Probing the Dirac Electrons in Condensed Matter: Graphene and Topological Insulators

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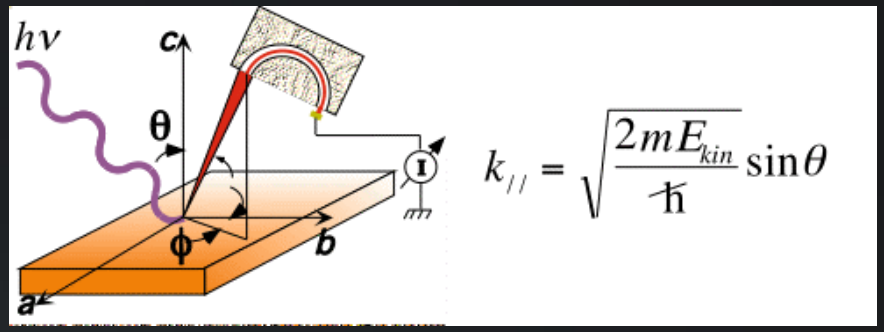
Dirac Electrons in Condensed Matter: A Photoemission View

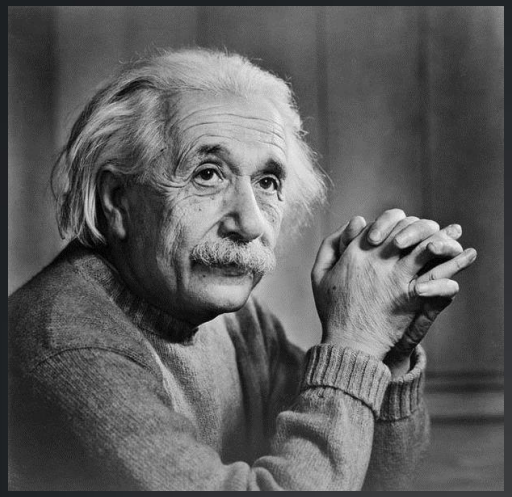
- ARPES
- Graphene
  - Nearly neutral
  - Heavily doped
  - Superconductivity
- Topological Insulators
  - Spin structure
  - Elastic scattering
  - Inelastic scattering

Angle Resolved Photoemission Spectroscopy (ARPES) - ideal probe of electronic structure

- Interesting (interacting) stuff is sometimes difficult to detect!



Hertz

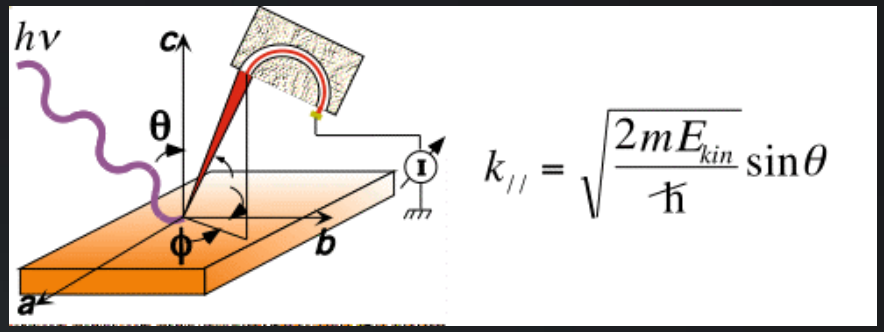


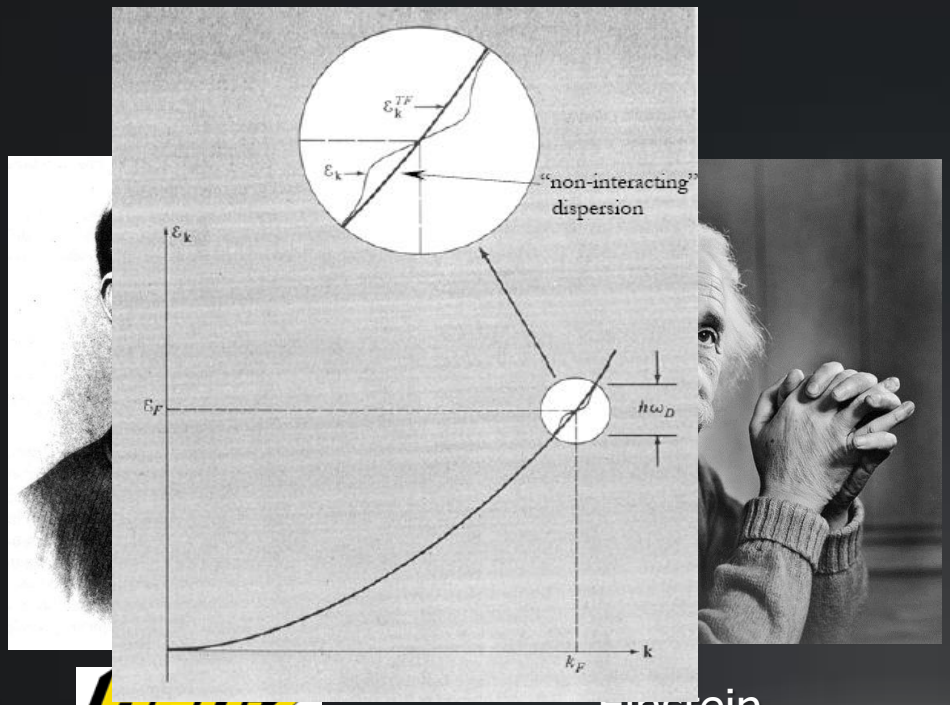
Einstein

- Band structure mapping, for a long, long time… even though it measures ImG(k,ω)

Angle Resolved Photoemission Spectroscopy (ARPES) - ideal probe of electronic structure

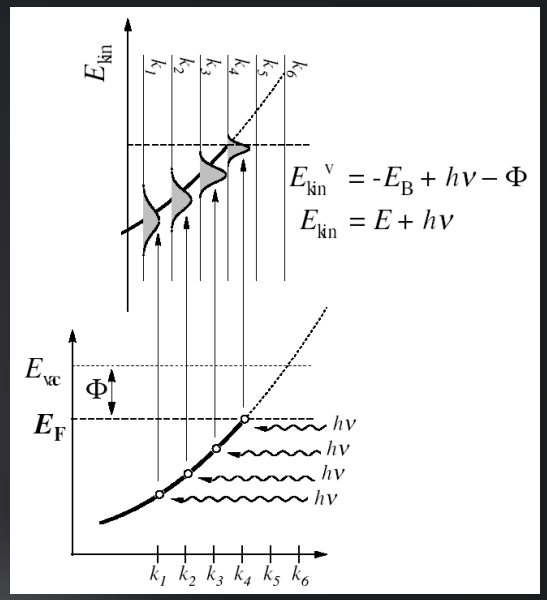
- Interesting (interacting) stuff is sometimes difficult to detect!





Einstein

Ashcroft/Mermin textbook "Solid State Physics"



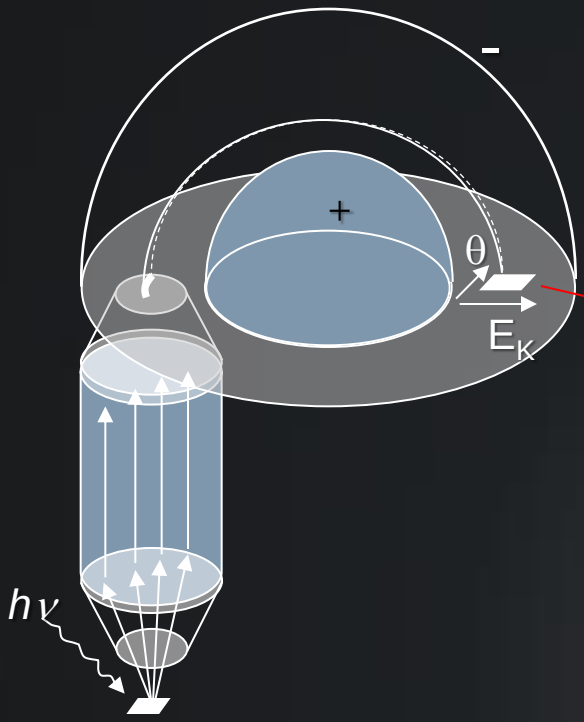
ARPES: $I(k,\omega) \propto A(k,\omega) \sim \mathrm{Im}G(k,\omega)$

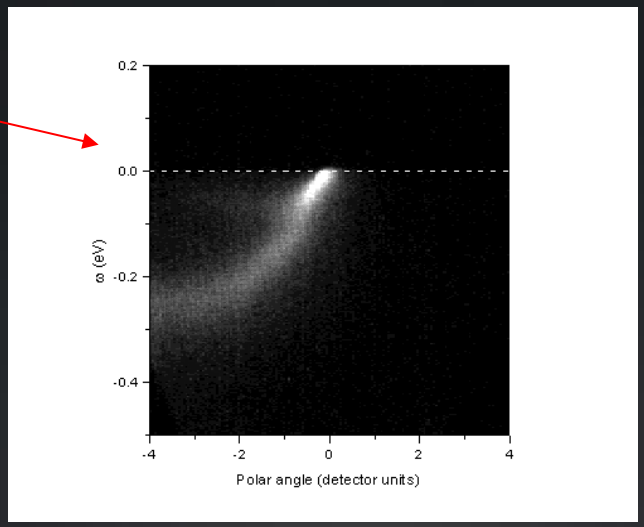
…ng, long
…es ImG(k,ω)

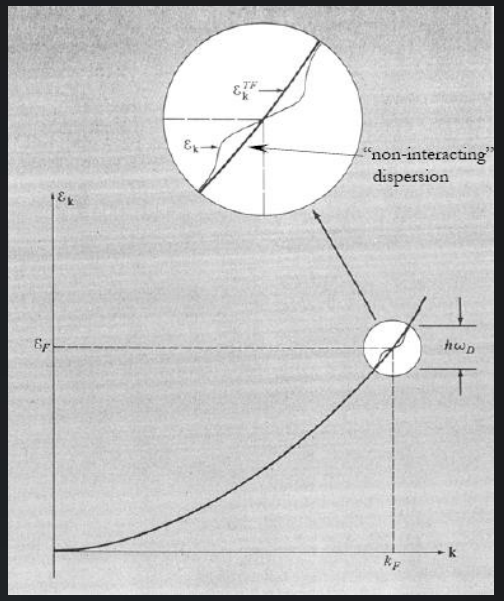
2D detection – revolution in ARPES

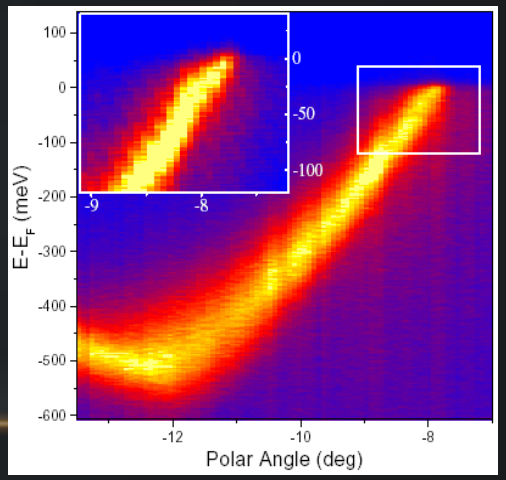
BNL group made a break-through in 1998:

2-Dimensional detection, high energy and angle resolution







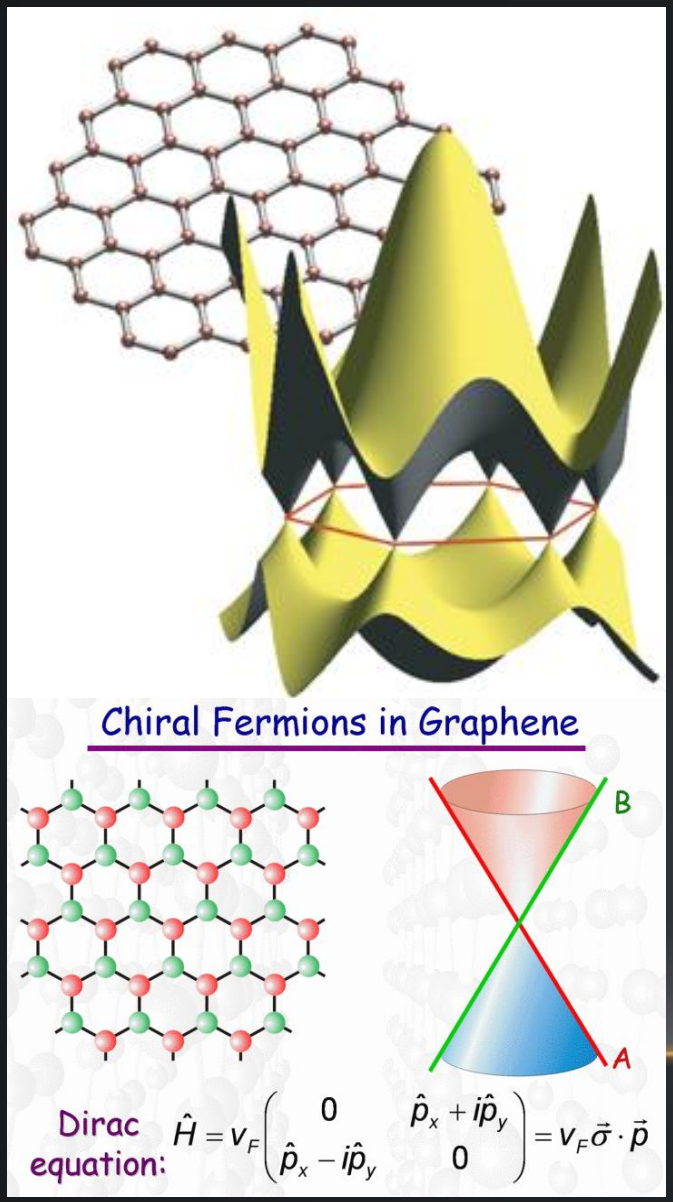


Resolution:

- ΔE~1-20 meV •(<1meV)
- Δθ~0.1-0.2° → Δk~0.005-0.01Å^{-1} at ~15eV photon energy

T. Valla *et al*, Phys. Rev. Lett. **83,** 2085 (1999).

Graphene's electronic structure



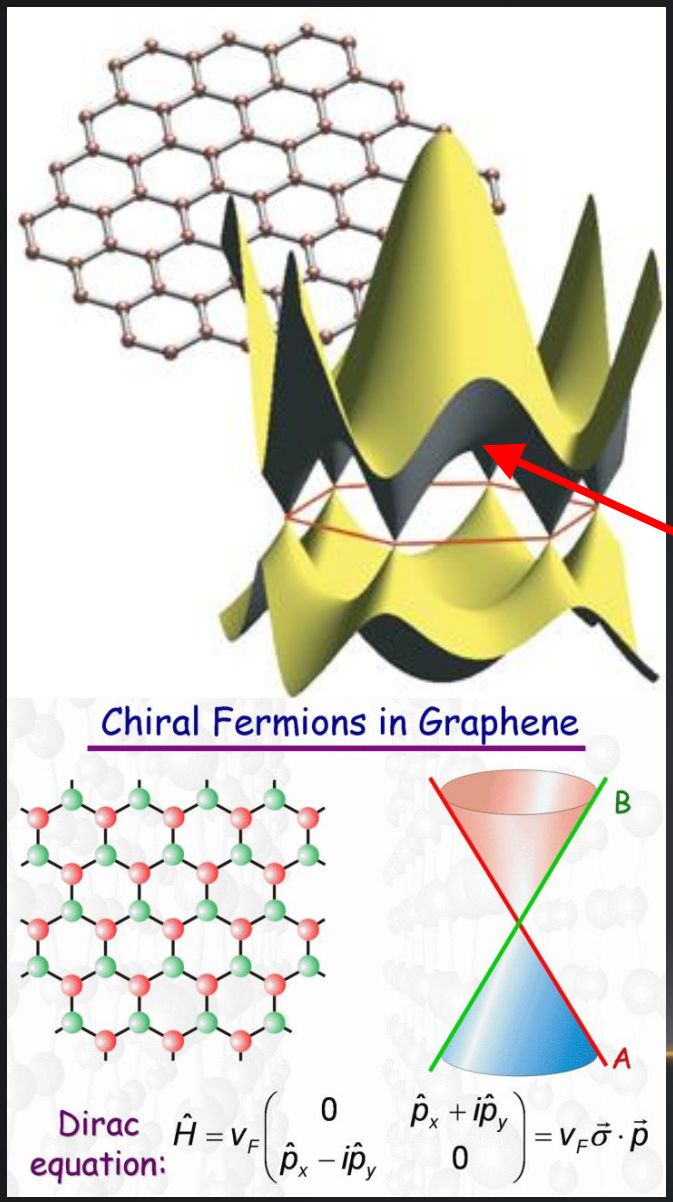
1) neutral (E_D at E_F)

Massless fermions

$$E(\pm q) \approx \pm v_F |q|$$

- QHE (even at RT)
- Huge mobilities, ballistic transport on a ~micron scale
- candidate for devices, electronics, spintronics, detectors…

Graphene's electronic structure



1) neutral (E_D at E_F)

Massless fermions

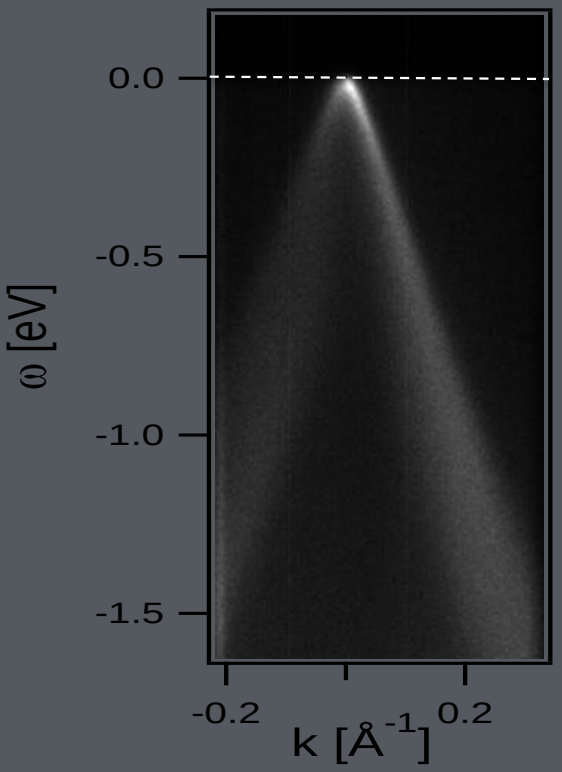
$$E(\pm q) \approx \pm v_F |q|$$

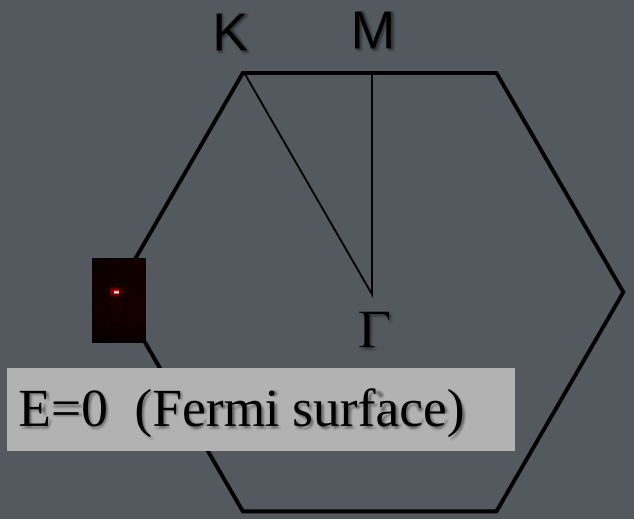
2) heavily doped (vHS at E_F) (~1/2 e^- per C)

massive fermions,

large DOS, strong interactions, superconductivity?

~Neutral regime: ARPES





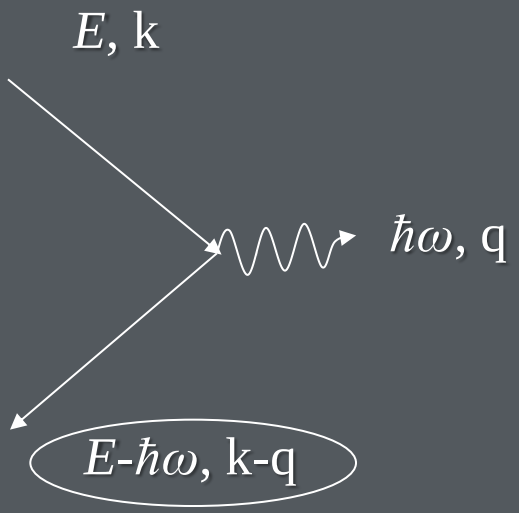
gr/SiO_2/Si

1) Dirac point ~at the Fermi level

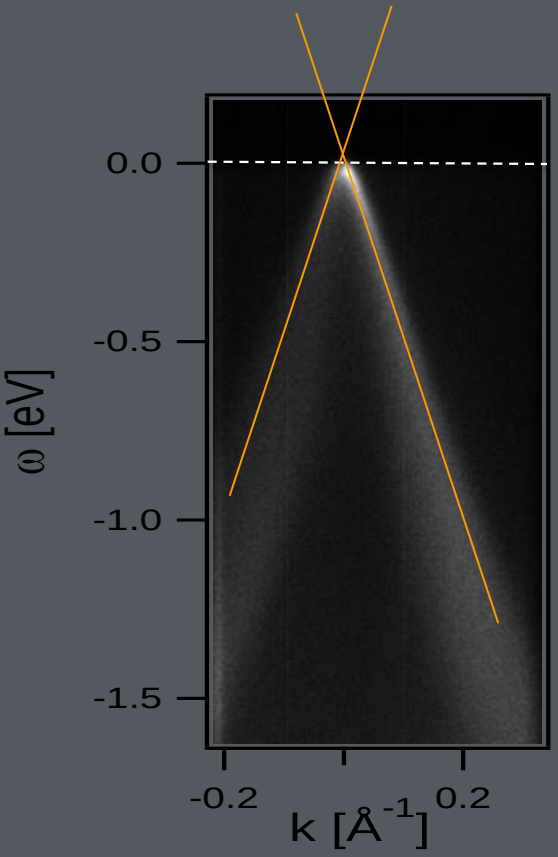
2) Weak electron-phonon coupling

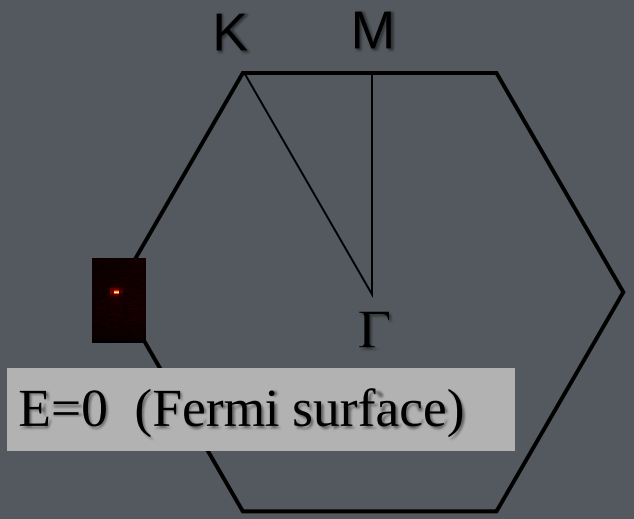
T. Valla, J. Camacho *et al*, Phys. Rev. Lett. 102, 107007 (2009)

~Neutral regime: ARPES



Restricted to a ~point





1) Dirac point ~at the Fermi level

2) Weak electron-phonon coupling

T. Valla, J. Camacho *et al*, Phys. Rev. Lett. 102, 107007 (2009)

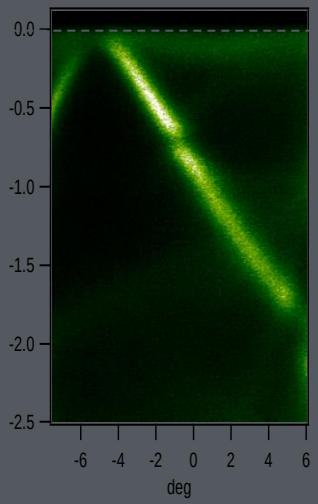
Heavy doping - graphene/Ir(111)

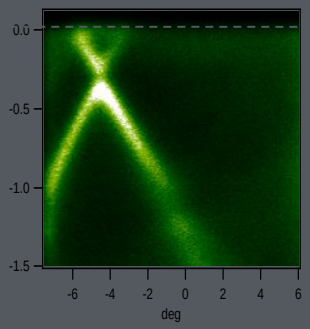
Li

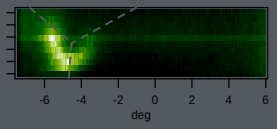
Na

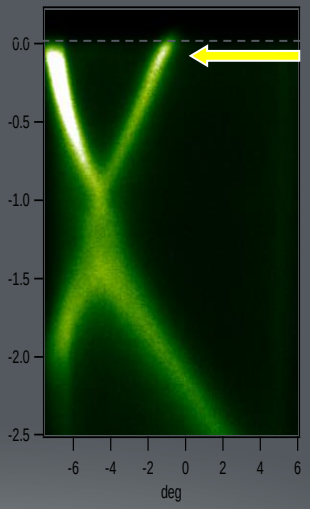
more Na

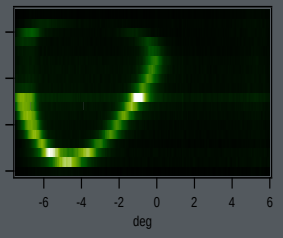
Graphene/Ir(111)

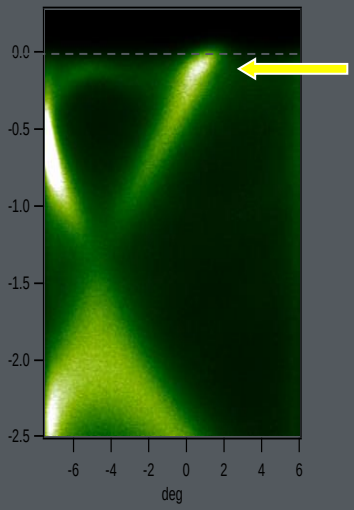


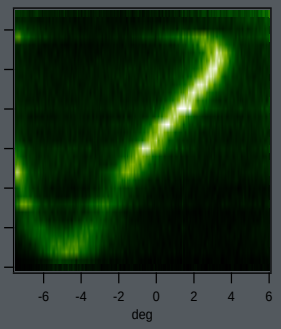






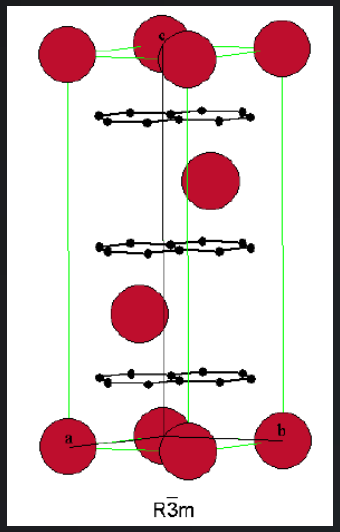




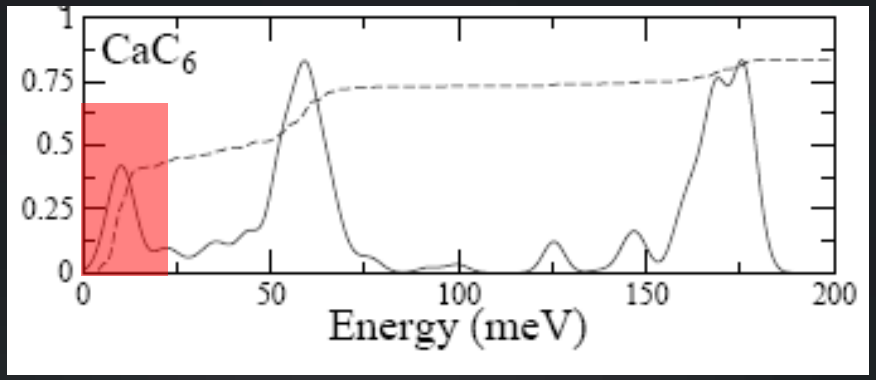


As FS grows, el-ph coupling strengthens!

Superconductivity in CaC_6 ("heavily doped graphene")



Superconducting, T_c~11.6K !

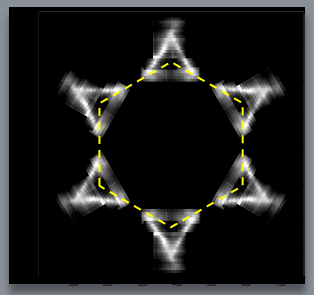


M. Calandra and F. Mauri, Phys. Rev. Lett. 95, 237002 (2005).

Theories: intercalate states couple to intercalate phonons

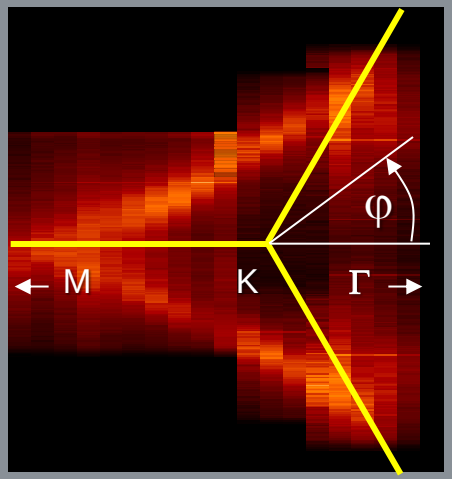
$\Rightarrow$ Graphene sheets unimportant!

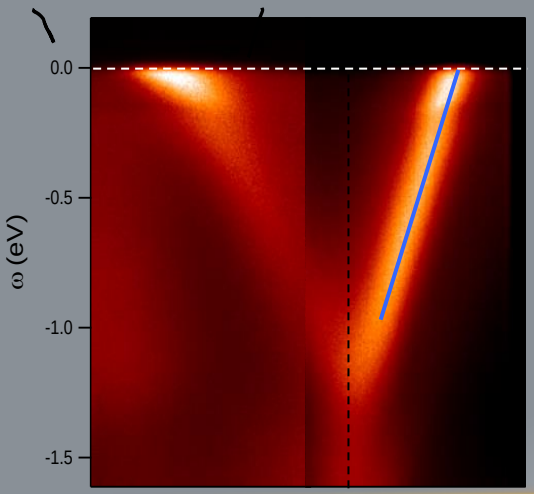
Experiment:

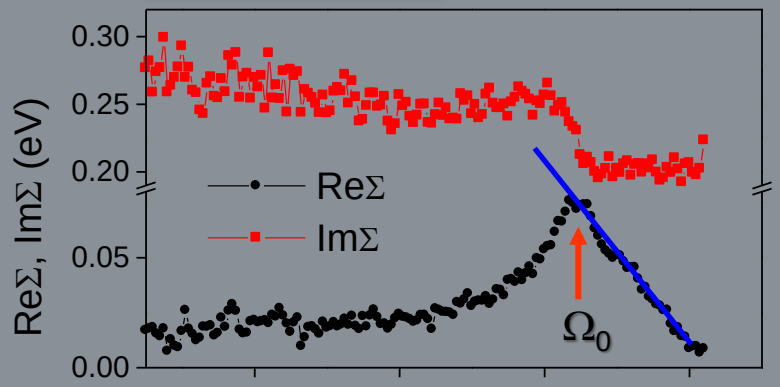


T. Valla, J. Camacho *et al*, Phys. Rev. Lett. 102, 107007 (2009)

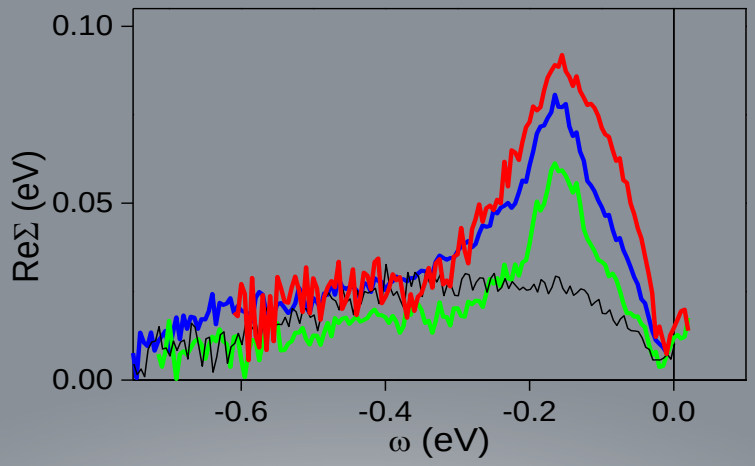
k -resolved!

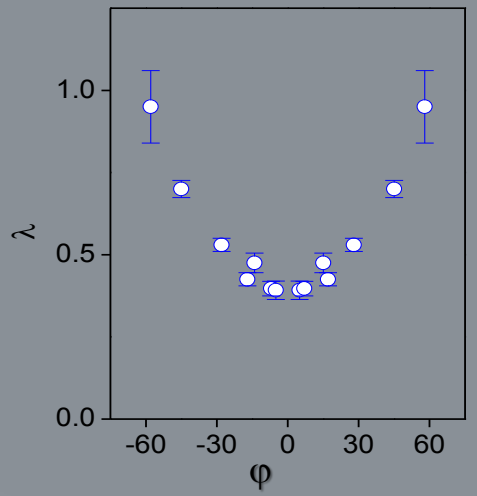






$$\lambda = -\frac{\partial \mathrm{Re}\,\Sigma}{\partial \omega}$$



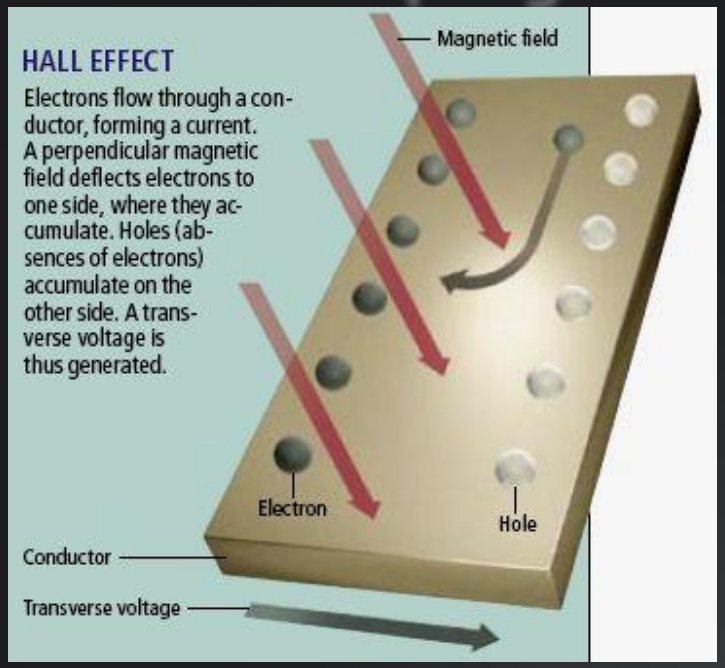


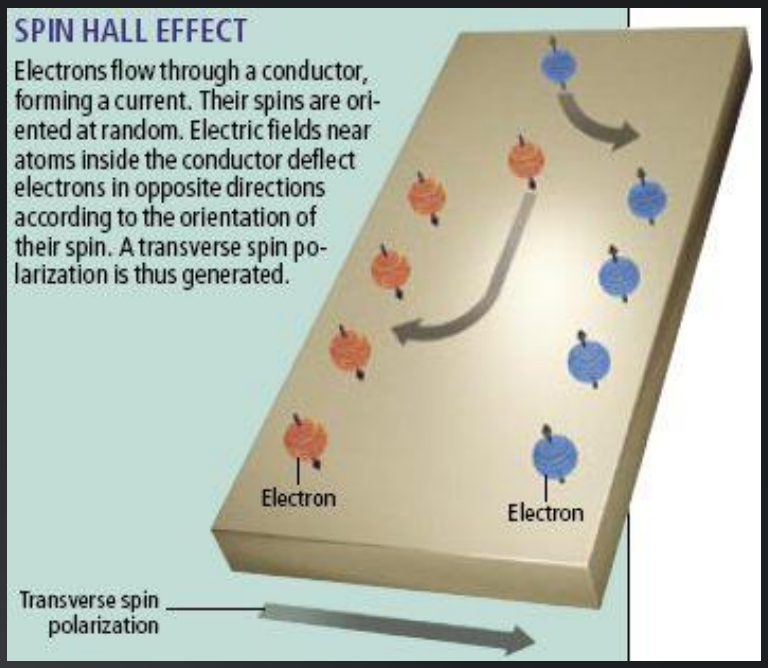
ARPES experiments: graphene states couple to graphene phonons

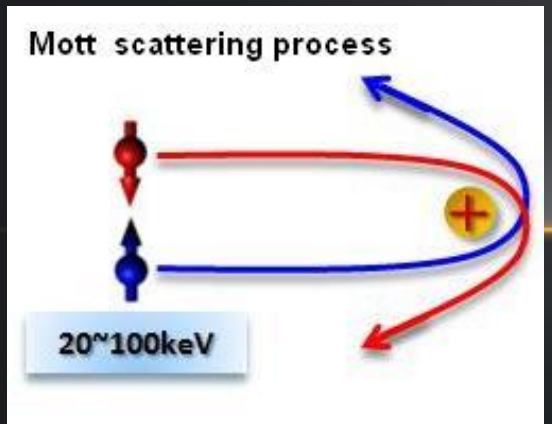
⇒ Graphene sheets responsible for SC!

Topological Insulators

Spin-orbit coupling



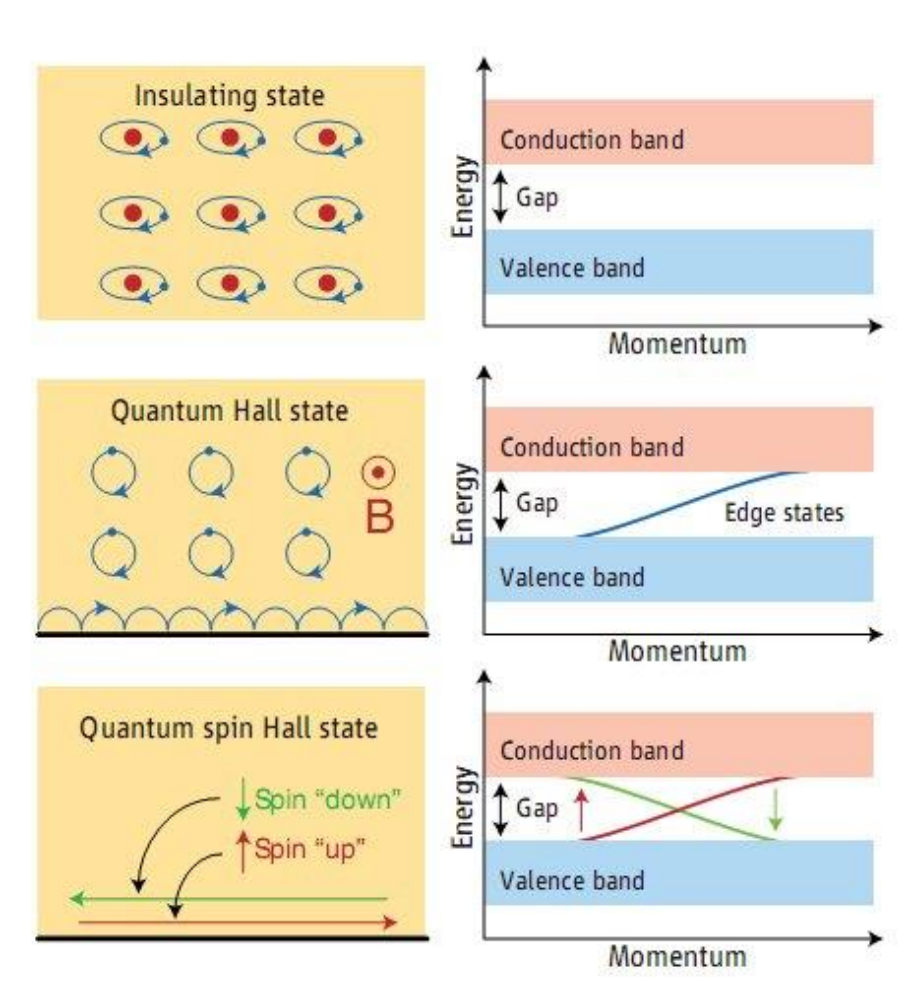




SHE: spins separate without magnetic field

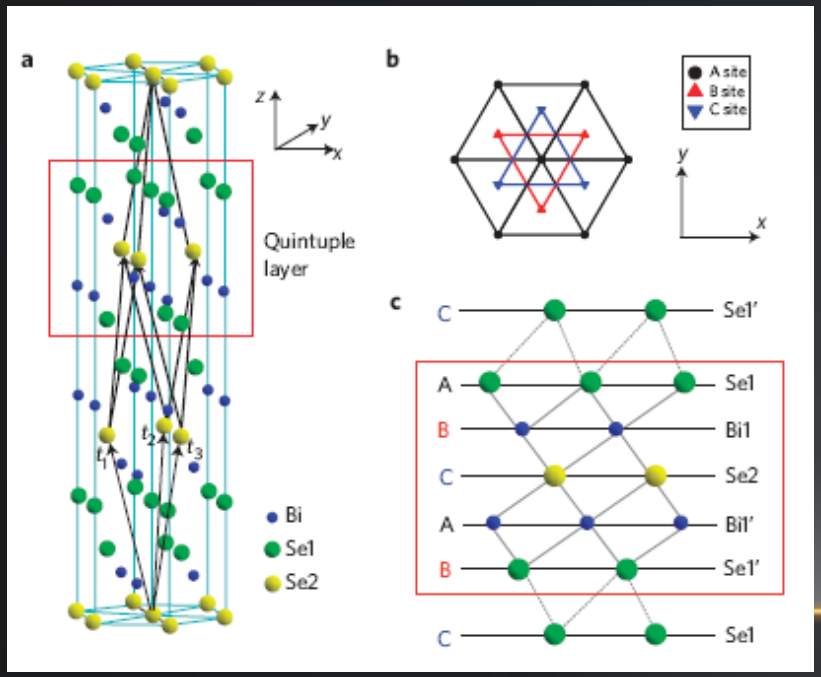
$$H_{SO} = \frac{\hbar}{4m_0^2c^2}\,\mathrm{p}(\sigma \times \nabla V(\mathrm{r}))$$

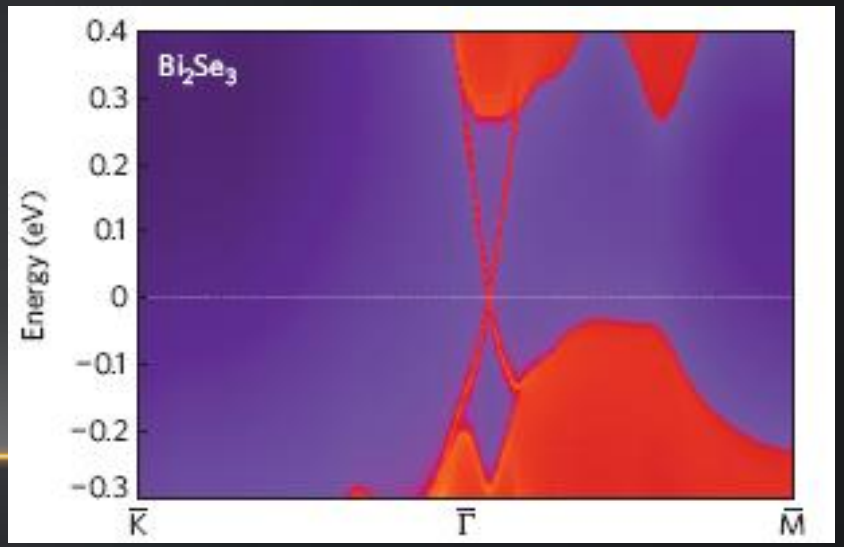
Topological Insulators:



Topological Gapless States on Surfaces of Topological Insulators

- "band inversion" due to spin-orbit coupling → topological insulator
- boundary states
- spin-helical surface states on a 3D topological insulator
- topologically protected





H. Zhang *et al*, Nature Physics **5**, 438 (2009)

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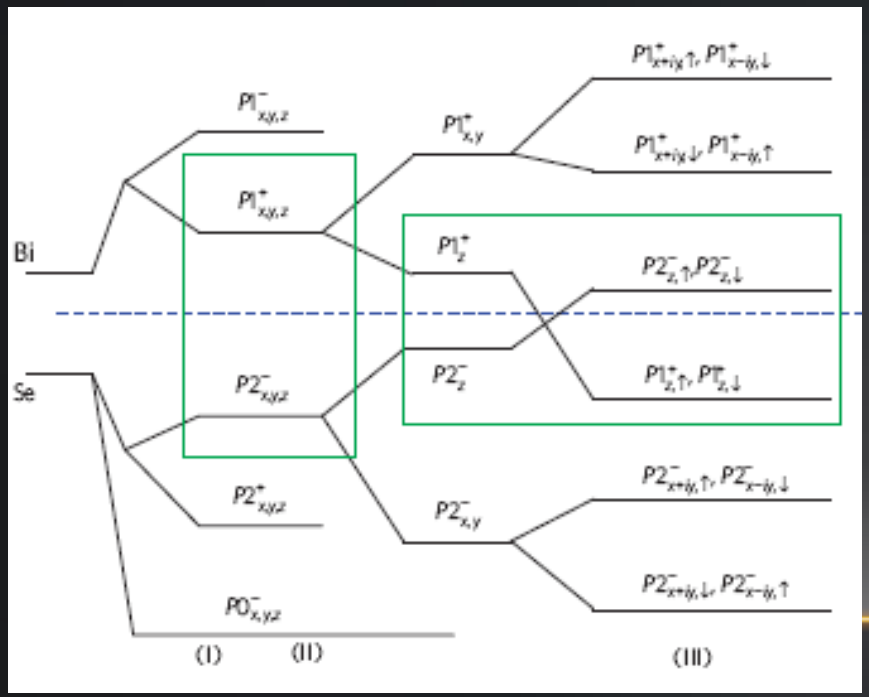

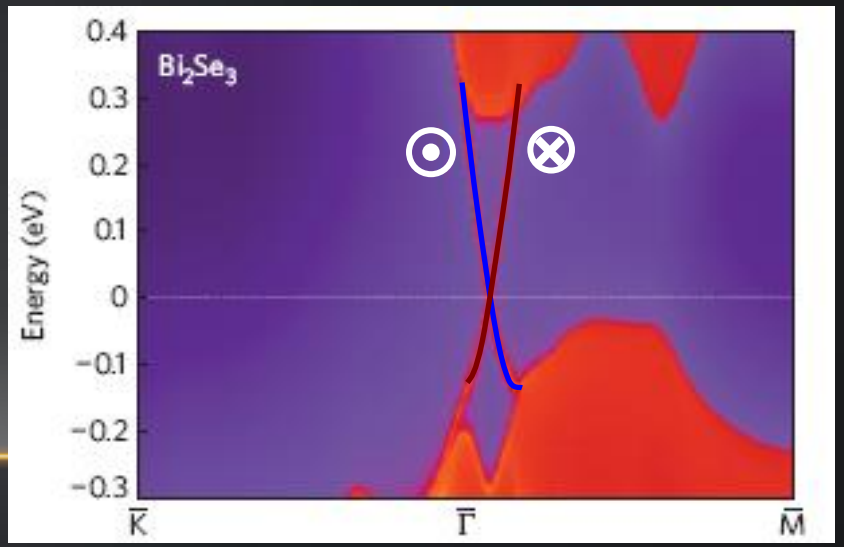

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Theories:

- TI/trivial insulator:

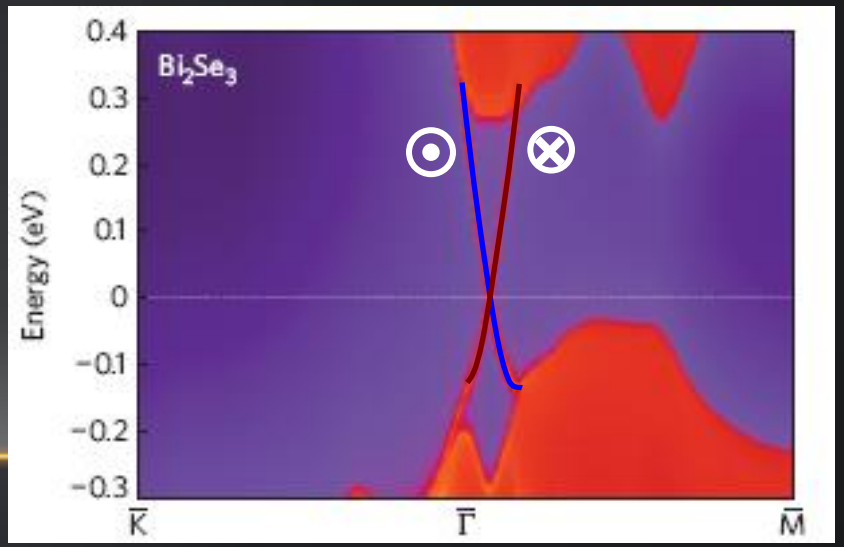
  gapless, dissipationless states

- TI/ferromagnet:

  "magnetic monopoles"

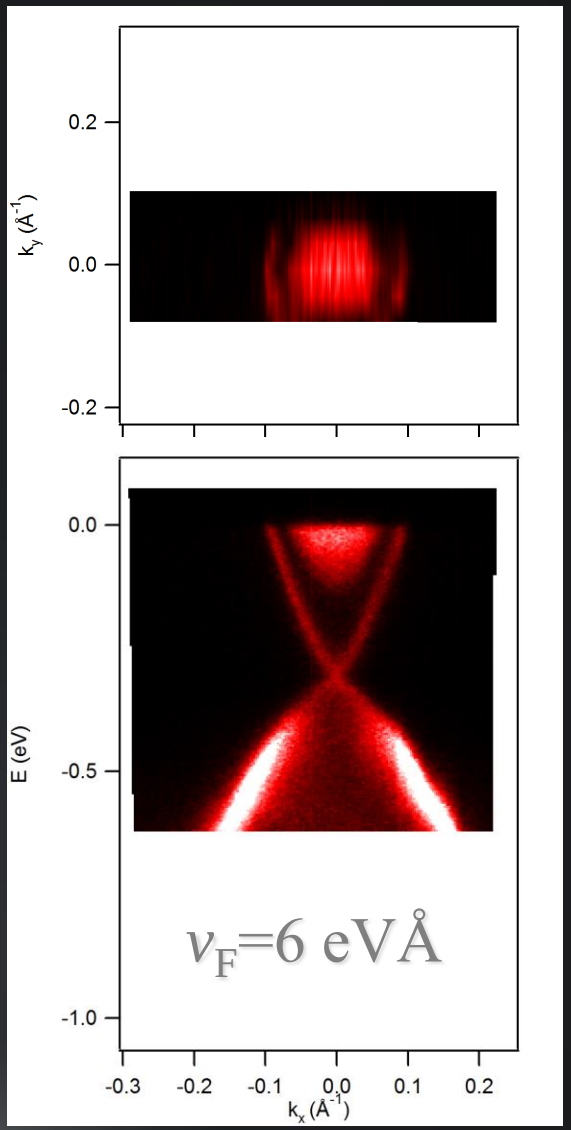
- TI/superconductor:

  Majorana fermions…



H. Zhang *et al*, Nature Physics **5**, 438 (2009)

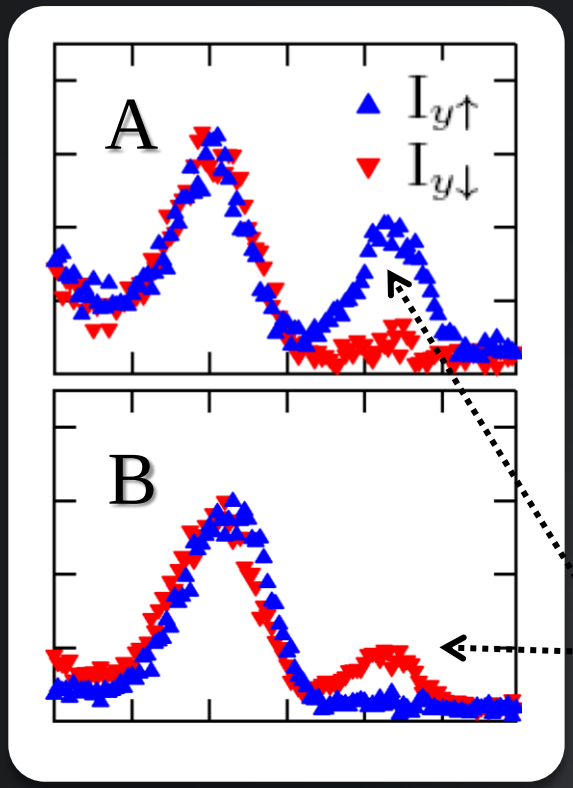
Experiments (Bi_2Se_3):

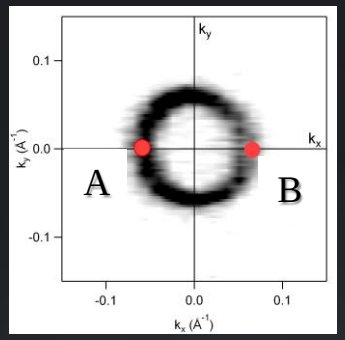


H.-J. Noh *et al*, EPL 81, 57006 (2008), (Bi_2Te_3)
D. Hsieh *et al*, NATURE 452, 970 (2008)….

Experiments (Bi_2Se_3):

Backscattering forbidden!

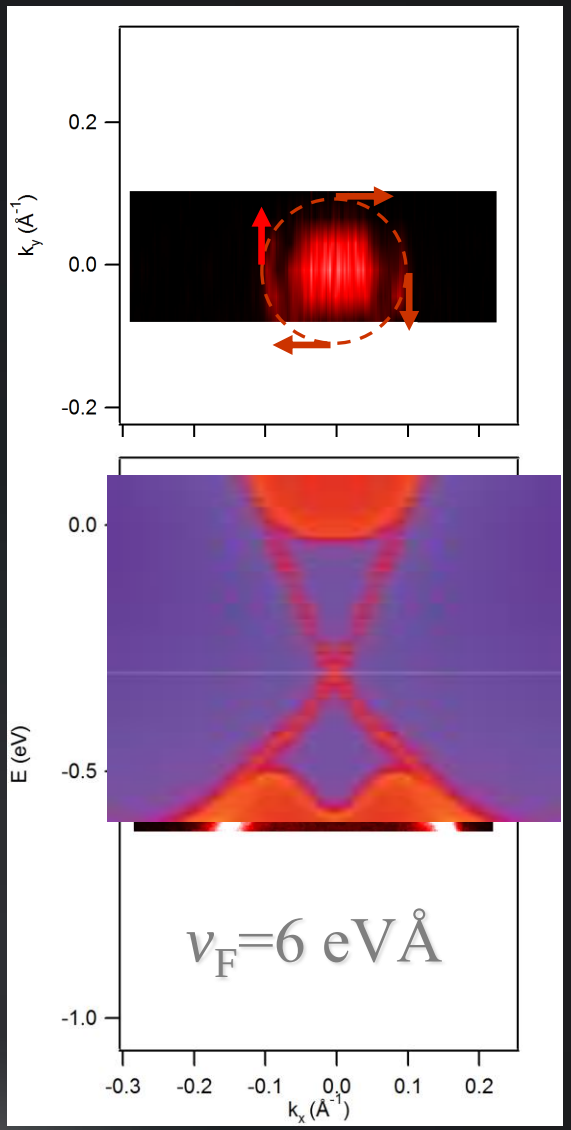




Surface state

$P_{TSS} \approx 100\%$

Z.-H. Pan *et al*., PRL **106**, 257004 (2011)



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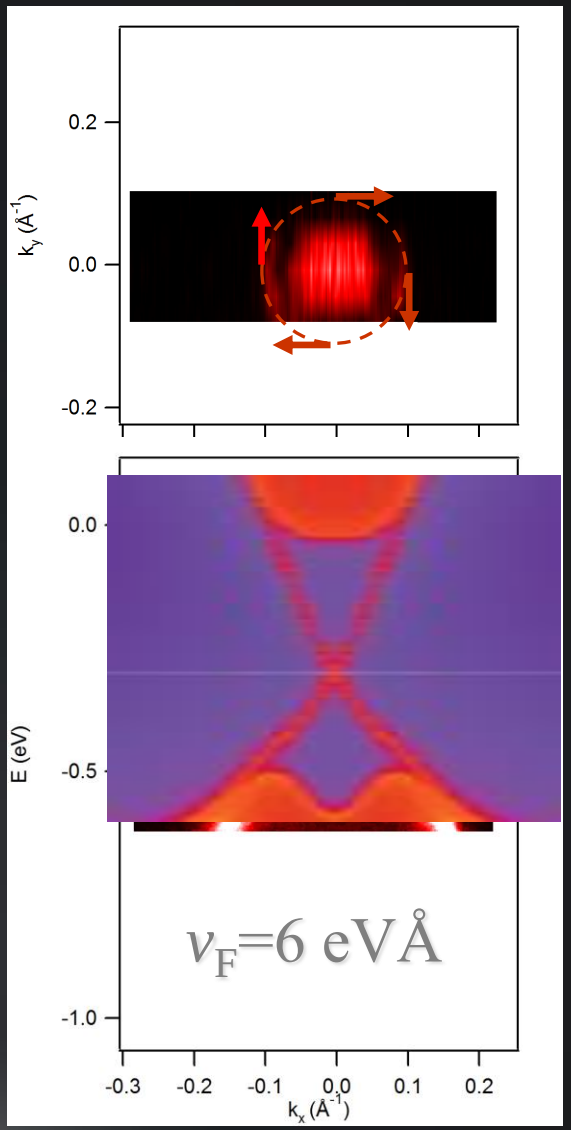
Experiments (Bi_2Se_3):

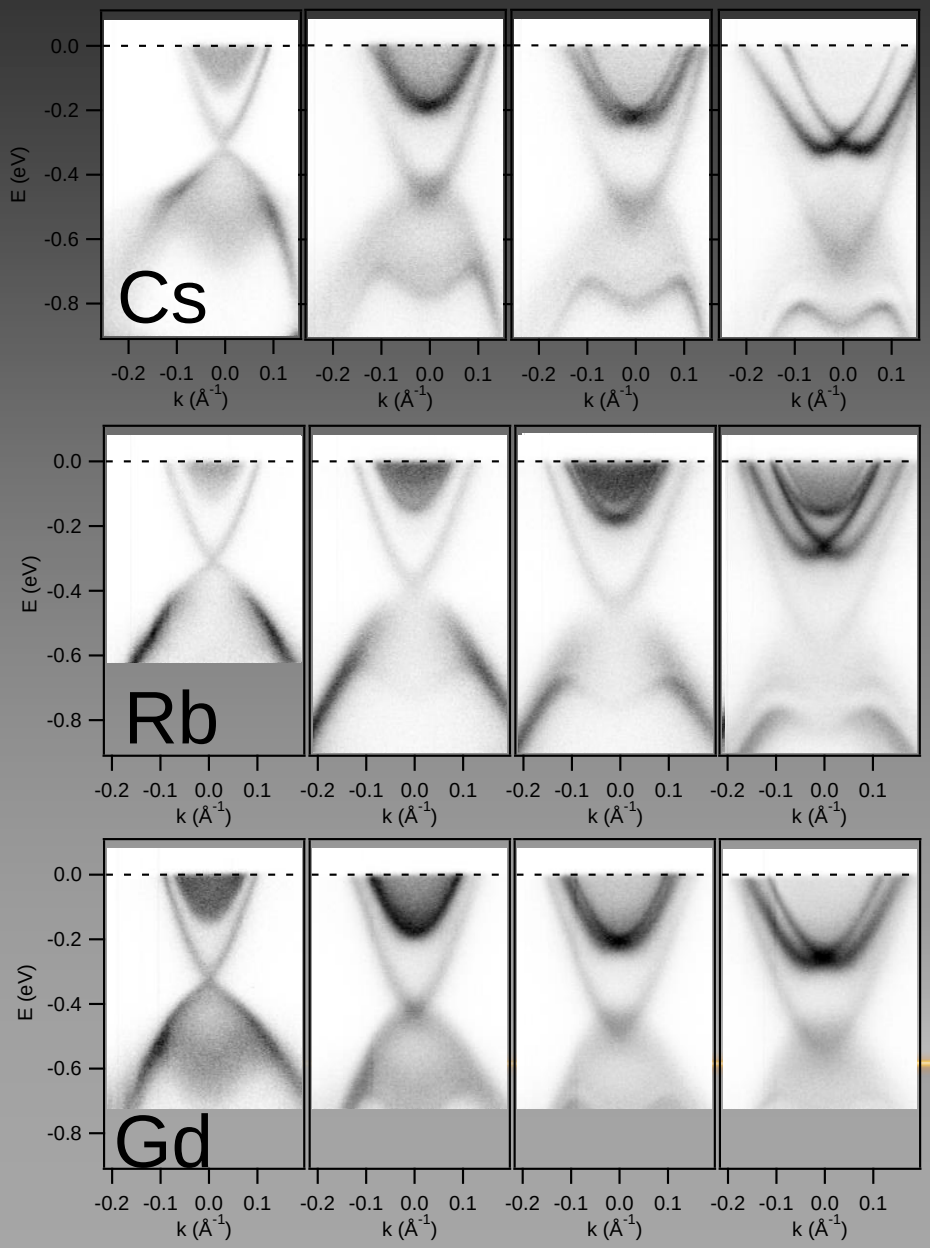
Backscattering forbidden!

Interband scattering?Inelastic scattering?



H.-J. Noh *et al*, EPL 81, 57006 (2008), (Bi_2Te_3)
D. Hsieh *et al*, NATURE 452, 970 (2008)….

Elastic Scattering



Impurities on Bi_2Se_3 surface

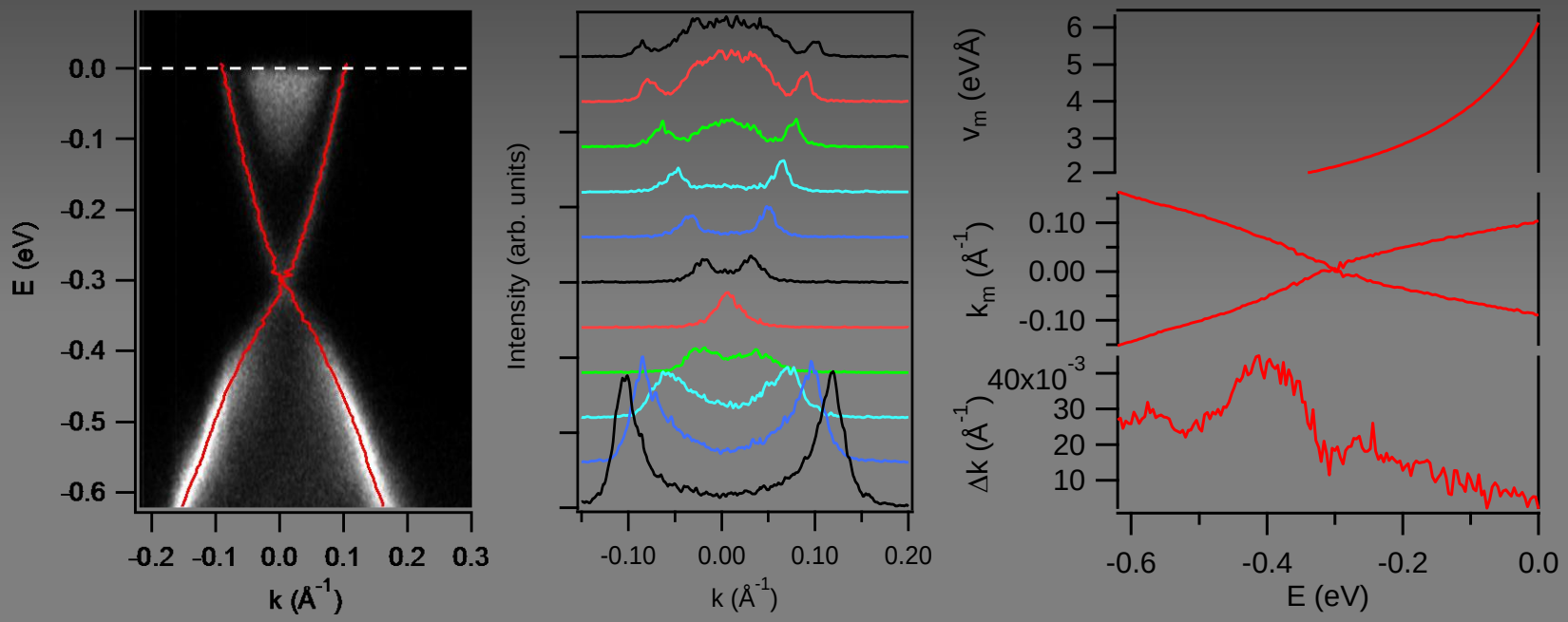
T. Valla, *et al*, PRL (2012).

Non-magnetic impurities

Magnetic impurities!

($\mu \approx 8\ \mu_B$)

Scattering rates from ARPES

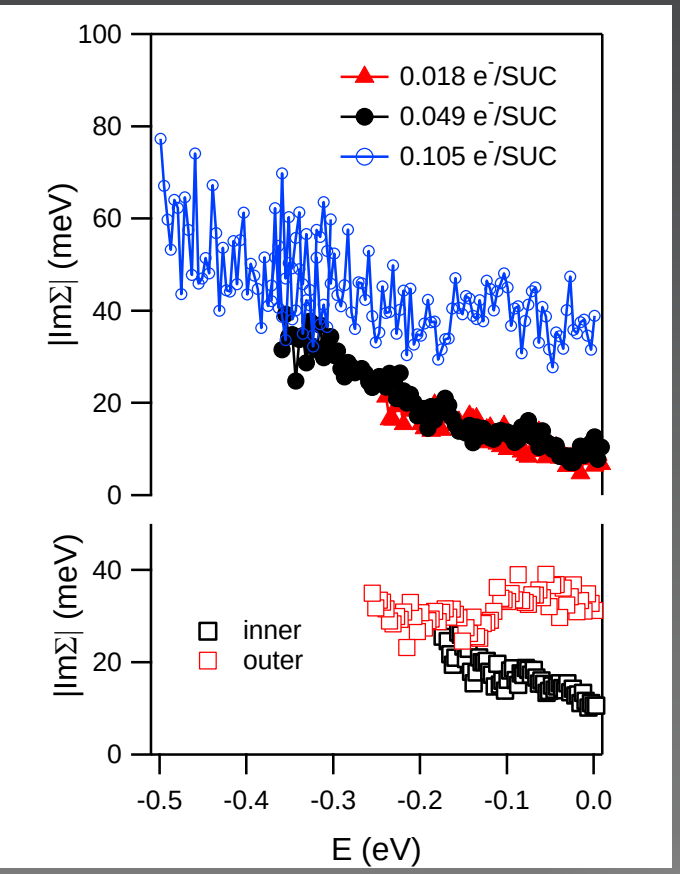


MDCs

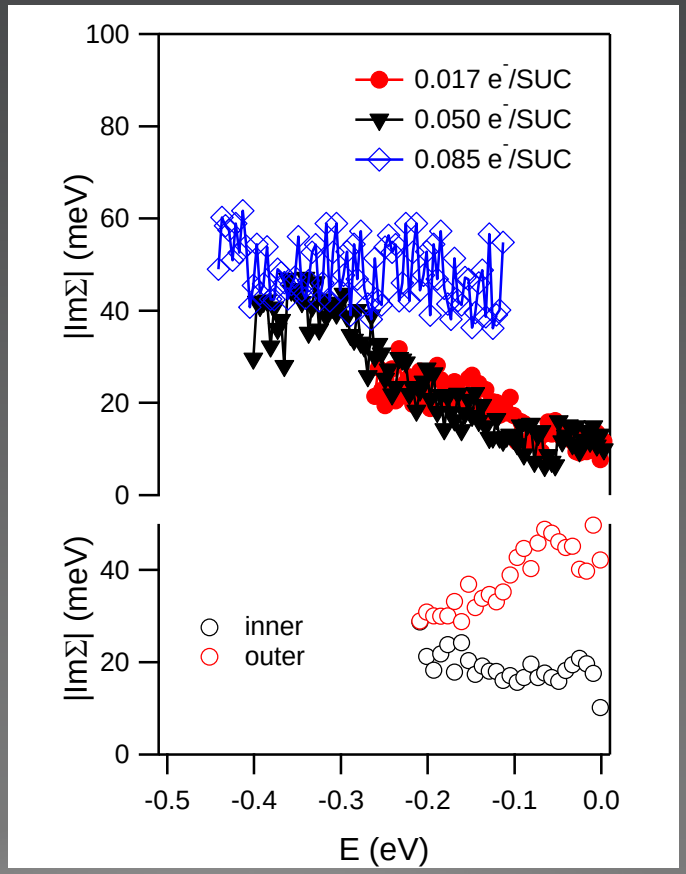
$\Gamma = 2|\mathrm{Im}\Sigma| = \Delta k v_m$

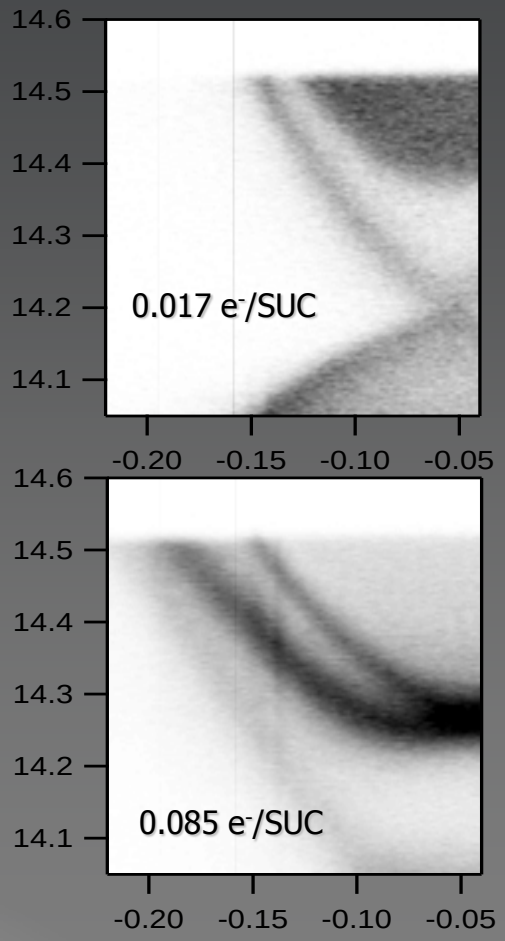
Scattering rates:

Rb



Gd

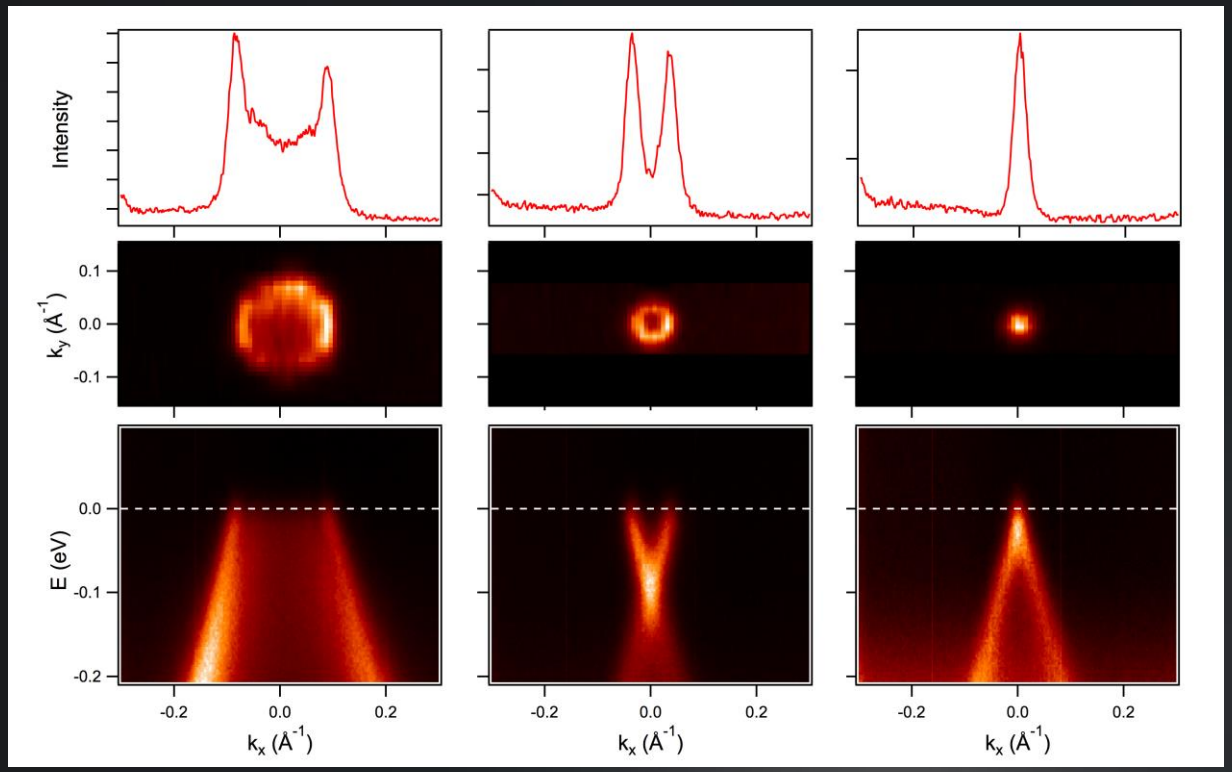


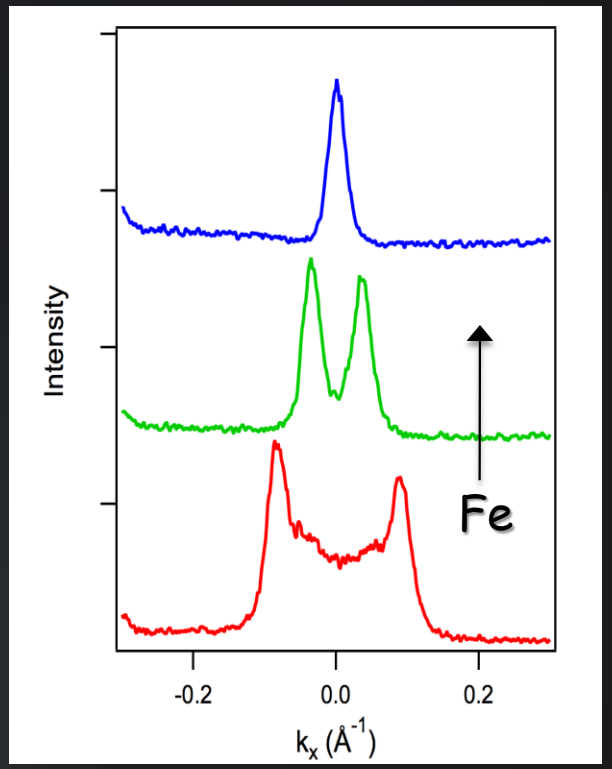


But, what about spin-flip?

Magnetic impurities on Sb_2Te_2Se (p-type)

Fe ⟶

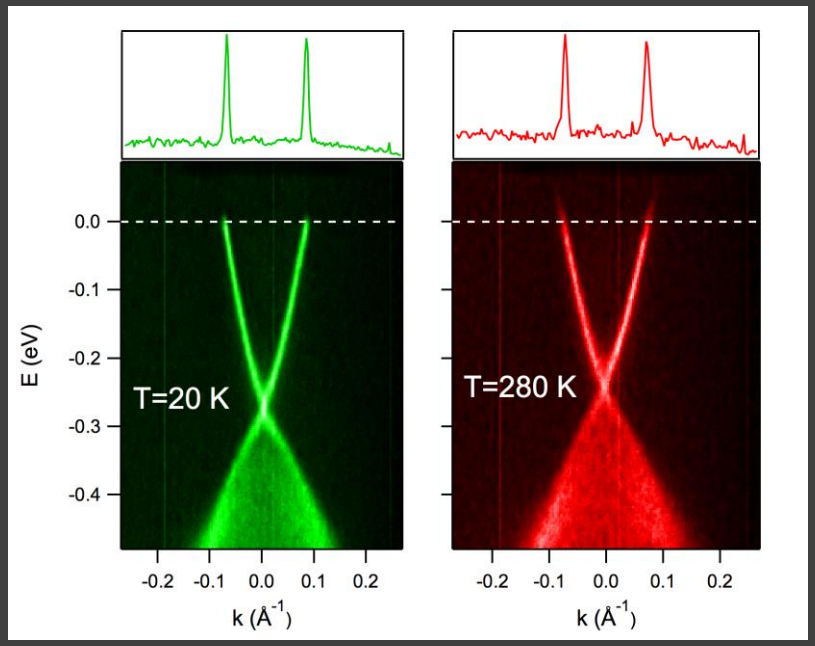




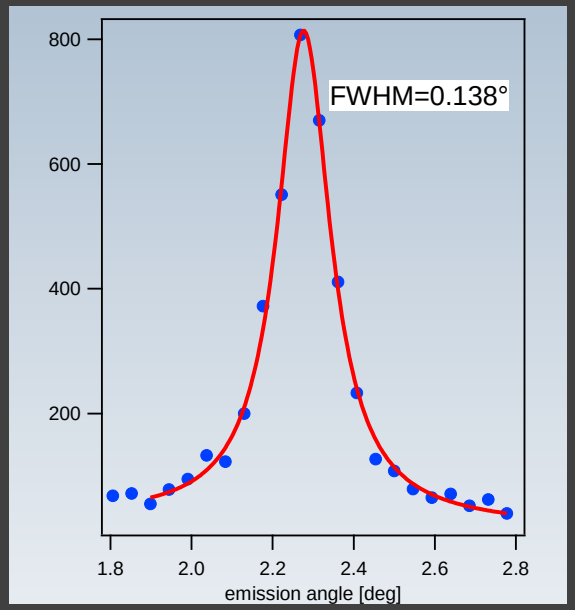
width the same – scattering the same!

Inelastic scattering

T-dependence and (a lack of) the electron-phonon coupling

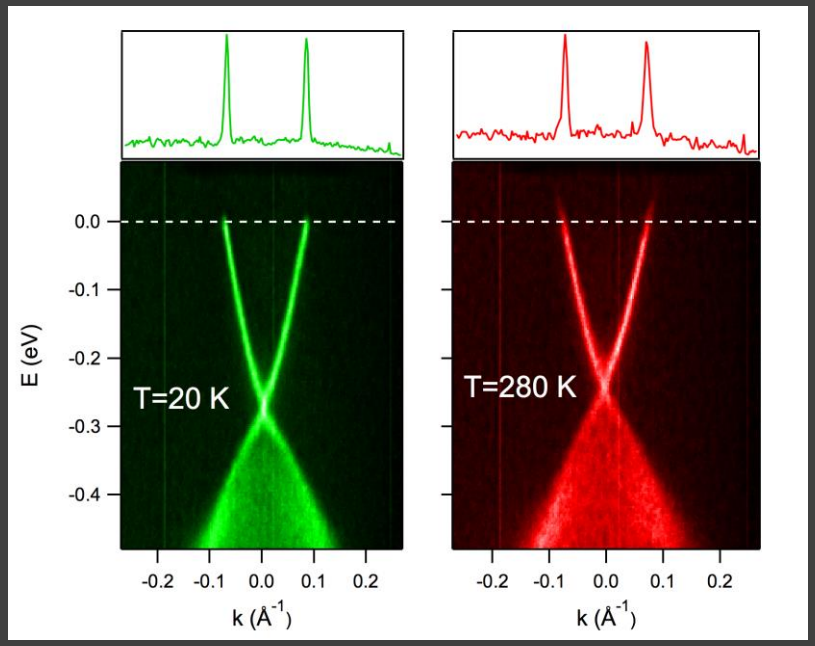


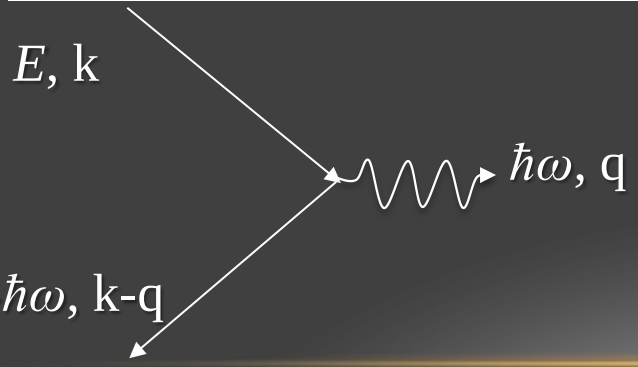
Z.-H. Pan, *et al*, Phys. Rev. Lett. **108**, 187001 (2012).



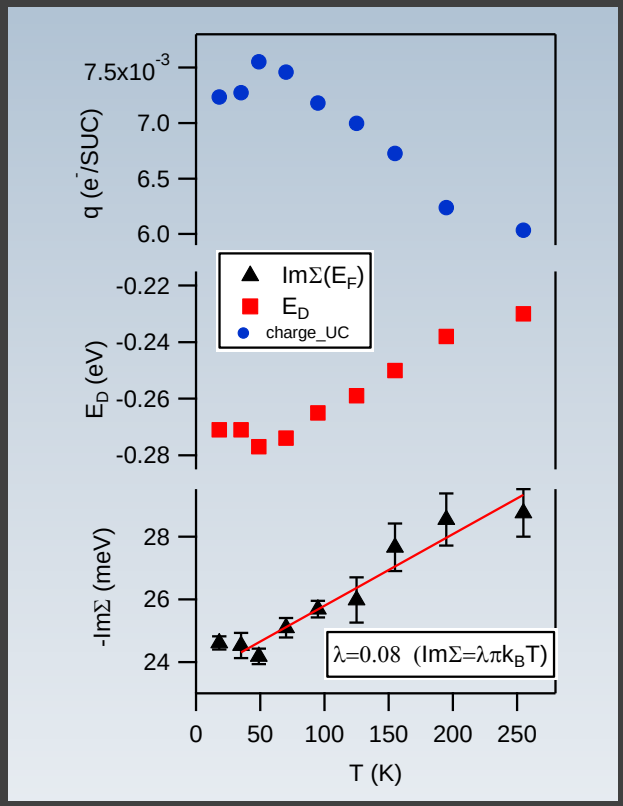
Inelastic scattering

T-dependence and (a lack of) the electron-phonon coupling





Z.-H. Pan, *et al*, Phys. Rev. Lett. **108**, 187001 (2012).



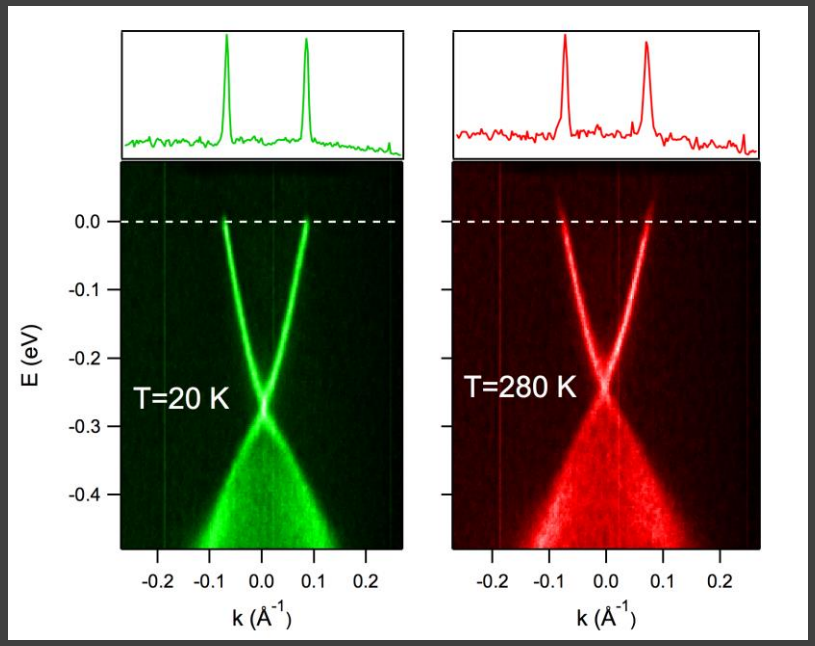
$$\mathrm{Im}\Sigma(\omega,T)=\pi\int_0^\infty \alpha^2F(\nu)[2n(\nu)+f(\nu+\omega)+f(\nu-\omega)]d\nu$$

$$\mathrm{Im}\Sigma(0,T)\approx\pi\lambda k_B T$$

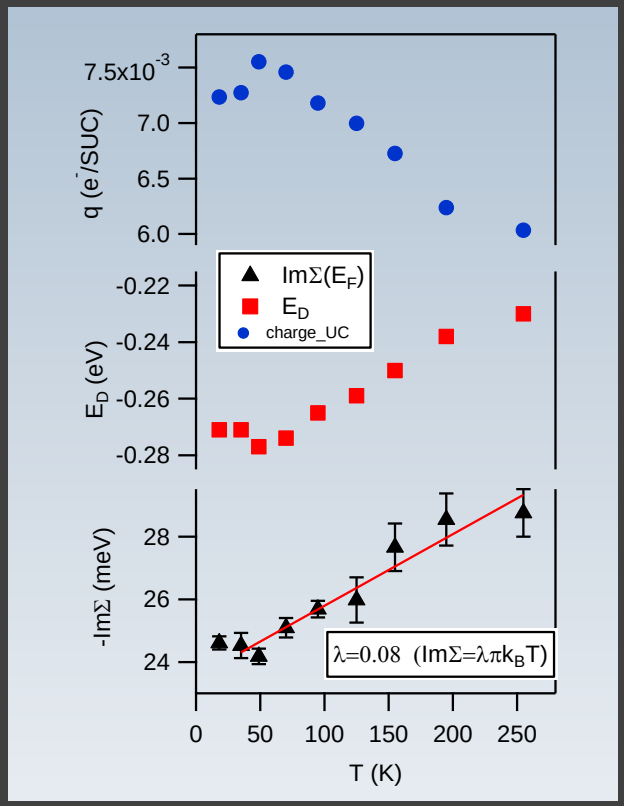
$$\lambda=0.076$$

Inelastic scattering

T-dependence and (a lack of) the electron-phonon coupling



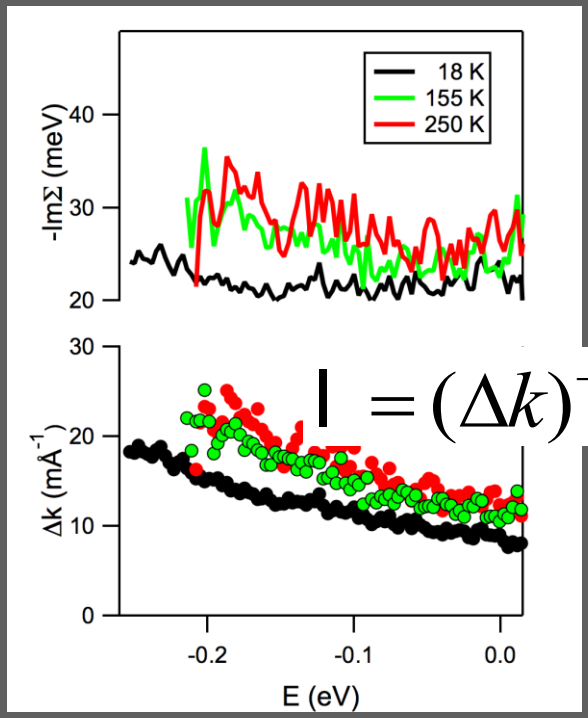
Z.-H. Pan, *et al*, Phys. Rev. Lett. **108**, 187001 (2012).



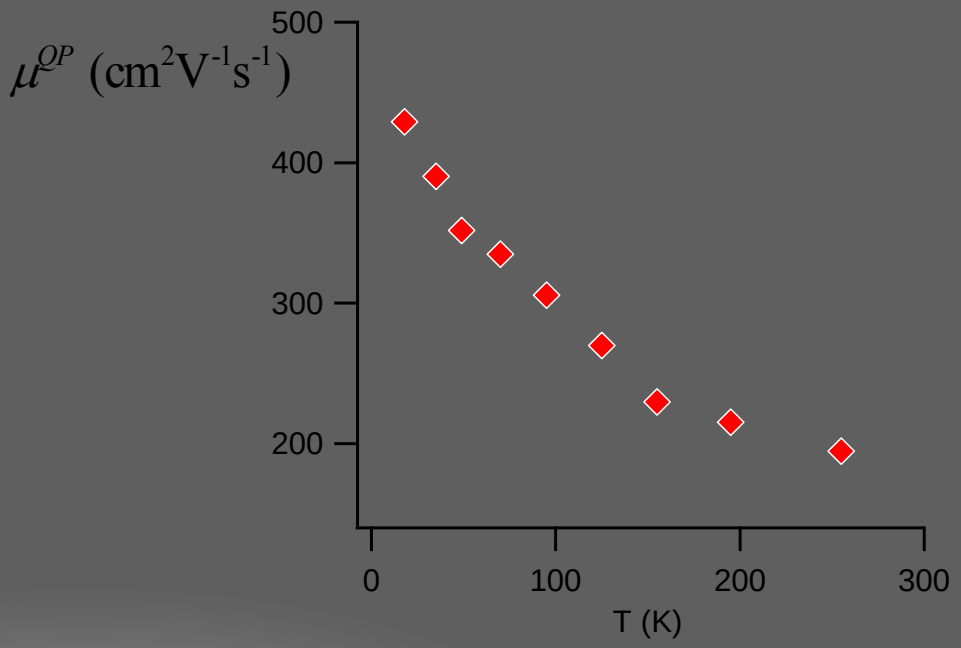
States coherent even at RT!

Relation to transport

Z.-H. Pan, *et al*, PRL, (2012).



$$l = (\Delta k)^{-1}$$



$$\mu = \frac{e\ell_{tr}}{\hbar k_F}$$

Huge mobilities - backscattering forbidden (but only for pristine surfaces)

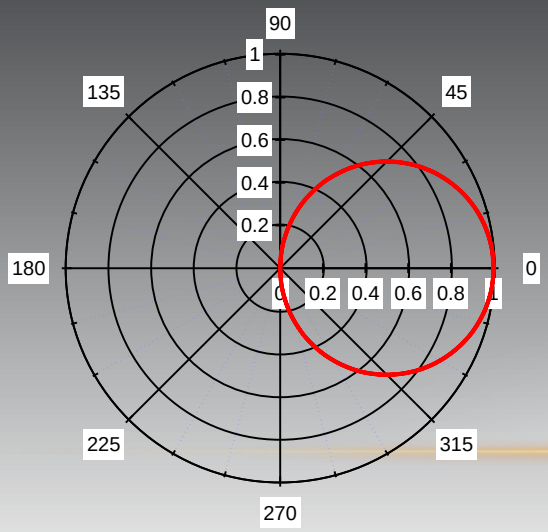
Relation to transport

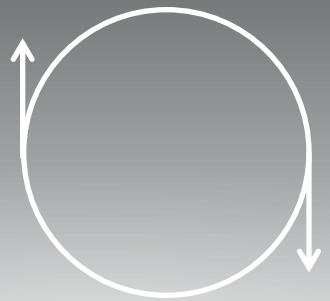
$$\Gamma(k) = 1/\tau(k) = 2\pi n_i \int \frac{d^2k'}{(2\pi)^2} \delta(\varepsilon_k - \varepsilon_{k'}) \left| T_{\mathbf{kk'}} \right|^2$$

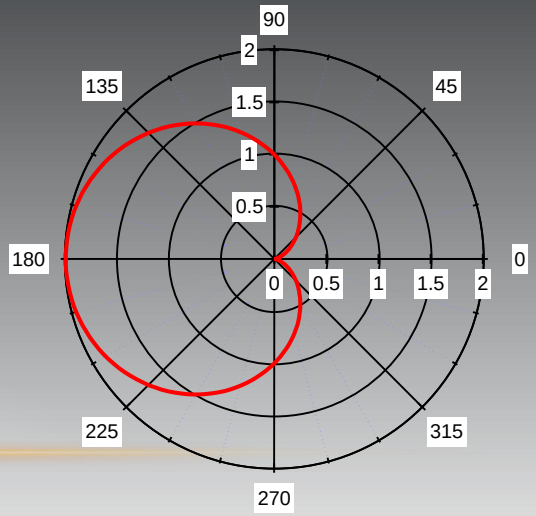
QP scattering rates

$$\Gamma_{tr}(k) = 1/\tau_{tr}(k) = 2\pi n_i \int \frac{d^2k'}{(2\pi)^2} \delta(\varepsilon_k - \varepsilon_{k'}) \left| T_{\mathbf{kk'}} \right|^2 (1 - \cos\theta')$$

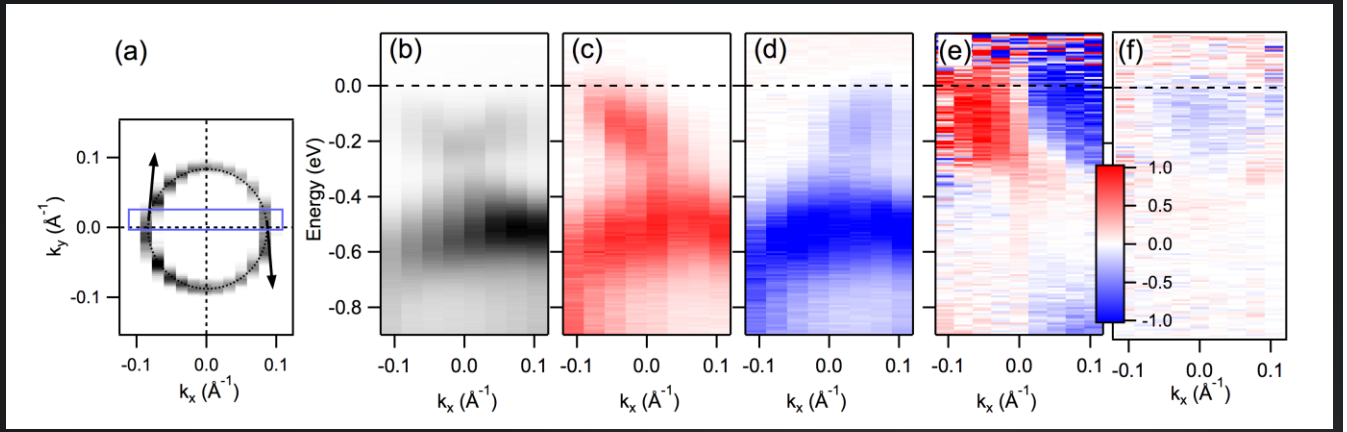
Transport scattering rates

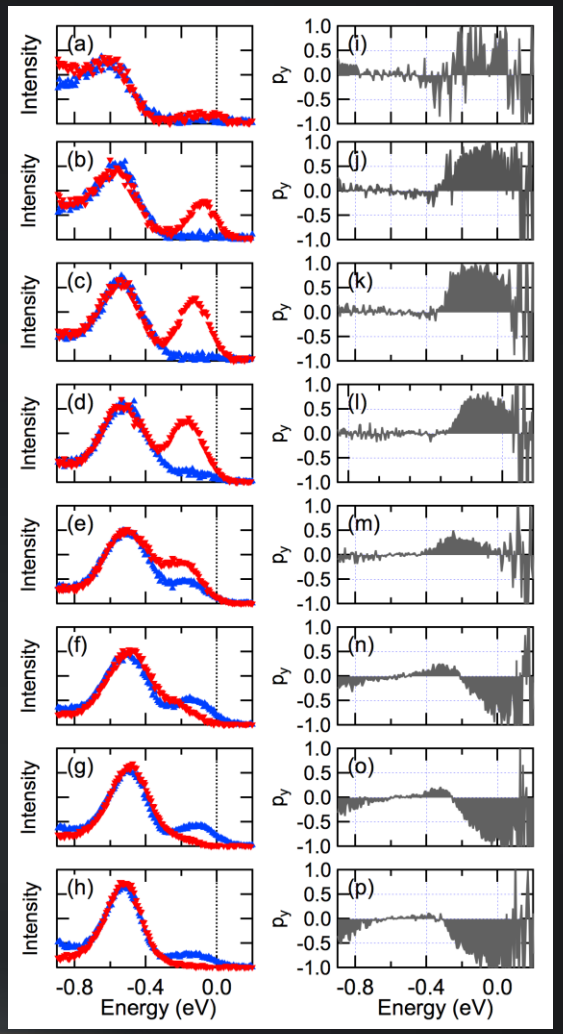






Spin-resolved ARPES at RT





States fully spin-polarized even at RT!

SUMMARY

Graphene:

- ~neutral graphene layers: transport - electronic structure
- Heavily doped graphene – superconductivity

Topological insulators:

- Magnetic moment of an impurity does not seem to play a role in the scattering
- Very weak e-ph coupling ⇒ state coherent at elevated temperatures
- State also fully polarized at room temperature
- Clean surfaces - large mobilities
- RT applications?
- New (insulating) materials!

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