Dirac Materials

A.V. Balatsky

- New class of materials
- What is the definition of Dirac Materials?
- Similarities and differences between d-wave superconductors, Graphene and Topological Insulators: All are Dirac materials with some common features
- Imaging of k and r space
- Local electronics and spins in graphene and TI
- Gap or no gap in TI?

Los Alamos NATIONAL LABORATORY

NORDITA

J. X. Zhu, I. Martin, M. Salkola, T. Das, – Los Alamos
D. Abergel, A. Black-Schaffer Nordita
H. Dahal - BC
T. Wehling, A. Lichtenstein, K. Scharnberg,
R. Wiesendanger – U Hamburg
M. Katsnelson – U Niemegen
J. Fransson- Uppsala
D.Arovas- UCSD
Z. Huang – UCSD, Los Alamos

Experiment: J.C. Davis group
Y.Zhao, V. Brar, M. Crommie -IETS
L. Mattos, H. Manoharan –Kondo graphene

The Dirac Equation

P. Dirac: "*The quantum theory of the electron*" (1928)

(from nobelprize.org)

Nobel Price 1933

$$i\hbar\partial_t\Psi = \left(c\vec{\alpha}\cdot\vec{p} + \beta mc^2\right)\Psi$$

with 4x4 Dirac matrices

$$\alpha_i = \begin{pmatrix} 0 & \sigma_i \\ \sigma_i & 0 \end{pmatrix},\ i = 1,2,3;\ \beta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Describing electrons, protons, quarks,neutrinos...

... with peculiar physical consequences:

- Spin 1/2 and Landé g=2
- Antiparticles
- Klein paradox and Zitterbewegung
- Spin orbit coupling

Dirac materials

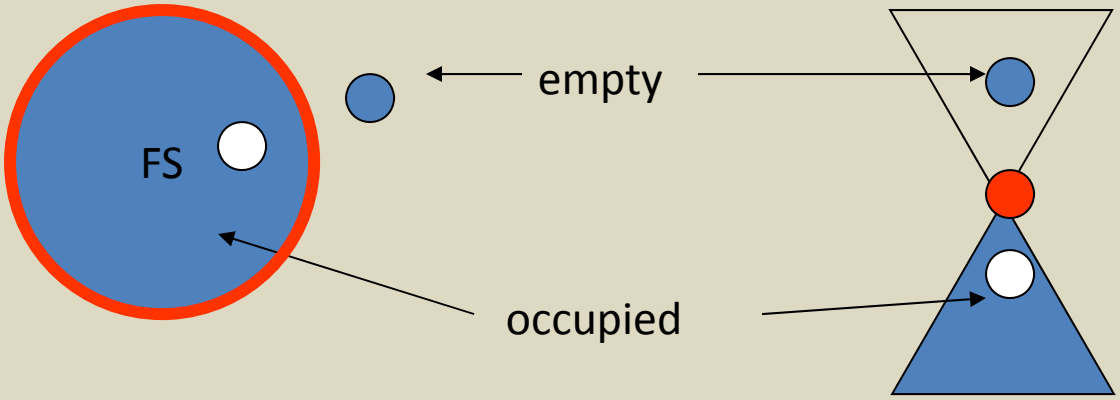
- Materials whose low energy electronic properties are a direct consequence of Dirac spectrum E = vk: specific heat ~T^d, penetration depth~T, optical conductivity~T^n
- How do we “design” Dirac Materials?
- Can be a collective state: 3He superfluid, heavy fermion, organic, high Tc superconductors, density wave states
- Band structure effect – graphene, Topological states, cold atom DM, artificial DM
- Not a Dirac equation (1928)

T. Wehling, A Black-Schaffer and A. V. Balatsky, Dirac Materials, Adv Phys, p1 v 90 (2014)

Dirac materials vs metals

Metals

Dirac materials
(3He included)



$E = v(k-k_F)$

$E = vk,\ k_F = 0$

Defining feature:

Dimensionality of zero energy states in one less(at least)

In the Dirac materials. Fewer excitations at low T.

Better control of response and less dissipation.

Important for future energy and device applications.

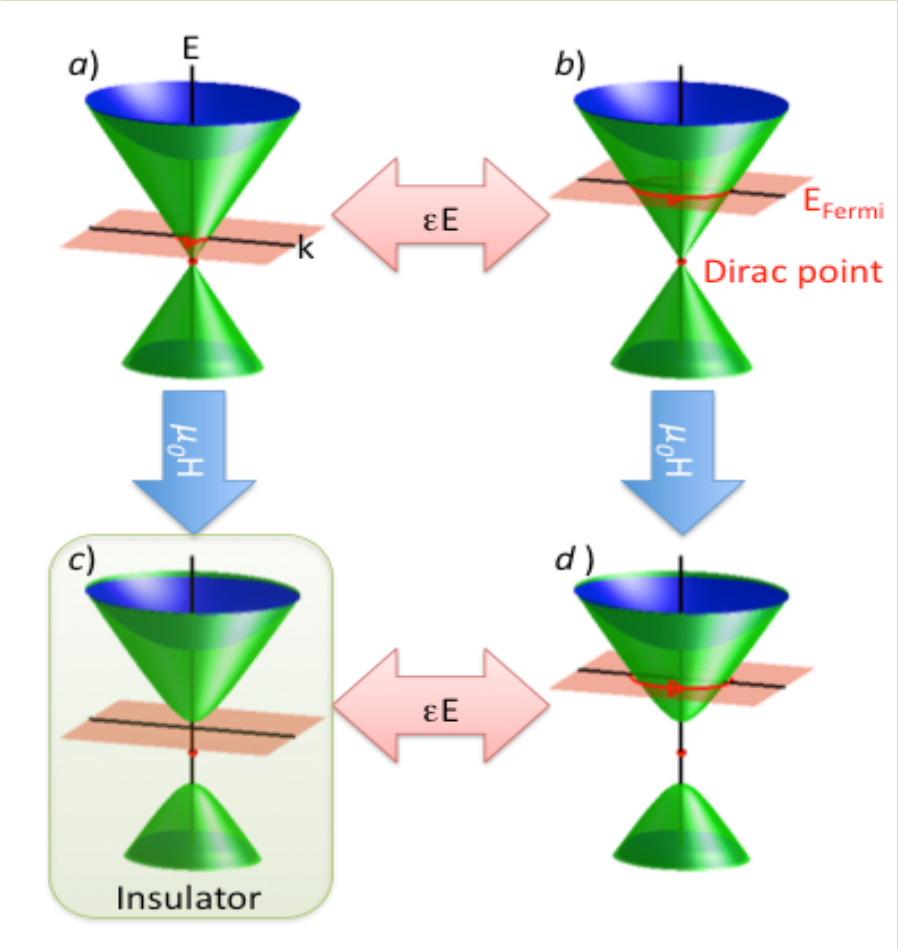
Material	Pseudospin	Energy scale (eV)	References
Graphene, Silicene, Germanene	Sublattice	1–3 eV	[5, 6, 17, 19, 36, 37]
Artificial Graphenes	Sublattice	10^{-8}–0.1 eV	[28, 29, 38–40]
Hexagonal layered heterostructures	Emergent	0.01–0.1 eV	[41–47]
Hofstadter butterfly systems	Energent	0.01 eV	[46]
Graphene-hBN heterostructures in high magnetic fields			
Band inversion interfaces	Spin-orbit ang. mom.	0.3 eV	[48–50]
SnTe/PbTe, CdTe/HgTe, PbTe			
2D Topological Insulators	Spin-orbit ang. mom.	< 0.1eV	[7, 8, 22, 24, 51, 52]
HgTe/CdTe, InAs/GaSb, Bi bilayer, ...			
3D Topological Insulators	Spin-orbit ang. mom.	$\lesssim 0.3$eV	[7, 8, 23, 52–55]
$Bi_{1-x}Sb_x$, Bi_2Se_3, strained HgTe, Heusler alloys, ...			
Topological crystalline insulators	orbital	$\lesssim 0.3$eV	[56–59]
SnTe, $Pb_{1-x}Sn_xSe$			
d-wave cuprate superconductors	Nambu pseudospin	$\lesssim 0.05$eV	[60, 61]
^{3}He	Nambu pseudospin	$0.3\,\mu$eV	[2, 3]
3D Weyl and Dirac semimetals	Energy bands	Unclear	[32–34]
Cd_3As_2, Na_3Bi			

Table 1. Table of Dirac materials indicated by material family, pseudospin realization in the Dirac Hamiltonian, and the energy scale for which the Dirac spectrum is present without any other states.

Why Dirac materials: path to control of electronic states

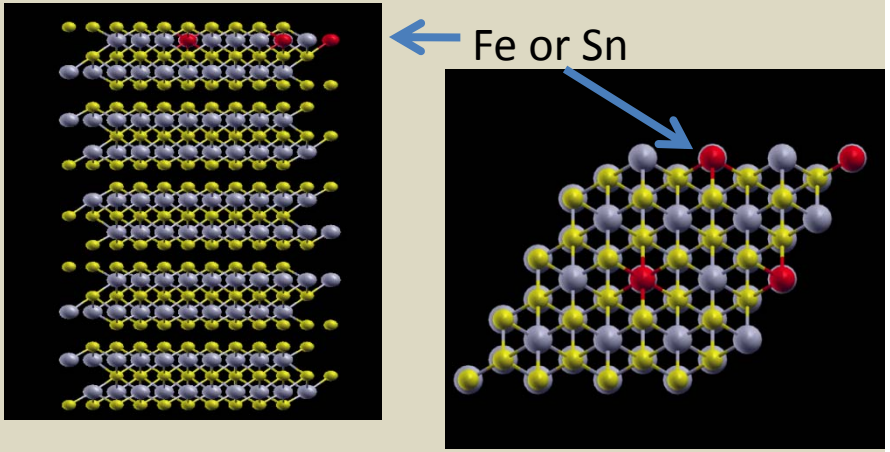
Tunability and control

1 With B, E fields

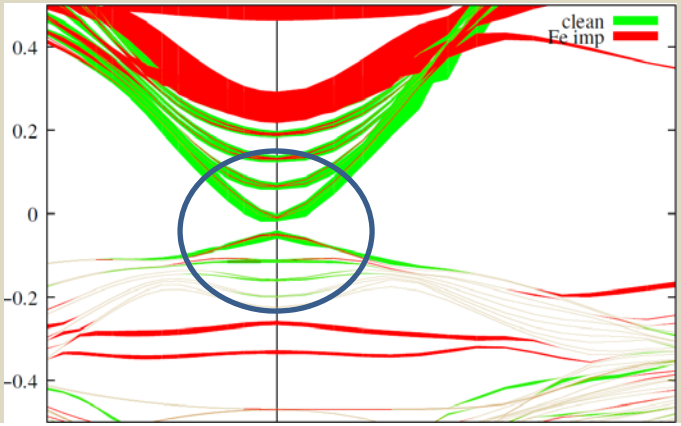


Bi2Se3

2 with doping and functionalization



3 with quantum size control: films, ribbons



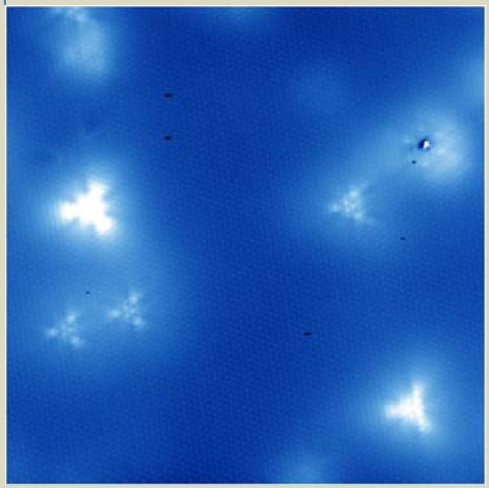
R-space vs K-space probes of Dirac Materials

time

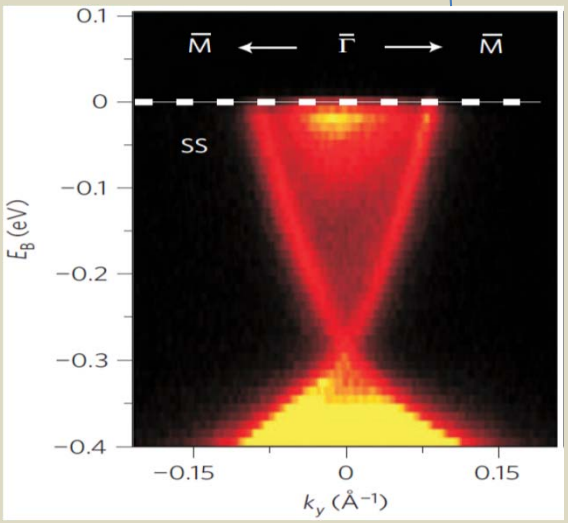
Local probes (r space)
STM, spin imaging with Kerr

Extended probes (k space)
Magnetotrasport, thermal conductivity

time



Theory
Guidance for search of new states
Ab initio, functionalization,
How protected are topological states



T. Hanaguri, A. Kapitulink, H. Manoharan
V. Madhavan, A. Yazdani

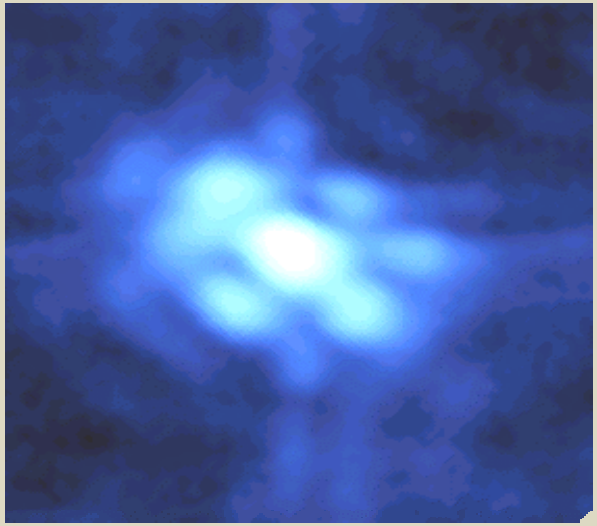
) Y. Xia *et al.*,
Nature Phys. **5**, 398 (2009)

S.C. Zhang et al RMP, Nov (2011)
A.C. Neto et al, RMP (2010)
A.V. Balatsky et al, v 78, 373 (2006)

Universal response to defects. Why Impurities?

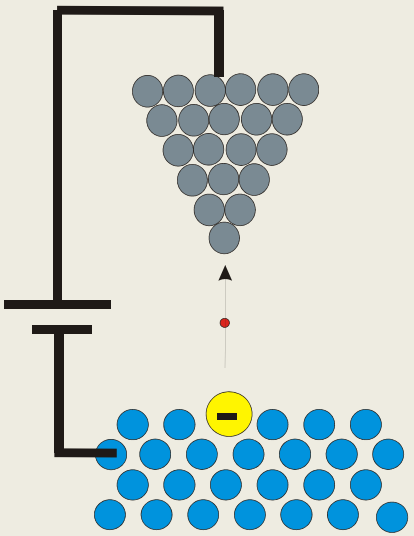
- Why *local* signatures and impurities?
  - *Scientific interests*: applications rely heavily on *functionalization*
  - *Observation* possible by Scanning Tunneling Spectroscopy (STS)
  - *Engineered* electronic states due to imp bands
  - *Microchips at one atom at time approach* ~ 100 impurity atoms/transistor
    mean lifetime pictures will break down.
  - Suggested Quantum Computation operations involve *deliberate local perturbations*

Local impurity resonances in d-wave superconductors

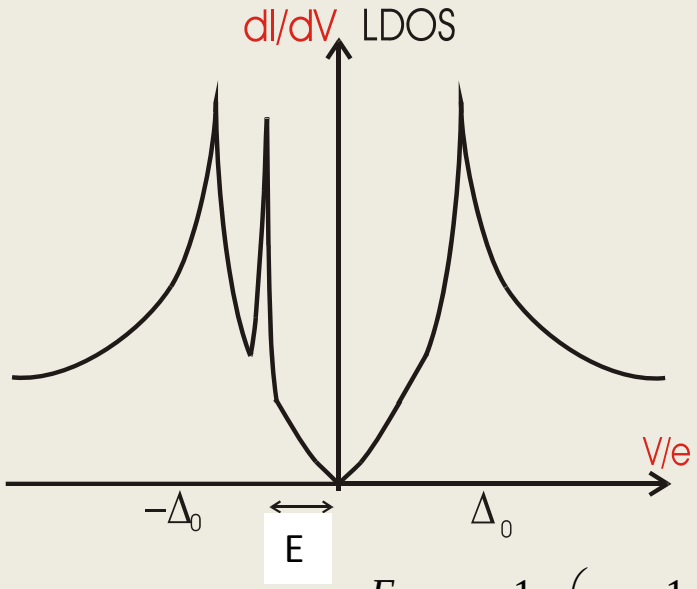


d-wave Superconductor:Impurity Resonances

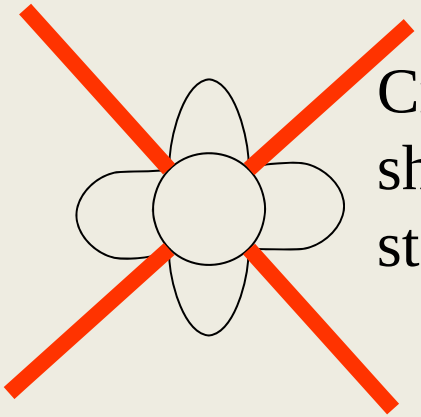
On-site potential
U>0



On-site LDOS

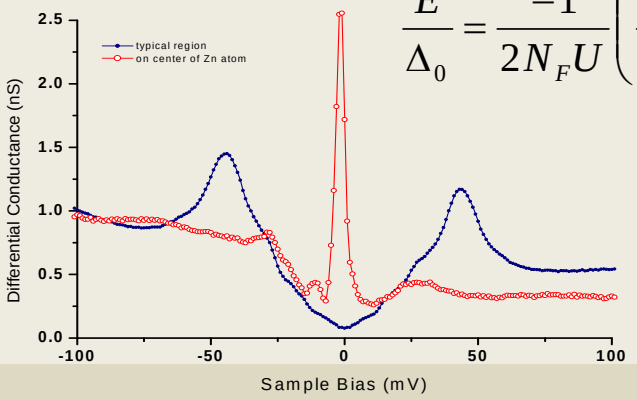


LDOS Image at Ω
$|\Psi|^2$ for impurity-state

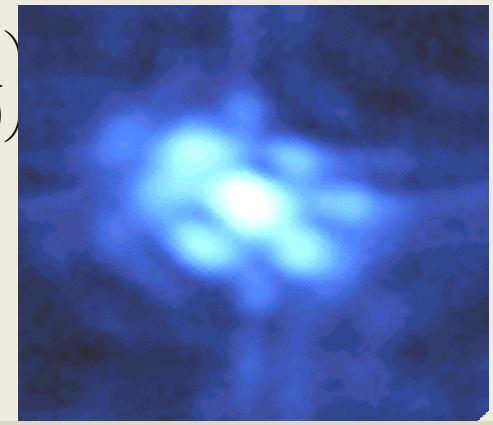


Cross shaped state

Rev. Mod Phys, **78**, p 373, (2006)



$$\frac{E}{\Delta_0} = \frac{-1}{2N_F U}\left(\frac{1}{\ln(8N_F U)}\right)$$



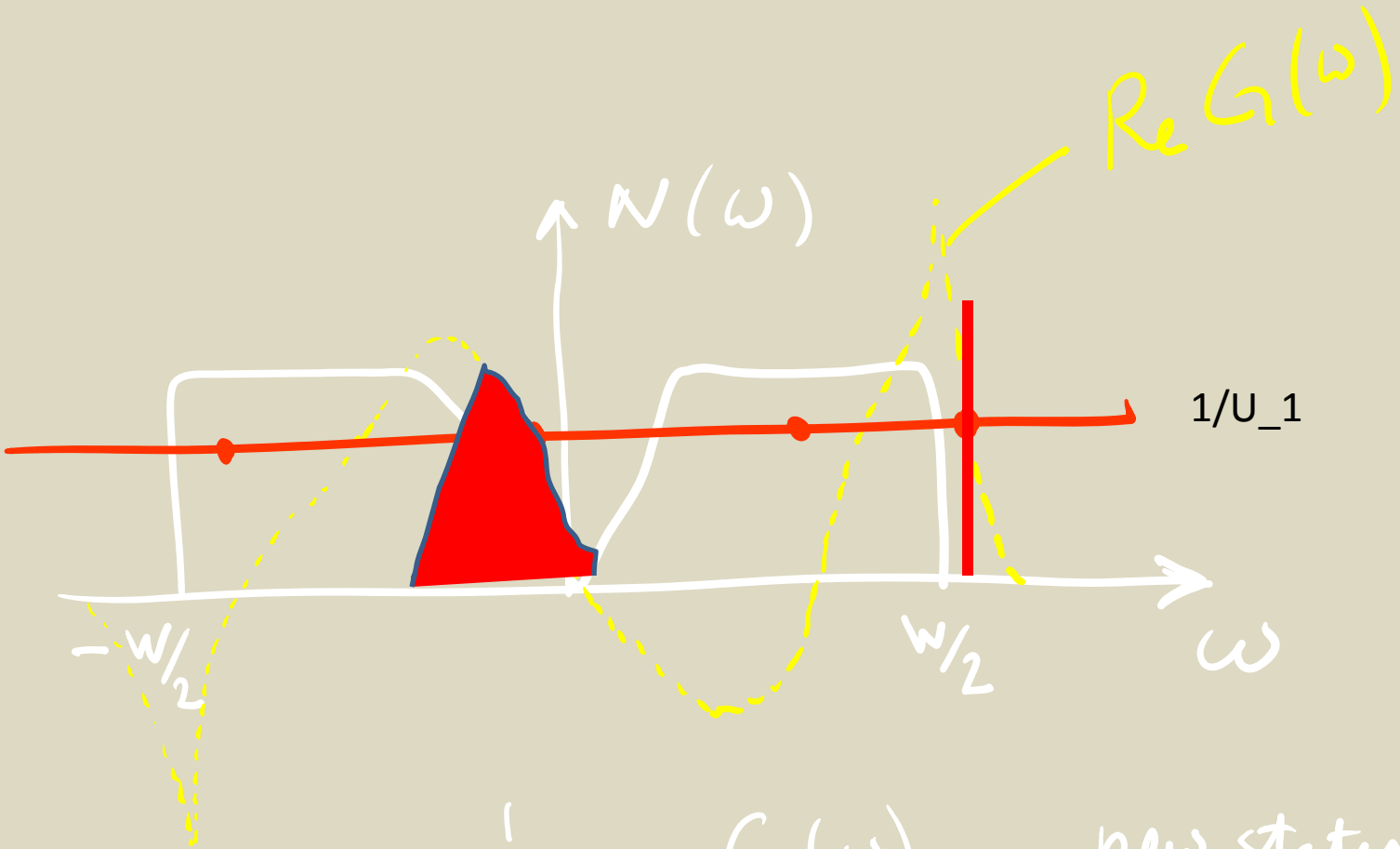
Impurity states in ANY Dirac point materials

$$T = \frac{U}{1 - U G(\omega)}$$

$$G(\omega) = \frac{1}{U} \leftarrow \text{small}$$

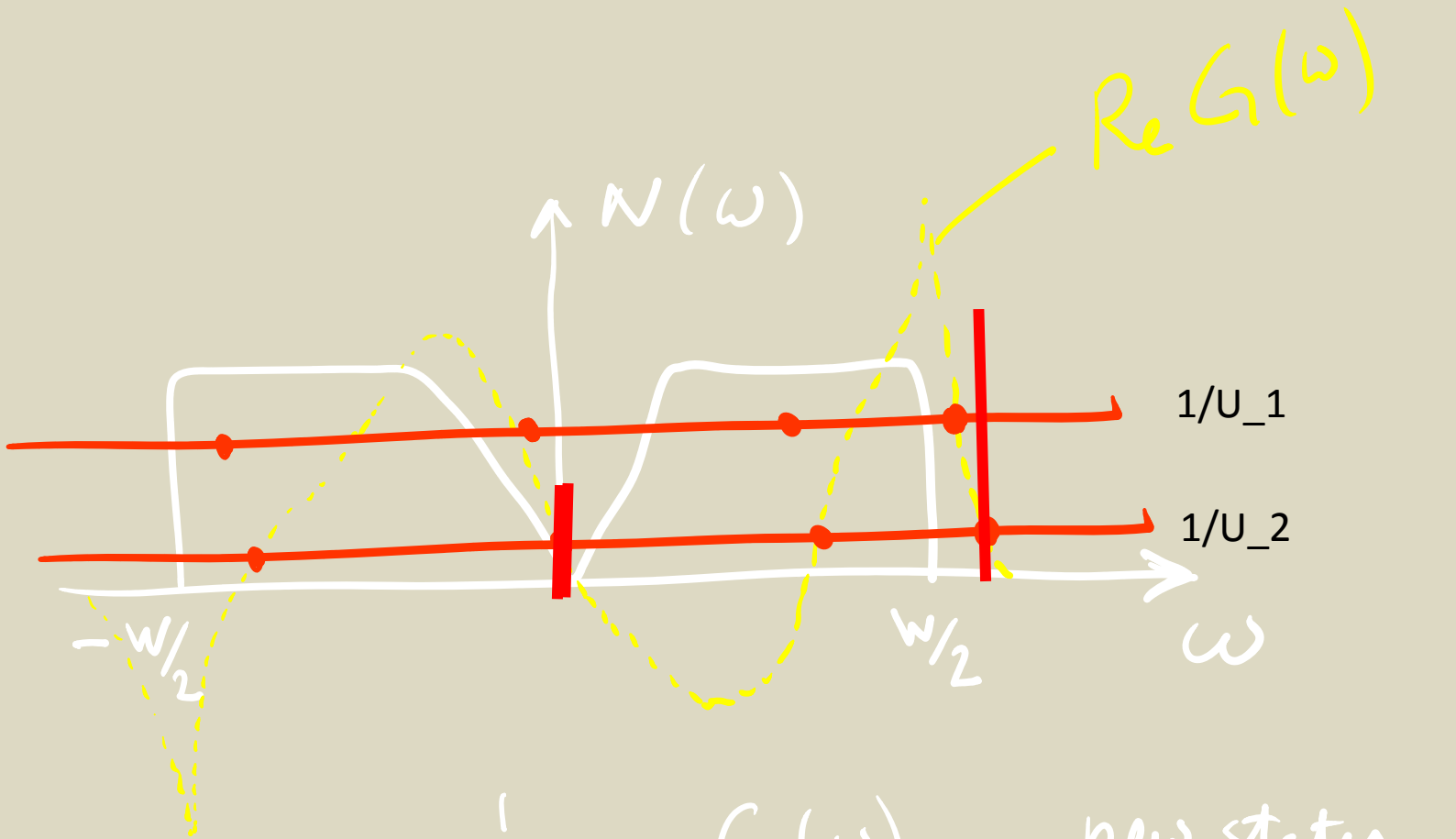
Impurity states in ANY Dirac point materials

Impurity states in ANY Dirac point materials



$\frac{1}{U} = G(\omega)$ - new states or resonances

Impurity states in ANY Dirac point materials



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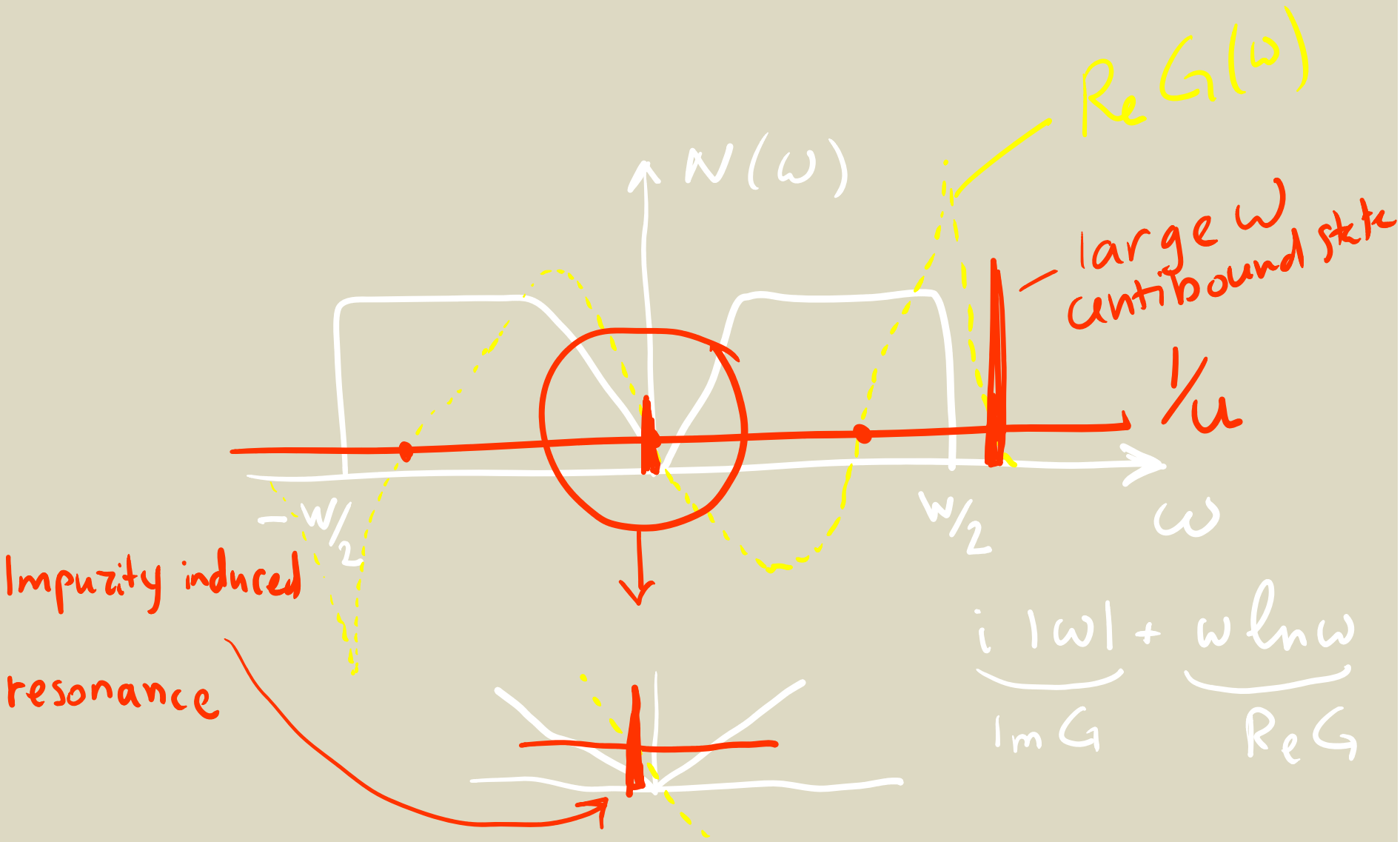
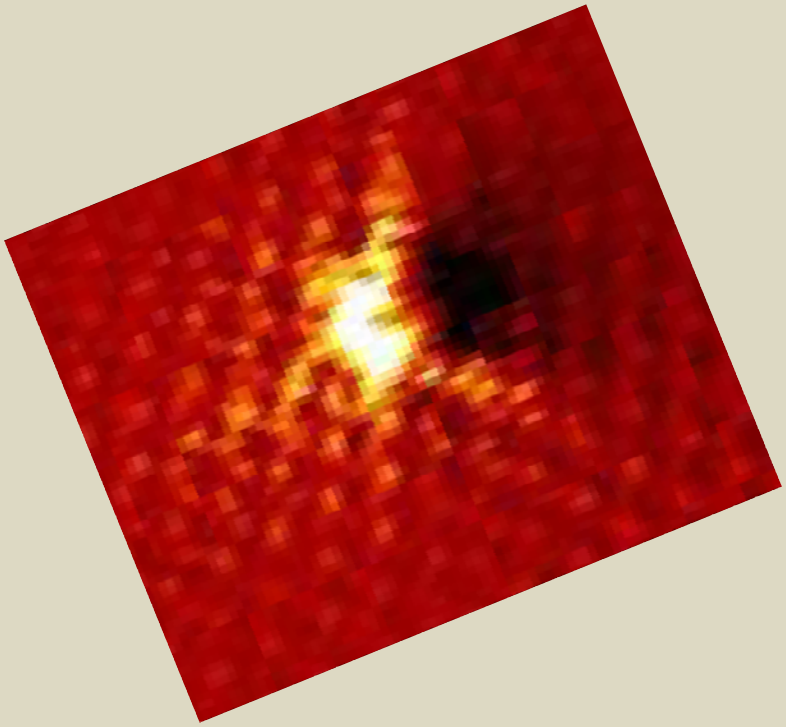
Impurity states in ANY Dirac point materials



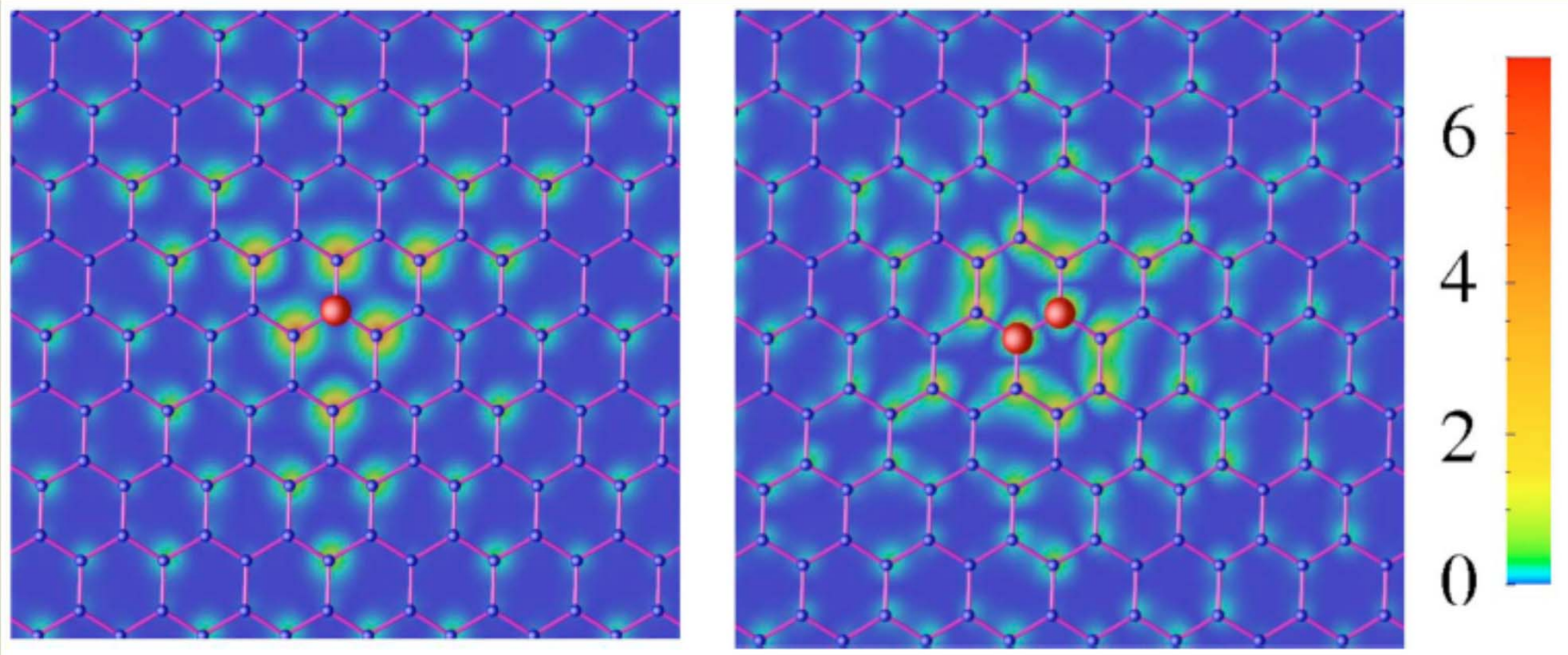
Local impurity resonances in Dirac Materials: Graphene



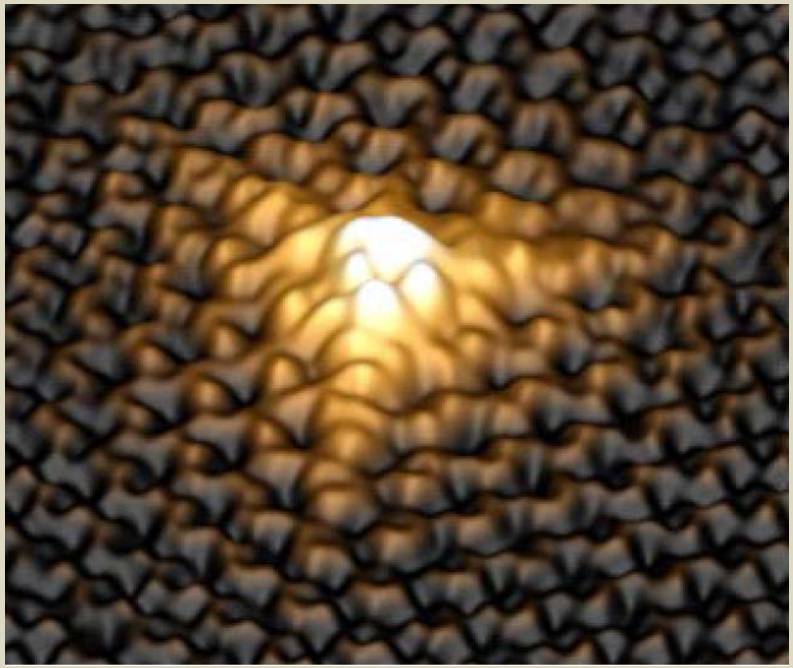
Real space signatures I

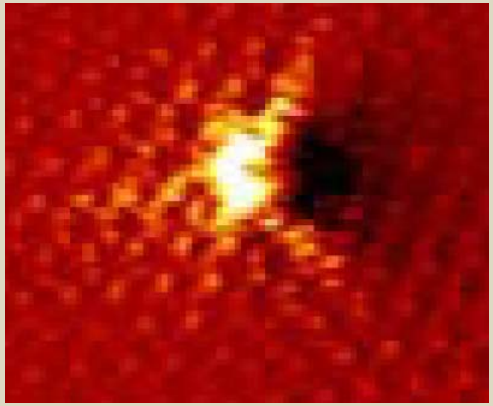
T. Wehling et. al., PRB 75, 125425 (2007), Peres, A.C Neto, Guinea, Falko

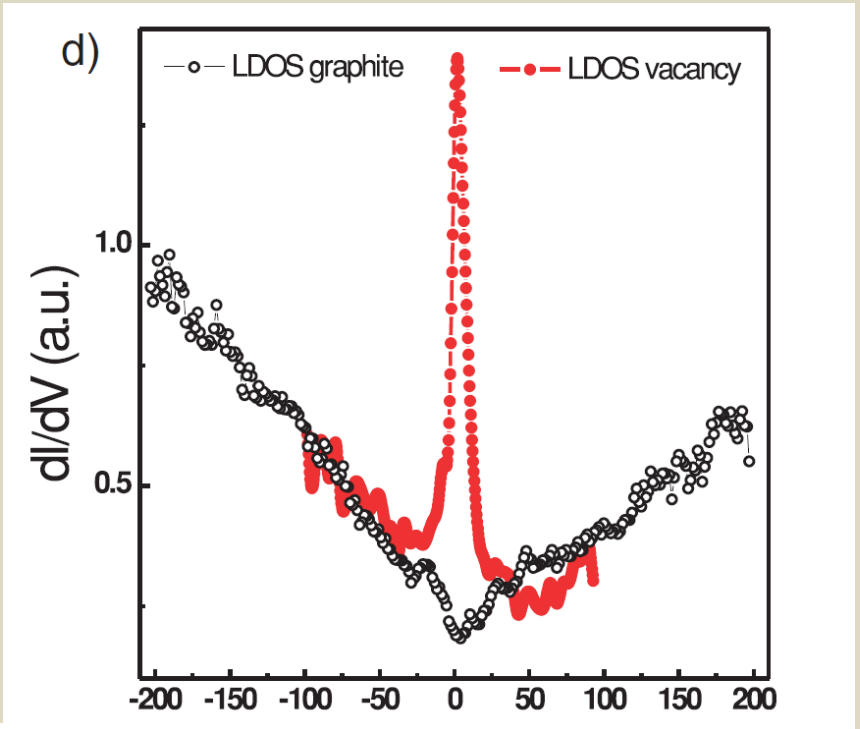
r-dependent LDOS at imp. resonance

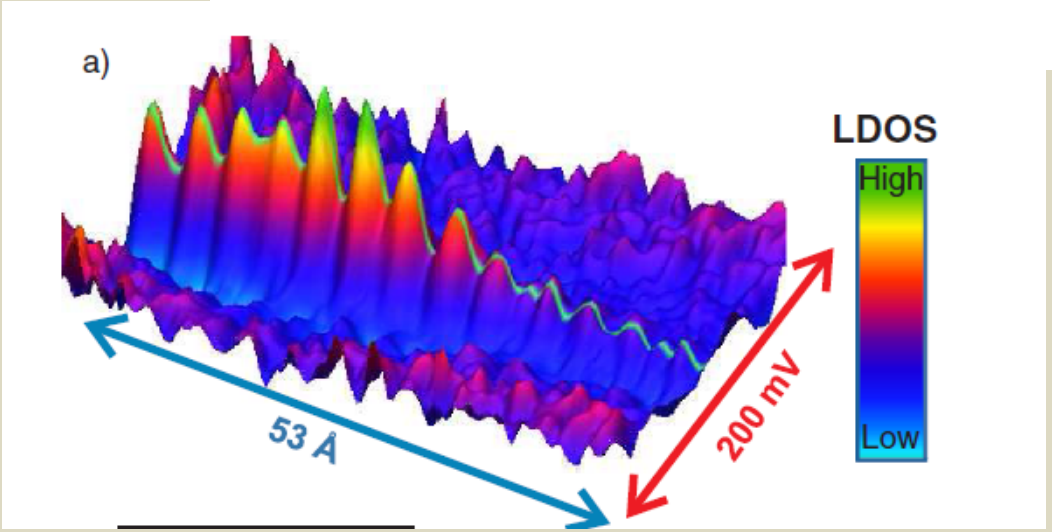


E_{imp}=0.1eV







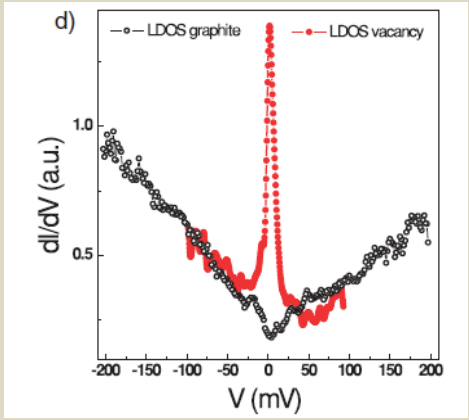


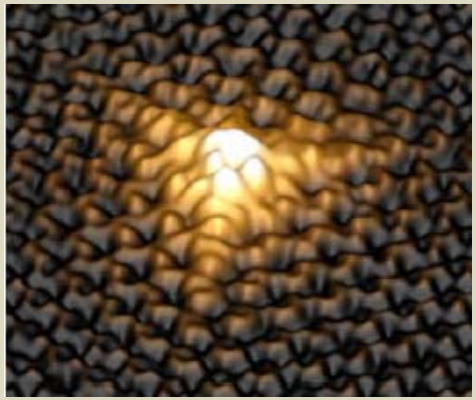
M.M. Udega etal, PRL104, 096804 (2010)

Universal response to local defects

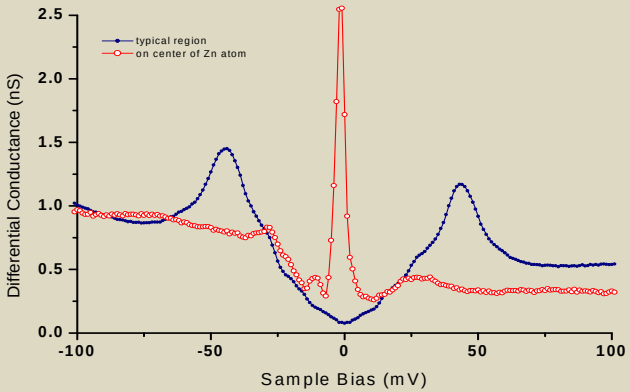
Hypothesis: ANY Dirac material has similar resonances

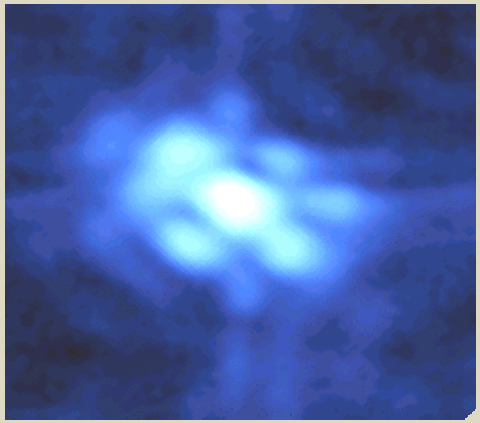
Graphene





D-Wave SC

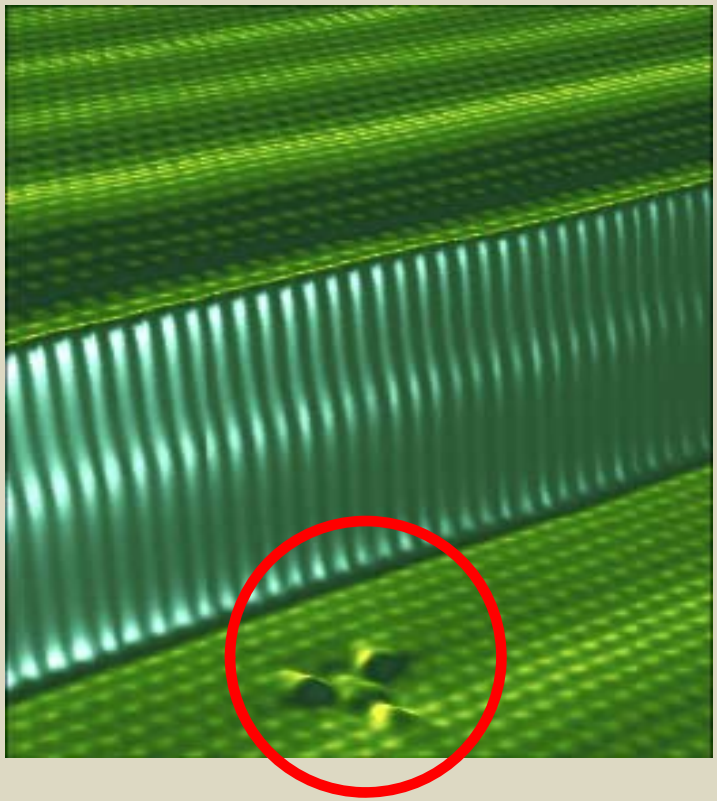




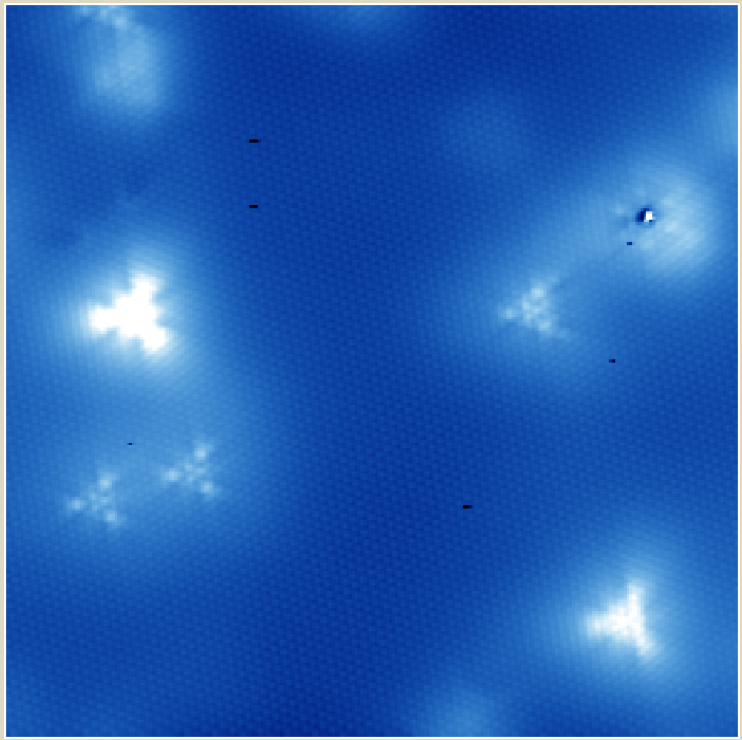
Local impurity resonances in Topological Insulators, probe of stability

Hanaguri etal, PRB 2010,
cond mat 1003.0100

Impurity resonances in Dirac Materials: Topological Insulators, probe of suppressed back scattering



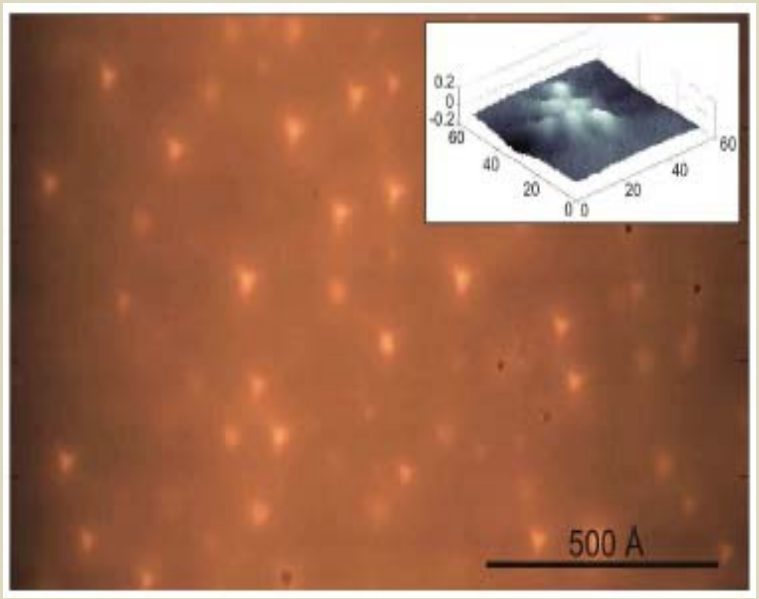
Gomes *et al*, arXiv:0909.0921 (2009)

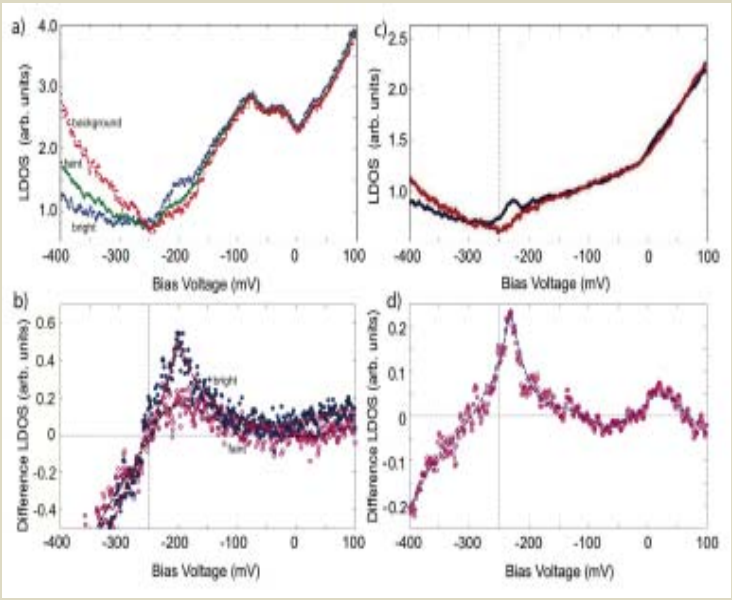


Hanaguri etal, PRB82, 081305(2010); Cheng, et al, PRL 105, 081305(2010).

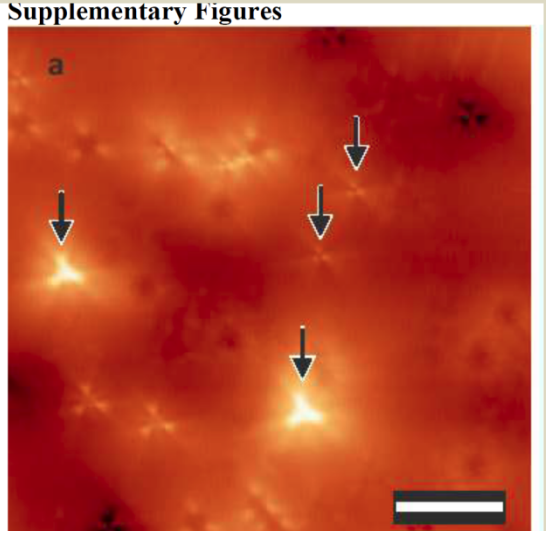
Resonance as seen in STM

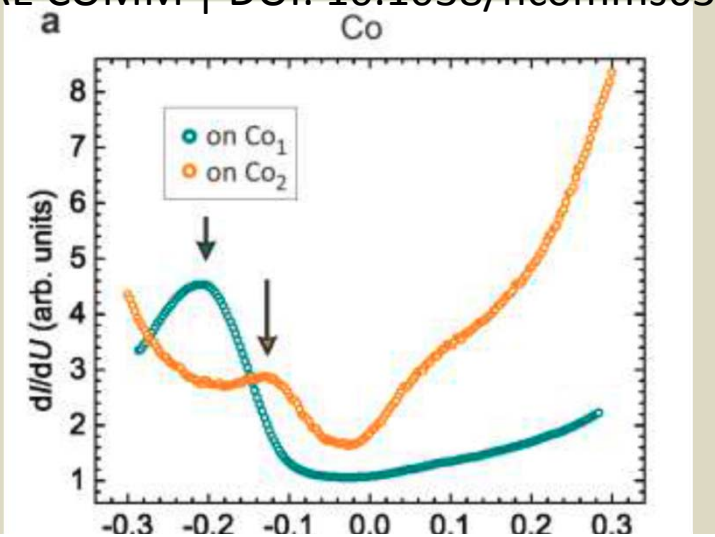
Z. Alpichev et al, PRL 108,206102,(2012)



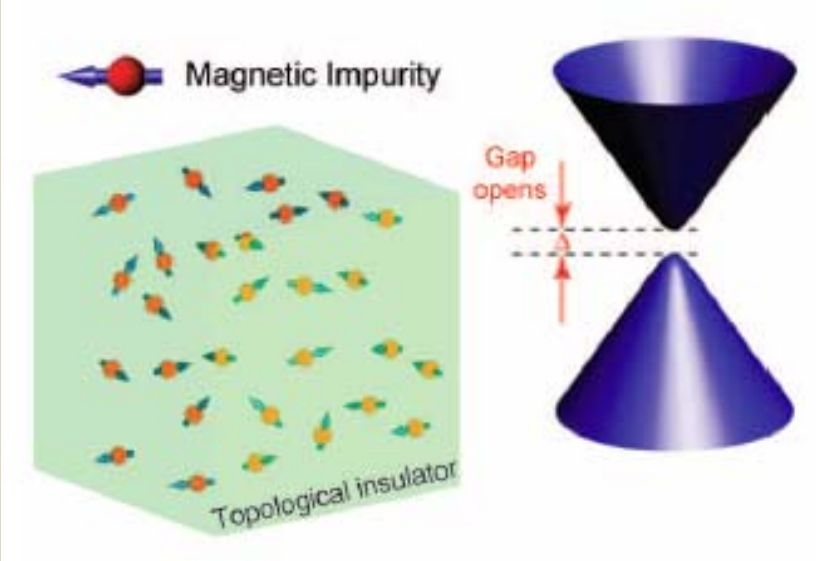


Sessi et al. NATURE COMM | DOI: 10.1038/ncomms6349, (2014)





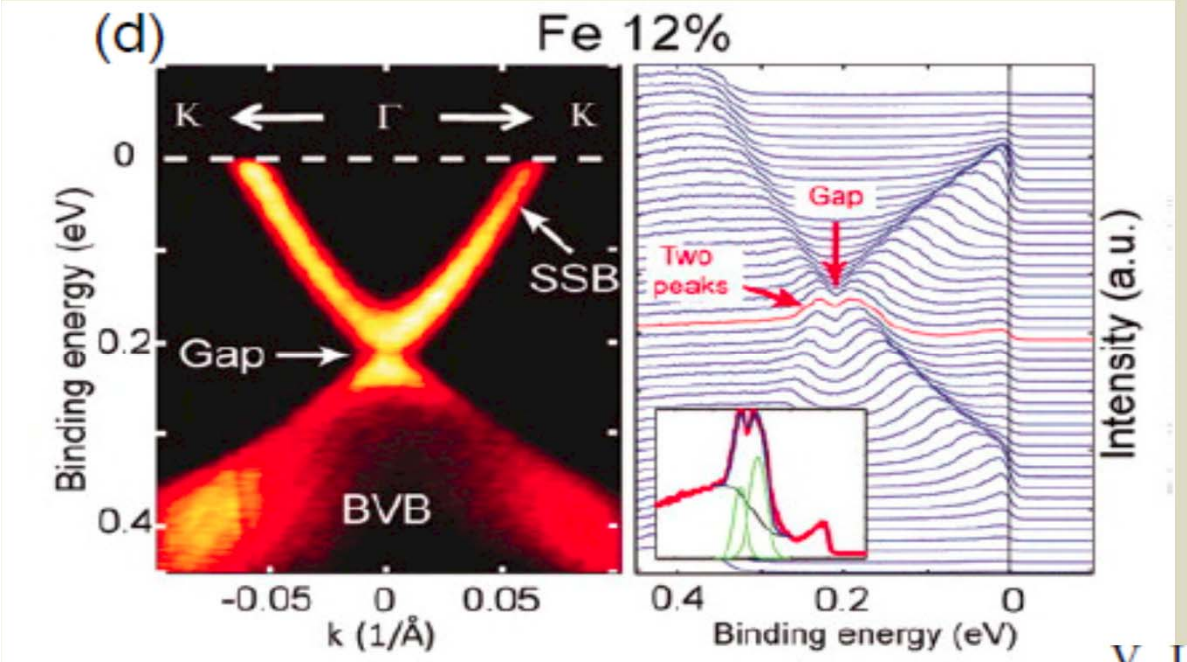
ARPES on magnetically doped TI and on films



$$H = \vec{k}\vec{\sigma} + S_z\sigma_z$$

$$E = \pm\sqrt{k^2 + S^2{}_z}$$

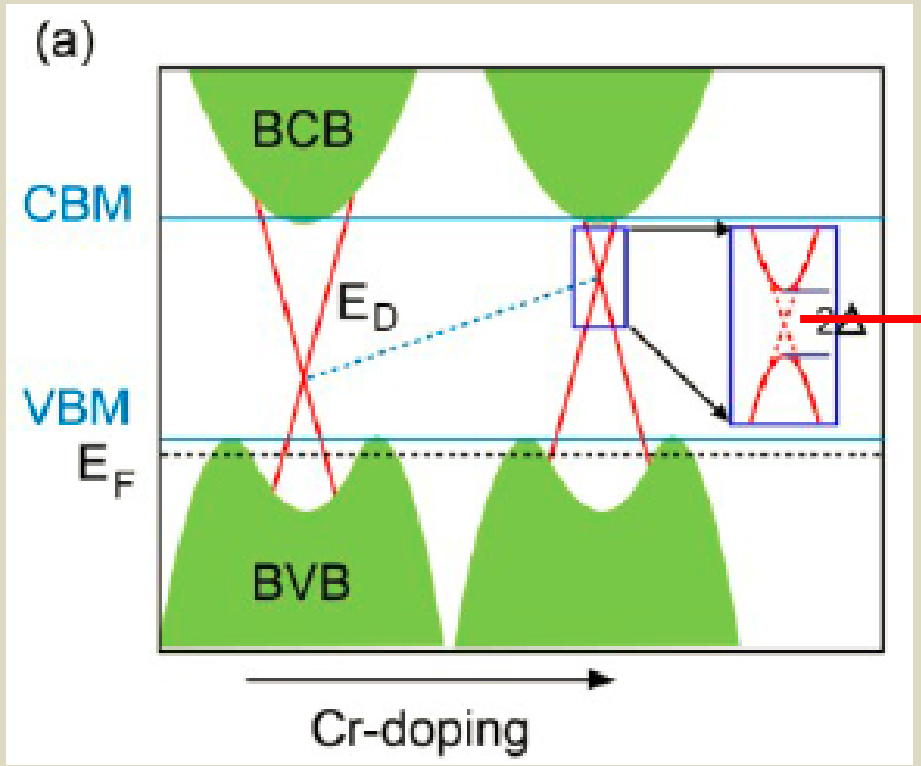
Fully gapped spectrum

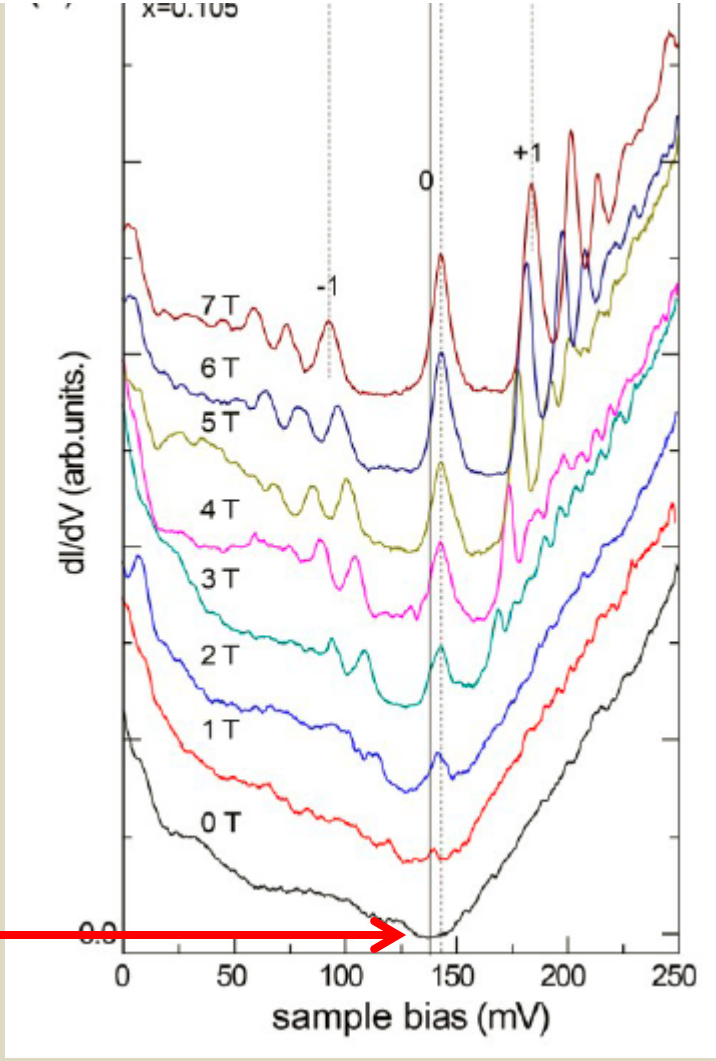


Y. L. Chen *et al.*, Science 329, 659 (2010)

Mass acquisition of Dirac fermions in Cr-doped topological insulator Sb_2Te_3 films

Yeping Jiang,[1,2,3] Zhi Li,[1] Canli Song,[1,2] Mu Chen,[1,2] Richard L. Greene, [3] Ke He,[1] Lili Wang,[1] Xi Chen,[2] Xucun Ma,[1,*] and Qi-Kun Xue[2,*]

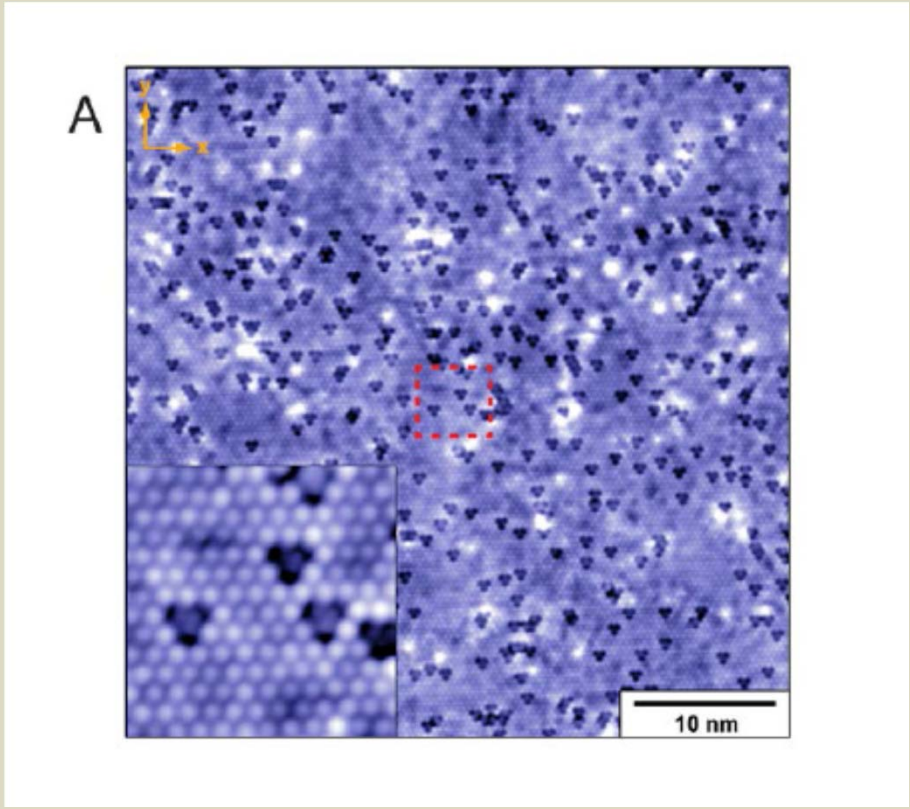


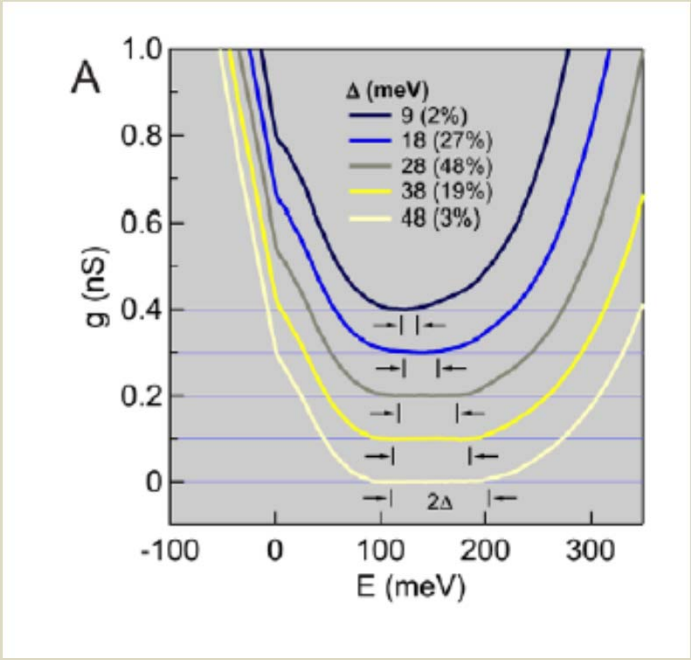


At B=0 at Dirac point now there should Be a true gap. The data show finite LDOS.

Gap or no gap for Cr doped sample.

Gap in FM ordered TI seen in STM





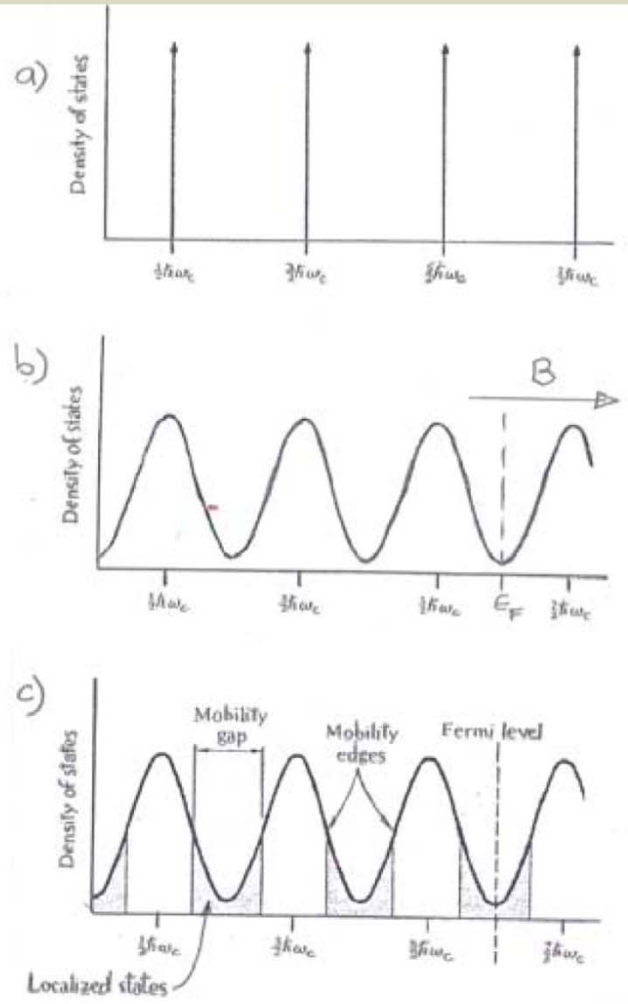
Imaging Dirac-Mass Disorder from Magnetic Dopant-Atoms in the Ferromagnetic Topological Insulator $Cr_x(Bi_{0.1}Sb_{0.9})_{2-x}Te_3$

hee Lee[1†], Chung Koo Kim[1†], Jinho Lee[1,2], S. J. L. Billinge[1,3], R. D. Zhon
A. Schneeloch[1,5], T. S. Liu[1,6], T. Valla[1], J. M. Tranquada[1], G. D. Gu[1], and J. C. Davis[1,7,8,9]

Robust conventional IQHE has mobility gaps, not real gaps

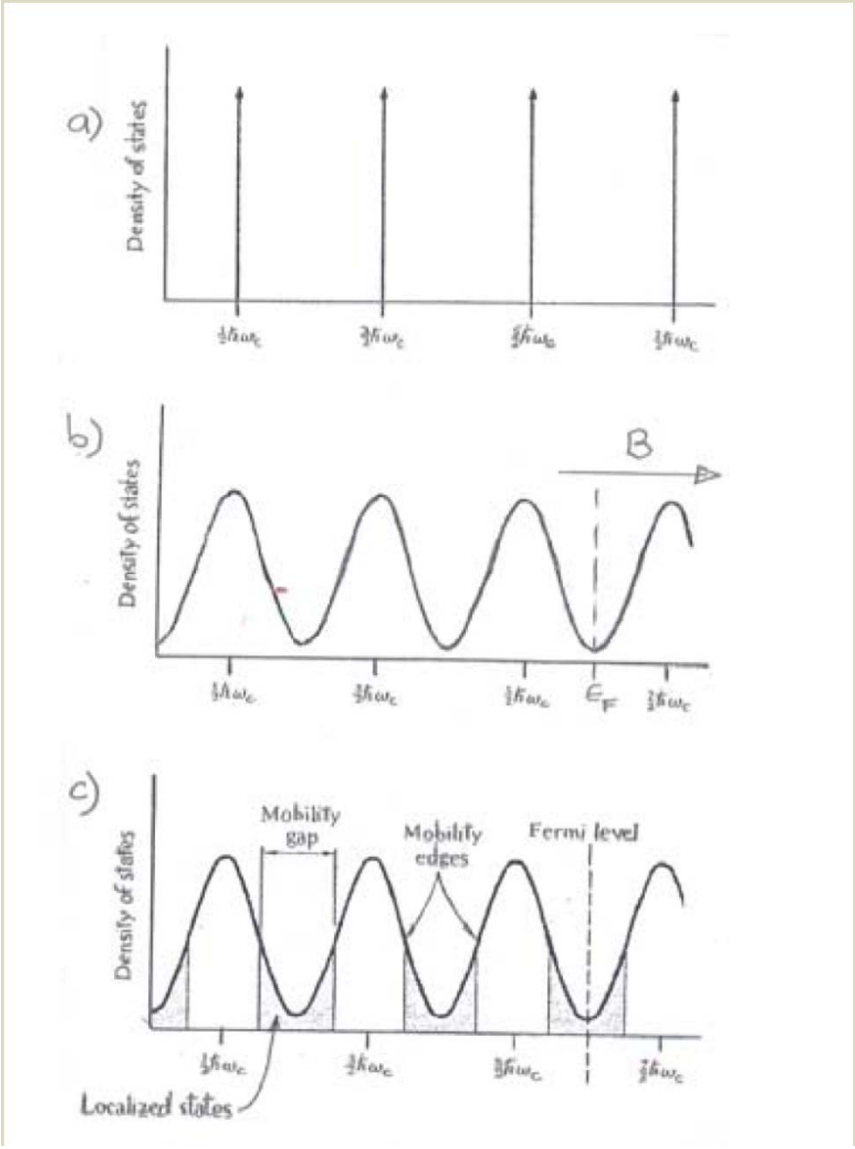
Figure 5: Density of states as a function of energy:

a) of an ideal 2D crystal;
b) of a 3D crystal or a 2D crystal at lower fields;
c) of a 2D crystal under higher applied fields.

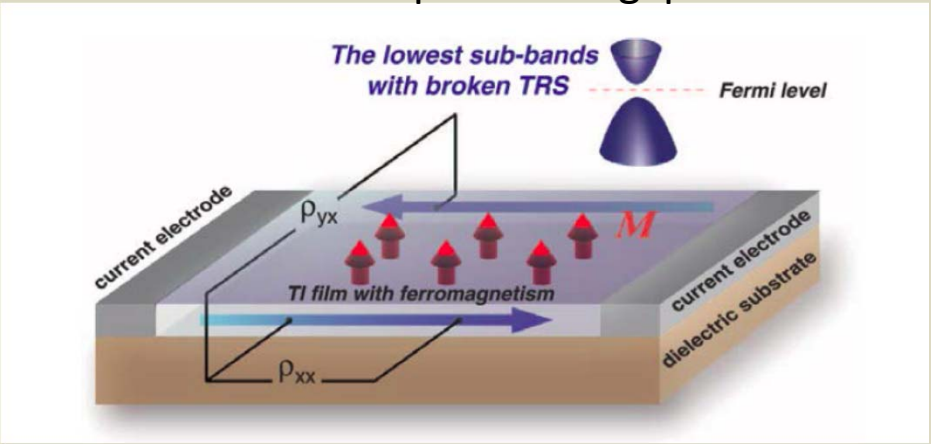


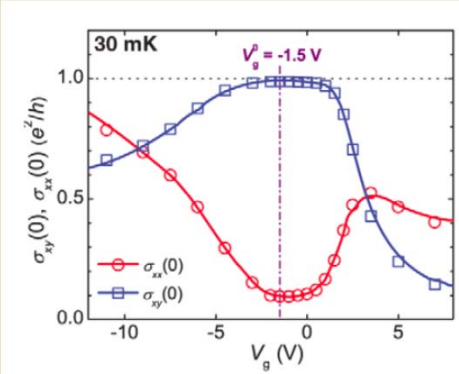
Gas vs Mobility gap in (A) QHE

Conventional IQHE



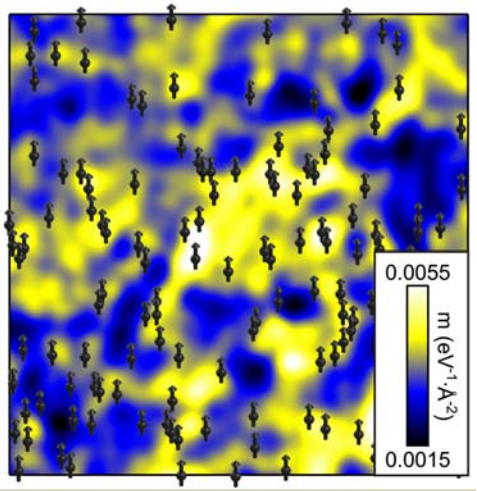
Anomalous QHE that
does not require a full gap either





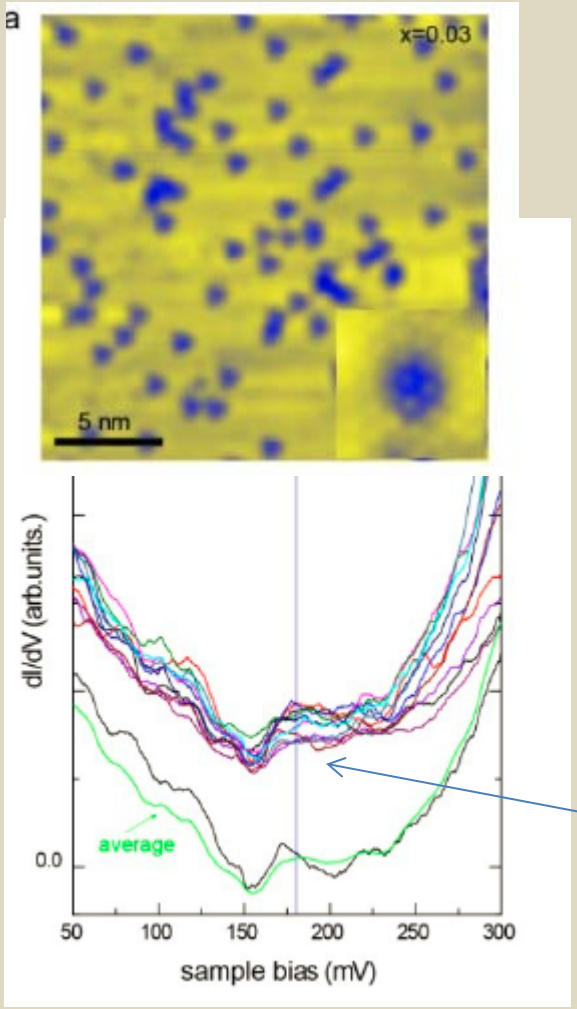
$Cr_{0.15}(Bi_{0.1}Sb_{0.9})_{1.85}Te_3$

Science **340**, 167



Mass acquisition of Dirac fermions in Cr-doped topological insulator Sb_2Te_3 films

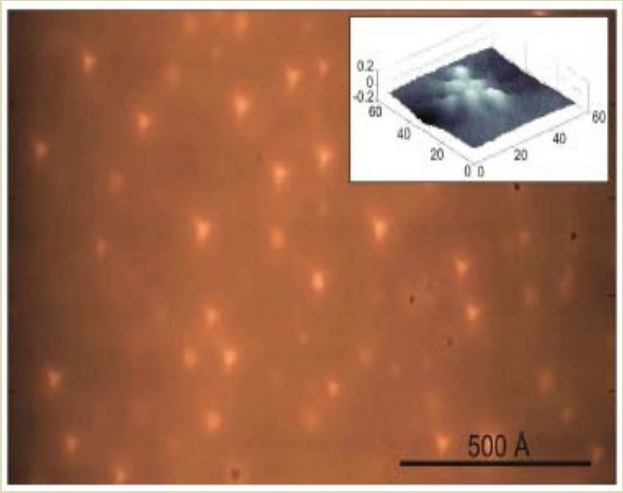
Yeping Jiang,[1,2,3] Zhi Li,[1] Canli Song,[1,2] Mu Chen,[1,2] Richard L. Greene, [3] Ke He,[1] Lili Wang,[1] Xi Chen,[2] Xucun Ma,[1,*] and Qi-Kun Xue[2,*]

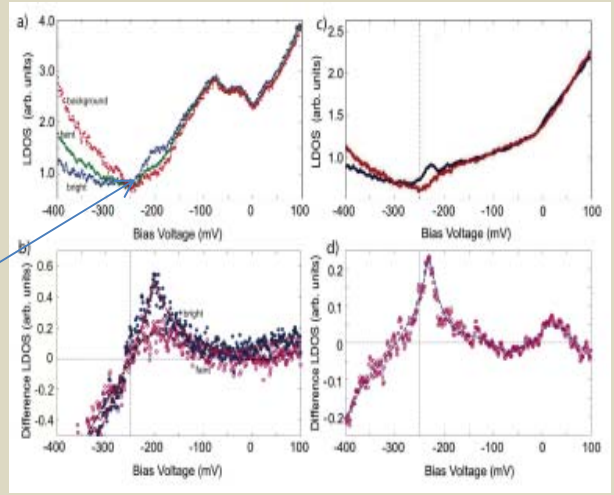


Zuocheng Zhang *et al.* Electrical control of the ferromagnetism in Cr doped Sb_2Te_3 diluted magnetic topological insulator. *to be submitted* (2013).

No gap at zero field

Z. Alpichev et al, PRL 108,206102,(2012)

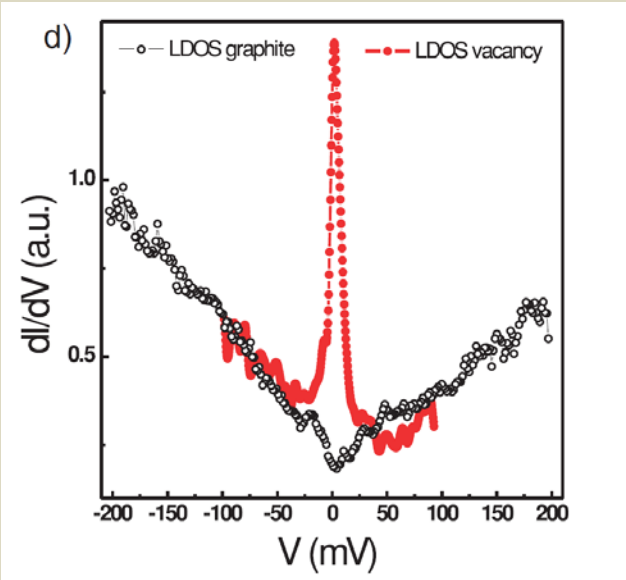




Competing trends due to magnetic scattering

Low energy resonance

- Every impurity (magnetic and nonmagnetic) will produce imp resonances inside Dirac cone = backscattering

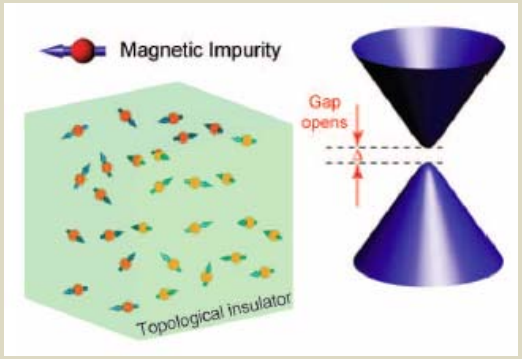


Magnetic scattering

Gap in Dirac spectrum

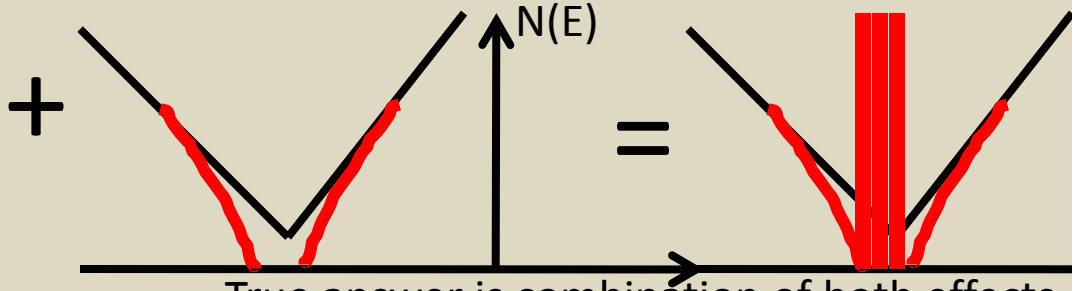
- Dirac fermion acquire a mass due to spin

Science ***329, 659 (2010);***
Y. L. Chen, *et al.*



$$H = \vec{k}\vec{\sigma} + S_z\sigma_z$$

$$E = \pm\sqrt{k^2 + S^2{}_z}$$



True answer is combination of both effects
Biswas, AVB PR B 81 , p233405 (2010),
A Black Schaffer et at, arXiv:1502.06403

Filling of Magnetic Impurity Induced
Gap in Topological Insulators by Potential Scattering

arXiv:1502.06403 , A. M. Black-Schaffer, A. V. Balatsky, J. Fransson

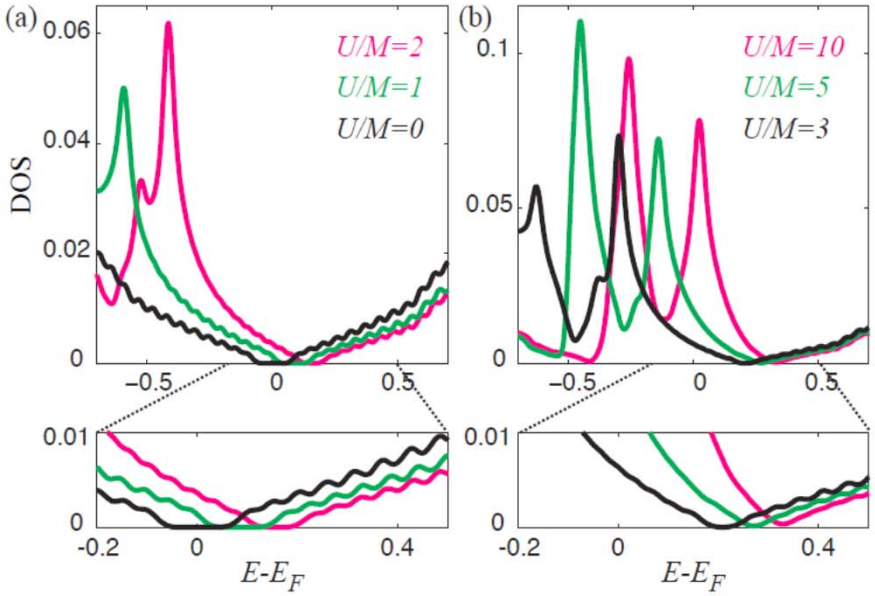


FIG. 3: Evolution of the surface local DOS (per energy and area unit)

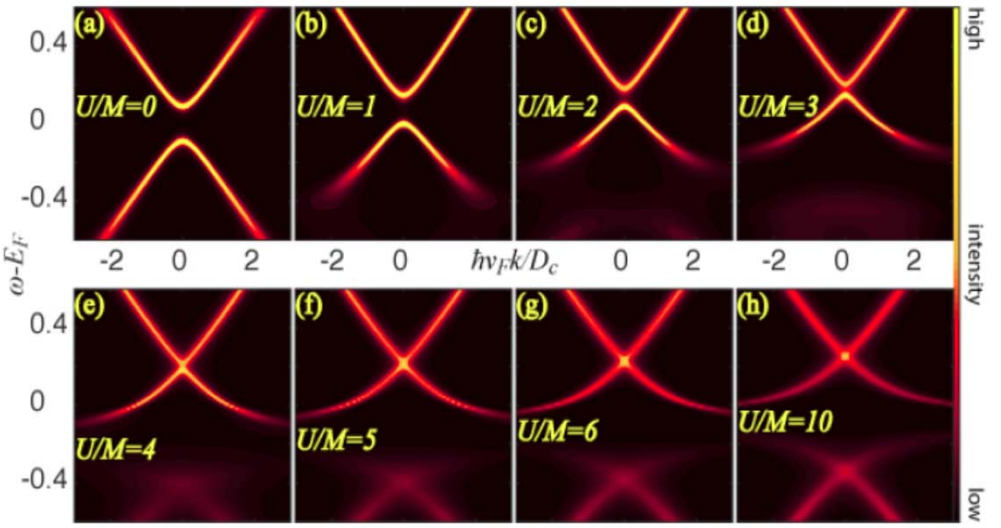
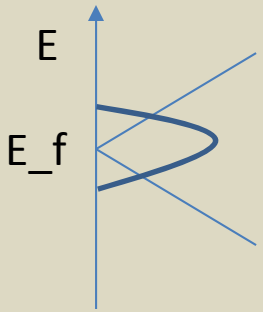
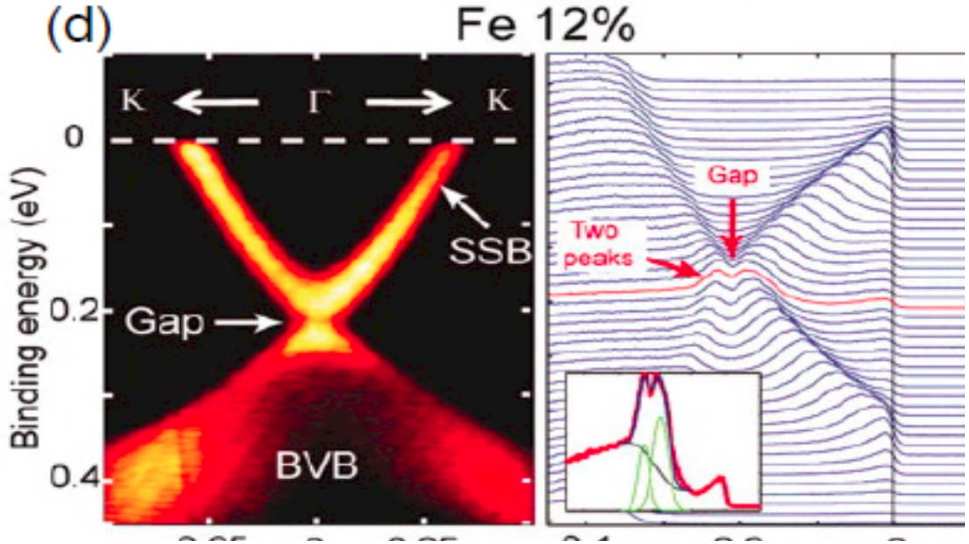


FIG. 1: Evolution of the band structure as function of the impurity potential $U/M = 0,\ 1,\ 2,\ 3,\ 4,\ 5,\ 6,$ and 10. Other parameters are

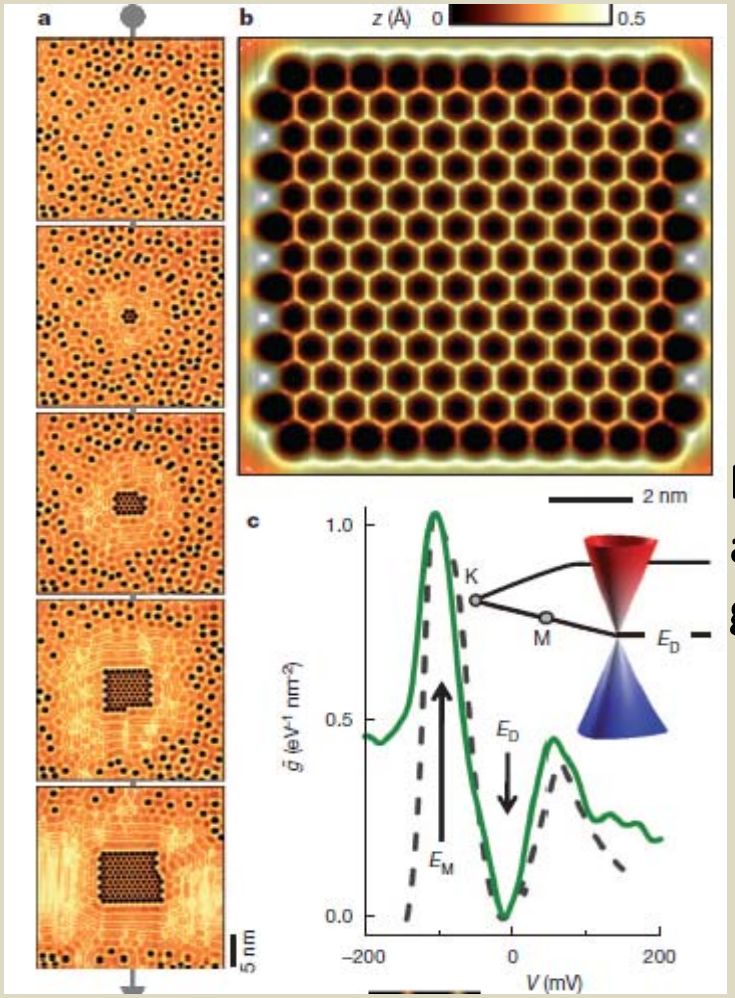


Science ***329, 659 (2010)***
Y. L. Chen, *et al.*

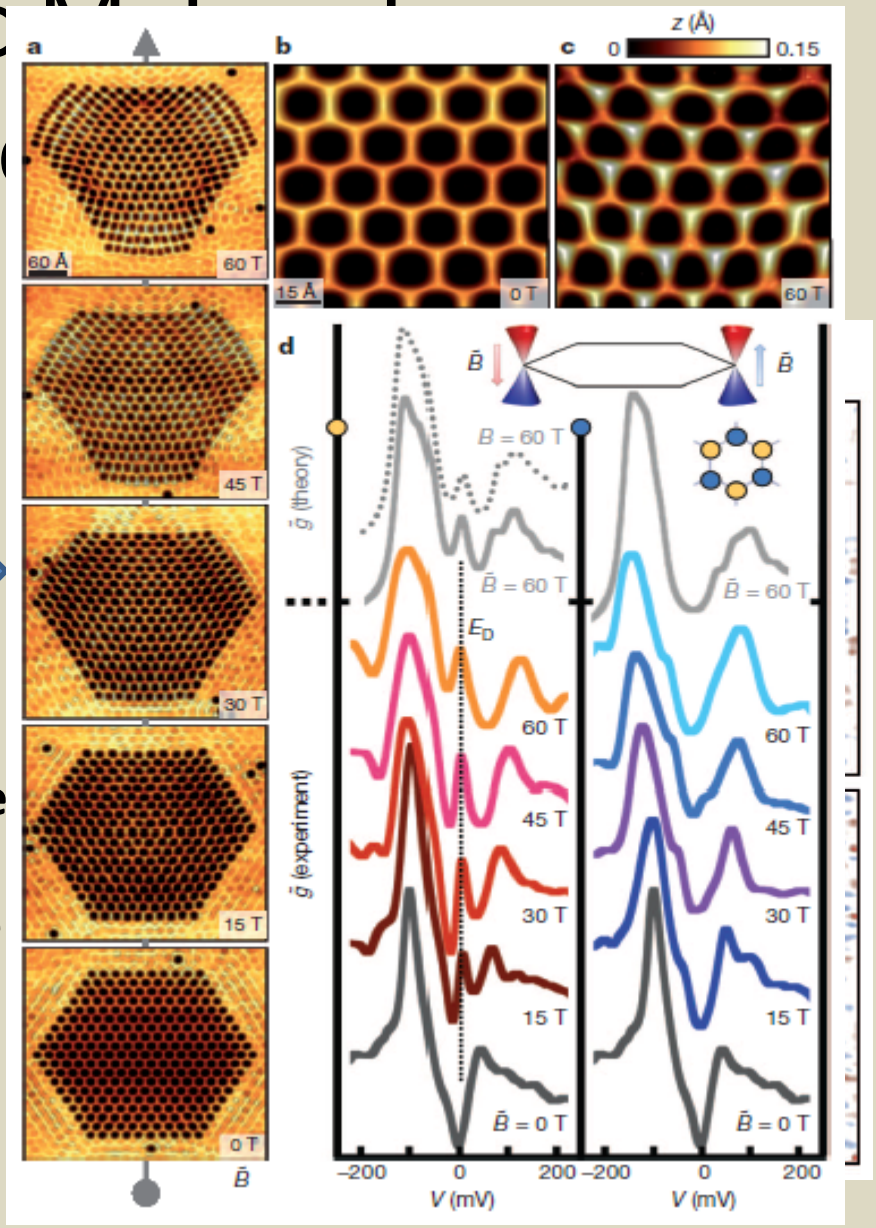


Artificial Dirac
Nanoscale functi

Graphene physics



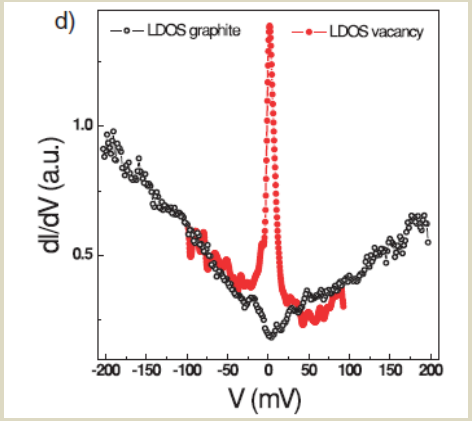
Nanoasse artificial graphene

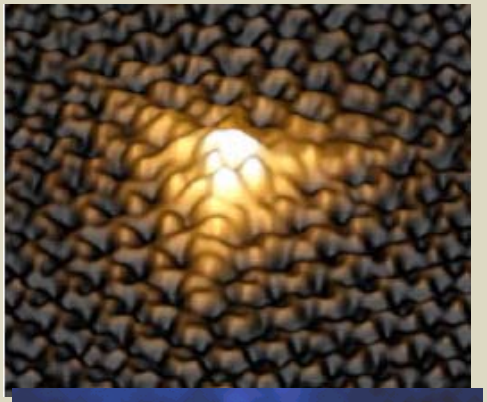


Manoharan group, Nature 483, p 306, 2012
doi:10.1038/nature10941

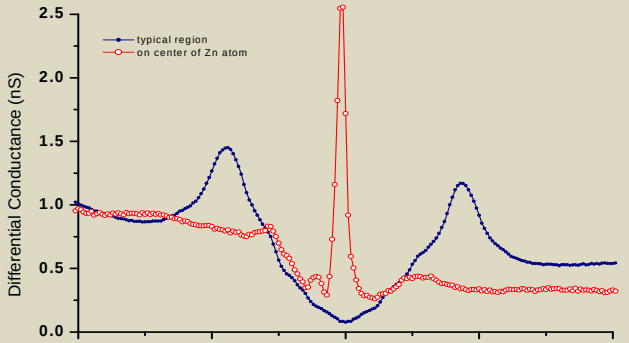
Universal response of Dirac materials to local perturbations

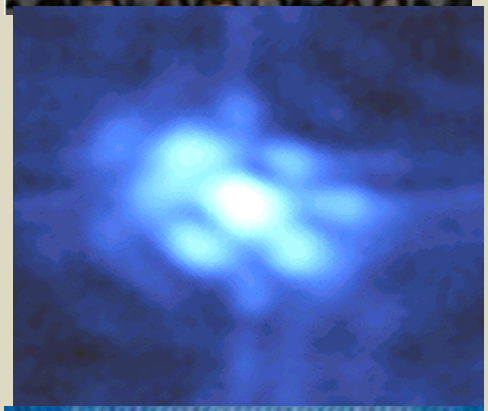
Graphene





D-Wave SC





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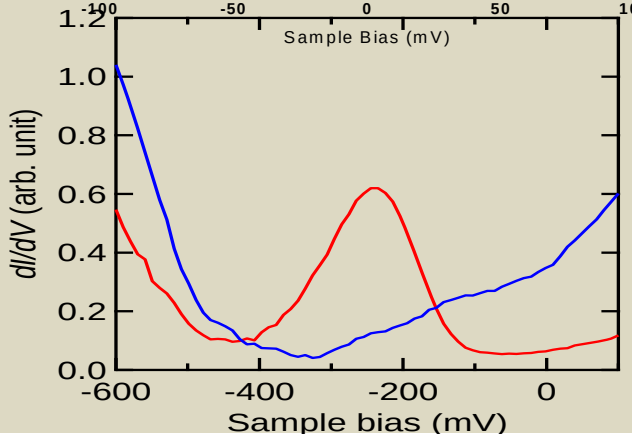

Conclusion

- Dirac materials is a class
- Convergence in multiple materials -> class.
- Defects as test of stability of Topological states
- The future is even more exciting with designed materials coming.
- New imaging to capture exciting new phenomena in quantum materials