STM spectroscopy on Cuprates and Pnictides

Vidya Madhavan, Boston College

Bosonic Modes

Boston College

F. C. Niestemski
J.-H. Ma
Shankar Kunwar
Ziqiang Wang

Oak Ridge National Laboratory and University of Tennessee

Pengcheng Dai,
Shiliang Li
Della Cruz

Institute of Physics, China

Hong Ding

Pseudogap

Boston College

J.-H. Ma
Z.-H. Pan
F. C. Niestemski
M. Neupane
Y.-M. Xu
Ziqiang Wang

Tohoku University, Japan

P.Richard
K. Nakayama,
T. Sato
T. Takahashi

Institute of Physics, China

H. Ding
H.-Q. Luo
L. Fang
H.-H. Wen

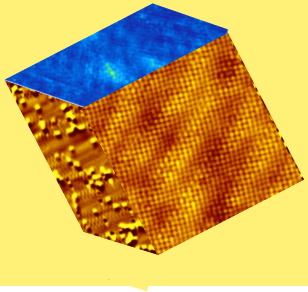
Pnictides

Quantum Matter Group, Cavendish Laboratory, Cambridge

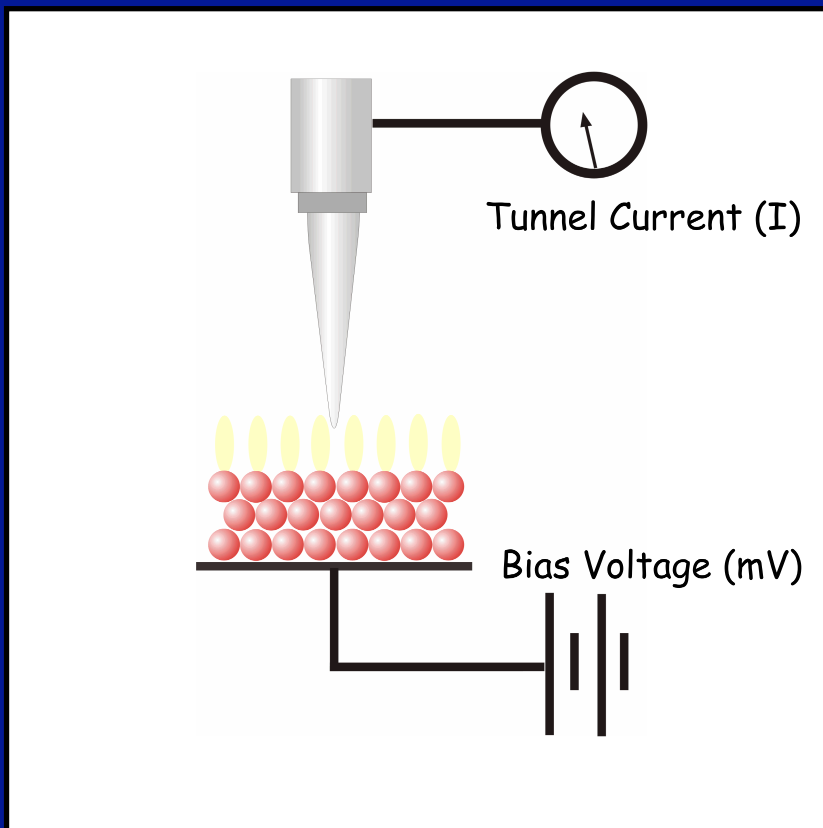
Suchitra Sebastian

Louisiana State University

Ward Plummer
Von Braun Nascimento

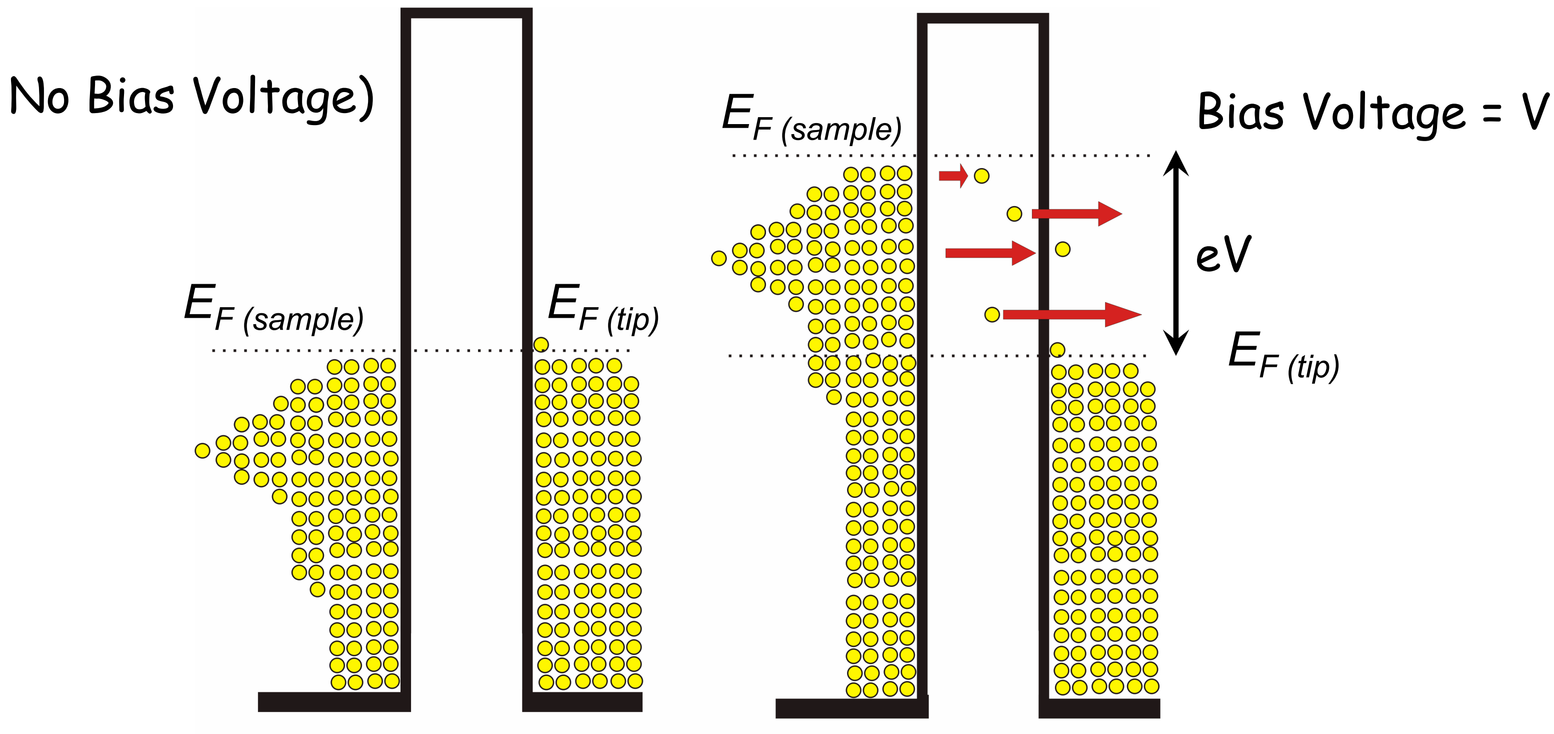


Scanning Tunneling Microscopy



- Imaging
- Atomic Manipulation
- Spectroscopy

STM Technique: Imaging



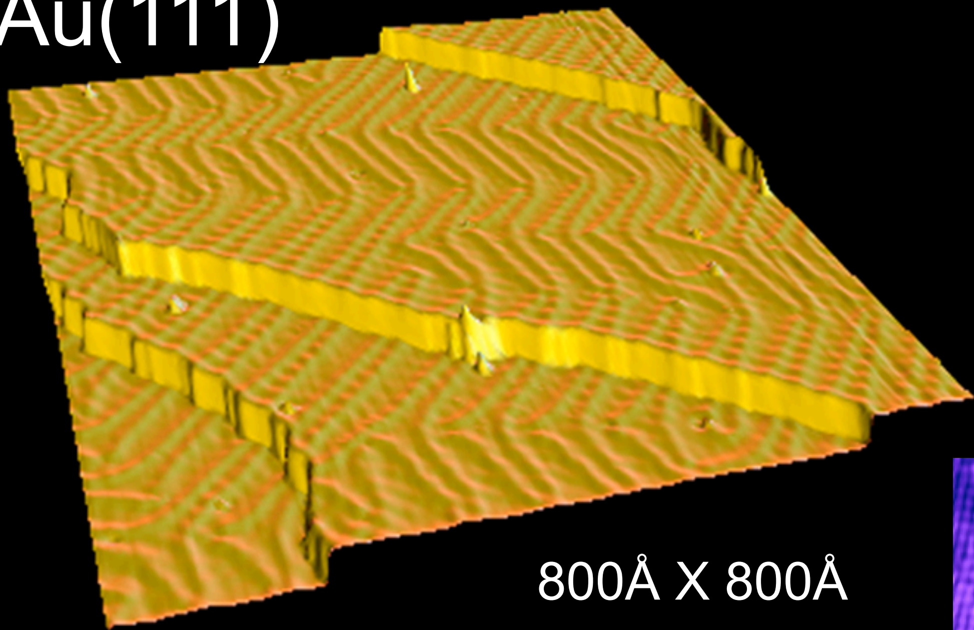
$$I(eV_b) = \int_0^{eV_b} \sum_n |\Psi_n(r)|^2 \delta(eV - E_n) dV = \int_0^{eV} \rho(r, eV) dV$$

$$I(eV) \approx \int_0^{eV} LDOS(E) dE \sim exp\ (-2kd)$$

I ~ *exp (-2kd)* ⇨ Measure *I(x, y)* to obtain image

STM Topography

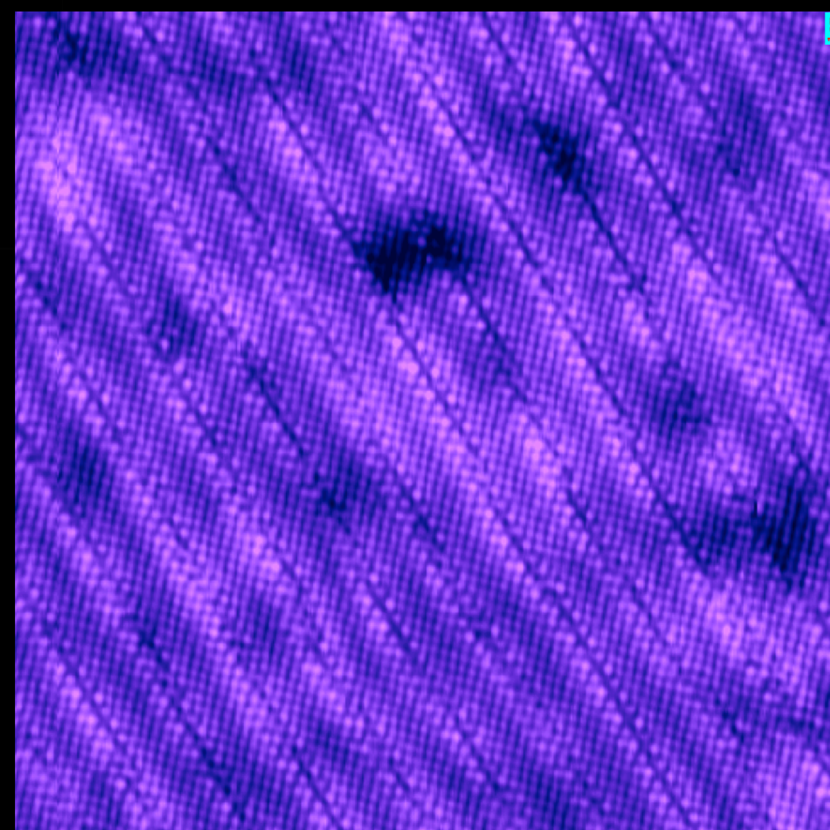
Au(111)



800Å X 800Å

W. Chen, V. Madhavan, T. Jamneala, M.F. Crommie
Phys. Rev. Lett. 80, 1469 (1998)

$Bi_2Sr_2CaCu_2O_{8+\delta}$



(256Å X 256 Å)

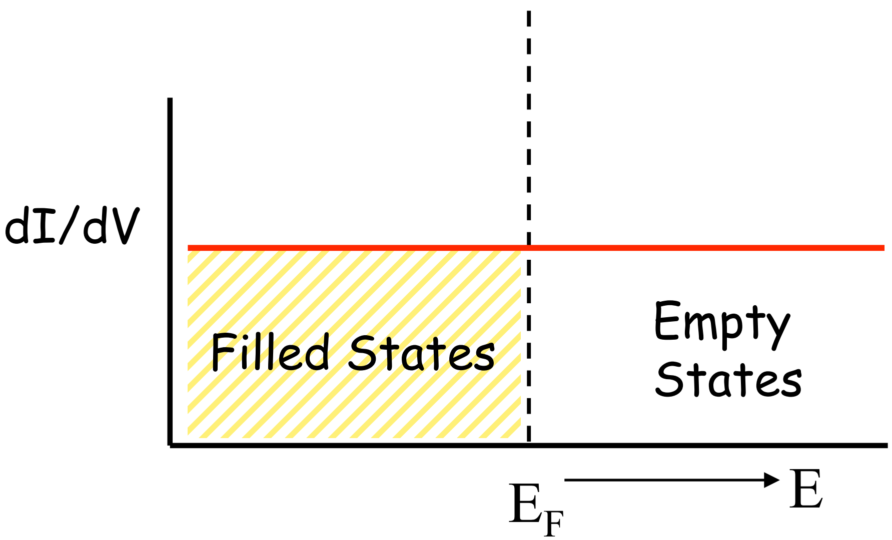
STM Technique: Spectroscopy

$$I(eV_b) = \int_0^{eV_b} \sum_n |\Psi_n(r)|^2 \delta(eV - E_n) dV = \int_0^{eV} \rho(r, eV) dV$$

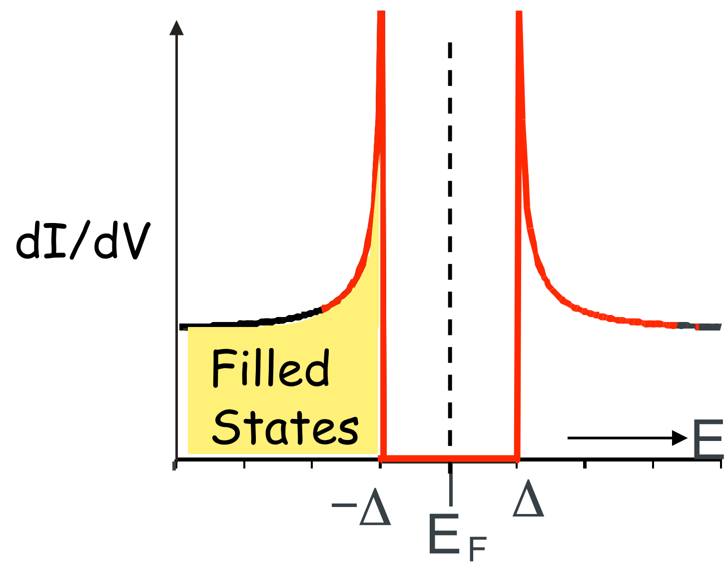
$$\rho(r, eV) = \textit{Local Density of States (LDOS)}$$

$dI/dV \propto LDOS(E)$ ⇒ *Measure dI/dV to obtain LDOS*

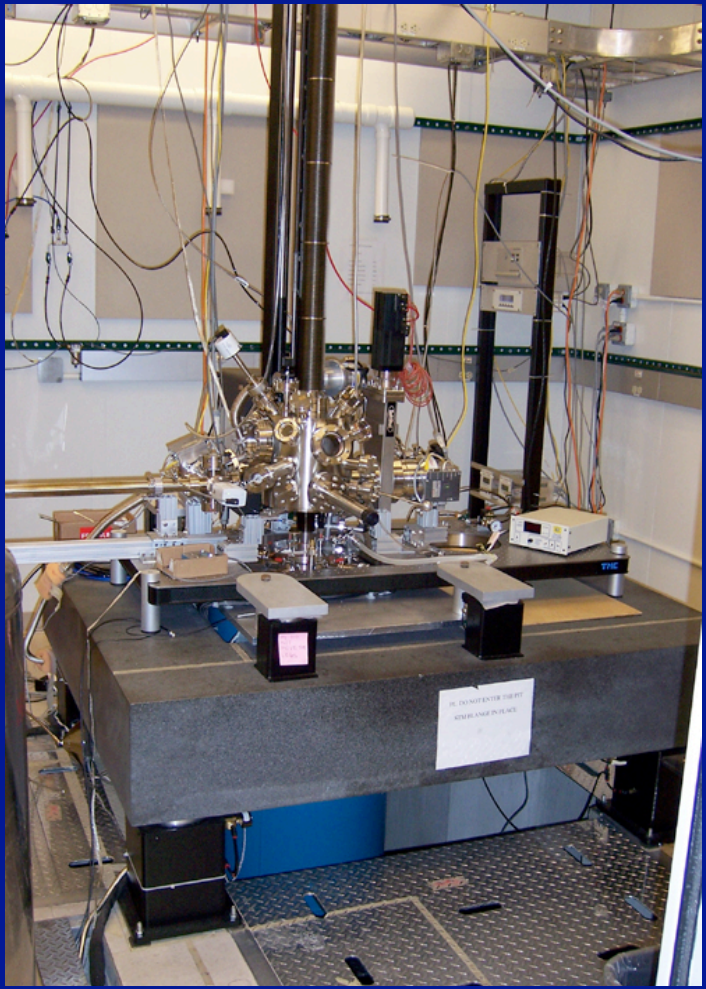
DOS Metal: Featureless near E_F



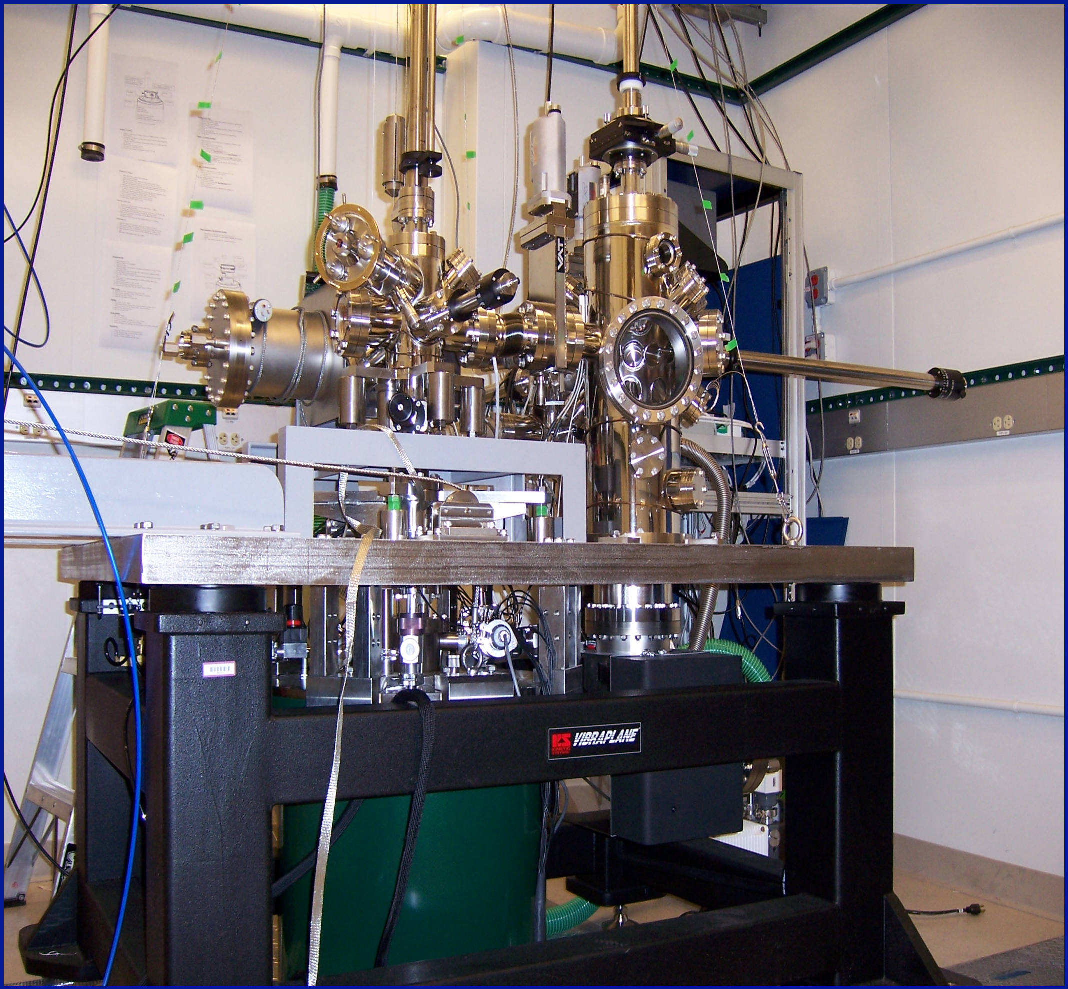
Conventional Superconductor



STMs at Boston College



Homebuilt STM

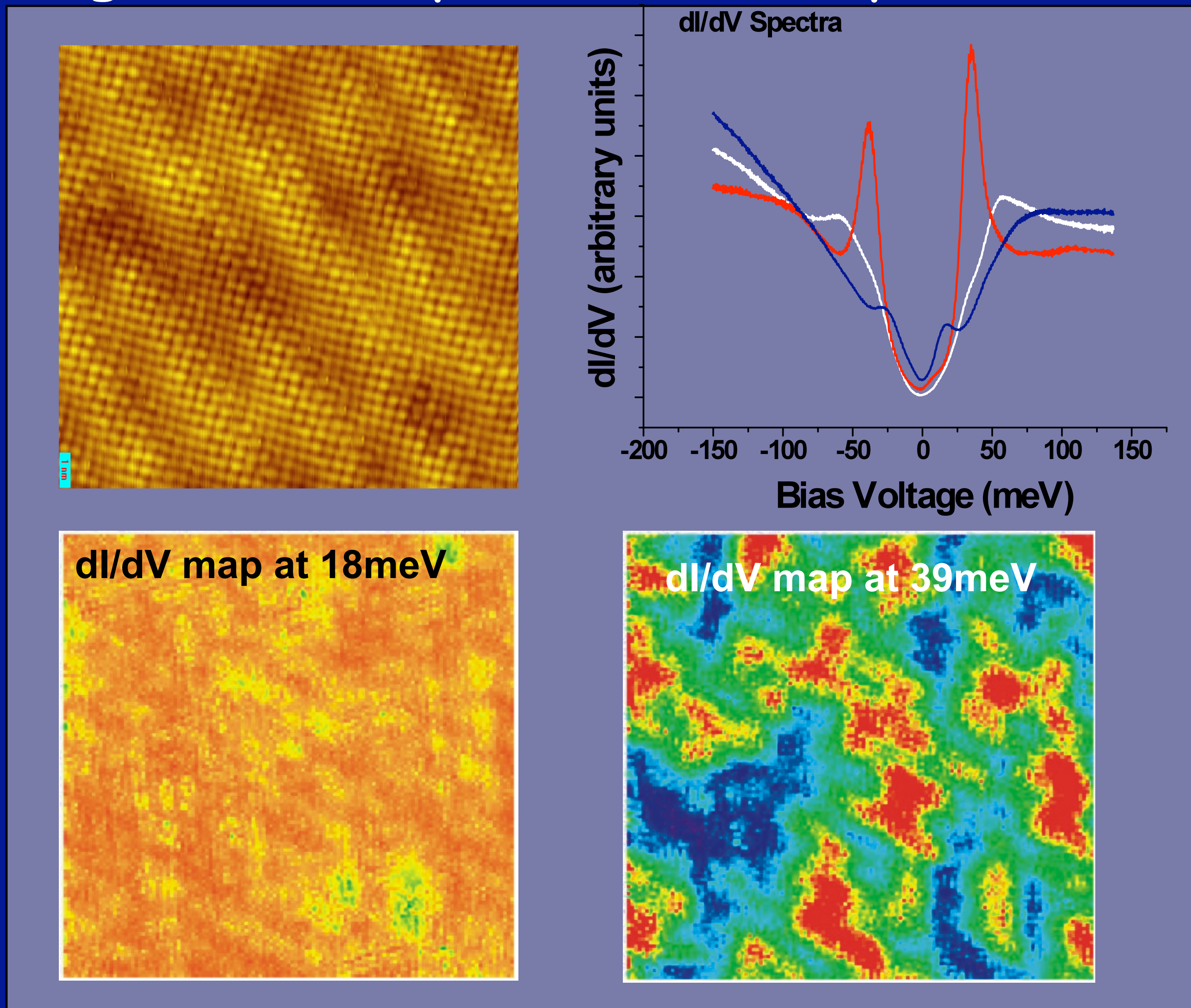


Custom Unisoku STM

Capability

- UHV, variable Temperature (2K-60K) STMs
- Move large distances (microns) to access different regions of the sample
- In-situ tip exchange
- 7Tesla Magnetic Field

Images and Maps on Underdoped BSCCO



Superconducting gaps and Pseudogaps: spectroscopic evidence for two competing, coexisting phases below T_c

Boston College

J.-H. Ma
Z.-H. Pan
F. C. Niestemski
M. Neupane
Y.-M. Xu

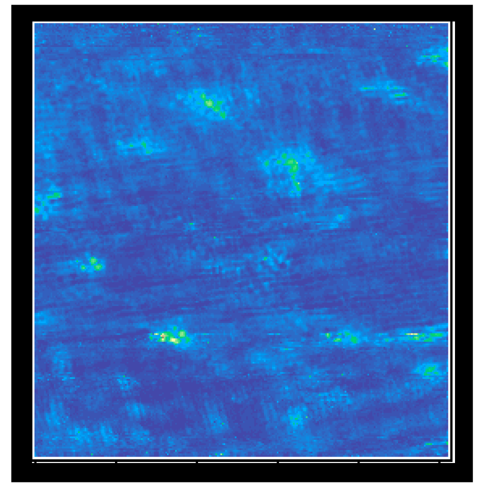
Ziqiang Wang
H. Ding

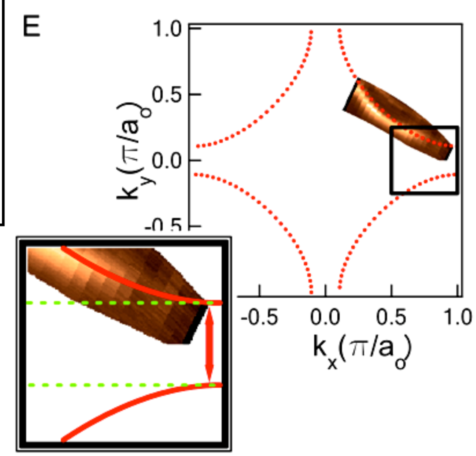
Tohoku University, Japan

P.Richard
K. Nakayama,
T. Sato
T. Takahashi

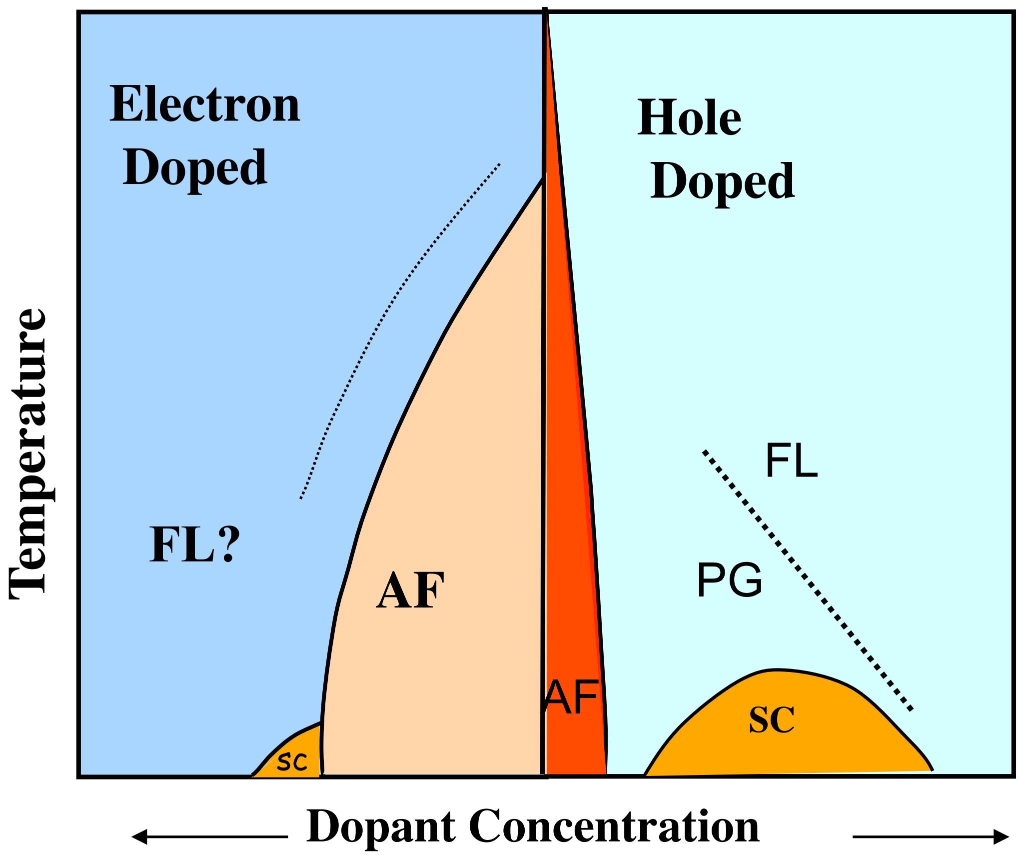
Institute of Physics, China

H.-Q. Luo
L. Fang
H.-H. Wen





Phase diagram-Cuprates



Pseudogap origin still under debate

No accepted microscopic theory (like BCS for conventional superconductors.

No consensus on pairing mechanism

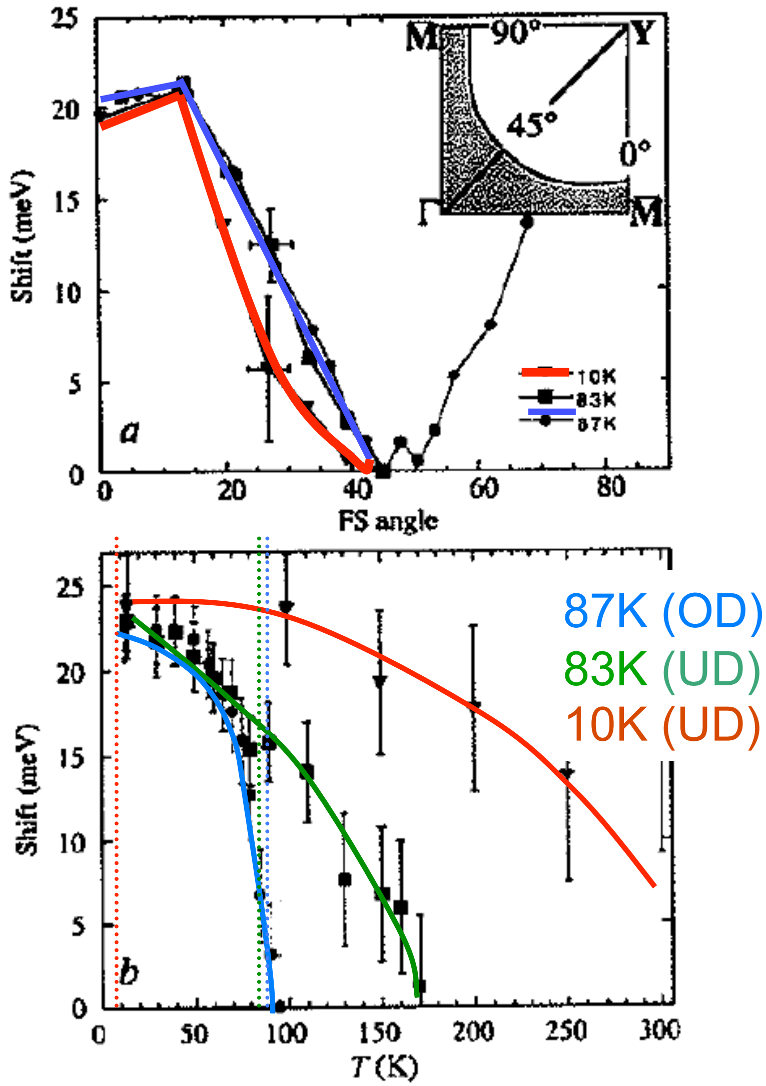
Pseudogap

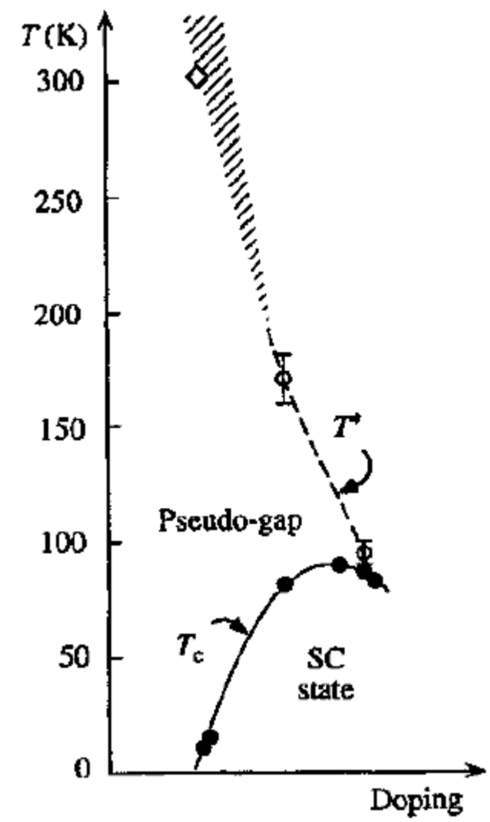
- First discovered as a gap in the spin-excitation spectrum far above T_c later in the charge channel by optical spectroscopy, resistivity, hall effect and specific heat measurements

- It is a pseudogap in the sense that it removes some but not all of the spectral weight from the region close to the Fermi energy

- Questions:
  - What is the origin of this gap?
  - how is it related to superconductivity?

Smooth Evolution through T_c ARPES

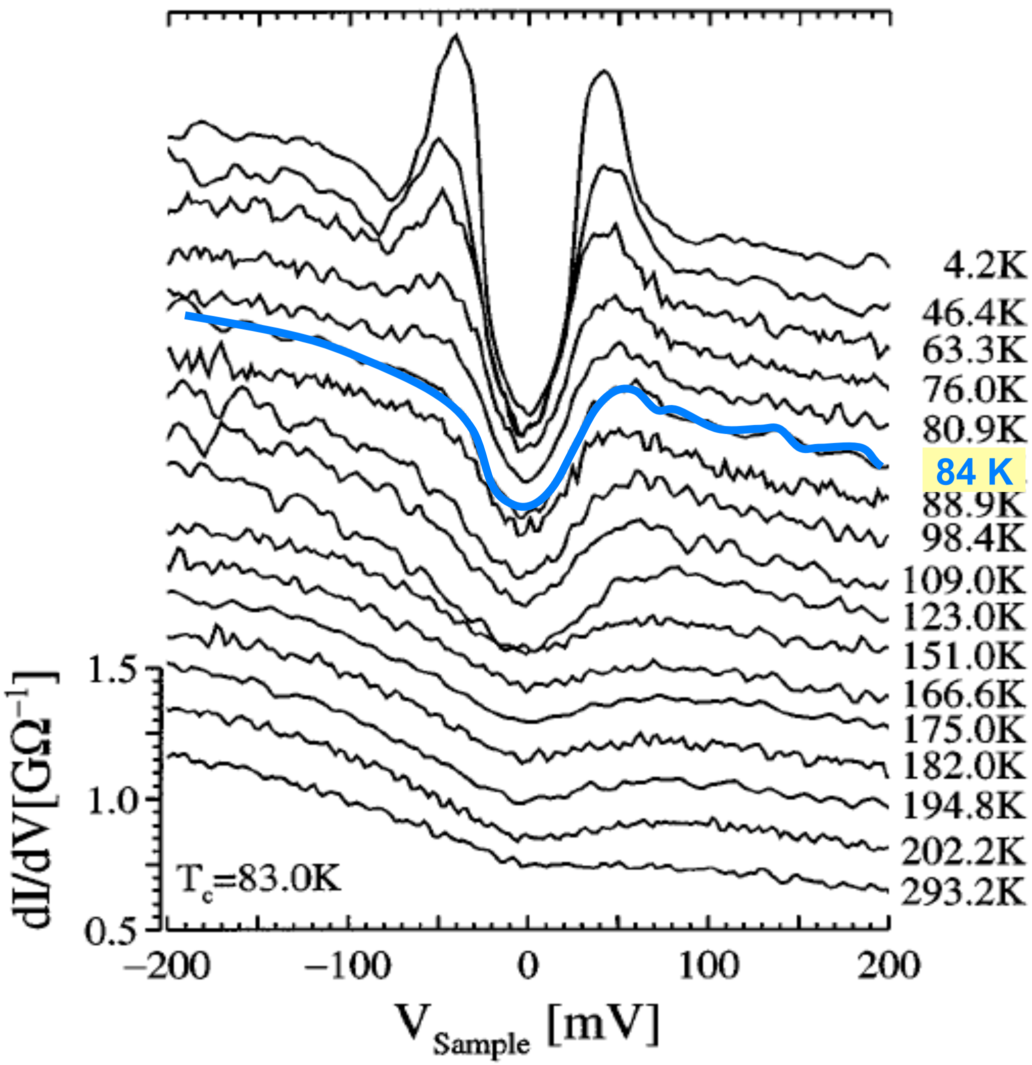




Ding *et al*, **Nature 382** 51, (1996)

FIG. 3 Momentum- and temperature-dependence of the gap estimated from leading edge shift (see text). a, k dependence of the gap in the 87 K

Smooth Evolution through T_c STM



Ch. Renner *et al*, **PRL 80**, 149 (1998)

Ø. Fischer *et al*, **RMP 79**, 353 (2007)

Pseudogap

Smooth evolution through T_c

Particle hole symmetric spectrum

Intimately connected to SC

Pair fluctuations?

Energy scale problem

Δ_{PG} scales with T^* not T_c

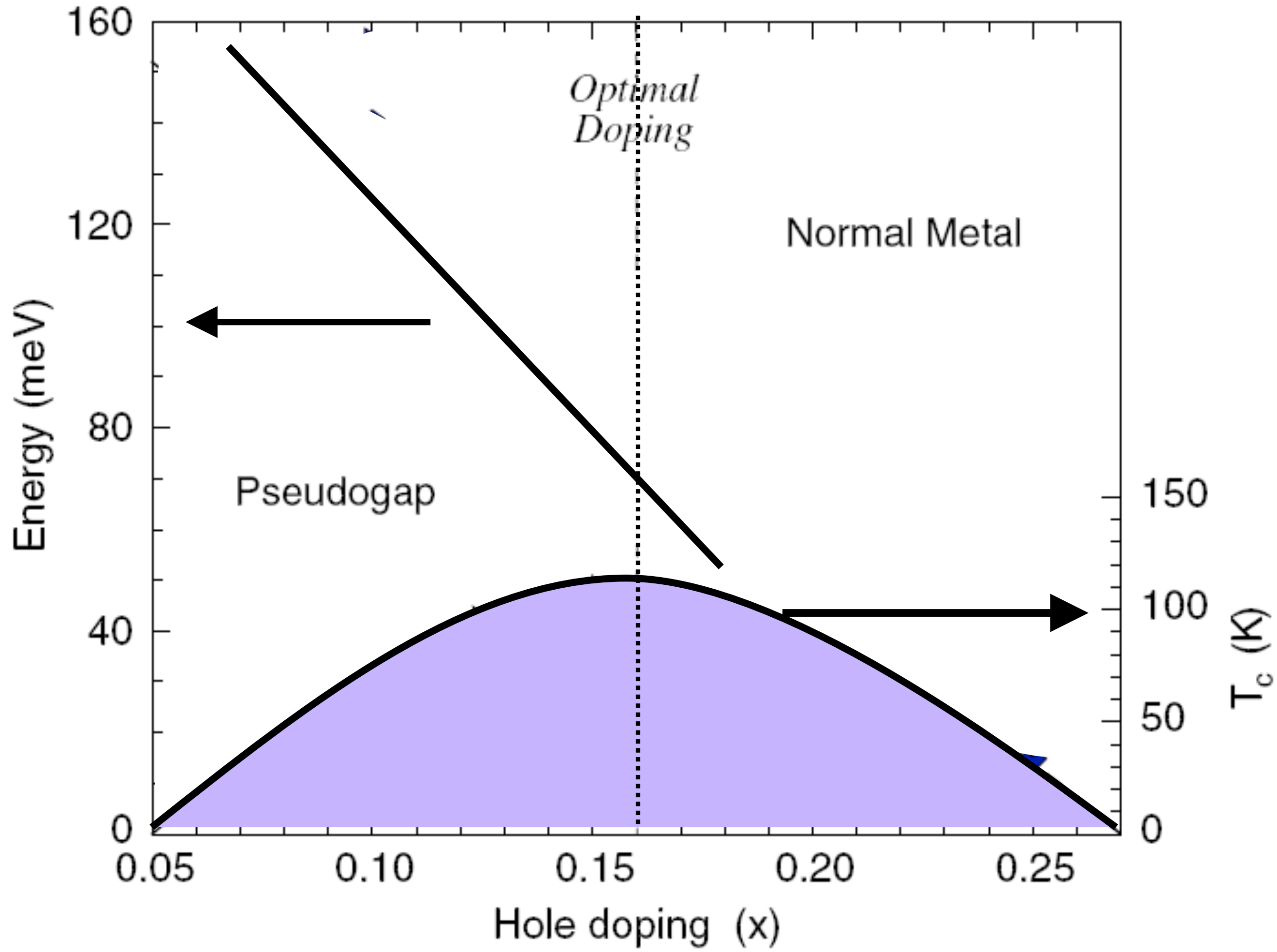


Figure 2. Pseudogap ($E_{pg} = 2\Delta_{pg}$) and superconducting ($E_{sc} \sim 5k_B T_c$) energy scales for a number of HTSCs with $T_c^{max} \sim 95$ K (Bi2212, Y123, Tl2201 and Hg1201). The datapoints were obtained, as a function of hole doping x, by angle-resolved photoemissio

Pseudogap

Scenario #1

Pair fluctuations

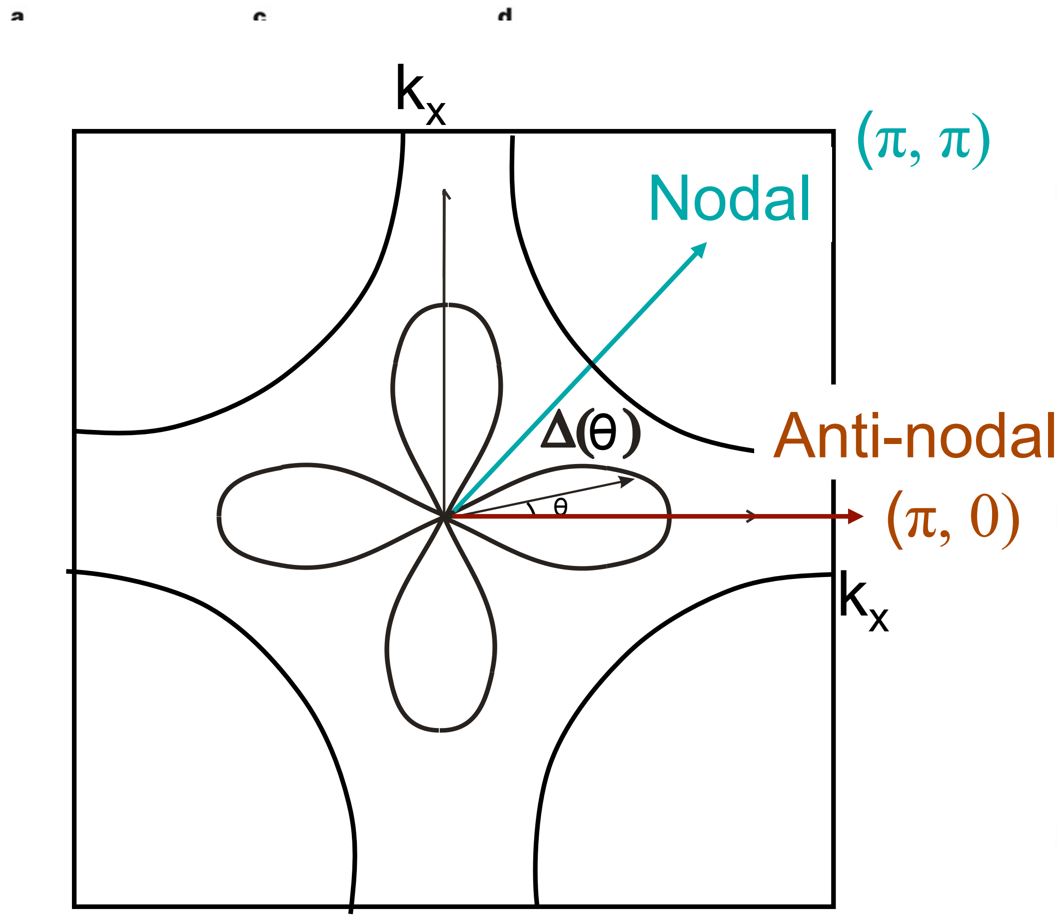
Scenario #2

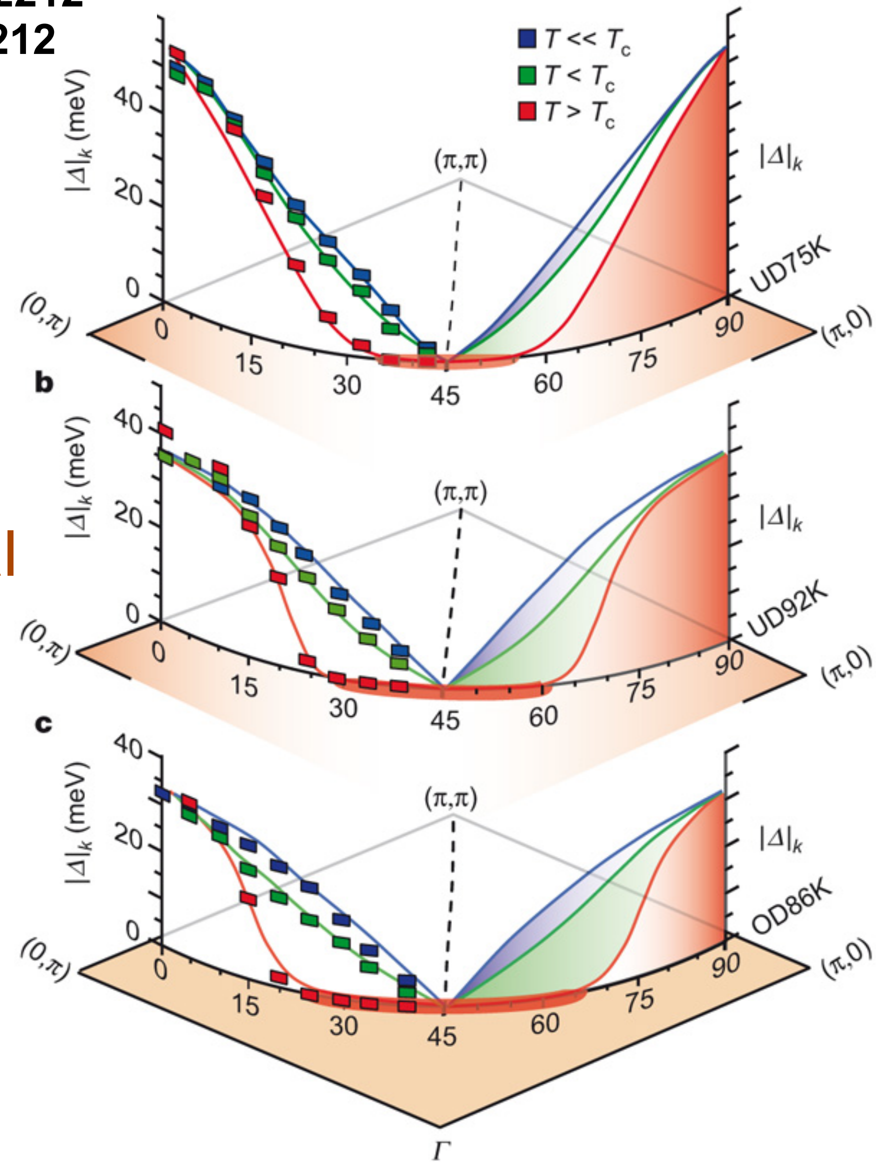
Competing phase

Nodal-Antinodal Dichotomy
and
Concept of two gaps in the superconducting phase

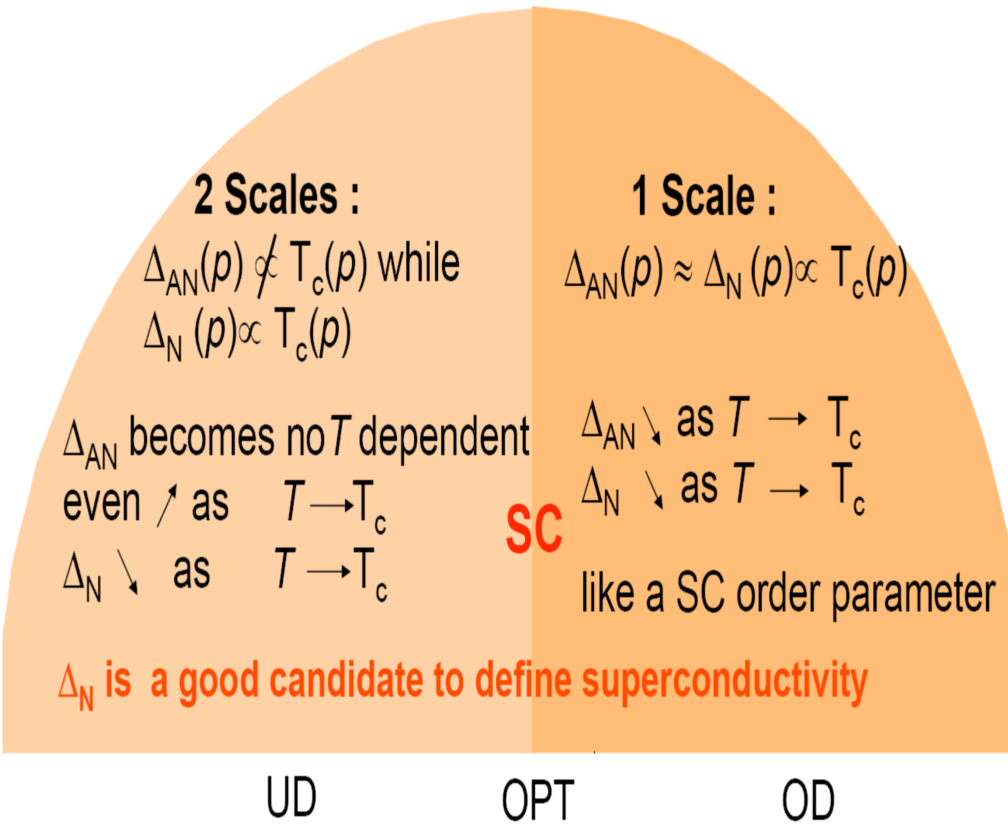
ARPES

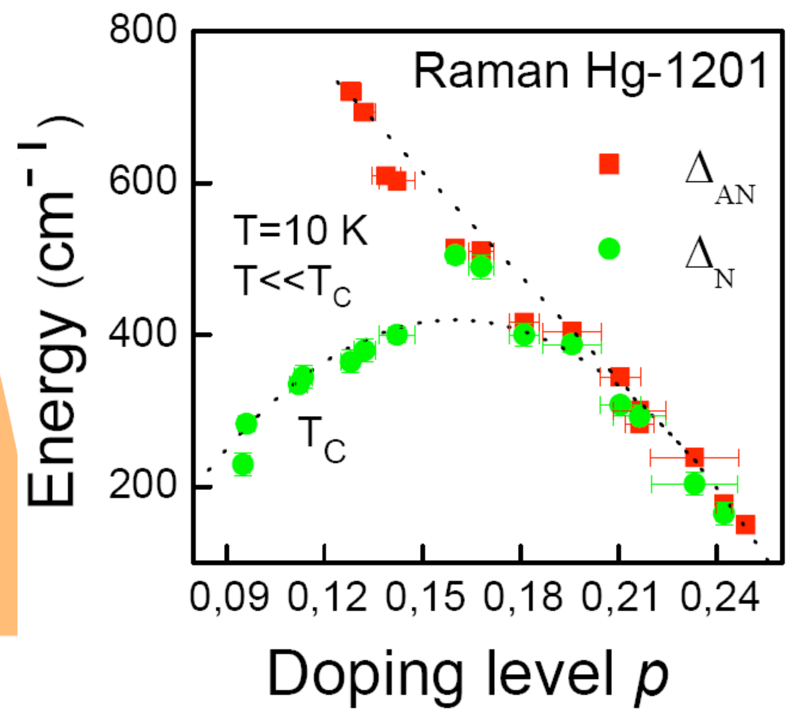
W.S. Lee, .. Z.X. Shen et al., Nature 450, 81 (2007): 2212
K. Tanaka et al., Science 314, 1910 (2006): Y sub 2212





Raman Spectroscopy





M. Le Tacon et al. Nature Physics 2, 537, 2006
W. Guyard et al. PRB 77, 24524, 2008

Two ‘gaps’ in Underdoped region?

Nodal and Antinodal gaps behave differently with doping and temperature

Nodal gap: Closes at T_c and the magnitude scales with T_c

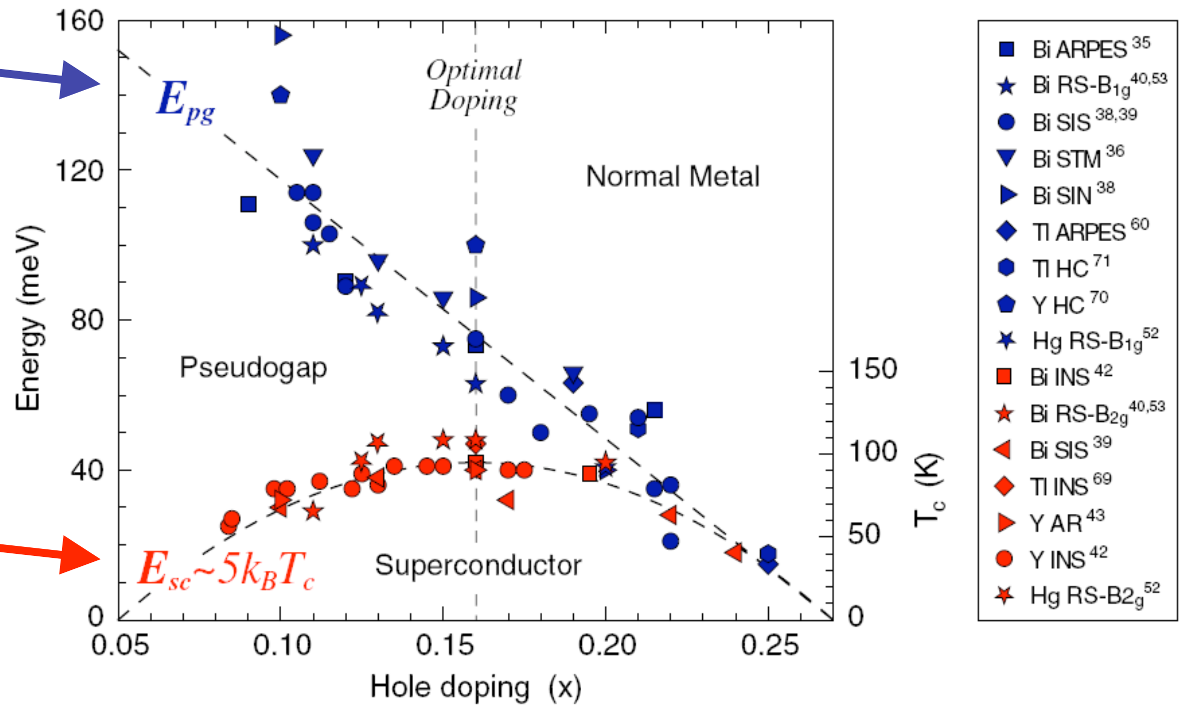
Antinodal gap: Persists beyond T_c and scales with PG temperature T^*

Explains great divide in data

S. Huefner, M.A. Hossain, A. Damascelli & G.A. Sawatzky,
***Rep. Prog. Phys.* 71, 062501 (2008)**

Techniques sensitive to antinodal gap

Techniques sensitive to nodal gap



Two kinds of gaps below T_C: what does it mean for the PG?

Scenario #1

Pair fluctuations/phase connected to SC

Nodal and Antinodal gaps have the same order parameter and scale with T^*

Above T_c coherence is destroyed but pair fluctuation gap persists

This gap disappears when the temperature dependent Fermionic damping exceeds the pair-energy

Nodal gap is smaller and hence disappears at lower temperatures

Scenario #2

Competing phase

Nodal gap is the superconducting gap and the antinodal gap comes from a competing phase

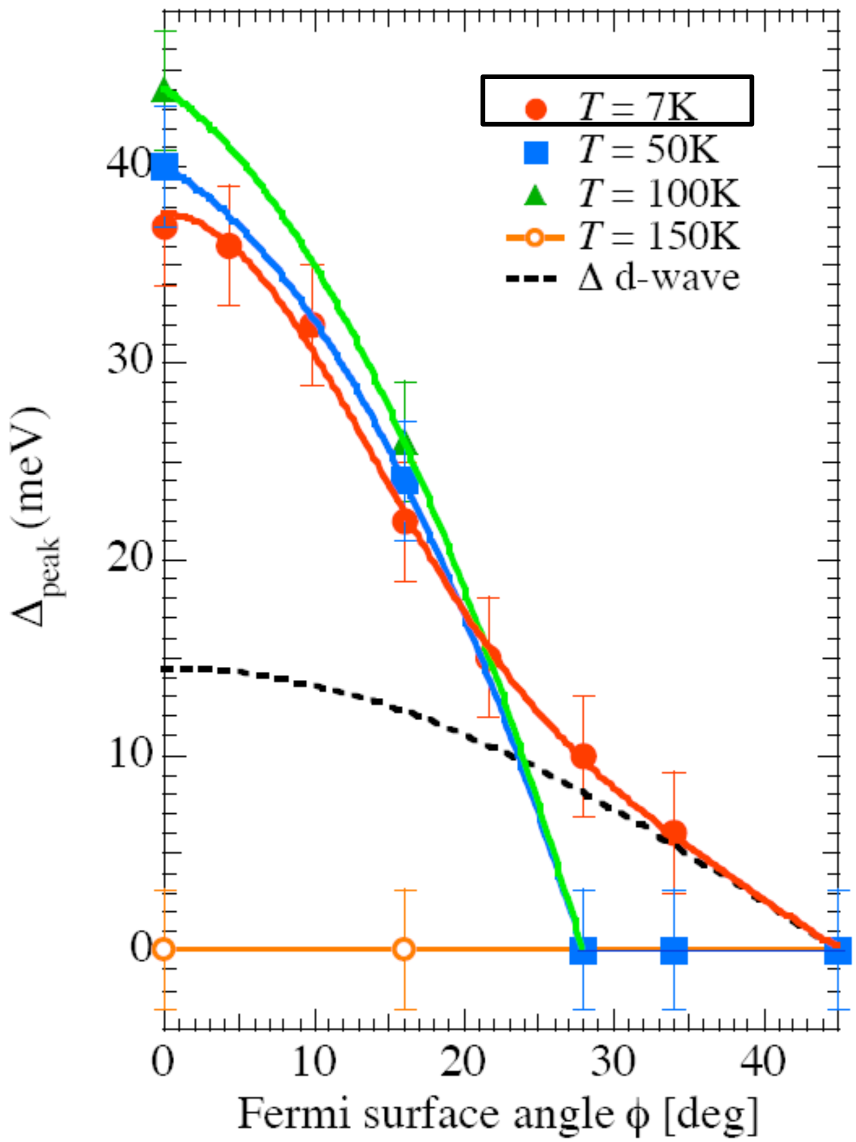
Nodal gap scales with T_c and antinodal gap scales with T^*

Both scenarios still consistent with data

A. V. Chubukov and Mike Norman, Phys. Rev. B 77, 214529 (2008)

STM and ARPES on La-Bi2201

ARPES La-Pb-2201



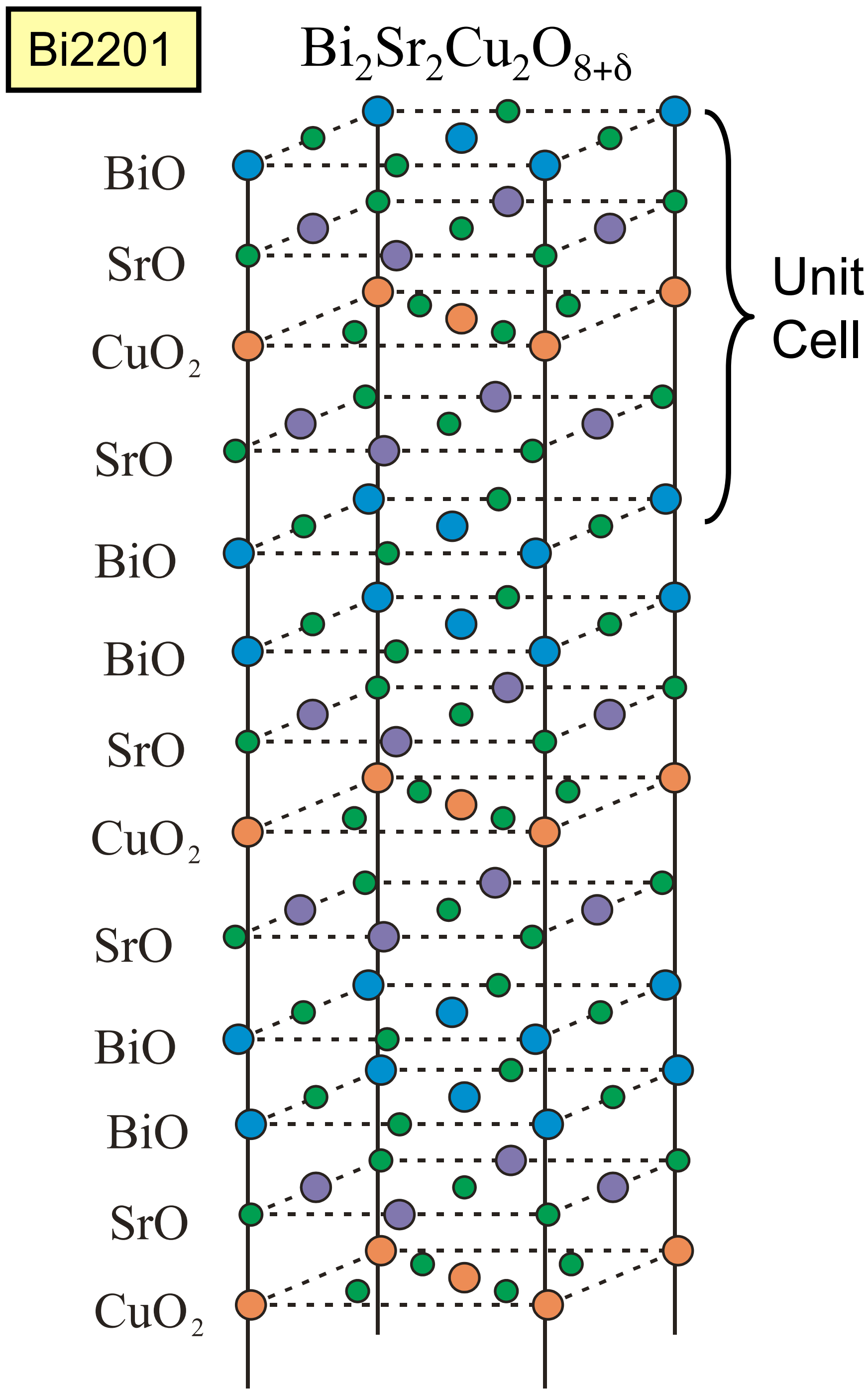
Takeshi Kondo et.al., Phys. Rev. Lett. **98**, 267004 (2007)

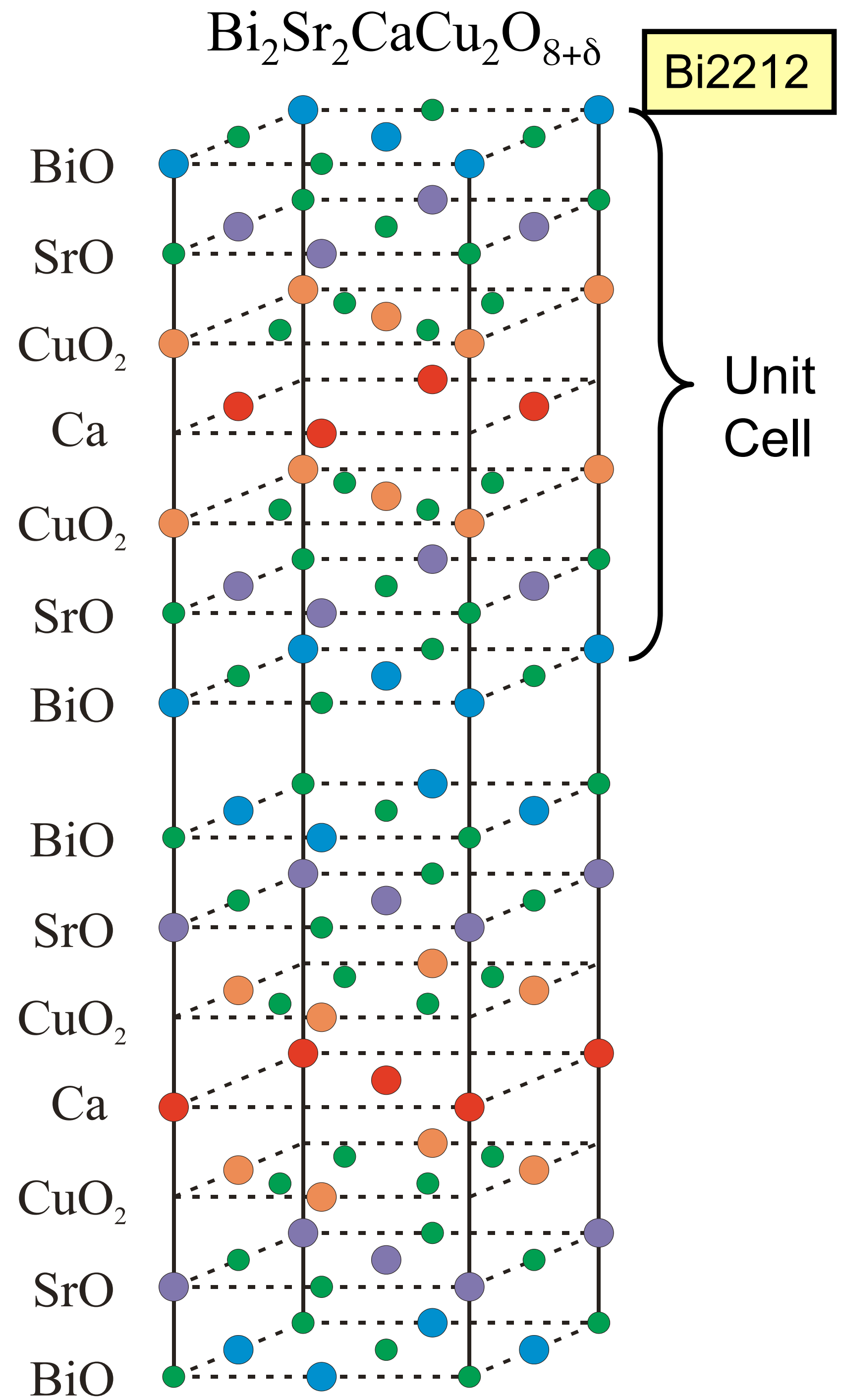
La-Bi2201

PG and superconducting gap energy scales well separated

Optimal T_c = 34K

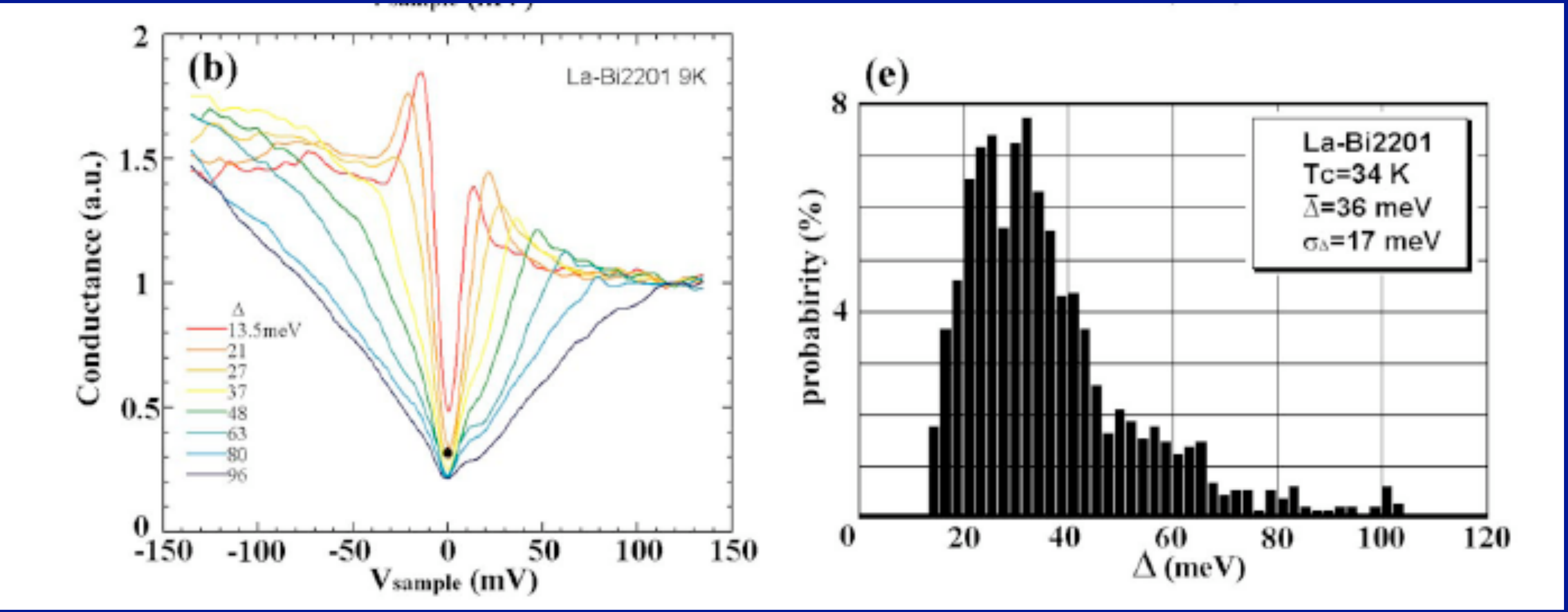
Perfect for both STM and ARPES measurements


Bi2201
$Bi_2Sr_2Cu_2O_{8+\delta}$
BiO
SrO
CuO_2
SrO
BiO
BiO
SrO
CuO_2
SrO
BiO
BiO
SrO
CuO_2
Unit Cell


$Bi_2Sr_2CaCu_2O_{8+\delta}$
Bi2212
BiO
SrO
CuO_2
Ca
CuO_2
SrO
BiO
BiO
SrO
CuO_2
Ca
CuO_2
SrO
BiO
Unit Cell

Earlier STM on La-Bi2201

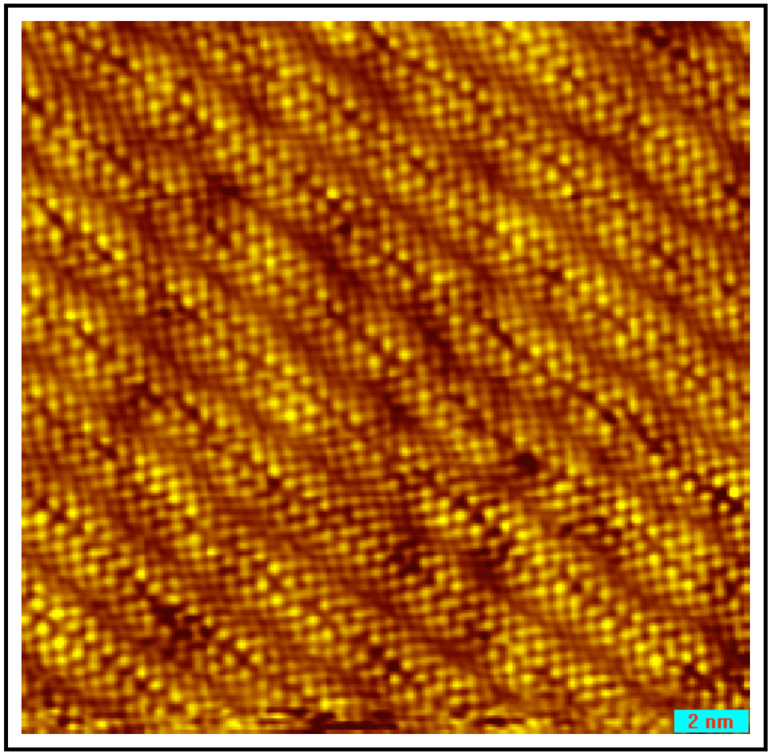
Problem: Using $2\Delta/k_bT_c = 8$, We expect $\Delta_{av} \sim 11meV$

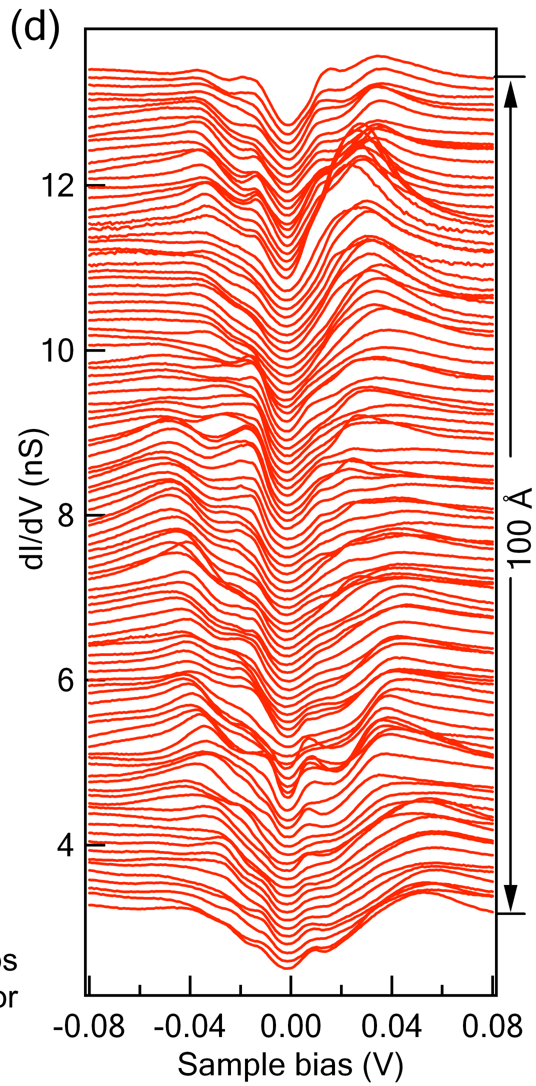


A. Sugimoto,S. Kashiwaya, H. Eisaki, H. Kashiwaya, H. Tsuchiura, Y. Tanaka, K. Fujita, and S. Uchida, Enhancement of electronic inhomogeneities due to out-of-plane disorder in $Bi_2Sr_2CuO_{6+\delta}$ superconductors observed by scanning tunneling spectroscopy, Phys. Rev. B **74**, 094503 (2006)

STM on 0.4La-Bi 2201

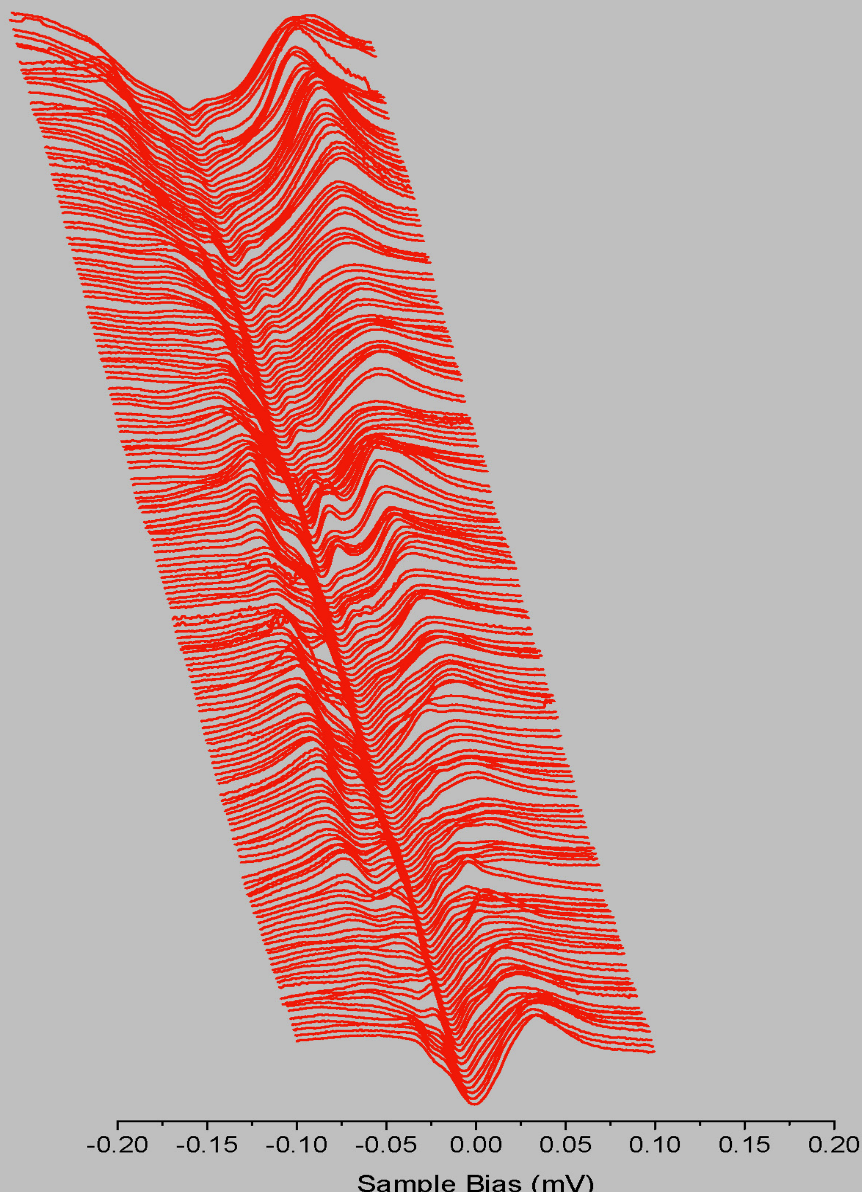
T_c = 32 K, (optimal T_c = 34K)



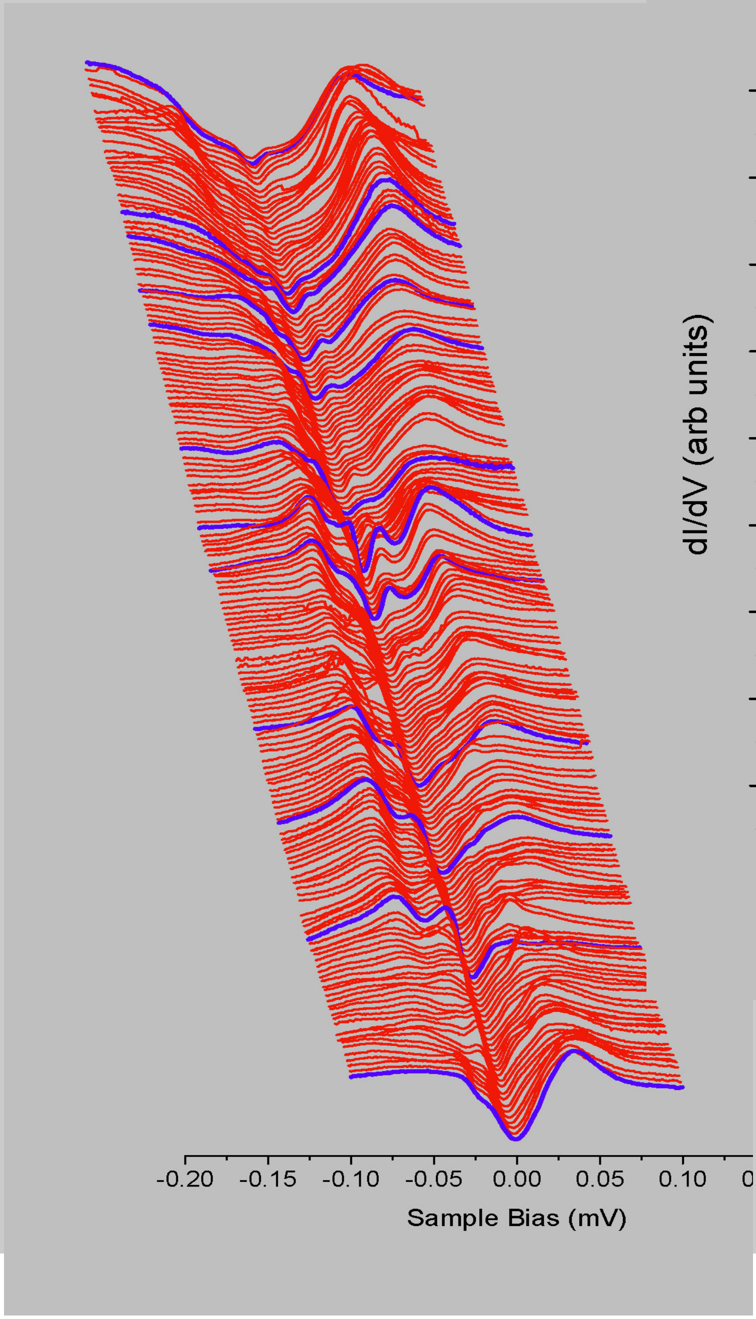


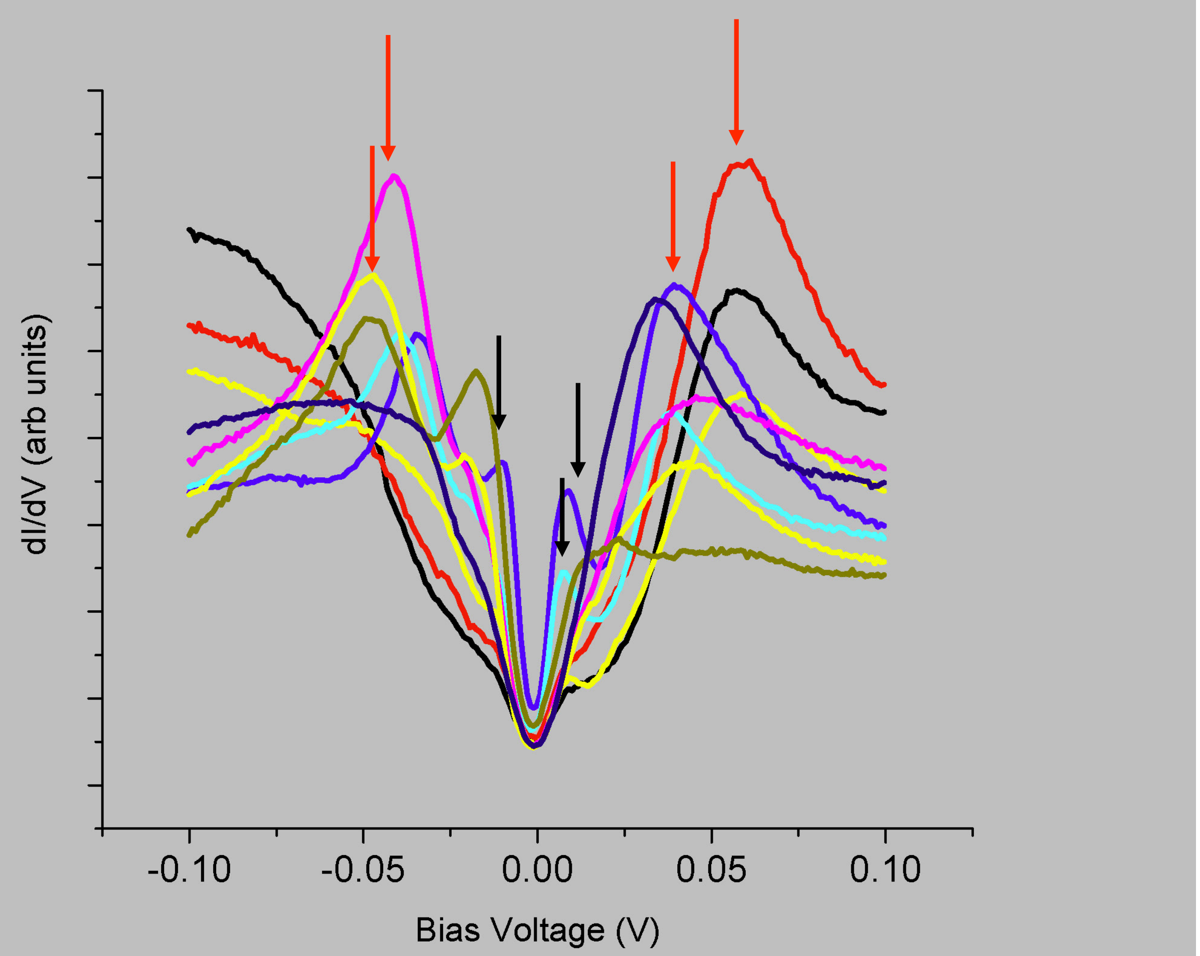
J.-H. Ma et. al., Coexistence of Competing Orders with Two Energy Gaps in Real and Momentum Space in the High Temperature Superconductor $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$, ***Phys. Rev. Lett.*** 101, 207002 (2008)

STM on La-Bi 2201



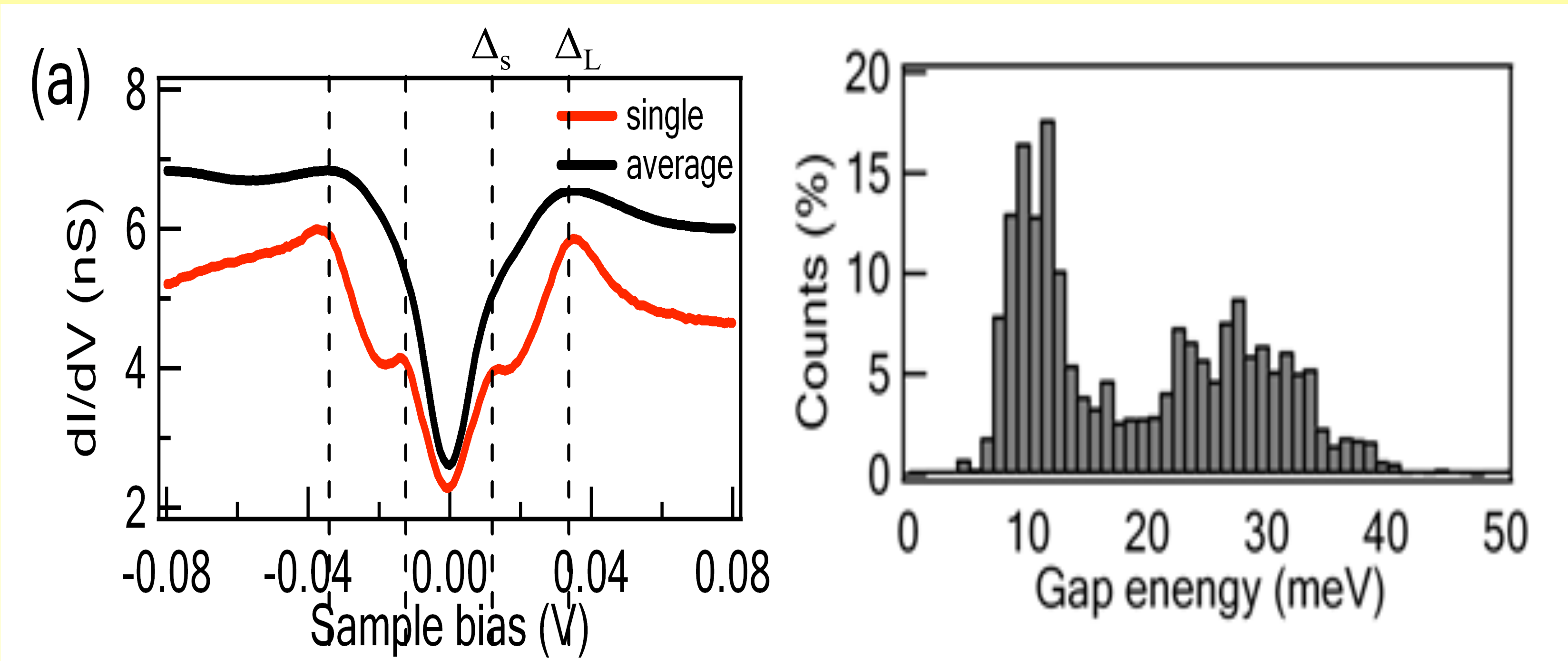
STM on La-Bi 2201





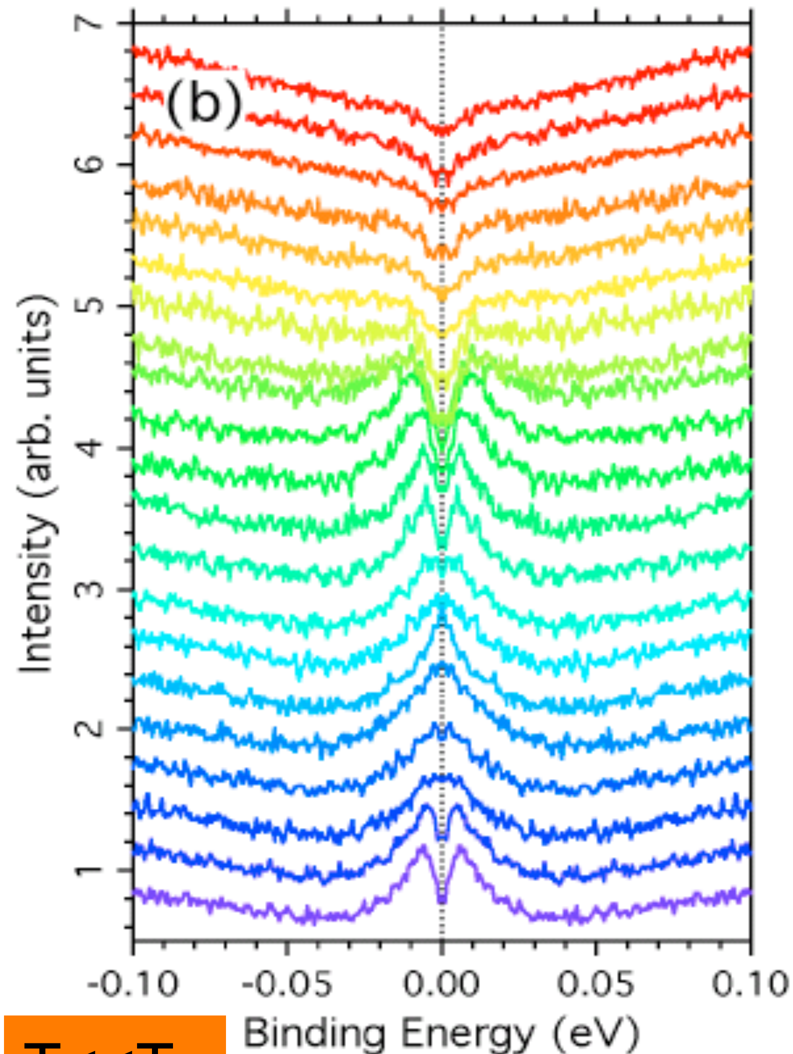
STM on 2201

$\Delta_{sav} \sim$ 12 meV
$\Delta_{Lav} \sim$ 30meV

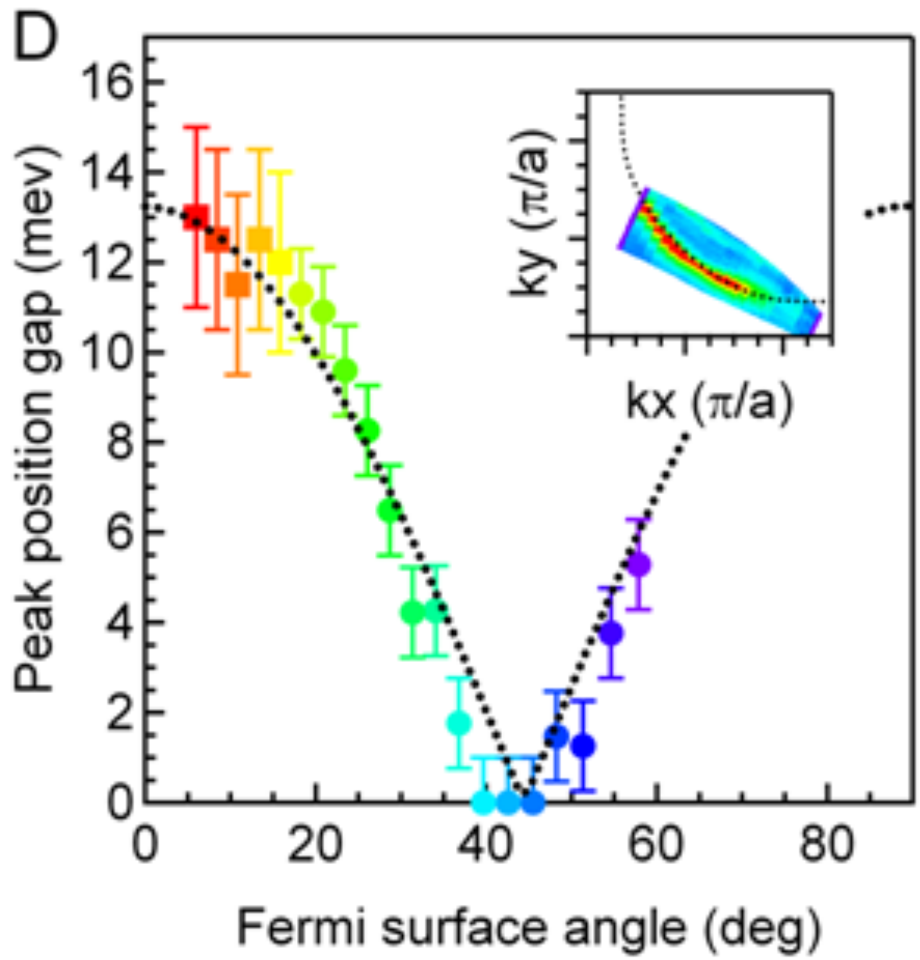


What do these two energy scales represent?

ARPES (EDC)

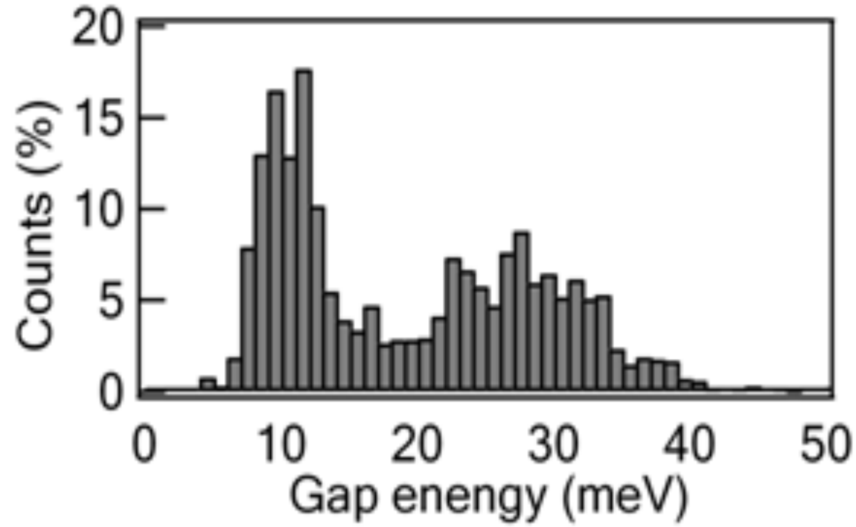


T<<T_C

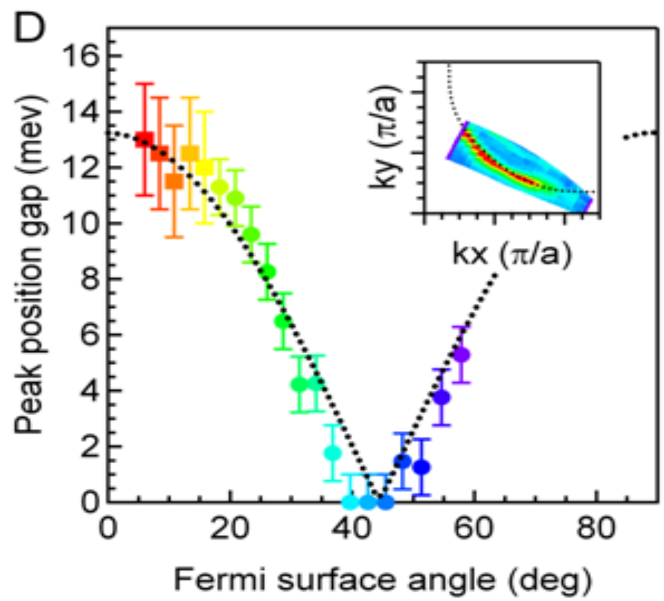


J.-H. Ma et. al., $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$, ***Phys. Rev. Lett.*** 101, 207002 (2008)

Comparison with ARPES



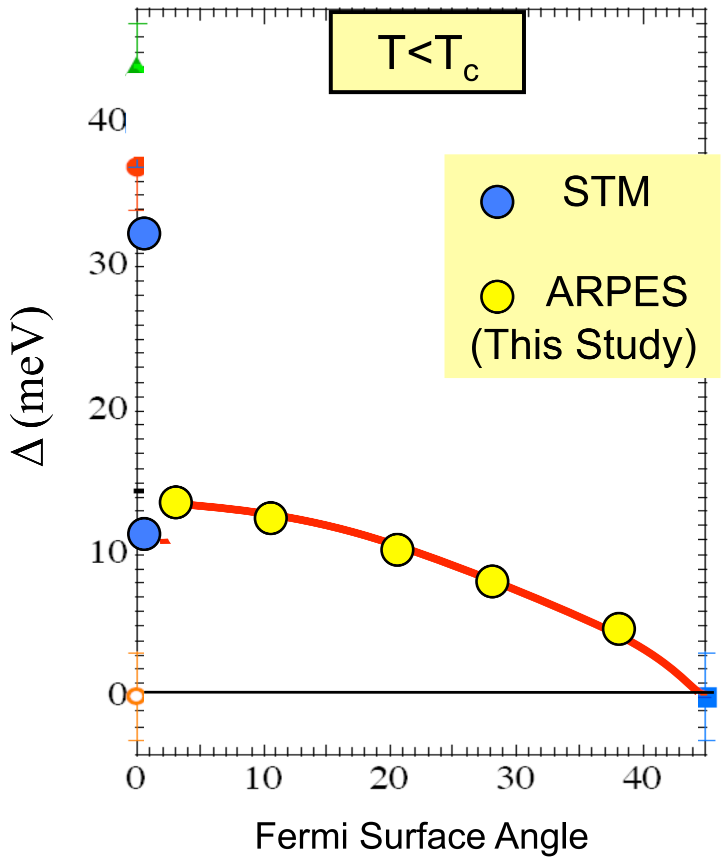
STM

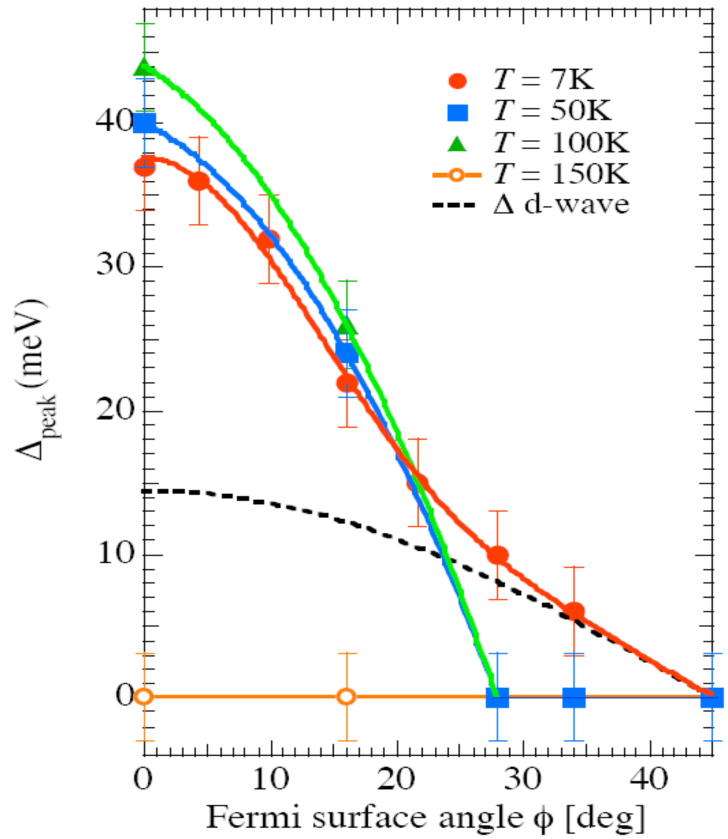


ARPES

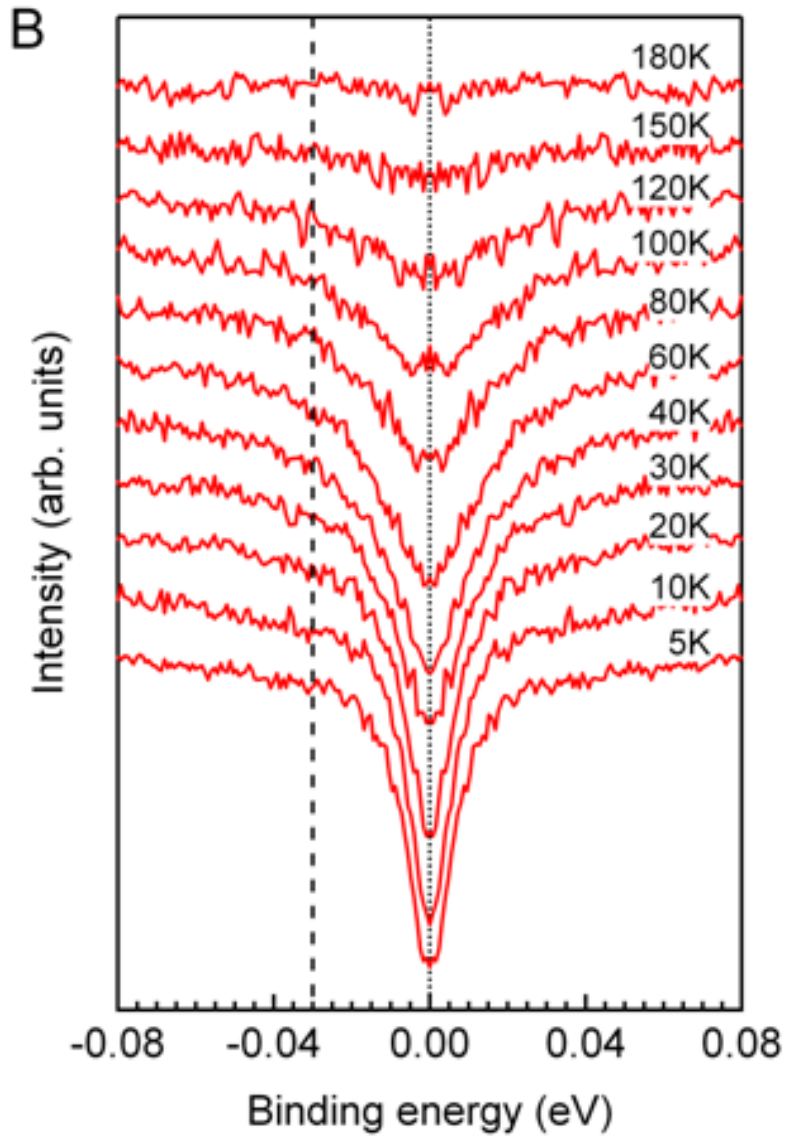
$T << T_C$

STM and ARPES





ARPES (EDC): Temperature Dependence

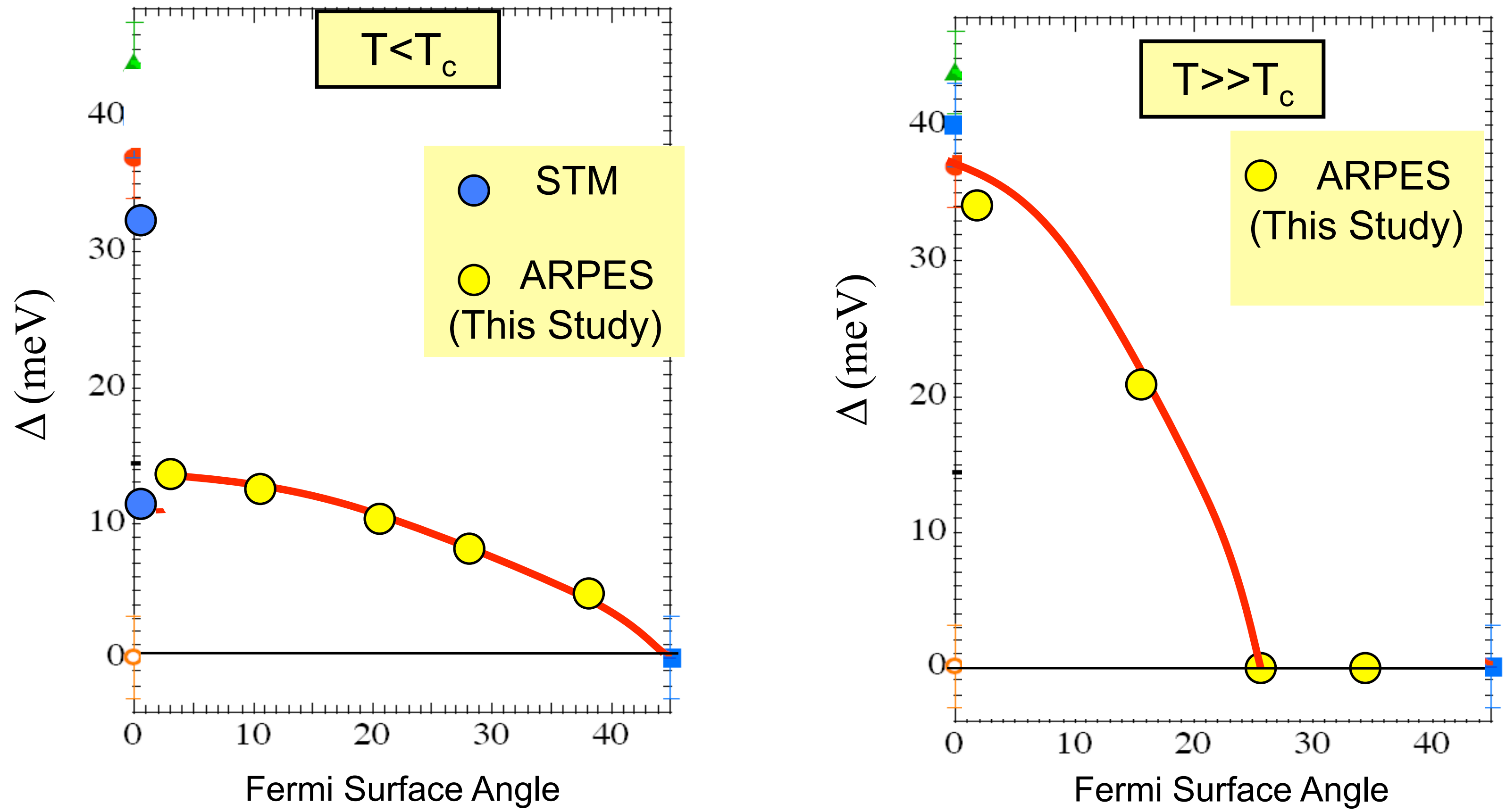


Δ_{AN} (> T_c) ~ Δ_L

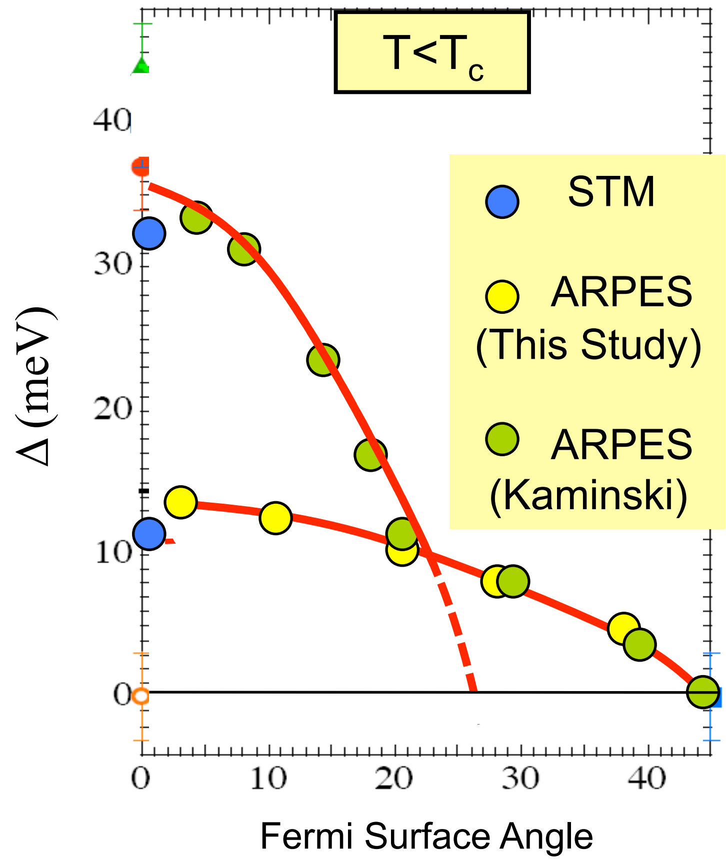
5K < T < T*

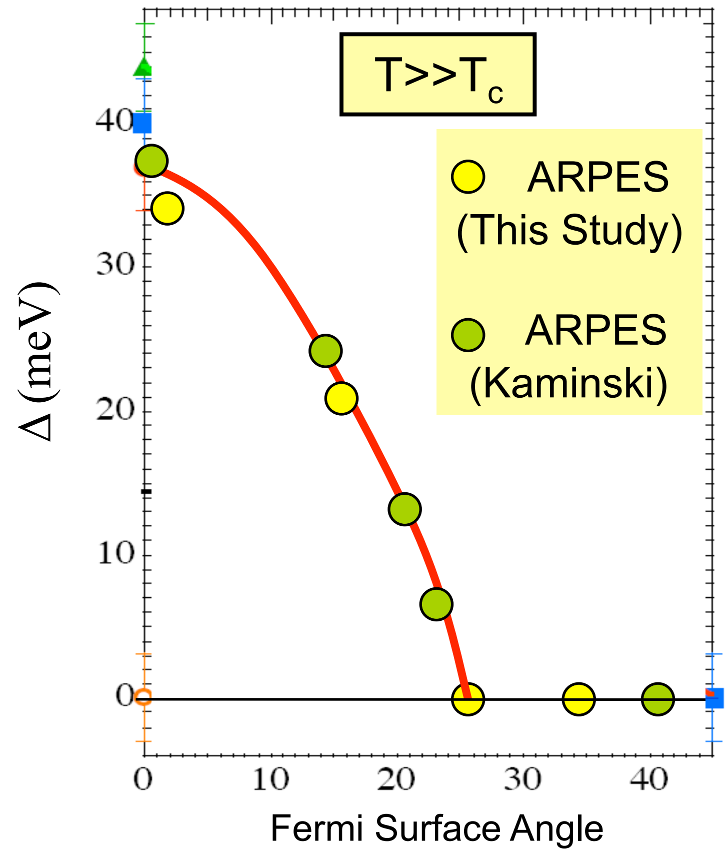
J.-H. Ma et. al., $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$, ***Phys. Rev. Lett.*** 101, 207002 (2008)

STM and ARPES



Summary



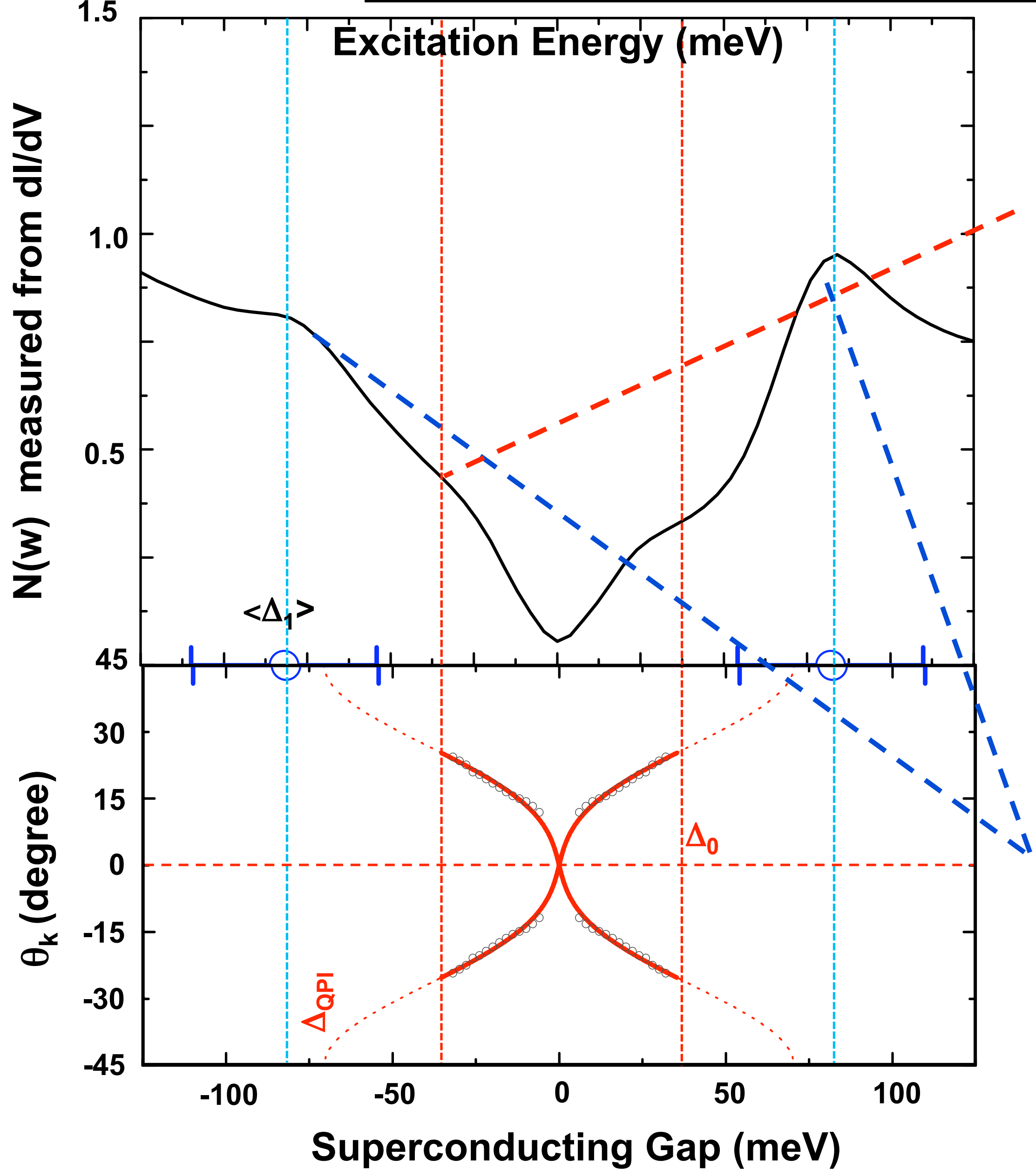


Coexistence of two gaps in real and momentum space below T_c

Larger gap arises from coexisting but competing phase

Has this been observed in 2212?

Underdoped Bi2212

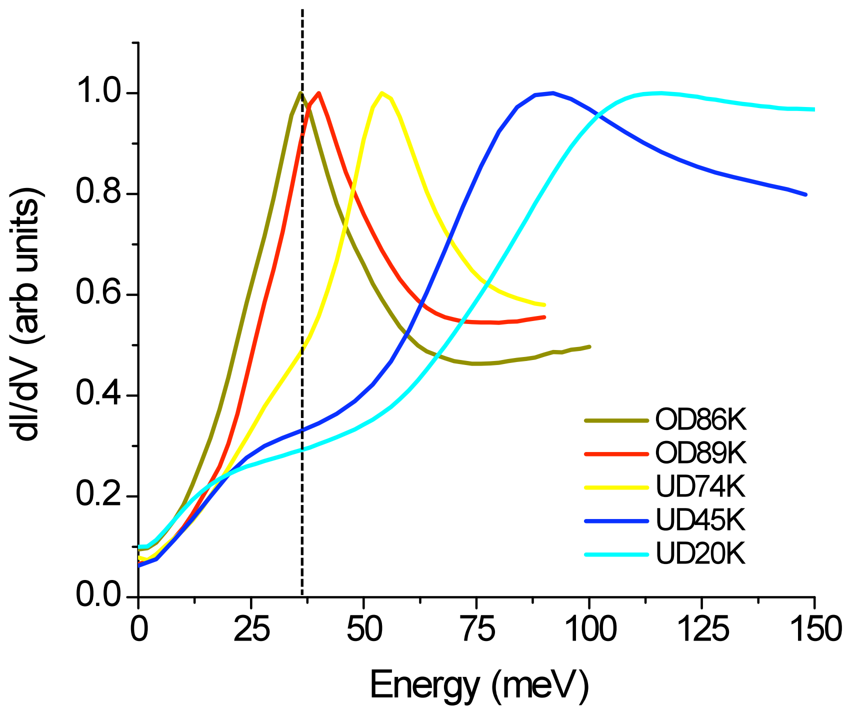


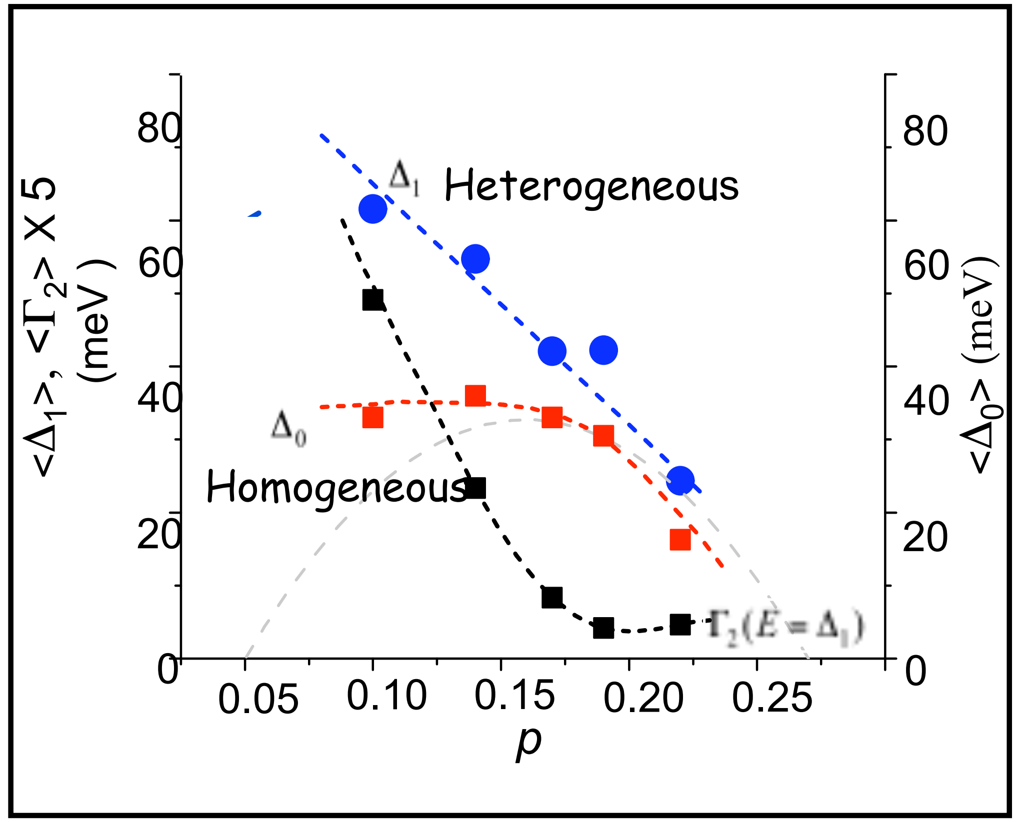
$E<\Delta_0$: see Bogoliubov QP

$E=\pm\Delta_1$: see *r*-space PG states

Evolution of average kink energy $\langle\Delta_0\rangle$ with p

Nature Physics 4, 319 (2008)





Courtesy: Seamus Davis

Open question: What is the nature of this competing phase?

Bi 2212

- Checkerboard charge modulation in large gap regions/underdoped 2212 (Periodicity ~$4a_0$)

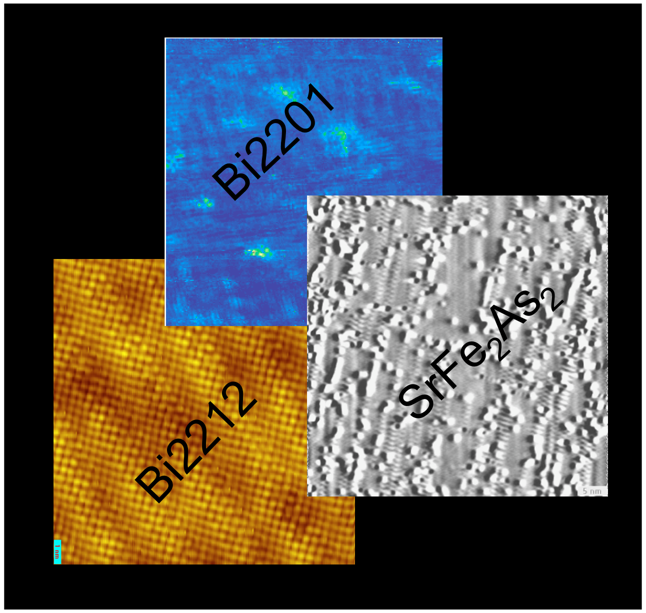
K. McElroy..J. C. Davis, et.al., Nature 422, 592 (2003)

- Checkerboard above T_c

M. Vershinin, A. Yazdani, Science 303, 1995 (2004)

- Checkerboard in Vortex core

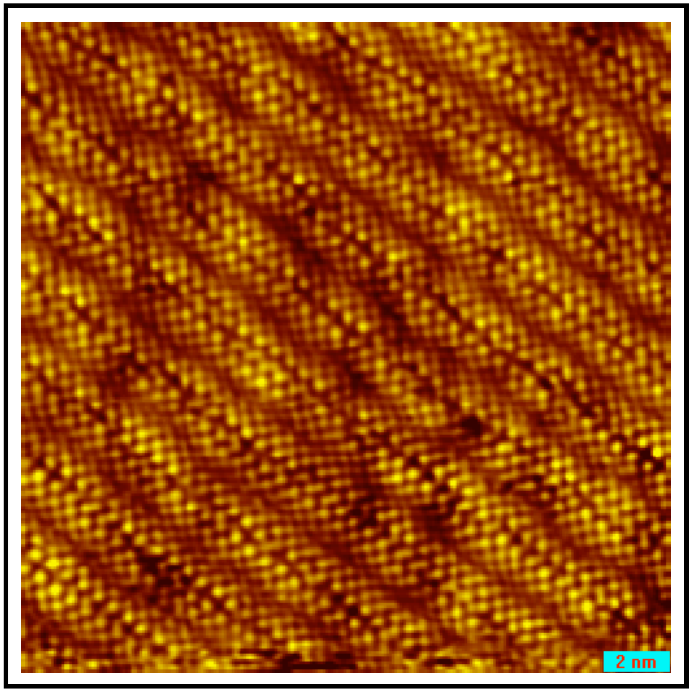
J. E. Hoffman, ..J. C. Davis, Science 295, 466 (2002)



Evidence for Charge Order in 2201

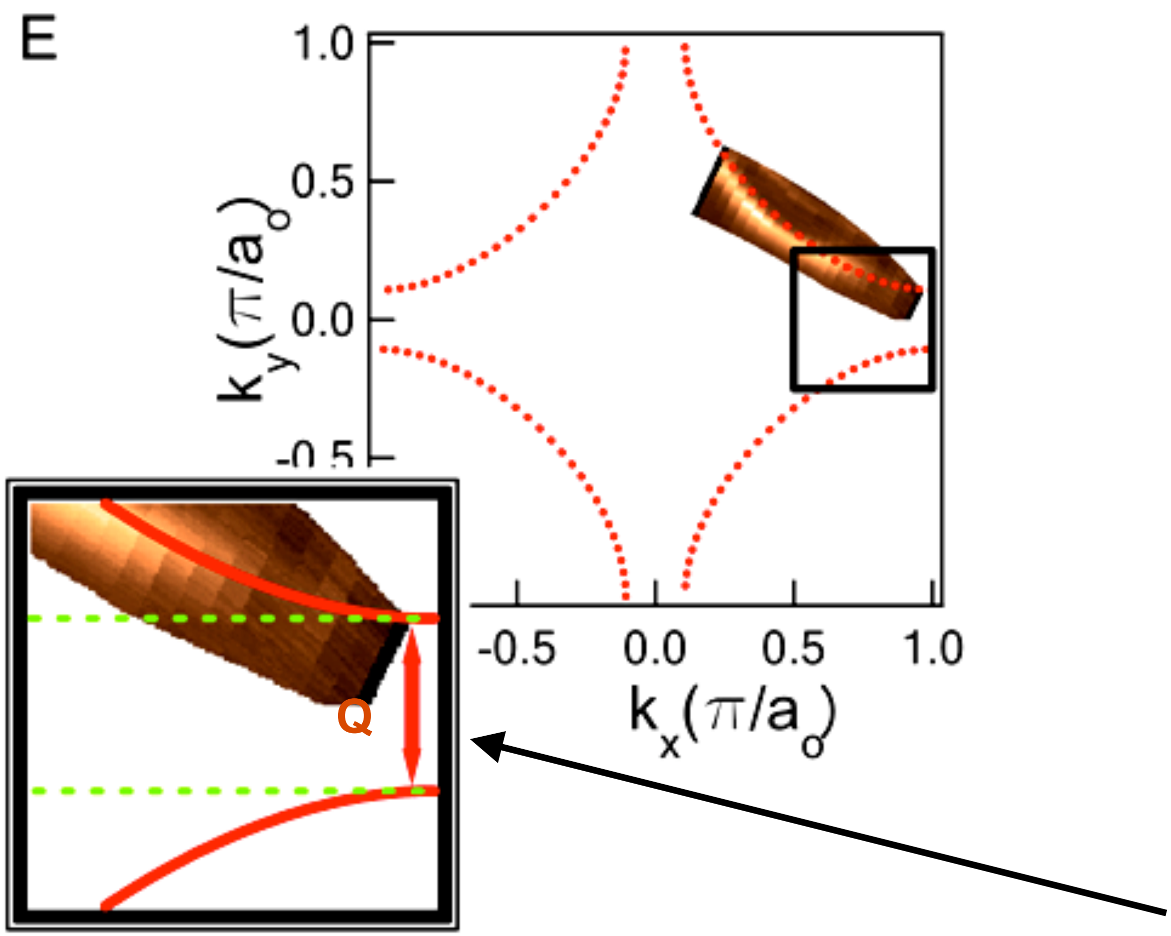
Charge Modulation

Periodicity~$5a_0$~19Å



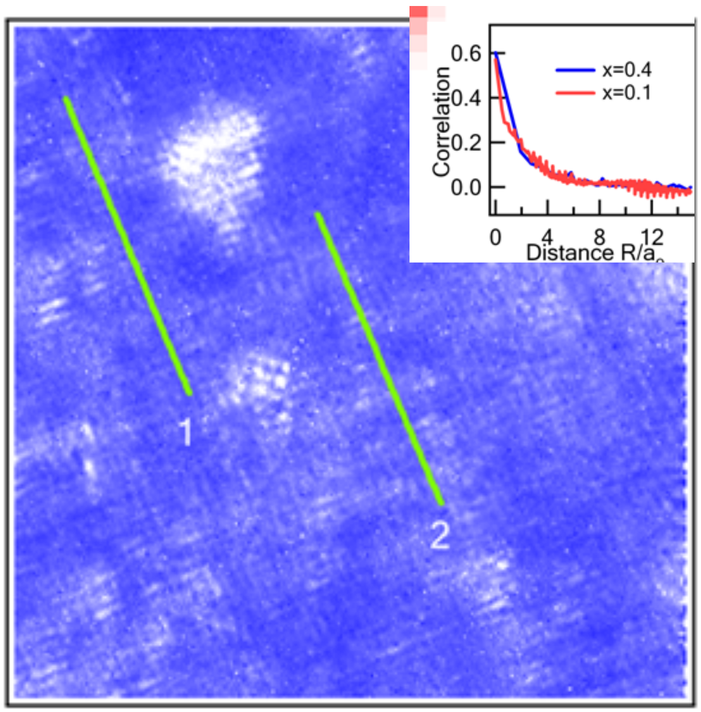
Is this a CDW?

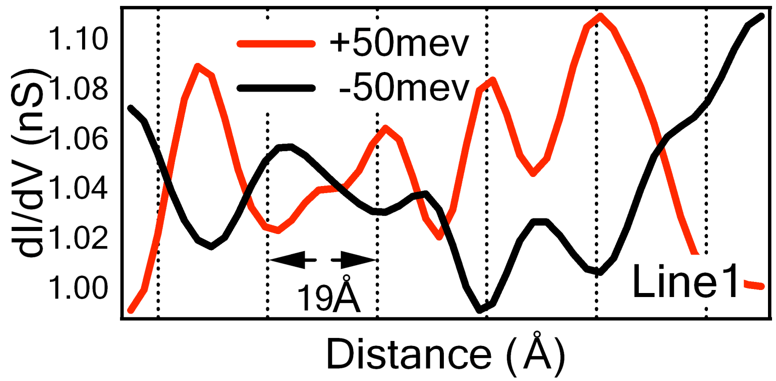
ARPES Nesting vector

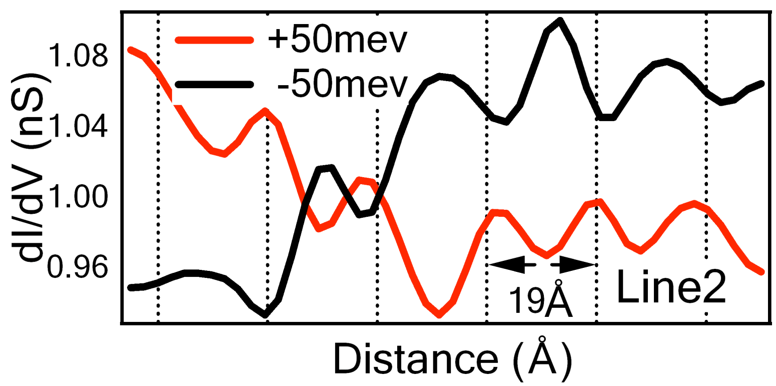


Q= 2π/5a

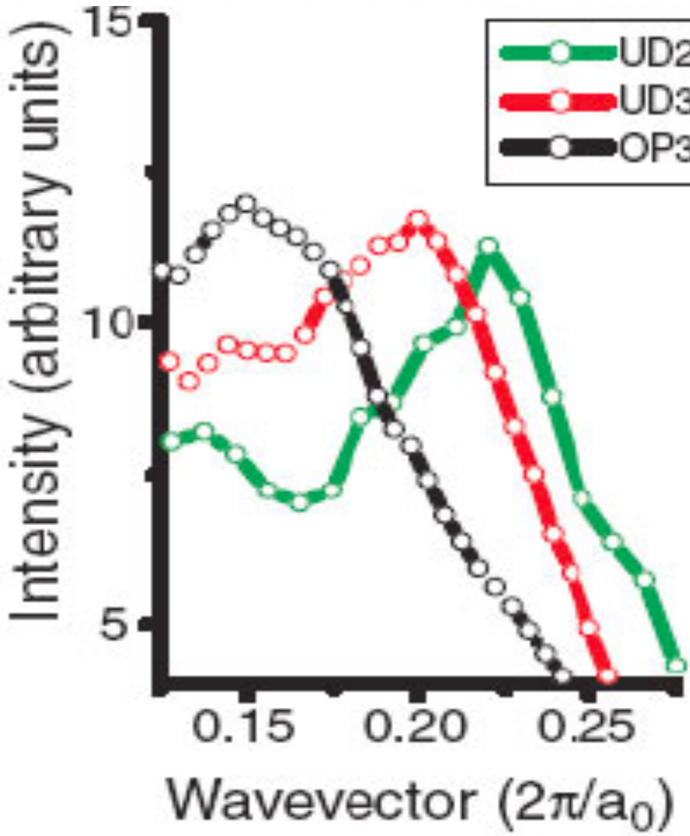
Evidence for CDW: contrast reversal

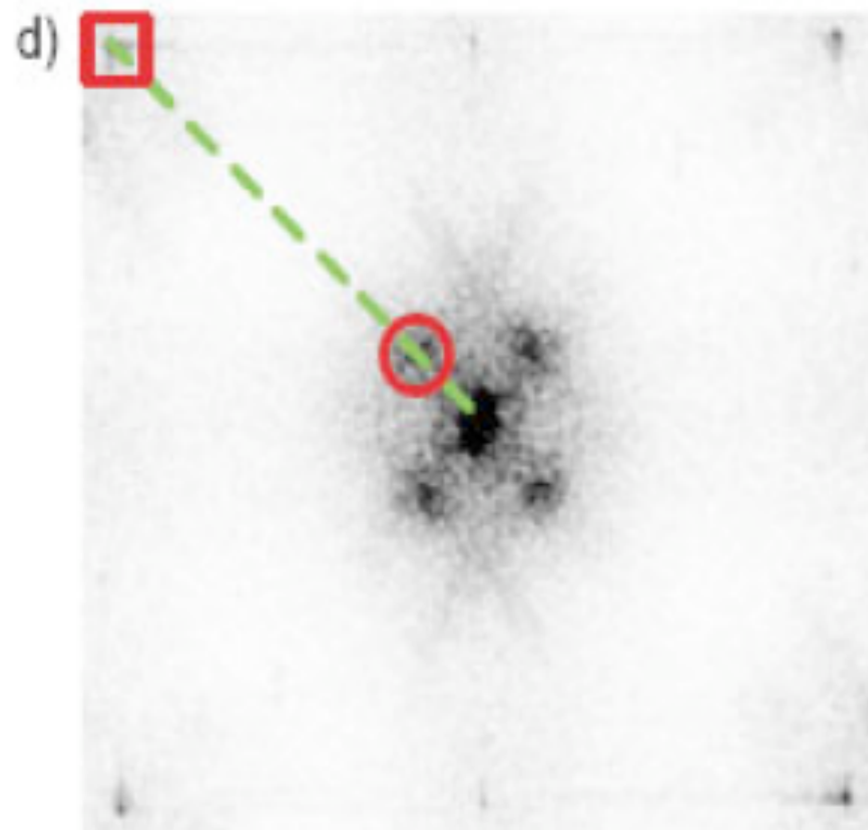






Doping dependence



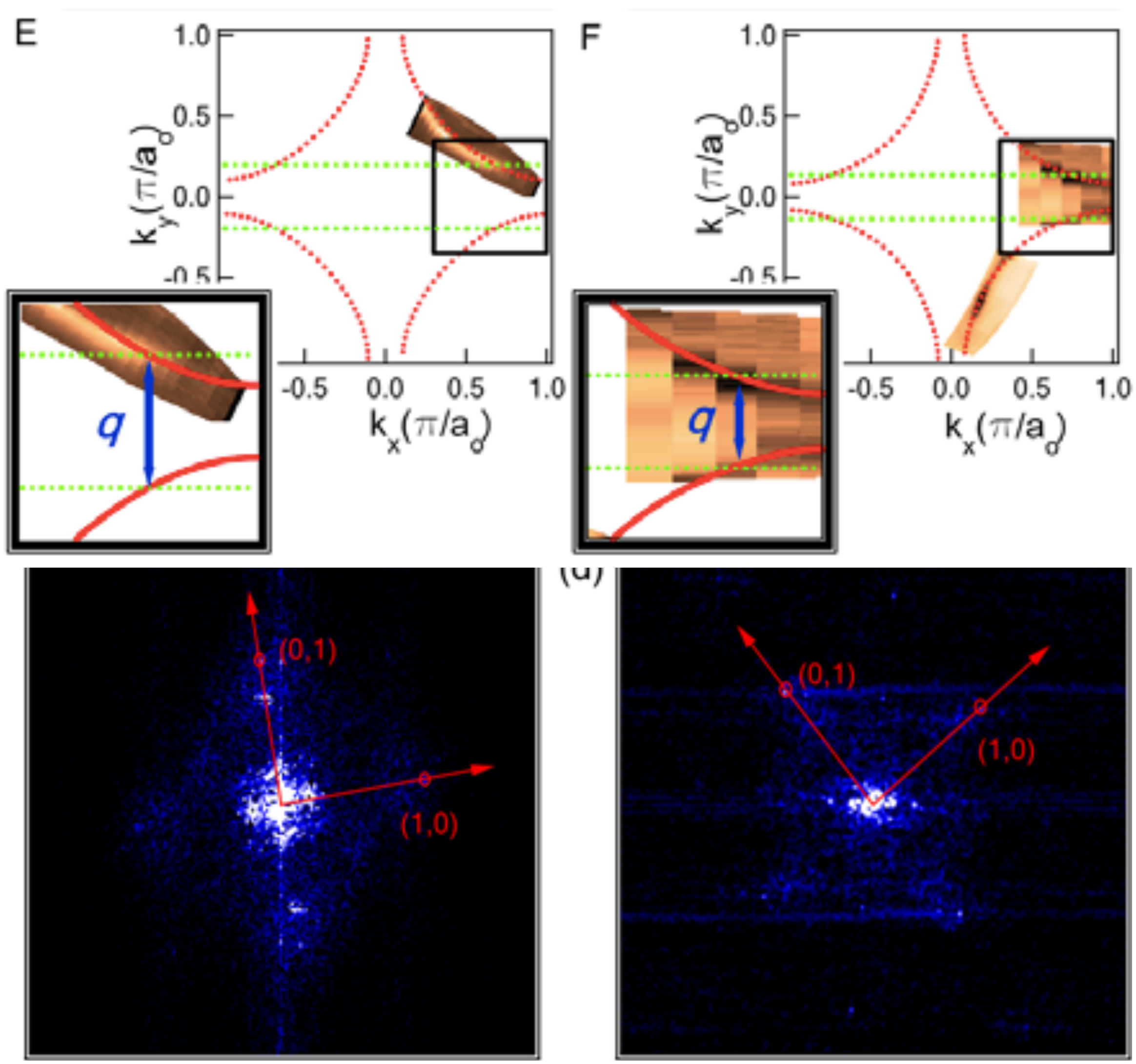


La-Pb-Bi2201

W. D. Wise.. E. W. Hudson, et.al.,

Nature Physics, Advanced Online Publication: 6 July 2008

Overdoped 2201: Charge Modulation Suppressed



Summary of our findings

We find two distinct energy scales (Δ_s and Δ_L) in the local STM spectra with a clear bimodal distribution

We find two gaps in the ARPES spectra whose energies correspond to those found in STM

The smaller gap is associated with a coherence peak. The larger gap that survives above T_c can be termed the pseudogap

The data suggests that larger gap in 2201 is due to a competing phase

We find one possible candidate for this competing phase: a weak charge density wave (periodicity ~$5a_0$) with the periodicity related to Fermi surface nesting vector (not conclusive however)

The only High Temperature Superconductor family until 2008: Cuprates

New[1] High T_c Superconductors: Pnictides

(Max T_c ~ 55K)

$LaFeAsO_{1-x}F_x$, etc
(1111)

$BaFe_2As_2$, $SrFe_2As_2$, etc
(122)

And others..

[1]Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono,
J. Am. Chem. Soc. **130, 3296 (2008).**

$SrFe_2As_2$ (Pnictide)

Pnictide (plural pnictides)

1. (chemistry),(dated) any binary compound of a pnictogen

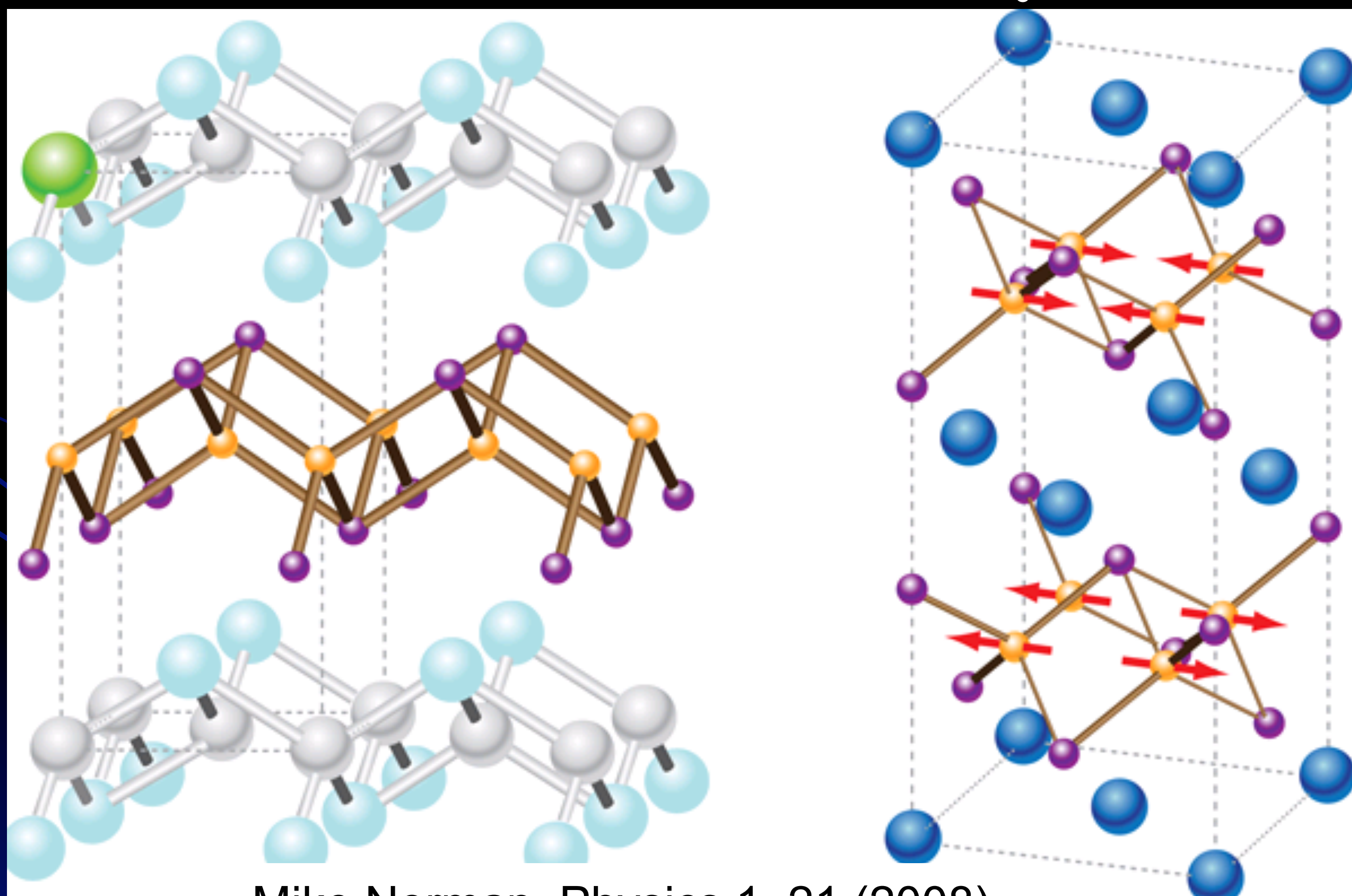
pnictogen (plural pnictogens)

1. (chemistry),(dated) any element from the nitrogen group of the periodic table; nitrogen, phosphorus, arsenic, antimony and bismuth

Pnictides: Crystal structure

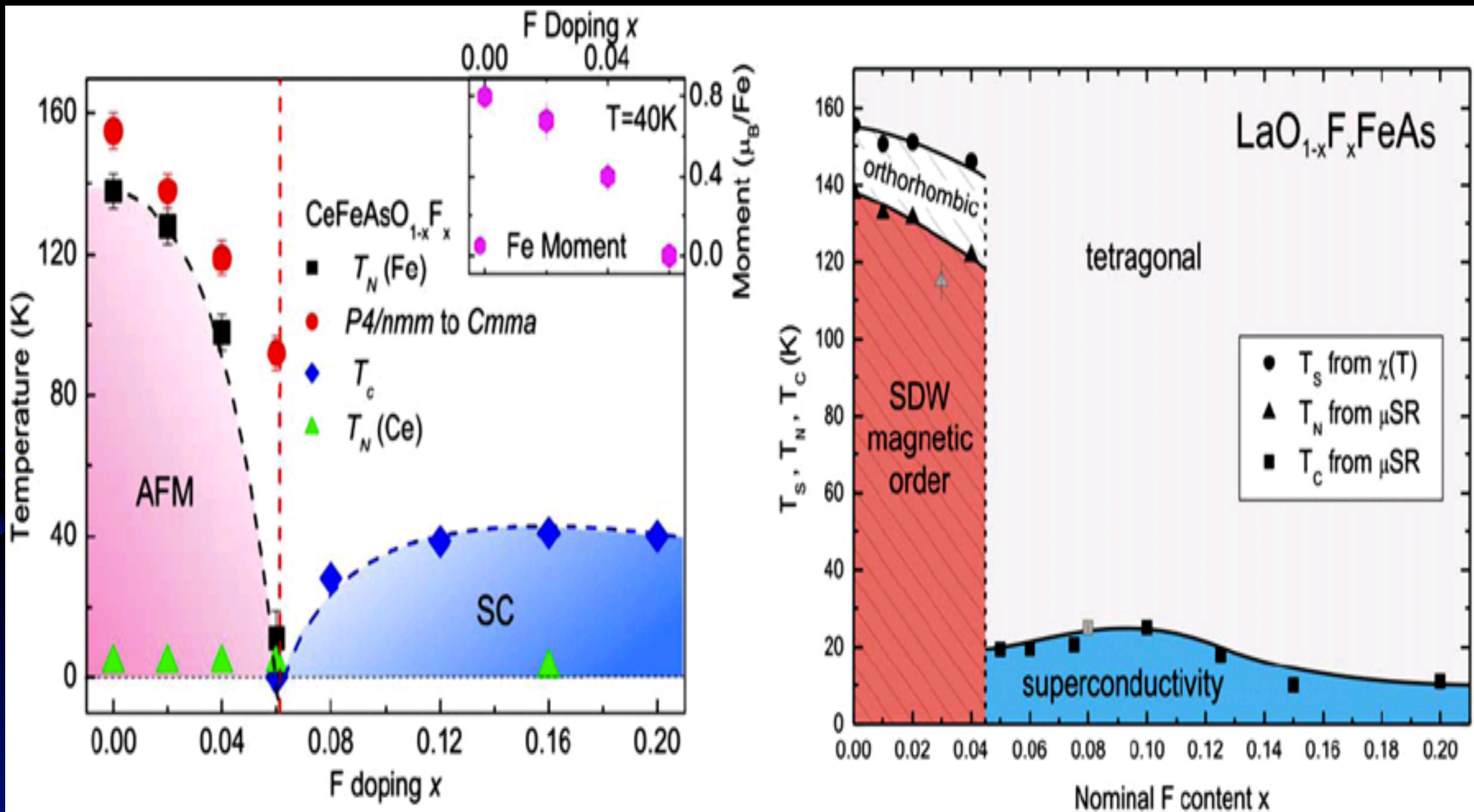
1111's
$LnFeAsO_xF_{1-x}$ (Ln is a rare earth and F is the dopant) (max T_c approximately 55 K)

122's
$Ba_{1-x}D_xFe_2As_2$ (Ba = Ca/Sr and D, the dopant atom, = Co/K) (max T_c approximately 37 K)



Mike Norman, Physics 1, 21 (2008)

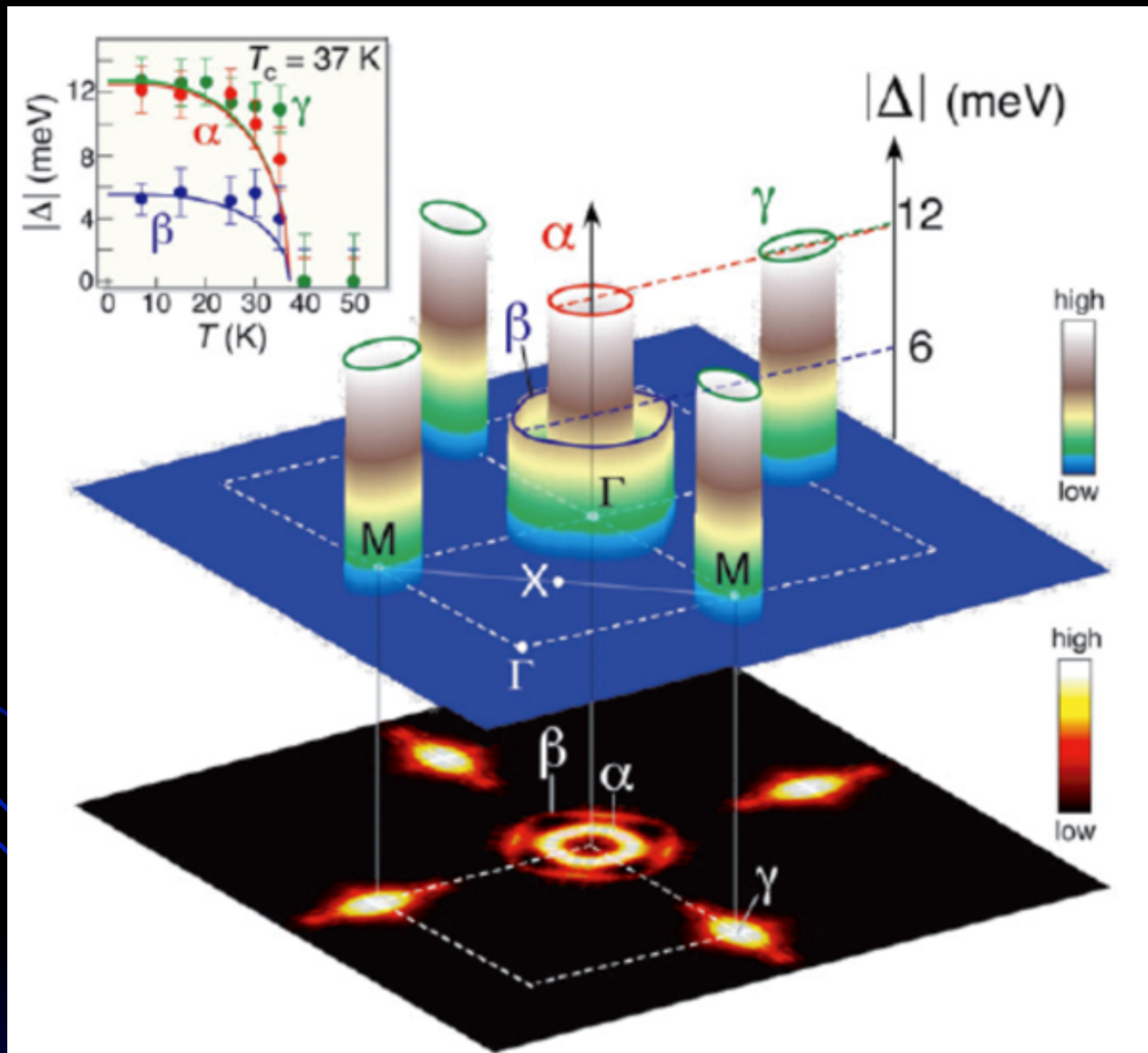
Phase Diagram



J. Zhao, et.al, arXiv:0806.2528.
H. Luetkens, et.al, arXiv:0806.3533.

Mike Norman, Physics 1, 21 (2008)

Superconducting Gap



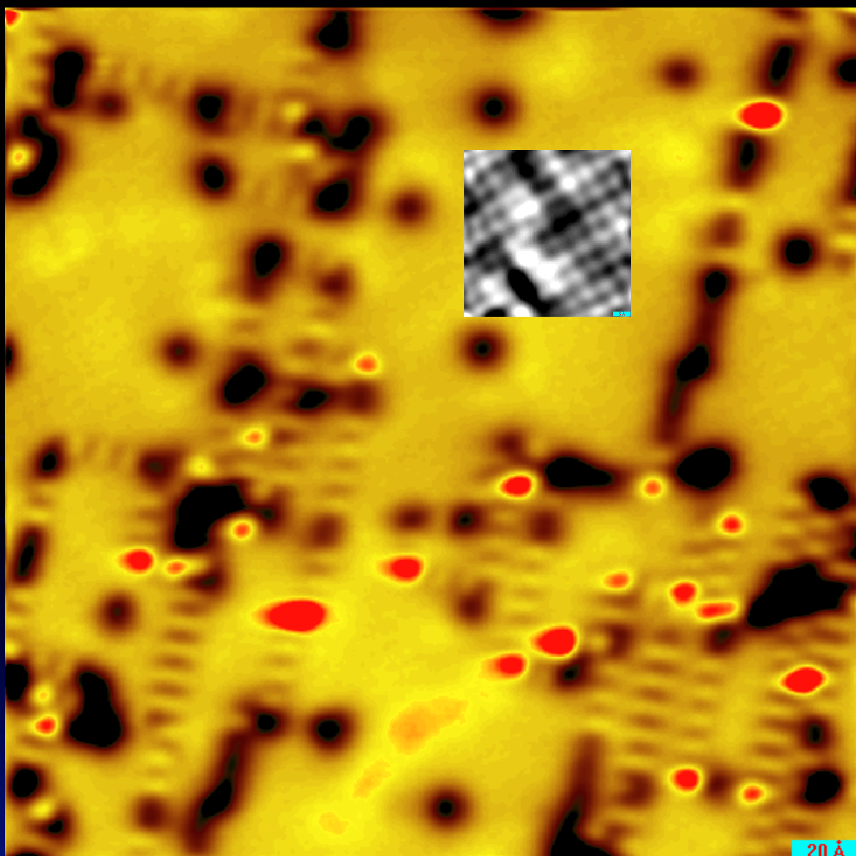
H. Ding *et al.*, Europhys. Lett. **83**, 47001 (2008)

STM on Parent Compound $SrFe_2As_2$

Parent Compound $SrFe_2As_2$

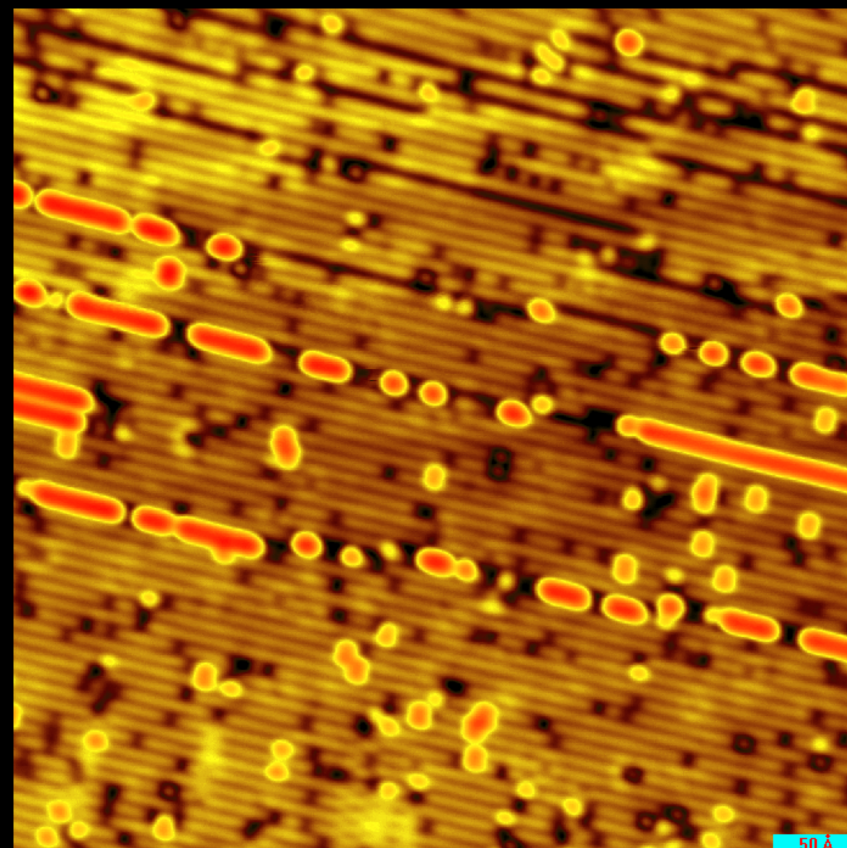
The Surface: 2 Types

Root 2 Region

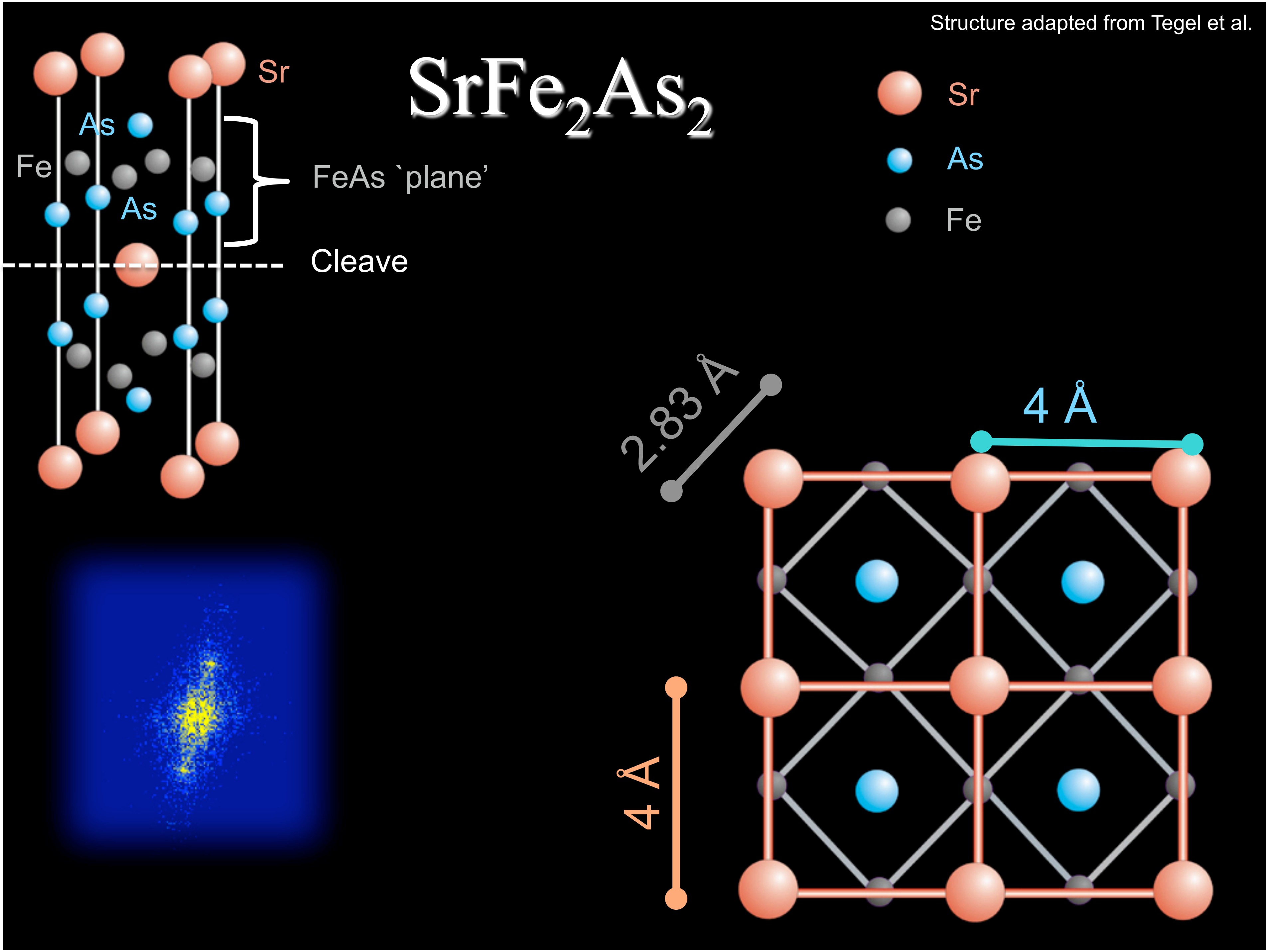


256 Å

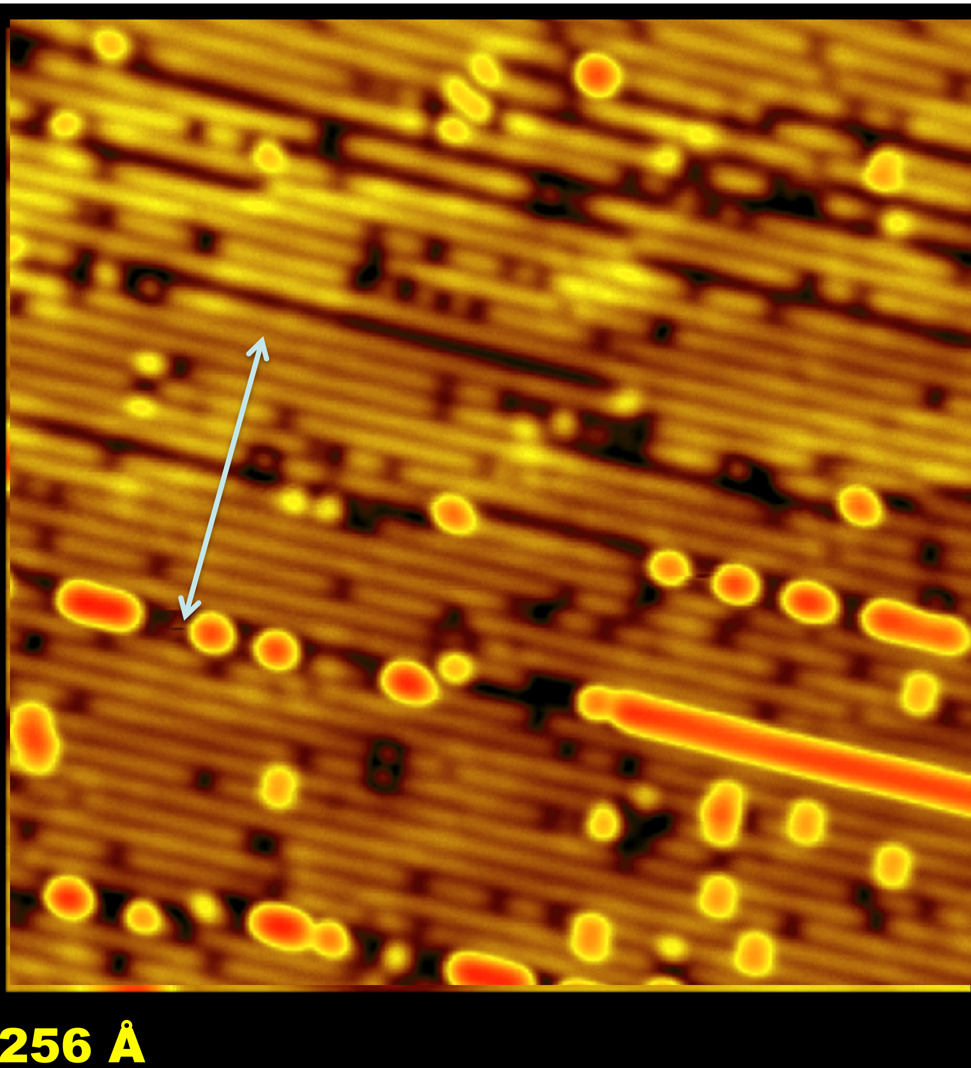
Striped Region

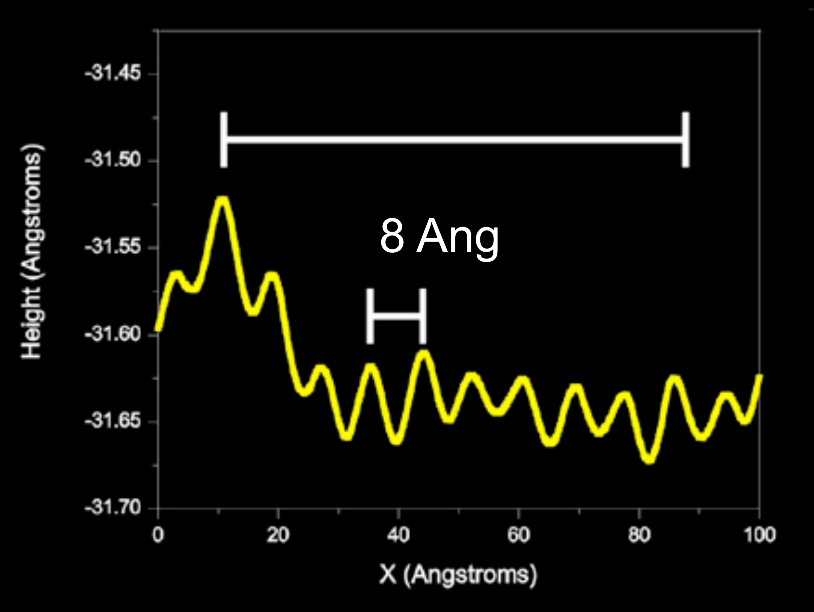


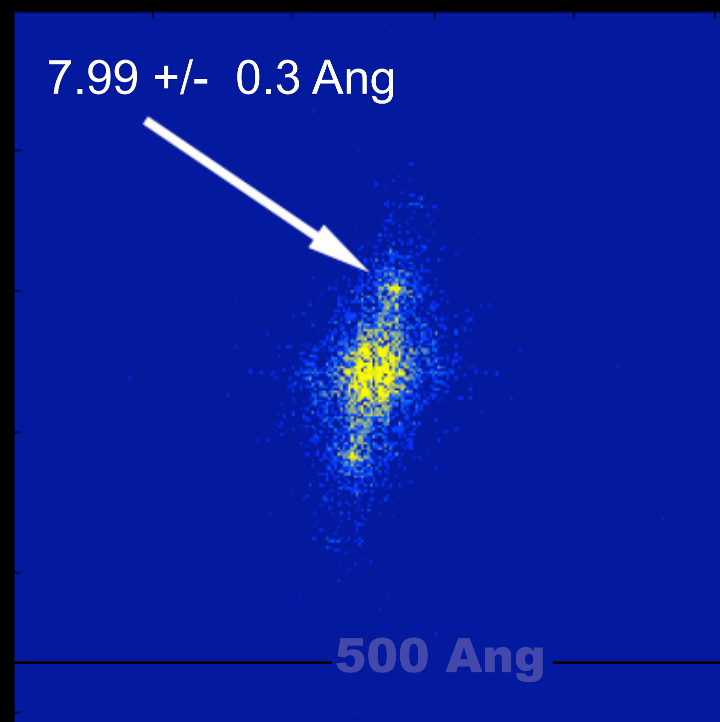
500 Å



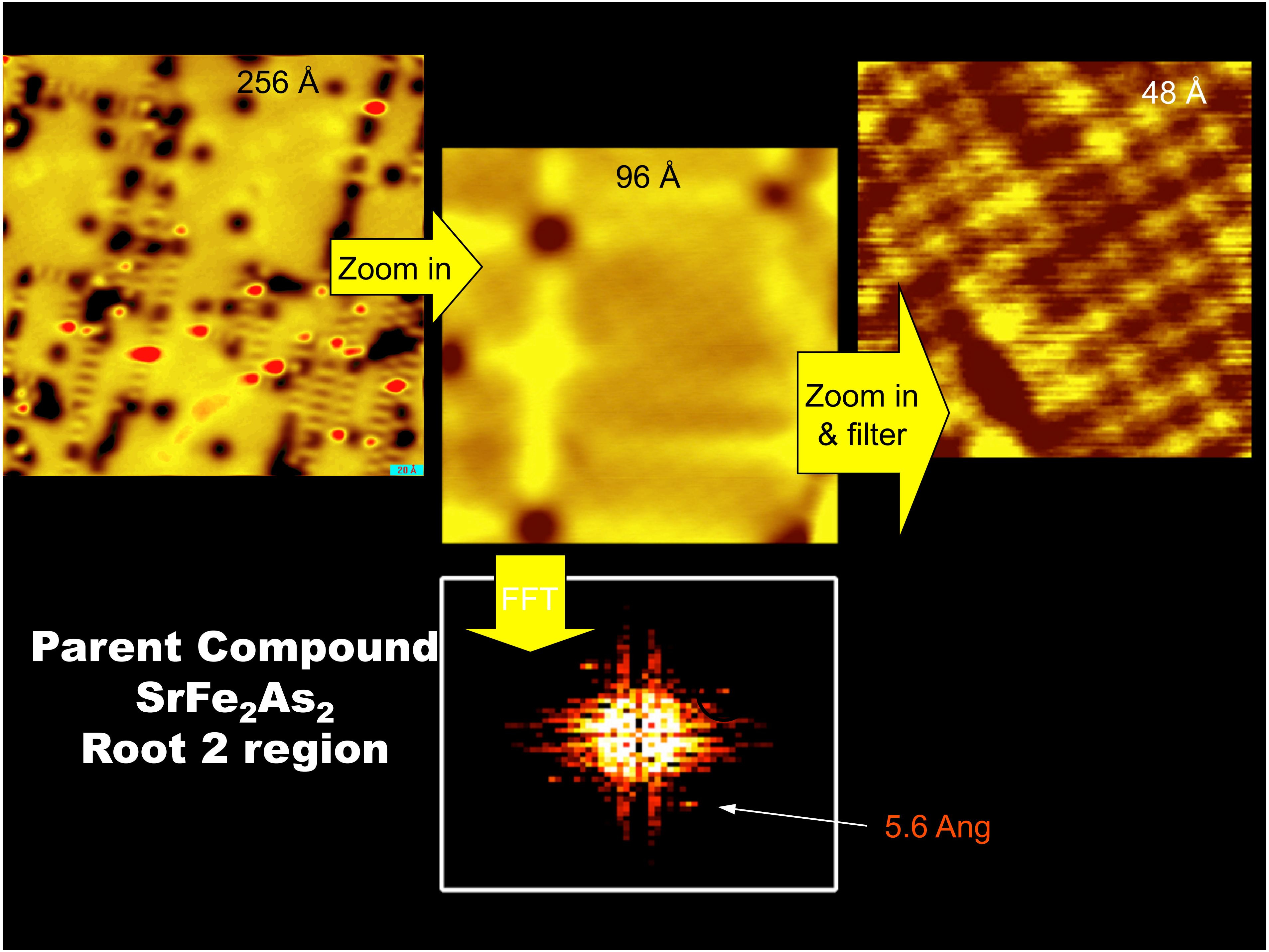
Structure adapted from Tegel et al.
SrFe2As2
Sr
As
Fe
As
FeAs `plane'
Cleave
Sr
As
Fe
2.83 Å
4 Å
4 Å

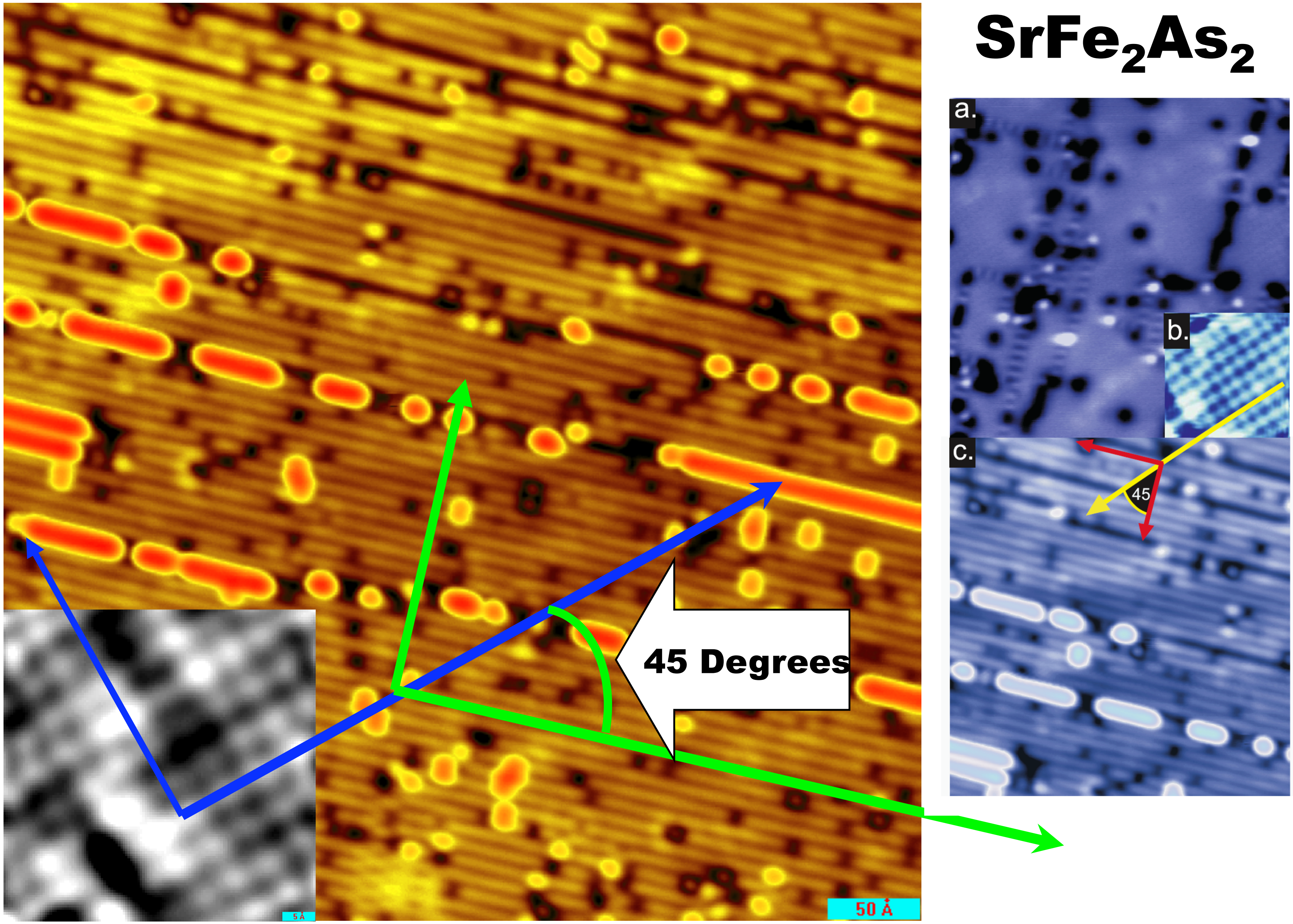




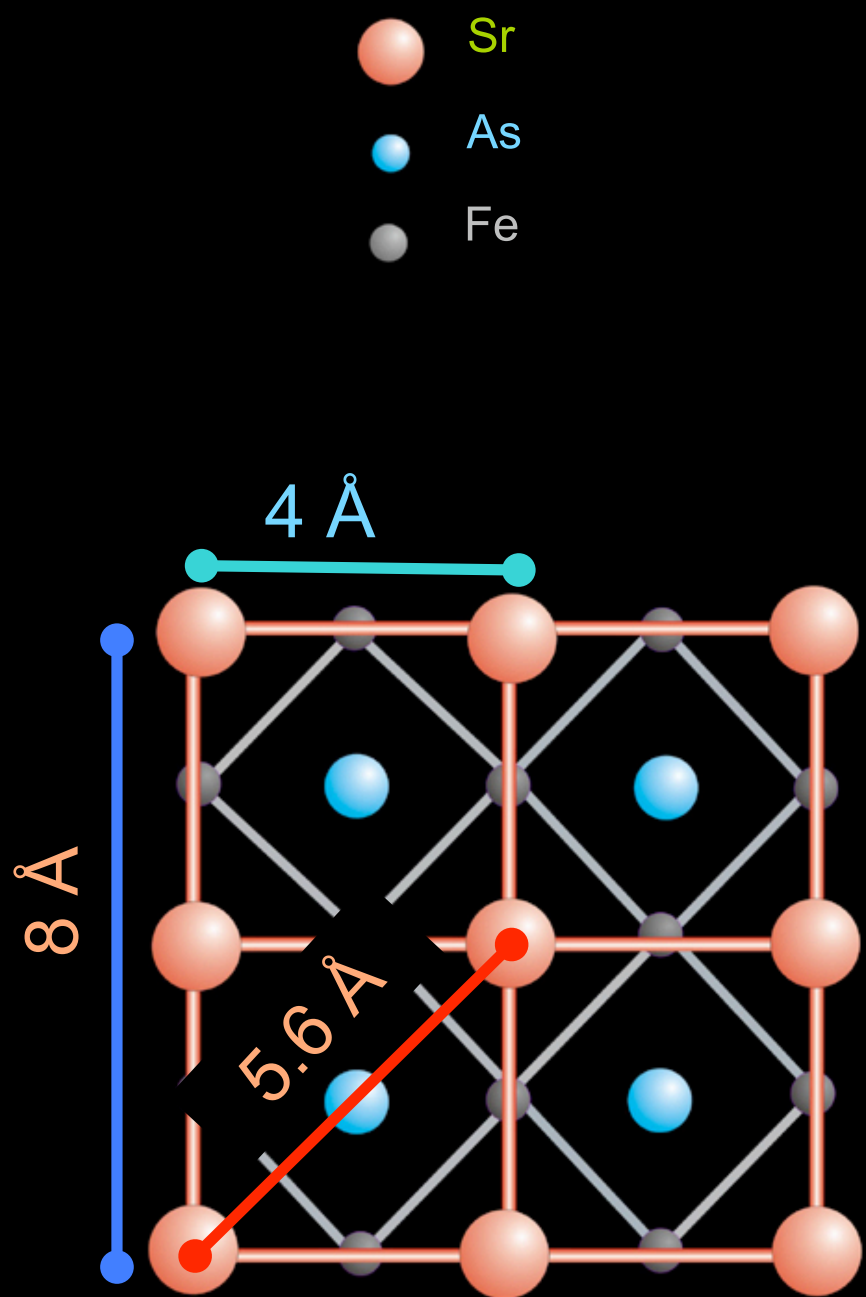


Parent Compound
$SrFe_2As_2$
Striped Region


256 Å
20 Å
Zoom in
96 Å
Zoom in
& filter
48 Å
FFT
Parent Compound
SrFe2As2
Root 2 region
5.6 Ang



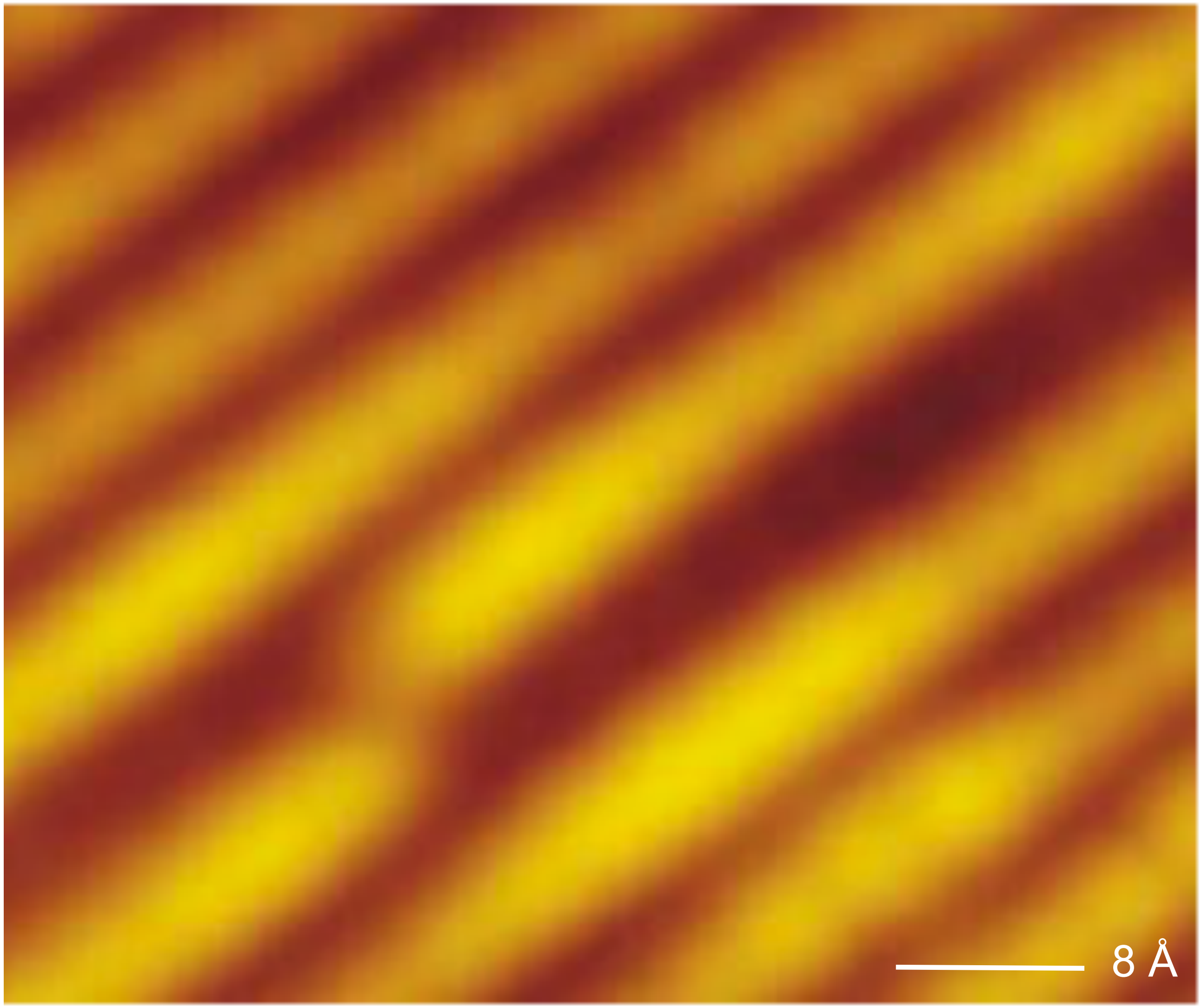
SrFe2As2
a.
b.
c.
45
45 Degrees
5 Å
50 Å



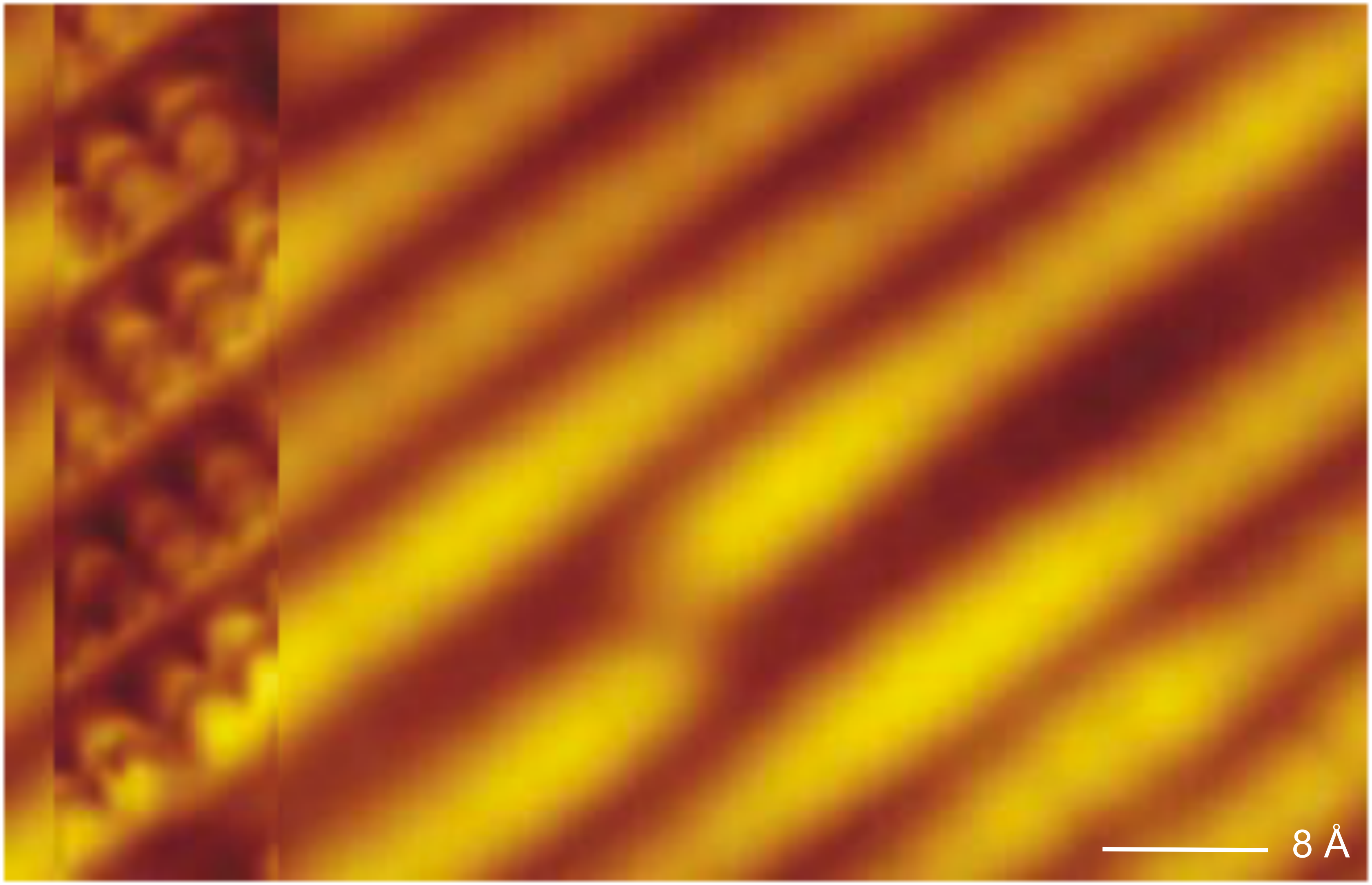
As or Sr atoms?

What leads to 8Å and 5.6Å periodicity?

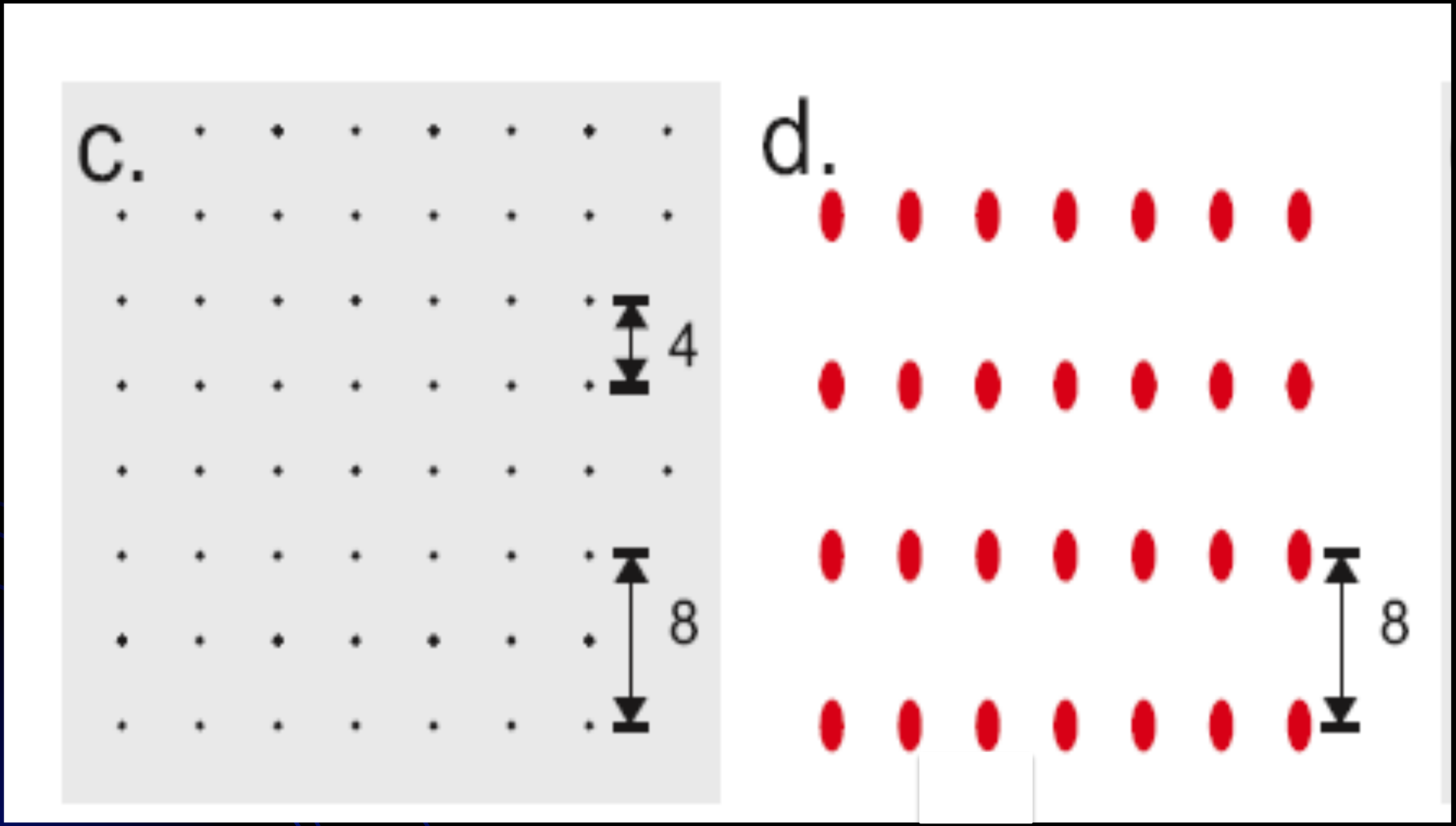
Stripes

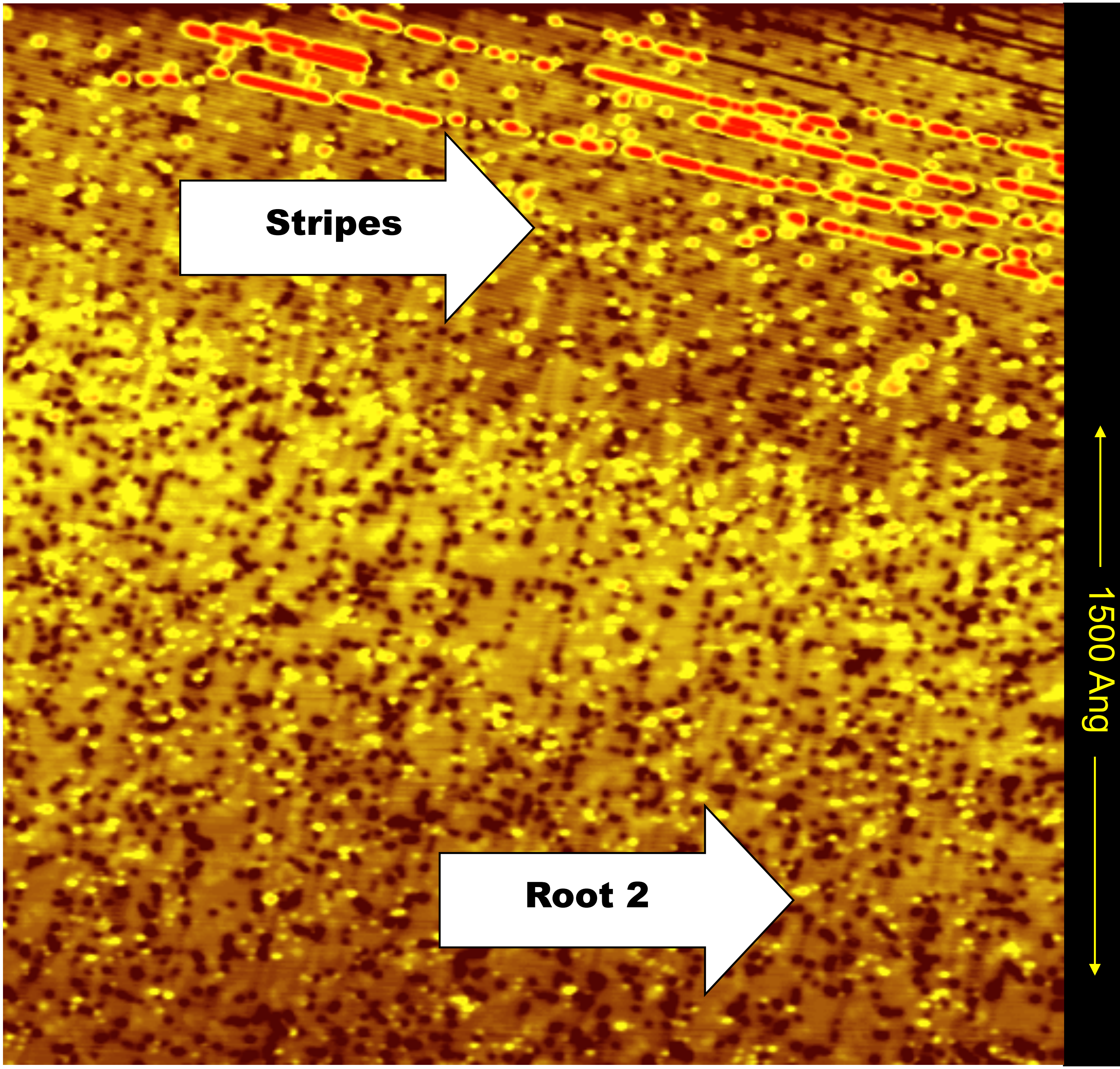


Stripes: Dimerized Rows of Atoms



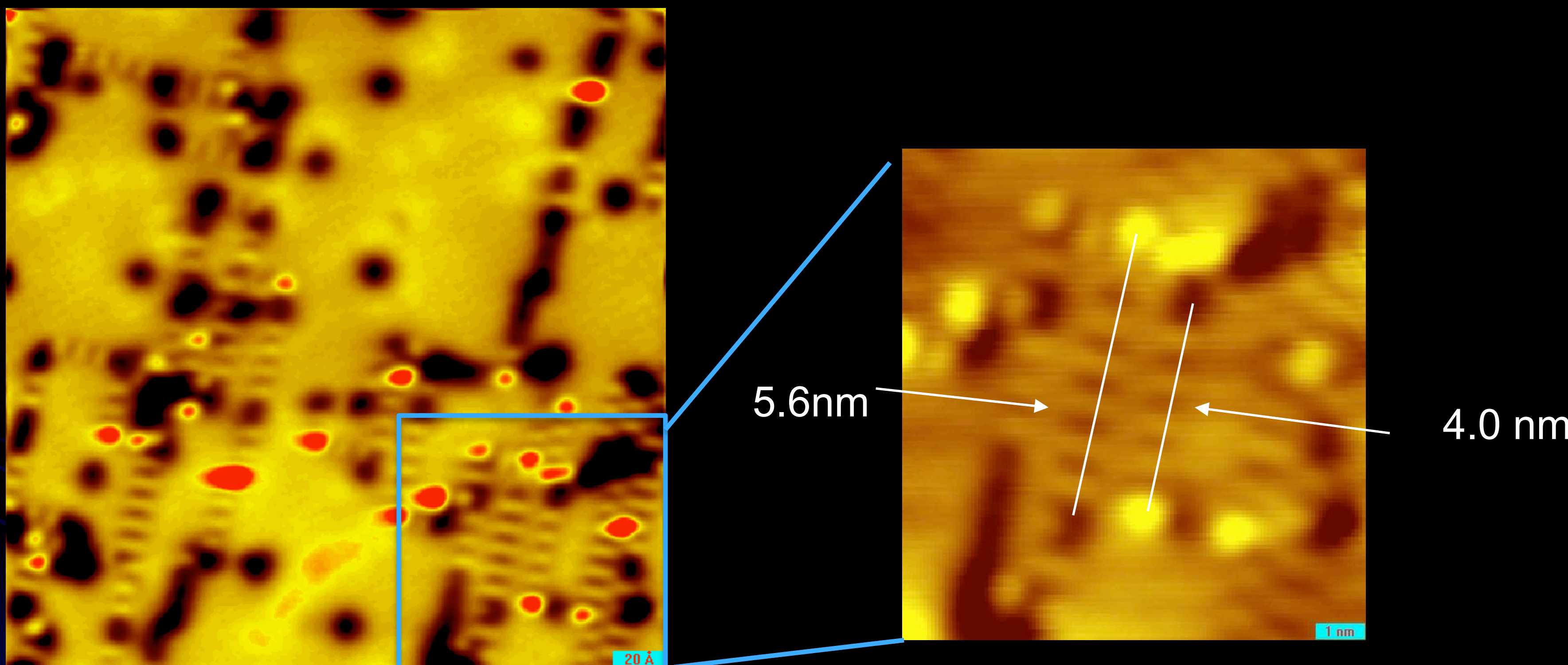
Stripes: Dimerized Rows of As/Sr Atoms





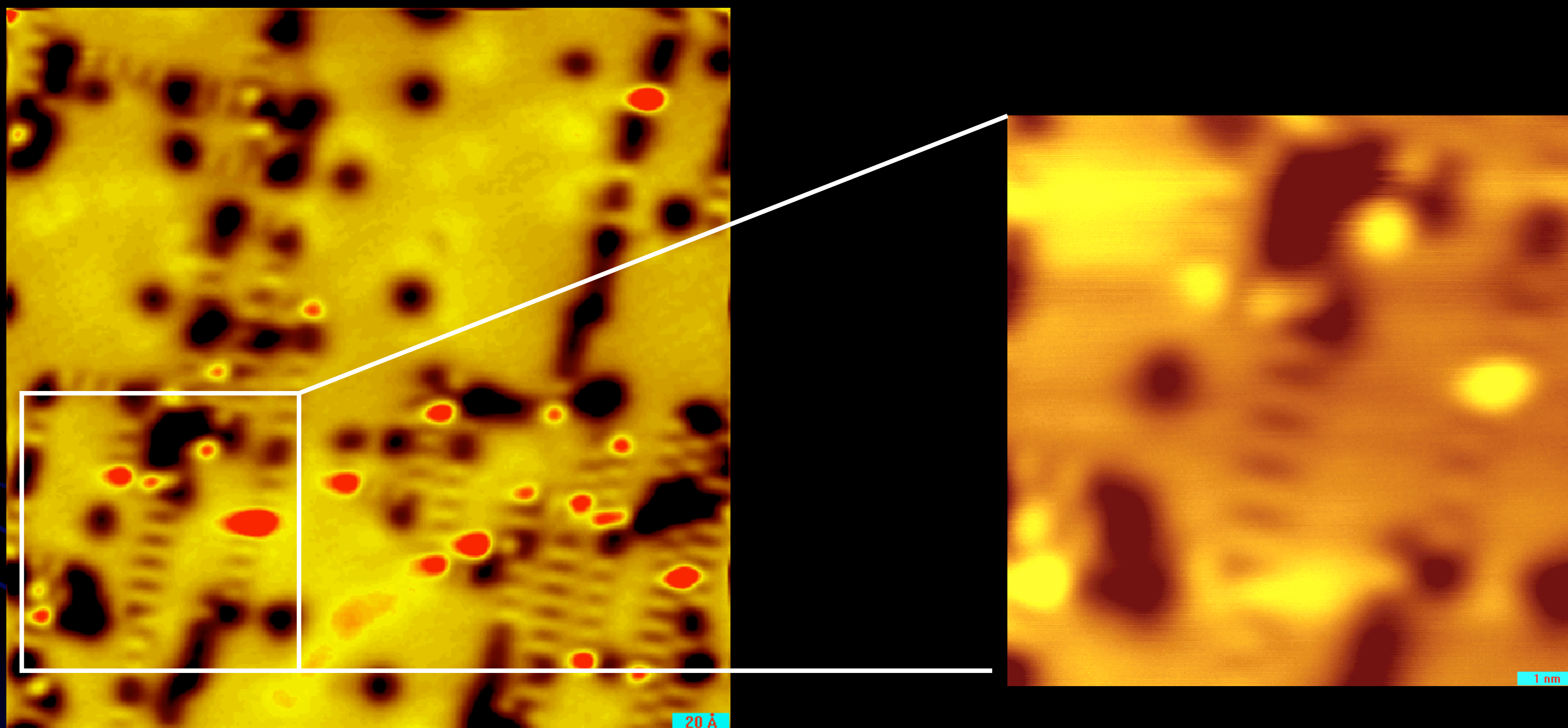
The two regions
Can transition
Between
Each other
With no
Apparent
Step Edge

Local Stripes in Root 2 Region



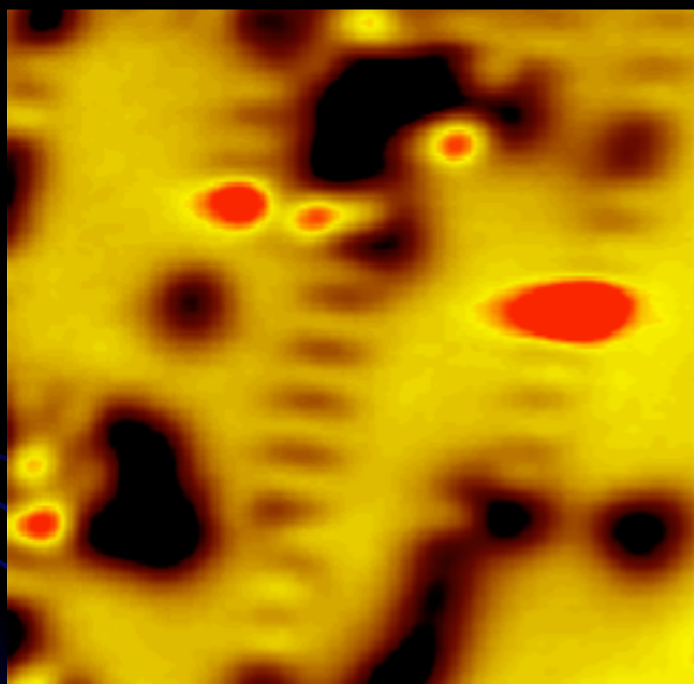
8Å Periodicity

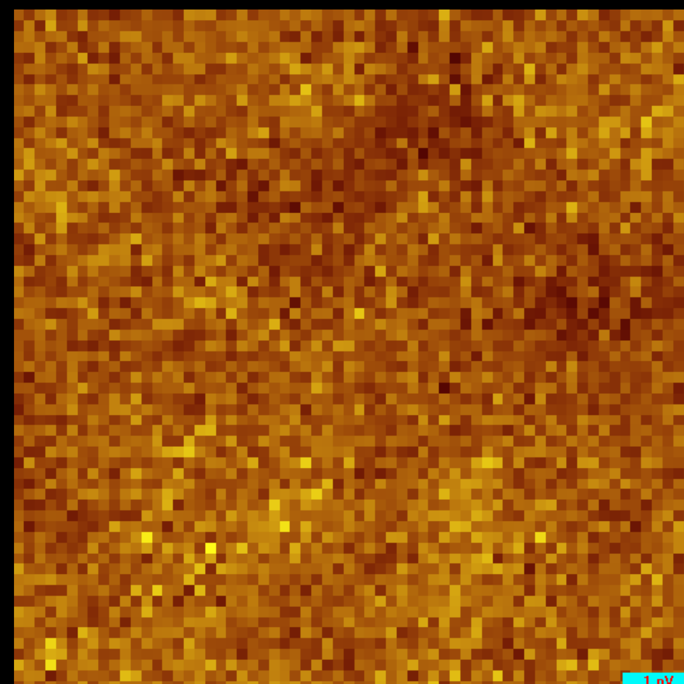
Root 2 dI/dV Energy Slices



Map at -153meV

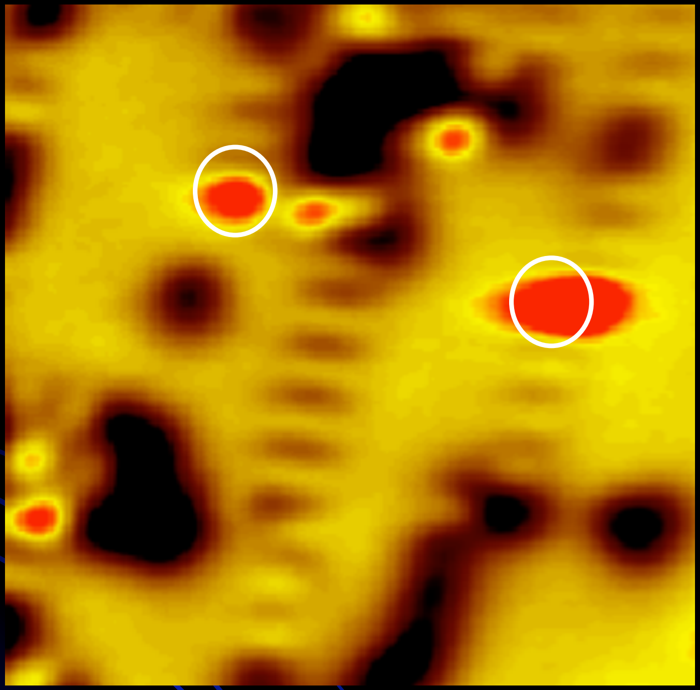
Topography

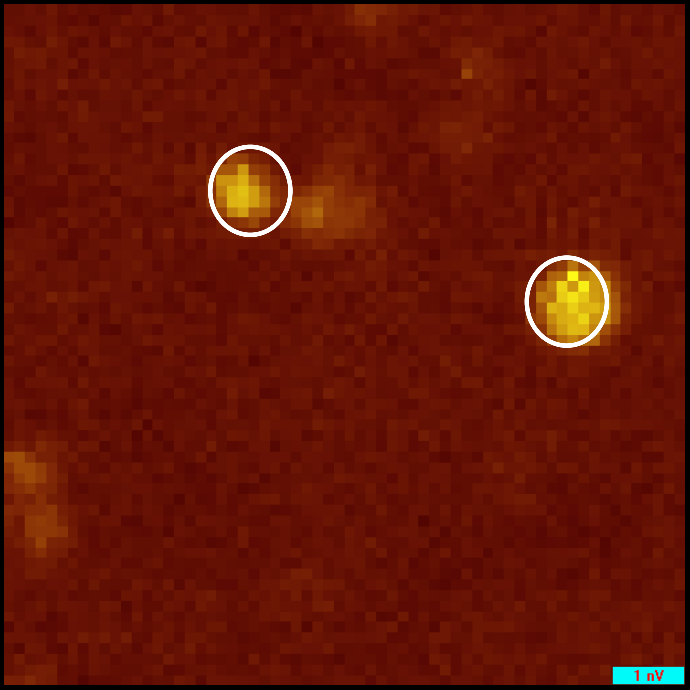




Map at -54.4 meV

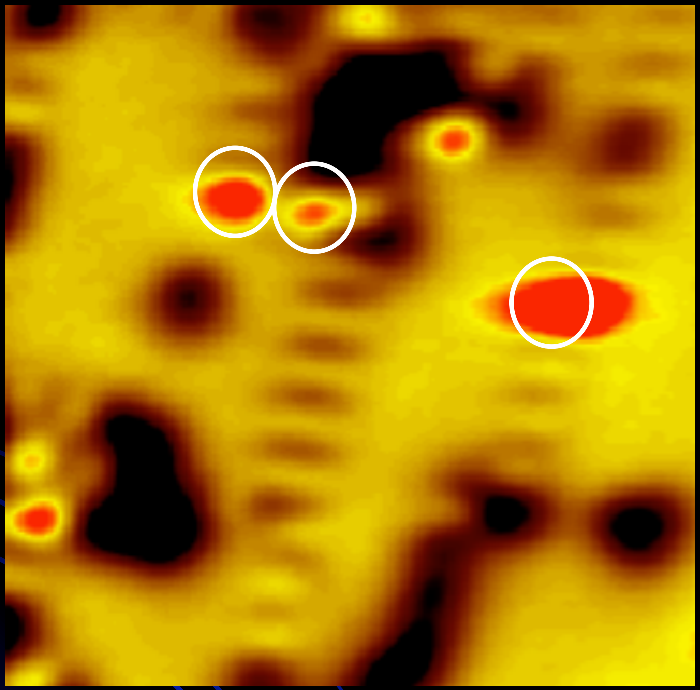
Topography

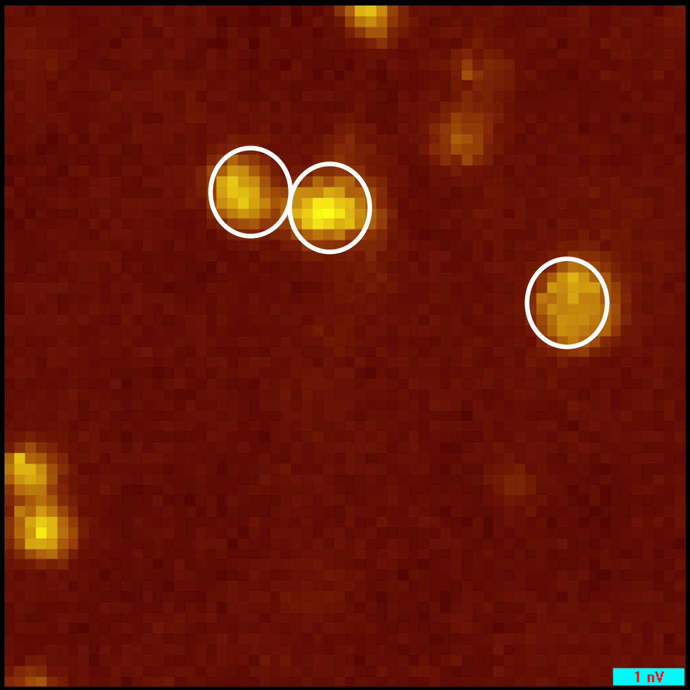




Map at 80.4 meV

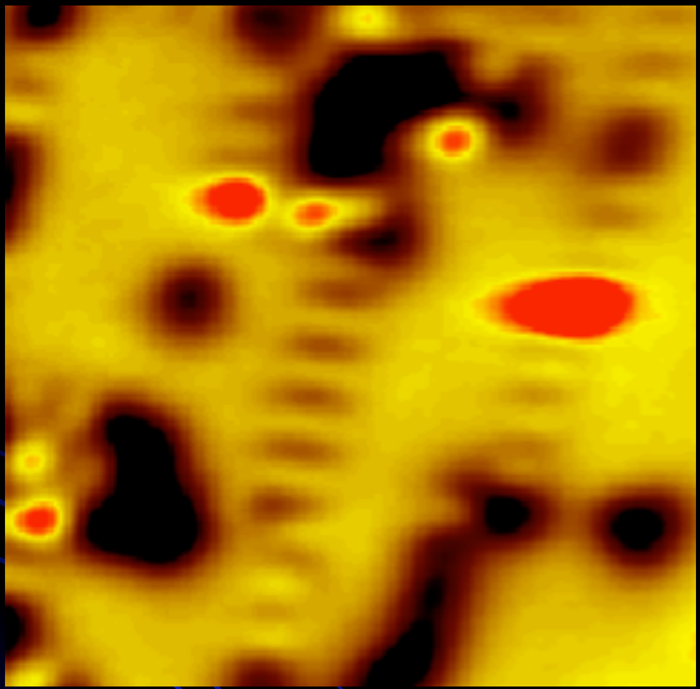
Topography

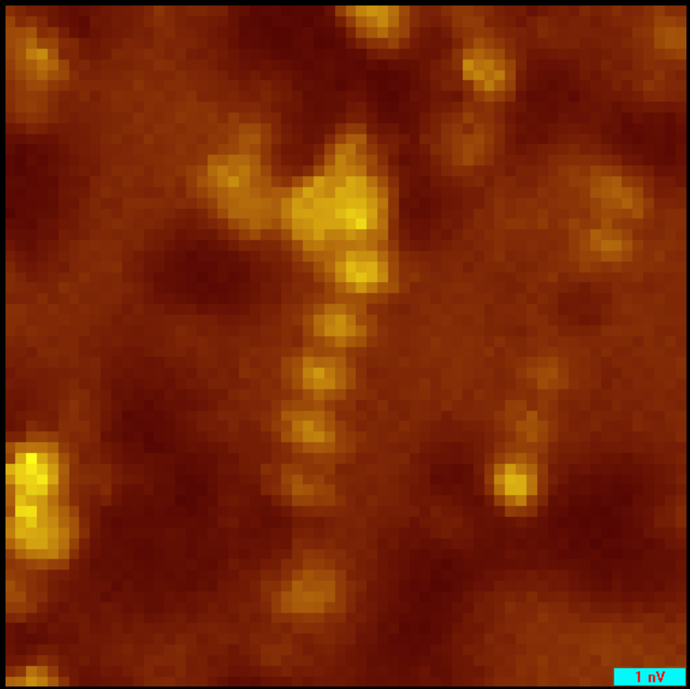




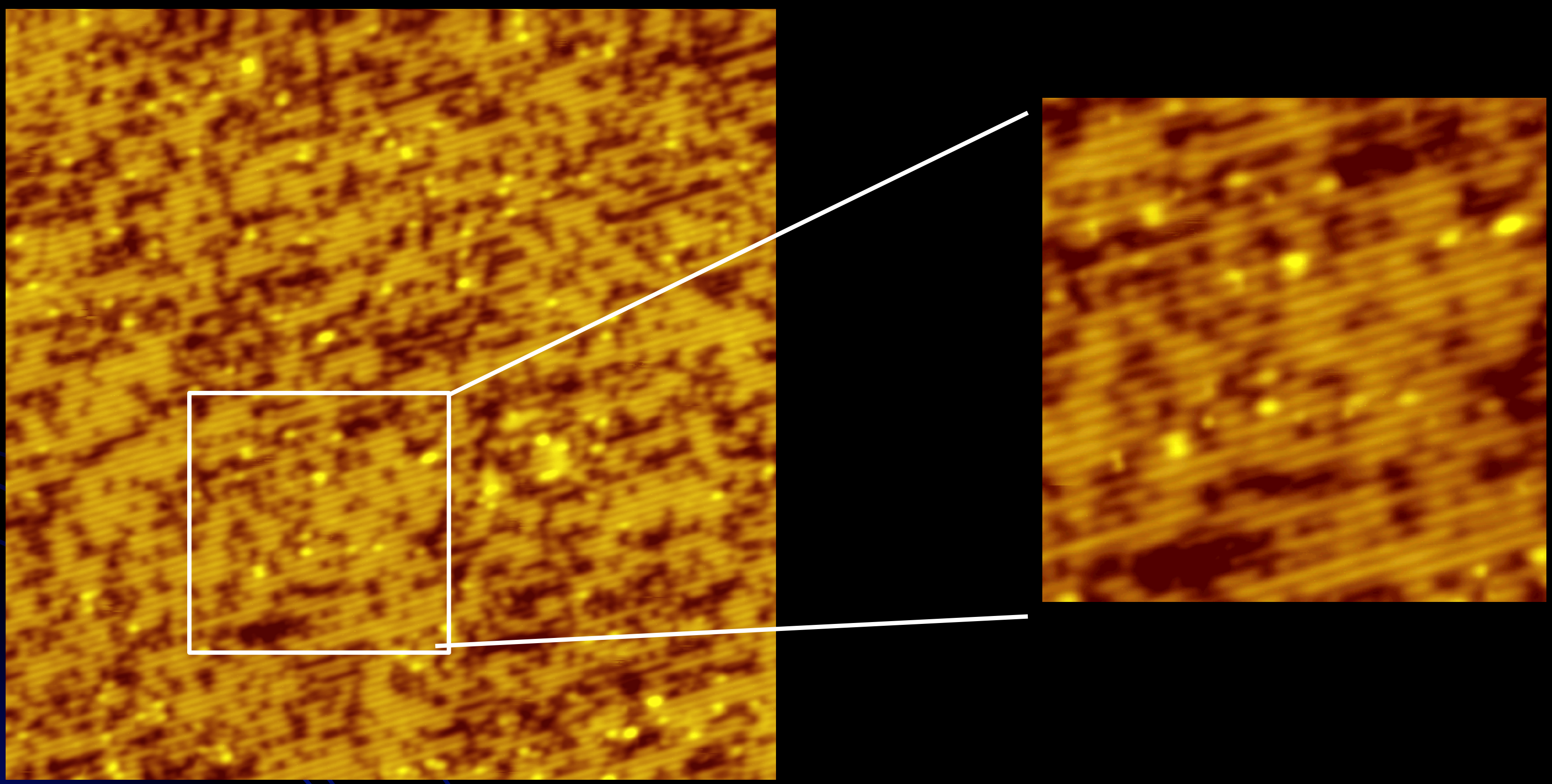
Map at 153 meV

Topography



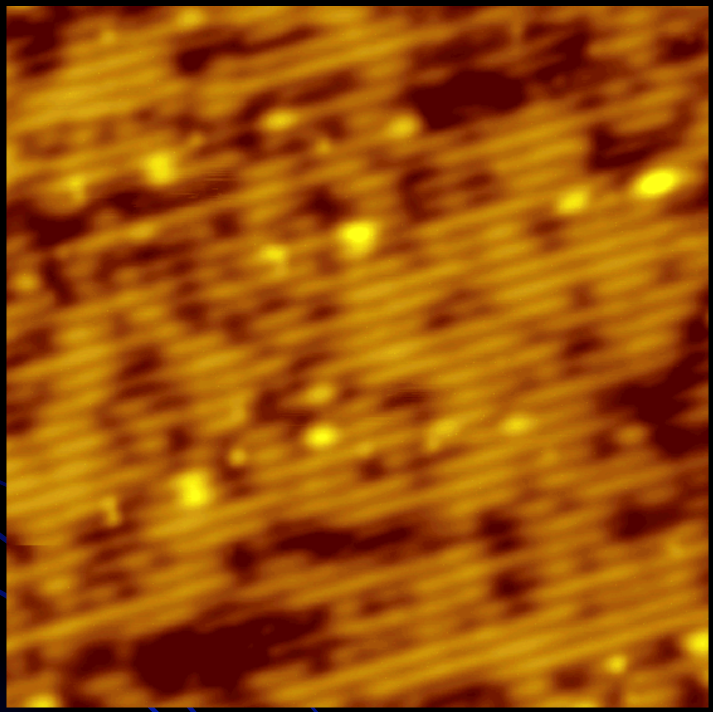


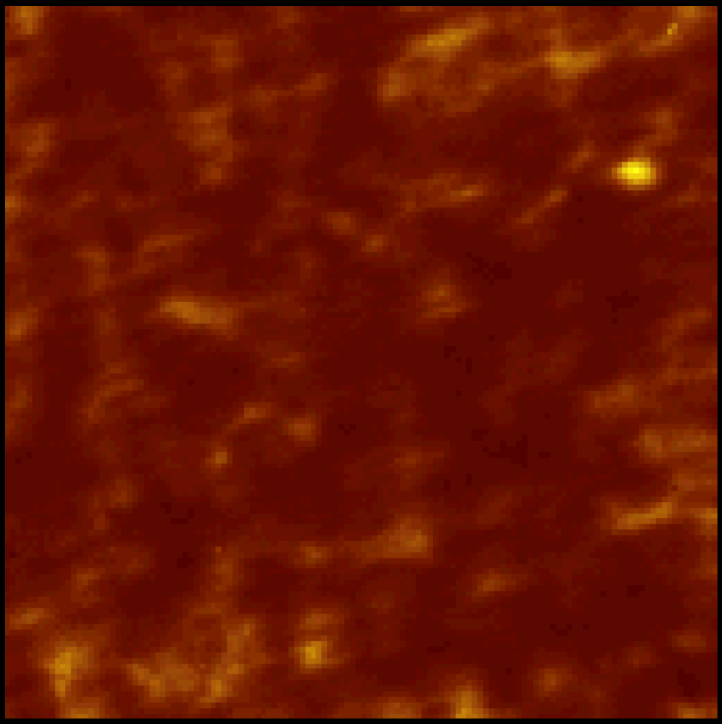
Stripe dI/dV Energy Slices



Map at -150 meV

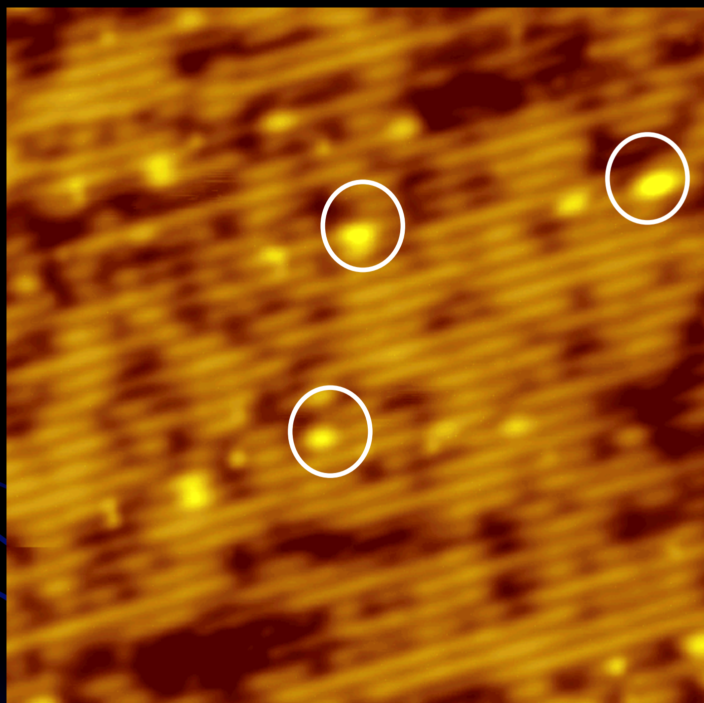
Topography

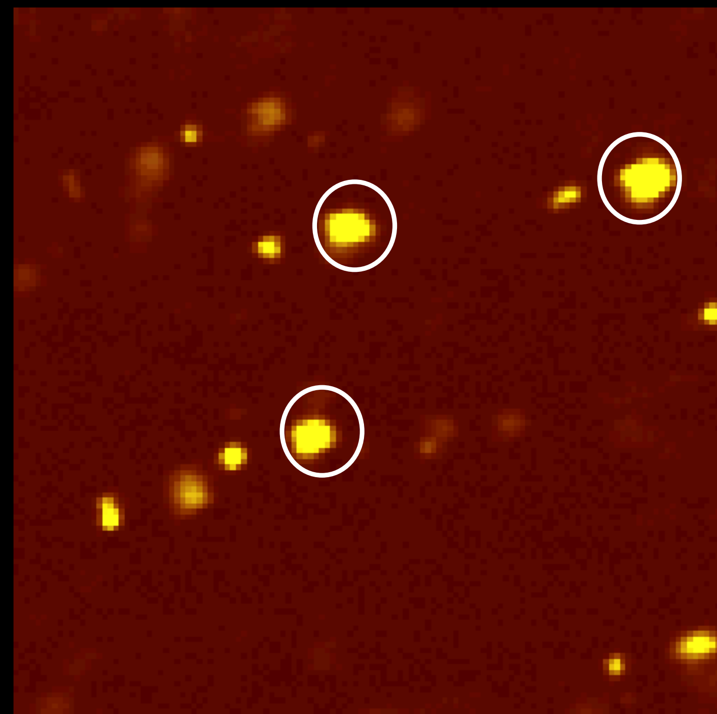




Map at -40 meV

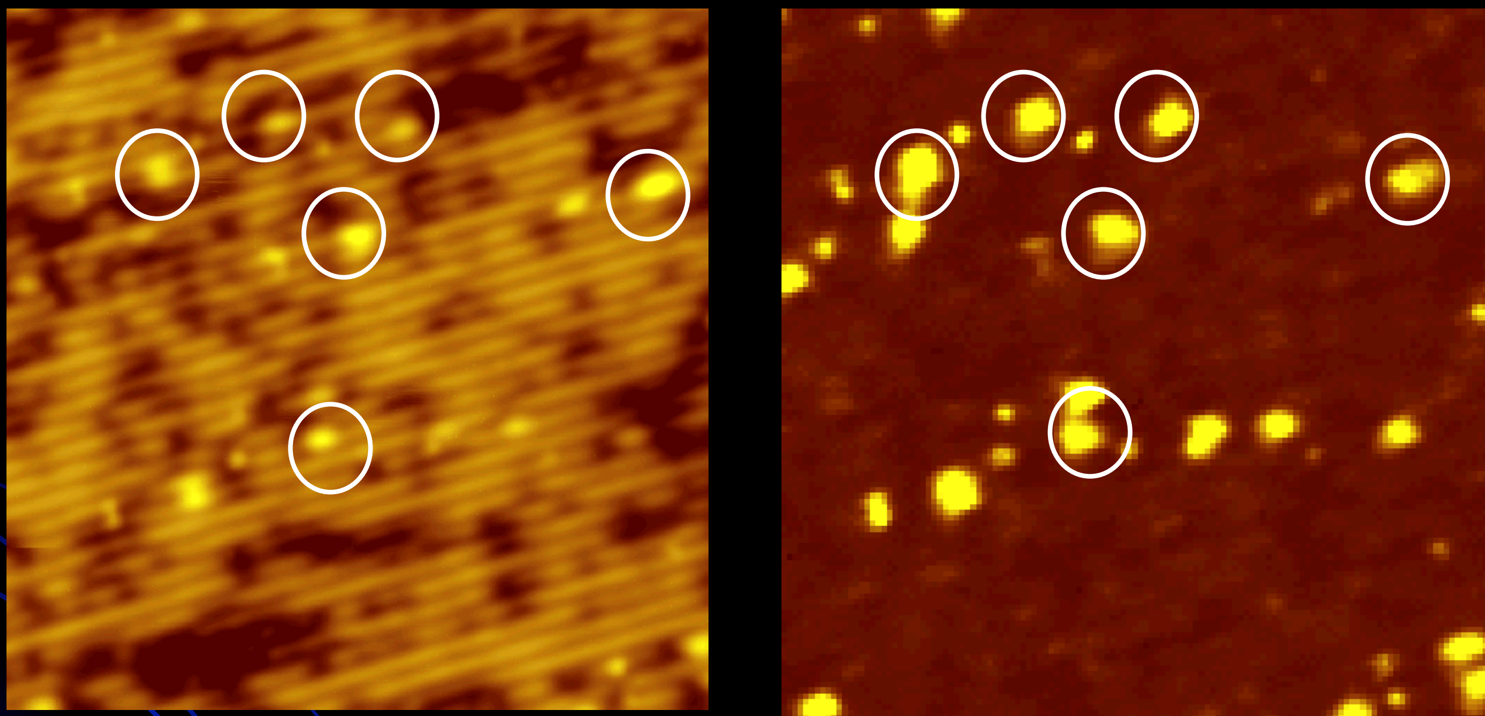
Topography





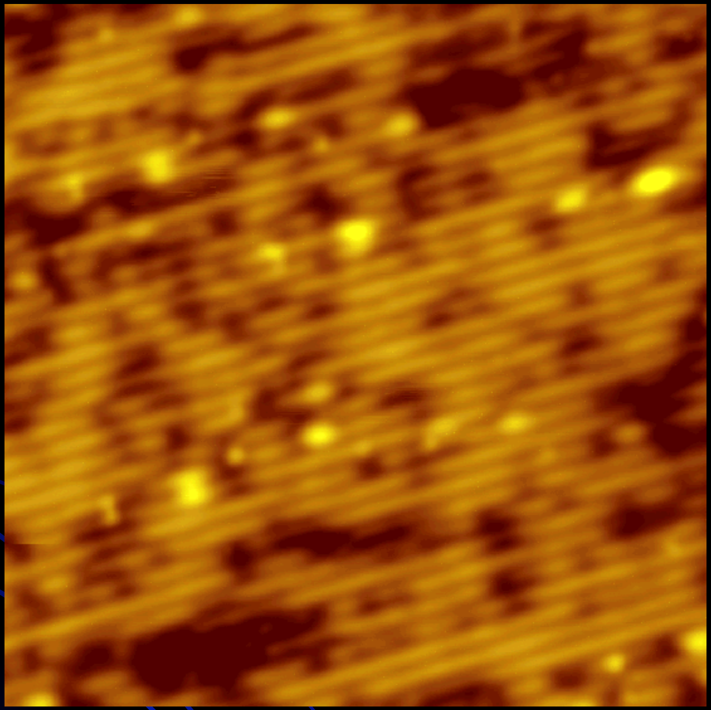
Map at 75 meV

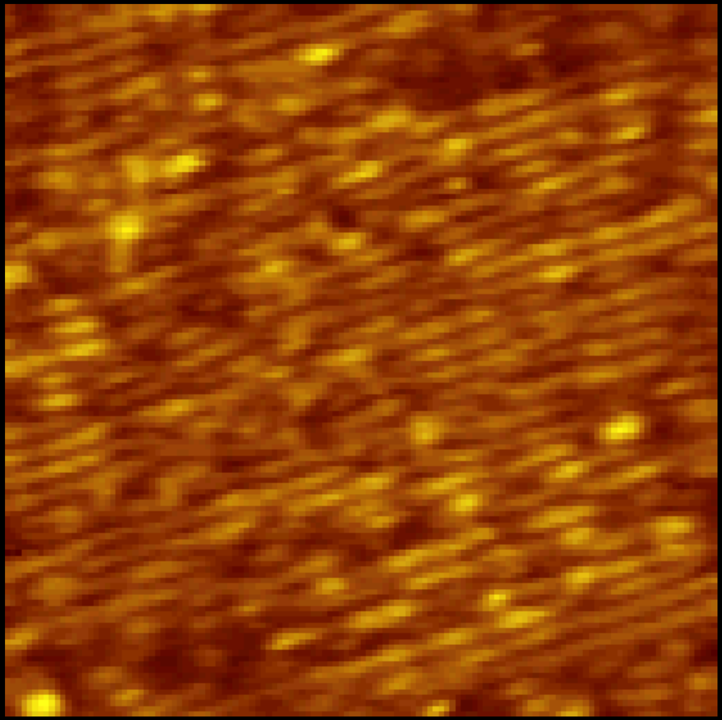
Topography



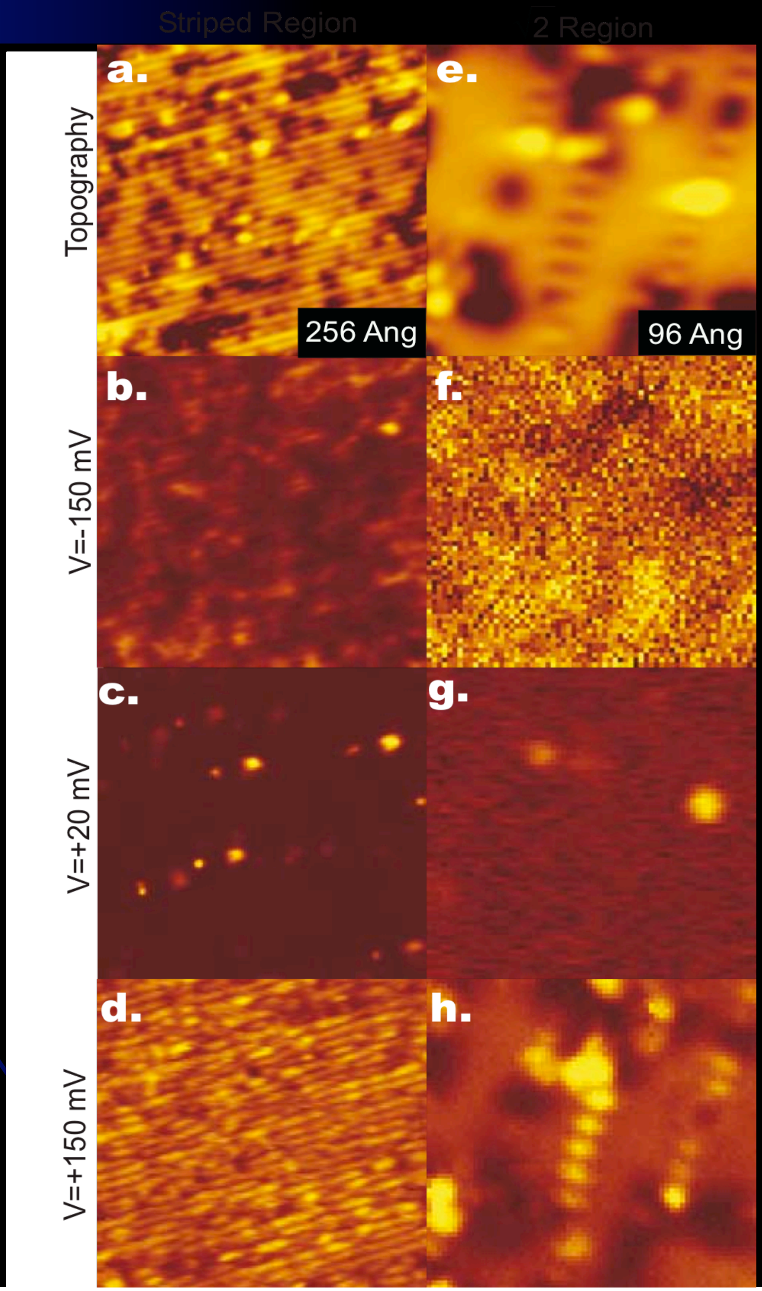
Map at 150 meV

Topography

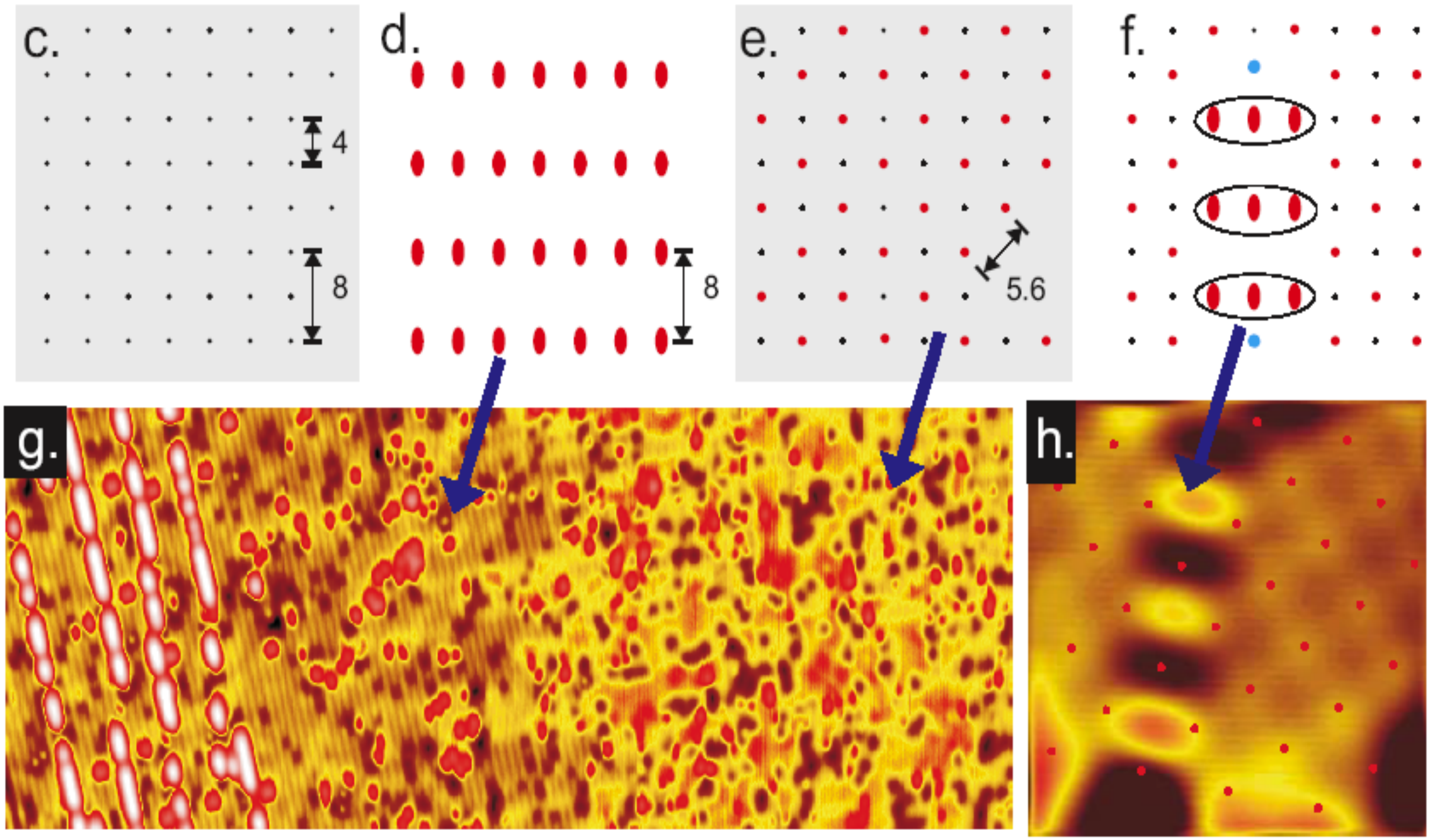




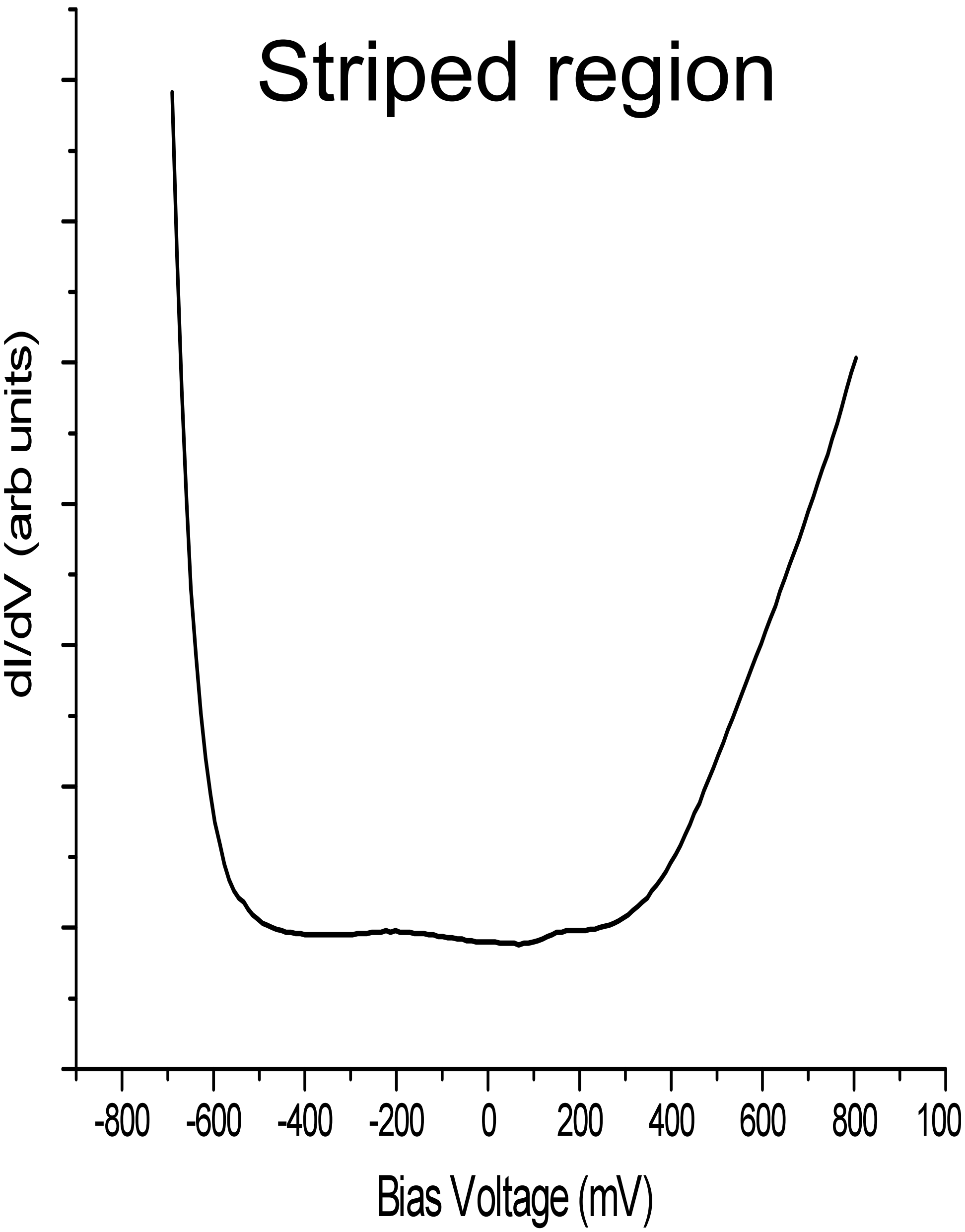
Comparison: Stripes and Rt2 LDOS

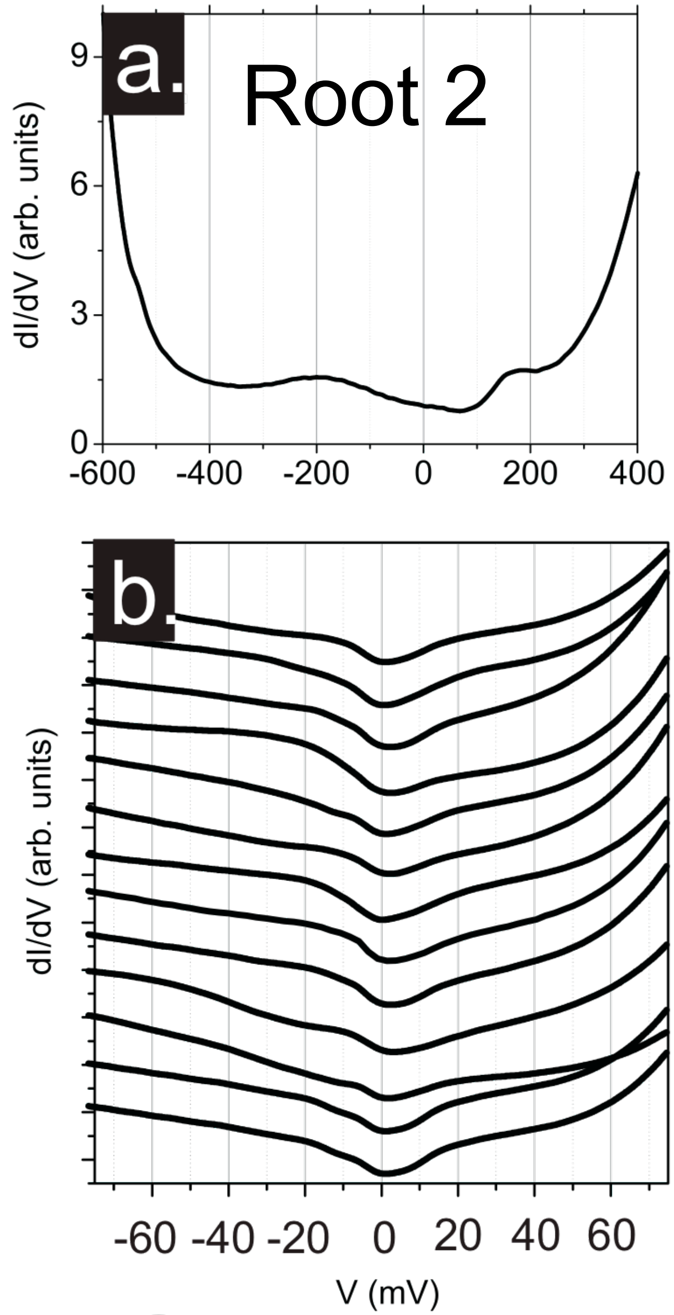


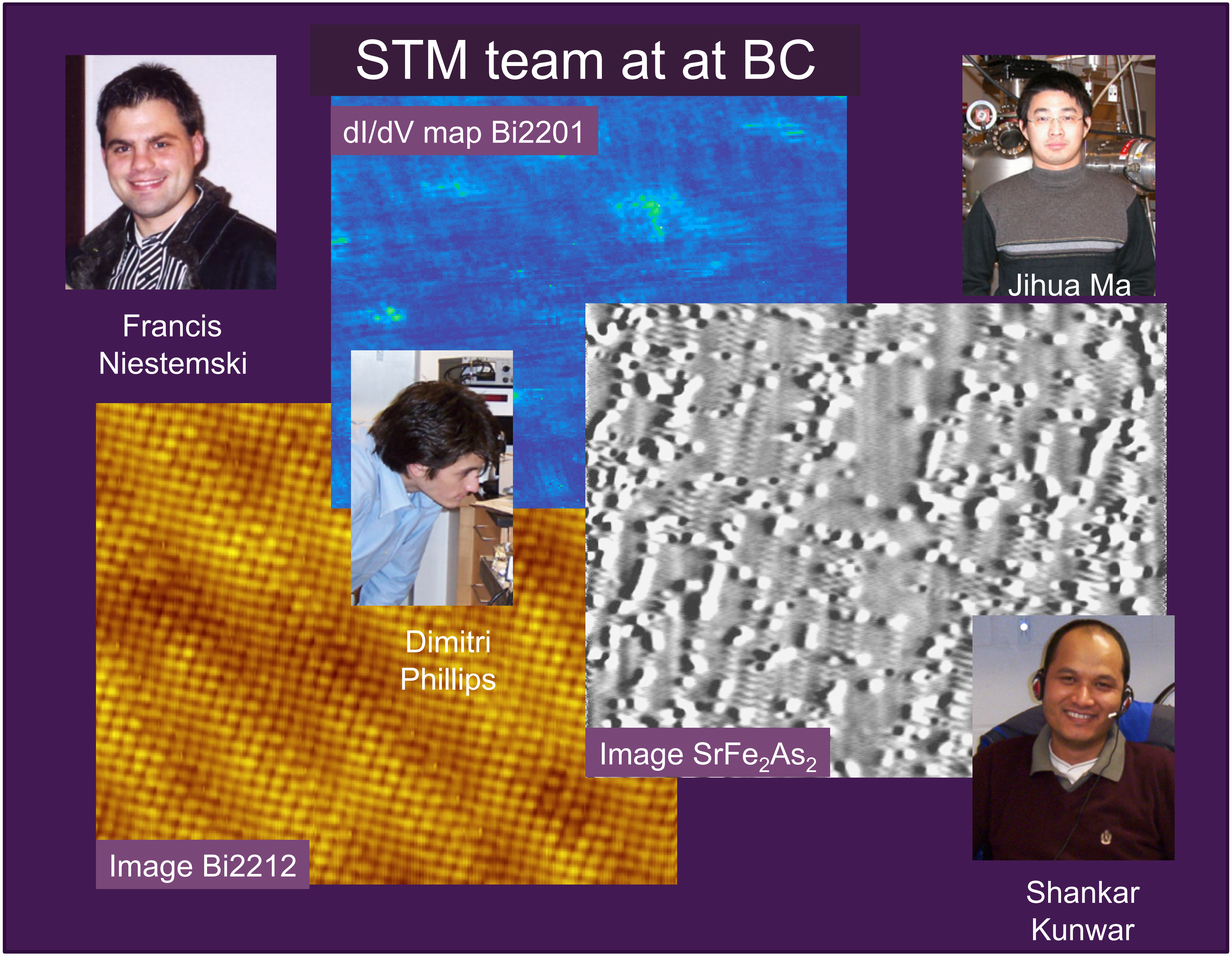
Proposed Schematic of Root 2 and Striped Regions



Density of States: dI/dV spectra


Striped region
dI/dV (arb units)
-800 -600 -400 -200 0 200 400 600 800 100
Bias Voltage (mV)


a.
Root 2
dI/dV (arb. units)
9
6
3
0
-600 -400 -200 0 200 400
b.
dI/dV (arb. units)
-60 -40 -20 0 20 40 60
V (mV)


STM team at at BC
dI/dV map Bi2201
Francis Niestemski
Jihua Ma
Dimitri Phillips
Image Bi2212
Image $SrFe_2As_2$
Shankar Kunwar