Inhomogénéités dans les cuprates, extrinsèques ou intrinsèques?

Tristan Cren

- Dimitri Roditchev, William Sacks, Jean Klein

  Institut des Nanosciences de Paris, CNRS, University Paris 6
- Nathan Jenkins, Alexandre Piriou, Ivan Maggio-Aprile, Yanina Fasano and Oystein Fischer

  DPMC, University of Geneva

Inhomogeneities in cuprates, extrinsic or intrinsic?

- Gap vs. Pseudogap as seen by STS
  - Effect of temperature, vortex and disorder
  - Supermodulation and oxygen dopants
- Dispersive modulations
  - Bogoliubov excitations, the octet model
  - Fermi arcs
- Non-dispersive modulation
  - The 4x4 modulation in the pseudogap state, around vortex cores
- Conclusion

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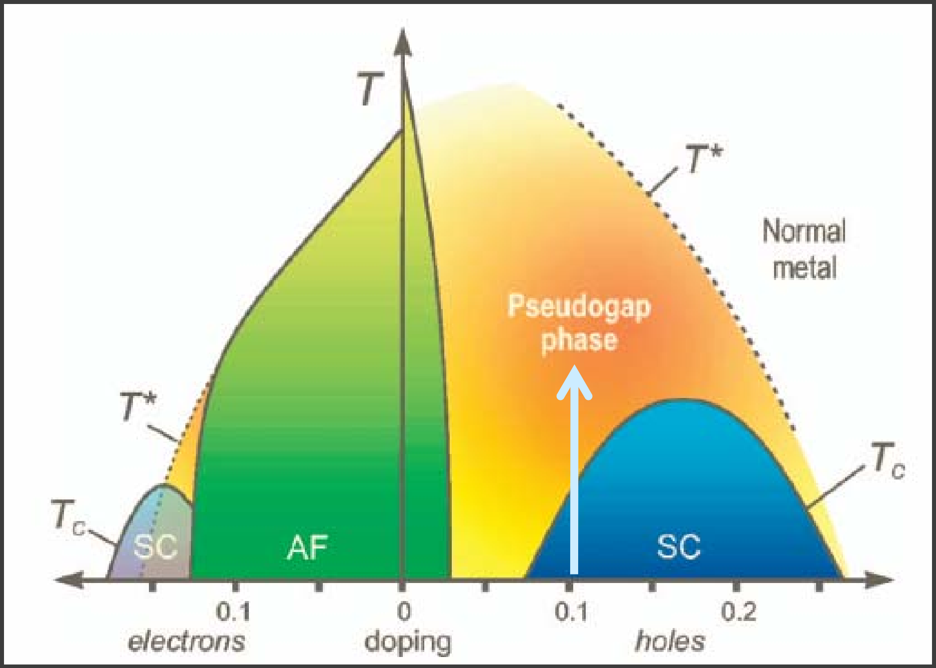
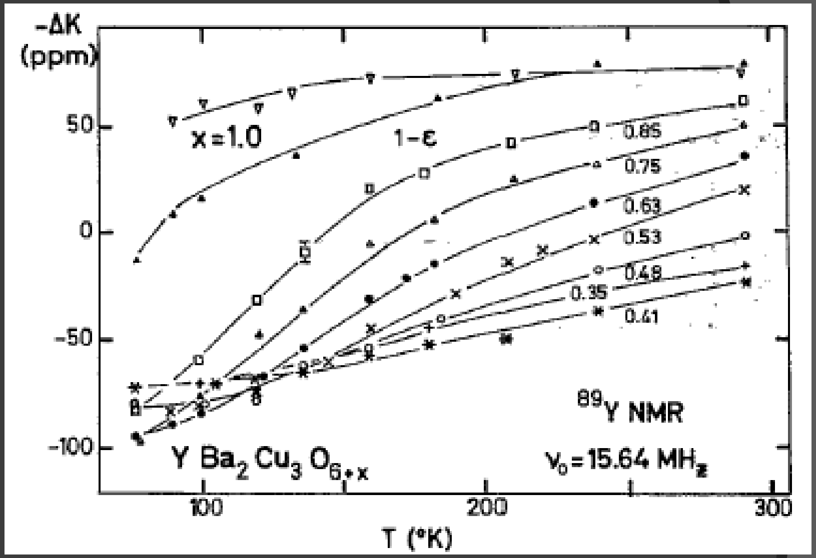
The « normal » state in underdoped cuprates: the pseudogap

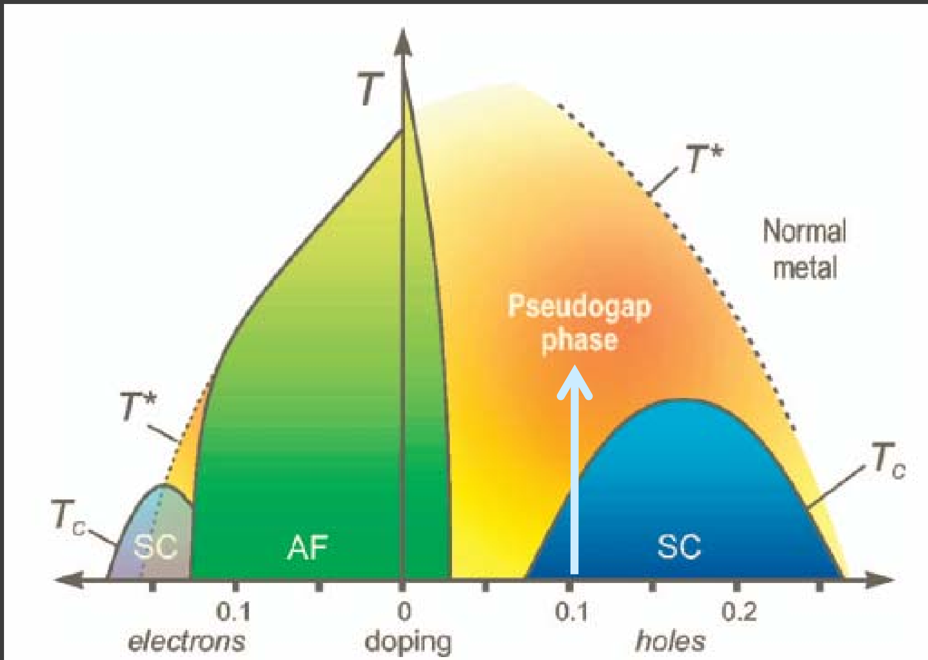


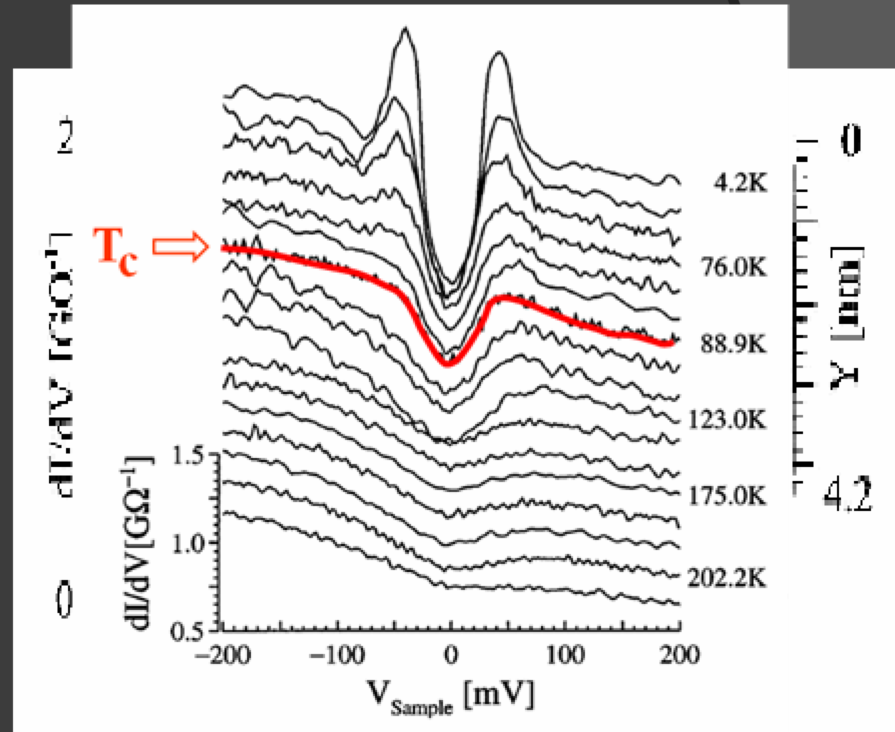


Knight shift in NMR,
Alloul et al., PRL **63**,1700 (1989)

The rapid decrease of the static paramagnetic susceptibility is a signature of the opening of a pseudogap below T*.

The « normal » state in underdoped cuprates: the pseudogap



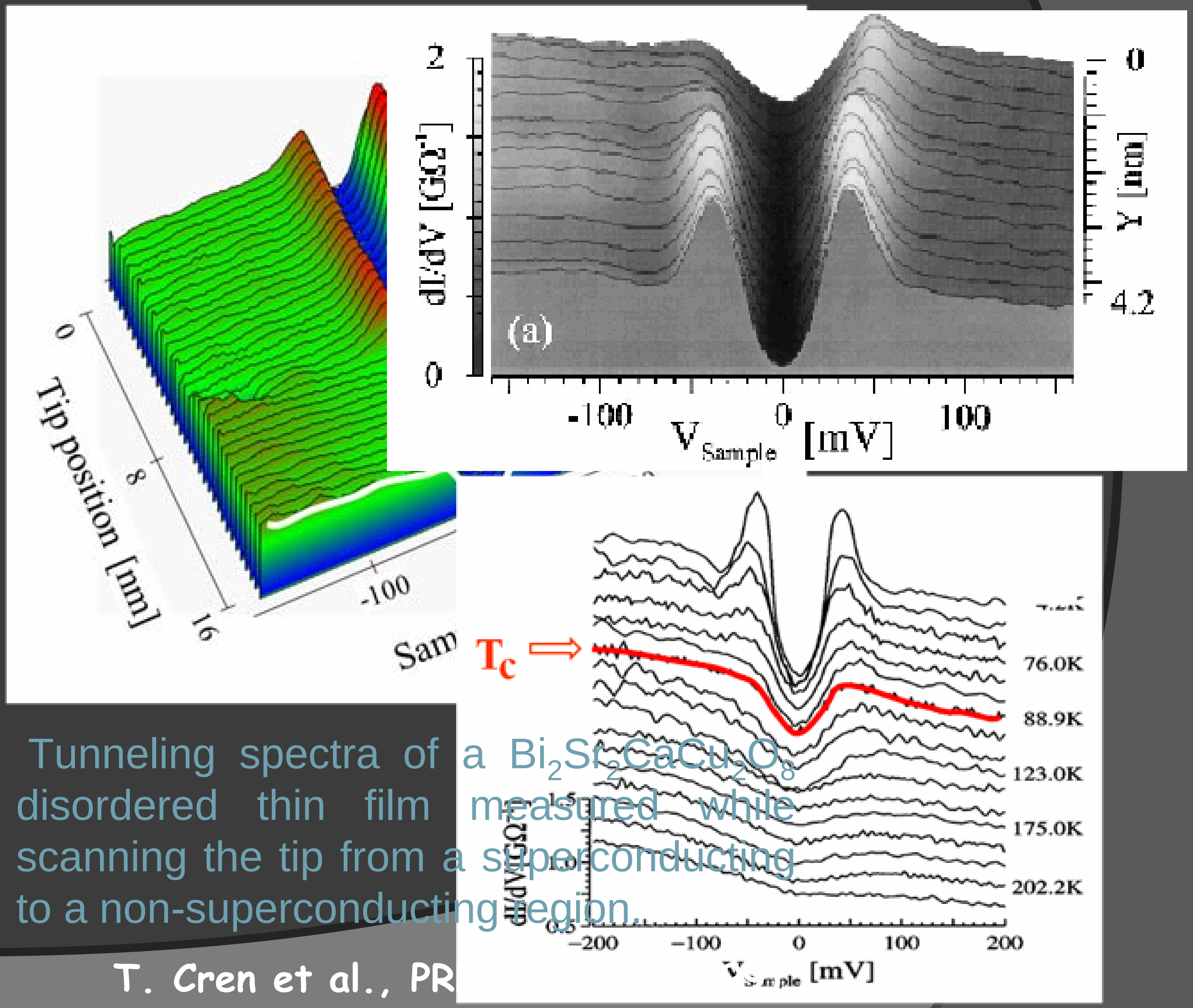


The density of states at T > Tc: The normal state exhibits a pseudogap.

The gap size in the vortex cores is similar to the pseudogap.

C. Renner et al., PRL 80, 149 (1998)
C. Renner et al., PRL 80, 3606 (1998)

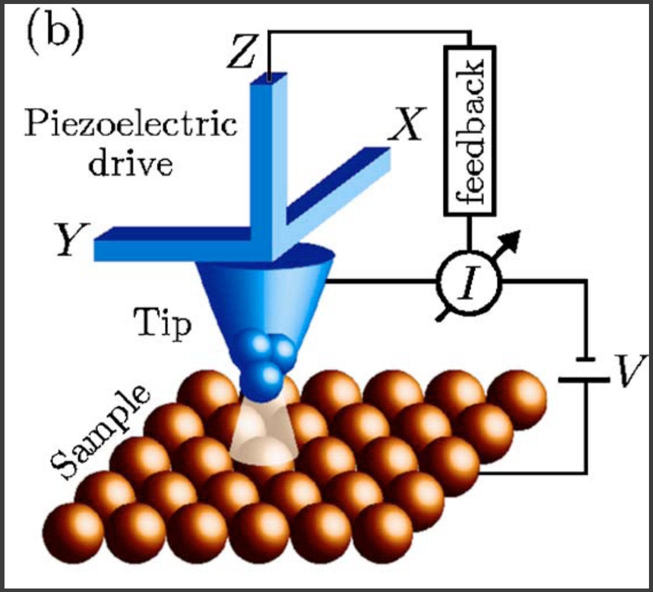
Scanning tunneling spectroscopy: The low temperature pseudogap

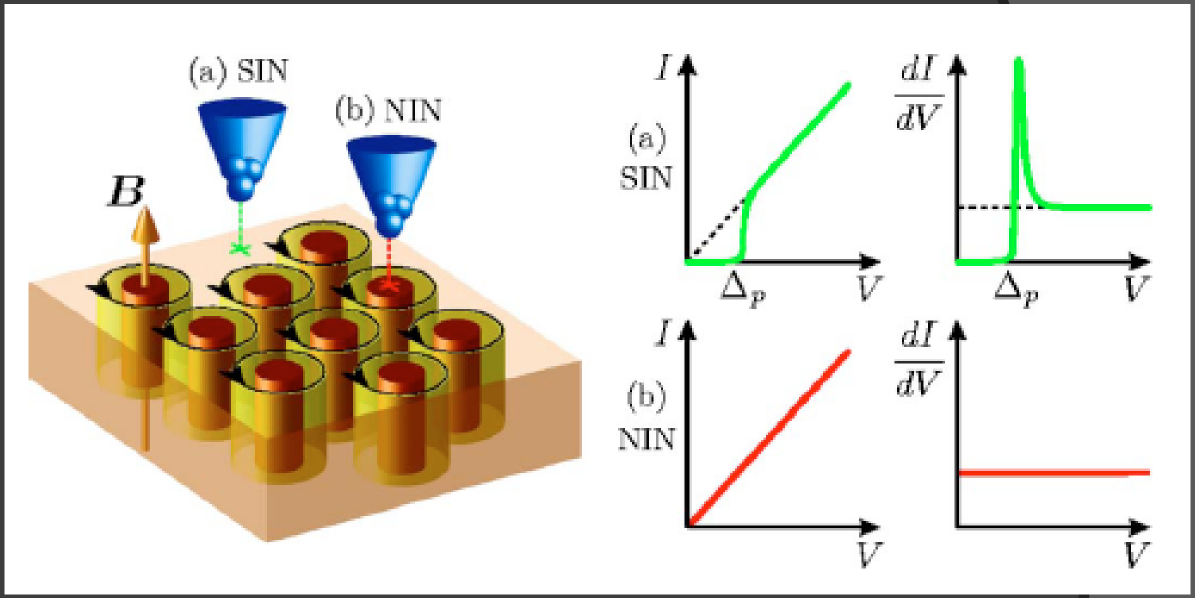


Tunneling spectra of a $Bi_2Sr_2CaCu_2O_8$ disordered thin film measured while scanning the tip from a superconducting to a non-superconducting region.

T. Cren et al., PR

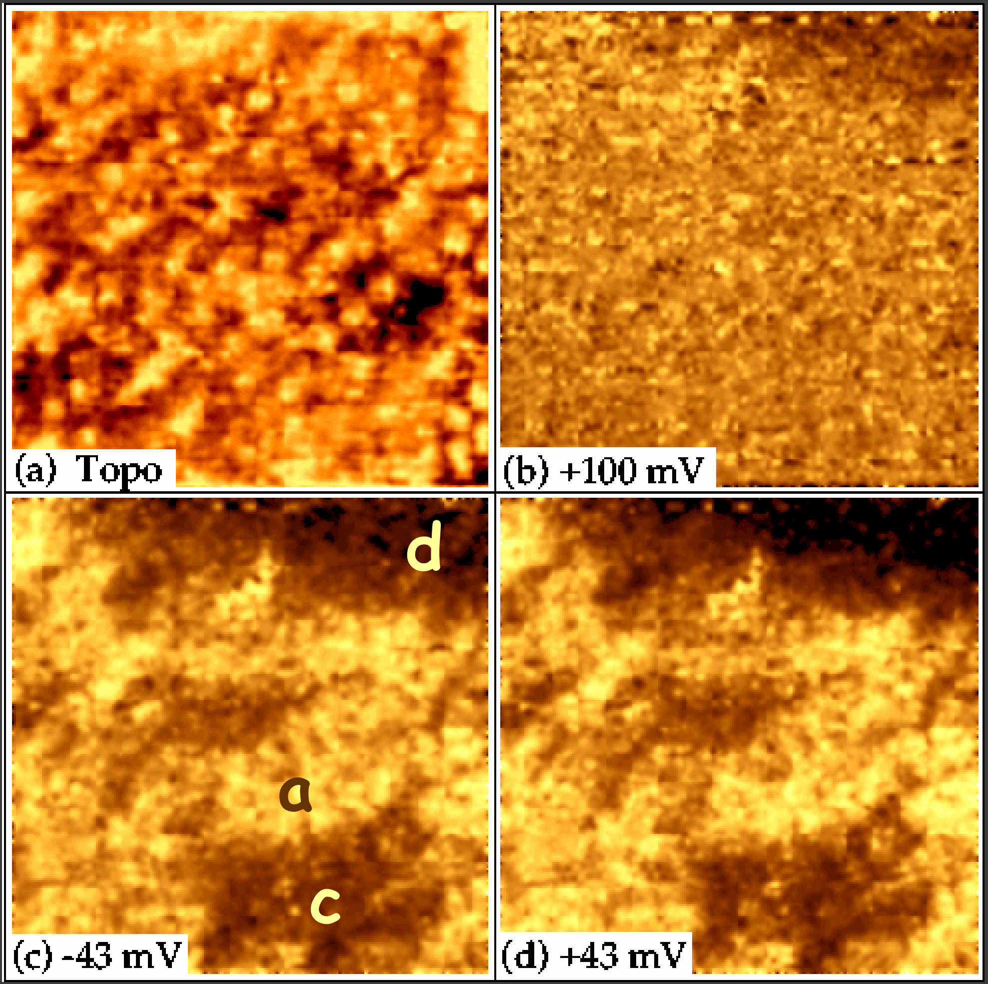
Scanning tunneling spectroscopy

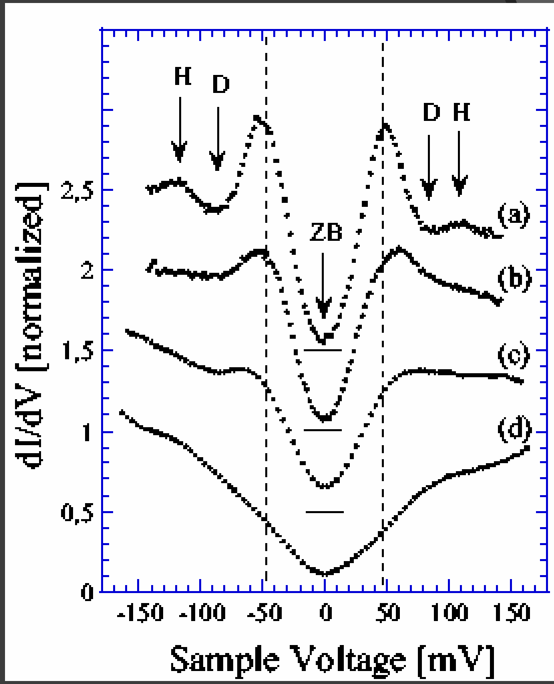




$$dI / dV \propto N(eV, \vec{r}) \quad (\mathrm{T} = 0\,\mathrm{K})$$

Spatially Resolved Spectroscopy on $Bi_{2-x}Pb_xSr_2CaCu_2O_7$





(a) Superconducting state

(c) Pseudogap state

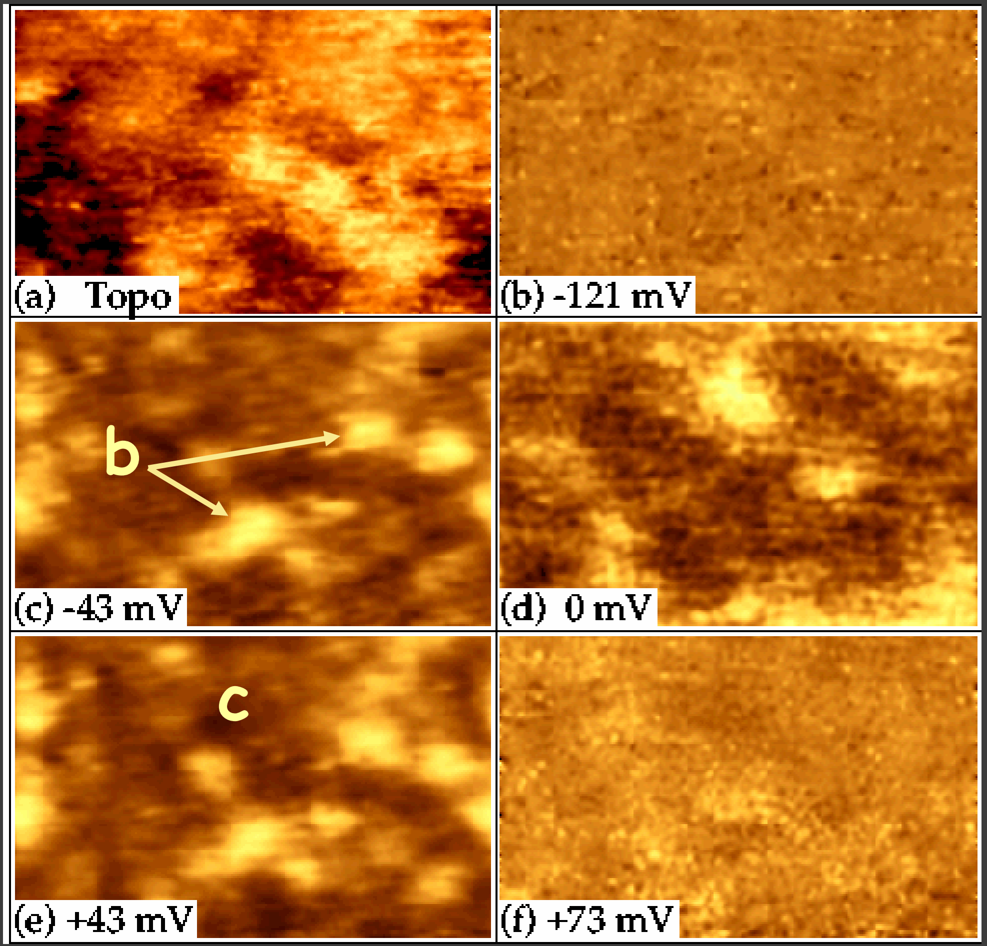
(d) Large pseudogap ?

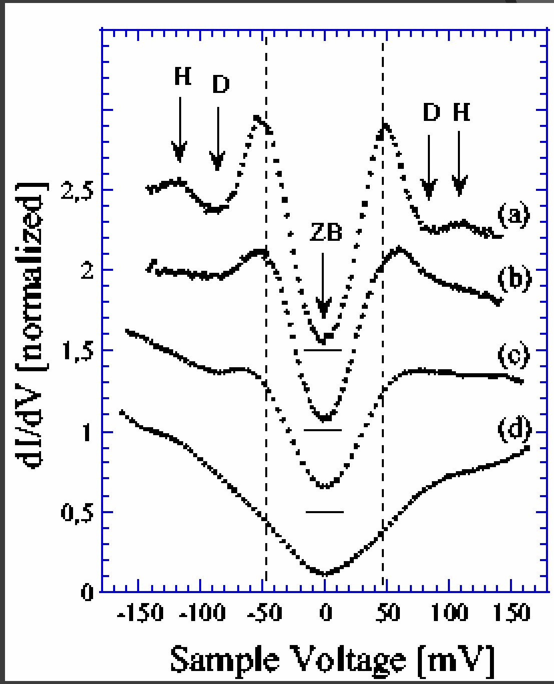
a: topography, 150x150 nm^2

b,c,d: conductance maps (V_T = 250 mV, I_T = 200 pA)

T. Cren et al., EPL 54, 84 (2001)

Spatially Resolved Spectroscopy on $Bi_{2-x}Pb_xSr_2CaCu_2O_7$





(a) Long range superconductivity

(b) Small range superconductivity

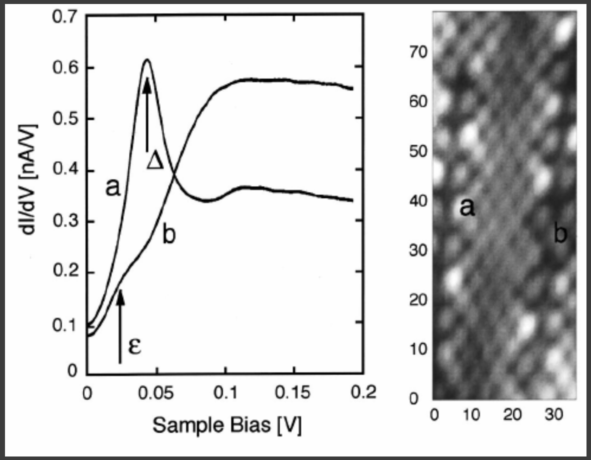
(c) Pseudogap

a: topography, 30x20 nm^2

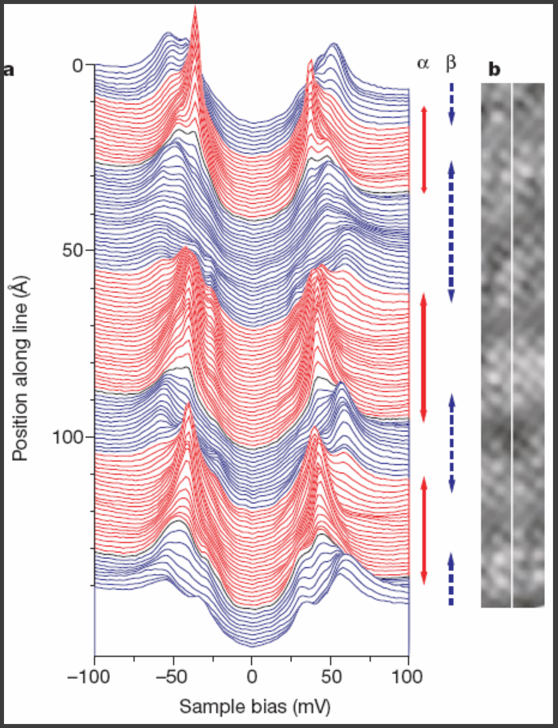
b,c,d: conductance maps (V_T = 140 mV, I_T = 100 pA)

T. Cren et al., EPL 54, 84 (2001)

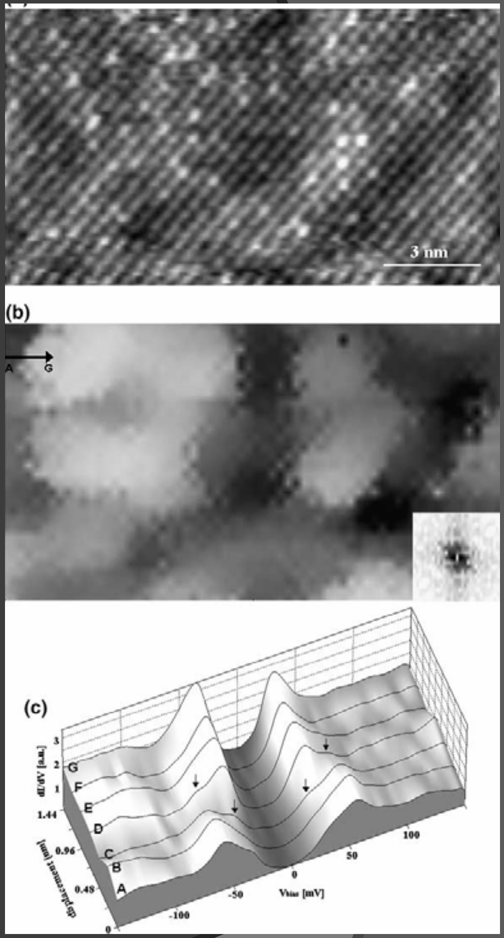
Inhomogeneities in Bi2212



C. Howald et al., Phys. Rev. B 64, 100504 (2001)



K.M. Lang et al., Nature 415, 412 (2002)



A.Sugimoto et al., Physica C 426, 390 (2005)

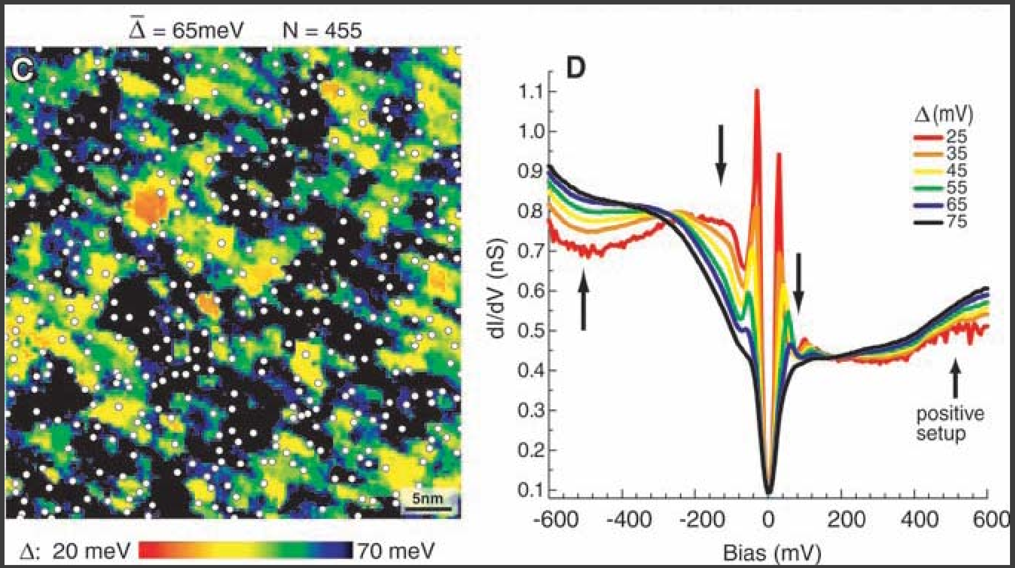
Inhomogeneities in Bi2212 monocrystals

Atomic resolution image and gapmap of Bi-Pb 2212

Origin of gap-pseudogap inhomogeneities

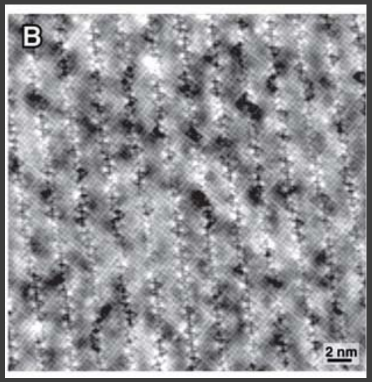
- What is the origin of the pseudogap patches?
  - Substitution
  - Oxygen disorder
  - Supermodulation

Oxygen dopants disorder

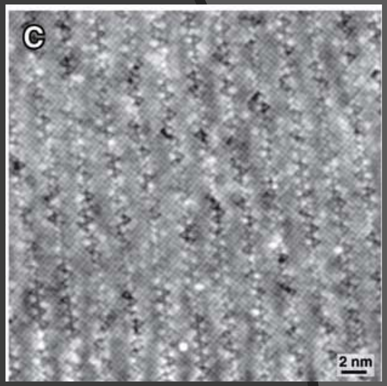


Gap-map and oxygen distribution

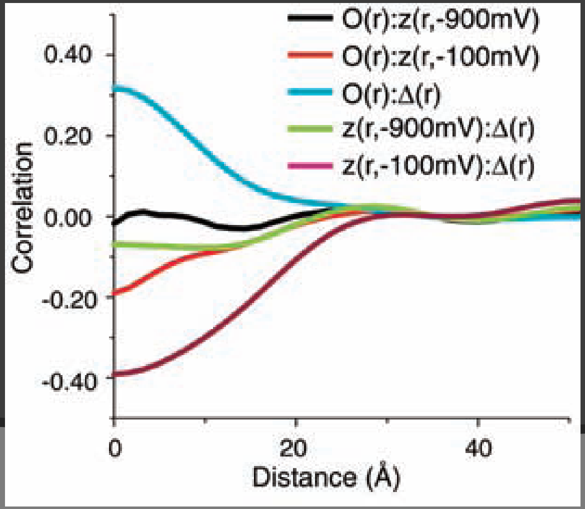
Signature of oxygen dopants



Topography at -100mV

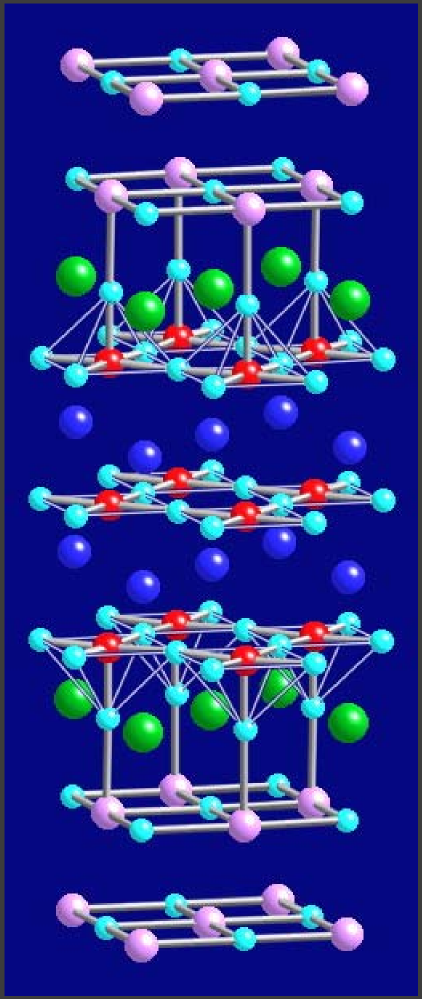


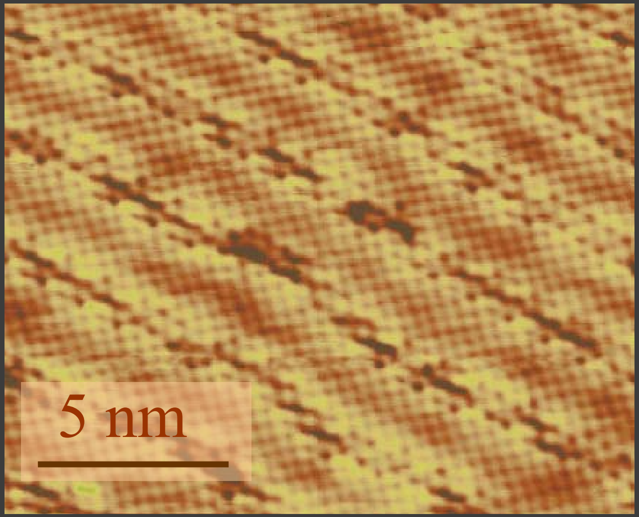
Topography at -900mV

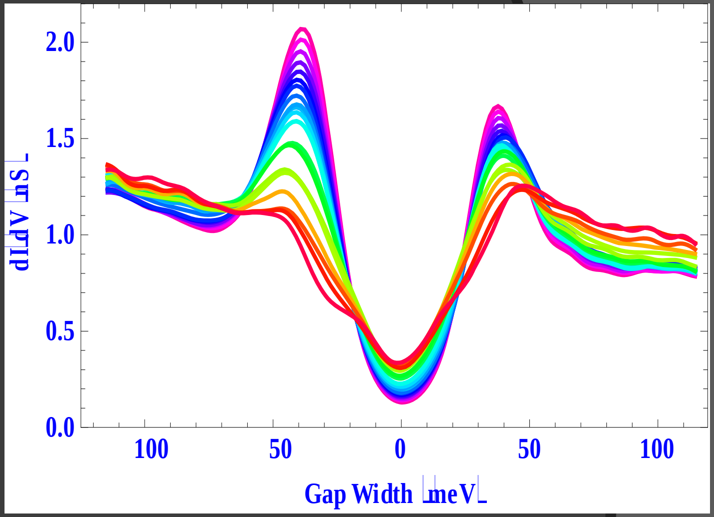


Cross-correlations among the simultaneously measured Z(r,V), Δ(r) and O(r) images showing a clear correlation between the gap, the oxygen and the structural disorders.

Supermodulation in $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$





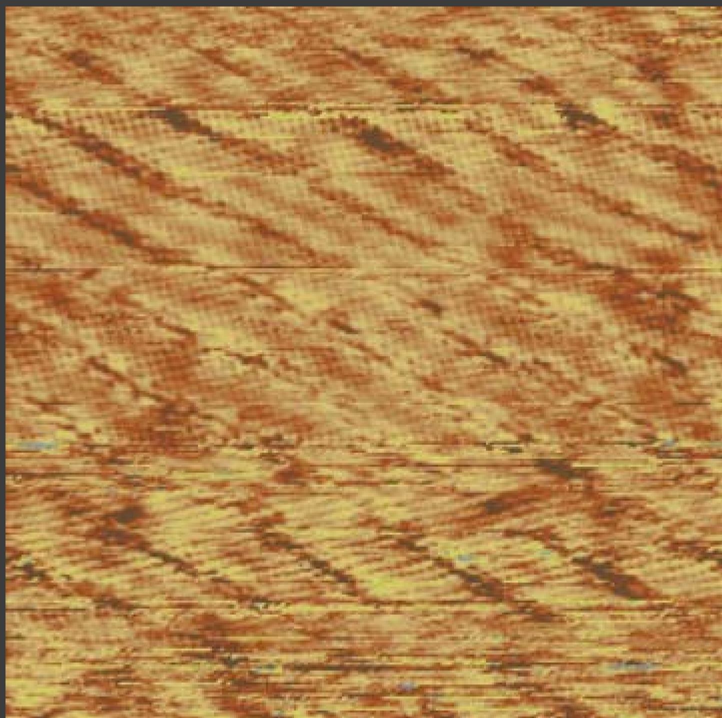


- **Triple-layered high-Tc**
- **Tc max = 111 K**

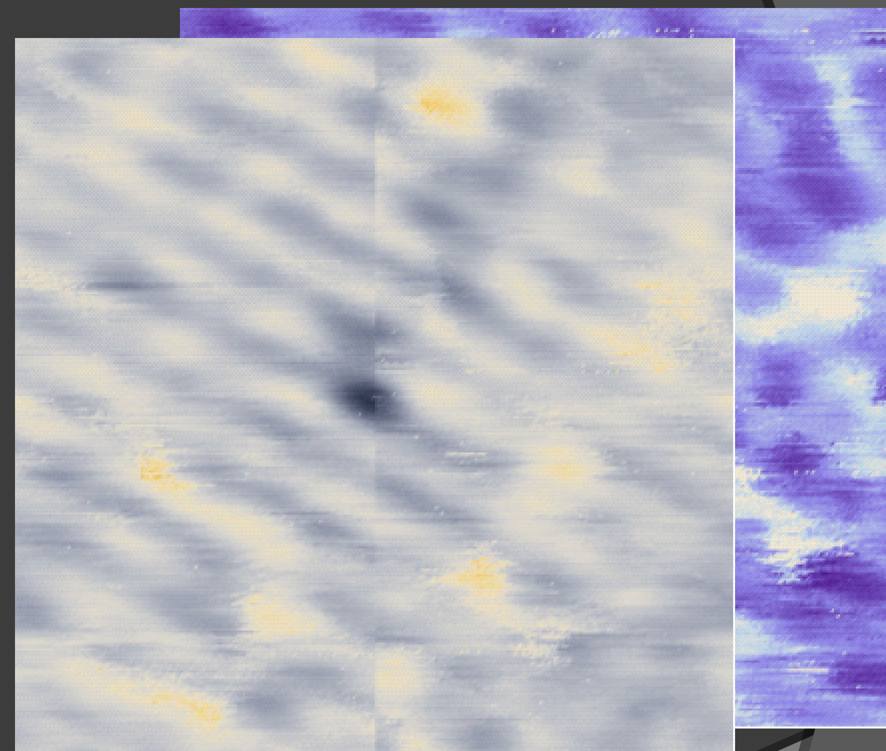
Nathan Jenkins, Alexandre Piriou, Ivan Maggio-Aprile,
Yanina Fasano and Oystein Fischer
DPMC, University of Geneva

Gap vs. Supermodulation

Overdoped Bi2223, Tc of 109.5 K, transition width of 0.8 K.



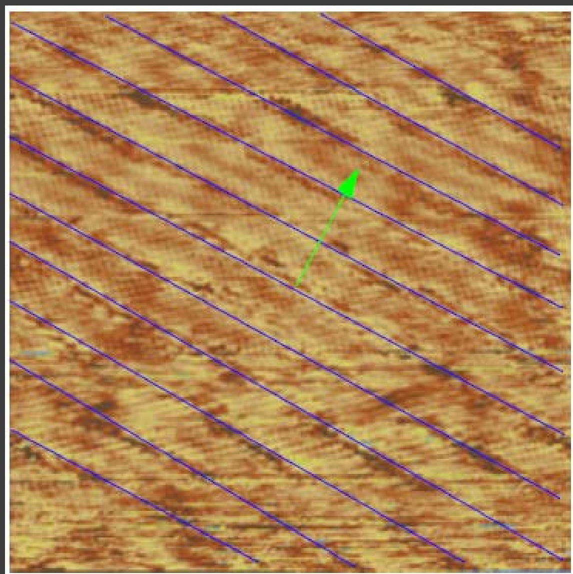
Atomic resolution topographic image showing the supermodulation

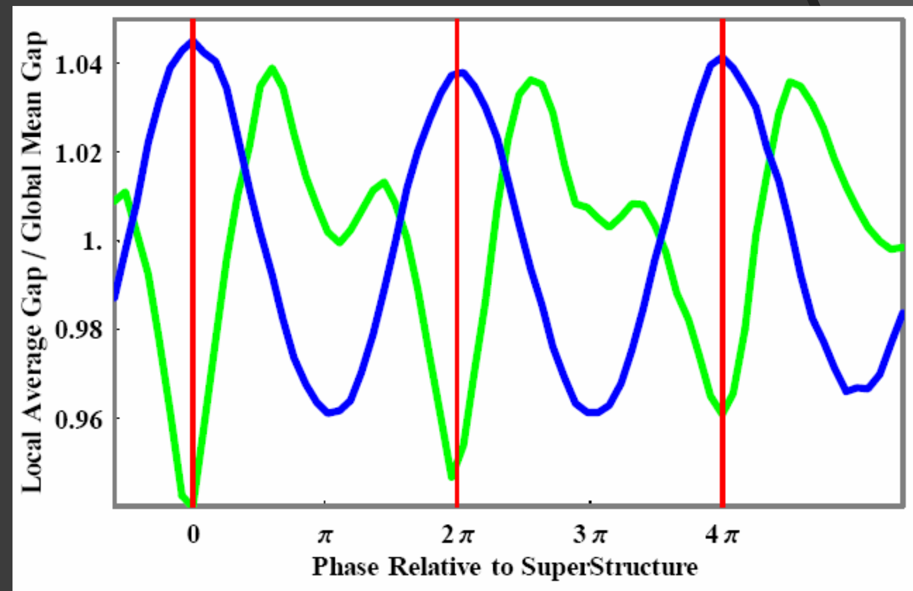


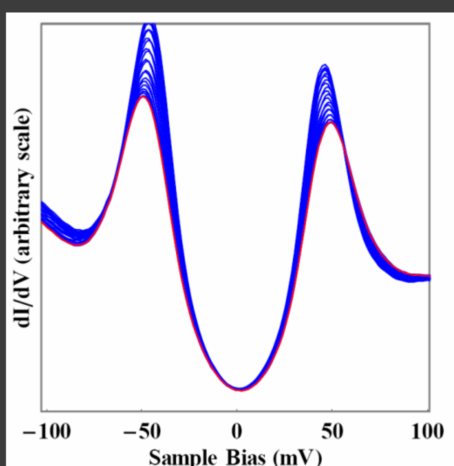
Cross correlation of the topography and gap-map: Anticorrelation

Gap map at 5.3 K and 6.0 T

Gap vs. Supermodulation







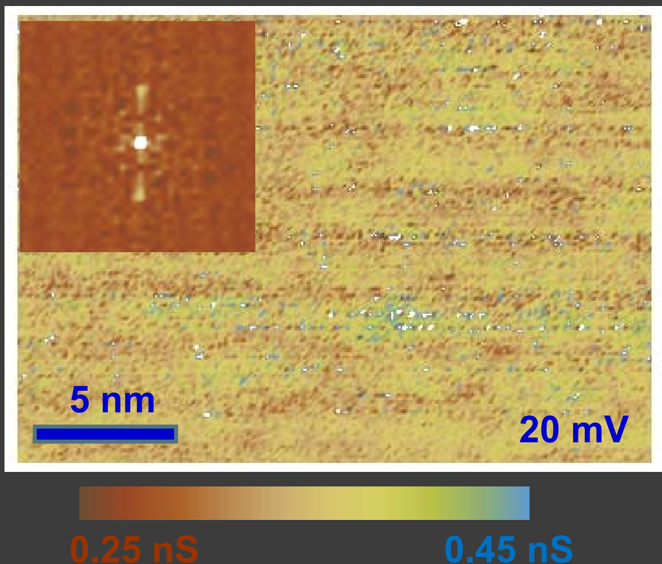
Roughly sinusoidal gap modulation of 8%. The peak height is also modulated.

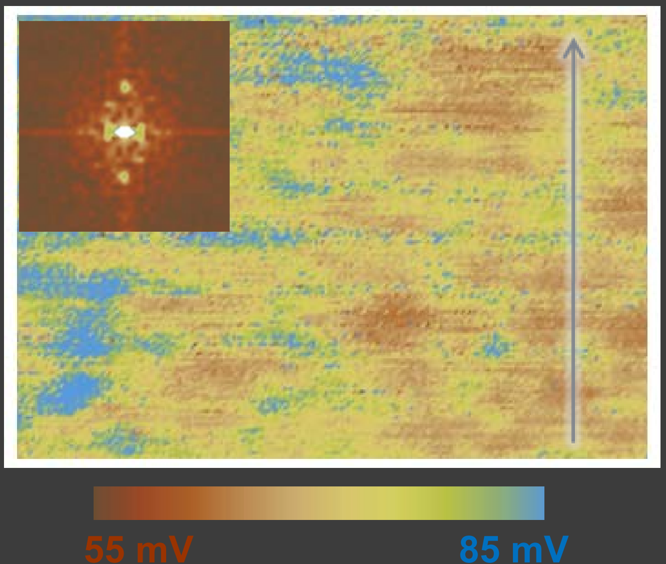
Similar effects observed in Bi2212

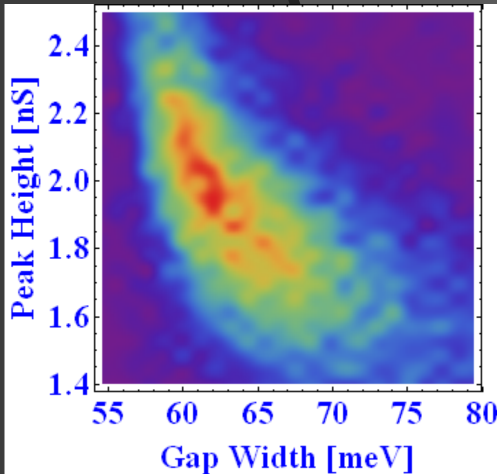
B. M. Andersen, Phys. Rev. B 76, 020507 (2007)

Gap vs. Supermodulation in underdoped Bi2223

Underdoped Bi2223, T_c = 103 K, ΔT_c = 3.5 K.





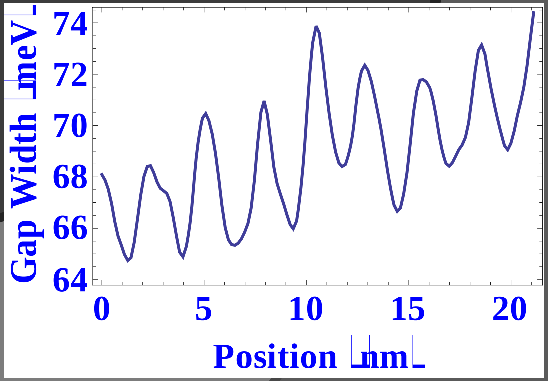


Peak-height vs. Gap

The 2.7 nm supermodumation is seen in the conductance map at all voltages.

The 2.7 nm modulation is also present in the gap-map.

The gap modulation amplitude is roughly 8%

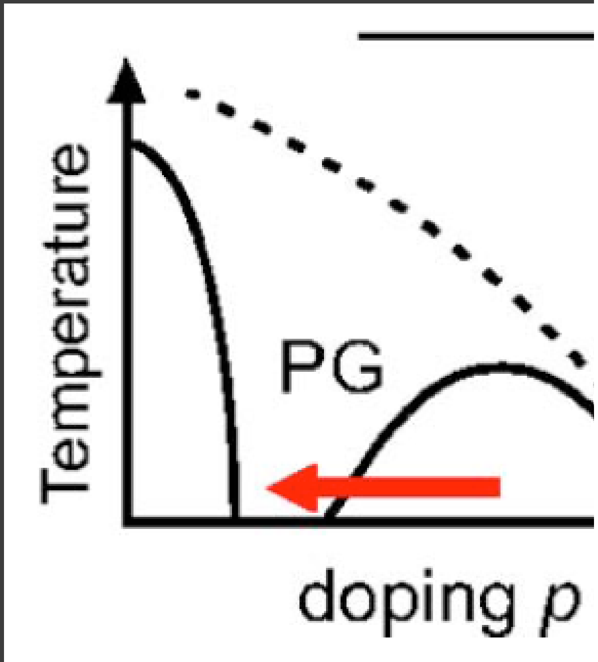


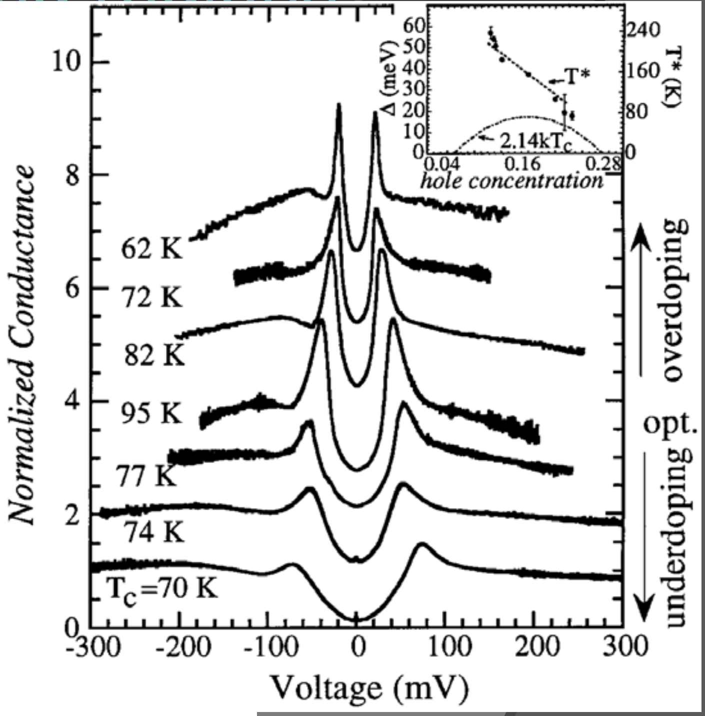
T = 5.3 K, H = 0 T

Pseudogap patches

- What is the origin of the pseudogap patches?

  - Extremely underdoped regions?

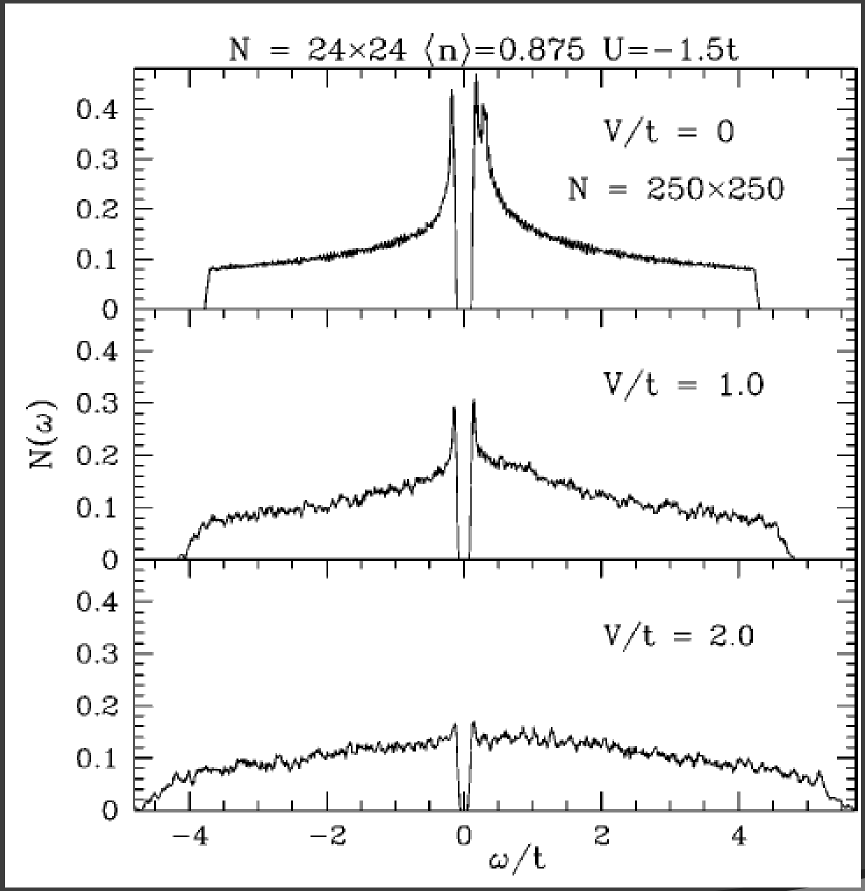


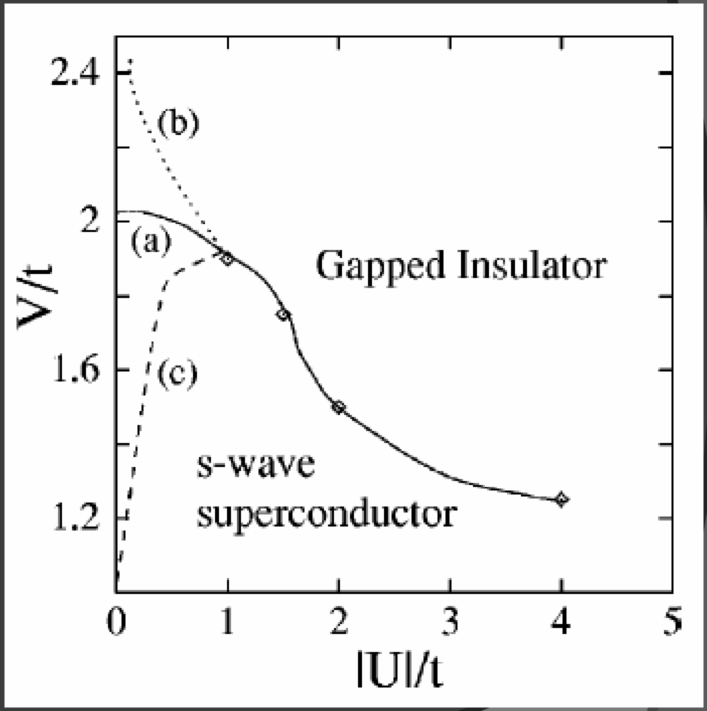


Miyakawa et al., PRL 83, 1018 (1999)

Pseudogap patches

- What is the origin of the pseudogap patches?
  - Incoherent pairing induced by disorder?





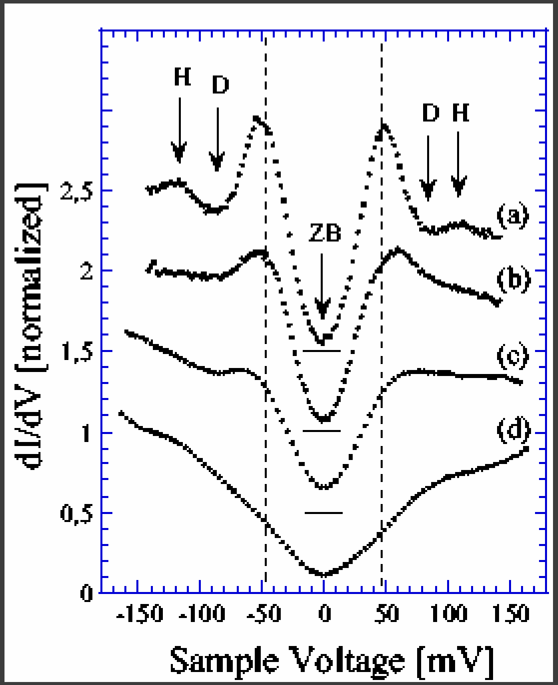
Inhomogeneous pairing in highly disordered s-wave superconductors

Amit Ghosal, Mohit Randeria, and Nandini Trivedi, PRB 65, 014501 (2001) & Ibib.,PRL. 81, 3940 (1998)

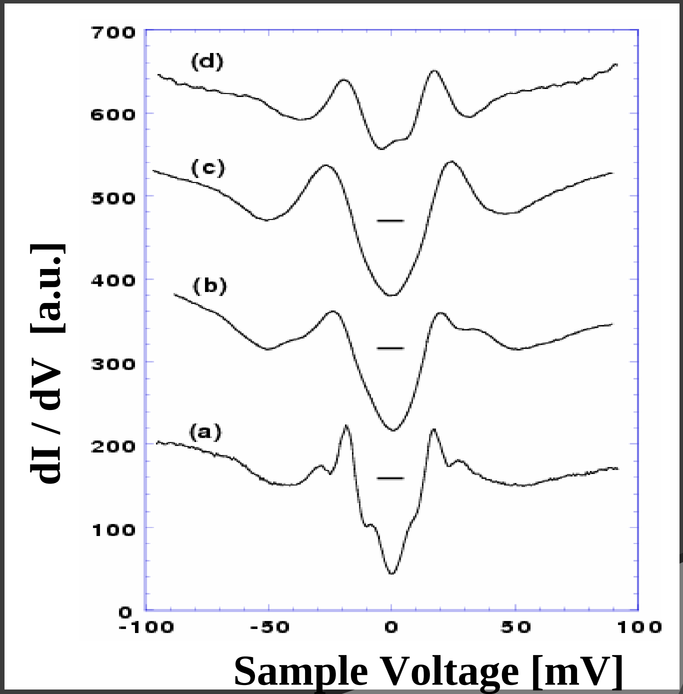
C. Huscroft, R.T. Scalettar, PRL 81, 2775(1998)

The peak-dip-hump structure as a measure of the superconducting amplitude

The gap Δ is no more related to the amplitude of the order parameter. The peak-dip-hump structure seems to be a good indicator of the local amplitude of the condensate.

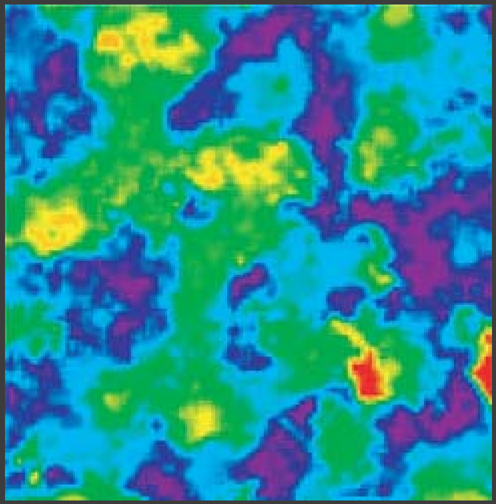


Conductance spectra in Bi-Pb-2212 single-crystal

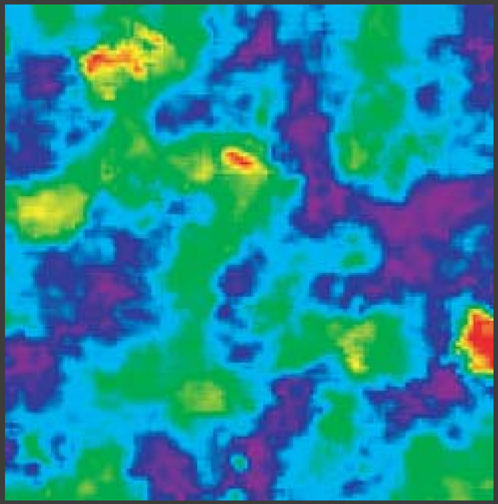


Scanning Tunneling Spectroscopy of an $YBa_2Cu_3O_7$ thin film at 4,2 K.

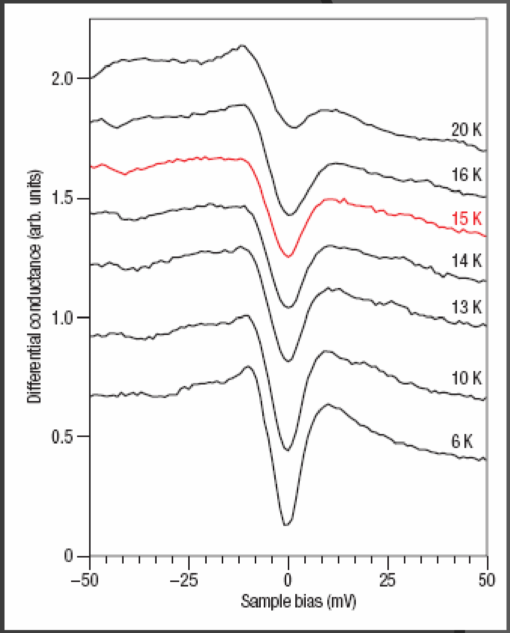
The two gap in Bi2212 : Nodal coherent excitations

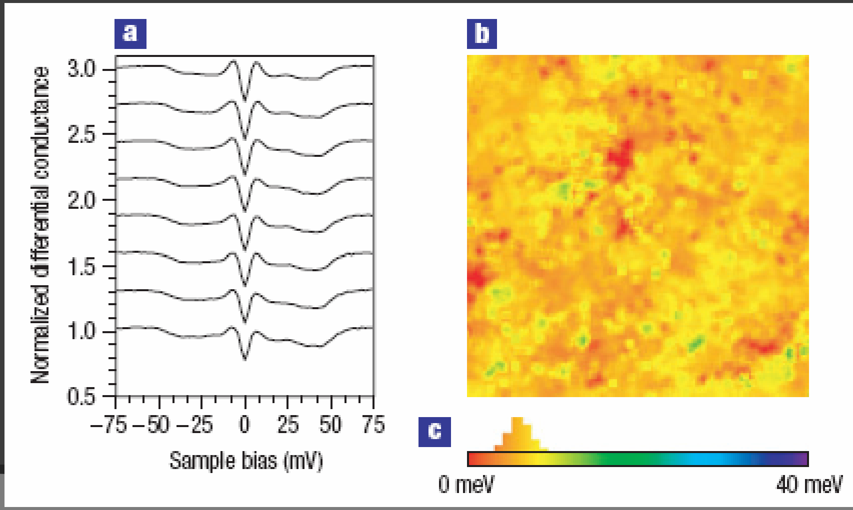


Gap-map @5K, T<Tc



Gap-map @17K, *T>Tc*





Normalized spectra and gap-map:

g(E,r,6K)/g(E,r,16K)

Homogeneous 6 meV minigap: nodal coherent excitations?

Hudson et al., Nat. Phys. 3, 805 (2007)

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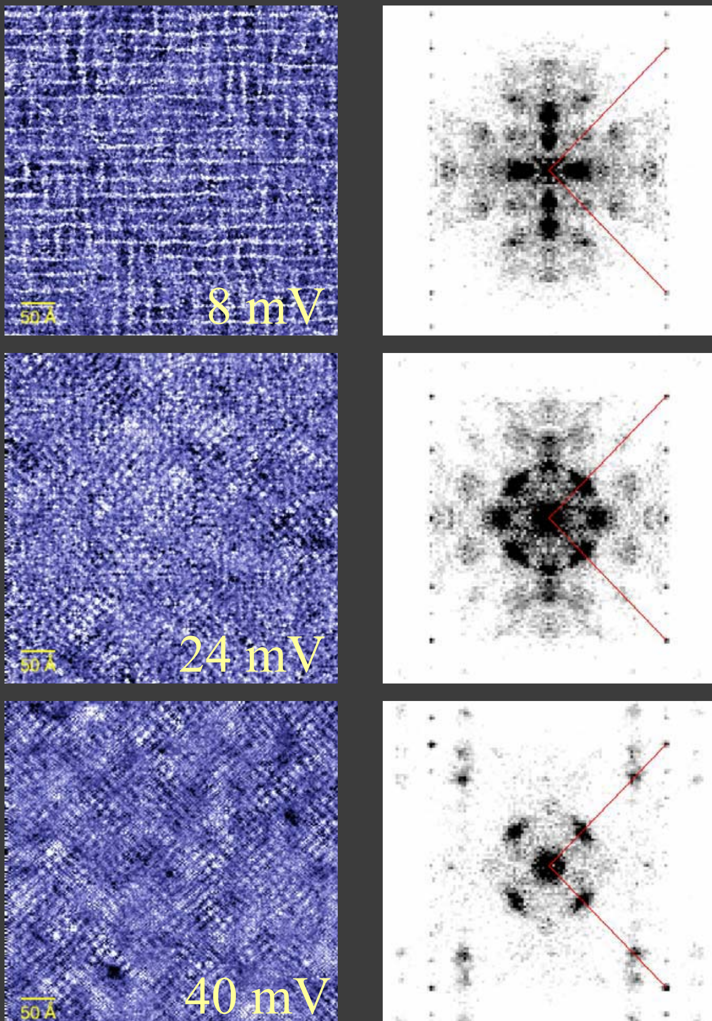
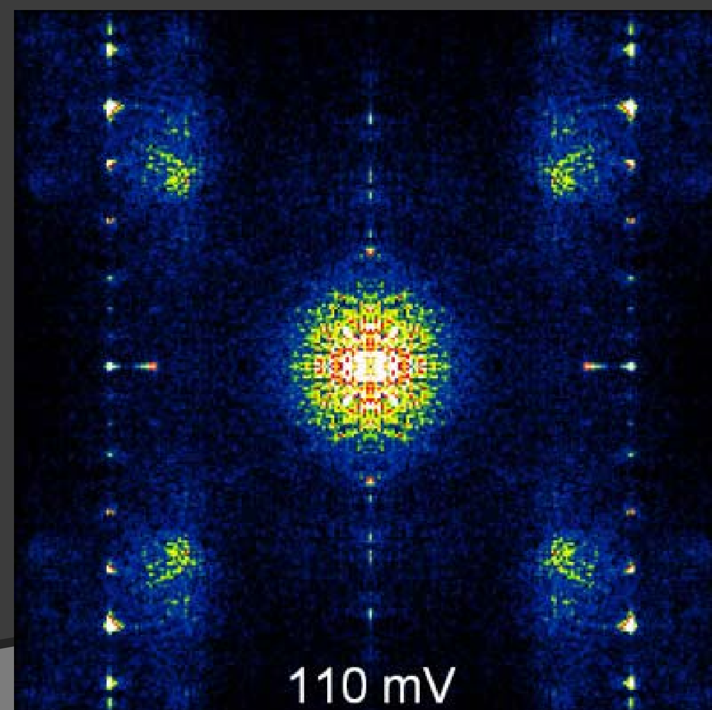
Quasiparticles Interferences



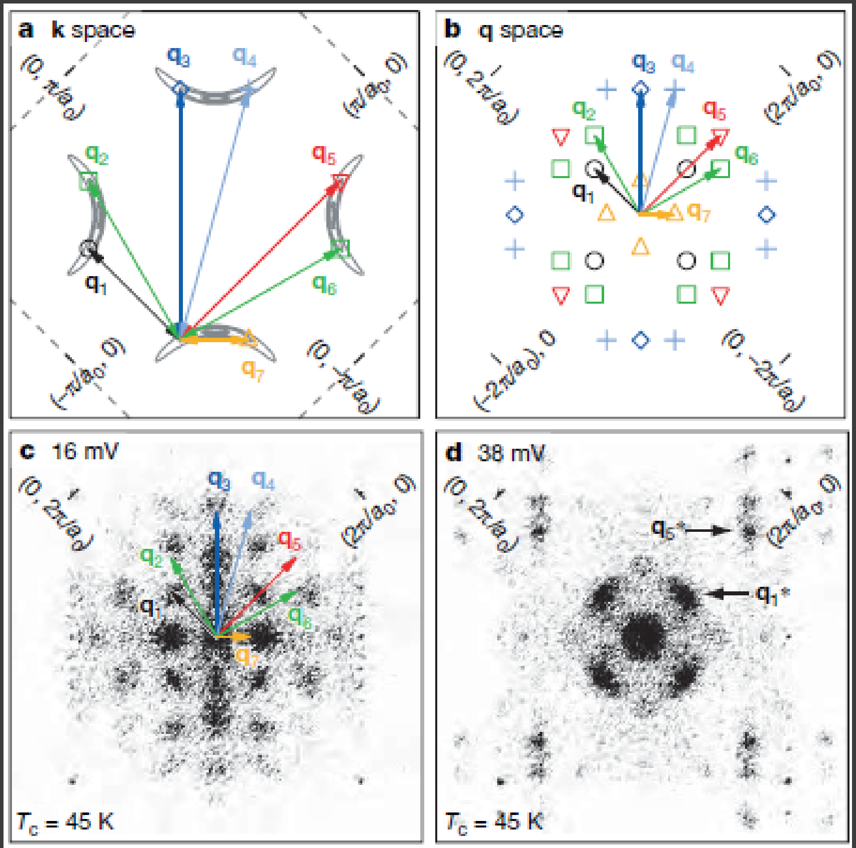
$Bi_2Sr_2Ca_{0.8}Dy_{0.2}Cu_2O_8$ $T_c = 45$ K

Z maps and their Fourier transform, the Z maps are defined by:

$$Z(\boldsymbol{r}, V) = \frac{\frac{\mathrm{d}I}{\mathrm{d}V}(\boldsymbol{r}, +V)}{\frac{\mathrm{d}I}{\mathrm{d}V}(\boldsymbol{r}, -V)}$$



Bogoliubov Quasiparticles Interferences



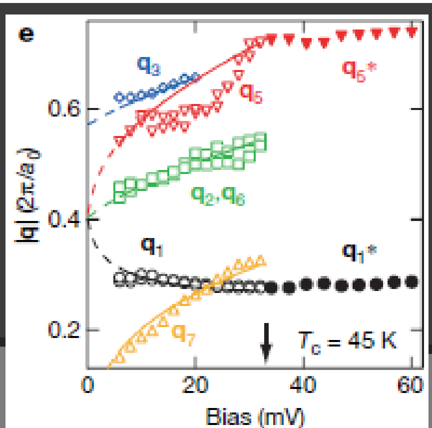
The diffusion **q** vectors are given by to the Bogoliubov arcs :

$E_k^2=\varepsilon_k^2+\Delta_k^2$ =cte

Fourier transform of the Z maps defined by :

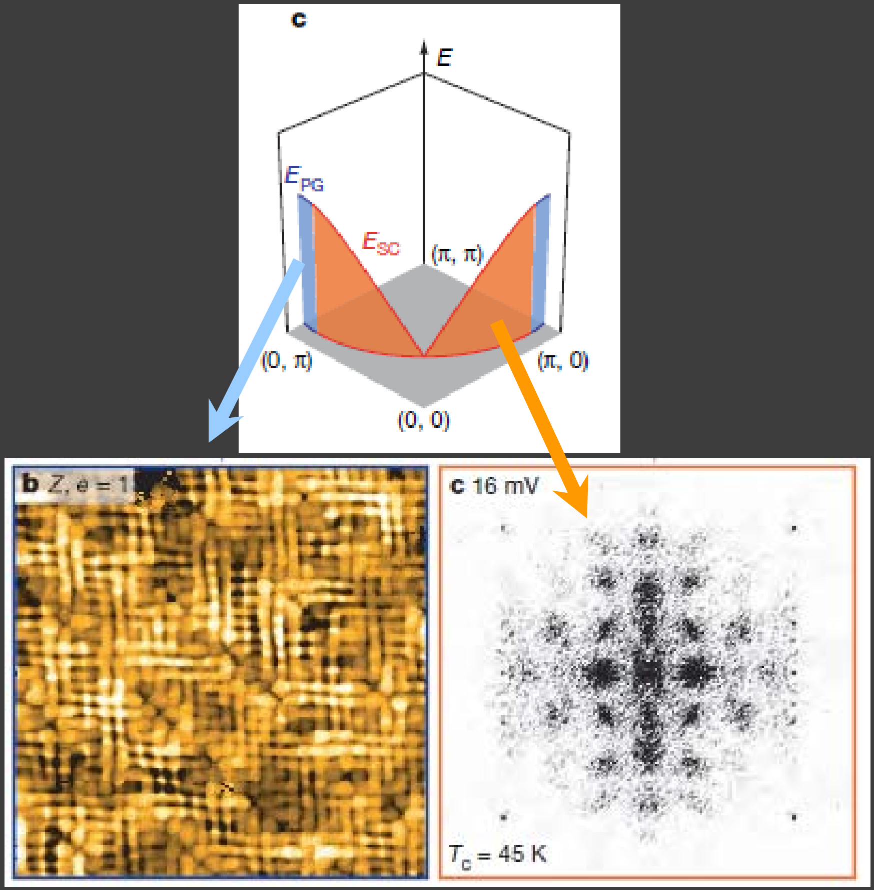
$$Z(\mathbf{r},E=eV)\equiv\frac{g(\mathbf{r},+V)}{g(\mathbf{r},-V)}=\frac{|u(r,eV)|^2}{|v(r,eV)|^2}$$

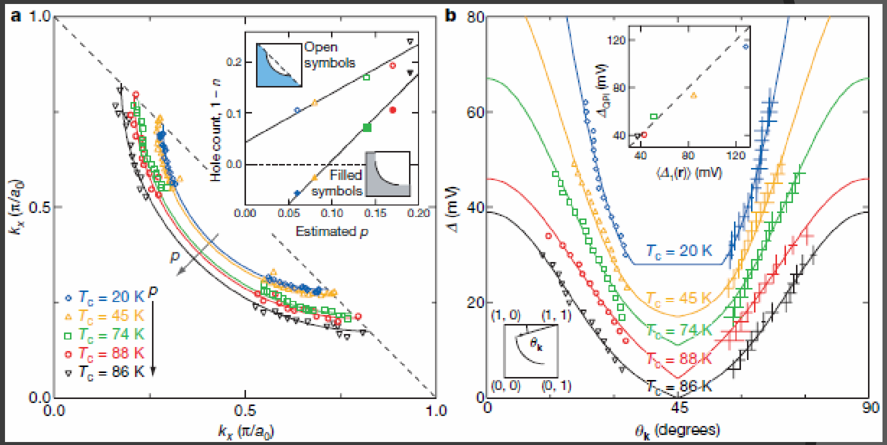
$$\Psi=\prod\left[u(r-r')+v(r-r')c_\downarrow^\dagger(r)c_\uparrow^\dagger(r')\right]|0\rangle$$



A dispersive structure is observed near the nodes, while a non-dispersive $4\text{x}4a_0$ pattern appears at higher energy near the antinodes.

The low-energy nodal quasiparticle interferences versus the non-dispersive 4x4 pattern

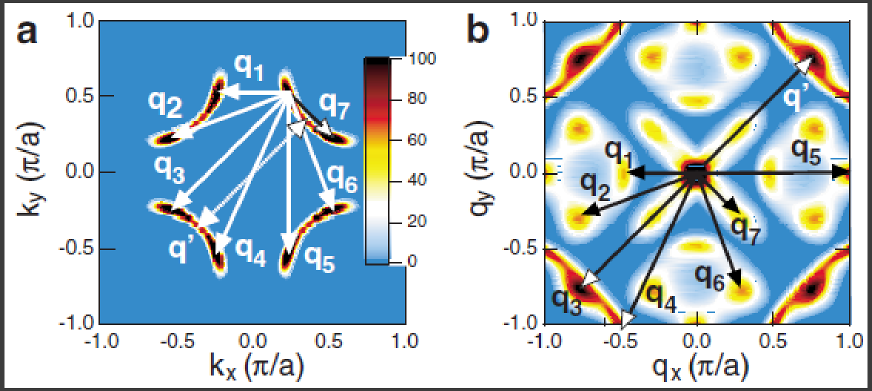




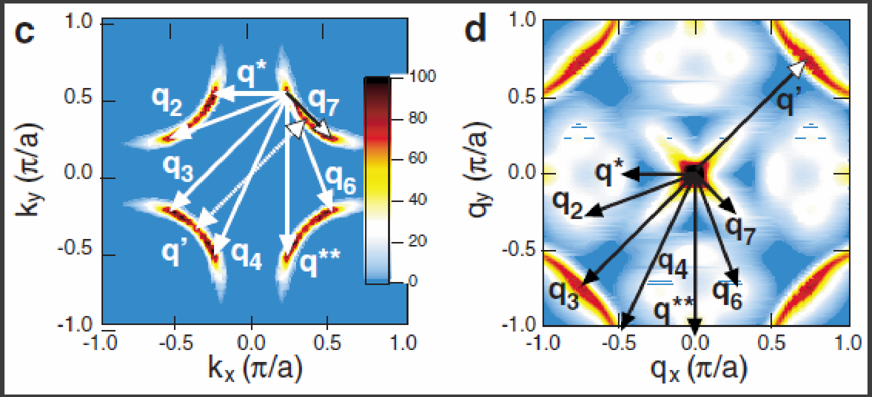
4x4 pattern

Bogoliubov quasiparticles Interferences

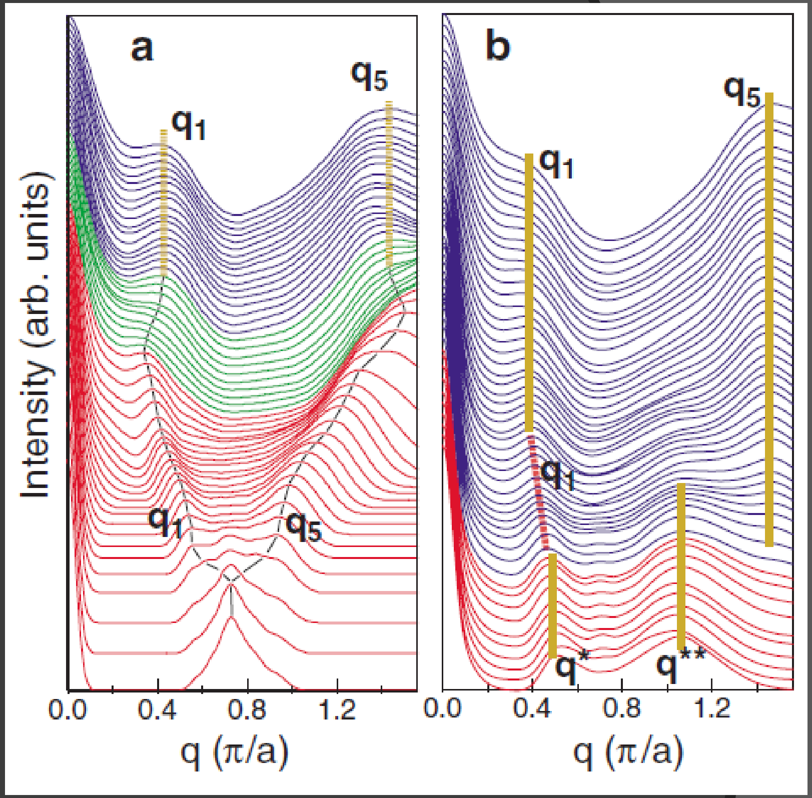
Bogoliubov arcs as seen by ARPES



Constant energy intensity map and autocorrelation at 18 meV in the superconducting state of Bi2212, showing all the vectors consistent with the octet model.



Constant energy intensity map and autocorrelation at 0 meV in the pseudogap state, showing all the vectors consistent with the octet model.

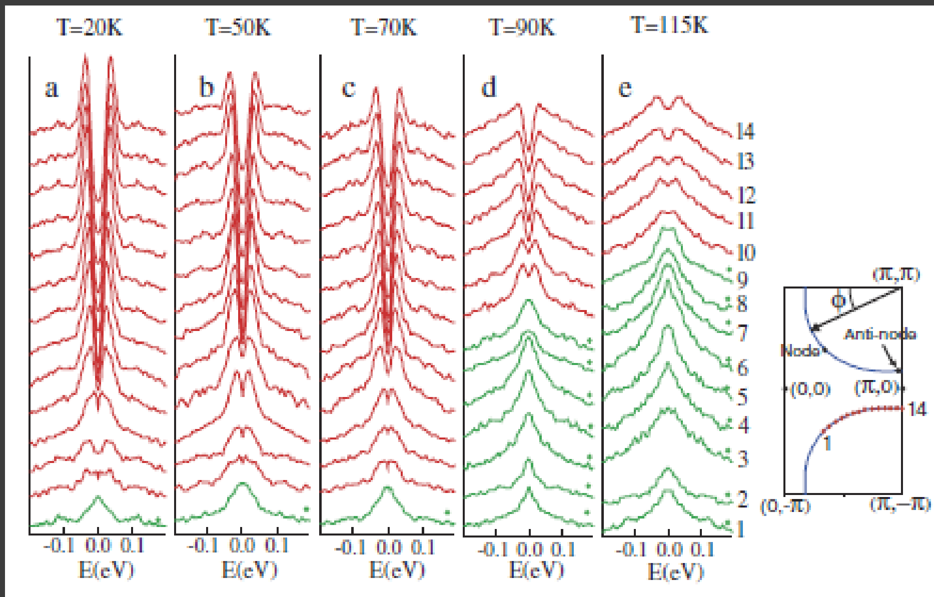


Superconducting state pseudogap state

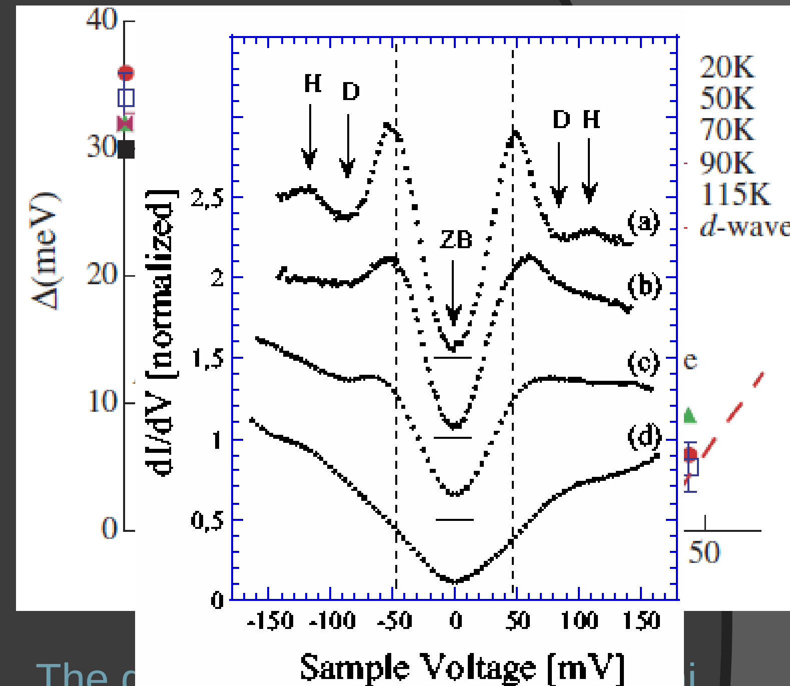
The correlation in the superconducting state measured from 0 to 98 meV show a strong dispersion at low energy, while q1 and q5 in the pseudogap are almost non-dispersive.

U. Chatterjee et al., PRB 76, 012504 (2007)

Fermi arcs as seen by ARPES



Symmetrized energy distribution curves (EDCs) for a Bi2212, *Tc* = 80 K, sample at various temperatures. The different EDCs cover the whole Fermi surface from the node (lowest curve) up to the antinode (uppermost curve).



The gap as function of φ the Fermi surface angle measured from the zone boundary.

The gapless angles in the pseudogap state corresponds to the « Fermi arcs ».

(a) Long range superconductivity

(b) Small range superconductivity

(c) Pseudogap

Below Tc the Fermi arcs are reduced to the nodes (45°) while the gap amplitude at the antinodes 0° is almost unchanged. Nevertheless, a strong peak-dip-hump structure appears at 0° in the superconducting state.

U. Chatterjee et al., PRL 99, 157001 (2007)

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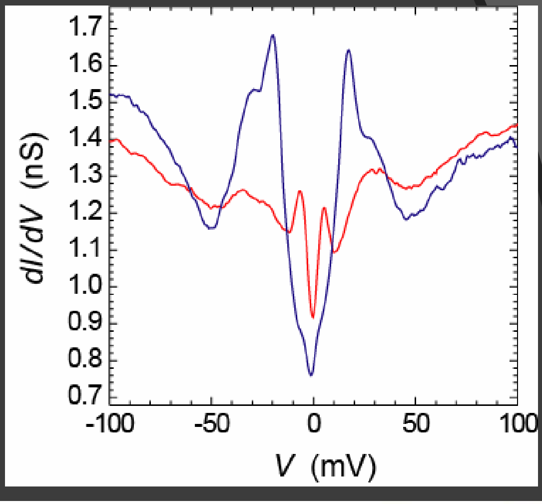
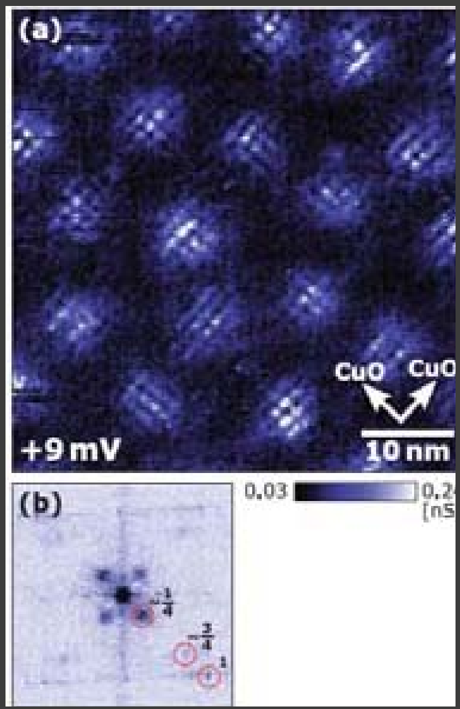
Vortices in Bi2212 and YBCO

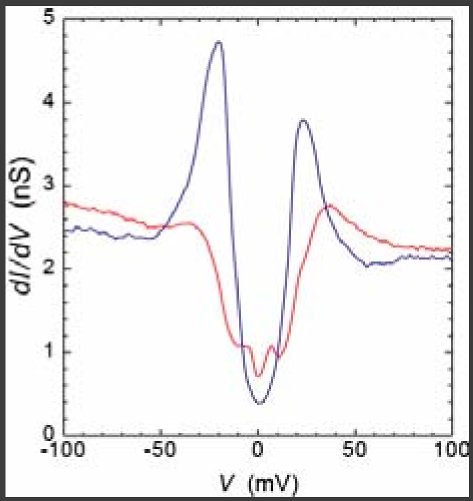
4x4 square pattern in the vortex core of Bi2212, modulation along CuO bonds

(Hoffmann et al., Science 295, 466 (2002).

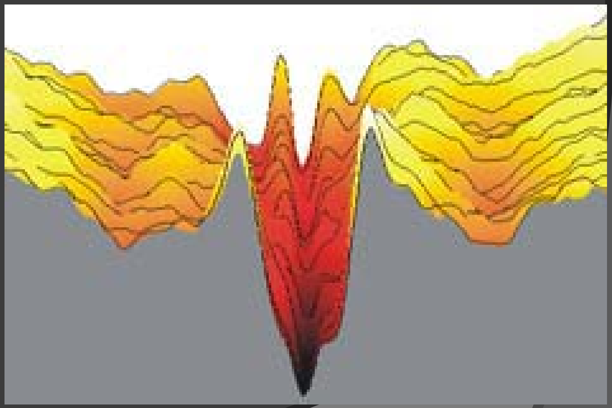
YBaCuO, 6T, 4.2K







G. Levy et al., PRL 95, 257005 (2005)



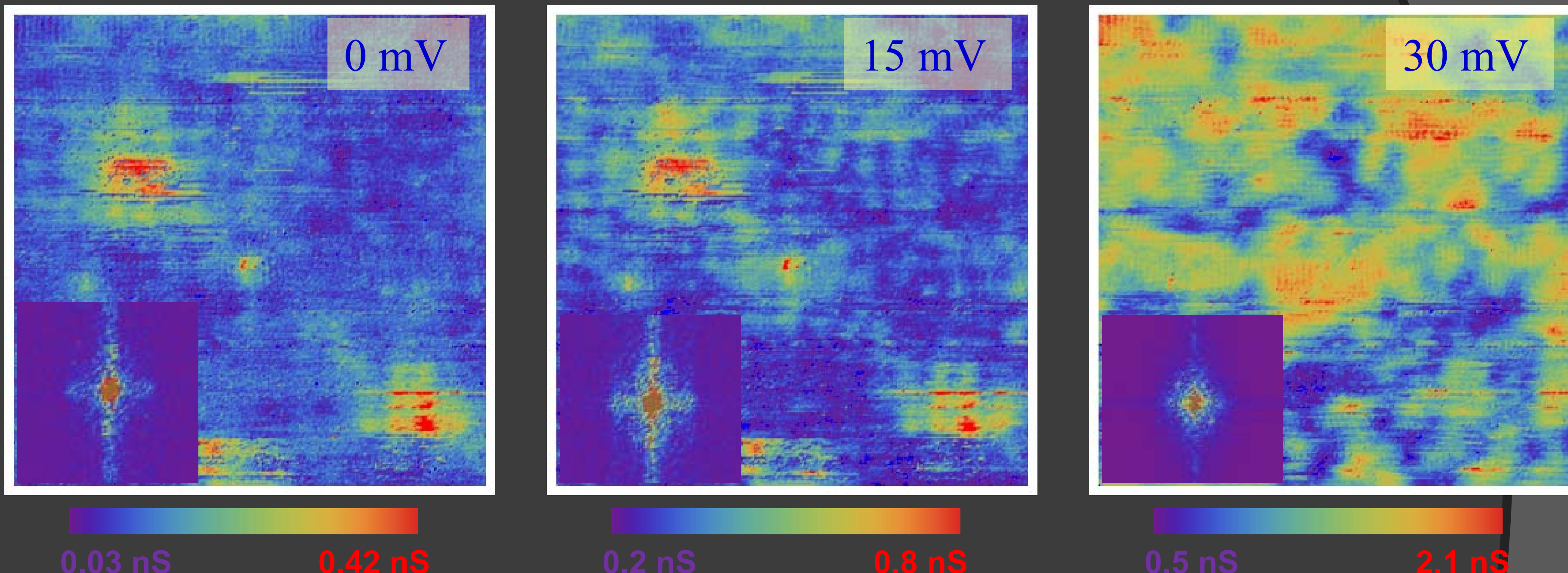
Matsuda et al. (2007)

***I. Maggio-Aprile* et al., PRL 75, 9208 (1995)**

-Non-dispersive 4x4 square pattern

-Seen in pseudogap phase

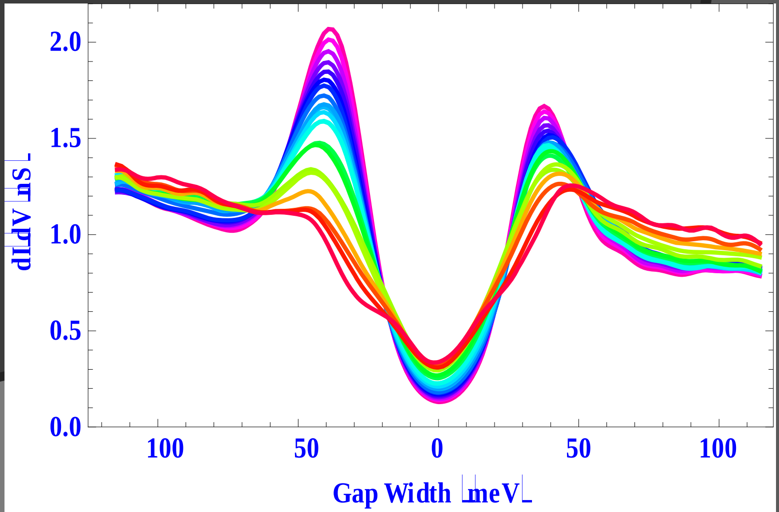
Vortices in overdoped Bi2223



Conductance maps 30x30 nm,
H = 6 T, T = 5.2 K

The 4x4 pattern seems to propagate in the weak superconducting regions.

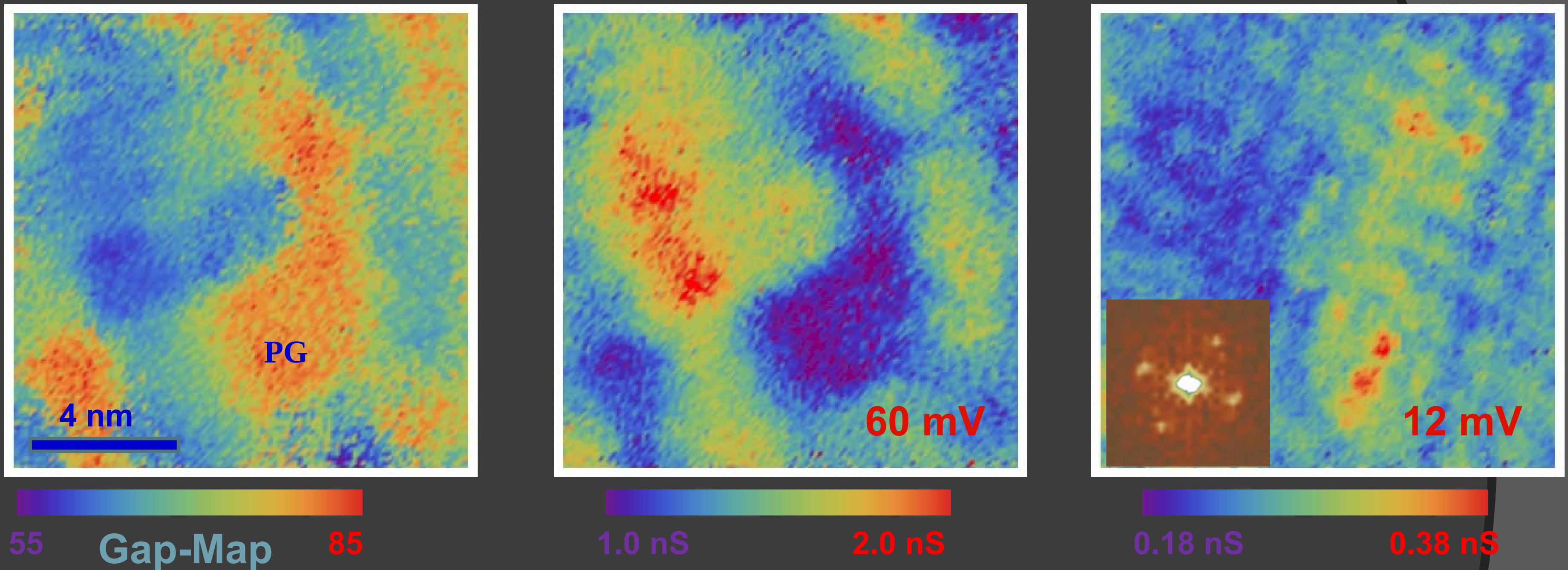
Vortex profile

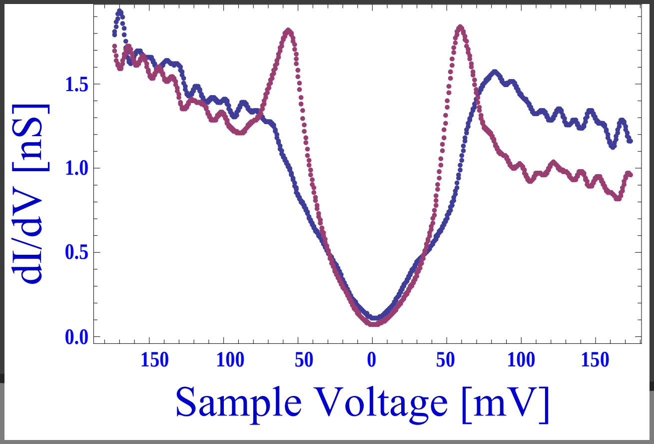


Tc = 103 K, ΔTc = 0.8 K.

Pseudogap patches in underdoped Bi2223

Underdoped Bi2223, T_c = 103 K, ΔT_c = 3.5 K.

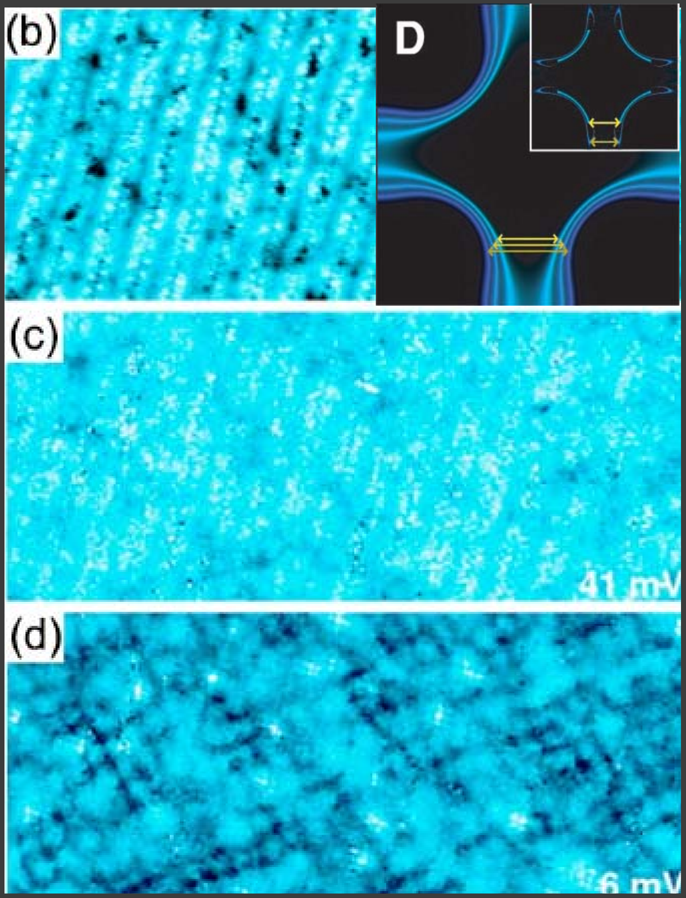


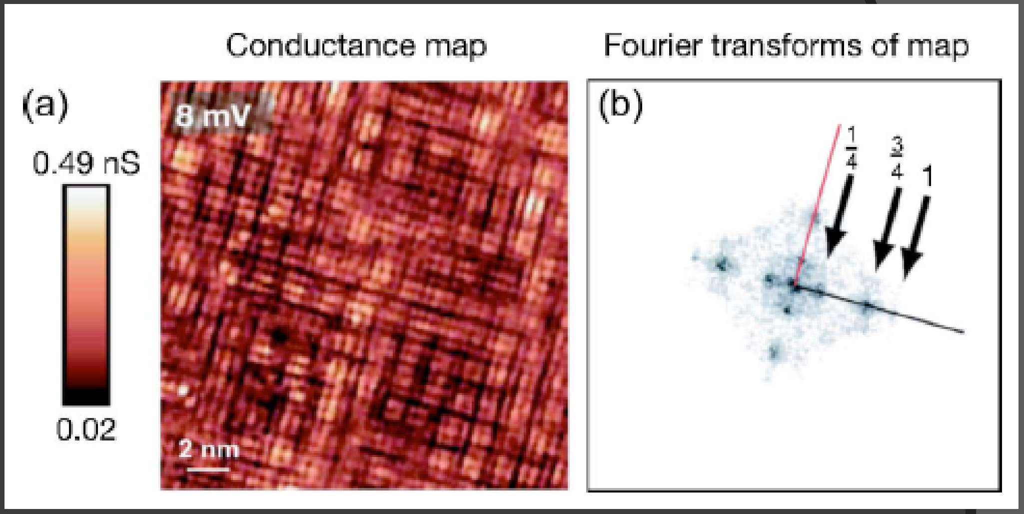


T = 5.3 K, H = 0 T

- **The 4x4 pattern is present in the pseudogap–like regions but also in the weak superconducting regions**
- **Same sub-gap states as in vortex cores**

4x4 pattern in the pseudogap phase





4x4 charge modulation in strongly underdoped $Ca_{2-x}Na_xCuO_2Cl_2$. Non-dispersive.

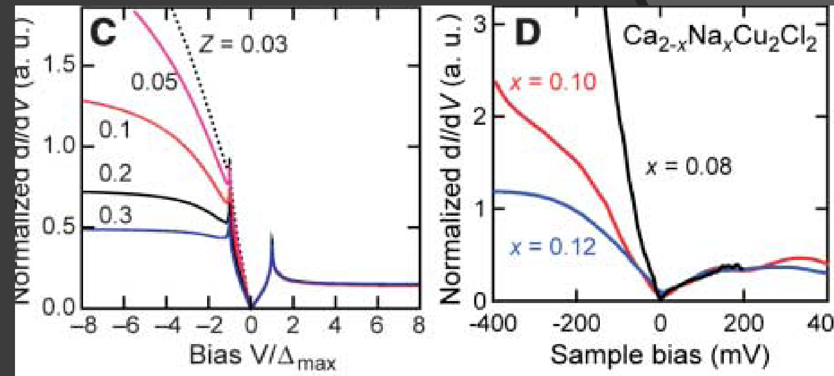
T. Hanaguri et al., Nature403, 1001 (2004)

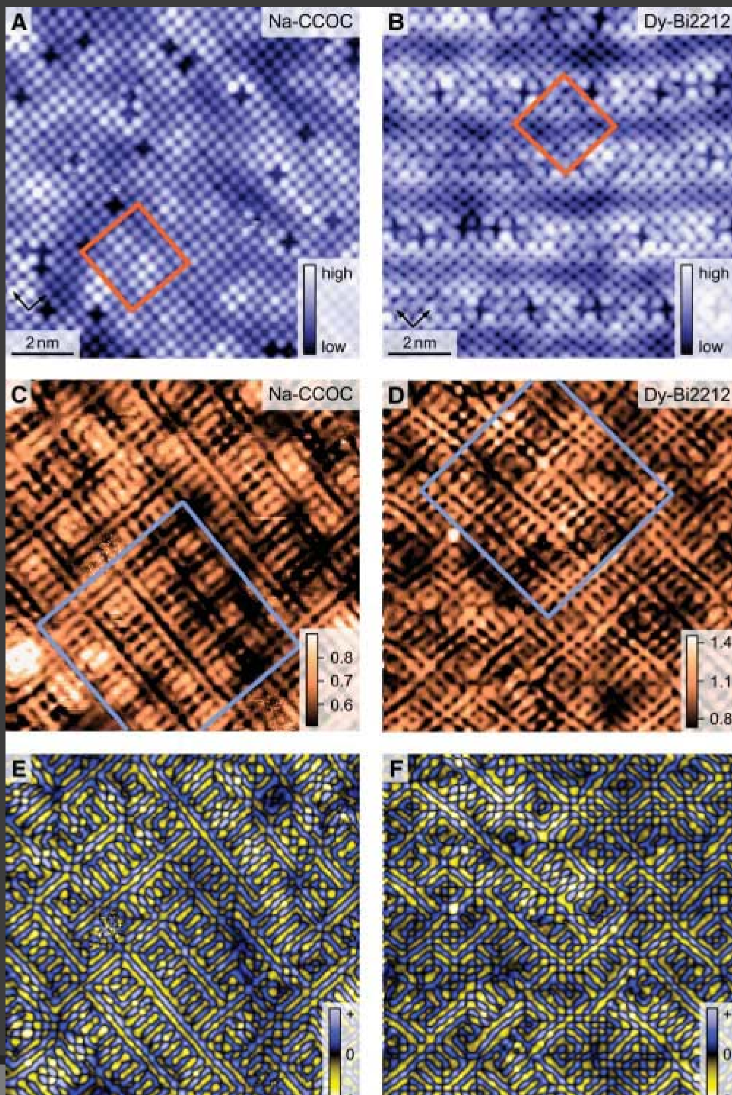
Bi2212, T=100K. A ~ 4x4 square pattern is seen in pseudogap phase above Tc.

M. Vershinin et al., Science 303, 1995 (2004)

Unidirectionnal $4a_0$ structure in underdoped cuprates
Partial hole localization?

Y. Kohsaka et al., Science 315, 1380 (2007)





Images of <u>strongly underdoped</u> Na-CCOC and Dy-Bi2212

Asymmetry R maps taken at 150 mV:

$R(r, V) = I(r, V)/I(r, -V) \sim 2n/(1-n)$

Large R (bright) correponds to more symmetric tunneling spectra.

Images of ΔR (Laplacian) computed from the asymmetry maps showing the atomic-scale arrangements of the spatial patterns.

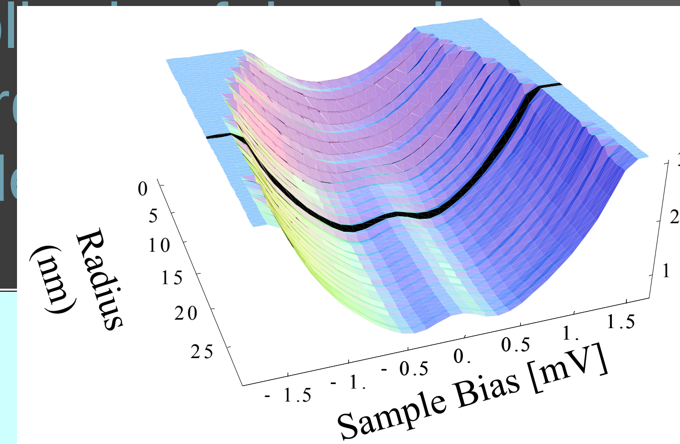
Bond-Centered Electronic Glass or Stripes?

Conclusions

- Strong sensitivity of the gap and pseudogap towards weak disorder, probably **extrinsic.**
- The amplitude of the peak-dip-hump structure seems correlated to the superconducting order.
- The nodal excitations are clearly related to the superconducting order.
- The $4a_0$ modulation seems to be an **intrinsic** feature of the strongly-underdoped and pseudogap phases : hole localization, stripes?
- The weaker the superconducting order, the stronger the $4a_0$ modulation: orders in competition?

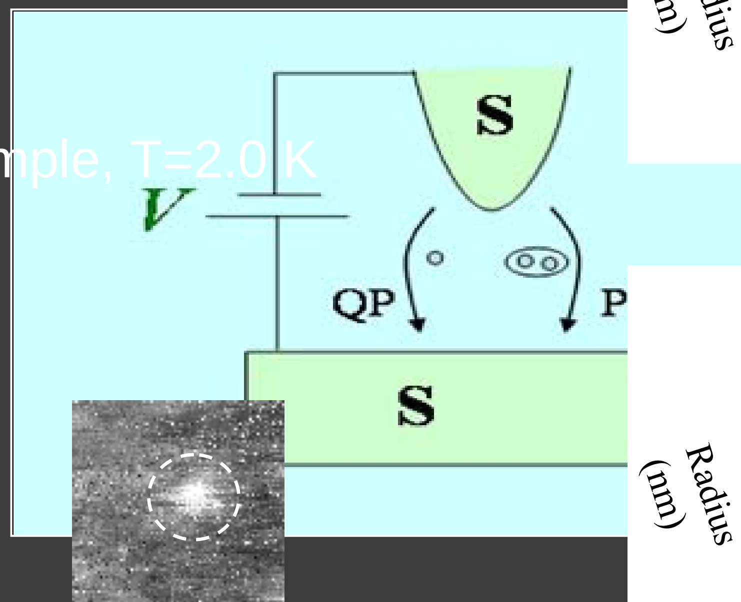
How to determine the local superfluid density

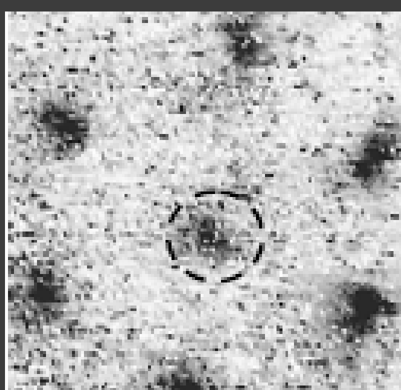
- The gap is no more related to the ampl
parameter : 2Δ/kTc diverges with underd
- The Josephson current could help to de
order parameter



Josephson profile

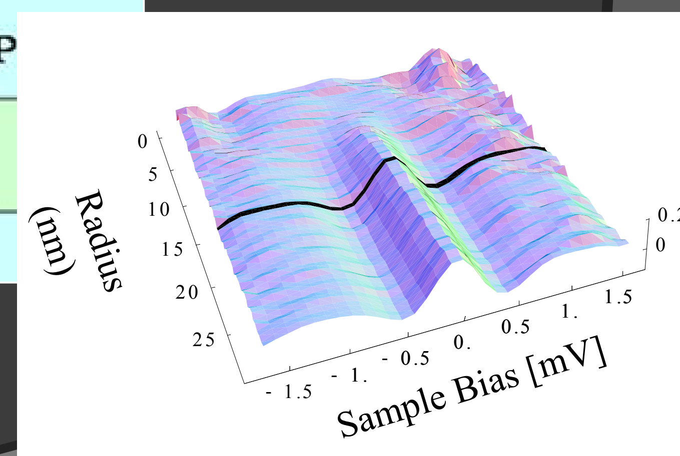
MgB$_2$ tip, V$_3$Si sample, T=2.0 K





SIS conductance map
H=1,15 T, 150x150 nm^2

Josephson map



Josephson profile, background substracted