Explore two-dimensional world using photoemission technique

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Outline

1. What are the grand challenges

2. Angle-resolved photoemission spectroscopy (ARPES)

- From Einstein’s photoemission to Present
- Conventional ARPES

3. Future directions of ARPES

- Time resolution
- Spin and time resolution

Grand challenges

- **Energy problem**

  Solar energy, hydrogen fuel, nuclear energy ??

- **Understanding Emergent Phenomena**

  Phenomena which are not the properties of the individual elementary components BUT of the assembly of such components:

  Strongly correlated electron systems : high T_C superconductors

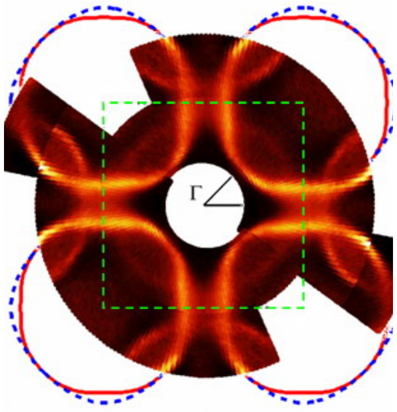
  Magnetism made of non-magnetic elements

- **The ultra-fast**

  Sciences in the picosecond, femtosecond, attosecond time scale

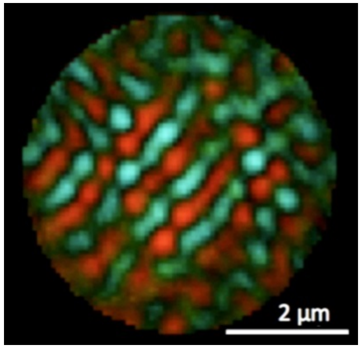
Why do we need to study electrons?

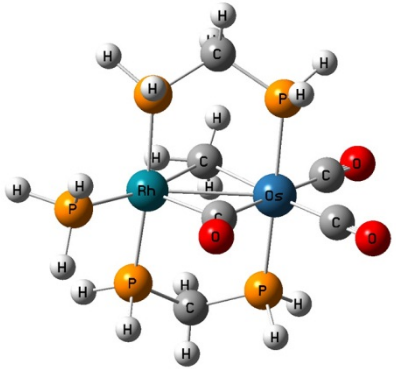
Ultimately, the



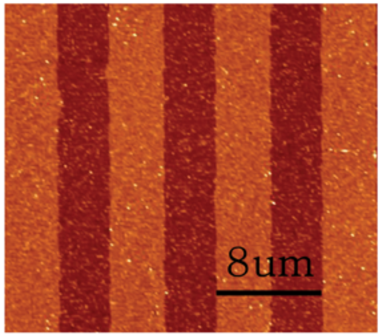
electric,

magnetic,





chemical,



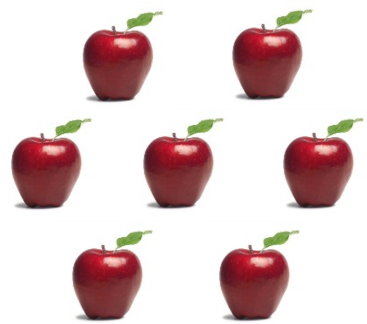
mechanical,

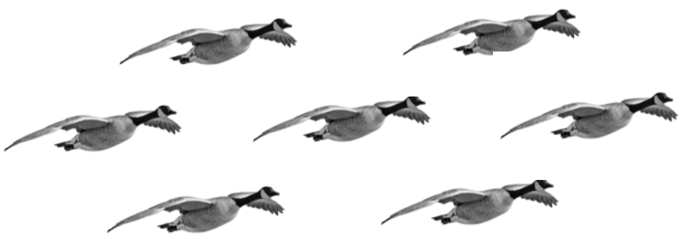
optical, thermal, and structural properties of matter depend on the behavior of electrons and location of atoms.

Highly correlated systems

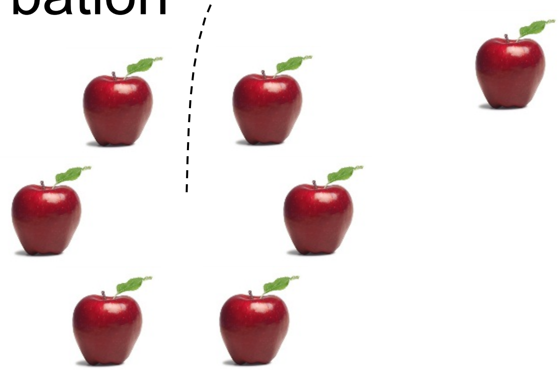
Non-correlated system | **Correlated system**

Ground state





With external perturbation



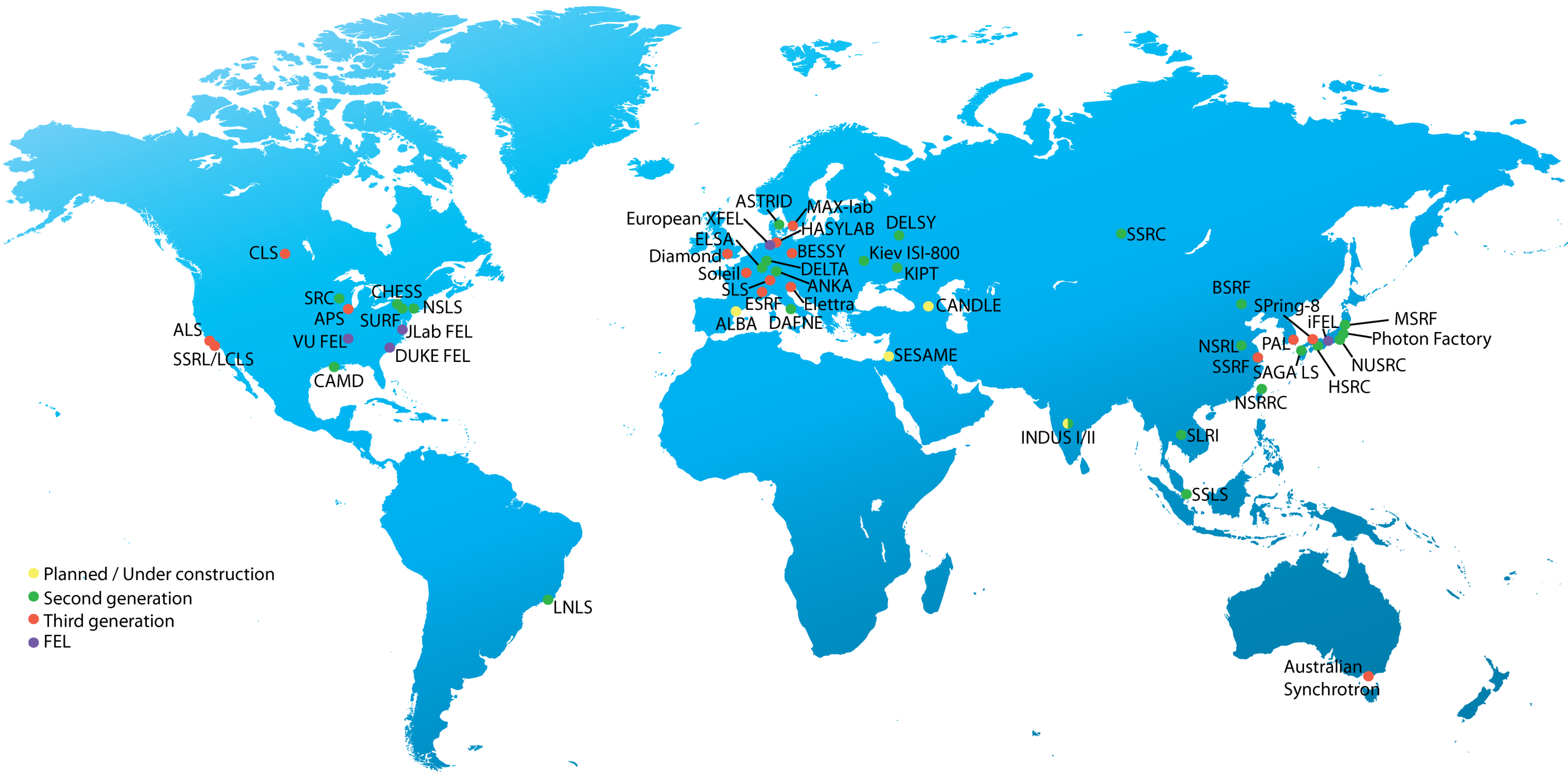
The responses are different due to correlation effects!

Energy scale of importance

- **Superconducting gap** ~ 1 – 100 meV
- **Optical phonons** ~ 40 – 200 meV
- **Magnons** ~ 10 – 40 meV
- **Pseudogap** ~ 30 – 300 meV
- **Multiphonons and multimagnons** ~ 50 – 500 meV
- **Orbital fluctuations** ~ 100 meV – 1.5 eV
- **Mott gap** ~ 1 eV – 3 eV

Requirement: High **energy** and **momentum** resolution
with **tunable** photons with high **flux**
at very low **temperature**

World map of synchrotron

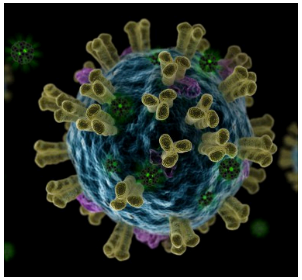


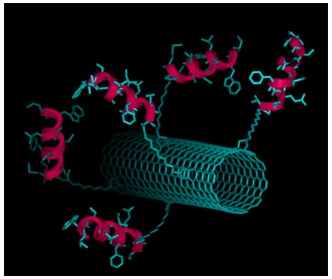
Dimensionality: 3-dimension

Dimensionality: 2-dimension

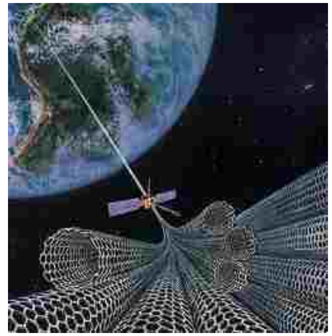
Dimensionality: 1-dimension

Carbon Allotropes





Potential medical use
- Drug delivery
- Target cancer cells

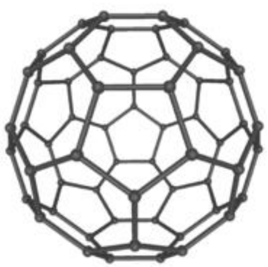


Space elevator

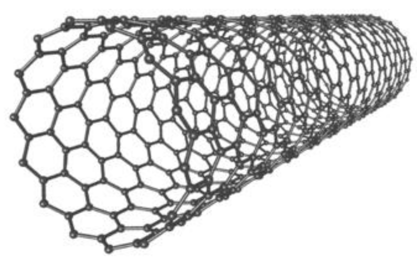
Soft, layered substance
Pencil, lubricant, electrode

Hardest substance
Jewellery

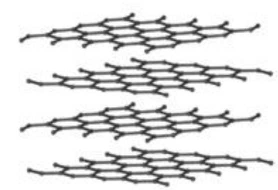
0d 1d 2d 3d



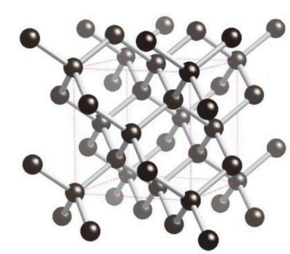
Bulkyball
Fullerene
Nobel prize in chemistry
(1996)



Carbon Nanotube
Benjamin Franklin Medal
(2002)



Graphite



Dimaond

Carbon Allotropes

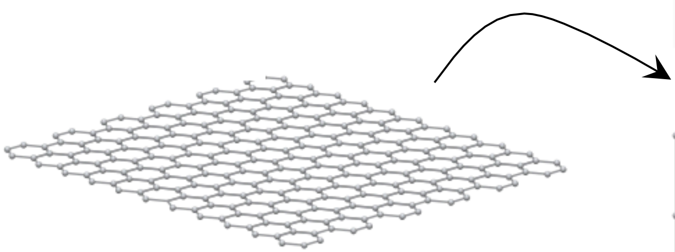
Massless Dirac Fermion proved
K. Geim
P. Kim

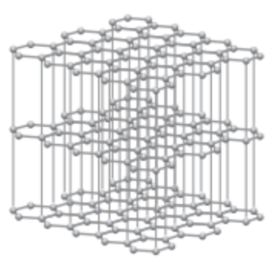
Massless Dirac equation of Graphene
G. W. Semenoff

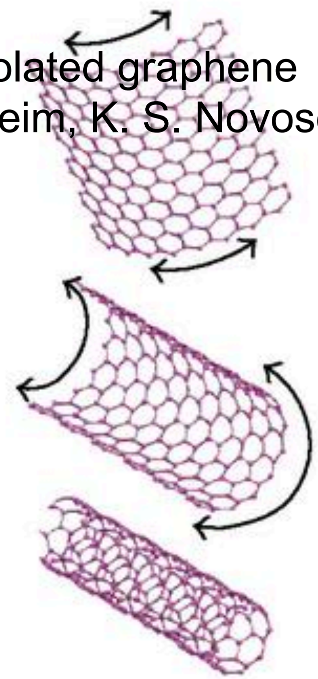
1947 1984 2004 2005

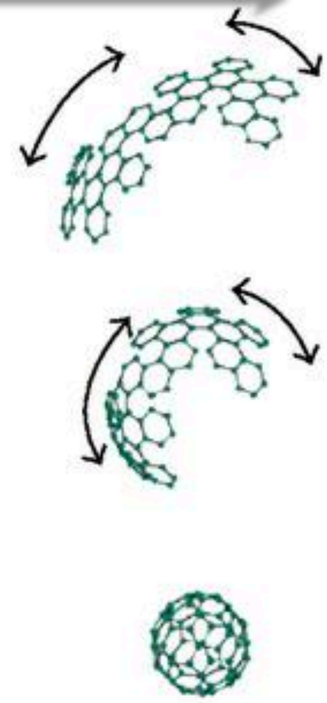
Theory of Graphene
P. R. Wallace

Isolated graphene
A. K. Geim, K. S. Novoselov









Considered only as a toy model

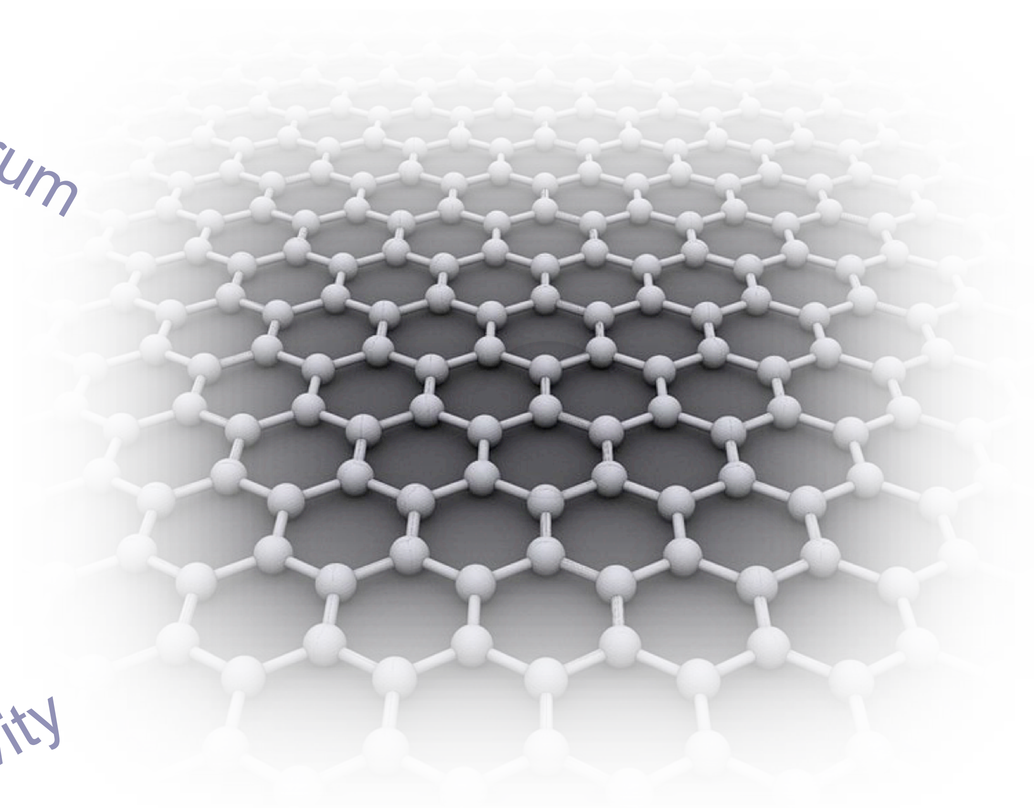
Abnormal quantum Hall effect

One atom thick honeycomb lattice

Half metallicity

Linear energy spectrum

Chirality



Flexible display

Spin valve

High Conductivity

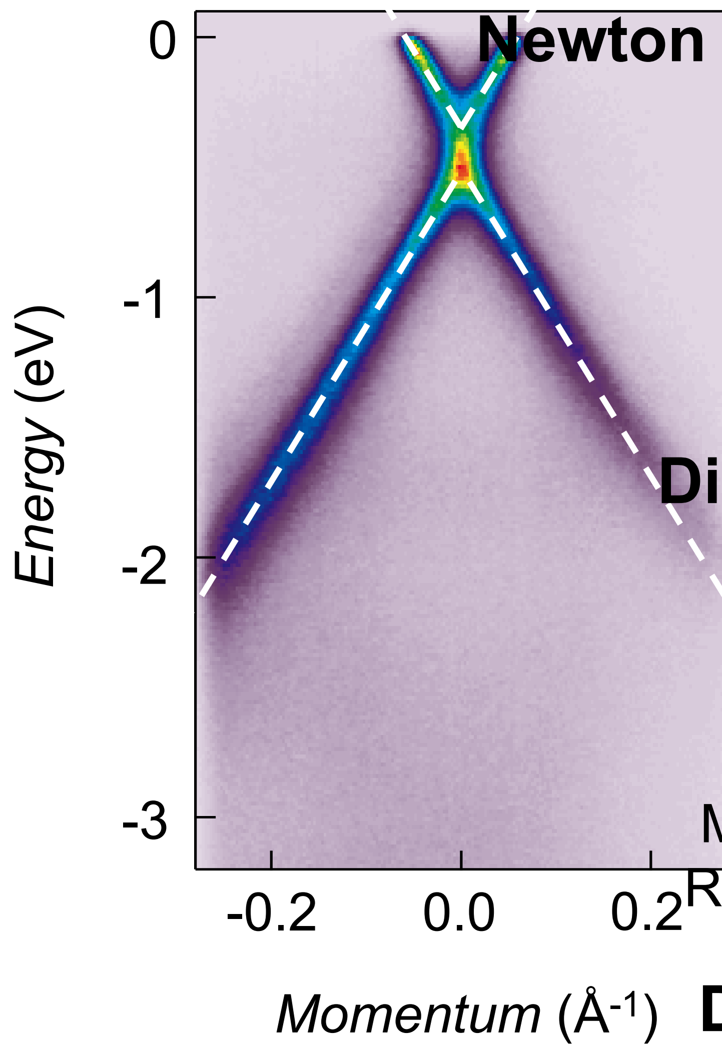
Magnetism

1 THz transistors

Strength and plasticity

Quantum spin Hall effect

Dirac Fermions realized in the Lab



Newton or Schroedinger eq.

$$E = \frac{p^2}{2m^*}$$

Dirac's equation

$$E = v_F^* p$$

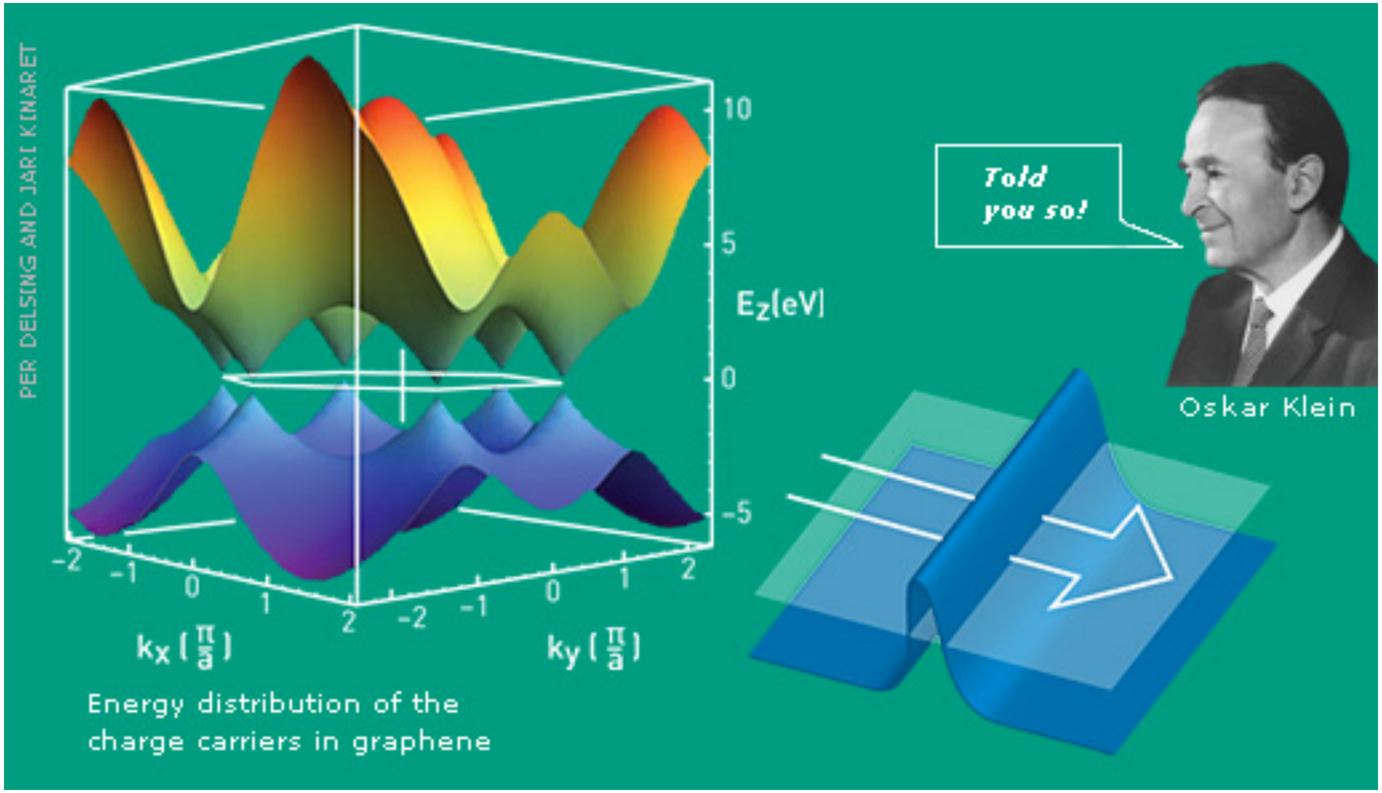
Massless particle

Relativistic particle

Dirac Fermion

High energy physics in the space realized in a Lab

Klein tunneling



O. Klein, Zeitschrift fur Physik 53, 157 (1929)
M. I. Katsnelson et al., Nat. Phys. 2, 620 (2006)
A. F. Young et al., Nat. Phys. 5, 222 (2009)

What has graphene done for us so far?

Companies

3D Graphene Lab inc.

GRAPHENE SUPERMARKET®

GRAPHENE INDUSTRIES

GROUP NanoXplore inc.
Unleashing the Power of Graphene

solanpv

XG sciences
THE MATERIAL DIFFERENCE

haydale

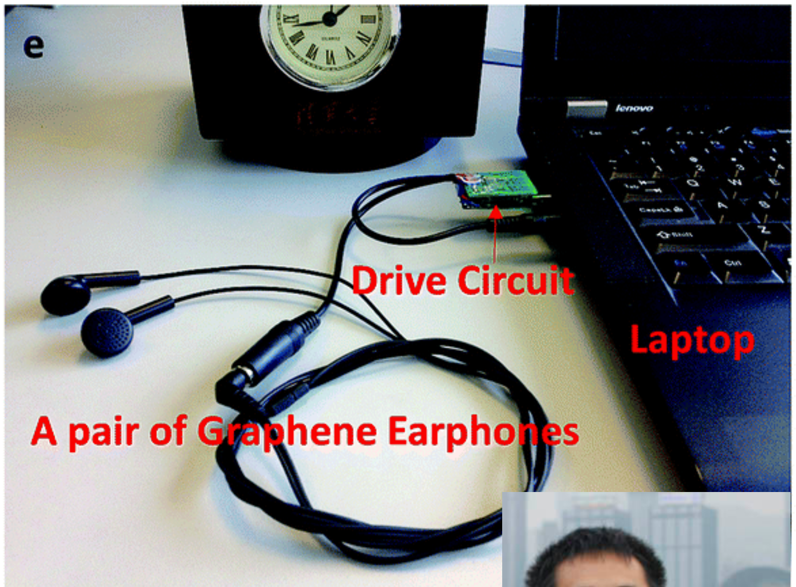
Graphene Frontiers

GRAPHENE technologies

GRAPHENEA

What has graphene done for us so far?

Companies



Entertainment

the BIG BANG THEORY WIKI

Season 3, Episode 14

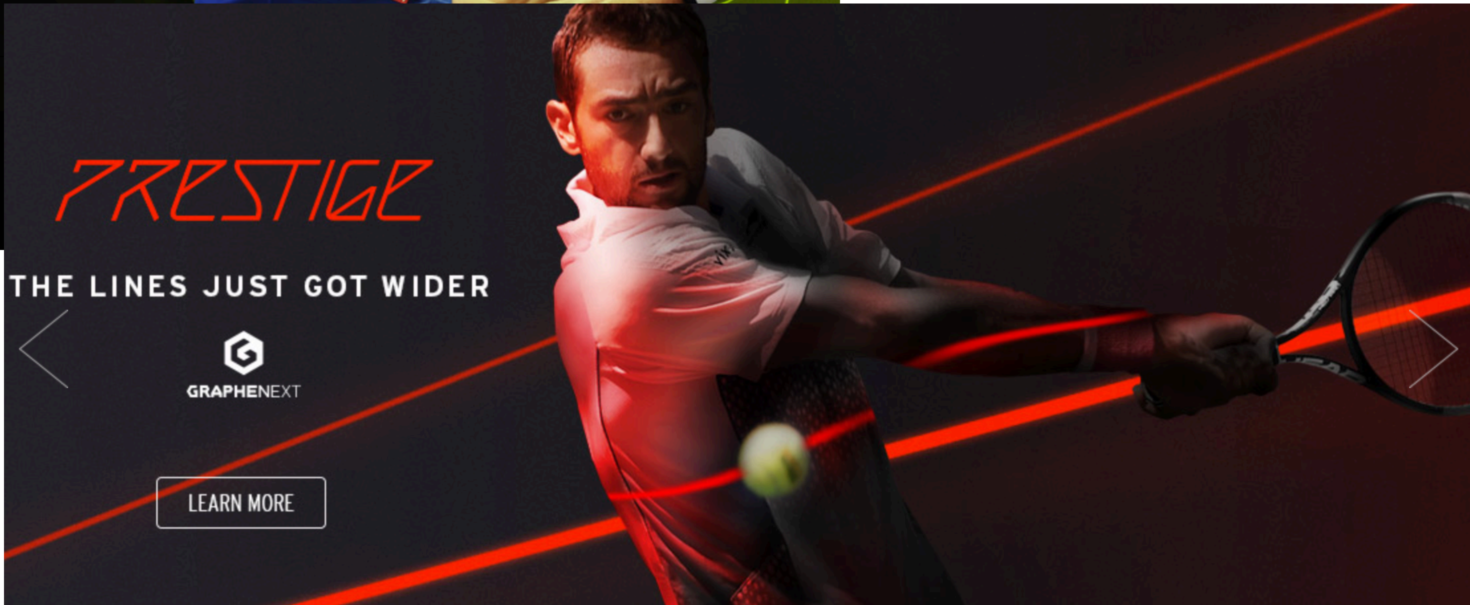
What has graphene done for us so far?

Companies

Entertainment

Sports

WTA Rank 1
Novak Djokovic



WTA Rank 2
Andy Murray

What has graphene done for us so far?

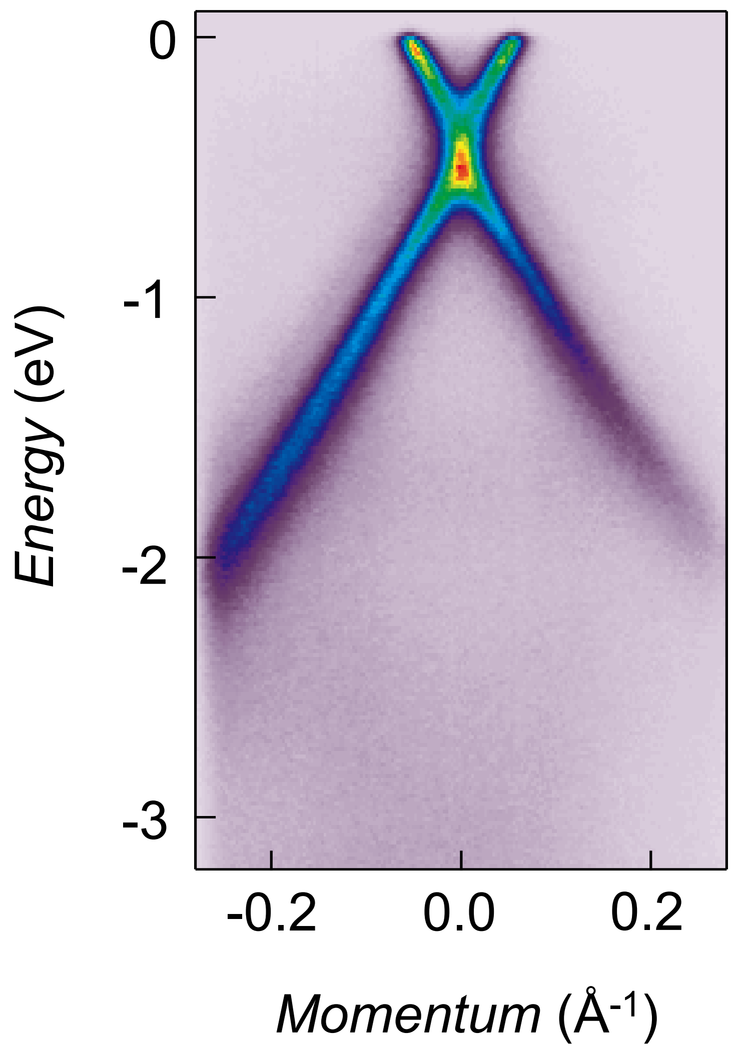
Companies

Entertainment

Sports

Graphene Ln, Tallahassee, FL, USA

Dirac Fermions realized in the Lab



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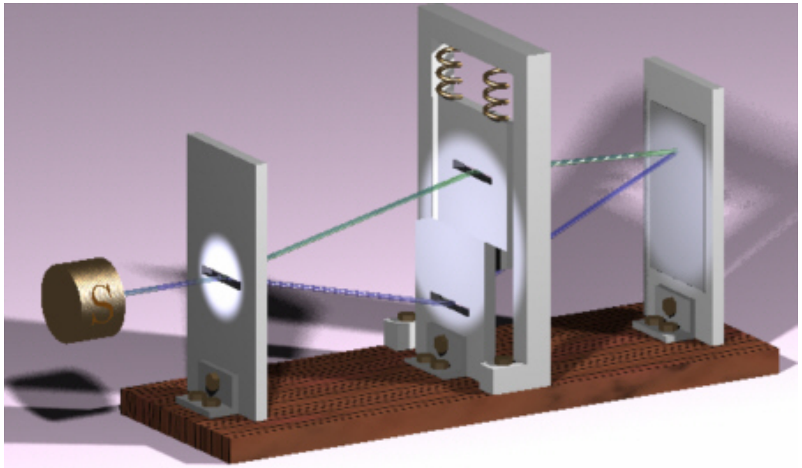
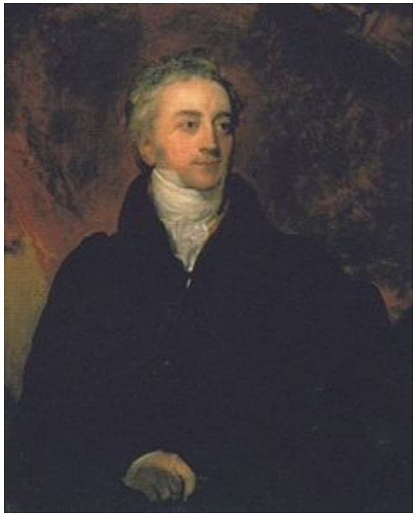
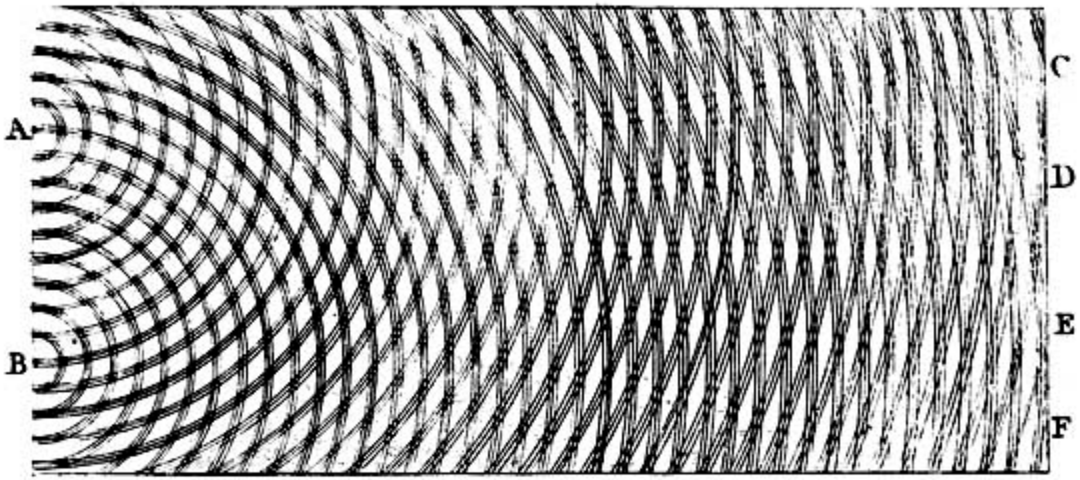
Light as a wave: 1803





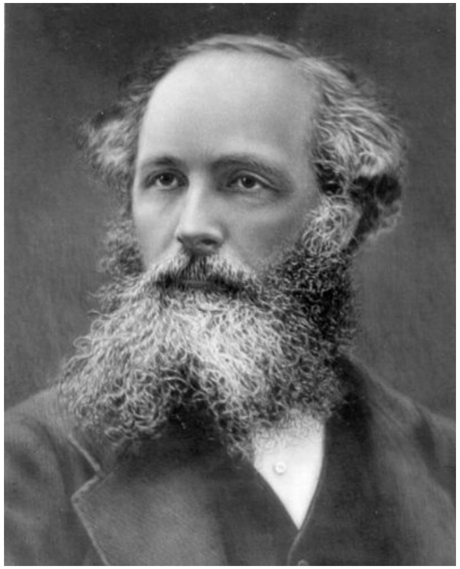
Thomas Young
Light as a wave (1803)



Young's sketch of the light waves emerging from two narrow slits
A course of lectures on natural philosophy and the mechanical arts, Vol. 1 (1807)

Maxwell

Describe the propagation of Electromagnetic radiation

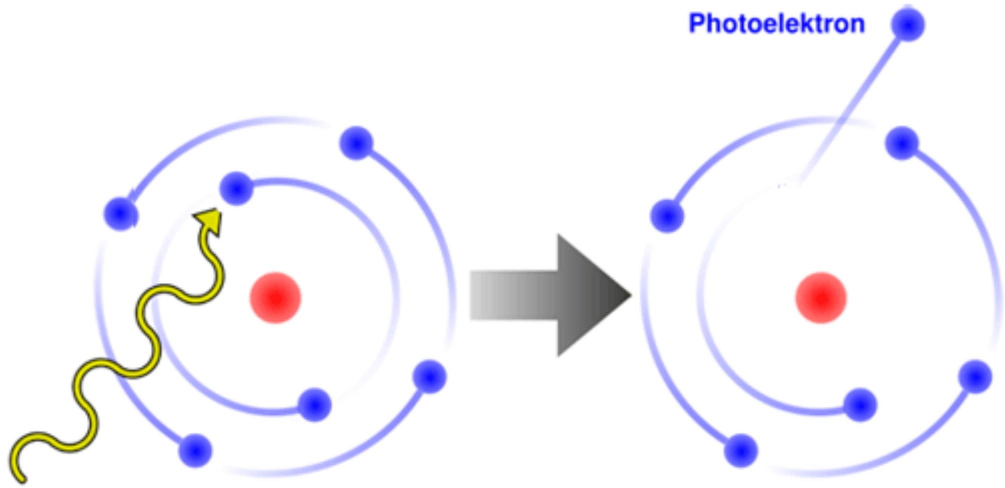


James C Maxwell
Electromagnetism (1865)

$$E_z = E_{z0} \cos[w(t - \frac{z}{c}) + \theta]$$

$$c = \frac{1}{(\varepsilon_0 \mu_0)^{1/2}}$$

Photoelectric effect



Heinrich Hertz
Photoelectric effect (1887)

Einstein's equation

Einstein's Photoelectric Equation

The electron leaves
the body with energy

$$\frac{1}{2}mv^2 = hv - P$$

where h is planck's constant, v is the light frequency, and P is the work that electron has to do in leaving the body.

Albert Einstein
Photoelectric equation (1905)

Einstein's 1905 – age 26

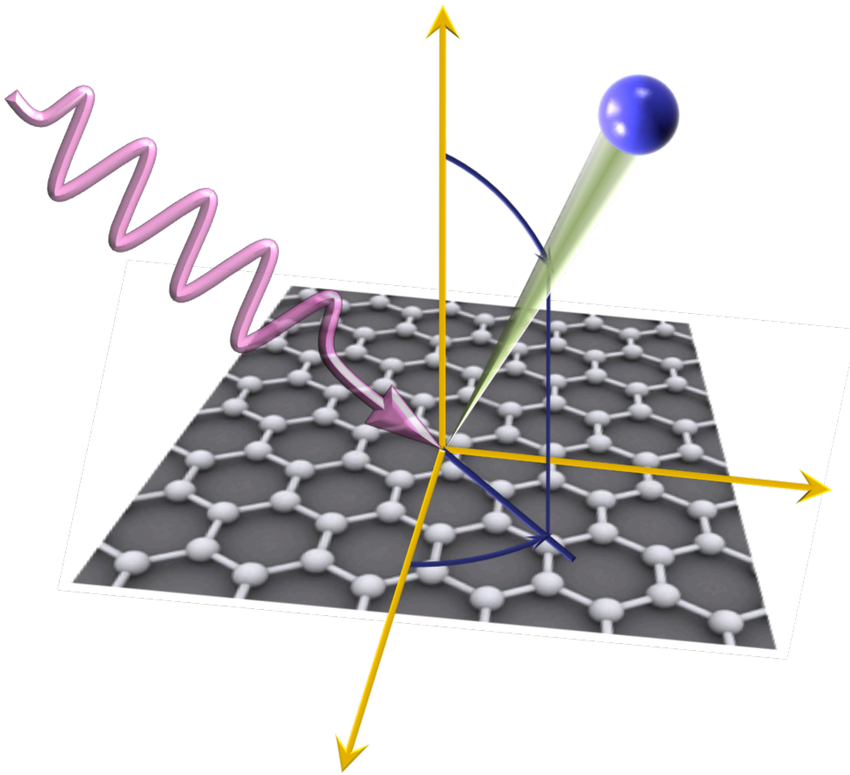
" A storm broke loose in my mind"

March	**Quantum nature of light and photoelectric effect**

1921 Nobel prize

May	**On "Brownian Motion" or random bouncing of small particles in a surrounding fluid**
June	**Special theory of relativity c=speed of light** **c same in all reference frames and is max speed**
September	**Consequence of Special Relativity** $E = mc^2$

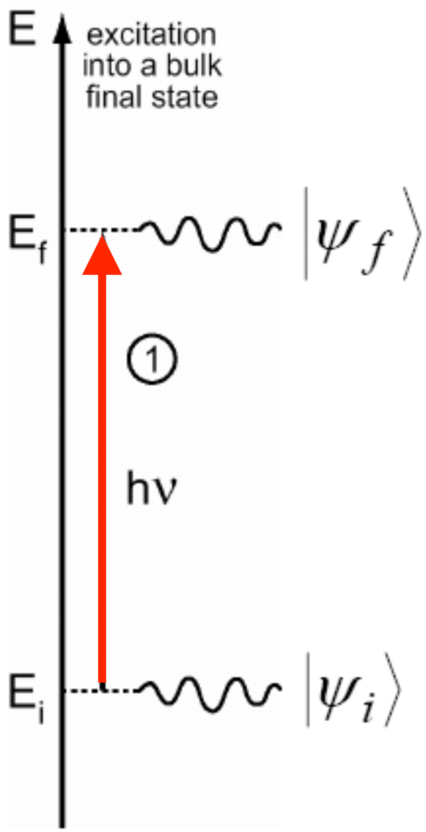
How to measure electrons?



Three step model

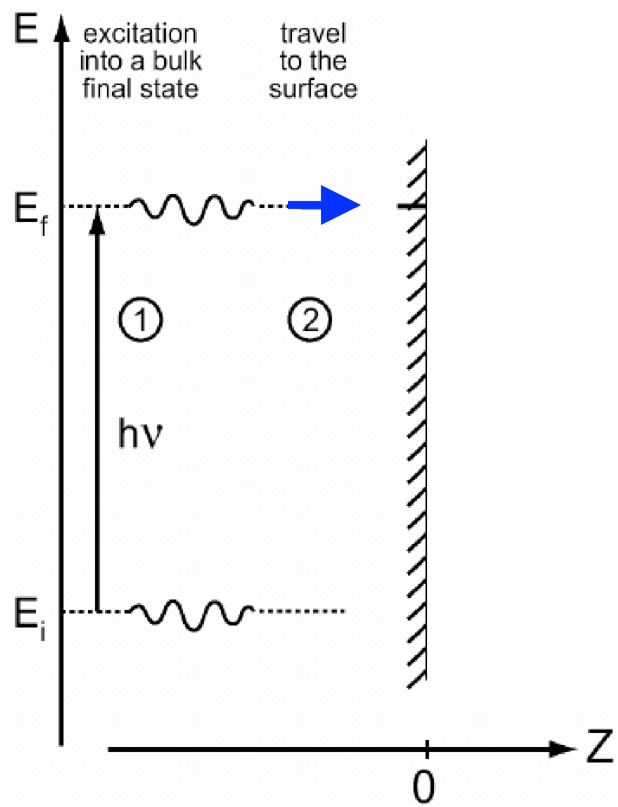
Step I

Transition in the solid



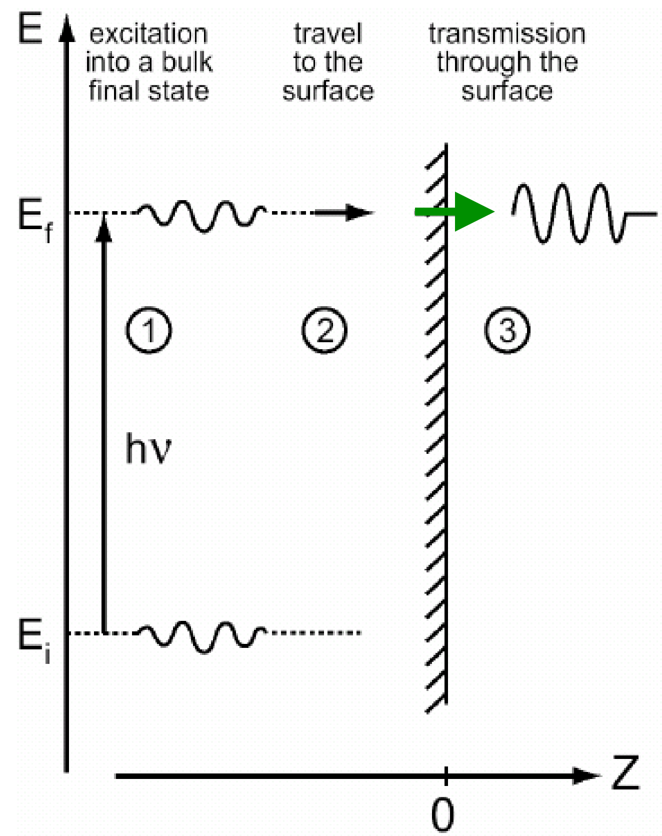
Step II

Transmission to surface



Step III

Transmission into vacuum



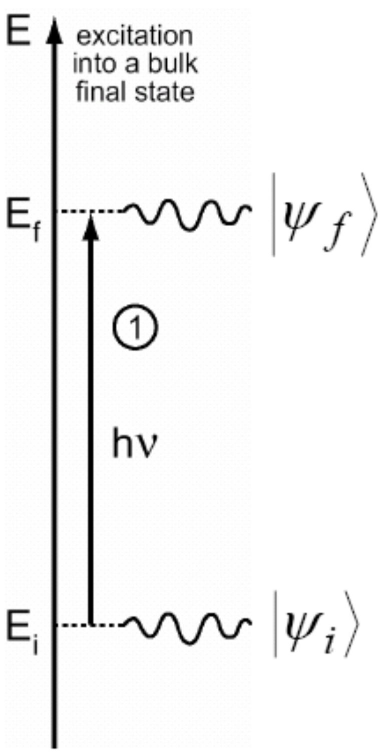
Step I: photoexcitation process

$$w_{i \to f} \propto \left| \langle \psi_f | \vec{A} \cdot \vec{p} | \psi_i \rangle \right|^2 \delta(E_f - E_i - h\nu)$$

Typical photon wavenumber

$$\kappa = 2\pi \frac{E}{hc} = 2\pi \frac{E\ [\text{eV}]}{12400\ [\text{eV - Å}]}$$

$$= .01 \text{ to } .05 \text{ Å}^{-1} \quad (\text{for } E = 20 \text{ to } 100 \text{ eV})$$



- **Photon impact very little momentum in PES process**
- **Photon-stimulated transition not allowed**

Momentum conservation:

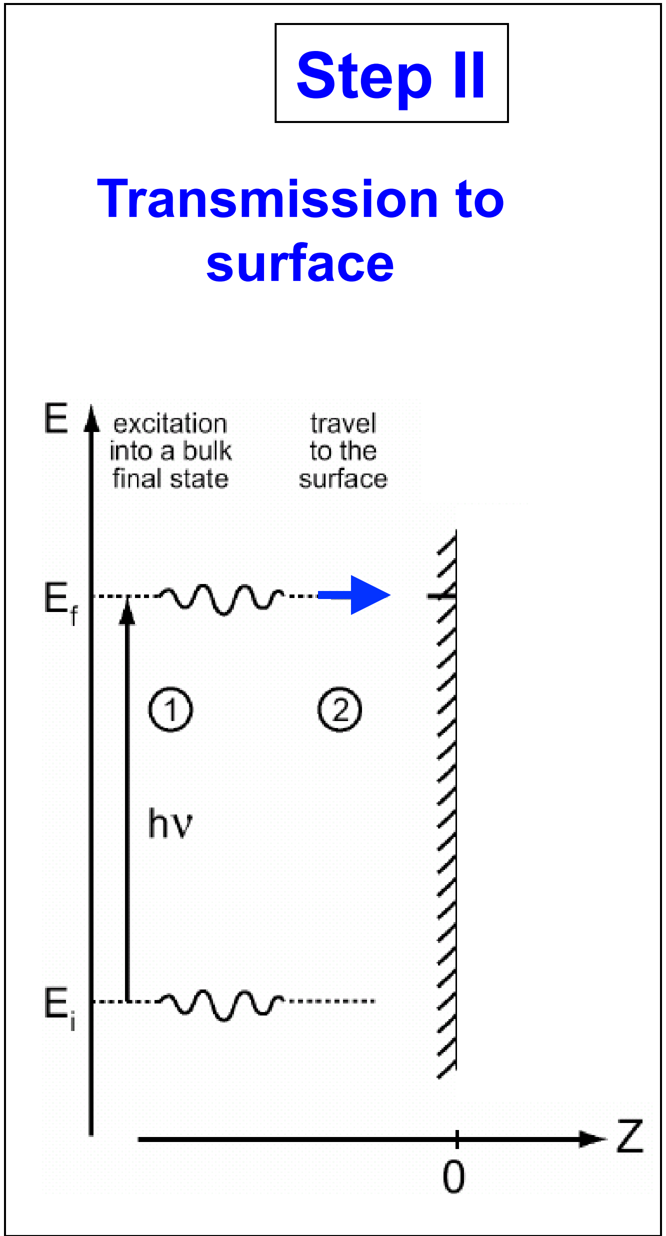
$$\underline{k}_f = k_i + G + \cancel{k_{photon}}$$

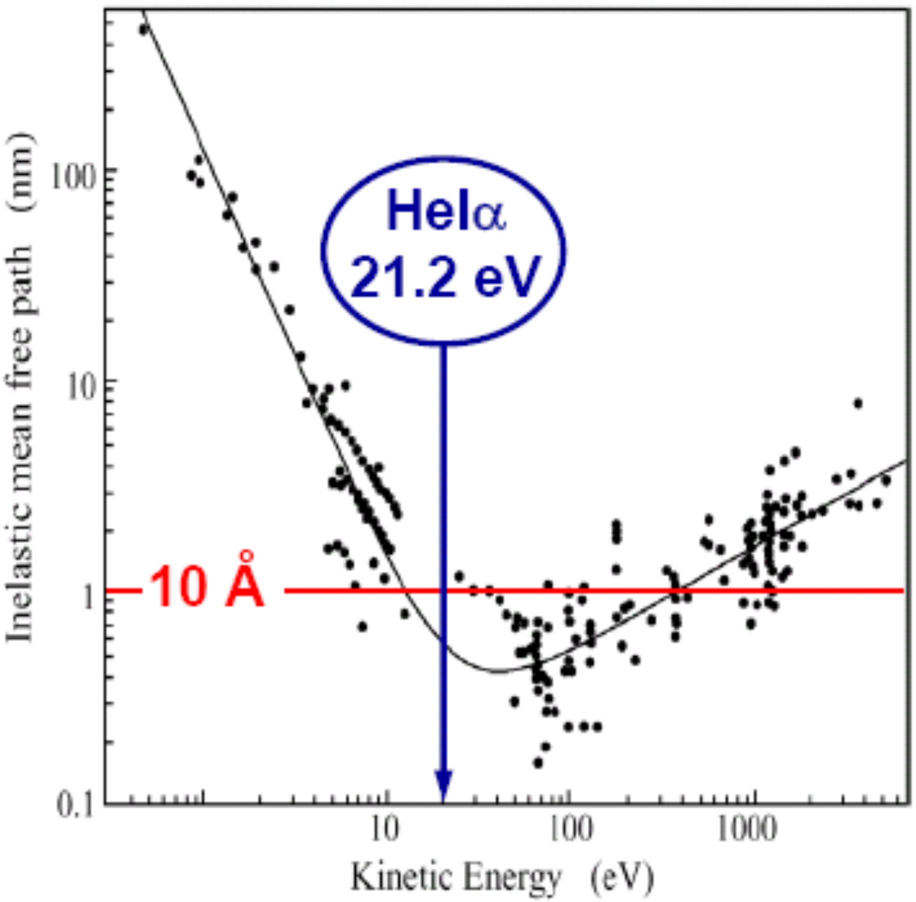
only"vertical" transitions

Energy conservation:

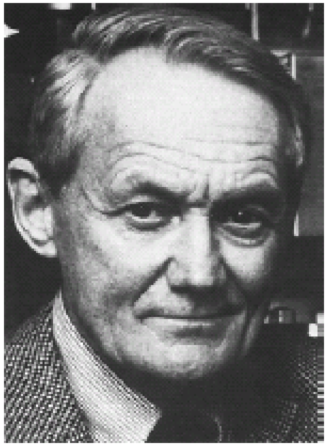
$$E_f = E_i + h\nu$$

Step II: transport to surface



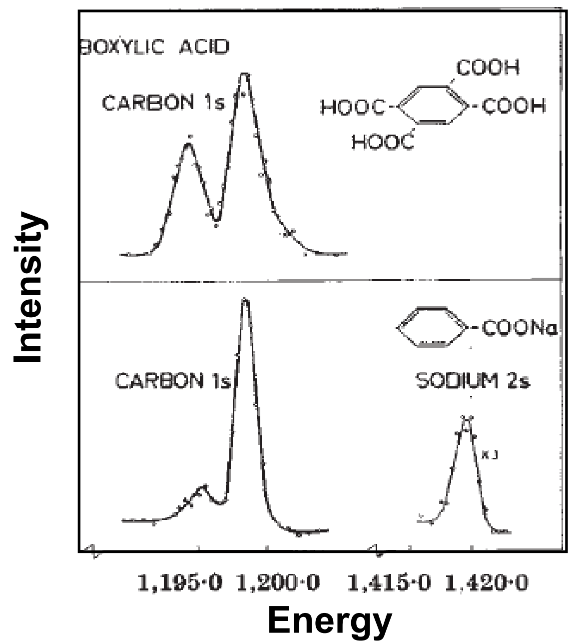


Photoemission core-level spectroscopy

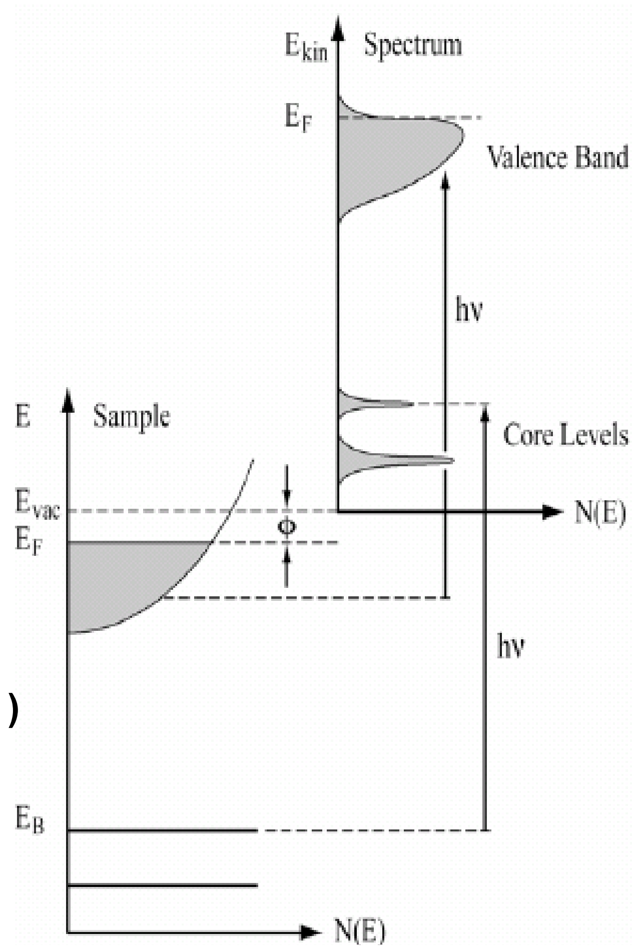


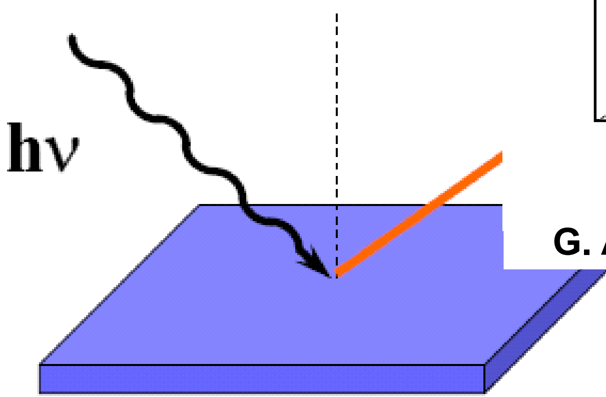
K.M. Siegbahn

energy conservation: $$E_{kin} = h\nu - E_B - \Phi$$

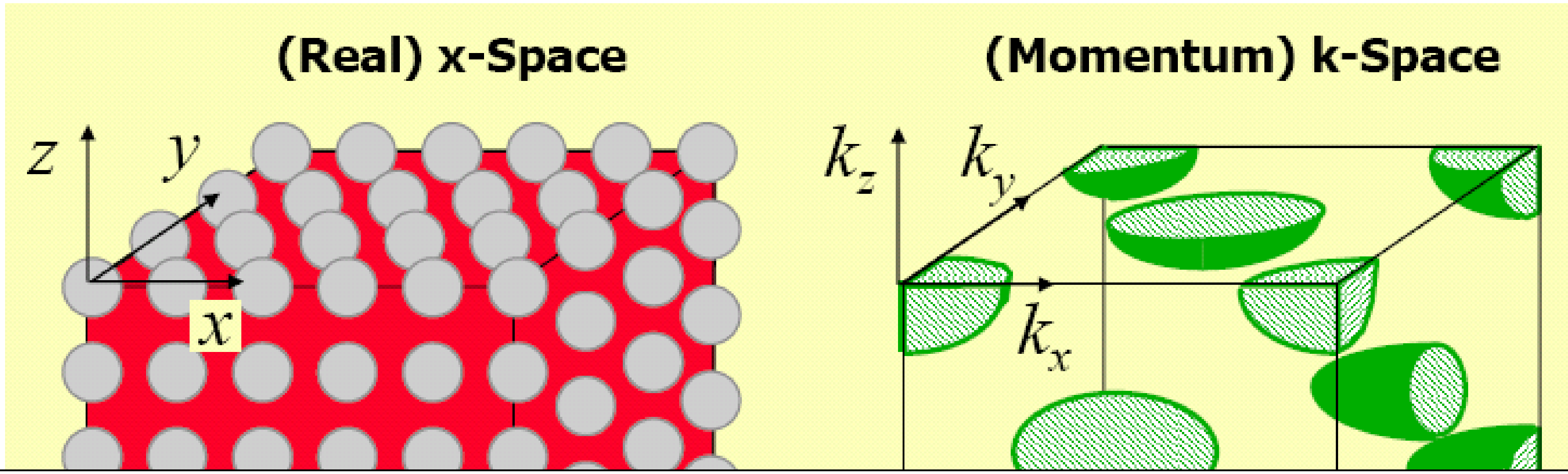


G. Axelson *et al.*, Nature (1967)





valence electron & momentum resolution?



Many properties of solids are determined by electrons near E_F

(conductivity, magnetoresistance, superconductivity, magnetism)

Only a narrow energy slice around E_F is relevant for these properties

(kT = 25 meV at room temperature)

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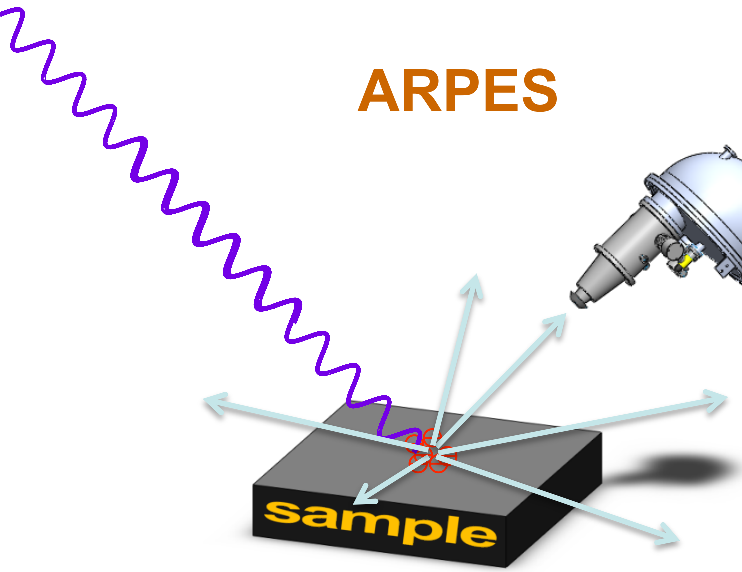
Providing momentum resolution

ARPES



Successful with QMs:

HTC cuprates

CMR manganites

Graphene

Topological Insulators

⋮

Energy conservation

$E_B = \hbar\omega - E_K - \Phi_A$

Angle / momentum conservation

$k_{\parallel} \propto \sqrt{E_k}\,\sin\theta$

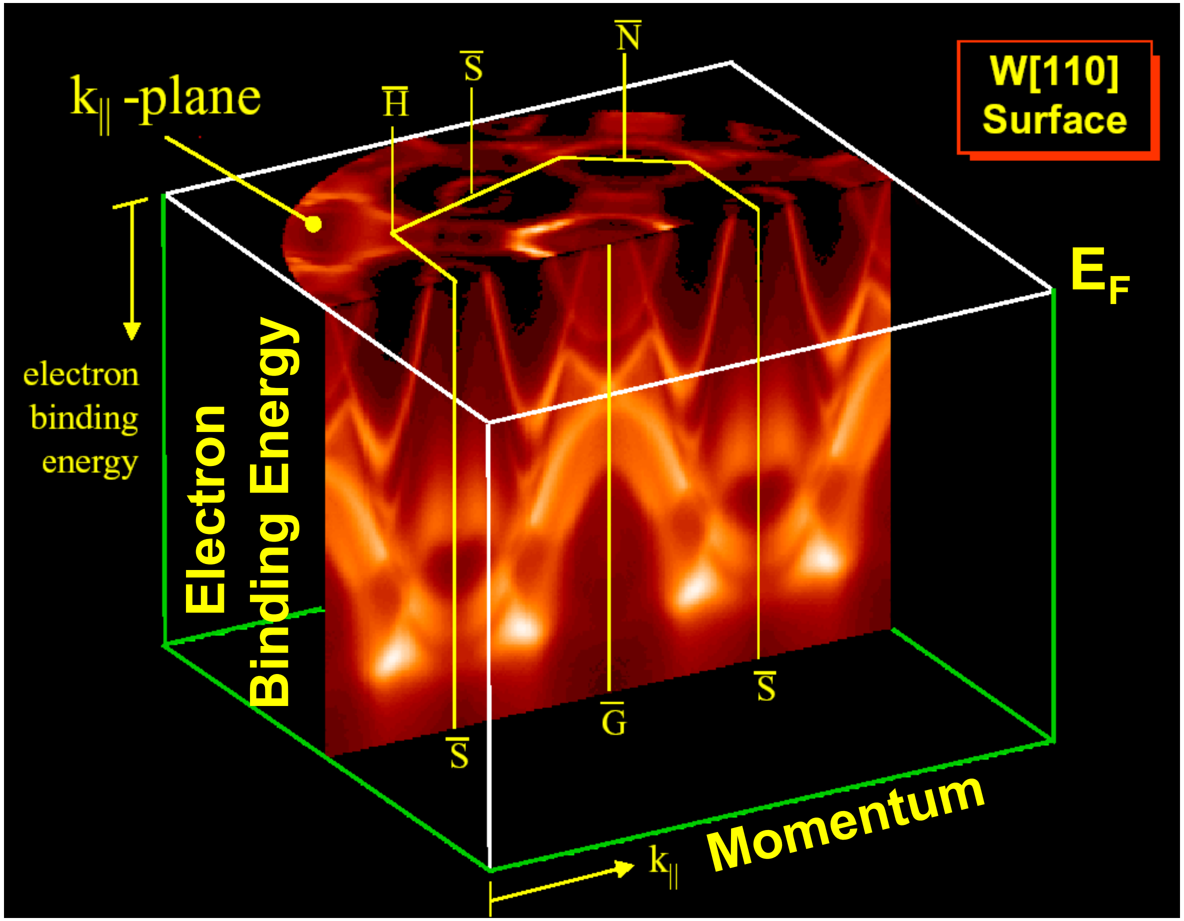
Photoelectron intensity

$$I(k,\omega) \propto A(k,\omega)\left|M(k,\omega)\right|^2 f(\omega)$$

A(k,ω) spectral function
M(k) Matrix element
f(ω) Fermi function

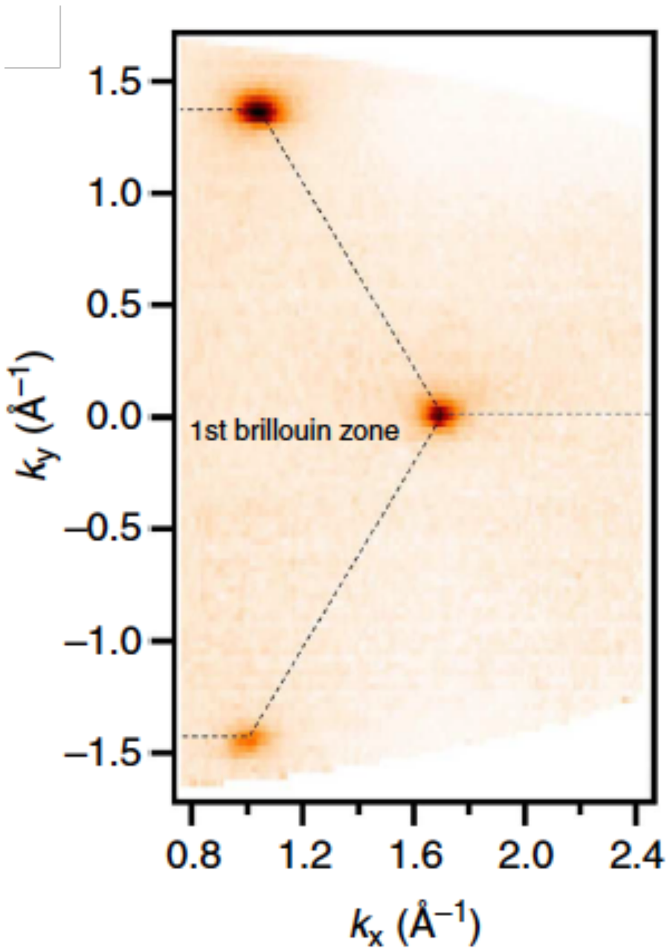
What do we learn from momentum resolution?

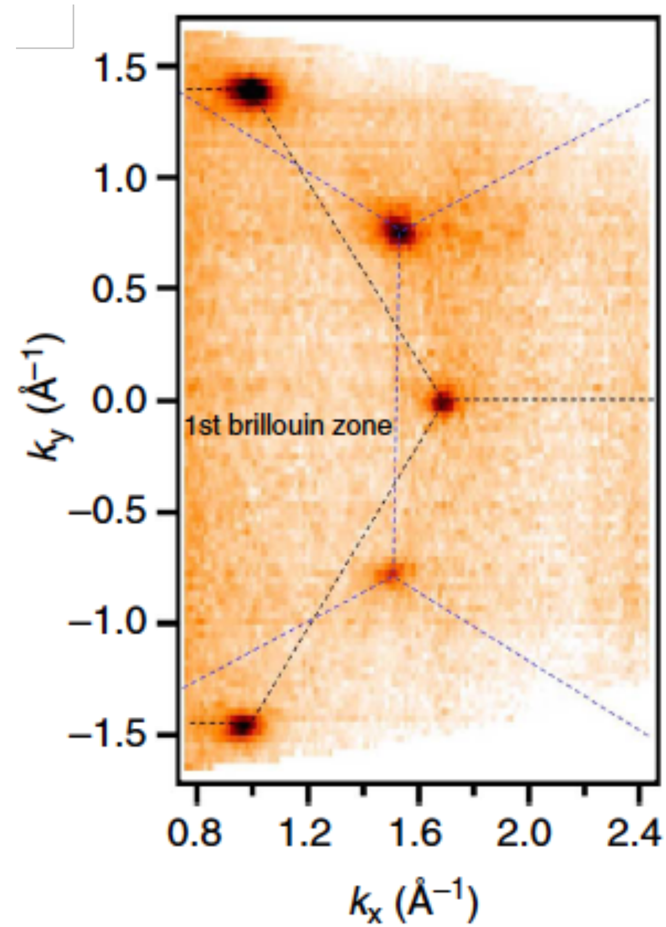
- Energy vs. wave vector (k) - Band structure
- Fermi surface
- Charge carrier density



What do we learn from momentum resolution?

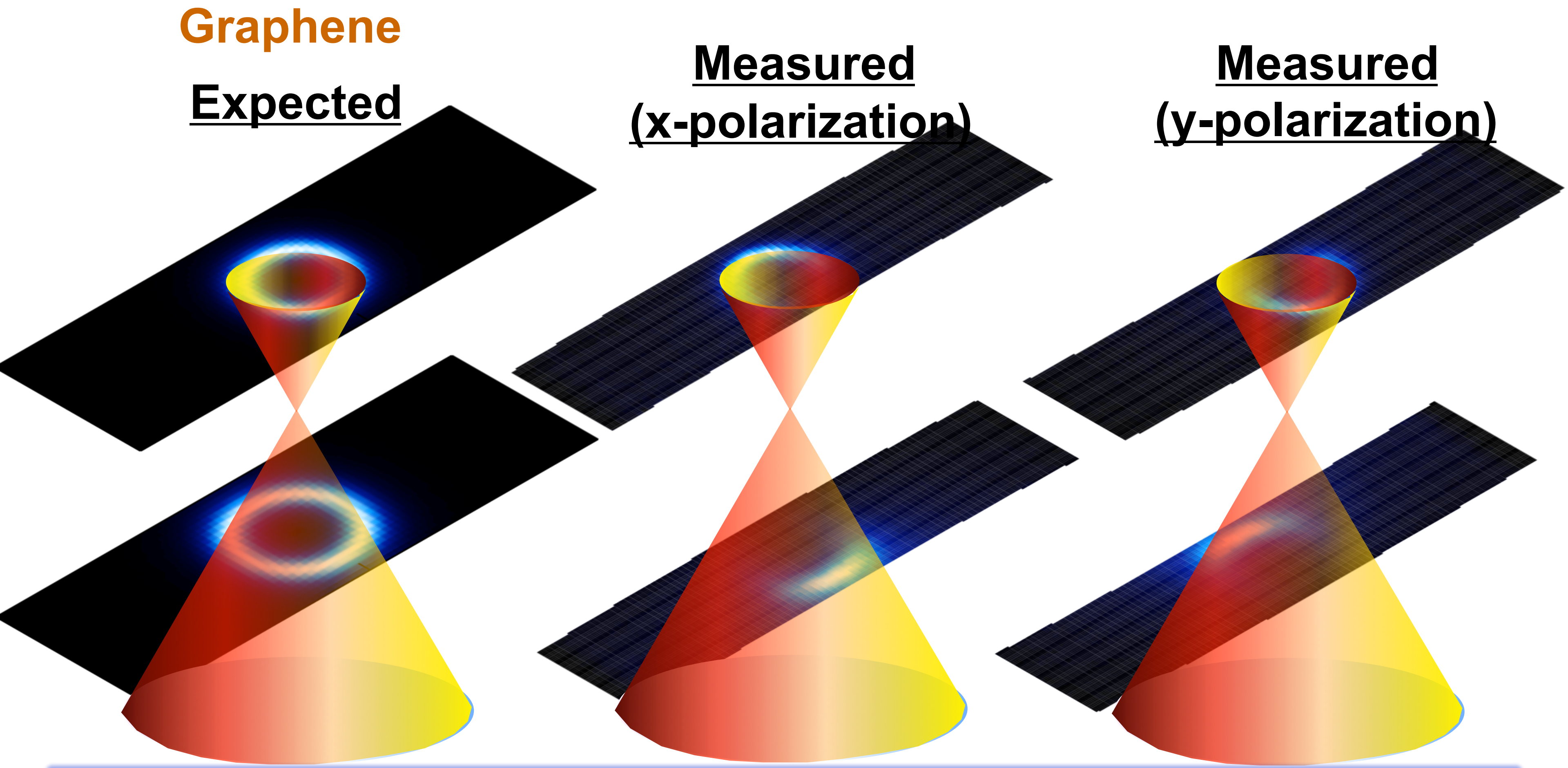
- **Geometric structure**





Park, Hwang (2015)

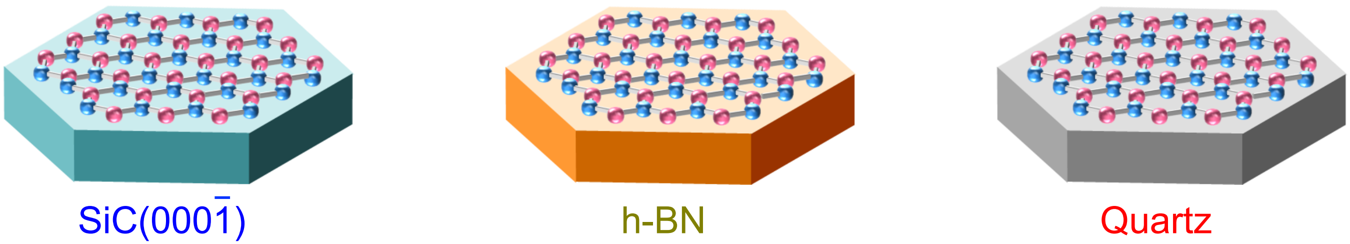
What do we learn from momentum resolution?

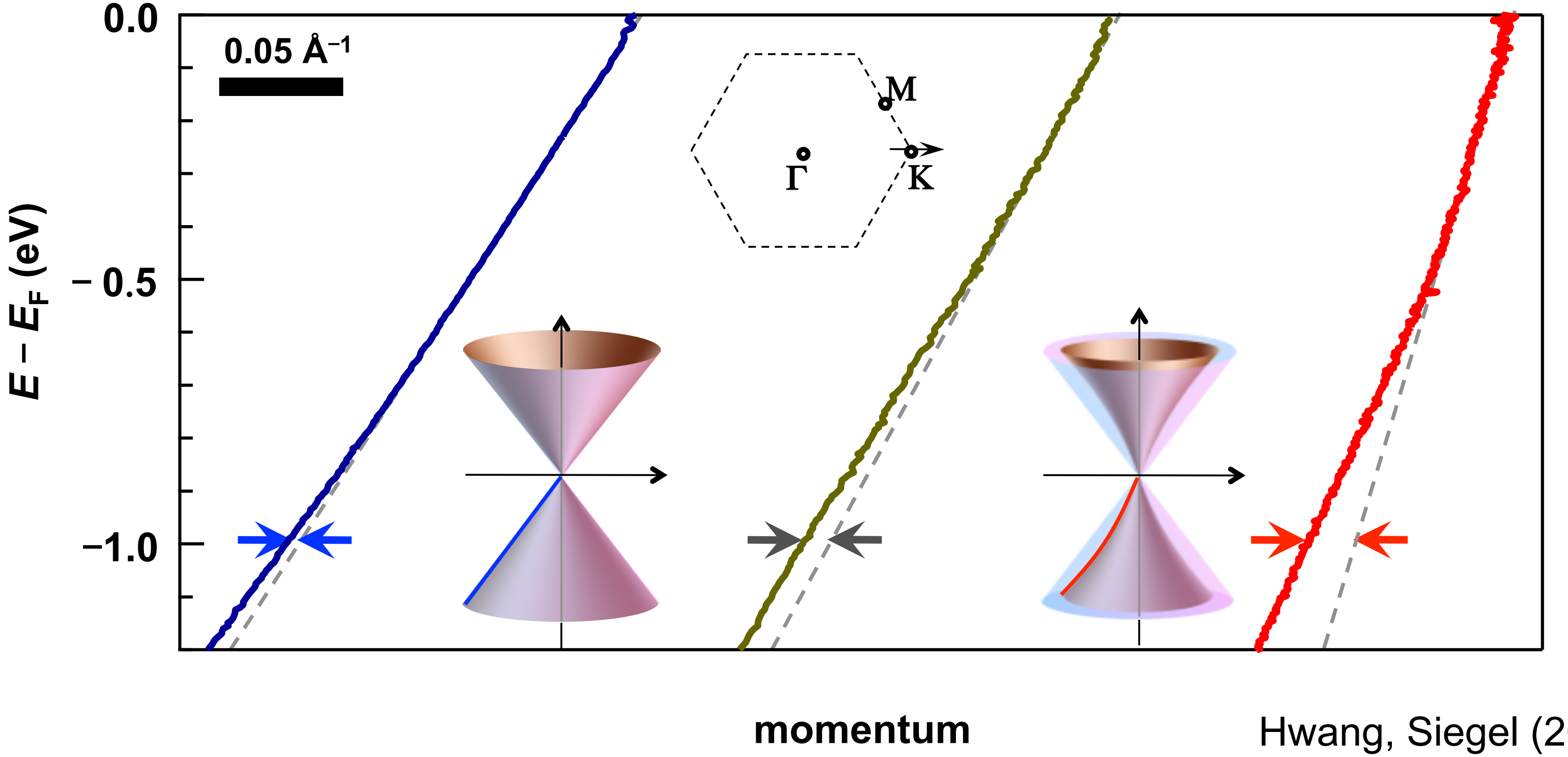


π/n **rotation of ARPES intensity** ⇨ $n\pi$ **Berry's phase**

Hwang (2011)

Graphene on a dielectric substrate





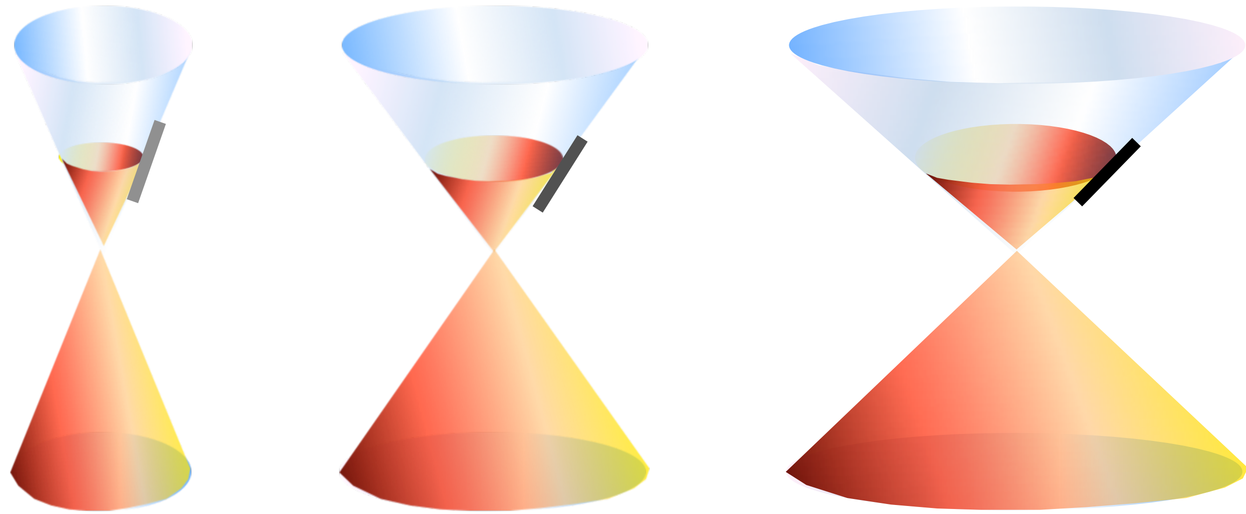
Hwang, Siegel (2011, 2012)

1. Departure from linearity

Strong electron-electron interactions in graphene

Fermi liquid

$$E = \frac{\hbar^2}{2m^*}k^2$$

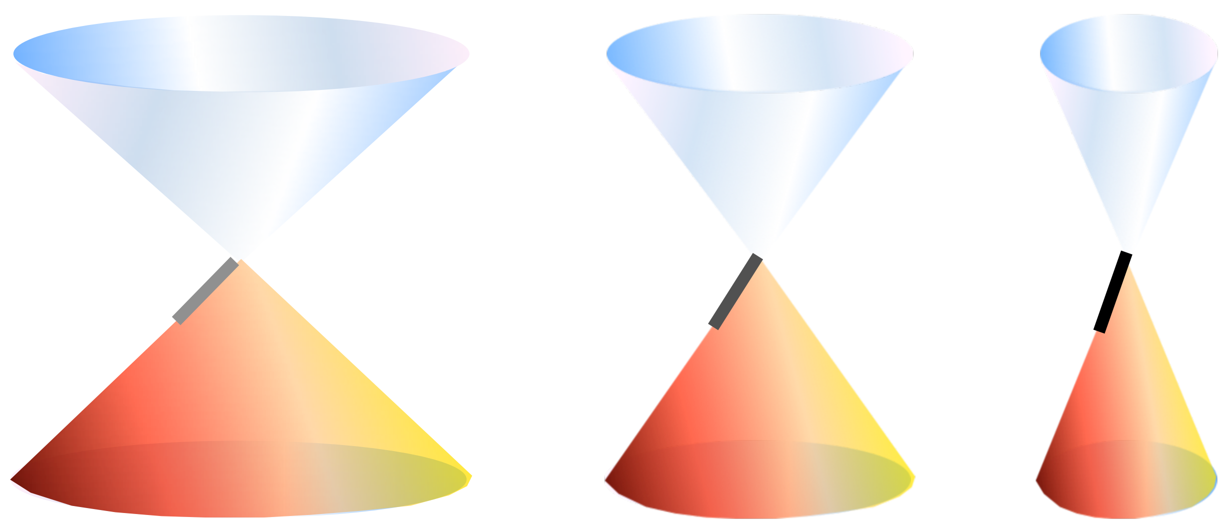


Increasing electron-electron interactions →

Charge neutral graphene

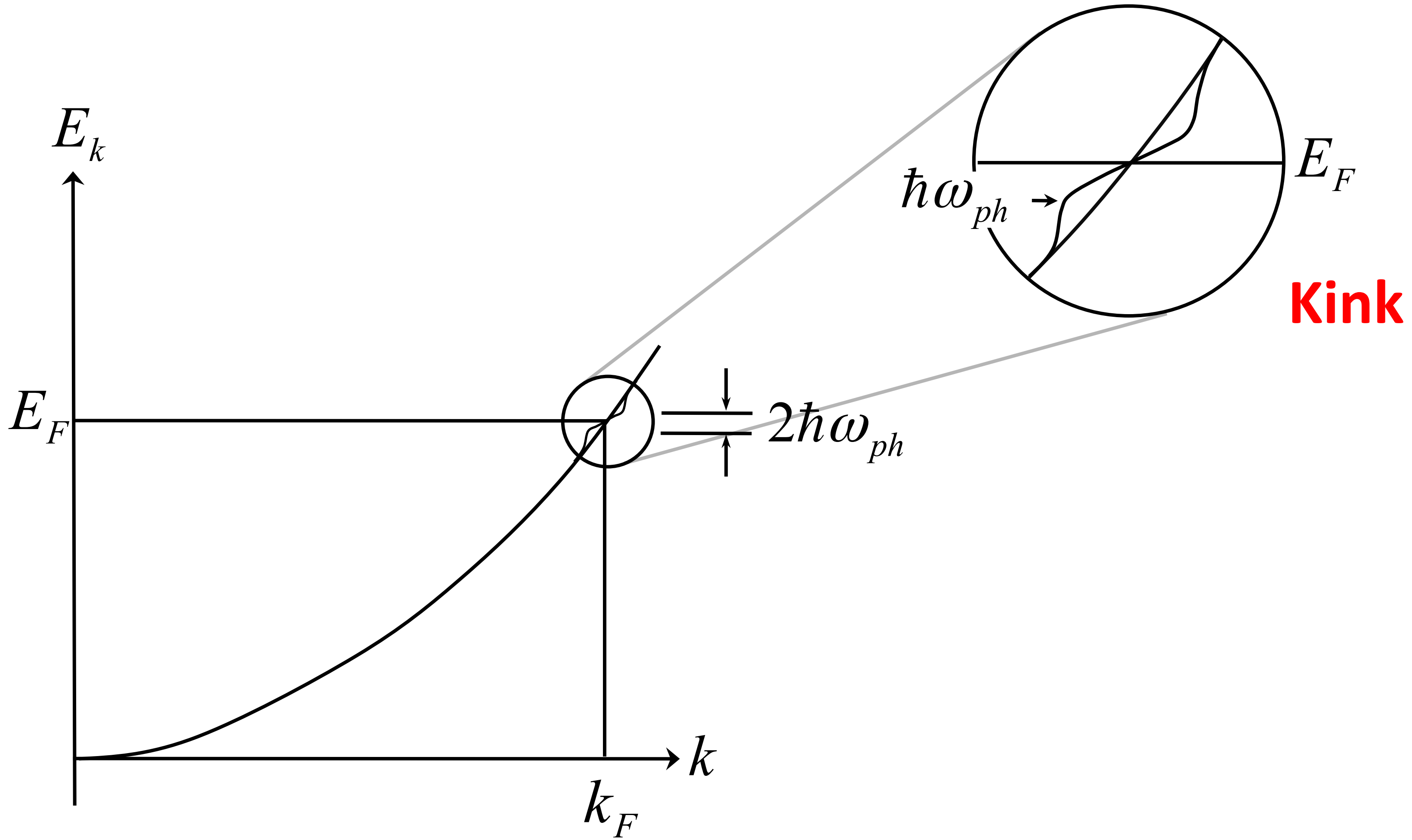
$$E = \hbar v_F^* k$$

$$\boxed{\textbf{Non-Fermi liquid}}$$



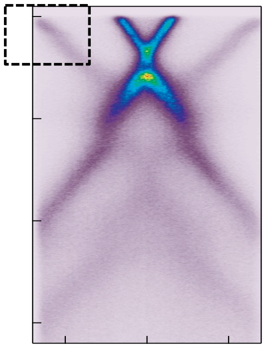
Electron-phonon coupling

Electron-phonon coupling

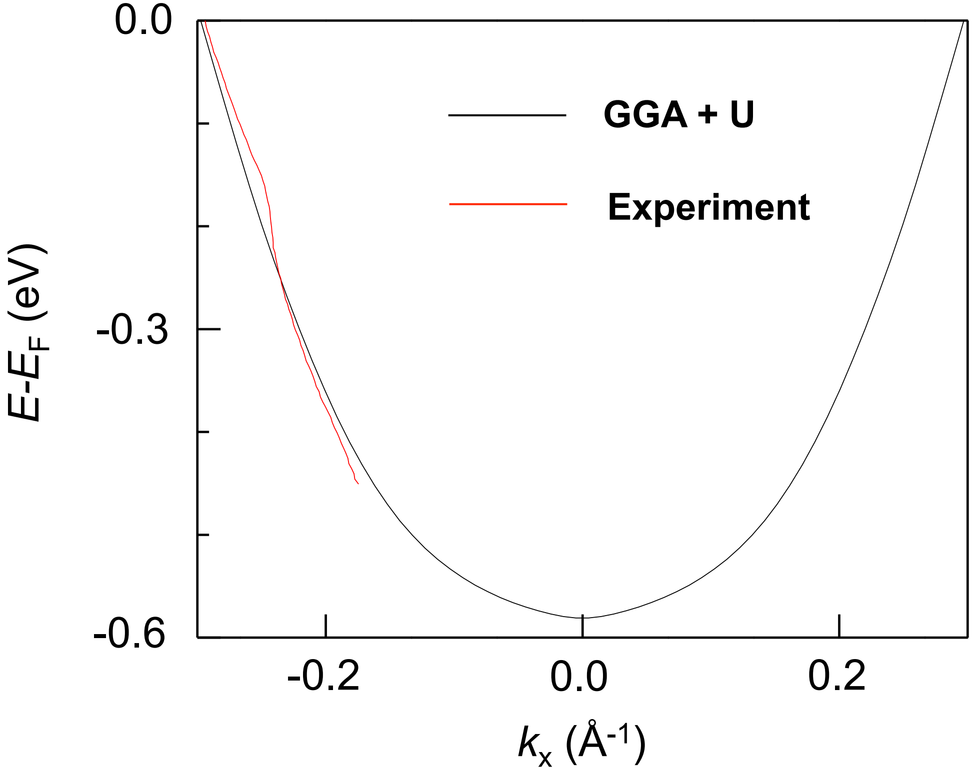


Ashcroft/Mermin, "*Solid State Physics*"

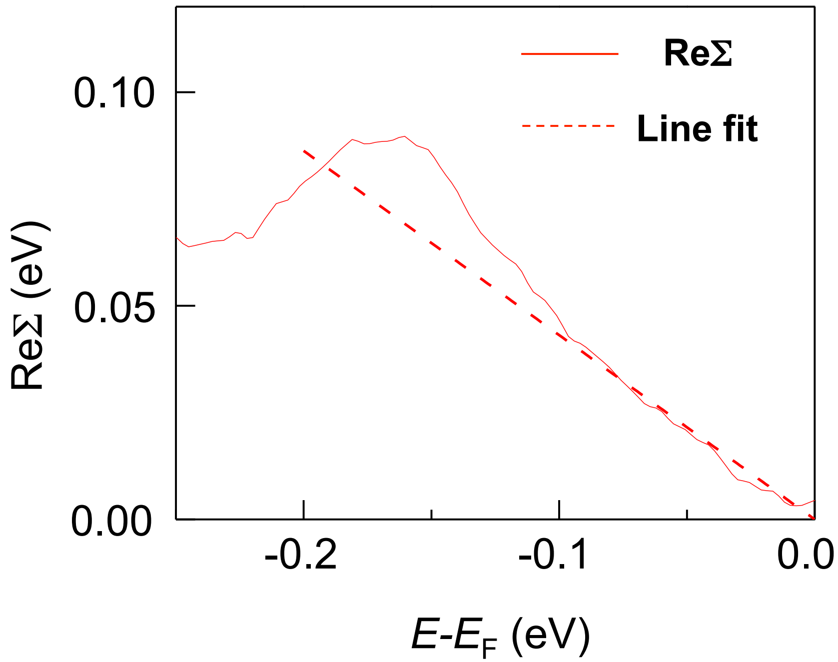
Electron-phonon coupling in Yb/Graphene



Graphene + Yb



Self-energy by electron-phonon coupling



$$\lambda = \frac{d\,\mathrm{Re}\Sigma(E)}{d\,E}$$

$\boxed{\lambda = 0.02 \sim 0.05}$

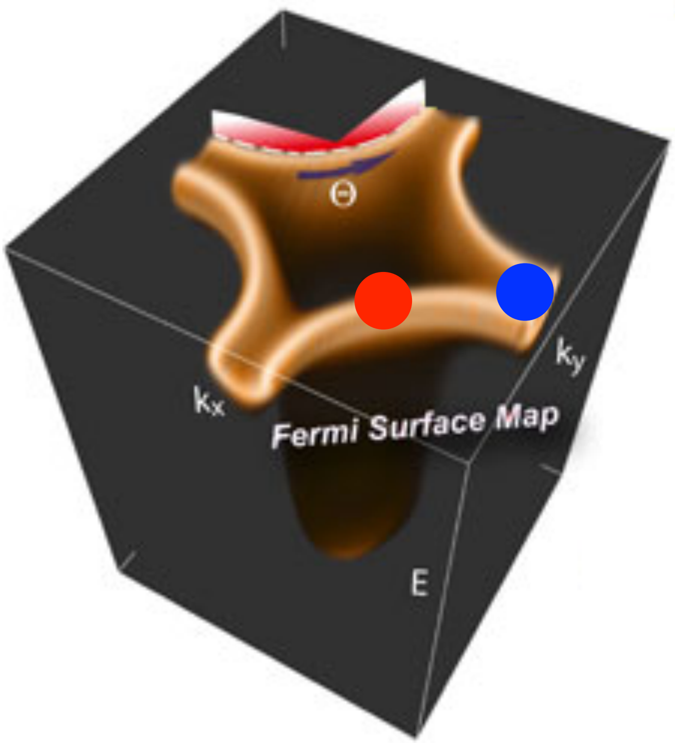
$\boxed{\lambda = 0.43 \sim 0.51}$

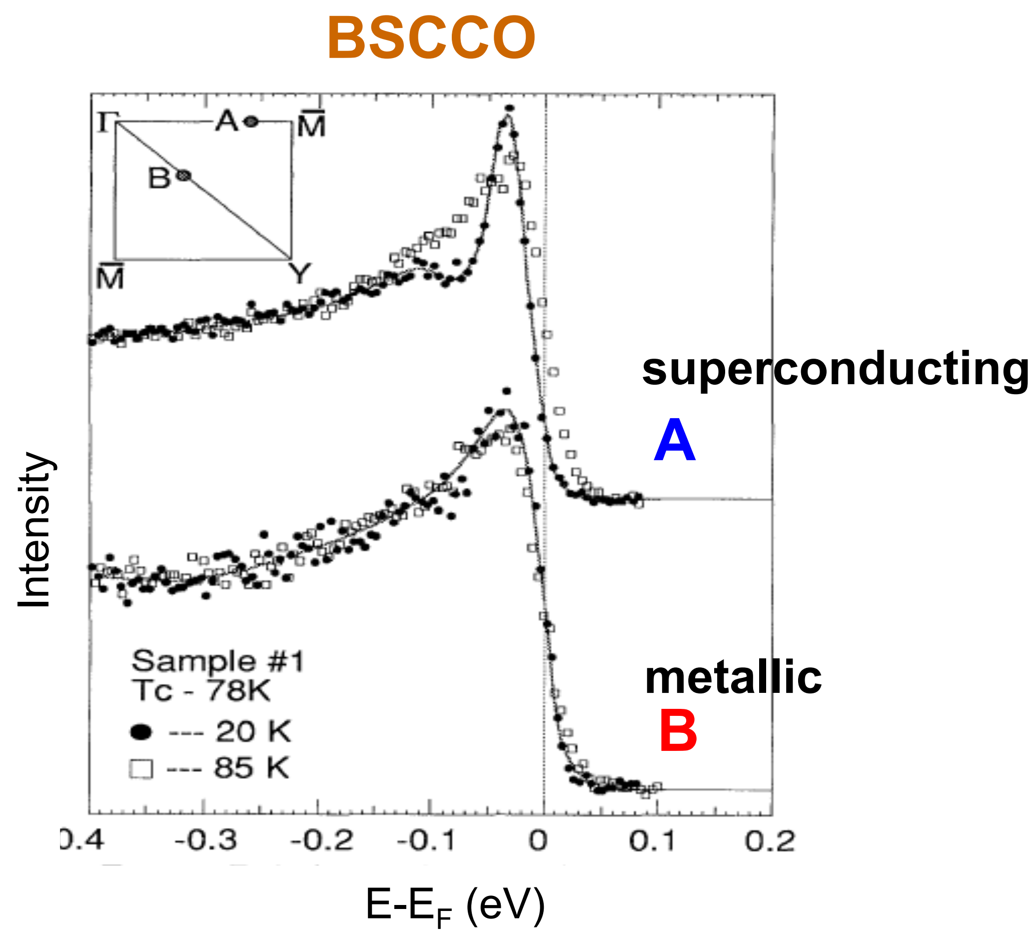
$0.23 < \lambda < 1.12$

(Conventional superconductors)

Hwang (2014)

Anisotropic superconductivity

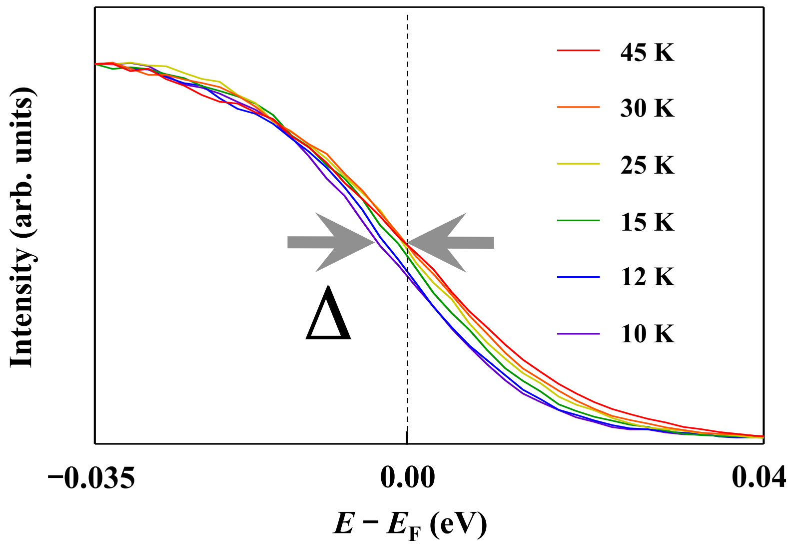


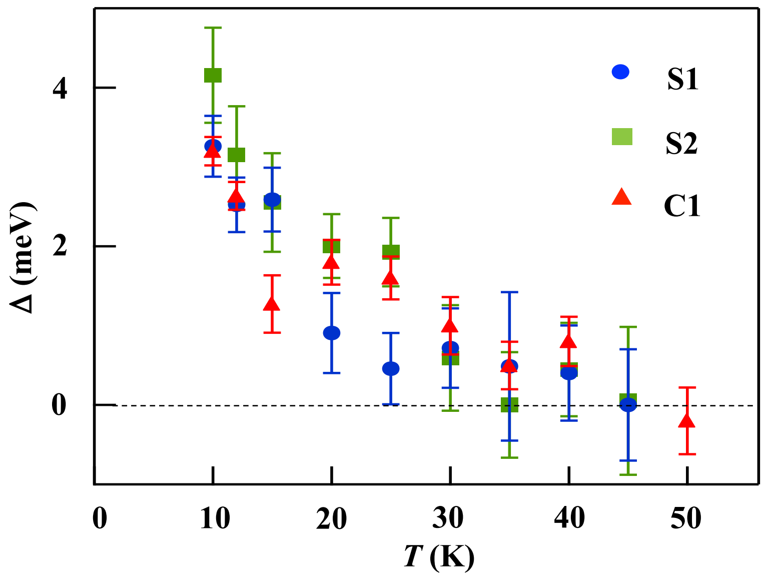


Z.X. Shen (1993)

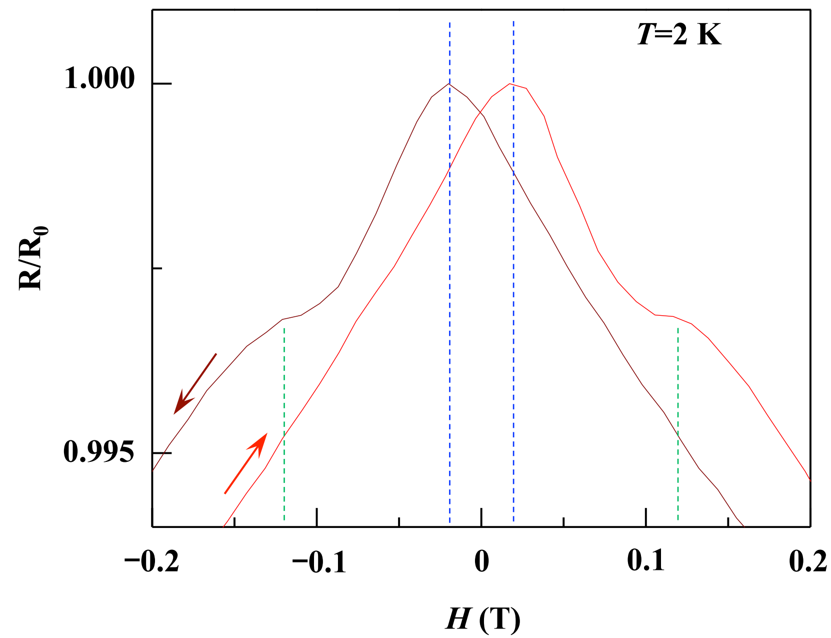
Magnetism in S/Graphene

Graphene + S





Transport measurements



Magnetic effects directly tied to the graphene band structure

Hwang (2016)

Outline

1. What are the grand challenges

2. Angle-resolved photoemission spectroscopy (ARPES)

- From Einstein's photoemission to Present
- Conventional ARPES

3. Future directions of ARPES

- Time resolution
- Spin and time resolution

The future of photoemission

What is missing? Time and Spin

Time resolved photoemission

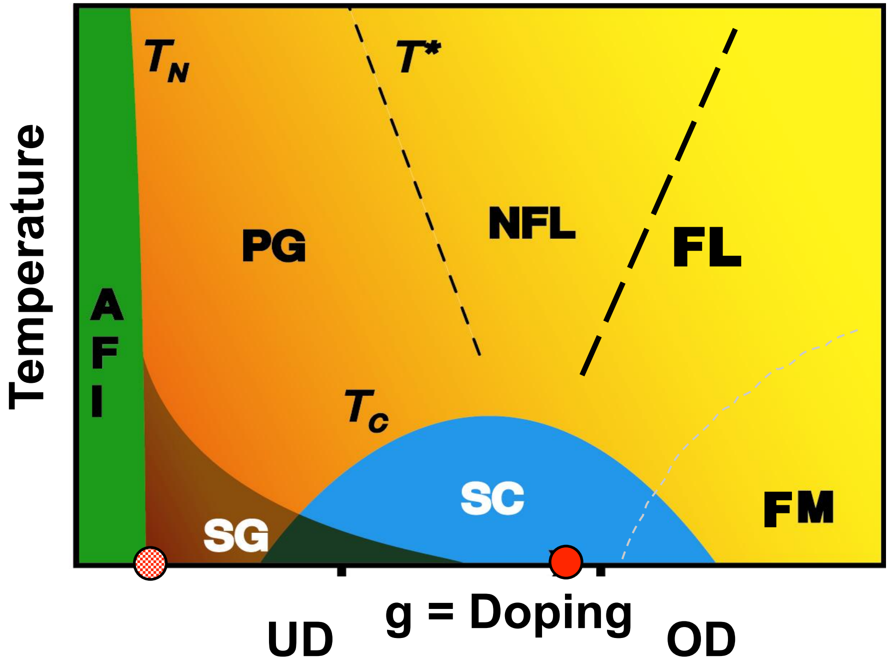
To study excitation and phase transitions

Spin resolved photoemission

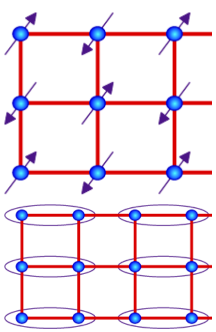
To access spin degrees of freedom

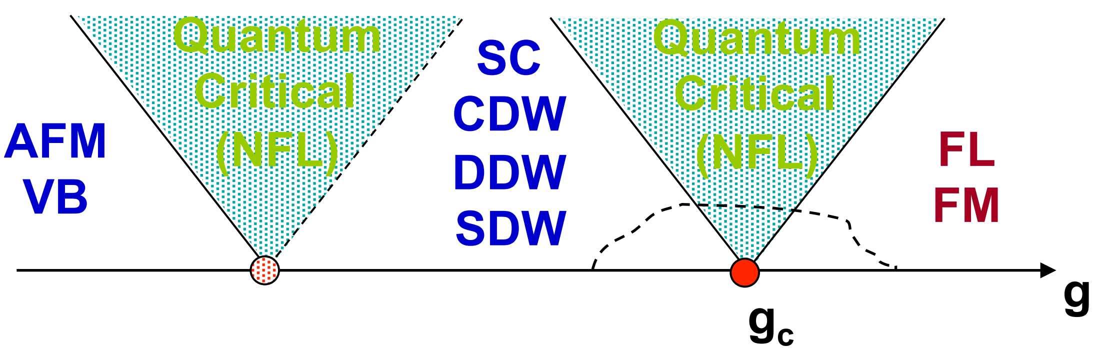
The mystery of high T_C superconductivity

- Why do we need these additional resolutions?



1) Is there a Quantum Critical Point?
2) What is the nature of NFL region?
3) What defines the Pseudogap (PG) phase?
4) What are the basic excitations?
5) Is SC a consequence of QCP or is it hiding the QCP?
6) Are PG and SC state competing states of matter?

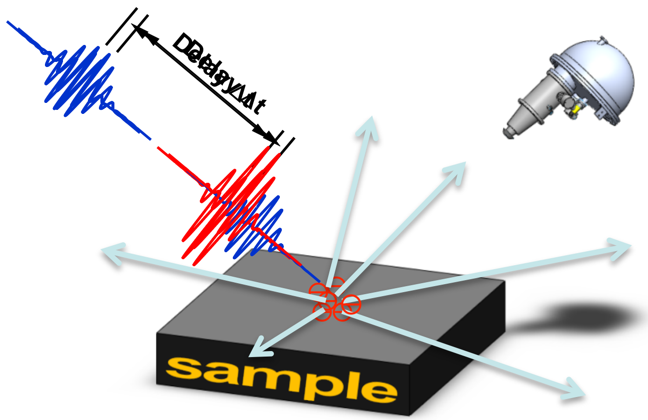




We need time and spin resolutions

Time-resolved ARPES

Pump-Probe, ultrafast ARPES:



Energy conservation

$E_B = \hbar\omega - E_K - \Phi_A$

Angle / momentum conservation

$k_{\parallel} \propto \sqrt{E_k}\,\sin\theta$

Time Resolution

$A(k, \omega, t-t')$

Possibilities:

Quasiparticle lifetimes

Ultrafast phase transitions

Closing/opening of gaps

Coherent oscillations

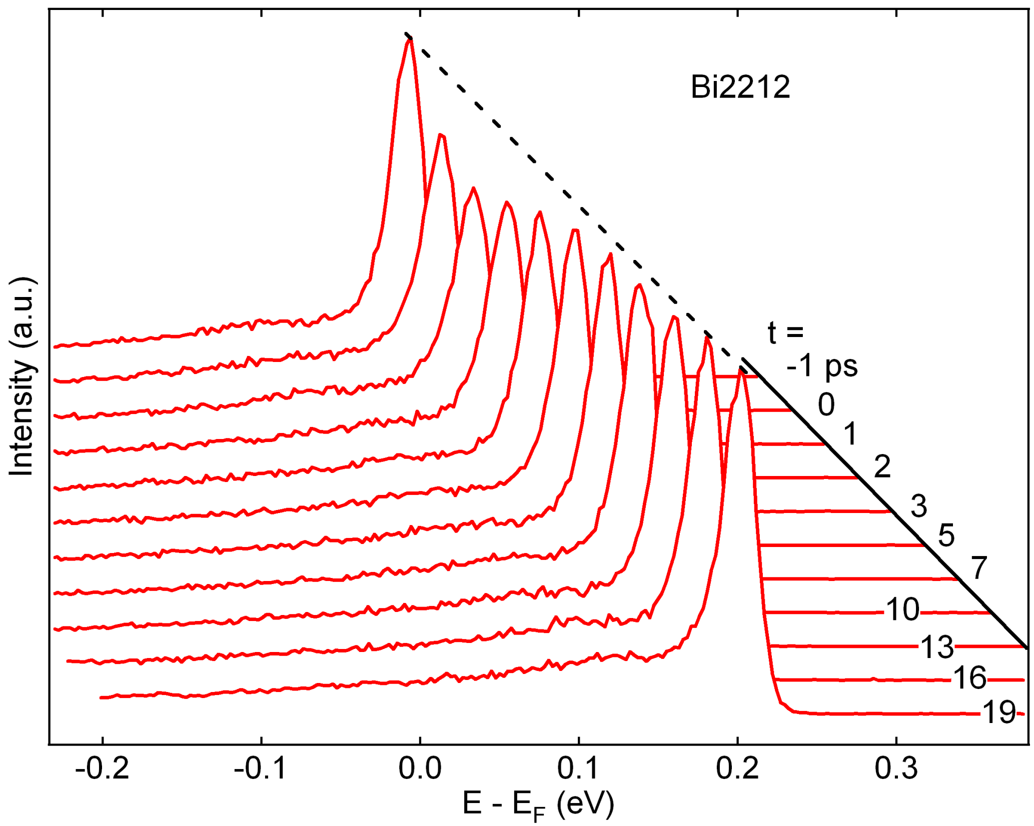
⋮

Photoelectron intensity

$$I(k,\omega,t) \propto A(k,\omega,t-t')\,|M(k,\omega)|^2 f(\omega)$$

What do we measure with time-resolved ARPES?

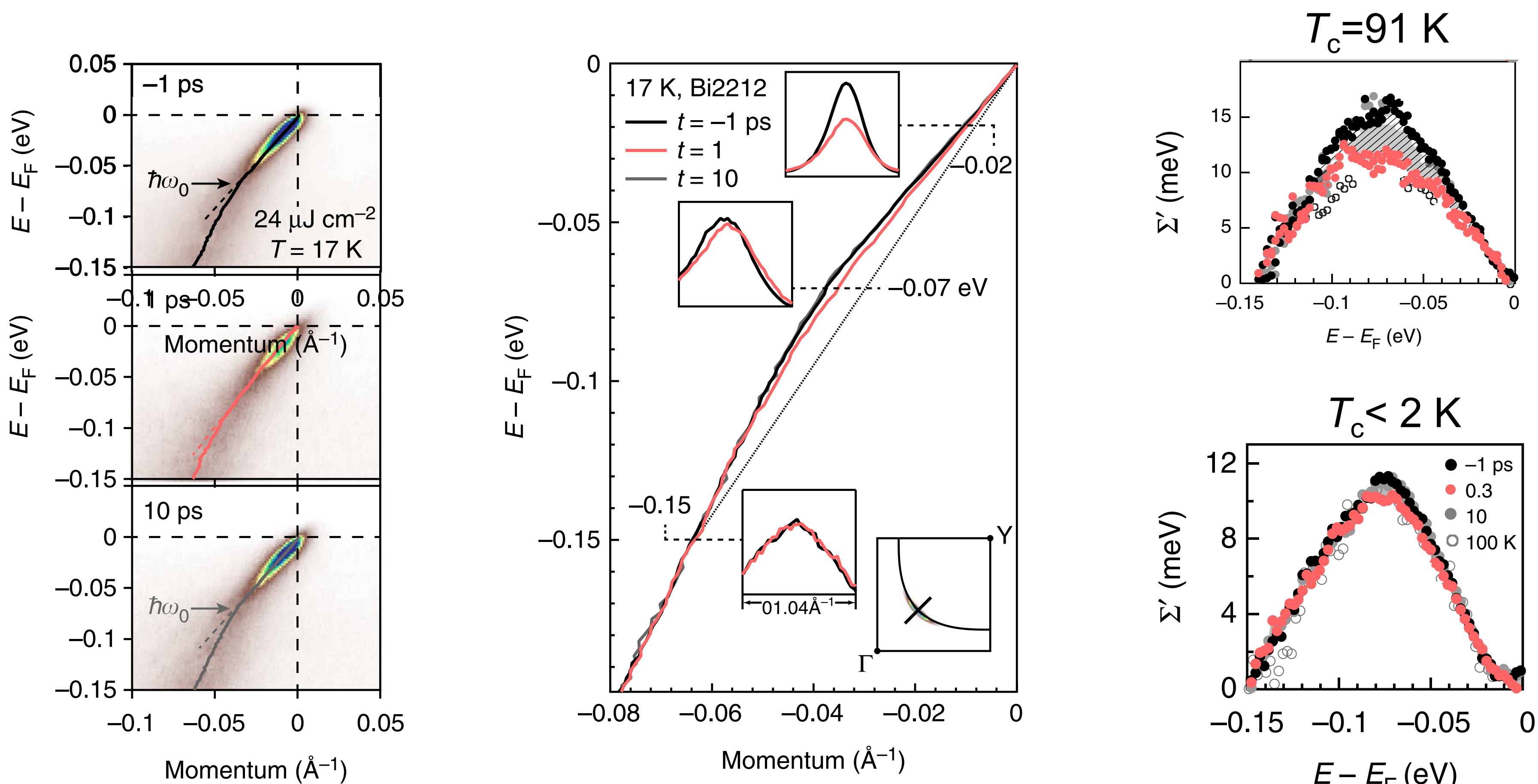
Directly measure electronic response / recovery dynamics
- **(non-equilibrium)**



Hwang (unpublished)

The power of time + momentum resolution

High-T_c superconductors



Zhang, Hwang (2014)

The future of photoemission

What is missing? Time and Spin

Time resolved photoemission

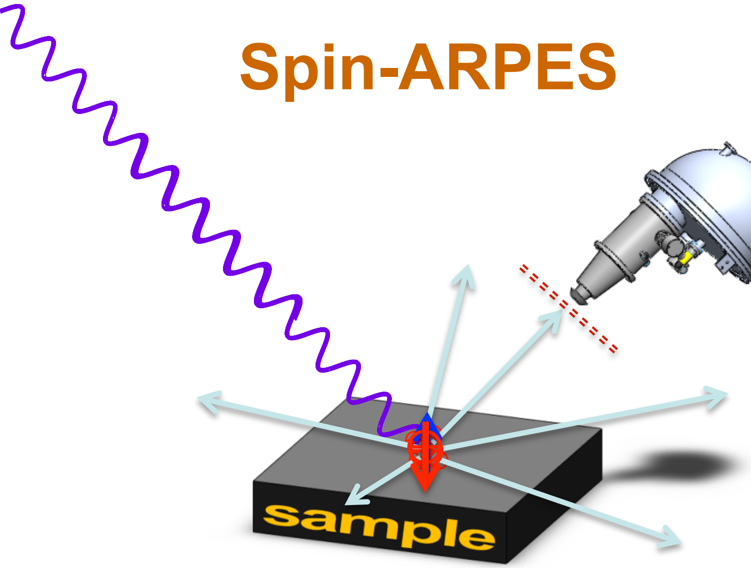
To study excitation and phase transitions

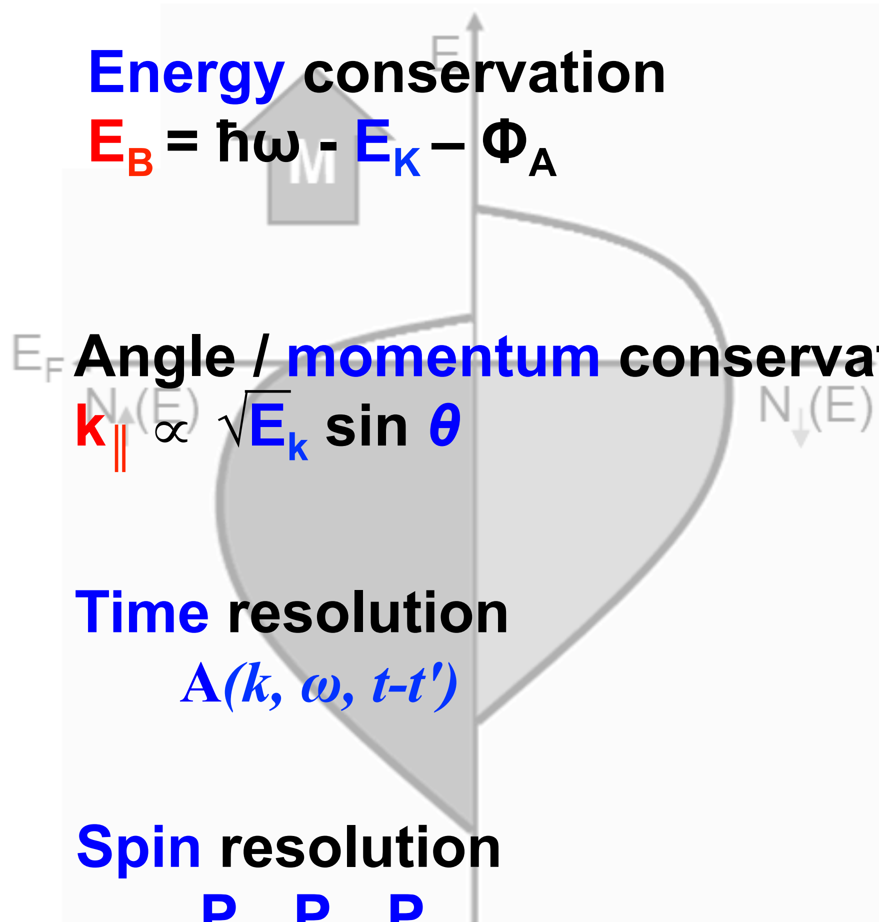
Spin resolved photoemission

To access spin degrees of freedom

Spin + time-resolved ARPES

Spin-ARPES





Energy conservation

$E_B = \hbar\omega - E_K - \Phi_A$

Angle / momentum conservation

$k_\parallel \propto \sqrt{E_k} \sin \theta$

Time resolution

$A(k, \omega, t\text{-}t')$

Spin resolution

P_x, P_y, P_z

<u>Critical for:</u>

Fundamental magnetism

Magnetic phase transitions

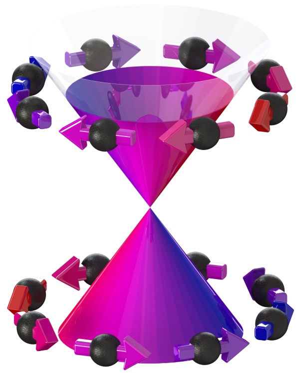
Topological Insulators

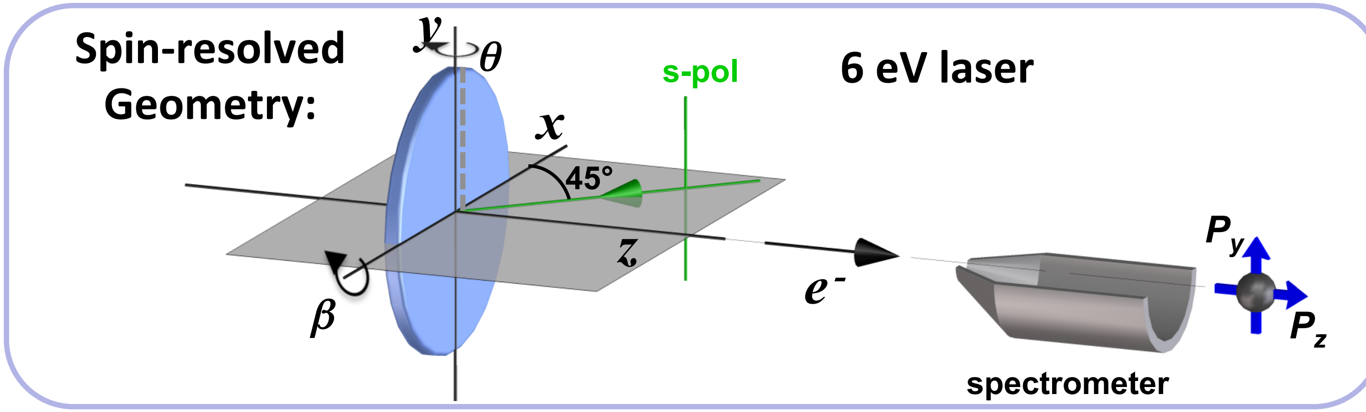
Colossal magnetoresistance

FeAs superconductors

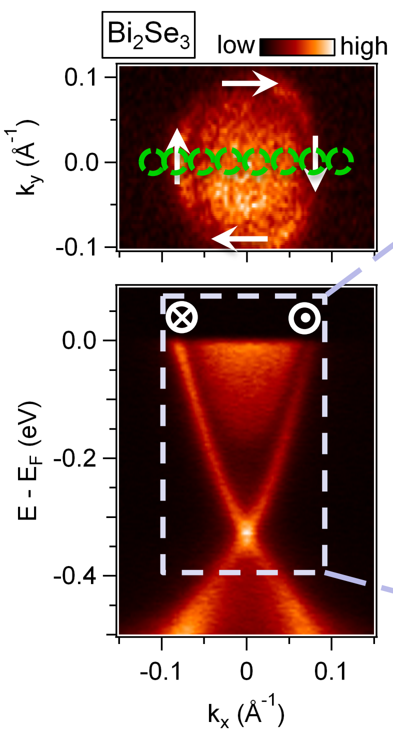
⋮

Light-spin interactions in topological insulator

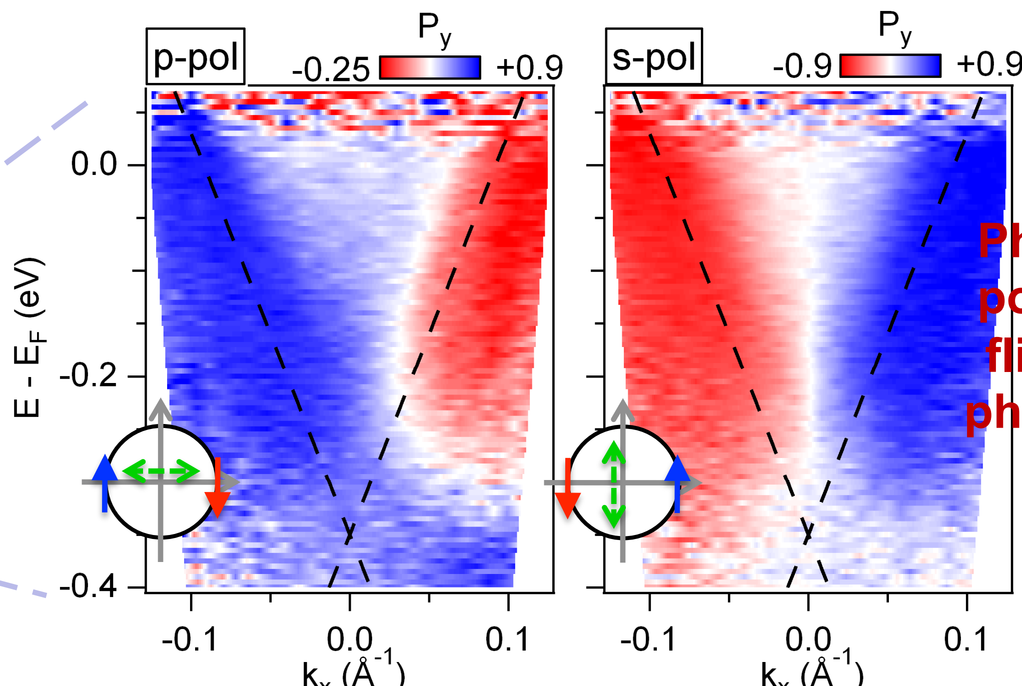




Standard ARPES:



Full Spin Polarization Maps:



Photoelectron spin polarization is fully flipped by rotating photon polarization!

Jozwiak, Hwang (2013)

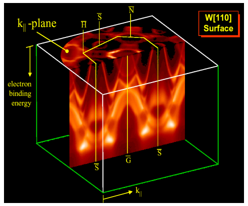
What have we learned?

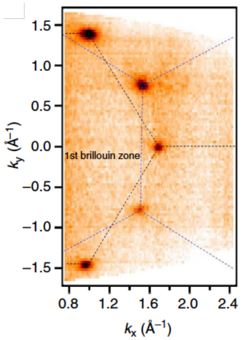
ARPES

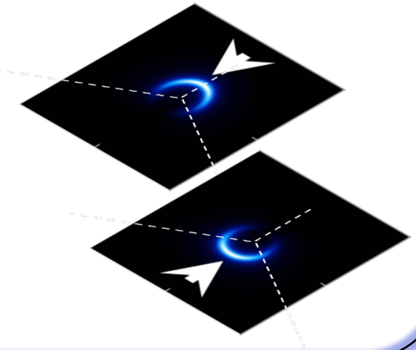
A **powerful** tool to **understand electronic properties** of a material

Electron band structure

- Fermi surface
- Geometric structure
- Quantum mechanical phases
- Many-body effects







Future of ARPES

Time-resolved ARPES

: *study excitation and phase transitions*

Spin-ARPES

: *fundamentals of magnetism*