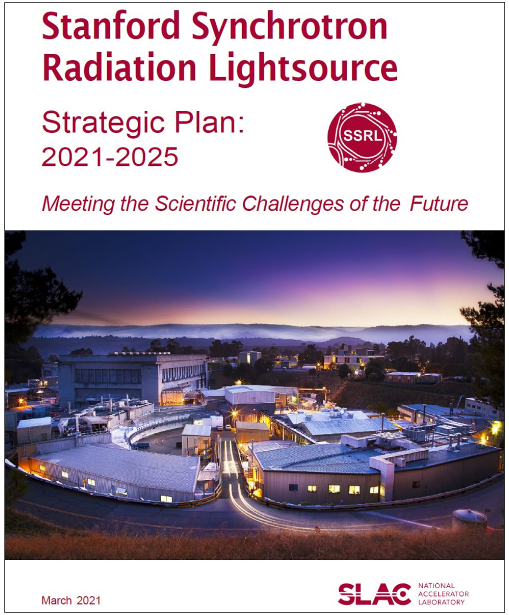
# ARPES on Quantum Materials

Donghui Lu

SSRL Town Hall Meeting, January 19, 2022

SSRL
U.S. DEPARTMENT OF ENERGY | Stanford University
SLAC NATIONAL ACCELERATOR LABORATORY

# SSRL Science Foci Areas


Stanford Synchrotron Radiation Lightsource

Strategic Plan: 2021-2025

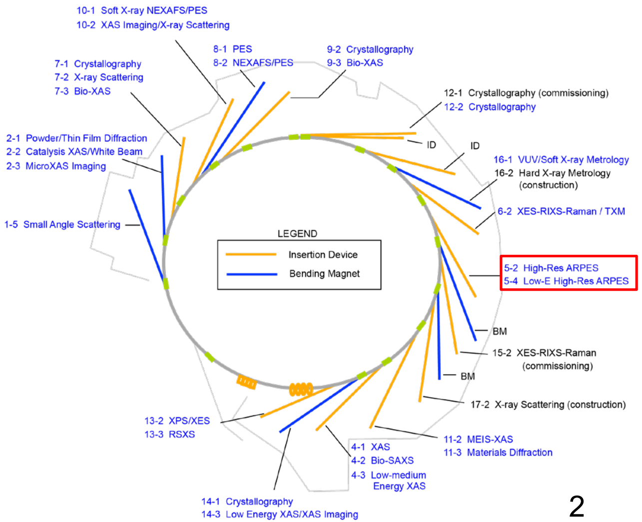
*Meeting the Scientific Challenges of the Future*

March 2021

SLAC NATIONAL ACCELERATOR LABORATORY

## Three Scientific Foci

- Accelerating Materials Design
- Understanding Catalytic Function & Interfacial Reactions with Atomic Precision
- Identifying How Collective Function Emerges from Constituent Interactions
  - Quantum Materials
  - Structural Molecular Biology
  - Geo- and Biogeochemistry




- BL5-2/5-4: High Resolution ARPES

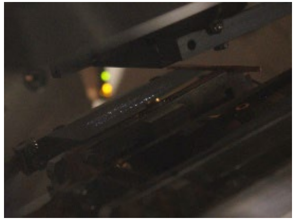
# Development of ARPES Program at SSRL

**2000** — BL5-4
General User Program

**2007** — BL5-4
Analyzer Upgrade

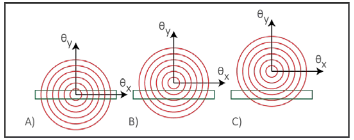
**2009** — BL5-2
Funding Approval

**2014** — BL5-2
1st Light



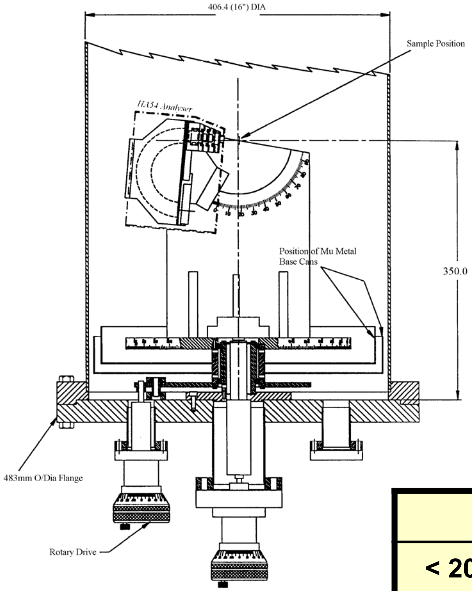
**2017** — BL5-2
General User Program

**2019** — BL5-2
Analyzer Upgrade

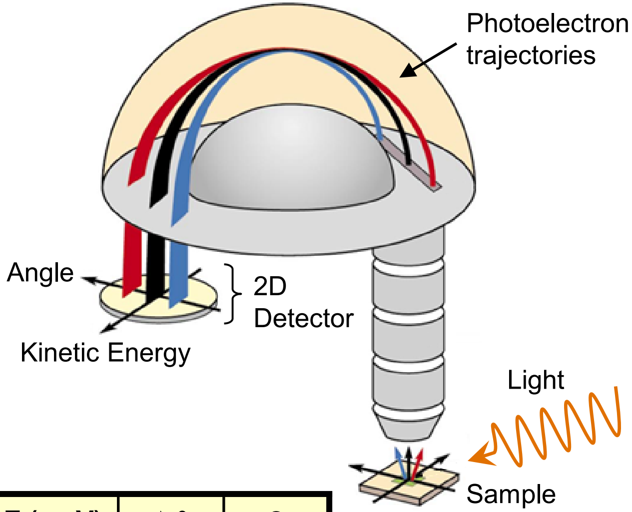


# Evolution of Hemispherical Analyzer

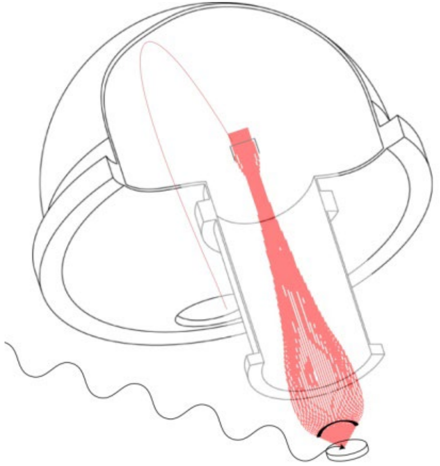
**1st gen (BL5-3)**
**pre 2000**

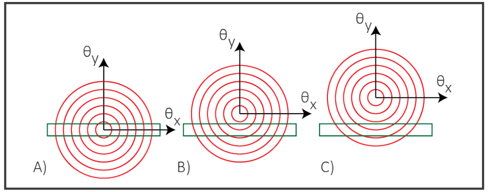



**2nd gen (BL5-4)**
**2000 –**




**3rd gen (BL5-2)**
**2014 –**





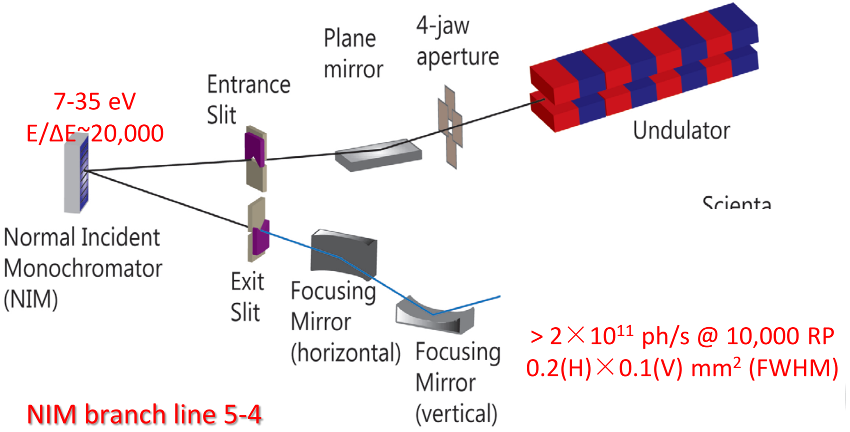

| | Δ E (meV) | Δ θ | Θ |
|---|---|---|---|
| < 2000 | *20-40* | *2 °* | *2 °* |
| now | *2-5* | *0.3 °* | *30 °* |

- Significantly improved energy/angular resolution and efficiency

# Two Complementary ARPES Branch Lines at BL5

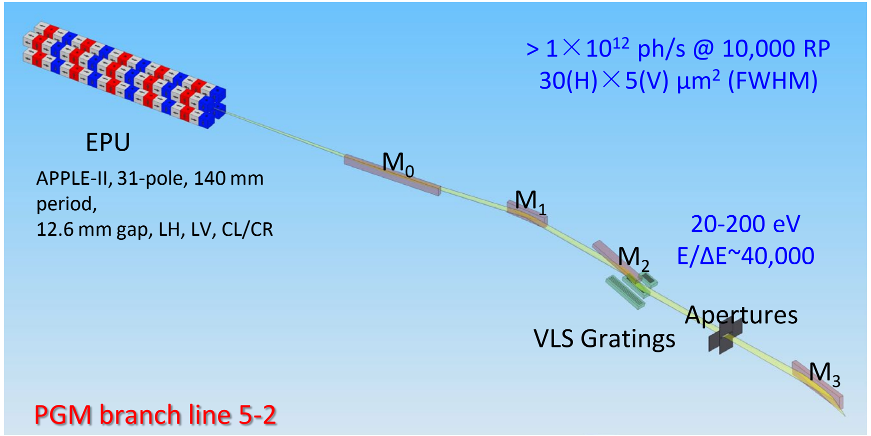
## BL5-4: high resolution with excellent stability

- Complementary low photon energy (7 – 40 eV)
- High energy resolution (~2 meV)
- Excellent energy stability (~1 meV)
- Excellent vacuum quality (~2×$10^{-11}$ torr)
- Wide temperature range (5 – 400 K)
- Local heating with small heater on sample stage
  ⇨ Minimized outgassing during temperature cycle



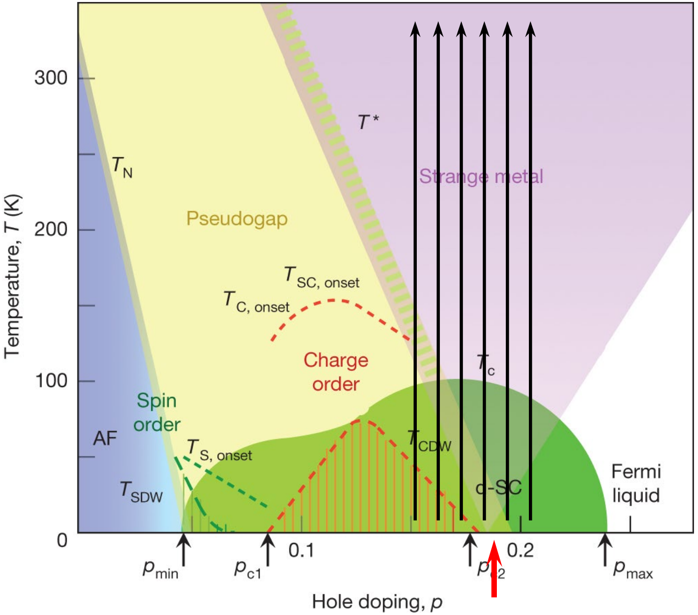

## BL5-2: micro-focusing with full polarization

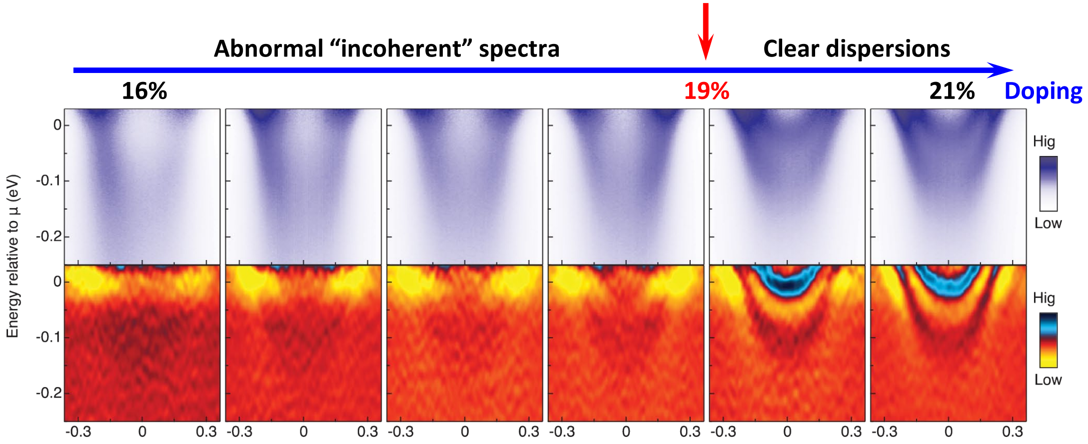
- Wider photon energy (20 – 200 eV)
- Full polarization control: LH, LV, CL/CR
- High energy resolution (~2 meV)
- Micro-focused beam with excellent stability (~30×5 $\mu m^2$)
- Advanced analyzer with electron deflectors (DA30-L)
- Integrated DAQ software for automation (python)
- In-situ thin-film growth chambers (MBE)
- Sample environment, operando-ARPES



# Vertical Phase Boundary at a Critical Doping in Bi2212

S.-D. Chen *et al.*, Science 366, 1099 (2019)



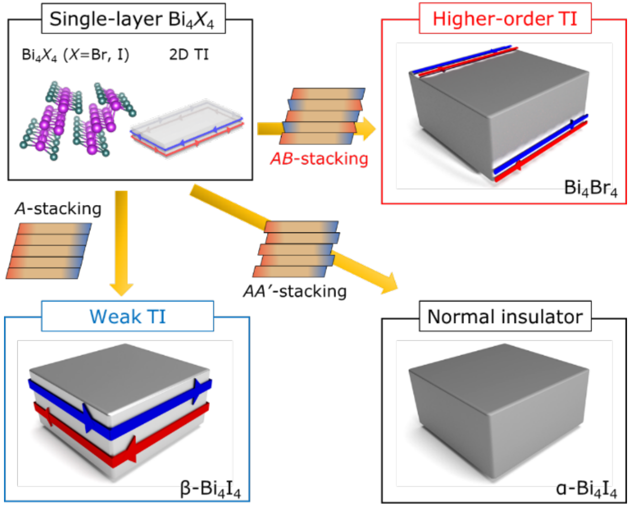

- Systematic doping and temperature dependence study across a critical doping
- Wide range temperature dependence enabled by local sample heating to minimize sample aging

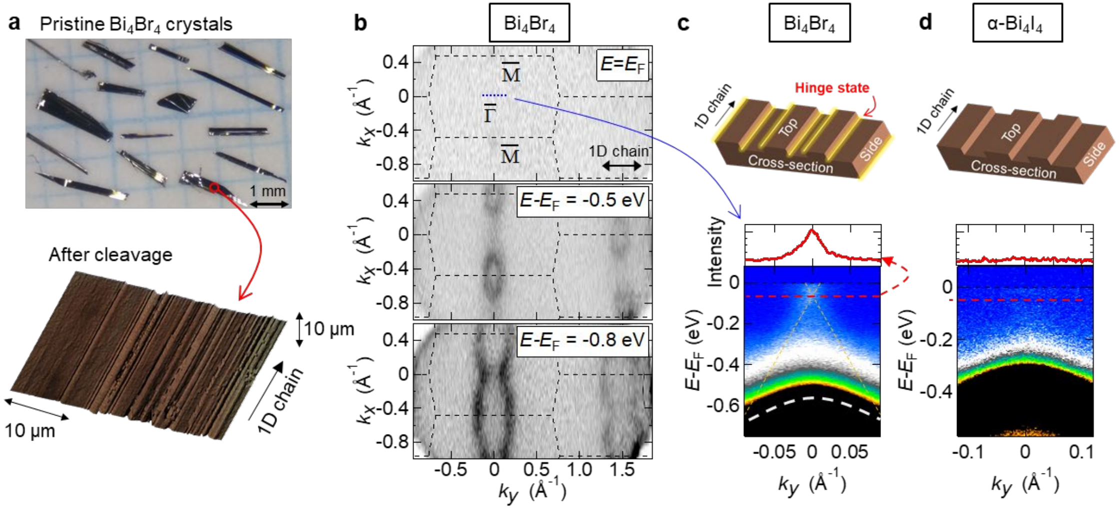
At 250 K well above Tc:

- >19%: coherent, quasiparticle-like antinodal dispersion
- <19%: broad, incoherent, quasiparticle not well defined
- Vertical phase boundary at 19% suggested
- Challenge existing interpretation of pseudogap QCP

# Designing Higher-order Topological Insulator

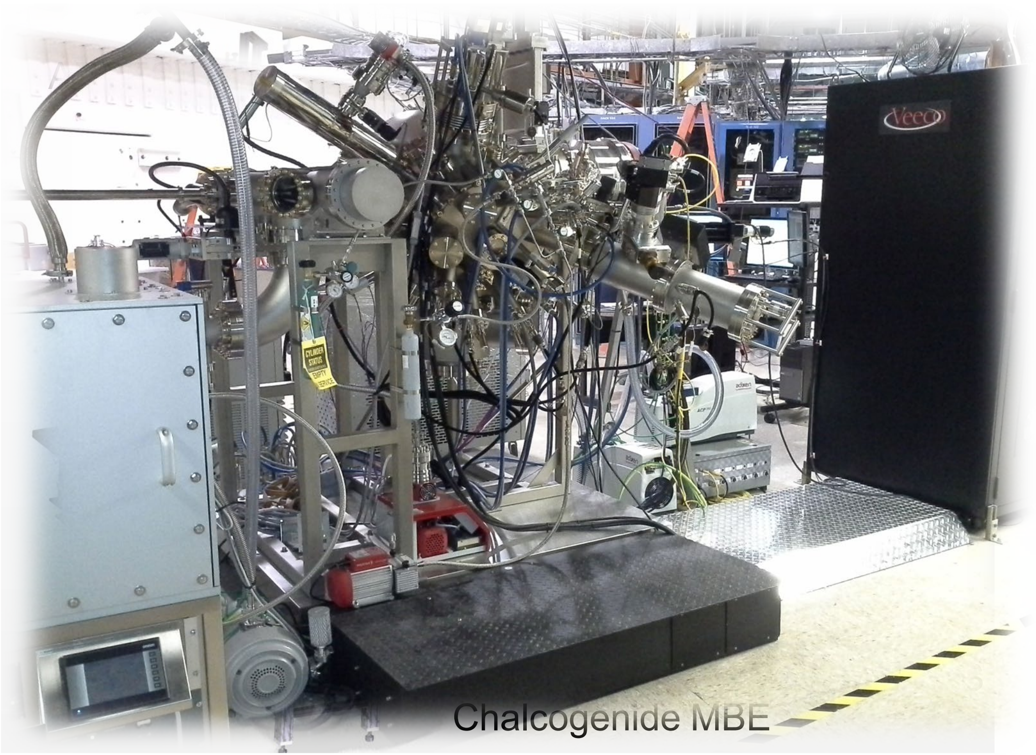
R. Noguchi *et al.*, Nature Materials 20, 476 (2021)



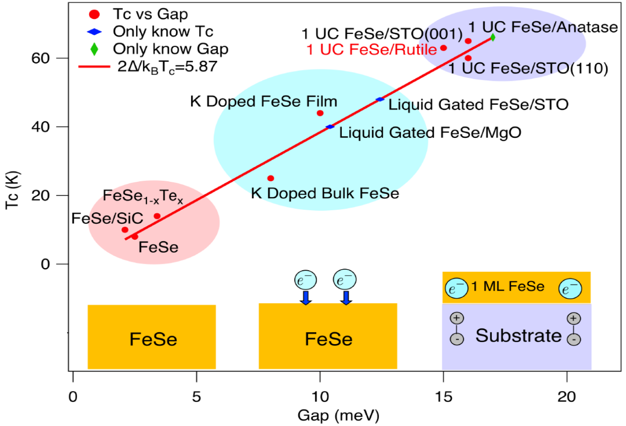




- First experimental demonstration that various topological states can be achieved by van der Waals stacking of quasi-1D chains
- A new playground for engineering topologically non-trivial edge states towards future spintronics applications
- Enabled by micro-focused beam

# Sophisticated Material Synthesis Capabilities




- oxide MBE, chalcogenide MBE
- ARPES, STM/STS, RHEED, LEED
- *in-situ* growth, transfer and characterization
- Fe-SC, topological insulators, TMDC, Cuprates…

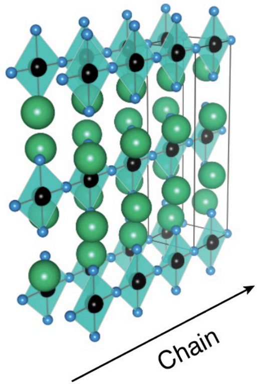



Lee *et al.*, Nature **515**, 245 (2014)
Zhang *et al.*, PRL **117**, 117001 (2016)
Zhang *et al.*, PRB **94**, 115153 (2016)
Rebec, Jia *et al.*, PRL **118**, 067002 (2017)
Zhang *et al.*, Nat Commu **8**, 14468 (2017)

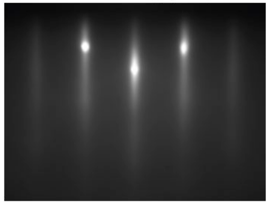
# Revealing Cuprate Microscopic Ingredients through 1D Chains

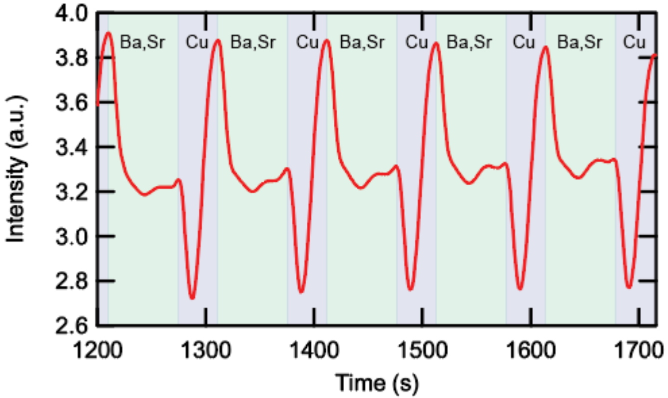
Z. Chen *et al.*, Science 373, 1235 (2021)

## ***First*** synthesis of chain cuprate thin film with controlled ***doping***

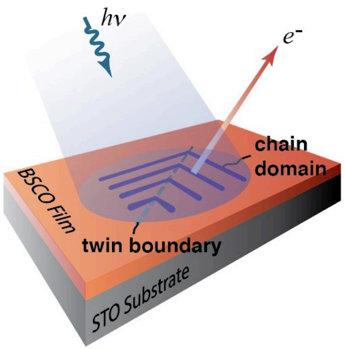


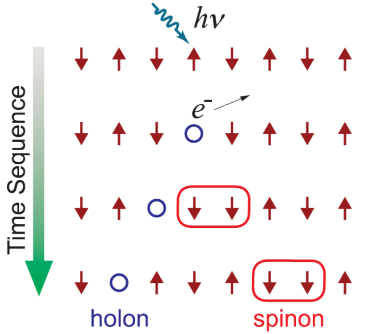

Atomic layer-by-layer growth of $Ba_{2-x}Sr_xCuO_{3+\delta}$




Hole doping control via ozone annealing temperature



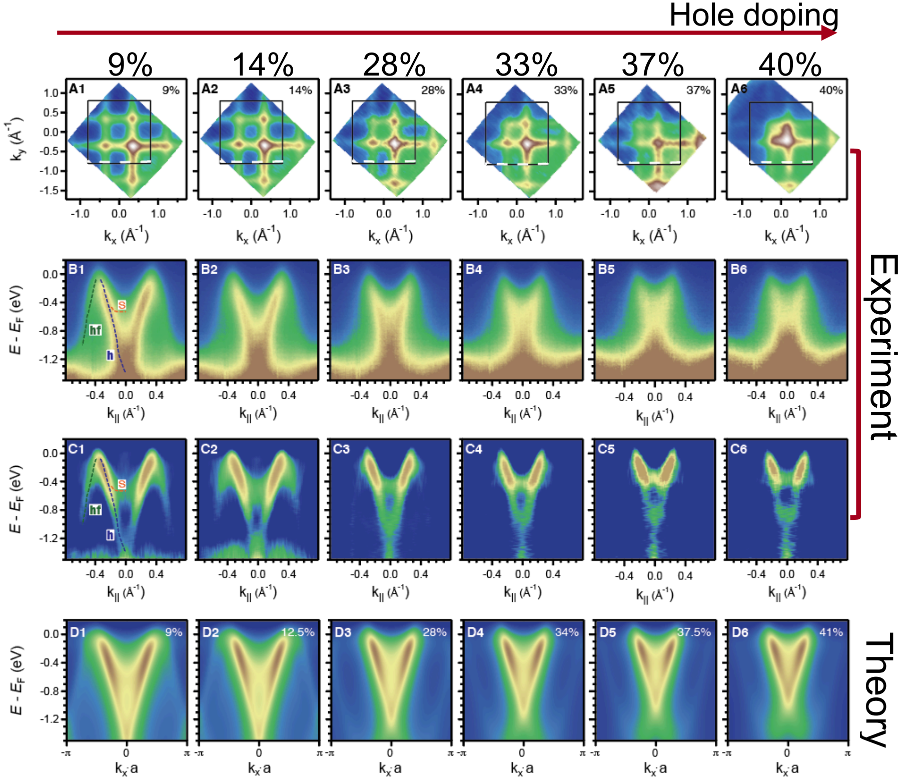

In-situ ARPES provides opportunities :

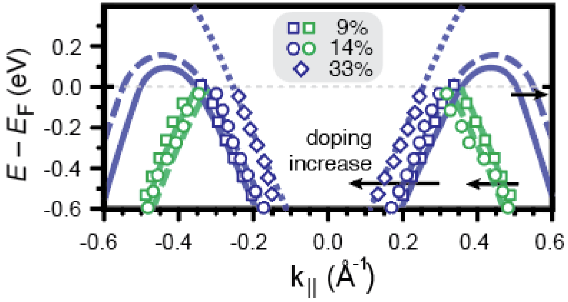
- to study the rich 1D strongly correlated physics
- **determine microscopic model and ingredients for general cuprate materials, because theoretical models can only be reliably solved in 1D.**

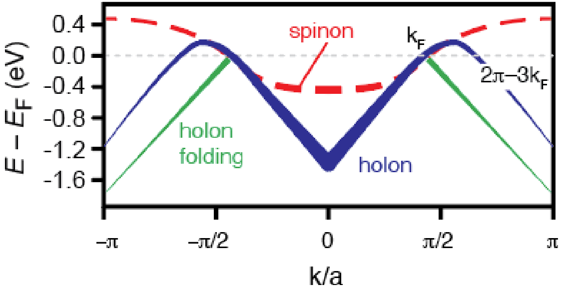
# Revealing Cuprate Microscopic Ingredients through 1D Chains

Z. Chen *et al.*, Science 373, 1235 (2021)

## Marked theory-experiment comparability




- Single-band Hubbard model describe major dispersions up to 40%
- First identification of a folded branch from holon-holon interaction
- A simple Hubbard model is deficient in accurately reproduce experimental results

# Collabortators

## Cuprates

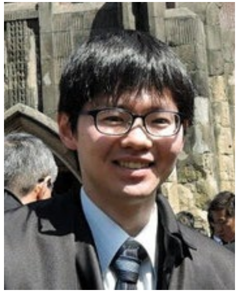
Yu He
Stanford U

Sudi Chen
Stanford U

Makoto Hashimoto
SSRL

Zhi-Xun Shen
Stanford U

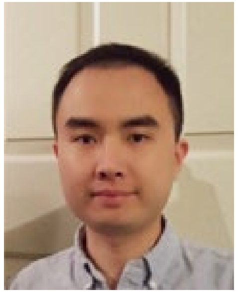
## Topological Insulators



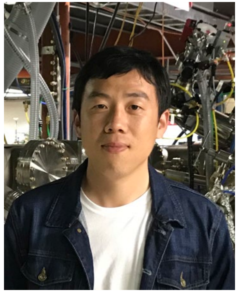
Ryo Noguchi
U Tokyo

Takeshi Kondo
U Tokoyo

## MBE-ARPES



Zhuoyu Chen
SIMES



Zhong Yong
SIMES

Rob Moore
SIMES/ORNL