



Electron Spectroscopy Lab

Exploring electronic structure through spectroscopy



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Acknowledgements:

TIFR: PESLab, E. V. Sampathkumaran, A Thamizhavel,
PL Paulose, Bahadur Singh (DFT)

MK Sanyal (SINP), Tanusri and Priya (SNBNCBS),
Geetha Balakrishnan (St. Andrews).

Carlo Carbone (Elettra), Giovanni de Ninno (Slovenia),
Luca Petaccia (Elettra), Denis Vyalik (Germany), Saroj
Dash (Max IV Lab), Christoph Schlueter (Petra III),
Thomas Pruschke and Martin Wenderoth (Goettingen)

Funding

Major funding: DAE, Govt. of India.

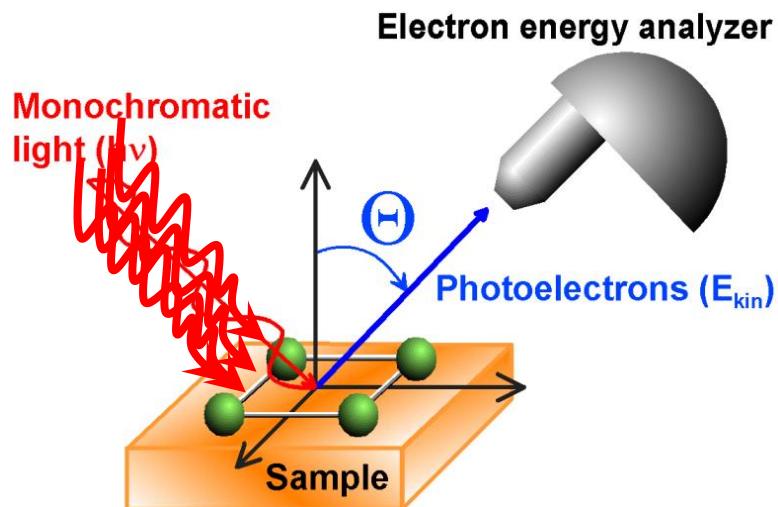
DAE-SRC-OI Award (BRNS, DAE),
Swarnajayanti Fellowship (DST), JC Bose
Fellowship (DST)

India-DESY Program (DST), Indo-Italian
Programme of cooperation (DST, Italian
Ministry of foreign affairs)

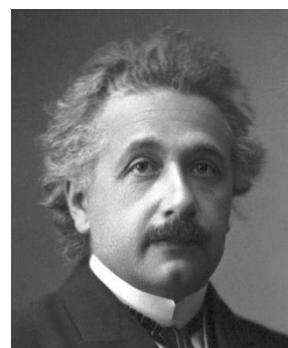
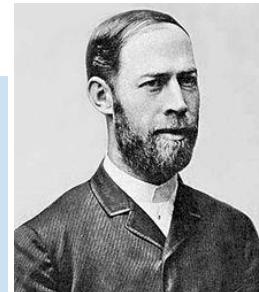


Workshop and International conference on Electronic
Structure Theory of Emergent Spin Orbit Driven Phenomenon

Photoemission spectroscopy



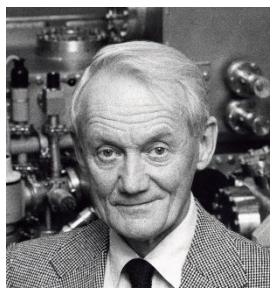
Heinrich Rudolf Hertz:
Discovered photoelectric
effect (1887)



Albert Einstein: Nobel
Prize (Physics, 1921)
"... for his
discovery of the law of the
photoelectric effect."



Karl Manne Siegbahn, Uppsala University
Nobel Prize (1924) for x-ray spectroscopy.



Kai Siegbahn, Uppsala University
Nobel Prize (1981) for developing the method of Electron
Spectroscopy for Chemical Analysis (ESCA), now usually described
as x-ray photoelectron spectroscopy (XPS).

PES using various types of photon sources

Laboratory source

XPS: x-ray photoemission spectroscopy [Al $K\alpha$ (1486.6 eV), Mg $K\alpha$ (1253.6 eV)]

UPS: ultra-violet photoemission spectroscopy [Helium I: 21.2 eV, 23.1 (1.5%), 23.7 (0.5%). He II: 40.8 eV, 48.4 (<10%), 51.0 (<1%)]

Laser-ARPES: Laser photoemission spectroscopy [energy < 10 eV]

SRPES: synchrotron radiation photoemission spectroscopy

VUVPES: photon energy in ultra-violet ranges

SXPES: soft x-ray photoemission spectroscopy

HAXPES: hard x-ray photoemission spectroscopy

Depending on the type of resolutions

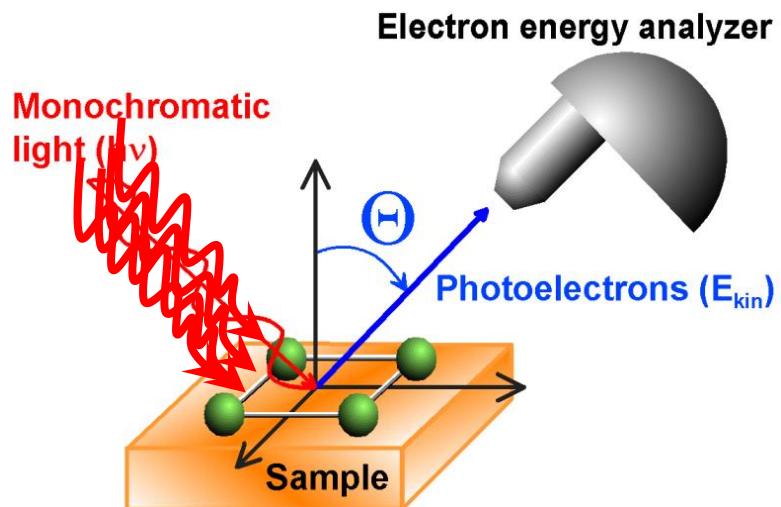
HRPES: high resolution (energy) photoemission spectroscopy

ARPES: angle-resolved photoemission spectroscopy

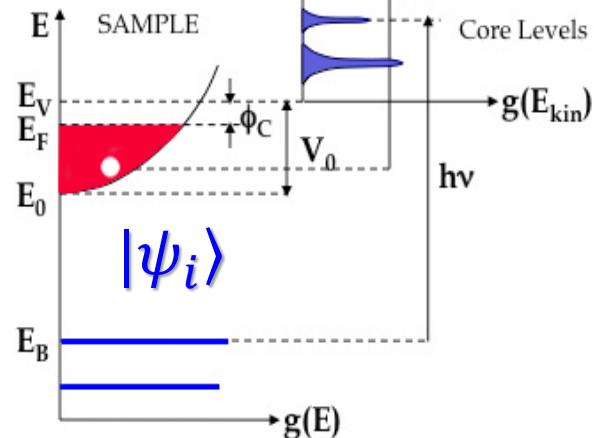
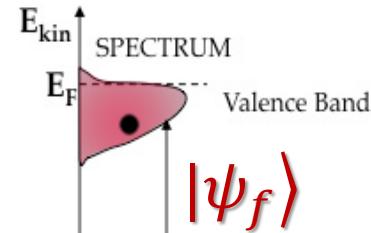
Tr-ARPES: time-resolved ARPES

SPPES: spin-resolved photoemission spectroscopy

Photoemission spectroscopy



Directly probes the spectral function of the occupied part of the electronic structure



Peak Intensity :

$$I(\epsilon) \propto \sigma(\epsilon) \cdot R(\epsilon) \cdot L(\epsilon) \cdot e^{-x/\lambda} \cdot DOS$$

$R(\epsilon)$ = Resolution broadening

$L(\epsilon)$ = Lifetime broadening (electron and hole)

$\sigma(\epsilon)$ = Photoemission cross-section

λ = inelastic mean free path of photoelectron

- Probes the (local) spectral function at a fast time scale.
- Sensitive to orbital character of the electronic states
- Surface sensitivity can be tuned to learn surface and bulk electronic structure

Photoemission intensity

$$I(\epsilon) \propto \sigma(\epsilon).R(\epsilon).L(\epsilon).e^{-x/\lambda}.DOS$$

The transition probability from *Fermi's Golden rule*

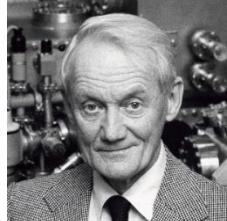
$$\sigma(\epsilon) \propto |\langle \psi_f | A.p | \psi_i \rangle|^2 \delta(\epsilon_f - \epsilon_i - h\nu)$$

↑
Matrix element

Conservation rules (four quantum numbers in solid)

1. Energy: $h\nu = \epsilon_f - \epsilon_i = \epsilon_{bin} + \epsilon_{kin} + \varphi$ $\varphi \Rightarrow$ work function
2. Momentum: $k_f = k_i \pm G$ G = Reciprocal lattice vector
3. Spin: $\Delta s = 0$
4. Symmetry

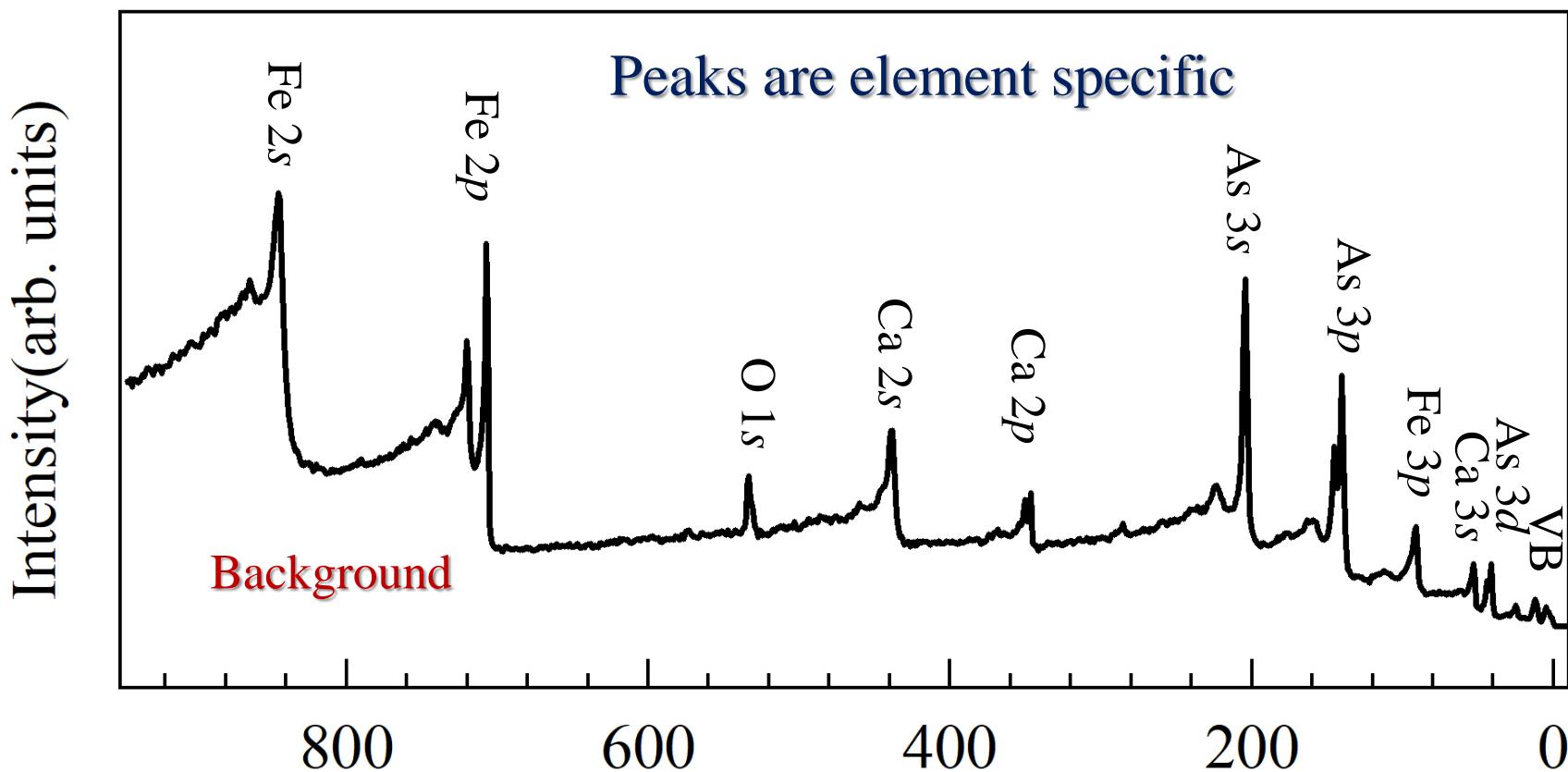
Once you know these four quantities, you know everything about the electronic structure → electronic properties



XPS data

20	Ca 2s 2p 3s 3p 4s	430. 356. 52. 33. 5.4	26	Fe 2s 2p 3s 3p 3d	829. 722. 98. 66. 7. 13.1	33	As 2s 2p 3s 3p 4s As 3d 4p	1479. 1330. 195. 144. 17. 52. 7.9
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Atomic Data and Nuclear Data Tables 32, 1-155 (1985)



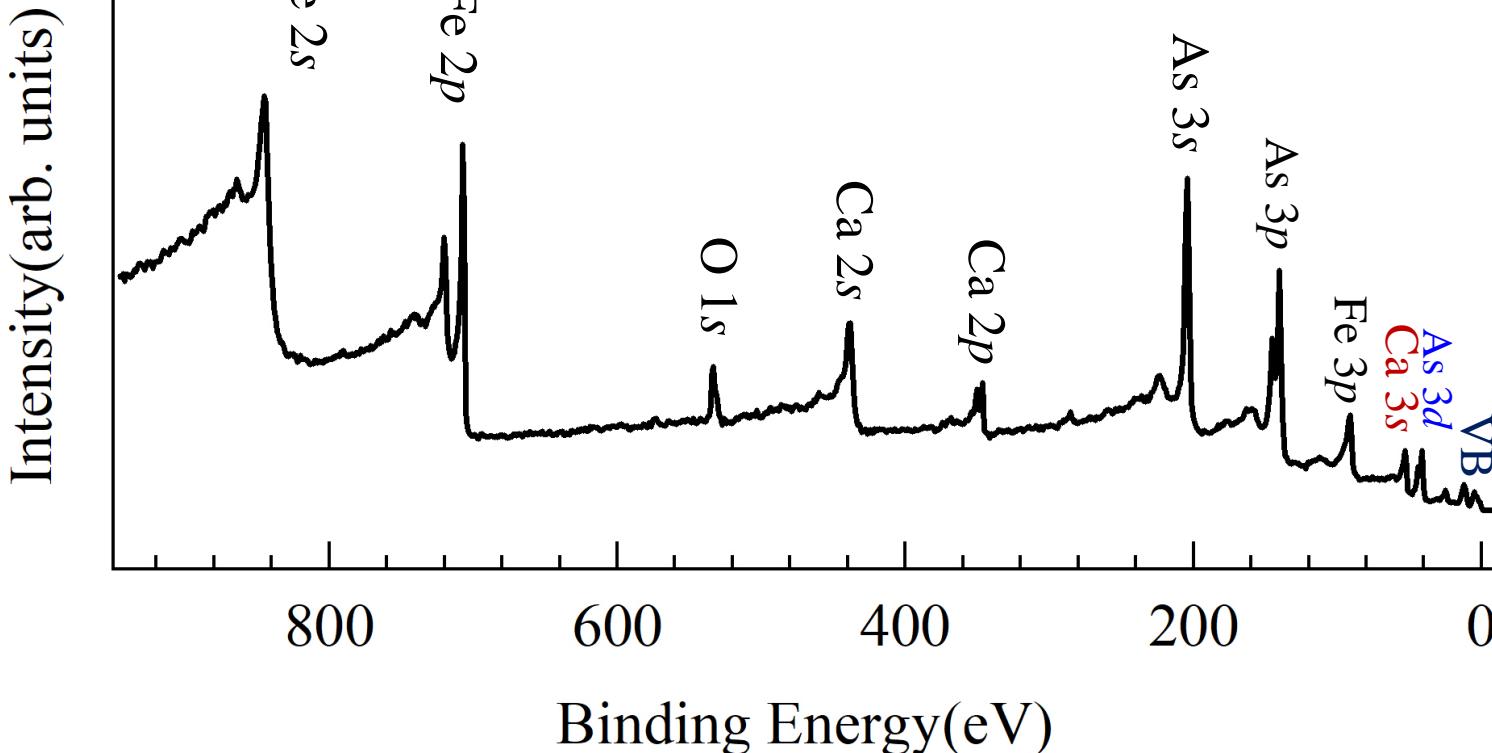
ESCA

Electron Spectroscopy for Chemical Analysis

How to find the compound ?

Amount of each element from **peak intensity**: area under the curve weighted by photoemission cross section.

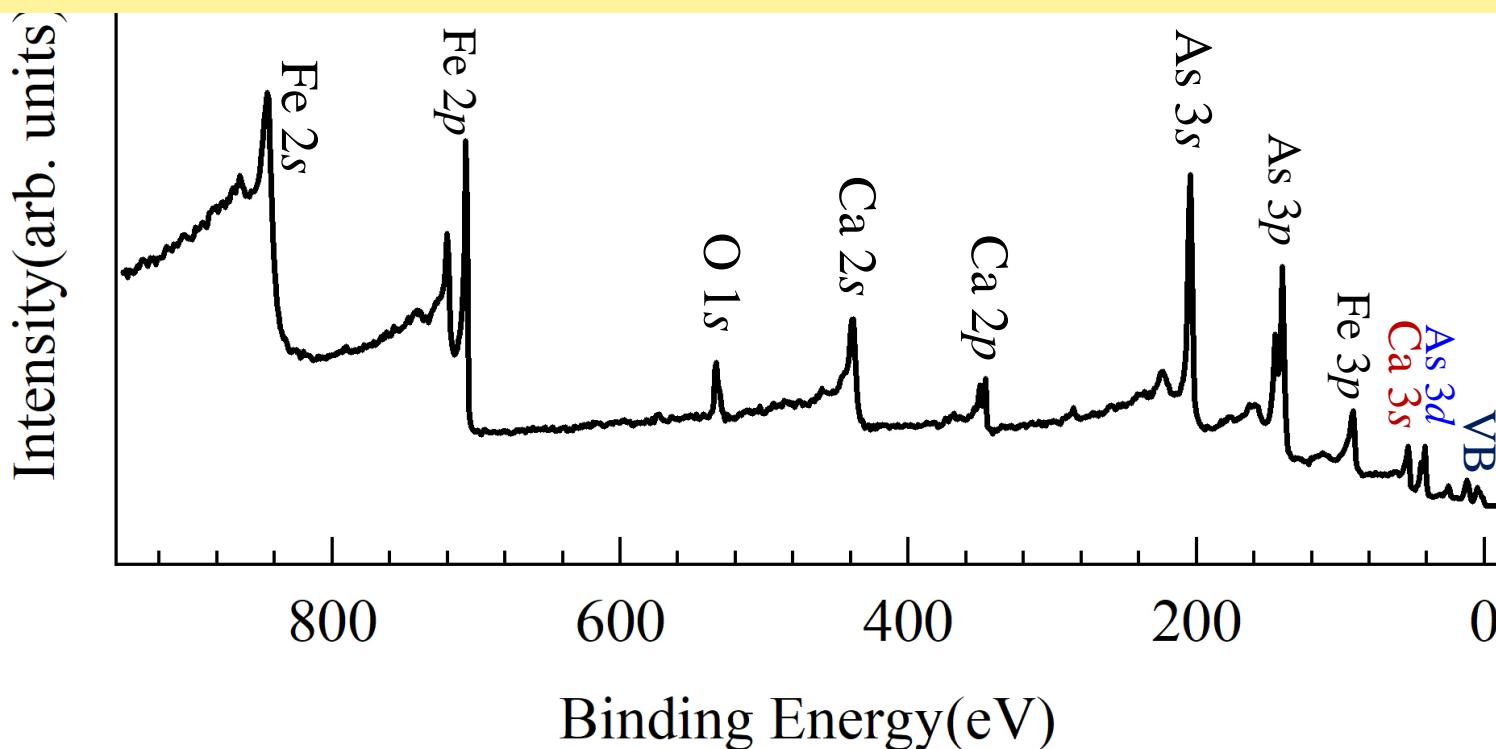
Problem: don't know exact energy range for a peak, background, cross-section may vary due to solid state effects



How to find the compound ?

Valency: – if one knows valency correctly, it is easy as each material is charge neutral – binding energy depends on valency. More positive charge, more difficult to knock out electrons → binding energy is higher.

Problem: determination of valency is difficult, multiple valency, materials are not ionic, final state effects



How to find the compound ?

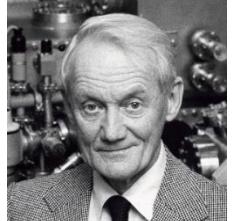
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Problem: determination of valency is difficult, multiple valency, materials are not ionic, final state effects

So, one has to use both the methods carefully

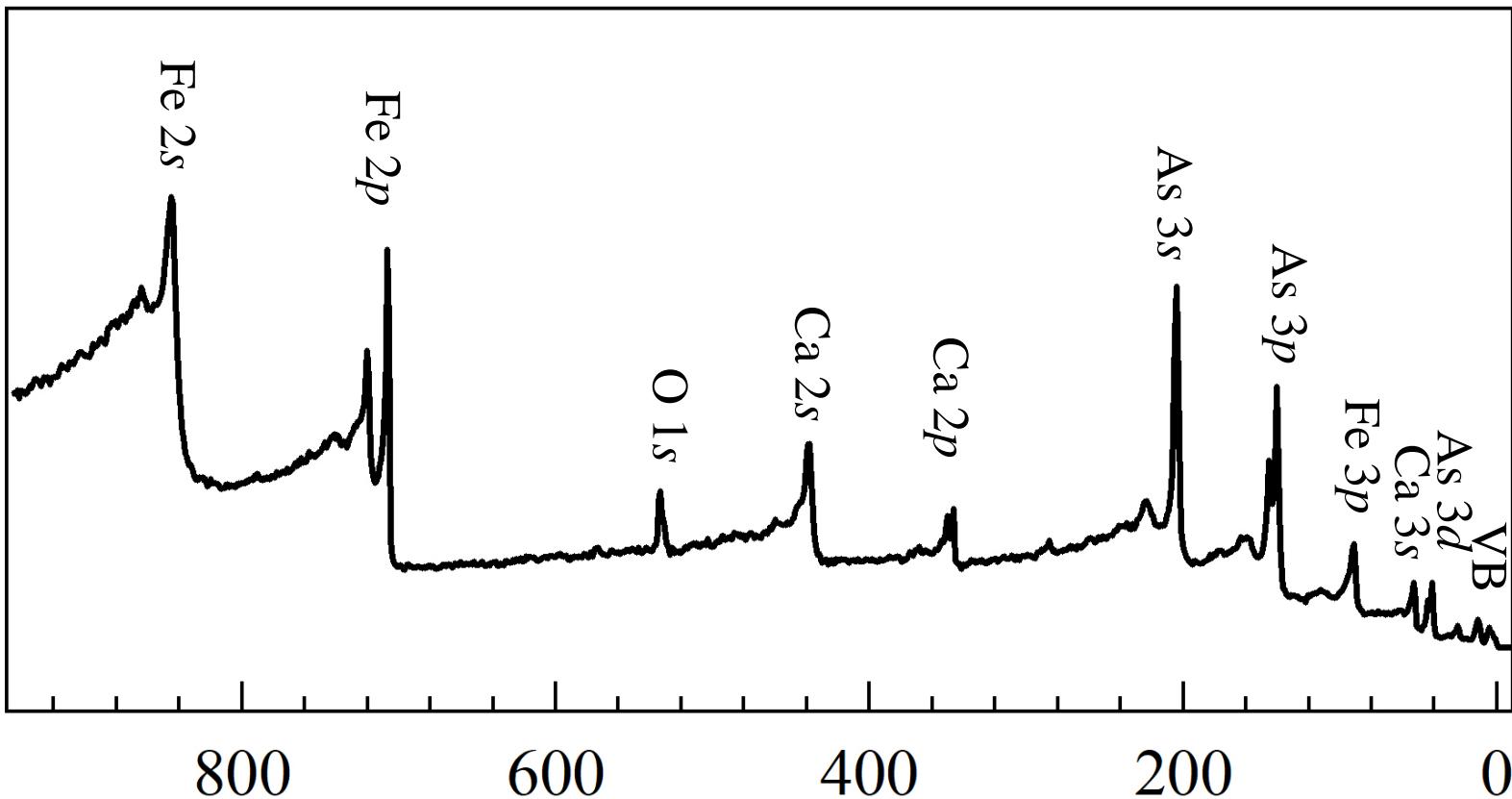


XPS

20	Ca	2s	829	3	As	2s	1479	2
	Ca	2p	722	2	As	2p	1330	9
	Ca	3s	98	3	As	3s	195	6
	Ca	3p	66	3	As	3p	144	0
	Ca	4s	7	4	As	4s	17	4
26	Fe	2s	13.1	As	3d	52	0	0
	Fe	2p		As	4p	7	7	9
	Fe	3s						
	Fe	3p						
	Fe	3d						

Atomic Data and Nuclear Data Tables 32, 1-155 (1985)

Intensity(arb. units)



ESCA

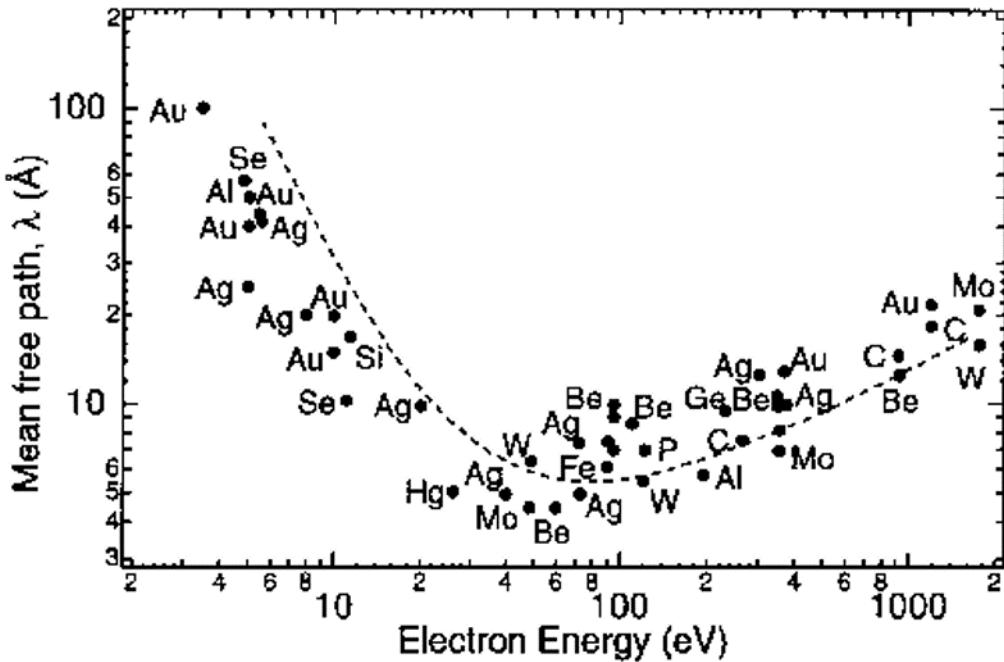
Electron Spectroscopy for Chemical Analysis

Binding Energy(eV)

CaFe_2As_2

Electron escape depth

$$I(\epsilon) \propto \sigma(\epsilon).R(\epsilon).L(\epsilon).e^{-x/\lambda}.DOS$$

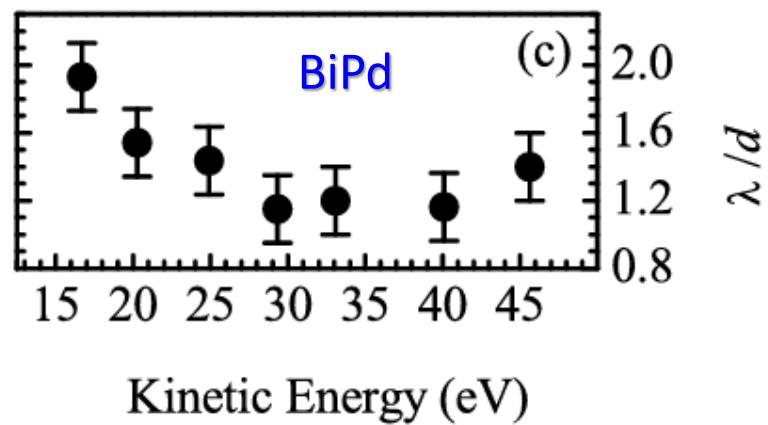


Minimum $\rightarrow \sim 40 - 100$ eV

Low energy side \rightarrow increases rapidly

High energy side $\rightarrow \lambda \propto \sqrt{\epsilon_{kin}}$

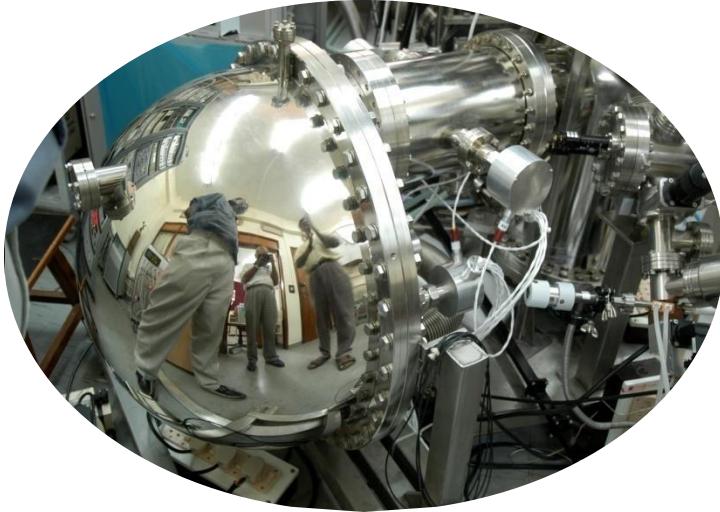
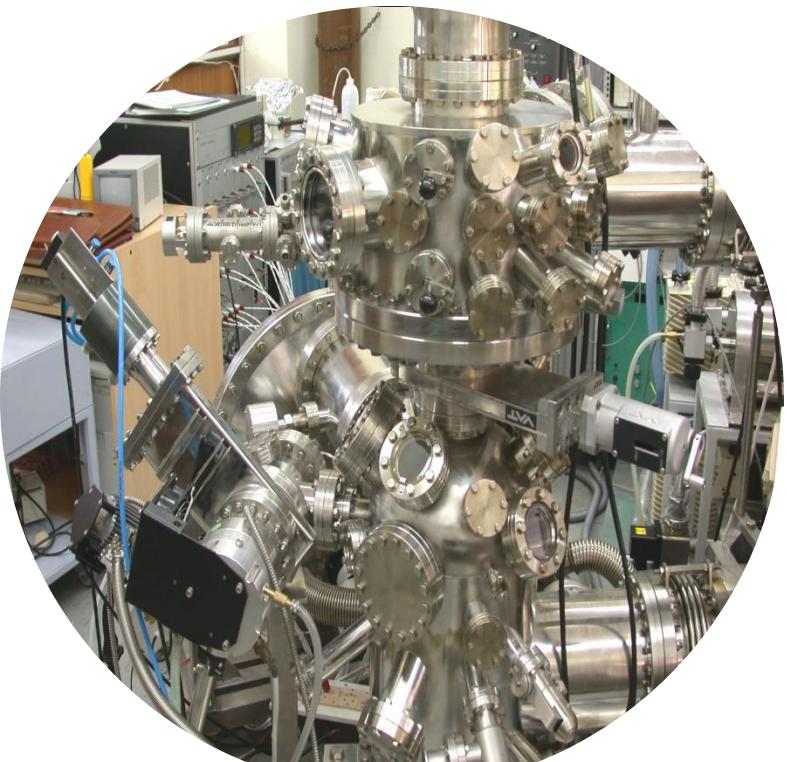
Quality is the key



How such spectrometers are made

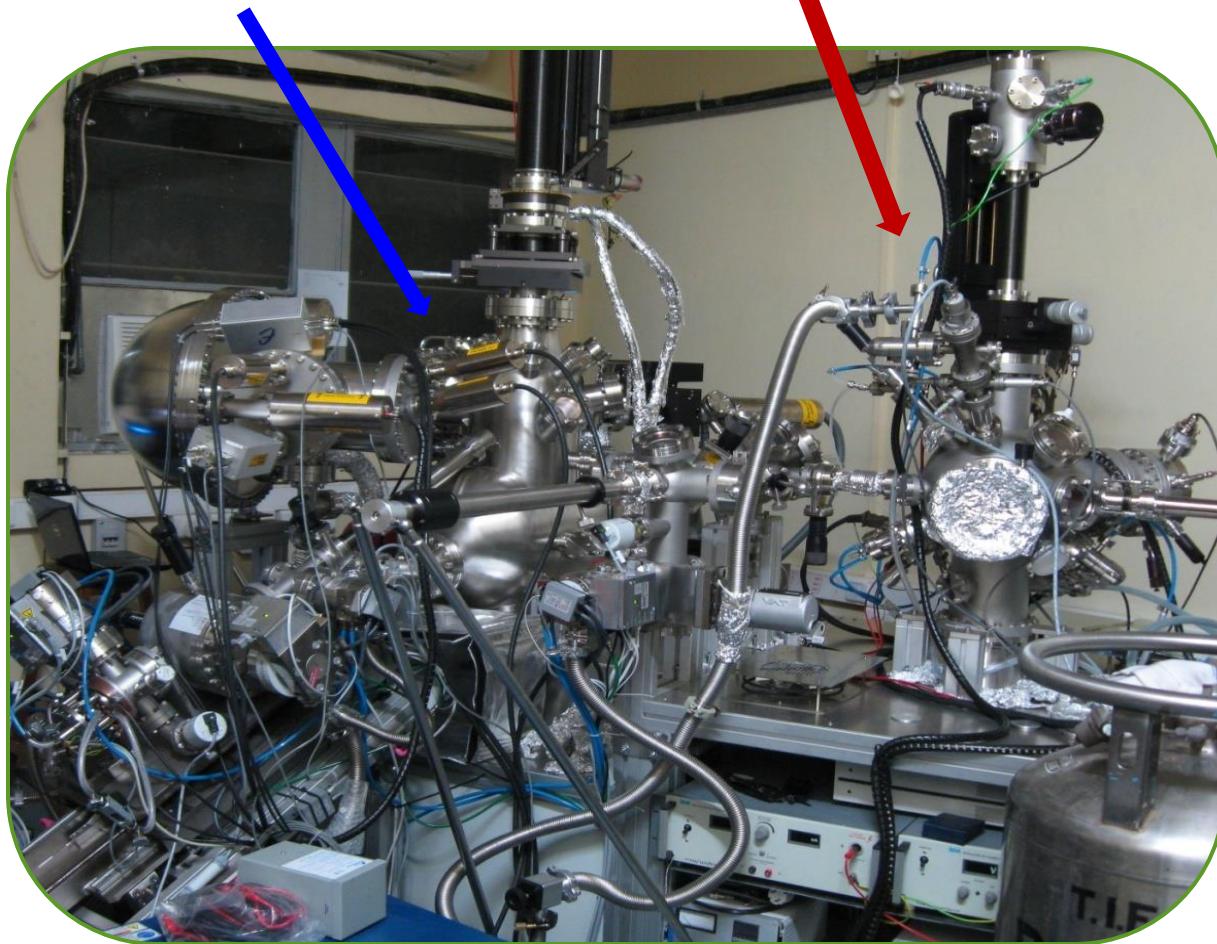
- Ultra high vacuum (UHV)
 - ~ 10^{-11} torr (~ 10^{-14} atm)
 - Vacuum Pumps, vacuum measurement system, photon sources and electron detectors.
- Screening of external fields : Magnetic, electrostatic *etc*
- Sample manipulations inside UHV chamber
- Sample preparation facility inside UHV chamber.
- Sample characterization
- Sample cooling facility *etc...*

HIGH RESOLUTION ARPES AT TIFR

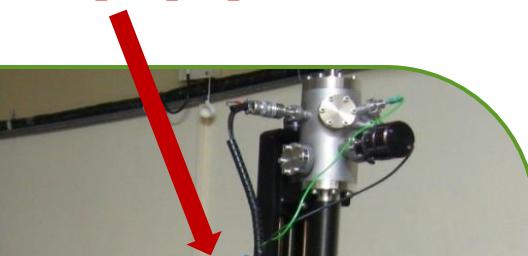


Spin Resolved Photoemission (SRPES) and High Resolution Electron Energy Loss Spectrometer (HREELS)

Spectrometer chamber



Sample preparation chamber



HREELS



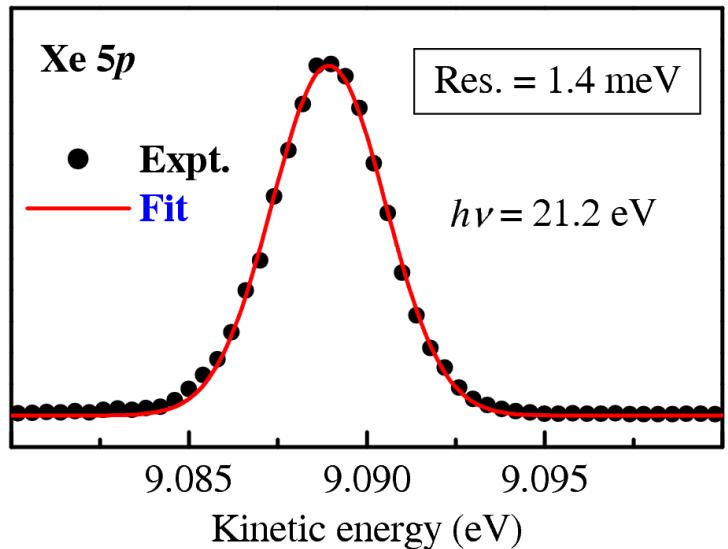
Mott Detector



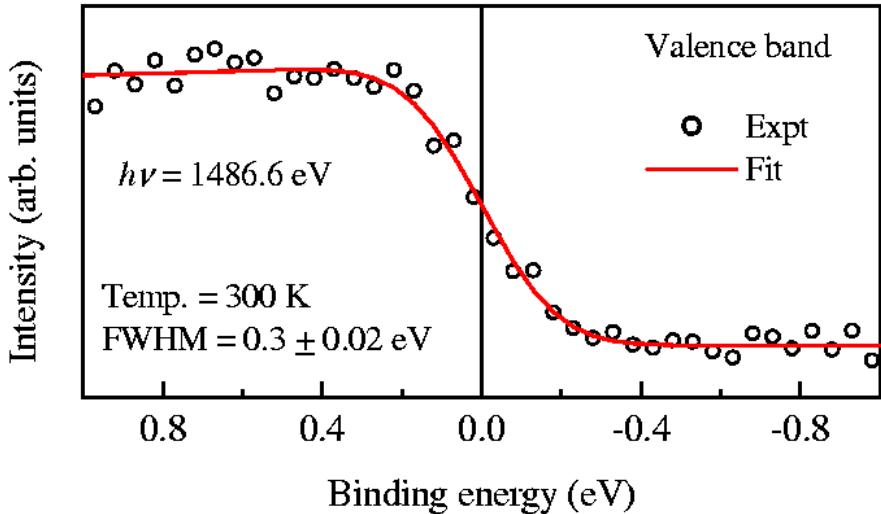
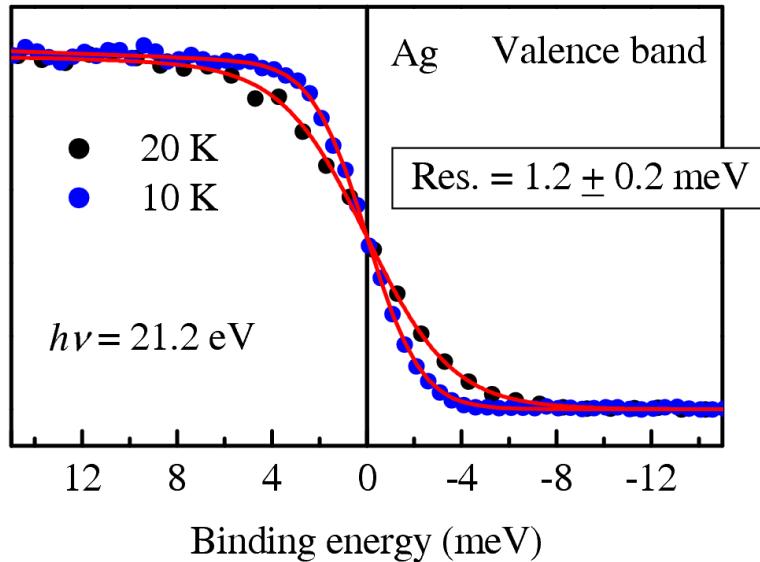
The whole system is kept in ultra high vacuum condition

ENERGY RESOLUTION

Intensity (arb. units)



Intensity (arb. units)



Energy resolution at 50 eV pass energy and 1486.6 eV photon energy $\sim 300 \text{ meV}$

Photon energy = 21.2 eV

Pass energy = 2 eV

Polycrystalline high purity Ag

Resolution $\sim 1.4 \text{ meV}$

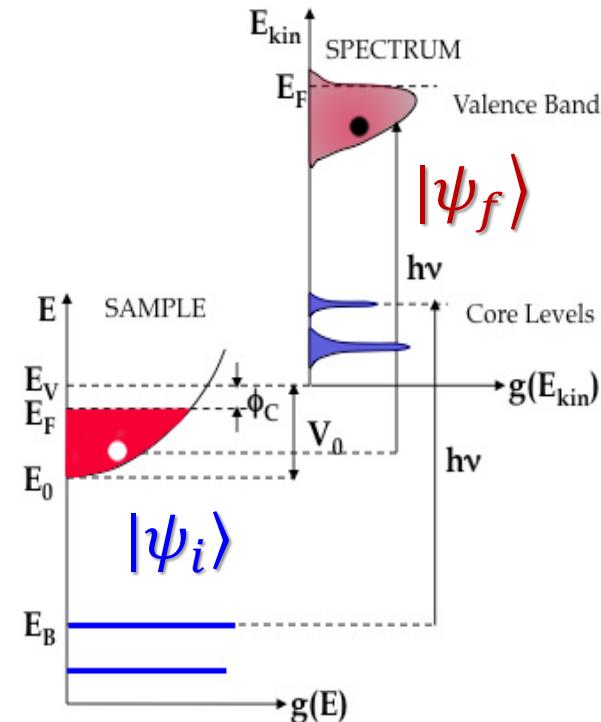
Photoemission intensity

$$I(\epsilon) \propto \sigma(\epsilon) \cdot R(\epsilon) \cdot L(\epsilon) \cdot e^{-x/\lambda} \cdot DOS$$

The transition probability - *Fermi's Golden rule*

$$\sigma(\epsilon) \propto |\langle \psi_f | A \cdot p | \psi_i \rangle|^2 \delta(\epsilon_f - \epsilon_i - h\nu)$$

Matrix element



$|\psi_f\rangle$ is the final state, which is detected by the detector and $|\psi_i\rangle$ is the initial state

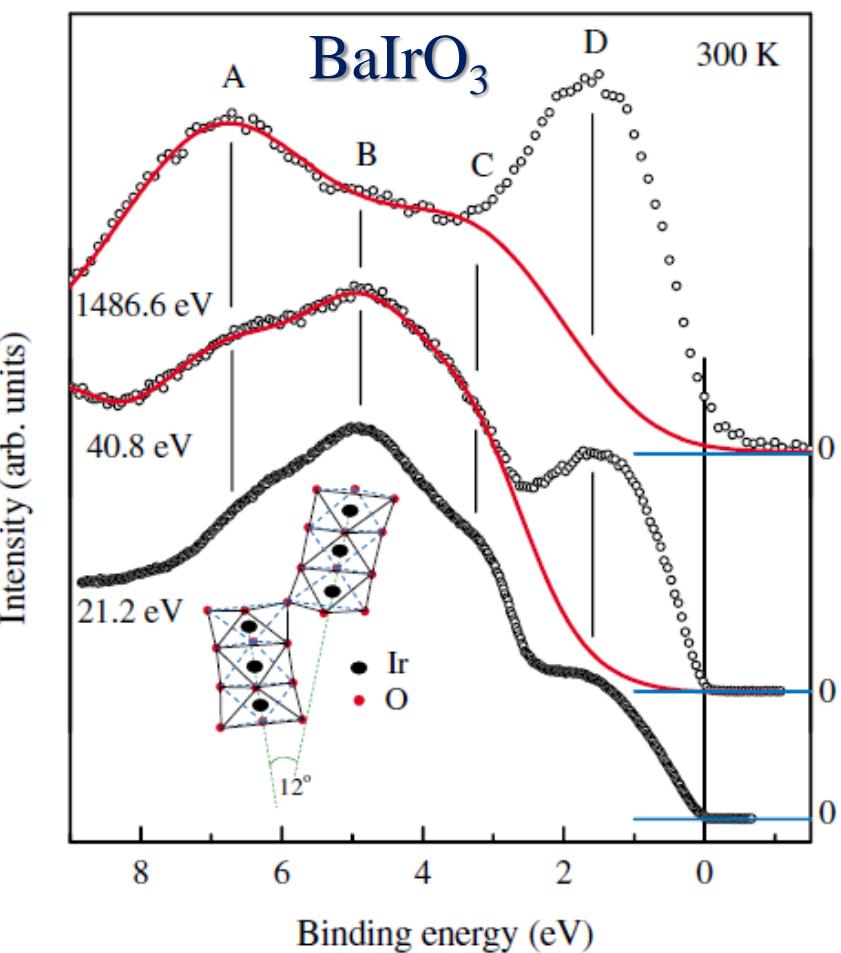
→ Energy of the photoelectrons is high (photon energy is about 10 eV – 10 keV)

→ free electrons like (frequency of oscillation depends on kinetic energy)

→ they represent the photoemission from a state, $|\psi_i\rangle$

seems like initial state derives photoemission signal ☺

Matrix element effect $|\langle \psi_f | A.p | \psi_i \rangle|^2$



$$\text{Bonding} \Rightarrow (|\psi_1(x)\rangle + |\psi_2(x)\rangle)$$

$$\text{Antibonding} \Rightarrow (|\psi_1(x)\rangle - |\psi_2(x)\rangle)$$

Although the same thing is studied

→ different photon energy gives different response !

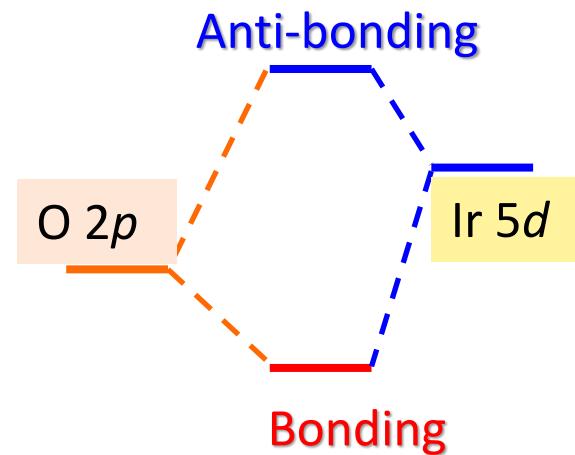
Total **four** distinct peaks

B and C are weak in XP spectrum
B&C → non-bonding oxygen

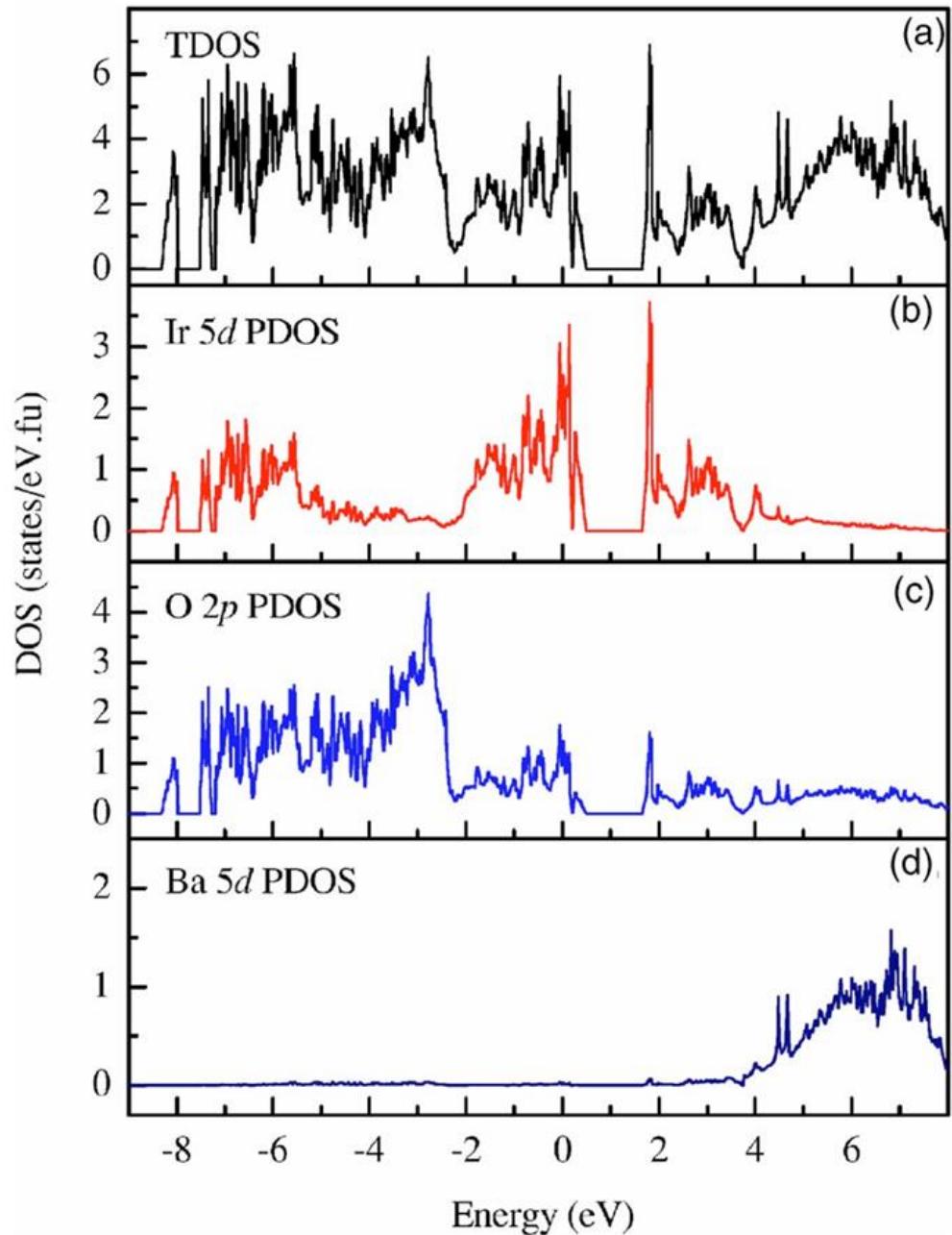
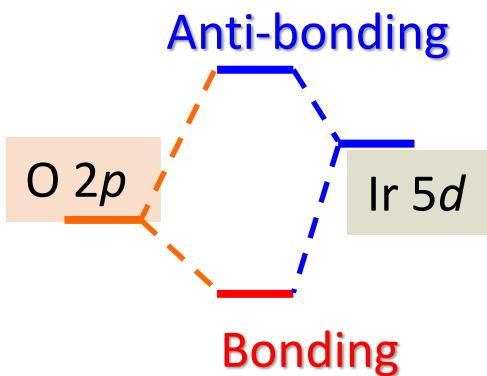
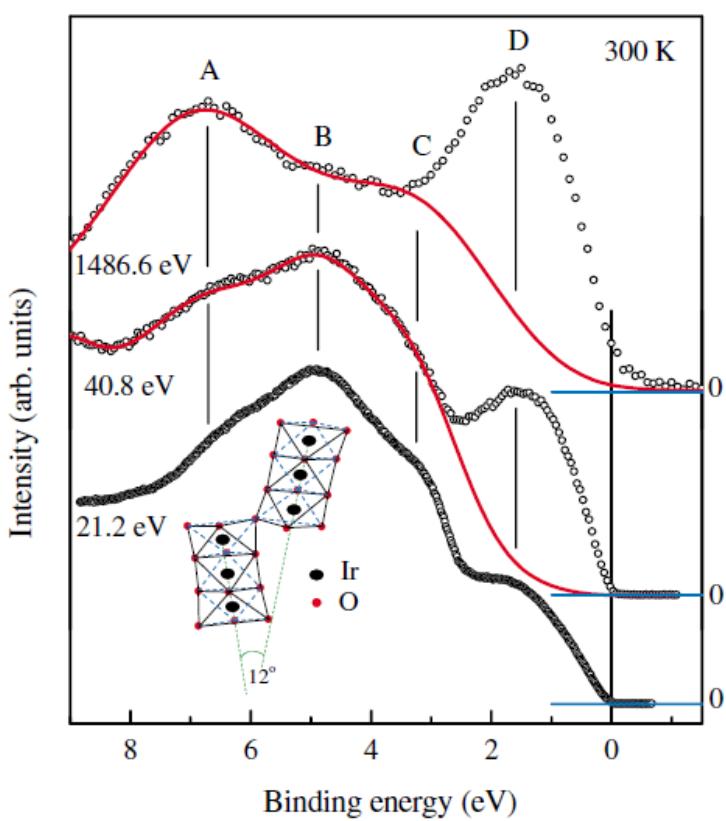
A & D present in all the spectra

A → change in intensity less strong
→ Dominant O 2p

D → Change in intensity is strongest
→ Dominant Ir 5d

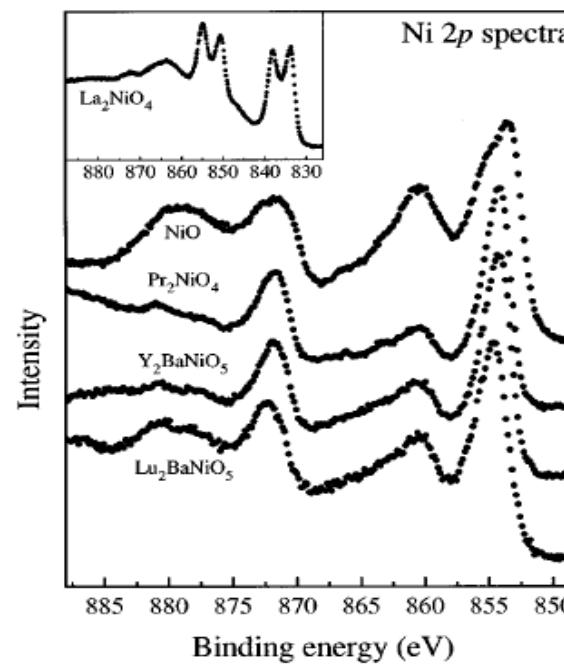
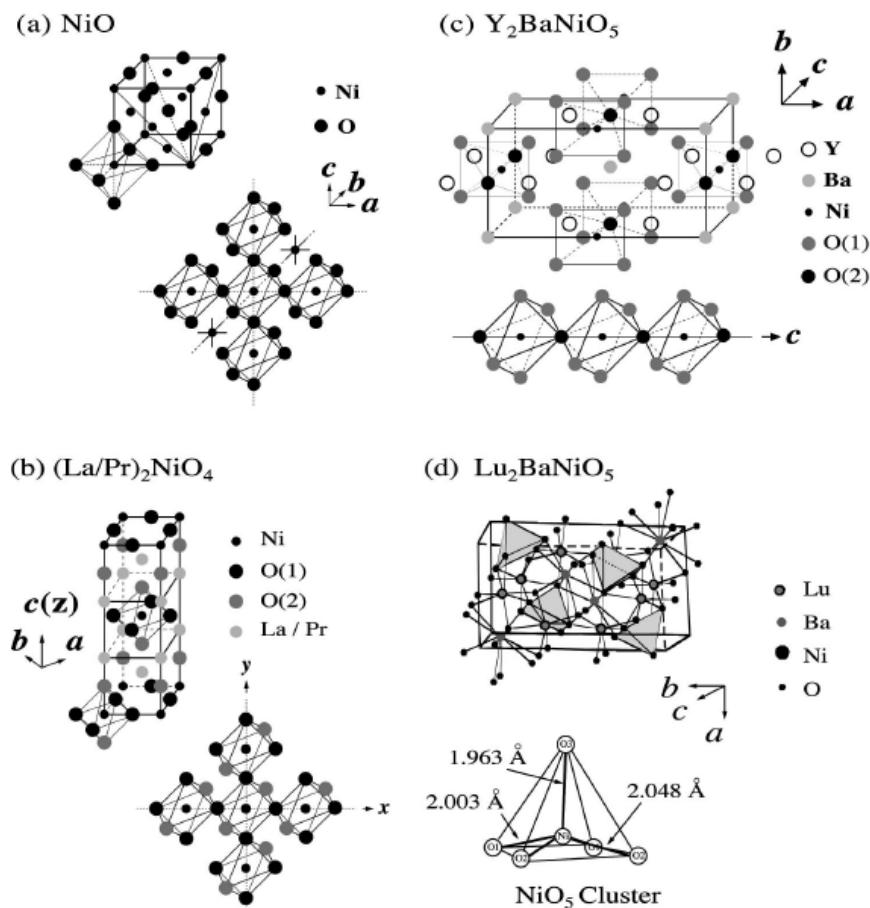


Matrix element effect



Evolution of electronic structure with dimensionality in divalent nickelates

K. Maiti, Priya Mahadevan,* D. D. Sarma†



Many peaks !!

Final state effect

Things are not so simple !!

Let's think the scenario in a slightly different way

Ground state, $|n\rangle \Rightarrow |n - 1\rangle + e$ → properties of the detected electron is linked to the $|n - 1\rangle$ state via various conservation rules.

Since, $|n - 1\rangle$ state is an excited states, it can assume any of the eigenstate of the final state Hamiltonian → if it has say 5 excited states, we get 5 peaks for the photoemission from one initial state, $|n\rangle$

Means, for excitation from a state, $|\psi_i\rangle$, the energy of the photoelectron depends on in which $|n - 1\rangle$ state it has left the material behind.

Final state effect

Ground state, $|n\rangle \Rightarrow |n-1\rangle + e$ → properties of the detected electron is linked to the $|n-1\rangle$ state via various conservation rules.

$$h\nu = \epsilon_{bin} + \epsilon_{kin} + \varphi$$

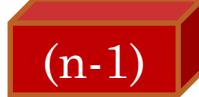
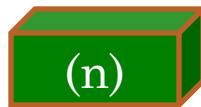


$$\epsilon_{bin} = h\nu - \epsilon_{kin} - \varphi$$

$$+ e \text{ ---}$$

$$+ e \text{ ---}$$

$$+ e \text{ ---}$$



- Energy of electron + energy of $(n-1)$ state is fixed by the photon energy
- For higher final state energy, electron KE is lower → peak at higher BE!!

Higher binding energy in PES doesn't always mean more stable state.

- Although excitation is from one state, we get three peaks here!!

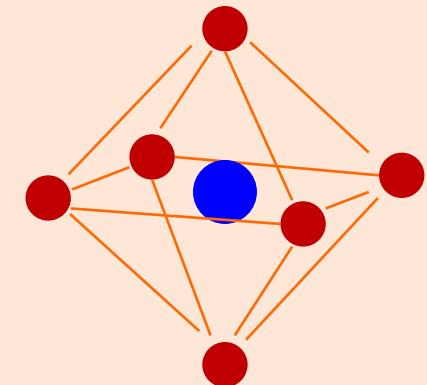
Photoemission spectrum is essentially derived by the final states

Let's put things in better perspective – process for core level PES

Ground state, $|n\rangle \xrightarrow{h\nu} |n-1\rangle + e$ → properties of the detected electron is linked to the $|n-1\rangle$ state via various conservation rules.

Since, $|n-1\rangle$ state is an excited state, it can assume any of the eigenstates of the final state Hamiltonian → A typical **final state Hamiltonian** in a transition metal oxide is written as

$$\begin{aligned}
 H = & \sum_{\alpha,\sigma} \epsilon_{d\alpha} d_{\alpha\sigma}^\dagger d_{\alpha\sigma} + \sum_{i,\sigma} \epsilon_p p_{i\sigma}^\dagger p_{i\sigma} + \sum_{\alpha i, \sigma} (t_{dp}^{\alpha i} d_{\alpha\sigma}^\dagger p_{i\sigma} + h.c) + \sum_{ij, \sigma} (t_{pp}^{ij} p_{i\sigma}^\dagger p_{j\sigma} + h.c) \\
 & + \sum_{\alpha\beta\gamma\delta, \sigma_1\sigma_2\sigma_3\sigma_4} U_{dd}^{\alpha\beta\gamma\delta} d_{\alpha\sigma_1}^\dagger d_{\beta\sigma_2}^\dagger d_{\gamma\sigma_3} d_{\delta\sigma_4} \\
 & + \sum_{\mu,\sigma} \epsilon_c c_{\mu\sigma}^\dagger c_{\mu\sigma} + \sum_{\alpha\beta\mu\nu, \sigma_1\sigma_2\sigma_3\sigma_4} U_{dc}^{\alpha\beta\mu\nu} d_{\alpha\sigma_1}^\dagger d_{\beta\sigma_2} c_{\mu\sigma_3}^\dagger c_{\nu\sigma_4} \\
 & + \sum_{\mu\nu, \sigma\sigma'} \xi_{2p}^{\mu\nu} \langle \mu | l.s | \nu \rangle c_{\mu\sigma}^\dagger c_{\mu\sigma'}
 \end{aligned}$$



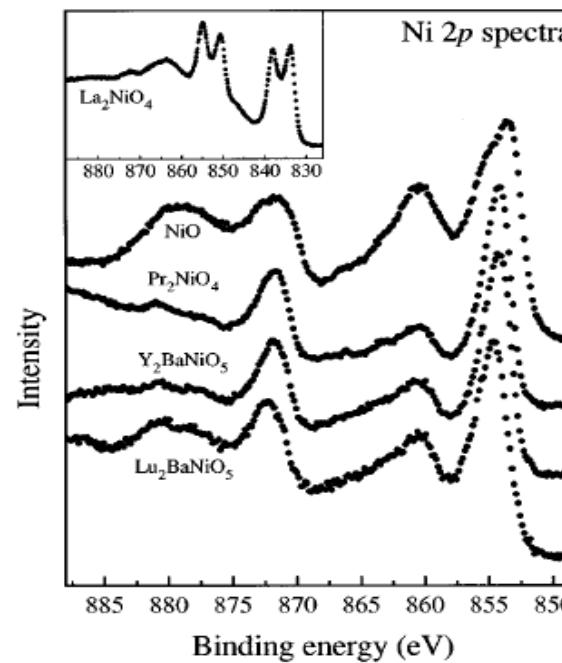
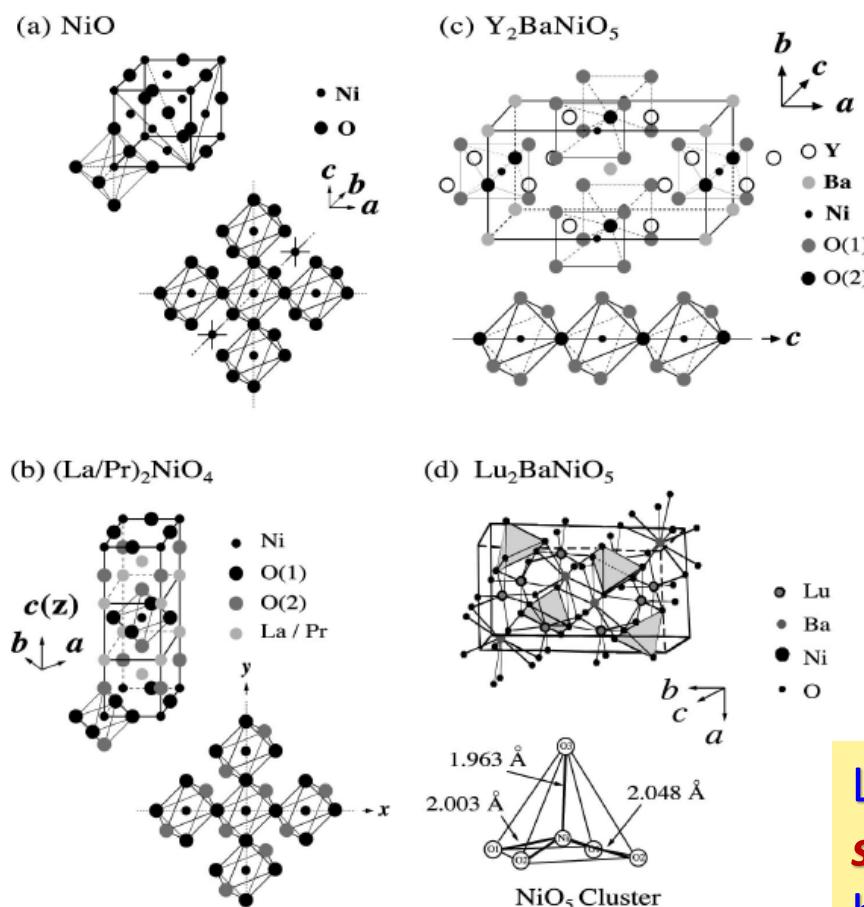
If U is zero, $|\psi_f\rangle$ will be similar to $|\psi_i\rangle$. $|\psi_f\rangle$ s are orthogonal → overlap integral with $|\psi_i\rangle$ is non-zero essentially for the lowest energy state.

$$\sigma(\epsilon) \propto |\langle \psi_f | A.r | \psi_i \rangle|^2$$

If U is non-zero, an electron in $|\psi_i\rangle$ may get excited to any of the eigenstates, $|\psi_f\rangle$ producing multiple signals for the same core level excitation.

Evolution of electronic structure with dimensionality in divalent nickelates

K. Maiti, Priya Mahadevan,* D. D. Sarma†



Many peaks due to final state effects.
Relative intensities are different in different dimensions!!
Spin-orbit splitting

Lowest binding energy peak is called **well screened peak** – screening of the core hole by an electron from the ligands.

Higher binding energy peaks are poorly screened peaks – core hole is not screened by electrons from neighbours → these are called **satellites**

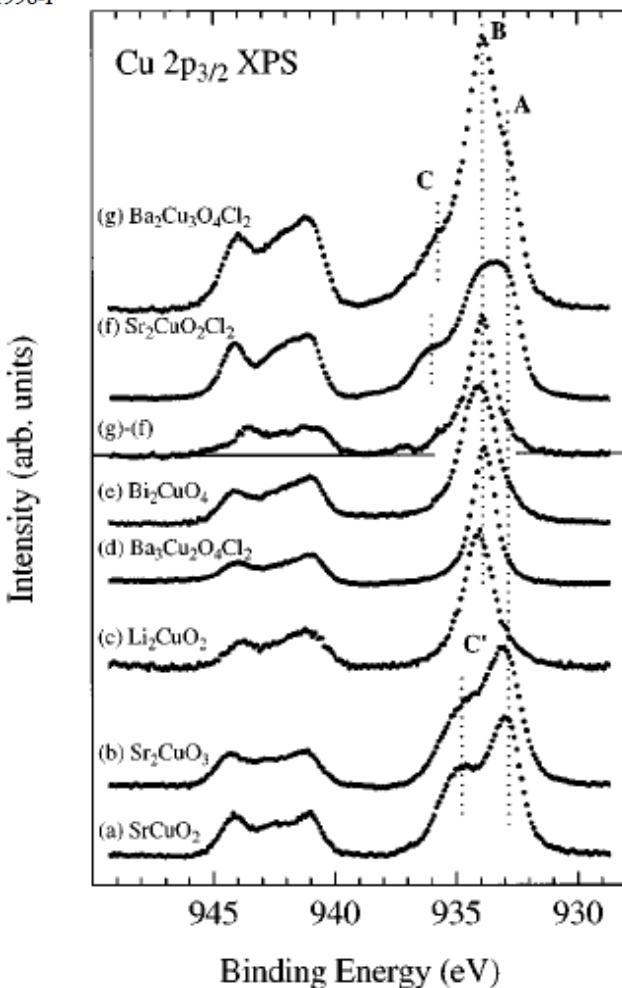
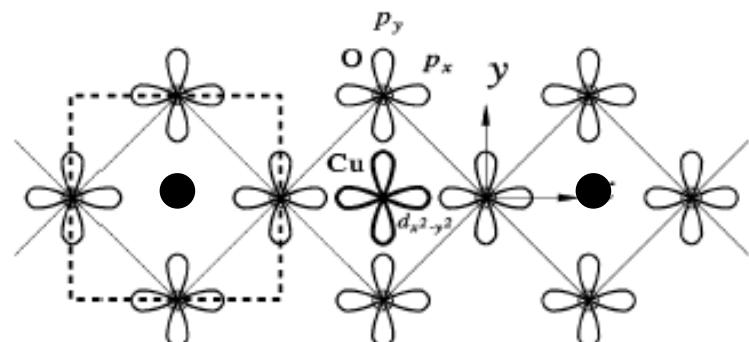
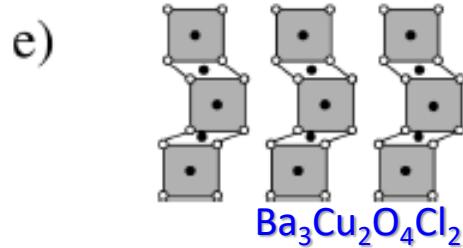
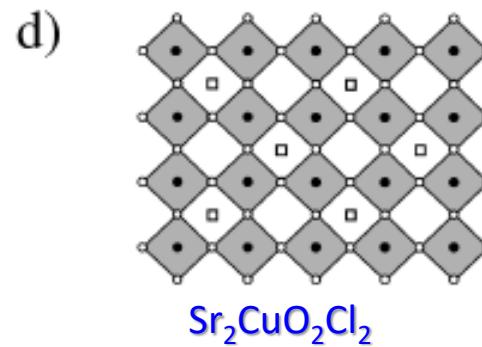
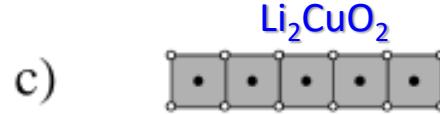
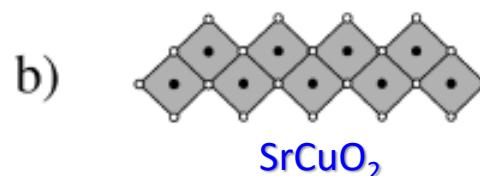
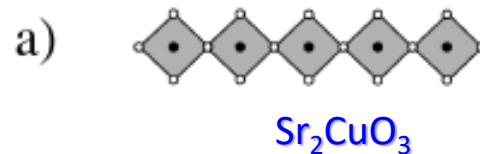
Cu-O network-dependent core-hole screening in low-dimensional cuprate systems: A high-resolution x-ray photoemission study

T. Böske,* K. Maiti,[†] O. Knauff, K. Ruck, M. S. Golden, G. Krabbes, and J. Fink

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T. Osafune, N. Motoyama, H. Eisaki, and S. Uchida

Department of Superconductivity, Faculty of Engineering, University of Tokyo, Yayoi 2-11-16, Bunkyo-ku, Tokyo 113, Japan



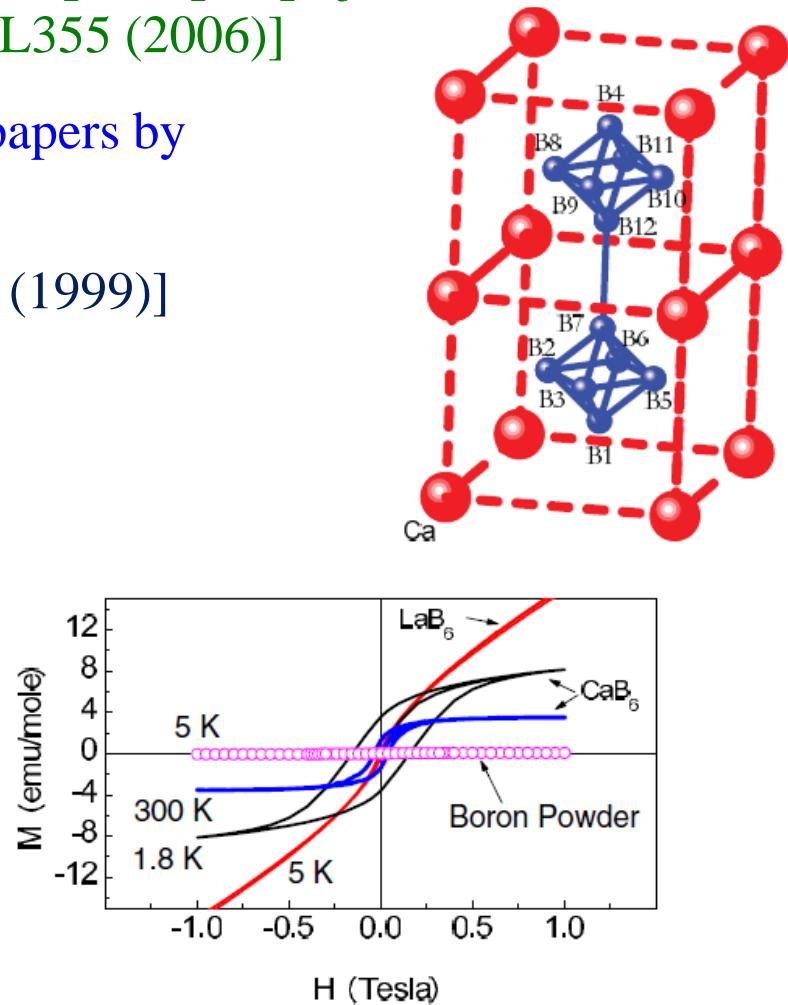
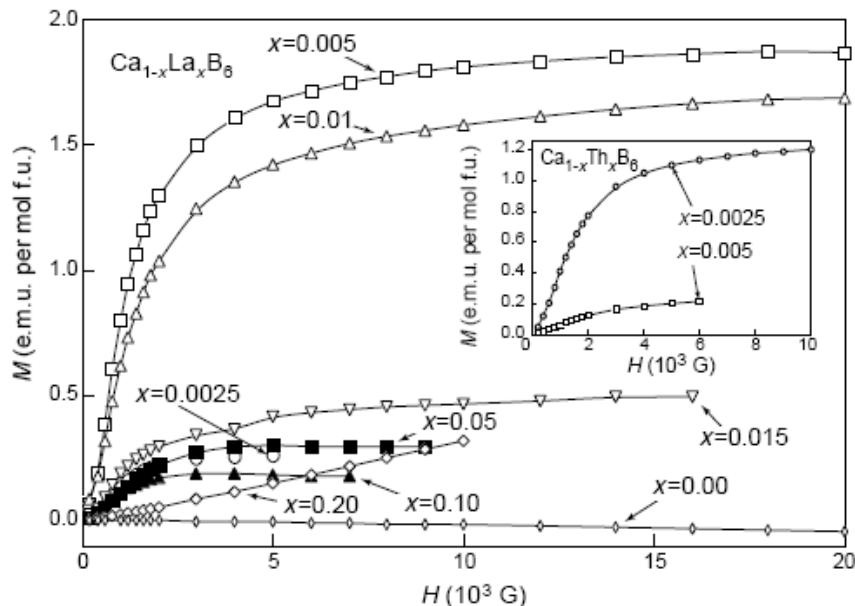
Well screened peak consists of
multiple features A, B and C

Screened peak energy depends on the location of the hole, it's itineracy and it's interaction with the carriers located at other sites.

Unusual ferromagnetism in non-magnetic materials

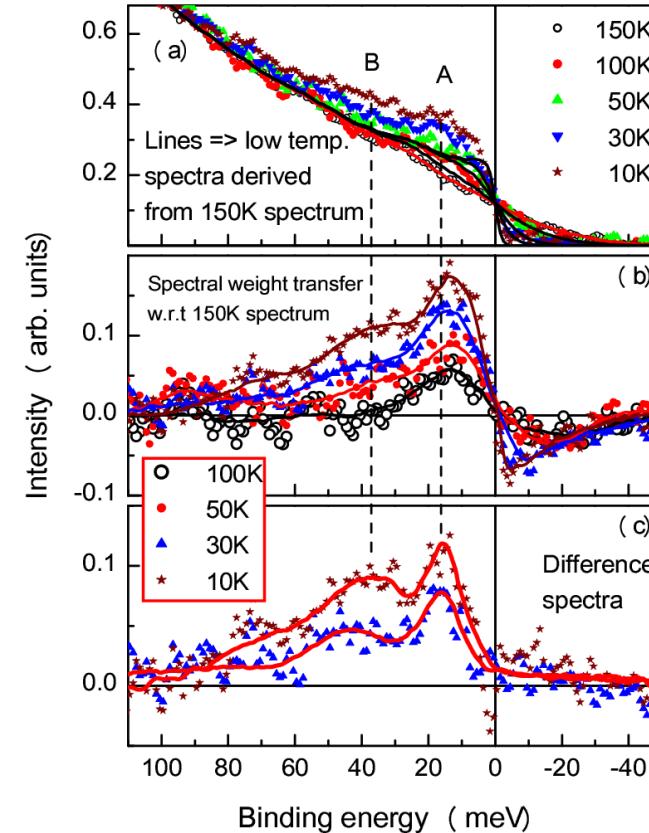
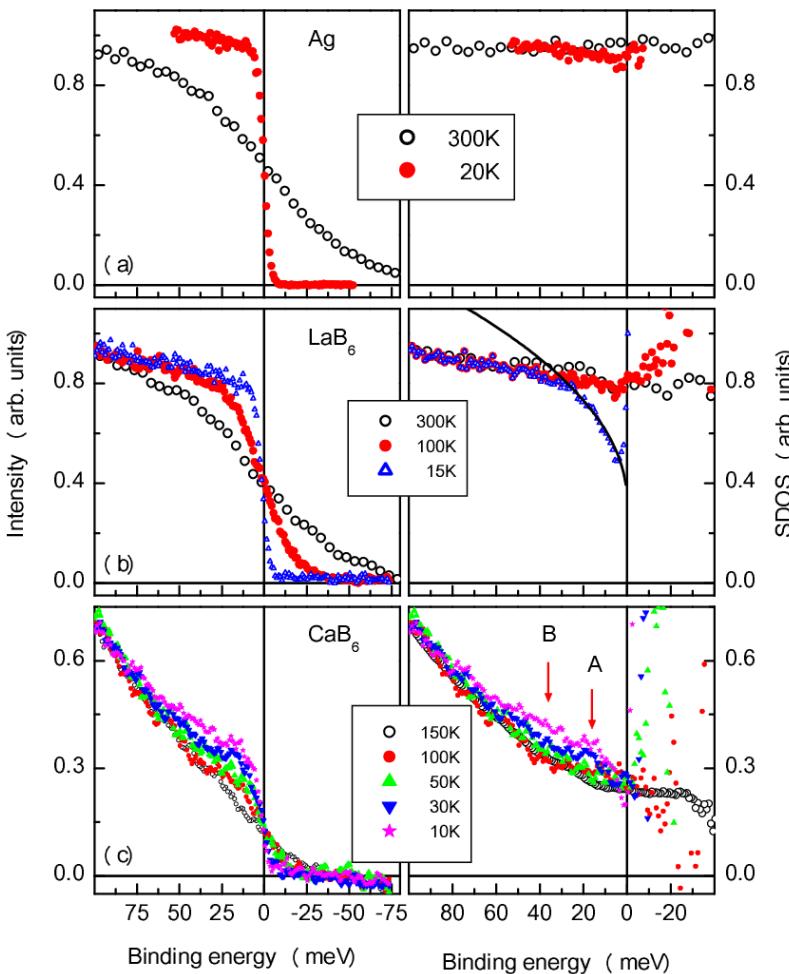
Many materials in varied forms exhibit ferromagnetism although there is no magnetic element present in the material.

- Thin films of nonmagnetic oxides such as HfO_2 , TiO_2 , In_2O_3 [Nature **430**, 630 (2004); PRB **73**, 132404 (2006); JPCM **18**, L355 (2006)]
- CeO_2 , TiO_2 , Al_2O_3 , MgO , ZnO , etc. [many papers by Prof. C. N. R. Rao]
- CaB_6 ...[D.P. Young *et al.* Nature **397**, 412 (1999)]



Revelation of the Role of Impurities and Conduction Electron Density in the High Resolution Photoemission Study of Ferromagnetic Hexaborides

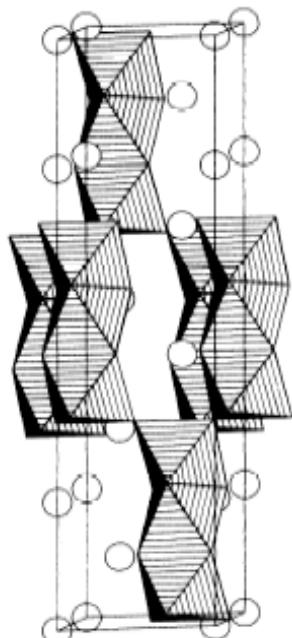
Kalobaran Maiti,* V. R. R. Medicherla, Swapnil Patil, and Ravi Shankar Singh



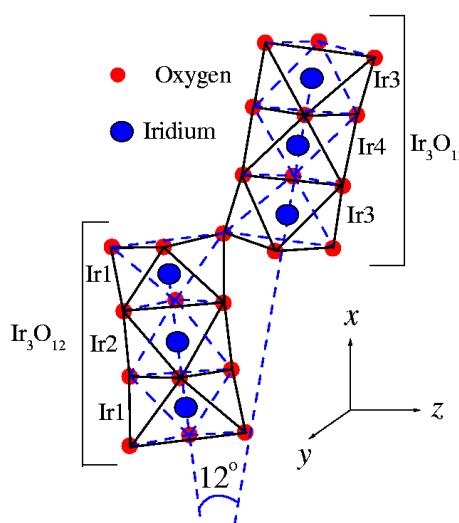
B 2p electrons behave like *d*-electrons

Origin of Charge Density Wave Formation in Insulators from a High Resolution Photoemission Study of BaIrO₃

Kalobaran Maiti, Ravi Shankar Singh, V. R. R. Medicherla, S. Rayaprol, and E. V. Sampathkumaran

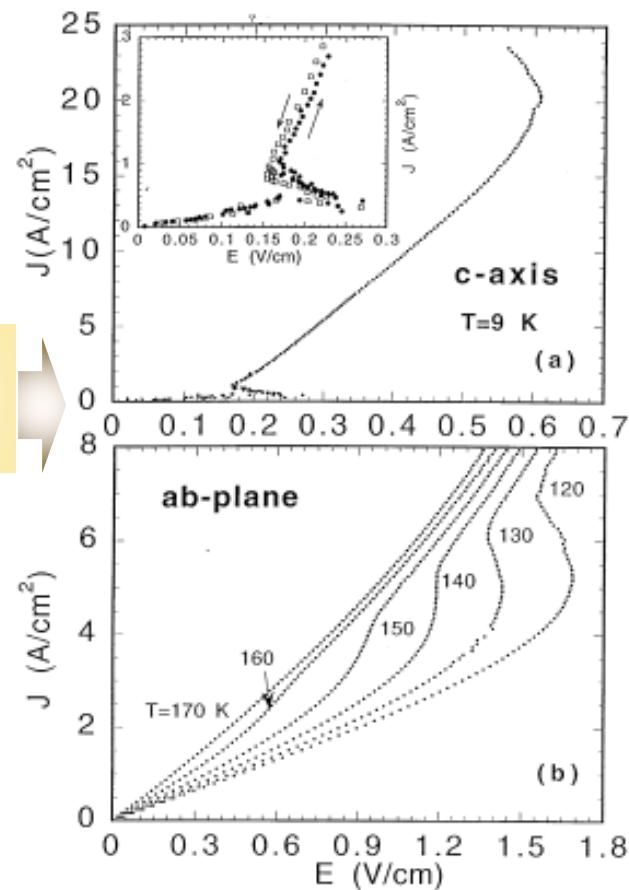


Orthorhombic



BaIrO₃: Monoclinic
(Space group C2/m)

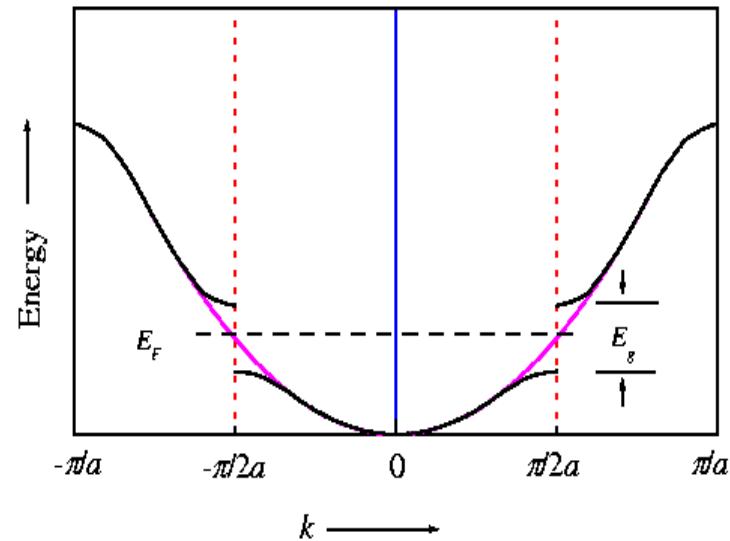
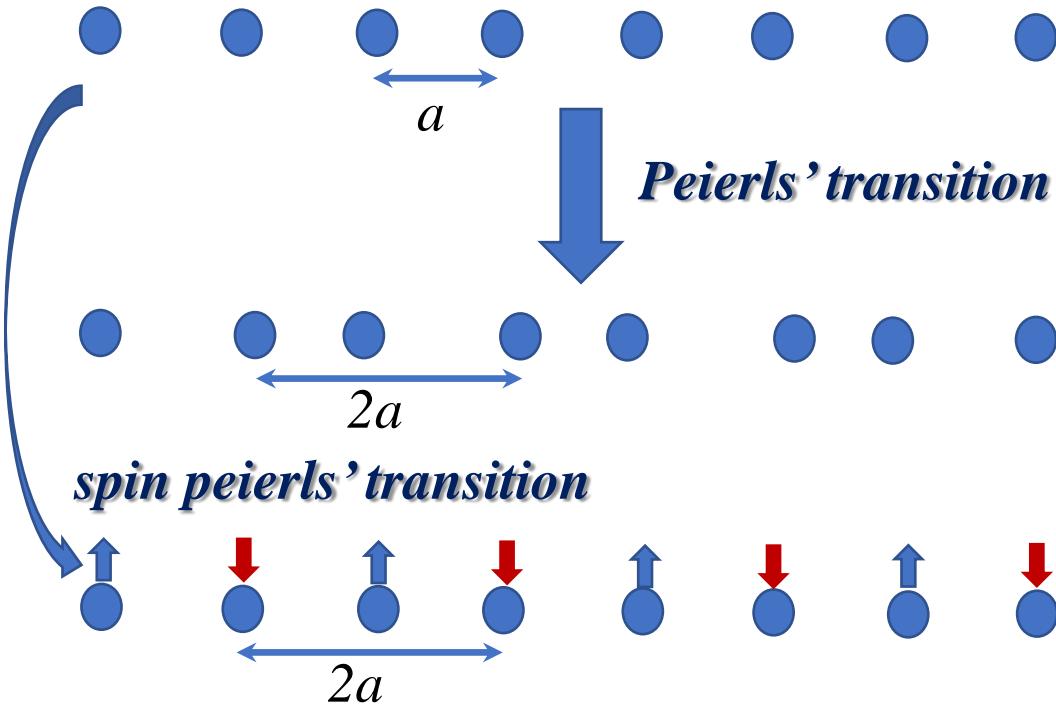
**Violate
Ohms law**



- Anisotropy in transport
- Anomalous J vs. E curve
- Signature of Lattice coupling in optical conductivity.
CDW transition / giant non-linear conduction!!

G. Cao *et al.* Solid State Commun. **113**, 657 (2000)

Peierls' transition / spin peierls' transition



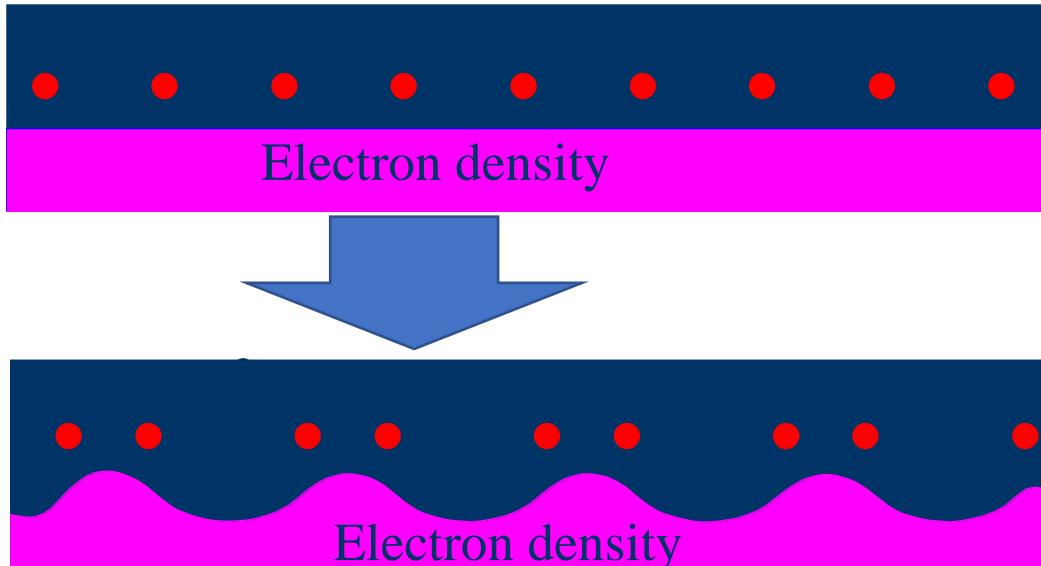
A gap opens up at the middle of the band leading to lowering energy for a half filled band

→ gap at the Fermi level

Metal to insulator transition

Brillouin zone boundary shift from $\pm \frac{\pi}{a}$ to $\pm \frac{\pi}{2a}$

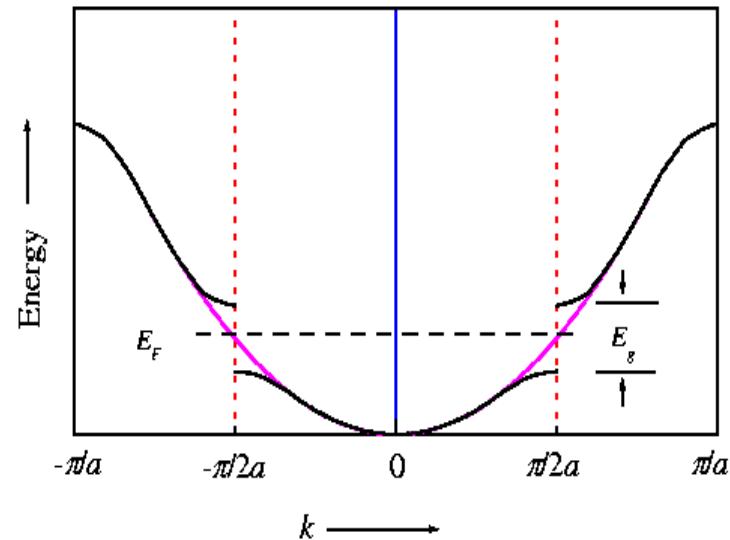
Charge density wave (CDW) / spin-density wave (SDW)



Brillouin zone boundary shift from
 $\pm \frac{\pi}{a}$ to $\pm \frac{\pi}{2a}$

Requires electrons at the Fermi level!

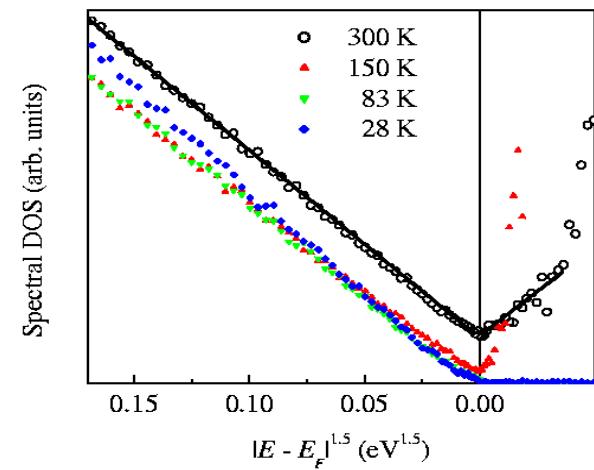
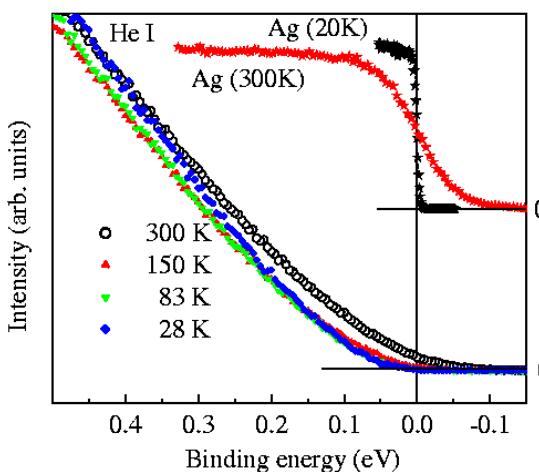
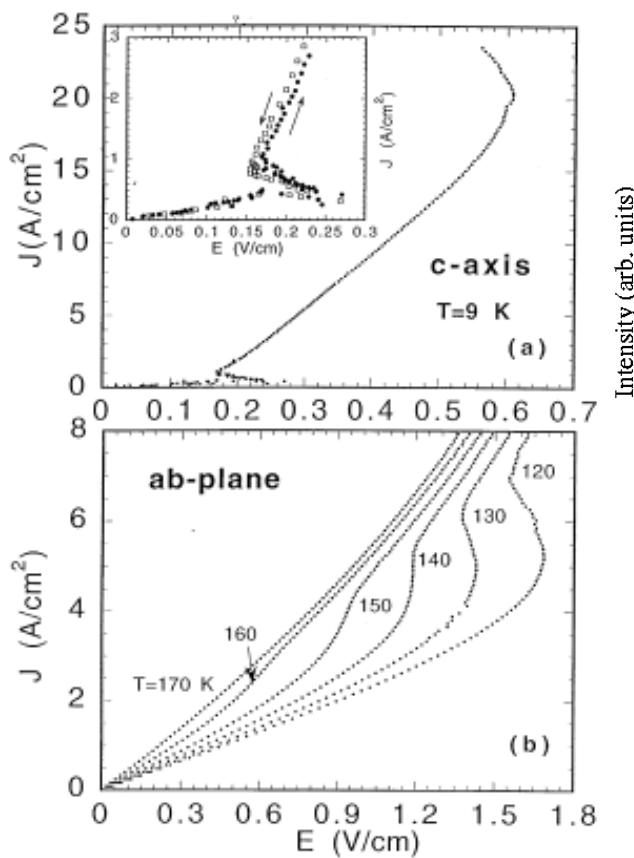
BaIrO₃ is an insulator at room temperature. So, why unusual transport?



A gap opens up at the middle of the band leading to lowering energy for a half filled band
→ gap at the Fermi level
Metal to insulator transition

Origin of Charge Density Wave Formation in Insulators from a High Resolution Photoemission Study of BaIrO₃

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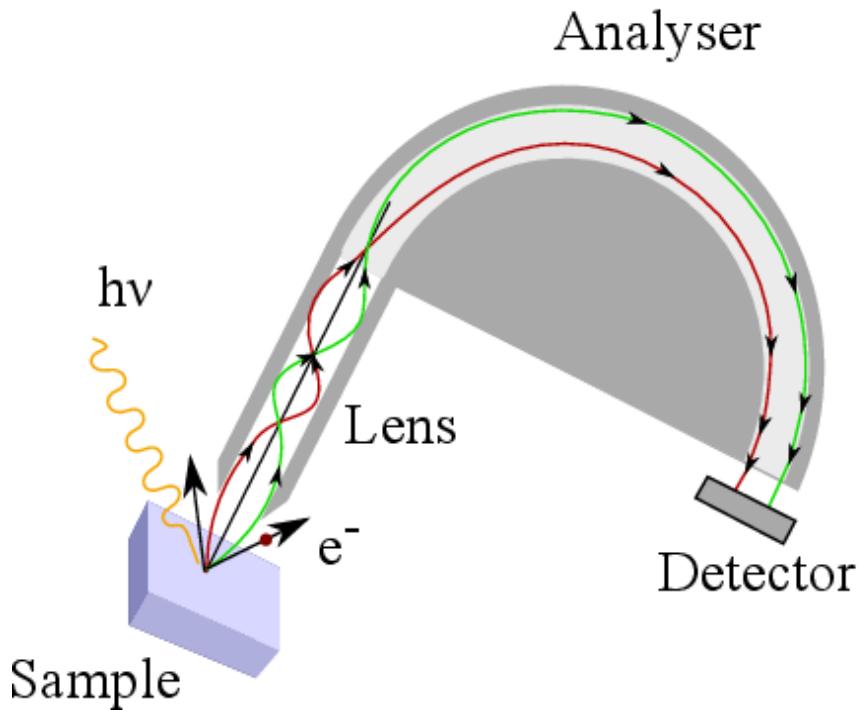


- At 300K, **finite intensity at e_F** ,
- **Large spectral modification** at e_F across 170 K,
- **Hard gap** at lower temperatures
- **Exponent of 1.5** in spectral function

Localized electrons at the Fermi level leads to anomalies!!

Angle resolved photoemission spectroscopy (ARPES)

Derive from experiment:



$$|k_{||}| = \frac{1}{\hbar} \sqrt{2m\epsilon_{kin}} \sin\theta$$

1. *kinetic energy* - ϵ_{kin}

2. *Angle of emission* - θ

m = mass of electron

V_0 = inner potential

$$\epsilon_{kin} = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m}$$

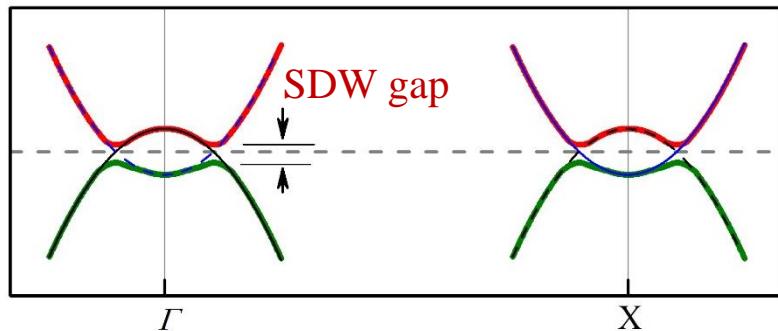
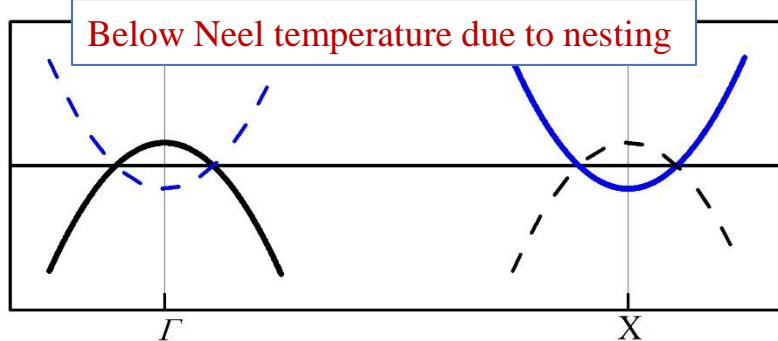
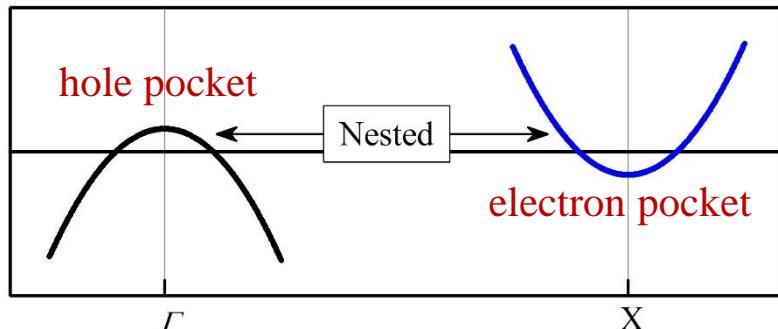
$$\vec{k} = \vec{k}_{\perp} + \vec{k}_{||}$$

$$\vec{p} = \hbar \vec{k} = \sqrt{2m\epsilon_{kin}} \hat{k}$$

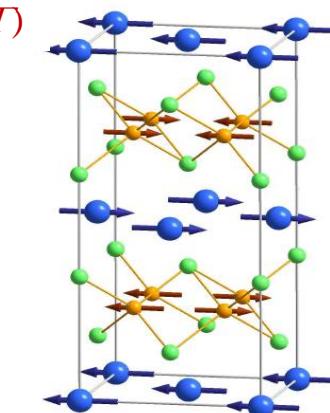
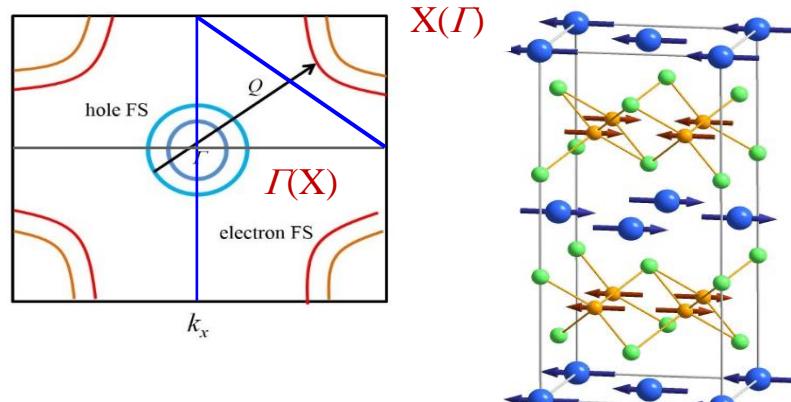
$$|k_{\perp}| = \frac{1}{\hbar} \sqrt{2m(\epsilon_{kin} + V_0) - \hbar^2 k_{||}^2}$$

$k \rightarrow$ reciprocal lattice vector

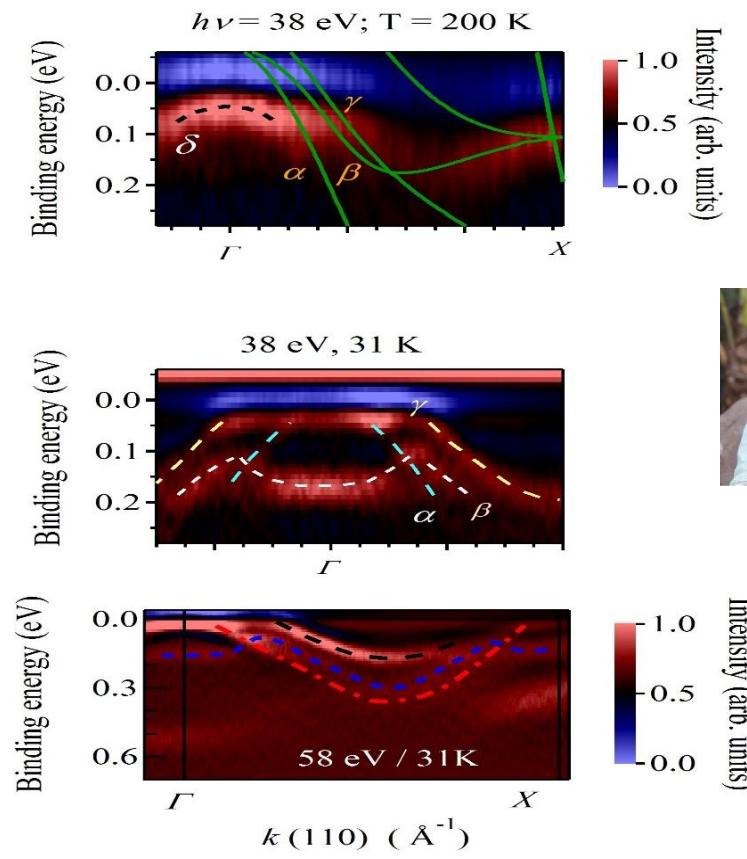
SDW transition



One can see how bands are folded due to SDW transition

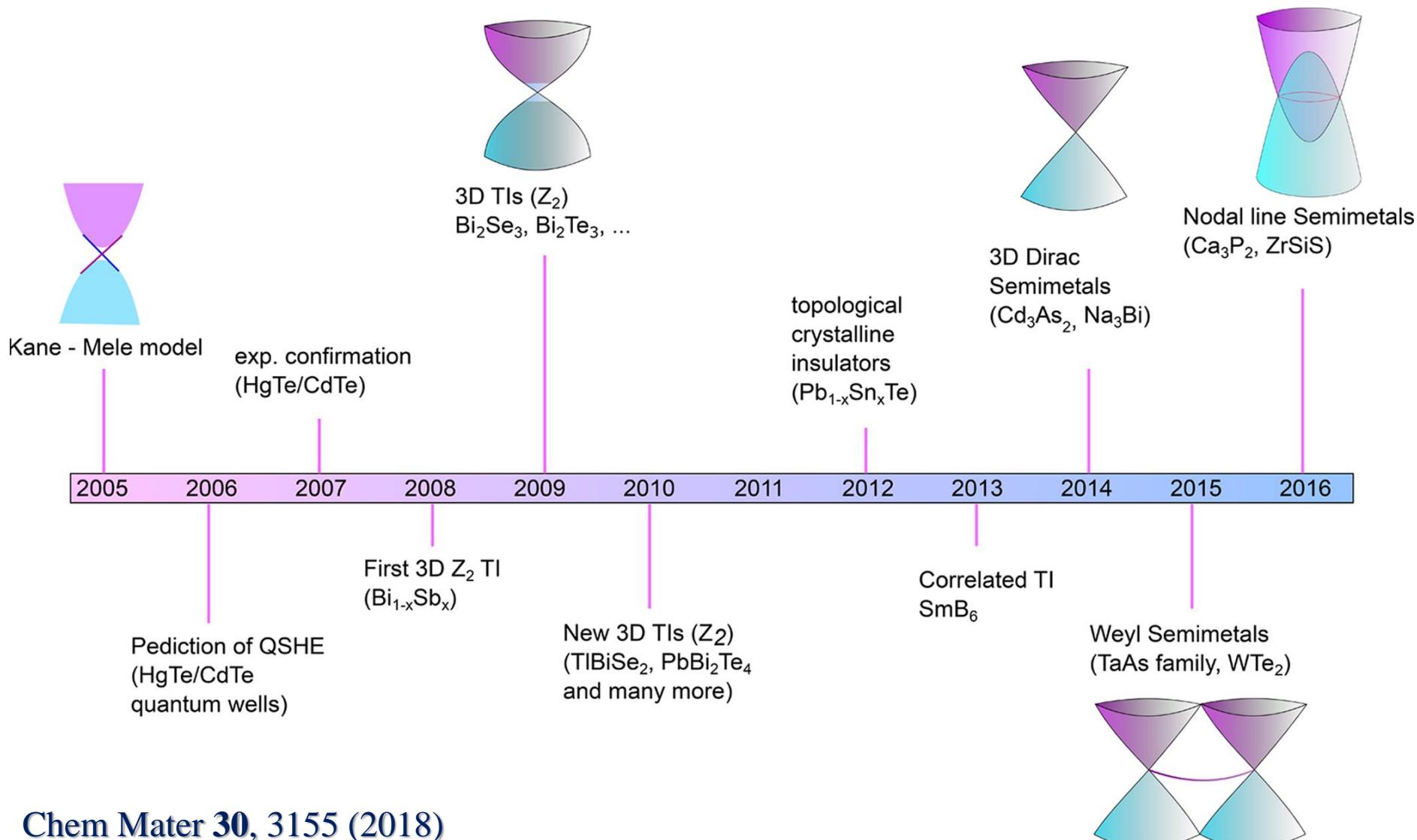


a - AFM
&
 b - FM

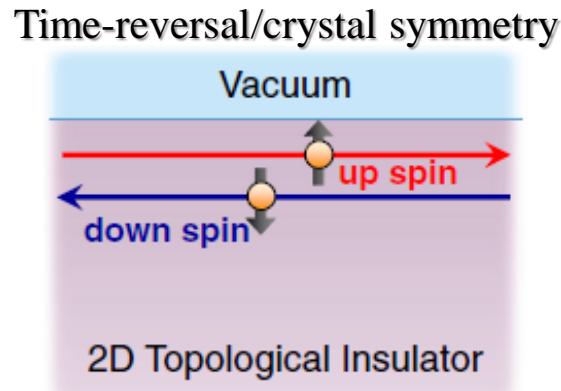
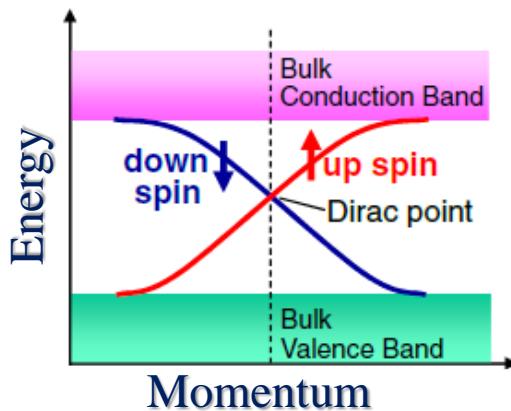


Topological properties in condensed matter systems

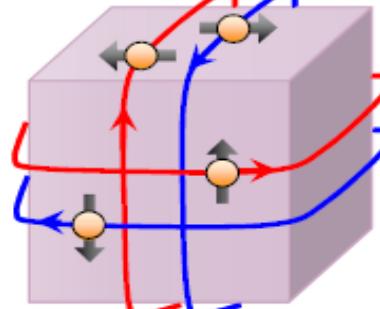
Timeline



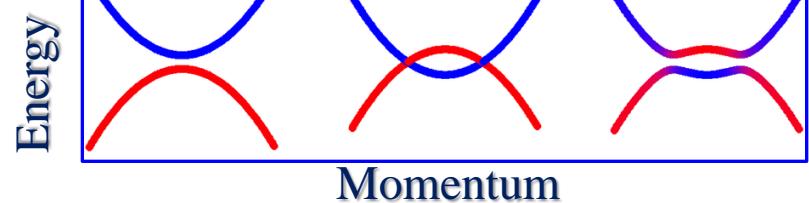
Topological insulators: bulk insulators with symmetry protected metallic surface states.



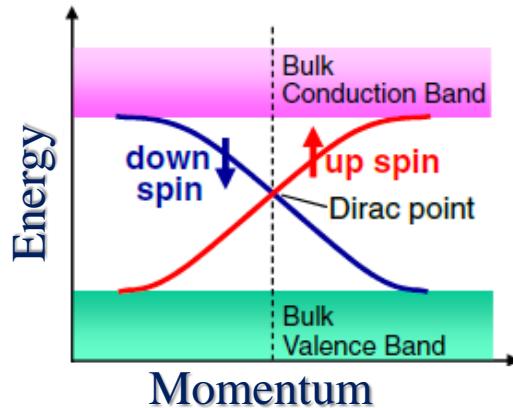
3D materials



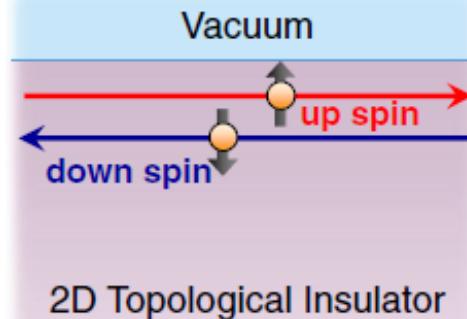
Strong spin-orbit coupling
→ Band inversion



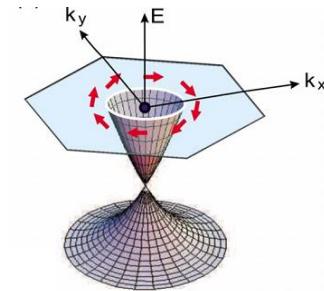
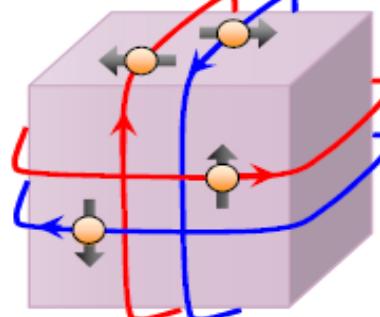
Topological insulators: bulk insulators with symmetry protected metallic surface states.



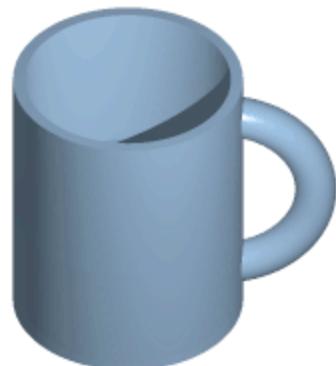
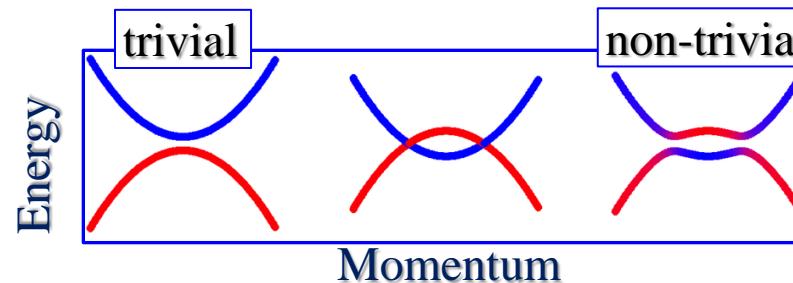
Time-reversal/crystal symmetry



3D materials



Strong spin-orbit coupling
→ Band inversion



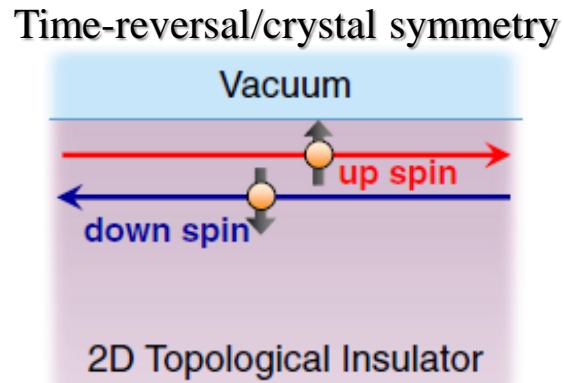
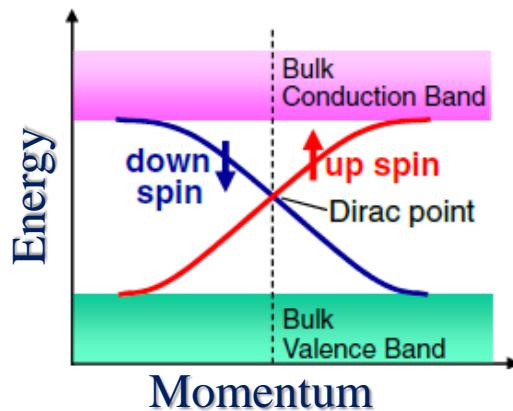
Continuous deformation of a mug
into a doughnut (torus)

Deformation of a cow into a sphere.

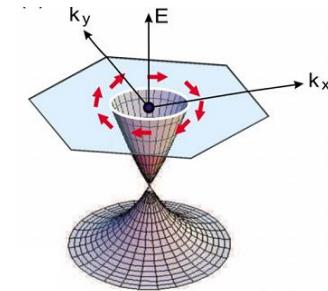
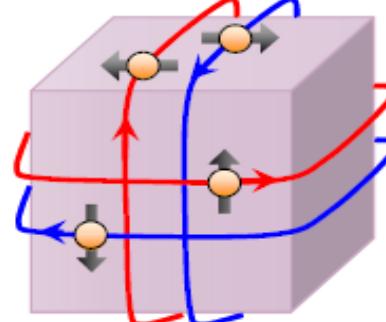
Topologically distinct



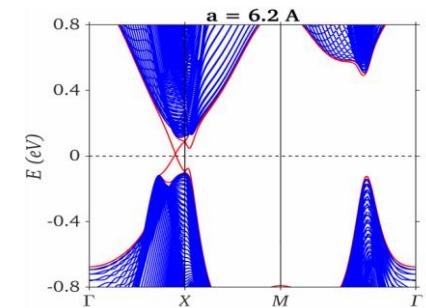
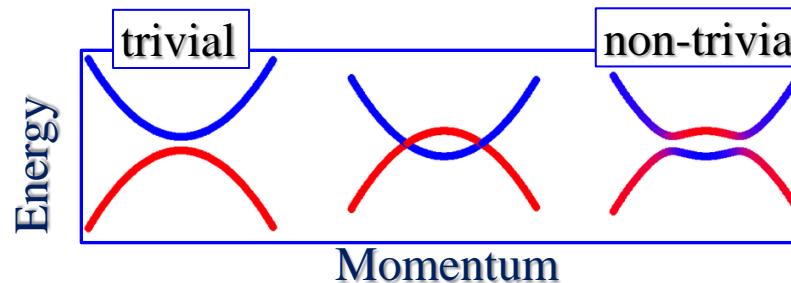
Topological insulators: bulk insulators with symmetry protected metallic surface states.



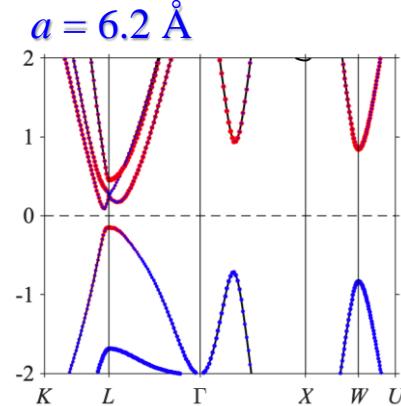
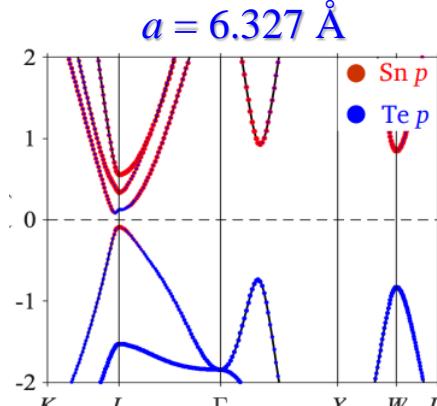
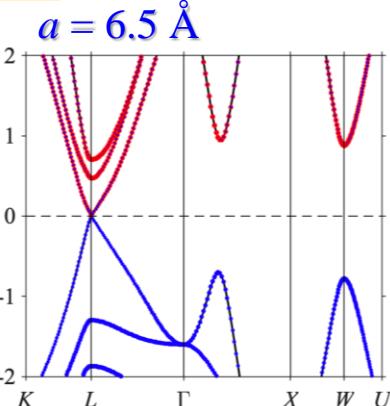
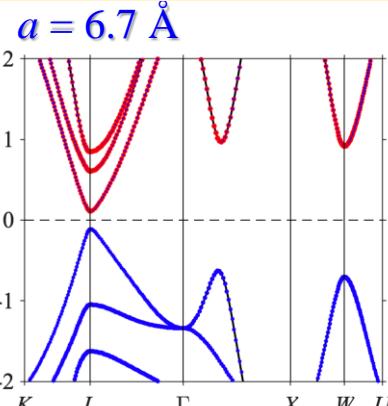
3D materials



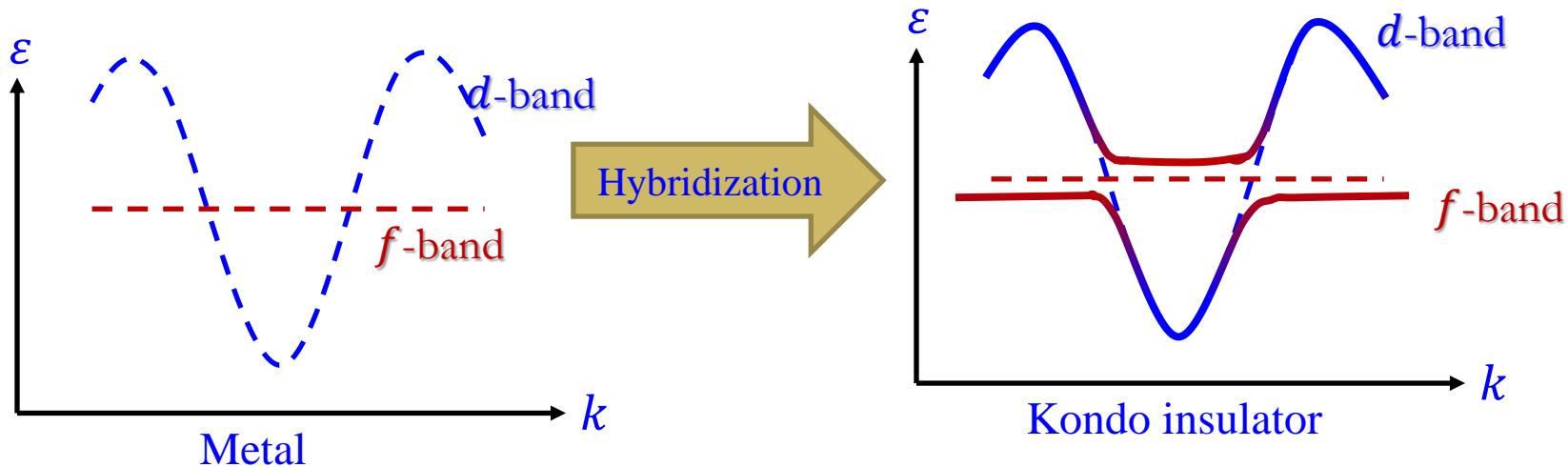
Strong spin-orbit coupling
→ Band inversion



Band structure of SnTe



Rare-earth based materials



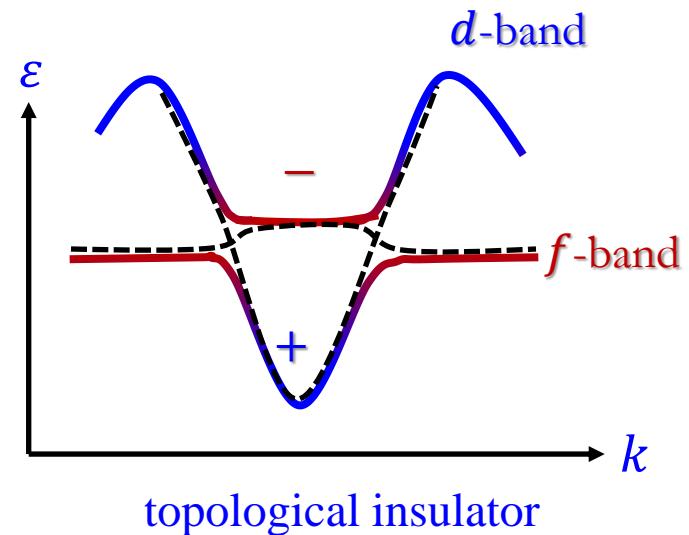
Hybridization gap is $\sim 1 - 10$ meV

Spin-orbit coupling of *f*-electrons is strong ~ 0.5 eV
→ good for topological properties

Parity of *f*-states is odd ($l = 3$) while the conduction electrons can have even/odd parity depending on the states. For *d*-states ($l = 2$), it is even parity.

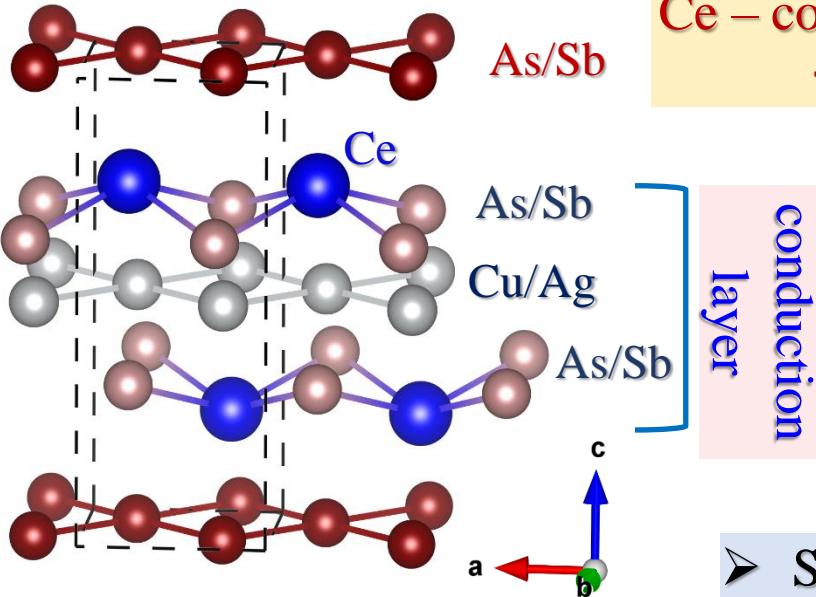
Crossing of different parity bands changes the sign of Z_2 -index → topological insulators.

Topological properties at low temperatures,
while it is normal metal at high temperatures.



Two-dimensional (2D) networks

Squarenet structure – Ce112



Ce – cond. layer hybridization
→ Kondo effect



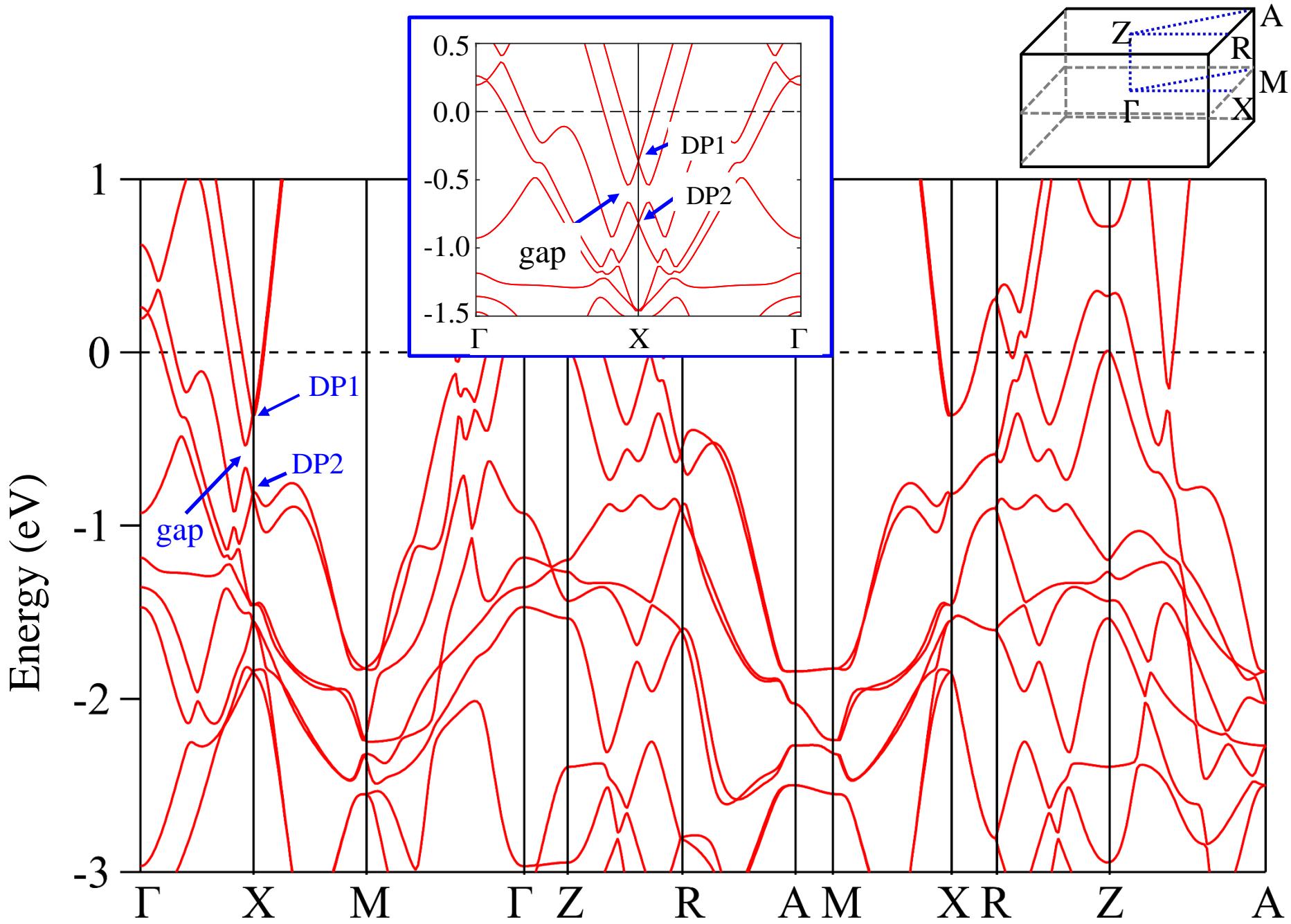
CeCuSb₂, CeAgSb₂ and CeAgAs₂ are AFM
CeCuAs₂ good Kondo materials

Unit cell has two non-equivalent As/Sb atoms

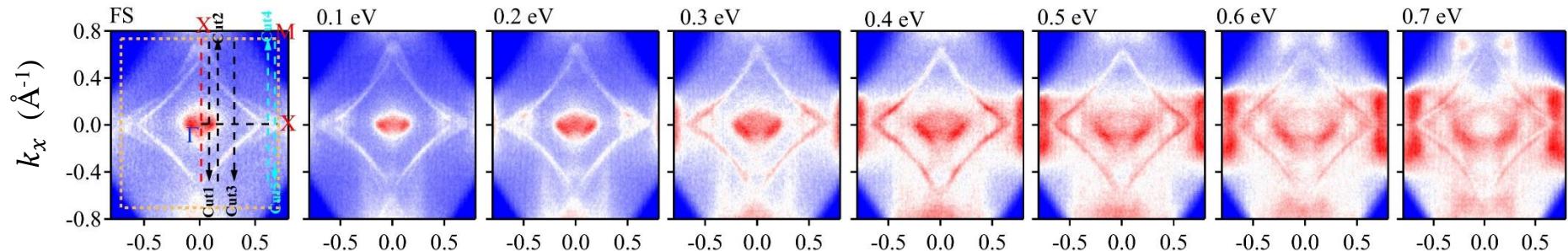
Dirac cone → Nodal line

Non-symmorphic symmetry → no gap at Dirac point due to SOC

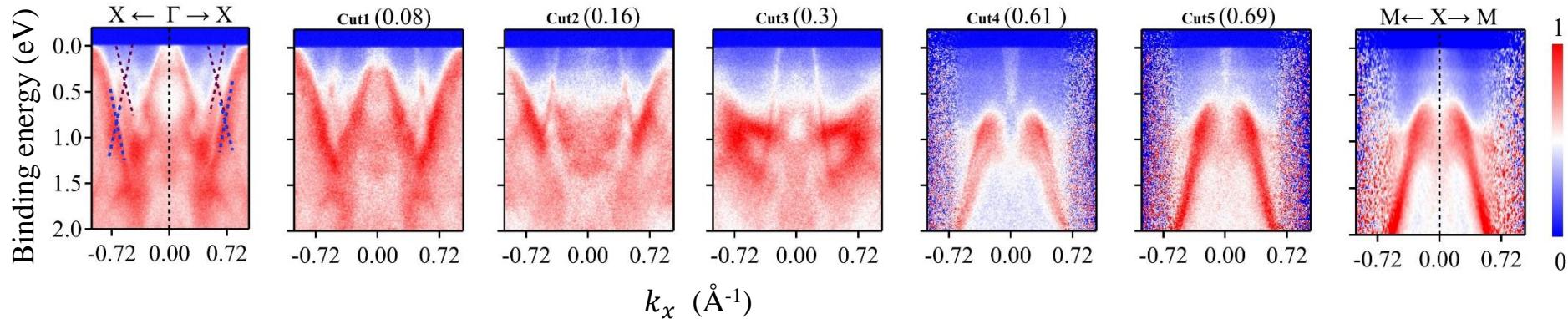
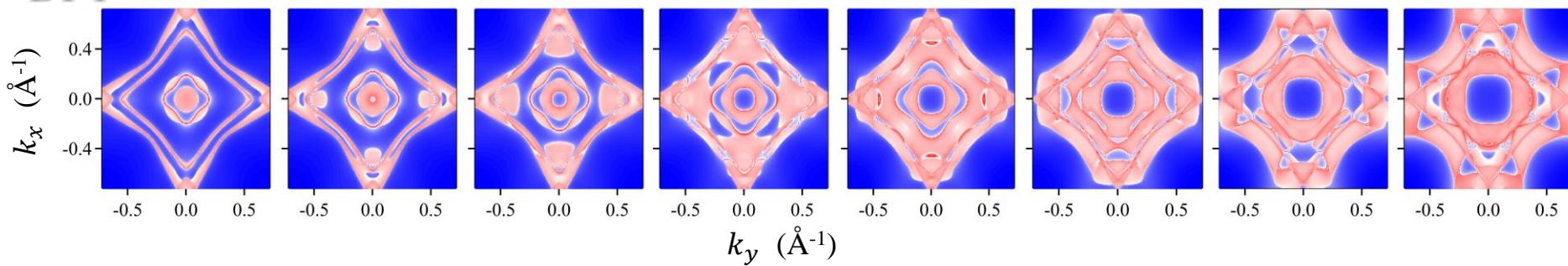
- Squarenets are sandwiched by two Ce-layers
- Squarenet-Ce distance is large → weak hybridization.
- Samples cleave in between these two layers exposing Ce or As/Sb layer as top layer
- A great system to study interaction of Dirac fermions in presence of electron correlation

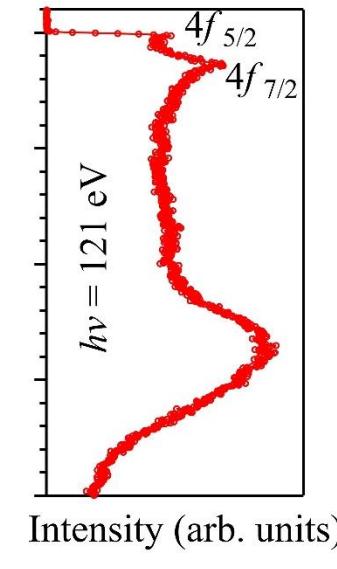
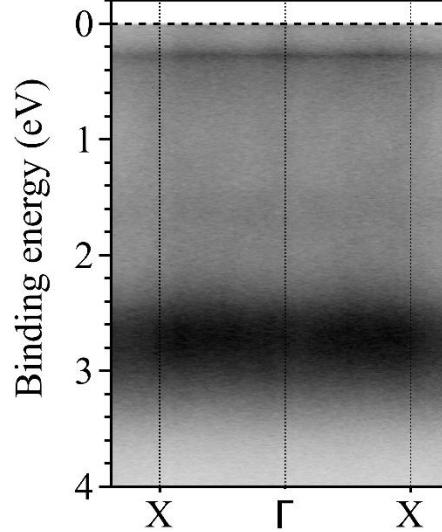
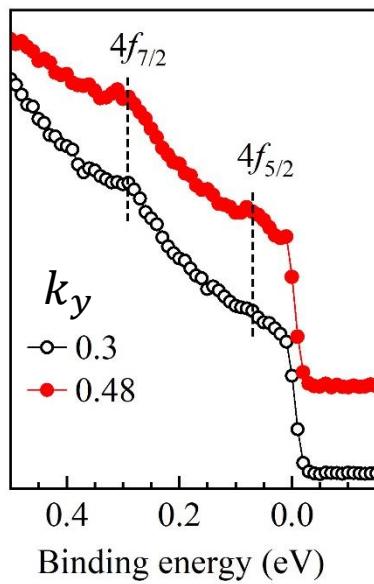
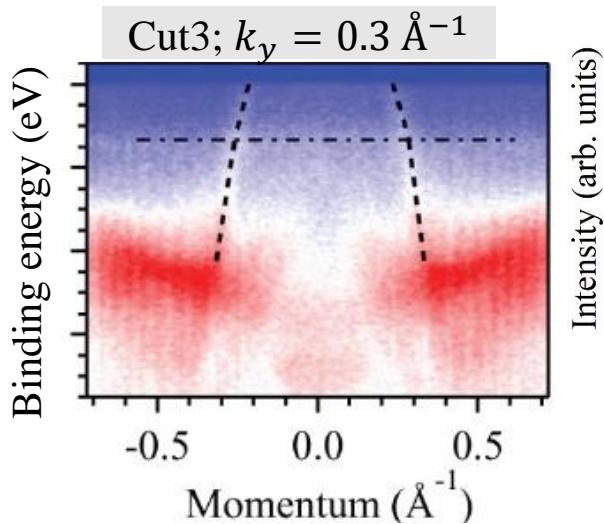
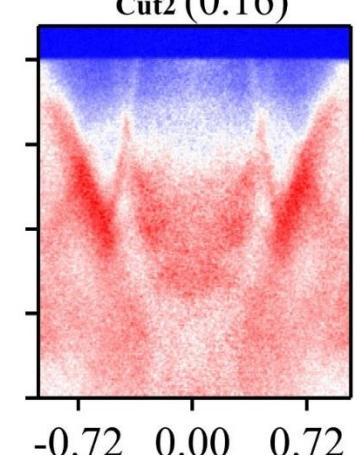
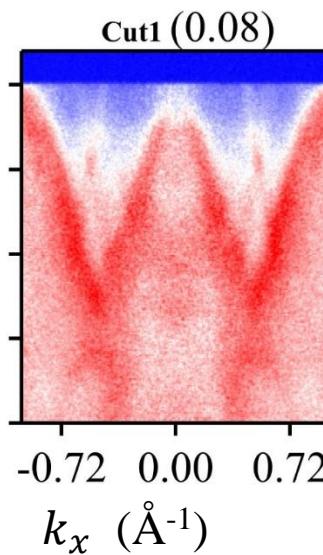
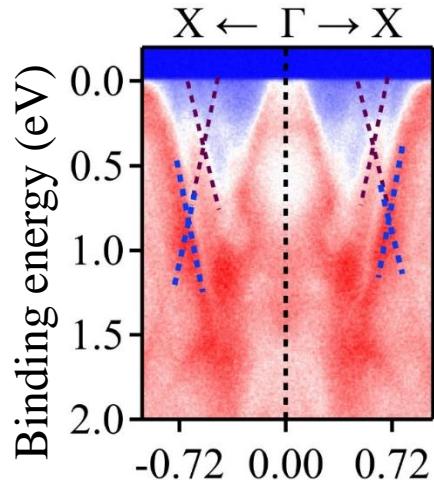
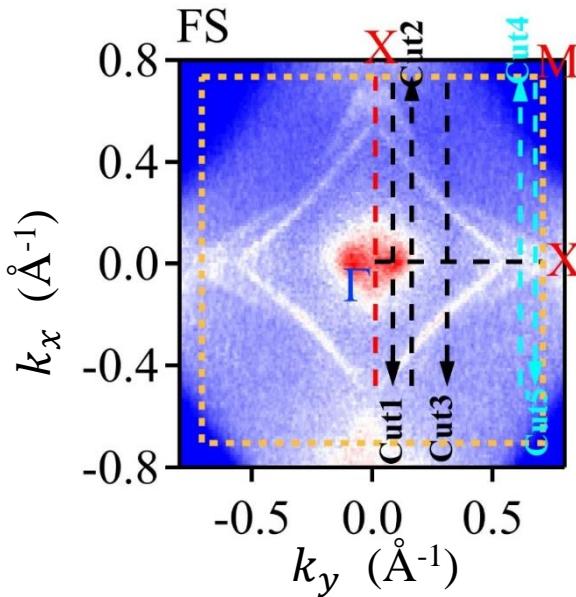


ARPES



DFT





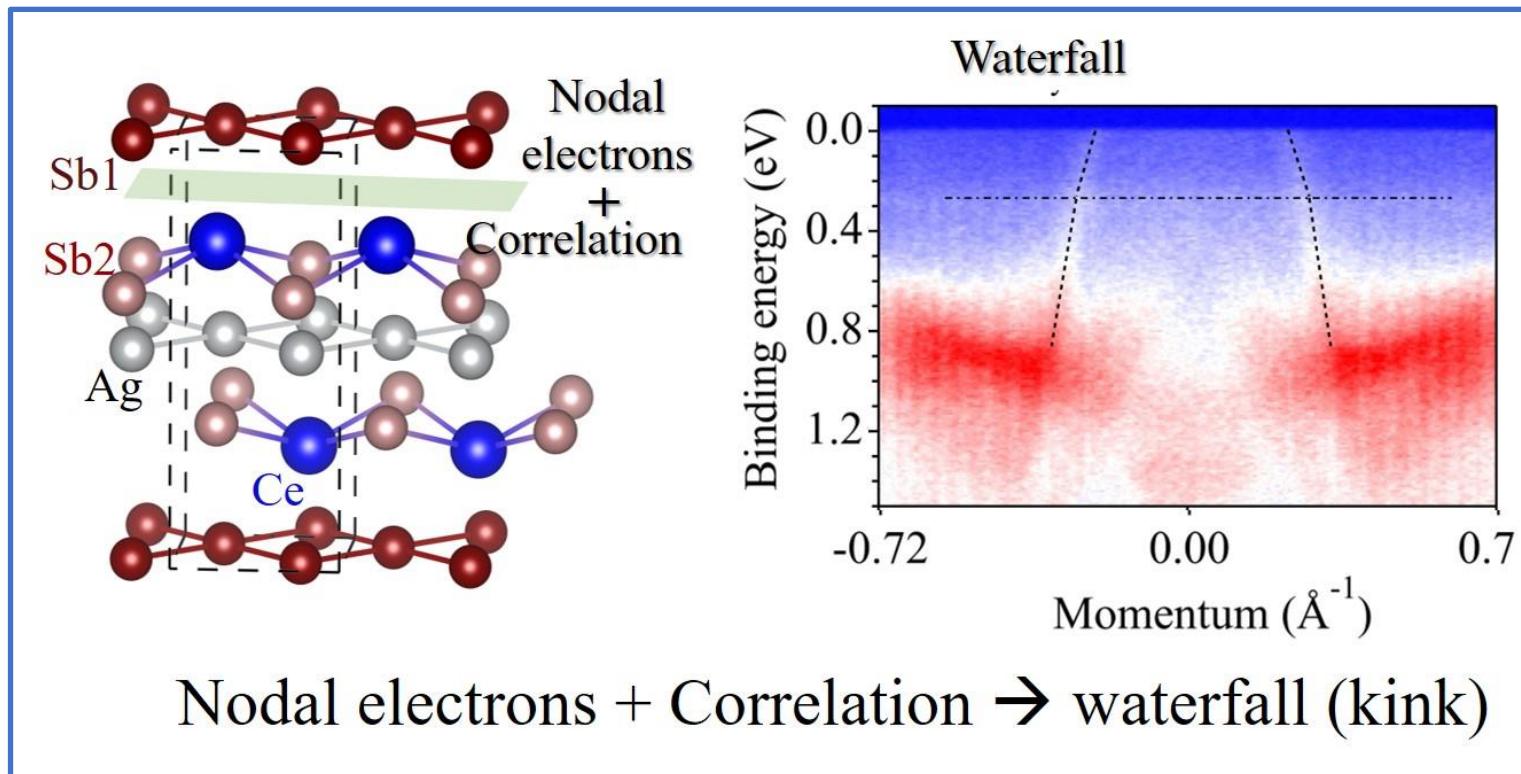
Highly dispersive Dirac bands
bends near Ce 4f signal – kink

Slope ($\hbar\nu_F$) = 5.1 eV.Å near ϵ_F and = 9.5 eV.Å @BE ≥ 2.8 eV

For comparison - ZrSiS (= 4.3 eV.Å) graphene (= 6.7 eV.Å)

Ce(Cu/Ag)(As/Sb)₂

- No f_0 peak in CeCuSb₂ and CeCuAs₂!
- ARPES of CeAgSb₂: Nodal line due to Dirac fermions from squarenet structure.
- Slope of the Dirac bands is large
- Dirac band bending near Ce 4f band – similar to phonon induced ‘kink’ (waterfall)



Superconducting transition temperature

Some examples in Fe-compounds

1111 class ~ 57 K

[Nat. 453, 761 (2008);
J. Supercond Nov Magn. 21, 213
(2008).]

122 class ~ 38 K

[PRB 78, 180508(R) (2008)]

111 class ~ 18 – 31 K

[PRB 78, 060505(R) (2008)]
[EPL 88, 47008 (2008)]

11 class ~ 8 – 37 K

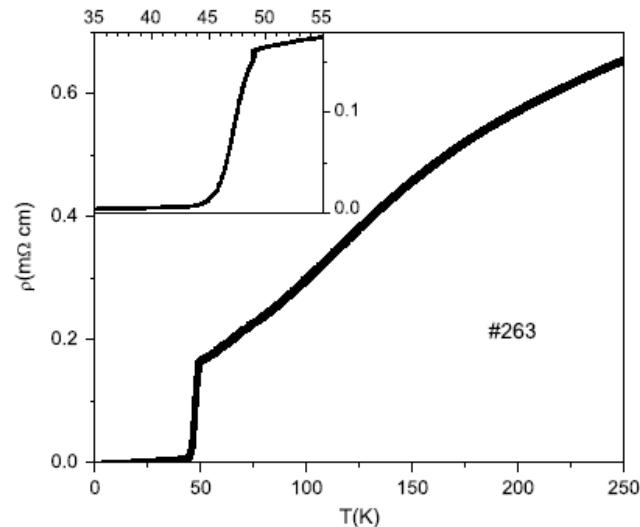
[PRB 82, 180520(R) (2010)]
[PNAS 105, 14262 (2008)]

1 ML FeSe/SrTiO₃ – $T_c \sim 100$ K
[Nat. Mater. 14, 285 (2014)]

Unusual superconducting state at 49 K in electron-doped CaFe₂As₂ at ambient pressure

Bing Lv^a, Liangzi Deng^{a,b}, Melissa Good^a, Fengyan Wei^{a,b}, Yanyi Sun^a, James K. Meen^{a,c}, Yu-Yi Xue^{a,b}, Bernd Lorenz^{a,b}, and Ching-Wu Chu^{a,b,d,1}

PNAS | September 20, 2011 | vol. 108 | no. 38 | 15705–15709



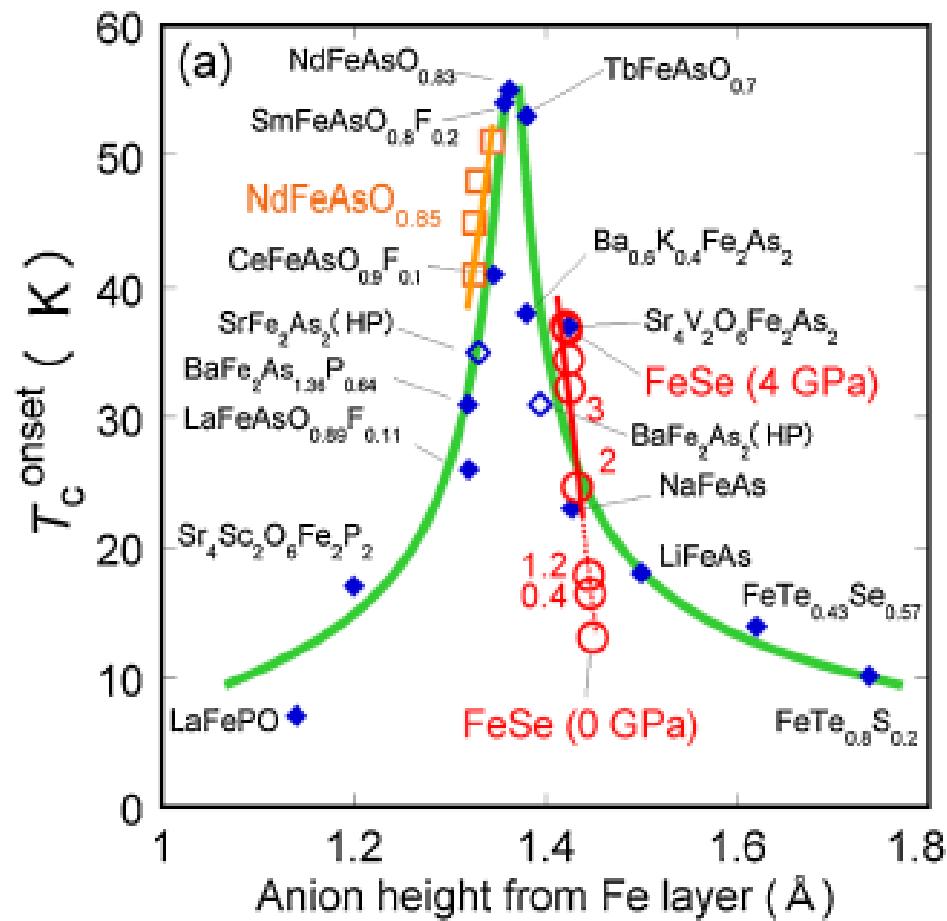
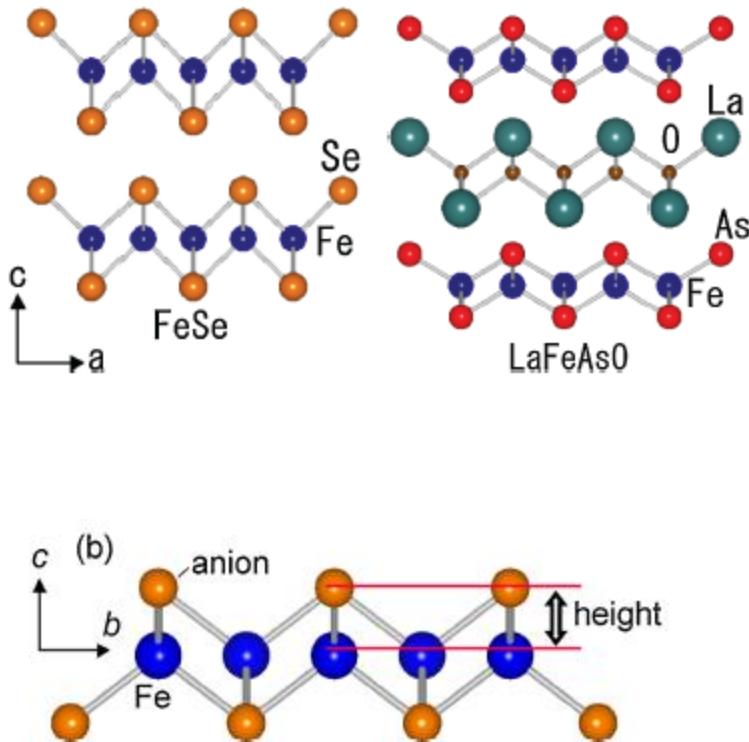
Ca_{1-x}Pr_xFe₂As₂ $x \sim 0.127$

Two transitions

- (i) 49 K critical field < 4 Oe
- (ii) 21 K critical field > 5 T

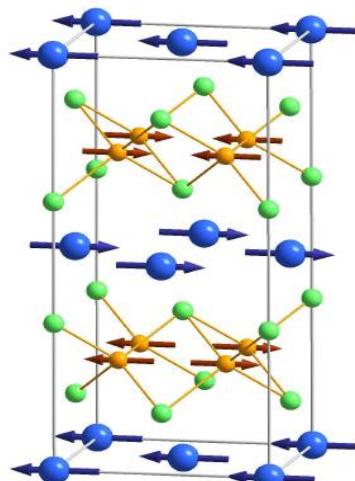
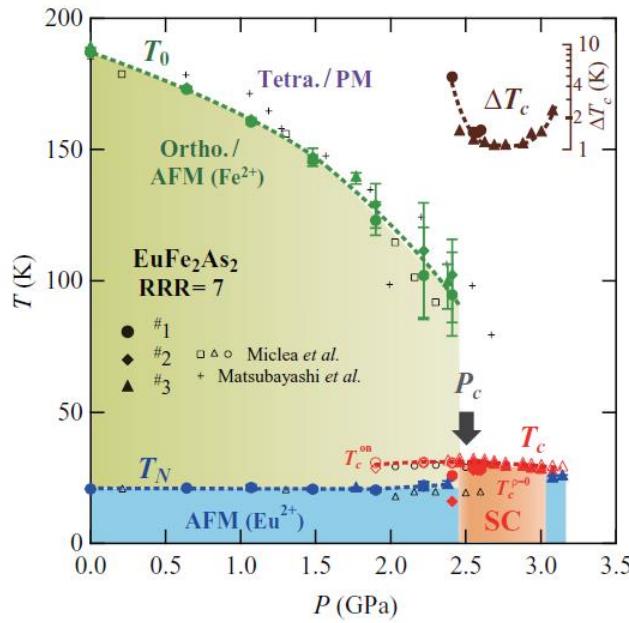
Anion height (pnictogen height)

Higher pnictogen height → lower hybridization → lower kinetic energy



EuFe_2As_2

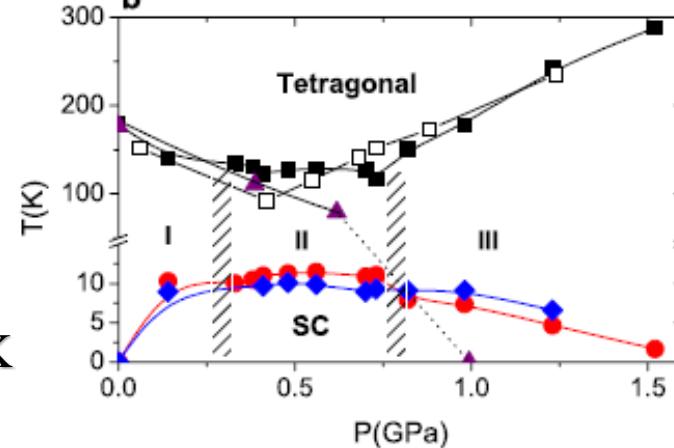
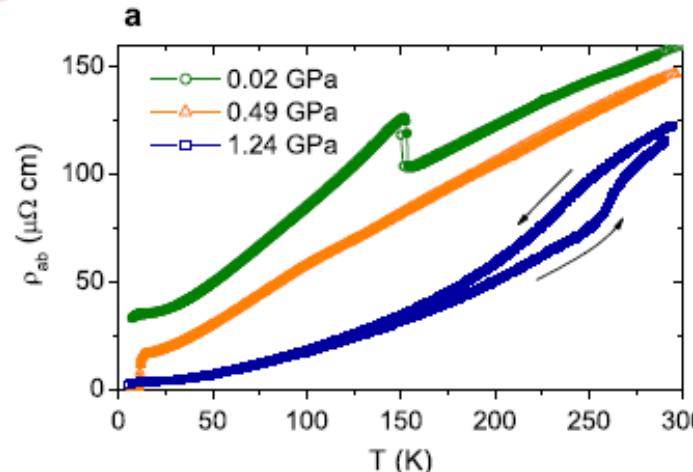
Phys. Rev. B **83**, 214513 (2011)



Magnetic structure at 2.5 K

CaFe_2As_2

H. Lee *et al.* Phys. Rev. B **80**, 024519 (2009)



$P < 0.3 \text{ GPa} \rightarrow$
Tetragonal to
Orthorhombic

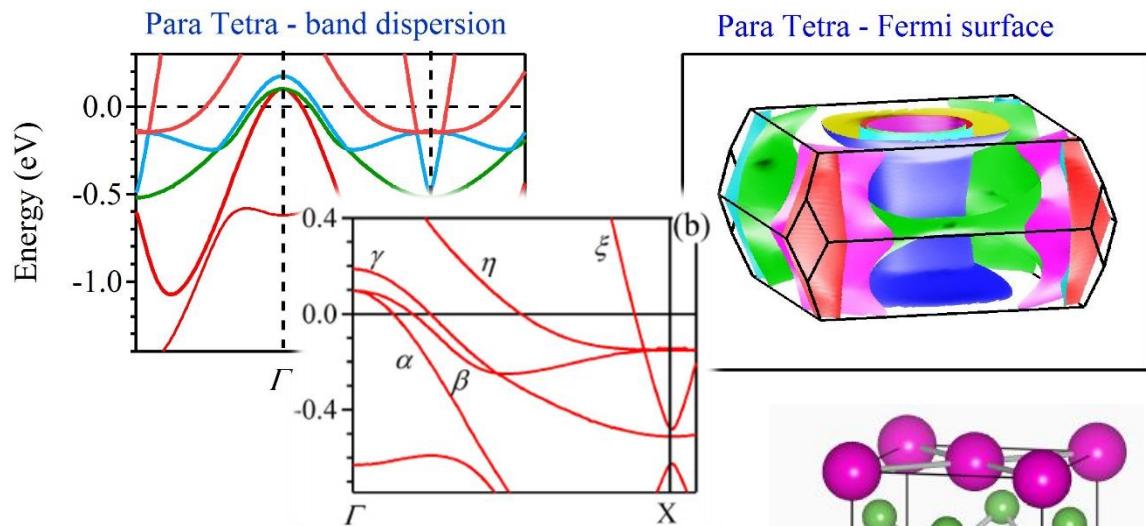
$0.3 < P < 0.8 \text{ GPa} \rightarrow$
Tetragonal to
Orthorhombic + cT

$P > 0.8 \text{ GPa} \rightarrow$
Tetragonal to cT
phase (hysteresis in
resistivity)

Triangles \rightarrow SDW
transition

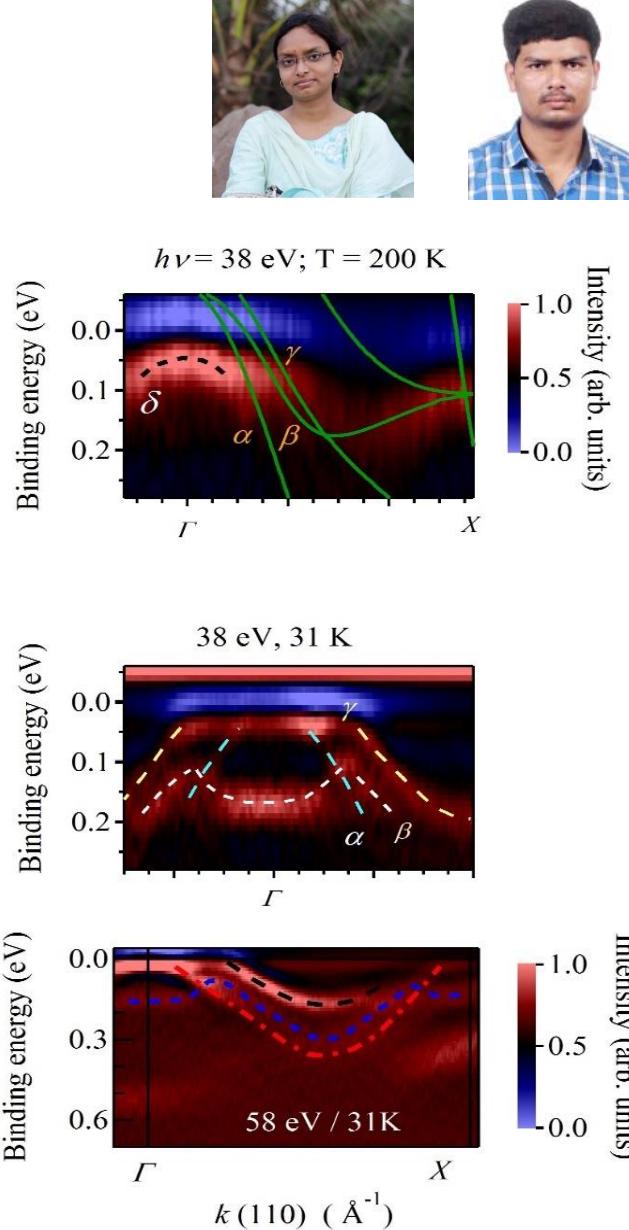
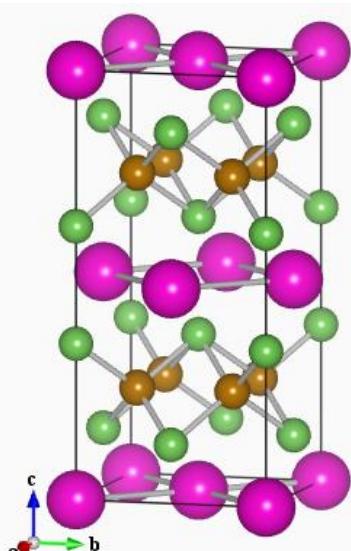
Fe-moments \rightarrow AFM along a -axis & FM along b -axis.
Eu-moments \rightarrow AFM along c -axis

Energy band structure of CaFe_2As_2



Three hole pockets at $\Gamma - \alpha, \beta, \gamma$
Two electron pockets at X

$\beta(d_{xz}/d_{yz})$ band forms SDW state
 $\gamma(d_{xy})$ - electrons have weaker dispersion and not sensitive to magnetism



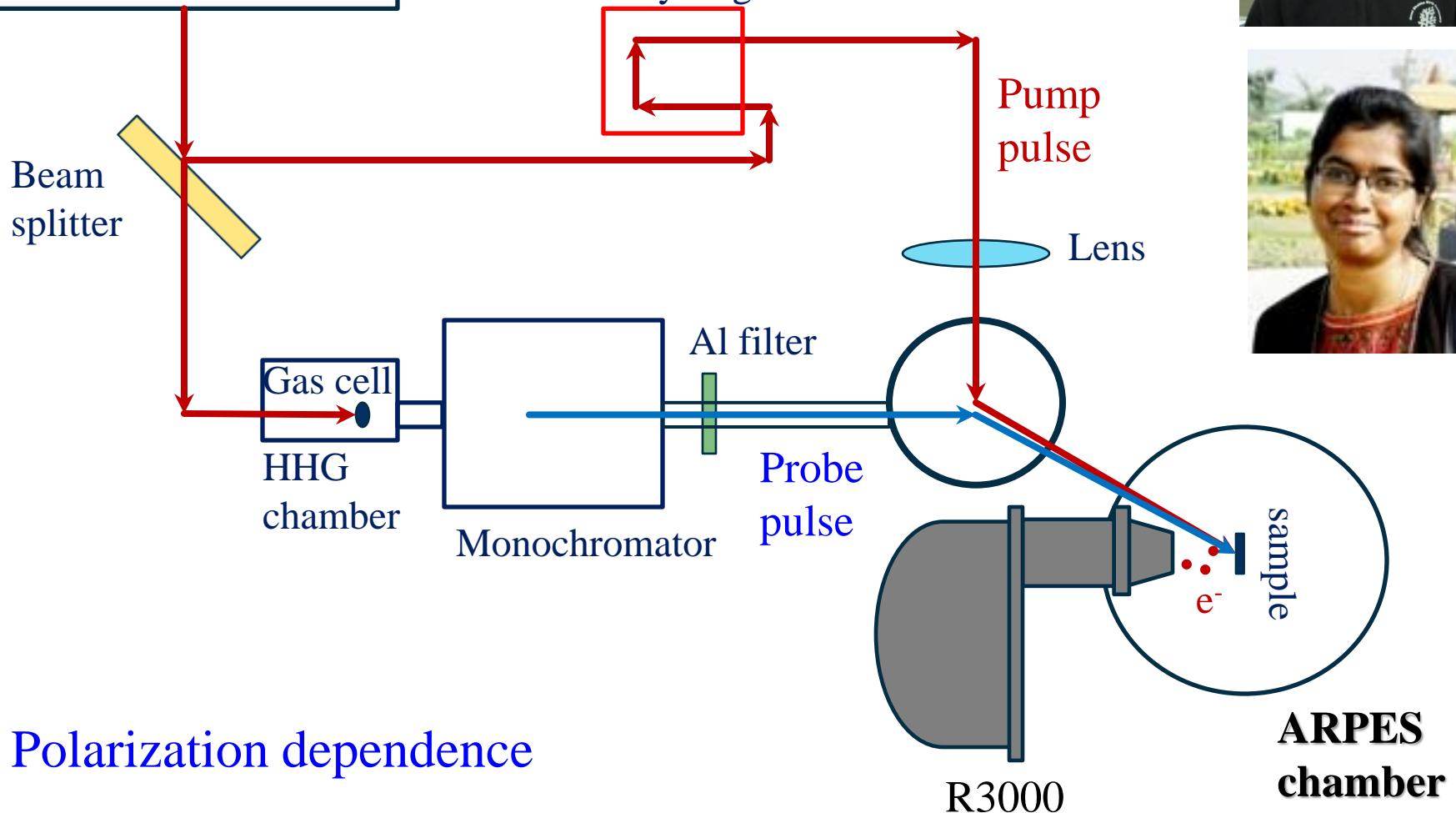
Orbital selective Mottness !! How to detect them ?

Sci. Rep. 7, 6298 (2017)
Phys. Rev. B 97, 054505 (2018)

Time-resolved ARPES – Ninno Lab (Slovenia)

CITIUS

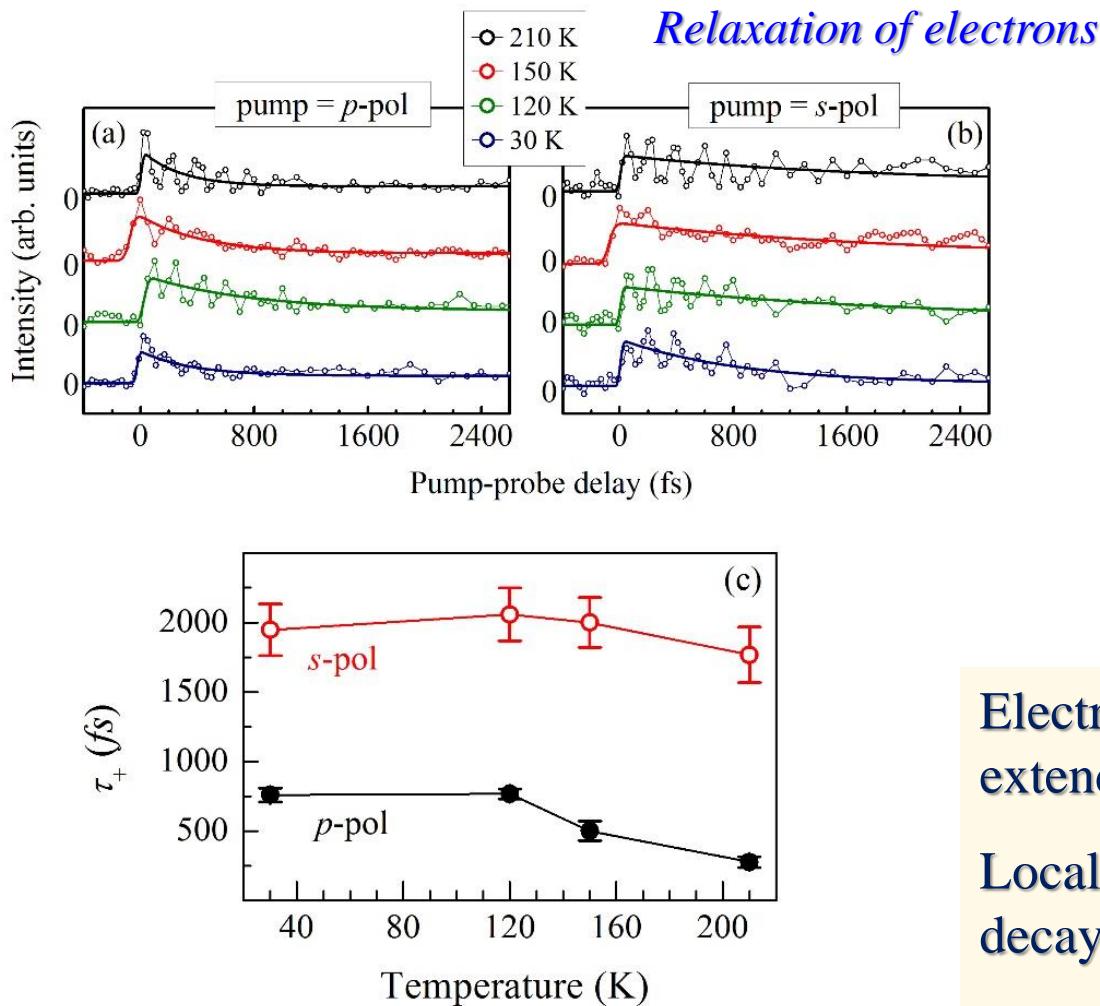
Ti : Sapphire Laser
(1.5 eV [805 nm], 50 fs, 5 kHz)



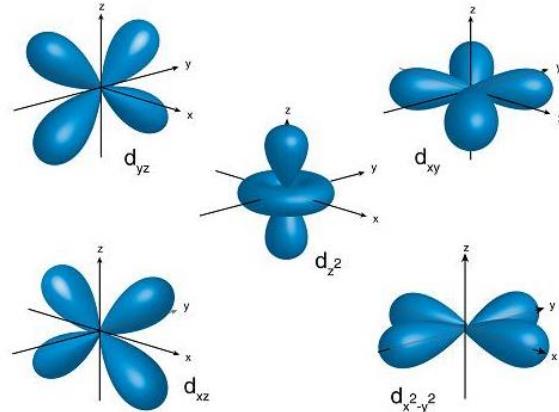
Orbital-dependent electron dynamics in Fe-pnictide superconductors

Ganesh Adhikary,^{1,*} Barbara Ressel,¹ Matija Stupar,¹ Primož Rebernik Ribič,² Jurij Urbančič,¹ Giovanni De Ninno,^{1,2,†} D. Krizmancic,³ A. Thamizhavel,⁴ and Kalobaran Maiti^{4,‡}

Phys. Rev. B **98**, 205142 (2018)



$s\text{-pol} \rightarrow d_{xy}, d_{yz}$ states
 $p\text{-pol} \rightarrow d_{xz}$ states



Electrons having relatively more extended states show smaller decay time

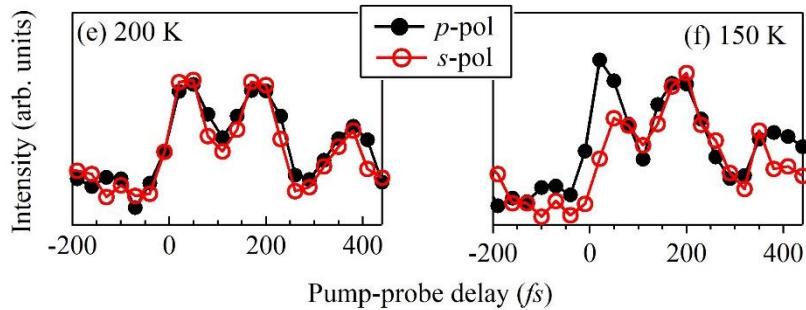
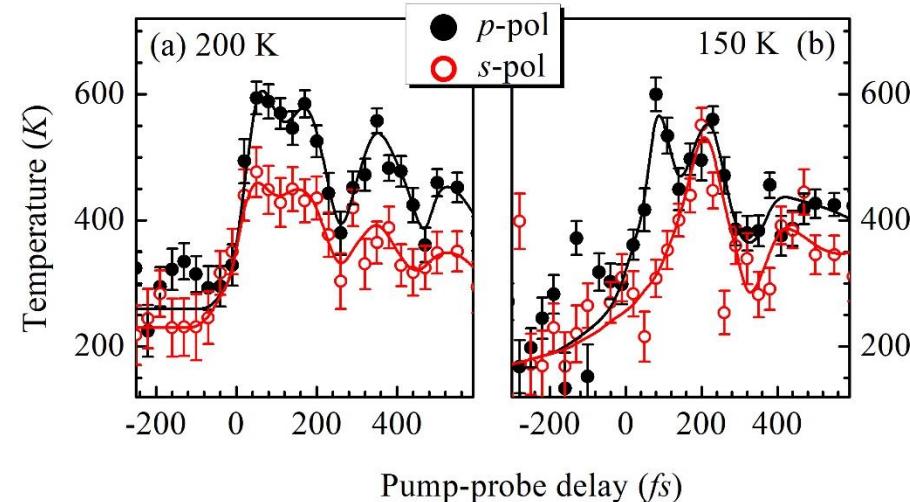
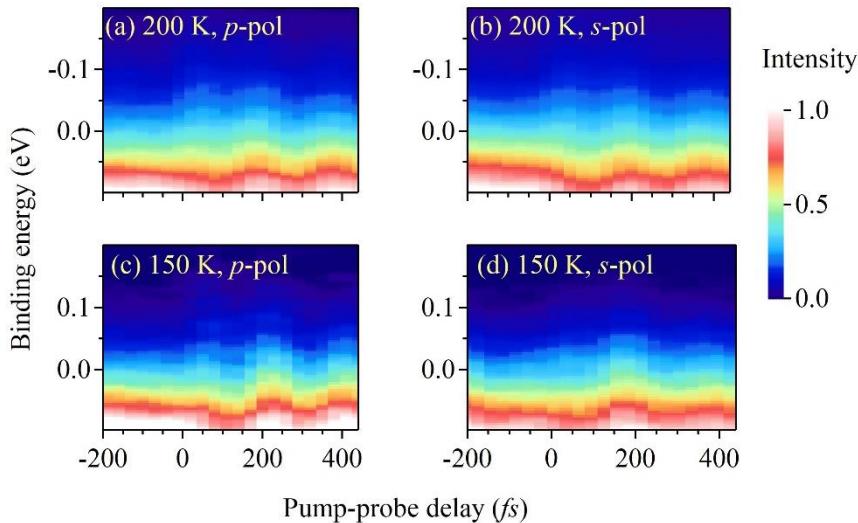
Local character seems to have reduced decay channels

Opening of SDW gap leads to increase in decay time

Orbital selective behavior – Mottness

Orbital selective dynamics in Fe-pnictides triggered by polarized pump pulse excitations

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One can heat magnetic electrons without disturbing other electrons

To our knowledge, there is no other method exists to make such selective heating.

Thank you