

ARPES on FeSe /SrTiO₃ Films and Silicene

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Colleagues and Collaborators

➤ ARPES System Development, Maintenance and Improvement;

Chuangtian Chen, Yong Zhu, Guochun Zhang, Xiaoyang Wang

Zuyan Xu, Guiling Wang, Hongbo Zhang, Yong Zhou

Technical Institute of Physics and Chemistry, CAS, China

➤ FeSe Thin Films on SrTiO₃ (001)

Wenhai Zhang, Yun-Bo Ou, Qing-Yan Wang, Zhi Li, Lili Wang,

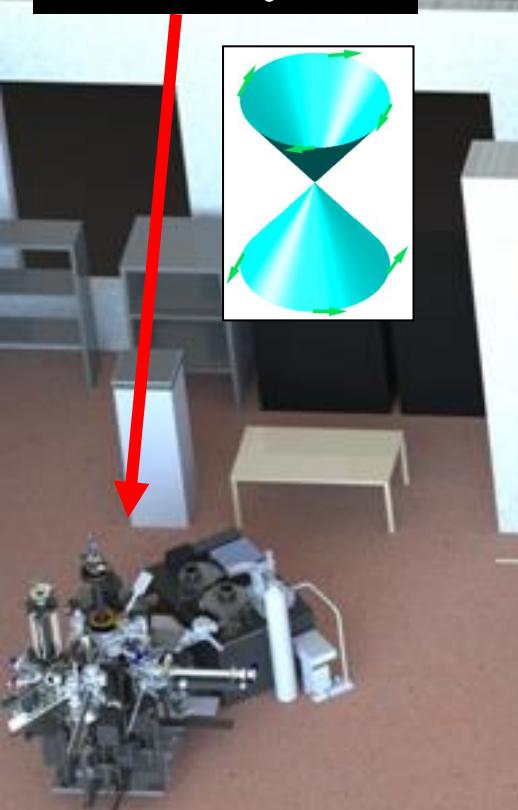
Xucun Ma and **Qikun Xue**, Institute of Physics, CAS & Tsinghua University

➤ Theoretical Discussions

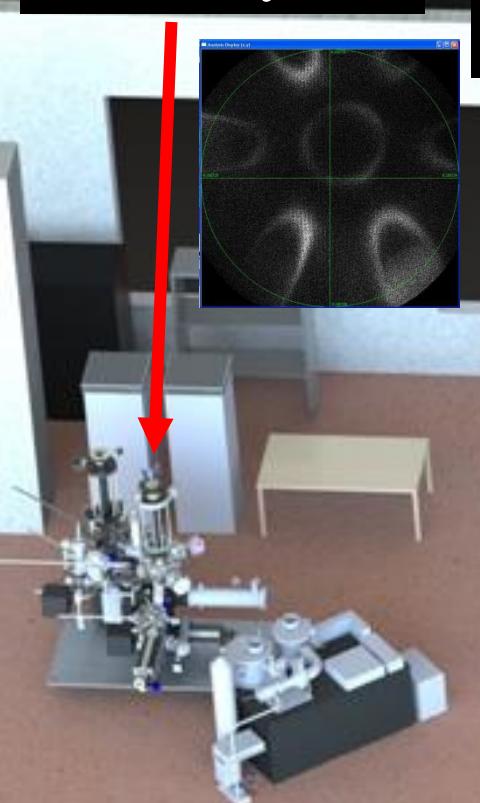
Jiangping Hu, Dung-hai Lee, Qianghua Wang, Tao Xiang, Qimiao Si

VUV Laser Photoemission Lab at IOP

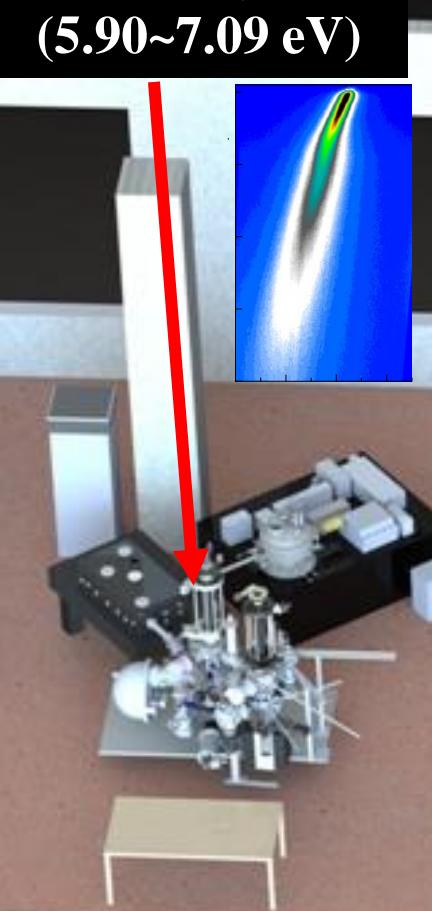
Spin-Resolved
ARPES system



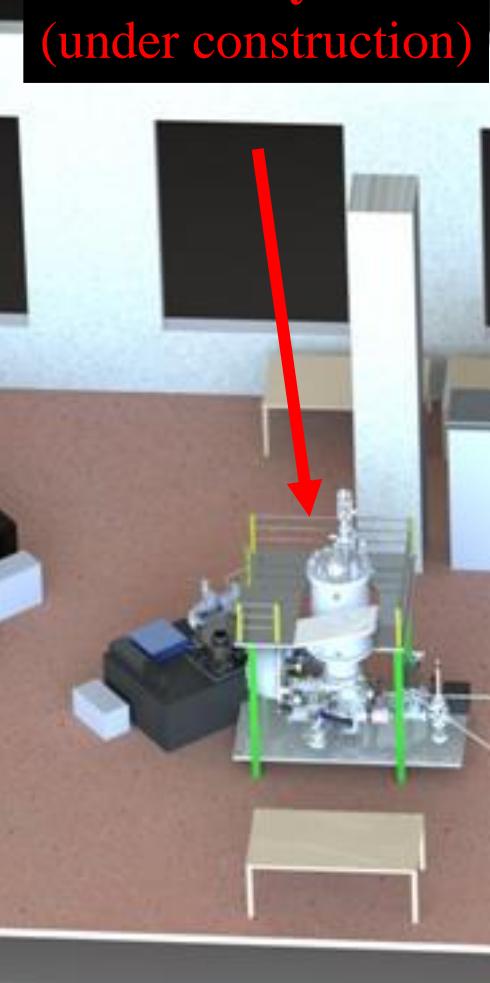
2-D Momentum
ARPES system



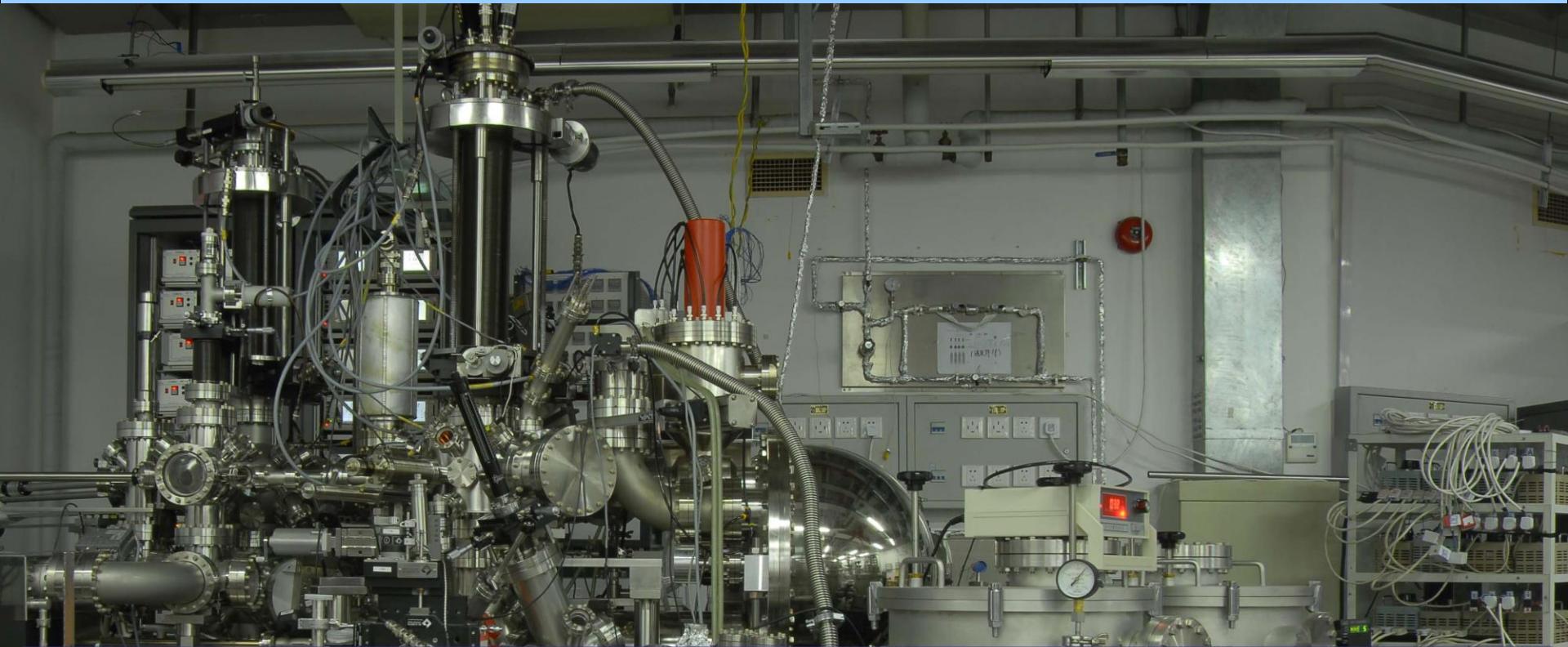
Tunable Laser
ARPES system
(5.90~7.09 eV)



He 3 (<1K)
ARPES system
(under construction)



VUV Laser Spin-Resolved ARPES



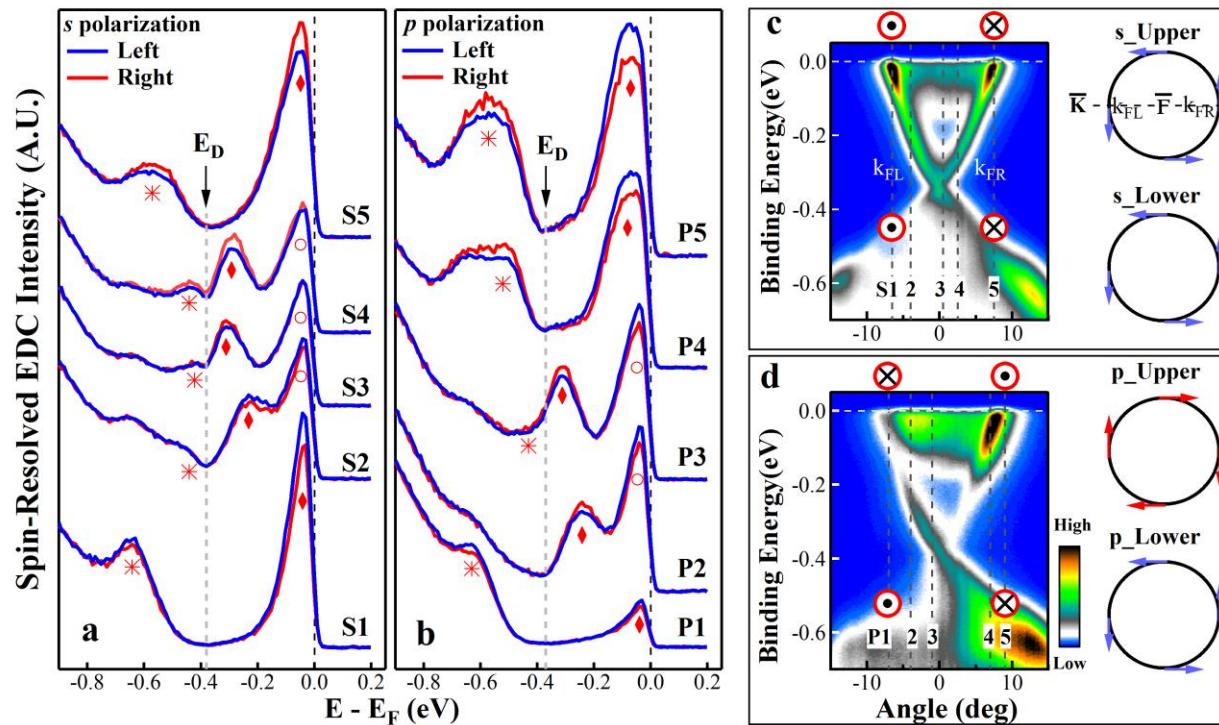
- ARPES (E, k) → **Spin-Resolved ARPES (E, k, s)**
- Energy Resolution: From 50~100meV for Synchrotron
to **2.5 meV** for VUV-laser
- Photon flux: Increase by **100~1000** times.

ARTICLE

Received 29 May 2013 | Accepted 5 Feb 2014 | Published 28 Feb 2014

DOI: 10.1038/ncomms4382

Orbital-selective spin texture and its manipulation in a topological insulator

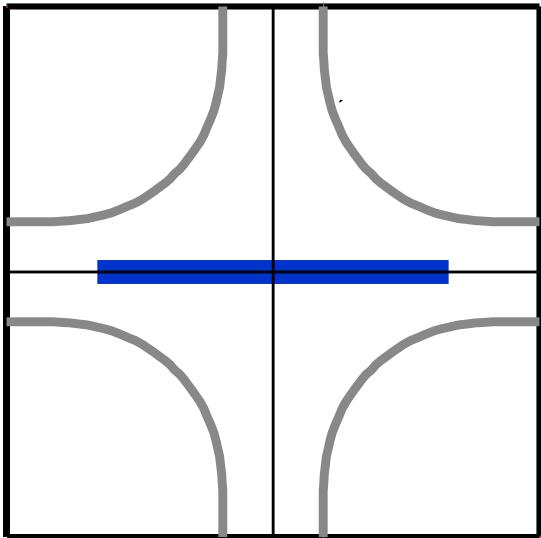


VUV Laser 2D Momentum ARPES: From 1D to 2D Angular Detection

Hemi-Spherical Analyzer



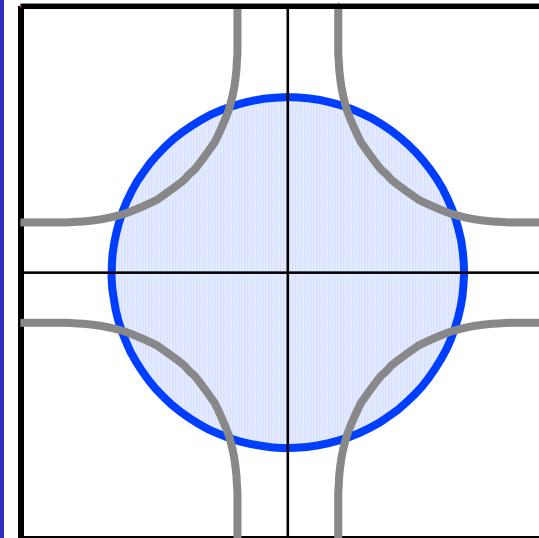
- Energy Res.: better than 1meV
- Angular Res: 0.1~0.4 Degree
- Angle Range: 1D: +-15 Deg.



Time-of-Flight Analyzer

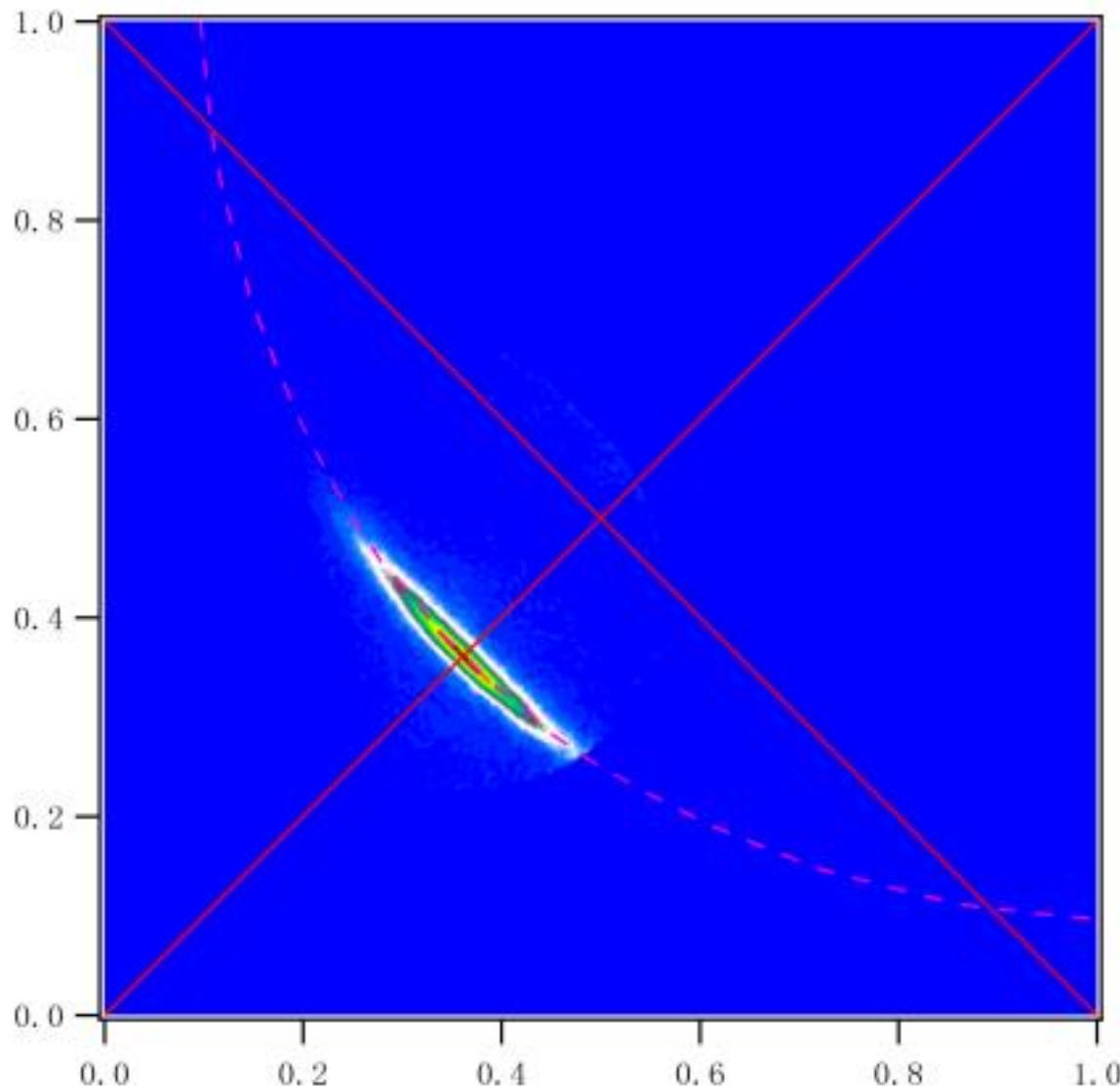


- Energy Res.: ~0.15meV
- Angular Res.: 0.08 Degree
- Angle Range: 2D: +-15Deg.



Efficiency of Angle Detection Improved by **250** times

2D Momentum ARPES Measurements- Bi2212 Fermi Surface



Y. X. Zhang, X. J. Zhou et al., unpublished.

ARPES on FeSe/SrTiO₃ Films

- [1].Defa Liu, Wenhao Zhang, Daixiang Mou, Junfeng He, Xucun Ma, Qikun Xue and X. J. Zhou et al., Nature Communications 3, 931 (2012);
- [2].Shaolong He, Junfeng He, Wenhao Zhang, Lin Zhao, Xucun Ma, Qikun Xue and X. J. Zhou et al., Nature Materials 12, 605 (2013);
- [3].Xu Liu, Defa Liu, Wenhao Zhang, Junfeng He, Xucun Ma, Qikun Xue and X. J. Zhou et al., Nature Communications 5, 5047 (2014);
- [4].Junfeng He, Xu Liu, Wenhao Zhang, Lin Zhao, Xucun Ma, Qikun Xue and X. J. Zhou et al., PNAS. 111,18501 (2014).

Possible High T_c in Single-Layer FeSe Film on SrTiO₃

CHIN. PHYS. LETT. Vol. 29, No. 3 (2012) 037402

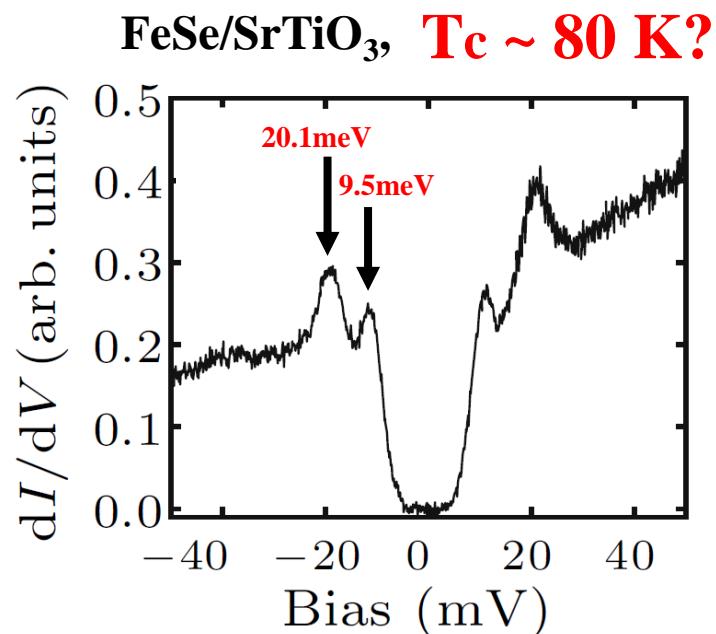
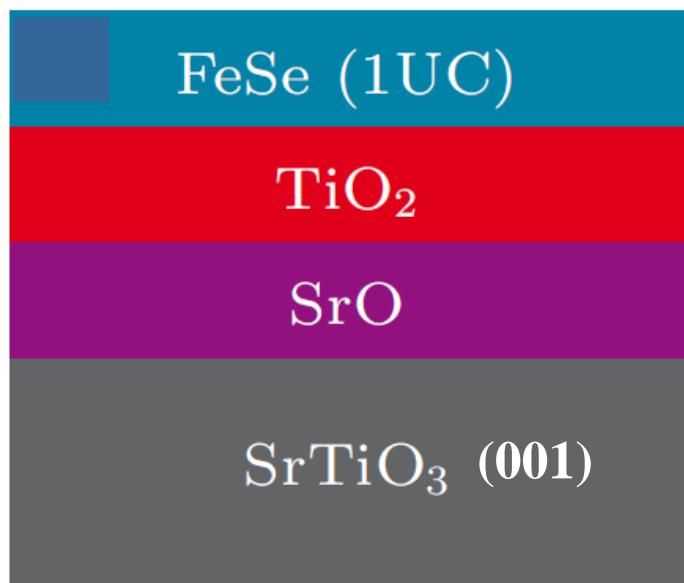
Interface-Induced High-Temperature Superconductivity in Single Unit-Cell FeSe Films on SrTiO₃ *

WANG Qing-Yan(王庆艳)^{1,2†}, LI Zhi(李志)^{2†}, ZHANG Wen-Hao(张文号)^{1†}, ZHANG Zuo-Cheng(张祚成)^{1†}, ZHANG Jin-Song(张金松)¹, LI Wei(李渭)¹, DING Hao(丁浩)¹, OU Yun-Bo(欧云波)², DENG Peng(邓鹏)¹, CHANG Kai(常凯)¹, WEN Jing(文竞)¹, SONG CanLi(宋灿立)¹, HE Ke(何珂)², JIA Jin-Feng(贾金锋)¹, JI Shuai-Hua(季帅华)¹, WANG Ya-Yu(王亚愚)¹, WANG Li-Li(王立莉)², CHEN Xi(陈曦)¹, MA Xu-Cun(马旭村)^{2***}, XUE Qi-Kun(薛其坤)^{1**}

¹State Key Lab of Low-Dimensional Quantum Physics, Department of Physics, Tsinghua University, Beijing 100084

²Institute of Physics, Chinese Academy of Sciences, Beijing 100190

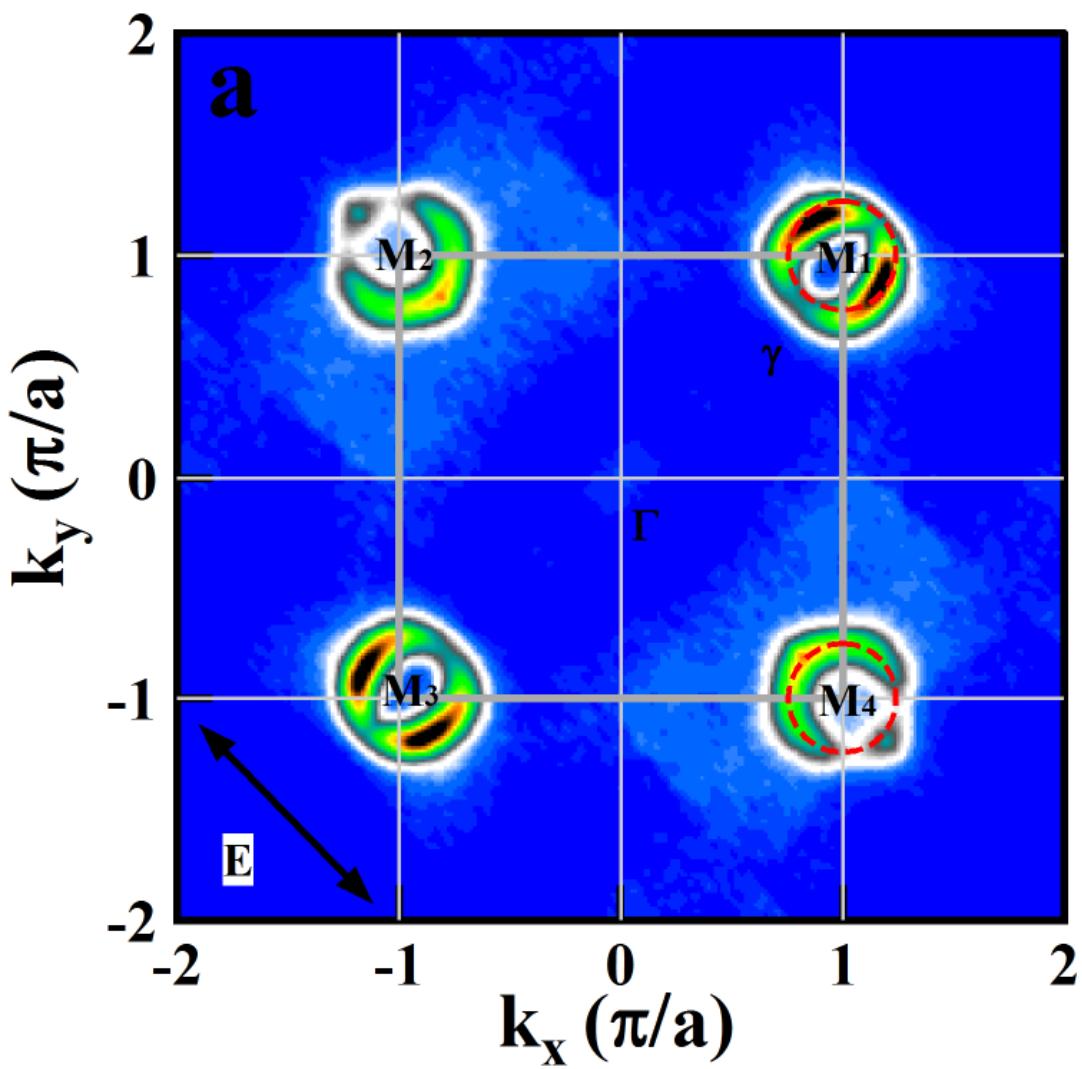
(Received 1 February 2012 and accepted by ZHU Bang-Fen)



ARPES on Single-Layer Superconducting FeSe/SrTiO₃

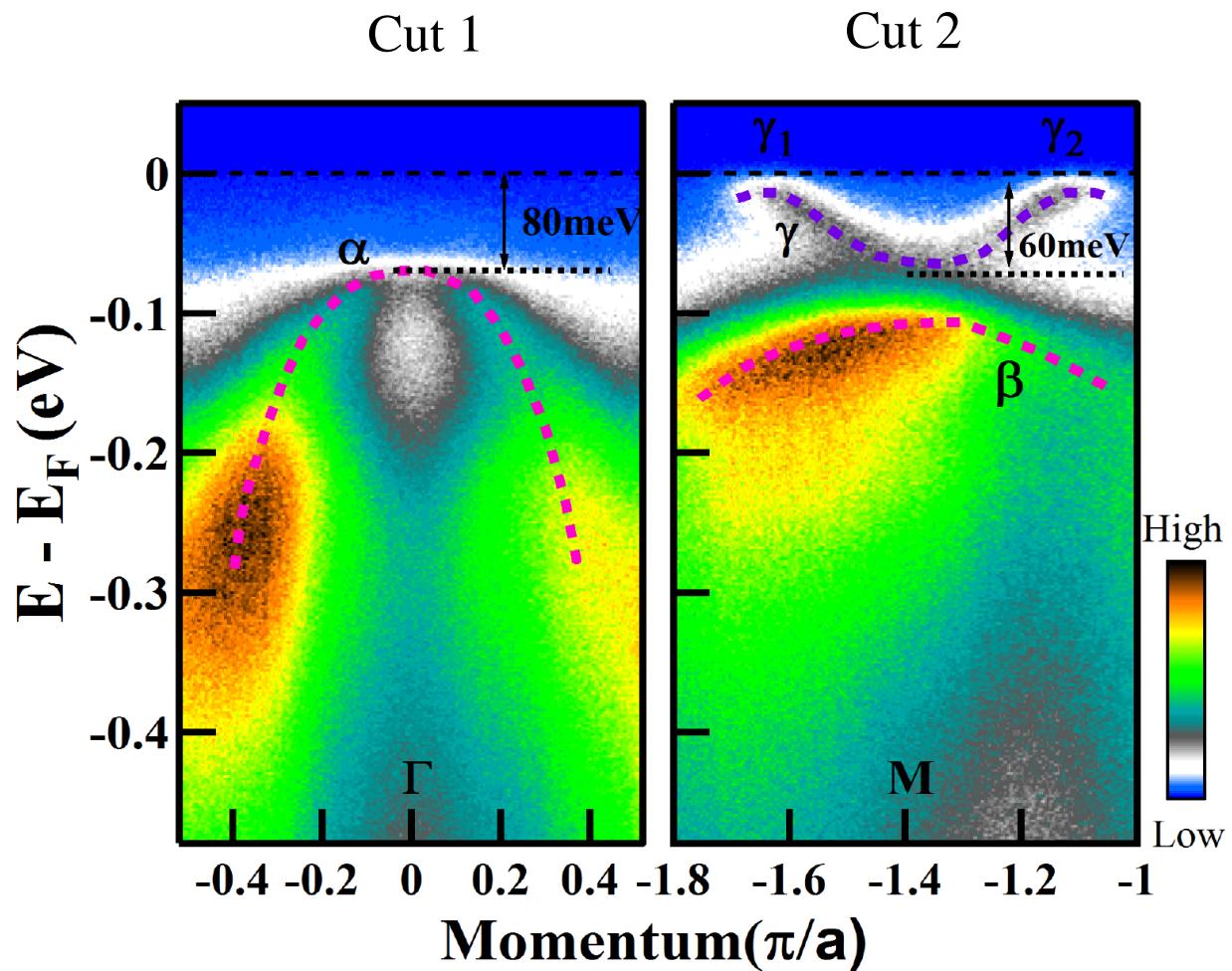
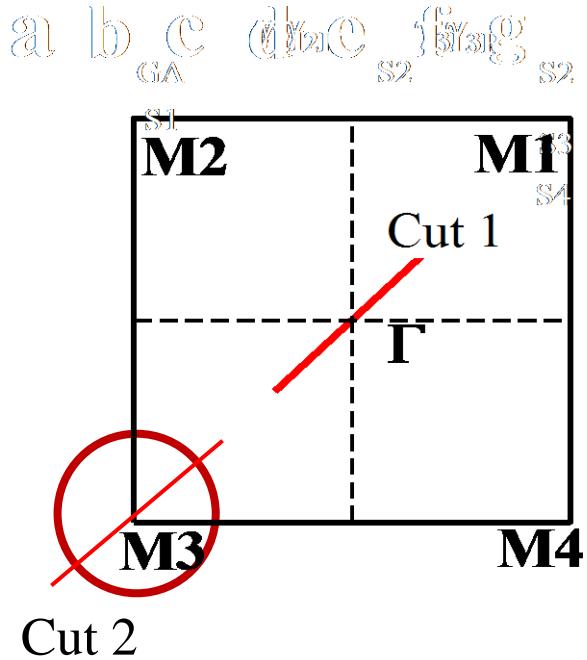
D. F. Liu , W. H. Zhao, D. X. Mou, J. F. He, X. C. Ma, Q. K. Xue, X. J. Zhou et al.,
Nature Communications 3, 931 (2012).

Fermi Surface of Single-Layer Superconducting FeSe/SrTiO₃



- Only one Fermi surface γ around M ;
- No signature of any Fermi surface around Γ .

Band Structure of Single-Layer Superconducting FeSe/SrTiO₃

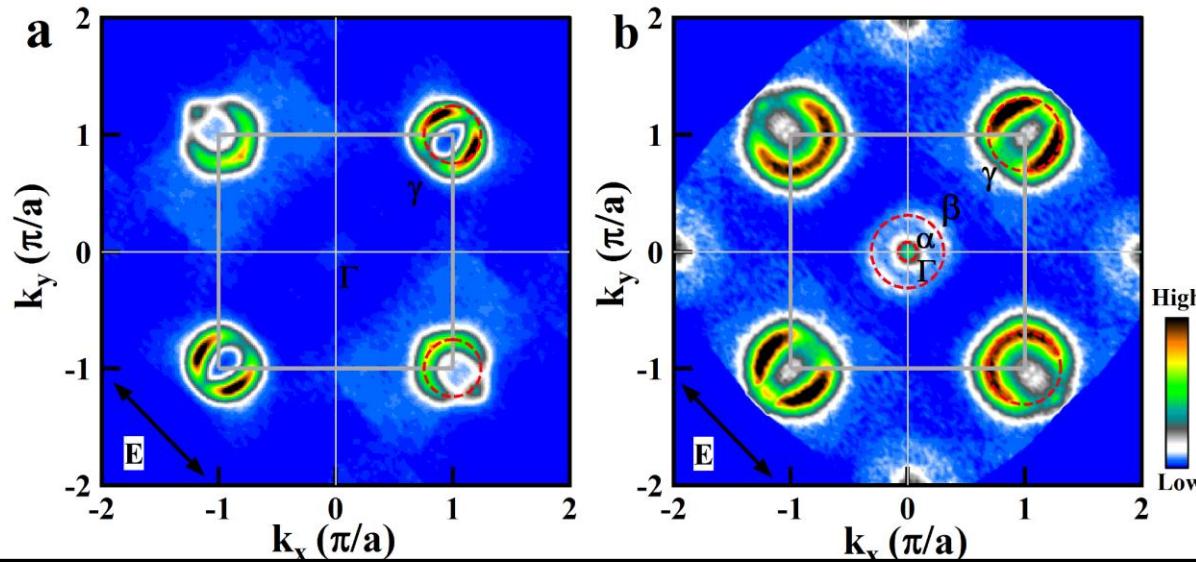


Fermi Surface Topology of the Iron-Based Superconductors

Class I

Single-Layer
FeSe
 $T_c \sim 65$ K

D. F. Liu et al.,
Nature Commun.
3(2012)931.



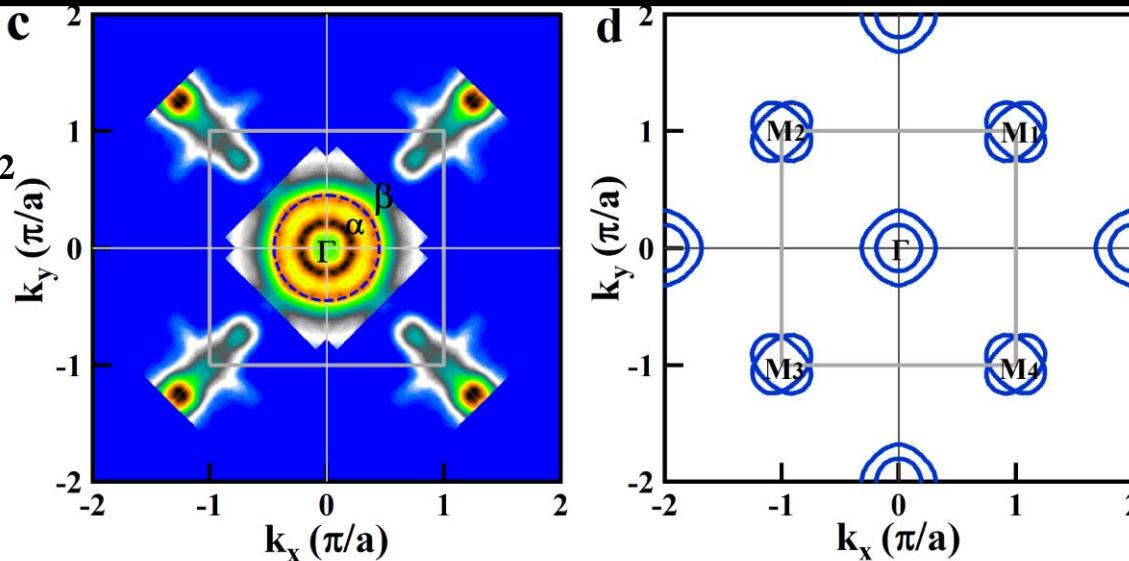
$A_xFe_{2-y}Se_2$
 $T_c \sim 32$ K

D. X. Mou et al.,
Phys. Rev. Lett.
6 (2011) 410.

Class II

$(Ba_{0.6}K_{0.4})Fe_2As_2$

L. Zhao et al.,
Chin. Phys. Lett.
25 (2008) 4402.

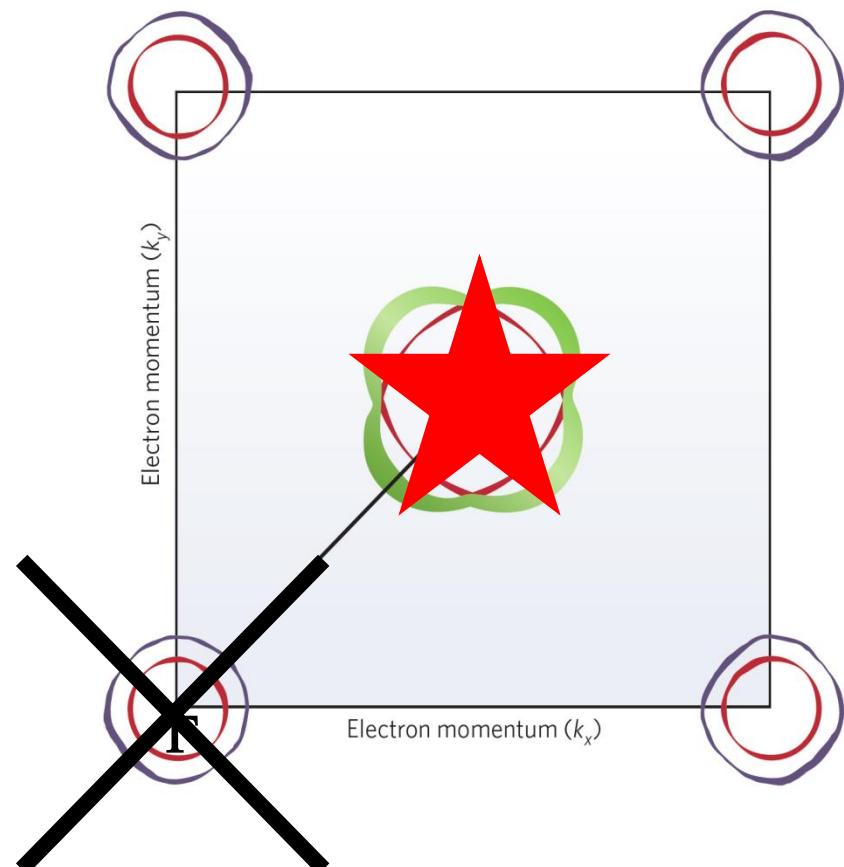


Bulk
 $Fe(Se,Te)$

A. Tamai et al.,
Phys. Rev. Lett.
104 (2010) 097002.

Implications on Superconductivity Mechanism

--Challenges Fermi Surface Nesting Picture

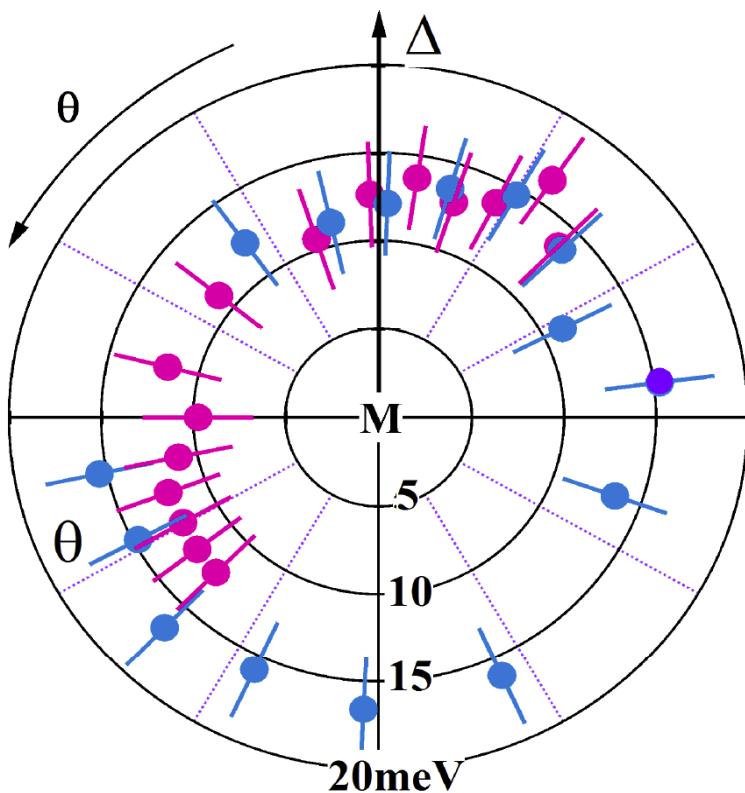


If Fermi surface topology
is critical to
superconductivity, then

Hole-Like Fermi Surface
near Γ is NOT necessary;

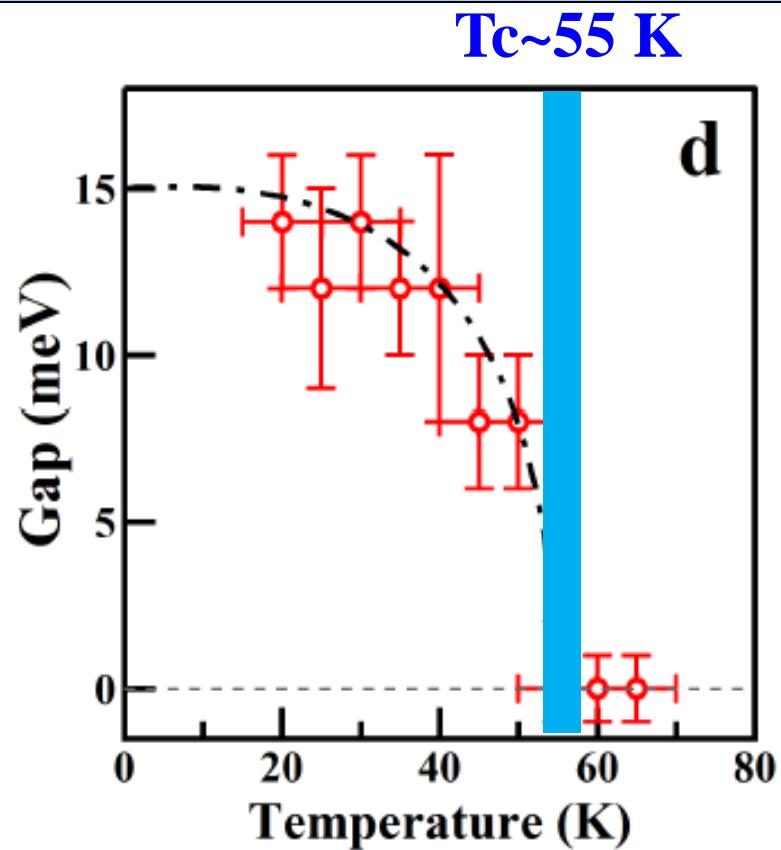
Electron-Like Fermi
Surface near M is crucial.

Momentum and Temperature Dependence of the Energy Gap



Nearly isotropic energy gap;

2D Character → No Gap Node.

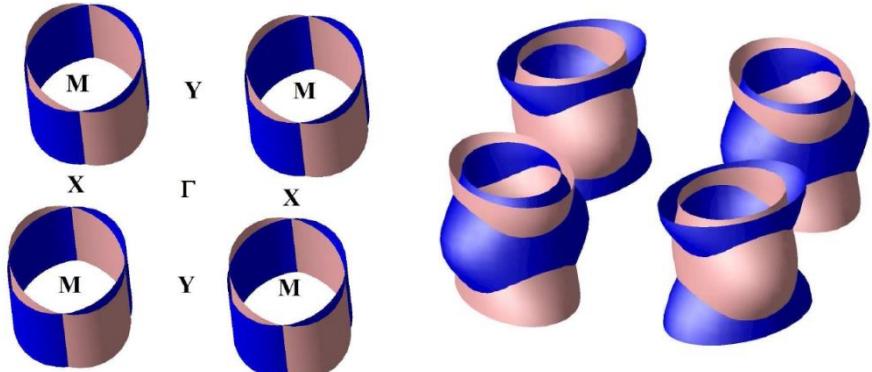
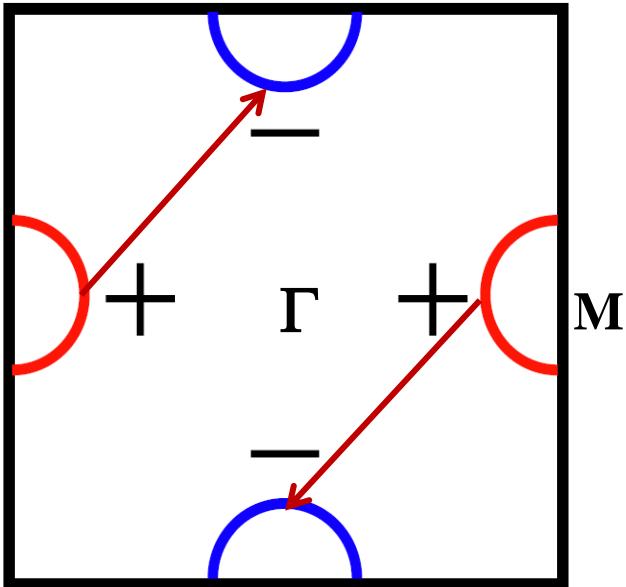


Nearly BCS form;

Tc~55K.

Pairing Order Parameter?

$d_{x^2-y^2}$ gap symmetry



I. Mazin,
Phys. Rev. B84, 024529 (2011).

K. Kuroki et al., PRL 101, 087004 (2008);
T. A. Maier et al., Phys. Rev. B 83, 100515(R) (2011)..
Fa Wang et al., Europhys. Lett. 93, 57003 (2011)..

- Scattering between electron-like Fermi surface favors d-wave gap;
- Two Fermi surface sheets at a given M, due to two Fes in one unit cell, may give rise to gap nodes;
- No gaps nodes observed in ARPES measurements.

Phase Diagram and Electronic Indication of Superconductivity at 65K in Single-Layer FeSe/SrTiO₃

S. L. He, J. F. He, W. H. Zhang, L. Zhao, X. C. Ma, Q. K. Xue, X. J. Zhou et al.,
Nature Materials 12, 605 (2013).

MBE Preparation of FeSe Films: Two Steps

Step 1

As-prepared FeSe Films
grown at a low temperature
 $\sim 300\text{C}$
(Non-superconducting)



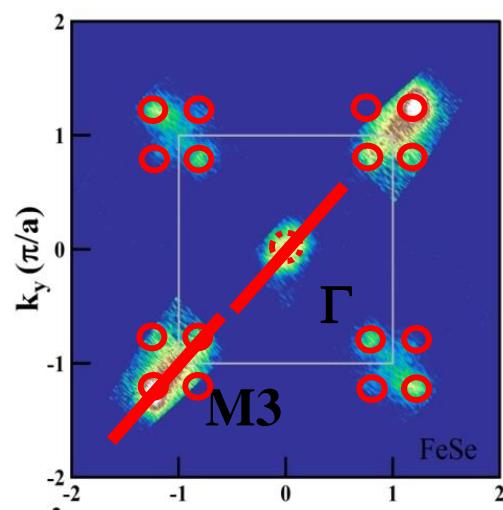
Step 2

FeSe Films
annealed at a high temperature
 $450\text{--}500\text{C}$
(Superconducting)

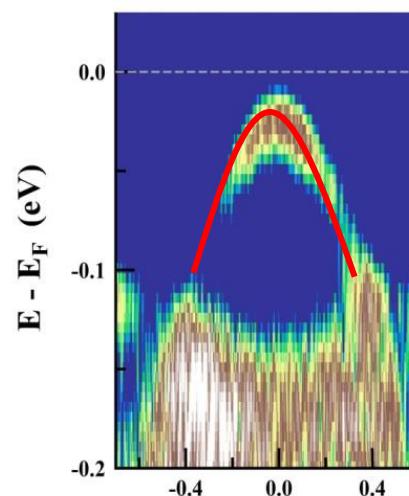
Electronic Structure of the *As-Prepared* Non-Superconducting Single-Layer FeSe/SrTiO₃ Films

“Fermi Surface” and Band Structure of Non-Superconducting Phase

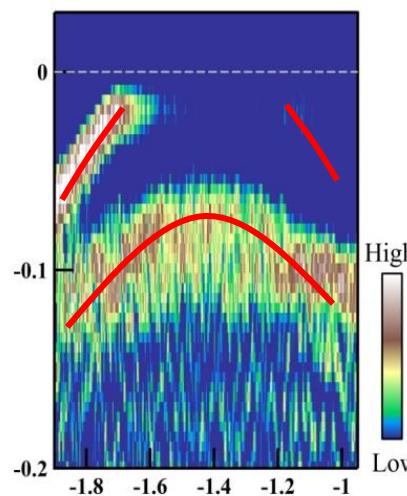
“Fermi Surface”



Γ Cut

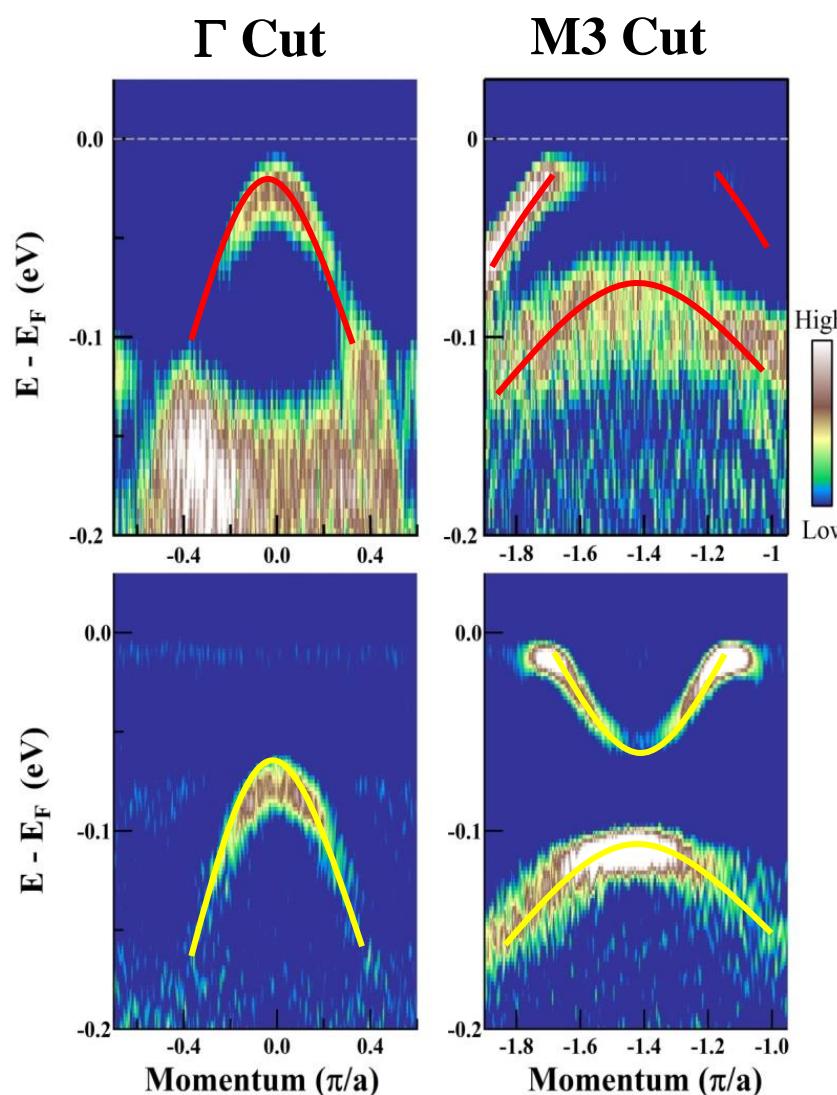
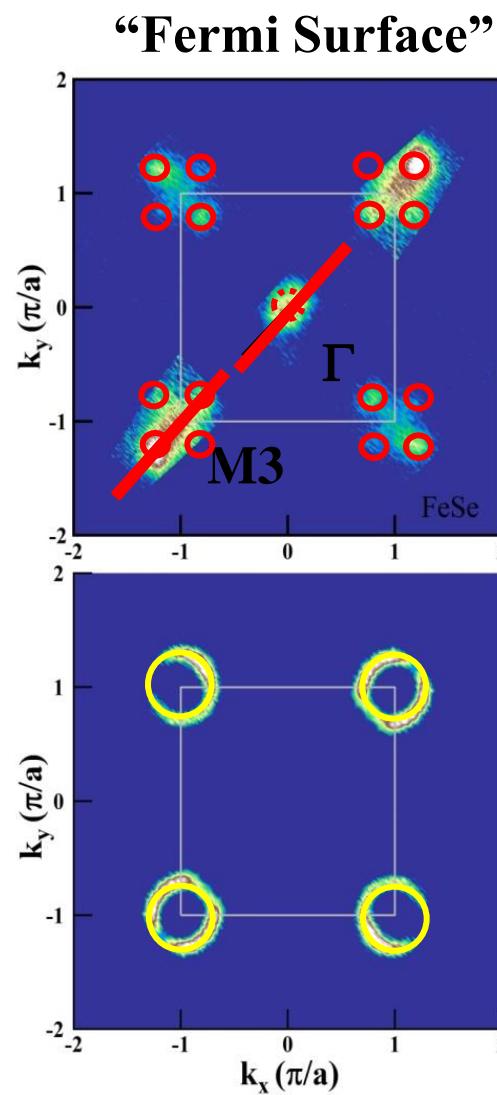


M3 Cut



As-prepared
Non-superconducting

Non-Superconducting vs Superconducting Phases



As-prepared
Non-superconducting

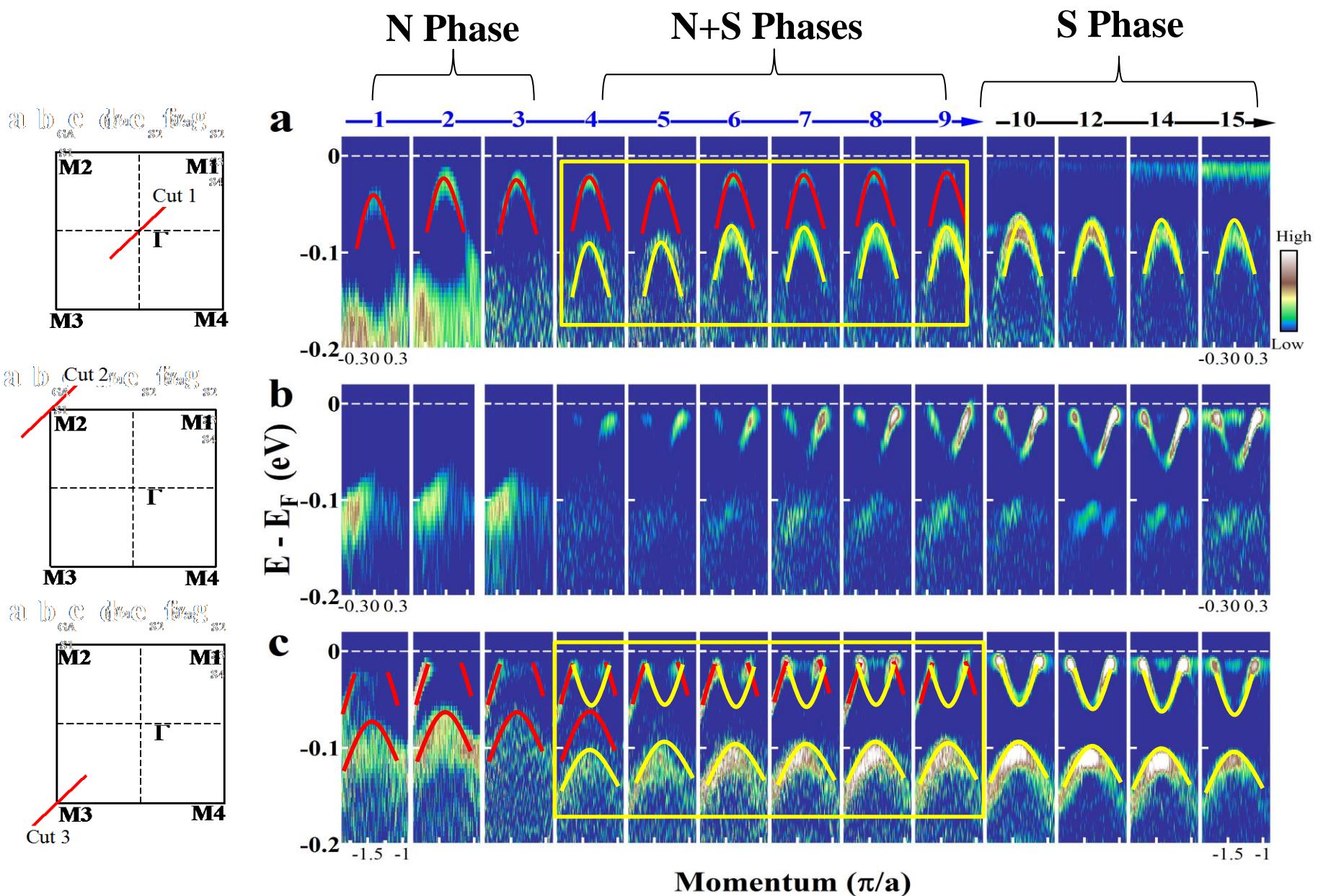
N Phase

Annealed
Superconducting

S Phase

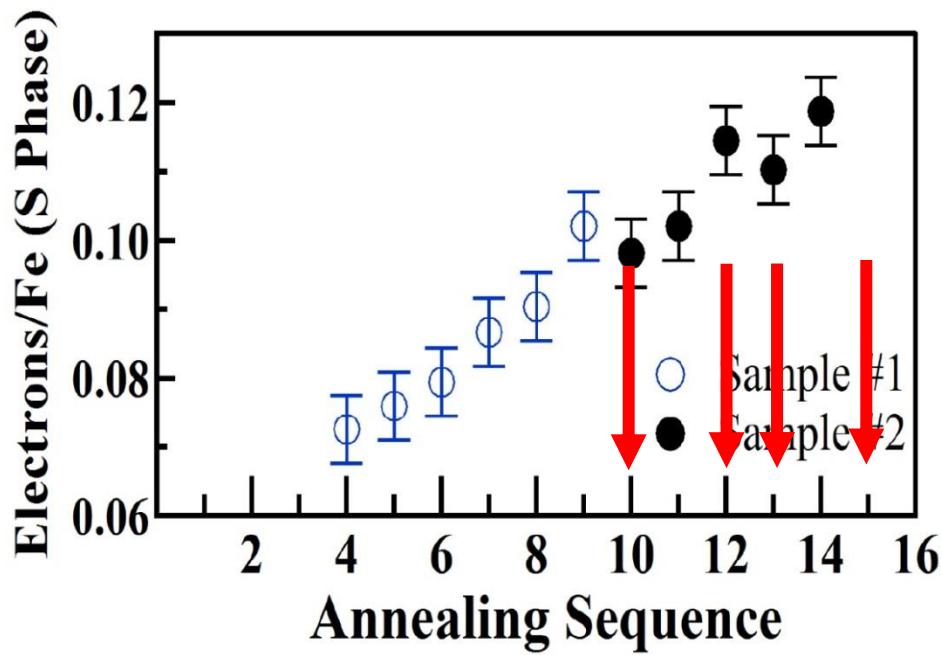
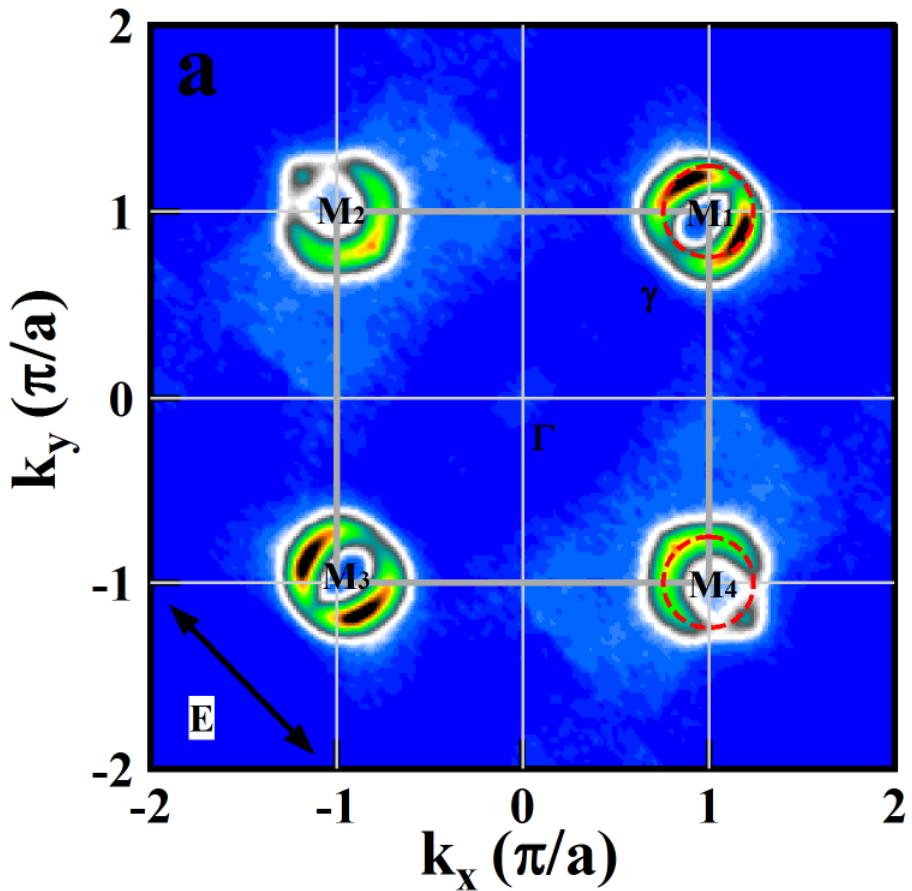
Evolution from N phase to S phase

Band Structure Evolution with Vacuum Annealing in Single-Layer FeSe/SrTiO₃



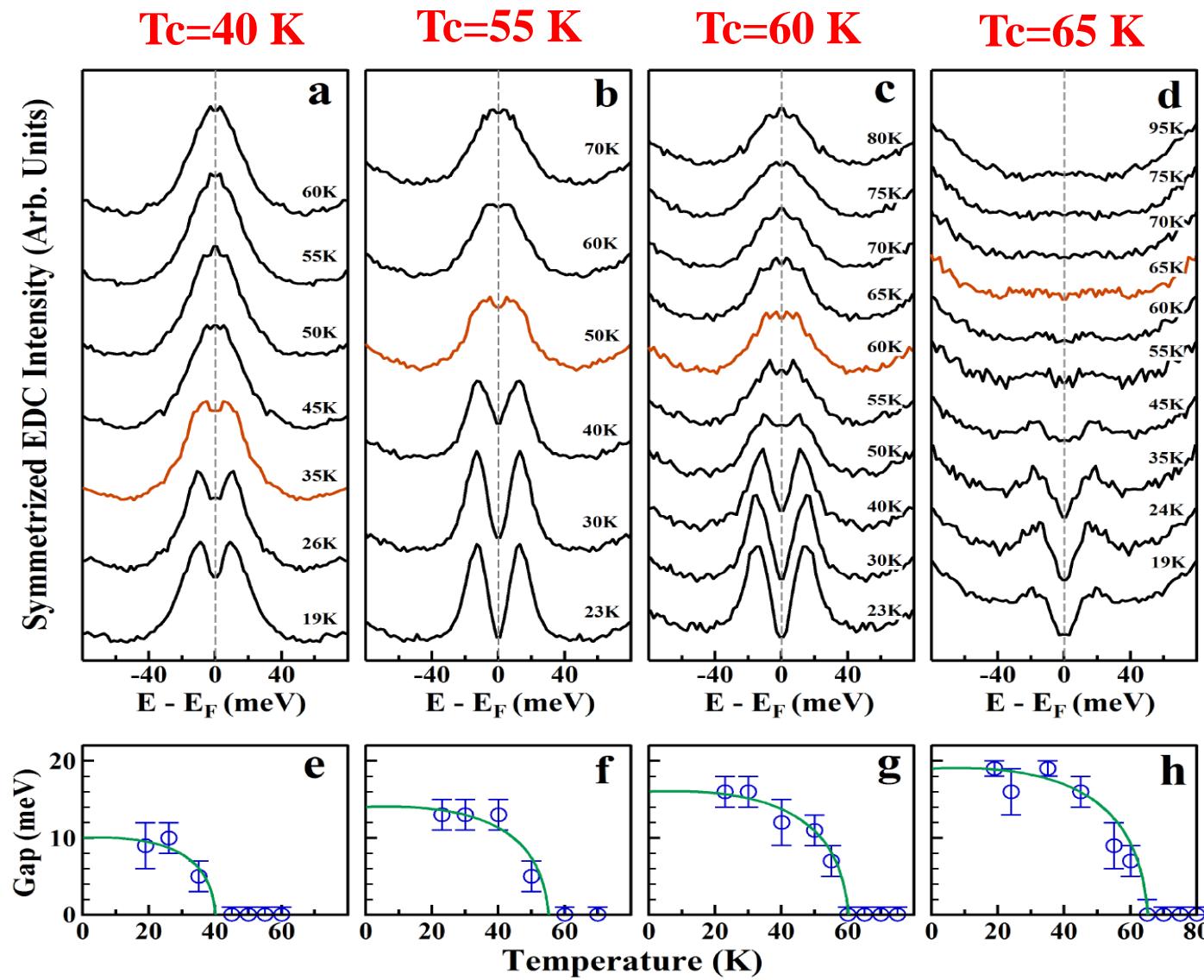
Doping-Evolution of Superconductivity in the S Phase.....

Electron Counting in S Phase of Single-Layer FeSe/SrTiO₃

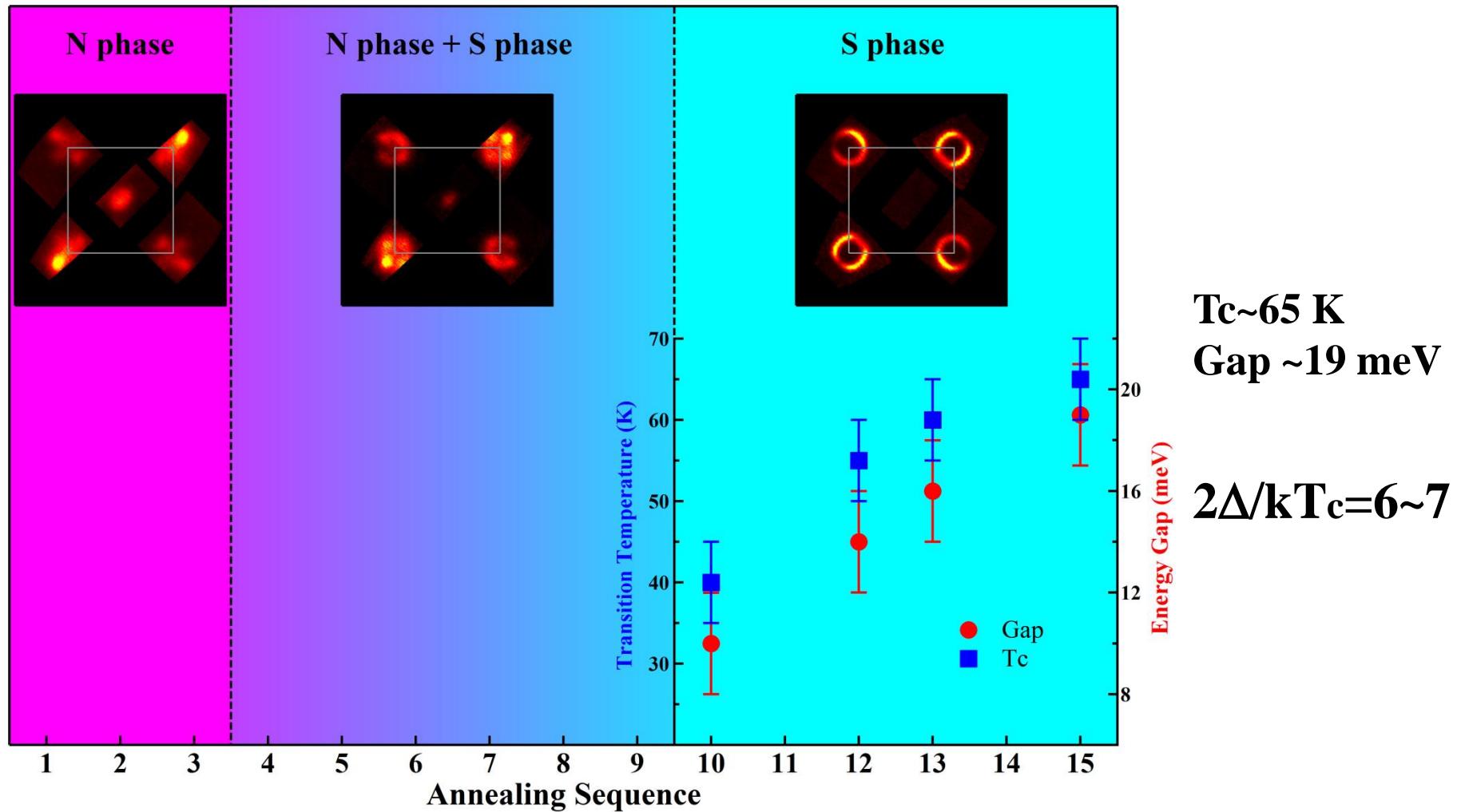


- S phase has only an electron-like Fermi surface sheet near M;
- Assuming two Fermi surface sheets near M.

Energy Gap of Single-Layer FeSe under Different Annealing Conditions



Phase Diagram of Single-Layer FeSe/SrTiO₃ Film

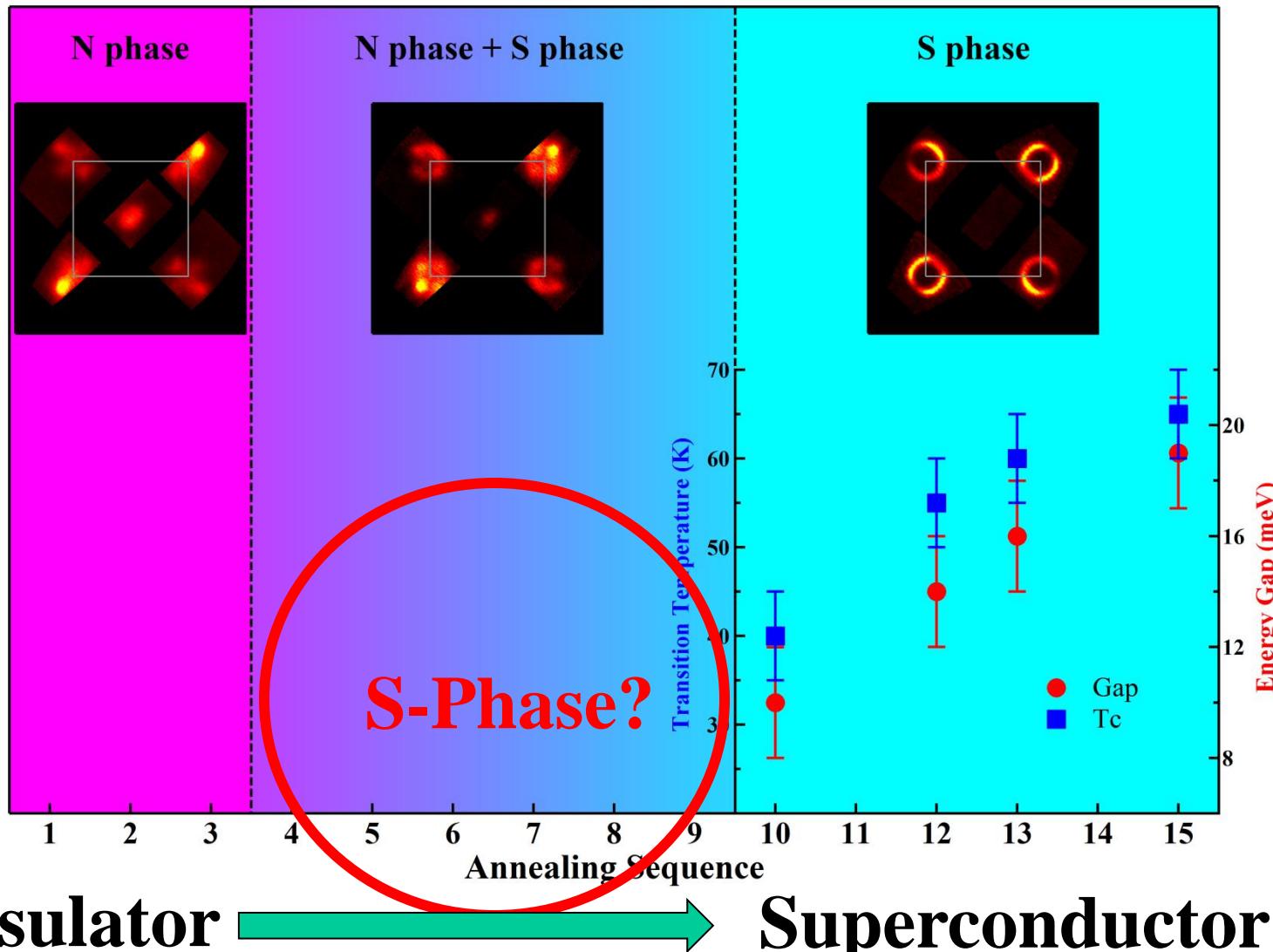


Electronic Evidence of an Insulator-Superconductor Transition in Single-Layer FeSe/SrTiO₃ Films.

Junfeng He, Xu Liu, Wenhao Zhang, Lin Zhao, X. C. Ma, Q. K. Xue, X. J. Zhou et al.,

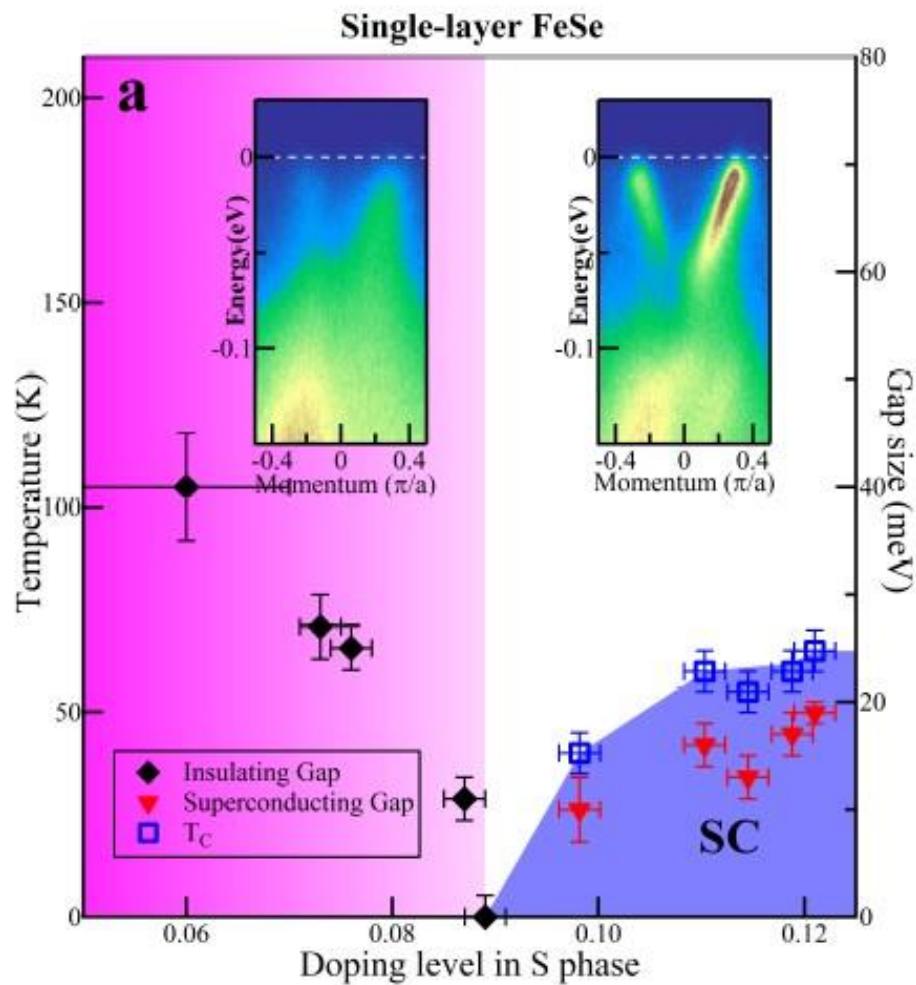
PNAS. 111, 18501 (2014).

Phase Diagram of Single-Layer FeSe/SrTiO₃ Film



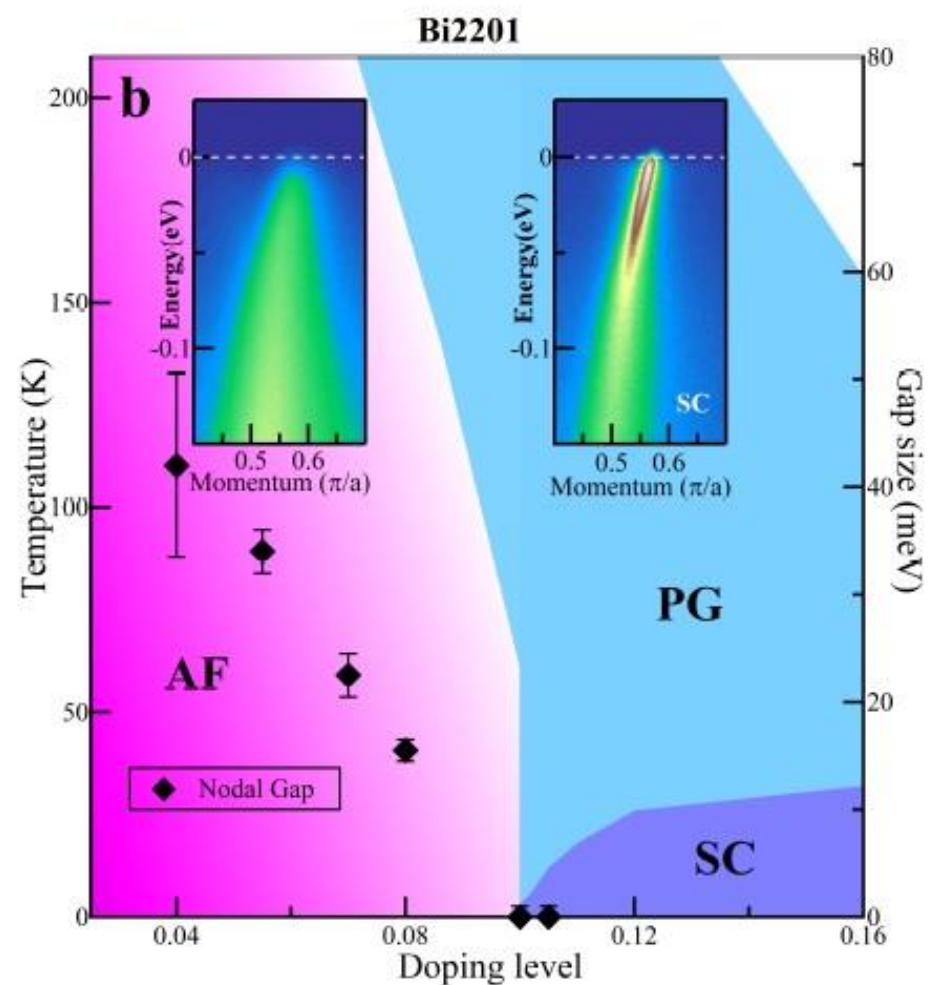
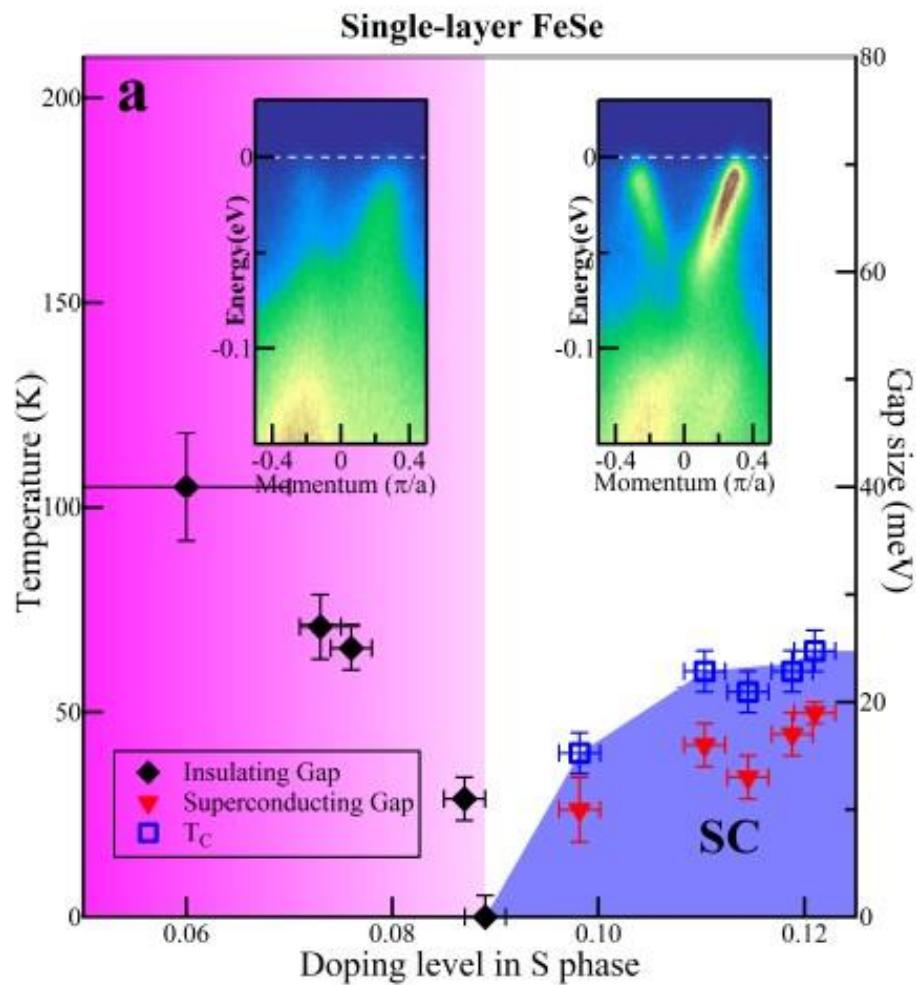
S. L. He, X. J. Zhou et al., Nature Materials 12, 605 (2013).

Phase Diagram of S-Phase of Single-Layer FeSe/SrTiO₃



J. F. He, X. J. Zhou et al.,
PNAS. 111, 18501 (2014).

Similar Electronic Phase Diagrams

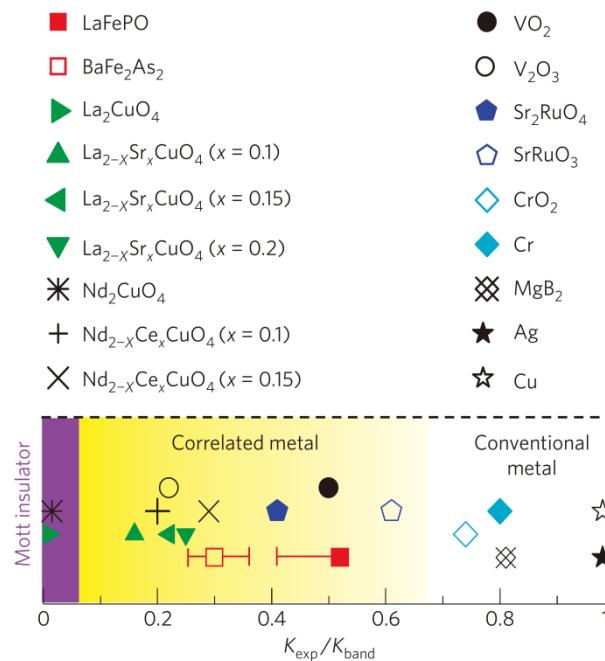


J. F. He, X. J. Zhou et al.,
PNAS. 111, 18501 (2014).

Y. Y. Peng, X. J. Zhou et al.,
Nature Communications, 4, 2459 (2013).

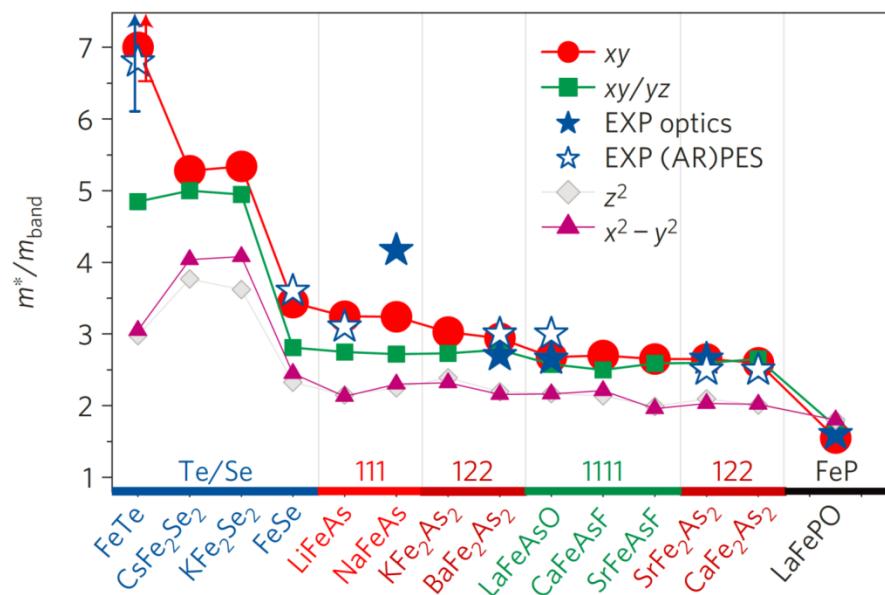
Strong Correlation in Single-Layer FeSe/SrTiO₃ Film

1. Existence of Electron Correlation in Fe-based Compounds



M. M. Qazibash et al., Nature Phys. 5, 647 (2009)

2. Stronger Electron Correlation in 11-Based Compounds

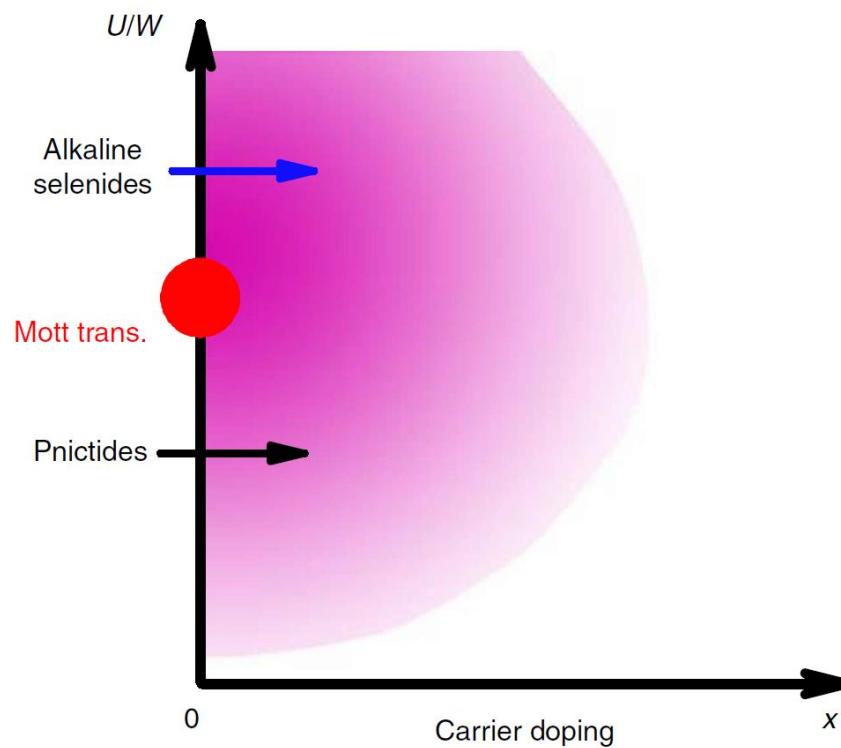


Z. P. Yin et al., Nature Mater. 10, 932 (2011).

3. Enhanced electron correlation due to reduced dimensionality—2D film;
4. Enhanced electron correlation due to tensile strain in single-layer FeSe film
(Bulk FeSe: 3.76 Å, Single-layer FeSe/SrTiO₃ film: 3.80 Å)

Doping of the Orbital-Selective Mott Insulator?

- Fe-based compounds are on the verge of doped Mott insulator;
- Single-Layer FeSe/SrTiO₃ has particularly strong electron correlation.
- Similarity between Single-layer FeSe/SrTiO₃ Film and the underdoped La-Bi2201.

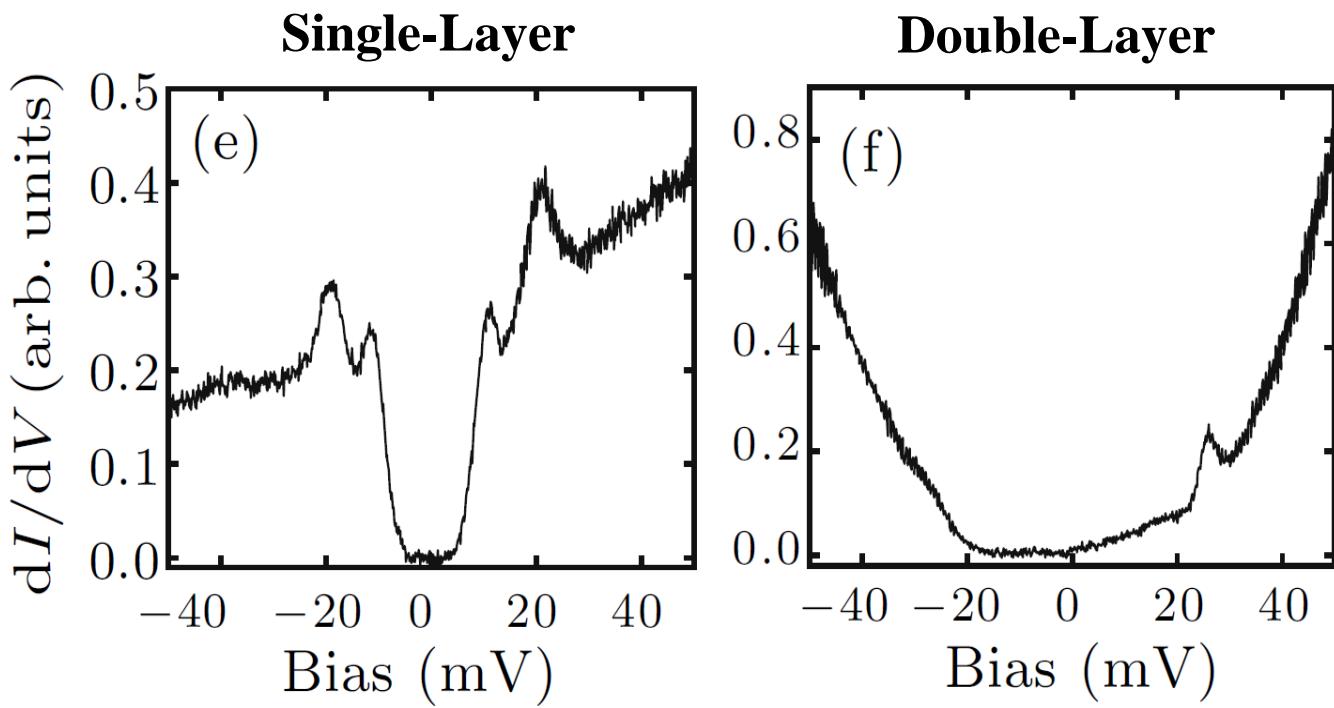
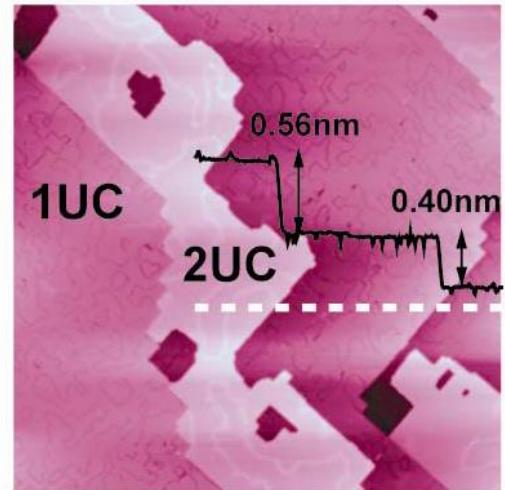


- Q. M. Si and E. Abrahams, Phys. Rev. Lett. 101, 076401 (2008).
R. Yu et al., Nature Communications 4, 2783 (2013).
R. Yu and Q. M. Si, Phys. Rev. Lett. 110, 146402 (2013).

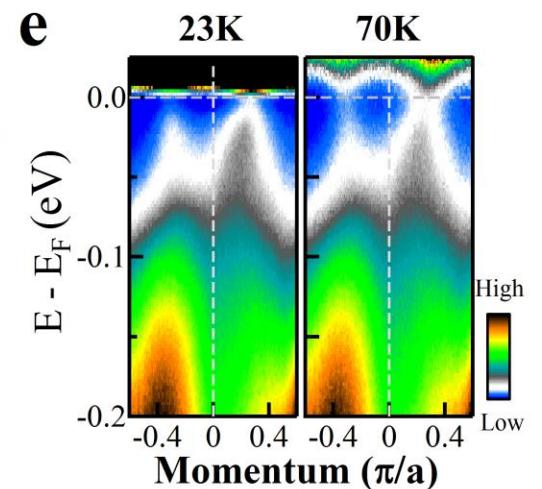
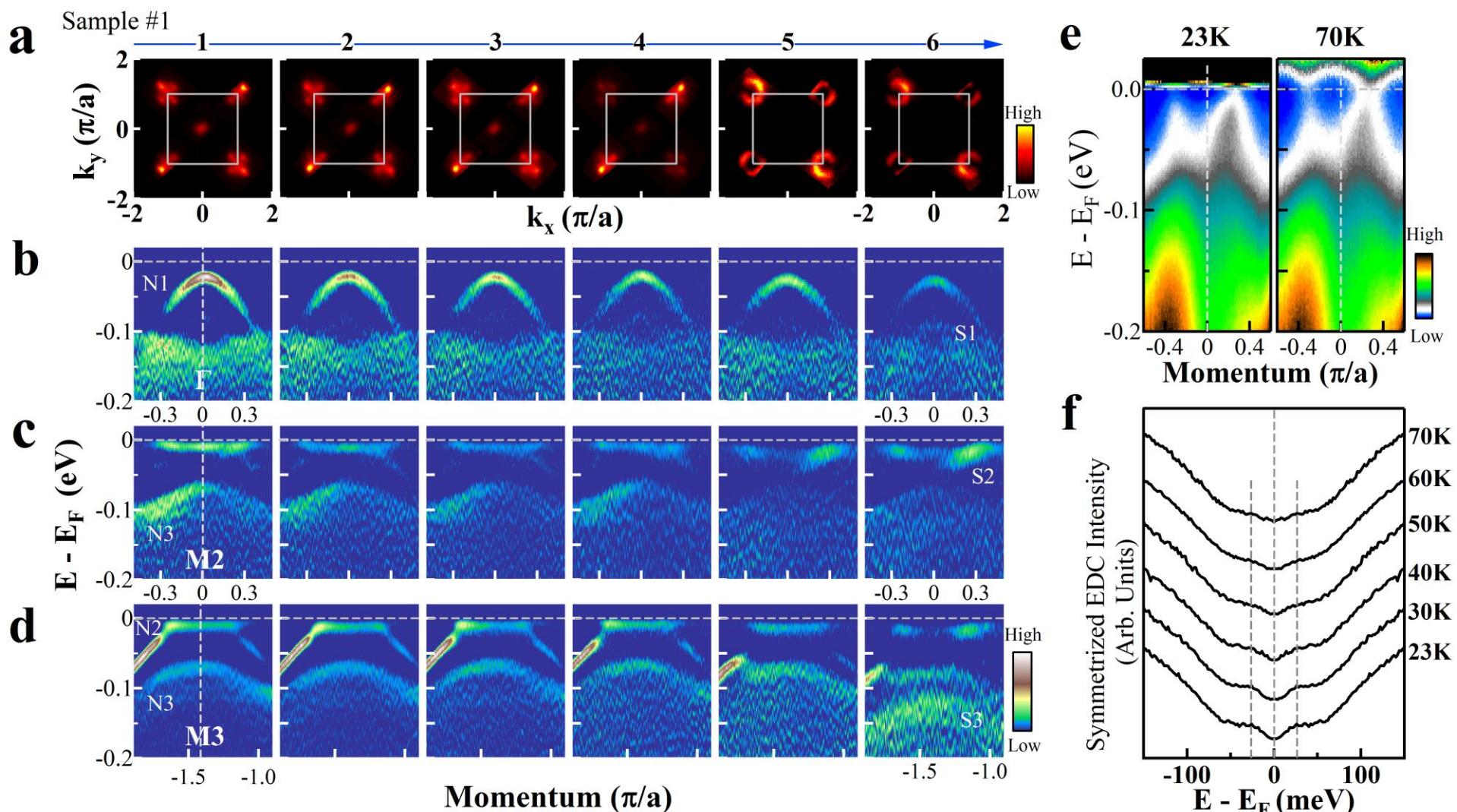
Dichotomy of Electronic Structure and Superconductivity between the Single-Layer and Double-Layer FeSe/SrTiO₃

X. Liu, D. F. Liu, W. H. Zhang, J. F. He, X. C. Ma, Q. K. Xue, X. J. Zhou et al.,
Nature Communications 5, 5047(2014).

Distinct Behaviors between Single-Layer and Two-Layer FeSe/SrTiO₃: STM/STS



Vacuum Annealing of Double-Layer FeSe/SrTiO₃ at 350C for different Times



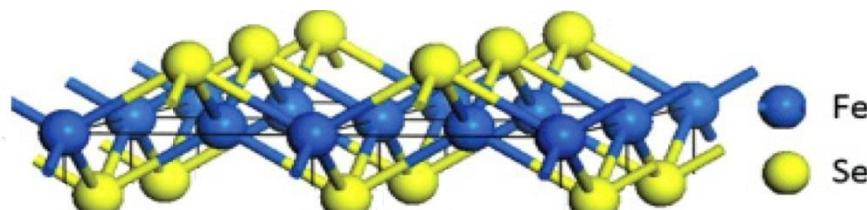
1. The **N** phase remains dominant after annealing;
2. There is a transition from the **N** phase to the **S** phase.

- It is much harder to transform double-layer from the N phase into the S phase than the single-layer FeSe/SrTiO₃.
- It is possible to transform double-layer FeSe/SrTiO₃ from the N phase into the S phase.

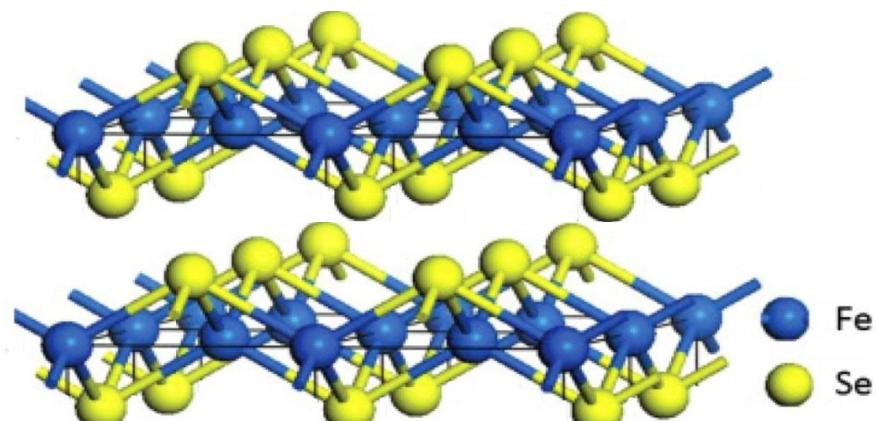
Why is Double-Layer FeSe/SrTiO₃ Difficult to be Doped?

- Charge transfer from oxygen loss in SrTiO_{3-δ};
- Charge transfer is shared by two FeSe layers;
- The more the number of layers, the more difficult to dope.

Single-Layer



Double-Layer



SrTiO₃ Substrate

SrTiO₃ Substrate

Summary on FeSe/SrTiO₃ Films

1. Distinct electronic structure of single-layer FeSe superconductor

Hole-like Fermi surface near Γ is not necessary for high-Tc superconductivity in the Fe-based superconductors.

2. Electronic phase diagram of single-layer FeSe/SrTiO₃ established

**There are two competing and coexisting phases (N phase and S phase) with distinct electronic structures;
Signature of high Tc~65 K observed.**

3. Insulator-superconductor transition observed in Single-Layer FeSe/SrTiO₃ films

Orbital-selective Mott transition?

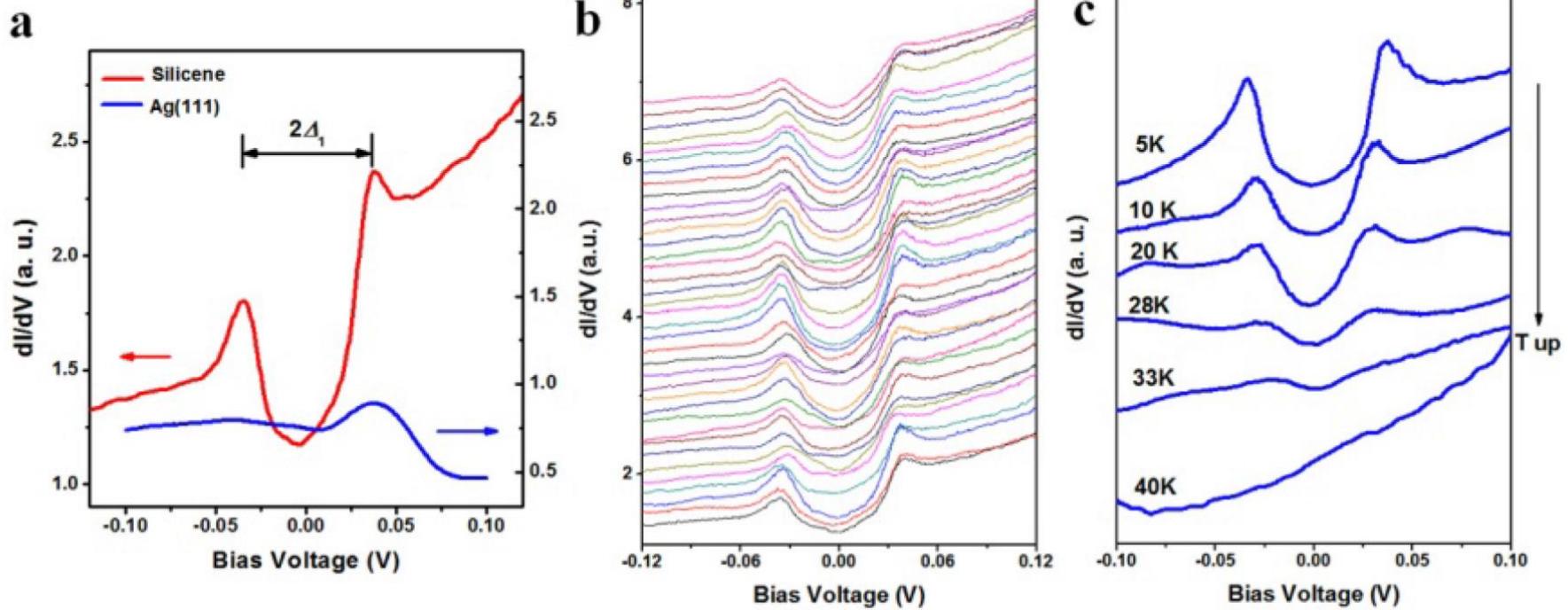
4. Dichotomy between single-layer and double-layer FeSe/SrTiO₃ Films

Origin of carrier doping from SrTiO₃ surface.

ARPES on Silicene (3x3)/Ag(111)

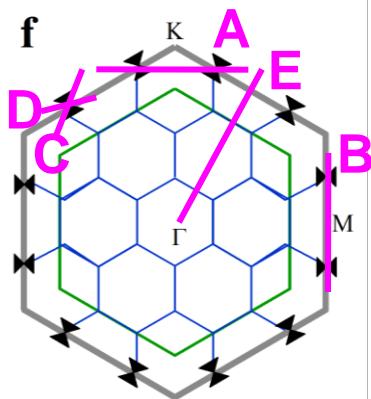
Ya Feng, Defa Liu, Baojie Feng, Xu Liu and X. J. Zhou et al.,
arXiv:1503.06278.

High Temperature Superconductivity in Silicene?

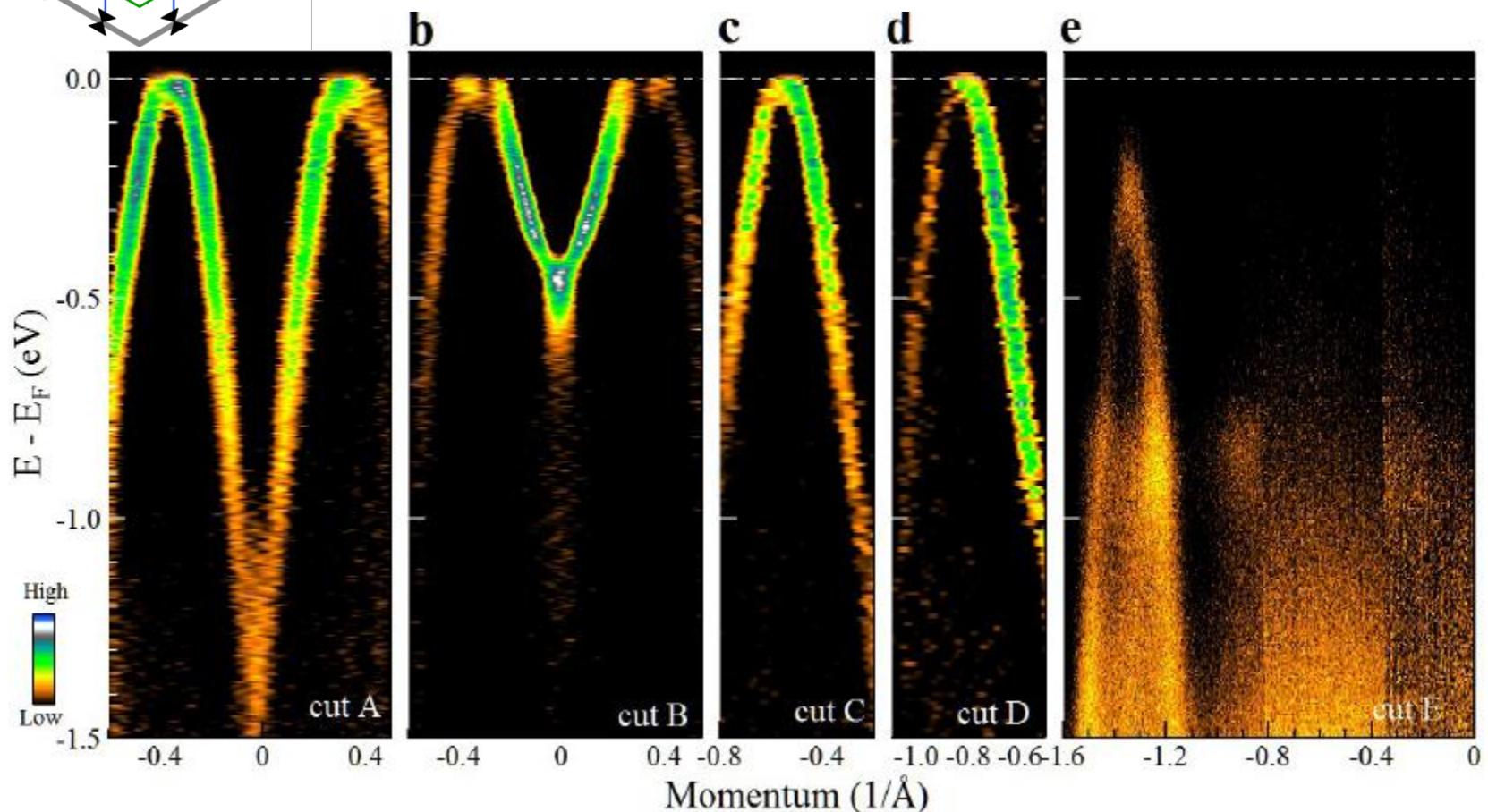


Gap like feature with $\Delta \sim 35$ meV is reported.
T_c over 100K?

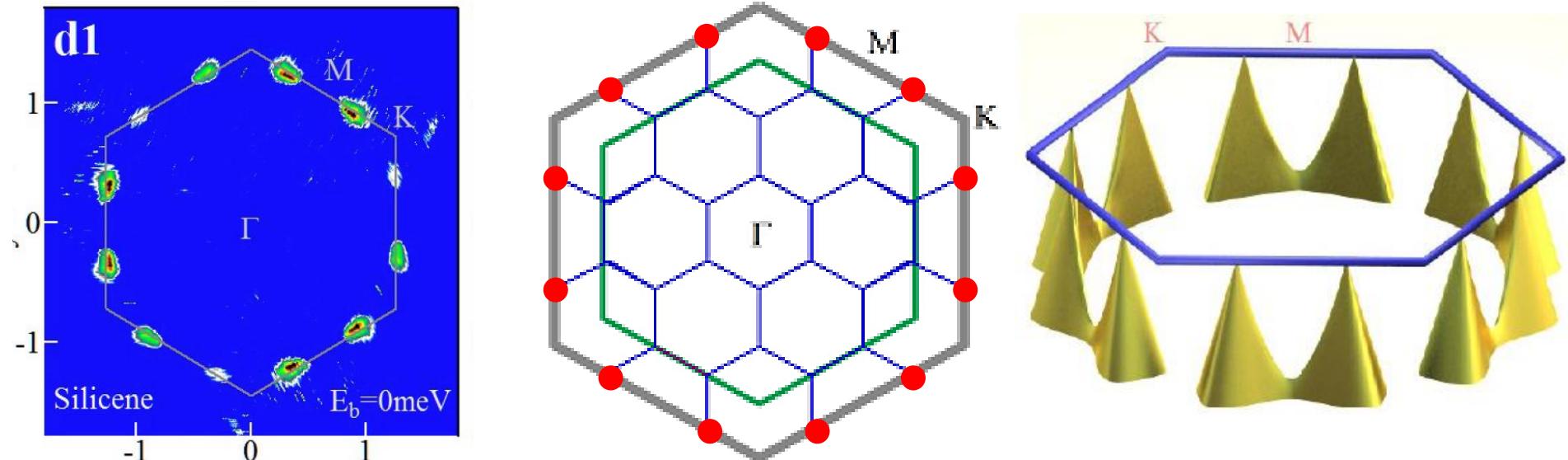
Band Structures of Silicene(3x3)/Ag(111)



- Cut A is different from Cut B → six pairs ; rule out two domains
- Cut C and Cut D further prove the existence of the Dirac cone
- Cut E shows a band top below Fermi level



Unusual Dirac Cones in Silicene(3x3)/Ag(111)



1. Six pairs of Dirac cones observed.
Not from Ag(1110), not from free-standing silicene;
2. Dirac cones lie on the edges of the first Brillouin zone of Ag(111).
No obvious connection with the 1st BZ of the primary silicene(1x1);
3. No band-folding and duplicate features in the reduced Brillouin zones.

The interaction between the pristine silicene film and the Ag(111) substrate is very important to produce such electronic structure.

Thanks