2013/01/21-23
Hongkong

Lecture: Introduction to ARPES

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Xingjiang Zhou

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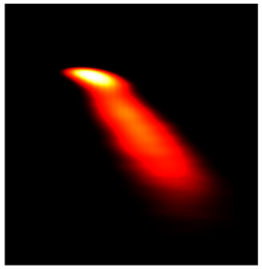
Beijing 100190, China

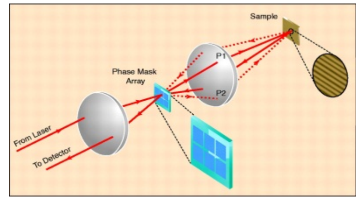
High-Tc Has Changed Landscape of Condensed Matter Physics

ARPES



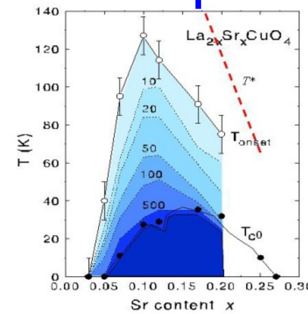
Nature 412(2001)510

Optical



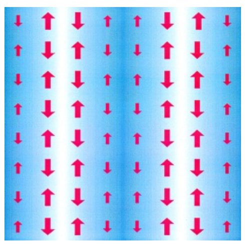
Science 300(2003)1410

Transport



Nature 406(2000)486

Neutron

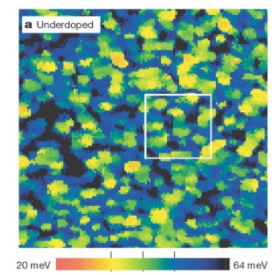


Nature375(1995)561

High Tc Superconductivity

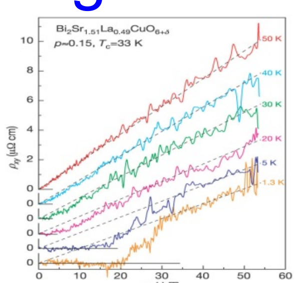
The Nobel Prize in Physics in 1987

STM



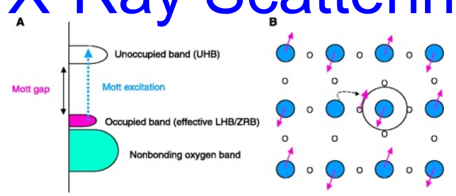
Nature 415(2002)412

High Magnetic Field



Nature 424 (2003)912

X-Ray Scattering



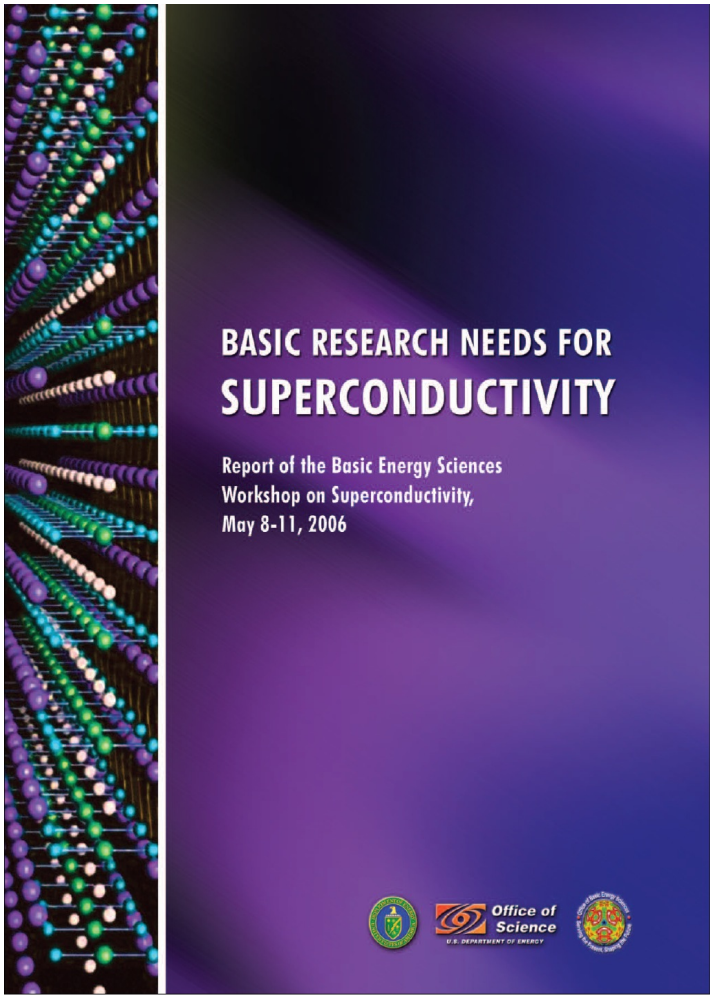
Science 288(2000)1811

High Pressure

Nature 365(1993)323

Experimental Tools for Superconductivity

DOE Report (2006)



ARPES *Techniques and Opportunities*

- *Angle-Resolved Photoemission Spectroscopy* (*ARPES*). Wavelike quantum states of the electrons are defined in momentum space (*k*-space). ARPES allows direct determination of the complete momentum-space electronic structure, $A(k, E)$, with remarkable energy and momentum resolution.

- *Spectroscopic Imaging-Scanning Tunneling Microscopy (SI-STM)*. This is the complementary technique to ARPES that allows mapping of the energy-resolved quantum states in real space (*r*-space) with atomic resolution and yet over large sample areas.

- *Microwave/terahertz/infrared/optical spectroscopies*. These probe the electronic excitations and charge dynamics in both the frequency and time domains. This information is the key to understanding the dynamical interactions of the electrons.

- *Resonant elastic and inelastic x-ray spectroscopy*. Resonant elastic and inelastic x-ray scattering can now reveal spin and charge density waves and superlattices with tiny modulation amplitudes. This information is critically important for understanding spatially periodic electronic states of matter.

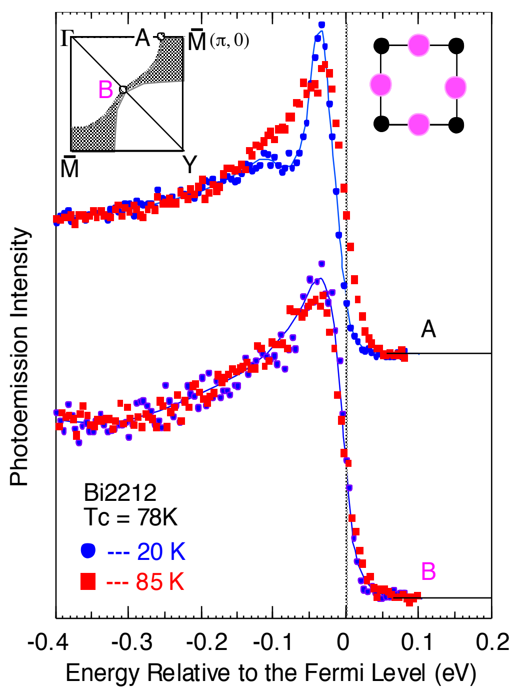
- *Neutron Scattering (NS)*. High-intensity NS — for example, from the Spallation Neutron Source — will allow precision measurements of both magnetic ground states and the complete spectrum of magnetic excitations in high-temperature and exotic superconductors.

- *NMR/NQR/μSR*. NMR measures spin dynamics, NQR measures the charge heterogeneity and dynamics, and μSR measures nanoscale variation in local magnetic field strength. These are essentially local spin/charge probes, but without imaging capabilities.

ARPES on High Temperature Cuprate Superconductors

d-wave Superconducting gap

ARPES on Superconducting gap

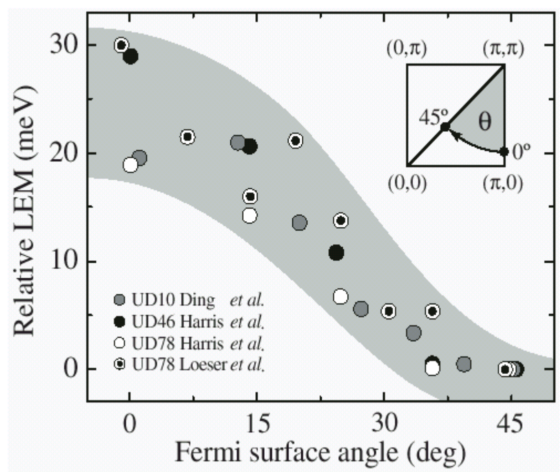


Z.-X. Shen *et al.*, Phys. Rev.Lett.70(1993)1553.

Pseudogap

ARPES on Pseudogap

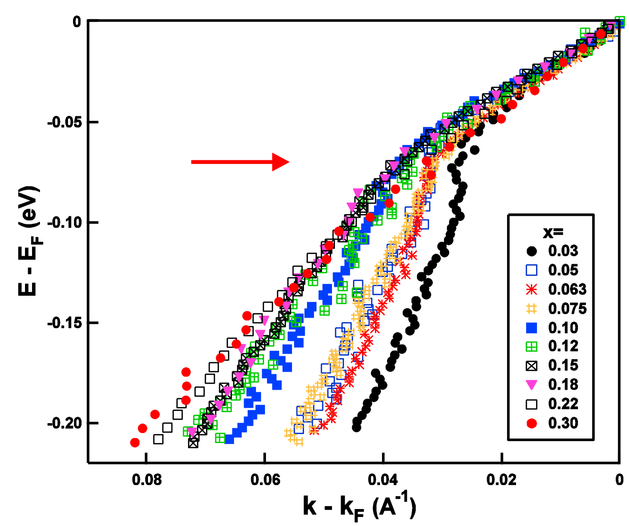
d-wave-like symmetry



Loeser et al., Science 273(1996)325.
Ding et al., Nature 382(1996) 51.

Many-Body Effects

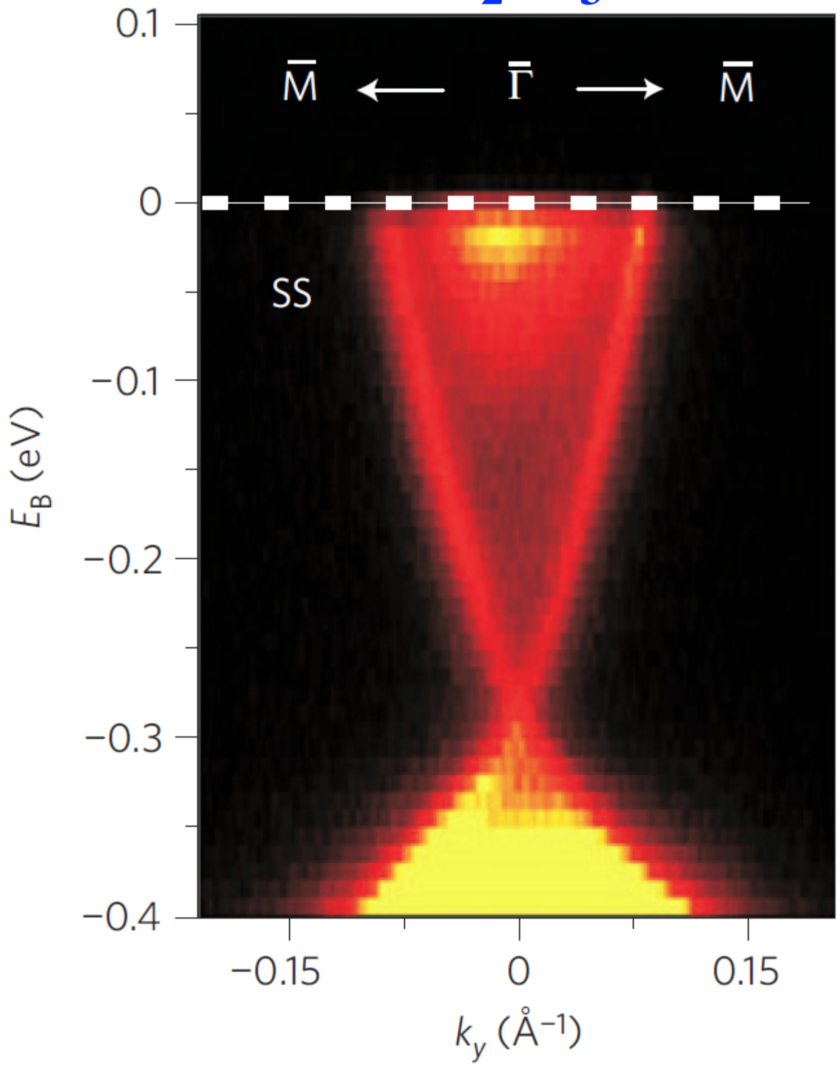
ARPES on Kink



A. Lanzara et al., Nature 412(2001)510.
X. J. Zhou et al., Nature 423(2003)398.

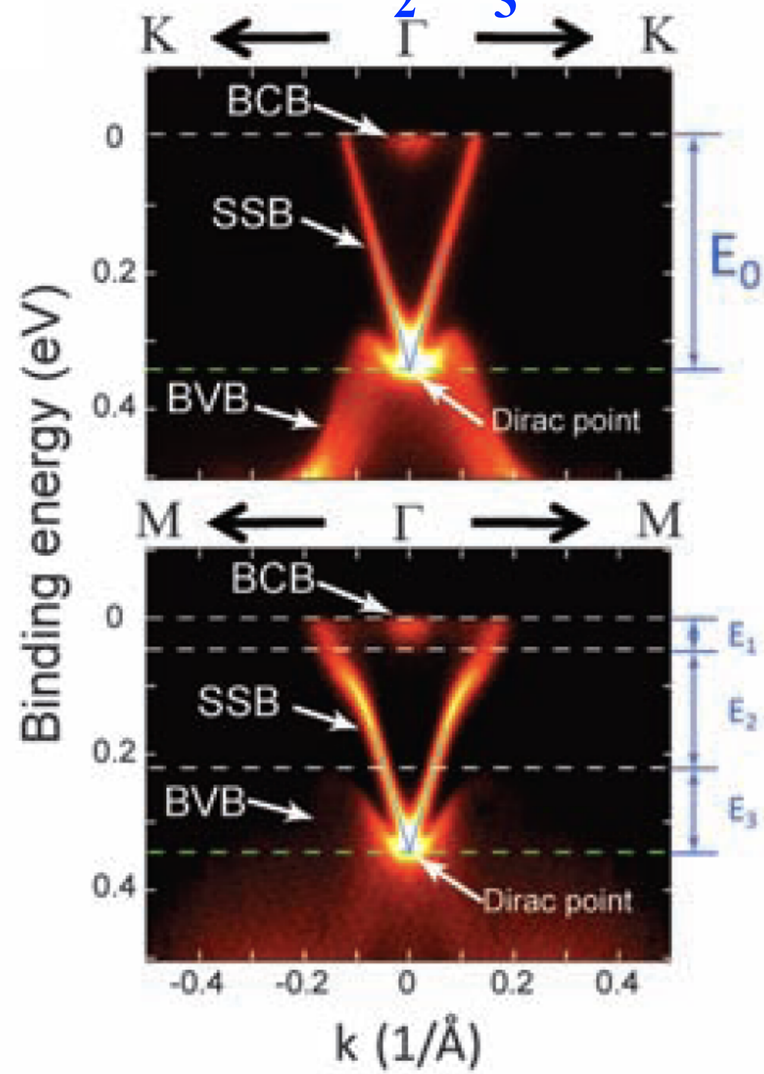
ARPES on Topological Insulators

Bi_2Se_3



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

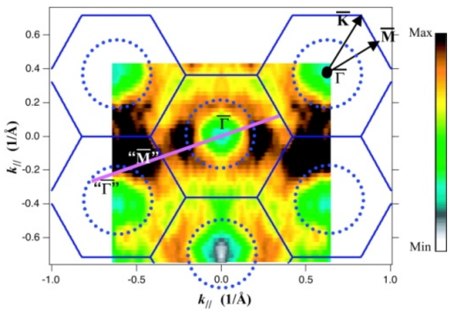
Bi_2Te_3



Y. L. Chen et al., Science 325 (2009)178.

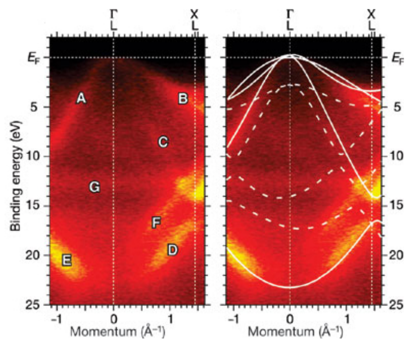
ARPES on Various Materials

C_{60}



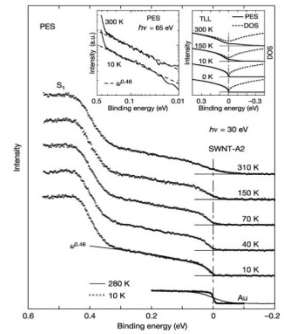
Science 300(2003)303

Diamond



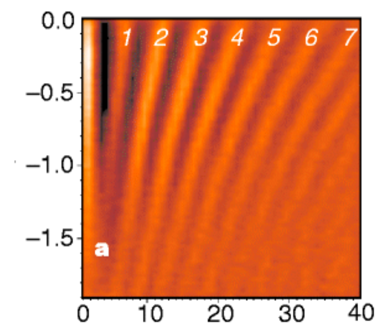
Nature 438(2005)647

Nanotube



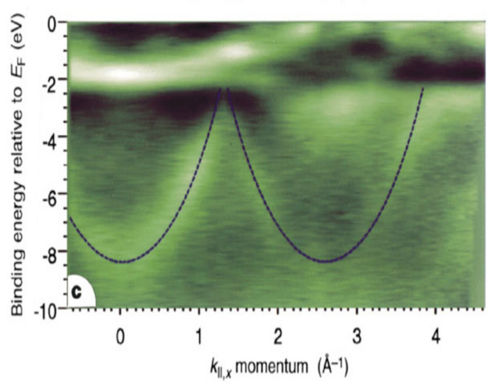
Nature 426(2003)540

Quantum Well



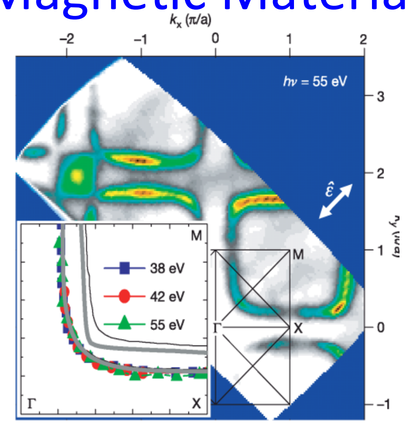
Nature 398(1999)132

Quasicrystal



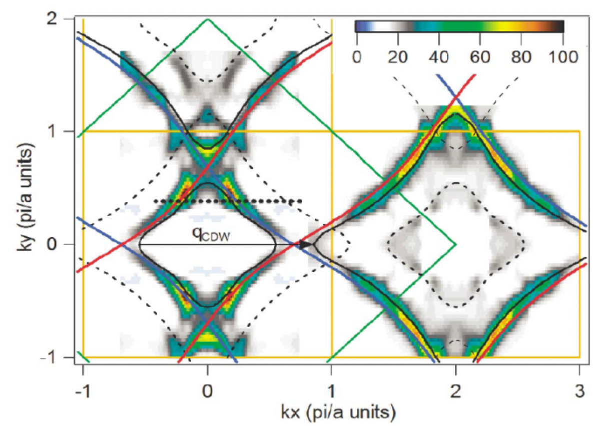
Nature 406(2000)602

Magnetic Materials



Nature 438(2005)474

CDW



Phys. Rev. Lett. 93(2004)126405

Content

- **What is ARPES?**

  Brief history, ARPES process,
  ARPES setup (Light sources, electron analyzer),
  ARPES resolutions, Matrix element effect

- **What can ARPES do?**

  Fermi surface mapping,
  Gap measurement
  Many-body effects

- **Latest and future development of ARPES**

  (Laser ARPES, spin-resolved, time-resolved, spatially-resolved)

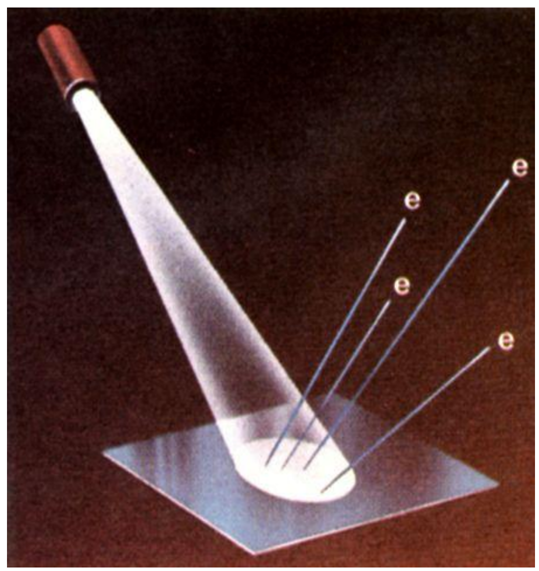
Brief History of ARPES

Principle of Photoemission—Photoelectric Effect

Discovery （1887)
German Physicist:
Hertz

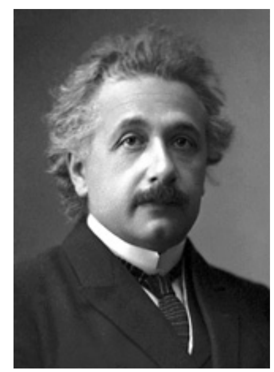
Heinrich Rudolf Hertz
(1857-1894)

Photoelectric Effect



Explanation （1905)：

The Nobel Prize in Physics 1921



Albert Einstein
(1879-1955)

“For his services to Theoretical Physics, and especially for his discovery of the law of **The Photoelectric Effect**"

Nobel Prizes in Photoemission Spectroscopy

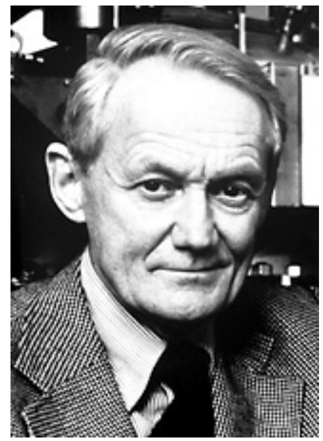
The Nobel Prize in Physics 1924

Karl Manne Georg Siegbahn (1886-1978)

"for his discoveries and research in the field of X-ray spectroscopy"

"The X-ray spectra and the structure of the atoms"

The Nobel Prize in Physics 1981



Kai M. Siegbahn (1918-2007)

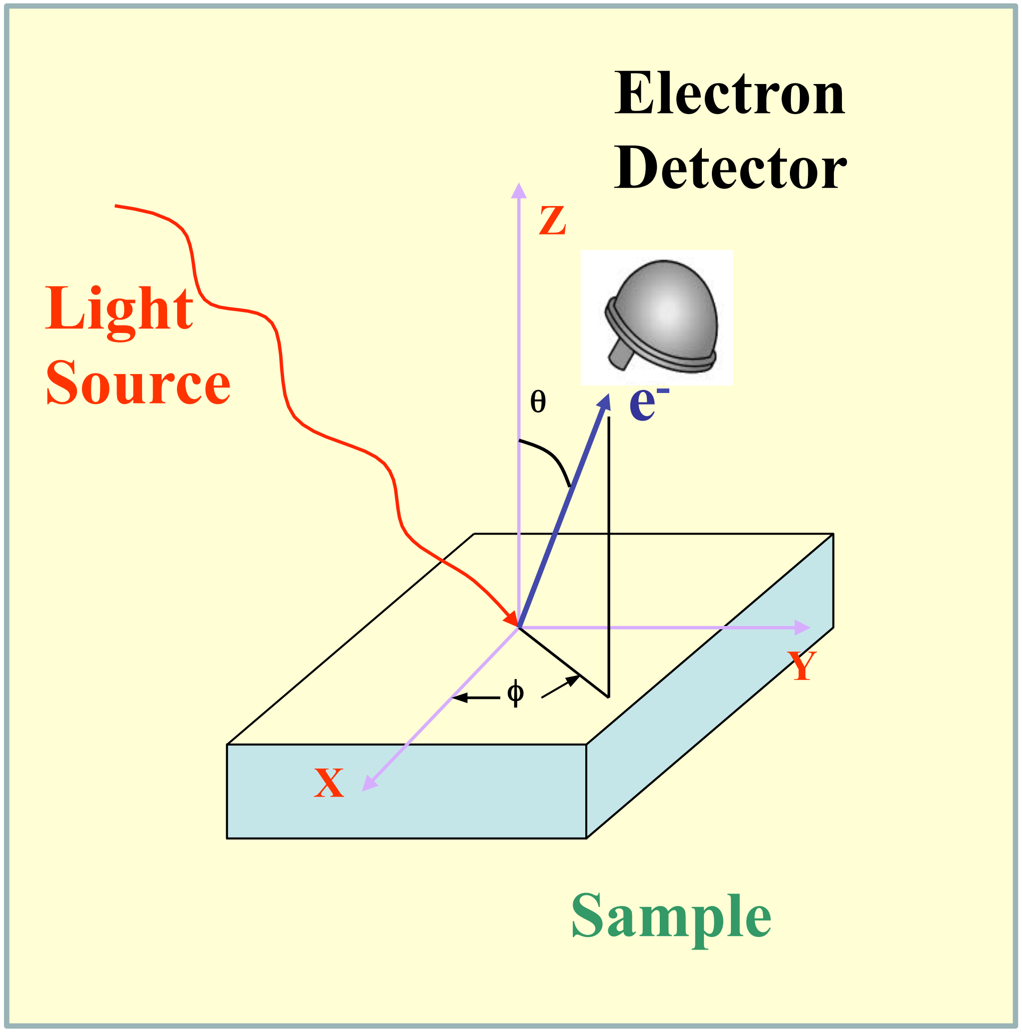
"for his contribution to the development of high-resolution electron spectroscopy"

"Electron Spectroscopy for Atoms, Molecules and Condensed Matter"

Classifications of Photoemission Techniques

Photoemission	Angle-Integraed	Angle-Resolved
Spin-integrated	E	E, k
Spin-resolved	E, s	E, s, k

*A*ngle-*R*esolved *P*hoto*e*mission *S*pectroscopy (ARPES)



Photoemitted electrons in Vacuum along different angles

$$E_{kin}, K_{||}$$

Energy Conservation: $E_B = h\nu - E_{kin} - \Phi$

Momentum Conservation: $K_{||} = k_{||} + G_{||}$

Electronic States in Solid:

$$\Psi(E, k, s)$$

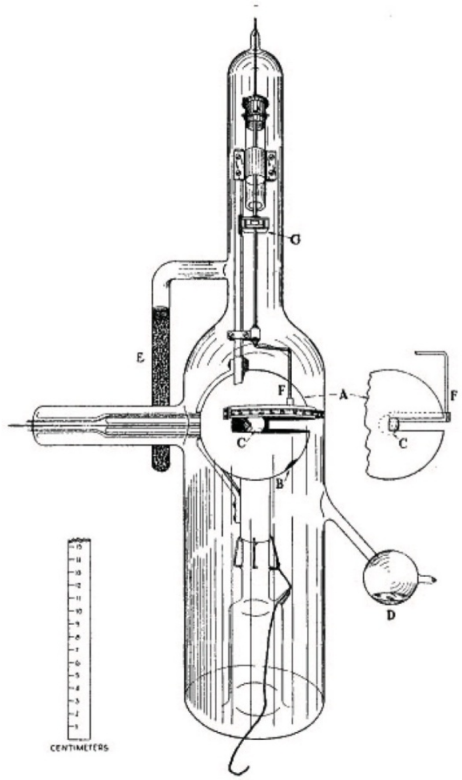
E-Energy ;

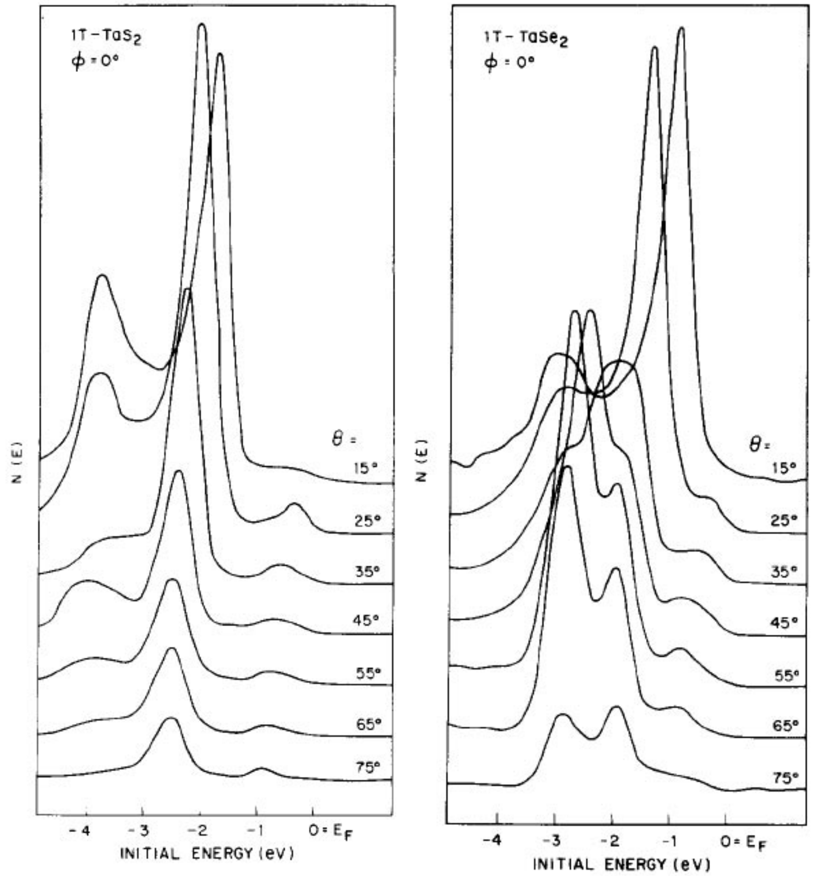
k-Momentum;

s-Spin.

First Angle-Resolved Photoemission Experiment of Band Mapping

Neville V. Smith
(1942-2006)



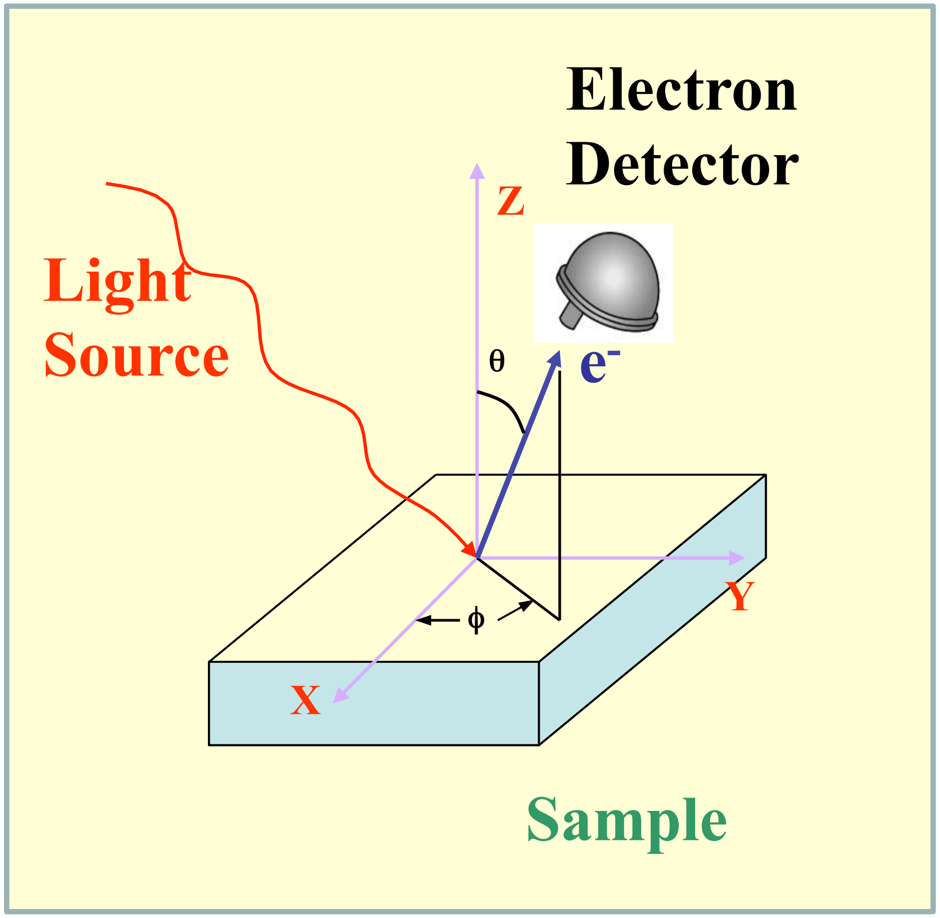


N. V. Smith, M.M. Traum and F.J. DiSalvo

Solid State Communications 15, 211 (1974)

*A*ngle-*R*esolved *P*hoto*e*mission *S*pectroscopy (ARPES)

$$E_K = \hbar^2/2m_e(K^2_{out}) = \hbar^2/2m_e(K^2_{x,out} + K^2_{y,out} + K^2_{z,out})$$



$$K_{x,out} = \sqrt{2m_eE_K}sin\theta$$

$$K_{y,out} = \sqrt{2m_eE_K}cos\theta sin\beta$$

$$K_{z,out} = \sqrt{2m_eE_K}cos\theta cos\beta$$

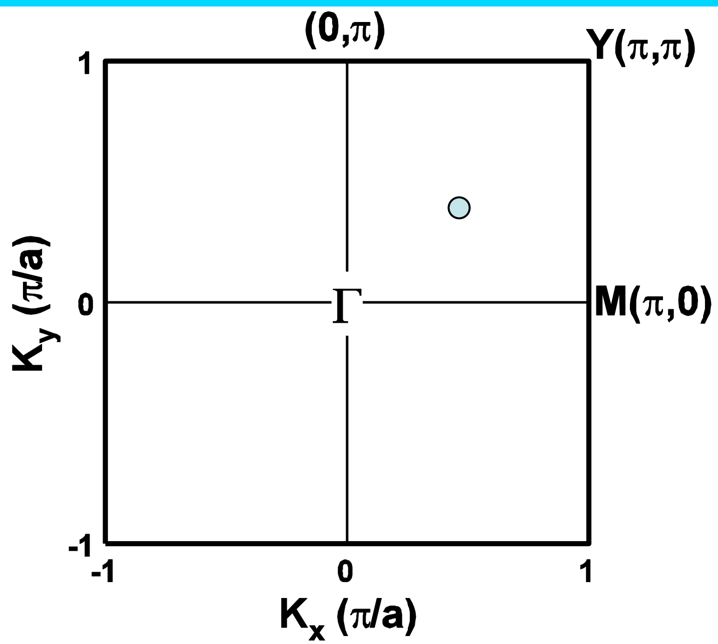
$$E_B = hv - \Phi - |E_K|$$

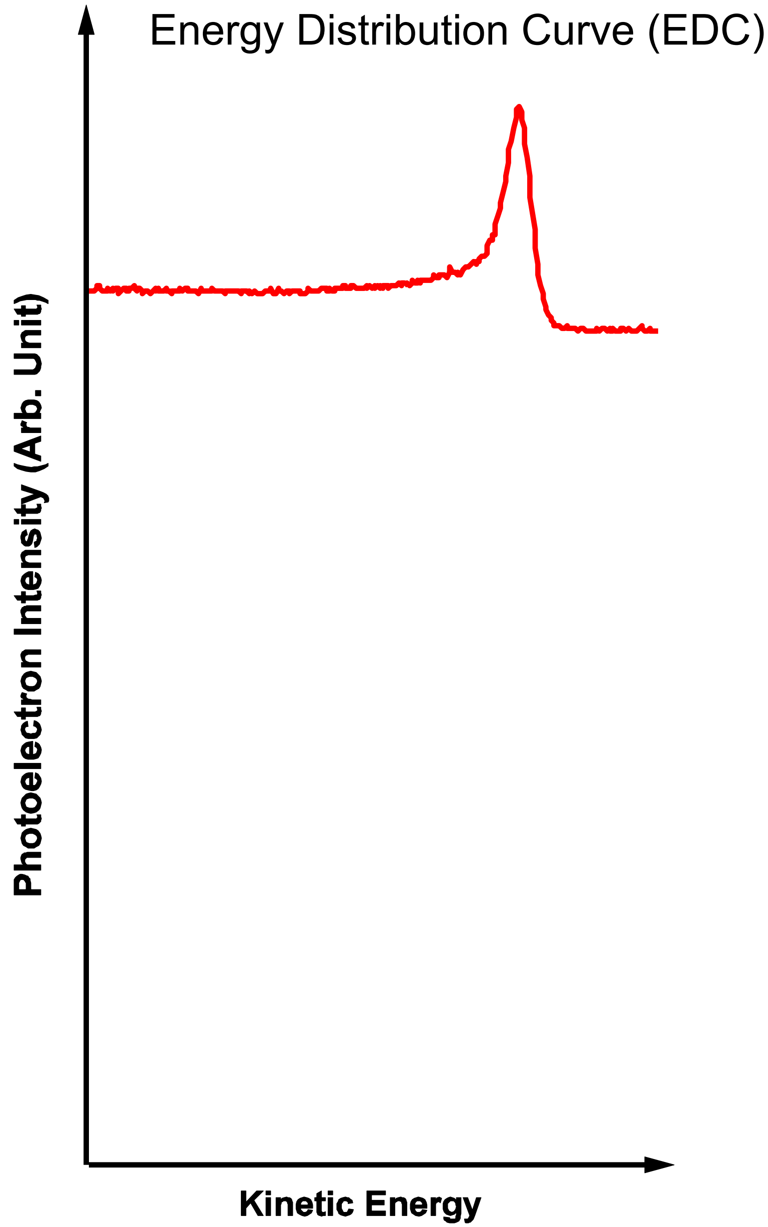
$$k_{x,i} = 0.512\sqrt{E_K}sin\theta$$

$$k_{y,i} = 0.512\sqrt{E_K}cos\theta sin\beta$$

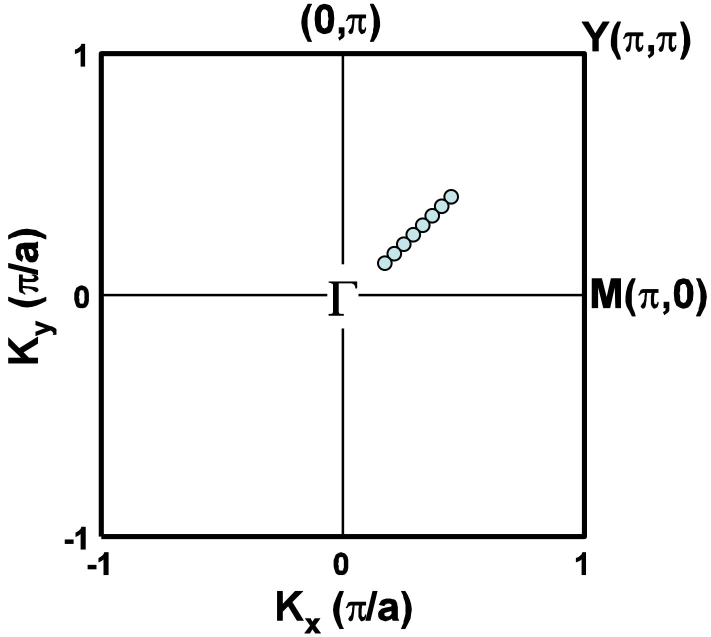
Photoemission Process

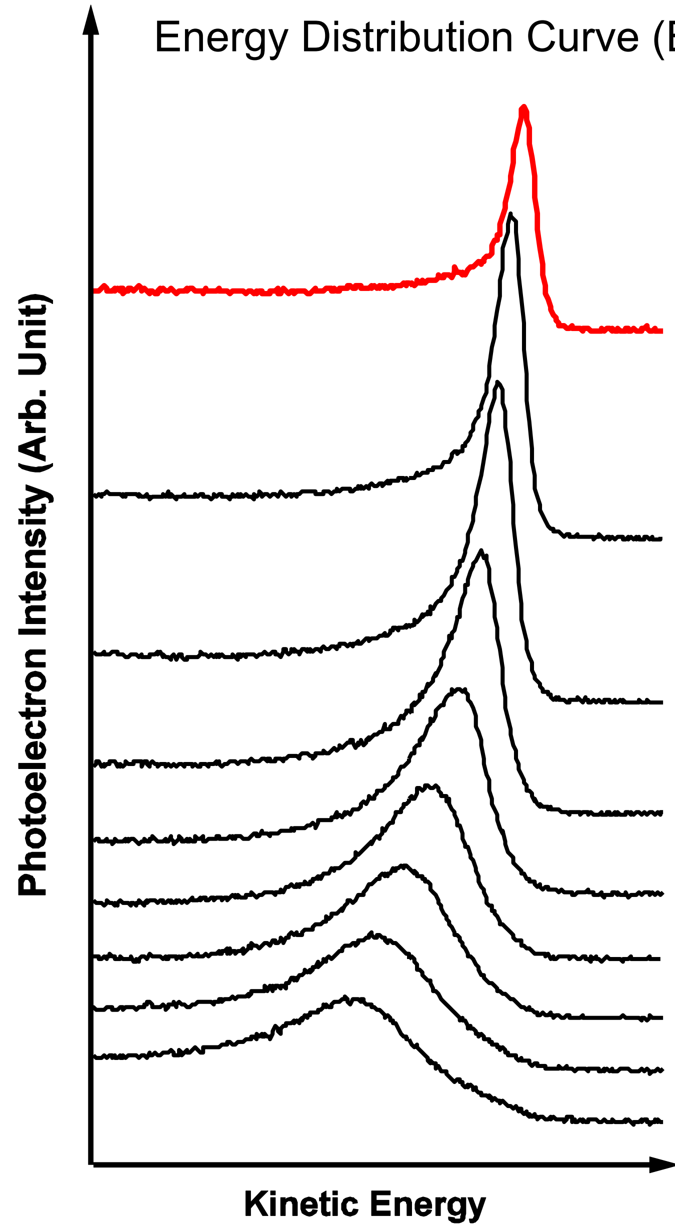
ARPES –Band Mapping and Fermi Surface



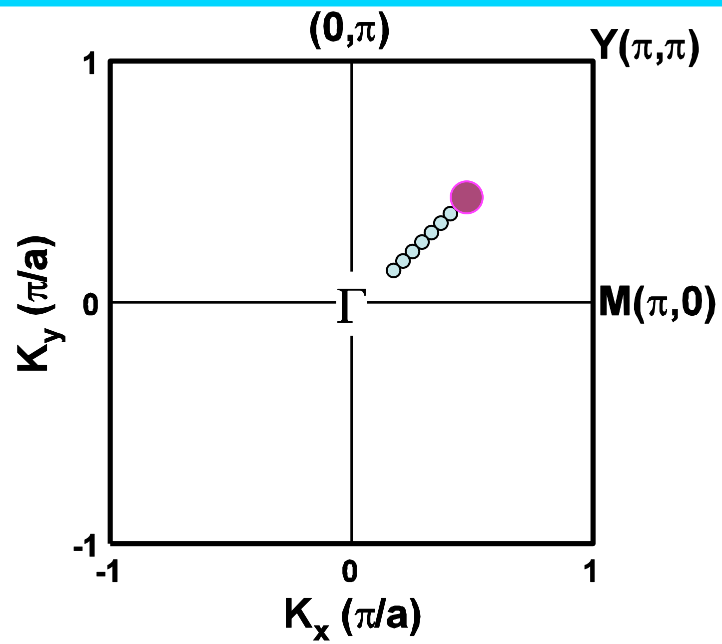


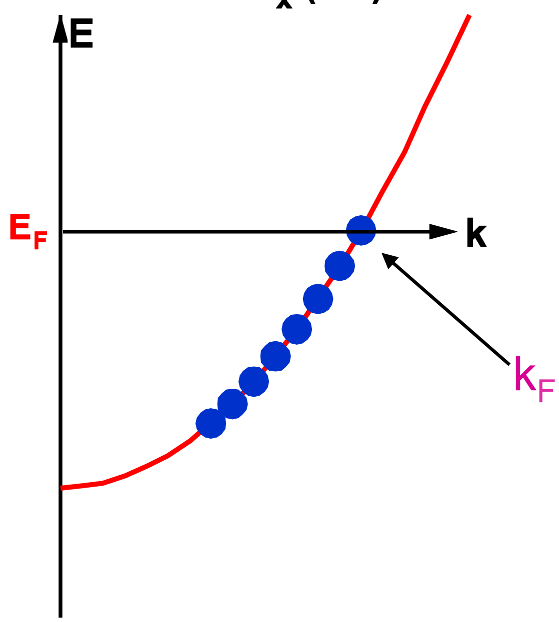
ARPES –Band Mapping and Fermi Surface

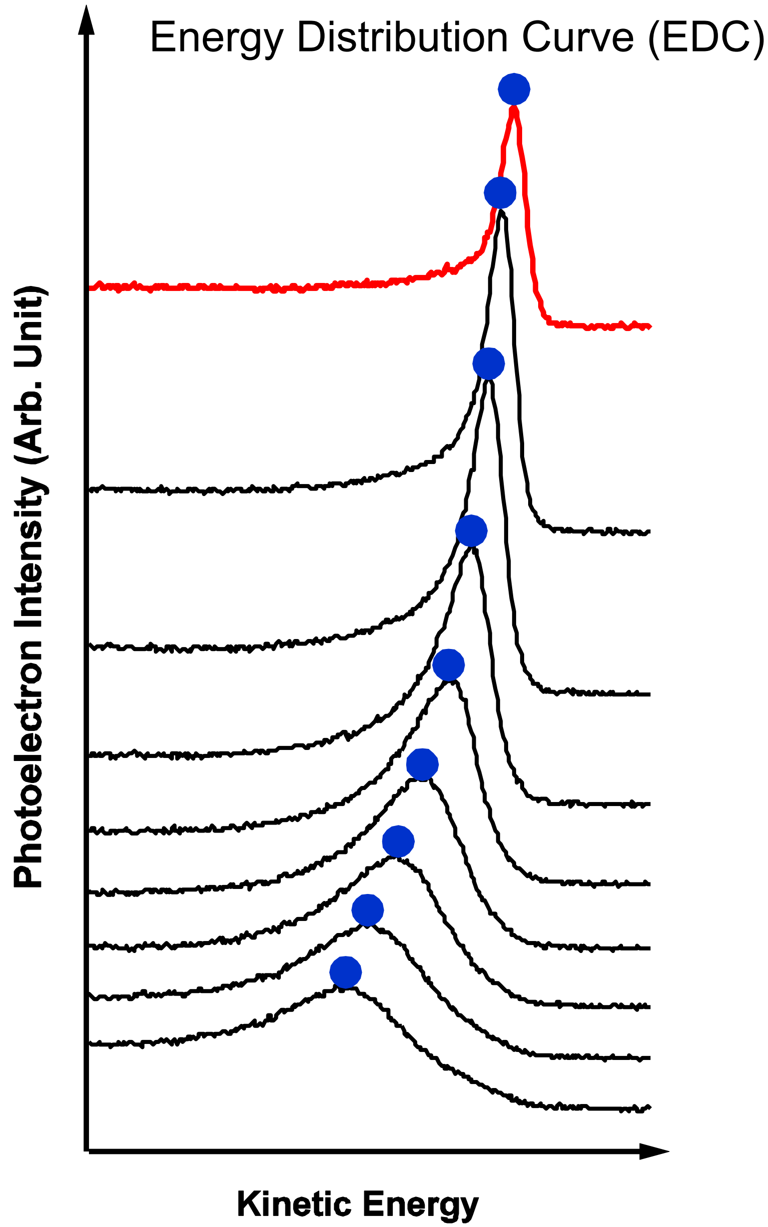




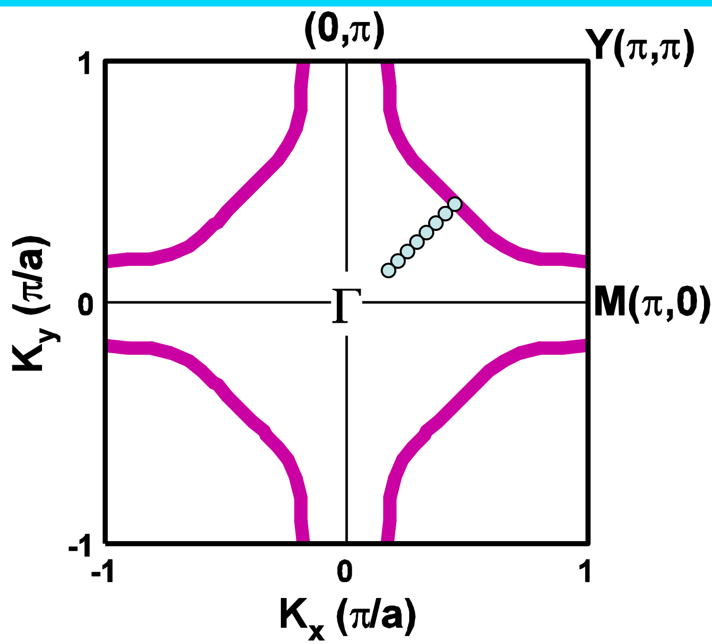
ARPES –Band Mapping and Fermi Surface

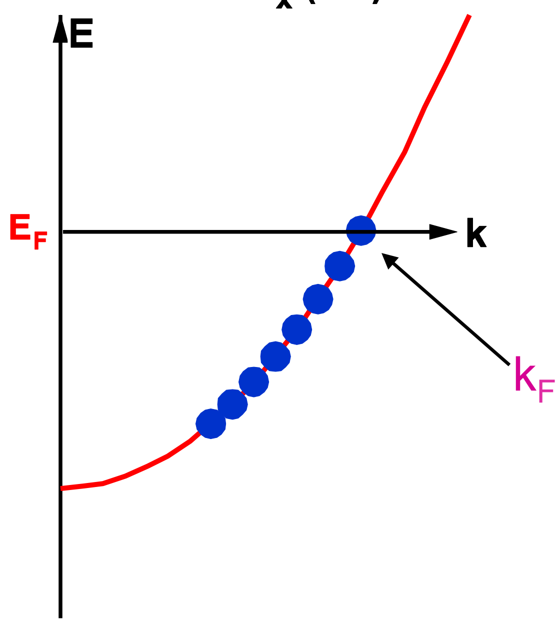


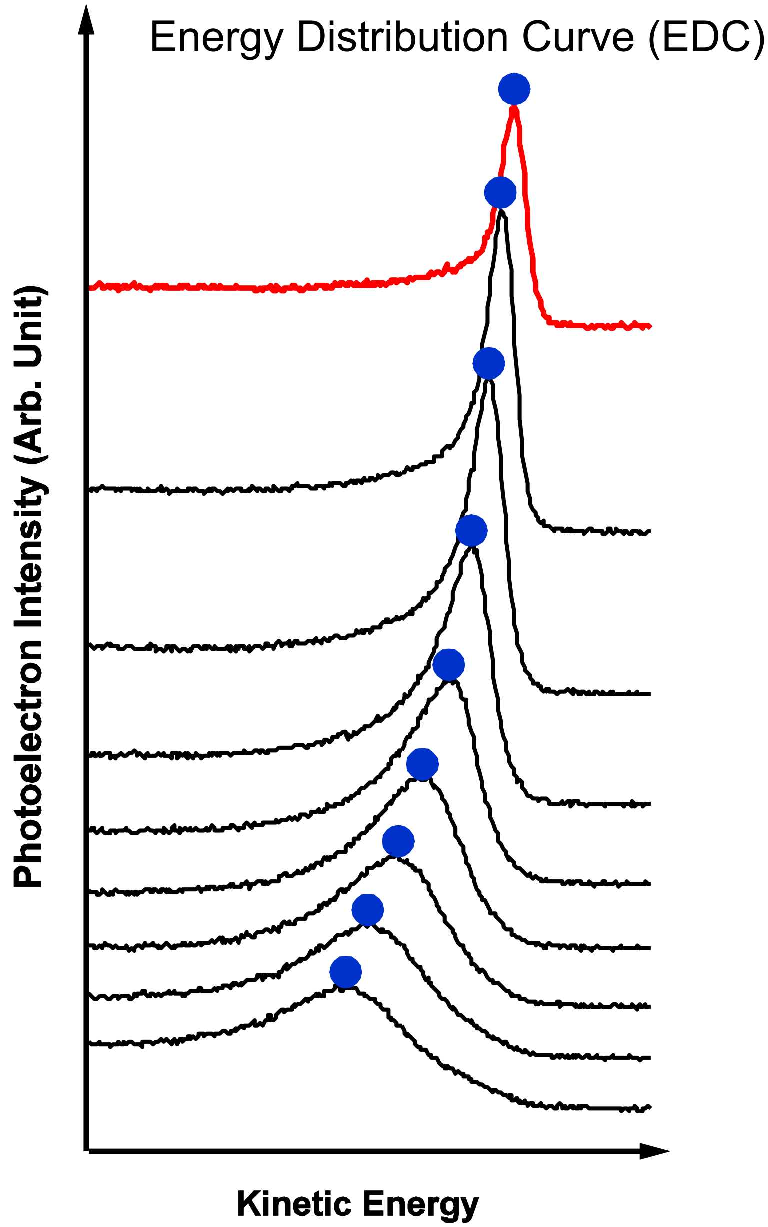




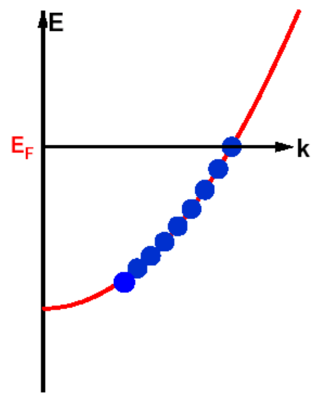
ARPES –Band Mapping and Fermi Surface







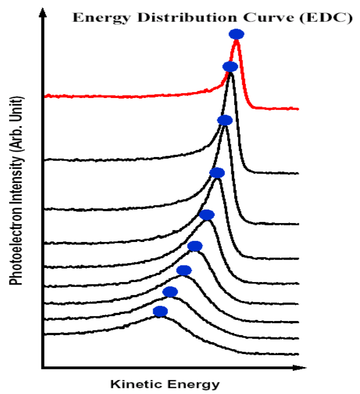
Power of ARPES:
Direct Measurement of Fundamental Parameters



E-k relation

Velocity: $v = dE/dk$

Effective mass: $1/m^* \sim d^2E/dk^2$

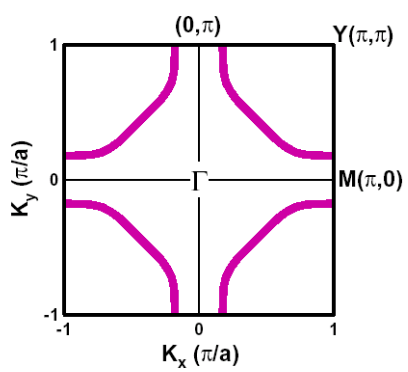


EDC lineshape

Scattering rate (τ): EDC Linewidth

Superconducting gap: EDC position

Pseudogap: EDC position



Fermi surface

Carrier density: FS volume

Nesting vector: FS topology

ELSEVIER Journal of Electron Spectroscopy and Related Phenomena 124 (2002) 289–315

JOURNAL OF ELECTRON SPECTROSCOPY and Related Phenomena

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Sudden approximation in photoemission and beyond

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Received 27 September 2001; received in revised form 2 November 2001; accepted 26 November 2001

$$G(\mathbf{k},\omega)=\frac{1}{\omega-\epsilon_{\mathbf{k}}-\Sigma(\mathbf{k},\omega)}$$

$$A(\mathbf{k},\omega)=-(1/\pi)\,\mathrm{Im}\,G(\mathbf{k},\omega)$$

Challenge: At which point the sudden approximation breaks down and how?

*A*ngle-*R*esolved *P*hoto*e*mission *S*pectroscopy (*ARPES*)
-- Direct Comparison between Theory and Experiment

$I(k,w)=I_0\,|M(k,w)|^2 f(w)\,A(k,w)$

Under the impulse approximation, photoemission measurement invloves only *single-particle spectral function*

$$A(k,\omega)=\frac{1}{\pi}\frac{\mathrm{Im}\sum(k,\omega)}{[\hbar\omega-E_k^0-\mathrm{Re}\sum(k,\omega)]^2+[\mathrm{Im}\sum(k,\omega)]^2}$$

Fermi Surface

Quasiparticle Dynamics

ReS(k,w): dispersion
ImS(k,w): scattering rate

Theories

Physical Properties

ARPES: A Bridge between Theory and Experiment

- **Conventinal Fermi Liquid:**

  $\mathrm{Im}\Sigma = -\beta\omega^2$

  $\mathrm{Re}\Sigma = \alpha\omega$

- **Marginal Fermi Liquid:**

  $\mathrm{Im}\Sigma = -\pi/2Cx$

  $\mathrm{Re}\Sigma = C\omega\ln(x/\omega c)$ where $x=\max(|\omega|,T)$

- **Electron-Phonon Coupling System**

$$\mathrm{Im}\Sigma = -\pi\int_0^\infty d\omega\alpha_k^2(\omega)F_k(\omega)[2n_B(\omega)+n_F(\omega+u)+n_F(\omega-u)]$$

$$\mathrm{Re}\Sigma = -\int_0^\infty d\omega\alpha_k^2(\omega)F_k(\omega)\ln\left|\frac{\omega+u}{\omega-u}\right|$$

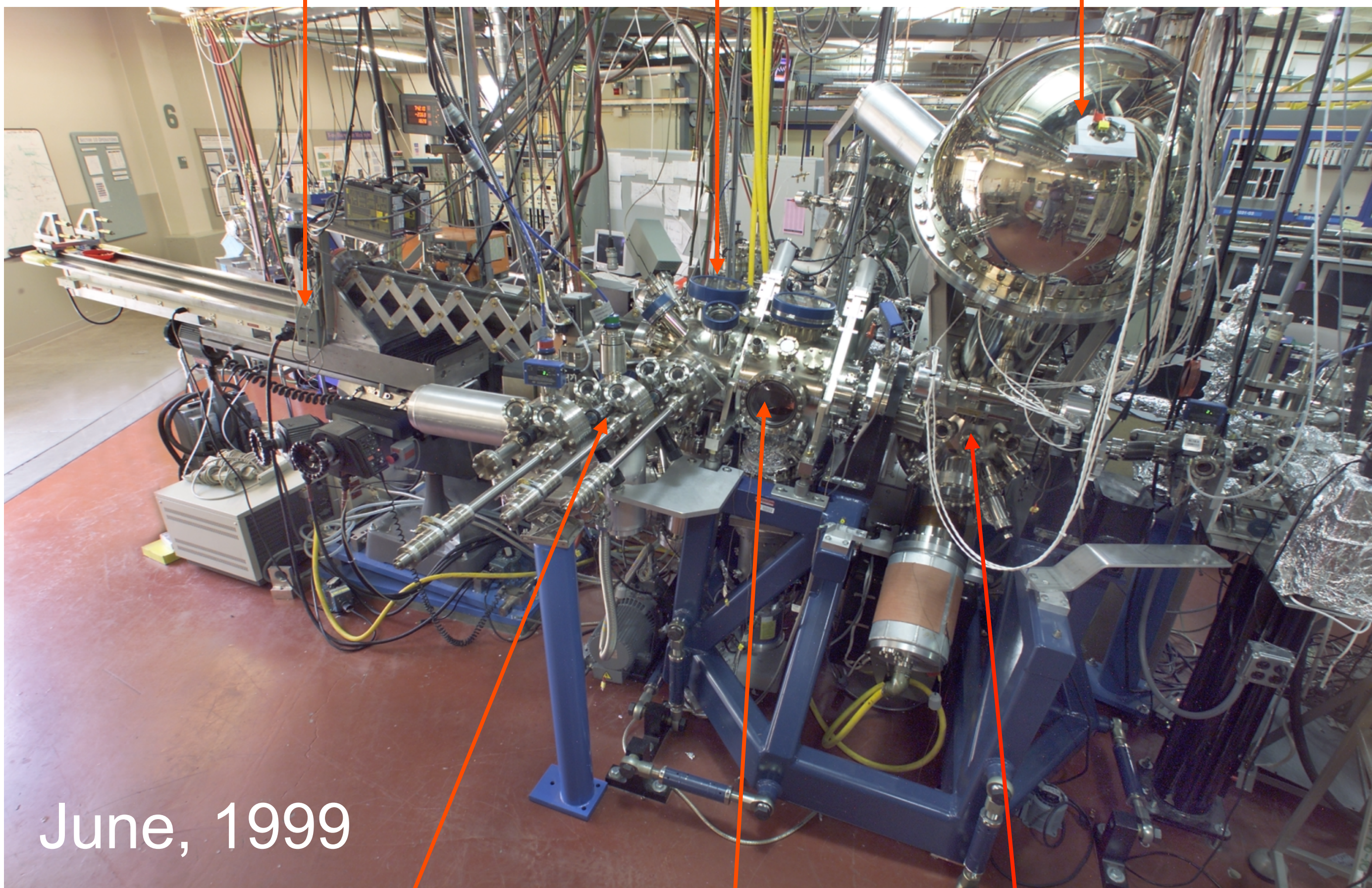
ARPES Experimental Setup

ARPES Endstation on BL10.0.1, ALS, LBNL

Manipulator

Prep Chamber

Scienta Analyzer



Beam in

Sample Transfer

Characterization Chamber

ARPES Chamber

Some Remarks about ARPES

- **ARPES is a surface-sensitive technique,**
  →ultra-high vacuum is necessary;

- **ARPES uses electron emission angle to determine the momentum**
  →magnetic field is not welcome;

- **Electrons have to travel to analyzer directly**
  →ARPES is not compatible with high-pressure, ultra-low temperature yet.

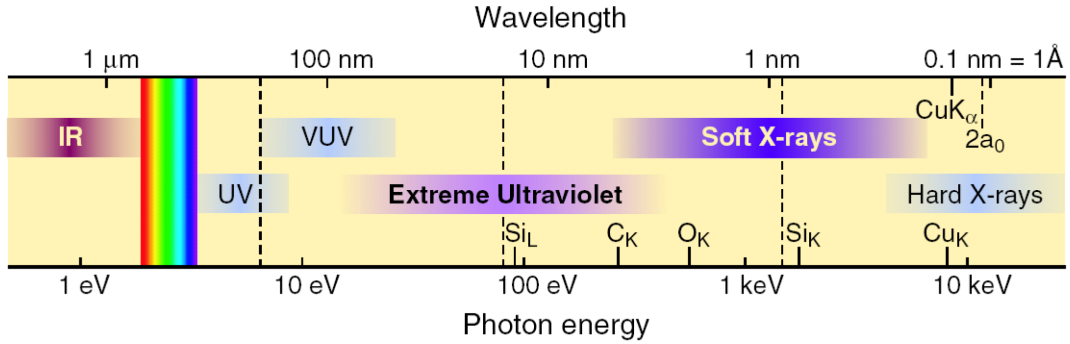
ARPES Light Sources

1. Synchrotron Light Sources;

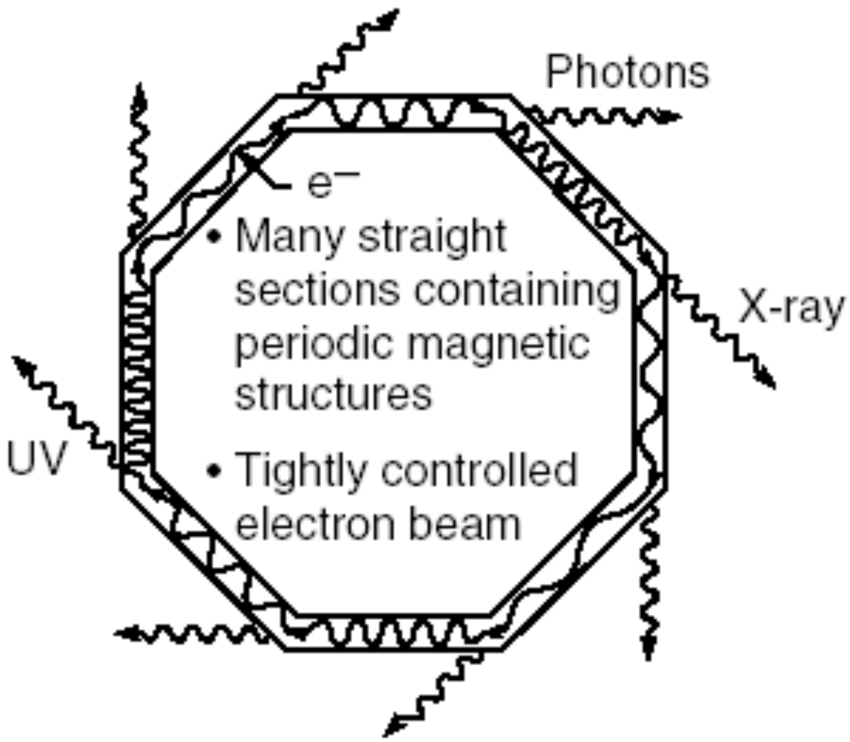
2. Gas Discharge Lamp;

3. UV and VUV lasers.

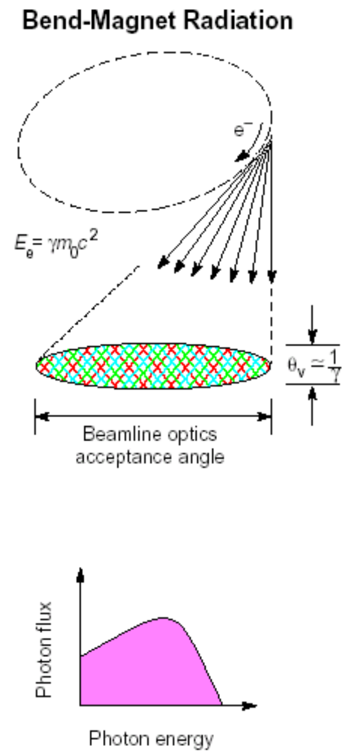
What is Synchrotron?

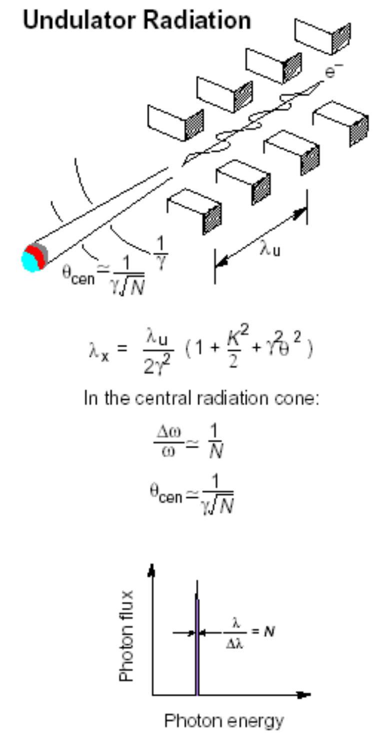


Principle: Charged particles with high energy (near speed of light) gives light when changing directions.

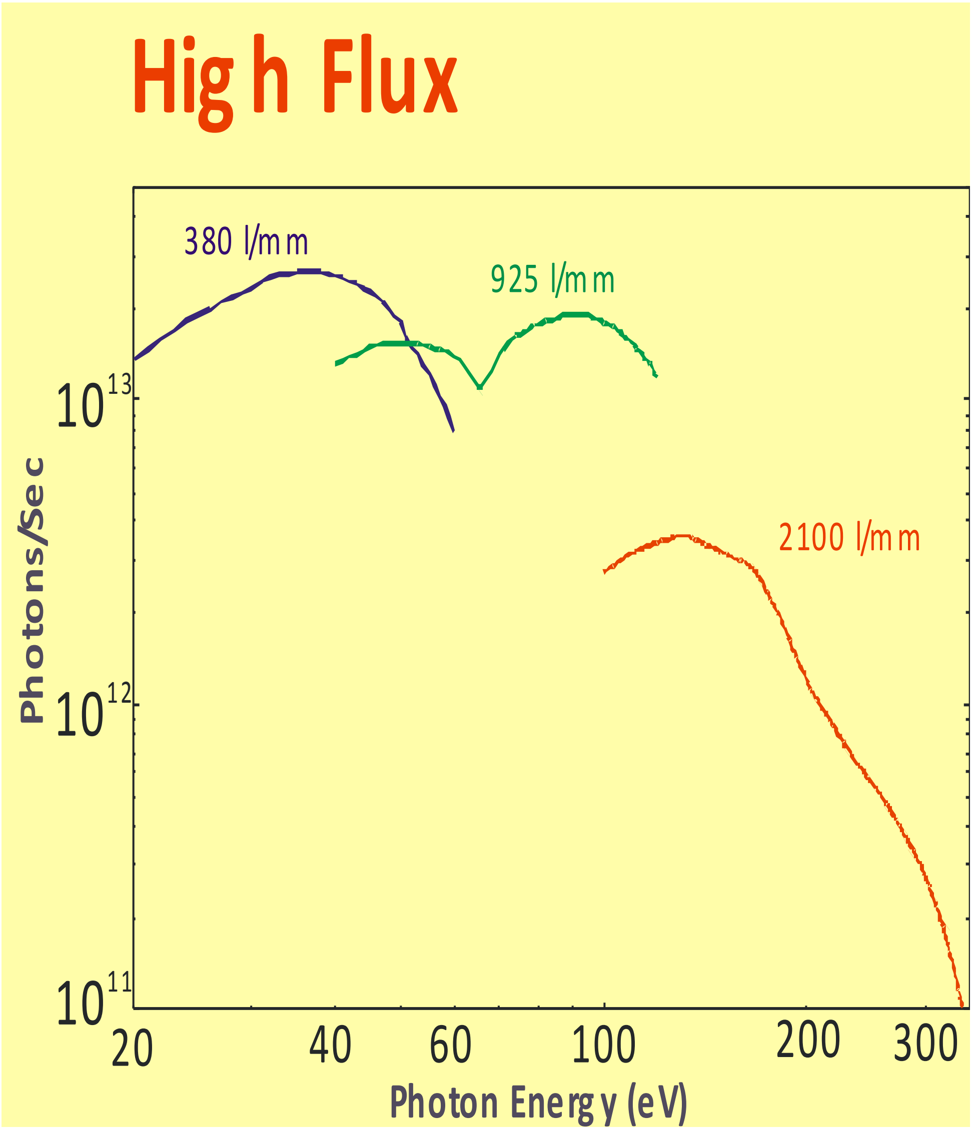


- Many straight sections containing periodic magnetic structures
- Tightly controlled electron beam





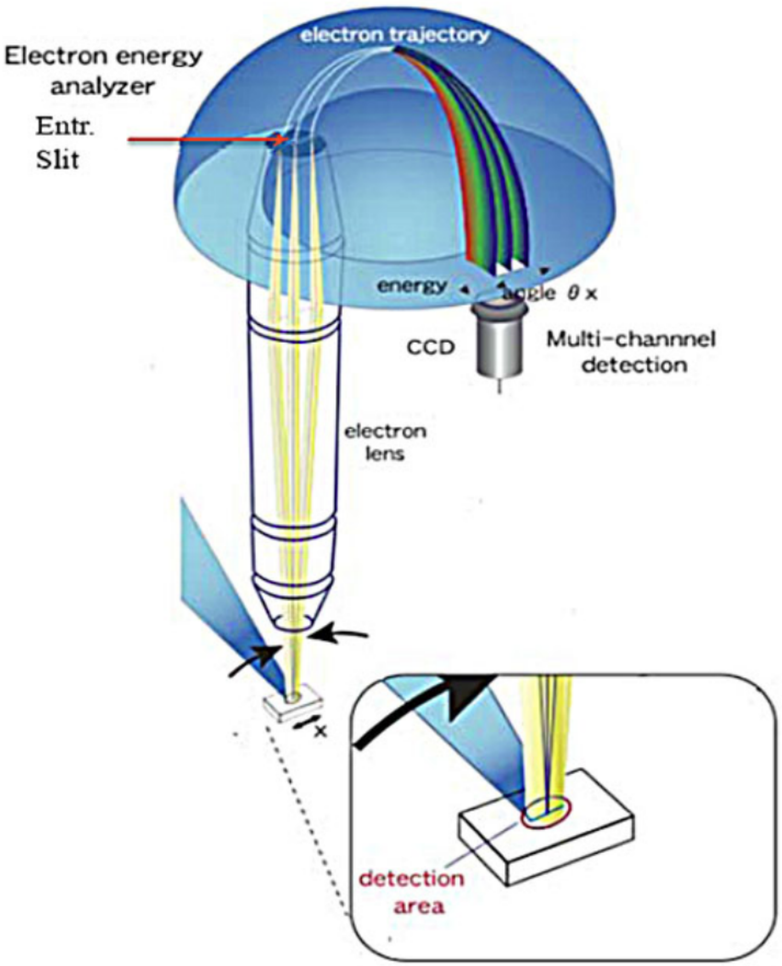
Synchrotron Source for ARPES: BL10.0.1 at ALS, Berkeley

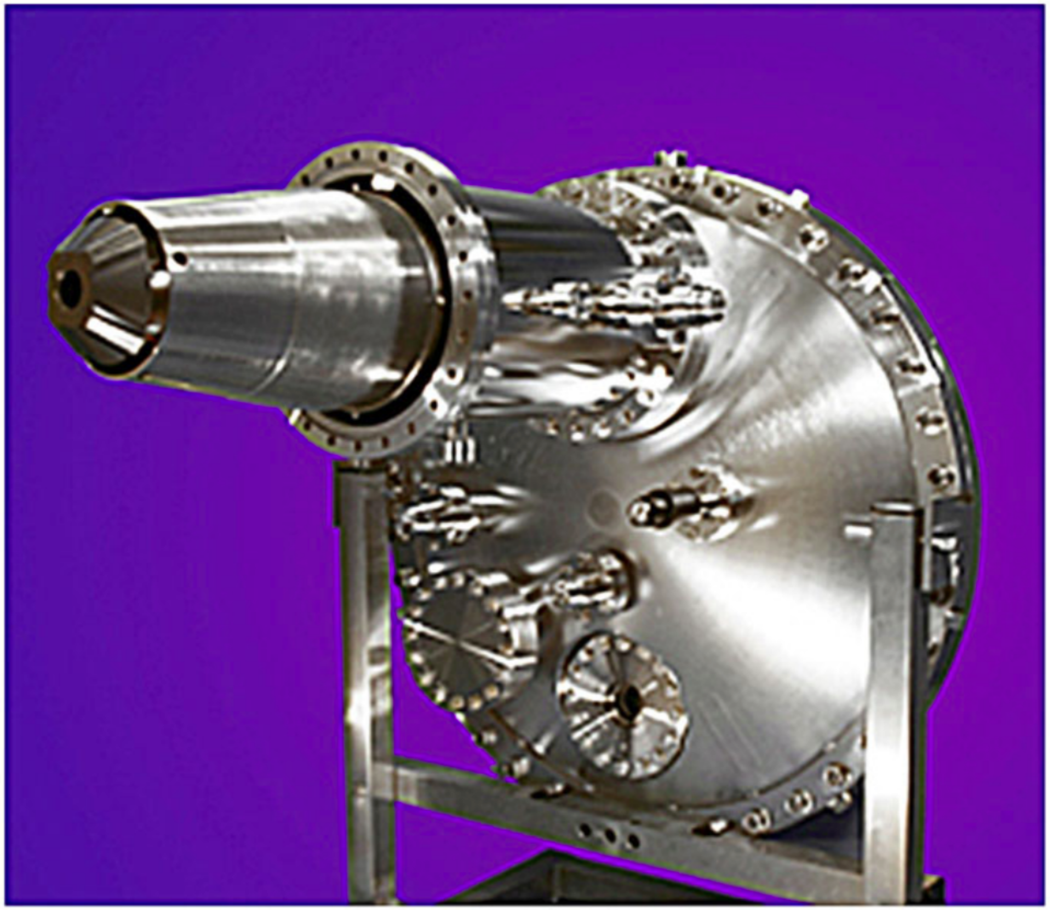


- **Wide Energy Range: 17-360 eV;**
- **High Energy Resolution;**

  (<5meV between 20-50eV)
- **High Flux.**

Electron Energy Analyzer

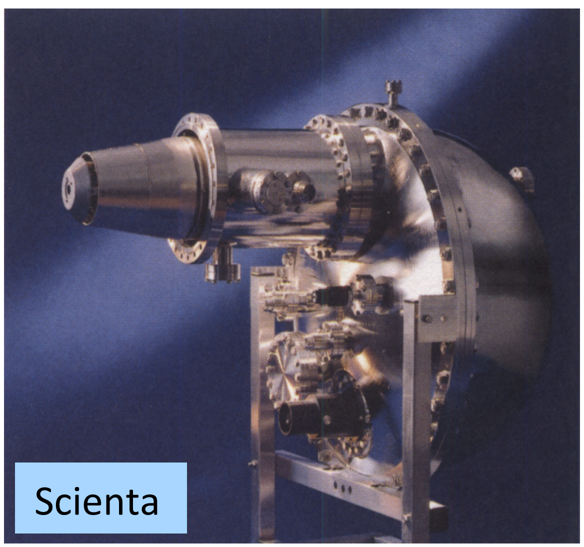




ARPES--Improved Resolution Brings New Discoveries

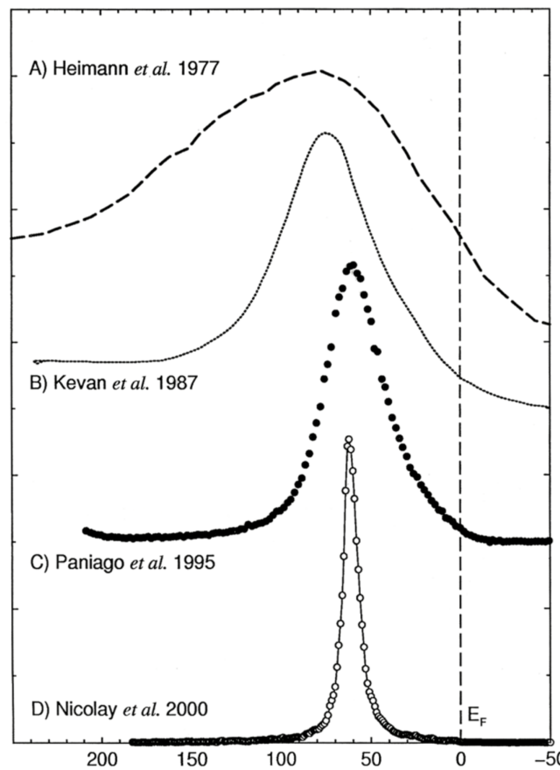
3rd Generation Synchrotron

Electron Energy Analyzer



	Energy Resolution (meV)	**Angle Resolution (degree)**
Previous	**20～40**	**~2**
Now	**<1**	**0.1**

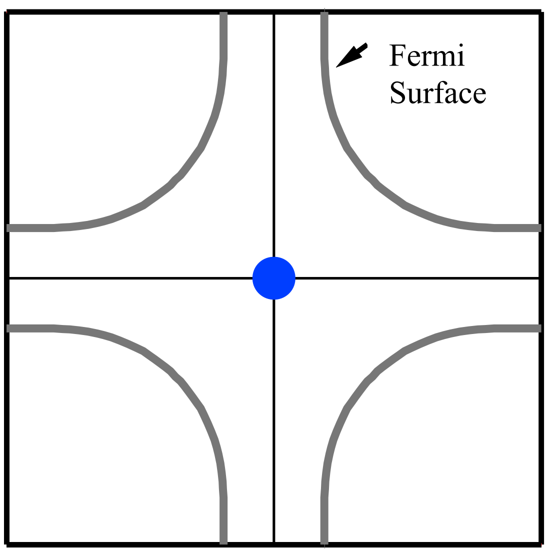
Ag(111) Surface State



G. Nicolay et al., Phys. Rev. B 63(2001)115415.

Evolution of Energy Analyzers: from 0D to 1D Angular Detection

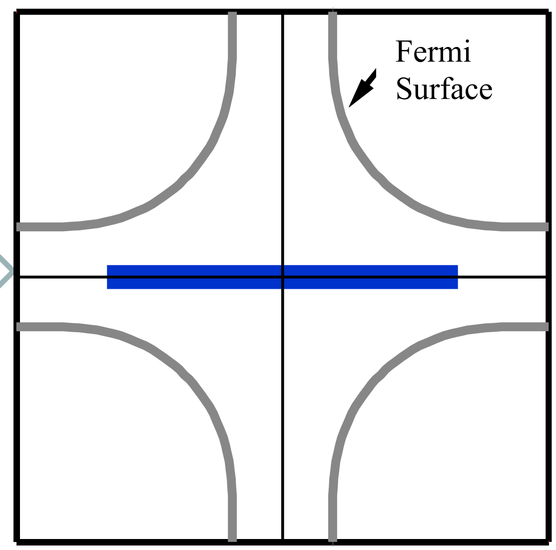
Before Scienta (~1997)



Angle Detection: 0D Point

Hemispherical Analyzer

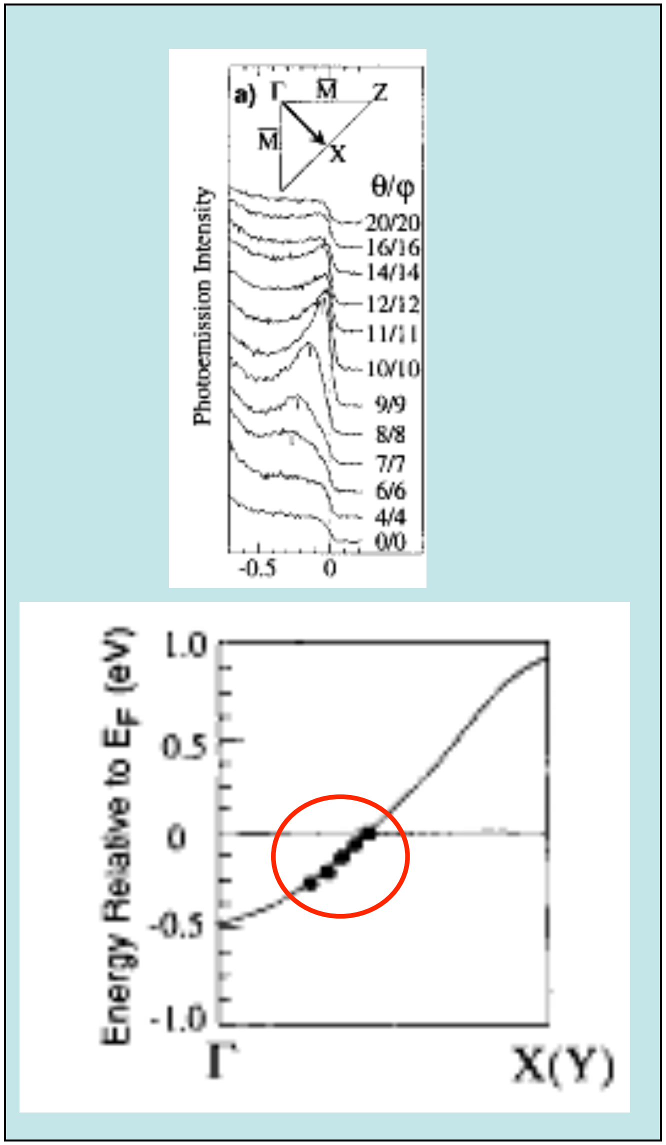
- Energy Resolu: <1meV
- Angular Resolu: 0.1~0.4 Degree
- Angle Coverage: 1D: +-15 degrees



Angle Detection: 1D Line

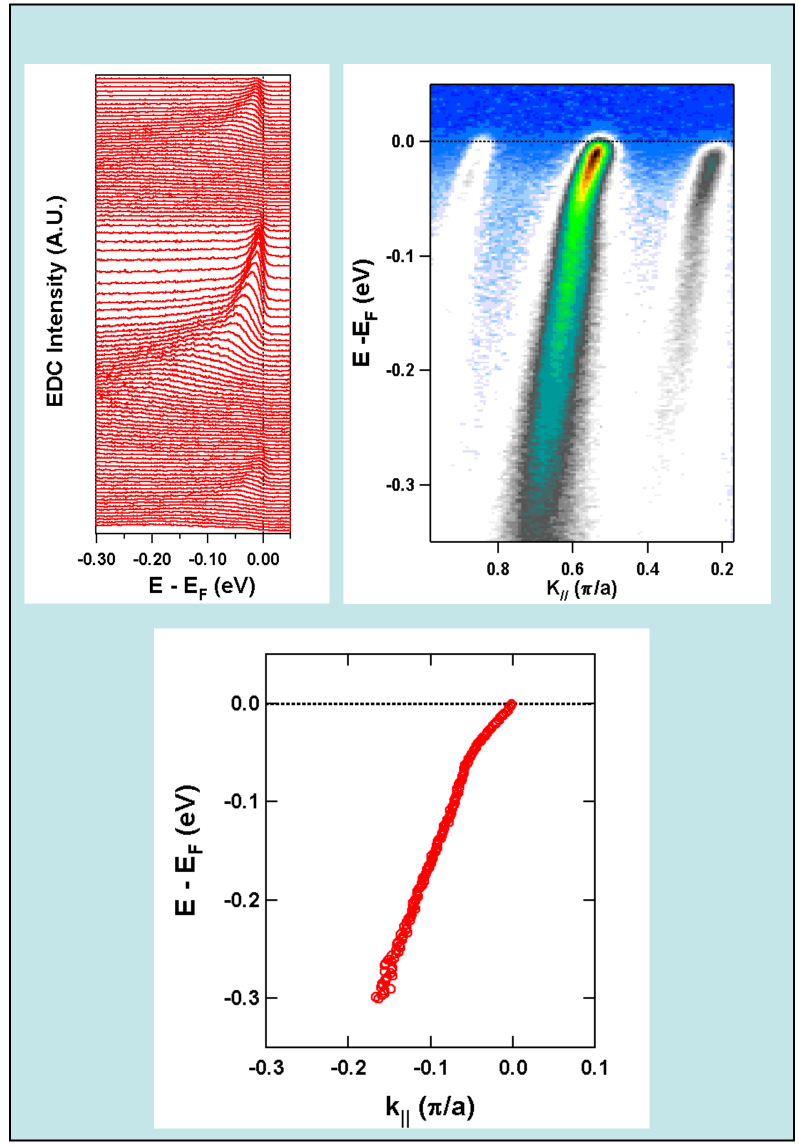
Better Resolution Reveals Electron Kinkiness in Cuprates

Angular Resolution: 2 degrees



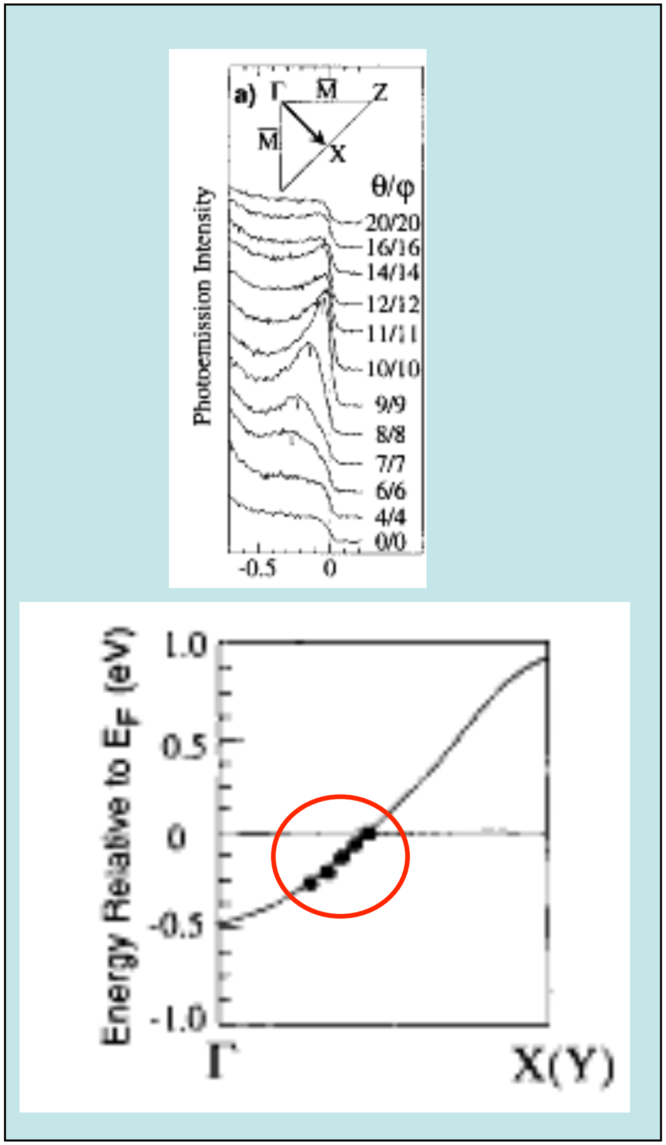
Dessau et al., PRL (1995).

Angular Resolution: 0.3 degree



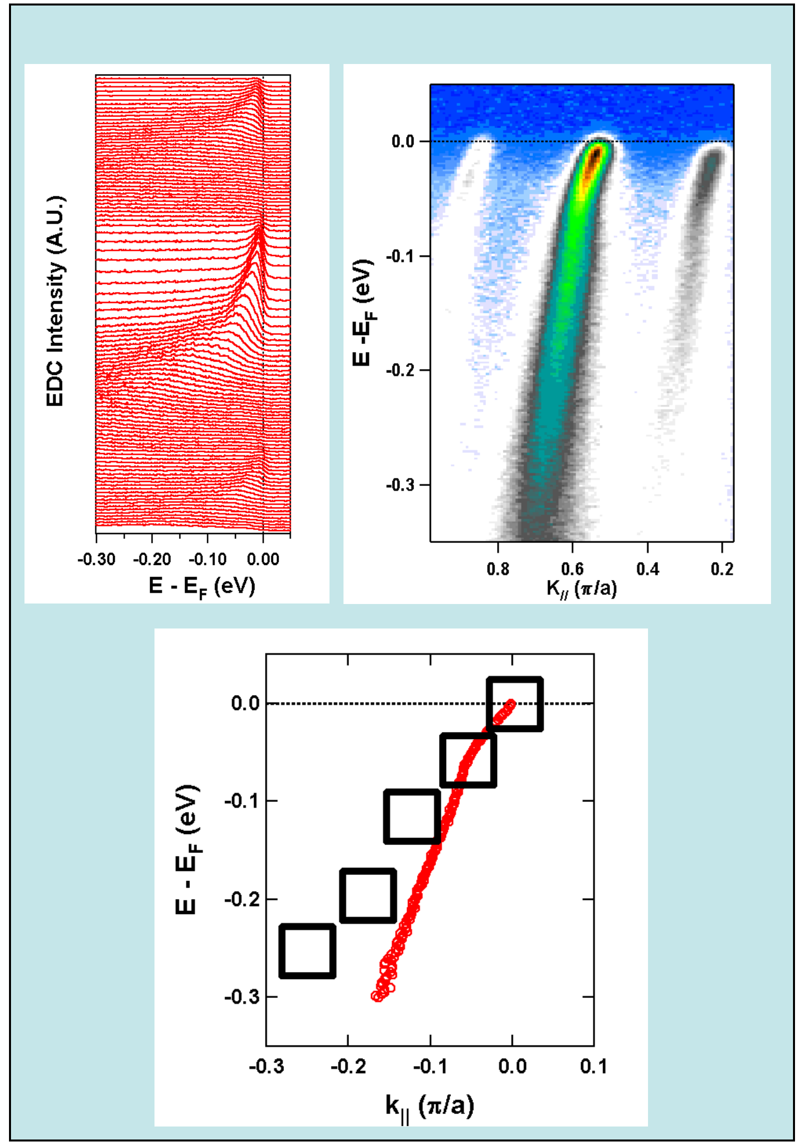
Better Resolution Reveals Electron Kinkiness in Cuprates

Angular Resolution: 2 degrees



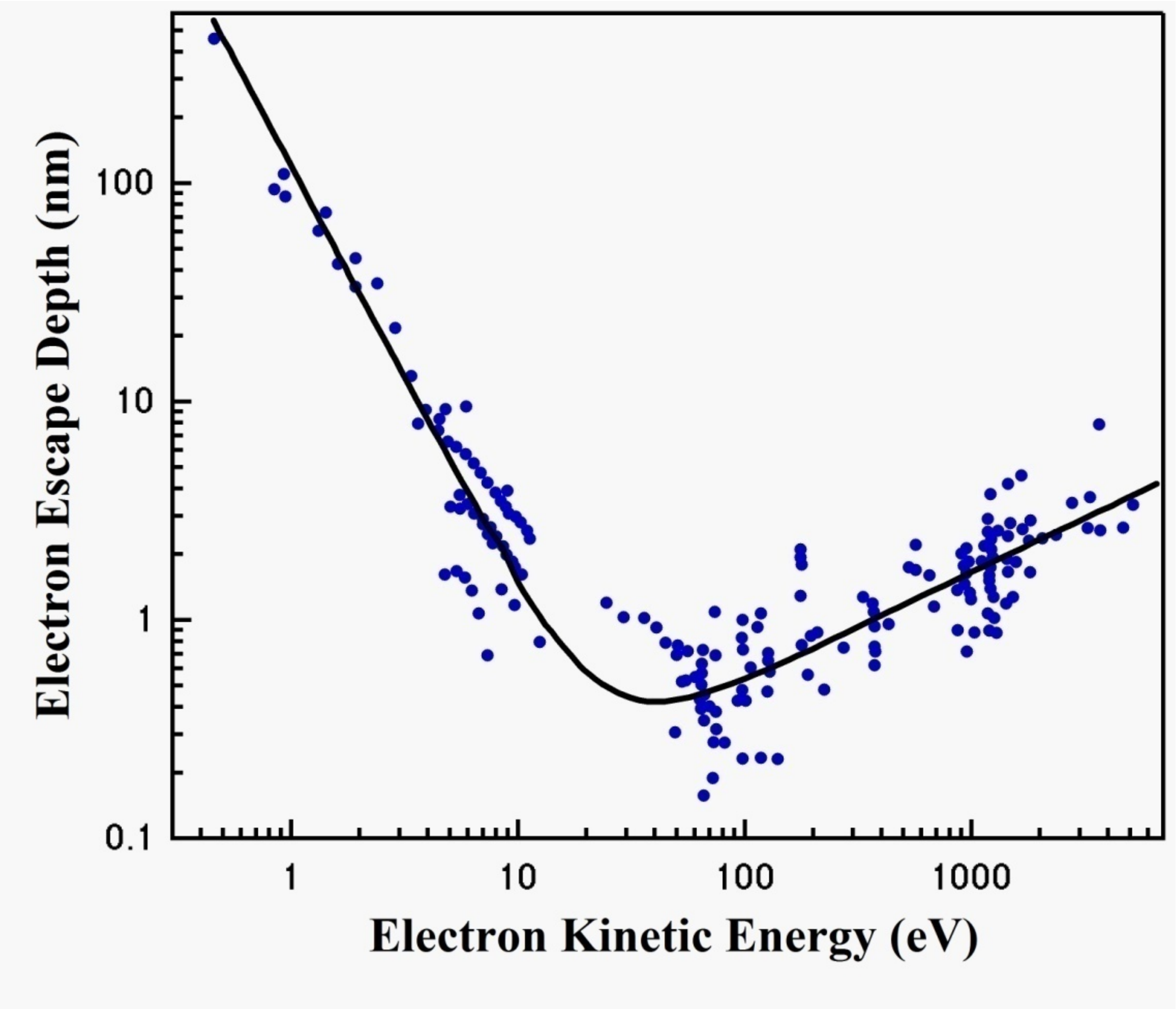
Dessau et al., PRL (1995).

Angular Resolution: 0.3 degree



Related Issues in Photoemission

Surface vs Bulk Property Measurements



Matrix Element Effect in Photoemission

$$I = A(k,\omega) \times |M(k,h\nu)|^2 \times F(\omega)$$

Measured Signal

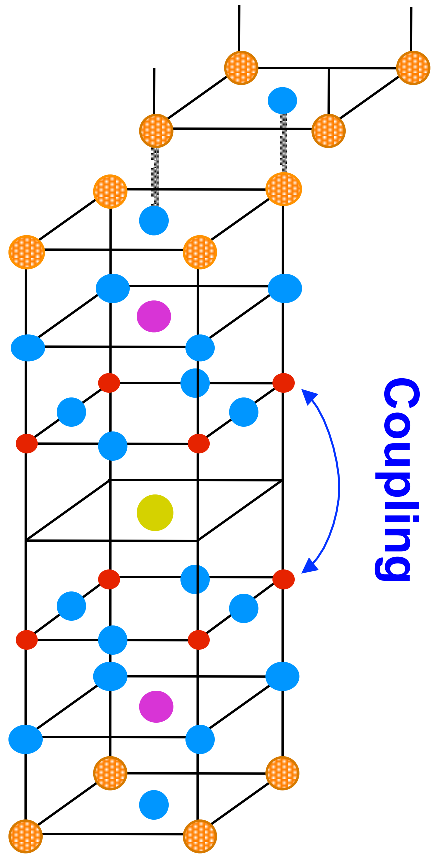
Single-particle spectral function
—Intrinsic property of materials

Fermi-Dirac Distribution

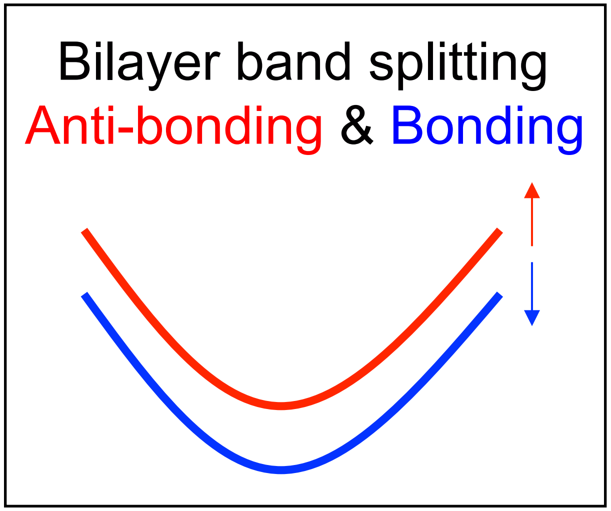
Matrix Element：
Depending on measurement conditions

- **Photon energy;**
- **Photon polarization;**
- **Momentum.**

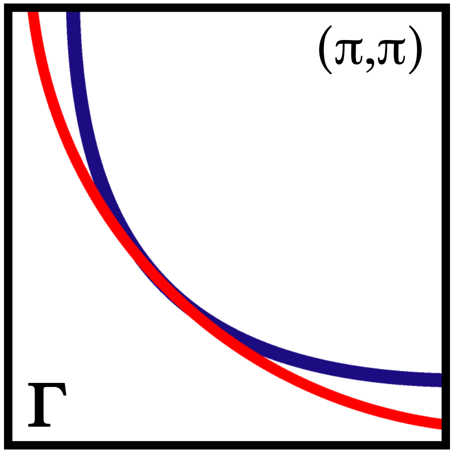
Bilayer Splitting in $Bi_2Sr_2CaCu_2O_{8+\delta}$



$Bi_2Sr_2CaCu_2O_{8+\delta}$
Bi2212
Tc=90K



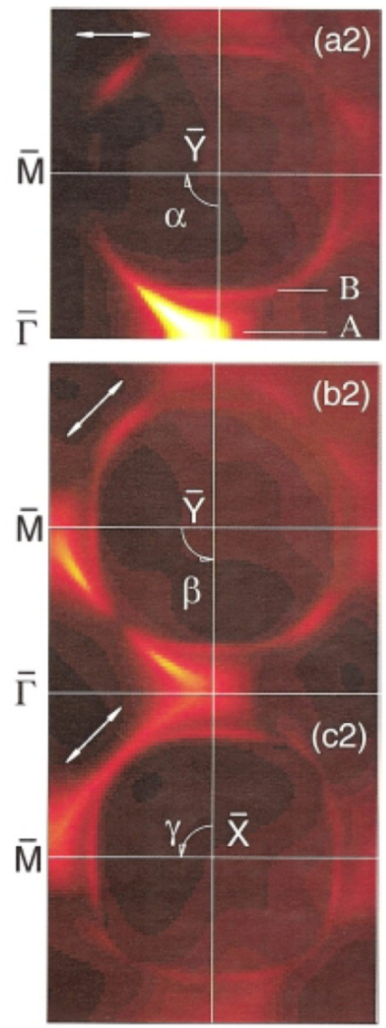
FS with
bilayer splitting



*A. I. Liechtenstein et al., PRB **54**, 12505 (1996)*

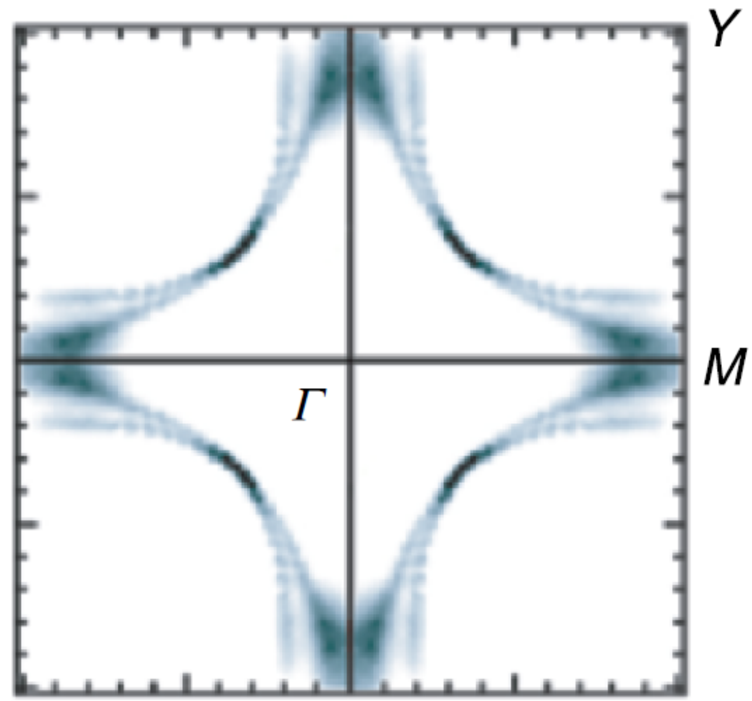
Calculations of Matrix Element Effect

Calculated



A. Bansil et al.,
Phys. Rev. Lett. 83(1999) 5154.

Measured

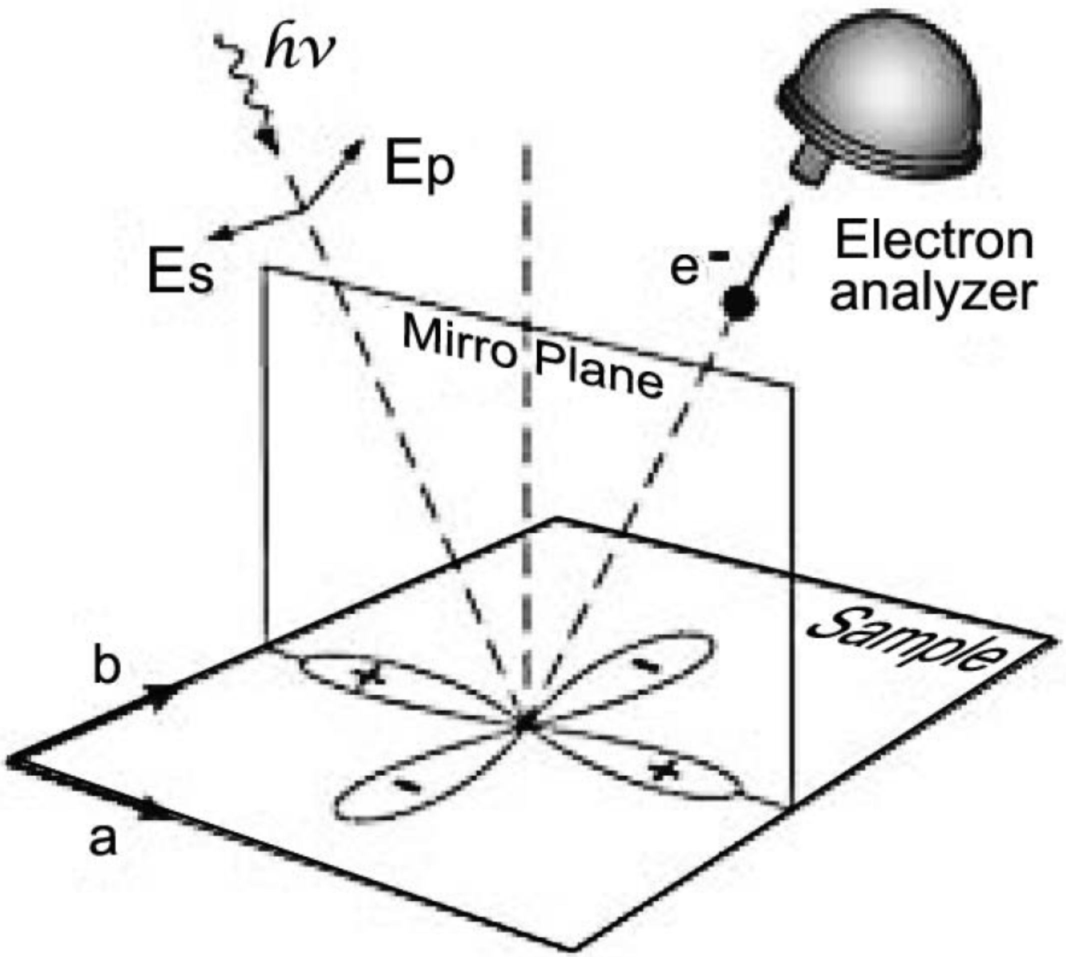


P. V. Bogdanov et al. Phys. Rev. B 64, 180505 (2001)
D. L. Feng et al., PRL 86 (2001) 5550.
Y. D. Chuang et al., PRL 87 (2001) 117002.

Challenge:

How to calculate Matrix Element Effect in correlated systems?

Light Polarization on Matrix Element Effect



To disentangle different orbitals

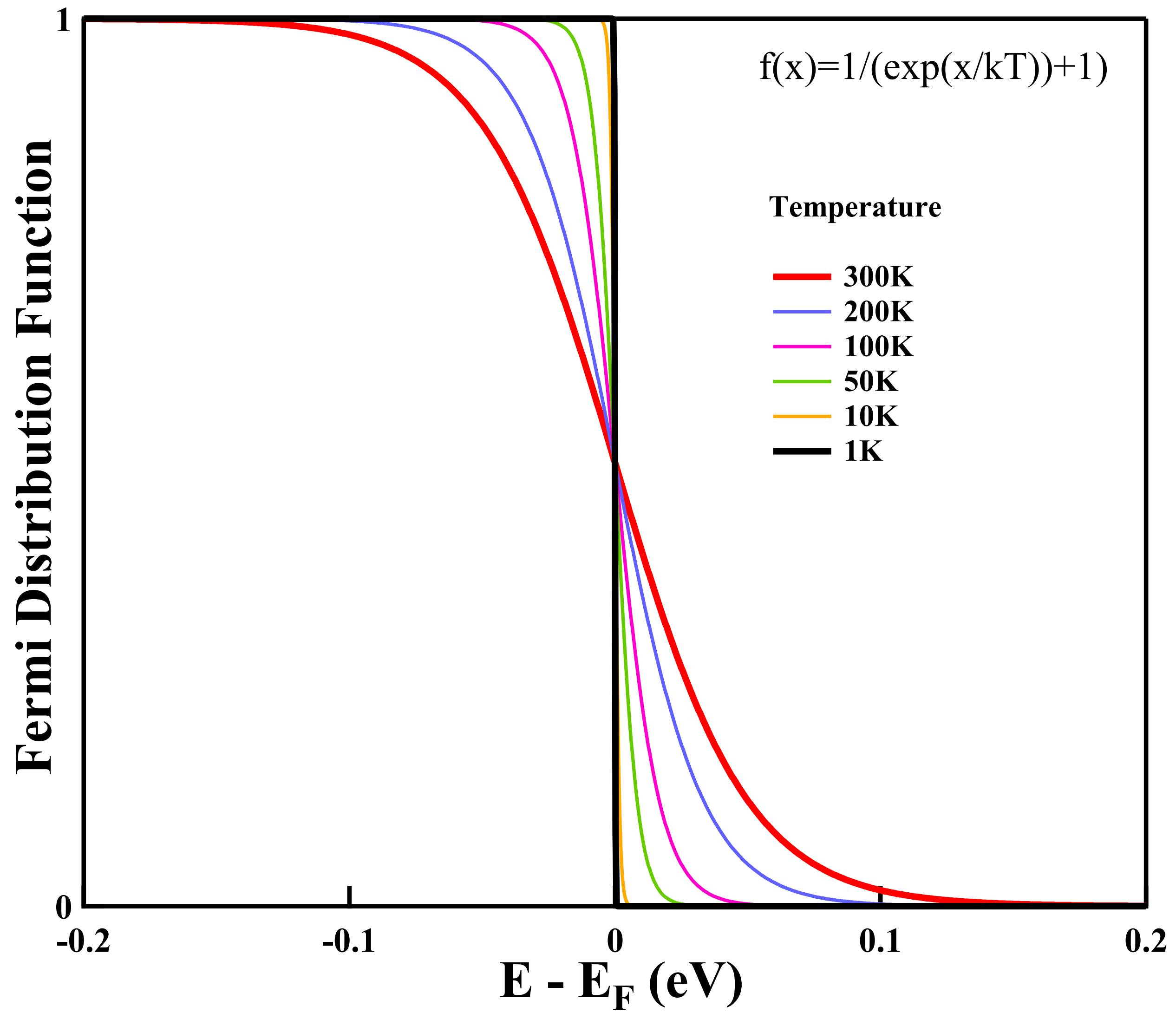
$$M_{ij}(E_f, K) \propto < \phi_{f,K} | A \cdot P | \phi_{i,K} >^2$$

Related Issues in Photoemission

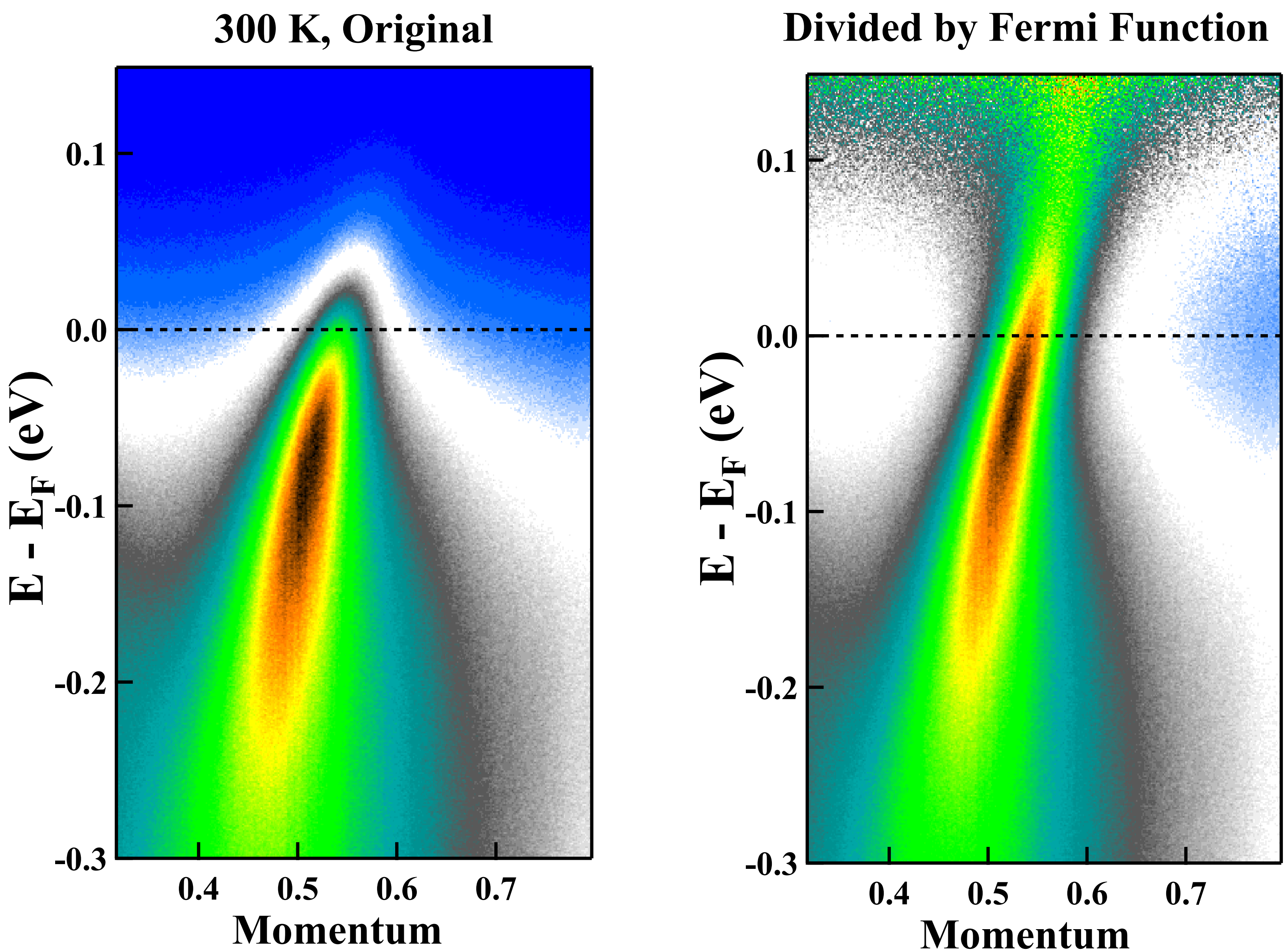
Photoemission Measured (Basically) Occupied States

Fermi-Dirac Distribution Function at Different Temperatures

$$I = A(k,\omega) \times |M(k,h\nu)|^2 \times F(\omega)$$



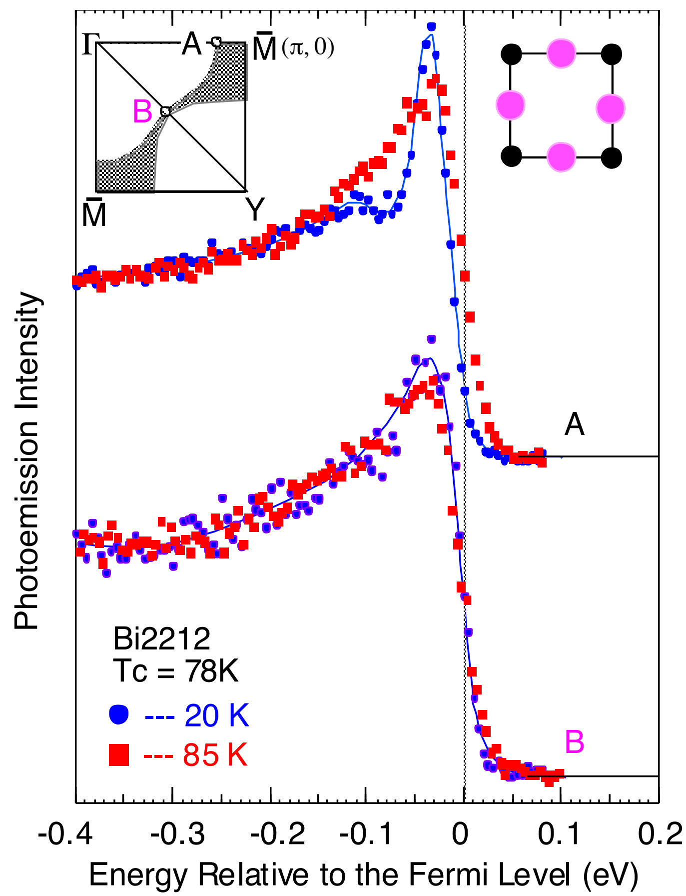
ARPES Measurement of Electronic States above Fermi Level



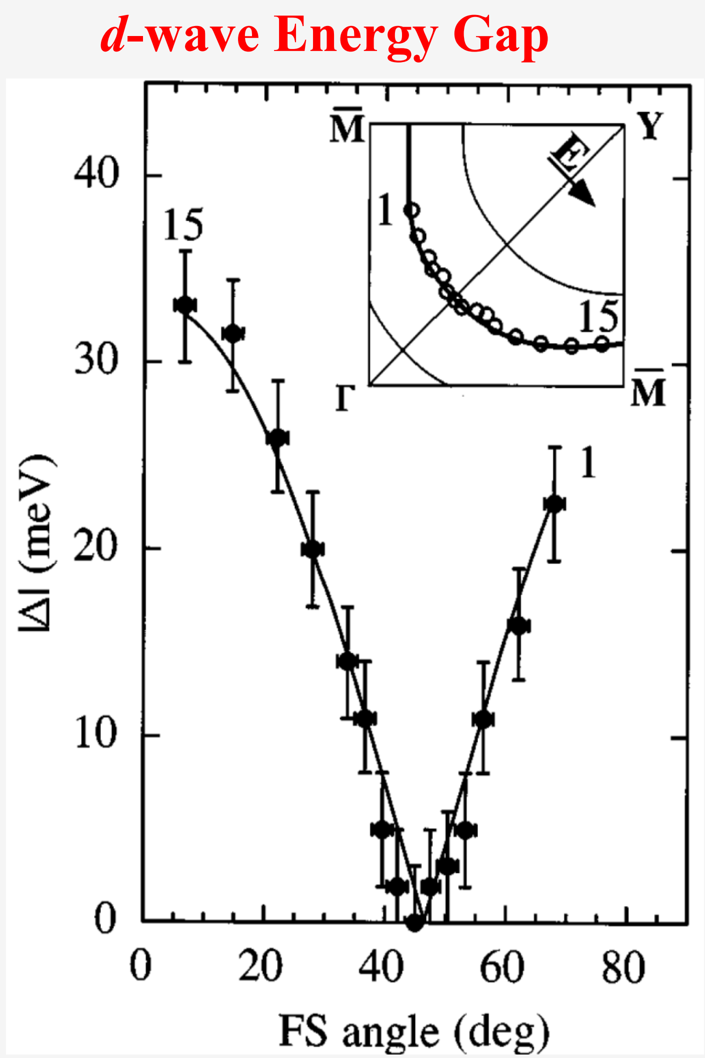
Data Analysis in ARPES –

Energy Gap

ARPES on Superconducting Gap of Cuprates

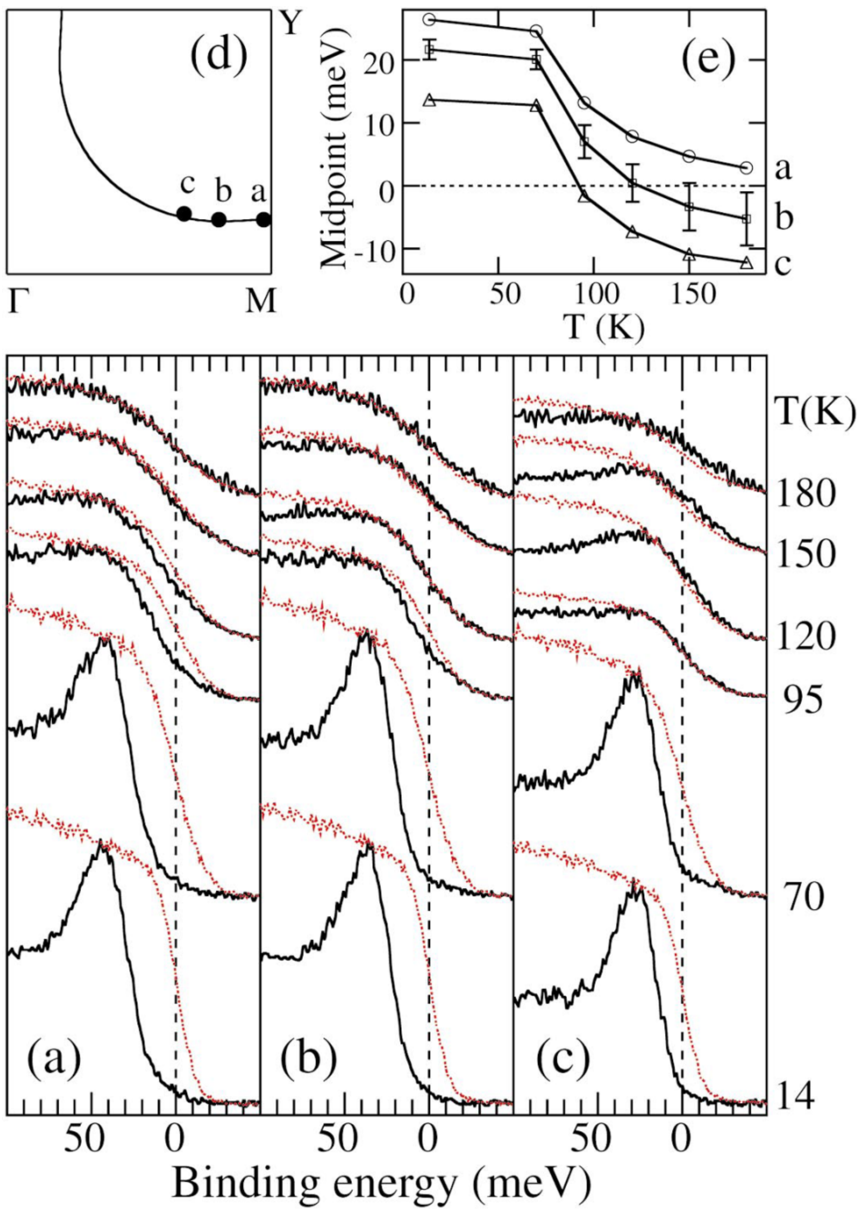


Z.-X. Shen *et al.*,
Phys. Rev. Lett. 70(1993)1553.



H. Ding et al., Phys. Rev. B 54 (1996)9678.

ARPES Observation of Pseudogap



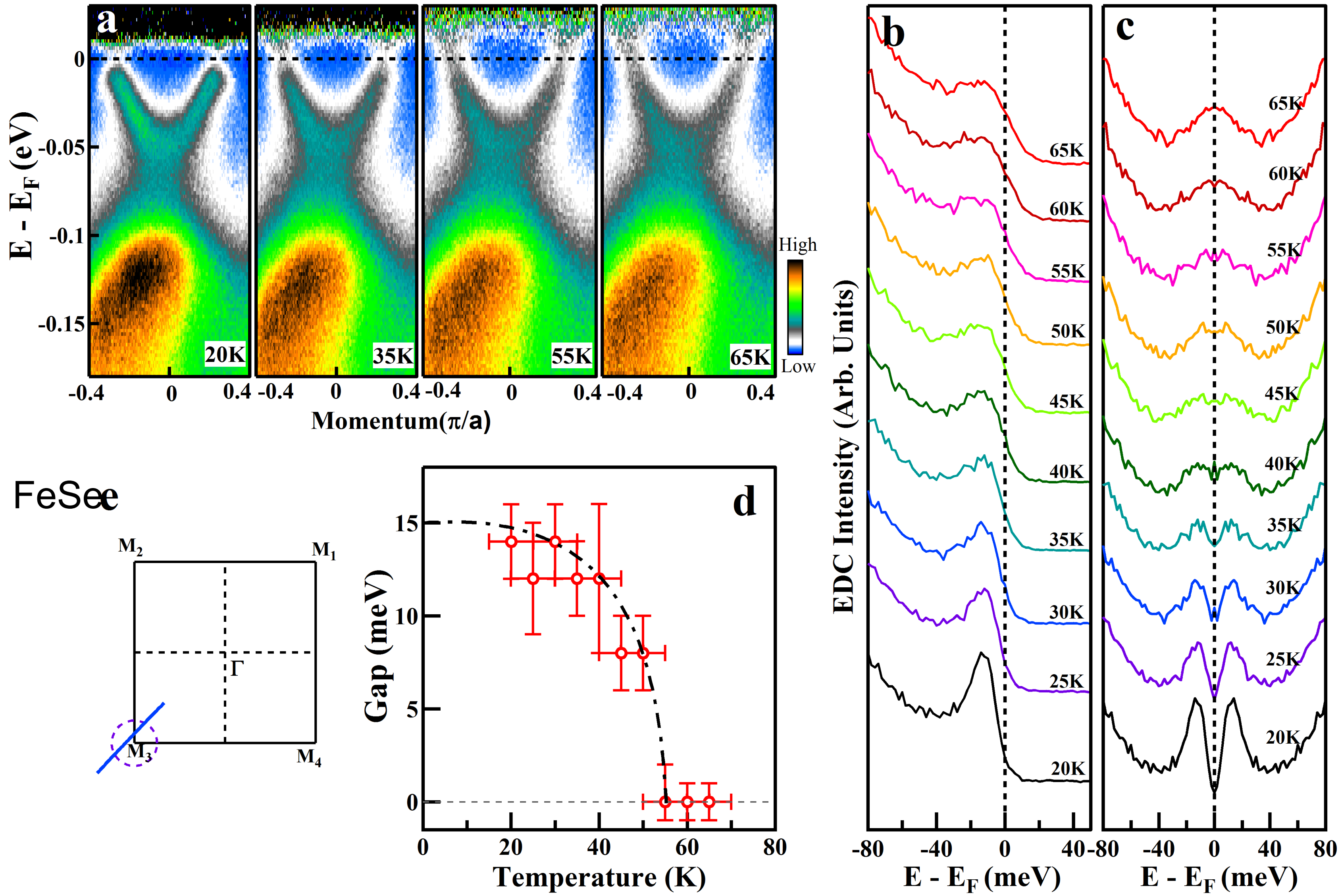
Bi2212
UD85K

D. S. Marshall et al.,
Phys. Rev. Lett. 76 (1996) 4841;

A. G. Loeser et al.,
Science 273 (1996) 325;

H. Ding et al.,
Nature (London) 382 (1996) 51.

Determination of Energy Gaps—EDC Symmetrization



D. F. Liu, X. J. Zhou et al., Nature Communications 3 (2012) 931.

How to Measure Energy Gap—EDC Symmetrization

$$I(k,\omega) = I_0(k,\nu,A)\, A(k,\omega)\, f(\omega) \qquad f(\omega) = \frac{1}{\exp\left(\frac{\omega}{k_B T}\right) + 1}$$

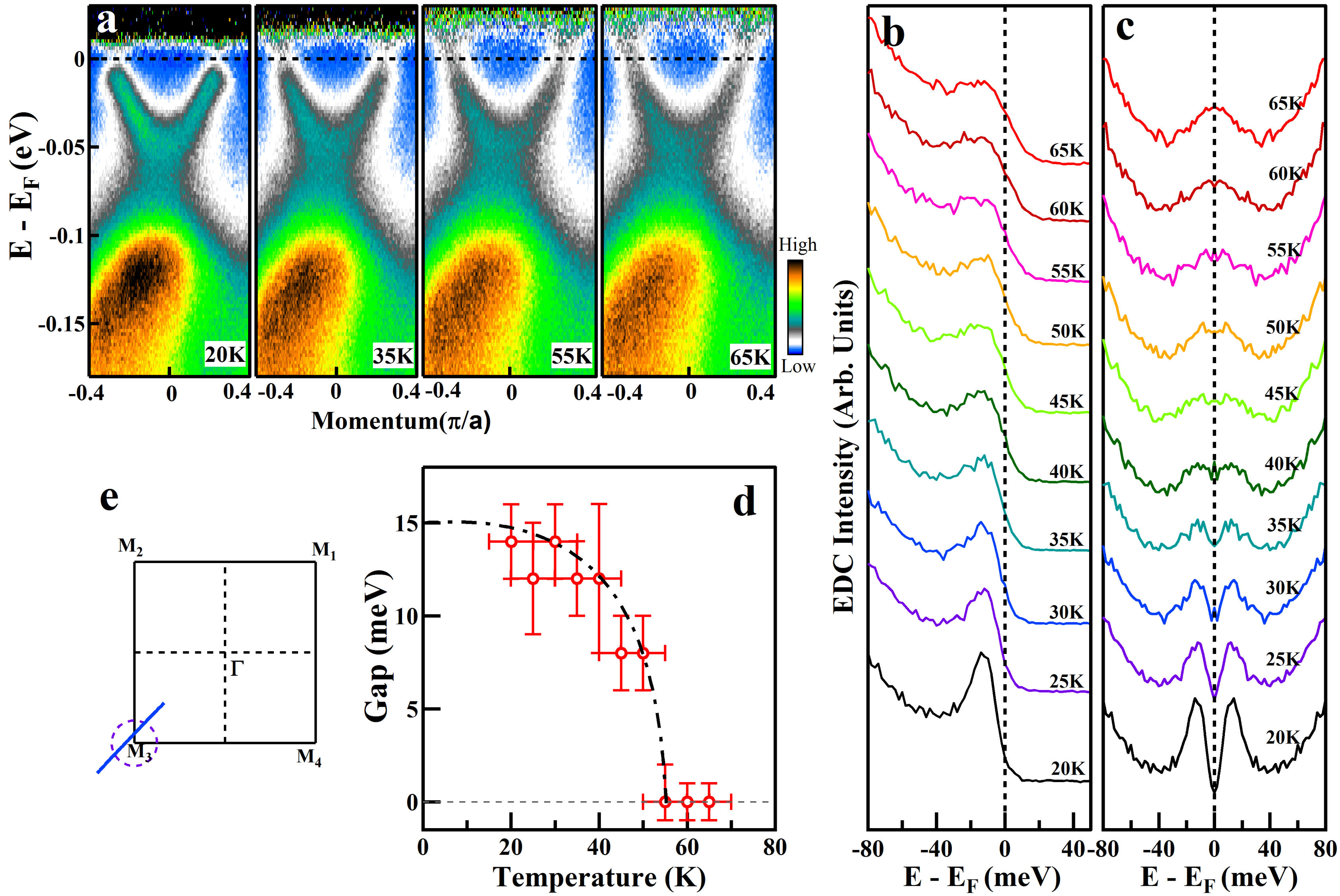
$$I(k,-\omega) = I_0(k,\nu,A)\, A(k,-\omega)\, f(-\omega) \qquad f(-\omega) = \frac{1}{\exp\left(\frac{-\omega}{k_B T}\right) + 1}$$

If $A(k,\omega) = A(k,-\omega)$,

Then $I = I(k,\omega) + I(k,-\omega) = I_0(k,\nu,A)\, A(k,\omega)$

Fermi distribution function is conveniently removed!

ARPES on Energy Gap--Single Layer FeSe

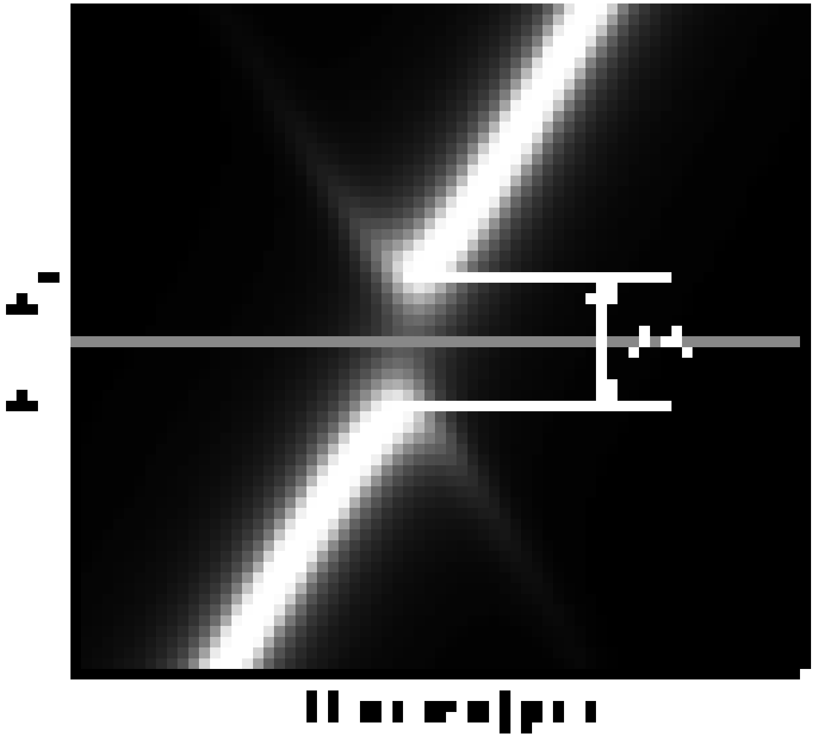


D. F. Liu, X. J. Zhou et al., Nature Communications 3 (2012) 931.

Superconducting Gap

1. Gap opens along the entire Fermi surface;

2. Gap opening has a particle-hole symmetry.



For superconducting gap,
in fact,
only one point at k_F satisfies
$A(k,\omega)=A(k,-\omega)$

ARPES as a powerful tool

for many-body effects

Power of ARPES – A Probe for Many-Body Effects

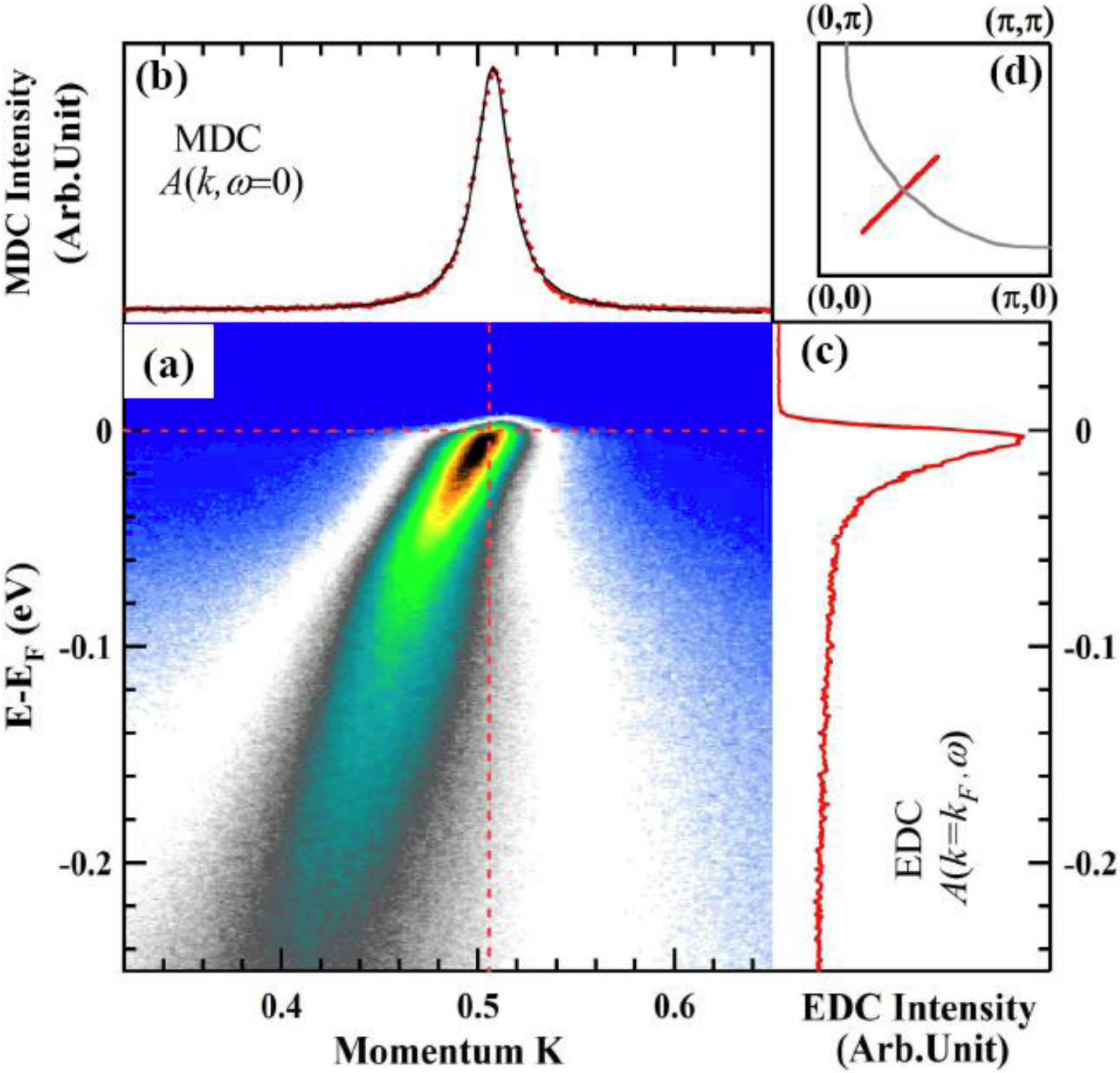
Under the sudden approximation, photoemission measures
single-particle spectral function

$$A(k,\omega) = \frac{1}{\pi}\frac{\mathrm{Im}\Sigma}{[\mathrm{h}\omega - E_k^0 - \mathrm{Re}\Sigma]^2 + [\mathrm{Im}\Sigma]^2}$$

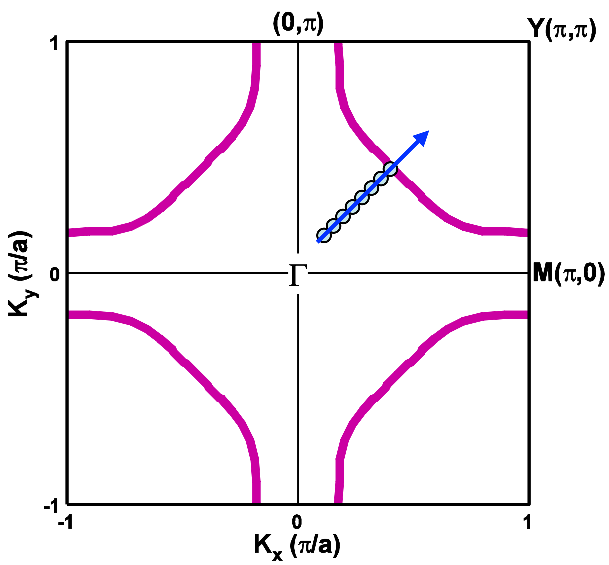
Electron self-energy: $\Sigma = \mathrm{Re}\Sigma + i\,\mathrm{Im}\Sigma$

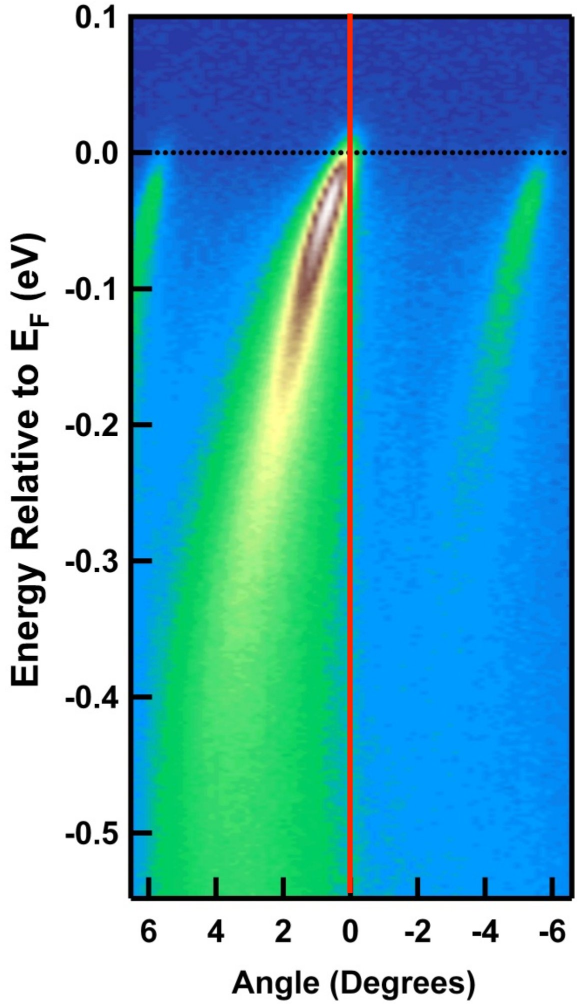
Many-Body Effects: **Interaction of electrons with other entities such as other electrons, phonons, magnons and etc.**

Energy Distribution Curve(EDC) vs Momentum Distribution Curve (MDC)

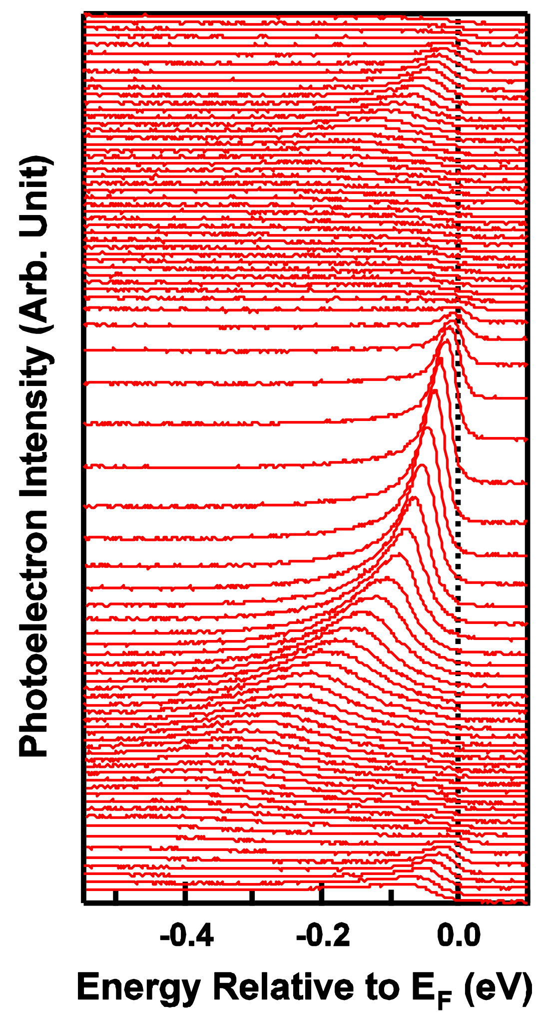


EDC Dispersion– It Is Difficult to Fit EDCs

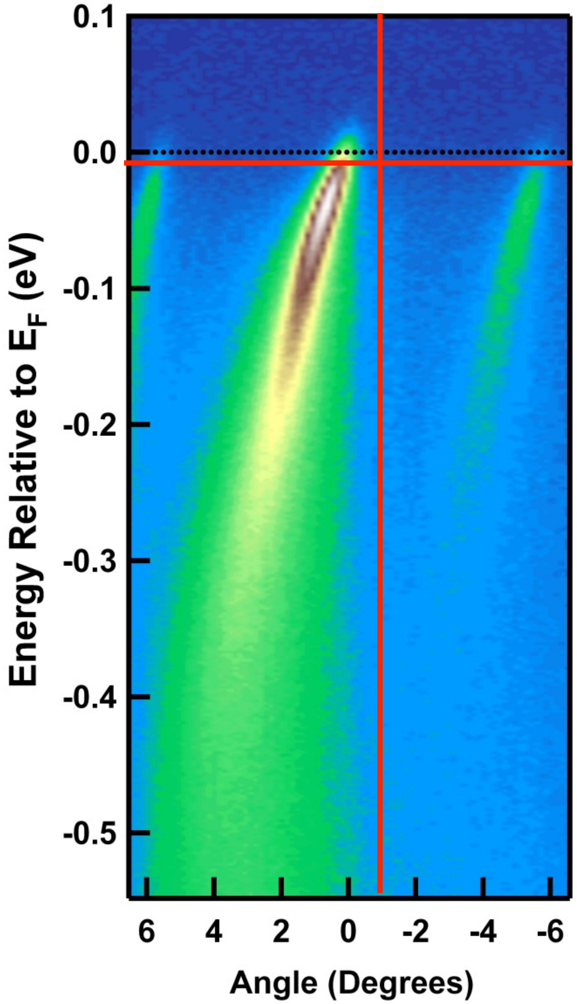


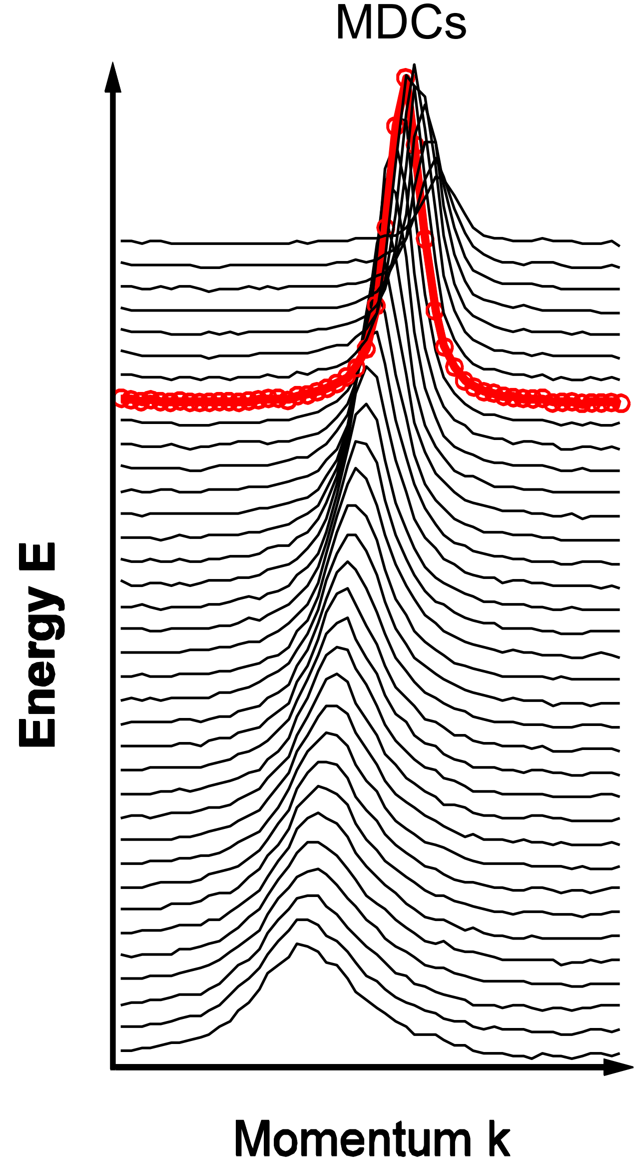


EDCs



MDC Dispersion: It Is Easy to Fit MDCs





Extract Electron Self-Energy from Dispersion and MDC Width

Spectral Function: $$A(k,\omega) = \frac{1}{\pi}\frac{\mathrm{Im}\Sigma}{(\omega - v_0 k - \mathrm{Re}\Sigma)^2 + (\mathrm{Im}\Sigma)^2} \qquad (1)$$

$$= \frac{1}{\pi}\frac{\mathrm{Im}\Sigma / v_0^2}{(k - (\omega - \mathrm{Re}\Sigma)/v_0)^2 + (\mathrm{Im}\Sigma / v_0)^2}$$

Lorentzian Lineshape: $$L(x) = \frac{H\,(\Gamma/2)^2}{(x - k_0)^2 + (\Gamma/2)^2} \qquad (2)$$

Compare Equ. (1) and (2):

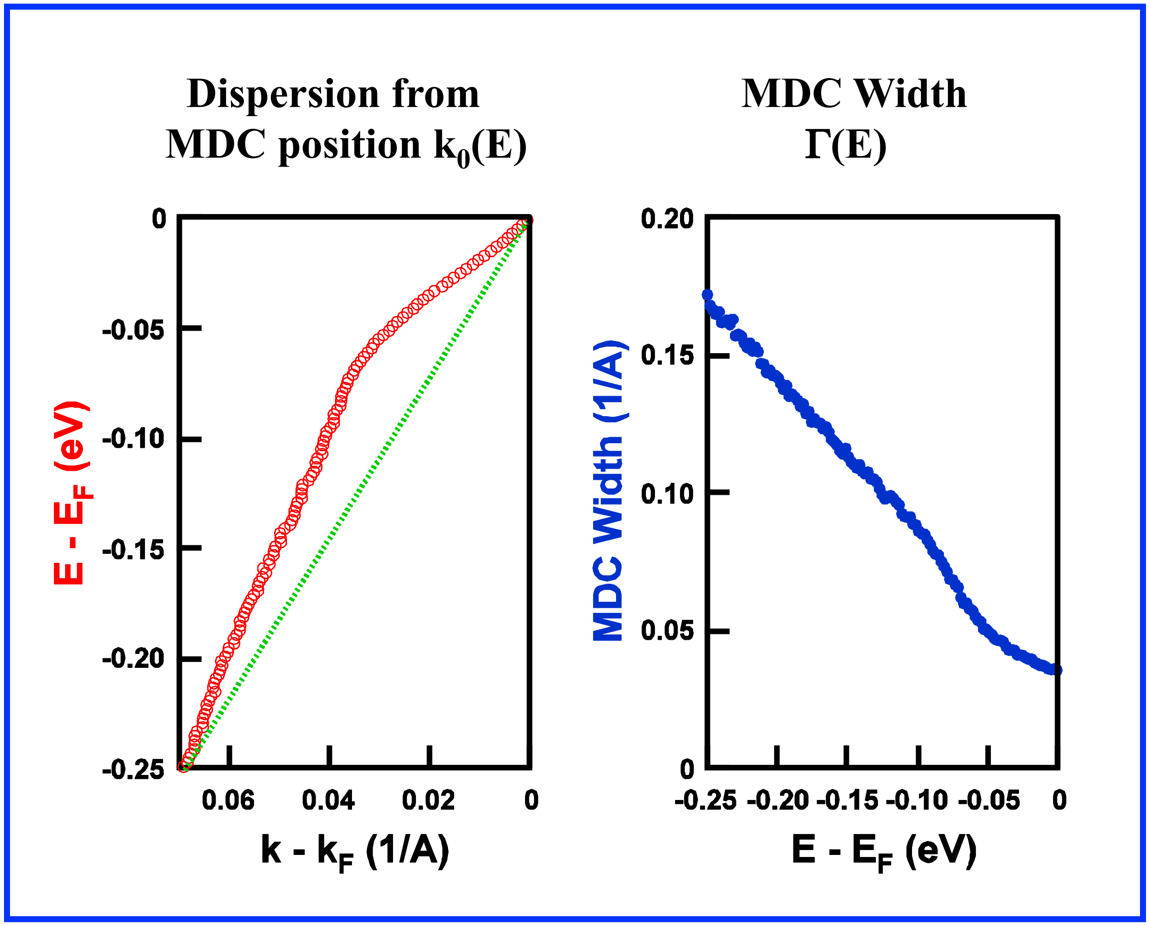
$$k_0 = (E - \mathrm{Re}\Sigma)/v_0$$

$$\Gamma/2 = \mathrm{Im}\Sigma / v_0$$

Therefore

$$\boxed{\begin{aligned} \mathrm{Re} &= E - k_0 v_0 \\ \mathrm{Im} &= (\Gamma/2) * v_0 \end{aligned}}$$

Dispersion and MDC Width -- Fitting MDCs



Lorentzian Fitting:

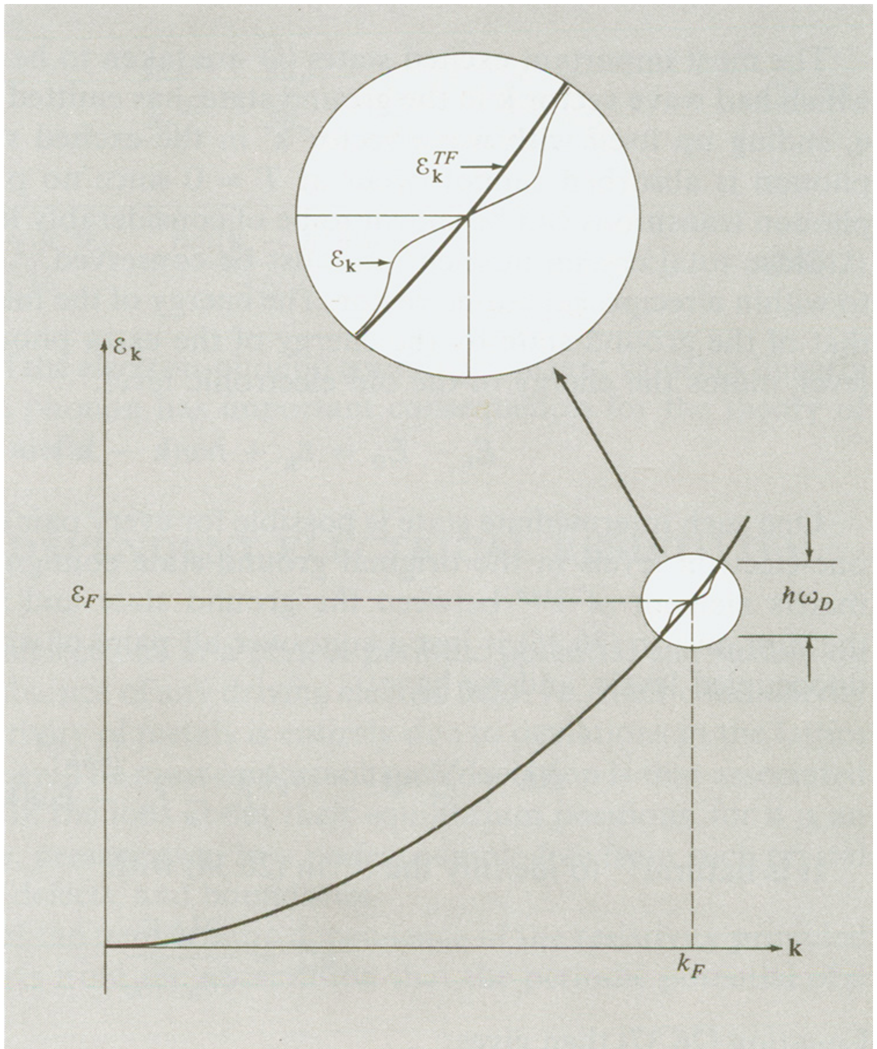
Peak position: k_0 (E)

Peak width: Γ(E)

$$\mathrm{Re}\Sigma = E - k_0 v_0$$

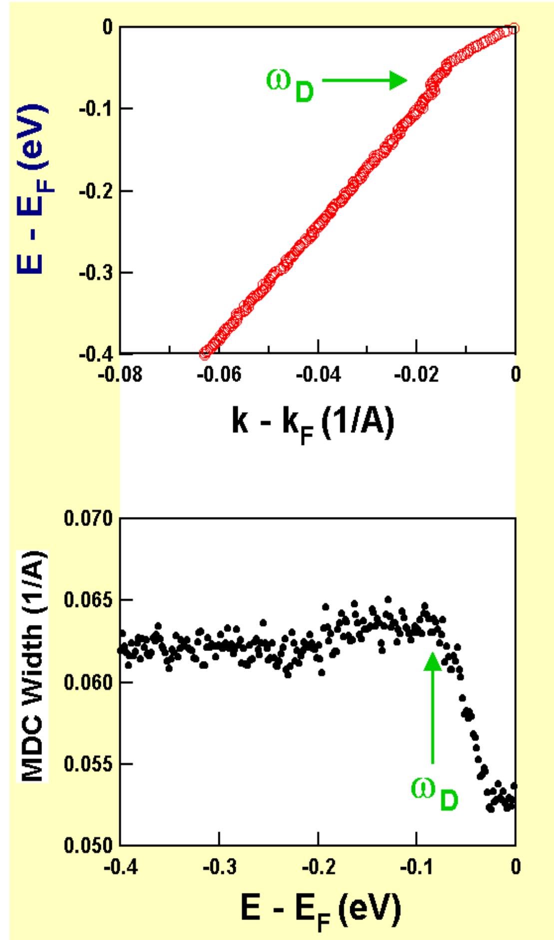
$$\mathrm{Im}\Sigma = (\Gamma / 2) * v_0$$

Manifestation of Many-Body Effects: **Band Renormalization**



Ashcroft-Mermin, Solid State Physics

Be(0001) Surface State

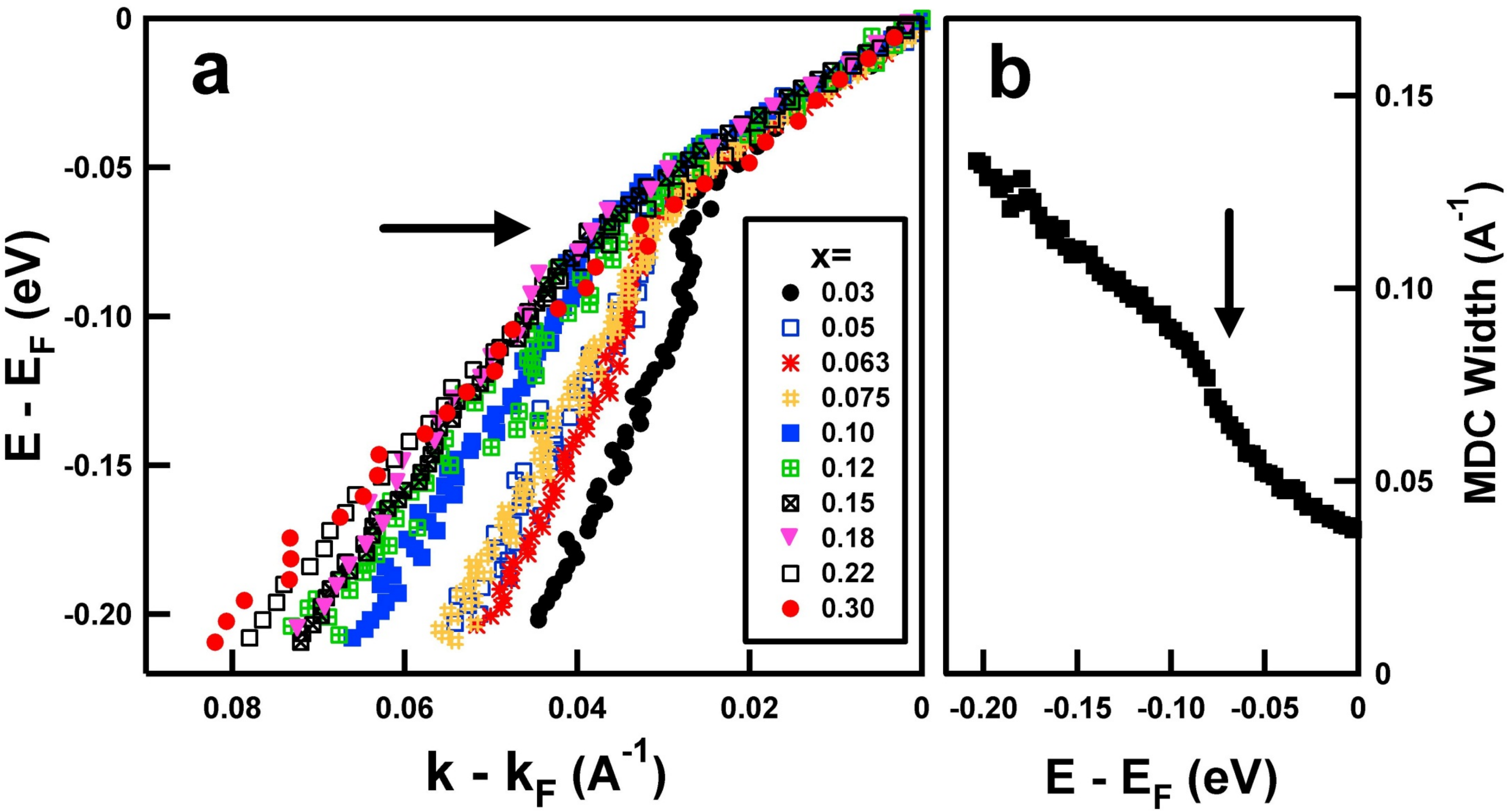


ReΣ

ImΣ

Hengsberger et al., PRL 83(1999)592.
S. Lashell et al., PRB 61(2000)2371.
S. J. Tang et al., Phys. Stat. Solidi. 241(2004)2345.

Many-Body Effects in High Temperature Superconductors



X. J. Zhou, Z. X Shen *et al., Nature 423, 398 (2003).*

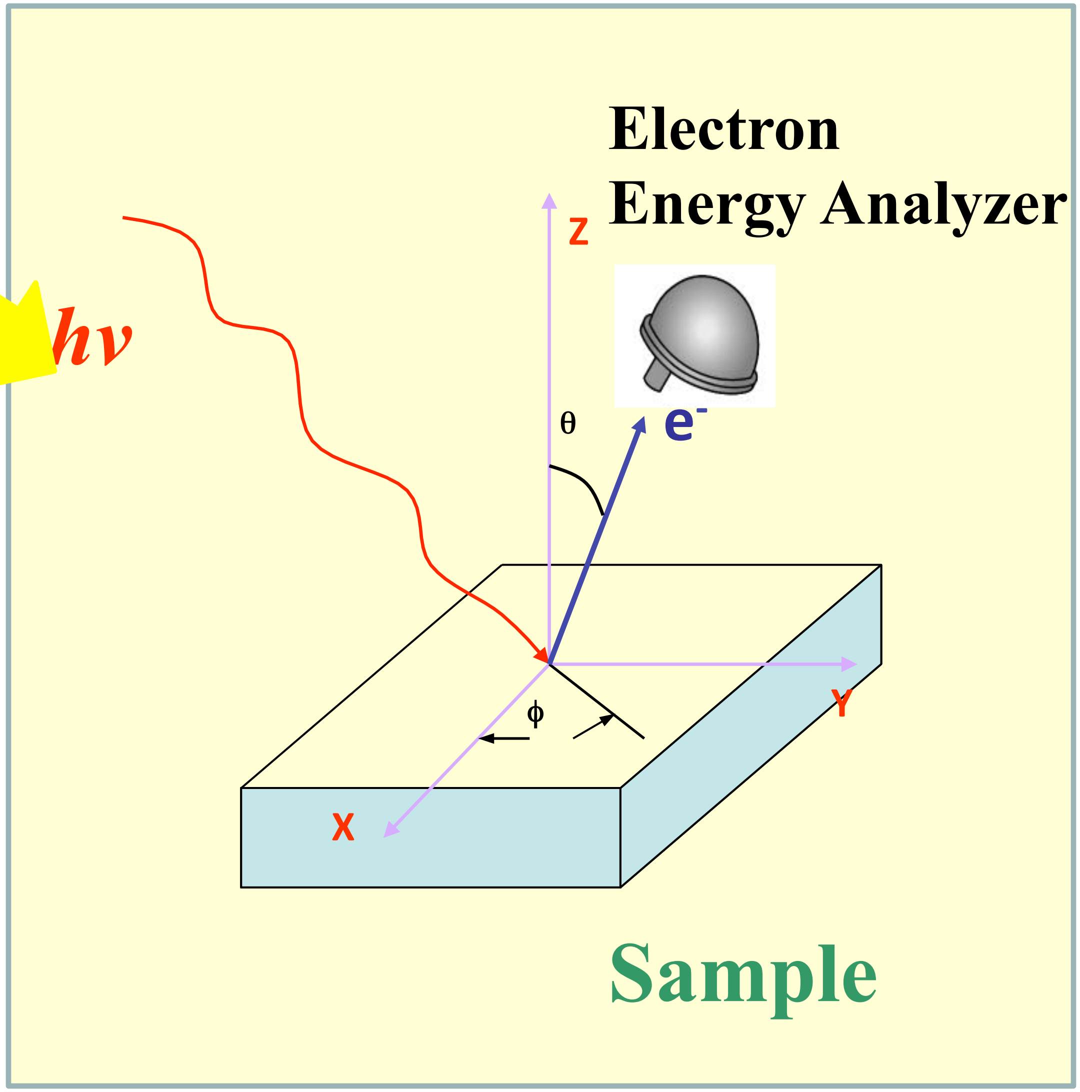
Latest Development –

Laser ARPES

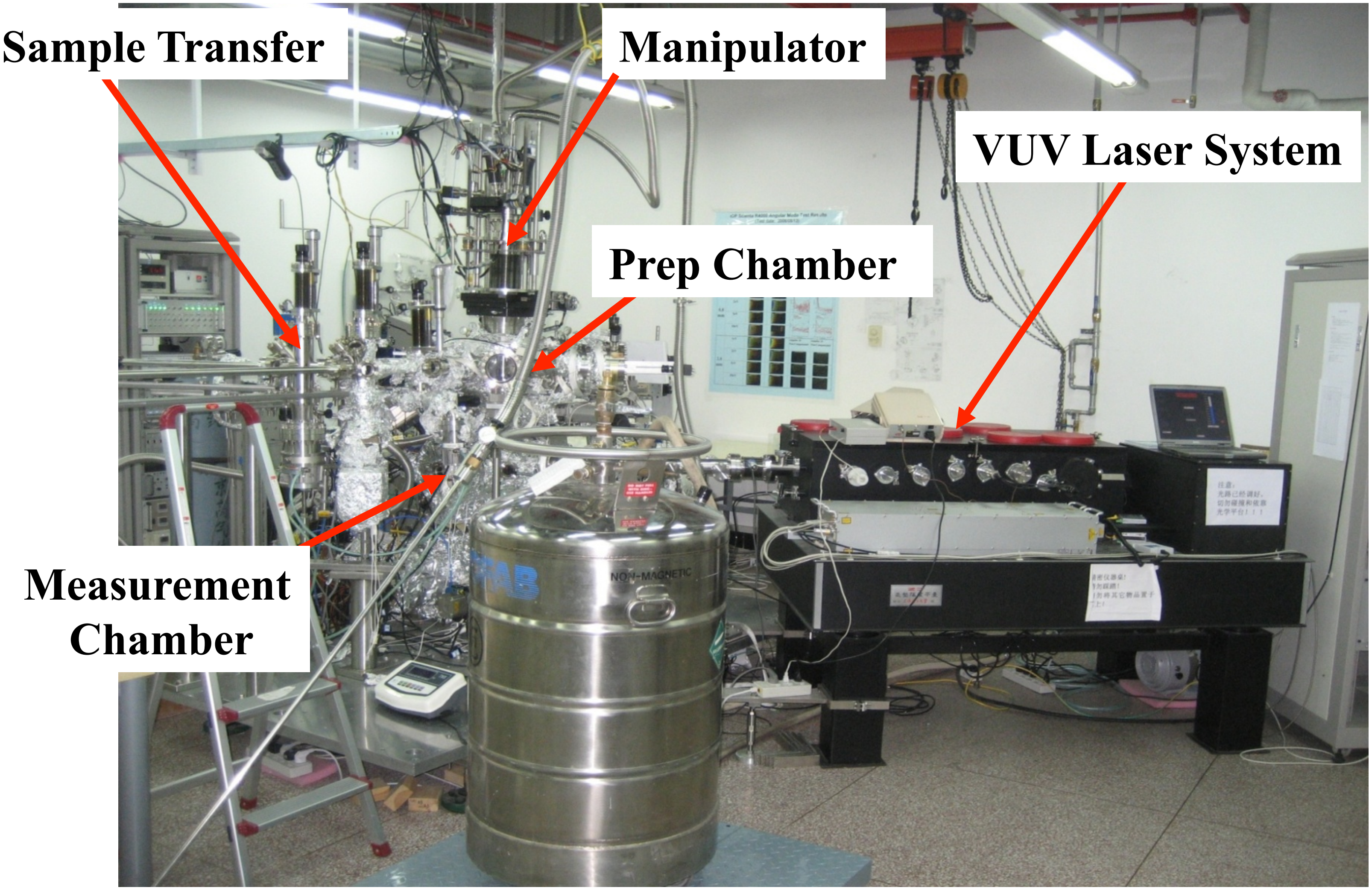
Light Sources for Photoemission Spectroscopy

- **Synchrotron Radiation**
- **Gas Discharge Lamp**
  He I, hv=21.2 eV
  He II, hv=40.8 eV
- **VUV Laser**
  hv=6.994 eV

VUV---
VacuumUltra-Violet
hv>6.5 eV

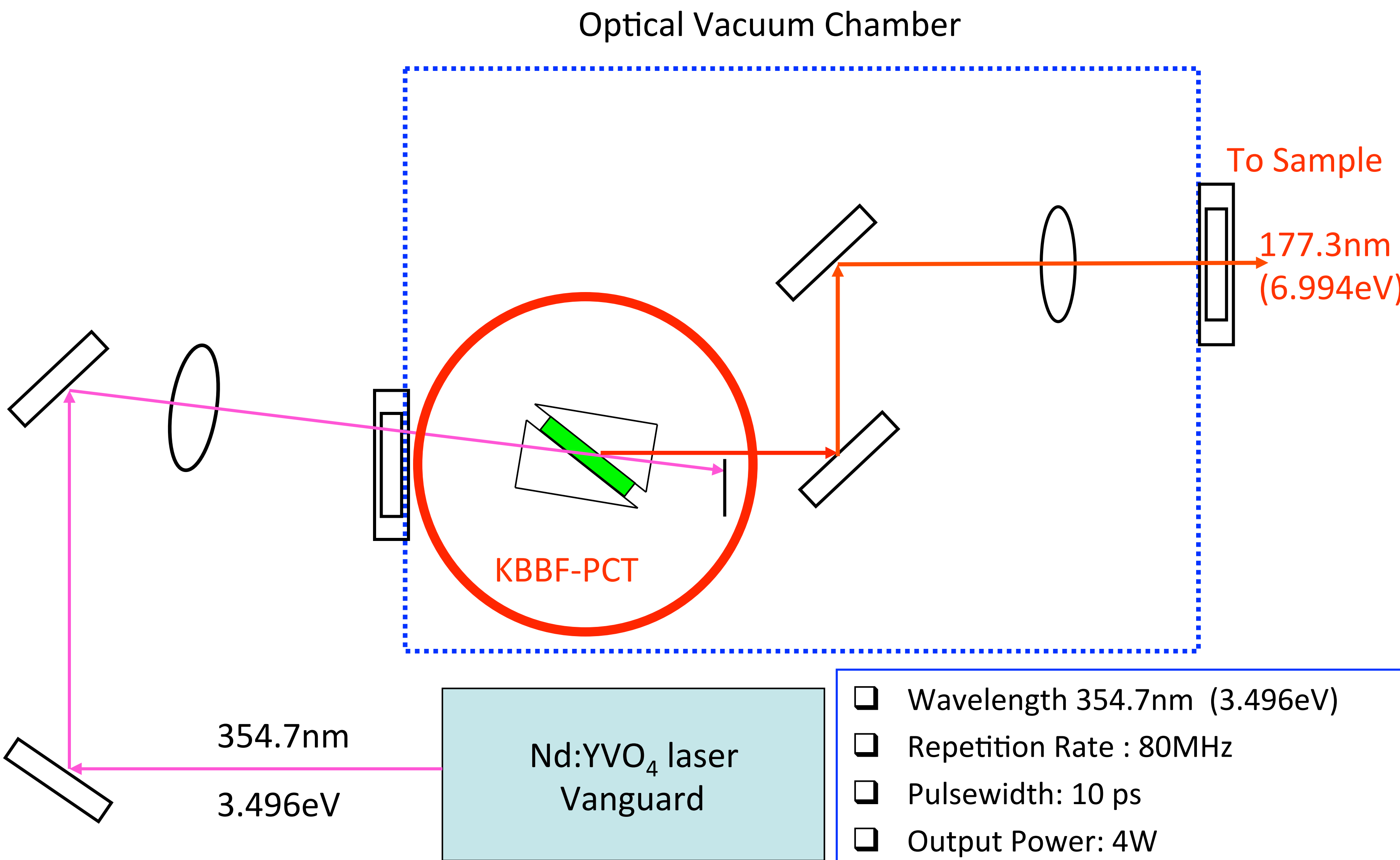


VUV Laser ARPES System at IOP



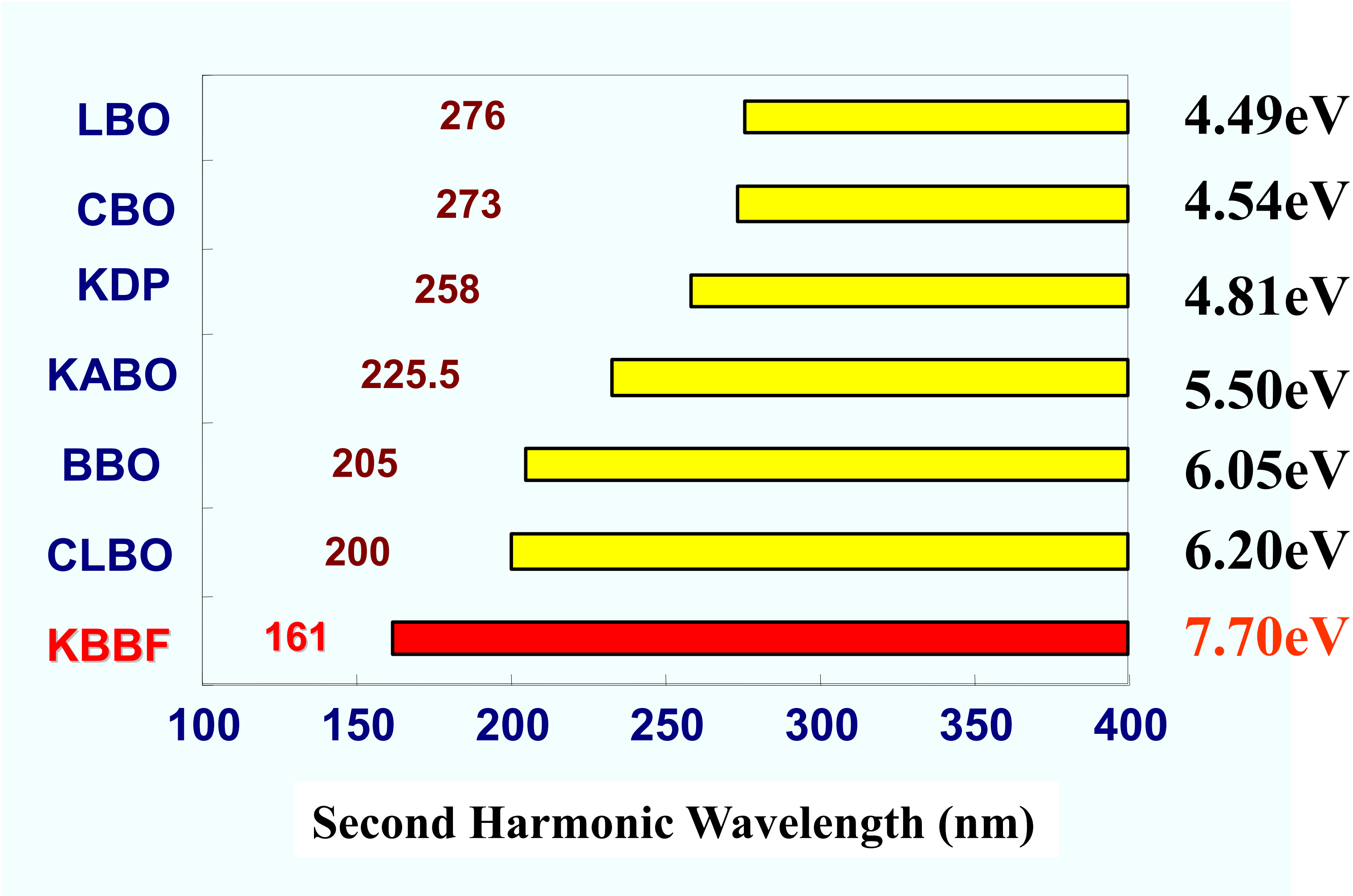
(Started development in early 2004, commissioned by the end of 2006)
Guodong Liu, X. J. Zhou *et al.,* Rev. Sci. Instrum. 79 (2008) 023105.

Generation of VUV Laser ($h\nu$=6.994 eV)



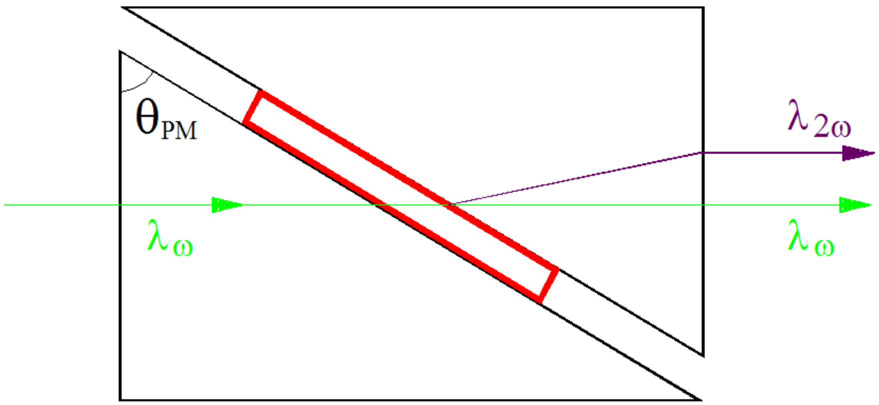
- ❑ Wavelength 354.7nm (3.496eV)
- ❑ Repetition Rate : 80MHz
- ❑ Pulsewidth: 10 ps
- ❑ Output Power: 4W
- ❑ Pulse Energy : 50nJ

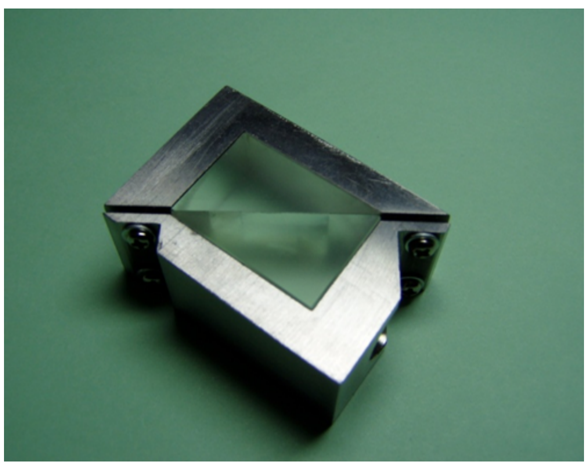
$KBe_2BO_3F_2$ (KBBF): New Non-Linear Optical Crystal



C. T. Chen, **Z. Y. Xu** et al., Chin. Phys. Lett. <u>18</u>(8), 1081 (2001).
J. Appl. Phys., Vol. 74, No. 11, 1 December 1993;
J. Appl. Phys. 77 (6), 15 March 1995
Appl. Phys. Lett. 68 (21), 20 May 1996

$KBe_2BO_3F_2$ (KBBF): New Non-Linear Optical Crystal





China's crystal cache

A Chinese laboratory is the only source of a valuable crystal. **David Cyranoski** investigates why it won't share its supplies.

One of Daniel Dessau's prized possessions is a small crystal of potassium beryllium fluoroborate (KBBF). Dessau, a solid-state physicist at the University of Colorado at Boulder, uses the crystal to convert the light of a US$100,000 laser into a deep ultraviolet, a good wavelength for studying the surface of superconductors. But because the laser light gradually degrades the crystal, Dessau has to save it for special projects. "It is a beautiful crystal," he says. "It would really move the field forward — if people could get it."

But Dessau can't get any more of it. Nor can Peter Johnson, a condensed-matter physicist at Brookhaven National Laboratory in Upton, New York, who was once promised it by Chuangtian Chen, the Chinese physicist who runs the only laboratory that knows how to make the crystals. And nor can any of a host of other solid-state physicists outside China. "There has been a limited release," says Johnson. "I don't know the politics behind it."

In fact, the politics is simple. The Chinese government is squeezing the crystal for every bit of academic and, eventually, commercial potential it can yield. In October 2008, the finance ministry sidestepped traditional scientific funding channels and started throwing 180 million renminbi (US$26 million) at a three-year national project to find better ways to produce and use KBBF. China has selected a handful of groups to work with Chen's crystal, including teams studying the newest type of superconductor, called pnictides.

China's monopoly of this crystal is no fluke. At a time when materials scientists and solid-state physicists elsewhere are seeing a lack of investment, their counterparts in China are surging ahead in a wide range of materials research for much the same reasons as they did with KBBF. The nation has accumulated a great depth of crystal-growing know-how over the past three decades; it has steadfast government support; and its scientists are willing to subsume themselves in a large team effort and take on the often thankless, sometimes dangerous and always tedious trial-and-error task of synthesizing new materials. "Many great discoveries in this field come from putting things together and getting the temperature and timing just right," says Christos Panagopoulos, a materials researcher at Nanyang Technological University in Singapore. The discovery process "doesn't require genius", he says.

> "You need a lot of equipment and you need to move slowly." — Chuangtian Chen

KBBF's ability to shorten the wavelength, and thereby boost the frequency, of laser light is an example of 'nonlinear' optics, a field that first blossomed in the 1960s as lasers became more widespread in laboratories. Under ordinary circumstances, light passing through water, glass or any other material will perturb the atoms only slightly, so that they vibrate in sync with the light wave. As a result, light can be reflected, refracted, scattered and absorbed ad infinitum without its frequency being affected. Nonlinear effects are evident only when the light is so intense that the vibrations it causes compete with the binding forces on the atoms. When highly perturbed, as in the case of high-intensity lasers, the atoms can absorb the energy of the incoming light and re-emit the light with a frequency that is double, triple or even some higher multiple of the original. A variety of materials have been discovered that can boost laser light to frequencies that the lasers alone cannot produce, and each has a set of signature frequencies that it can achieve.

China might easily have fallen behind in this field, as it did in so many others. Just as nonlinear optics started coming into its own, China was caught up in the Cultural Revolution, a particularly dark period starting in the mid-1960s when many academics were criticized as being elitist or impractical and sent to do farm work for 're-education'.

But Chen, now a spritely 71-year-old at the Technical Institute of Physics and Chemistry

J. RIORDAN

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C. T. Chen， Z. Y. Xu et al.,
Chin. Phys. Lett. 18(8), 1081 (2001).

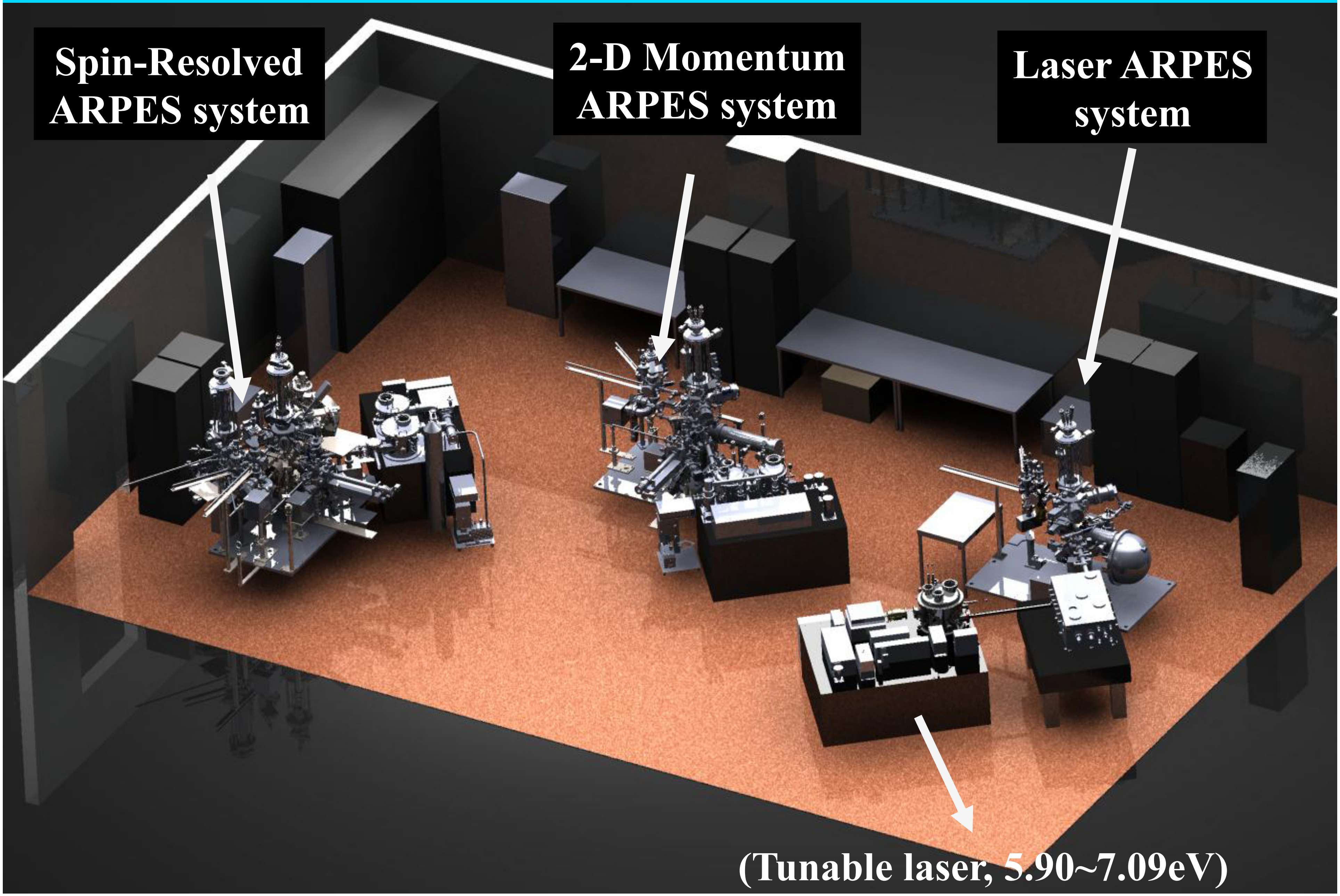
Nature Report, February, 2009

Advantages and Disadvantages of VUV Laser ARPES

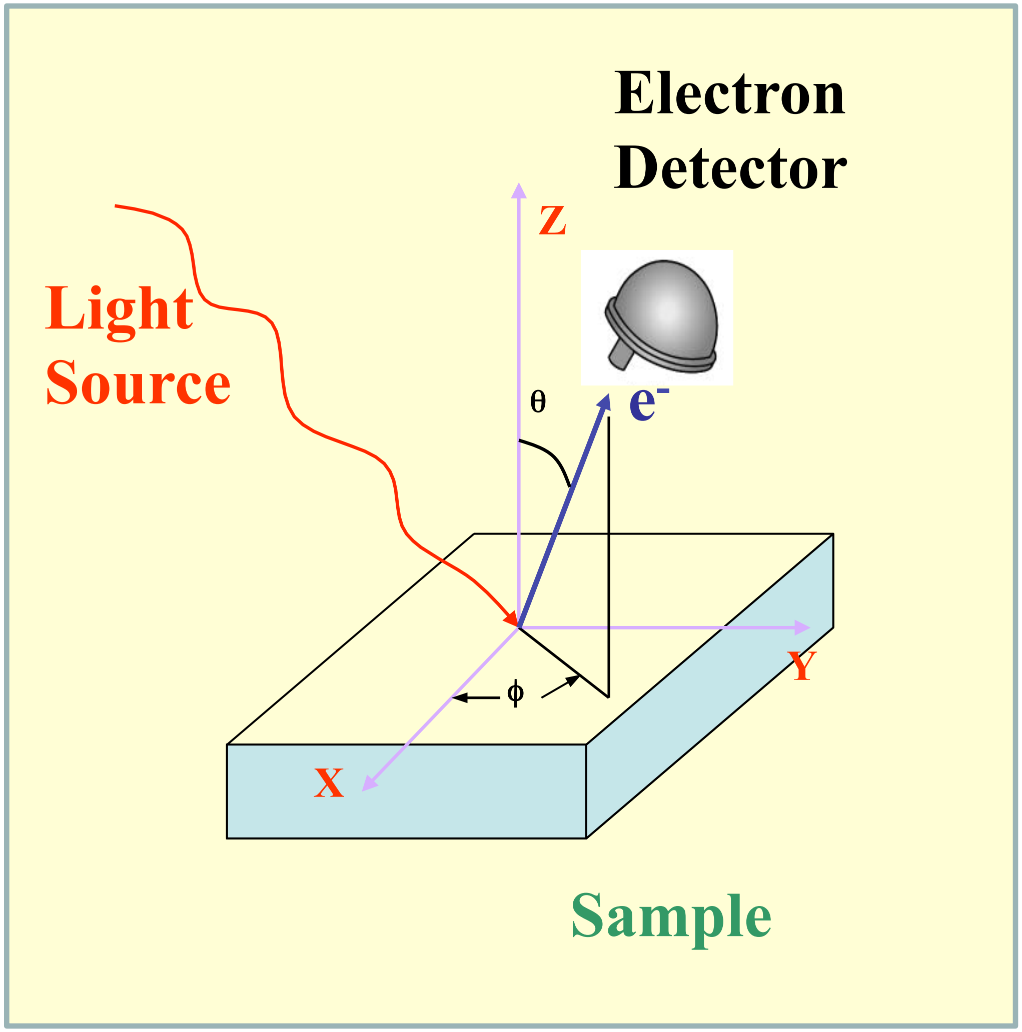
Light Source	VUV Laser	Synchrotron
Energy Resolution (meV)	0.26	5~15
Momentum Resolution ($Å^{-1}$)	0.0036 (6.994eV)	0.0091 (21.1eV)
Photon Flux(Photons/s)	10^{14}~10^{15}	10^{12}-10^{13}
Electron Escape Depth (Å)	30~100	5~10
Photon Energy Tunability	Limited	Tunable
k-Space Coverage	Small	Large

Laser and Synchrotron are complementary.

VUV Laser Photoemission Lab at IOP



*A*ngle-*R*esolved *P*hoto*e*mission *S*pectroscopy (ARPES)



Photoemitted electrons in Vacuum along different angles

E_{kin}, $K_{||}$

Energy Conservation: $E_B = h\nu - E_{kin} - \Phi$

Momentum Conservation: $K_{||} = k_{||} + G_{||}$

Electronic States in Solid:

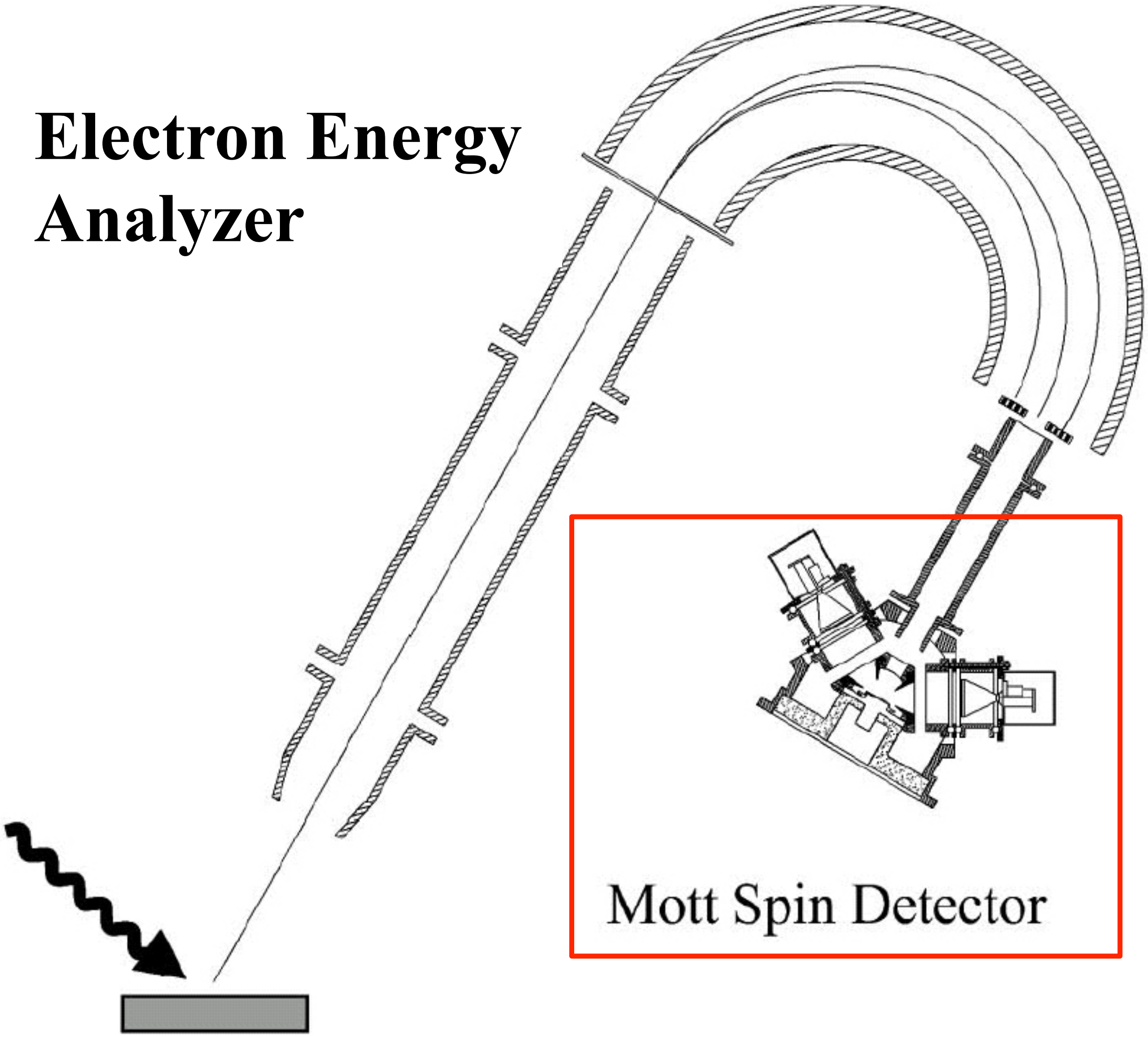
$\Psi(E, k, s)$

E-Energy ;

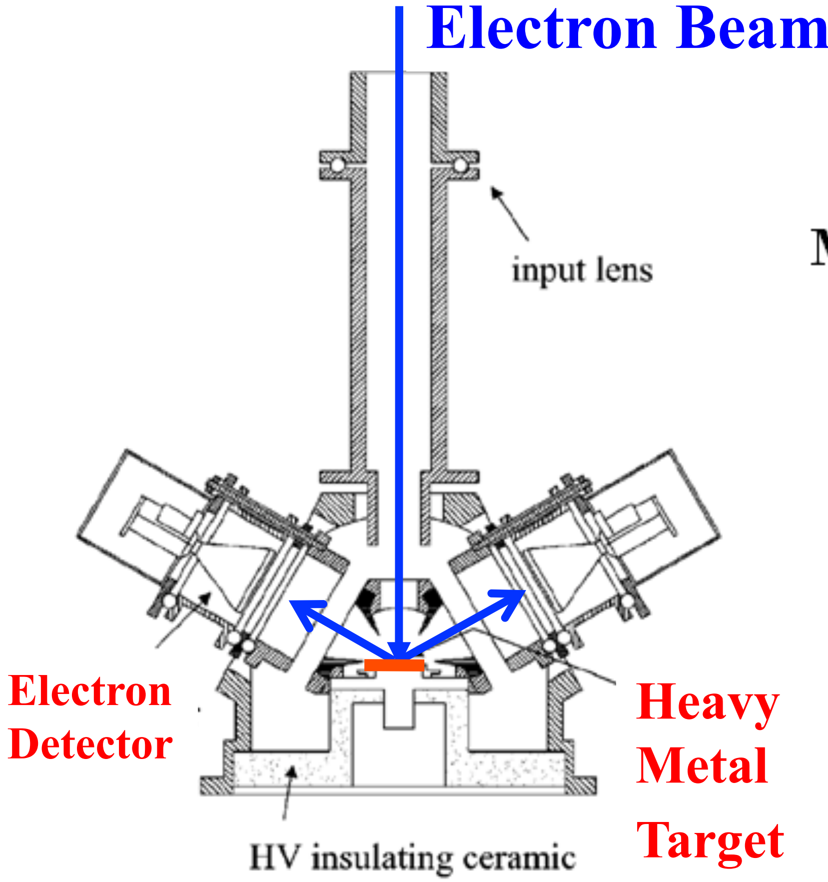
k-Momentum;

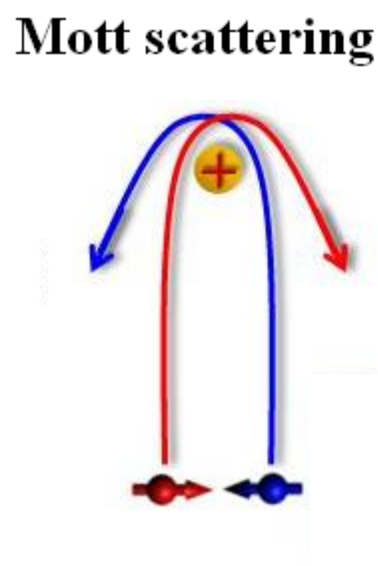
s-Spin.

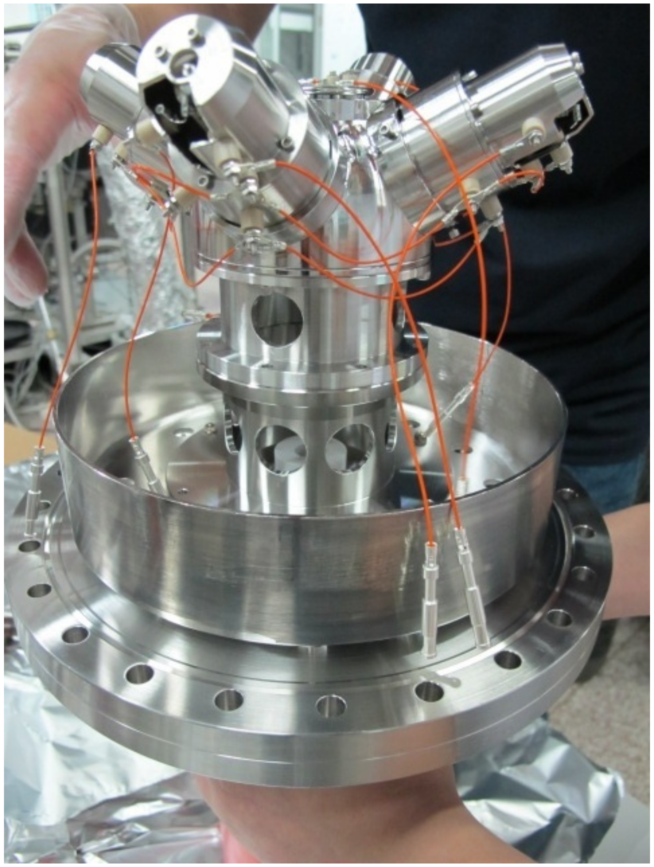
Principle of Spin-Resolved ARPES



Mott Spin Detector

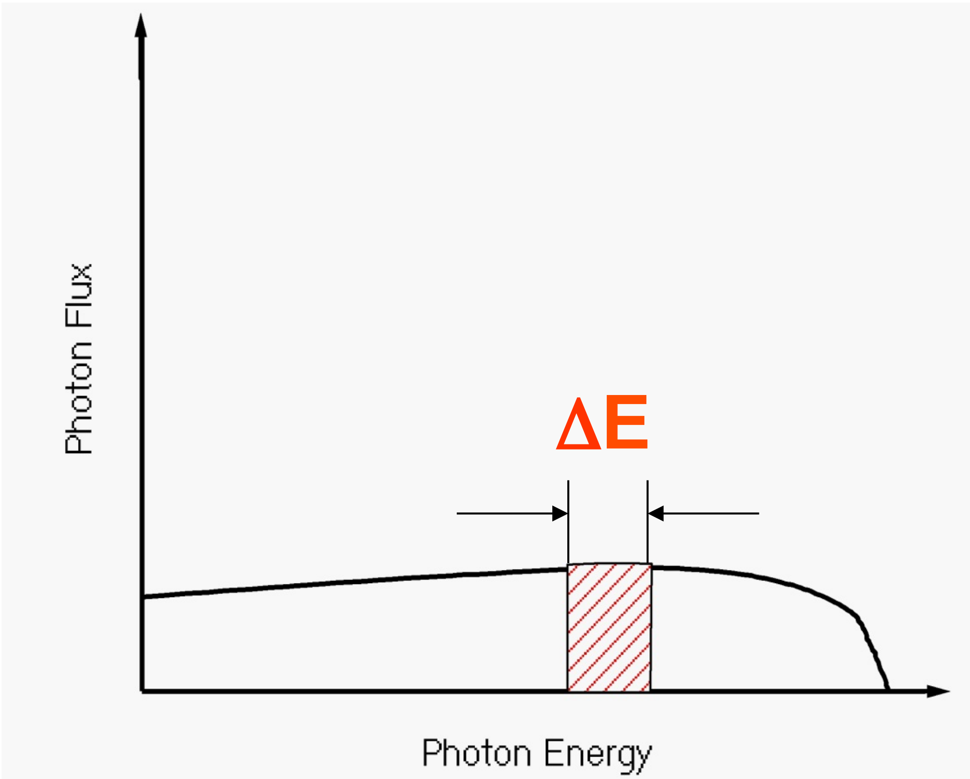






The efficiency of Mott Spin Detector is extremely low ~ 10^{-4}

Synchrotron Radiation-Based Spin ARPES



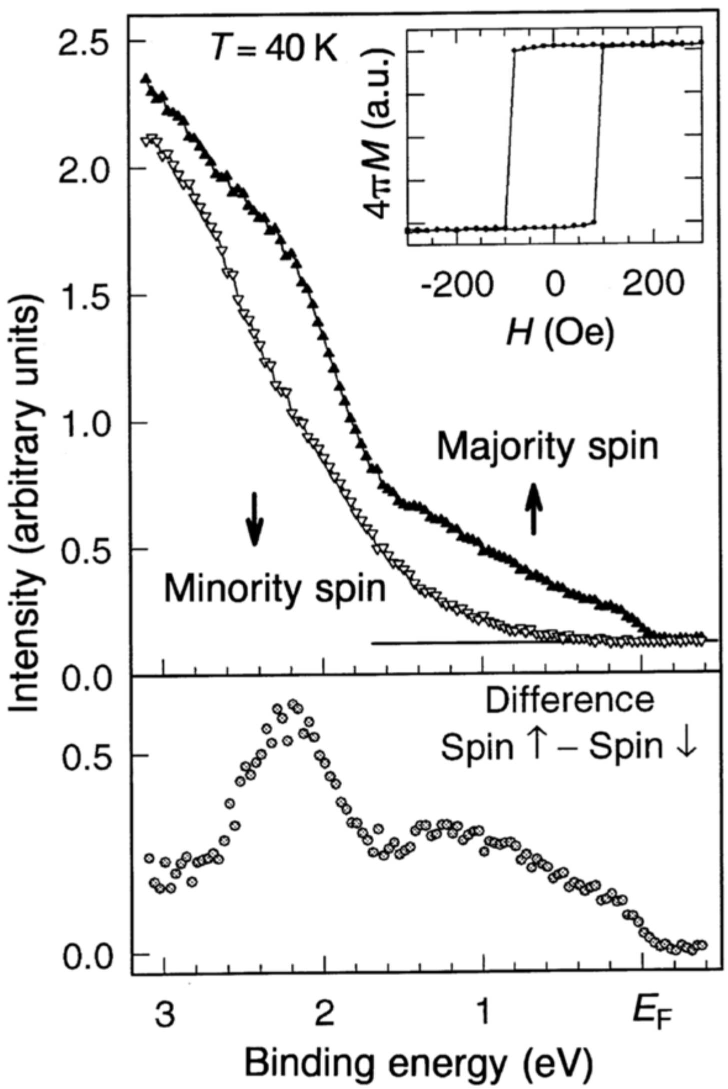
Energy Resolution ΔE is inversely proportional to Light intensity

In order to get decent signal intensity:

(1). Sacrifice of energy resolution to get high intensity;
(2). Angle-integrated measurements.

Direct Evidence for a Half-Metallic Ferromagnet

$La_{0.7}Sr_{0.3}MnO_3$



National Synchrotron Light Source (NSLS)
Brookhaven National Lab

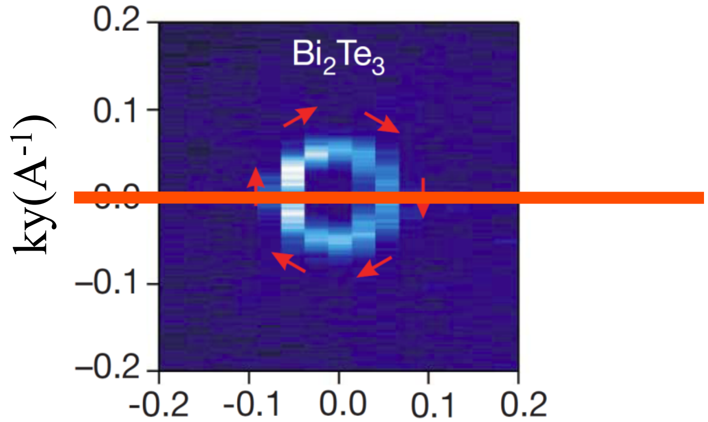
1.Energy Resolution: 200 meV

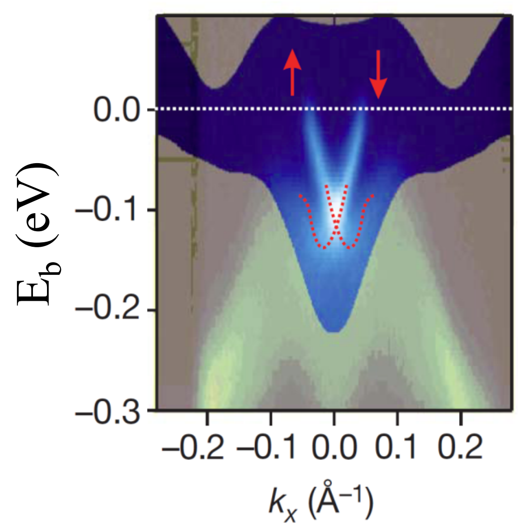
2.Angle-Integrated.

J. H. Park et al.,
Nature 392 (1998) 794.

Spin-Resolved ARPES on Topological Insulators

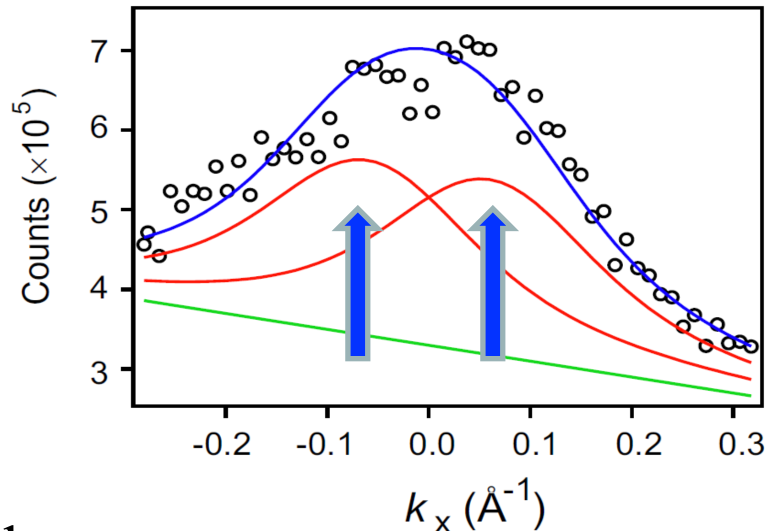
ARPES

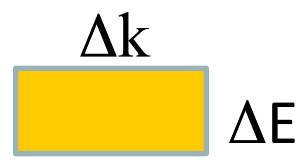




D. Hsieh et al.,
Nature 460 (2009)1101

Spin-Resolved





Δk—**Momentum Resolution**

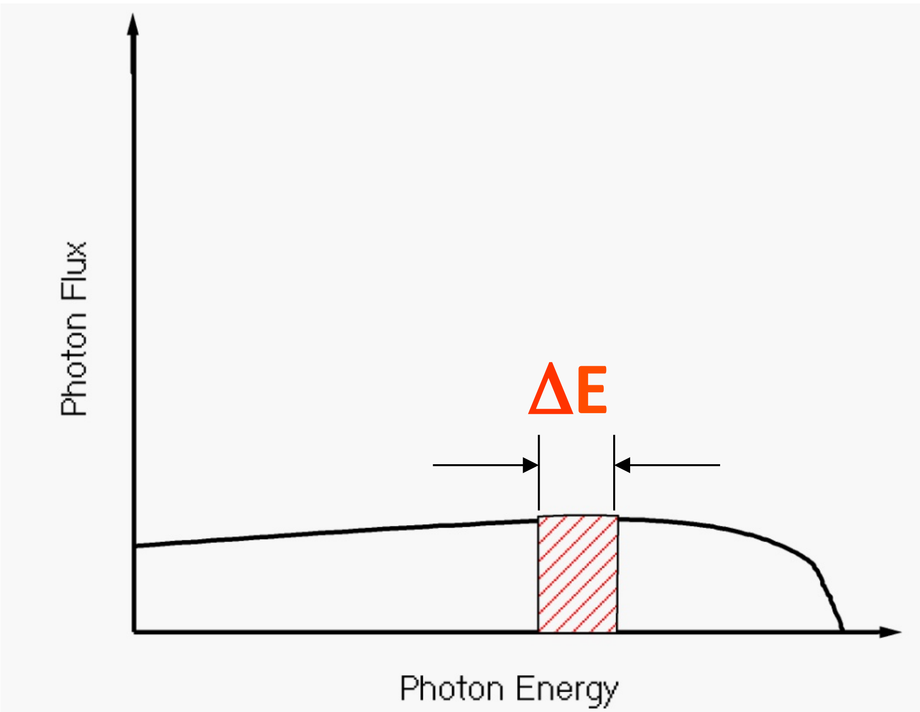
ΔE—**Energy Resolution~80meV**

Done at Swiss Light Source

Advantages of Laser in Spin-Resolved Photoemission

Synchrotron Radiation

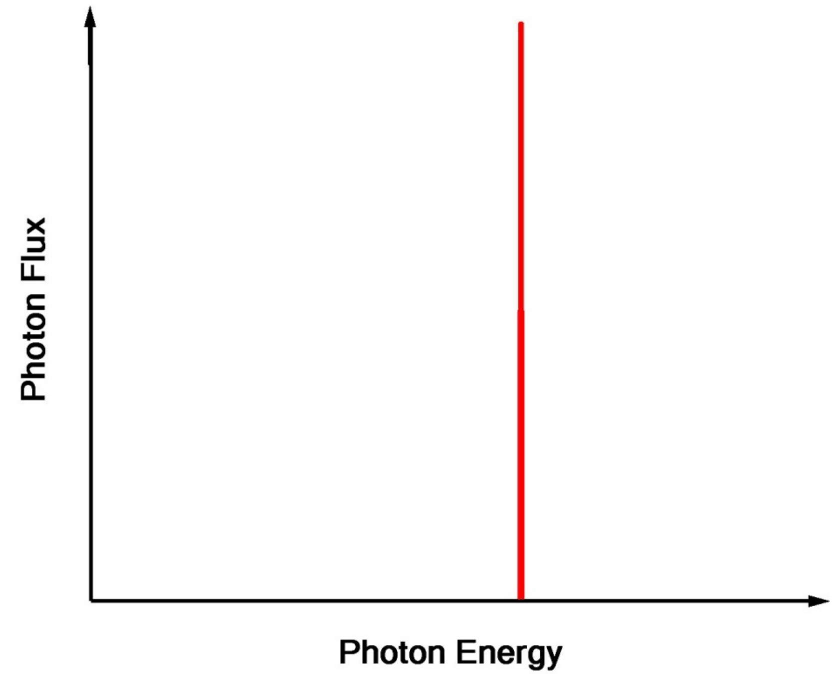
Energy resolution ΔE coupled with photon flux



Best energy resolution: ~50-100meV

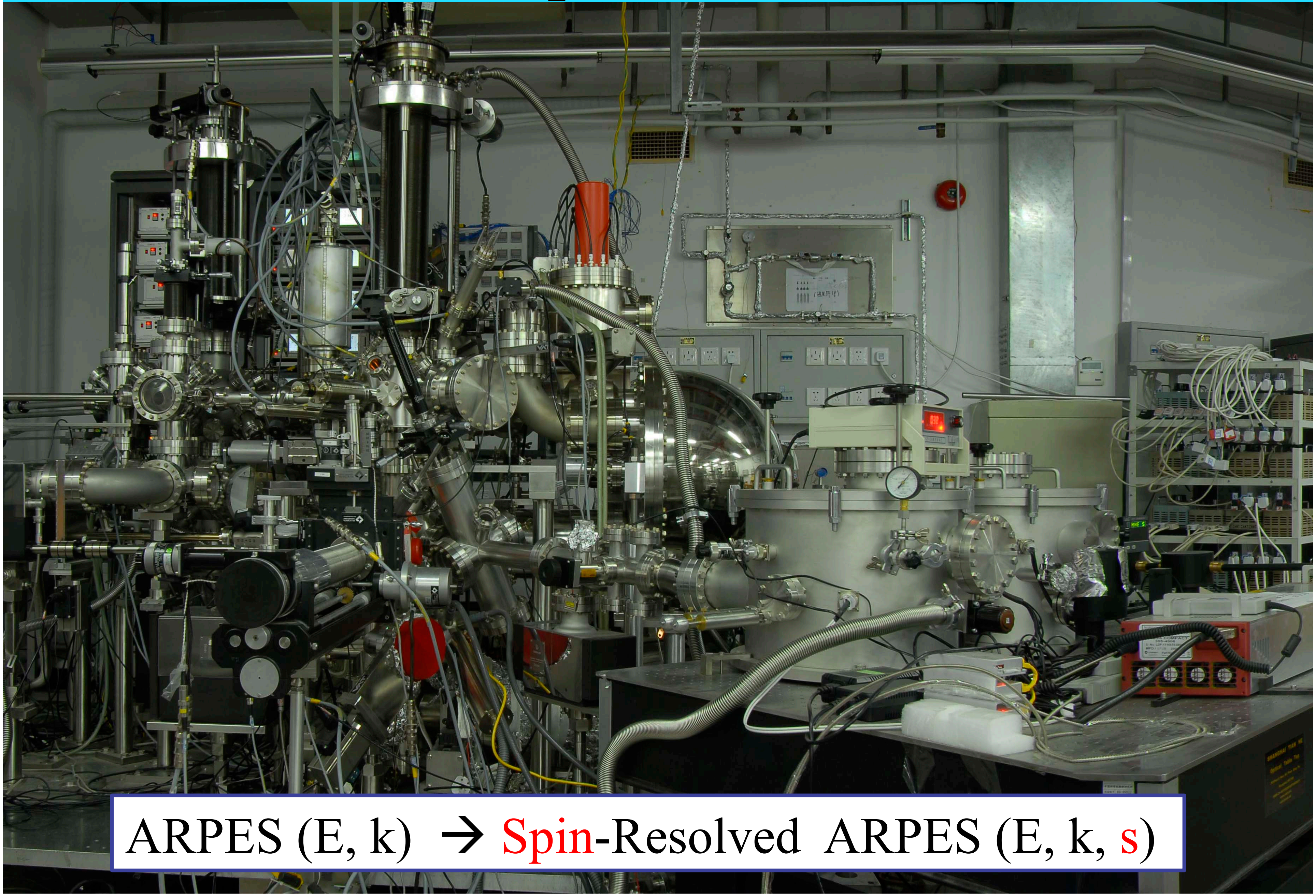
VUV Laser

Energy Resolution ΔE decoupled with photon flux



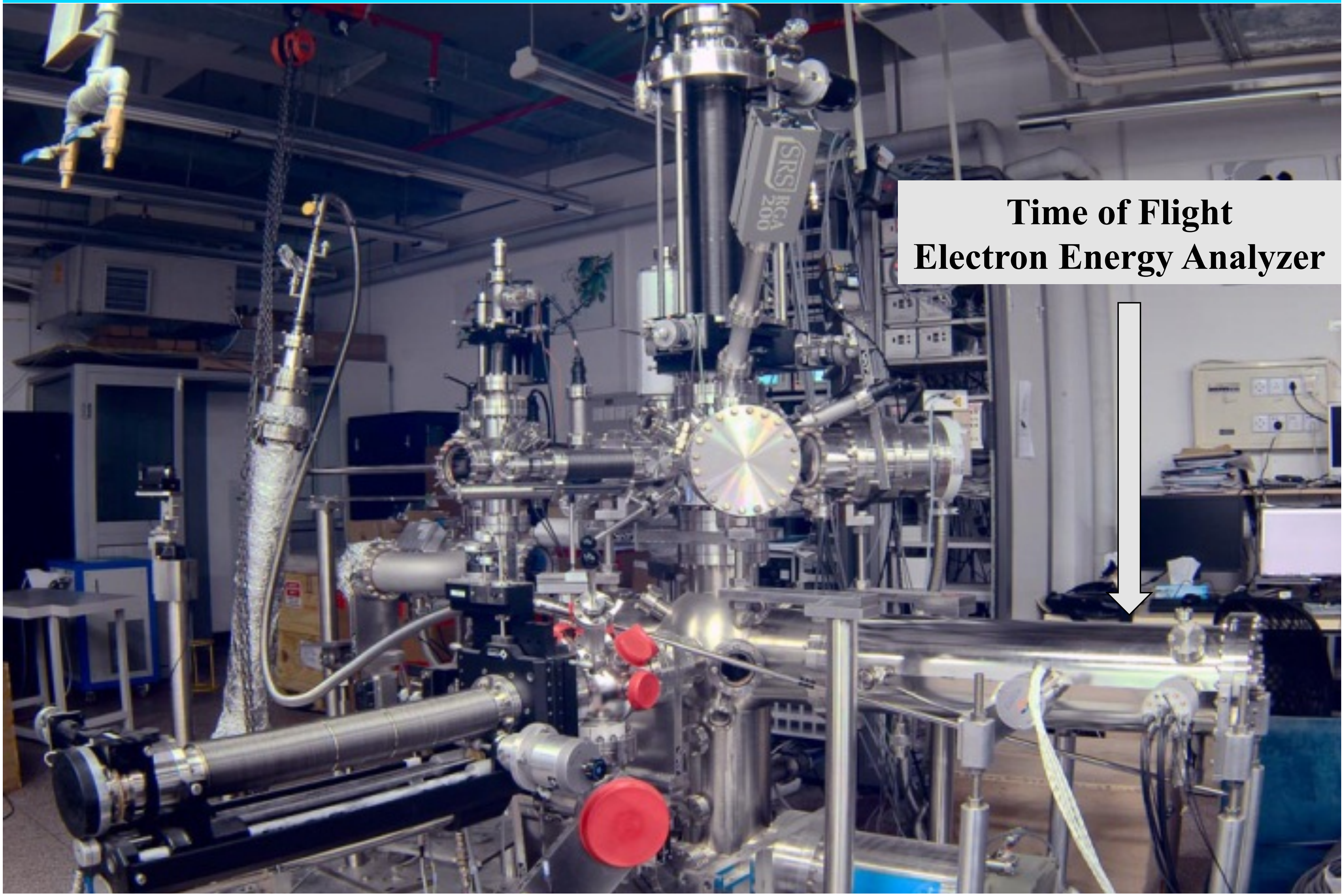
(1).Narrow linewidth (0.26meV);
(2).Extremely high photon flux (10^{15} photons/s).

VUV Laser Spin-Resolved ARPES



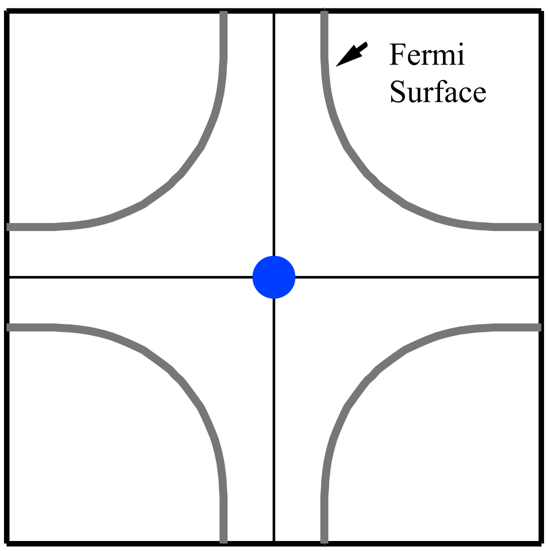
ARPES (E, k) → Spin-Resolved ARPES (E, k, s)

Laser ARPES Based on Time-of-Flight Analyzer



Evolution of Energy Analyzers: from 0D to 1D Angular Detection

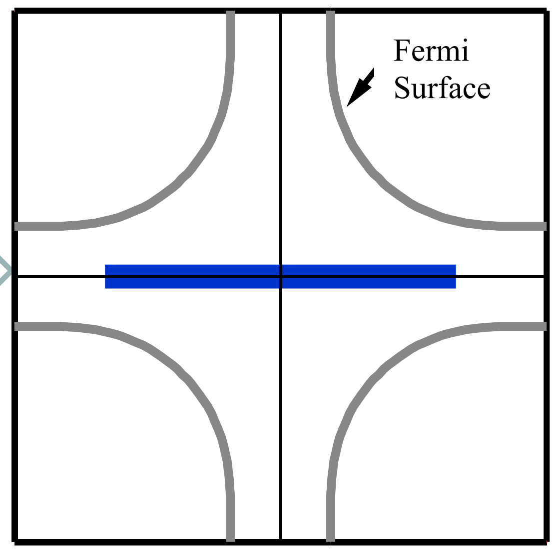
Before Scienta (~1997)



Angle Detection: 0D Point

Hemispherical Analyzer

- Energy Resolu: <1meV
- Angular Resolu: 0.1~0.4 Degree
- Angle Coverage: 1D: +-15 degrees

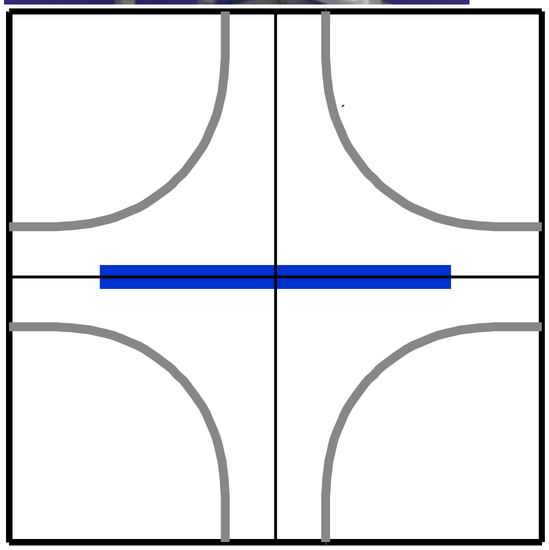


Angle Detection: 1D Line

Time of Flight Analyzer: From 1D to 2D Angular Detection

Hemi-Spherical Analyzer

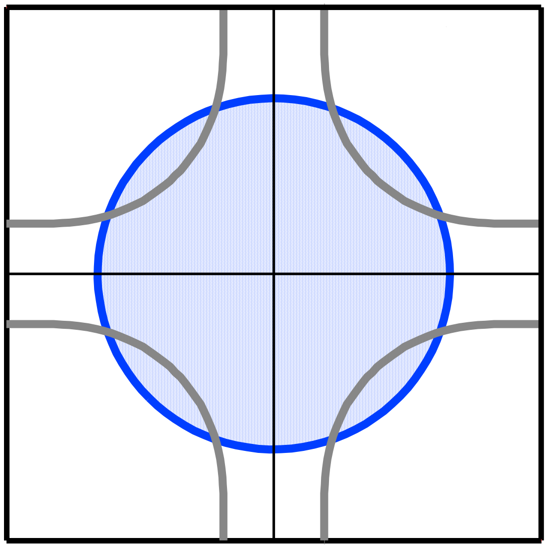
- Energy Res.: better than 1meV
- Angular Res: 0.1~0.4 Degree
- Angle Range: 1D: +-15 Deg.



Angle Detection: 1D Line

Time-of-Flight Analyzer

- Energy Res.: ~0.15meV
- Angular Res.: 0.08 Degree
- Angle Range: 2D:+-15Deg.



Angle Detection 2D Plane

Efficiency of Angle Detection Improved by 250 times

Other Developments and Future Developments

- **Ultra-Low Temperature ARPES;**
  He 3 pumping, Sample temperature<1 K;

- **Laser ARPES with Higher Photon Energy;**

- **Time-Resolved ARPES;**

- **Spatially-Resolved ARPES.**

Summary

In the past two decades, ARPES has continuously experienced dramatic improvements;

This improvement still keeps going;

Every time there is a significant improvement on resolution, there are new findings.

Thanks