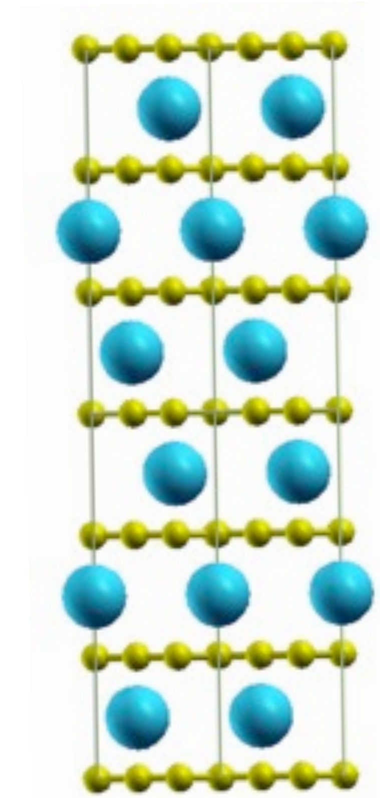
Bulk

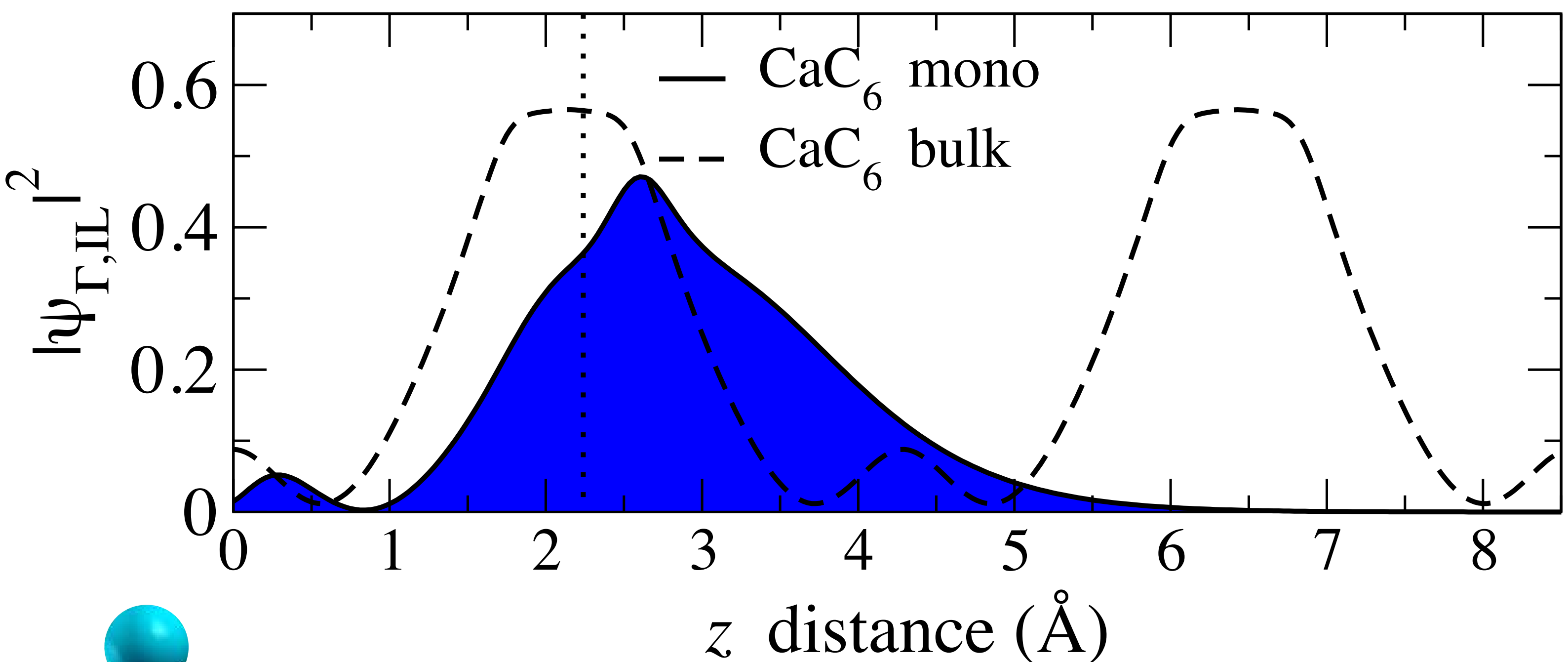


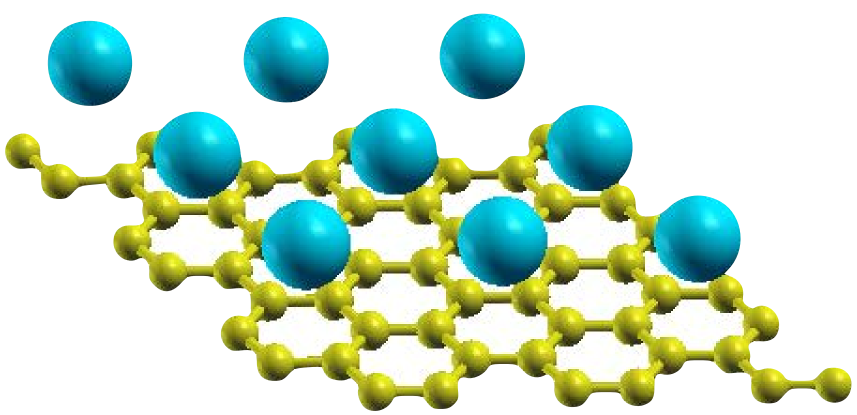
Monolayer

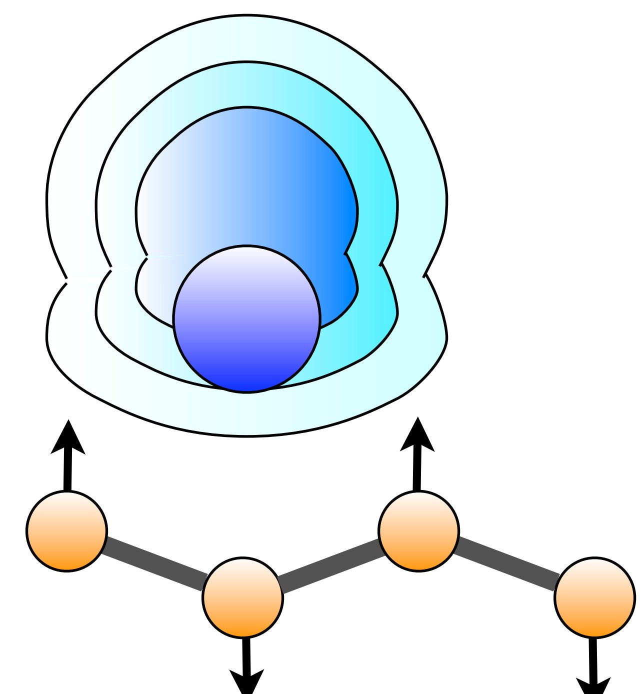


Ca on graphene:
The interlayer state





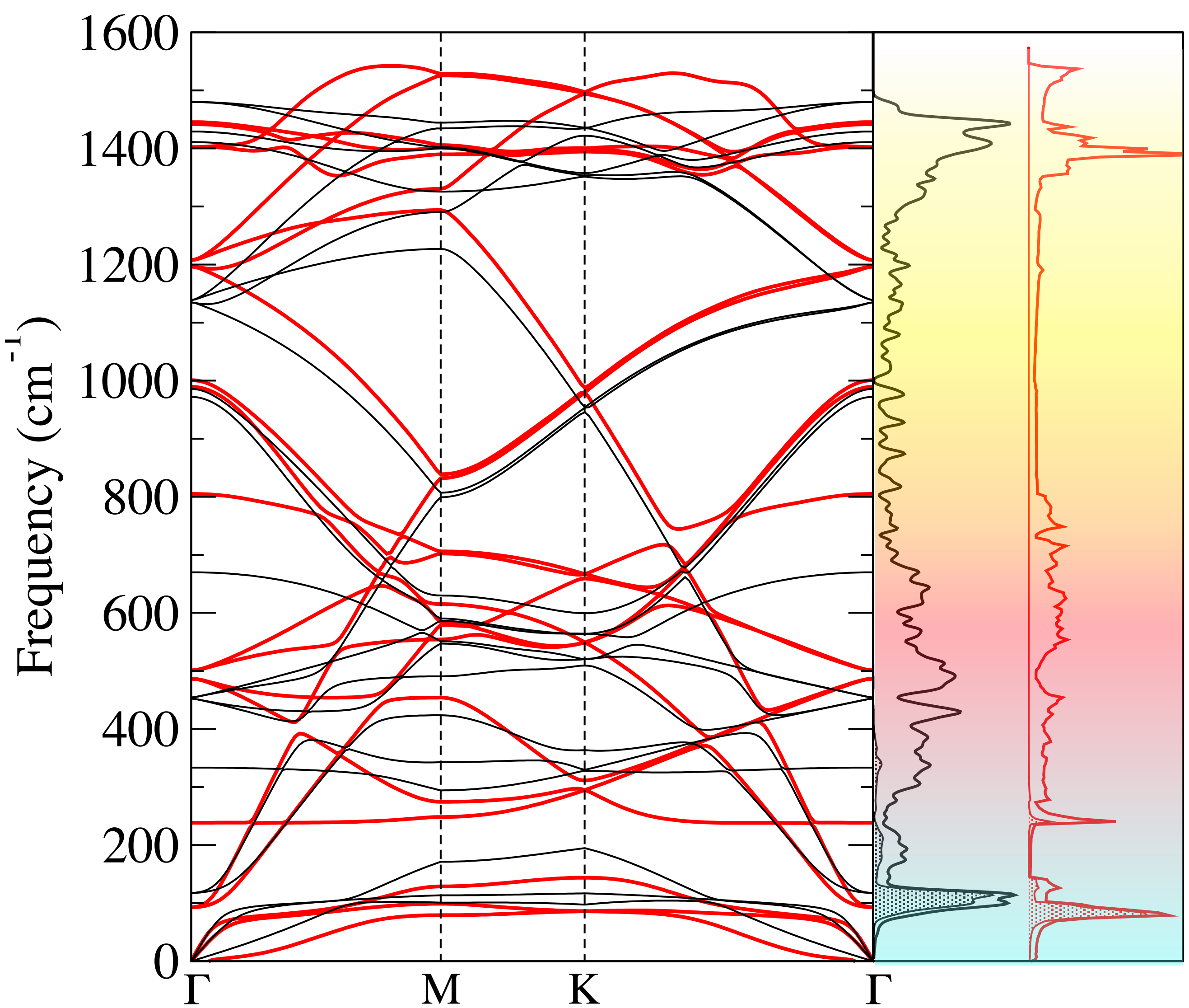


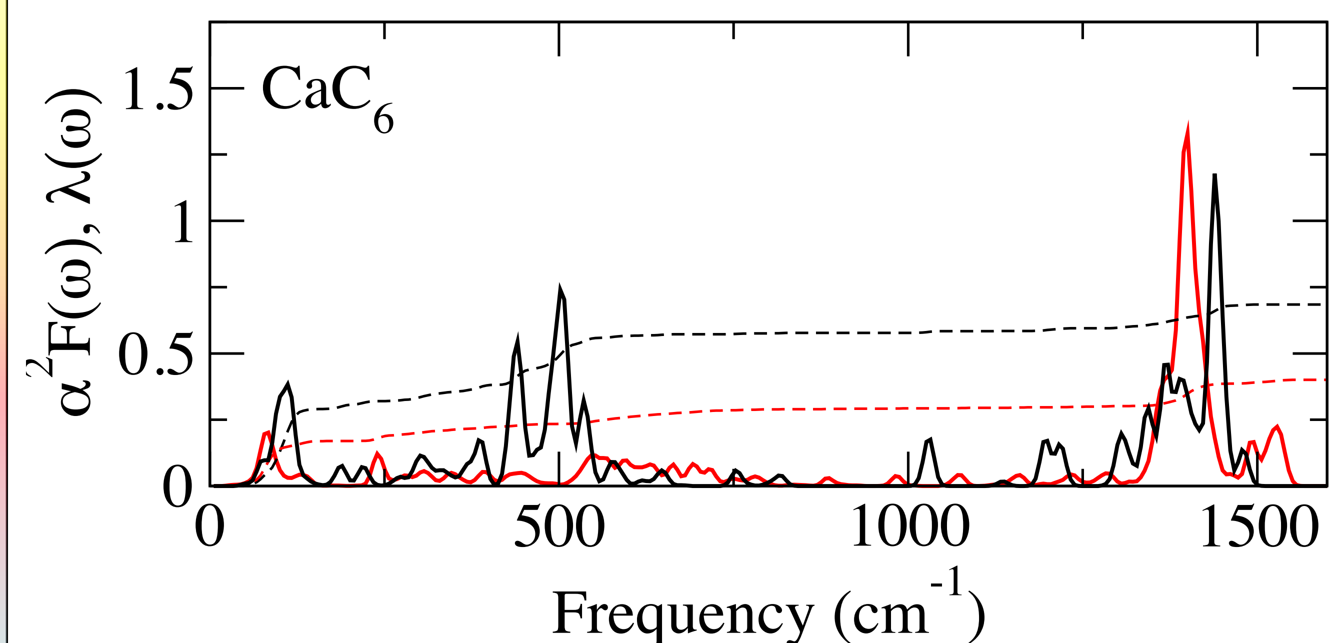


The IL moves away from graphene, reducing the electron-phonon coupling

with C_z modes

Ca on graphene: electron-phonon coupling





The coupling with C_z modes, present in the bulk compound, is small in the monolayer case

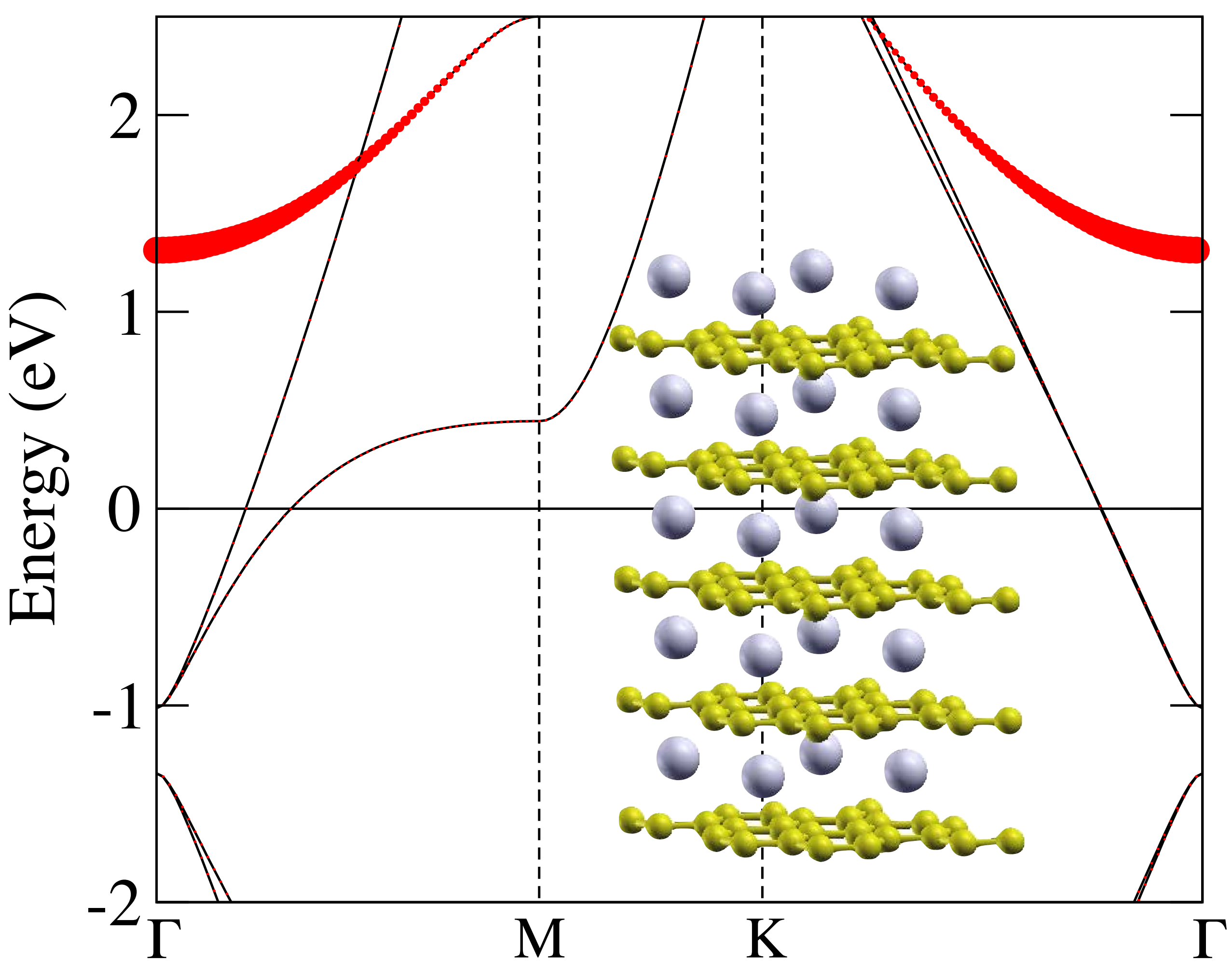
The total electron-phonon coupling is $\lambda = 0.40$ with an extimated T_c= 1.4 K ($\lambda = 0.70$ and T_c= 11.5 K)

Removal of quantum confinement reduces λ : Bulk better than Film

Lithium doped Graphene

- There is at least one case among GICs that can be further explored, stage-1 Lithium GIC, LiC_6.
- IL state is completely empty: the strong quantum confinement prevents its occupation
- It is not superconducting

Removal of confinement along c direction should bring the IL at the Fermi level



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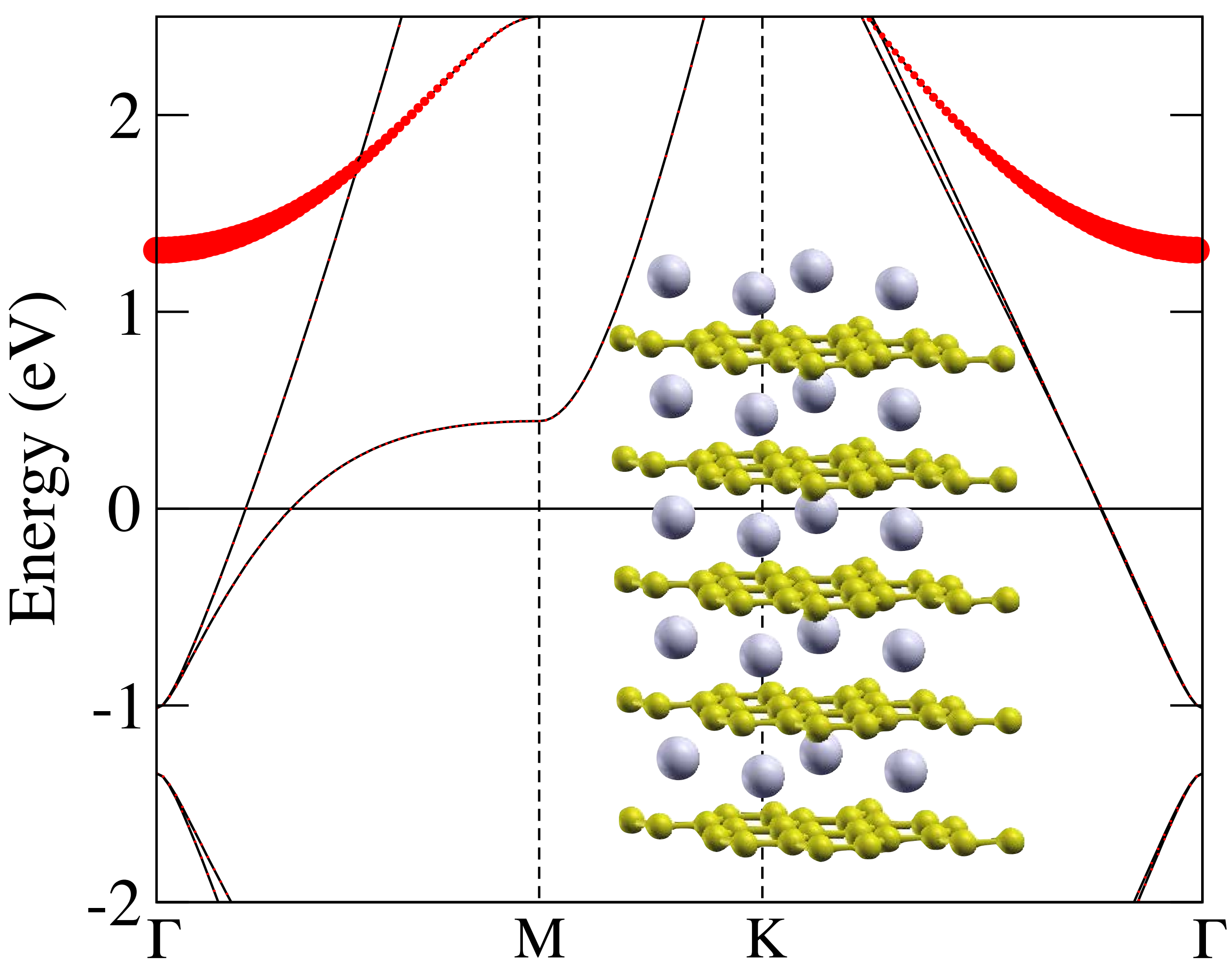
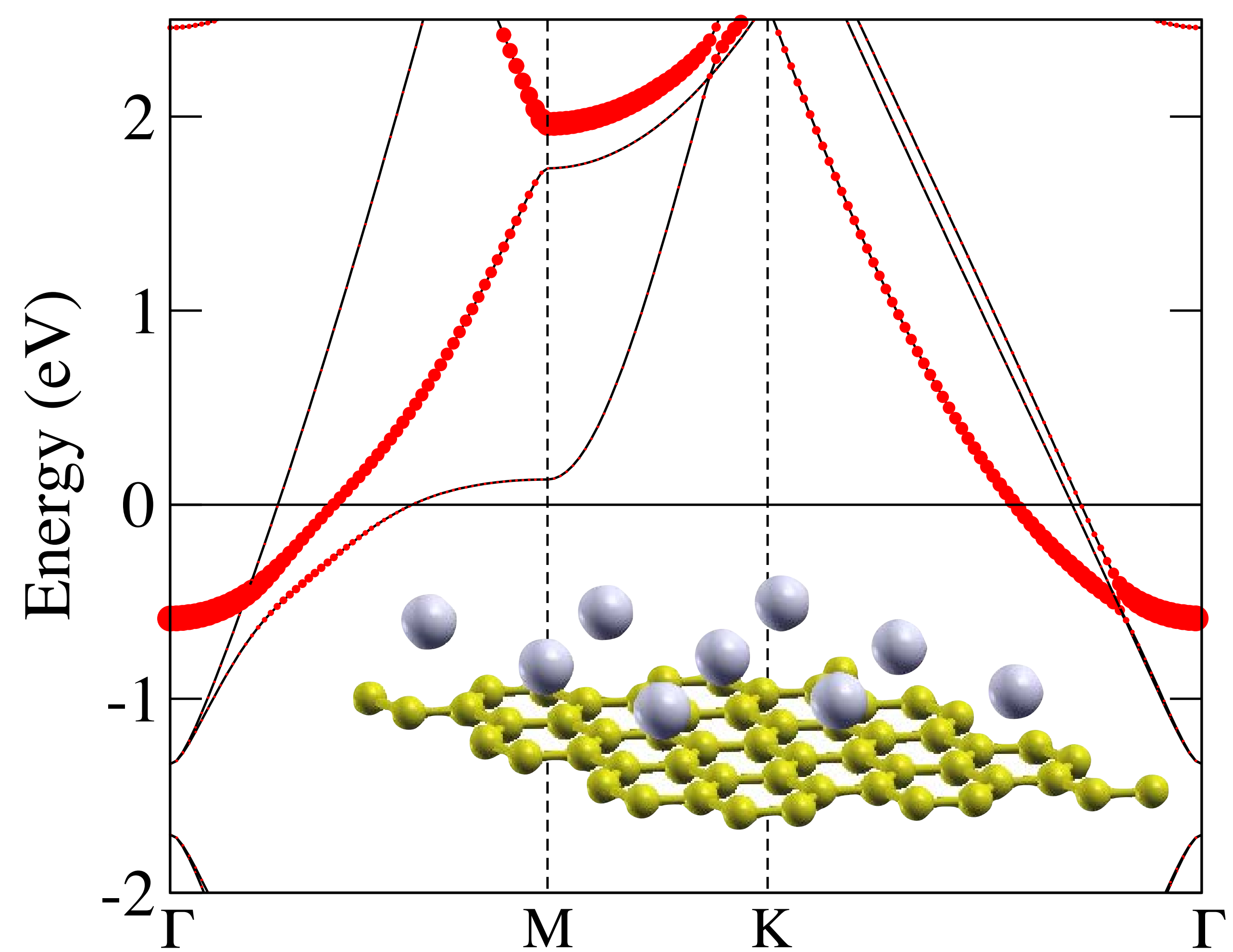
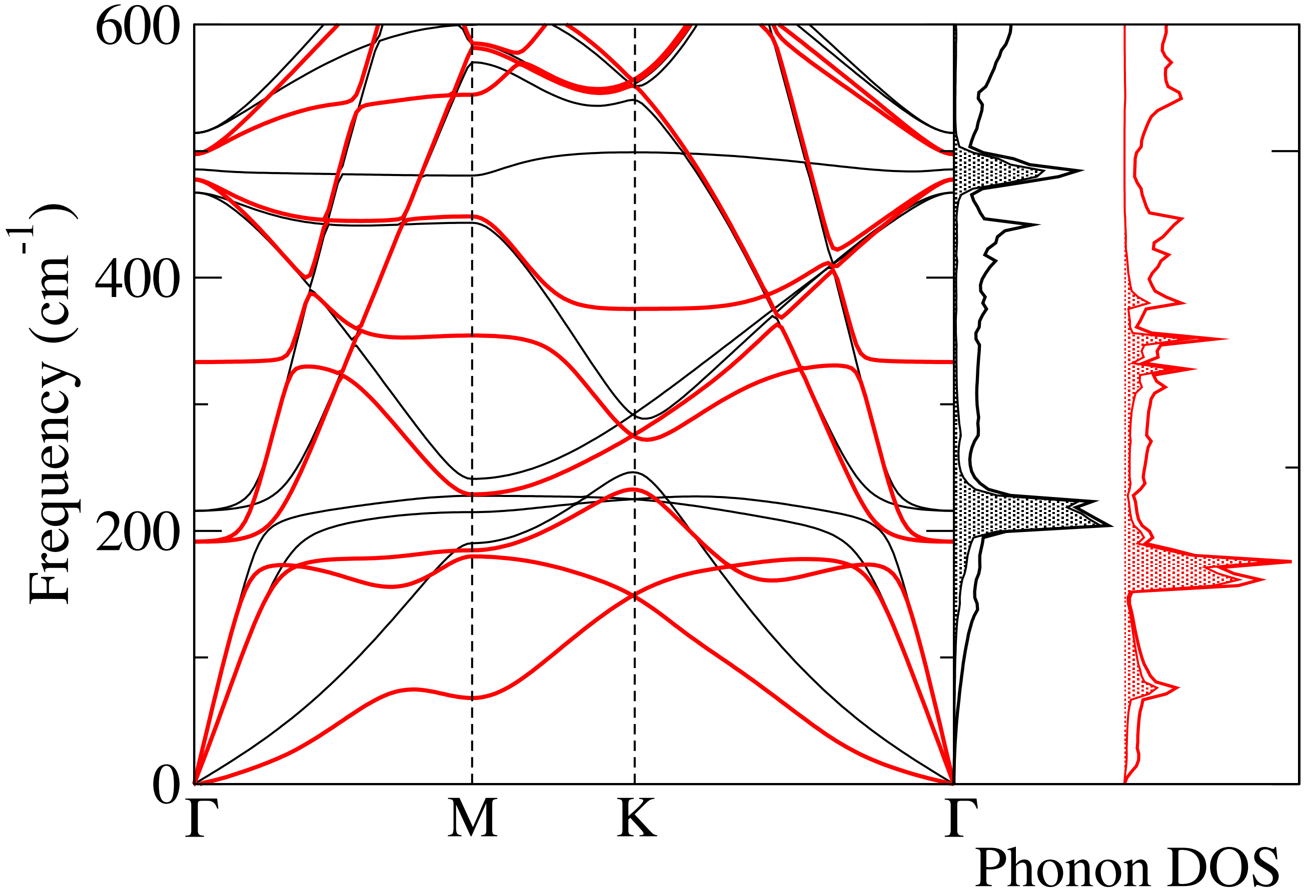
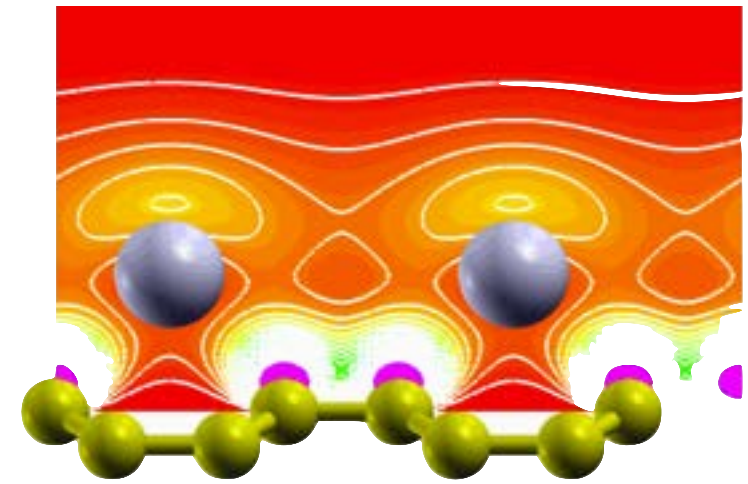
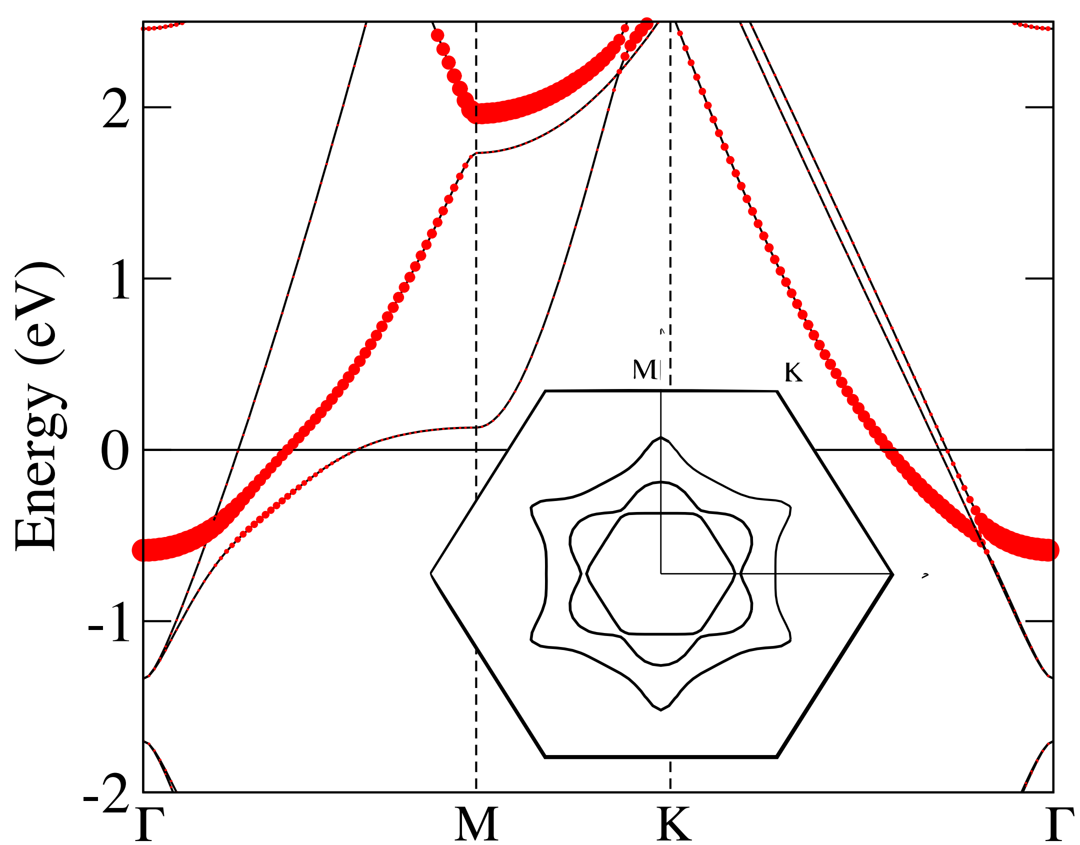


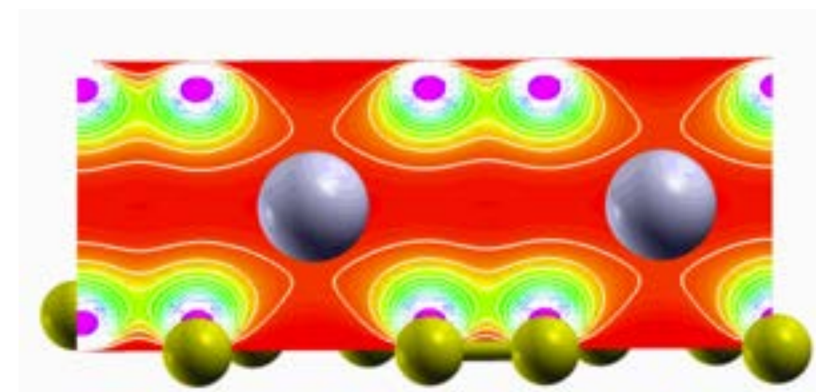


Lithium doped Graphene



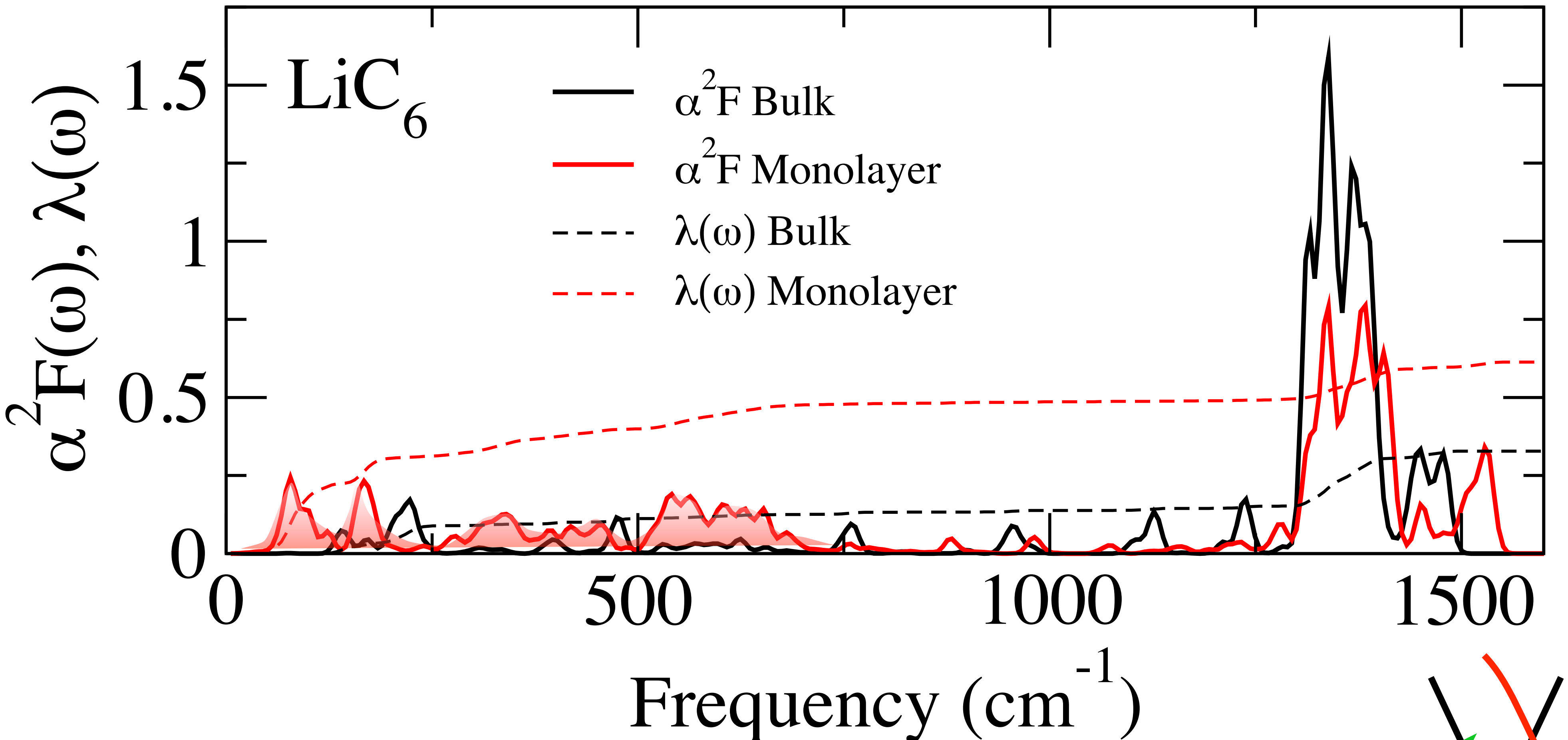


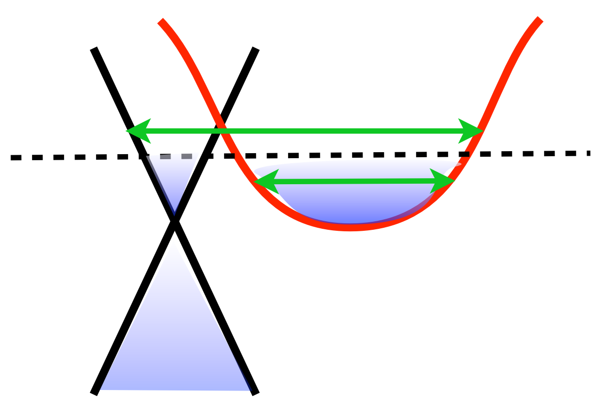




- IL state at the Fermi level
- Softening of Li and C_z modes
- Increase of DOS at E_F

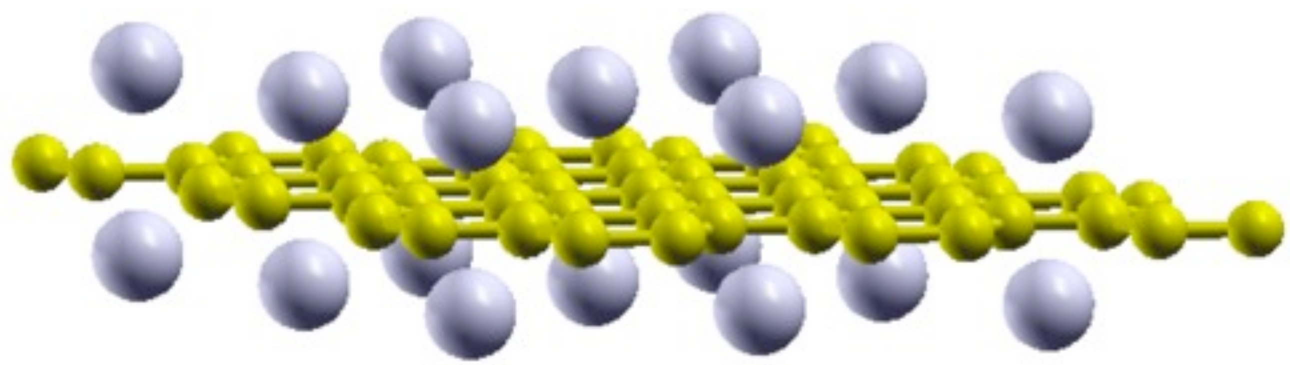
Lithium doped Graphene
Electron-phonon coupling

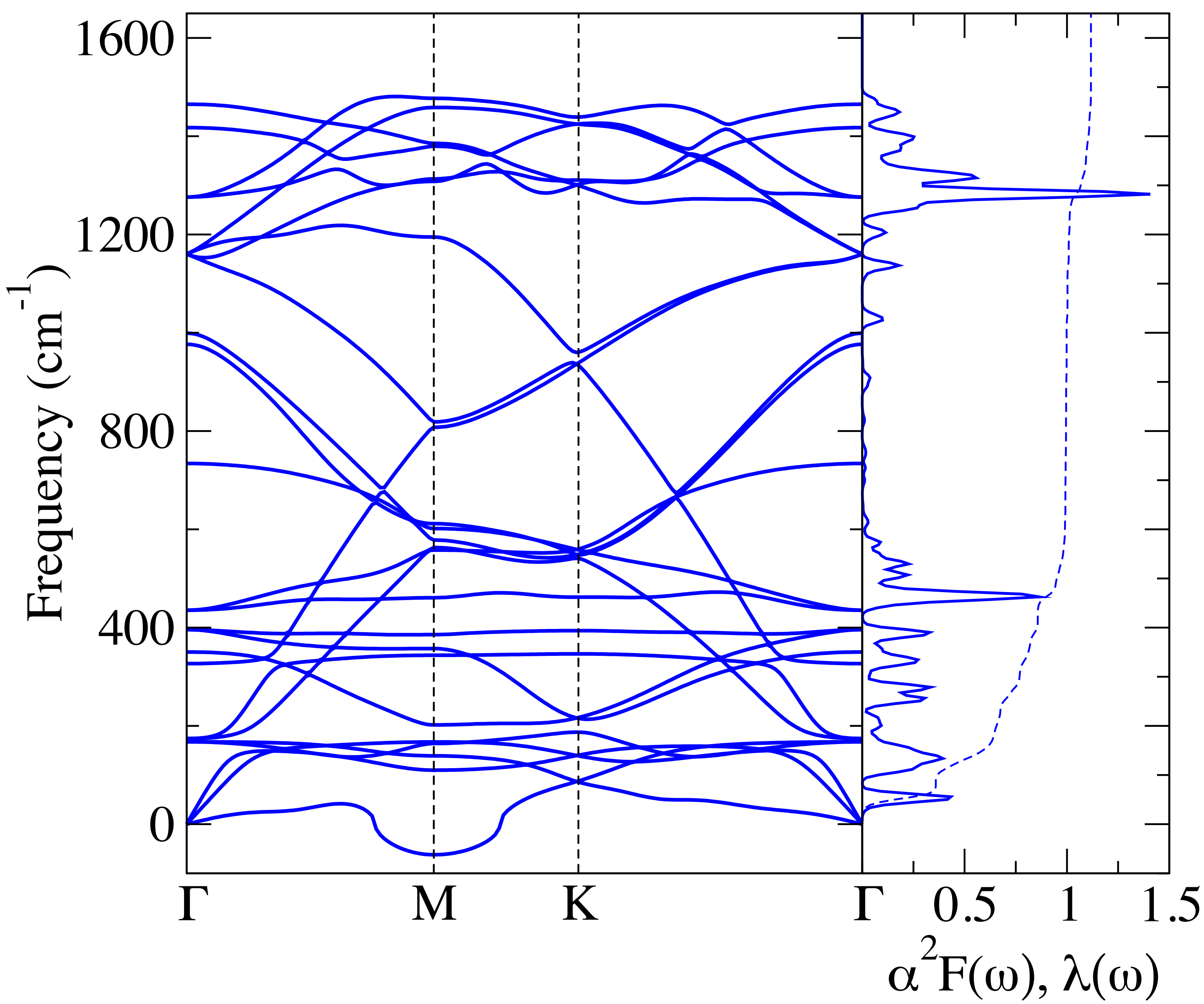


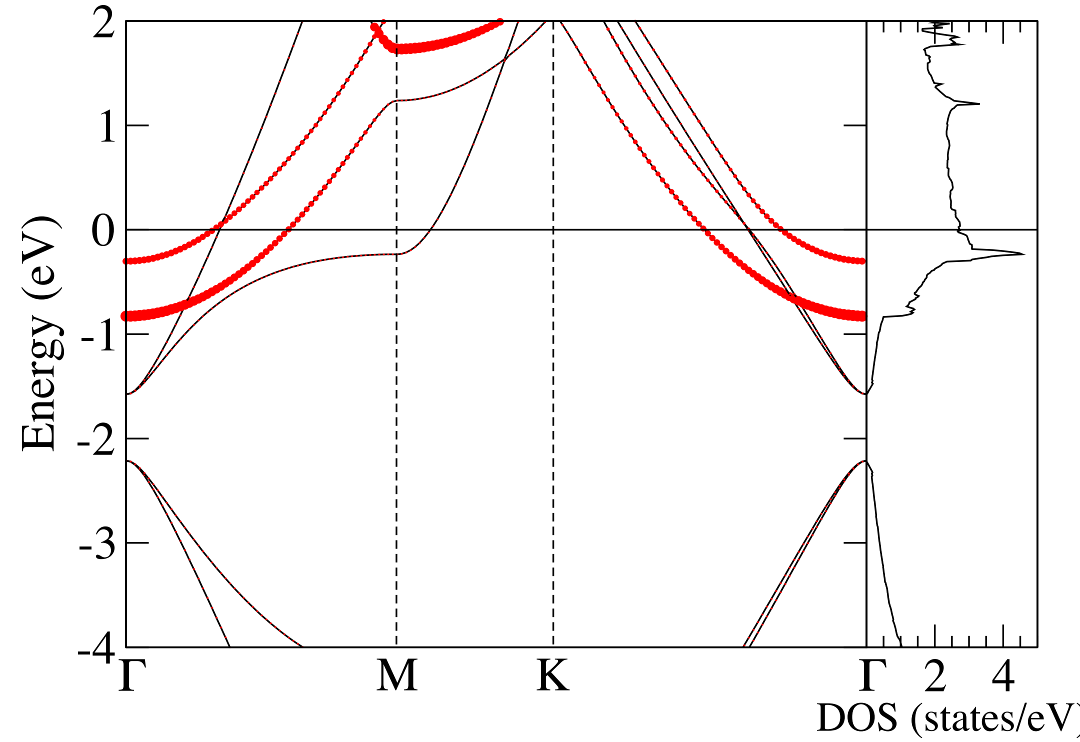


- Bulk LiC6 is not superconducting (no interlayer state)
- The interlayer state allows the coupling with "dormant" C_z modes
- Increases the DOS at the Fermi level
- Allows an additional intra-band and 2 inter-band scattering channels
- Increases the total electron-phonon coupling to $\lambda = 0.61$ and $T_c = 8.1$ K

Lithium on both sides of Graphene







$\lambda = 1.0$ and $T_c = 18$ K

Conclusions

- Rigid doping can not induce electron-phonon driven superconductivity
- Metal adatoms on graphene promotes the interlayer state at the Fermi level
- The coupling depends on the particular adatom, very different from the bulk counterpart
- Lithium on graphene has a sizable electron-phonon coupling
- and can induce superconductivity.

"How to make graphene superconducting"

G. Profeta, M. Calandra and F. Mauri

cond-mat arXiv: xxx.xxxx

Thank you
for your attention