Local Spectroscopy of $Bi_2Sr_2CaCu_2O_{8+\delta}$ *

Aharon Kapitulnik

Stanford University

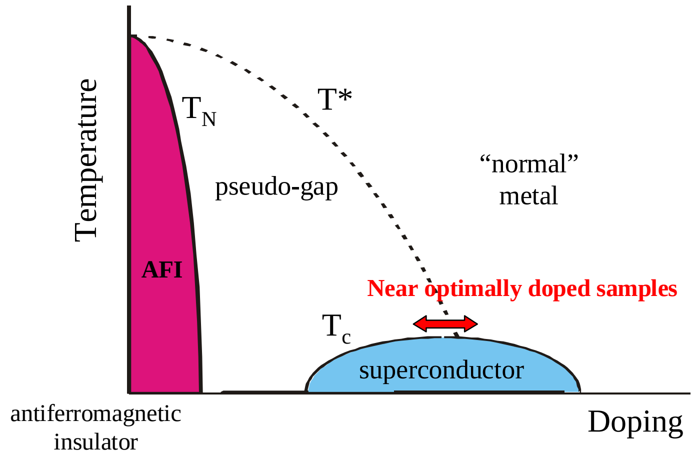
* **Thesis work of *Craig Howald***

* Early work done in collaboration with Ali Yazdani and Don Eigler
* Samples made by Patrick Fournier and Hiroshi Eisaki

Motivation

- STM provides spatial and energy resolved information
- Use STM to probe variations in DOS including non-superconducting regions, either native, or through local surface modification.
- Search for ordered electronic structures

High Tc Phase Diagram



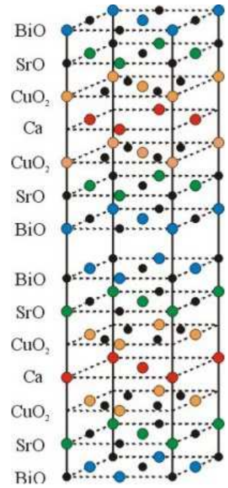
Scanning Tunneling Microscope

- Experiment performed with a low temperature UHV STM
  - Base temperature 6 K
  - Vacuum: <5×10^{-10} Torr at room temperature
  - Au, Ir tips cleaned by field emission and crashing on Au film
  - BSCCO cleaved in vacuum, exposing BiO surface.
  - Samples transferred to low temperatures in < 1 min.

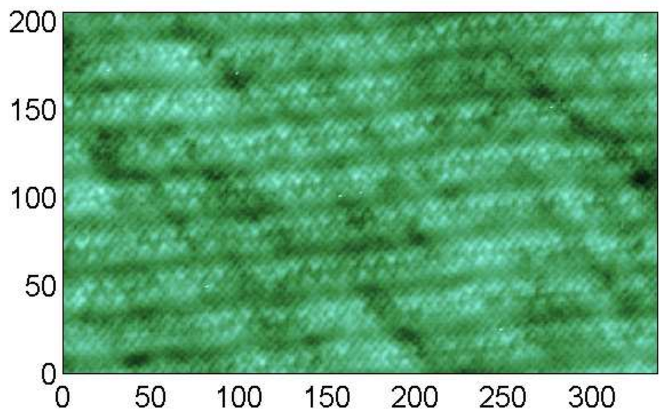
- Images typically taken at -200 mV, 100 pA

BiSrCaCuO

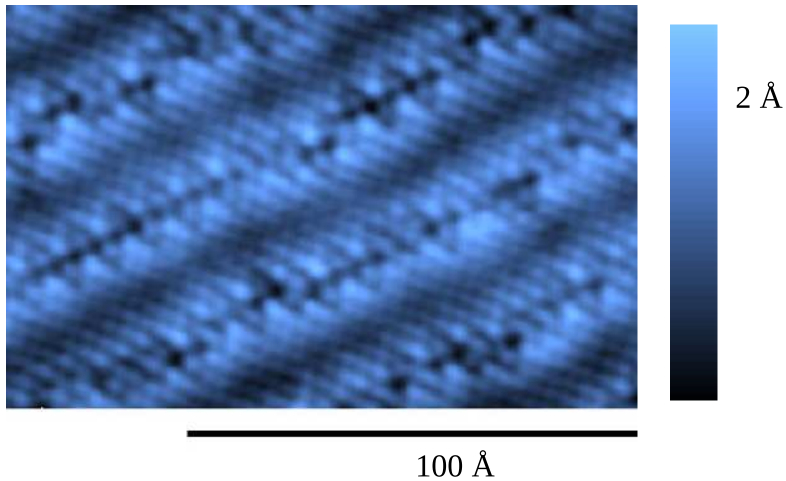
- $Bi_2Sr_2CaCu_2O_{8+\delta}$ (2212) →
  - Advantages
    - Cleaves easily, giving large, flat, clean, stable surfaces
    - Large, relatively homogeneous crystals can be grown with various dopings
    - Electronic structure and doping of Cu-O layers in the material are only weakly affected
  - Disadvantages
    - There is a superstructure modulation along the b-axis
    - Oxygen stoichiometry at the surface is just a guess….
    - Very sensitive surface, though this may be true of all HTSC



Topography



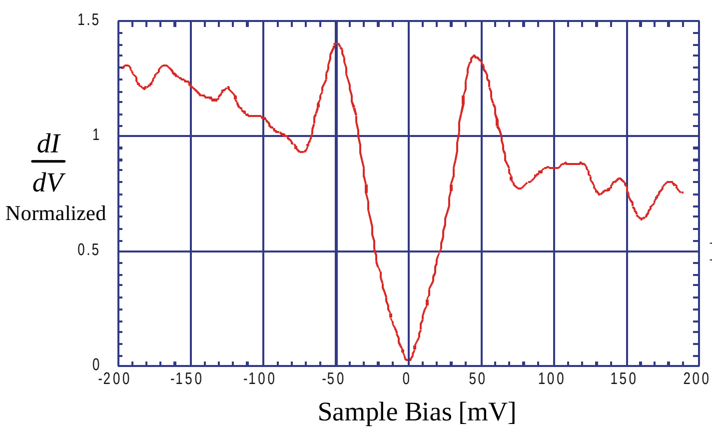
Zooming in



M.D. Kirk, J. Nogami, A.A. Baski, D.B. Mitzi, A. Kapitulnik, T.H. Geballe, and C.F. Quate, Science, 242, 1673 (1988)

Native Surface Spectrum

d-wave fit: $$\frac{N_S(E)}{N_N} = \int_{-\infty}^{\infty} \mathrm{Re} \int_0^{2\pi} \frac{d\theta}{2\pi} \frac{E}{\sqrt{E^2 - \Delta(\theta)^2}} \frac{e^{-\frac{(E-U)^2}{2\Gamma^2}}}{\sqrt{2\pi\Gamma^2}} dU$$



For most spectra:
$\Delta = 42 \pm 2$ mV
$\Gamma = 2 \pm 1$ mV

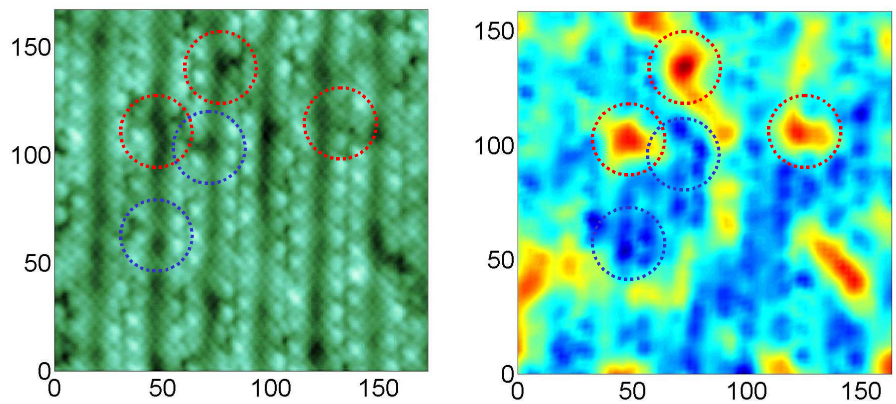
Minimum Gap found:

$\Delta \approx 30$ mV

Gap Size Distribution
(Slightly underdoped and slightly overdoped)

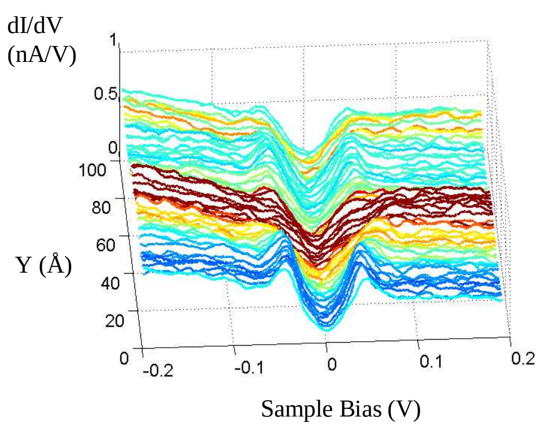
Topography

Gap Distribution
(Red=Large gap)



"Bad" regions are ~ 7%-15% of surface

Spectral Variation
Slightly underdoped BSCCO



Red=large gap
Blue=small gap

Dynamic range: 35-80 mV

Inhomogeneities of $Bi_2Sr_2CaCu_2O_{8+\delta}$ Films

T. Cren, D. Roditchev, W. Sacks, J. klein, J.-B. Moussy, C. Deville-Cavellin, and M. Lagues, PRL 84, 147 (2000)

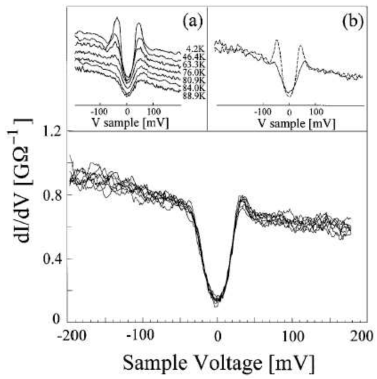


FIG. 2. Typical spectrum just beyond a superconducting region, which we attribute to the pseudogap. The spectrum is surprisingly similar to the data of Renner *et al.* [18] obtained at $T > T_c$, inset (a), and to the pseudogap structure, found at 4.2 K in the vortex core 7, inset (b) (lower curve).

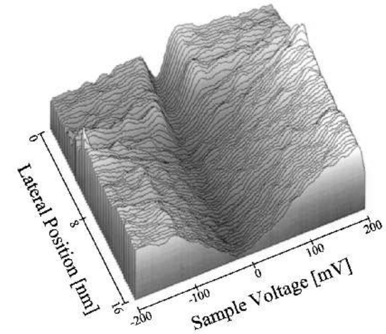
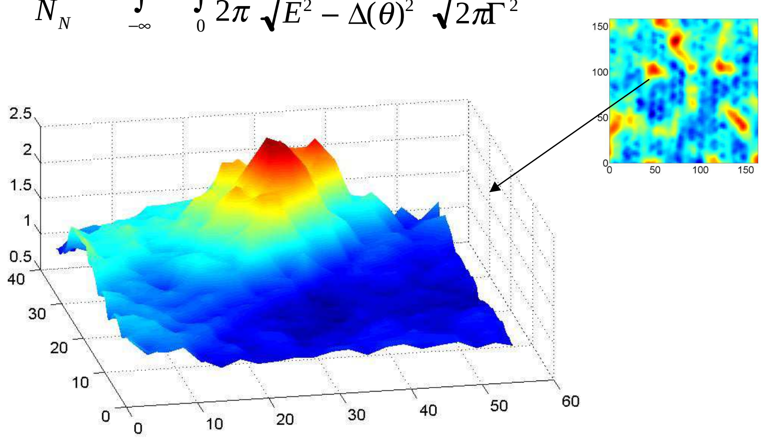


FIG. 4. The $dI/dV(V)$ spectrum variations as the tip is moved away from the pseudogap region. The changes from the pseudogap into a semiconducting form are seen.

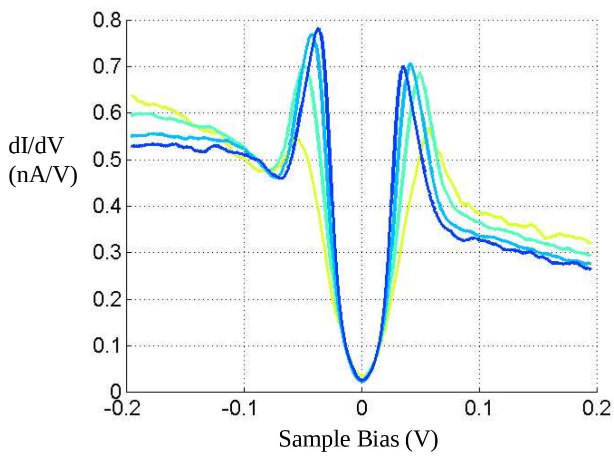
Close-up

Fit local spectra to a gap:

$$\frac{N_S(E)}{N_N} = \int_{-\infty}^{\infty} \mathrm{Re} \int_0^{2\pi} \frac{d\theta}{2\pi} \frac{E}{\sqrt{E^2 - \Delta(\theta)^2}} \frac{e^{-\frac{(E-U)^2}{2\Gamma^2}}}{\sqrt{2\pi\Gamma^2}} dU$$



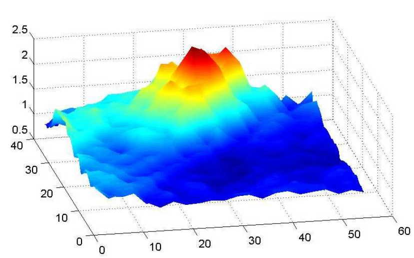
Variety of Spectra



Gap Size Structure in inhomogeneous regions

Fit local spectra to a gap:

$$\frac{N_S(E)}{N_N} = \int_{-\infty}^{\infty} \mathrm{Re} \int_0^{2\pi} \frac{d\theta}{2\pi} \frac{E}{\sqrt{E^2 - \Delta(\theta)^2}} \frac{e^{-\frac{(E-U)^2}{2\Gamma^2}}}{\sqrt{2\pi\Gamma^2}} dU$$

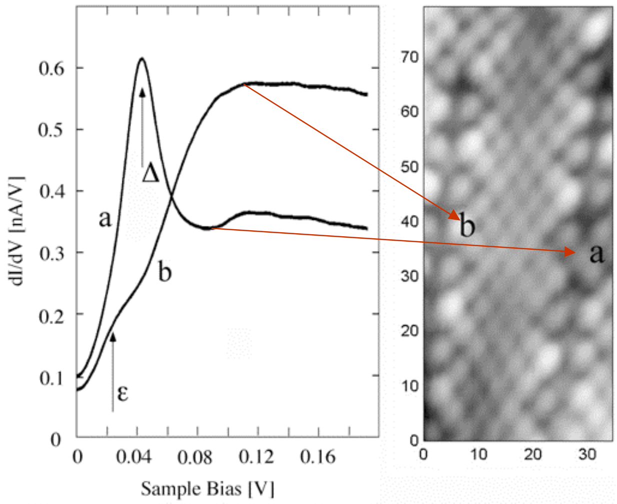


Fit of low energy range:

$$\frac{N_S(\varepsilon < \bar{\Delta}/3)}{N_N}$$

QuickTime™ and a Photo - JPEG decompressor are needed to see this picture.

Extremal Spectra

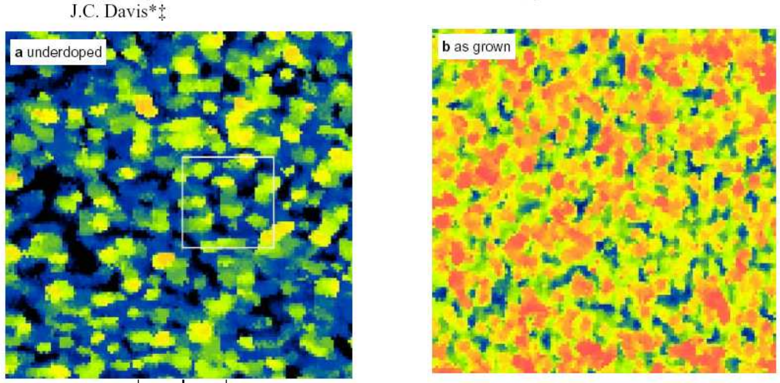


We cannot identify
Any specific impurity
Or defect under the
"bad" gap!

Reproducibility

Imaging the granular structure of high-T_c superconductivity in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$

K.M. Lang*, V. Madhavan*, J.E. Hoffman*, E.W. Hudson*†‡, H. Eisaki§¦ , S. Uchida§ & J.C. Davis*‡



Possible Explanations for Inhomogeneities

I. Local Effects of Disorder

1. Point defects due to impurities
2. Local variations in doping

II. Global Effects of disorder

1. Macroscopic variations in properties of crystals
2. Phase separation due to electron correlations and disorder

Point Defects

• Point defects exist on the native (cleaved) surface, or can be deposited from the tip or from an external source

*Yazdani, Howald, Lutz, Kapitulnik, and Eigler, PRL 83, 176 (1999).
*Hudson, Pan, Gupta, Ng, and Davis, Science 285, 88 (1999).
*Howald, Kapitulnik, PRB 64 (2001).

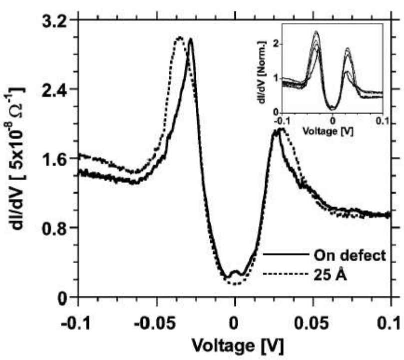
• Dopind of the Crystal with, e.g. Zn will create strong scatterers that will show up in the cleaved surface.

*Pan, Hudson, Lang, Eisaki, Uchida, and Davis, Nature 403 (2000).

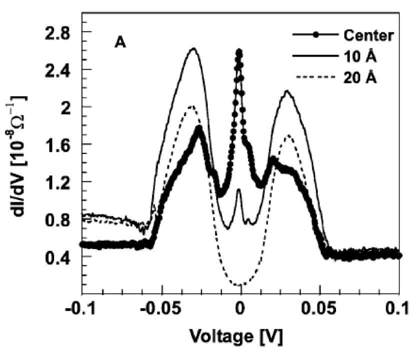
Spectroscopy Near Strong vs. Weak Scatterer

Yazdani, Howald, Lutz, Kapitulnik, and Eigler, PRL 83, 176 (1999).

Weak scatterer

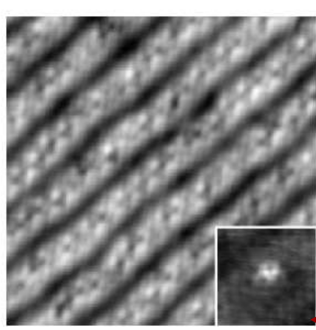


Strong scatterer



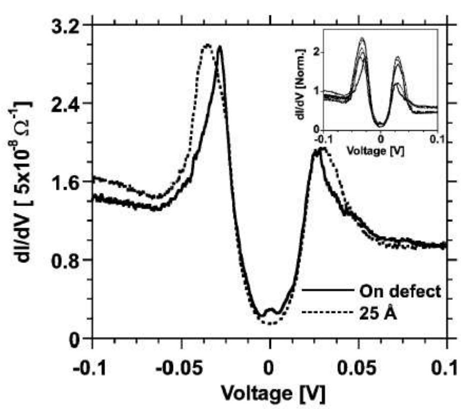
Native Surface Impurities of Nearly Optimally-Doped $Bi_2Sr_2CaCu_2O_{8+\delta}$

200Åx200Å topograph



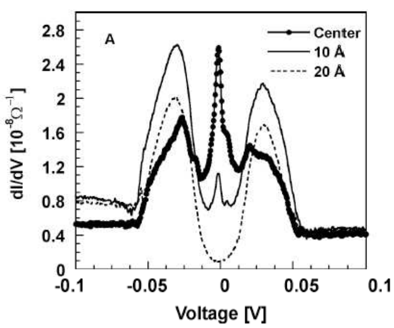
Native surface defect

Spectroscopy near an intrinsic defect

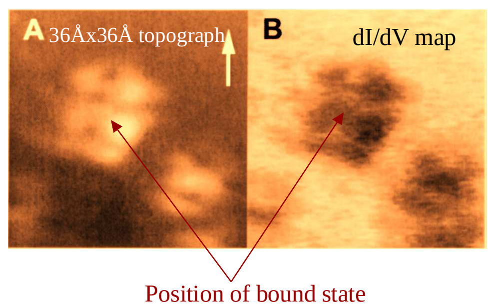


Impurity Induced Bound Excitation

Spectra acquired directly above a gold adatom on BSSCO, and at several distances from it:



Corresponding 36 Å x 36 Å topograph of the atomic impurity (A) and simultaneously acquired image showing the variation in dI/dV*1/I at constant current and voltage (1 nA, 36 mV) (B):



Results from the Berkeley Group

S. H. Pan,[1,*] E. W. Hudson,[1,†] A. K. Gupta,[2] K.-W. Ng,[2] H. Eisaki,[3,‡] S. Uchida,[3] and J. C. Davis[1]

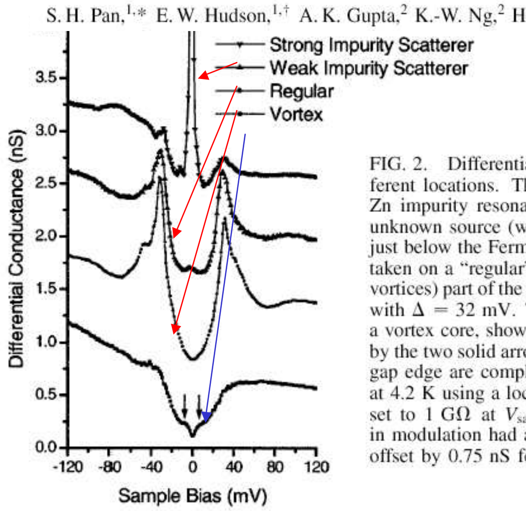
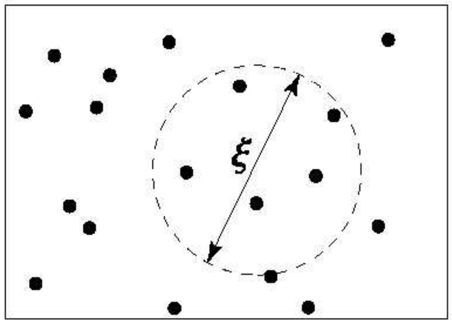


FIG. 2. Differential tunneling conductance spectra taken at different locations. The top two spectra, taken at the center of a Zn impurity resonance (strong) and an impurity resonance of unknown source (weak), respectively, show a peak in the DOS just below the Fermi energy (~ -1.5 mV). The third spectrum, taken on a "regular" (free of impurity resonances and magnetic vortices) part of the surface, shows a superconducting energy gap with $\Delta = 32$ mV. The bottom spectrum, taken at the center of a vortex core, shows two local maxima at ± 7 mV, as indicated by the two solid arrows. In addition, both coherence peaks at the gap edge are completely suppressed. All curves were obtained at 4.2 K using a lock-in technique. The junction resistance was set to 1 GΩ at $V_{\text{sample}} = -200$ mV, and the 447.3 Hz lock-in modulation had an amplitude of 500 μV_{rms}. The curves are offset by 0.75 nS for clarity.

Doping Induced Inhomogeneity

Ivar Martin and Alexander V. Balatsky [1]



$$n_\xi(\mathbf{r}) = \frac{N_\xi(\mathbf{r})}{\xi^2}$$

Fig. 1. The effective local doping at a particular point is defined through the random number of dopants which happen to be in the ξ-vicinity of this point.

* Cannot explain the kink and the low bias homogeneity

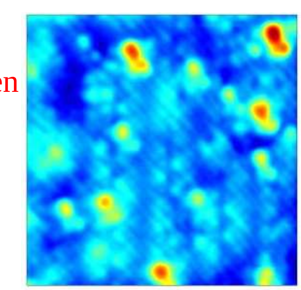
Ti adatoms

Interface formation: high-temperature superconductors with noble metals, reactive transition metals, and semiconductors.

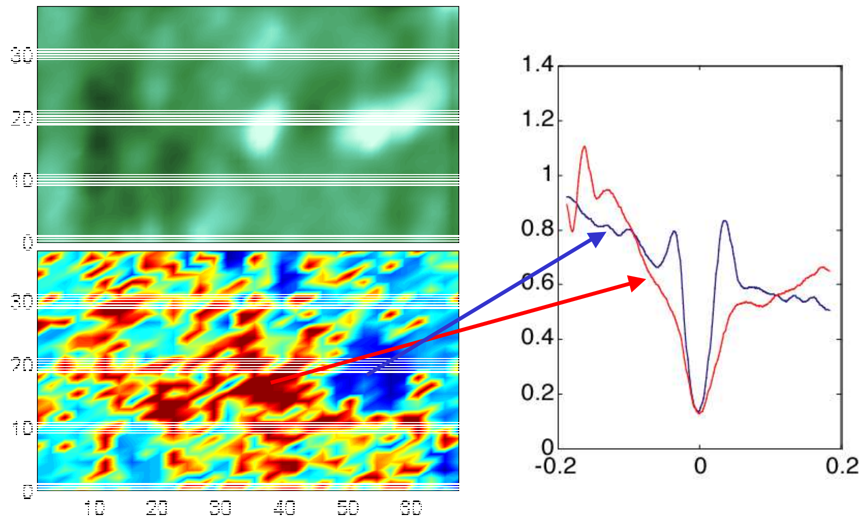
Gao, Y.; Meyer, H. M., III; Wagener, T.J.; Hill, D. M.; Anderson, S. G.; Weaver, J.H.; Flandermeyer, B.; Capone, D. W., II
AIP Conference Proceedings ; 1988; no.165, p.358-67

Ti is a strong oxidizer and thus, can be used to locally change the doping.

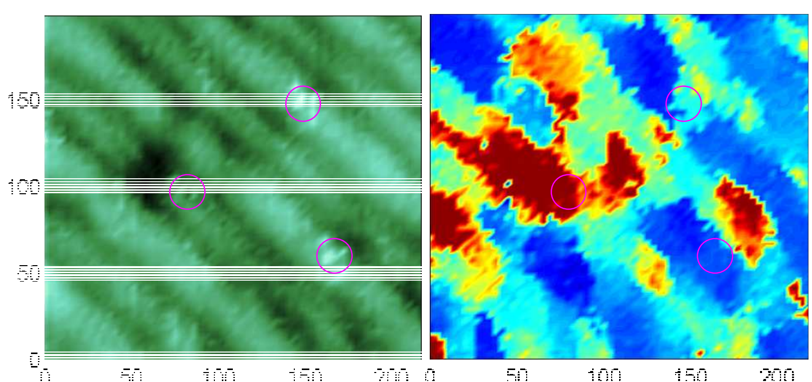
"While Au passivates the surface, the reactive transition metals (Ti, Fe) and Cu deplete oxygen from the substrate and form heterogeneous metal-oxide overlayers over a scale of a few tens of Angstroms."



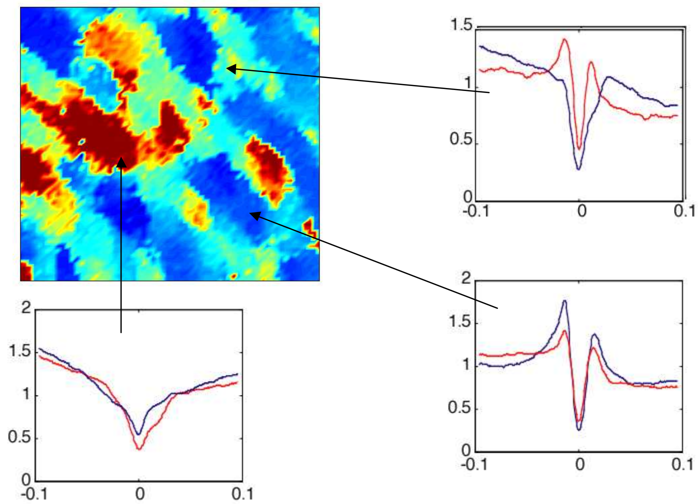
Ti on Bi2212



Ti on Bi2201



Change in Spectra



Summary of Ti Experiments

No correlation between Ti impurities and inhomogeneities was found!

Summary of Facts

- We find regions of suppressed superconductivity (7% - 20% near optimally doping).
- No zero bias anomalies of any kind are found.
- No obvious correlation with local disorder is found.
- Gap variation is continuous different than intentional variation or vortex core.
- Low bias is spectra are homogeneous throughout the sample.
- Center of "bad" region shows "normal behavior at low-bias and a pseudo-gap at high bias.

Possible Model: Phase Separation + Proximity Effect

- Strong Interactions, Disorder and possible proximity to a first-order phase transition cause the system to phase-separate into regions of "bad" and "good" superconductor. [V.J. Emery and S.A. Kivelson, Physica C 209, 597 (1993).]
- The size fraction of the bad regions depend on doping and disorder.
- Proximity effect due to the surrounding superconducting regions causes the smoothness of the spectra.
- The short coherence length of the superconductor causes the proximity length to be of order of the coherence length [G. Deutscher and K.A. Muller, Phys. Rev. Lett. 59, 1745 (1987).]

Phase Separation in Strongly Correlated Electron Systems

- In pure metals the kinetic energy is dominant and hence the electron density is very homogeneous, even in the presence of disorder.

However:

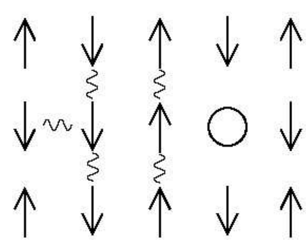
- In a highly correlated system, such as high-temperature superconductors, the electronic structure is much more prone to inhomogeneity, and "meso-scale" structures are likely to appear (e.g. **stripes**).

- High-Tc superconductors may be close to a first order transition and thus disorder will cause the system to break into domains of the two phases (Imry-Ma argument).

Phase separation and doped antiferromagnets

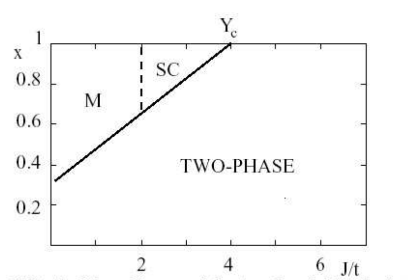
Frustration of a one hole's motion in an antiferromagnet.

As the hole moves it leaves behind a string of frustrated bonds.



Finite density of holes leads to phase separation to minimize frustration.

Two-phase: Hole rich phase and antiferromagnetic insulator



E. Carlson et al., 1998

Proximity effect in short coherence length superconductors

Origin of Superconductive Glassy State and Extrinsic Critical Currents in High-T_c Oxides

G. Deutscher
Department of Physics and Astronomy, Tel Aviv University, Ramat Aviv, 69978 Tel Aviv, Israel
and
K. A. Müller
IBM Research, Zurich Research Laboratory, CH-8803 Rüschlikon, Switzerland
(Received 20 July 1987)

$$(\Delta^{-1} d\Delta/dx)_{x=0} = b^{-1} = \frac{2}{L}\int_{-\infty}^{+\infty} dx\, \frac{\Delta(x)}{\Delta_0}\left[1 - \frac{N(x)}{N(0)}\right]$$

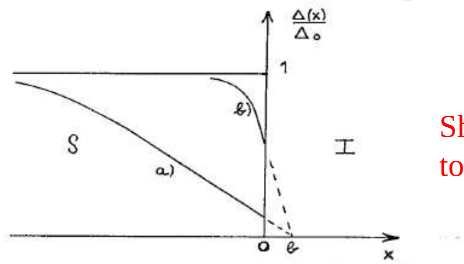


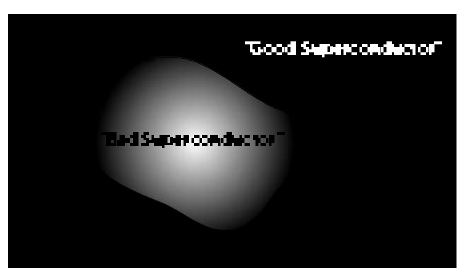
FIG. 1. Profile of the pair potential in a short-coherence-length superconductor near a superconductor-insulator boundary: (curve *a*) $T \lesssim T_c$; (curve *b*) $T \ll T_c$.

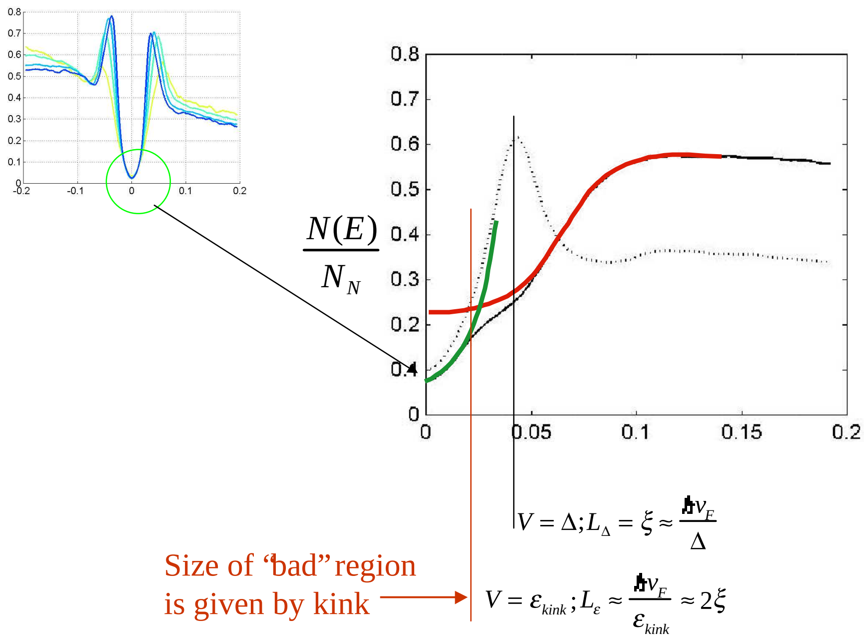
Short coherence length leads to proximity length of $b \sim \xi$

Proximity Effect and Phase-separated "Bad" Regions

Before Proximity Effect
(Two types of spectra)

After Proximity Effect
(continuous variation of spectra)





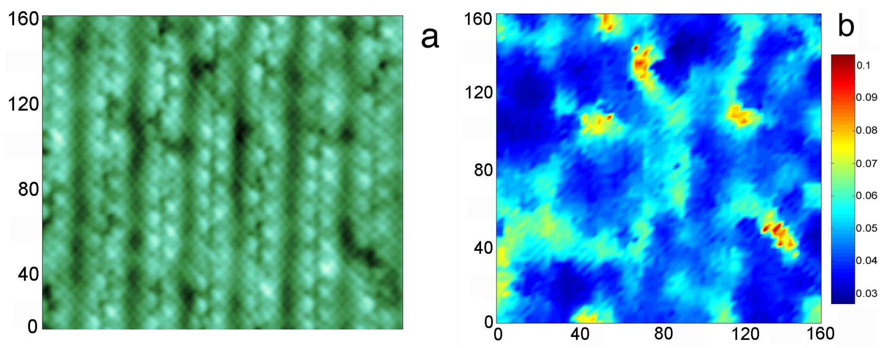
Conclusions for Inhomogeneities

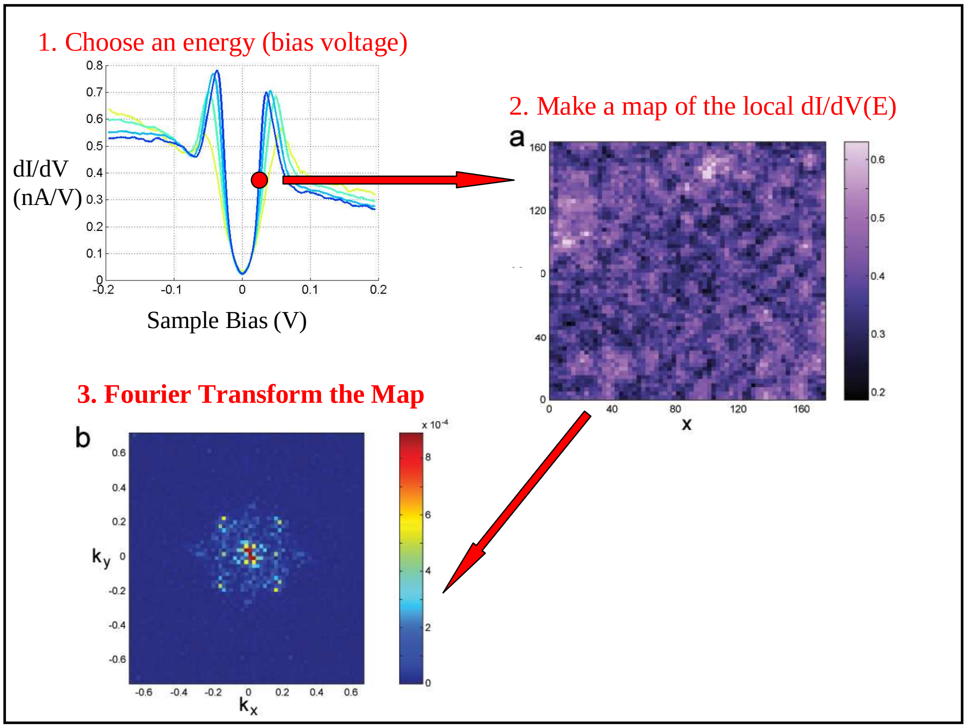
- All BSCCO Samples are inherently inhomogeneous.
- "Bad" regions do not seem to correlate with disorder on a microscopic scale, but depend On disorder on a macroscopic scale.
- Possible Phase separation and proximity effect of the separated regions are observed.

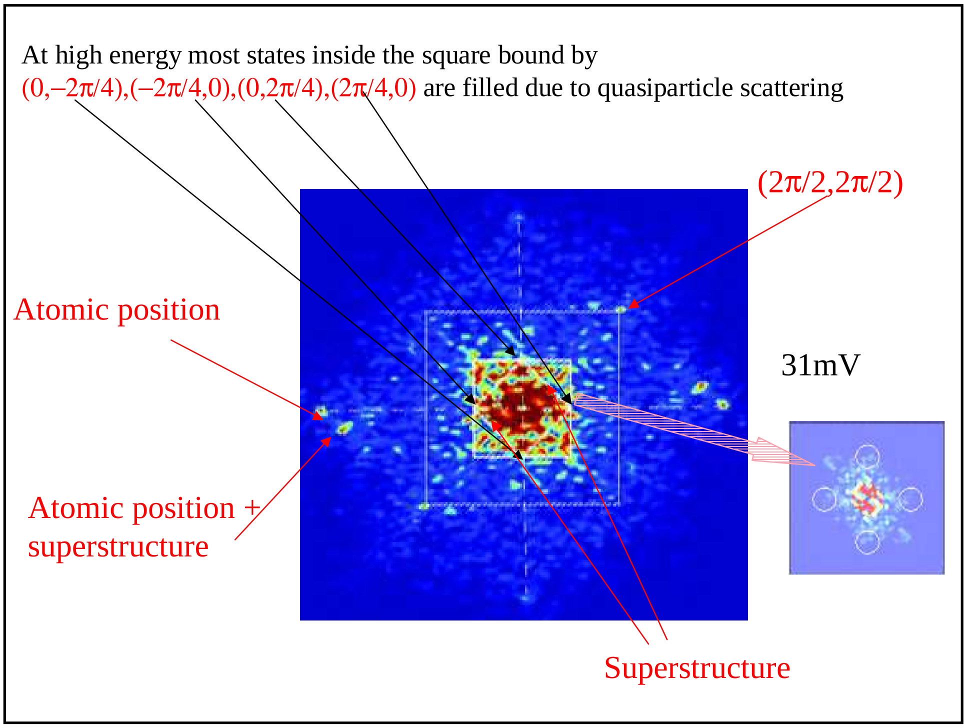
Energy dependent LDOS Variations

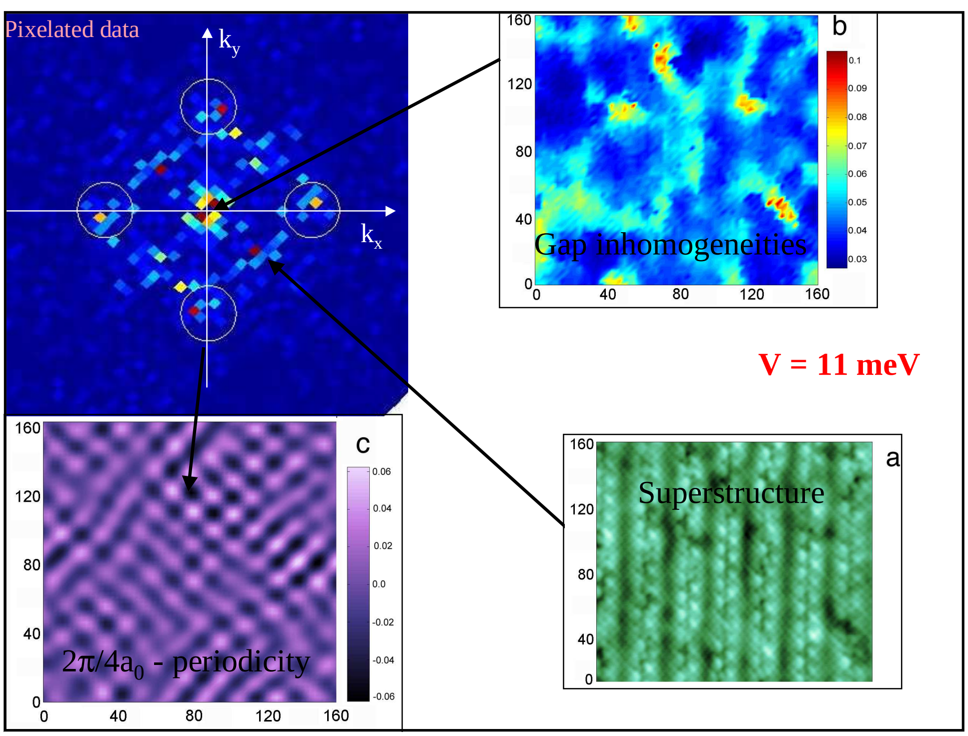
Topography

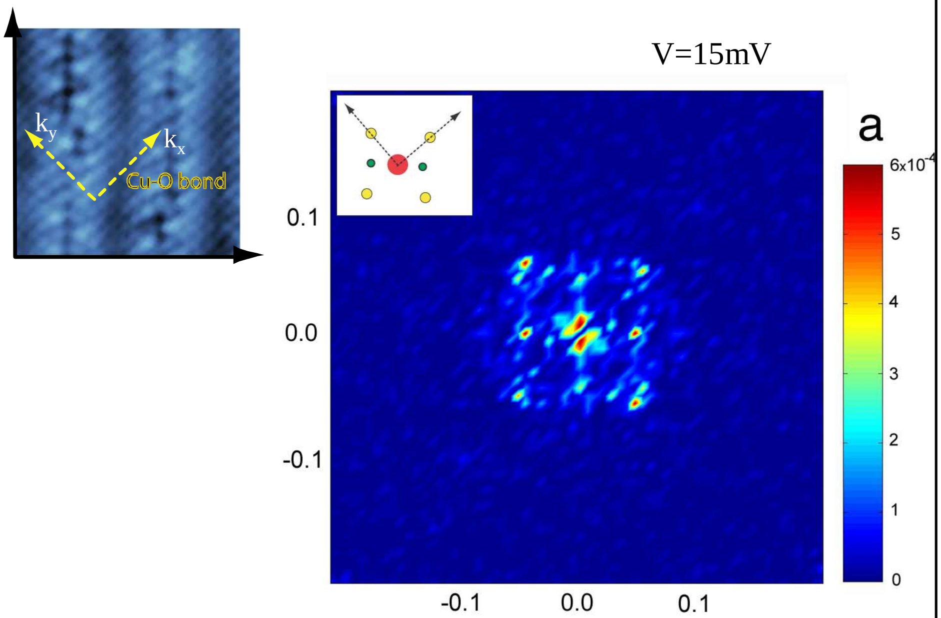
Gap Inhomogeneity






At high energy most states inside the square bound by
(0,–2π/4),(–2π/4,0),(0,2π/4),(2π/4,0) are filled due to quasiparticle scattering
(2π/2,2π/2)
Atomic position
31mV
Atomic position + superstructure
Superstructure


Pixelated data
k_y
k_x
Gap inhomogeneities
b
V = 11 meV
Superstructure
a
c
2π/4a_0 - periodicity

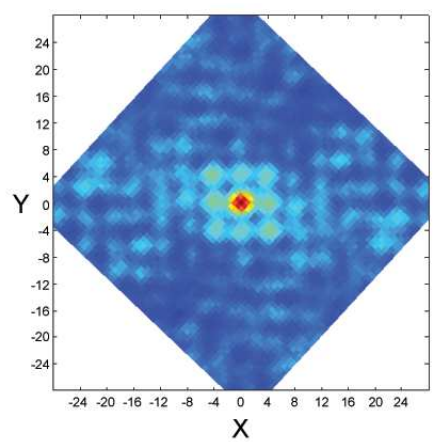


C. Howald et al. cond-mat/0201546

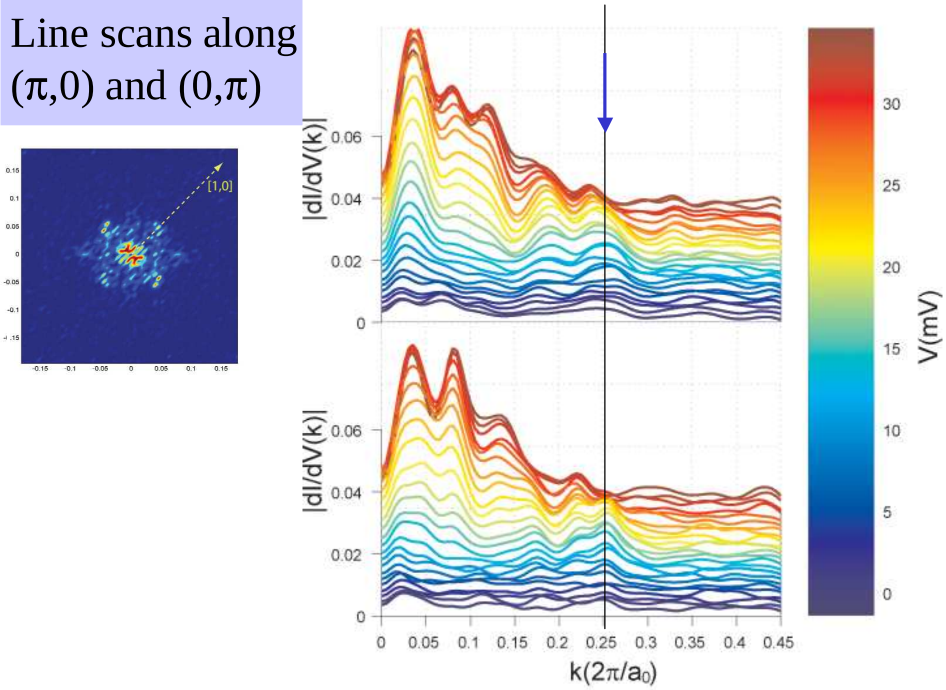
Autocorrelation

$$F(x,y) = \langle g(x_0,y_0)\,g(x_0+x,y_0+y) \rangle$$

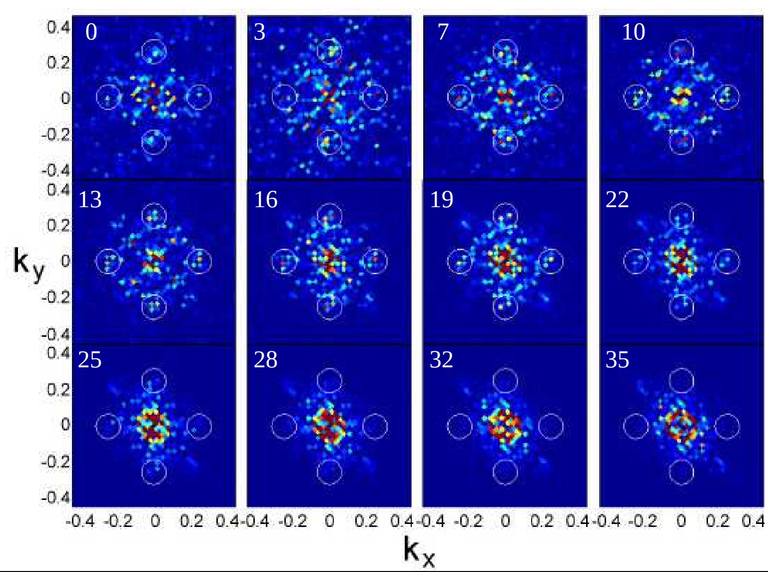
Order at least 7 periods
(~7x4x4Å=112Å)

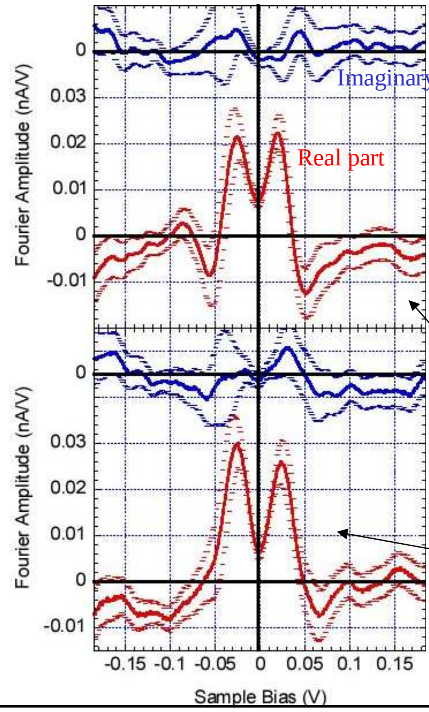


Line scans along (π,0) and (0,π)



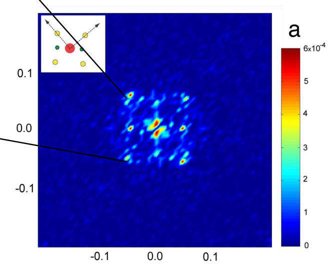
Variation of Power Spectrum





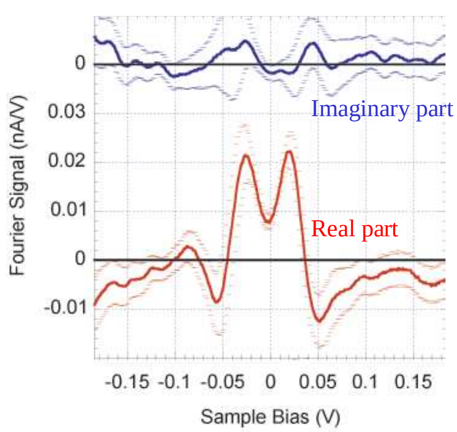
Energetics

- Imaginary part is consistent with zero
- Peaks at 20-25 mV
- States moving from above to below gap
- Magnitude is small



and Phase

(for the (1,0),(0,1) directions)



Imaginary part is very small, thus the phase is constant.

For the Fourier transform of a LxL map with arbitrary origin at $\boldsymbol{r_0}$

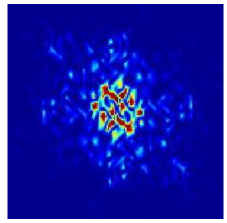
$$dI/dV \propto e^{-i\bar{k}\bullet r_0} N_L(\bar{k},E)$$

For a fixed $\boldsymbol{r_0}$, a constant phase
Means an energy independent $\boldsymbol{k}$

For a sample (i.e. STM picture) of dimensions LxL

The Fourier transform of the local density of states at energy E=V/e:

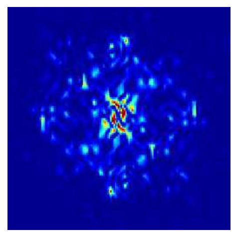
$$dI/dV \propto N_L(\bar{k},E)$$



E = 22 mV

The integrated Fourier transform of the local density of states up to energy E=V/e:

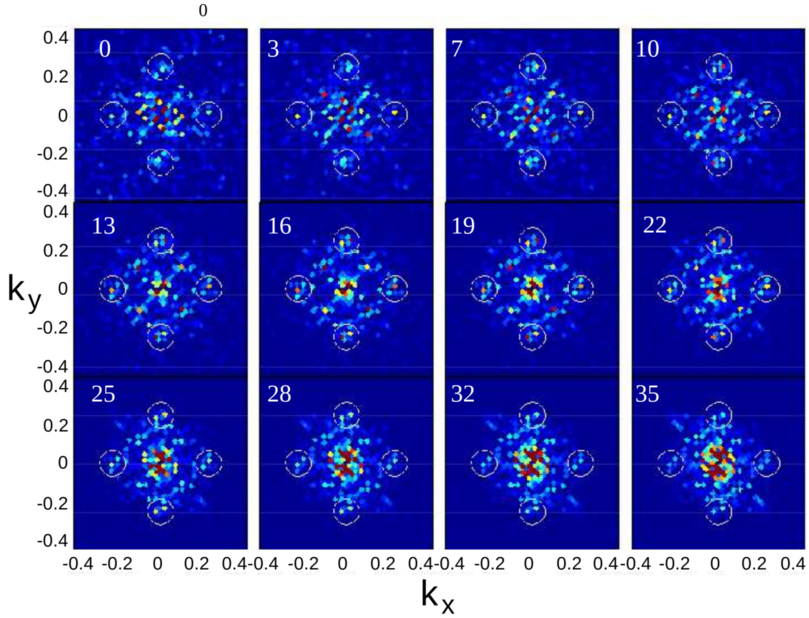
$$I/V \propto \tilde{N}_L(\bar{k},E) = \int_0^E N_L(\bar{k},E')dE'$$



E = 22 mV

$$I/V \propto \tilde{N}_L(\bar{k},E) = \int_0^E N_L(\bar{k},E')dE'$$

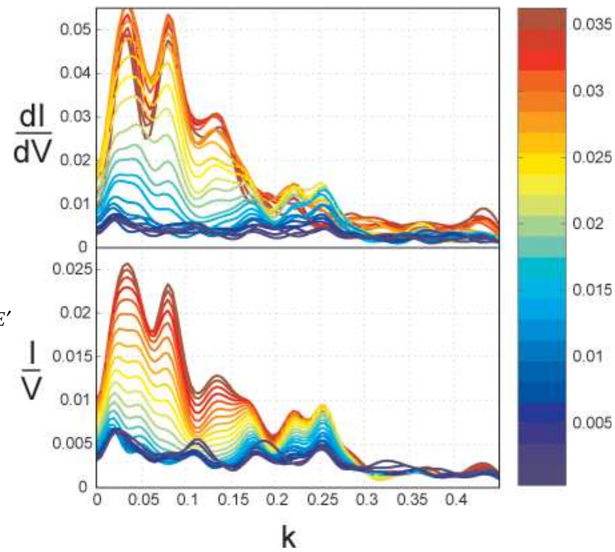
Between 0 mV and 35 mV



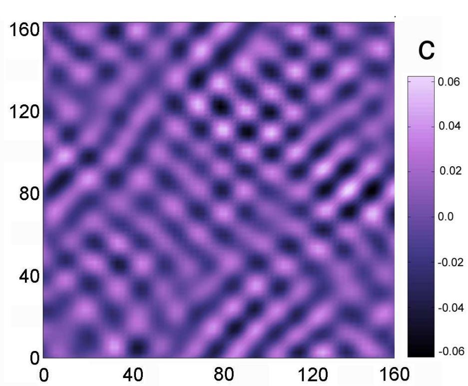
Comparison of line scans show that the peak at k=0.25 does not disperses

$$dI/dV \propto N_L(\bar{k},E)$$

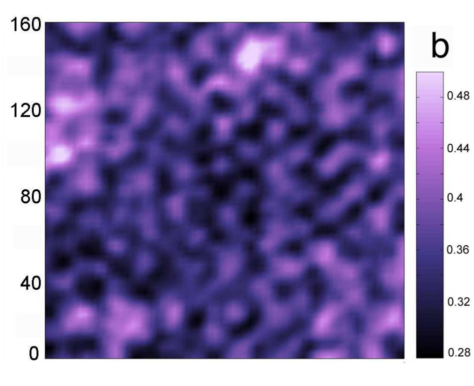
$$I/V \propto \tilde{N}_L(\bar{k},E) = \int_0^E N_L(\bar{k},E')dE'$$



Periodicity in Real Space



Filtered Data: Low-k and Superstructure filtered out



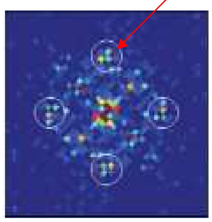
Raw data (adjacent-sub-atomic Points are smoothed)

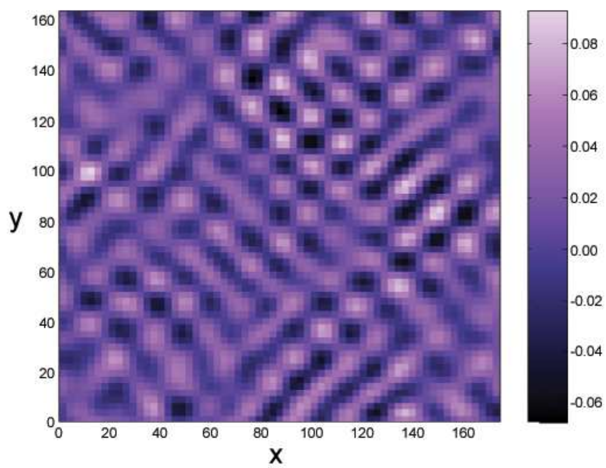
Filtered Data

$$N_f(\vec{r}, E) = \int d\vec{r}' f(\vec{r} - \vec{r}') N(\vec{r}', E)$$

Filter function: $f(\vec{r}) \propto \Lambda^2 e^{-r^2\Lambda^2/2}[\cos(\pi x/2a) + \cos(\pi y/2a)].$

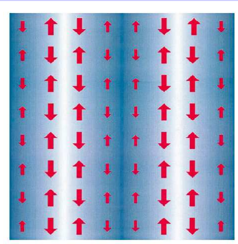
~36 pixels in filter



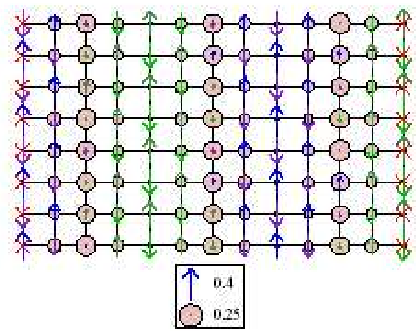


Stripes

- Phase separation in doped anti-ferromagnetic insulators
  - Theory
    - Zaanen and Gunnarson *PRB* **40**, 7391 (1989)
    - Schulz *PRL* **64**, 1445 (1990)
    - Emery and Kivelson *Physica C* **209**, 597 (1993)



Stripes in numerical simulations



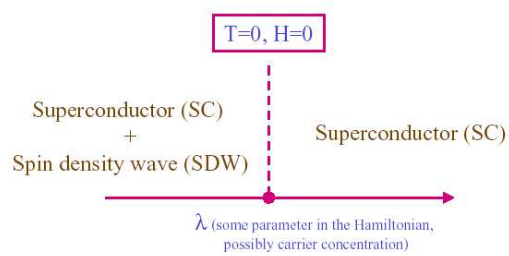
Hole density and spin moments on a 13×8 system (cylander) with 12 holes, $J/t = 0.35$, periodic boundary conditions along the y direction and π-shifted staggered magnetic field of magnitude $0.1t$ on the open edges. The diameter of the circles is proportional to the hole density $1 - \langle n_i \rangle$ and the length of the arrows is proportional to $\langle S_i^z \rangle$.

White and Scalapino, 2000

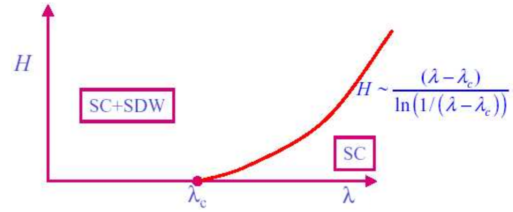
Stripes and quantum phase transition

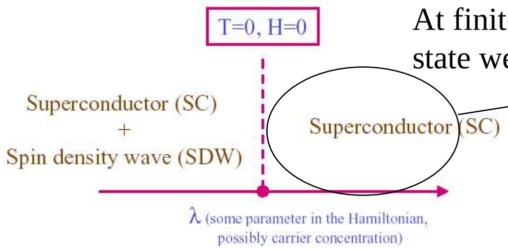
M. Vojta, C. Buragohain, and S. Sachdev, Phys. Rev. B **61**, 15152 (2000)

E. Demler, S. Sachdev, and Y. Zhang, cond-mat/0103192.



Add magnetic field:





At finite T, in the superconducting state we expect fluctuating stripes*

Disorder will pin the stripes!

* Peaks in $\chi(\mathbf{k},\Omega)$ at the characteristic stripe ordering vectors indicate a degree of local stripe order. The **k** width of these peaks can be interpreted as an indication of the spatial extent of local stripe order, and the low frequency cutoff as an indication of the typical stripe fluctuation frequency. So long as there is no spontaneous symmetry breaking, $\chi(\mathbf{k},\Omega)$ necessarily respects all the point-group symmetries of the crystal, and thus will necessarily always show peaks at quartets of **k** values, never the pairs of **k** values of a single-domain stripe ordered state.

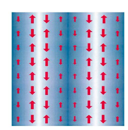
Direct observation of spin-stripes in the presence of vortices

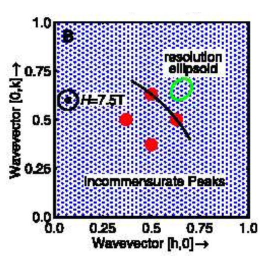
Spins in the Vortices of a High-Temperature Superconductor

B. Lake,[1] G. Aeppli,[2,3*] K. N. Clausen,[3] D. F. McMorrow,[3] K. Lefmann,[3] N. E. Hussey,[4,5†] N. Mangkorntong,[4] M. Nohara,[4] H. Takagi,[4] T. E. Mason,[1] A. Schröder[6]

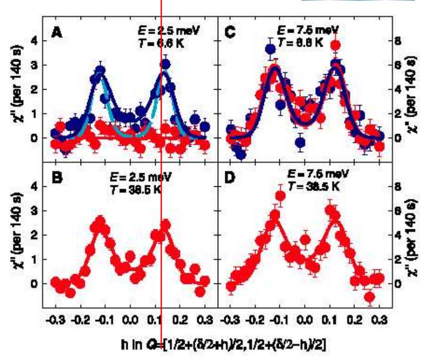
Science **291**, 1759

$$Q = \frac{2\pi}{8a}$$





Reciprocal space for the superconducting Cu-O planes of La1.837Sr0.163CuO4.
Spin fluctuations are observed at a quartet of incomensurate wave vectors (red circles.)



Translational Symmetry Breaking in the Superconducting State of the Cuprates: Analysis of the Quasiparticle Density of States

Daniel Podolsky, Eugene Demler, Kedar Damle, and B.I. Halperin
Department of Physics, Harvard University, Cambridge MA 02138

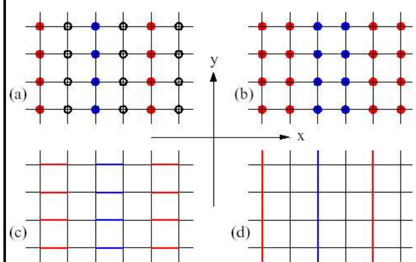


FIG. 1. Order parameters with wavevector $\mathbf{Q} = (\frac{2\pi}{4}, 0)$

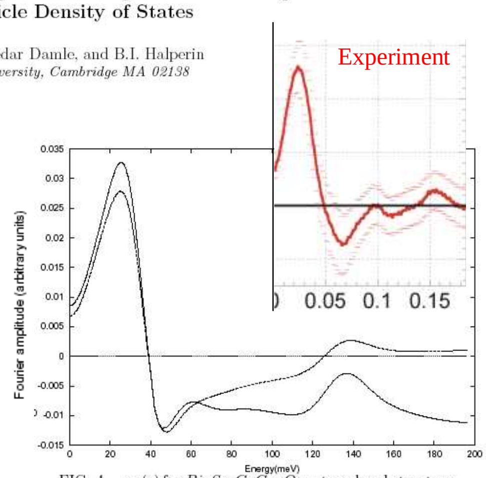
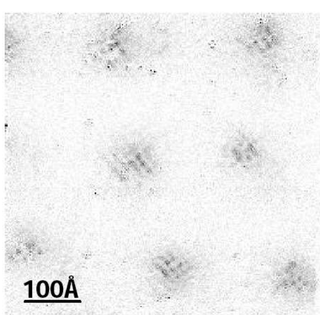


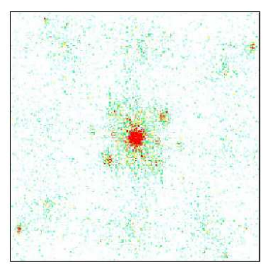
FIG. 4. $\rho_Q(\epsilon)$ for $Bi_2Sr_2CaCu_2O_{8+\delta}$ type band structure, ordering wavevector $Q = 2\pi/4$ and a combination of TSB orders: CDW and direct dimerization $V_k = -\frac{1}{8}V_k^2 + \frac{7}{8}V_k^3$ (solid line); direct longitudinal, direct transverse, and anomalous longitudinal dimerizations $V_k^3 + 0.42V_k^4 + 0.07V_k^5$ (long-dashed line). The same smearing as in Fig. 2 is assumed.

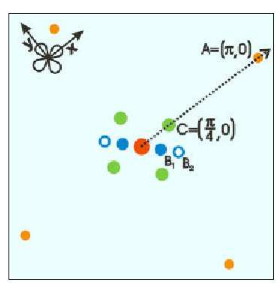
Direct observation of charge modulation in the presence of vortices

Discovery of a 'checkerboard' of quasiparticle states with four-unit-cell periodicity surrounding $Bi_2Sr_2CaCu_2O_{8+\delta}$ vortex cores.

J. E. Hoffman[1], E.W. Hudson[1*], K.M. Lang[1], V. Madhavan[1], S.H. Pan[1†], H. Eisaki[2‡], S. Uchida[2] & J.C. Davis[1,3]



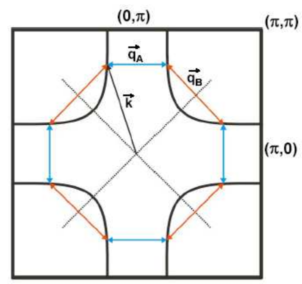




Can the modulation at H=0

be due to quasiparticle scattering?????

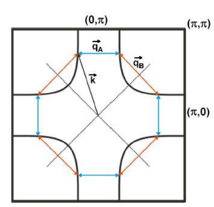
$$\bar{q} = \bar{k}' - \bar{k}$$

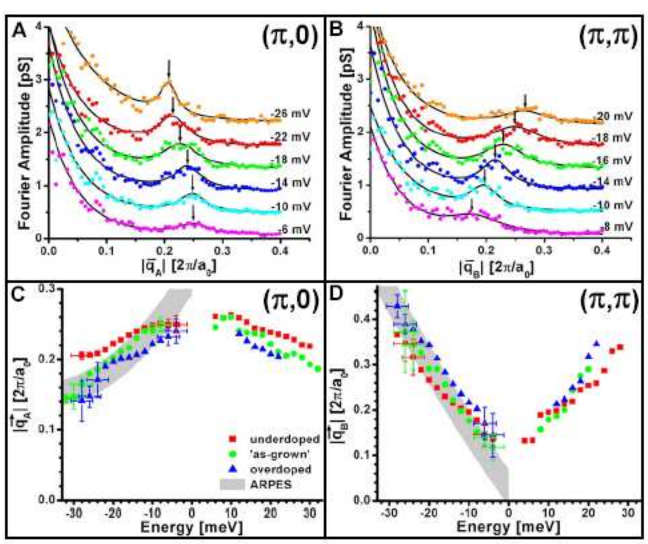


* Qiang-Hua Wang, Dung-Hai Lee, cond-mat/0205118

Imaging Quasiparticle Interference in $Bi_2Sr_2CaCu_2O_{8+\delta}$

J. E. Hoffman[1], K. McElroy[1], D.-H. Lee[1], K. M Lang[1,2], H. Eisaki[3,4,5], S. Uchida[5], J.C. Davis[1,6§]





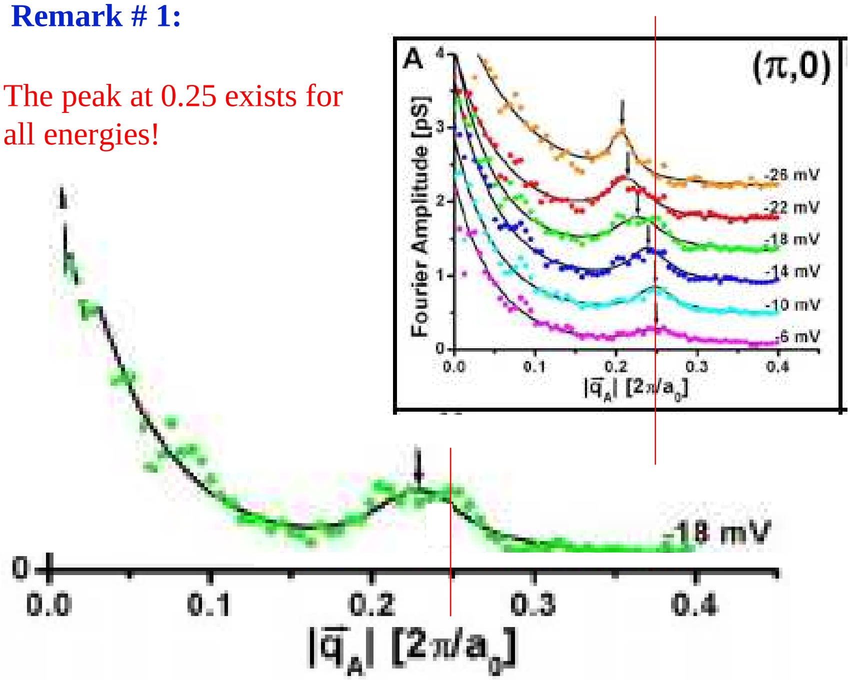
Calculations of Scattering also show NO peaks at low energies*

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

* Qiang-Hua Wang, Dung-Hai Lee, cond-mat/0205118

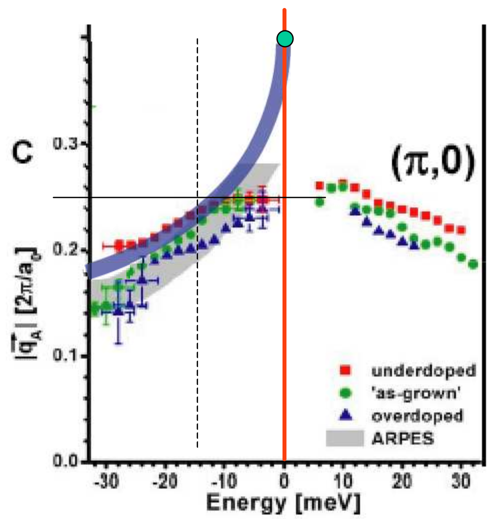
Remark # 1:

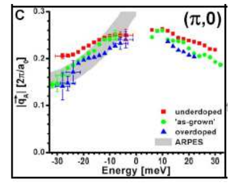
The peak at 0.25 exists for all energies!

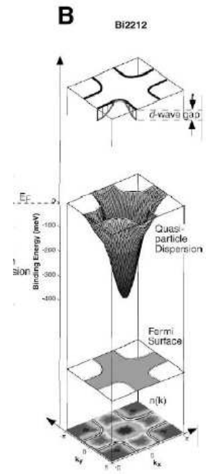


Remark # 2:

At low energies it does not fit band structure







Assuming quasiparticles with **k**-dependent energy: $E_k = \sqrt{\Delta_k^2 + \varepsilon_k^2}$

$$\Delta_k = \frac{\Delta_0}{2}\left[cos(k_x a) - cos(k_y a)\right] \quad \text{with} \quad \Delta_0 \sim 30 \div 40 meV$$

Consider scattering on the Fermi surface ($\varepsilon_k = 0$)

The scattering is from $\bar{k}$ to $\bar{k}'$ with a scattering wave-vector: $\bar{Q} = \bar{k}' - \bar{k}$

To get peaks due to scattering at $\frac{2\pi}{a}\langle \pm 0.25, 0\rangle$, and $\frac{2\pi}{a}\langle 0, \pm 0.25\rangle$

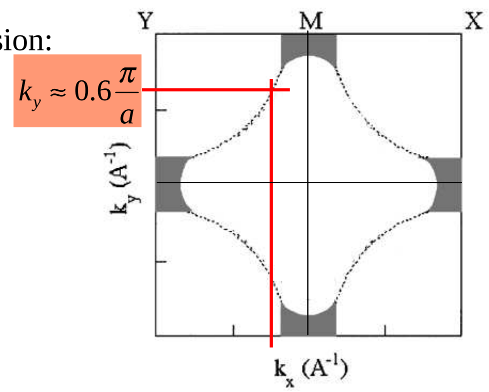
We take e.g. $\bar{Q} = \frac{2\pi}{a}\langle 0.25, 0\rangle$

So that $\bar{k} = \frac{\pi}{a}\langle 0.25, k_y\rangle; \bar{k}' = \frac{\pi}{a}\langle -0.25, k_y\rangle$

$$\vec{Q} = \frac{2\pi}{a}\langle 0.25, 0\rangle$$

$$\vec{k} = \frac{\pi}{a}\langle 0.25, k_y\rangle; \vec{k}' = \frac{\pi}{a}\langle -0.25, k_y\rangle$$

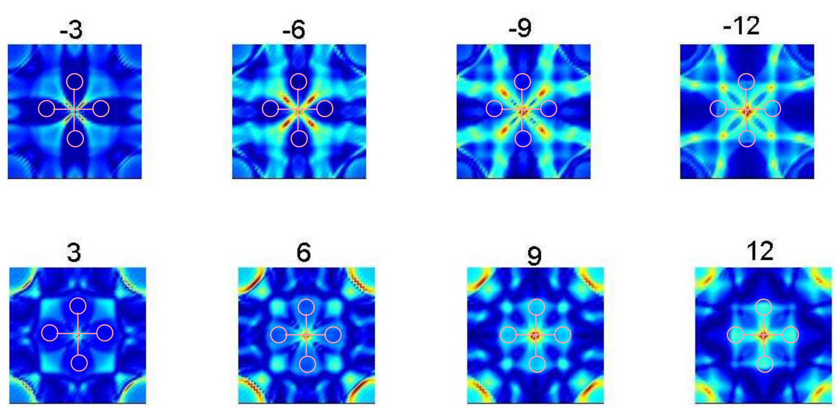
Find k_y from Photoemission:



Calculate min. E_k:

$$E_k^{\min} = \frac{30}{2}[\cos(\pi/4) - \cos(0.6\pi)] \approx 15meV$$

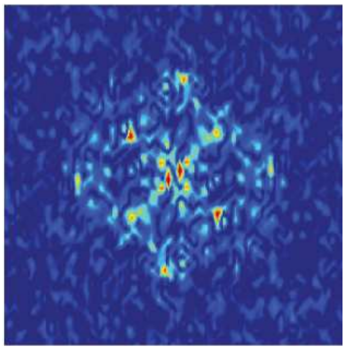
Calculations of Scattering also show NO peaks at low energies*



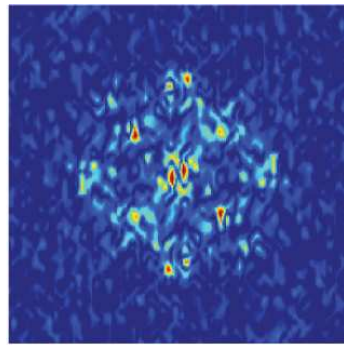
* Qiang-Hua Wang, Dung-Hai Lee, cond-mat/0205118

Note that for low energies integration is not doing much
because no quasiparticle interference contributes to the Fourier transform

e.g. E = 10 mV:

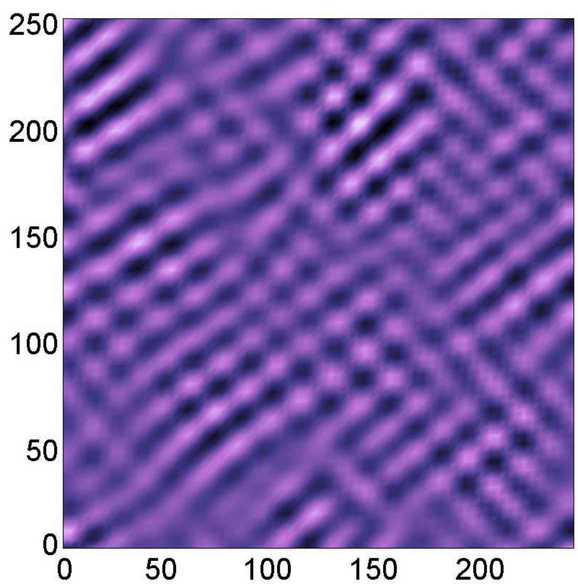


$$I/V \propto \tilde{N}_L(\bar{k},E) = \int_0^E N_L(\bar{k},E')dE'$$



$$dI/dV \propto N_L(\bar{k},E)$$

Stripes at H=0, filling the 2-dimensional space



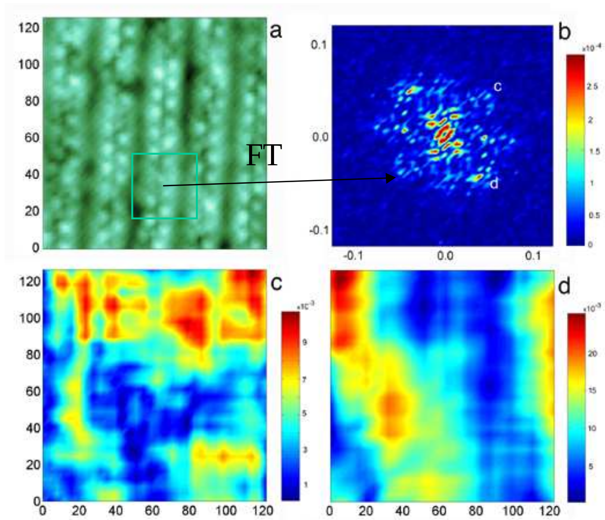
*Defects are independent of filter size

Is this a Nematic Phase?

One Dimensionality

Maps of spatial variation
of the "stripe" Bragg peaks.

Maps were created by Fourier transform of smaller areas of a larger picture.



Conclusions

- Inhomogeneities in local properties are intrinsic in these materials
- "Pinned fluctuating stripes" coexist with superconductivity in zero-field even with $T_c > 85$ K
- Possible nematic phase?