Angle-resolved photoemission spectroscopy on emergent quantum materials

Part -1

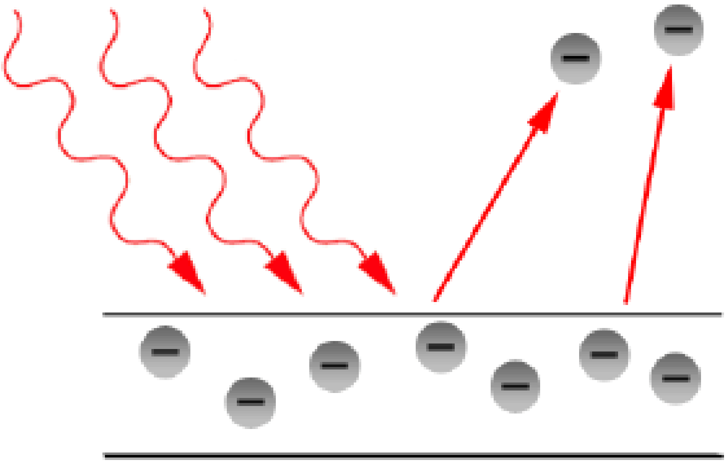
Outline

- Introduction to angle-resolved photoemission spectroscopy (ARPES)
  - The principle of ARPES
  - Current status of ARPES beamline at NSRRC

- The electronic structure of emergent materials
  - Surface states and quantum well states
  - Graphene based materials
  - Beyond graphene : 2D materials
  - Topological insulators (TIs)
  - Toward future electronic devices

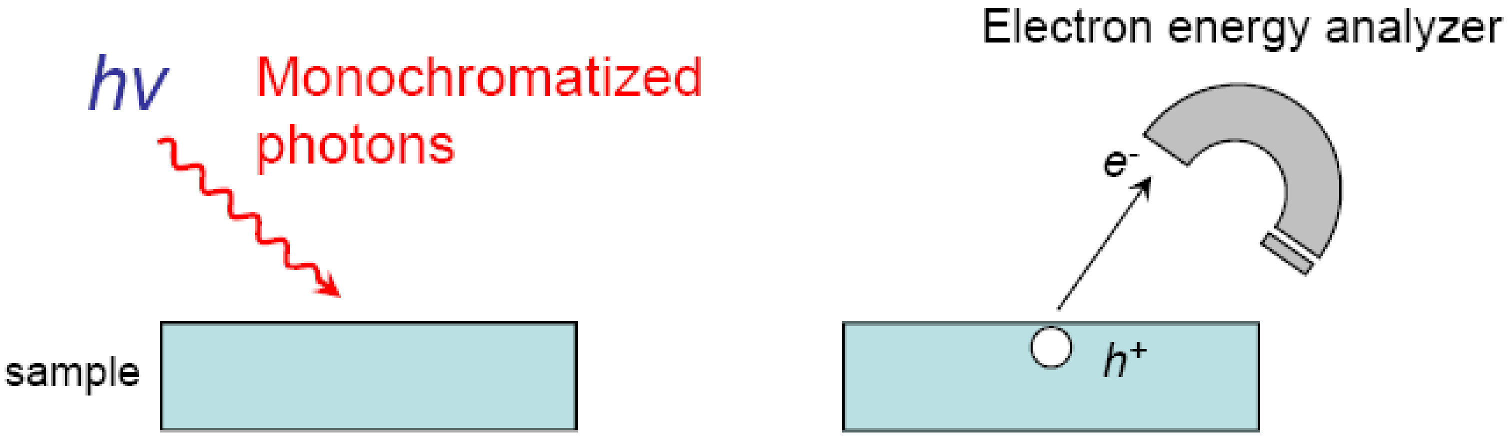
- Summary

What is photoemission?



Photon in –> electron out (emission)

What is photoemission spectroscopy? (photoelectron spectroscopy) (PES)



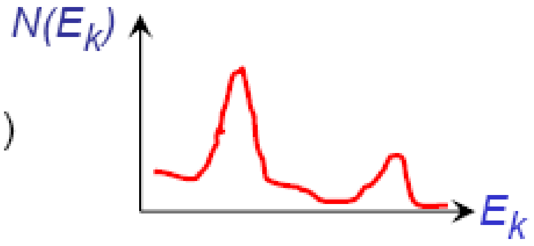
Initial state: ground (neutral) state

Final state: hole (excited) state

Conservation of energy

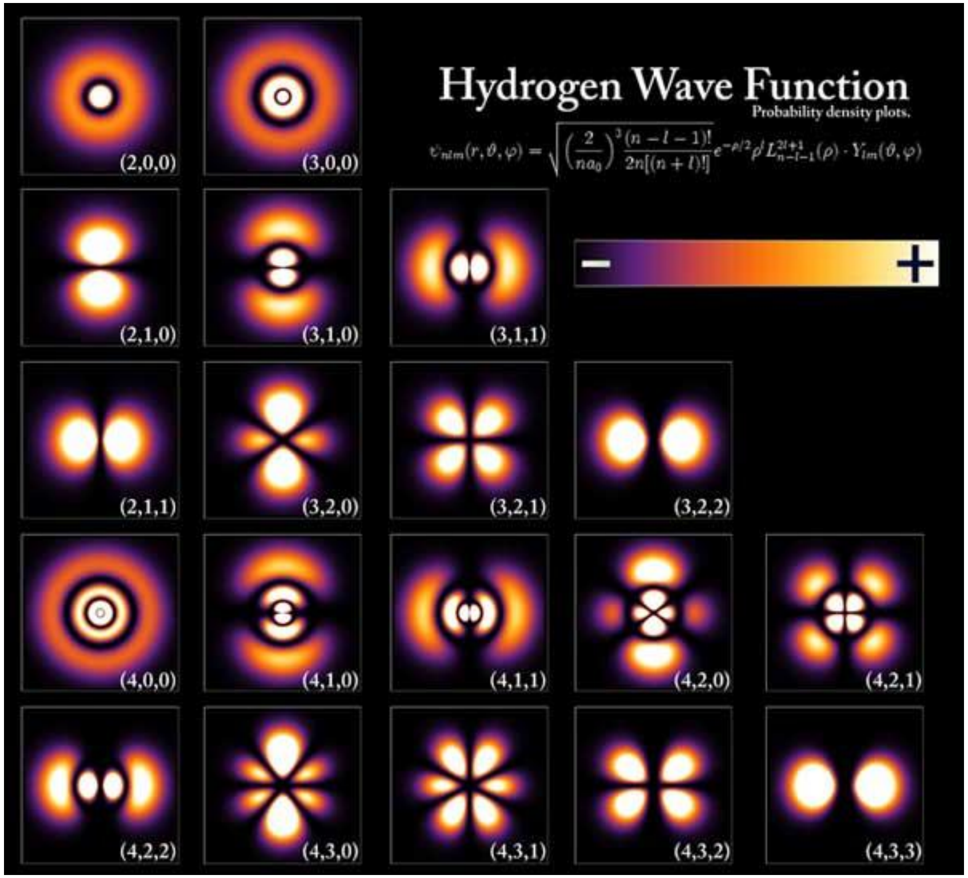
$E_k = h\nu + E_i - E_f$ (most general expression)

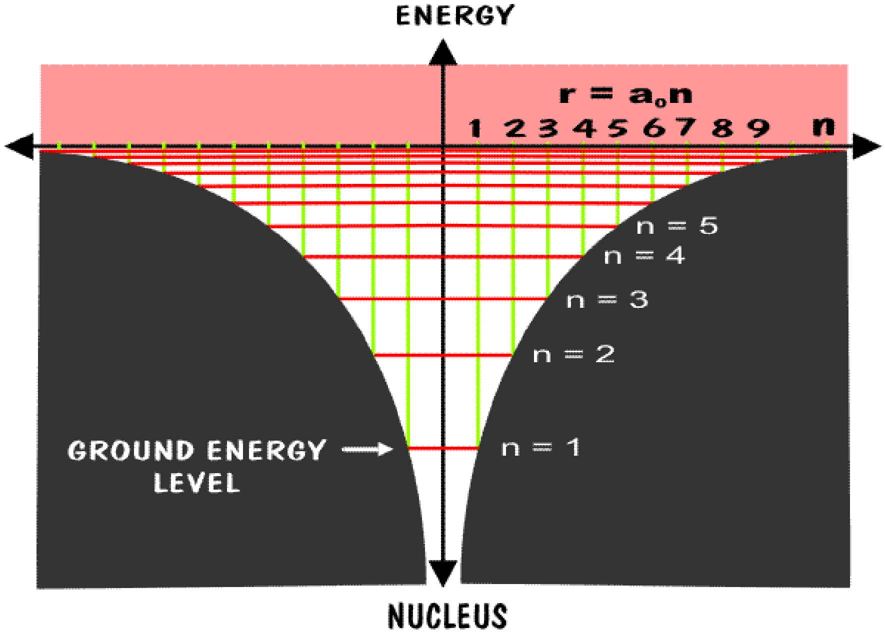
E_k : photoelectron kinetic energy
E_i (N) : total initial state system energy
E_f $(N\text{-}1)$: total final state system energy



Energy Distribution Curve (EDC) (Spectrum)

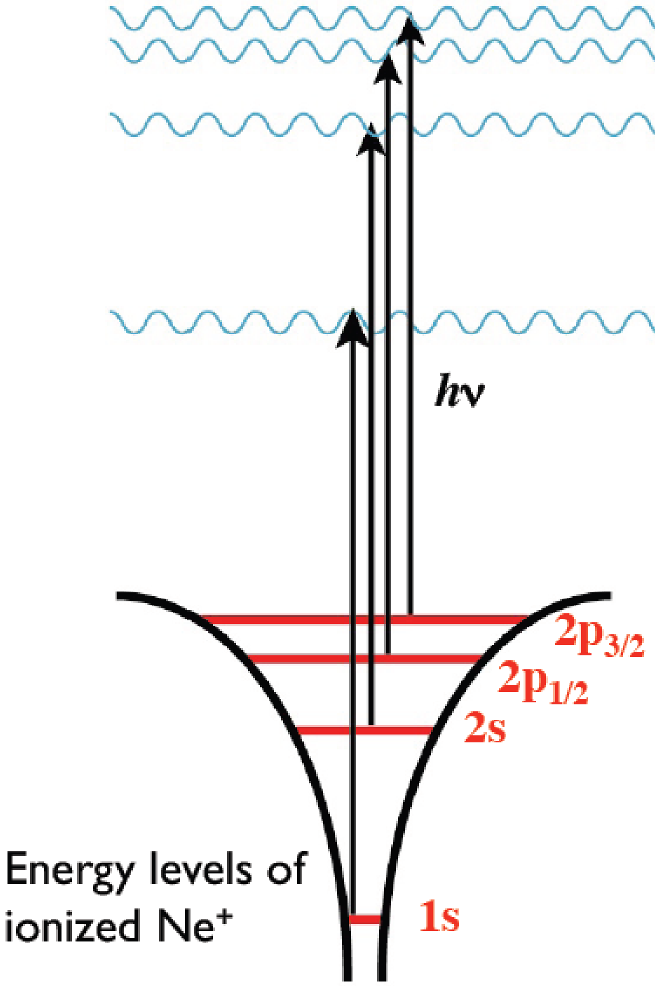
The energy level of hydrogen atom

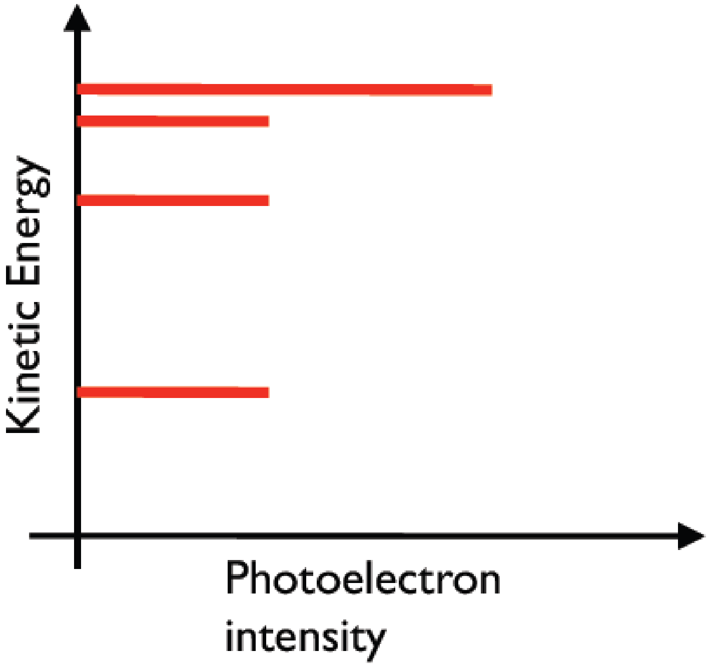




Electron ionization levels are formed from *discrete levels* in an atom

Energy conservation : $h\nu - E_I = KE$

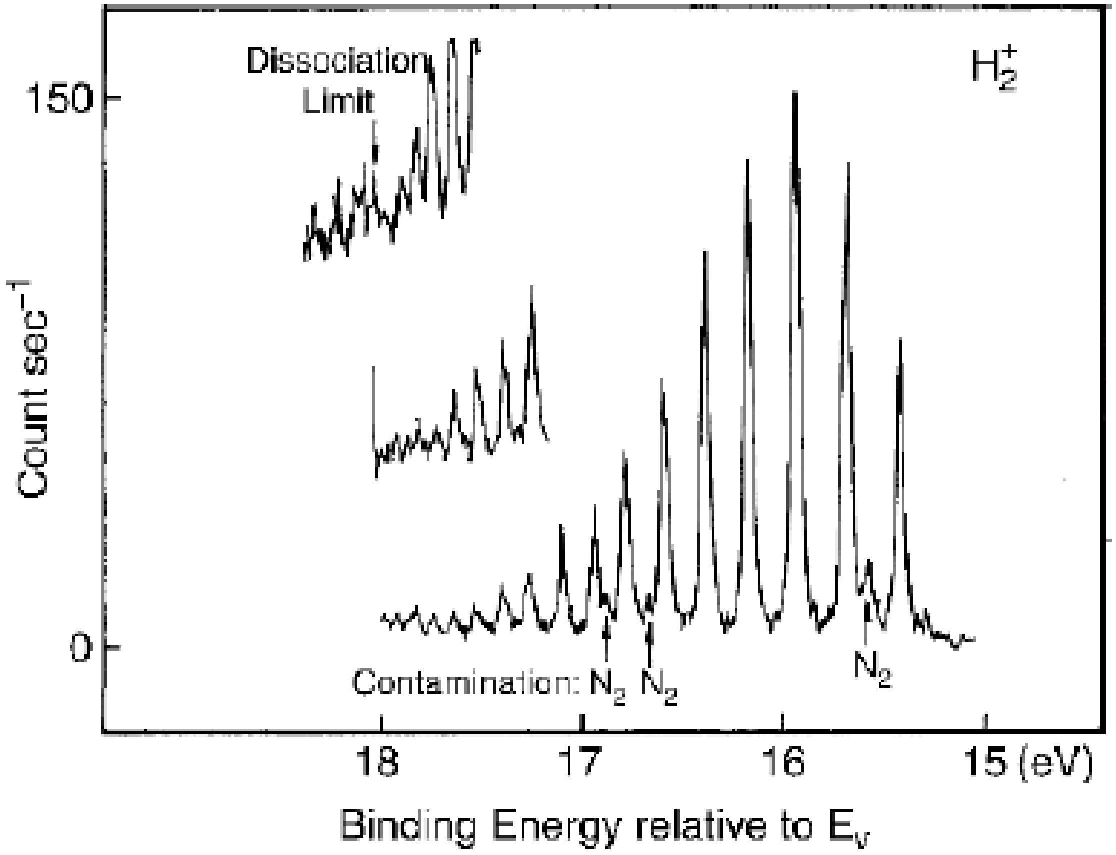




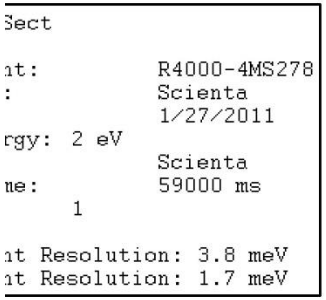
- no need to be on resonance or scan photon energies (e.g. NMR, optical measurements). Just need photons to have high enough energy!

Kyle Shen, IGERT Lecture 2008

Xeon gas phase test



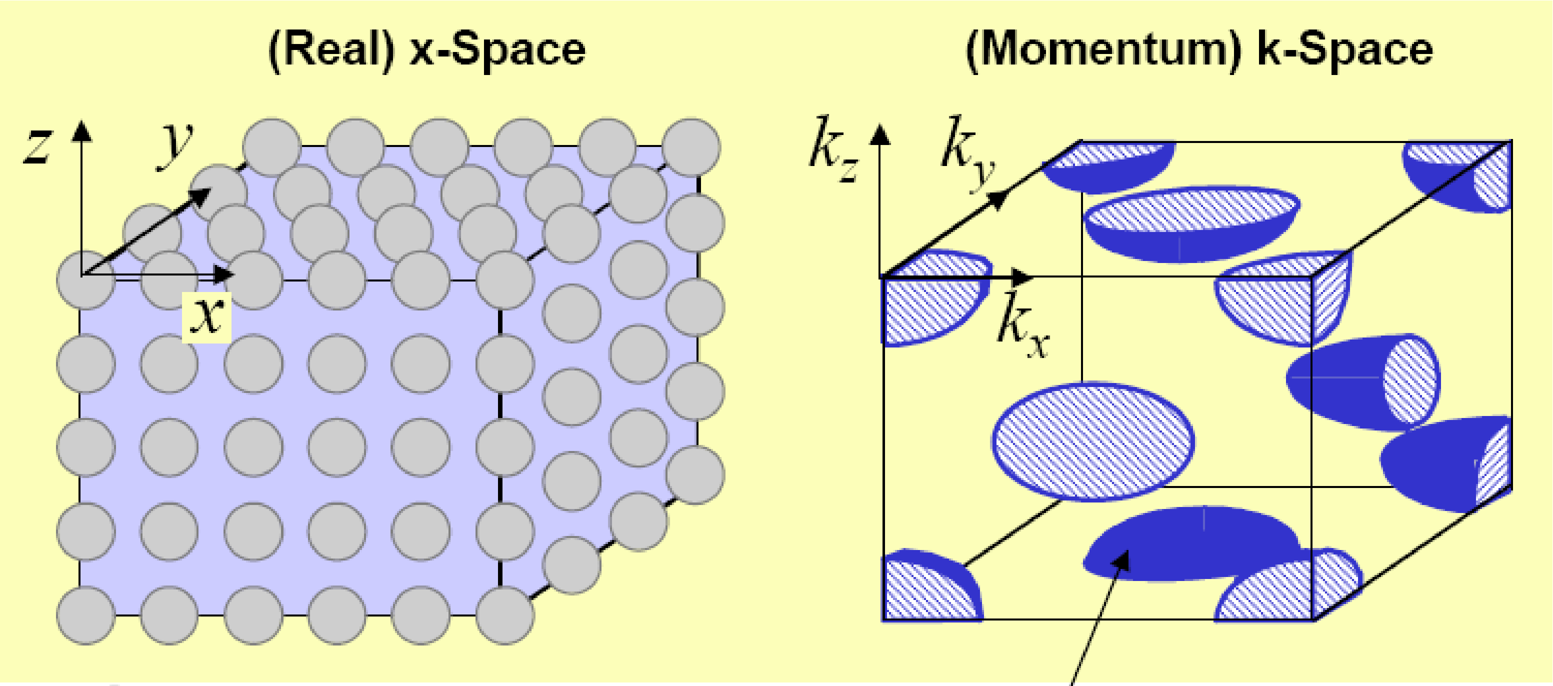
Kinetic Energy [eV]



```
Sect
nt:             R4000-4MS278
:               Scienta
                1/27/2011
rgy:  2 eV
                Scienta
me:             59000 ms
       1

nt Resolution: 3.8 meV
nt Resolution: 1.7 meV
```

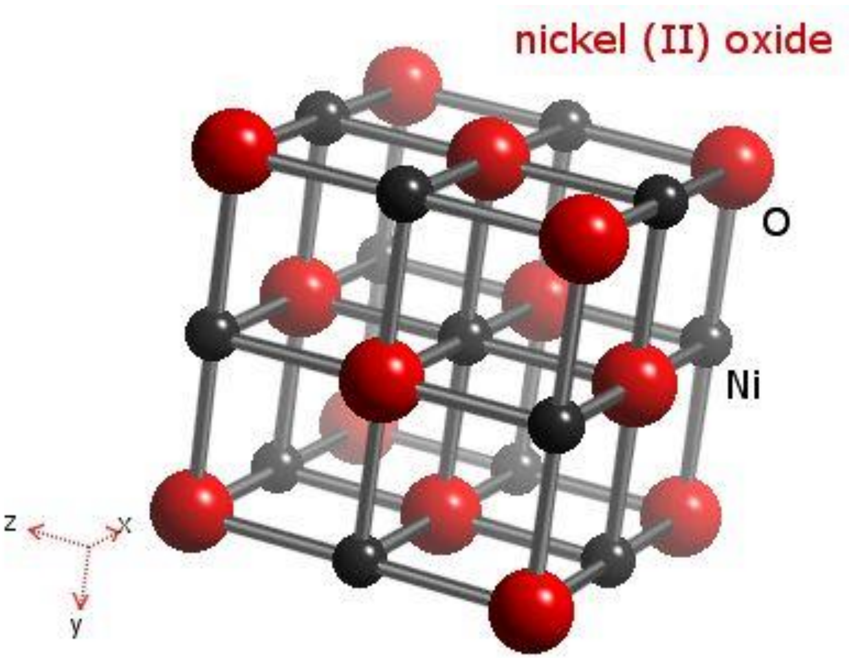
The crystal structure and momentum space



- ● Localized core electrons
- ▨ Delocalized valence band electrons

Constant-energy surface

Z. Hussain, ALS summer school



primitive vectors $\mathbf{a_1}$, $\mathbf{a_2}$, $\mathbf{a_3}$

reciprocal lattice vector $\mathbf{b_1}$,$\mathbf{b_2}$,$\mathbf{b_3}$

$$\vec{b}_1 = 2\pi \frac{\vec{a}_2 \times \vec{a}_3}{V}$$

$$\vec{b}_2 = 2\pi \frac{\vec{a}_3 \times \vec{a}_1}{V}$$

$$\vec{b}_3 = 2\pi \frac{\vec{a}_1 \times \vec{a}_2}{V}$$

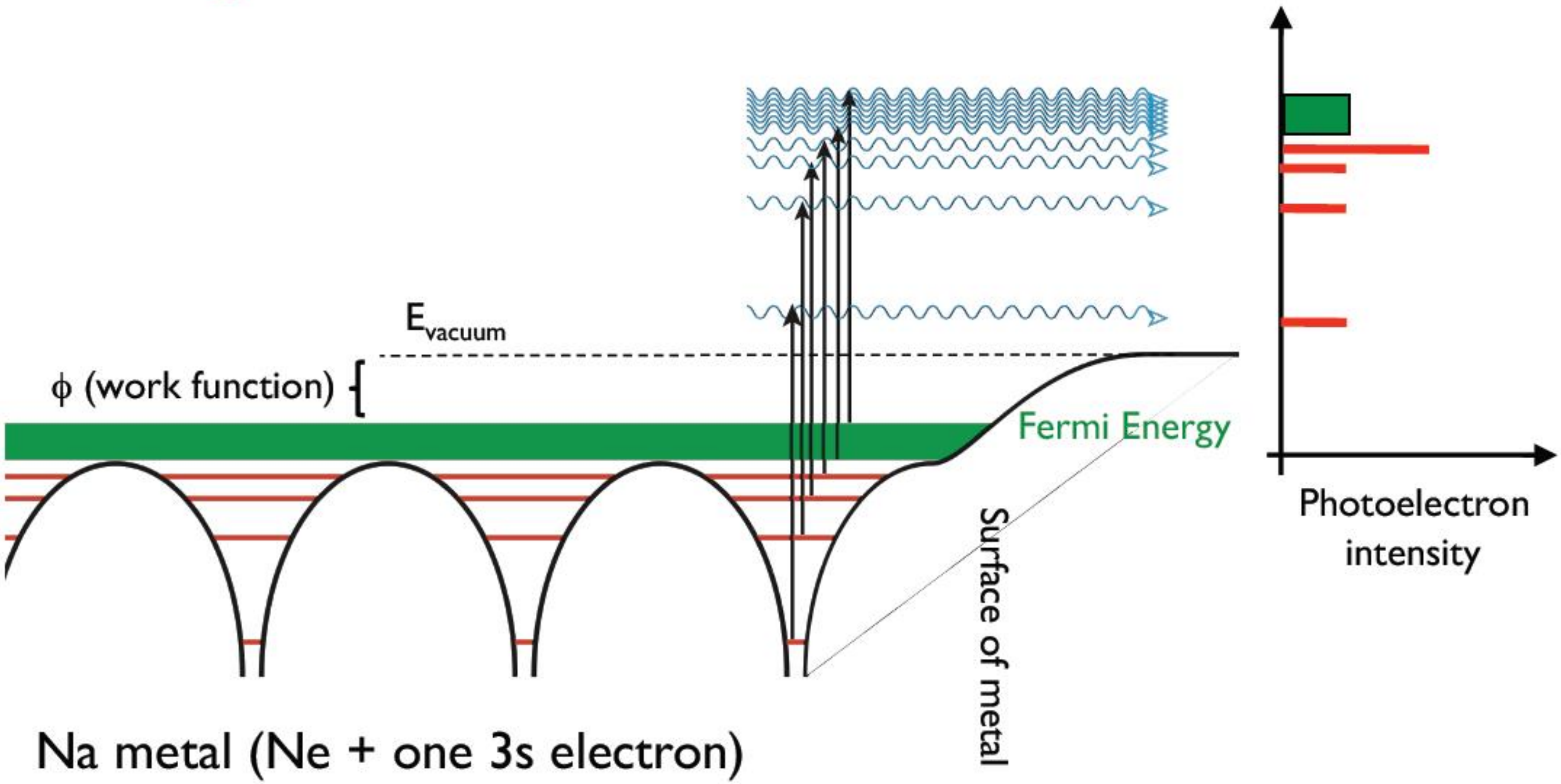
$$V = \vec{a}_1 \cdot \vec{a}_2 \times \vec{a}_3$$

reciprocal lattice **G** :

$$\vec{G} = l\vec{b}_1 + m\vec{b}_2 + n\vec{b}_3$$

l,m,n are any integers

- Deeply bound "*core*" electrons remain basically unchanged
- Outermost "*valence*" electrons hybridize forming continuous "*energy bands*"



Na metal (Ne + one 3s electron)

Kyle Shen, IGERT Lecture 2008

Band theory

Two approximations

Nearly free electrons. Electrons are non-interacting in a periodic crystal potential which is relatively weak and can be treated as a perturbation. As in the free-electron-gas model, they are still subject to the Pauli exclusion principle.

Free electron gas :
The interactions between electrons and between electrons and nuclei are turned off, subject only to the Pauli exclusion principle.

Tightly-bonding approximation

Electrons are tightly bound to particular atoms, overlapping only weakly with neighbors.

Fermi-Dirac Distribution

Almost every electronic transport property of solids is proportional to $D(\mathcal{E}_F)$.

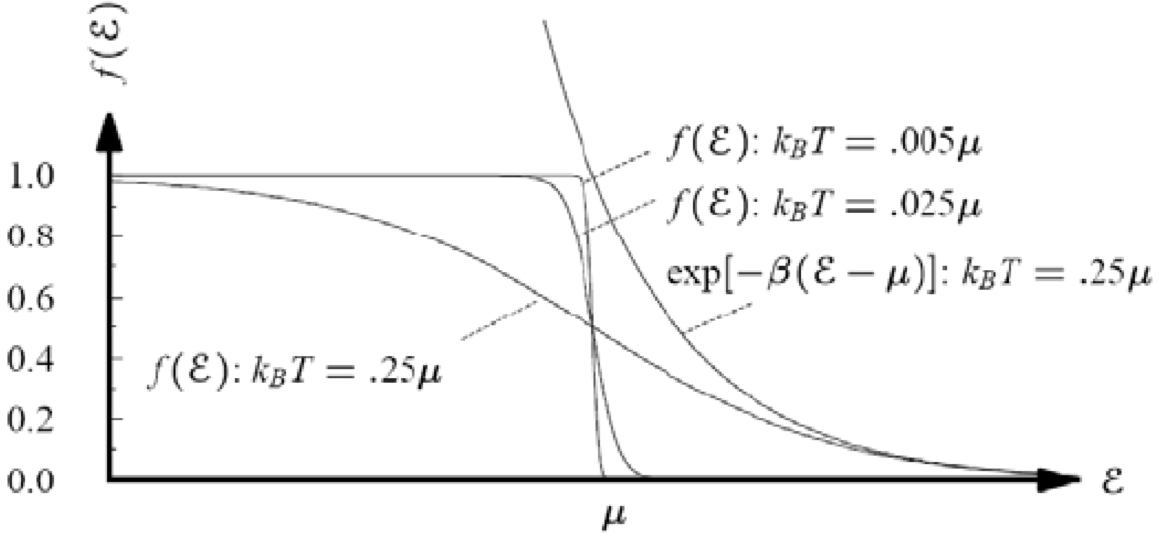
Thermal Properties of Free Electron Gas:

Fermi function

(Fermi-Dirac distribution)

$$f(\mathcal{E}) = \frac{1}{e^{(\mathcal{E}-\mu)/k_BT}+1}$$

RT ~ 25 meV



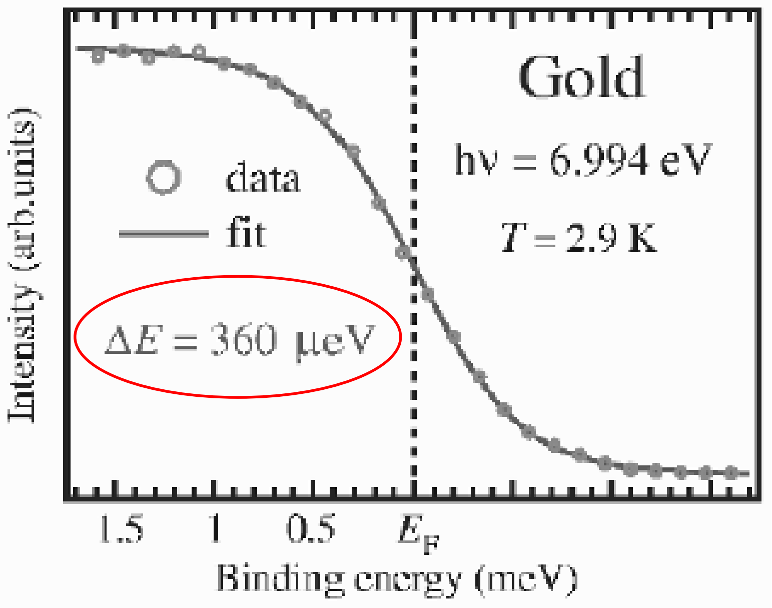


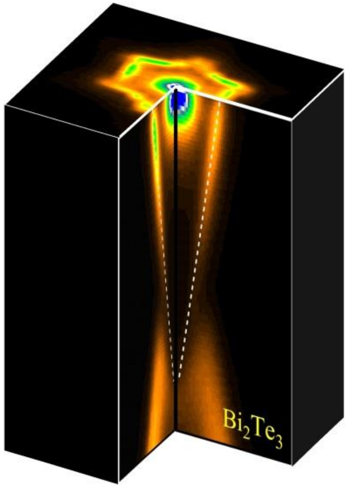
Fig. 2.3. Ultra-high resolution photoemission spectrum on a polycrystalline gold sample (evaporated Au film) for the determination of the energy resolution. The Fermi edge was measured at $T = 2.9\,\mathrm{K}$ using a frequency tripled ($KBe_2BO_3F_2$ crystal, KBBF) YVO_3 laser for the photoexcitation ($h\nu = 6.994\,\mathrm{eV}$) [15]

Hufner, Very high resolution photoelectron spectroscopy

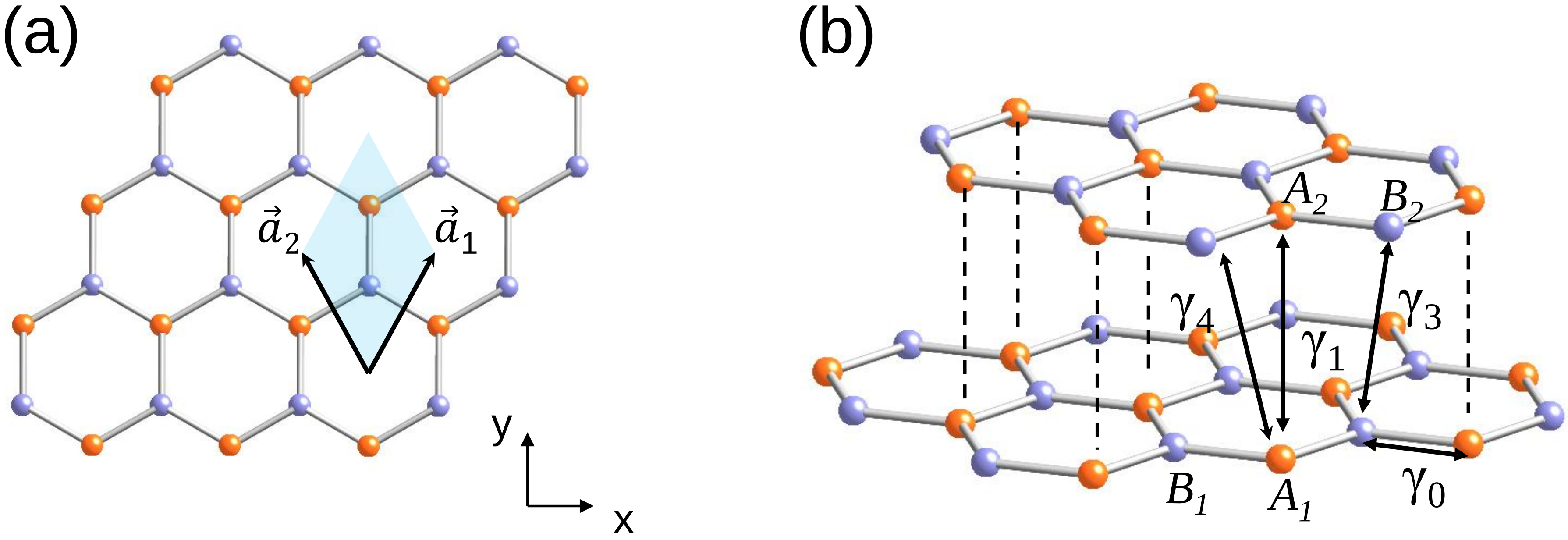
Why ARPES - key technique for the electronic structure mapping

- Angle-resolved photoemission spectroscopy (ARPES) is the most general tool to probe band structure, electronic interactions or spectral function mapping.

- Broad applications: surfaces, thin films, bulk materials, superconductors, magnetic/spin systems, complex materials, topological insulators, graphene based materials, charge density wave materials, low-dimensional systems, artificial stacks, device configurations, etc.

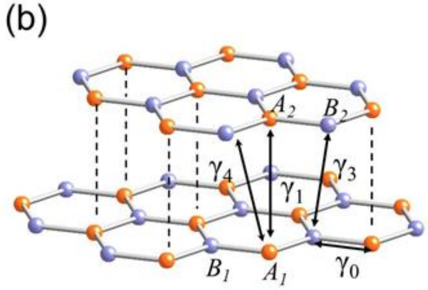


The unit cell of graphene



SWMc Hamiltonian of bilayer graphene

$$\mathrm{H}(\vec{k}) = \begin{pmatrix} E_0 + \Delta & \gamma_0 f(\vec{k}) & \gamma_1 & \gamma_4 f^*(\vec{k}) \\ \gamma_0 f^*(\vec{k}) & E_0 & \gamma_4 f^*(\vec{k}) & \gamma_3 f(\vec{k}) \\ \gamma_1 & \gamma_4 f(\vec{k}) & E_0 + \Delta & \gamma_0 f^*(\vec{k}) \\ \gamma_4 f(\vec{k}) & \gamma_3 f^*(\vec{k}) & \gamma_0 f(\vec{k}) & E_0 \end{pmatrix}$$

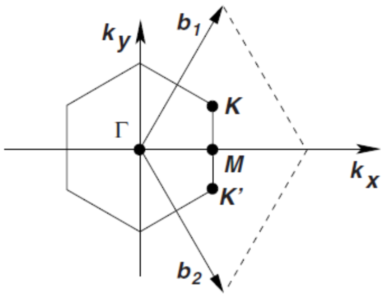


$$f(\vec{k}) = \exp\left(ik_x a_0/2\sqrt{3}\right) + 2\exp(-ik_x a_0/2\sqrt{3})\cos(k_y/2)$$

$$\vec{k} = (k_x, k_y)$$

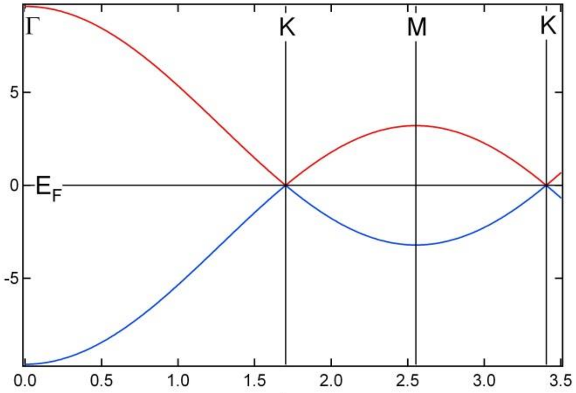
A. Gruneis et al., PRB (2008)

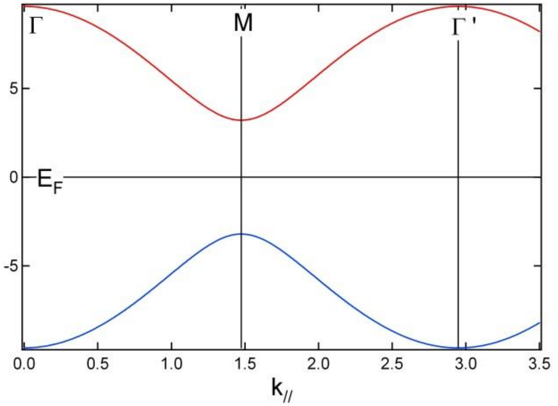
Pure 2D material : graphene

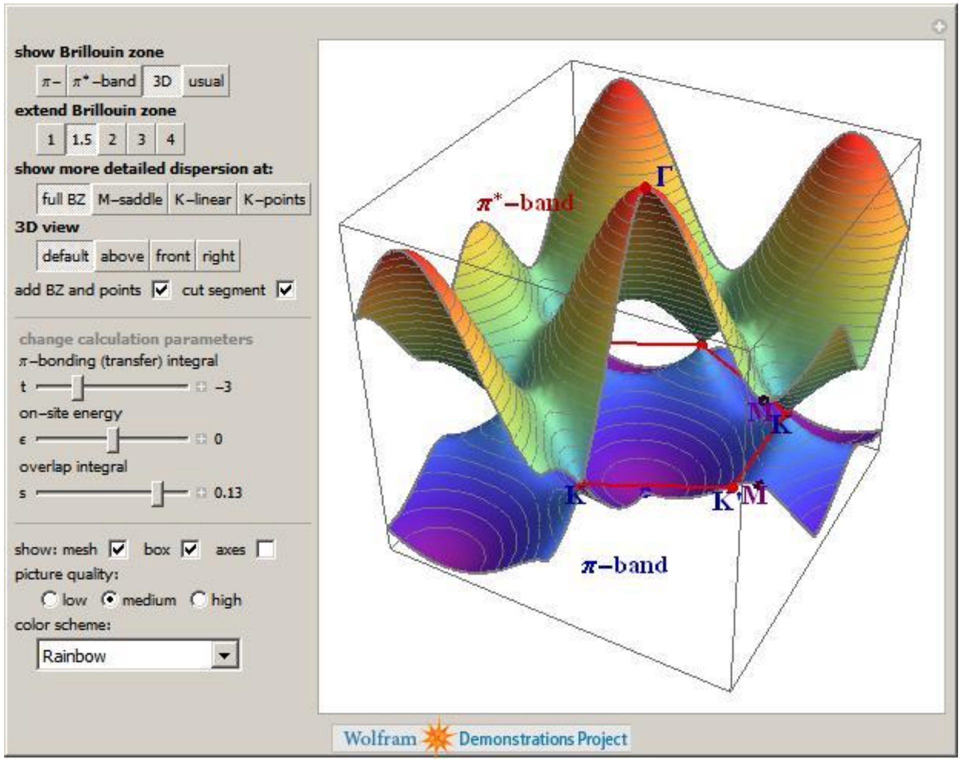


$$\boldsymbol{b}_1 = \frac{2\pi}{3a}(1,\sqrt{3}),\quad \boldsymbol{b}_2 = \frac{2\pi}{3a}(1,-\sqrt{3})$$

$$\boldsymbol{K} = \left(\frac{2\pi}{3a},\frac{2\pi}{3\sqrt{3}a}\right),\quad \boldsymbol{K}' = \left(\frac{2\pi}{3a},-\frac{2\pi}{3\sqrt{3}a}\right)$$







show Brillouin zone: π– | π*–band | 3D | usual

extend Brillouin zone: 1 | 1.5 | 2 | 3 | 4

show more detailed dispersion at: full BZ | M–saddle | K–linear | K–points

3D view: default | above | front | right

add BZ and points ☑ cut segment ☑

change calculation parameters

π–bonding (transfer) integral

t –3

on–site energy

ϵ 0

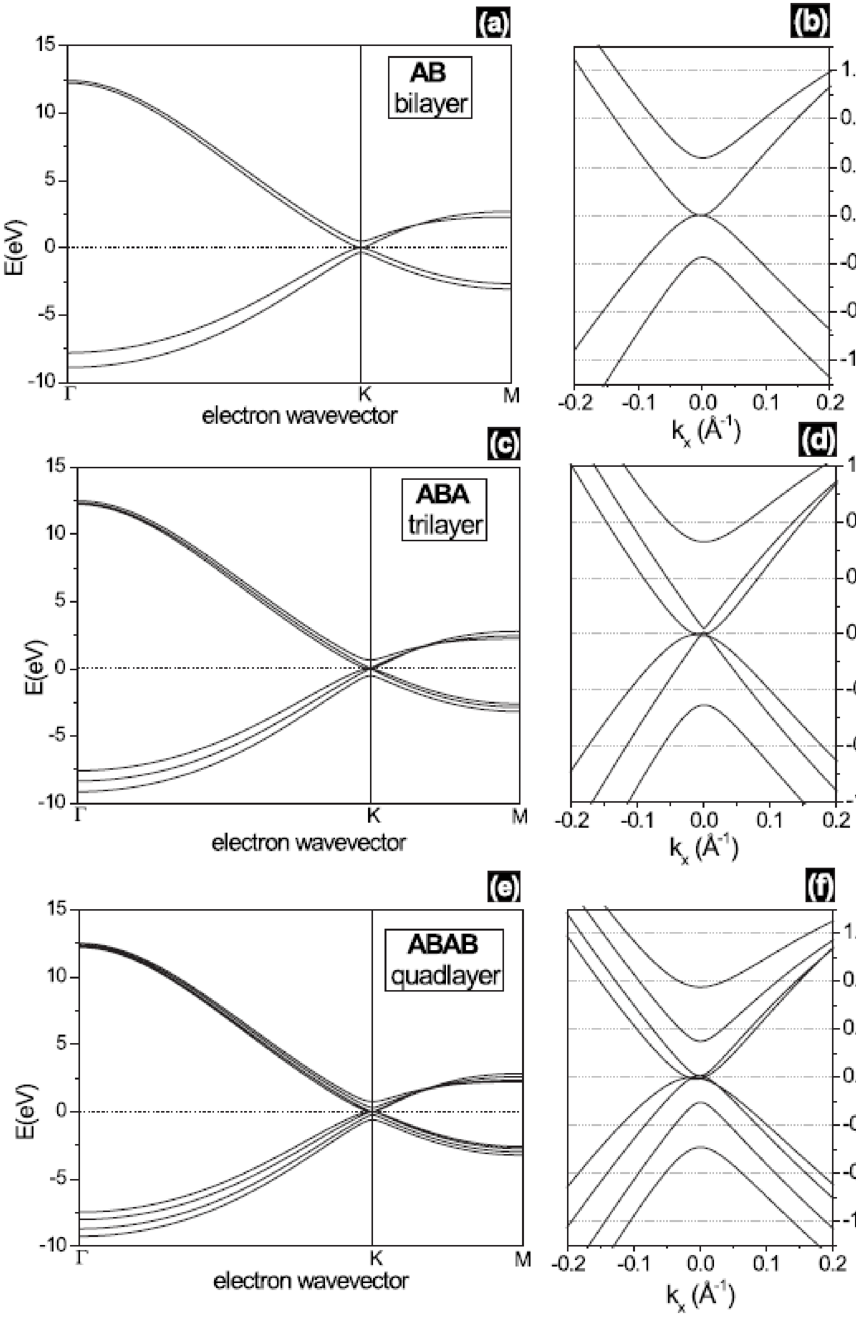
overlap integral

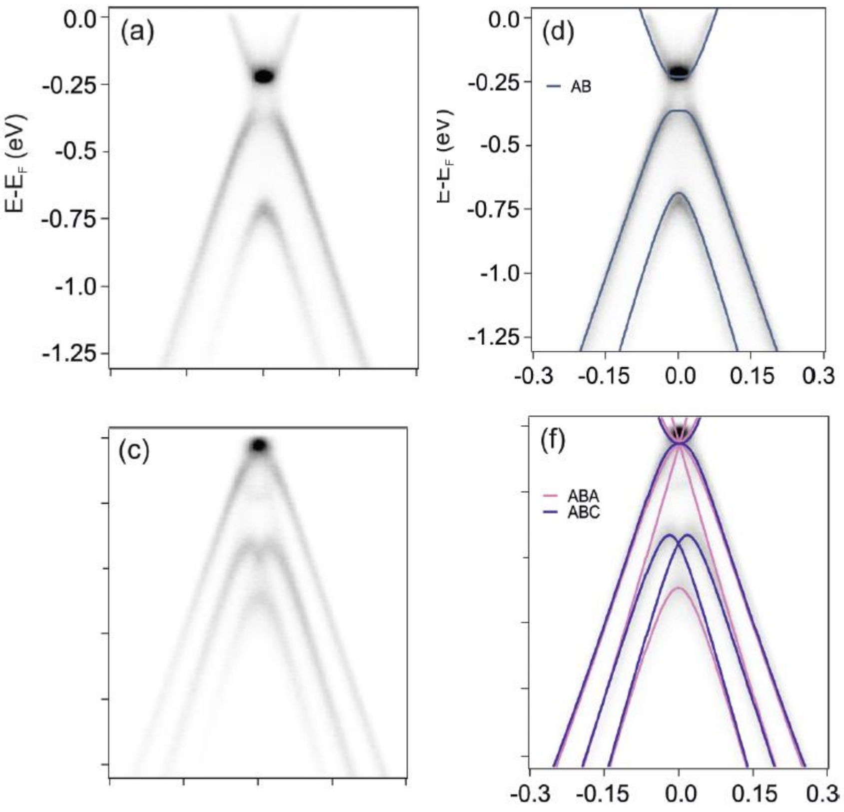
s 0.13

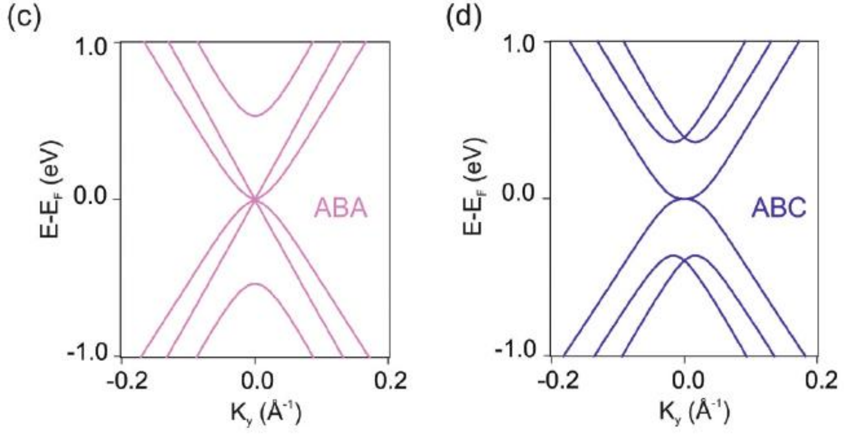
show: mesh ☑ box ☑ axes ☐

picture quality: ○ low ● medium ○ high

color scheme: Rainbow

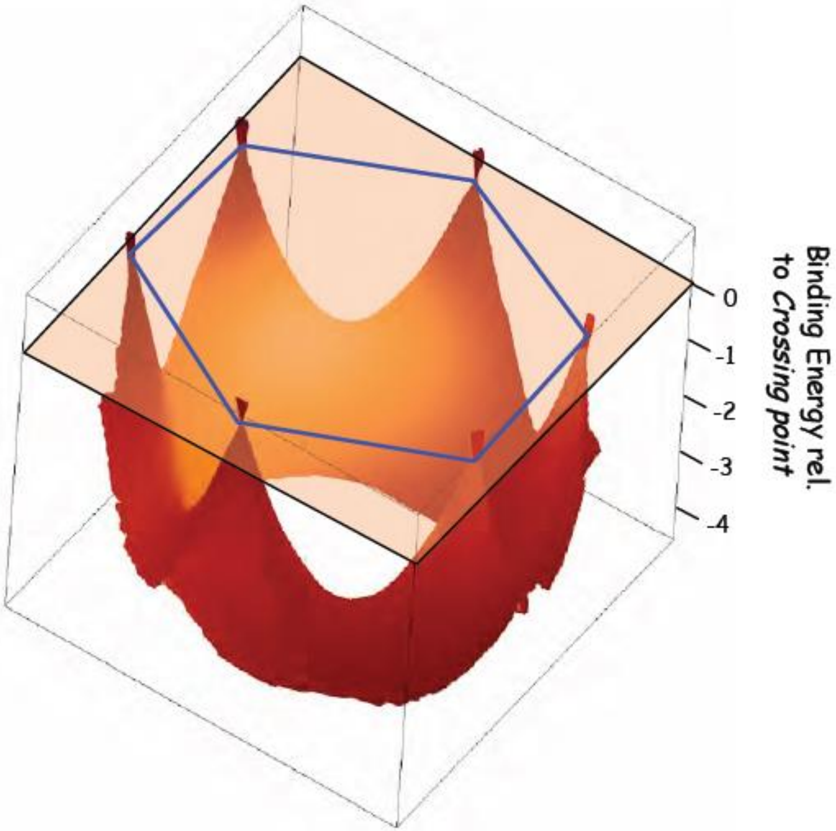


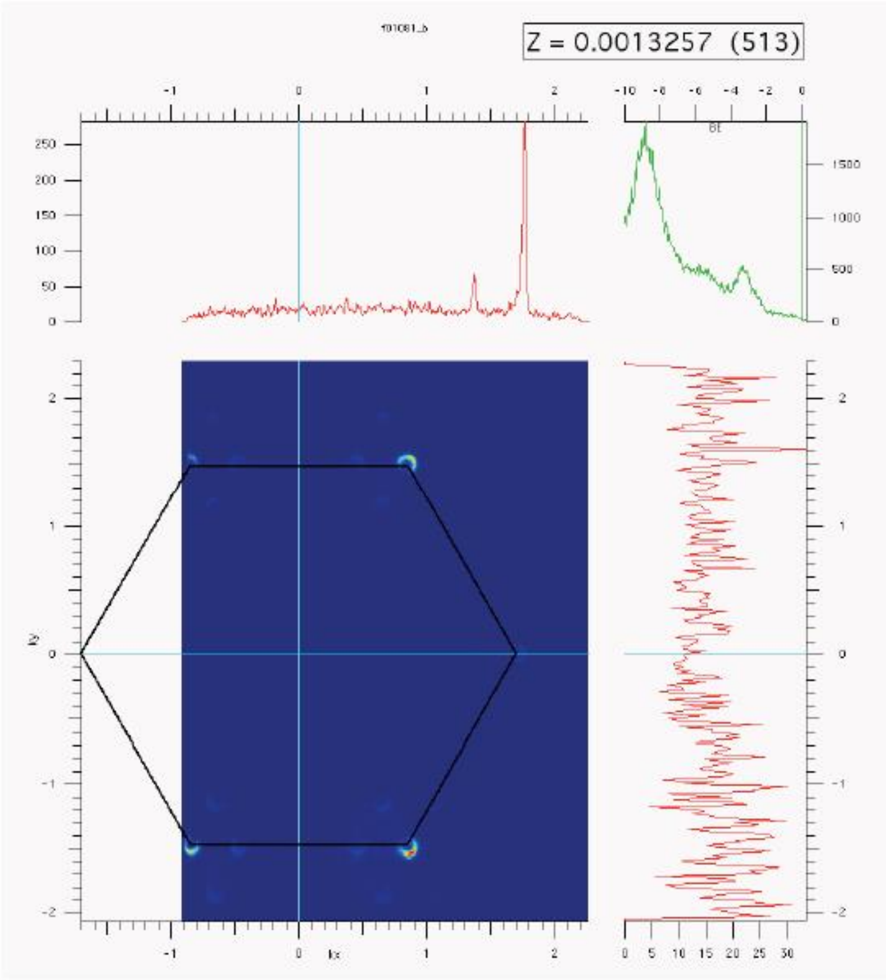




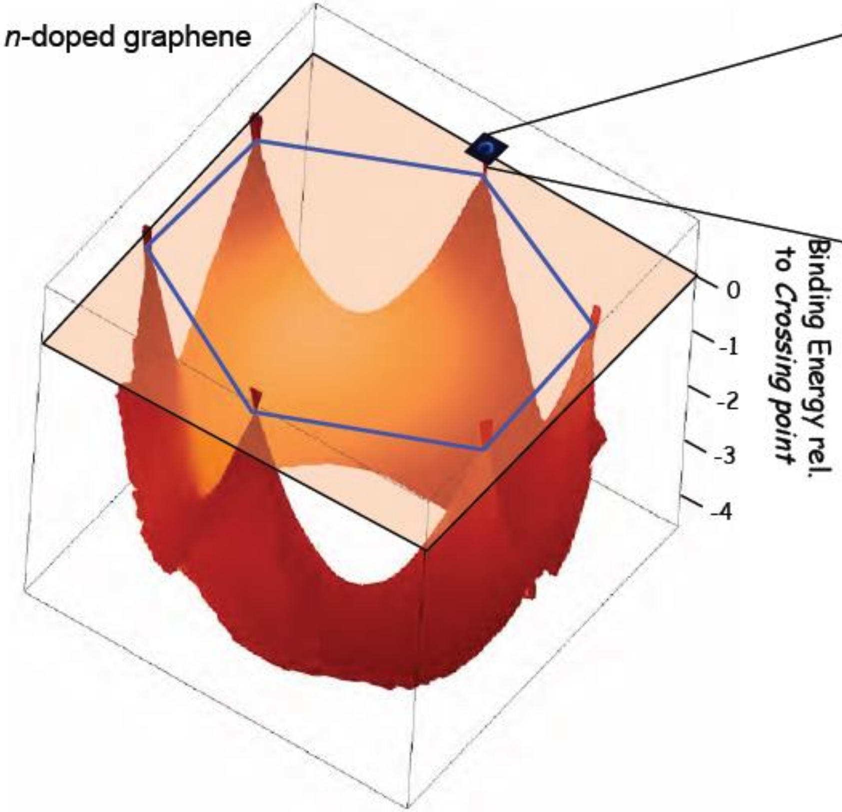
Coletti et al., PRB (2013)

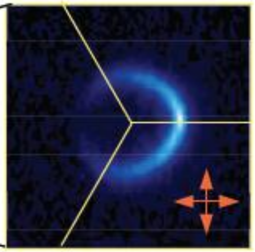
The band structure of graphene





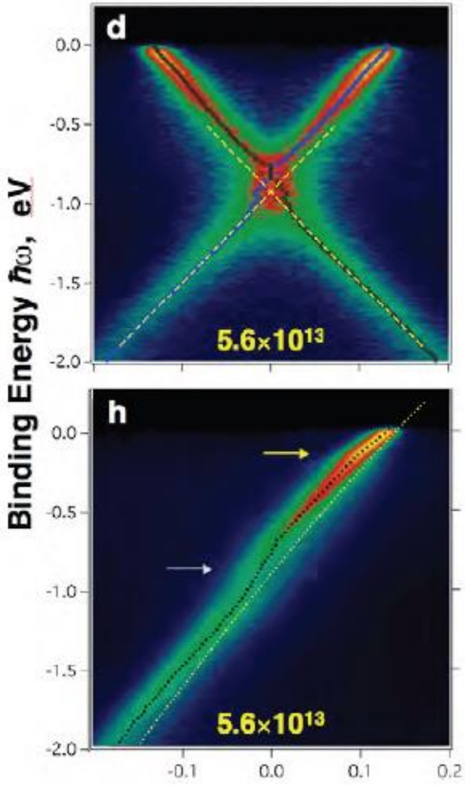
Beyond the one-electron picture





A Cut of the top of the cone is the Fermi surface

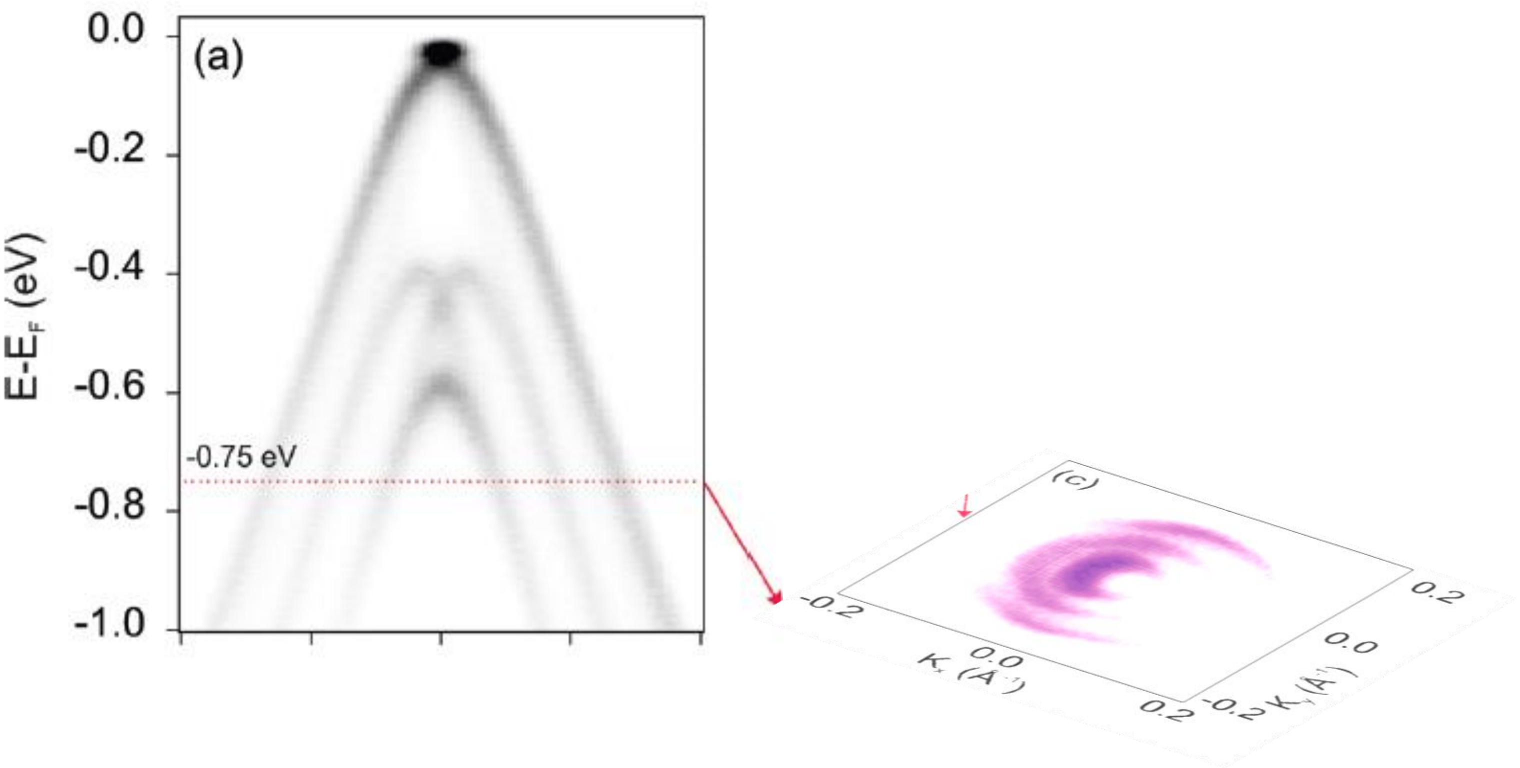
Cuts of the Bandstructure along ↕ and ↔



The bands are not straight!

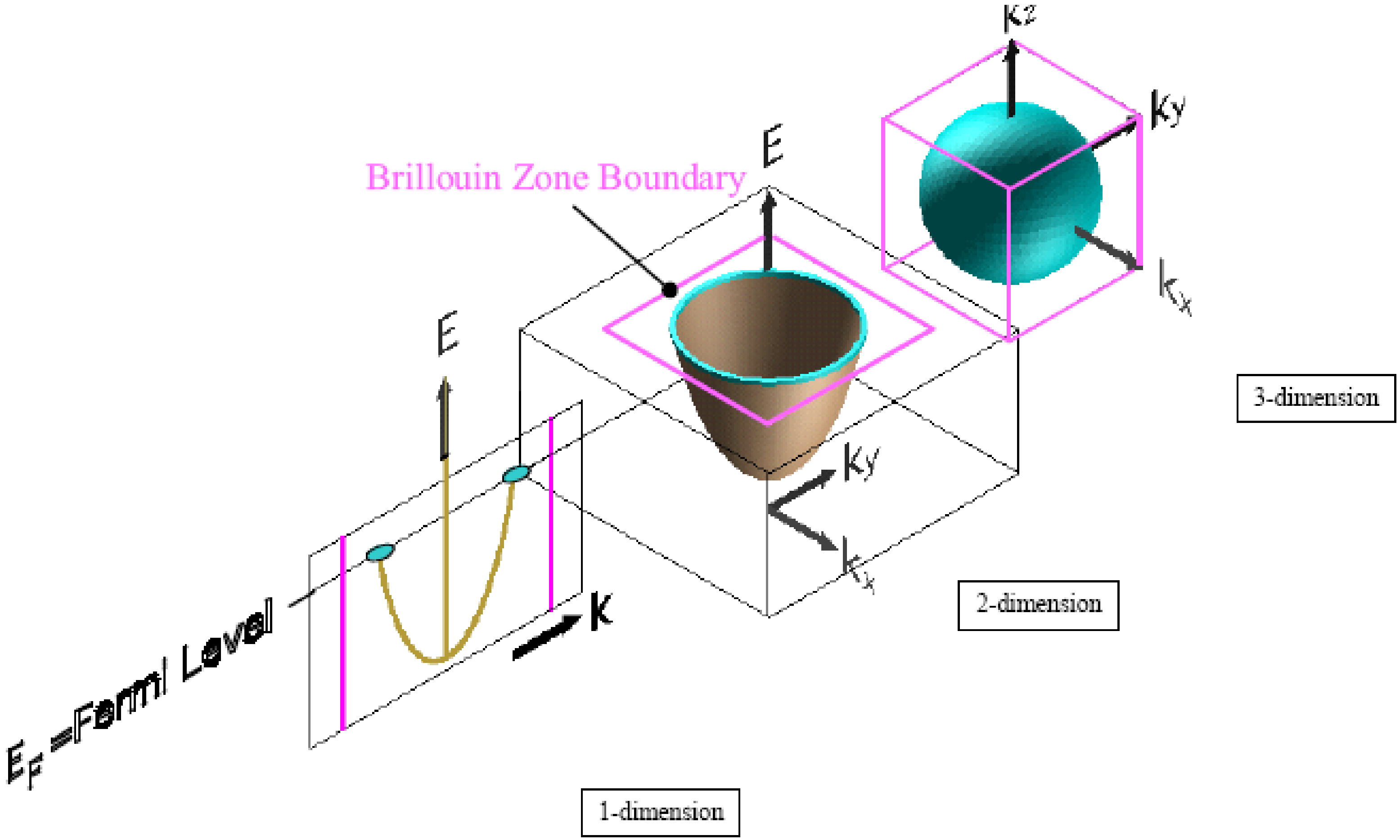
what is happening?

Constant energy mapping

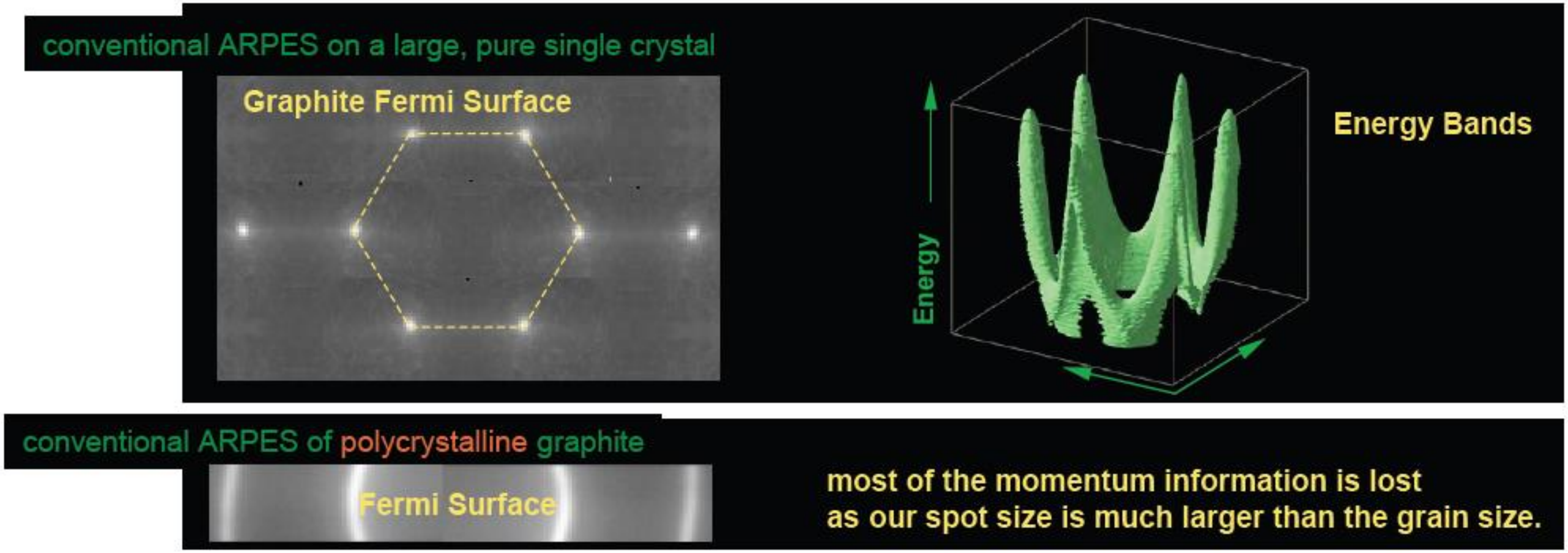


Coletti et al., PRB (2013)

Fermi Surface



Why orientation of solid so important



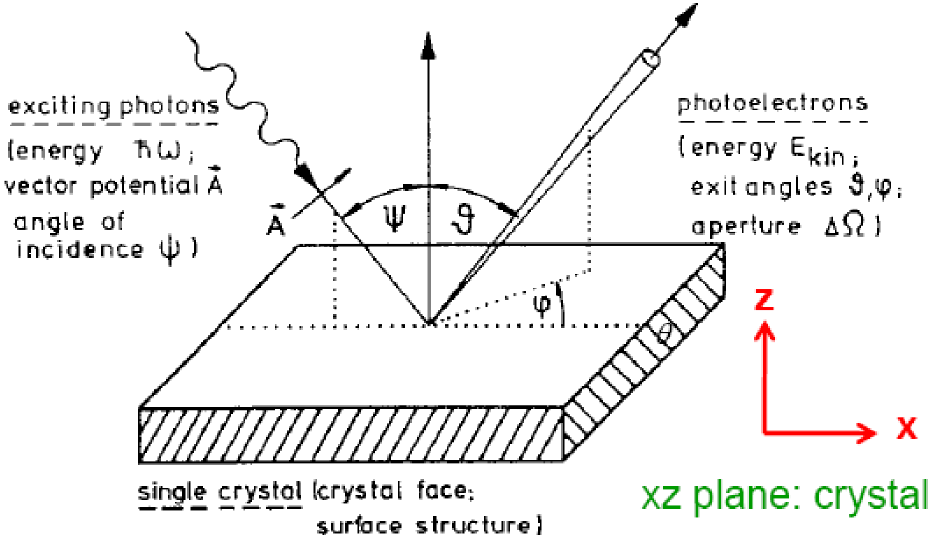
conventional ARPES on a large, pure single crystal

conventional ARPES of polycrystalline graphite

most of the momentum information is lost
as our spot size is much larger than the grain size.

How to probe the electronic structure of solids

Angular Resolved Photoemission Spectroscopy(ARPES)



xz plane: crystal symmetry plane

Electron emission angle: θ

Photon incident angle: ψ, *s*- and *p*-polarization

$$k_{//} = \sqrt{\frac{2m}{\hbar^2}E_k} \cdot \sin\theta$$

$$k_{//}(\text{Å}^{-1}) = 0.5123\sqrt{E_k(eV)} \cdot \sin\theta$$

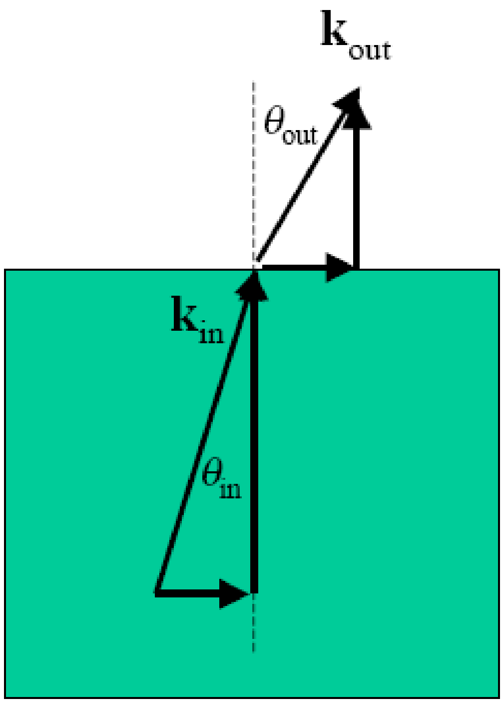
$k_{||}$(inside) = $k_{||}$(outside)

Conservation of liner momentum

Important for 3D and 2D band mapping

$$k_{\perp} = 0.5123\sqrt{(E_{kin}\cos^2\theta + V_0)}$$

Conservation of linear momentum parallel to the surface



Kinematic relations

$$k_{out} = \sqrt{\frac{2m}{\hbar^2} E_{kin}}$$

$$k_{in} = \sqrt{\frac{2m}{\hbar^2} (E_{kin} + V_0)}$$

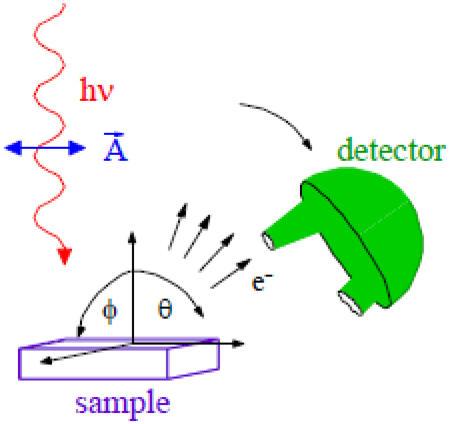
$$k_{out,\|} = k_{in,\|} \equiv k_{\|}$$

"Snell's Law"

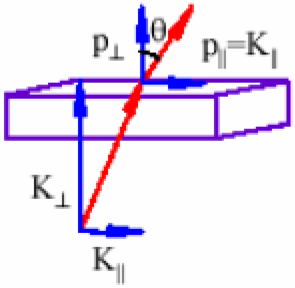
$$k_{\|} = \sin\theta_{out} \sqrt{\frac{2m}{\hbar^2} E_{kin}} = \sin\theta_{in} \sqrt{\frac{2m}{\hbar^2} (E_{kin} + V_0)}$$

Critical angle for emission

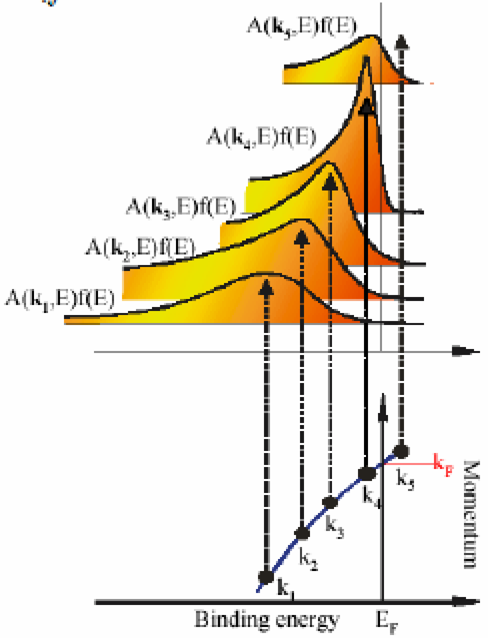
$$(\sin\theta_{out})_{\max} = \sqrt{\frac{E_{kin}}{E_{kin} + V_0}}$$



Electron momentum
Parallel to the surface is
conserved



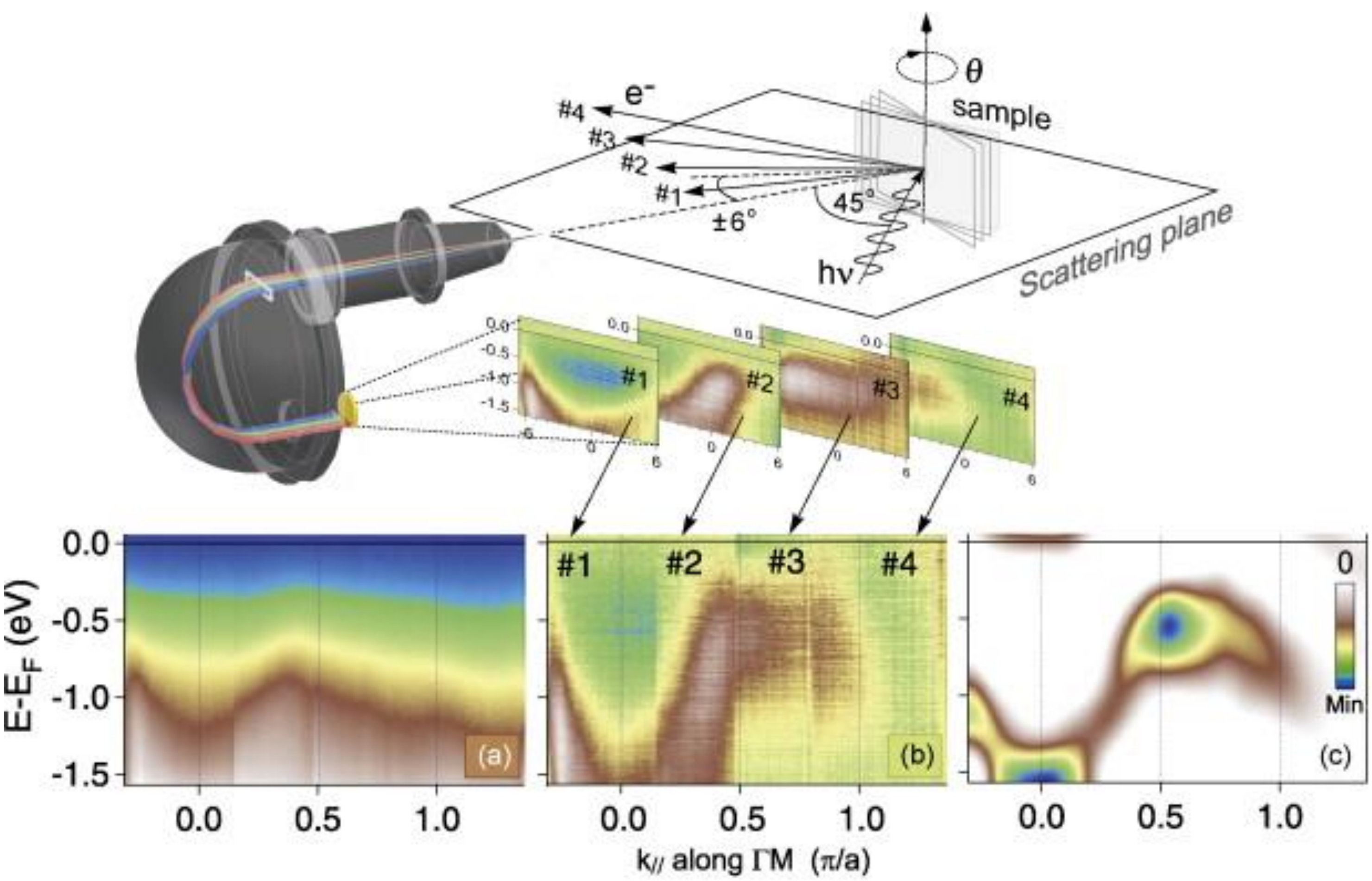
$$\text{Intensity} \propto \sum_{i,f} \left|\langle f|\vec{p}\bullet\vec{A}|i\rangle\right|^2 A(\vec{k},E)f(E)$$



$$\boxed{\begin{aligned} k_\perp &= 0.5123\sqrt{(E_{kin}\cos^2\theta + V_0)} \\ k_{//} &= 0.5123\sqrt{E_{kin}}\sin\theta \end{aligned}}$$

- Low photon energy provides better momentum resolution, but the covering range of BZ is also small.

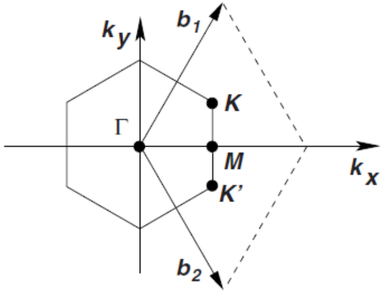
- We expect to study the electronic structure of solids at VUV region (10 eV~ 100 eV).



Krempasky et al., JESRP (2010)

$$k_{\perp} = 0.5123\sqrt{(E_{kin}\cos^{2}\theta + V_{0})}$$

$$k_{//} = 0.5123\sqrt{E_{kin}}\sin\theta$$



Lattice constant :
Graphene : 2.46 Å
Cu(111) : 2.08 Å
MoS_2 : 3.12 Å

- ✓ Assume the work function is 4.3 eV , please estimate the largest covering range of BZ at the Fermi level at 6 eV, 21.2 eV, 50 eV, 100 eV and 500 eV photon energy.
  Answer: 0.67 $Å^{-1}$, 2.11 $Å^{-1}$,3.46 $Å^{-1}$, 5.01 $Å^{-1}$, 11.4 $Å^{-1}$

- ✓ The angle between the incident beam and spectrometer is 50 degree, please estimate the covering range of BZ at 6 eV, 21.2 eV, 50 eV, 100 eV and 500 eV photon energy.
  Answer: 0.51 $Å^{-1}$, 1.61 $Å^{-1}$, 2.65 $Å^{-1}$, 3.83 $Å^{-1}$, 8.45 $Å^{-1}$

- ✓ The BZ in single layer graphene, the magnitude of ΓK is 1.703 $Å^{-1}$. If you plan to probe the band structure of graphene near the K-point, what are the required angle between the surface normal and spectrometer at 6 eV, 21.2 eV, 50 eV, 100 eV and 500 eV photon energy?
  Answer: mission impossible, 54 degree, 29.5 degree, 19.9 degree, 8.6 degree

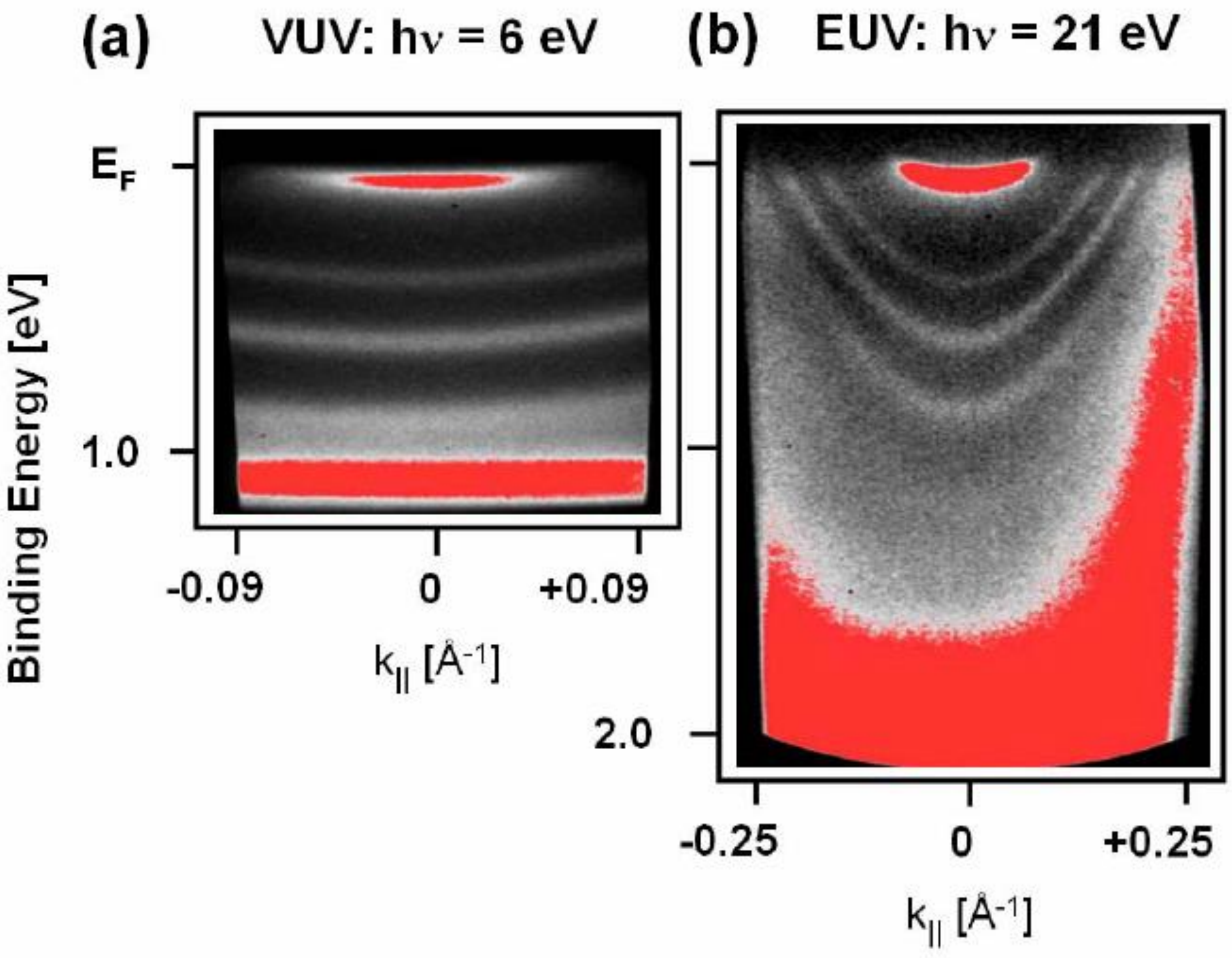
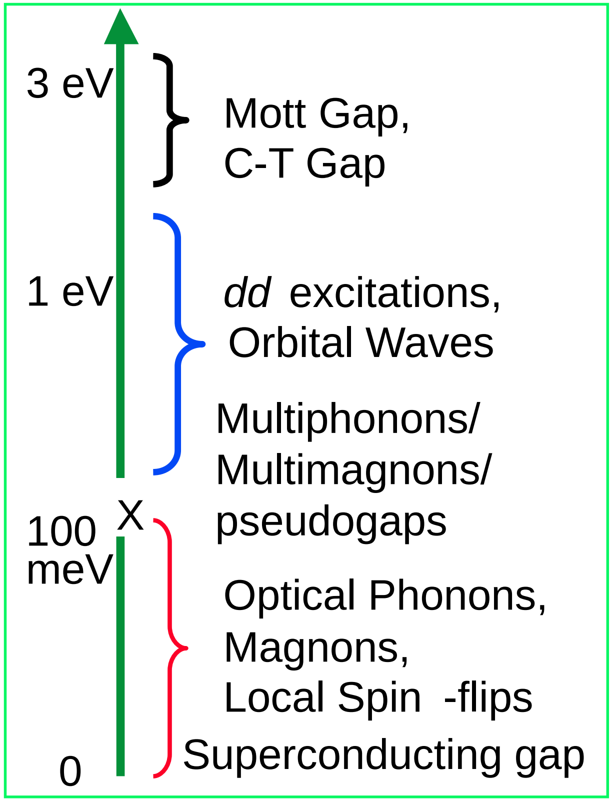


Figure 3. Angle-resolved photoemission spectra of the Shockley surface state and a series of quantum well states of 40 ML Ag/Cu(111) recorded at photon energies of 6 eV (fourth harmonic of the Ti:sapphire oscillator, 4(a)) and 21.22 eV (He I line of a discharge VUV lamp, 4(b)), respectively.

S Mathias et al., J. Physics : Conference series (2009)

- You need to understand the crystal structure of solids.
- The sample characterization, such as the orientation and crystalline, is quite important before the experiment.
- XRD, Laue diffraction and LEED are required.

Energy scale and important excitations



3 eV

Mott Gap,
C-T Gap

1 eV

dd excitations,
Orbital Waves

Multiphonons/
Multimagnons/
pseudogaps

X

100 meV

Optical Phonons,
Magnons,
Local Spin -flips

Superconducting gap

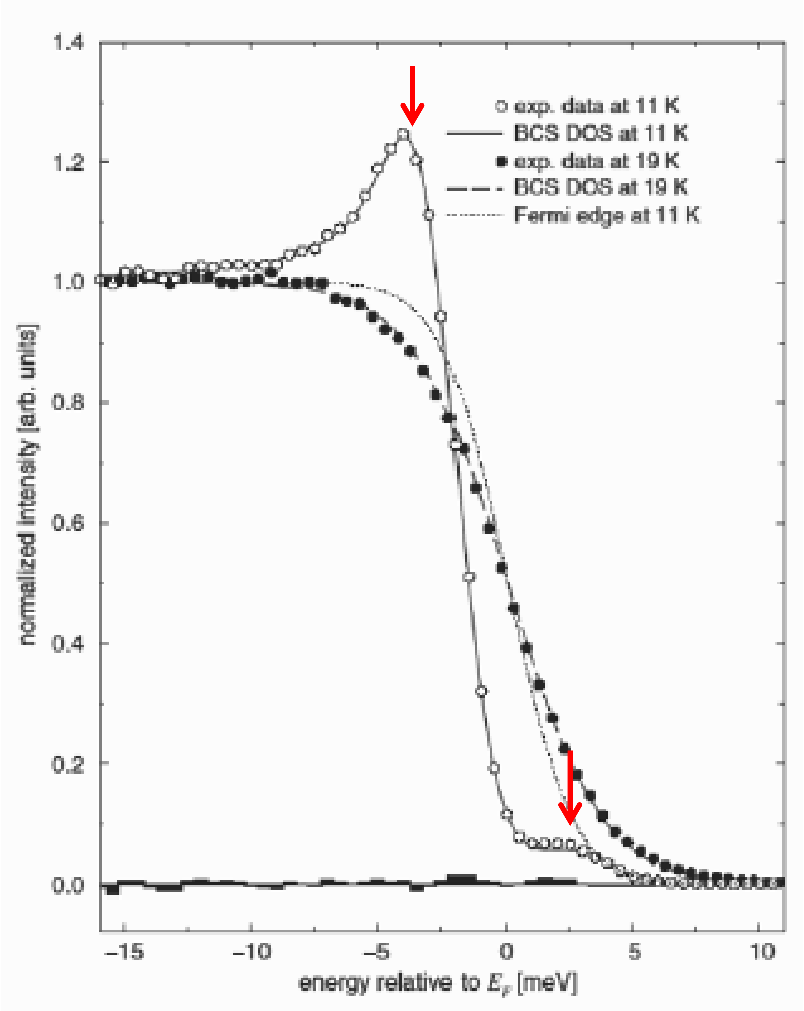
0

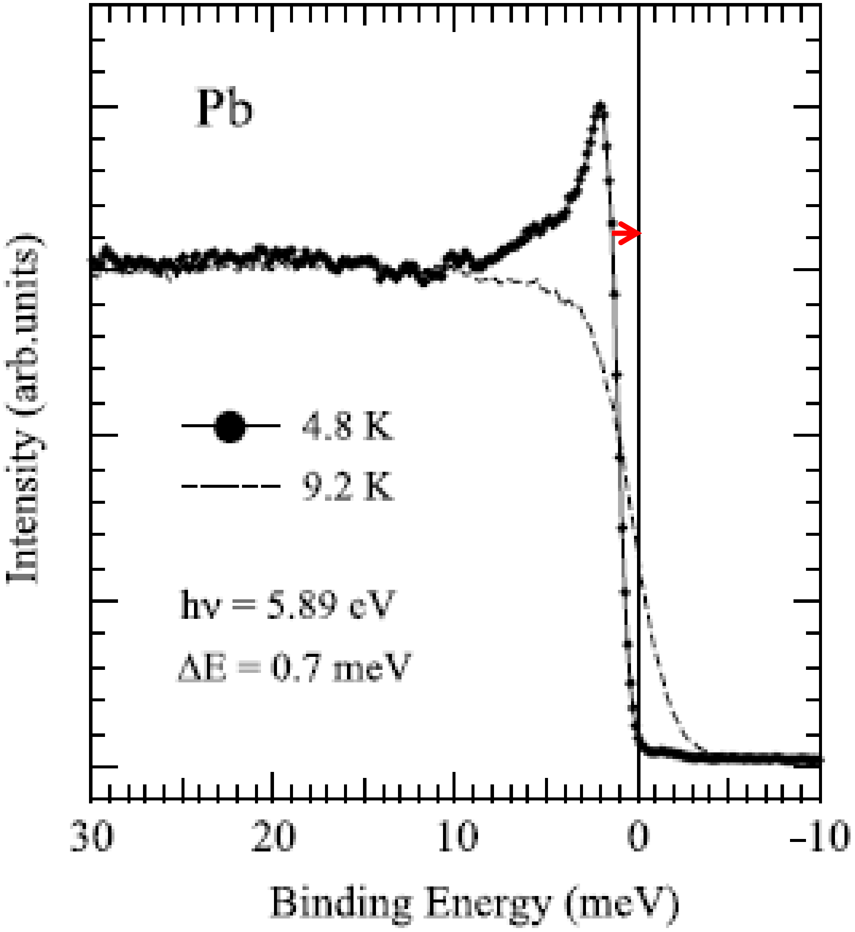
- Superconducting gap ~ 1 – 100meV
- Optical Phonons: ~ 40 - 200 meV
- Magnons: ~ 10 meV - 40 meV
- Pseudogap ~ 30-300 meV
- Multiphonons and multimagnons ~ 50-500 meV
- Orbital fluctuations (originated from optically forbidden *d-d* excitations): ~ 100 meV - 1.5 eV

Requirement: High Energy Resolution with High Intensity

Z. Hussain, ALS summer school

Superconducting gap





Hufner, Very high resolution photoelectron spectroscopy

Light sources and terminology

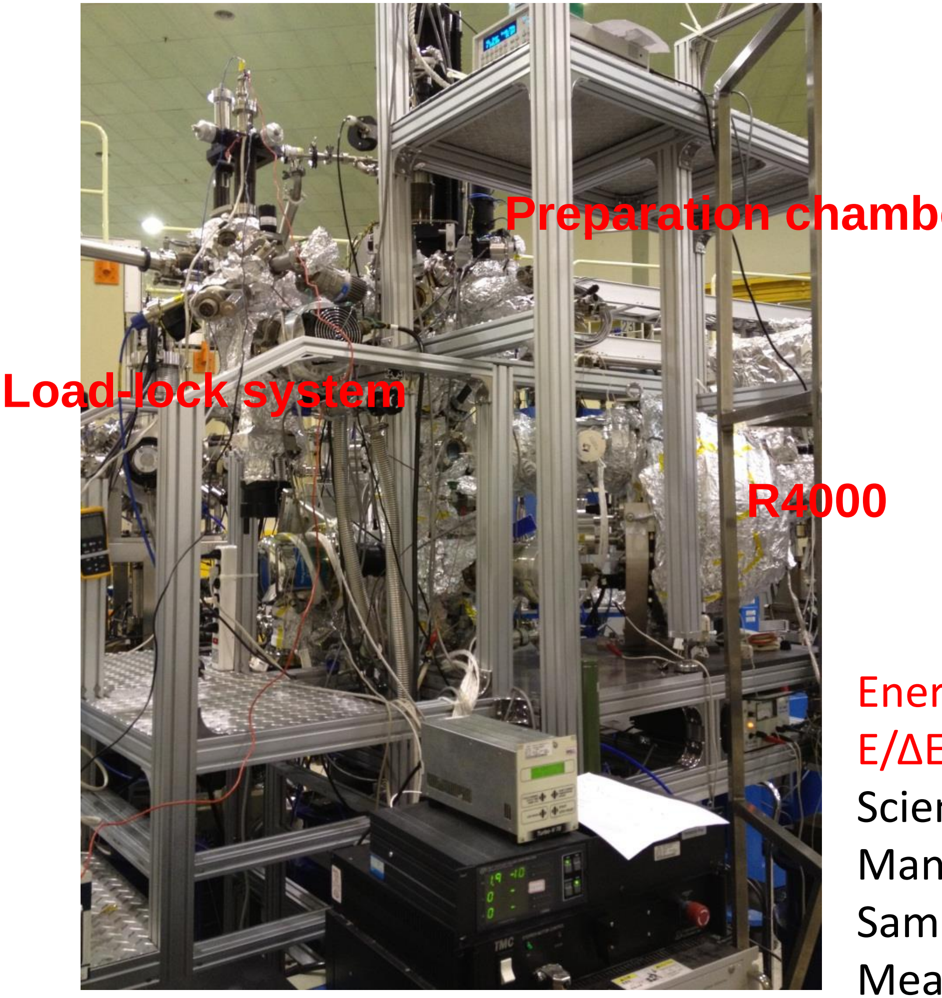
- **Ultraviolet Photoemission Spectroscopy (UPS)**
  - UV He lamp (21.2 eV, 40.8 eV)
  - Laser : 6 eV (BBO), 8 eV (KBBF), 11 eV (gas cell) or HHG (High harmonic generation)
  - Valence band PES, direct electronic state info.

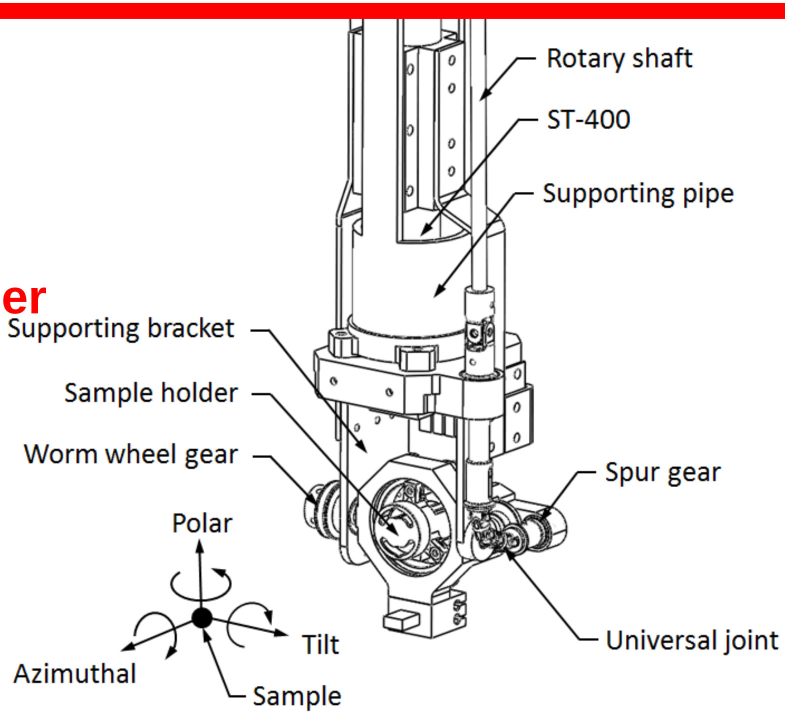
- X-ray Photoemission Spectroscopy (XPS)

  (Electron Spectroscopy for Chemical Analysis) (ESCA)
  - X-ray gun (Al: 1486.6 eV, Mg: 1253.6 eV)
  - core level PE, indirect electronic state info
  - chemical analysis

- **Synchrotron radiation**
  - continuous tunable wavelength
  - valance band and core level

Current status of ARPES end station at TLS





Energy range : 5 eV~120 eV

E/ΔE: 100,000 at 16 eV and 64 eV

Scienta R4000 analyzer

Manipulator : 6-axis motorized manipulator

Sample Preparation: *in-situ* cleave, thin film growth

Measurement temperature range : 10 K~ 350 K

Base pressure : 4.5x10^{-11} torr

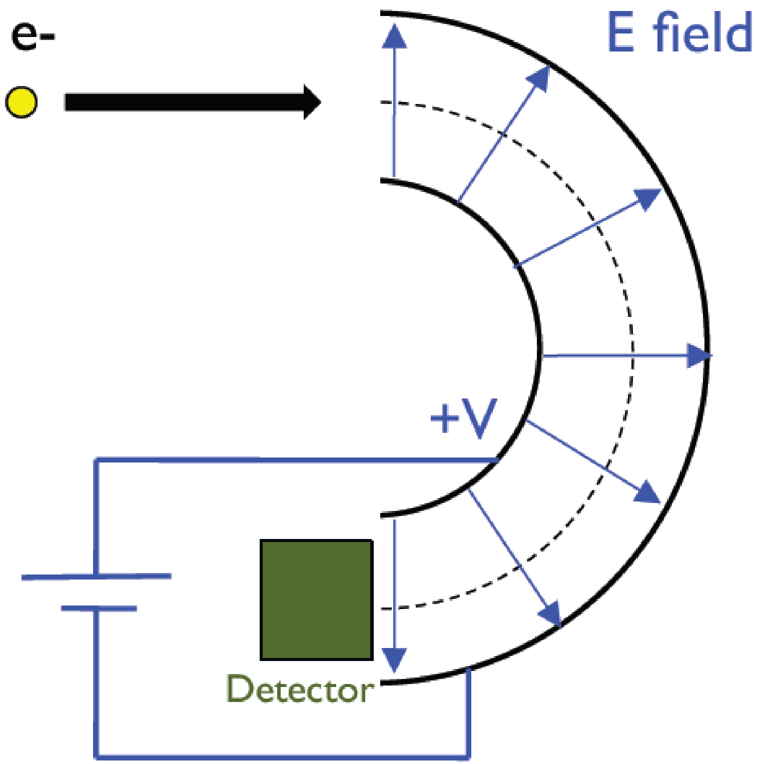
Basic principles of electron spectrometers / analyzers

- typical energy resolution ~ 0.1 to 0.01 eV. Best systems are ~ 0.001 eV.

- most electron analyzers operate using electrostatic optics (magnetic fields harder to control)

- detectors are typically channel plates (electron multipliers) with a CCD or current pulse output

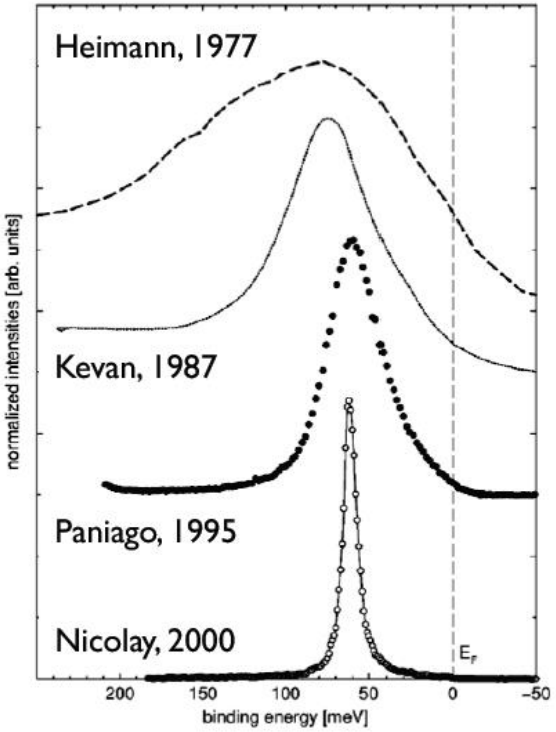
- detecting & manipulating electrons is relatively easy



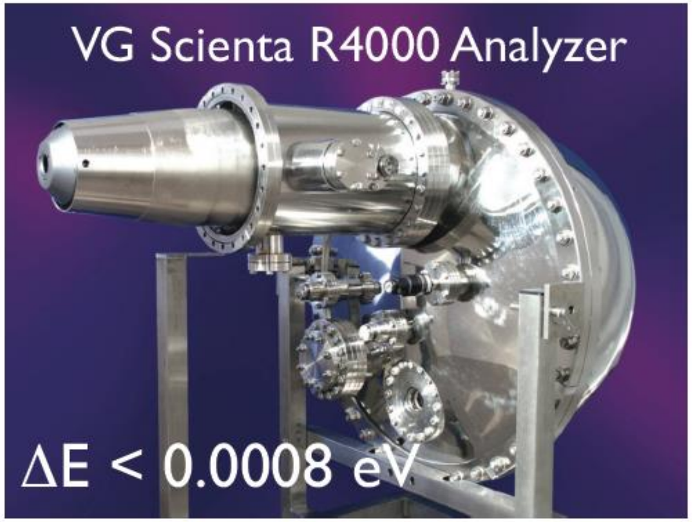
Kyle Shen, IGERT Lecture 2008

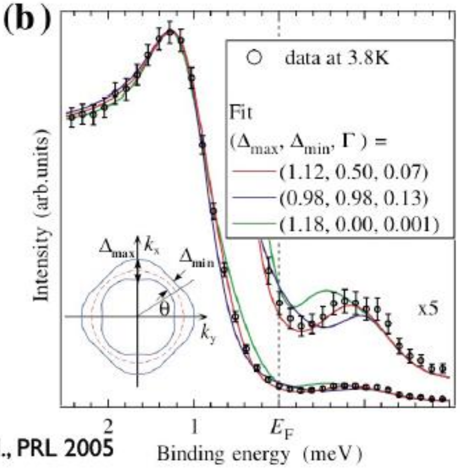
The state-of-the-art in electron spectroscopy

Evolution of instrumental resolution over time



F. Reinert *et al.*, PRB (2001)





T. Kiss et al., PRL 2005

Kyle Shen, IGERT Lecture 2008

Early ARPES experimental result

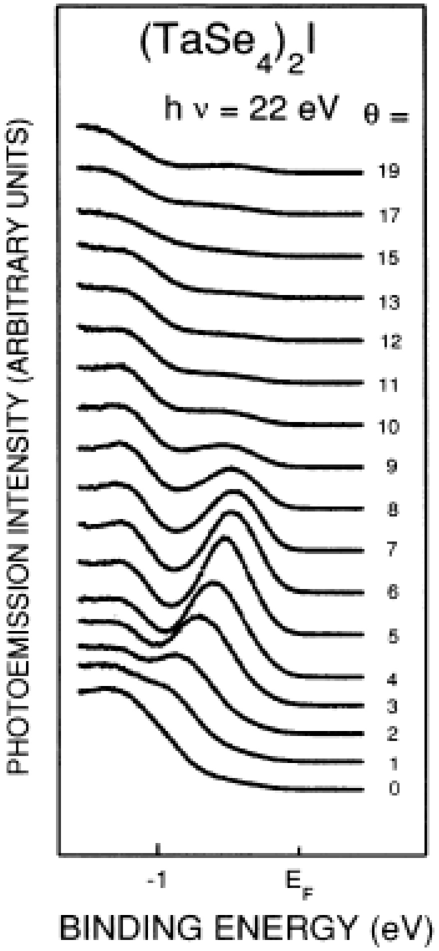


FIG. 1. A series of high-energy-resolution angle-resolved photoemission spectra, taken along the direction of the sample and for different values of the azimuthal angle.

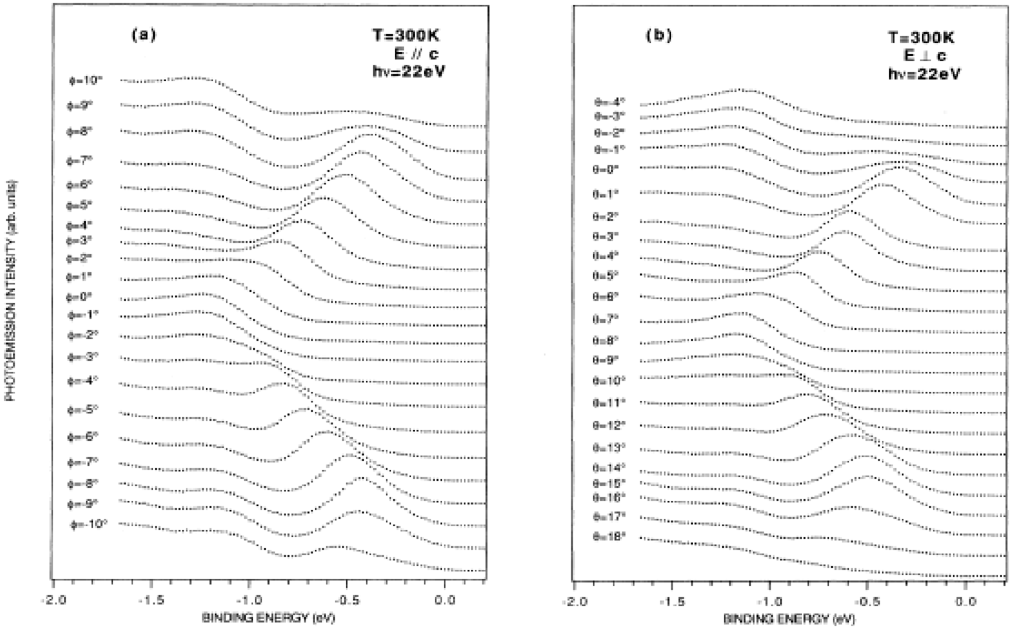
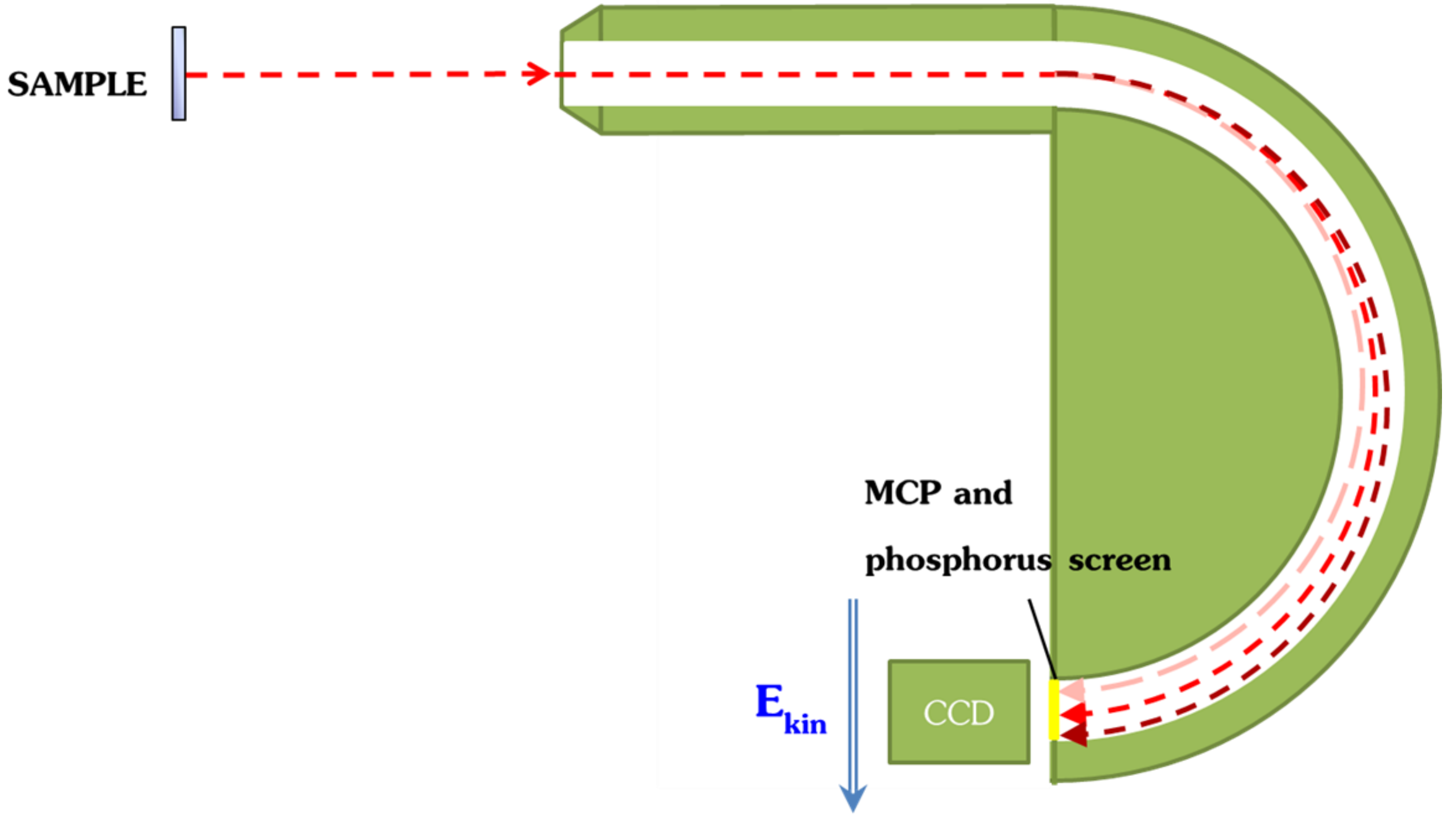
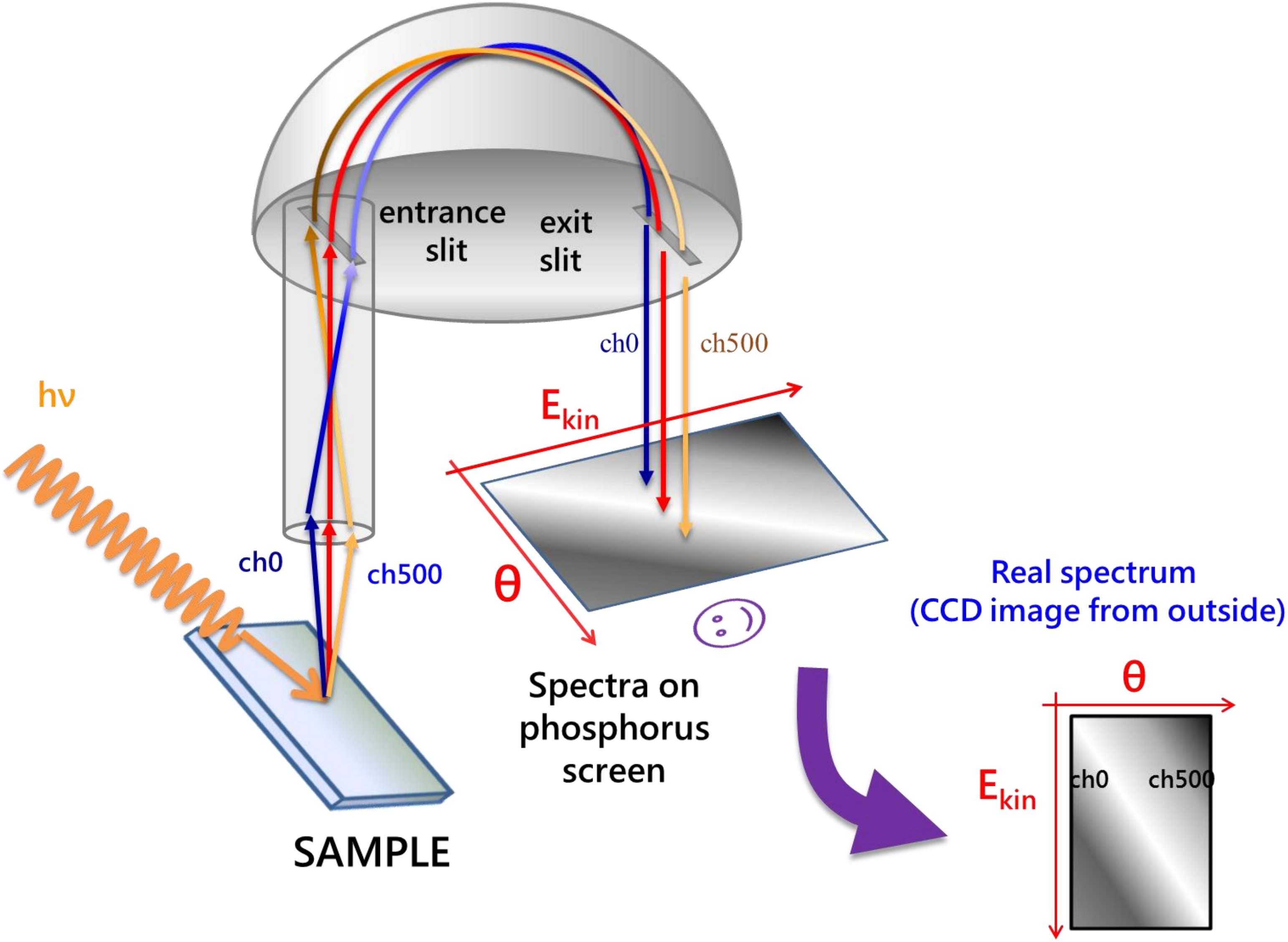


FIG. 1. Angle-resolved photoemission spectra taken using 22-eV photon energy, at room temperature, for photon electric field (a) parallel and (b) perpendicular to the conducting axis. The emission angle is along the conducting axis, with the surface normal defined as 0°.

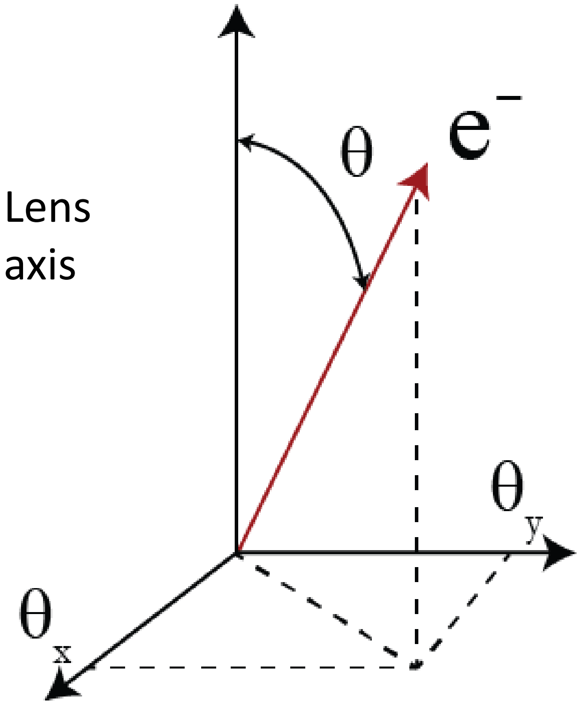
Now a 2-D detector with ± 30° and 0.1° angular resolution can be obtained.

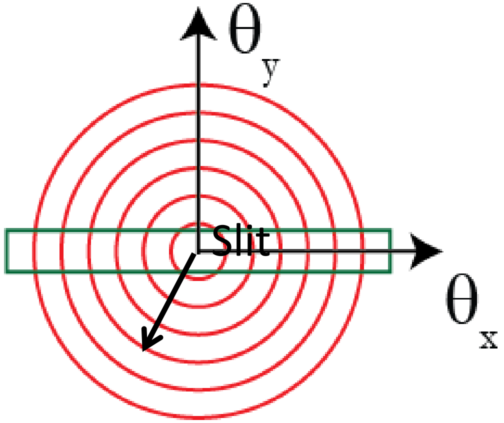
SCIENTA R4000 Side View




hν
ch0
ch500
SAMPLE
entrance slit
exit slit
ch0
ch500
E_{kin}
θ
Spectra on phosphorus screen
Real spectrum
(CCD image from outside)
θ
E_{kin}
ch0
ch500

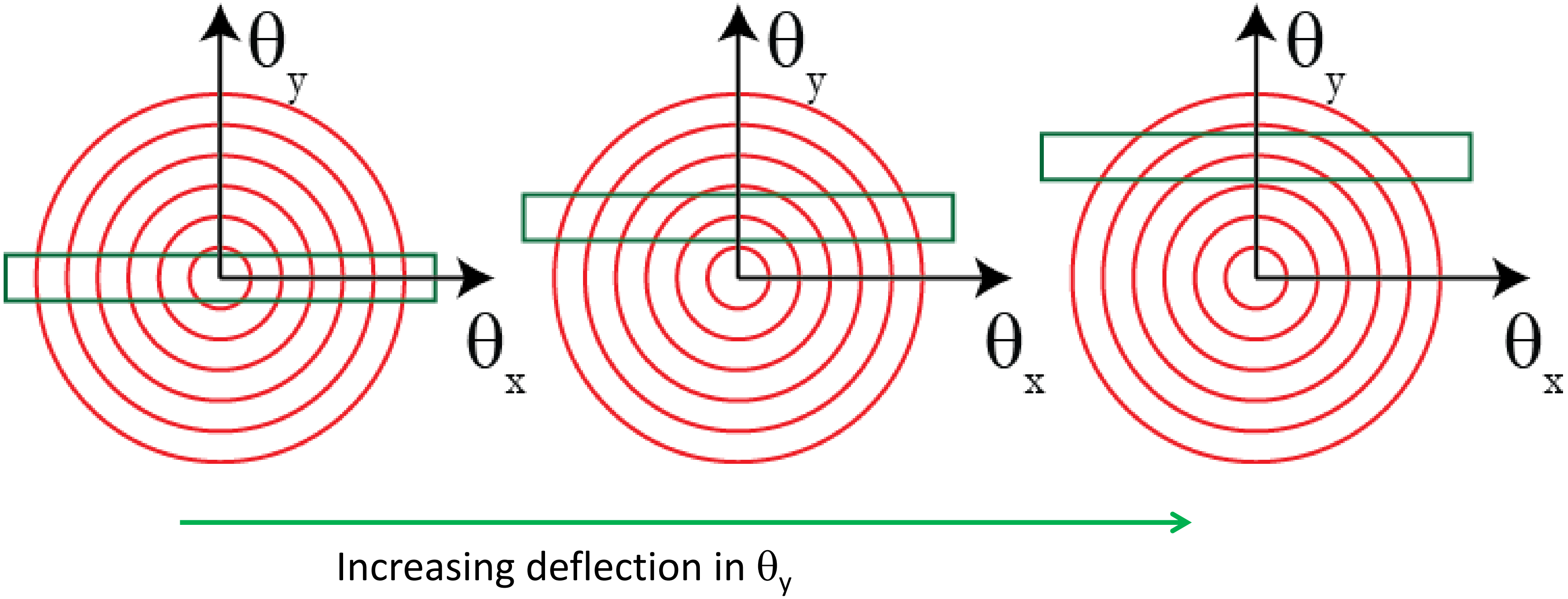
- Angle-resolved spectrometers collects electrons as a function of kinetic energy and emission angle
- Due to the slit, only angles along one axis (q_x) can be detected simultaneously



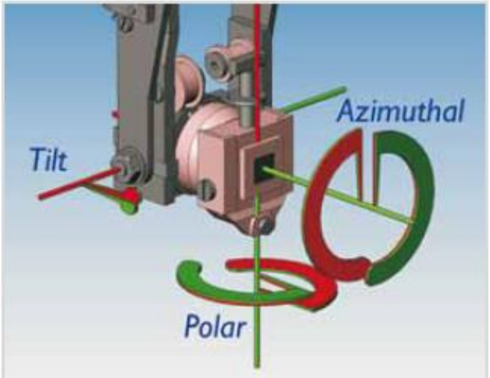


Constant energy mapping for ARPES Scan

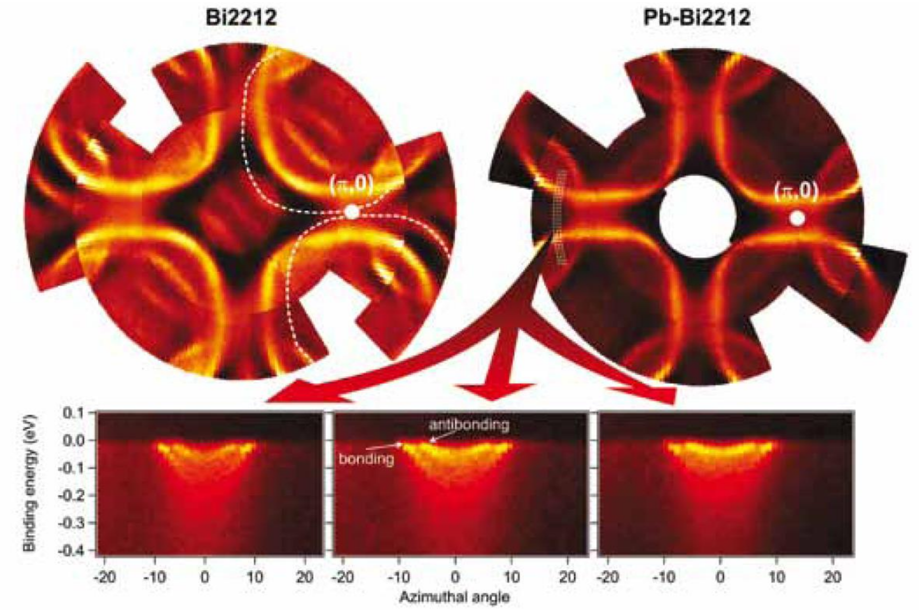
- Deflection can also be done in θ_y
- This enables **full cone detection**, $0<\theta<15°$, **without sample rotation**



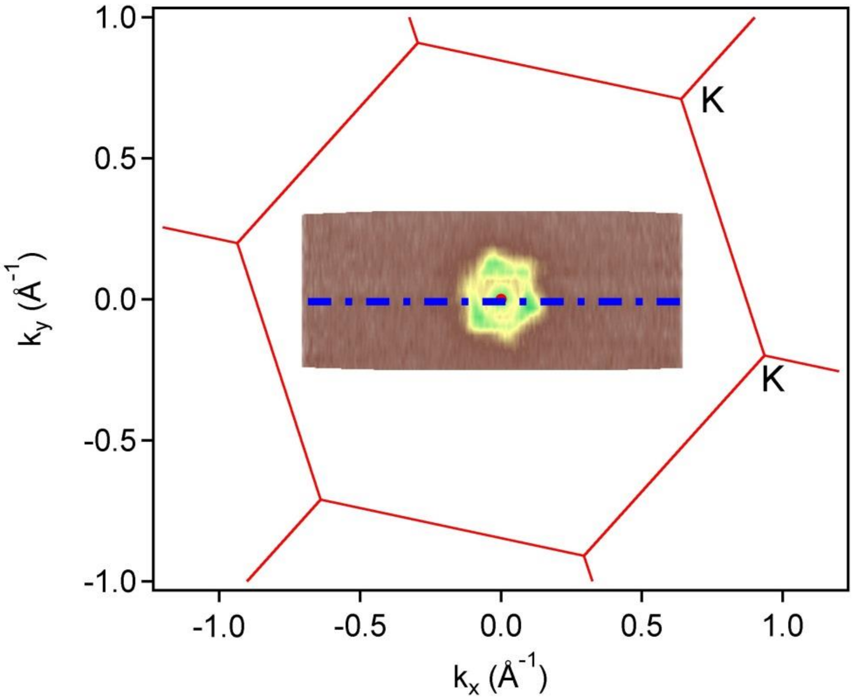
Angle is the soul of ARPES: Band mapping



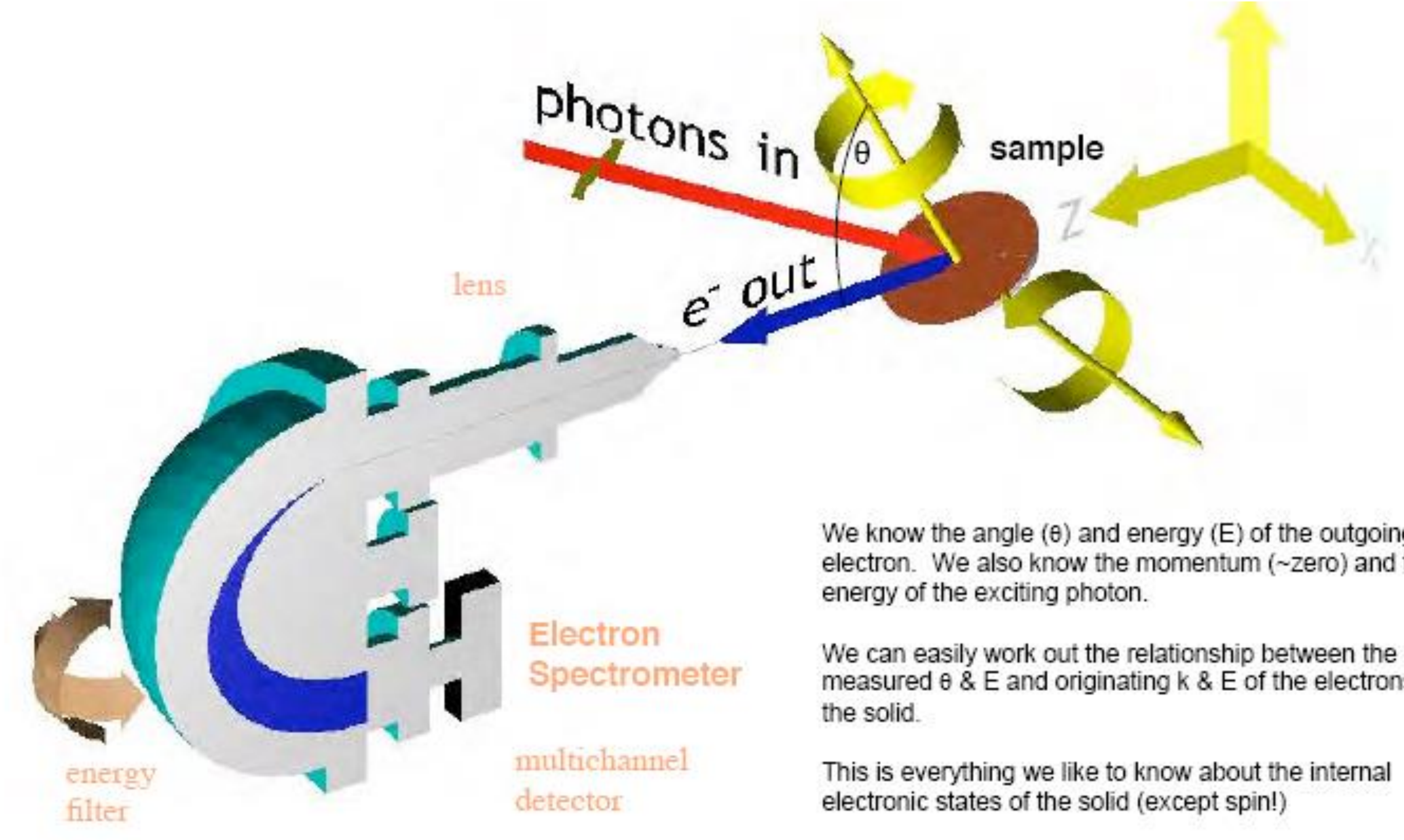
Azimuthal angle scan



Tilt angle scan



Experimental geometry



We know the angle (θ) and energy (E) of the outgoing electron. We also know the momentum (~zero) and the energy of the exciting photon.

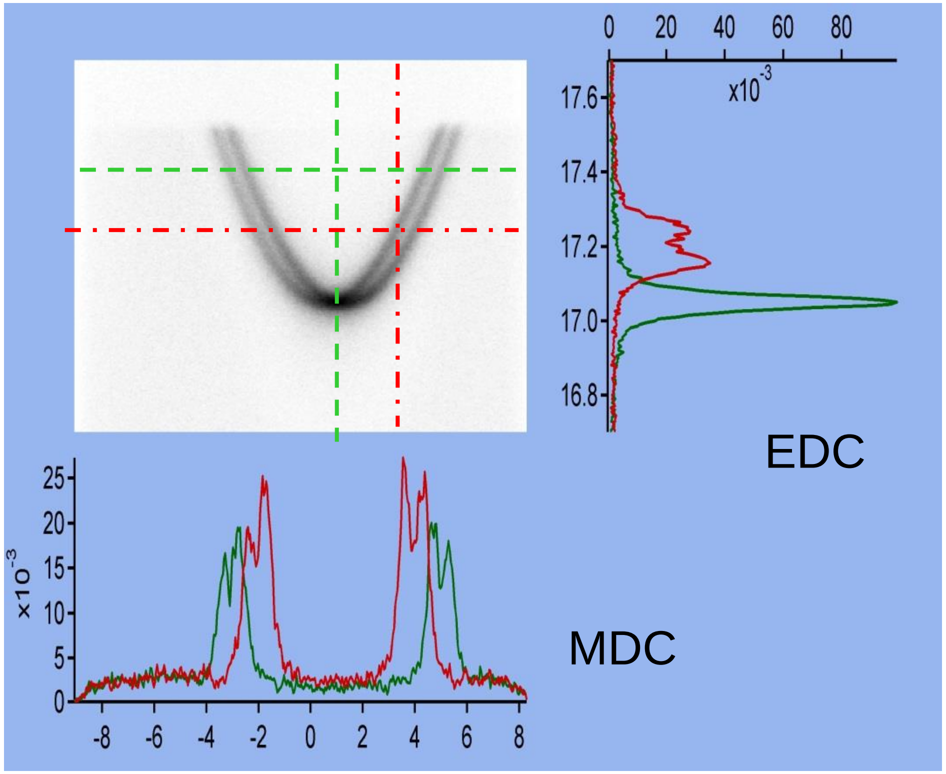
We can easily work out the relationship between the measured θ & E and originating k & E of the electrons in the solid.

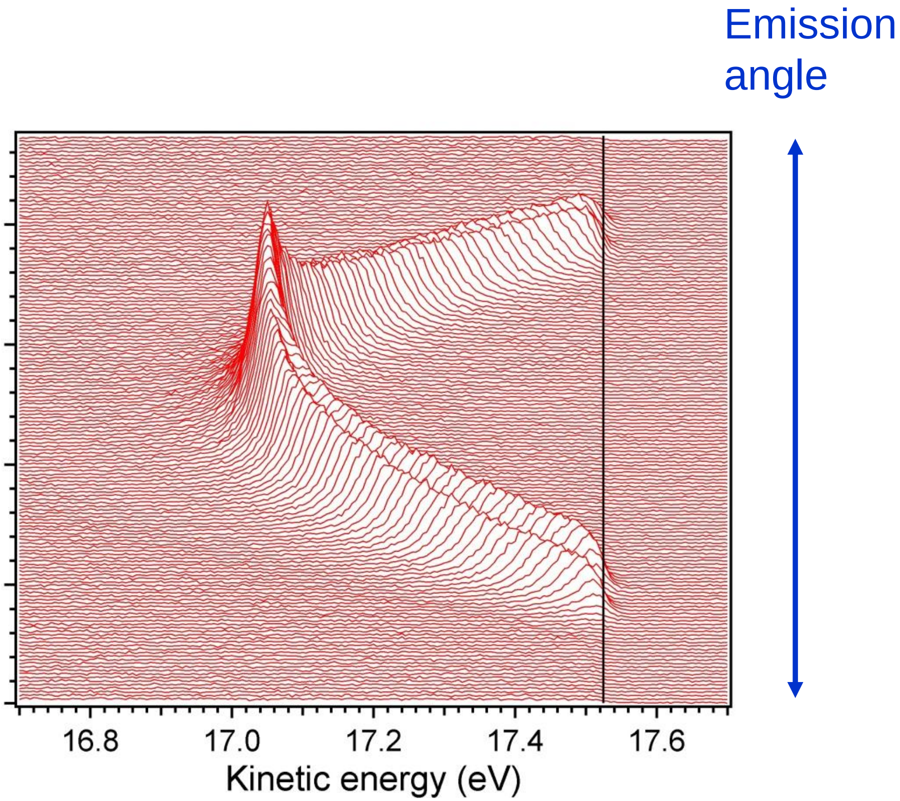
This is everything we like to know about the internal electronic states of the solid (except spin!)

Eli Rotenberg, ALS summer school

Typical Experimental Result

Accumulate spectra of Rashba effect on Au(111) as the angle is scanned

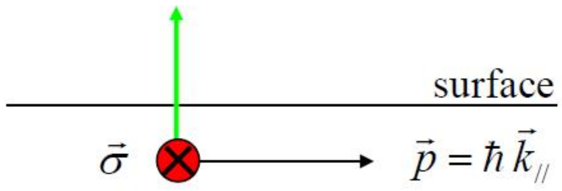




Au(111) : The inversion symmetry is broken at the surface

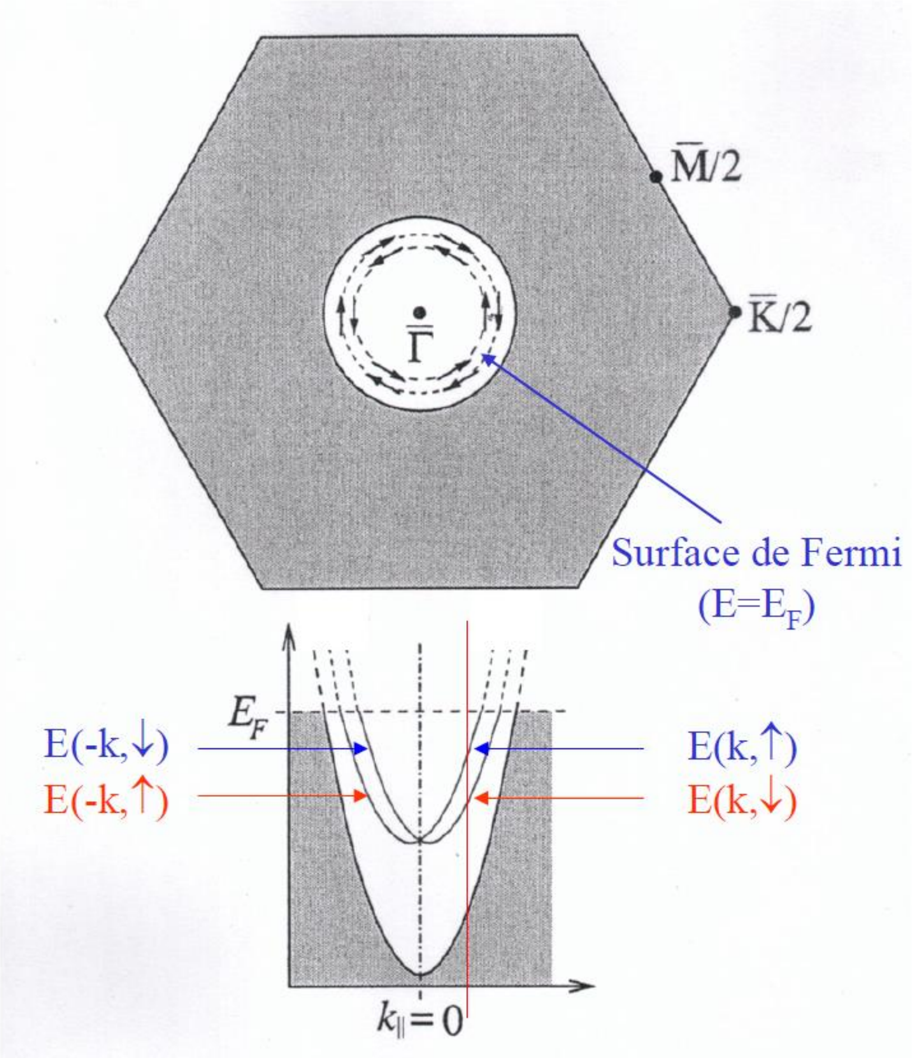
$$H_{so} = \frac{\hbar}{4m^2c^2}(\vec{\nabla}V \wedge \vec{p}).\vec{\sigma}$$

$$\vec{\nabla}V = \frac{dV}{dz}\vec{e}_z$$

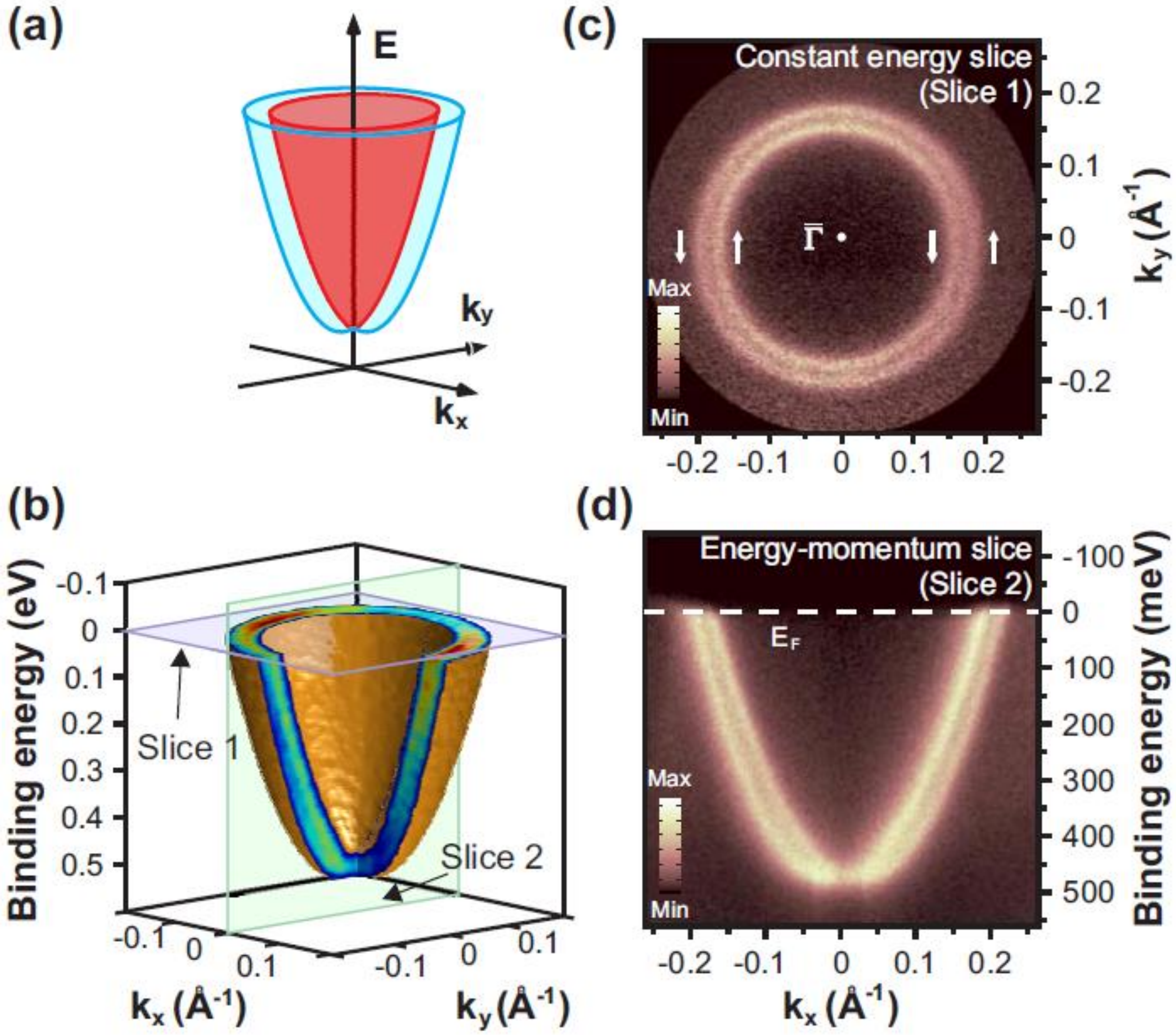


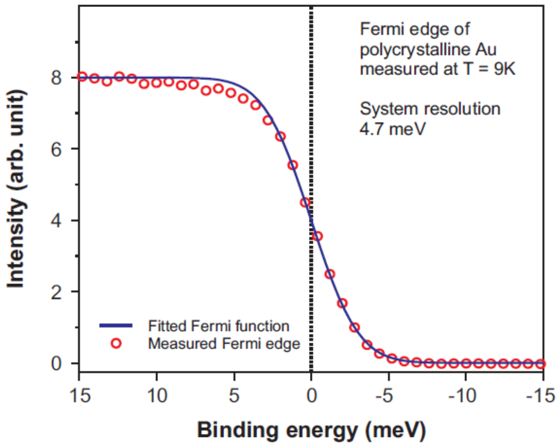
In a nearly free electron picture,
$\vec{\nabla}V$ is perpendicular to the surface

➡ two spin polarized SS bands

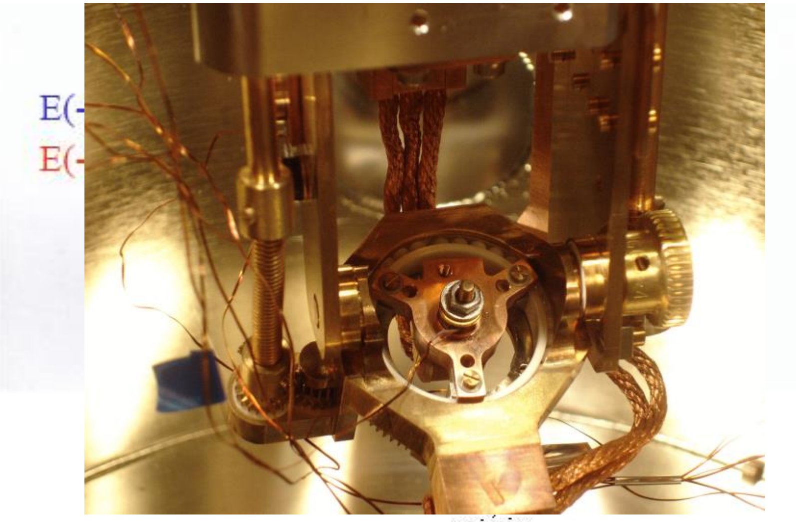


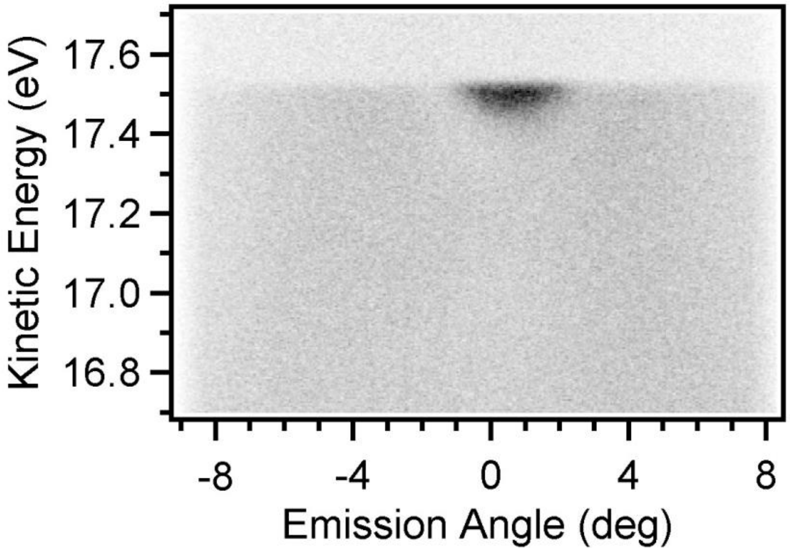
Surface state of Au(111)

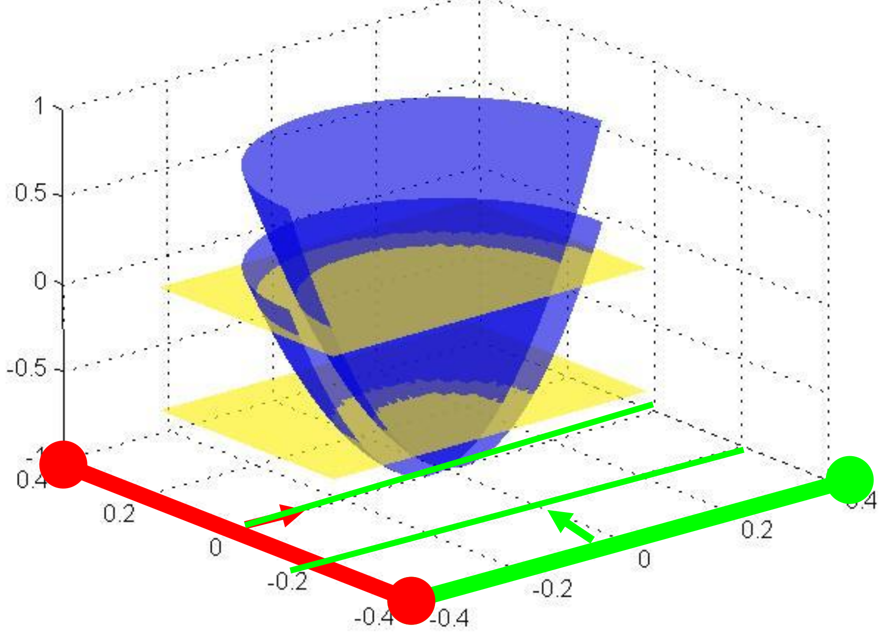


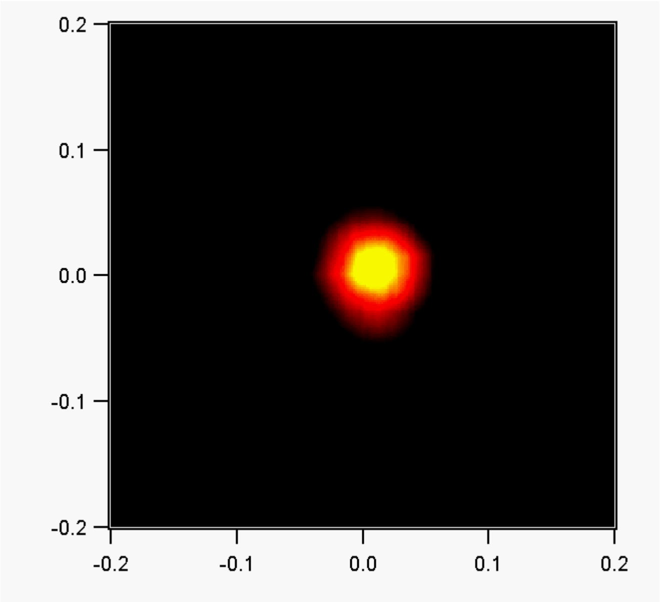


Rashba effect on Au(111)



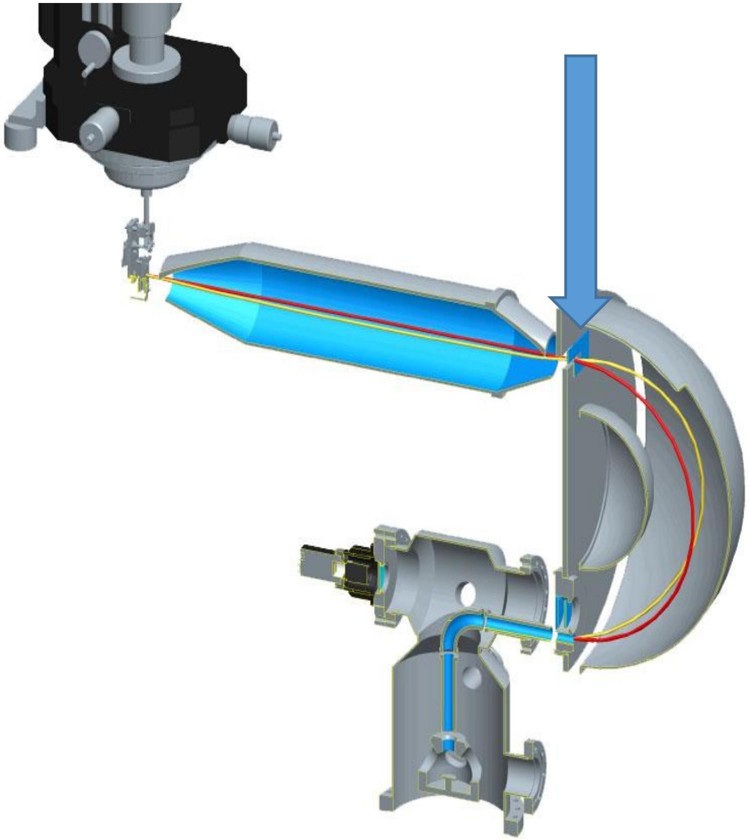




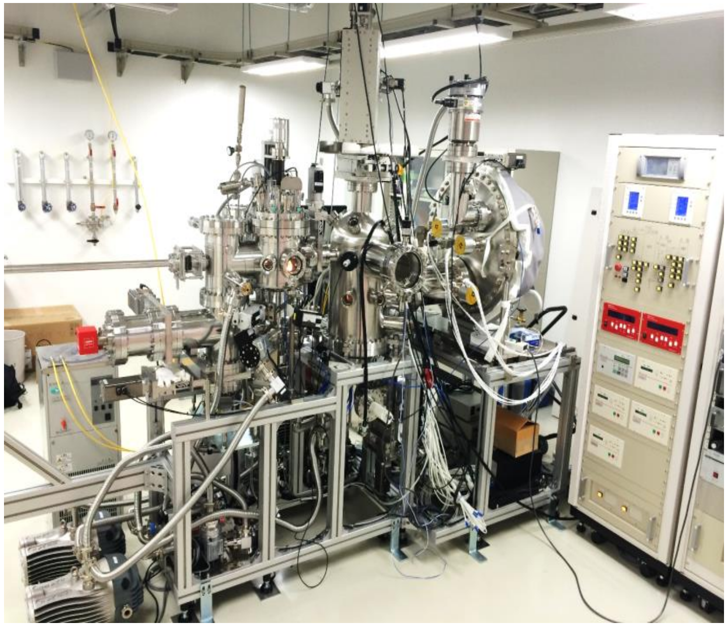


Deflector analyser

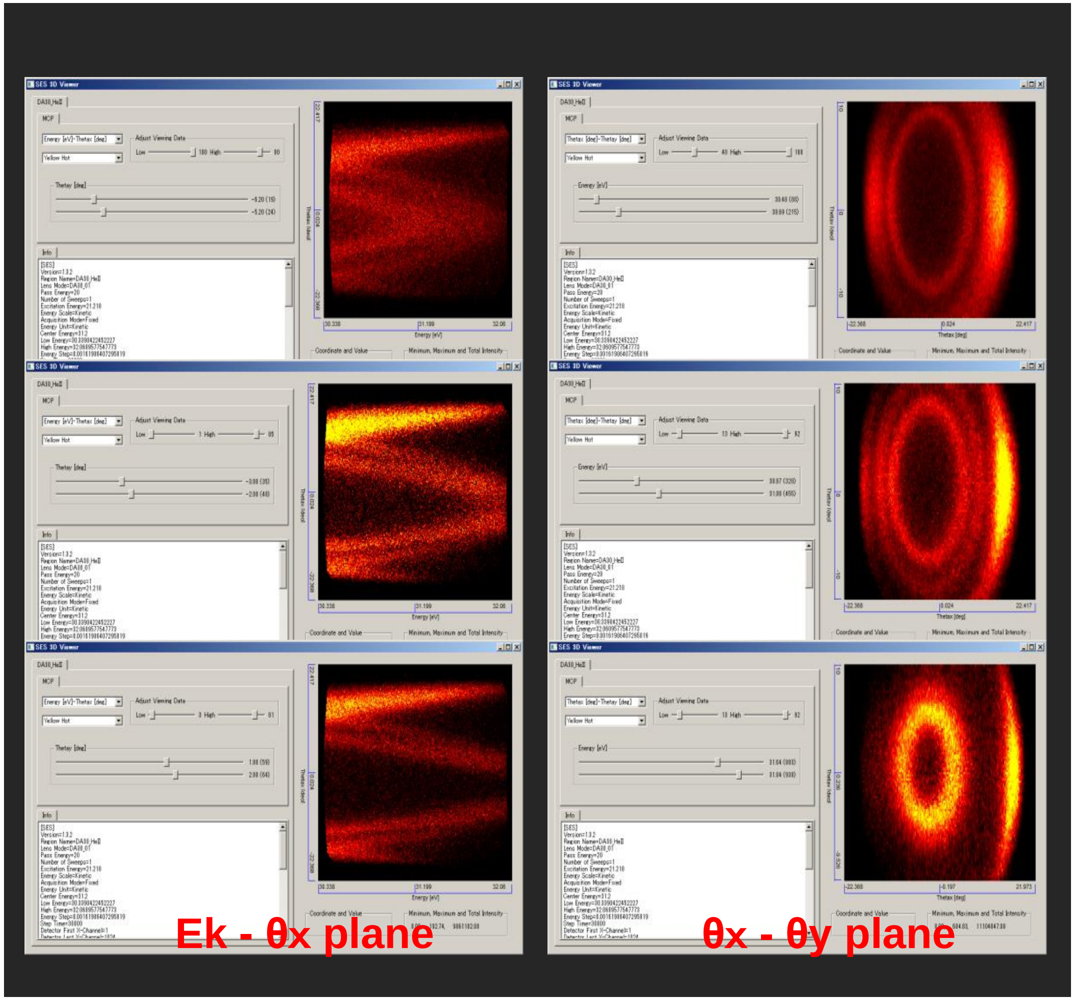
- With the deflector analyser, the electron trajectories can be deflected, to change the range of emission angles that reaches the detector
- Deflection can be done in q_x and in q_y.



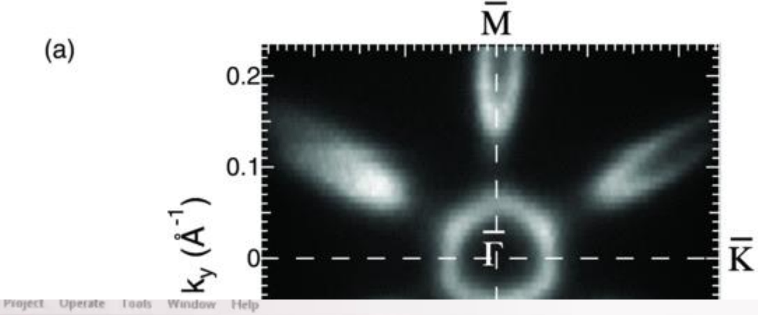
Graphite



Data courtesy : Dr. Yamane, IMS



The Fermi surface of Bi(111)



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SessionID Manta_G-125B
U485Hand 266929312
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End K.E. 4.1047
Width 0.0374
Step Size 0.000304
No Steps 123
ActScans 0
Frames 30
RegNo 54
PASS ENERGY PE005
Lens Mode L4Ang0dB
Center K.E. 4.1
DeflX -7.1875
DeflY 0
RegName FixedAcq
NameString Bi
Rel. Path DATA\A1#10\Jan16

NoXStep 201
StartX 15.625
EndX 15.625
XStepSize 0.15625
SKE 4.0673
EKE 4.10441
Z Scale 100

1) Adjust LensScale using Y Angle
2) Adjust Multiplier(Ek) to get correct X Scale

DeflArray 0
0
0
0.09178
-1.1499
-0.69981
-0.09856
0
-0
-3.20764

NoFiles 206

Bi00001_00199.txt
Bi00001_00200.txt
Bi00002_00000.txt
DM00001_00000.txt
Fix00001_00000.txt

'Modulation' is an added voltage of CMod*XDefl of definite polarity governed by sign(CMod)

DeflTable	Active Column		
Ek	2.5	5	7
Multiplier	0.14	0.175	0.235
(2) D1	-0.08	-0.08	-0.0942
(3)D2a	1	1	1
(4)D2b	0.6	0.6	0.6
L3Mod	0	-0.14	-0.1855
L4Mod	0	0	0
D1Mod	0	0	0
(8)D11D13	0	0	0
	0	0	0
DEFL10	0	0	0

LensScale 0.8
CrsrYDiff 15.8388
CrsrXDiff 15.625
YDiffMem 0
XDiffMem 0
Counter 54

Electron Escape Depth : Surface Sensitivity

Why are electrons so useful as probes of surfaces?

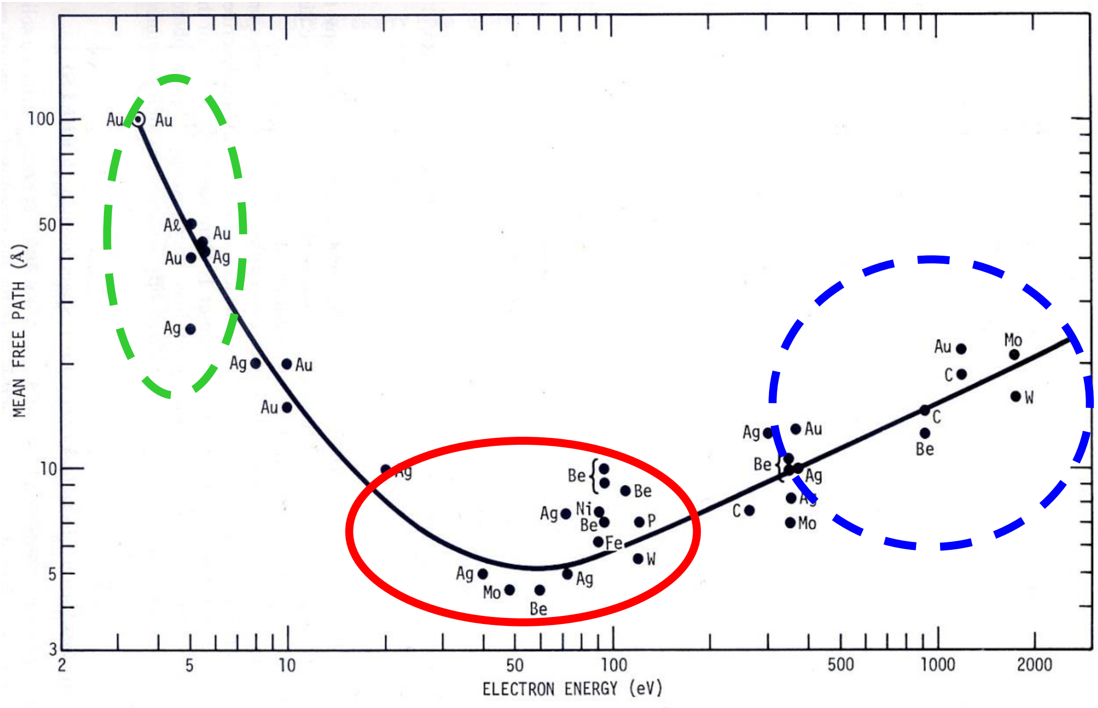
Or

Not so useful for studying bulk properties !!

Minimum due to electron-electron scattering, mainly plasmons

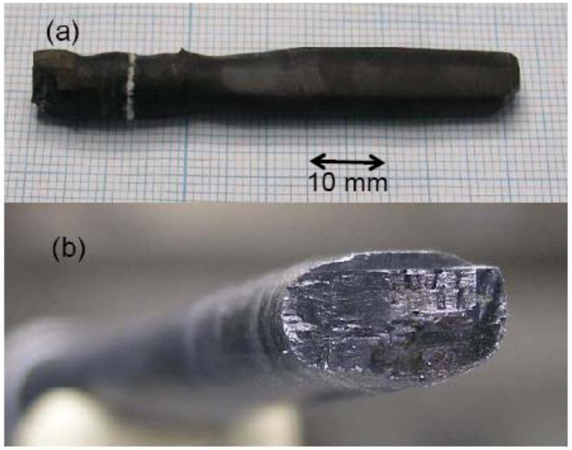
PES is a surface sensitive technique! (requires UHV)

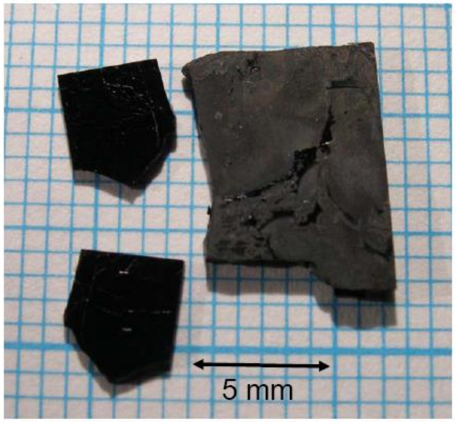
High energy photoemission: several keV to increase bulk sensitivity



The requirement of ARPES

- UHV environment : better than $1x10^{-10}$ Torr
- Single crystals or *in-situ* growth thin films
- Conductors or semiconductors
- Tunable photon energies





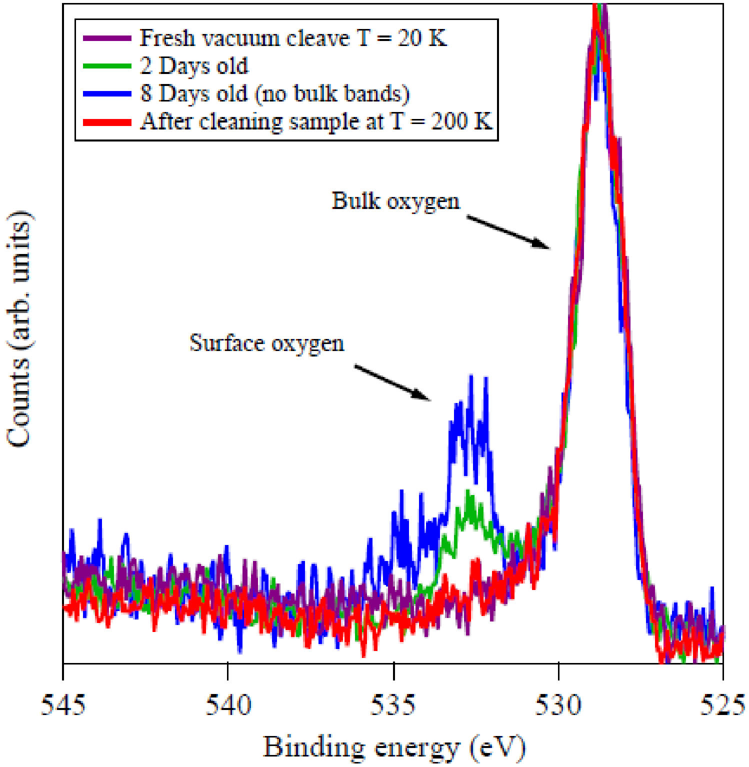
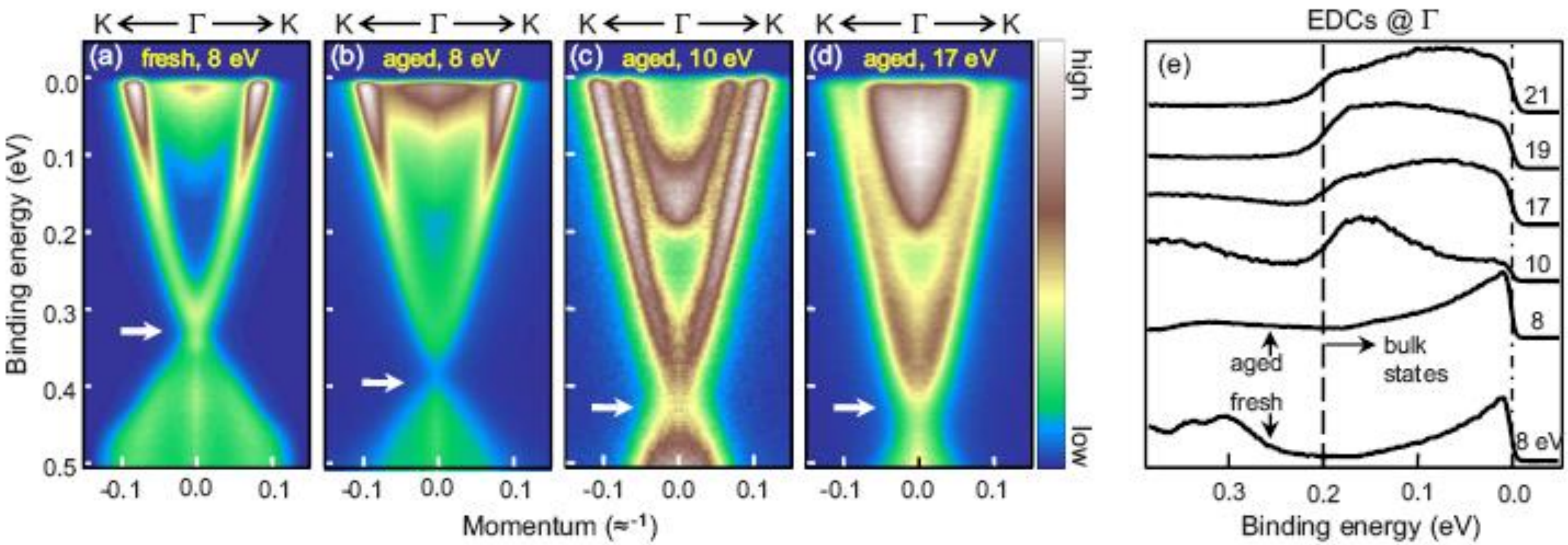


Figure 5.2: (color) The oxygen 1s peaks from Bi2212 at different times after the cleave. A constant background was subtracted from each spectrum to allow direct comparison. The peak derived from bulk oxygen is stable over time, while the surface oxygen peak grows as more oxygen sticks to the cold surface.

HC Hsu, Ph.D. Thesis NTNU(2010)
Koralek, U. Colorado Ph.D. Thesis (2007)

Single crystals or *in-situ* growth well-ordered thin films are favorable for ARPES measurement



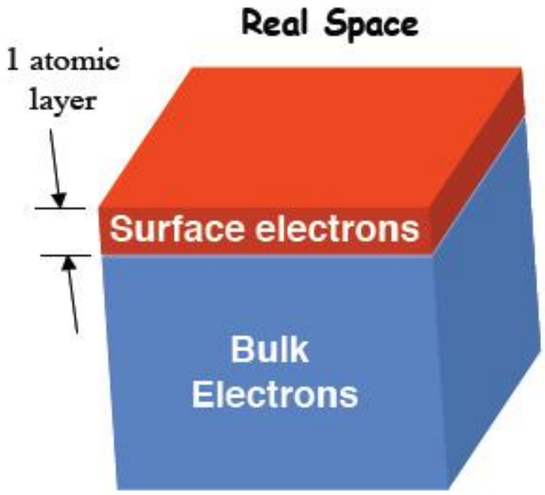
Base pressure : 1x10^{-10} Torr

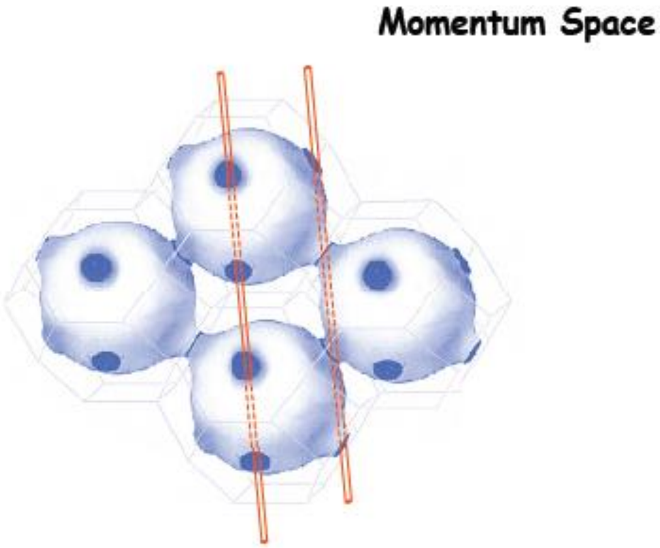
In-situ cleaved Bi$_2$Se$_3$ single crystal

Park et al., PRB (2010)

Using ARPES to study the electronic structure of 2D materials

Surface state





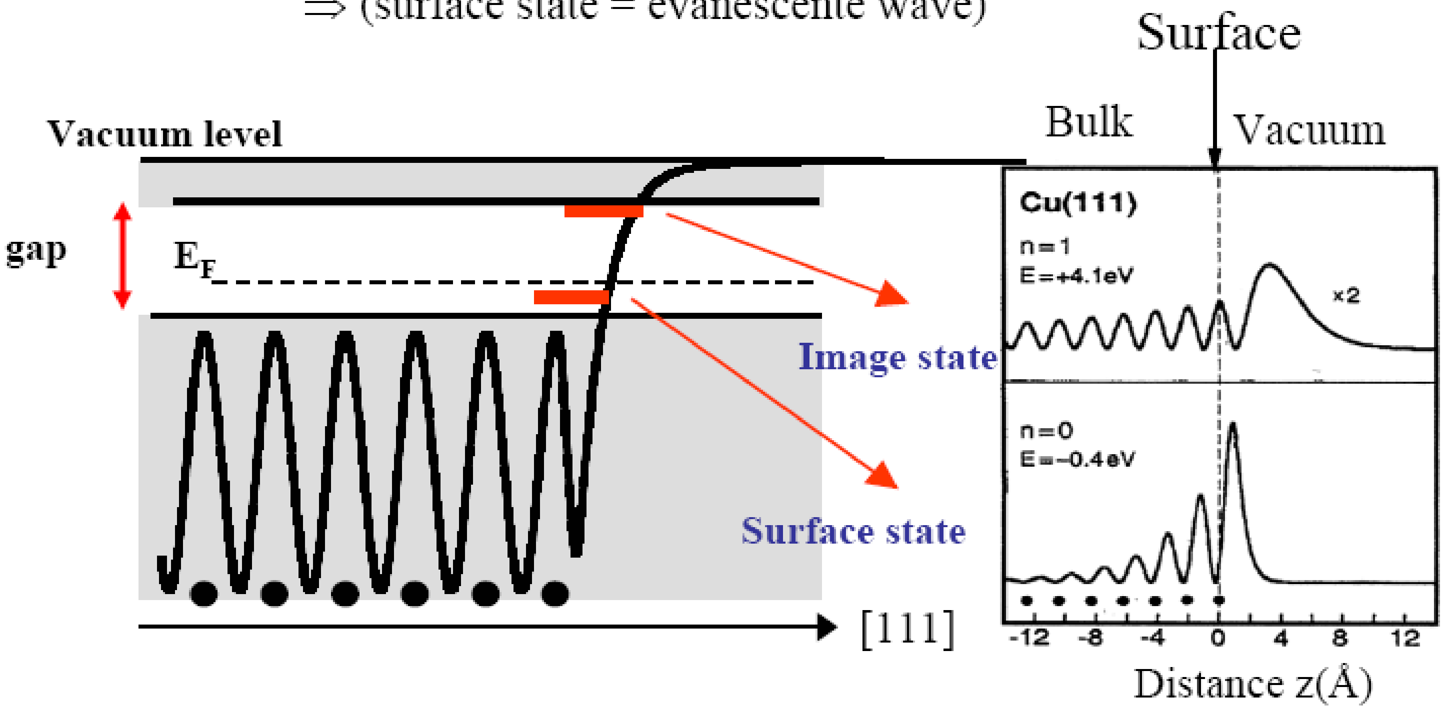
Surface states are highly localized in real space, therefore completely delocalized in k-space along *kz*.
– NO DISPERSION OF SURFACE STATES in kz direction

Eli Rotenberg, ALS summer school

- Surface = Breakdown of the translational symmetry

⇒Peculiar solution in the gap with a complexe wave vector $k_{[111]}$

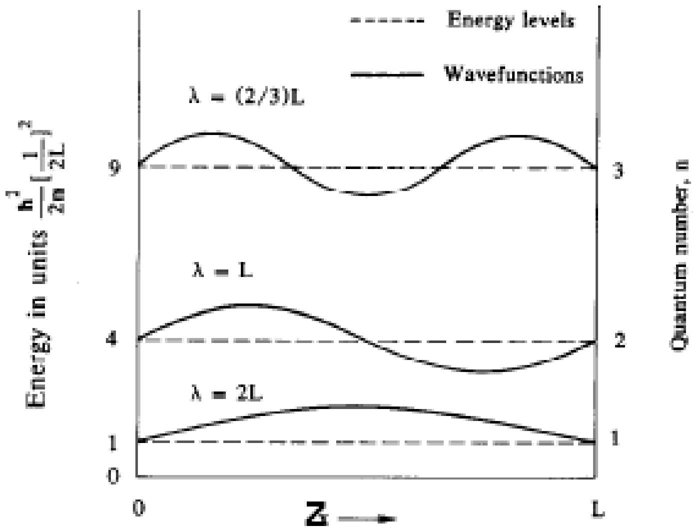
⇒ (surface state = evanescente wave)



→localisation of the electronic density at the surface

Surf. State is very sensitive to any structural modification

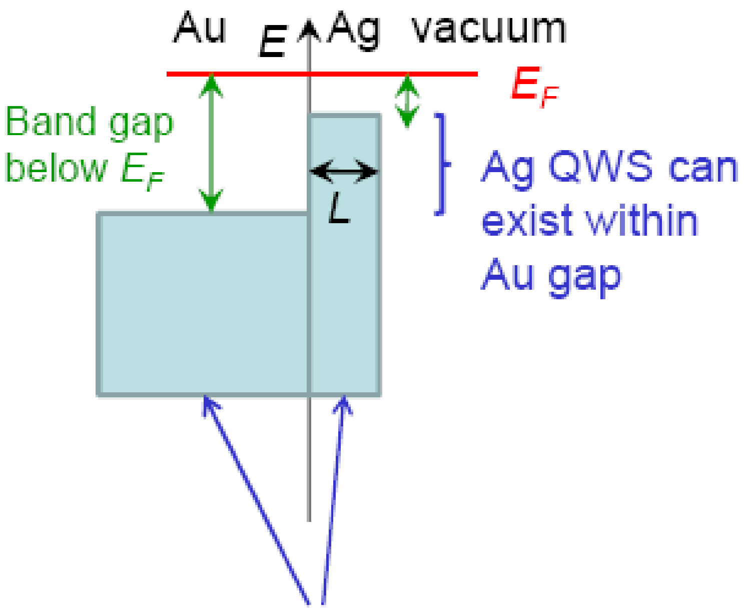
Quantum well states



Quantized discretely along z-direction
Energy levels depend on film thickness *L*

Nearly free electron like in xy-plane

Ag(111) thin films expitaxially grown on Au(111) substrate

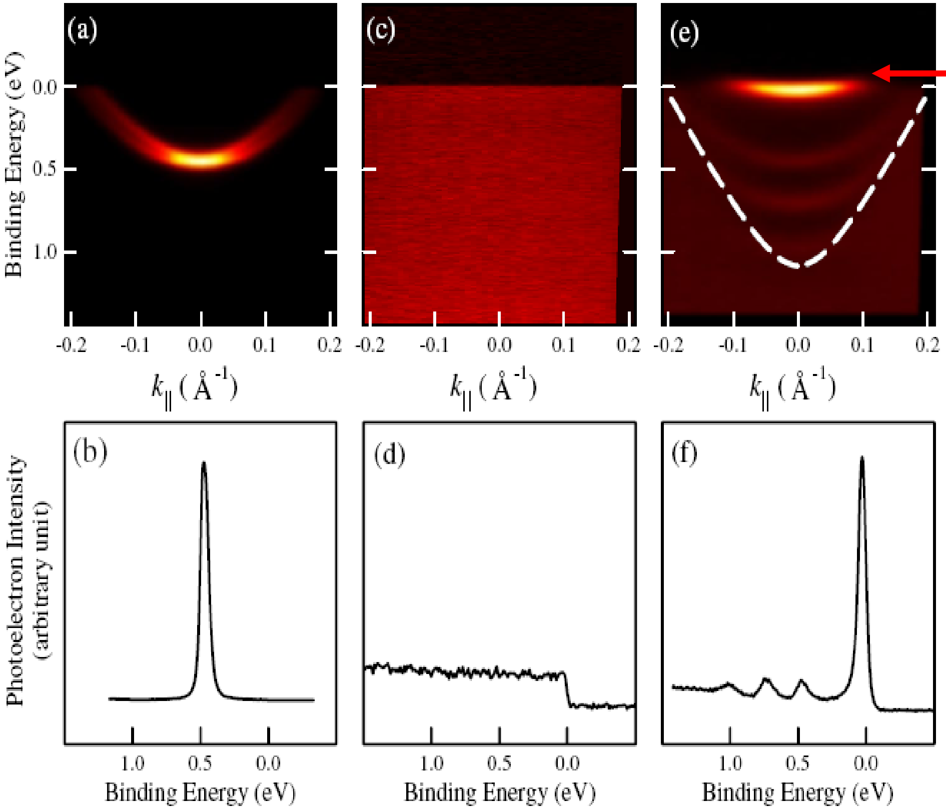


Band gap below E_F

Ag QWS can exist within Au gap

Bulk projected bands along ΓL of Au and Ag, respectively

Absolute coverage of thin films : Ag/Au(111) system



Ag S.S

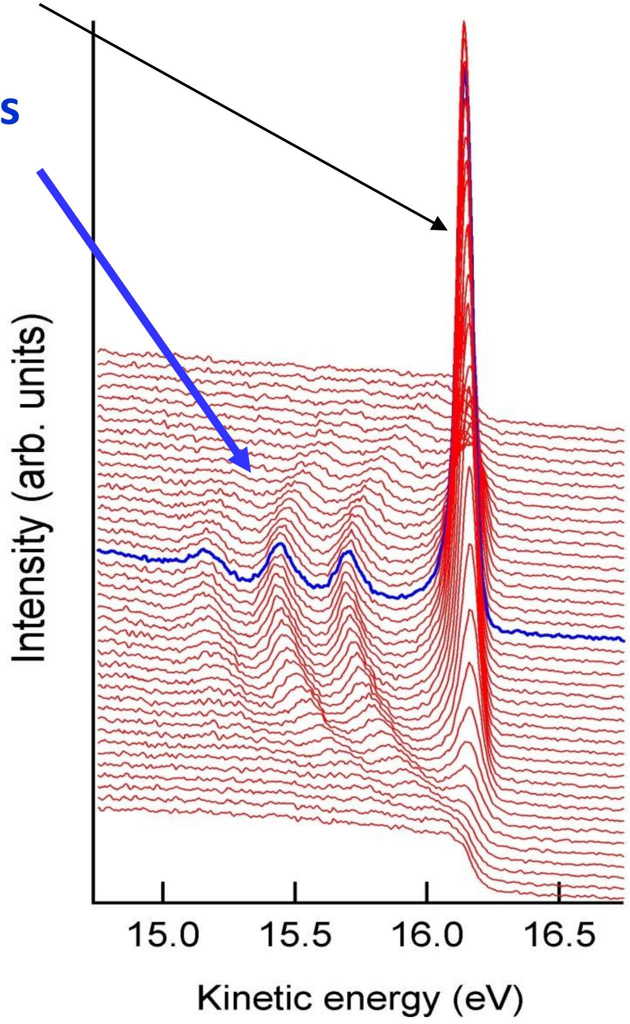
Ag QWs

Clean Au(111)

LT deposited Ag/Au(111)

Anneal to near RT

$k_{||} = 0$ normal emission EDCs



D. A. Luh et. al., PRL (2008)

Dynamically monitor the thin film growth mechanism

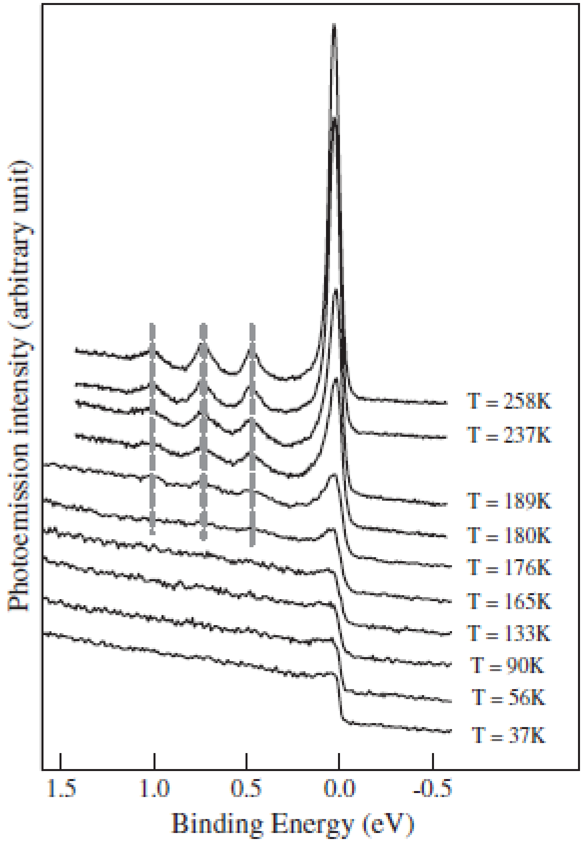
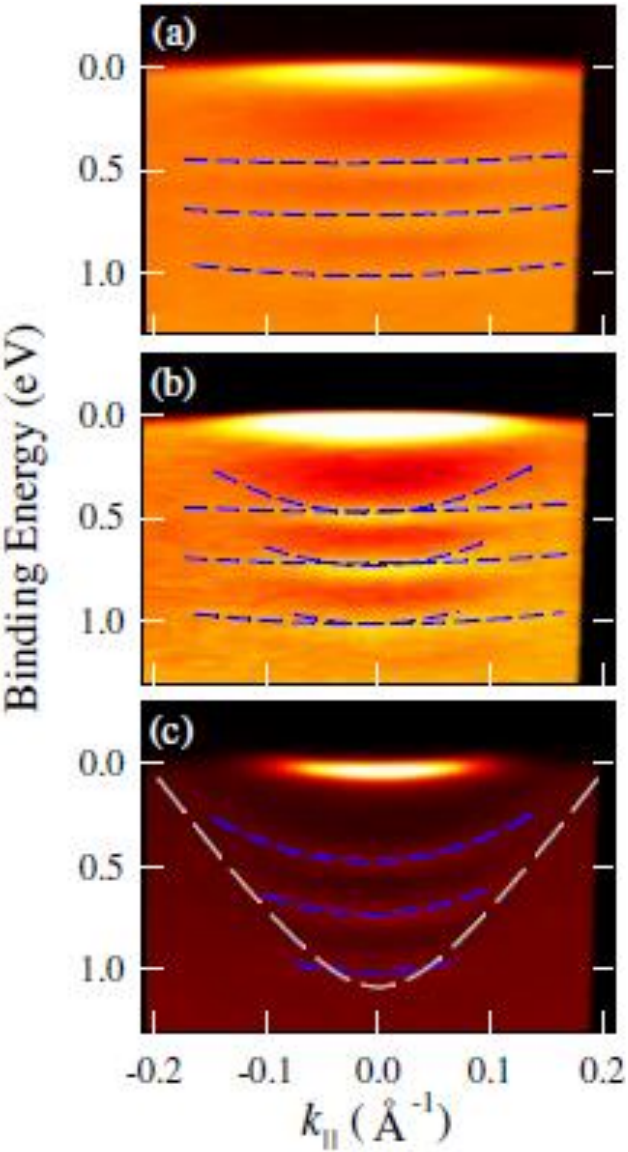
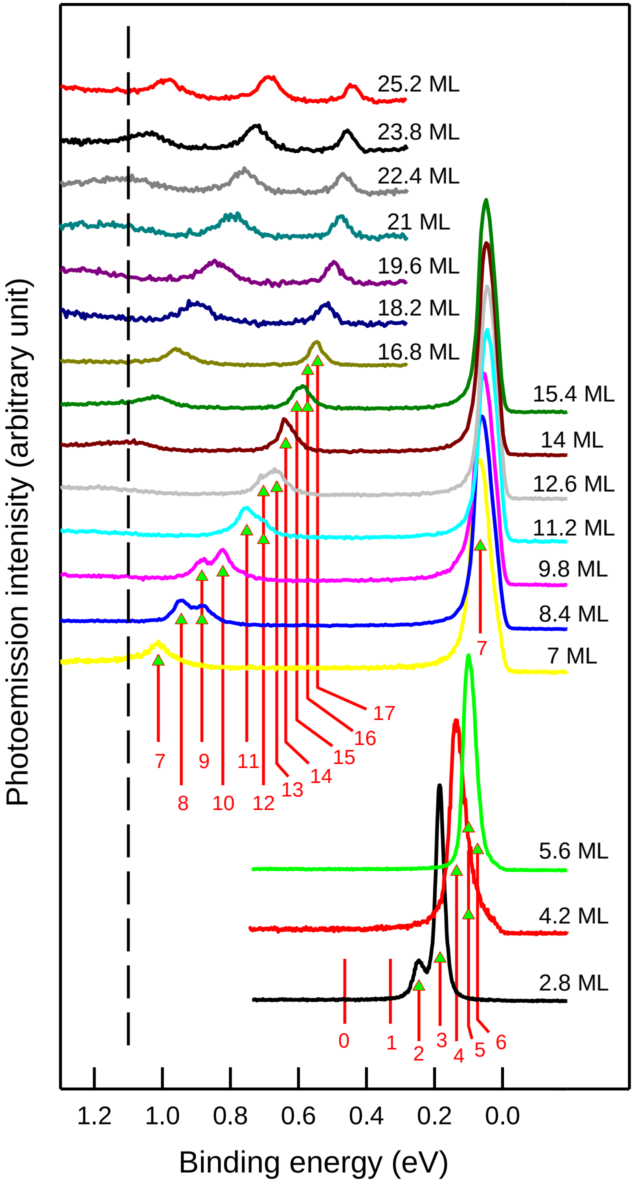
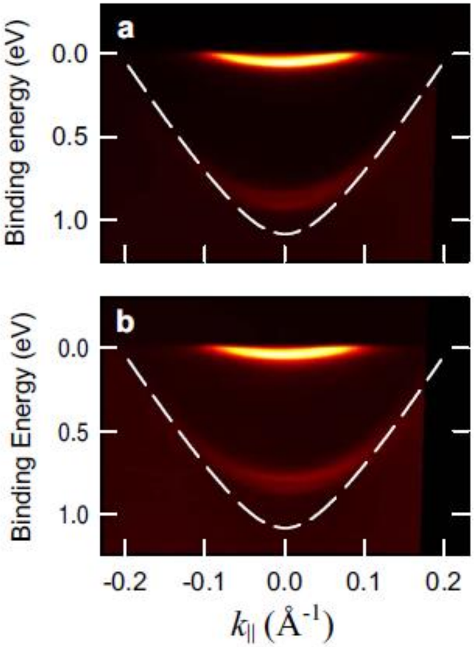
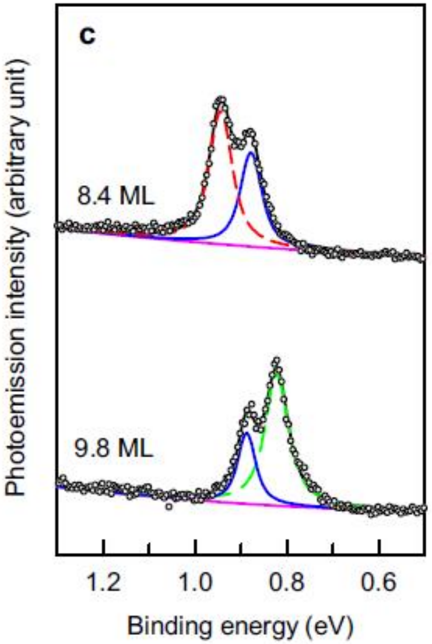


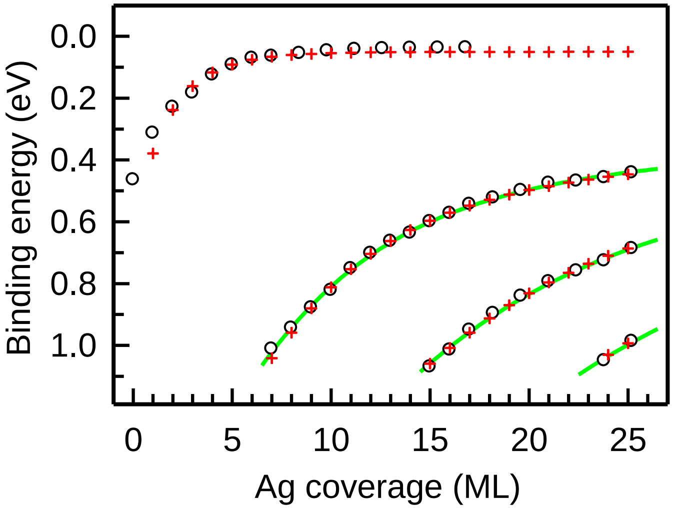
FIG. 2. Energy distribution curves of normal emission from Ag (22 ML) on Au(111) annealed at the indicated temperatures; intensities have been scaled variously for stacking presentation.









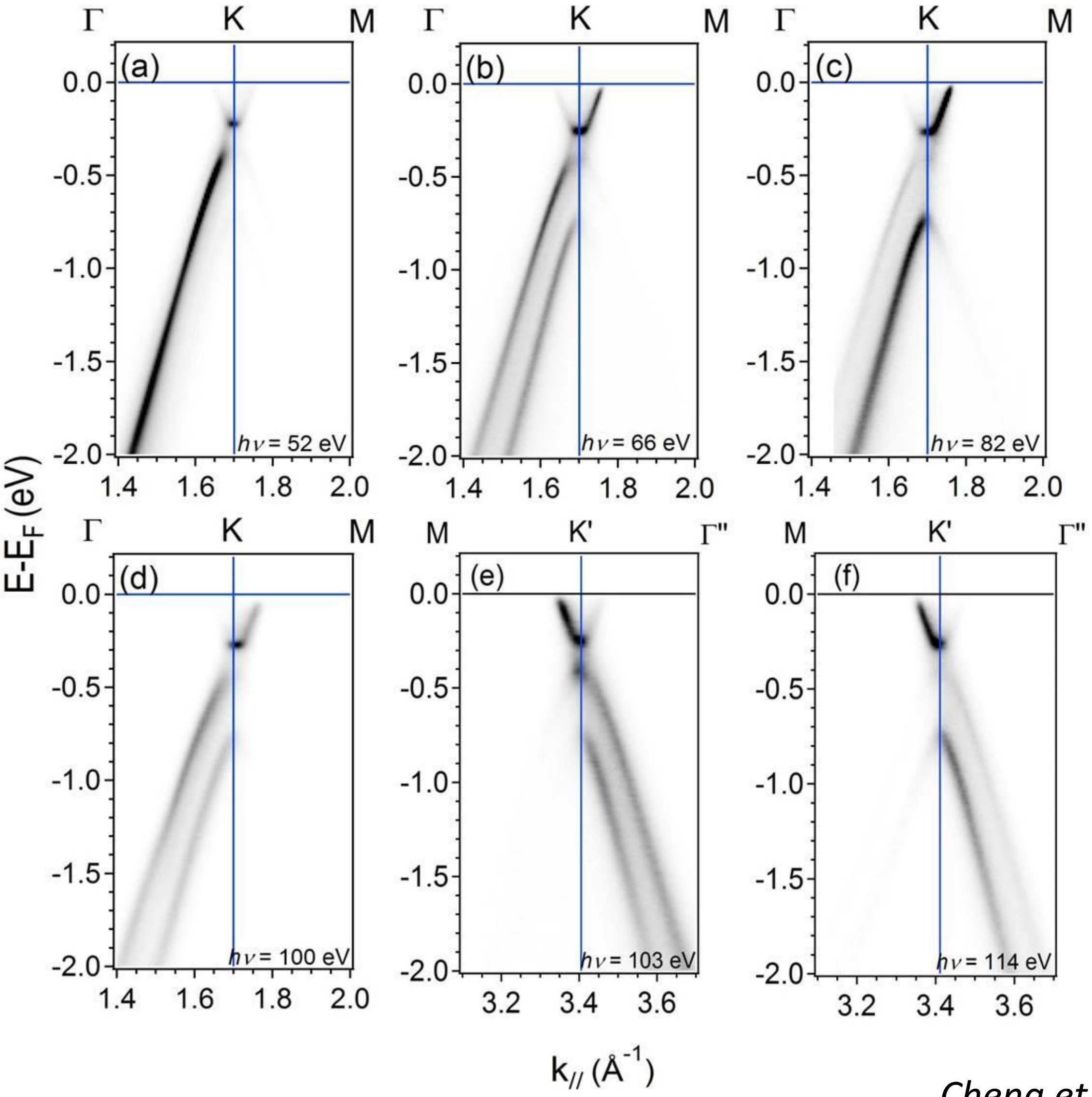


C.-M. Cheng et al., APL (2008)

C.-M. Cheng et al.,J. Phys. D: Appl. Phys. (2008)

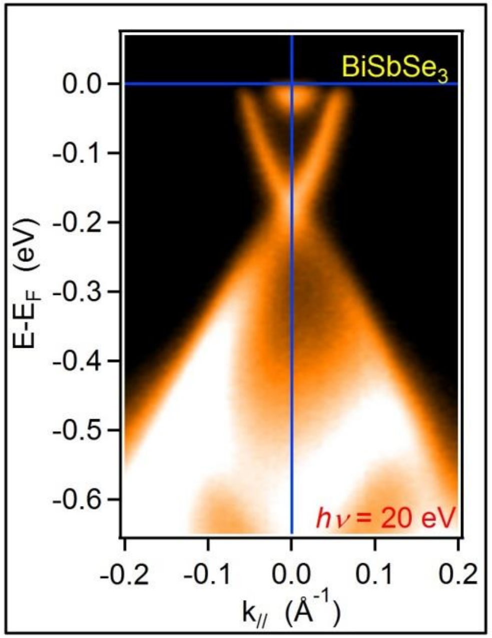
D.-A. Luh et al., PRB (2008)

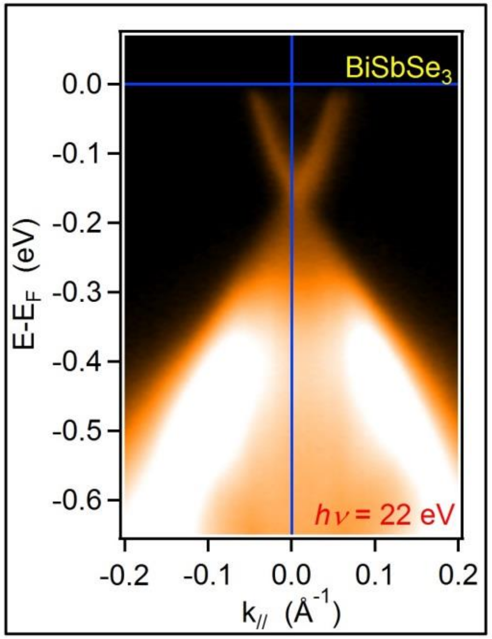
The examination of 2D behavior

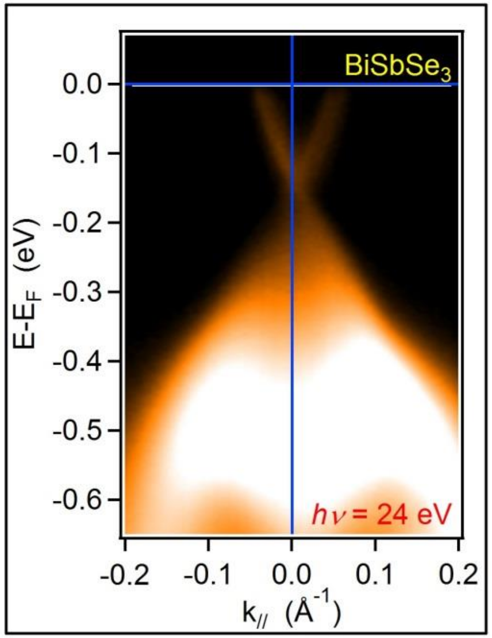


Cheng et al., submitted to PRB

The examination of 2D behavior : tuning incident photon energy







2D materials – An Overview

The most well-known 2D material : Graphene

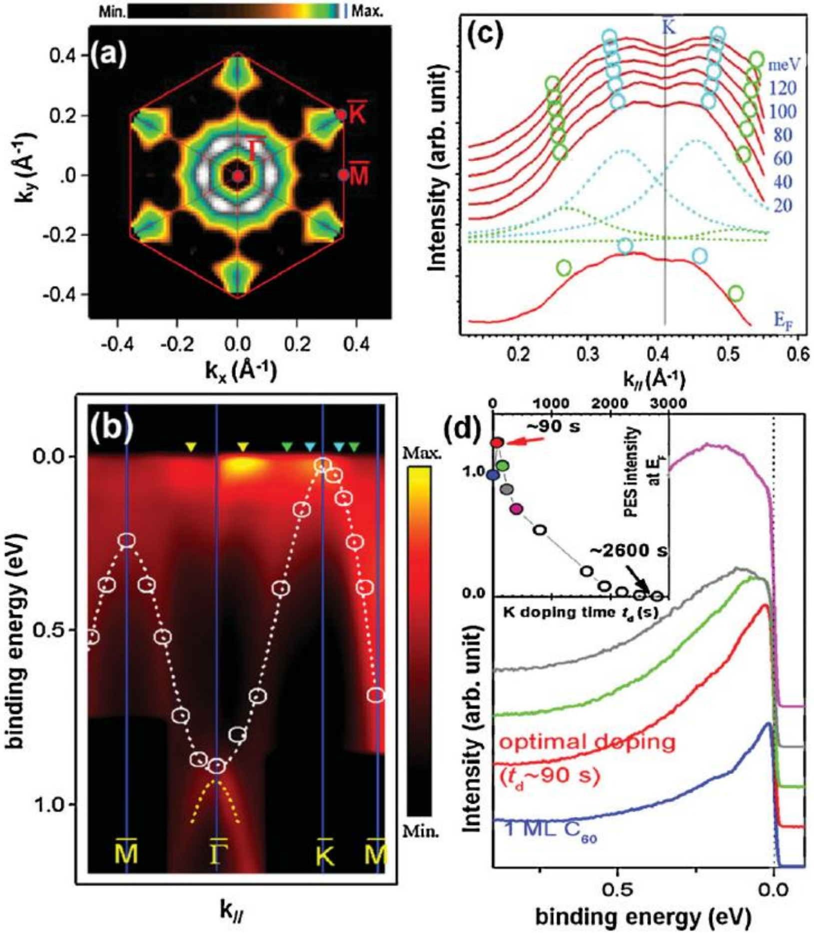
- ✓ First 2D materials studied in detail.
- ✓ Became famous by the works of Novolesov & Geim since 2004.
- ✓ High mobilities (> 100,000 cm2/Vs at RT) raised expectations in future electronic devices.
- ✓ Significant attention for 2D materials beyond graphene

The strictly two-dimensional material

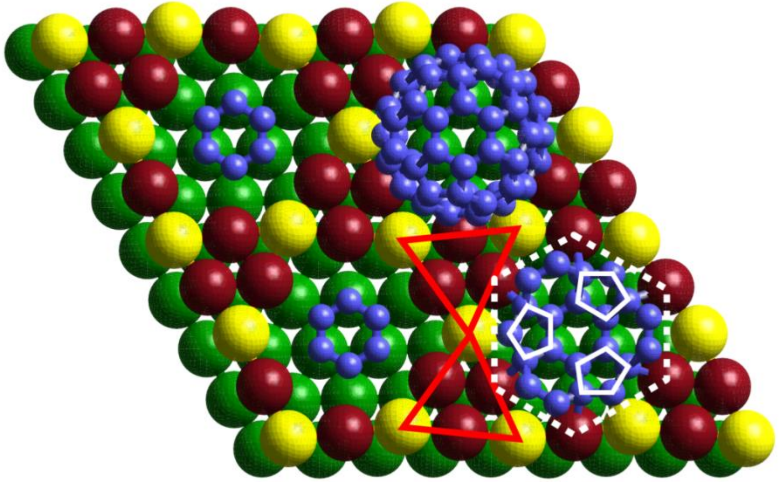
- 70 years ago, Landau argued that strictly 2D crystals were thermodynamically unstable and could not exist
- Before 2004, atomic monolayers only as integral part of 3D structure, grown epitaxially on top of monocrystal
- The discovery of graphene and other free-standing 2D atomic crystals (ex :single layer boron nitride and half-layer BSCCO)

New inroads into low-dimensional physics
New surprise to provide highly potential for application

Charge transfer process on ML C_{60}/Cu(111) system

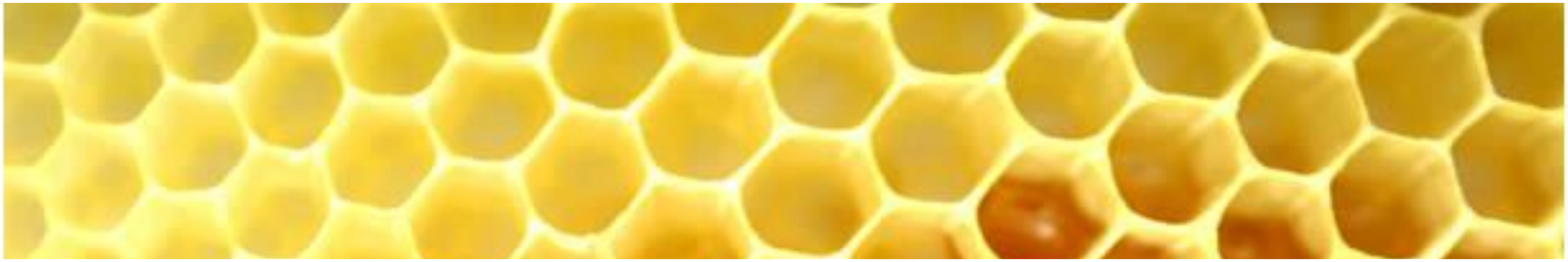


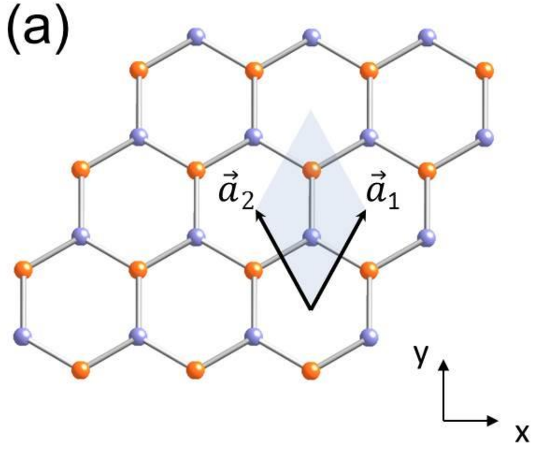
1. Large 7-atom vacancies.
2. Significant top Cu layer coherent distortion.
3. Nearly “optimal” C_{60}^{3-} doping purely by interface reconstruction.

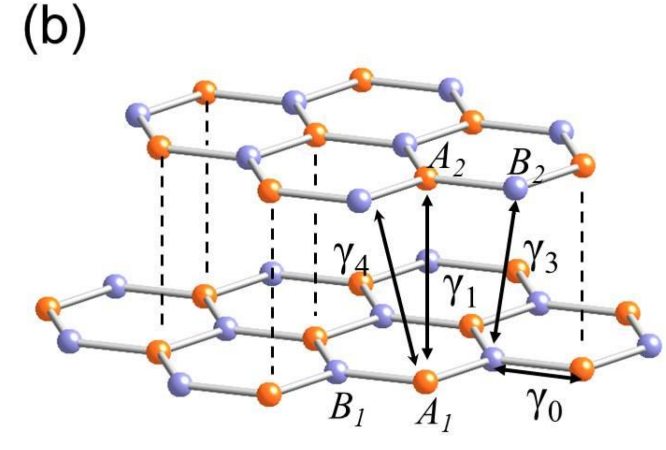


Ref: W.W. Pai et al., PRL 104, 036103 (2010)

What Is Graphene



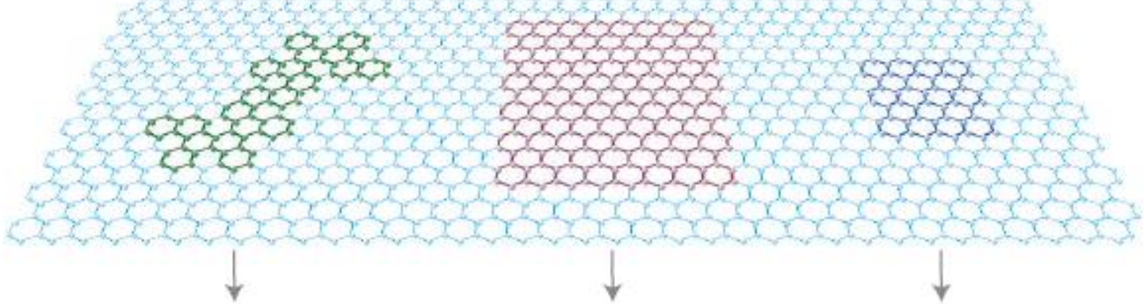




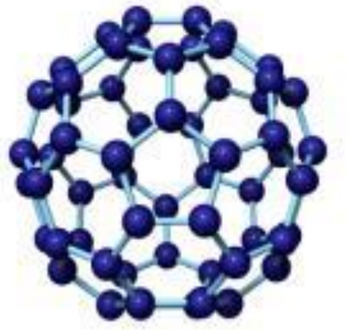
What is graphene

Very good conductors

Extremely thin and resistant



wrapped

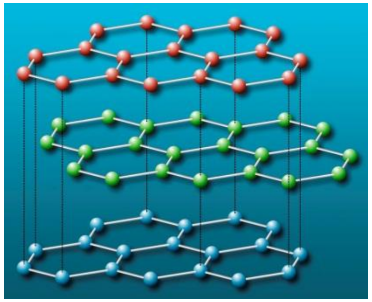


Zero dimensional:
fullerenes

Rolled

One dimensional:
carbon nanotubes

stacked

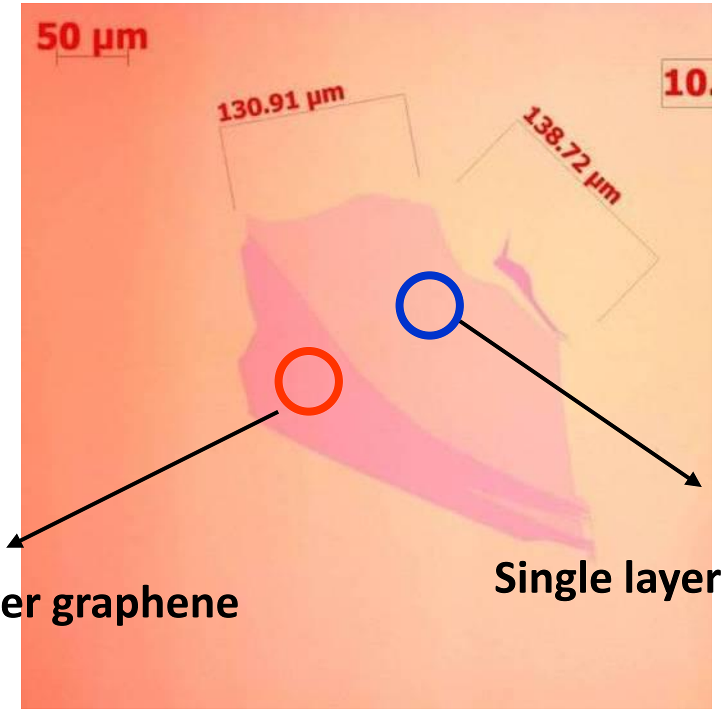


Three dimensional:
graphite

How to distinguish the thickness of graphene

SiO_2(200 nm)/Si

Optical microscopy

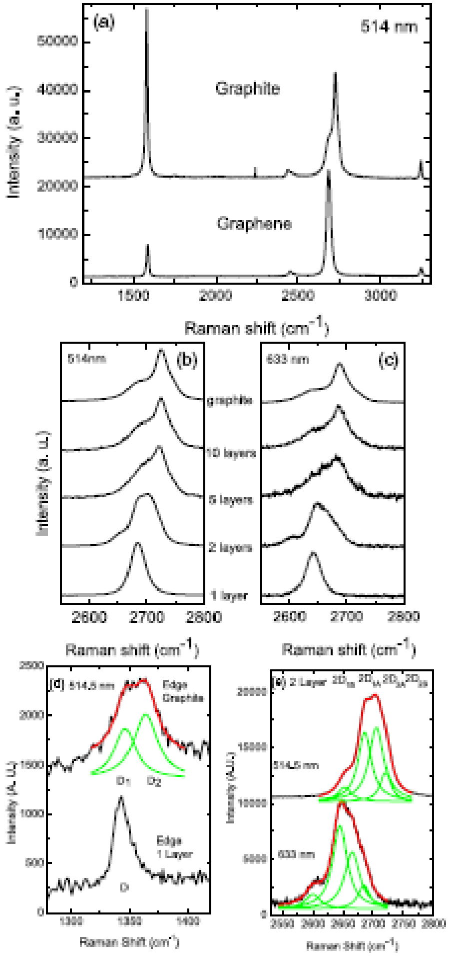


Bilayer graphene

Single layer graphene

B. özyilmaz , NUS, Singapore

Raman spectroscopy

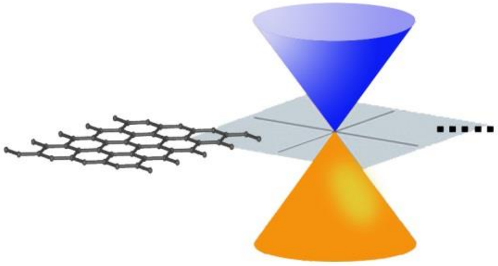


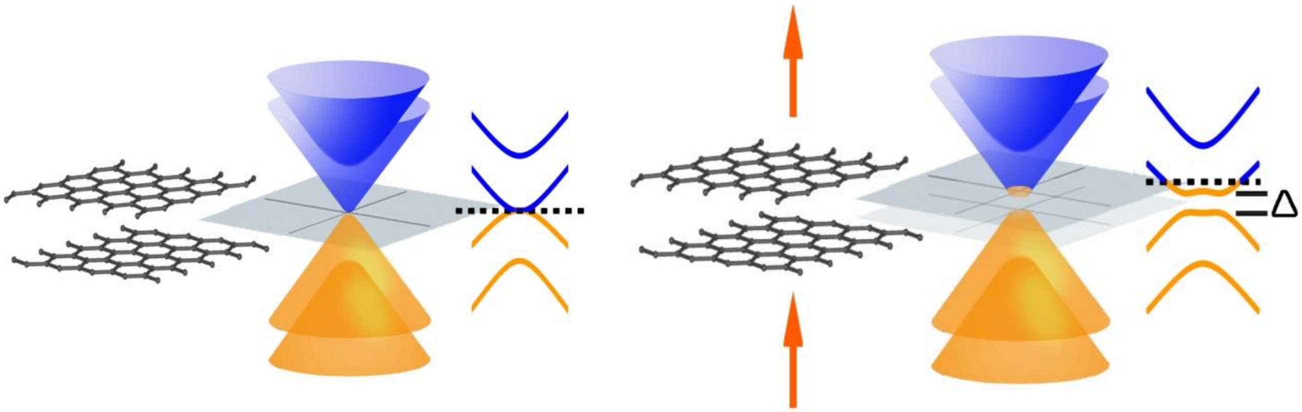
A. Ferrari , PRL 97,187401 (2006)

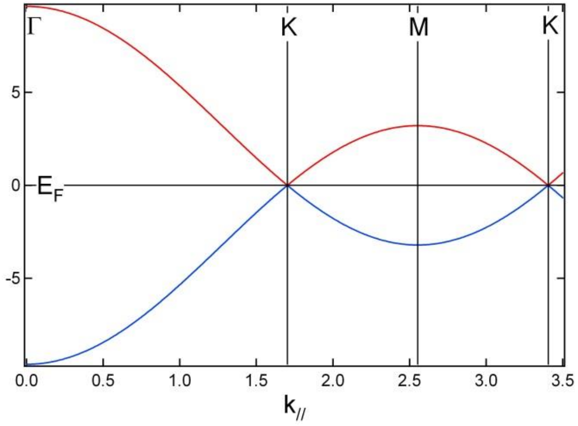
Single layer and bilayer graphene

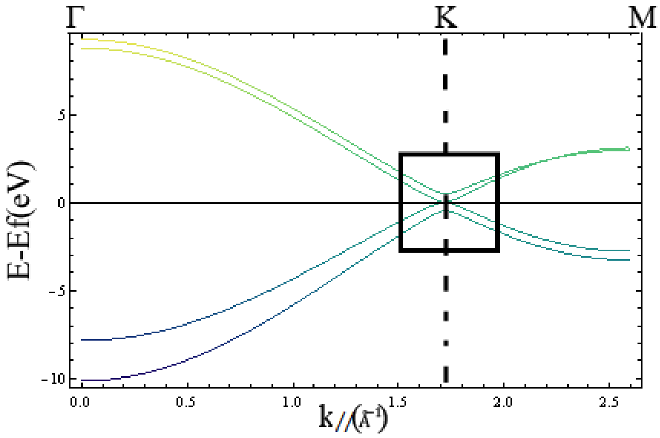
Single layer graphene

Bilayer graphene









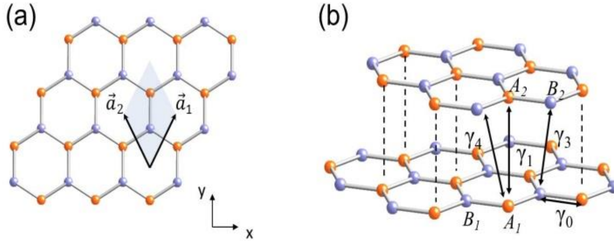
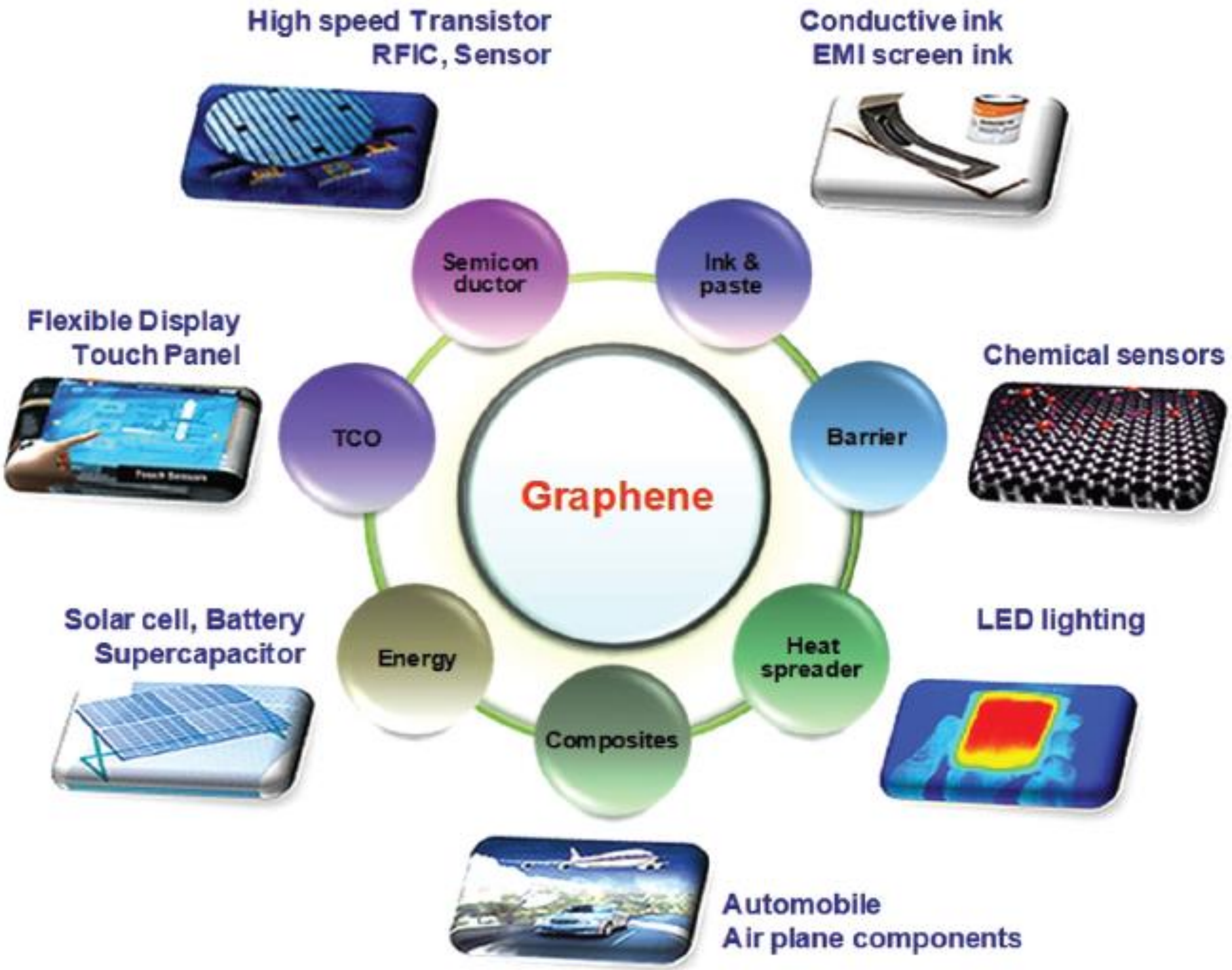


Image : http://infared.lbnl.gov.tw



Graphene

Semiconductor

High speed Transistor
RFIC, Sensor

Ink & paste

Conductive ink
EMI screen ink

TCO

Flexible Display
Touch Panel

Barrier

Chemical sensors

Energy

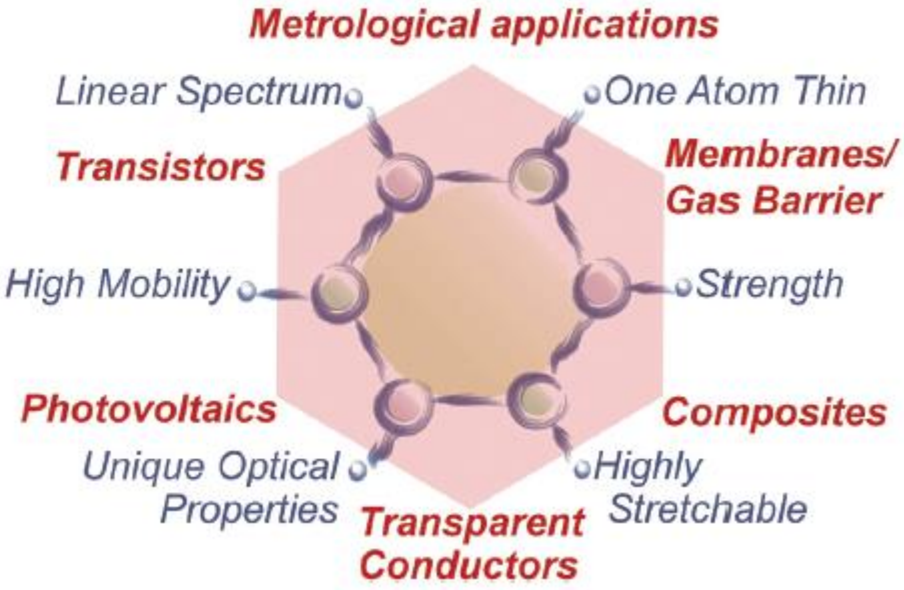
Solar cell, Battery
Supercapacitor

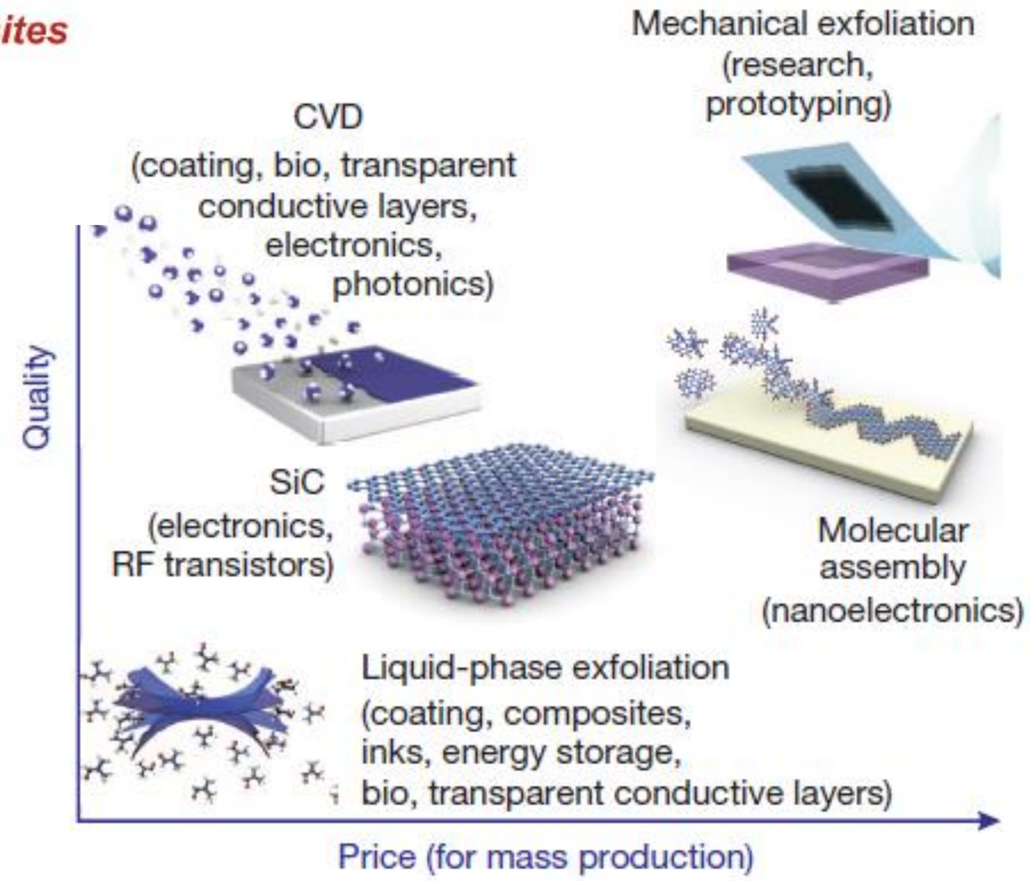
Heat spreader

LED lighting

Composites

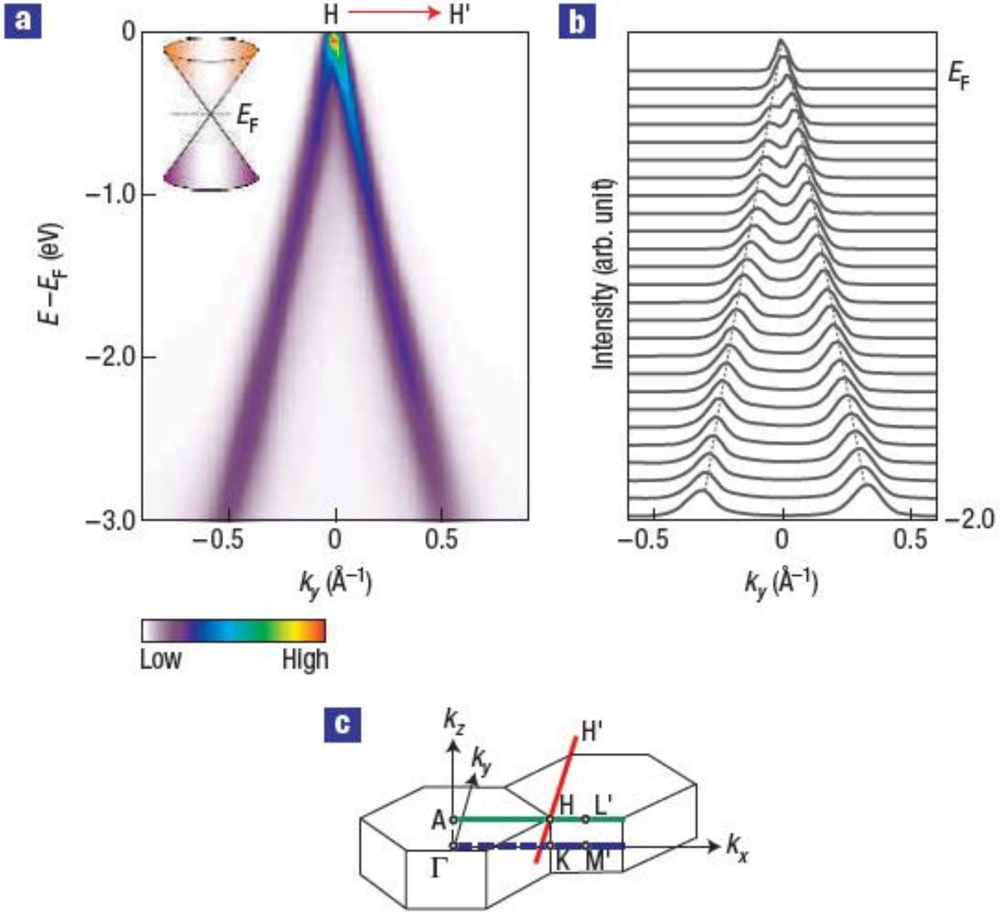
Automobile
Air plane components

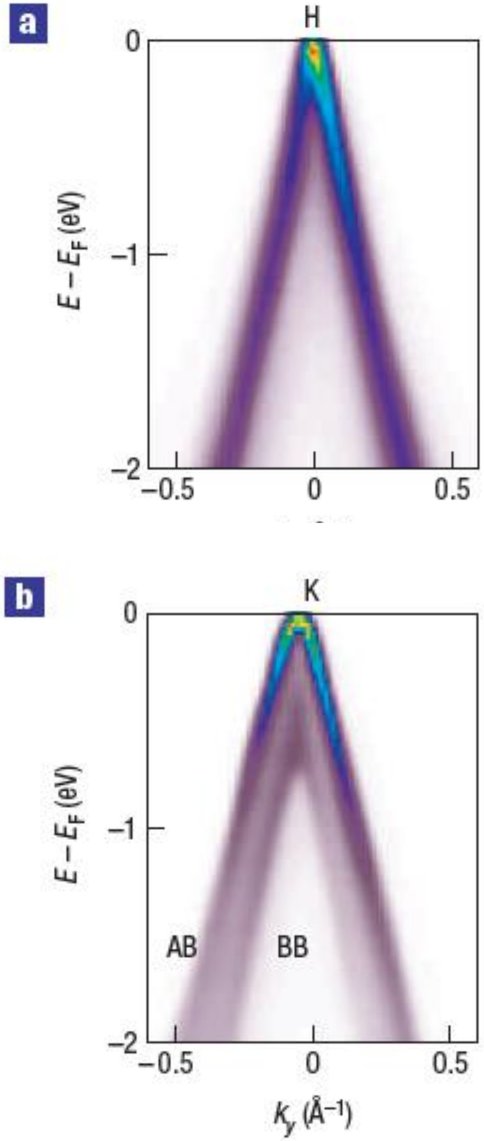




Novoselov et al., Nature (2012)

First treament: graphite

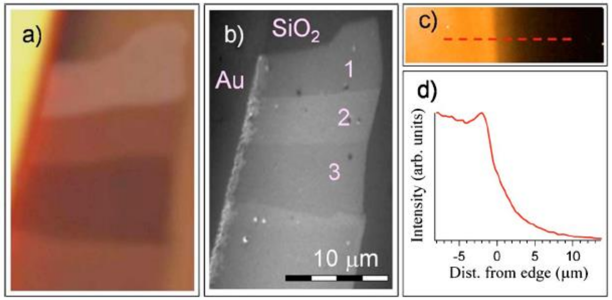




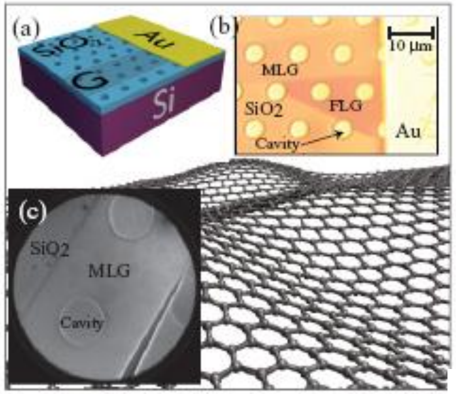
Zhou et al., Nature Physics 2, 595 (2006)

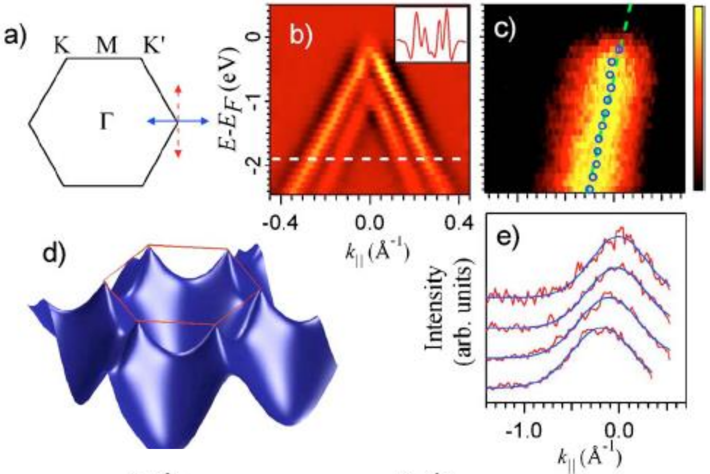
The experiments in graphene on SiO_2 (200nm) and suspended graphene

Graphene on SiO_2



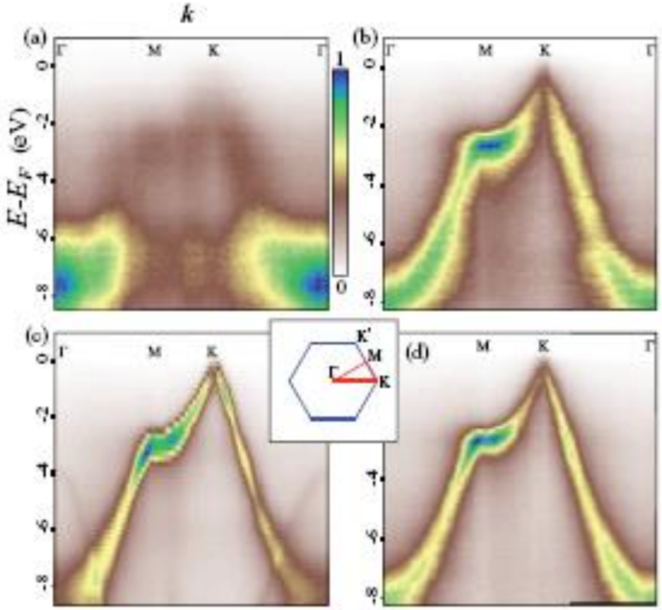
Suspended graphene



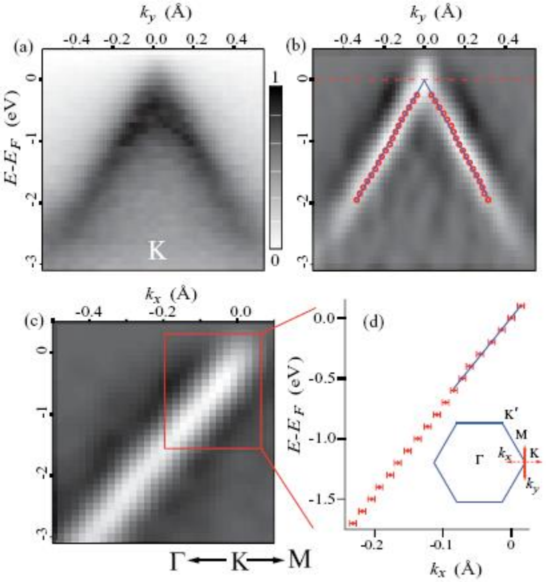


SLG/SiO2

graphite



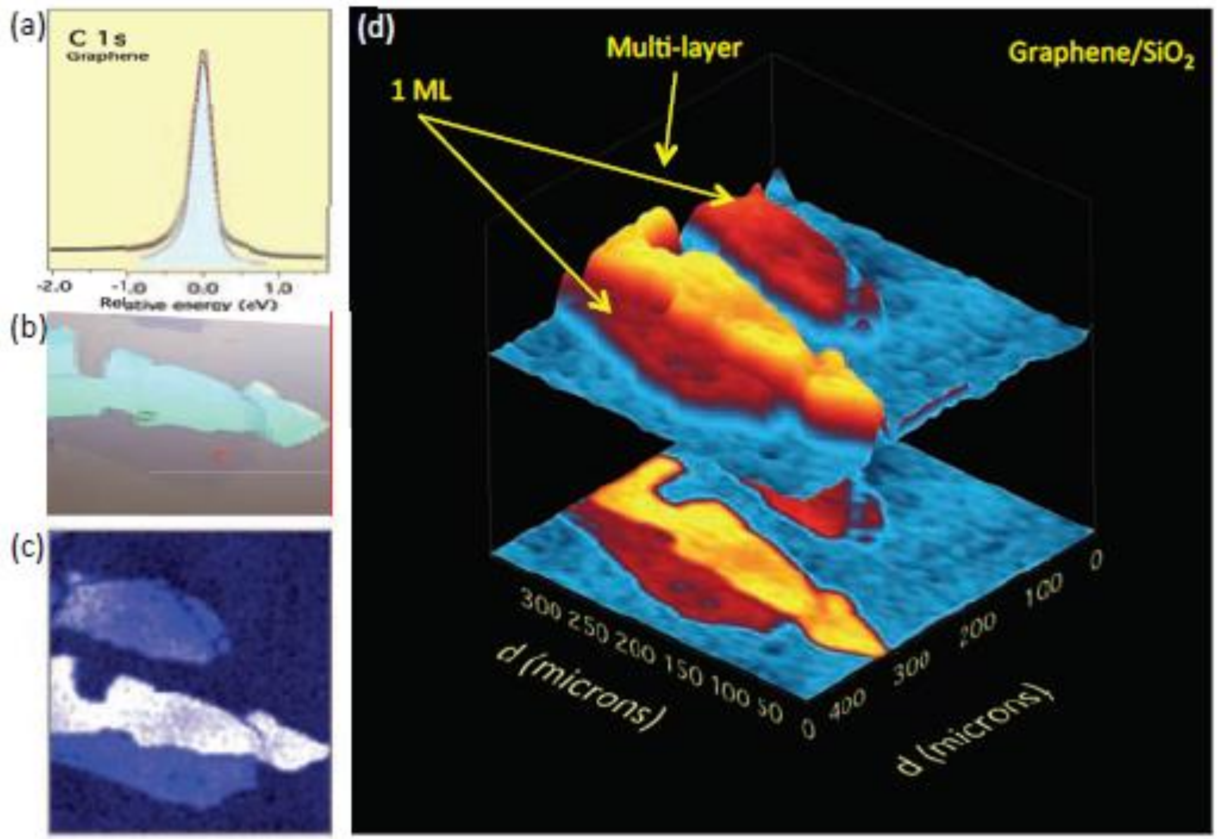
Suspended graphene



Knox et al., PRB 78, R201408 (2008)
PRB 84, 115401 (2011)

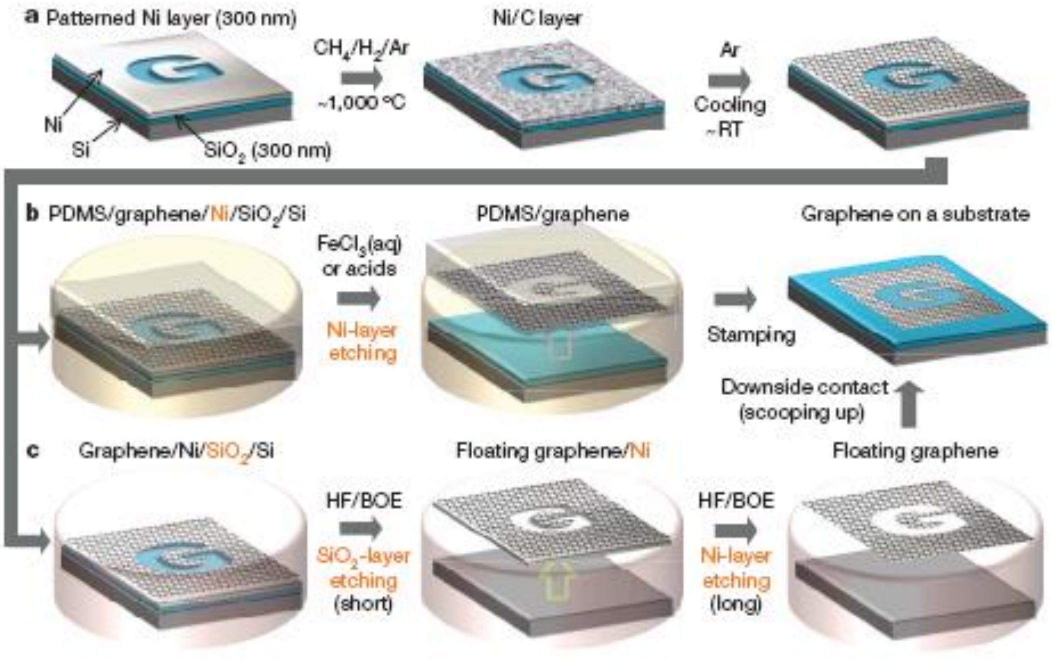
Multi-thickness domains in an exfoliated graphene

Nano-XPS results on exfoliated graphene samples on SiO_2 substrates at the ANTARES beamline, SOLEIL



Avila, Synchrotron Radiation News (2014)

CVD for large scale graphene film



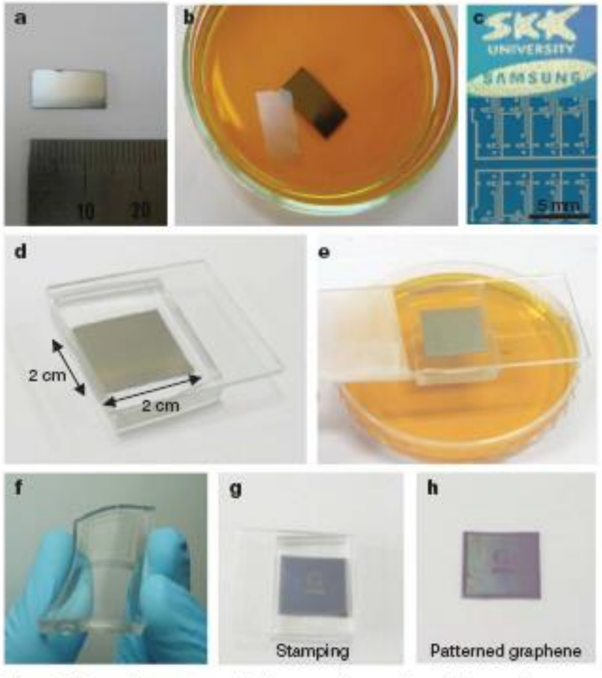
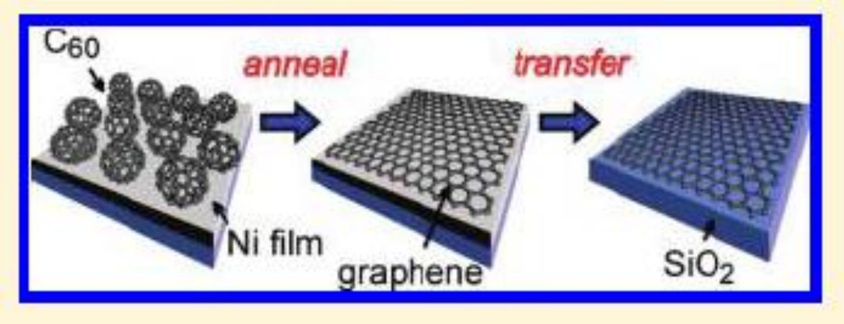
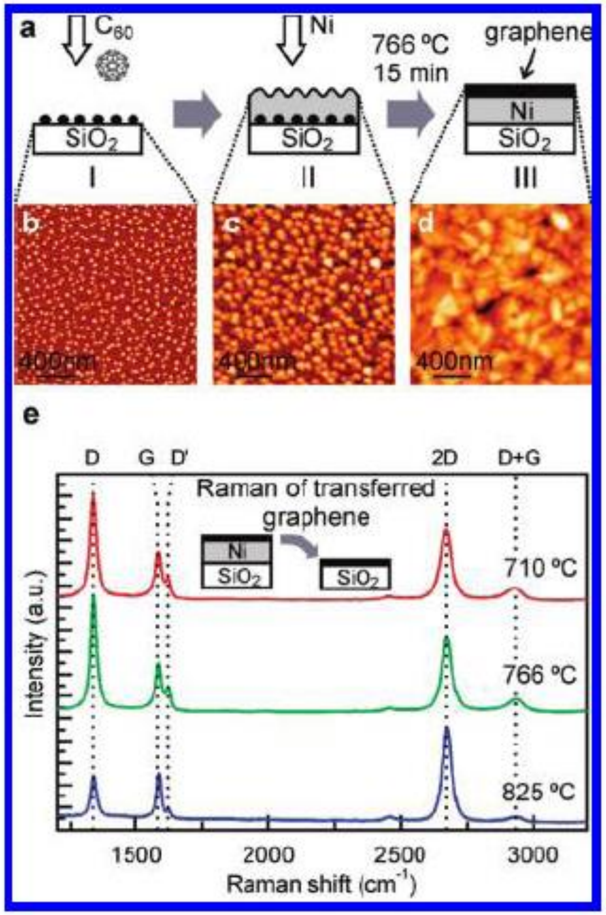


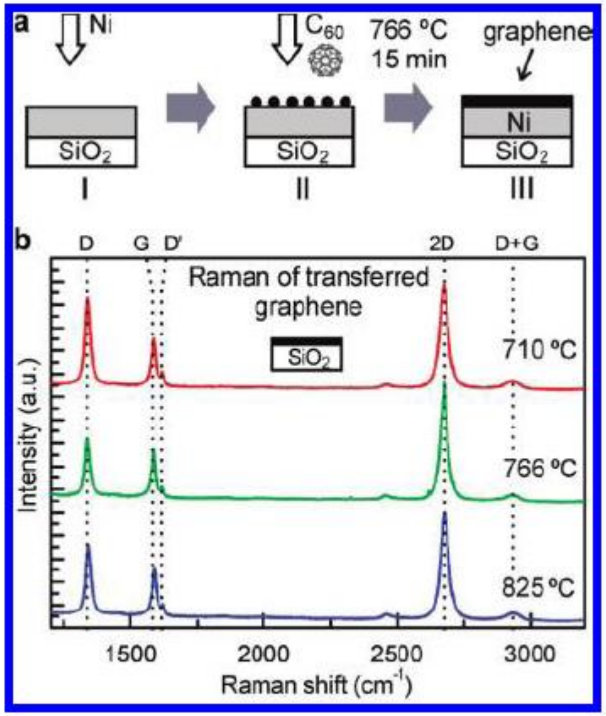
Figure 3 | Transfer processes for large-scale graphene films. a, A

Kim et al., Nature (2009)

Graphene formation by decomposition of C_{60}

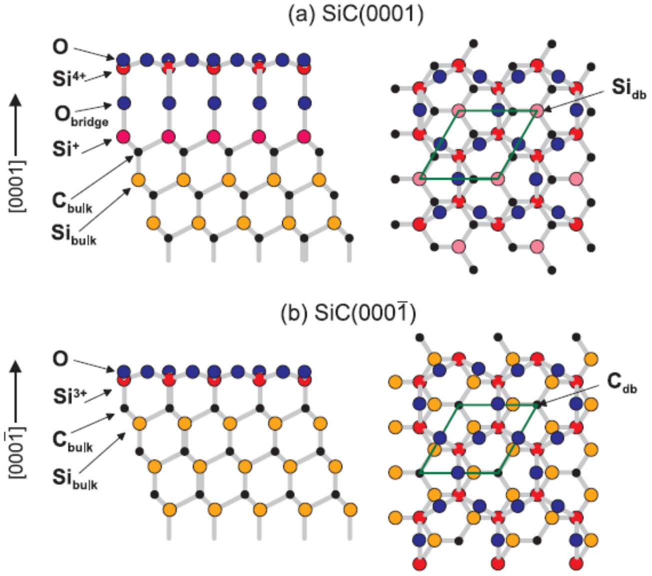


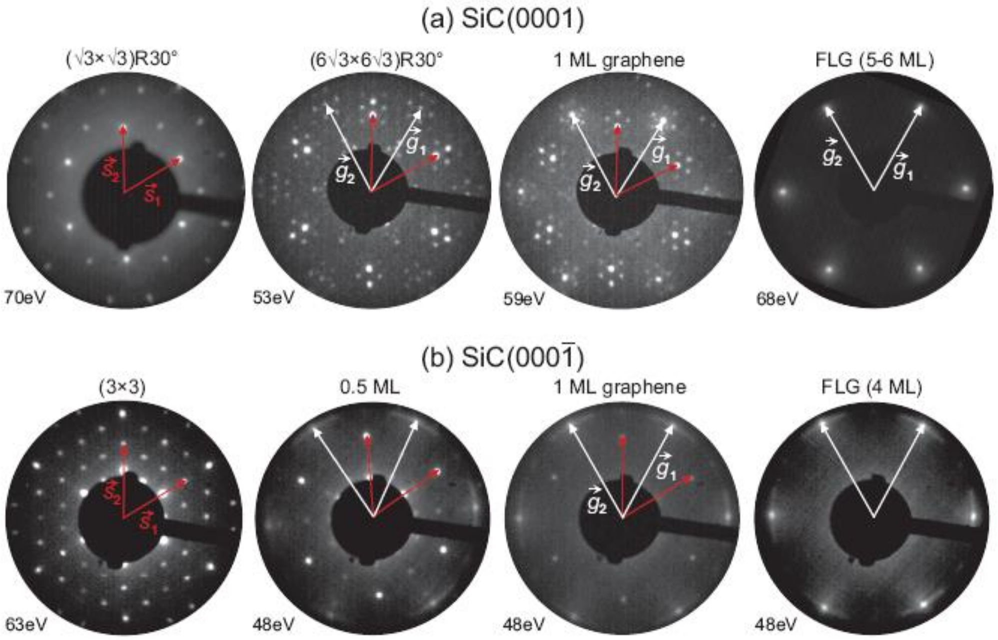


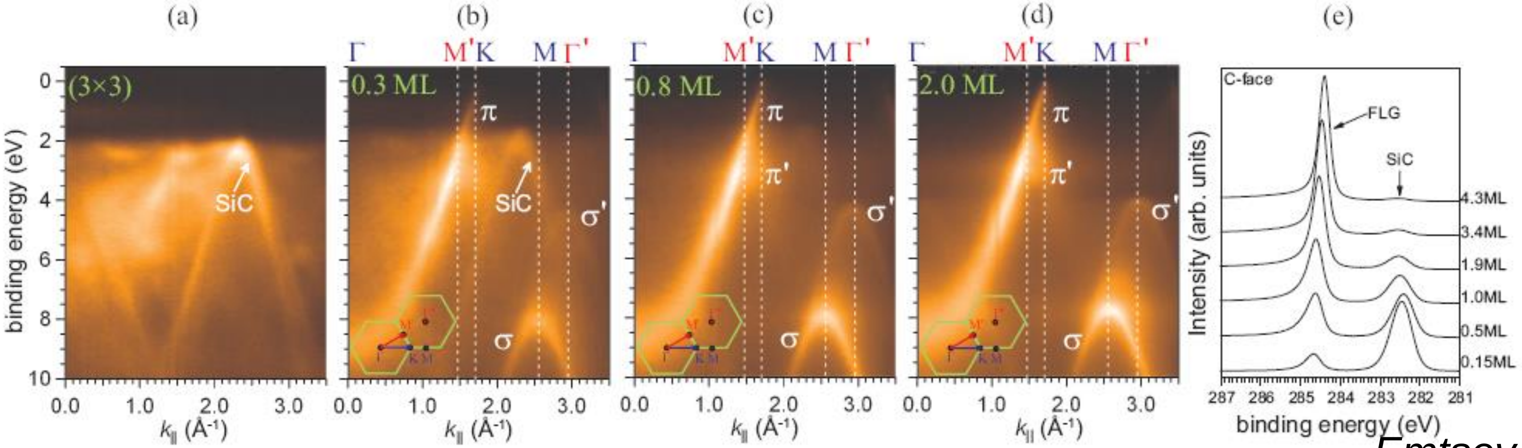


Perdigao et al., J. Physical Chemistry C (2011)

Epitaxial growth graphene on SiC



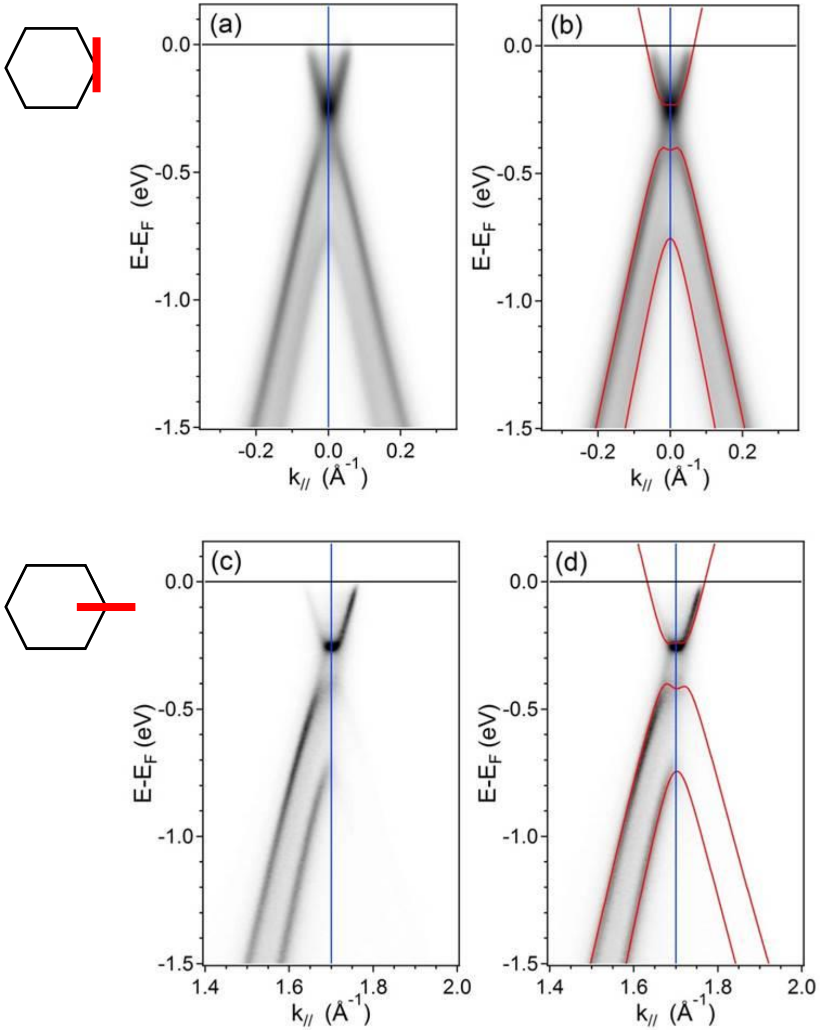




Emtsev et al., PRB (2008)

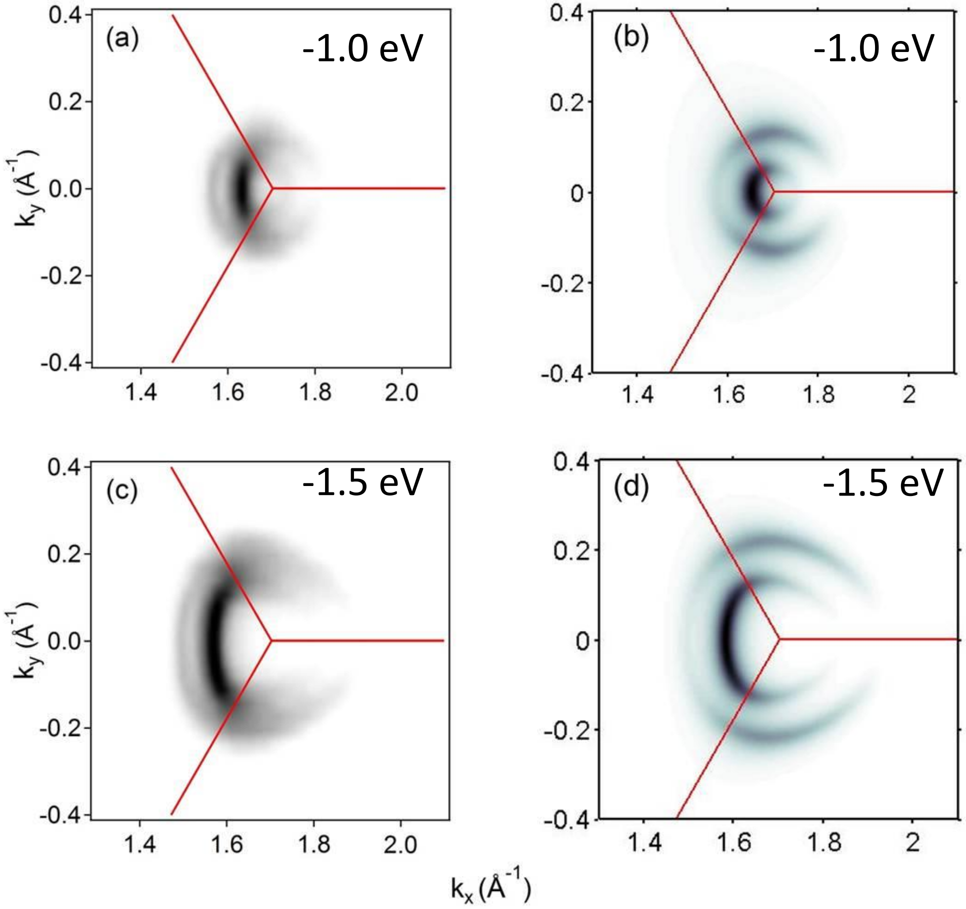
The electronic structure of bilayer graphene on SiC substrate

Data taken at 40 eV



Exp. at 82 eV

TB simulated



Cheng et al., submitted to PRB

A intrinsic gap exists or not ?

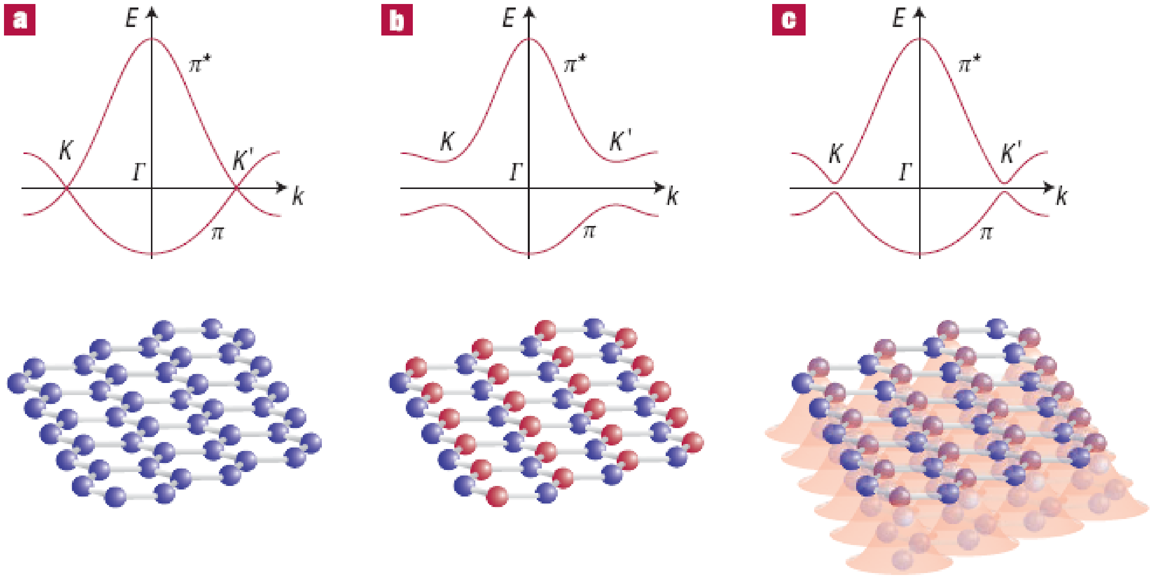


Figure 1 Schematic representation of crystal and electronic band structures (only π-bands are shown). **a**, Free-standing graphene. **b**, Boron-nitride. **c**, Epitaxial graphene. Symmetry between the sublattices in graphene guarantees gapless spectra around *K* points. This symmetry is broken in boron-nitride (one sublattice consists of boron atoms, another of nitrogen), which immediately opens a gap. In epitaxial graphene, the commensurate underlying potential gives rise to different on-site energies for the two sublattices, which opens a small gap around *K* points.

Novoselov, Nature Mat. (2007)