Imaging electron interference patterns using a scanning tunneling microscope

Jenny Hoffman¹,²
Kyle McElroy¹,³
Ray Simmonds⁴
Kristine Lang⁴,⁵
Eric Hudson⁶
Dung-Hai Lee¹
Hiroshi Eisaki⁷
Shin-ichi Uchida⁸
J.C. Séamus Davis³

¹. U. C. Berkeley
². Harvard University
³. Cornell University
⁴. NIST Boulder
⁵. Colorado College
⁶. M.I.T.
⁷. AIST- Tsukuba
⁸. University of Tokyo

Research Support: Hertz Foundation, ONR, NSF, NEDO
Simple clean metals: all info is in momentum space.

More complex materials: info is in real space inhomogeneity.
Simple clean metals: all info is in momentum space

Fermi surface of Cu: (Kittel, ISSP)

Bloch wave functions:
\[ \Psi_k (\vec{r}) = u_k (\vec{r}) \cdot e^{i\vec{k} \cdot \vec{r}} \]
\( \vec{k} \) = electron momentum

With no impurities, there is nothing to see in real space

For a given energy \( E \), add up all the states in \( k \)-space:

\[ DOS(E, \vec{r}) \]

\[ \propto \sum_k |\Psi_k (\vec{r})|^2 \delta(E - \varepsilon(\vec{k})) \]

insert Bloch wave function:

\[ \Psi_k (\vec{r}) = u_k (\vec{r}) \cdot e^{i\vec{k} \cdot \vec{r}} \]

Do the math \( \rightarrow \) find that DOS(\( r \)) is uniform in a metal!

BORING!
Dirty metal: potential no longer periodic

Fermi surface of Cu: (Kittel, ISSP)

\[ \vec{k} \text{ is a wavevector, so the system must uniform over several } \lambda = \frac{2\pi}{k} \text{ in order for } k \text{ to have any meaning} \]

Real surface of Cu: with step edges and impurities (Crommie, Nature (1993))

Image impurities in real space
Momentum space tool: 
Angle-Resolved Photoemission Spectroscopy (ARPES)

**Photoemission geometry**

Conserve energy:

\[ E_{\text{kin}} = h\nu - \phi - |E_B| \]

Conserve momentum:

\[ \vec{p}_\parallel = \hbar \vec{k}_\parallel = \sqrt{2m_e E_{\text{kin}}} \sin \vartheta \]

No spatial resolution: 
averages over > (100 um)²

Real space tool: 
Scanning Tunneling Microscopy / Spectroscopy (STM/STS)

**STM/STS diagram**
Momentum space tool:
Angle-Resolved Photoemission Spectroscopy (ARPES)

Real space tool:
Scanning Tunneling Microscopy Spectroscopy (STM/STS)

\[
\begin{align*}
E_{\text{kin}} &= \hbar \nu - \phi - |E_B| \\
\vec{p}_\parallel &= \hbar \vec{k}_\parallel = \sqrt{2m_e E_{\text{kin}}} \sin \vartheta
\end{align*}
\]

Conserve energy:
Conserve momentum:
No spatial resolution: averages over > (100 um)^2
Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$: a High-Tc Superconductor

High Tc cuprate phase diagram:

optimum $T_c \sim 90K$

AF Mott ins.  Superconductor

Carrier concentration

Temperature
High Temperature Superconductor: Doped Mott Insulator

- Hole
- Oxygen
- Spin $\frac{1}{2}$ Electron
- Carrier concentration
- Temperature
- AF Mott ins.
- Pseudo-gap
- “non-Fermi” liquid
- Fermi liquid?
- Superconductor
Momentum space tool:
Angle-Resolved Photoemission Spectroscopy (ARPES)

Real space tool:
Scanning Tunneling Microscopy/Spectroscopy (STM/STS)

1st Brillouin zone:


Map of superconducting $\Delta$:

Topography:

Summary of experimental techniques:

**Momentum space:**

- ARPES (Angle-Resolved Photo Emission Spectroscopy)

**Real space:**

- STM (Scanning Tunneling Microscopy)

**R-space & k-space:**

- FT-STS (Fourier Transform Scanning Tunneling Spectroscopy)
Traditional STM/STS Measurements

Local Density of States (X,Y,E)

Constant current mode:

\[ \int dE \]

Topography

dI/dV Map

dI/dV Spectrum

STM

STM/STS

STS
Scanning Tunneling Microscopy: R-space
Structure of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

Cleave Here Reveals BiO Surface

$T_c \sim 90$ K

photograph

$2 \times 600 \mu\text{m}$
Atomic resolution $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

STM topography

Cleave Here
Reveals BiO Surface

C $\rightarrow$ b $\rightarrow$ a

T = 4.2K, B = 0T
100pA, -100mV
Atomic resolution $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

STM topography

Cleave Here
Reveals BiO Surface

$280 \, \text{Å}$

T = 4.2K, B = 0T
100pA, -100mV
Atomic resolution $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

STM topography

Cleave Here Reveals BiO Surface

$T = 4.2K, B = 0T$
$100pA, -100mV$
Atomic resolution $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

STM topography

Cleave Here
Reveals BiO Surface

single Bi atom

T = 4.2K, B = 0T
100pA, -100mV

$70$ Å
Scanning Tunneling Spectroscopy: energy dependence
Expected DOS for a conventional s-wave superconductor

Gap Magnitude vs. k

DOS(E) after average over k

STM Experiment measured on NbSe$_2$

Expected k-averaged DOS for a $d_{x^2-y^2}$ Superconductor

Gap Magnitude vs. $k$

DOS(E) after average over $k$

STM Experiment measured on BiO plane
Typical Gap $\approx 45$ meV
[as-grown $T_c \approx 89$K]
Spectroscopic Mapping

Point dI/dV Spectrum

100 energies

- 100 x 128 x 128 = 1,600,000 measurements

- Registered to surface with atomic resolution for 2 days

Sample Bias (mV)

Energy (meV)

dI/dV map

at every location

100 Å
GapMap:

Map of $\Delta$ as a function of location
Evolution of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ gapmap with doping

Nature 413, 282 (2001)
STM measurements so far: all in real space

So much disorder!

This disorder gives us the key to turn STM/STS into a simultaneous R-space and k-space probe
Theory: Quasiparticle Interference from disorder scattering in the cuprates

Suppose you have some disorder potential $V$, such as gap disorder or point defects.

Each Fourier component $V(q)$ will cause elastic scattering between initial and final states whose momenta differ by $q$.

Power spectrum of scattering:

$$P(\varepsilon, \tilde{q}) \propto |V(\tilde{q})|^2 n_i(\varepsilon_i, k_i) n_f(\varepsilon_f, k_f)$$

Structure factor of disorder potential
Density of initial states
Density of final states

D. J. Scalapino, preprint
ARPES:
k-space
ARPES: Normal State Fermi Surface


Ding et al., PRL 78 2627 (1997)

Campuzano et al., PRL 64 2308 (1990)
Dessau et al., PRL 71 2781 (1993)
Aebi et al., PRL 72 2757 (1994)
ARPES: Normal State Fermi Surface & Band Structure

Parameterization: M. Norman

Based on data:
Ding et al.,

CCE (E): The location in k-space of states with energy E

contours from -100meV to +100meV

filled states (electrons)

empty states (holes)

Fermi Surface
ARPES: Superconducting anisotropic gap $\Delta(\mathbf{k})$

$\Delta(\mathbf{k}) = 0$ meV

occupied

unoccupied

$\Delta = 0$ meV

$E_F$

$\mathbf{k}_F$

$E$

$k$

$E_F$

$k$

$\mathbf{k}$

$\mathbf{k}$

$\mathbf{k}$

$\mathbf{k}$
ARPES: Superconducting anisotropic gap $\Delta(\vec{k})$

$\Delta(\vec{k}) = 10$ meV

$E_{F}$

$\Delta = 10$ meV

$k_{F}$

$k$
ARPES: Superconducting anisotropic gap $\Delta(\vec{k})$

$\Delta(\vec{k}) = 20$ meV
ARPES: Superconducting anisotropic gap $\Delta(\vec{k})$

$\Delta(k)=30$ meV

$E(k) = 30$ meV
ARPES: Superconducting anisotropic gap $\Delta(\vec{k})$

contours from -100meV to +100meV

Shen et al, PRL 70 1553 (1993)
Ding et al, PRB 54 9678 (1996)
Mesot et al, PRL 83 840 (1999)
0 meV CCE: the Fermi points
10 meV CCE
$20 \text{ meV} \text{ CCE}$
30 meV CCE
$40 \text{ meV CCE}$
Octet of regions at ends of ‘bananas’ have largest $|d\mathbf{k}|/dE$.

The octet of k-space locations at the tips of the ‘bananas’ provide maximum contribution to $n_{i,f}(E)$ and thus dominate elastic scattering processes.

Density of States:

$$n(E) = \int_{E(k)=E} \frac{1}{|\nabla_k E(k)|} dk$$
The scattering vectors of QI model

$k$-space:
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES
The scattering vectors of QI model

$k$-space:
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES

$q$-space:
- Scattering → standing waves $q = 2\pi/\lambda$
- Measure $q$ from FT of LDOS image
The scattering vectors of QI model

\( \mathbf{q} = \frac{2\pi}{\lambda} \)

- Measure \( q \) from FT of LDOS image

**k-space:**
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES

**q-space:**
- Scattering → standing waves \( q = \frac{2\pi}{\lambda} \)
- Measure \( q \) from FT of LDOS image
The scattering vectors of QI model

$k$-space:
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES

$q$-space:
- Scattering → standing waves $q = \frac{2\pi}{\lambda}$
- Measure $q$ from FT of LDOS image
The scattering vectors of QI model

\[ \mathbf{q} = \frac{2\pi}{\lambda} \]

- **q-space:**
  - Scattering → standing waves \( q = \frac{2\pi}{\lambda} \)
  - Measure \( q \) from FT of LDOS image

\[ (\pi, \pi), (\pi, 0) \]

**k-space:**
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES

**q-space:**

1. \( \mathbf{q}_1 \)
2. \( \mathbf{q}_2 \)
3. \( \mathbf{q}_3 \)
4. \( \mathbf{q}_4 \)
The scattering vectors of QI model

$k$-space:
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES

$q$-space:
- Scattering $\rightarrow$ standing waves $q = 2\pi/\lambda$
- Measure $q$ from FT of LDOS image
The scattering vectors of QI model

$k$-space:
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES

$q$-space:
- Scattering → standing waves $q = 2\pi/\lambda$
- Measure $q$ from FT of LDOS image
The scattering vectors of QI model

$k$-space:
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES

$q$-space:
- Scattering $\rightarrow$ standing waves $q = 2\pi/\lambda$
- Measure $q$ from FT of LDOS image

Total sets of $q_i$ (7X8) : 56
Inequivalent sets of $q_i$ : 32
Distinguishable via FT-STS : 16
The scattering vectors of QI model

$k$-space:
- unperturbed eigenstates
- not directly accessible to STM
- measured by ARPES

$q$-space:
- Scattering → standing waves $q = 2\pi/\lambda$
- Measure $q$ from FT of LDOS image

Total sets of $q_i$ (7X8) : 56
Inequivalent sets of $q_i$ : 32
Distinguishable via FT-STS : 16
Expected structure of FFT of LDOS(r,E) (for a fixed E)
Dispersion:

how does each $\vec{q}_i$ vary with $E$?
For example, look at the dispersion of: $\vec{q}_1 \parallel (\pm \pi,0) \text{ or } (0,\pm \pi)$
Expected energy dependence of $|\vec{q}_1|$ on $E$

A perspective view:

- $(\pi, \pi)$
- $(0, 0)$
- $(\pi, 0)$

$|q|$ vs $E$
Expected energy dependence of $|\vec{q_1}|$ on $E$

A perspective view:

- $E$
- $|q_1|$
- $q_1$
- $(\pi, \pi)$
- $(0, 0)$
- $(\pi, 0)$

| $q_1$ | $E$ | $|q_1|$ |
|-------|-----|-------|
|       |     |       |

$\pi, \pi$
Expected energy dependence of $|\vec{q}_1|$ on $E$

A perspective view:

$E$

$|q_1|$
Expected energy dependence of $|\vec{q}_1|$ on $E$
Expected energy dependence of $|\vec{q}_1|$ on $E$

A perspective view:

$$E$$

$$q_1$$

$$(\pi, \pi)$$

$$(0, 0)$$

$$(\pi, 0)$$

$|q_1|$

$E$
For example, look at the dispersion of:
\[ \vec{q}_7 \parallel (\pm \pi, \pm \pi) \]
Expected energy dependence of $|\vec{q}_7|$ on $E$

A perspective view:
Expected energy dependence of $|\vec{q}_7|$ on $E$
Expected energy dependence of $|\vec{q}_7|$ on $E$
Expected energy dependence of $|\vec{q}_7|$ on $E$

A perspective view:
Expected energy dependence of $|\vec{q}_7|$ on $E$

A perspective view:
Motivation 1: Search for all 16 sets of $q$-vectors predicted by QI model.

Problem: To detect the all 16 sets of $q$-vectors we need dispersion information from twice reciprocal unit cell.

--> Very large $q$-space required
Motivation 2: To measure all dispersions => check FS and $\Delta(k)$

As predicted from ARPES-determined FS

Problem: To detect the dispersions characteristic of the quasiparticle interference model, we need to resolve <1% reciprocal unit cell in energy steps of few meV.

--> High resolution in q-space required
How to get high resolution in a large $q$-space?

Real space: $g(\vec{r}, E)$

$q$-space: $g(\vec{q}, E)$

- real-space resolution $dx \rightarrow q$-space extent $\Rightarrow dx < 1.3 \ \text{Å}$
- real-space extent $L \rightarrow q$-space resolution $\Rightarrow L > 450 \ \text{Å}$

Need Å stability of STM over days...
Reminder: STM tunneling current depends exponentially on tip-sample separation.
STM requires very low vibrations:

Vertical Floor Vibrations

- IBM Almaden
- Berkeley
- Cornell
- MIT
- NIST (Maryland)
- Urbana (Illinois)
Compare to industrial vibration criteria:

Vertical Velocity (1/3-octave band)

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Detail Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workshop</td>
<td>n/a</td>
</tr>
<tr>
<td>Office</td>
<td>n/a</td>
</tr>
<tr>
<td>Residential</td>
<td>75</td>
</tr>
<tr>
<td>Op-theatre</td>
<td>25</td>
</tr>
<tr>
<td>Vc-A</td>
<td>8</td>
</tr>
<tr>
<td>Vc-B</td>
<td>3</td>
</tr>
<tr>
<td>Vc-C</td>
<td>1</td>
</tr>
<tr>
<td>Vc-D</td>
<td>0.3</td>
</tr>
<tr>
<td>Vc-E</td>
<td>0.1</td>
</tr>
</tbody>
</table>

µin/s (1/3-octave band) vs. frequency (Hz)

Almaden, Berkeley, Cornell, MIT, NIST, Urbana
Compare to industrial vibration criteria:

Vertical Velocity (1/3-octave band)

<table>
<thead>
<tr>
<th>detail size (µm)</th>
<th>workshop</th>
<th>office</th>
<th>residential</th>
<th>op-theatre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n/a</td>
<td>n/a</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>vc-A</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-B</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-C</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-D</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-E</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-G</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-H</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-I</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-J</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-K</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-L</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vc-M</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

These criteria don’t even exist!!!!
Current construction in Pierce

- sand-filled cinder blocks
- rigid insulation
- air gap
- sheetrock
- inner sound room
- pipes cast in concrete
- non-rigid pipe
- pump
- expt. dewar
- 20 ton concrete slab
- 3 air springs
- basement
Formwork for base slab
Poured concrete for base slab
Formwork for floating slab

(note embedded pipes)
STM/STS Instrument Design

- Massive Lead + Concrete Cryostat
- STM + High Field Magnet
- Sample Exchange from RT
- Cryogenic UHV Cleavage

 STM Head

Acoustic 'Bunker'

Finally, some data...

Bi-2212

T_c = 76 K

Δ ~ 51 meV

545 Å

topograph
Imaging quasiparticle wavefunctions

\[ g(\vec{r}, E) \]

\[ g(\vec{q}, E) = \sqrt{P(\vec{q}, E)} \]

Bi-2212

\( T_c = 76 \text{ K} \)

\( \Delta \approx 51 \text{ meV} \)
Imaging quasiparticle wavefunctions

\[ g(\vec{r}, E) = \sqrt{P(\vec{q}, E)} \]

<table>
<thead>
<tr>
<th>Energy (meV)</th>
<th>Bi-2212</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ E_q ]</td>
<td>T_c = 76 K</td>
</tr>
<tr>
<td>[ E_g ]</td>
<td>( \Delta \approx 51 \text{meV} )</td>
</tr>
</tbody>
</table>

FFT
These phenomena are highly repeatable:

& they agree qualitatively with model:

(π,π)

(p,0)

\( p \sim 0.19 \)

\( g(\vec{q}, E) \)

\( p \sim 0.14 \)

\( g(\vec{q}, E) \)

\( p \sim 0.10 \)

\( g(\vec{q}, E) \)

\( \pi, \pi \)

\( \pi, 0 \)

\( \vec{q}_1 \)

\( \vec{q}_2 \)

\( \vec{q}_3 \)

\( \vec{q}_4 \)

\( \vec{q}_5 \)

\( \vec{q}_6 \)

\( \vec{q}_7 \)

Science 297, 1148 (2002)
Nature 422, 520 (2003)
Cond/mat 0404005
Measuring the dispersion of the $q_i(E)$

Measuring the dispersion of the $q_i(E)$

Measuring the Fermi Surface:

\[ \tilde{q}_1(E) = (2k_{1x}(E), 0) \]
Measuring the Fermi Surface:

\[ \tilde{q}_1(E) = (2k_{1x}(E),0) \]

\[ \tilde{q}_2(E) = (k_{1x}(E) + k_{1y}(E),k_{1y}(E) - k_{1x}(E)) \]
Measuring the Fermi Surface:

\[ q_1(E) = (2k_{1x}(E),0) \]

\[ q_2(E) = (k_{1x}(E) + k_{1y}(E), k_{1y}(E) - k_{1x}(E)) \]

\[ q_3(E) = (k_{1x}(E) + k_{1y}(E), k_{1x}(E) + k_{1y}(E)) \]
Measuring the Fermi Surface:

\[ \bar{q}_1(E) = (2k_{1x}(E), 0) \]

\[ \bar{q}_2(E) = (k_{1x}(E) + k_{1y}(E), k_{1y}(E) - k_{1x}(E)) \]

\[ \bar{q}_3(E) = (k_{1x}(E) + k_{1y}(E), k_{1x}(E) + k_{1y}(E)) \]

\[ \bar{q}_4(E) = (2k_{1x}(E), 2k_{1y}(E)) \]
Measuring the Fermi Surface:

\[ \bar{q}_1(E) = (2k_{1x}(E), 0) \]

\[ \bar{q}_2(E) = (k_{1x}(E) + k_{1y}(E), k_{1y}(E) - k_{1x}(E)) \]

\[ \bar{q}_3(E) = (k_{1x}(E) + k_{1y}(E), k_{1x}(E) + k_{1y}(E)) \]

\[ \bar{q}_4(E) = (2k_{1x}(E), 2k_{1y}(E)) \]

\[ \bar{q}_5(E) = (0, 2k_{1y}(E)) \]
Measuring the Fermi Surface:

\[ \tilde{q}_1(E) = (2k_{1x}(E),0) \]

\[ \tilde{q}_2(E) = (k_{1x}(E) + k_{1y}(E), k_{1y}(E) - k_{1x}(E)) \]

\[ \tilde{q}_3(E) = (k_{1x}(E) + k_{1y}(E), k_{1x}(E) + k_{1y}(E)) \]

\[ \tilde{q}_4(E) = (2k_{1x}(E), 2k_{1y}(E)) \]

\[ \tilde{q}_5(E) = (0, 2k_{1y}(E)) \]

\[ \tilde{q}_6(E) = (k_{1x}(E) - k_{1y}(E), k_{1y}(E) + k_{1x}(E)) \]
Measuring the Fermi Surface:

\[ q_1(E) = (2k_{1x}(E), 0) \]

\[ q_2(E) = (k_{1x}(E) + k_{1y}(E), k_{1y}(E) - k_{1x}(E)) \]

\[ q_3(E) = (k_{1x}(E) + k_{1y}(E), k_{1x}(E) + k_{1y}(E)) \]

\[ q_4(E) = (2k_{1x}(E), 2k_{1y}(E)) \]

\[ q_5(E) = (0, 2k_{1y}(E)) \]

\[ q_6(E) = (k_{1x}(E) - k_{1y}(E), k_{1y}(E) + k_{1x}(E)) \]

\[ q_7(E) = (k_{1x}(E) - k_{1y}(E), k_{1y}(E) - k_{1x}(E)) \]

For each energy:
- 7 measured quantities \( q_i(E) \)
- 7 equations
- 2 unknowns \((k_x, k_y)\)
System is vastly overdetermined!
ARPES & STM: Fermi surface comparison

FT-STS $|\Delta(k)|$ : Reasonable agreement with ARPES

Fit:

$$\Delta(\theta_k) = \Delta_0[A\cos(2\theta_k) + B\cos(6\theta_k)]$$

What about global doping dependence?
Dispersion of q-space peaks

(0, π) anti-nodal Cu-O-Cu bond

(π, π) nodal 45° from bond

\[ |q_1| \approx \frac{2\pi}{a_0} \sim 78\text{K} \text{ underdoped} \]

\[ |q_7| \approx \frac{2\pi}{a_0} \]

Energy [meV]

Dispersion of q-space peaks

(0,\pi) anti-nodal
Cu-O-Cu bond

(\pi,\pi) nodal
45° from bond

\[ \text{Energy [meV]} \]

\( |q_1| \) [2\(\pi/a_0\)]

\( |q_7| \) [2\(\pi/a_0\)]

\[ \text{Energy [meV]} \]

\( \sim 78\text{K underdoped} \)

'as-grown'

\[ \text{Science 297, 1148 (2002).} \]
Dispersion of q-space peaks

(0,\pi) anti-nodal Cu-O-Cu bond

(\pi,\pi) nodal 45° from bond

\[ |q_1| \approx 2\pi/a_0 \]

\[ |q_7| \approx 2\pi/a_0 \]

\[ \sim 78K \text{ underdoped} \]
\[ \text{'as-grown'} \]
\[ \sim 85K \text{ overdoped} \]

Doping trend fits expectation, agrees with ARPES

\( (\pi, 0) \) anti-nodal

\( (\pi, \pi) \) nodal

These FT-STS techniques are powerful and flexible

<table>
<thead>
<tr>
<th>Nanoscale Disorder</th>
<th>Quasiparticle Interference</th>
<th>Impurity States</th>
<th>Vortex States</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

- **Nanoscale Disorder**
  - 15 nm Gapmap, B=0
  - 64 nm 12 mV LDOS, B=0
  - 26 nm -9mV LDOS, B=0
  - 56 nm 0-12mV LDOS, B=5T

- **Quasiparticle Interference**
  - 26 nm

- **Impurity States**
  - 25 nm

- **Vortex States**
  - 30 nm

References: