SSRL 50 Years – VUV and Soft X-ray Materials Science

April 20, 2023

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Stanford Institute for Materials and Energy Sciences
Stanford University and SLAC National Accelerator Laboratory

Stanford University | U.S. DEPARTMENT OF ENERGY

Acknowledgement – Piero Pianetta, Ingolf Lindau, Donghui Lu, and Makoto Hashimoto

Outline

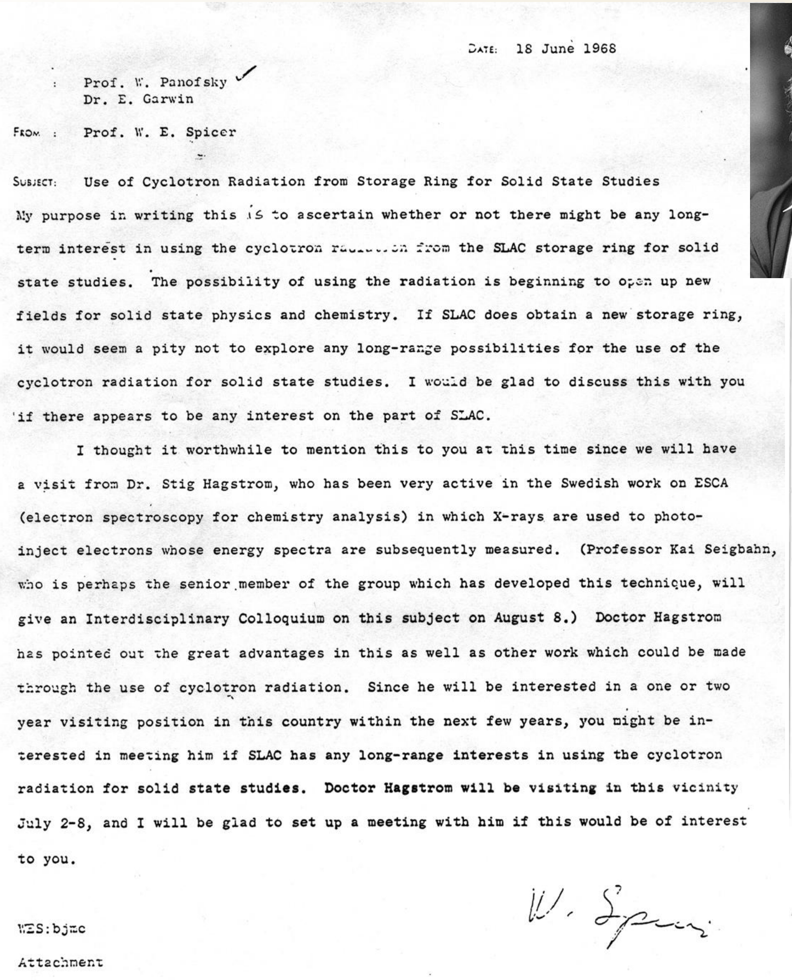
- Pioneering days
- Case Study – Angle-resolved photoemission from quantum materials
- Building an ecosystem – bridging other activities at SLAC and Stanford
- Some reflections

Historical Context—Motivation

- State of the art high energy physics storage ring, SPEAR, began operation at SLAC in 1972
- Would be used to study uncharted territory in particle physics and ultimately discovered quarks and lepton

- Could this source of high intensity x-rays be used to do something novel for materials/chemistry/biology?
- Demonstration experiment showing that an x-ray beam could be extracted from SPEAR and some useful science could be performed

Pioneering Days



DATE: 18 June 1968

: Prof. W. Panofsky ✓
Dr. E. Garwin

FROM : Prof. W. E. Spicer

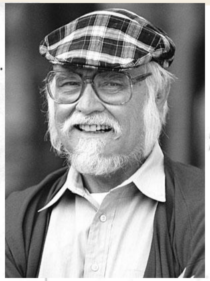
SUBJECT: Use of Cyclotron Radiation from Storage Ring for Solid State Studies

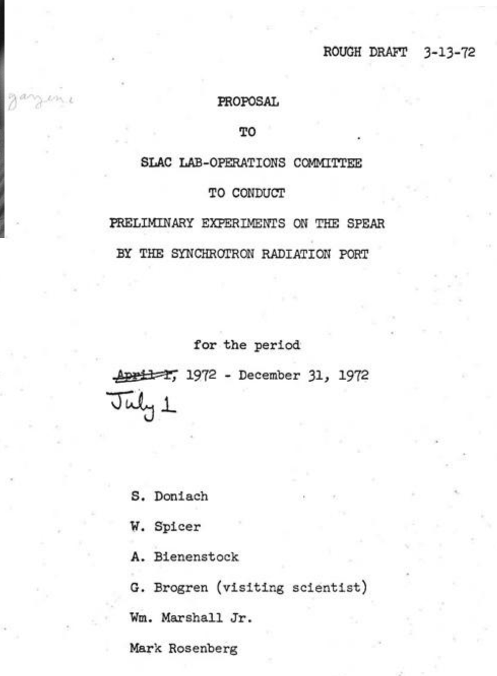
My purpose in writing this is to ascertain whether or not there might be any long-term interest in using the cyclotron radiation from the SLAC storage ring for solid state studies. The possibility of using the radiation is beginning to open up new fields for solid state physics and chemistry. If SLAC does obtain a new storage ring, it would seem a pity not to explore any long-range possibilities for the use of the cyclotron radiation for solid state studies. I would be glad to discuss this with you if there appears to be any interest on the part of SLAC.

I thought it worthwhile to mention this to you at this time since we will have a visit from Dr. Stig Hagstrom, who has been very active in the Swedish work on ESCA (electron spectroscopy for chemistry analysis) in which X-rays are used to photo-inject electrons whose energy spectra are subsequently measured. (Professor Kai Seigbahn, who is perhaps the senior member of the group which has developed this technique, will give an Interdisciplinary Colloquium on this subject on August 8.) Doctor Hagstrom has pointed out the great advantages in this as well as other work which could be made through the use of cyclotron radiation. Since he will be interested in a one or two year visiting position in this country within the next few years, you might be interested in meeting him if SLAC has any long-range interests in using the cyclotron radiation for solid state studies. Doctor Hagstrom will be visiting in this vicinity July 2-8, and I will be glad to set up a meeting with him if this would be of interest to you.

W. Spicer

WES:bjmc
Attachment





ROUGH DRAFT 3-13-72

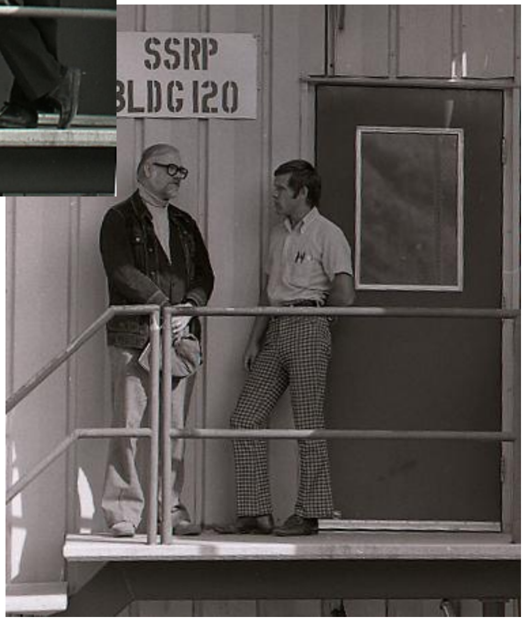
PROPOSAL
TO
SLAC LAB-OPERATIONS COMMITTEE
TO CONDUCT
PRELIMINARY EXPERIMENTS ON THE SPEAR
BY THE SYNCHROTRON RADIATION PORT

for the period
~~April 1,~~ July 1 1972 - December 31, 1972

S. Doniach
W. Spicer
A. Bienenstock
G. Brogren (visiting scientist)
Wm. Marshall Jr.
Mark Rosenberg

Proposal led by Doniach,
Spicer and Bienenstock (1972)

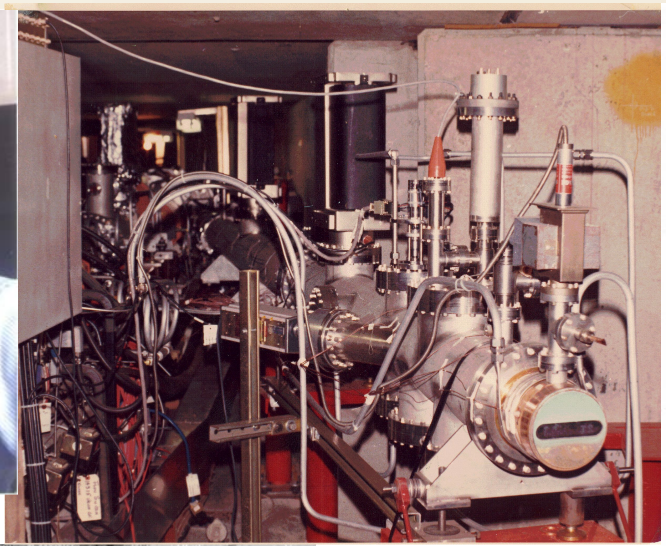
Doniach
Bienenstock
Winick

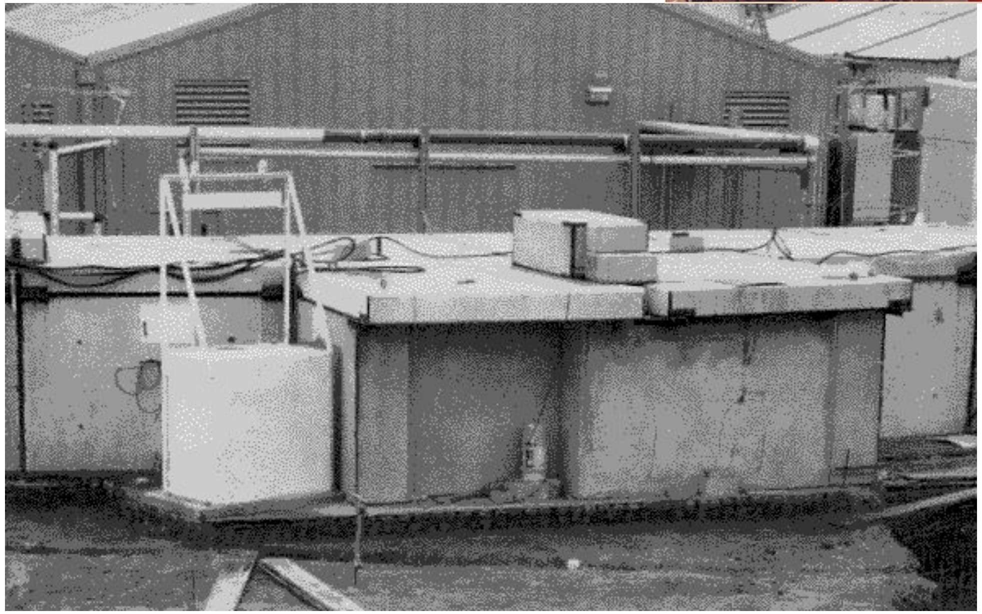


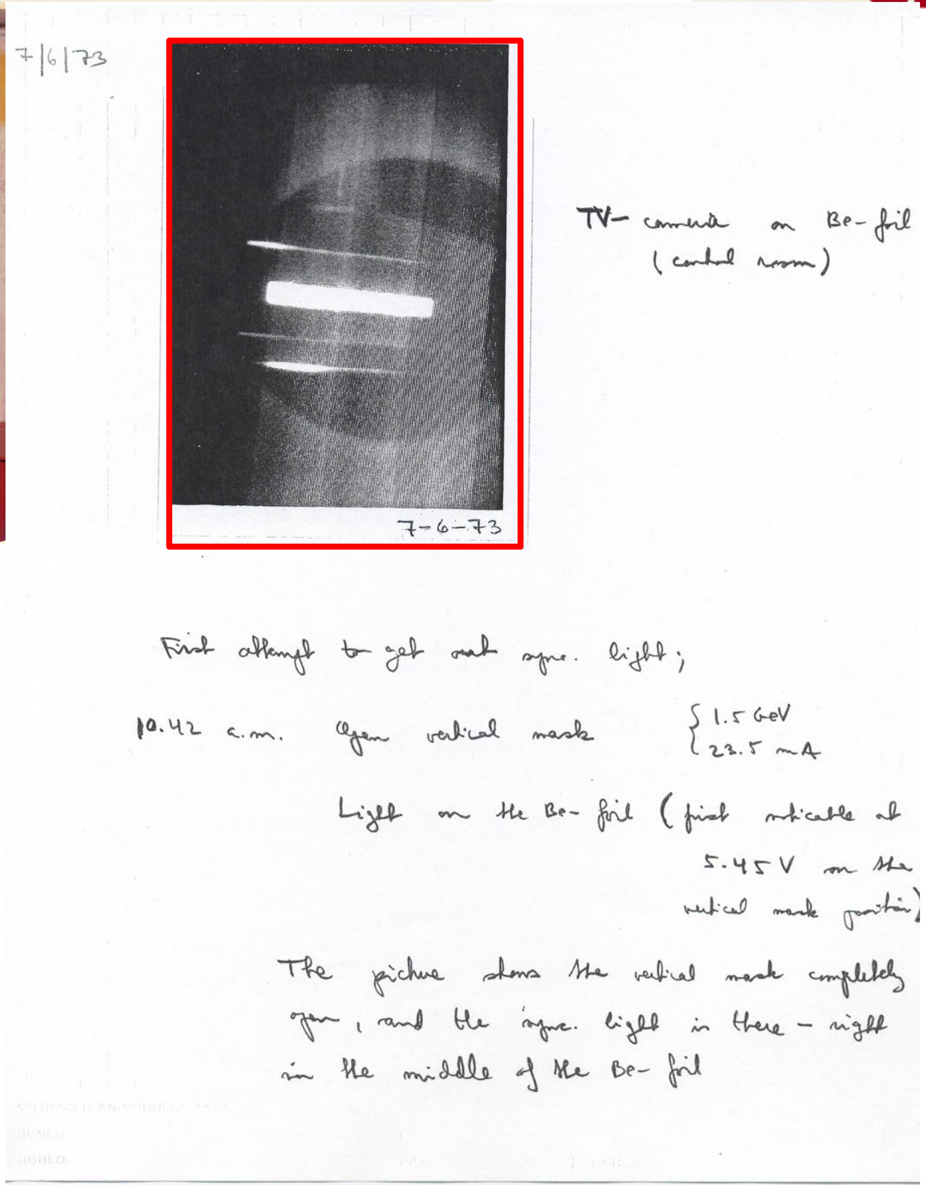
Spicer and Lindau

Spicer's 1968 letter to Panofsky

Pioneering Days - Seeing the Light, 1973







7/6/73

7-6-73

TV– camera on Be-foil
(control room)

First attempt to get out sync. light;

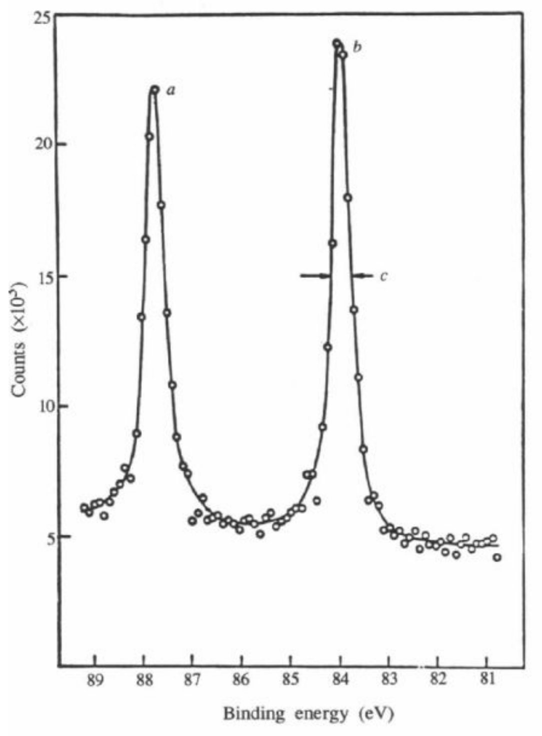
10.42 a.m. Open vertical mask { 1.5 GeV, 23.5 mA }

Light on the Be-foil (first noticeable at 5.45 V on the vertical mask position)

The picture shows the vertical mask completely open, and the sync. light in there – right in the middle of the Be-foil

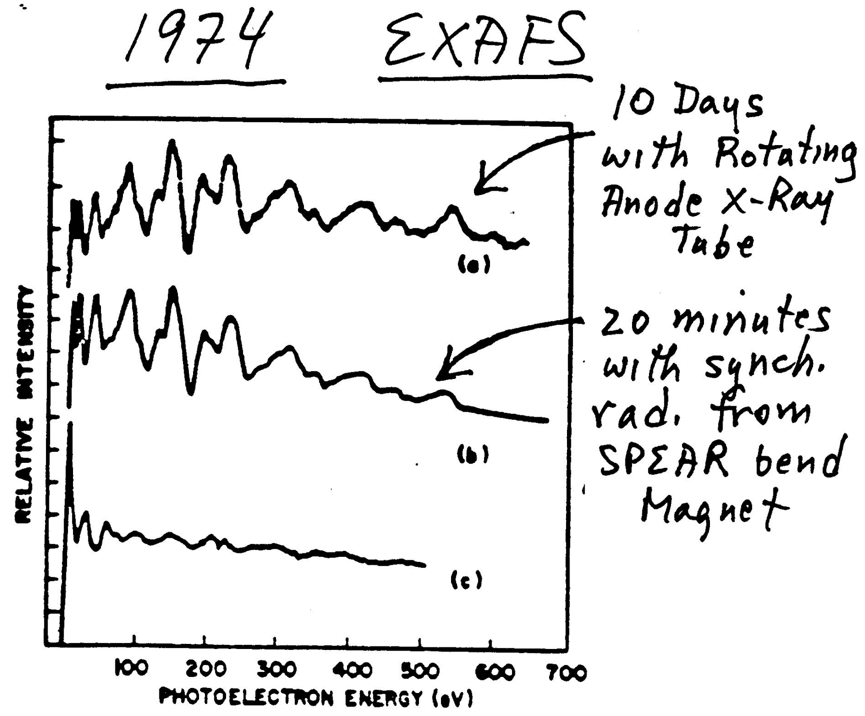
First Public Reports, 1974

Photoemission from Au 4f



"X-ray Photoemission with Use of Synchrotron Radiation," I. Lindau P. Pianetta, S. Doniach and W. E. Spicer, SSRP, Stanford University, Proc. IV International Conf. on Vac. Ultraviolet Rad. Phys., Hamburg, July 22-26, 1974, p. 805. (Invited Paper)

Lindau, Pianetta, Doniach, Spicer, Nature 250, 214 (1974)

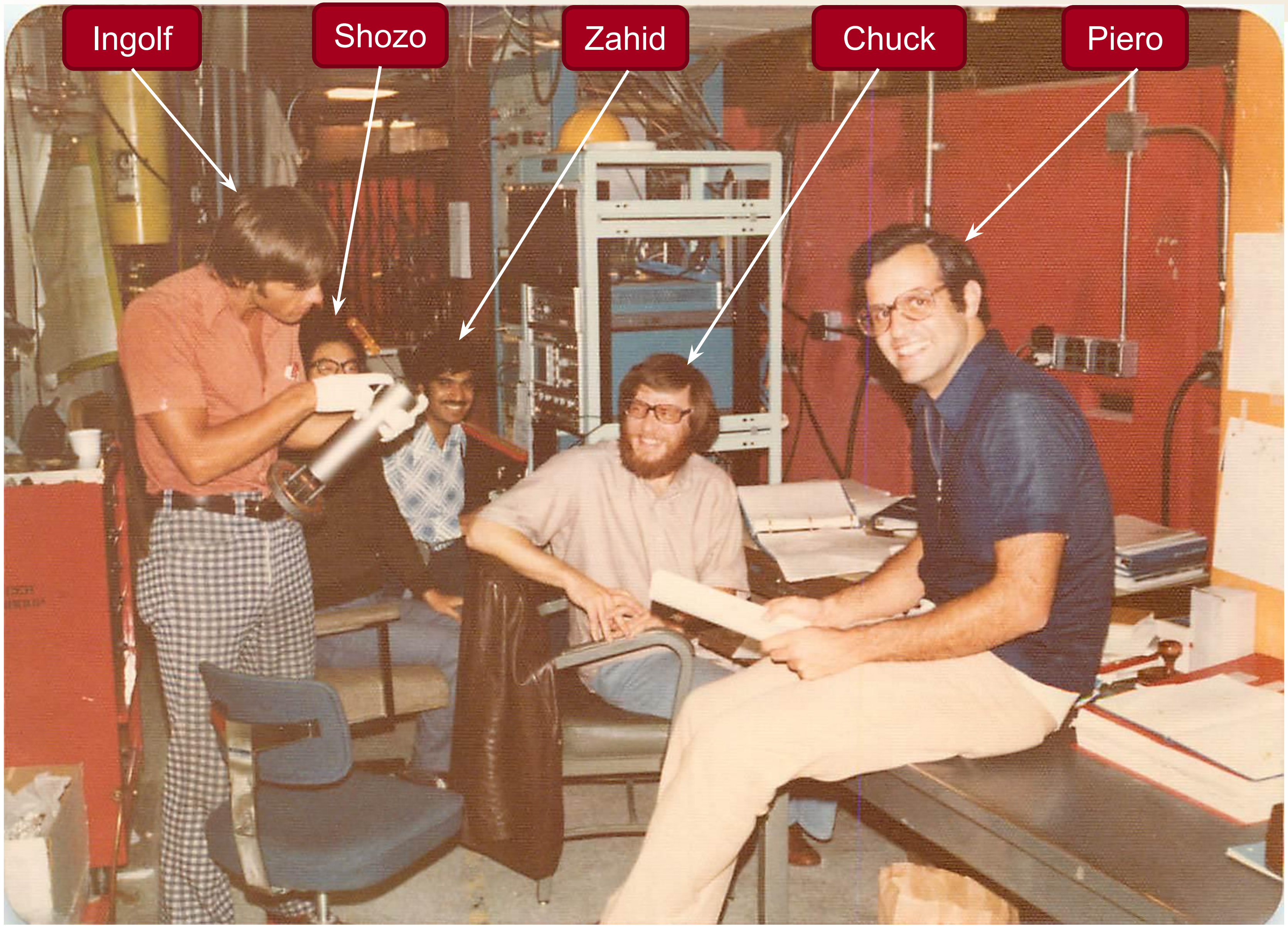


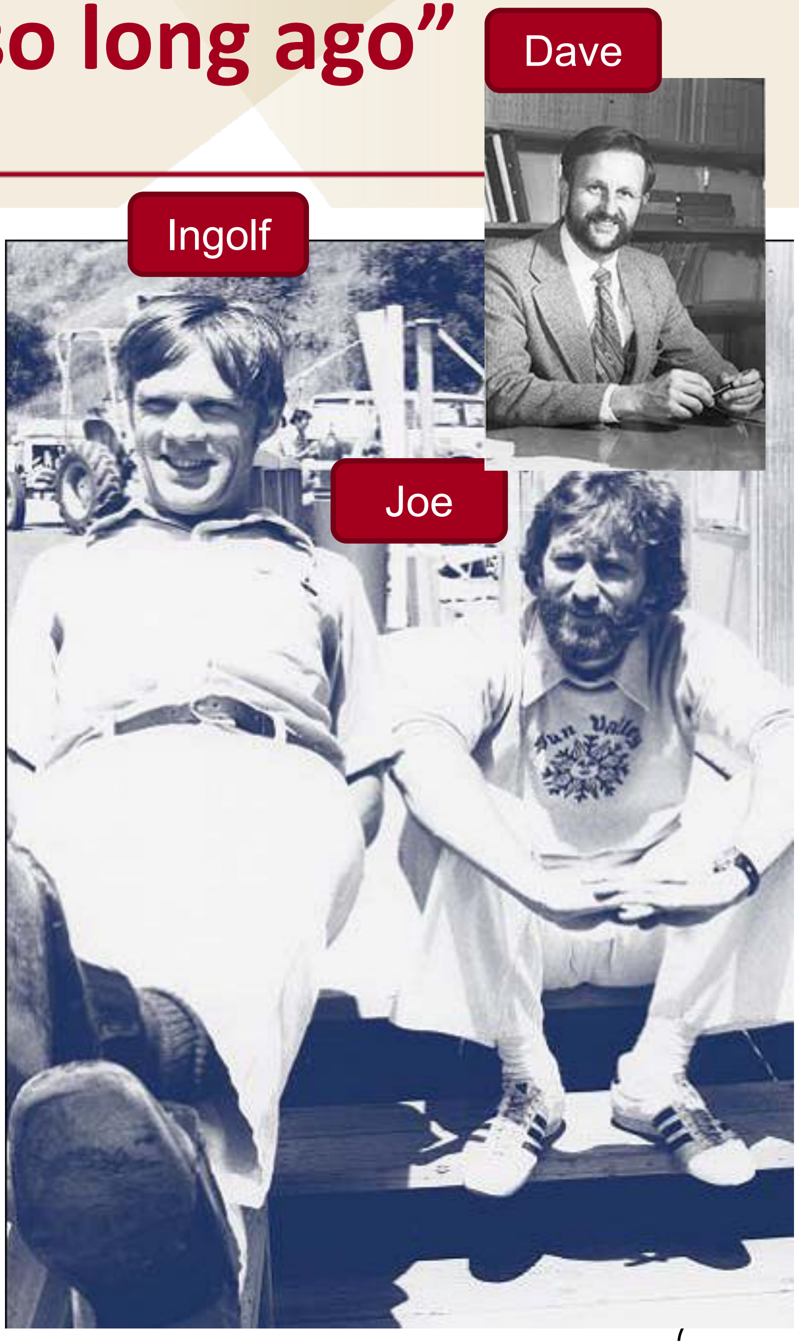
"EXAFS Measurements at SPEAR," P. Eisenberger, Bell Laboratories, B. Kincaid, S. Hunter, Stanford University, D. Sayers, E. A. Stern, University of Washington, and F. Lytle of Boeing Aerospace Co., Proc. IV International Conf. on Ultraviolet Rad. Phys., Hamburg, July 22-26, 1974, p. 806.

Eisenberger, Kincard, Hunter, Sayers, Stern, and Lytle (1974)

“Those were such happy times – and not so long ago”

Some VUV and Soft X-ray Experimenters





Semiconductor and Metal Surfaces

SLAC

VOLUME 35, NUMBER 20 PHYSICAL REVIEW LETTERS 17 NOVEMBER 1975

Determination of the Oxygen Binding Site on GaAs(110) Using Soft-X-Ray-Photoemission Spectroscopy*

P. Pianetta, I. Lindau, C. Garner, and W. E. Spicer
Stanford Electronics Laboratories and Stanford Synchrotron Radiation Project, Stanford University, Stanford, California 94305

(Received 25 August 1975)

The first steps in the oxidation of GaAs(110) are examined through shifts in the As and Ga 3*d* levels as a function of oxygen exposure. We observe a large chemical shift in the As 3*d* levels (about 4 eV) while the Ga 3*d* levels were shifted by less than 1 eV. This gives direct evidence for oxygen bonding to arsenic at the GaAs(110) surface, and illustrates the change in chemical character which can take place in atoms at the surfaces of compounds.

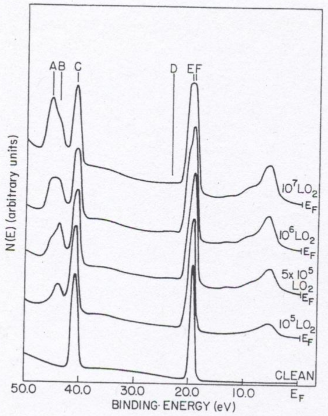


FIG. 1. Photoemission spectra of clean and oxidized GaAs(110) for 100-eV photon energy.

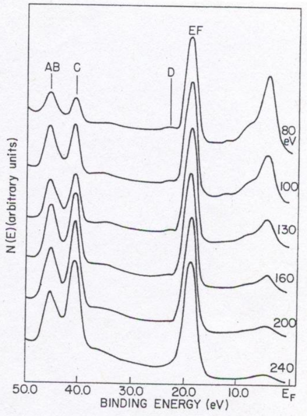


FIG. 2. Photoemission spectra of heavily oxidized (10^7 L) GaAs(110) as a function of photon energy.

PHYSICAL REVIEW B VOLUME 14, NUMBER 12 15 DECEMBER 1976

Angle-resolved photoemission from valence bands of Cu and Au single crystals using 32–200-eV synchrotron radiation*

J. Stöhr, G. Apai, P. S. Wehner, F. R. McFeely, R. S. Williams, and D. A. Shirley
Materials and Molecular Research Division, Lawrence Berkeley Laboratory and Department of Chemistry, University of California, Berkeley, California 94720

(Received 14 June 1976)

The directional anisotropy in photoemission from valence bands of Cu and Au single crystals has been studied in the photon energy ranges $32 \leq h\nu \leq 200$ eV, and $32 \leq h\nu \leq 130$ eV, respectively. Angle-resolved photoemission energy distributions were obtained for electrons emitted in the [001] and [111] directions. Dramatic differences were found between the two directions and strong variations with energy were obtained over the entire energy range. The results are discussed in terms of final-state band-structure effects and/versus strong inelastic damping in the final state. For Cu, spectra taken at $h\nu = 90$ eV along the same symmetry directions at high (90°) and low (35°) take-off angles from the surface show a pronounced narrowing of the *d* band at low take-off angles. This is attributed to a preferential sampling of the local density of states at the surface by using an appropriate photon energy and take-off angle. The energy dependence of the Au 5*d* intensity has been measured and is found to decrease by a factor of ~ 50 over the investigated photon energy range 40–190 eV.

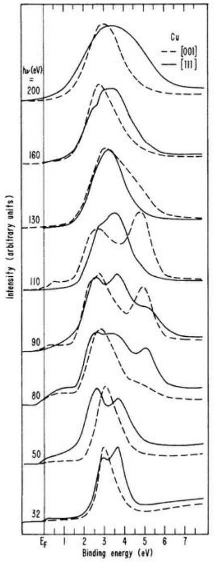


FIG. 4. Comparison of photoemission spectra taken along the Cu [001] and [111] directions (dashed and solid lines, respectively) for various photon energies. The experimental geometry was the same as for Fig. 3.

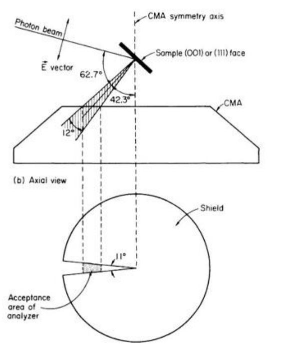


FIG. 1. Experimental geometry for angle resolved photoemission studies of Cu and Au single crystals. A cylindrical-mirror analyzer (CMA) is modified by means of a slit aperture (shield) to allow angle resolved measurements. The effective angular resolution is ±6° in the horizontal and ~±4° in the vertical plane.

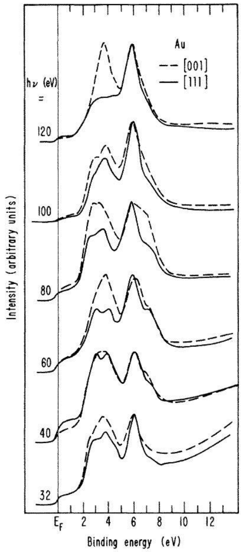
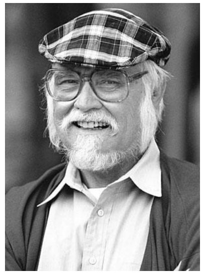
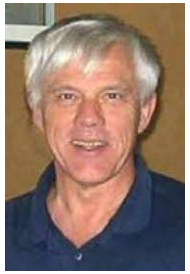


FIG. 8. Comparison of photoemission energy distributions along the [001] and [111] direction of Au (dashed and solid lines) in the range $32 \leq h\nu \leq 120$ eV. The spectra were taken from Fig. 7.

Photoemission Study of Correlated Materials





Jim Allen

Anderson Hamiltonian description of the experimental electronic structure and magnetic interactions of copper oxide superconductors

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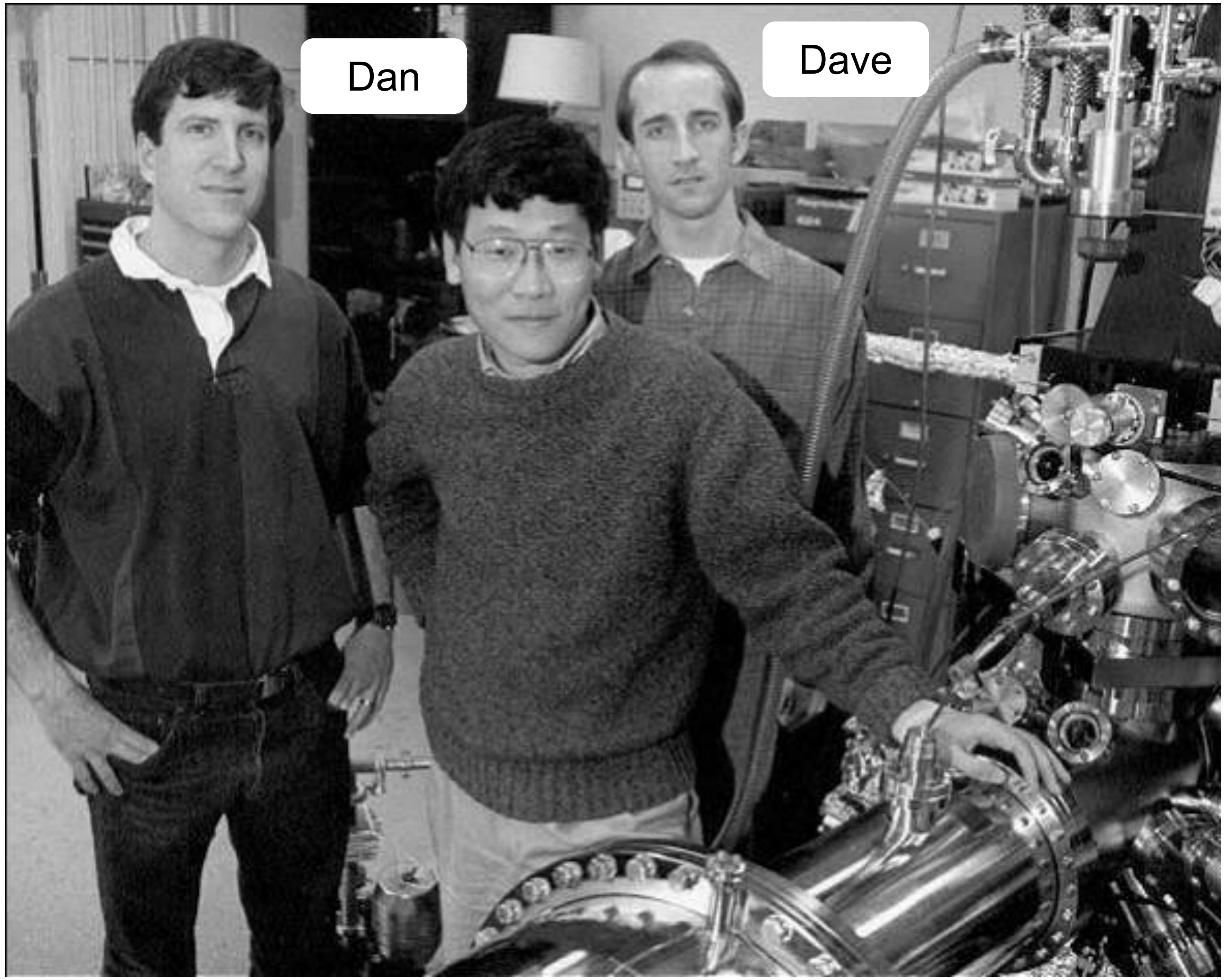
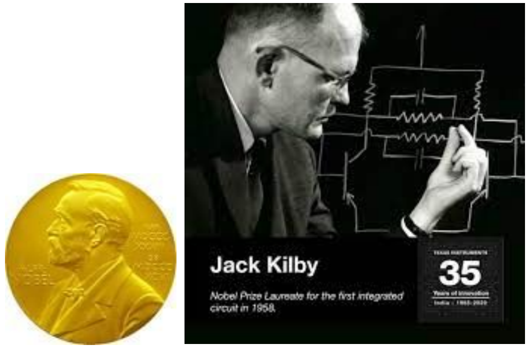
J. Z. Sun and T. H. Geballe
Department of Applied Physics, Stanford University, Stanford, California 94305
(Received 20 July 1987)



Scientific foundation for next generation quantum materials

Invention of transistor (1957 Nobel Prize)

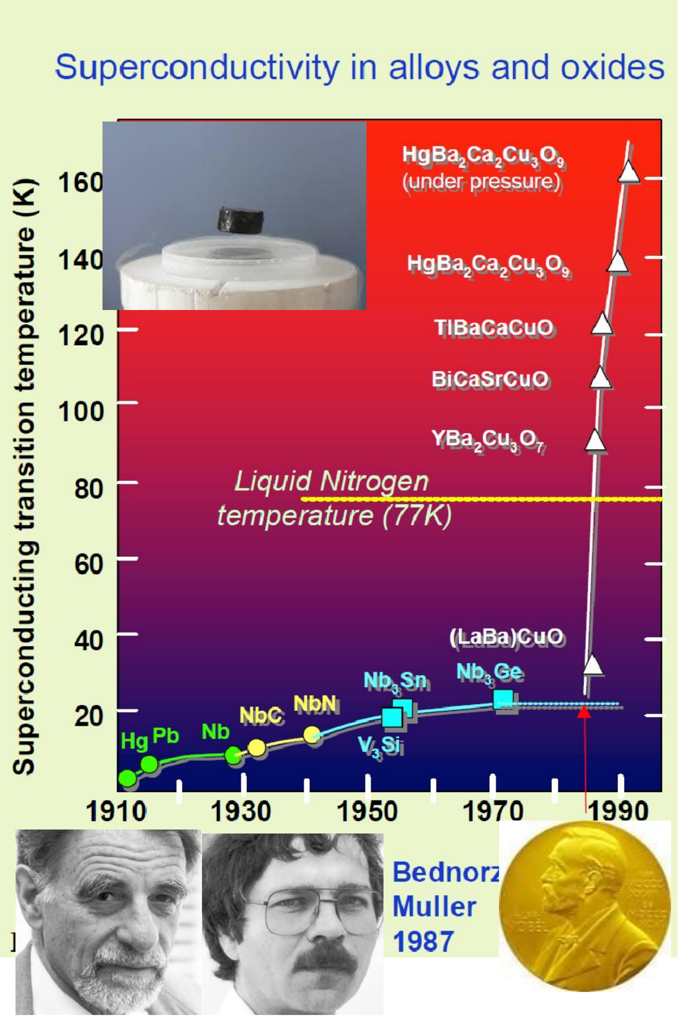


Invention of Integrated circuit (2000 Nobel Prize)

First generation quantum theory played a vital role in the development of "1st generation of quantum technologies" like semiconductors.

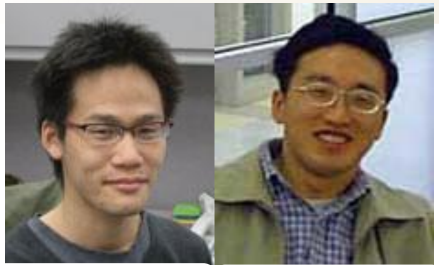
Adequate quantum theory is yet to be developed for other classes of quantum materials, for example cuprate high temperature superconductors.

Precision measurement of key quantum parameters is imperative to the development of "next generation quantum theory" – in the search for the next "magic material"

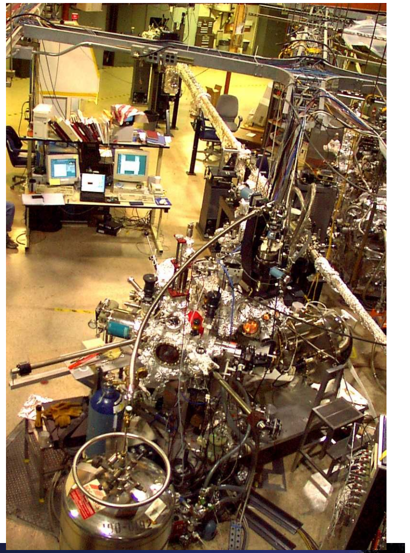


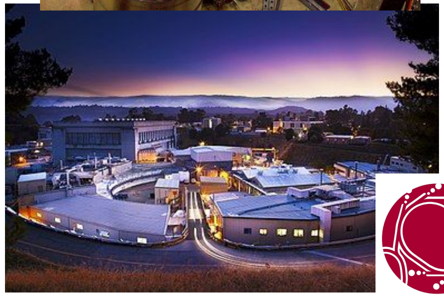
SIMES SLAC

Modern Angle-Resolved Photoemission Spectroscopy (ARPES)

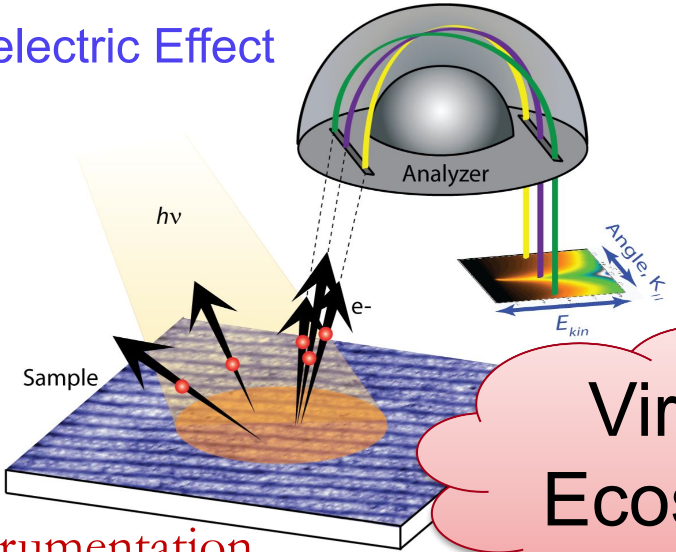


Makoto Donghui



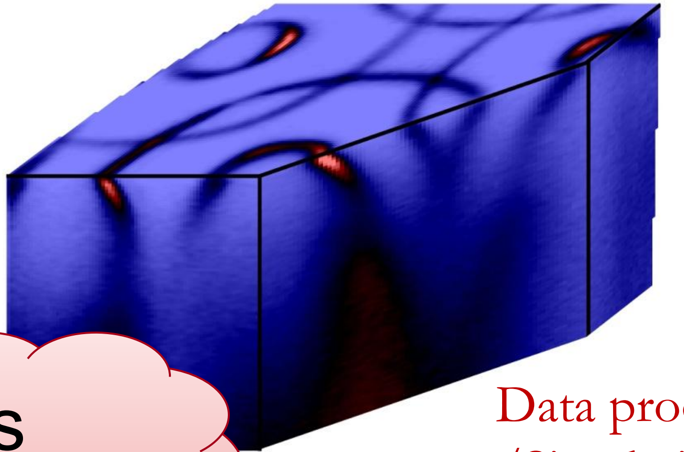


Photoelectric Effect

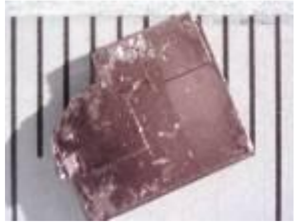


Instrumentation

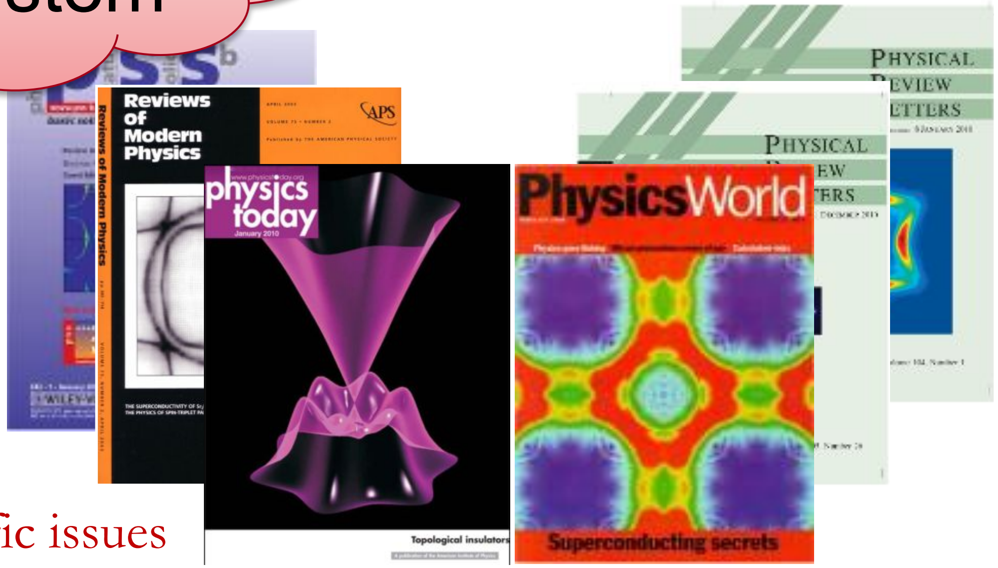
Virtuous Ecosystem



Data processing /Simulation



Materials/Samples environment



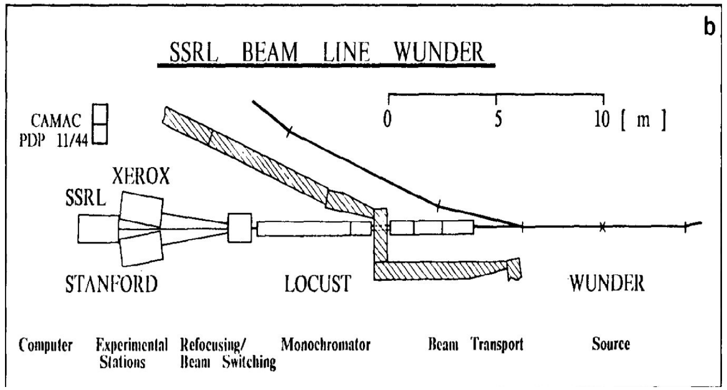
Scientific issues

Evolution of ARPES Program at SSRL

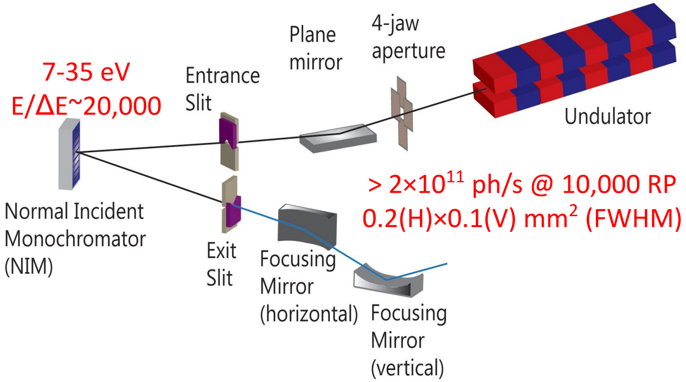
BL-5 produces ~ 30% of synchrotron related ARPES papers in high impact journals – Science, Nature journals, PRL, PRX, PNAS (1990-2022)

SSRL SiMES SLAC

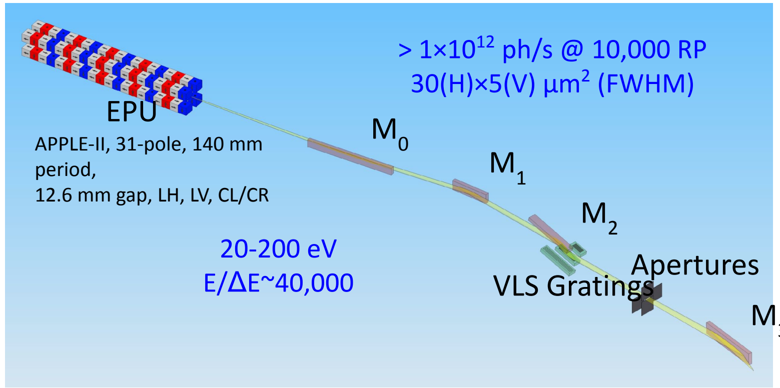
BL 5-3 (Before 1999)



BL5-4 (2000 –)



BL5-2 (2017 –)

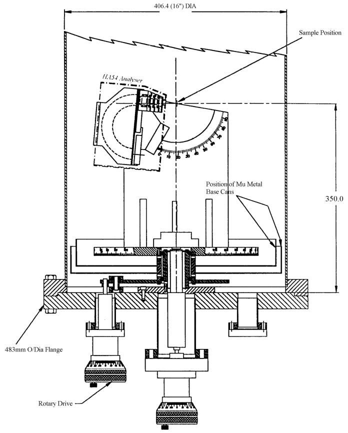


Multi-channel detector (1991)

2000 — **BL5-4 GU Program**

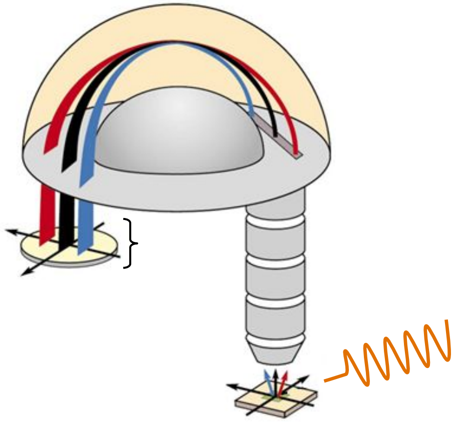
2017 — **BL5-2 GU Program**

BL5-3 VSW HA50

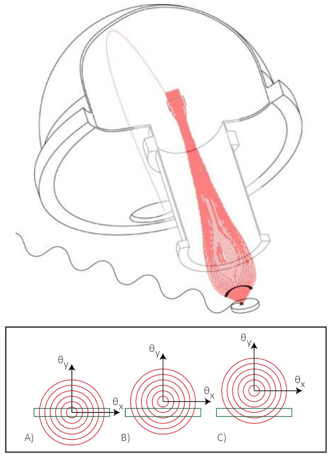


	Δ E (meV)	Δ θ	Θ
< 2000	*20-40*	*2°*	*2°*
now	*2-5*	*0.3°*	*30°*

BL5-4 Scienta R4000



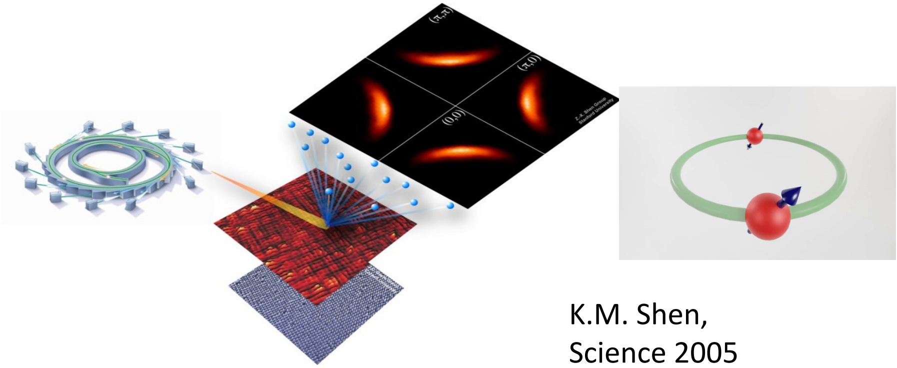
BL5-2 Scienta DA30-L



Probing important quantum numbers of electrons
Angle-resolved photoemission spectroscopy (ARPES)

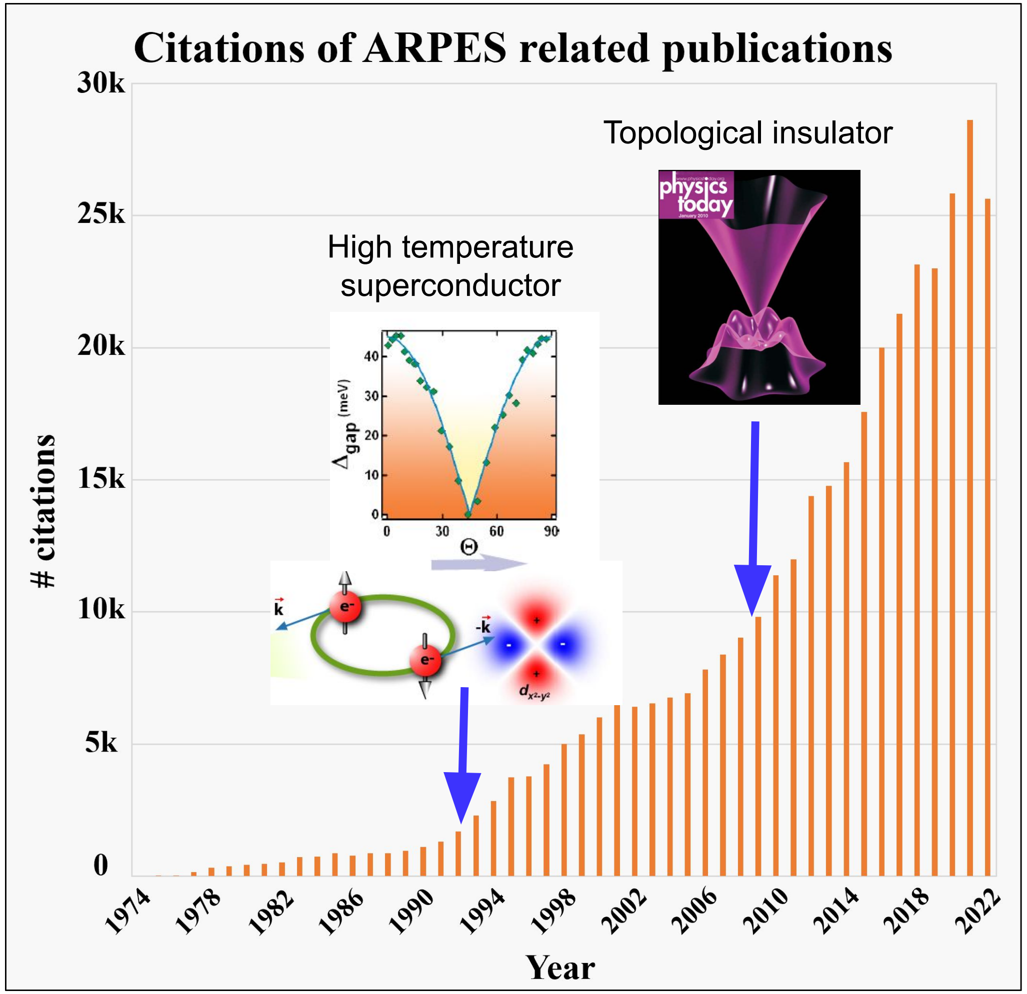
SLAC

Synchrotron based photoemission records energy and momentum of electrons



K.M. Shen, Science 2005

Dessau et al., Phys. Rev. Lett. **66**, 2160 (1991)
Z.X. Shen, et al, Phys. Rev. Lett. **70**, 1553 (1993)
B.O. Wells et al., Phys. Rev. Lett **74**, 964 (1995)
Z.X. Shen et al., Science **267**, 343 (1995)
A.G. Loeser et al., Science, **273**, 325 (1996)
A. Lanzara et al., Nature, **412**, 510 (2001)
N.P. Armitage et al., Phys. Rev. Lett. **87**, 147003 (2001)
K. Tanaka et al. Science, **314**, 1910 (2006)
D. Hsieh et al., Nature **452**, 970 (2008)
Y. L. Chen et al., Science **325**, 178 (2009)
Y. He et al., Science, **362**, (2018)
S.D. Chen et al., Science, **366**, 6469 (2019)
Z.Y. Chen et al., Science, **373**, 1235 (2021)
S.D. Chen et al., Nature, **601**, 562 (2022)



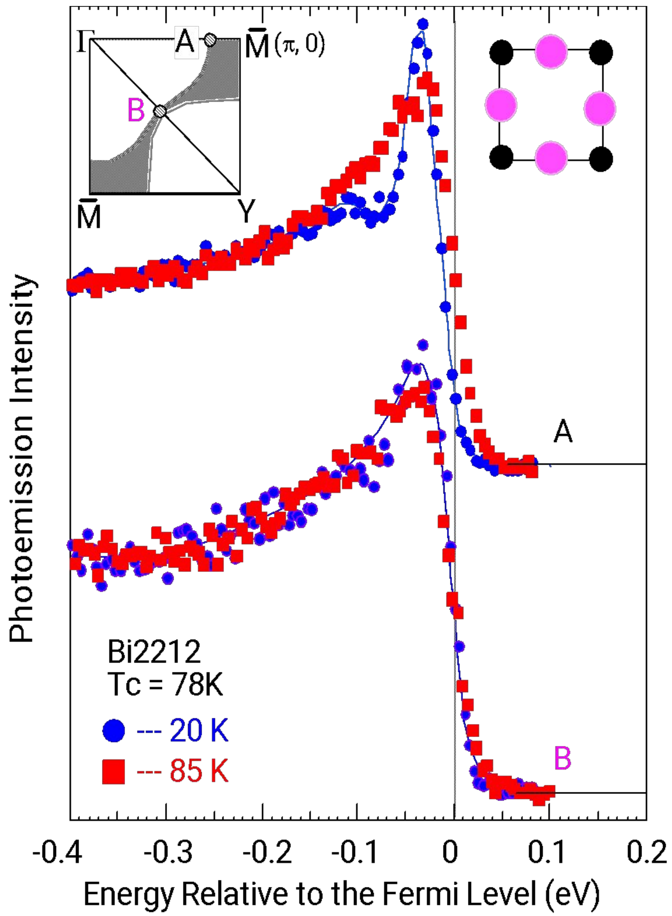
SSRL SIMES SLAC ALS ADVANCED LIGHT SOURCE

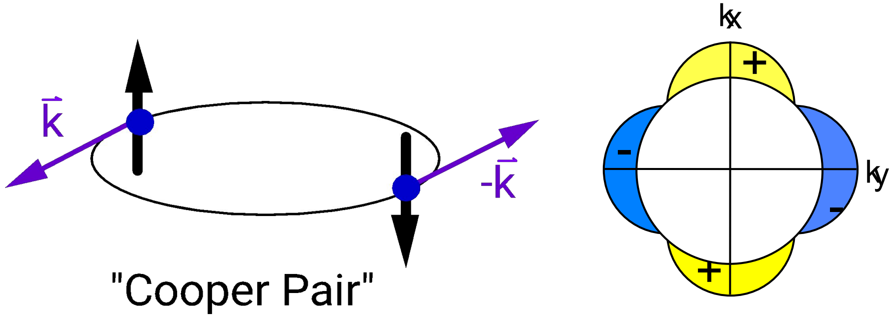
ARPES : Then and Now

30 years ago

SLAC

1993 : Detection of an anisotropic d-wave gap





One EDC with 30 meV & ±1° resolution :

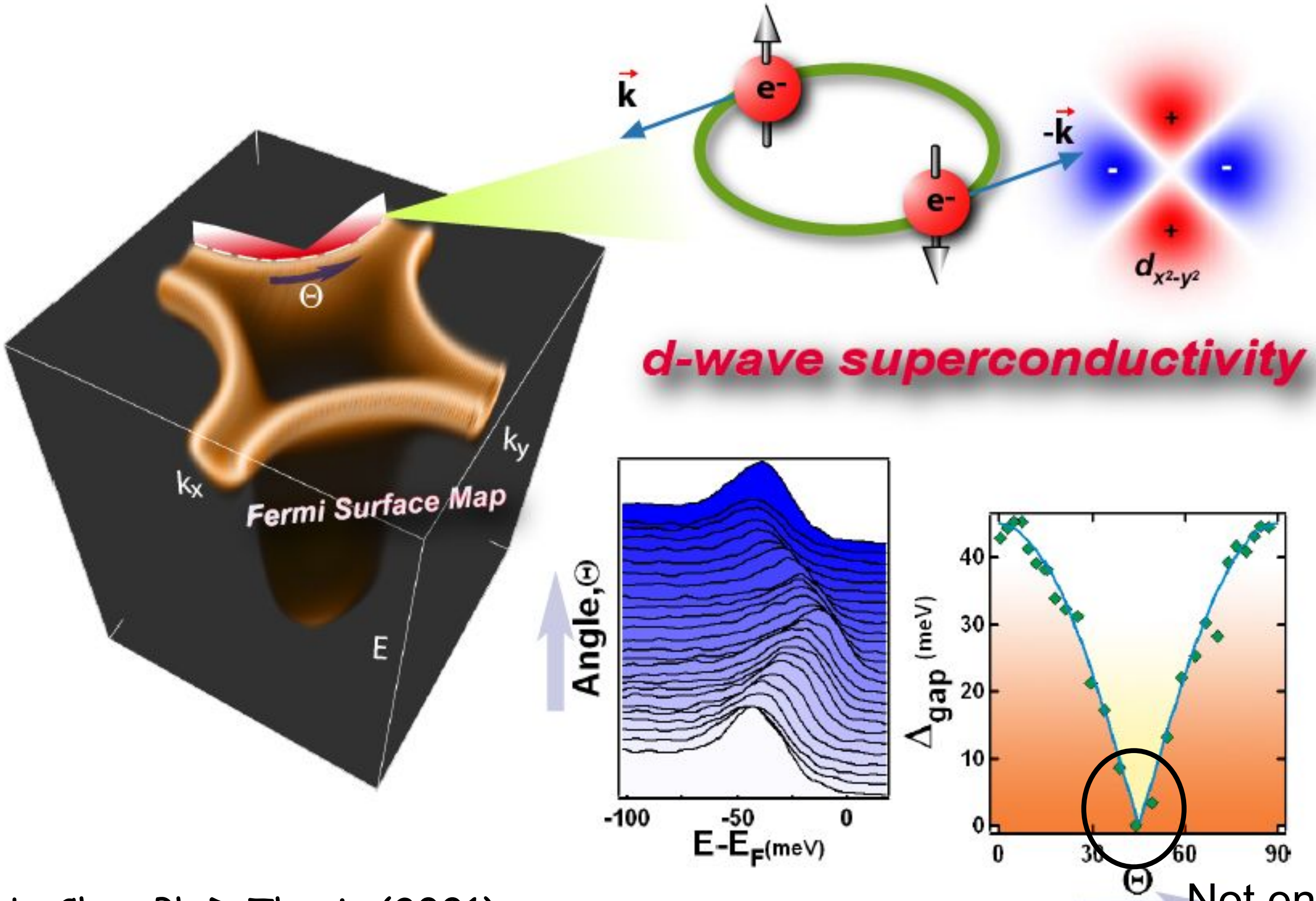
3 hours per spectrum

Shen, Dessau, Wells, *et al.*, PRL **70**, 1553 (1993)

SSRL SiMES

D-wave Superconductivity

20 years ago



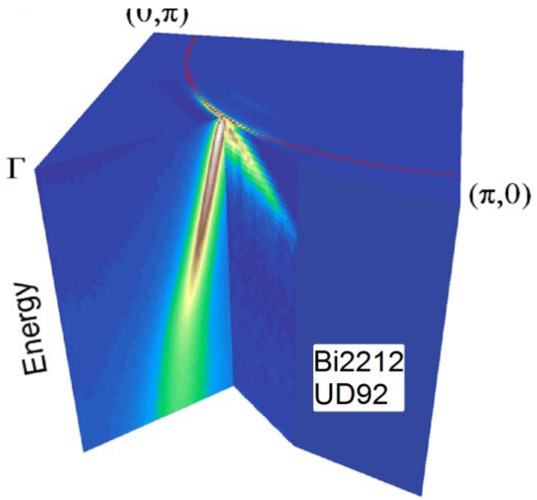
Not enough data

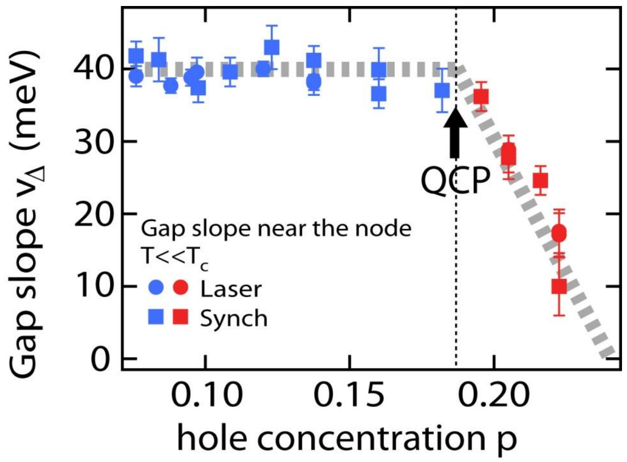
P. Bogdanov, Y.L. Chen Ph.D Thesis (2001)

M. Hashimoto et al., Nature Physics 6, 414-418 (2010)

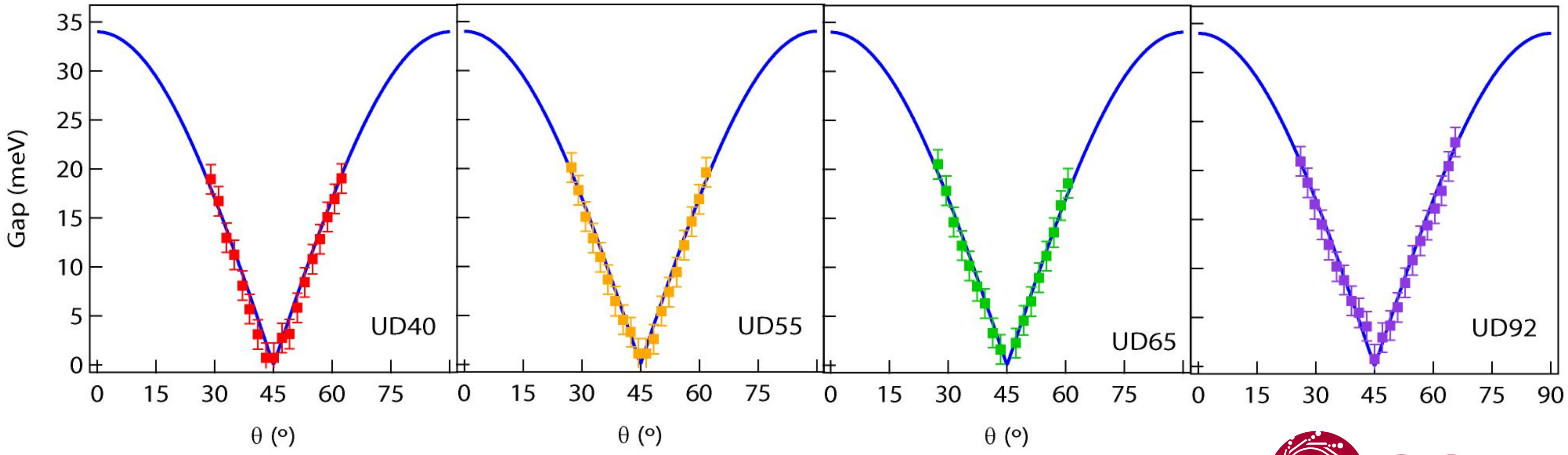
Precision Measurement of the d-Wave Node

10 years ago





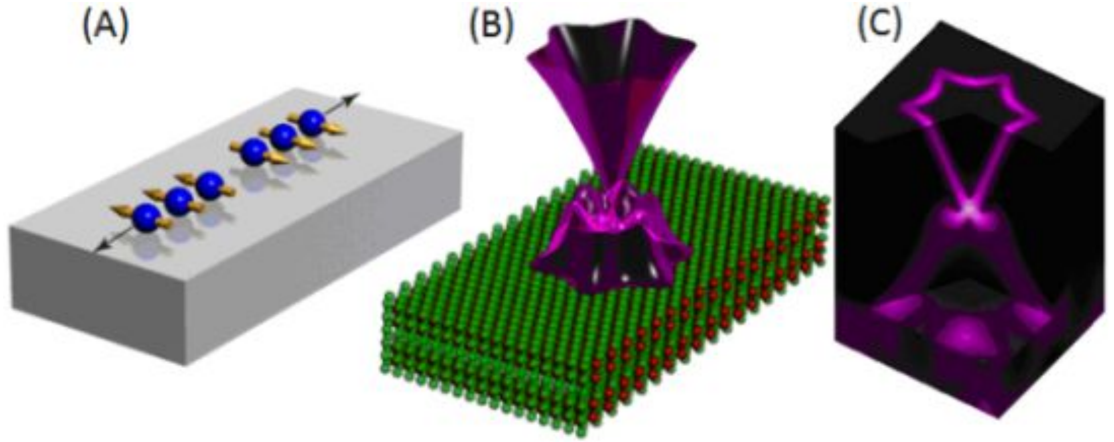
Inna

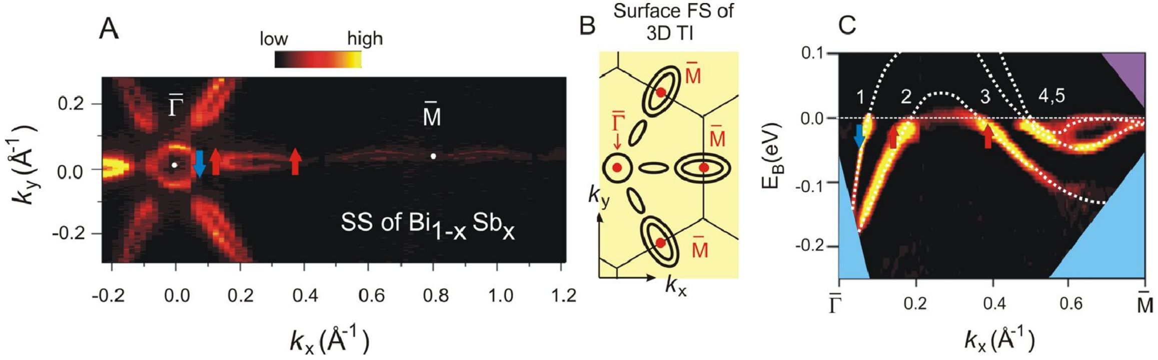


SSRL SIMES SLAC

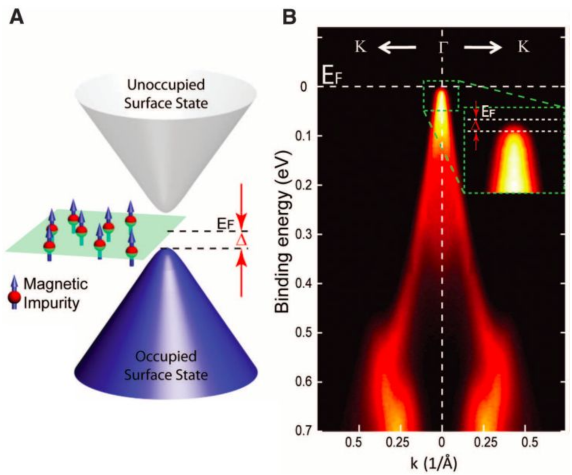
Topological states of quantum matter

Discovery of 3D topological insulators using synchrotron lightsources – role of wavefunctions





D. Hsieh *et al.*, *Nature* **452**, 970 (2008)
Y. L. Chen *et al.*, *Science* **325**, 178 (2009)
Y. L. Chen *et al.*, *Science* **329**, 659 (2010)

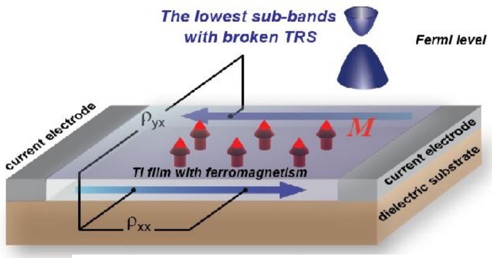


Synchrotron-ARPES reveals key features of topological insulators in momentum space:

- Bulk band gap with band inversion
- Odd number of robust Dirac cones on the surface
- Massive Drac surface states by time-reversal symmetry breaking

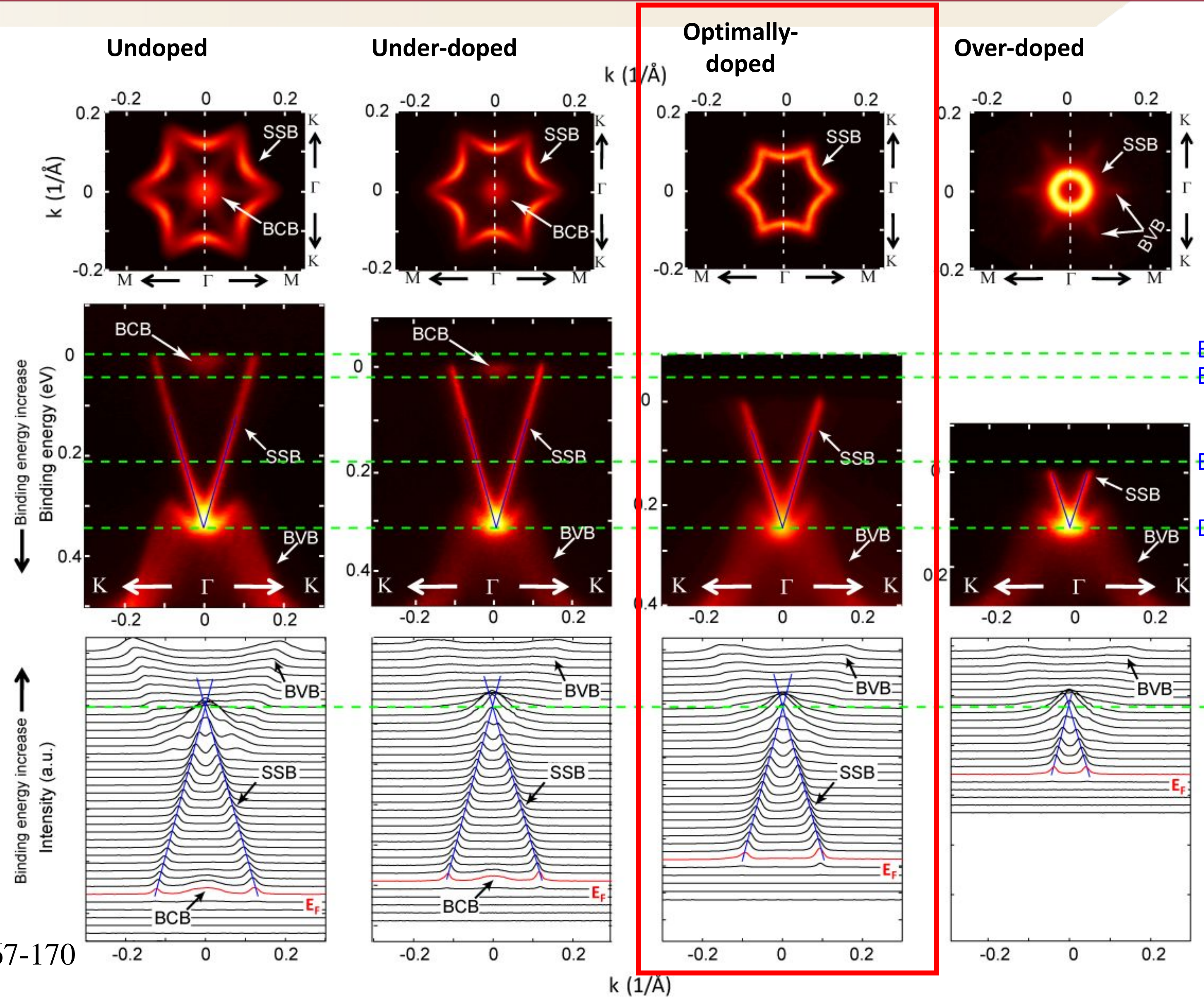
“Hydrogen Atom” of topological insulator - Bi2Te3

Quantum Anomalous Hall



$Cr_{0.15}(Bi_{0.1}Sb_{0.9})_{1.85}Te_3$

Chang et al. 2013, Science **340**, 167-170



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

Sample
Fisher group

Yulin

University Groups trained by the ARPES program at SSRL

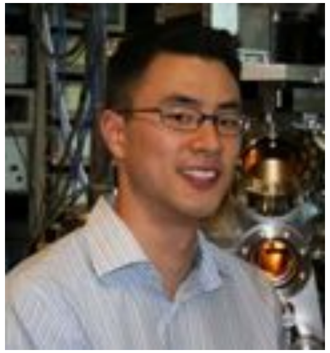

Dan Dessau
UC Boulder


Barry Wells
U Connecticut


Peter Armitage
Johns Hopkins


Zahid Hasan
Princeton

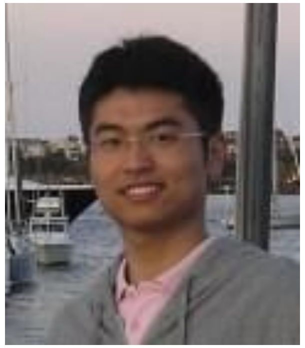

Alessandra Lanzara
UC Berkeley


Kyle Shen
Cornell


Tanja Cuk
UC Boulder


Inna Vishik
UC Davis


Ming Yi
Rice


Shuolong Yang
U of Chicago


Heike Pfau
Penn State


Yu He
Yale

Building Science Ecosystems

SSRL played a vital role incubating several Joint SLAC-Stanford interdisciplinary Research Institutes and Centers:

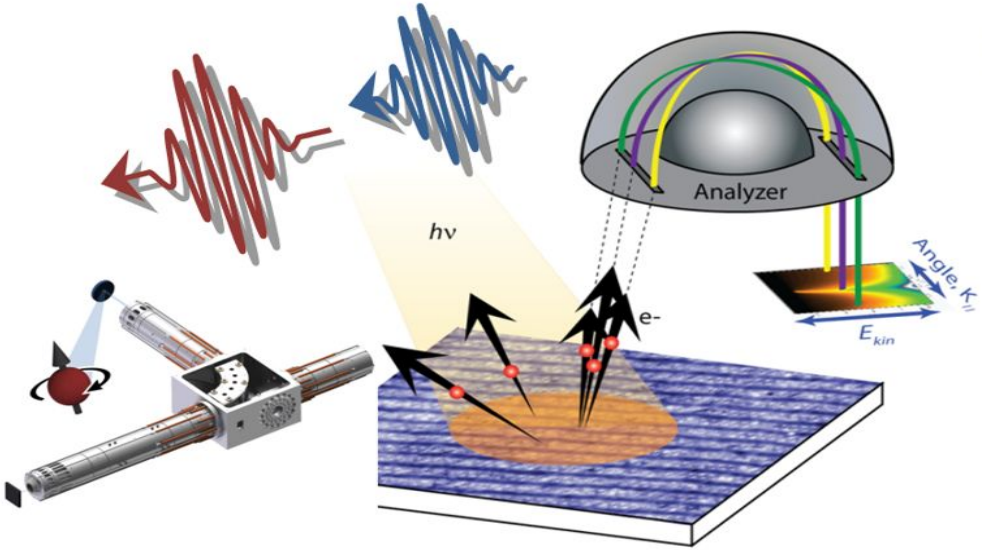
- Photon Ultrafast Laser Science and Engineering (PULSE): https://ultrafast.stanford.edu/
- Stanford Institute for Materials and Energy Sciences (SIMES): http://simes.stanford.edu/
- SUNCAT: http://suncat.slac.stanford.edu/

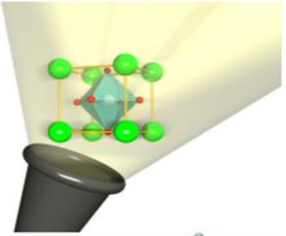
Building an Ecosystem

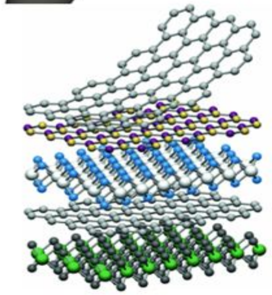
Synergetic activities using advanced instrumentation, synthesis/control and simulation

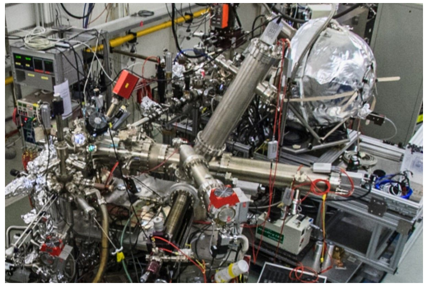
SLAC

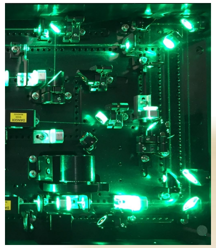
Towards complete experiments to advance quantum materials – energy, momentum, spin, time, space …

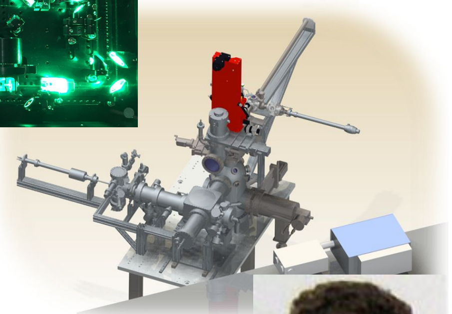













Jonathan


Patrick

Lab based tools


Tom

SIMES LCLS SSRL ALS ADVANCED LIGHT SOURCE SLAC

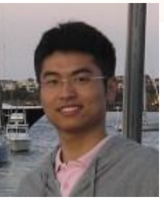
Bridge to LCLS and LCLS-II

How do electrons and atoms behave on their natural length and time scales?

SLAC

10^{-12-13} m 10^{-13-15} sec

Simon



Shuolong

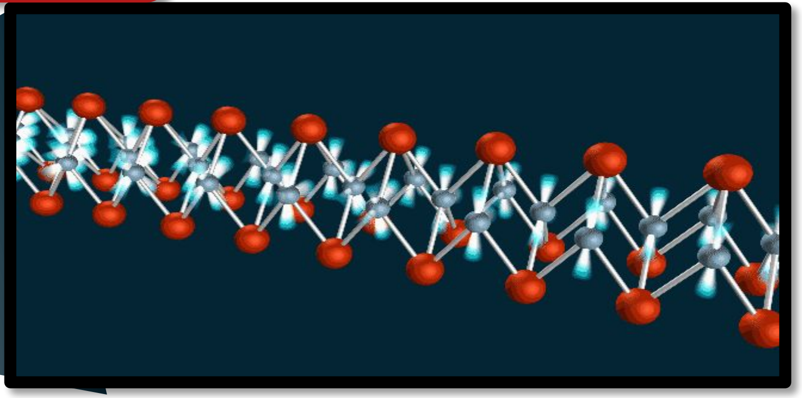
Jonathan

Patrick

Wei-Sheng

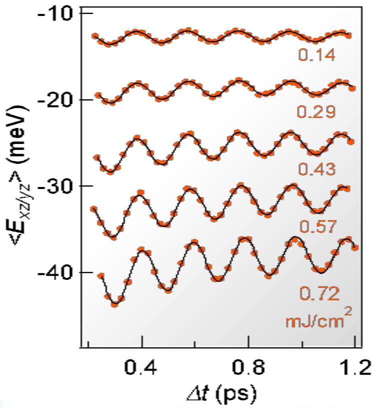
Diling

Ultra-bright & ultra-fast x-ray laser for recording movies of electrons and atoms in motion

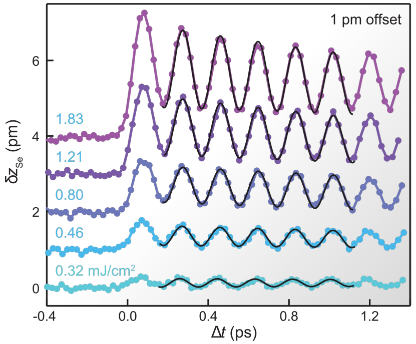


F. Schmitt et al., Science 321, 1649 (2008)
J.A. Sobota, et al., Phys. Rev. Lett., **108**, 117403 (2012)
S.L. Yang et al, Phys. Rev. Lett. **122**, 176403 (2016)
S. Gerber, et al, Science 357, 71 (2017)
J.A. Sobota et al., Rev. Mod. Phys. **93**, 025006 (2021)
S. Sakamoto et al, Phys. Rev. B. **105**, L161107 (2022)
J.A. Sobota et al, Phys. Rev. B. **107**, 014305 (2023)

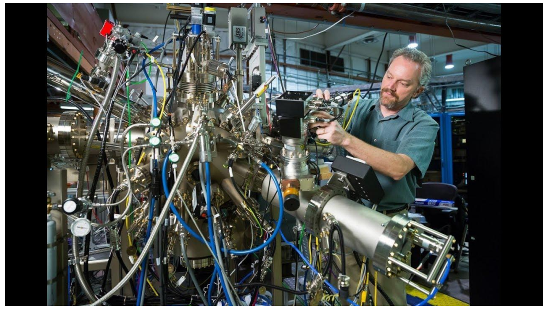
Electrons



Atoms



- Thin Films grown at SSRL were important for this experiment
- "THz lock-in" using LCLS achieved precision not possible any other way
- Harmonious cooperation of electrons and atoms enhances properties



Rob Moore

SiMES LCLS SSRL

Expanding Soft X-ray Capability at SSRL

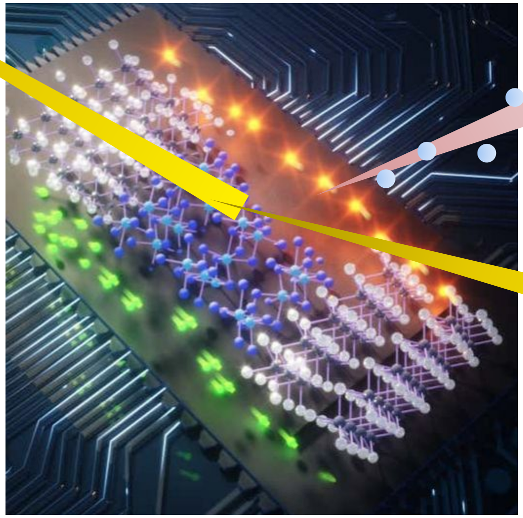
Donghui Makoto Jun-Sik

Complementary light sources

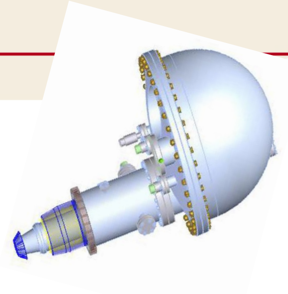
- micro(nano)-focused beam
- Soft x-ray for ARPES (heterostructure)
- Lasers for ultra-high-resolution, spin-resolved, and time-resolved ARPES

$h\nu_{in}$

QIS materials & device



e^-

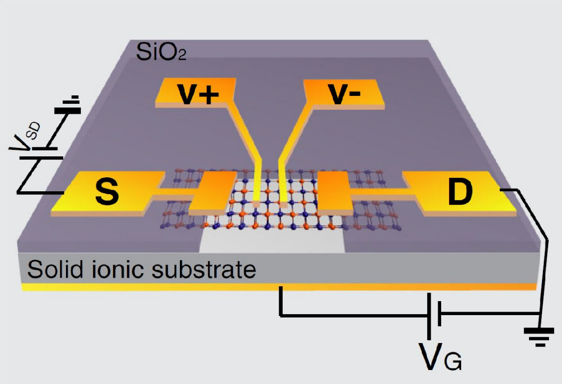


$h\nu'_{out}$

Multimodal characterization tools

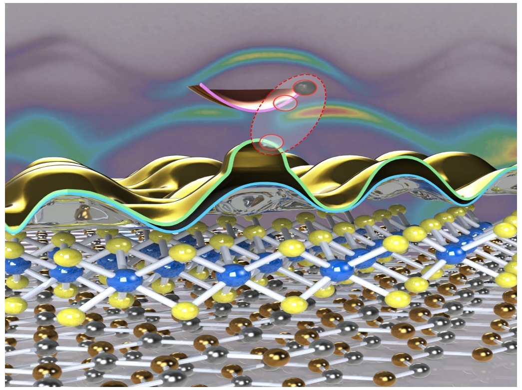
- ARPES (+ *multi-channel spin detector*)
- Momentum microscope (PEEM)
- STM, AFM

- RSXS/RIXS with advanced detector
- X-ray Raman spectroscopy



in-situ device fabrication & versatile sample environment

- *in-situ* clean environment (inert gas, UHV) for sample exfoliation/device fabrication
- micro(nano)-precision sample manipulator



Historical Context — Reflection

- State of the art high energy physics storage ring, SPEAR, began operation at SLAC in 1972
- Would be used to study uncharted territory in particle physics and ultimately discovered quarks and lepton

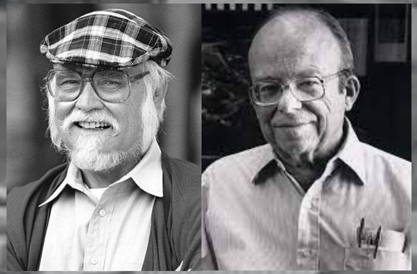
- Could this source of high intensity x-rays be used to do something novel for materials/chemistry/biology?
- Demonstration experiment showing that an x-ray beam could be extracted from SPEAR and some useful science could be performed

Historical Context — Reflection

- Could this source of high intensity x-rays be used to do something novel for materials/chemistry/biology?

- What we have learnt?

- Open to new ideas – also partnership SLAC/Stanford



- Build a transformative tool in a science rich environment (1973-1975 – “November Revolution” and beyond …)

- Invest in young people … creating a pipeline of young talent

SSRL 50 Years – the Future is Bright

April 20, 2023

Zhi-xun Shen
Stanford Institute for Materials and Energy Sciences
Stanford University and SLAC National Accelerator Laboratory

Acknowledgement – Piero Pianetta, Ingolf Lindau, Donghui Lu, and Makoto Hashimoto