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Scanning Tunneling Spectroscopy of the Cuprates

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FNSNF
Swiss National Science Foundation

UNIVERSITÉ DE GENÈVE

MaNEP
SWITZERLAND

Special thanks to...

Øystein
Fischer

Ivan
Maggio-Aprile

Alexandre
Piriou

... from the Geneva
STM group ...

... and to some of its former members

Nathan
Jenkins

Yanina
Fasano

Giorgio
Levy

Martin
Kugler

Bart
Hoogenboom

Christoph
Renner

Main players

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Review

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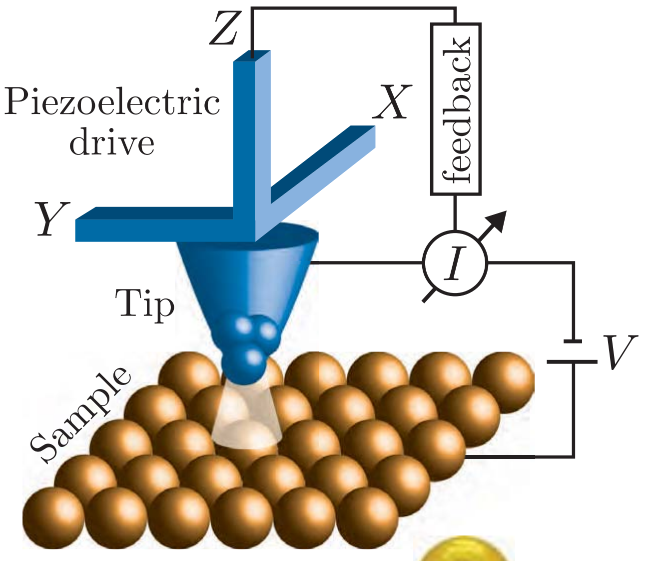
Outline

- Introduction to the STM and STS techniques
- What the STM can tell about the cuprate phase diagram
- Looking for the signature of the pseudogap at $T = 0$
- Contrasts between real-space and momentum-space physics
- Conclusions

Introduction to scanning tunneling microscopy / spectroscopy (STM / STS)

STM / STS

Principle — Orders of magnitude — Operating modes



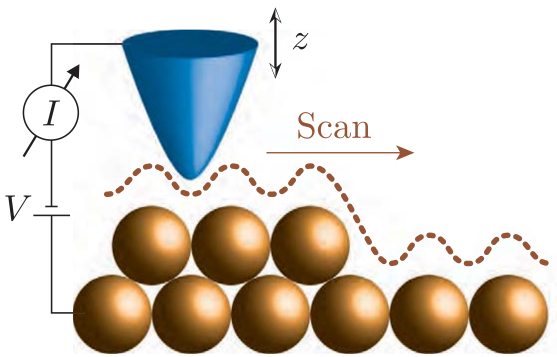
Binnig *et al.* (1982)

Typical current	nano-Ampere
Typical voltage	Volt
Typical resistance	giga-Ohm
Spatial resolution	sub-Å
Energy resolution	sub-meV
Typical time between two tunneling events	0.1 nano-second
Typical electron relaxation time	0.004 ns (1 meV)

Spectroscopy (STS)

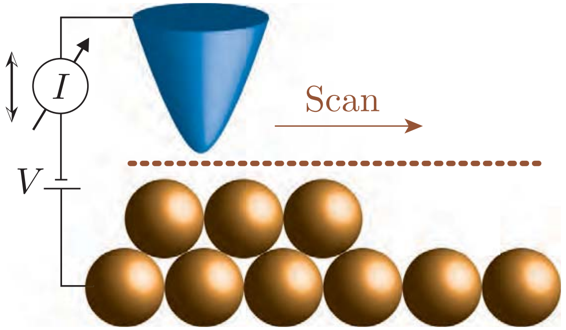
- Use constant-current mode for topography
- At each point, open feedback loop to freeze the height *z*
- Sweep voltage and measure the *I*(*V*) and/or *dI*/*dV* curve

Constant-current mode



$I = \text{cste} \;\Rightarrow\; \text{Image} = z(x,\, y)$

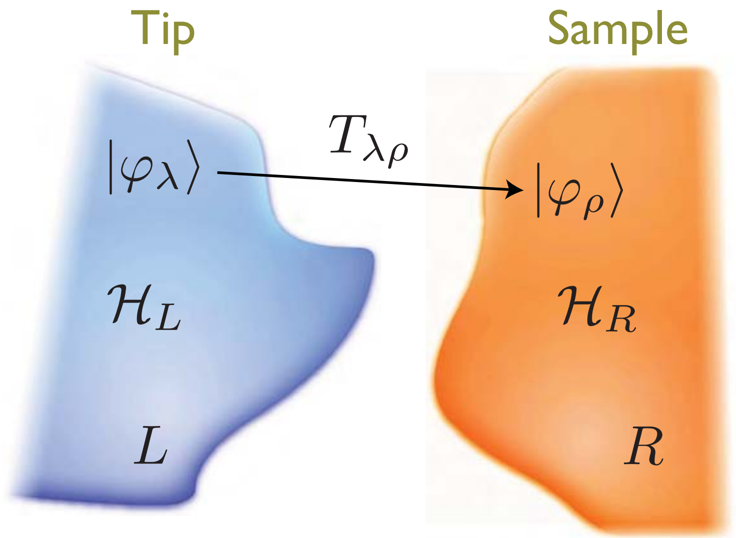
Constant-height mode

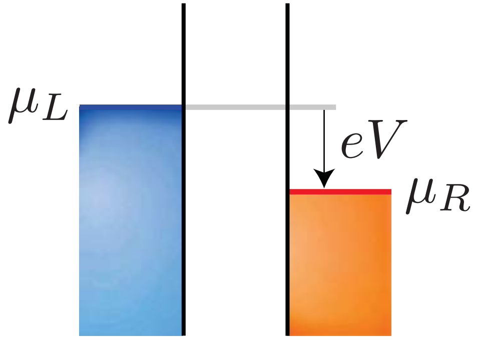


$z = \text{cste} \;\Rightarrow\; \text{Image} = I(x,\, y)$

STM / STS

Interpretation of experimental results — Tunneling Hamiltonian





Theory

- The electrodes are initially isolated, and in contact with two different reservoirs
- The tunneling of electrons is treated perturbatively by turning on a *tunneling Hamiltonian*

Cohen *et al.* (1962)

Tunneling Hamiltonian $\mathcal{H}_T = \sum_{\lambda\rho} T_{\lambda\rho} c^\dagger_\rho c_\lambda + \text{h.c.}$

Tunneling current at lowest order in $T_{\lambda\rho}$

$$I = \frac{2\pi e}{\hbar} \sum_{\lambda\rho} |T_{\lambda\rho}|^2 \int d\omega \, [f(\omega - eV) - f(\omega)] A_\lambda(\omega - eV) A_\rho(\omega)$$

STM / STS

Interpretation of experimental results — Matrix element and LDOS

Tunneling matrix element

Bardeen (1961)

$$T_{\lambda\rho} = -\frac{\hbar^2}{2m}\int_S \left[\varphi_\rho^*(\boldsymbol{r})\boldsymbol{\nabla}\varphi_\lambda(\boldsymbol{r}) - \varphi_\lambda(\boldsymbol{r})\boldsymbol{\nabla}\varphi_\rho^*(\boldsymbol{r})\right]\cdot \boldsymbol{dS}$$

Application to the STM

Tersoff *et al.* (1983)

See also Chen (1990)

$$T_{s\rho} \propto \varphi_\rho^*(\boldsymbol{r}_{\mathrm{tip}})$$

s-wave
tip

Sample
wave function

Position of
tip apex

Sample
LDOS

Paradigm for the
interpretation of
STM measurements
on the cuprates

STM tunneling conductance

$$\sigma(\boldsymbol{r}_{\mathrm{tip}}, V) \equiv \frac{dI}{dV} \propto \int d\omega\,[-f'(\omega - eV)]\,N_{\mathrm{sample}}(\boldsymbol{r}_{\mathrm{tip}}, \omega)$$

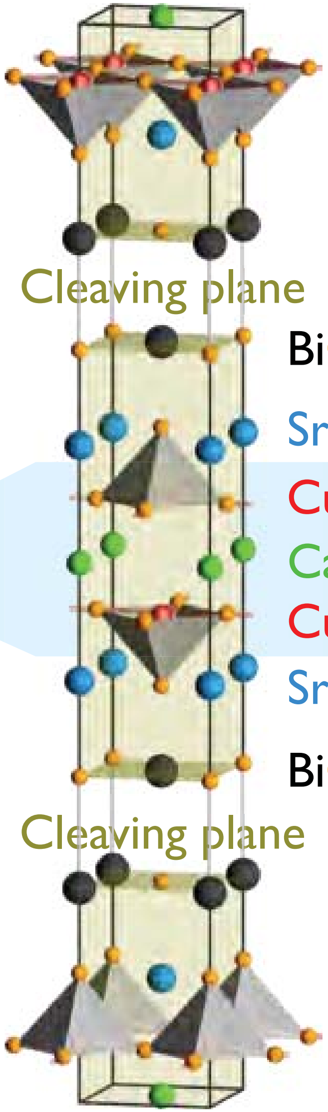
STM / STS

Application to the cuprates — The Bi-based family

$Bi_2Sr_2CuO_6$ (Bi-2201)

$Bi_2Sr_2CaCu_2O_8$ (Bi-2212)

$Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223)



Bi-2201:

BiO
SrO
CuO_2
SrO
BiO

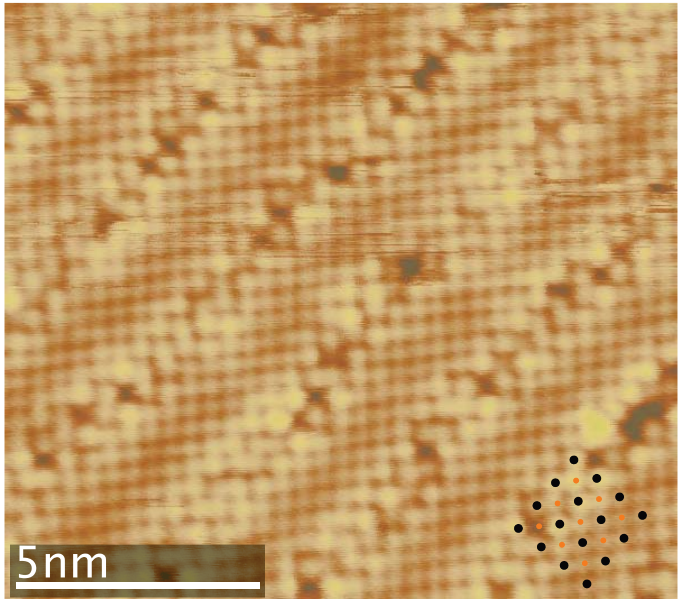
Bi-2212:

BiO
SrO
CuO_2
Ca
CuO_2
SrO
BiO

Bi-2223:

BiO
SrO
CuO_2
Ca
CuO_2
Ca
CuO_2
SrO
BiO

Bi-2223



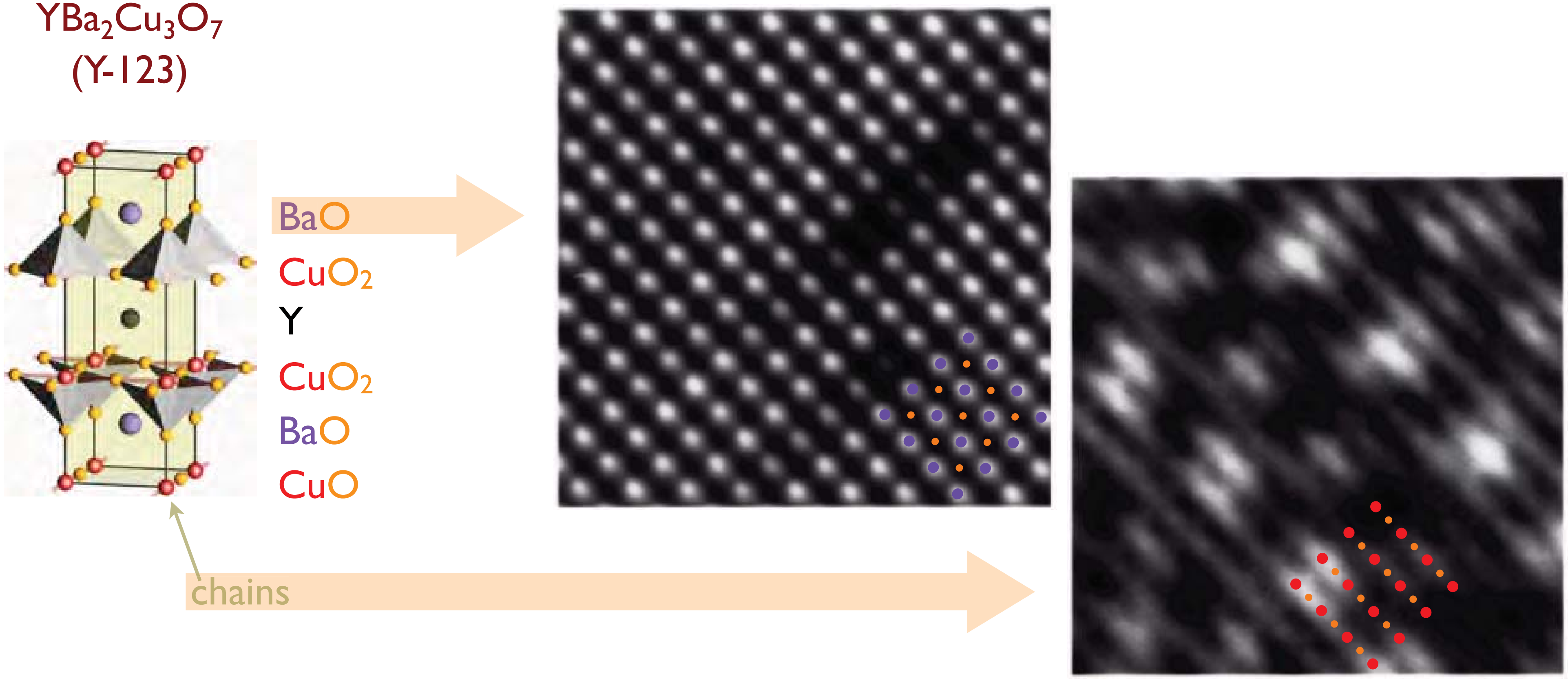
Jenkins *et al.* (2009)

- The topography images the BiO layer (high bias)
- The low-bias spectroscopy measures the CuO_2 layers

STM / STS

Application to the cuprates — «YBaCuO»

$YBa_2Cu_3O_7$
(Y-123)



BaO

CuO_2

Y

CuO_2

BaO

CuO

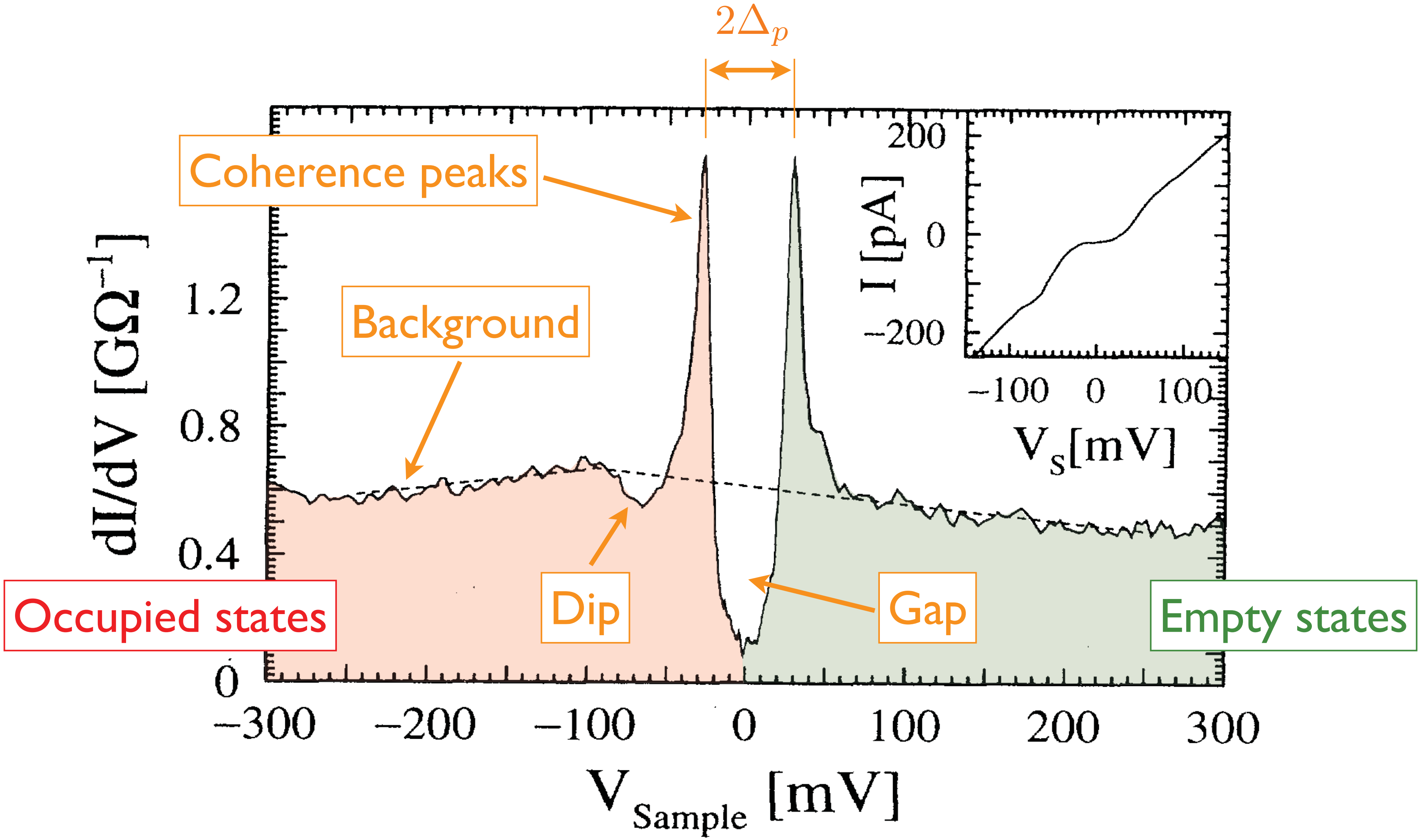
chains

Pan *et al.* (1999)

- There is no cleaving plane in Y-123
- Measurements are done on as-grown or chemically etched surfaces

Typical spectrum

Terminology



$2\Delta_p$

Coherence peaks

Background

Dip

Gap

Occupied states

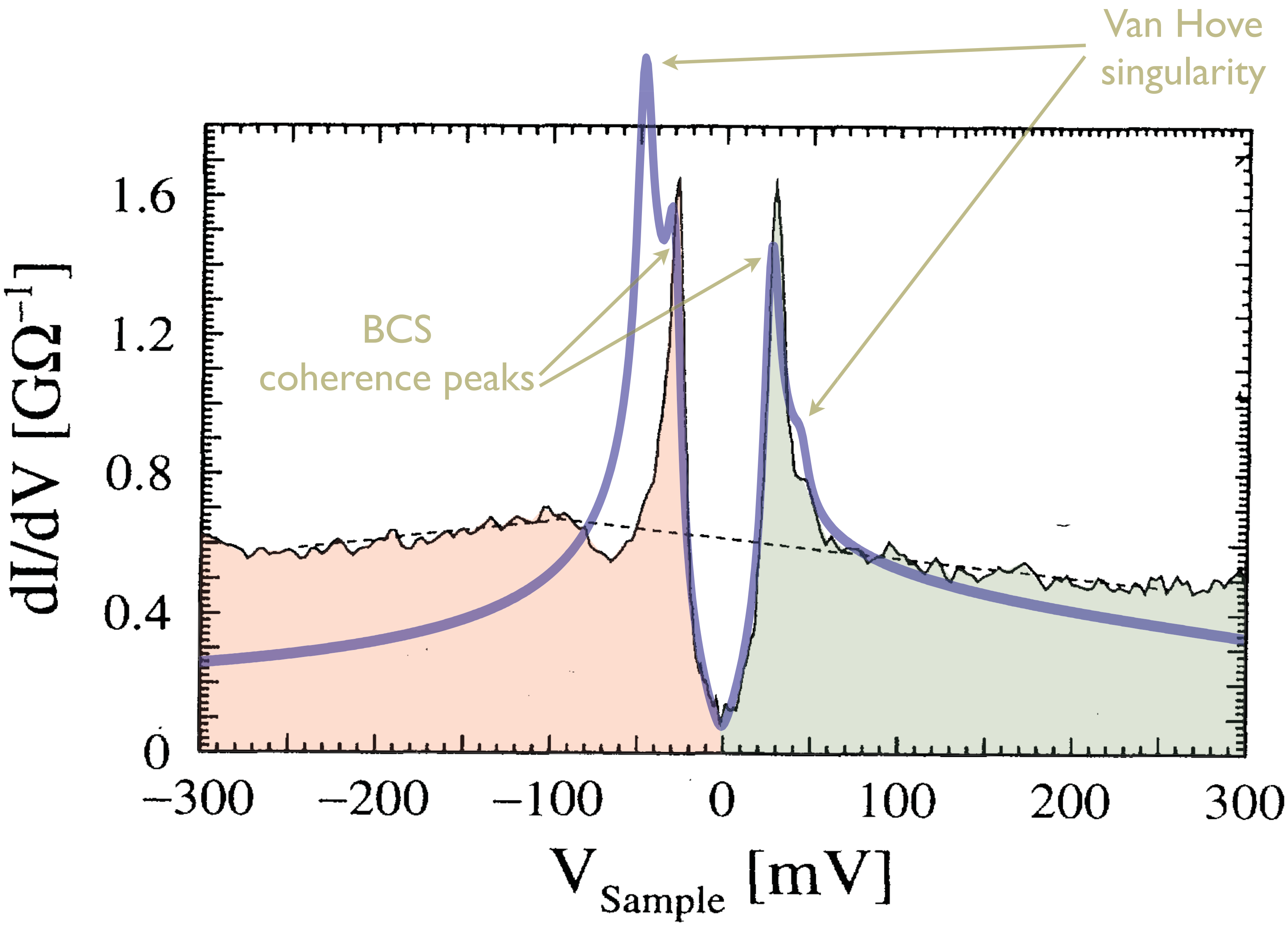
Empty states

Optimally-doped Bi-2212 (92K)

Renner *et al.* (1995)

Typical spectrum

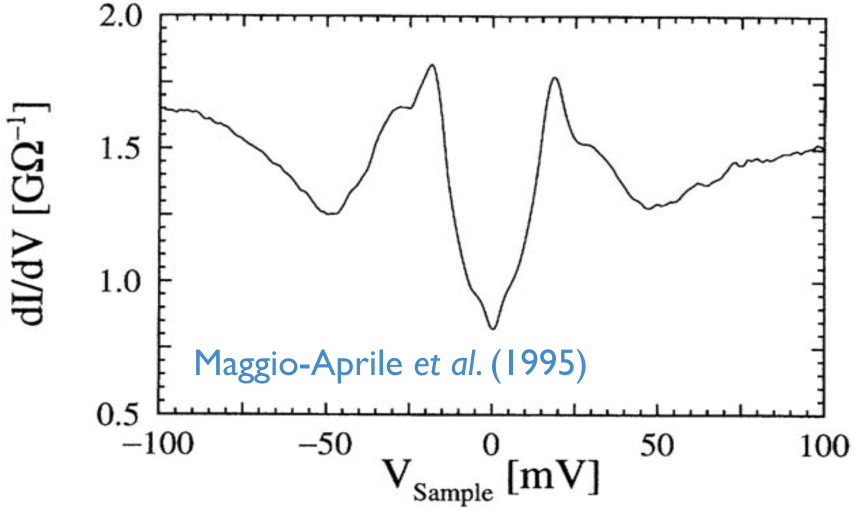
Comparison with BCS theory for *d*-wave superconductivity



Band structure [Norman *et al.* (1995)] + BCS *d*-wave gap

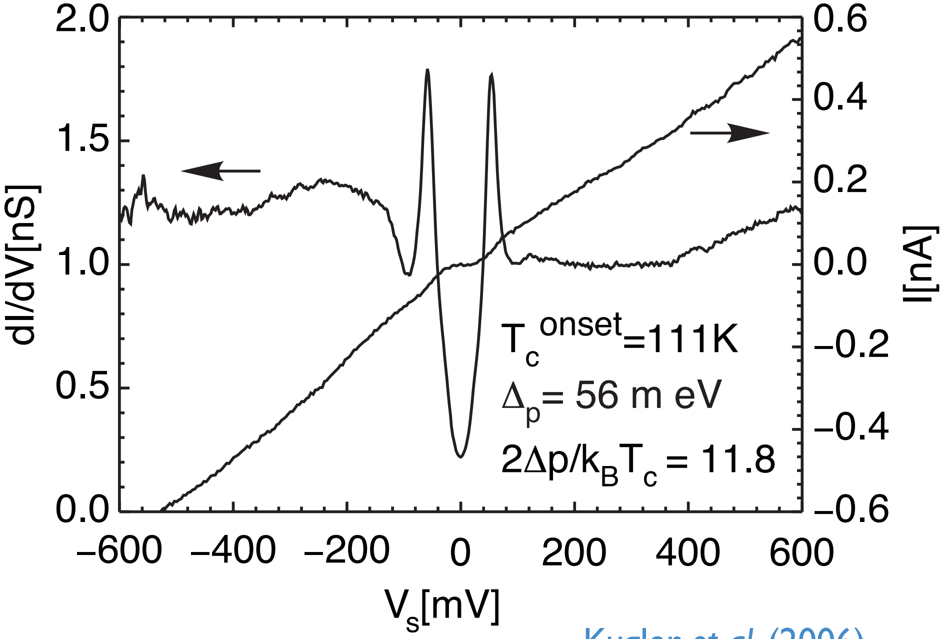
Other examples

Y-123



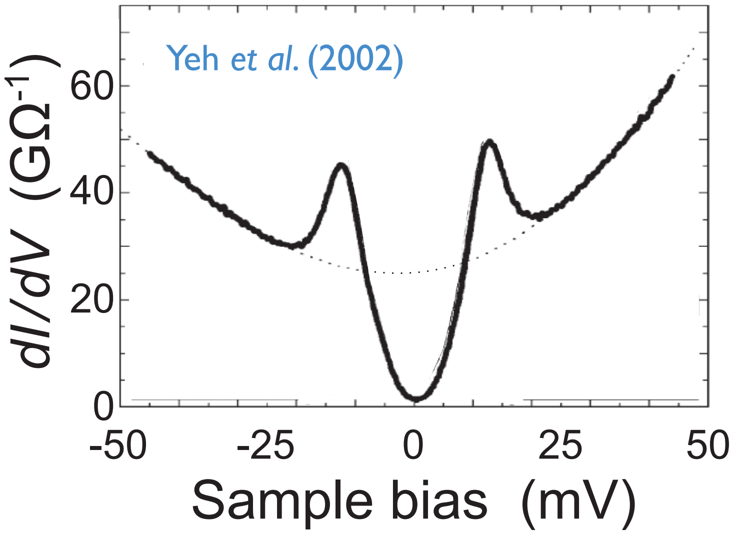
Maggio-Aprile *et al.* (1995)

Bi-2223



Kugler *et al.* (2006)

$Sr_{1-x}La_xCuO_2$



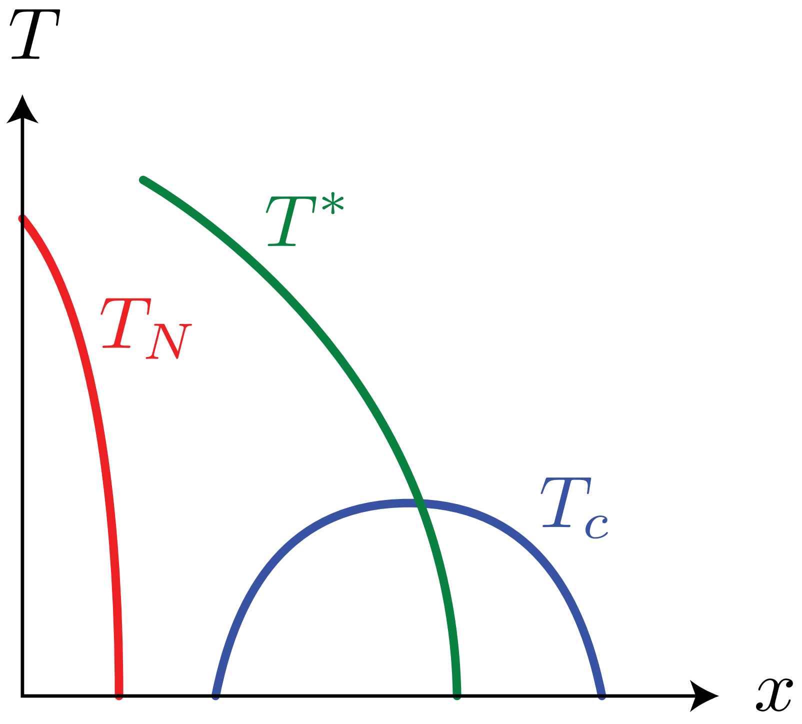
Yeh *et al.* (2002)

See also **Bi-2201** Boyer *et al.* (2007)

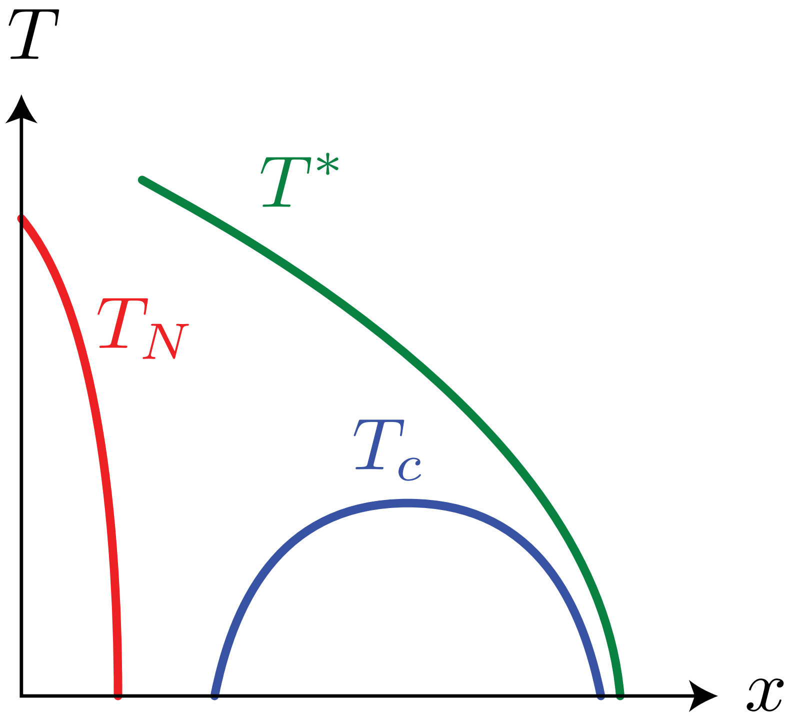
$Nd_{2-x}Ce_xCuO_4$ (Nd-214) Hayashi *et al.* (1998)

Phase diagram

The fundamental question



?



Quantum critical point
Competing orders

Precursor pairing
Phase fluctuations

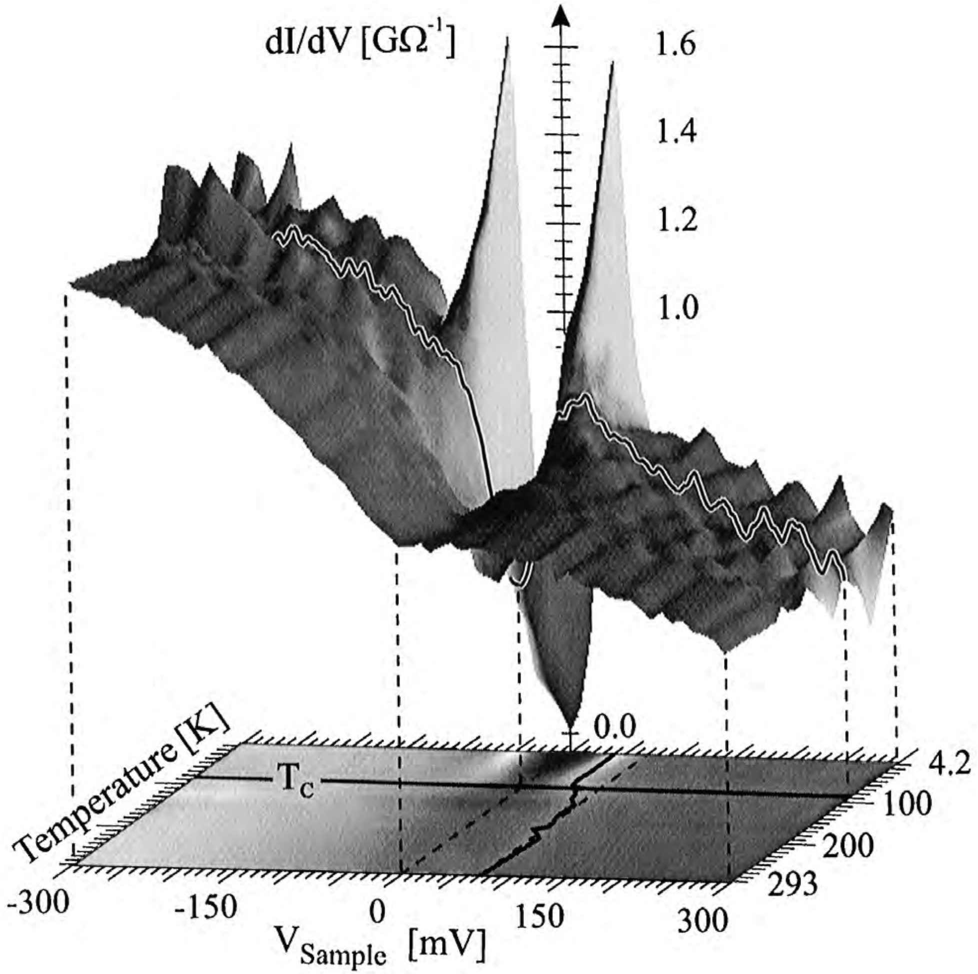
Phase diagram

How can the STM contribute?

- The STM allows to measure:

  1) the half-width of the gap in the excitation spectrum: Δ_p

  2) the temperature at which this gap first appears: T^*



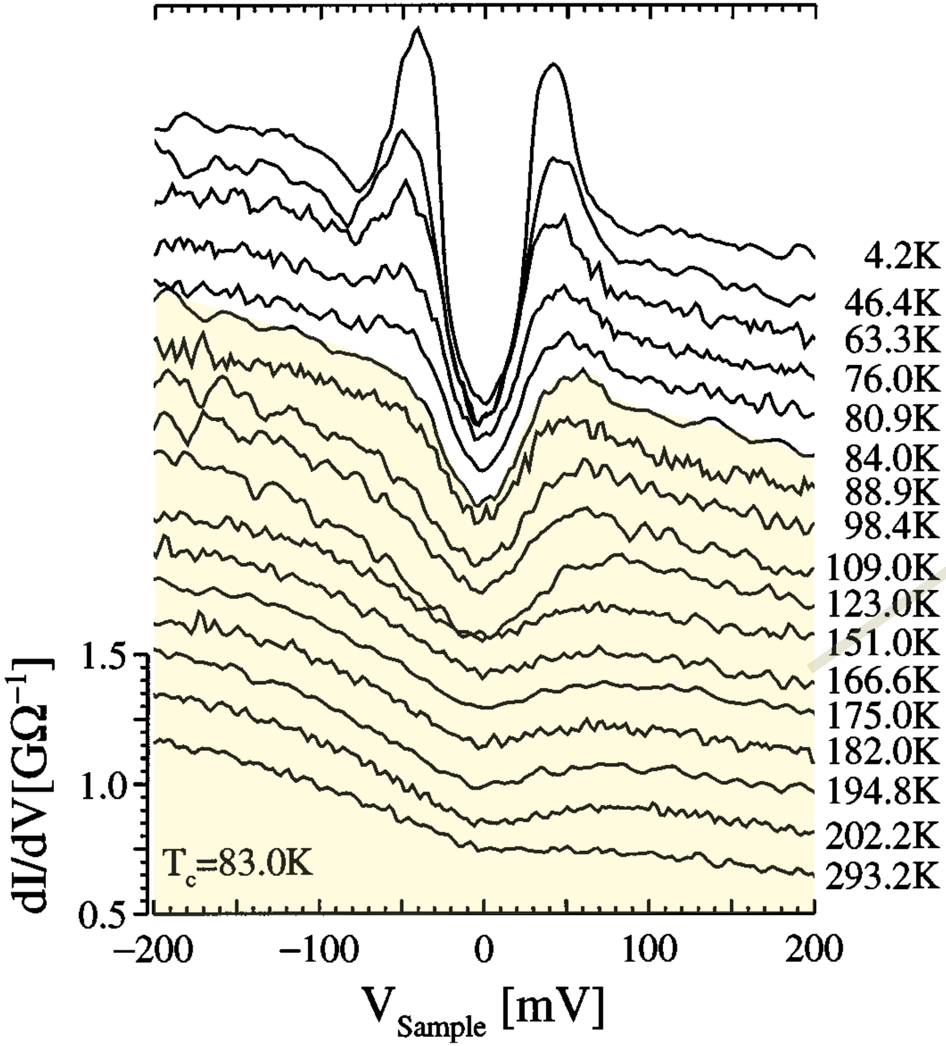
Renner *et al.* (1998)

- The doping x and the critical temperature T_c are measured by other means

Phase diagram

Some STM measurements

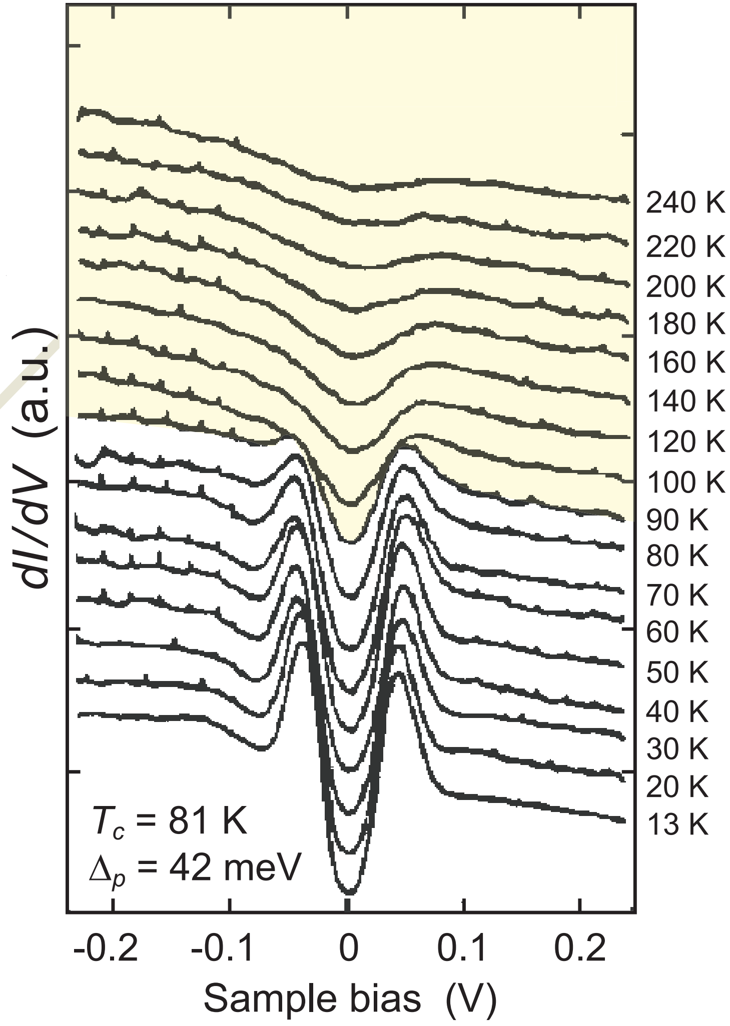
Underdoped Bi-2212 (83K)



Renner *et al.* (1998)

$T > T_c$

Overdoped Bi-2212 (81K)

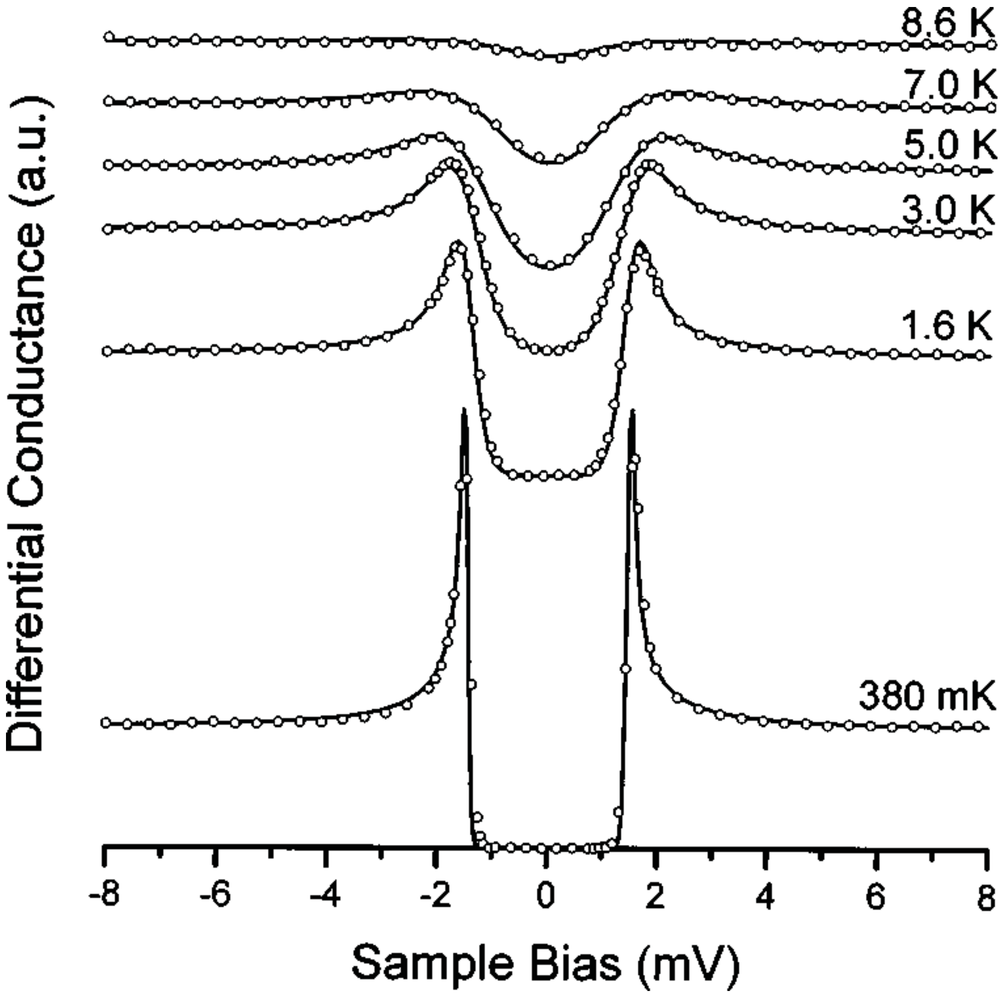


Matsuda *et al.* (1999)

Phase diagram

T-dependence of STM spectrum in a conventional BCS superconductor

Niobium (9K)

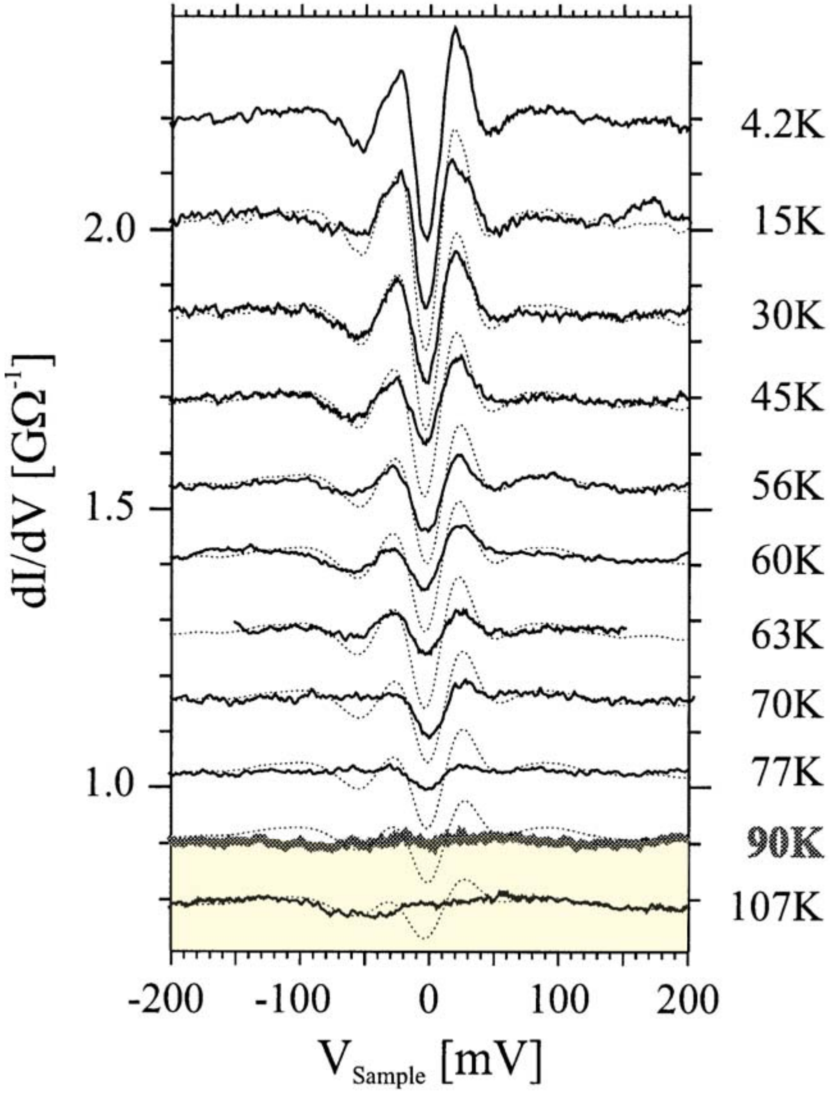


Pan *et al.* (1998)

Phase diagram

Some STM measurements

Optimally-doped Y-123 (92K)



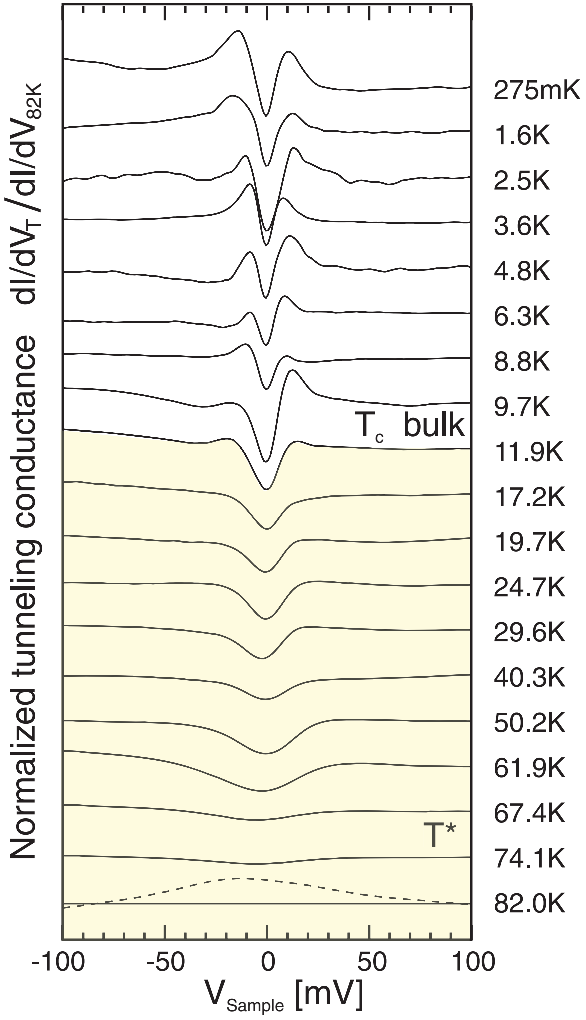
Maggio-Aprile *et al.* (2000)

See also

NdBa$_2$Cu$_3$O$_{7-\delta}$
(Nd-123)

Nishiyama *et al.* (2002)

Bi-2201 (10K)

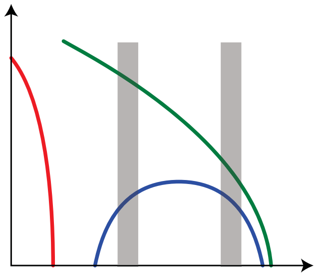


Kugler *et al.* (2001)

Phase diagram

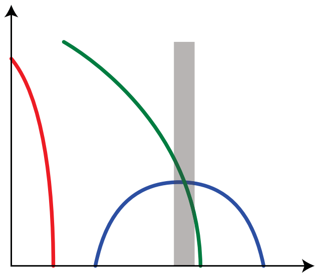
Absence of universality

- A gap is observed above the bulk T_c in underdoped and overdoped Bi-2212



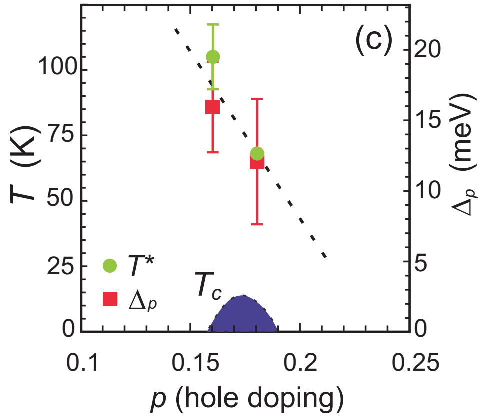
?

- No gap is observed above the bulk T_c in optimally-doped Y-123 and Nd-123



?

- A large pseudogap phase is observed in Bi-2201



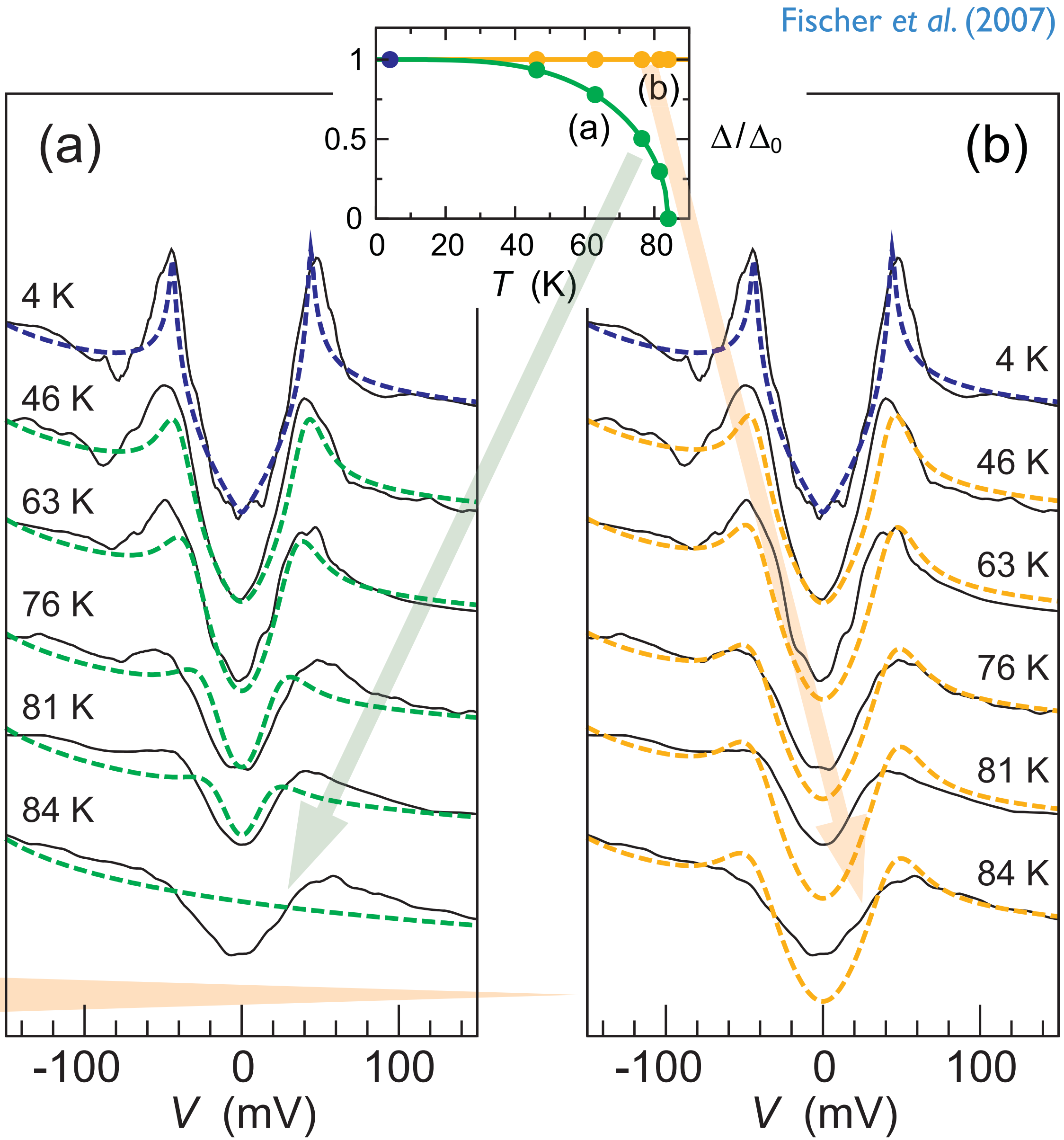
Fischer *et al.* (2007)

Phase diagram

Facts about the gap Δ_p — Temperature dependence

- The gap does not close at T_c like a BCS gap, but is rather temperature independent

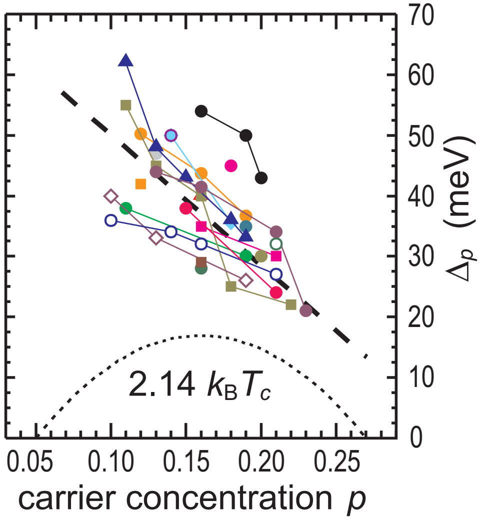
- The gap fill's in more rapidly than would be expected from thermal fluctuations


Fischer *et al.* (2007)

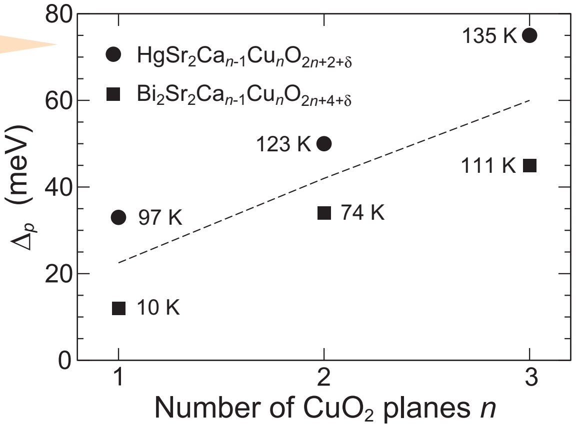
Phase diagram

Facts about the gap Δ_p — Scaling relations

Fischer *et al.* (2007)

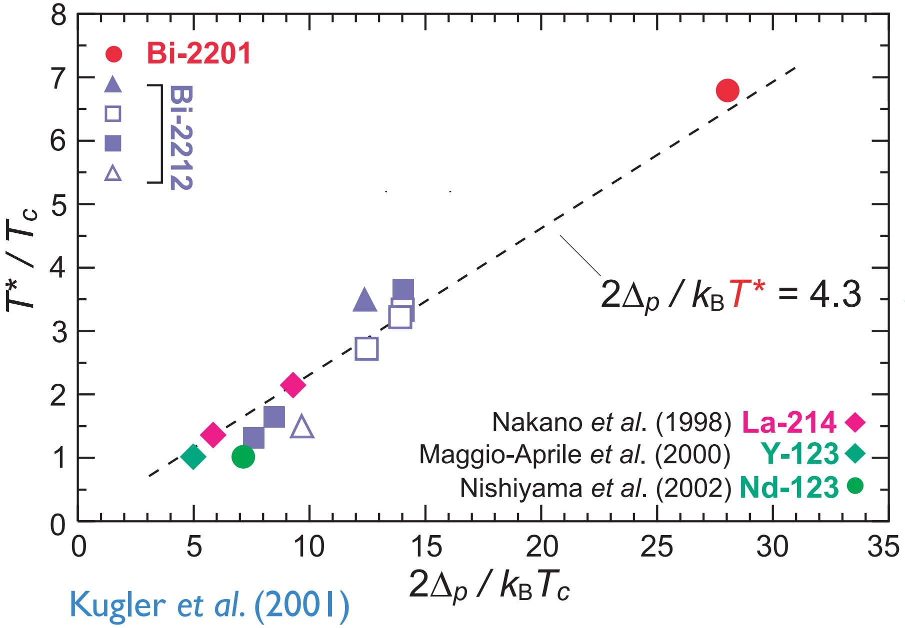


- Δ_p decreases monotonically with hole doping
- Δ_p does not scale with T_c like in the BCS theory



- Δ_p increases with the number of CuO_2 layers

Wei *et al.* (1998)
Kugler *et al.* (2001)
Renner *et al.* (1998)
Kugler *et al.* (2006)



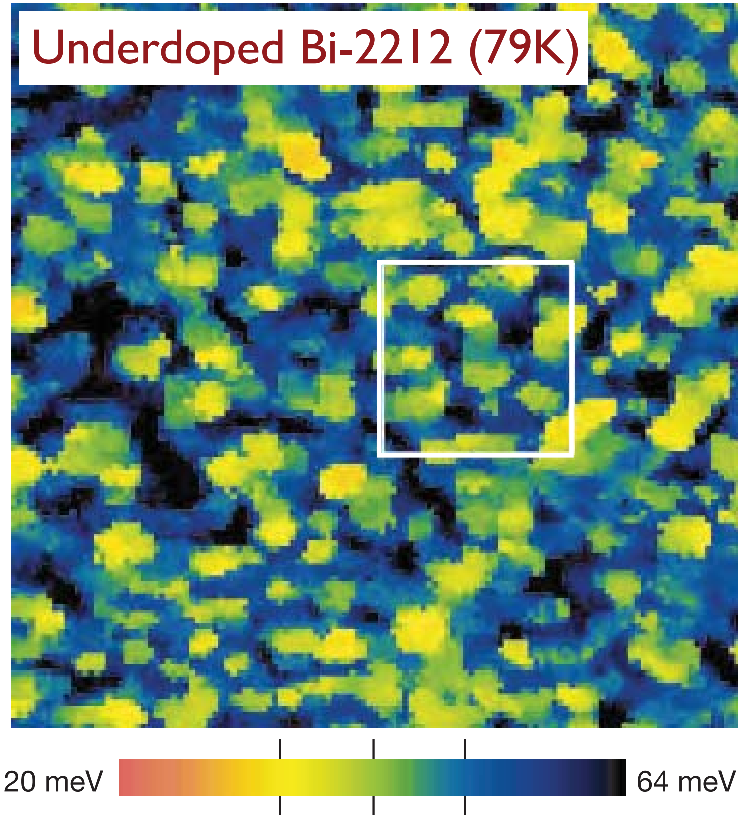
Kugler *et al.* (2001)

- A BCS *d*-wave ratio seems to bind Δ_p to T^*

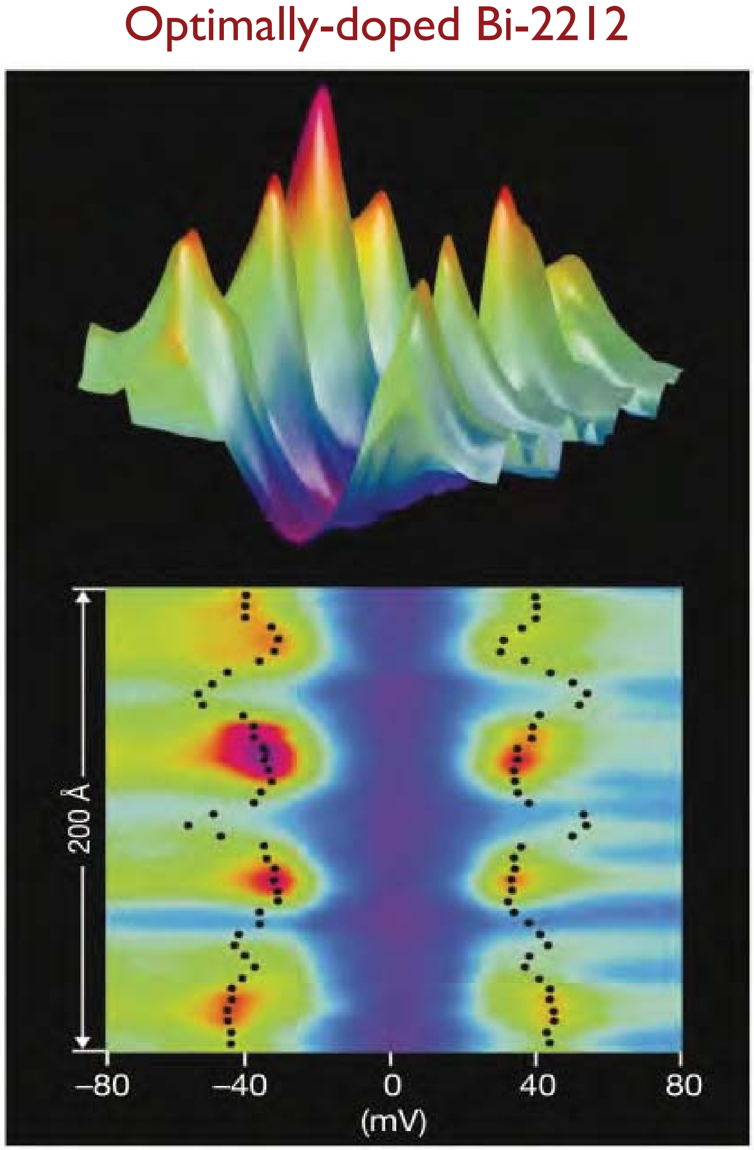
Nakano *et al.* (1998)

Phase diagram

The problem of inhomogeneity...



Lang *et al.* (2002)



Pan *et al.* (2001)

STM studies have shown that the cuprates have inhomogeneous properties over a length scale of typically 5 nm.

Spatial inhomogeneities

What are they?

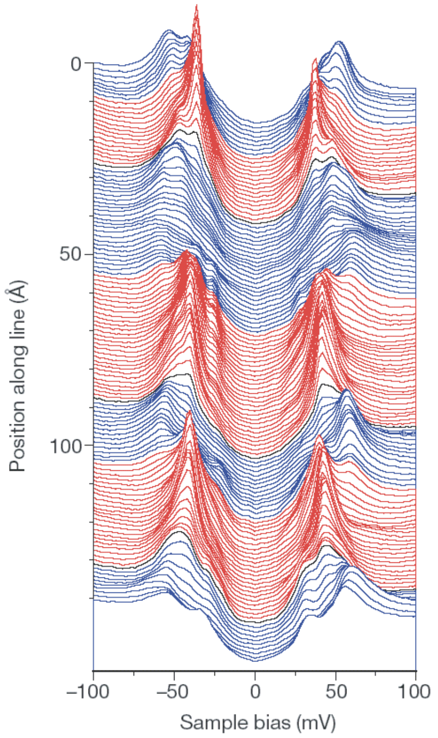
- The various characteristics of the STM spectra (gap width, coherence peaks, etc...) can be spatially inhomogeneous

- Is this the signature of an intrinsic electronic phase separation?
- Is it due to stoichiometric disorder?

Spatial inhomogeneities

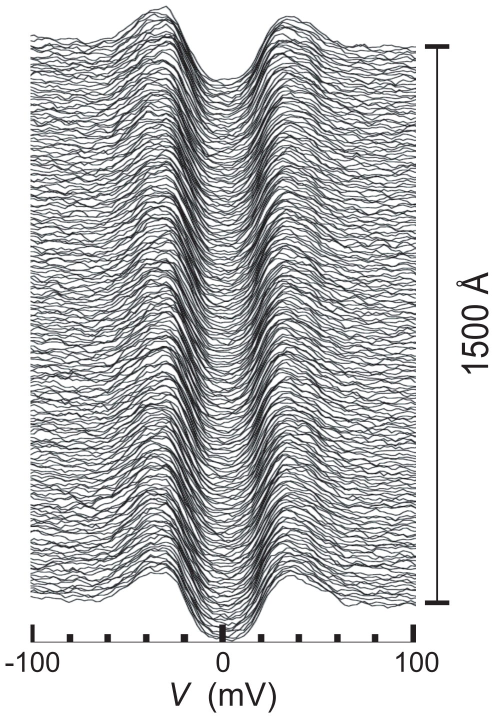
Homogeneous samples with high T_c do exist

Bi-2212 (79K)



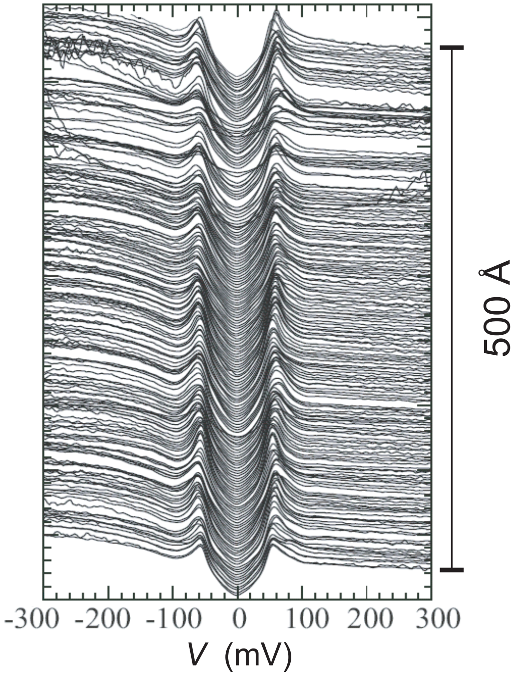
Lang *et al.* (2002)

Bi-2212 (71K)



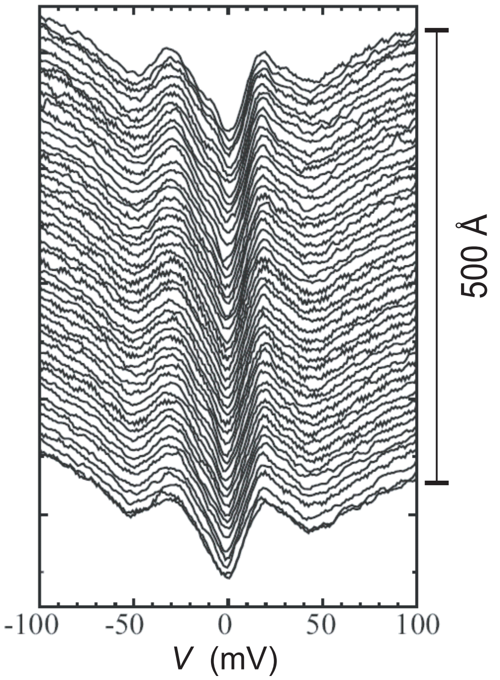
Renner *et al.* (1998)

Bi-2223 (109K)



Kugler *et al.* (2006)

Y-123

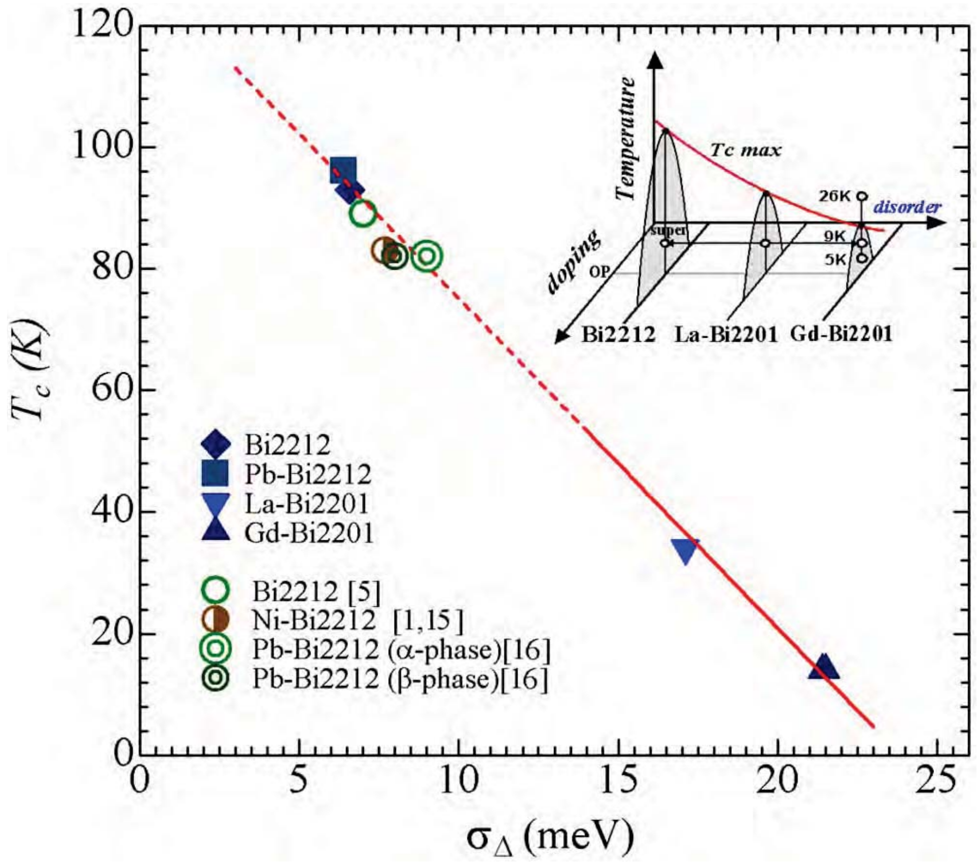


Maggio-Aprile *et al.* (1996)

Inhomogeneities are not necessary for high T_c

Spatial inhomogeneities

Inhomogeneities do not favor superconductivity



Sugimoto *et al.* (2006)

Inhomogeneity seems to reduce T_c

Spatial inhomogeneities

Additional observations

- A strong spatial inhomogeneity implies a broad superconducting transition, and inversely

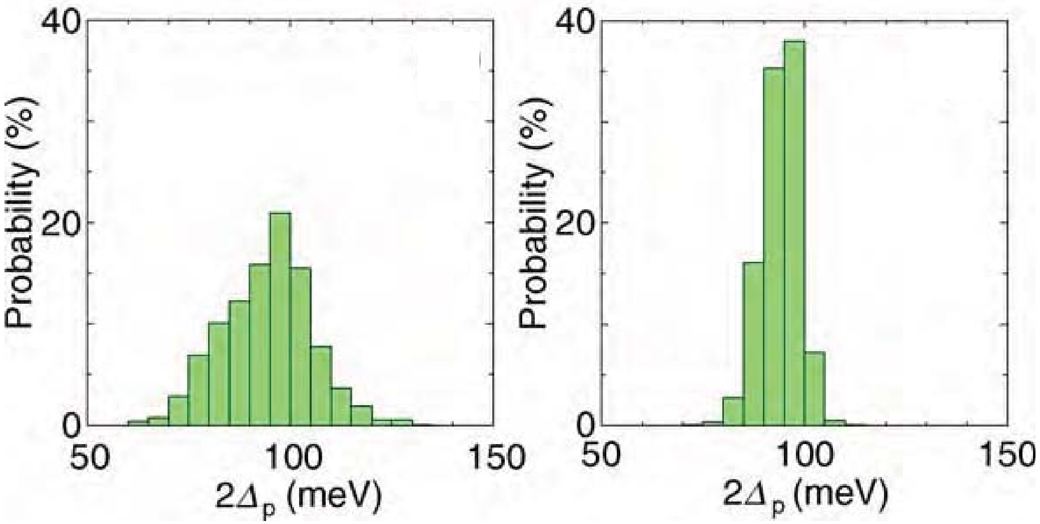
Hoogenboom *et al.* (2003)

Monomo *et al.* (2005)

Kugler *et al.* (2006)

- The spread of the gap in different regions of the same sample can be different (even inhomogeneities are inhomogeneous...)

Underdoped Bi-2212



Matsuba *et al.* (2003)

Spatial inhomogeneities

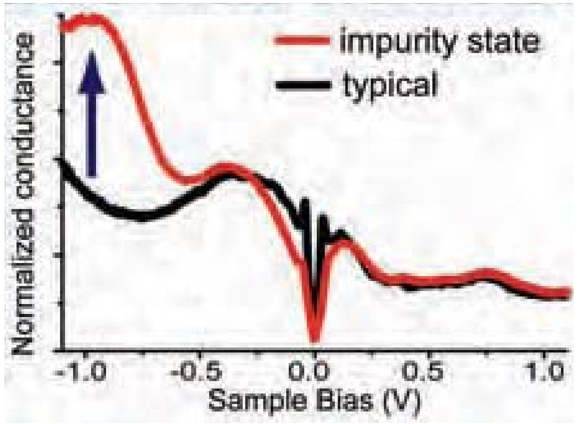
Relation with oxygen impurities

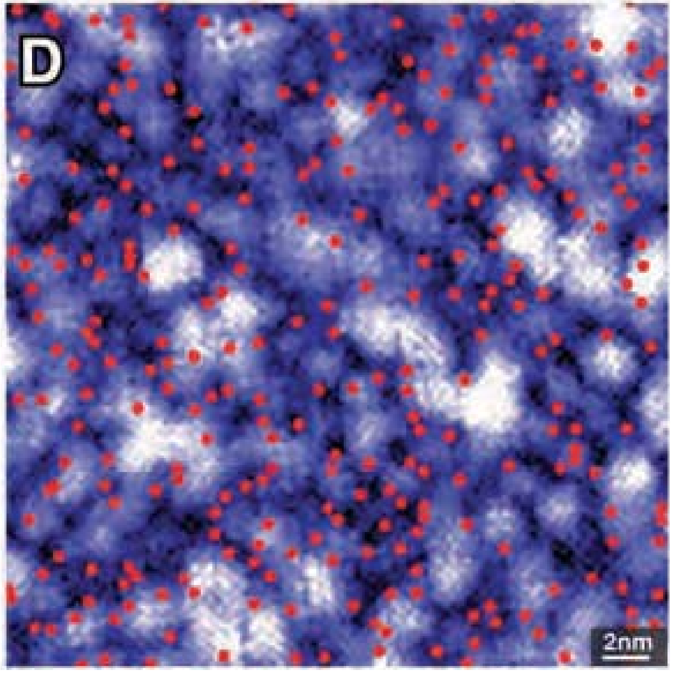
- Inhomogeneities are correlated with the positions of oxygen impurities

- Oxygen annealing increases inhomogeneity

Kinoda *et al.* (2003)

Bi-2212





McElroy *et al.* (2005)

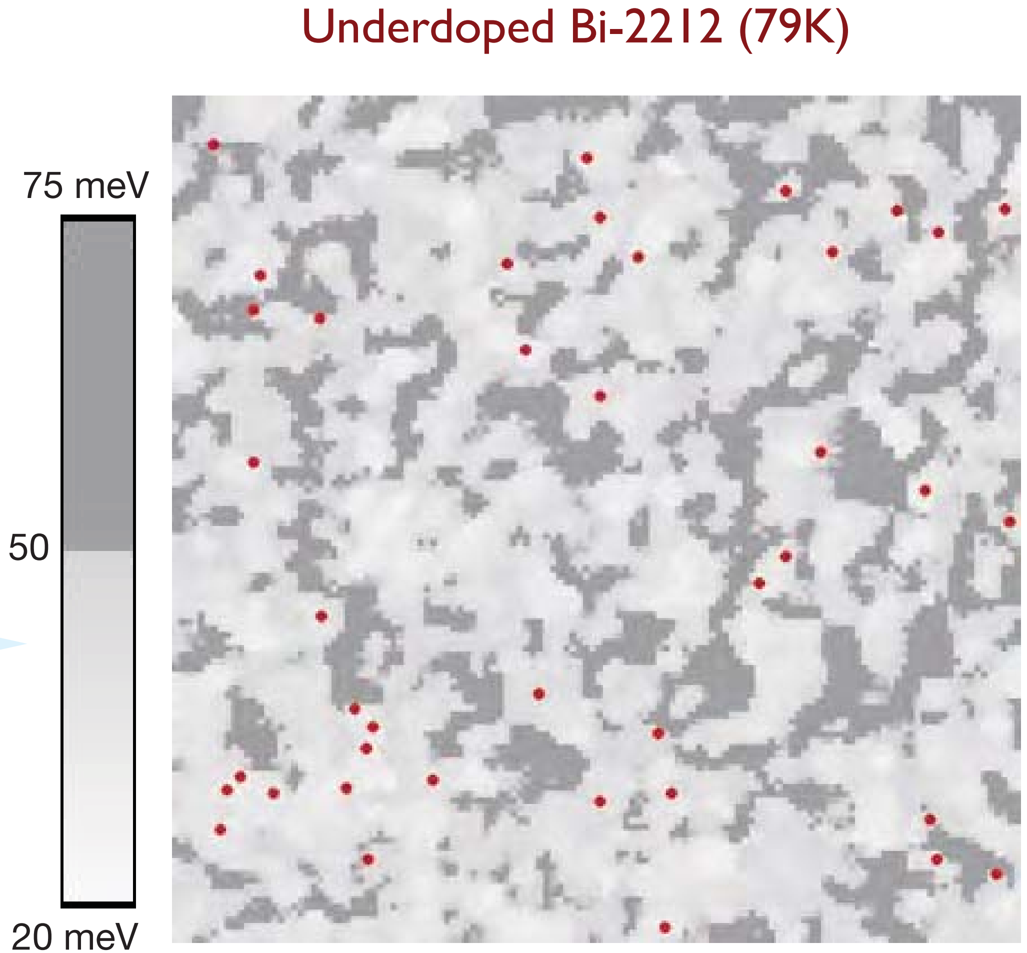
Spatial inhomogeneities

Relation with other impurities

- Pb substitutions for Bi have no effect on inhomogeneity

Kinoda *et al.* (2003)

- Low-energy resonances typical of Ni impurities are never detected in regions having a large gap (pseudogap?)

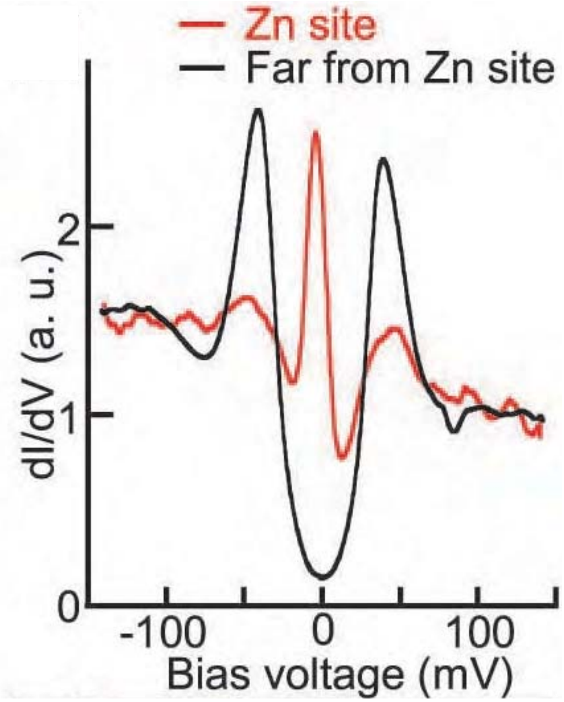


Lang *et al.* (2002)

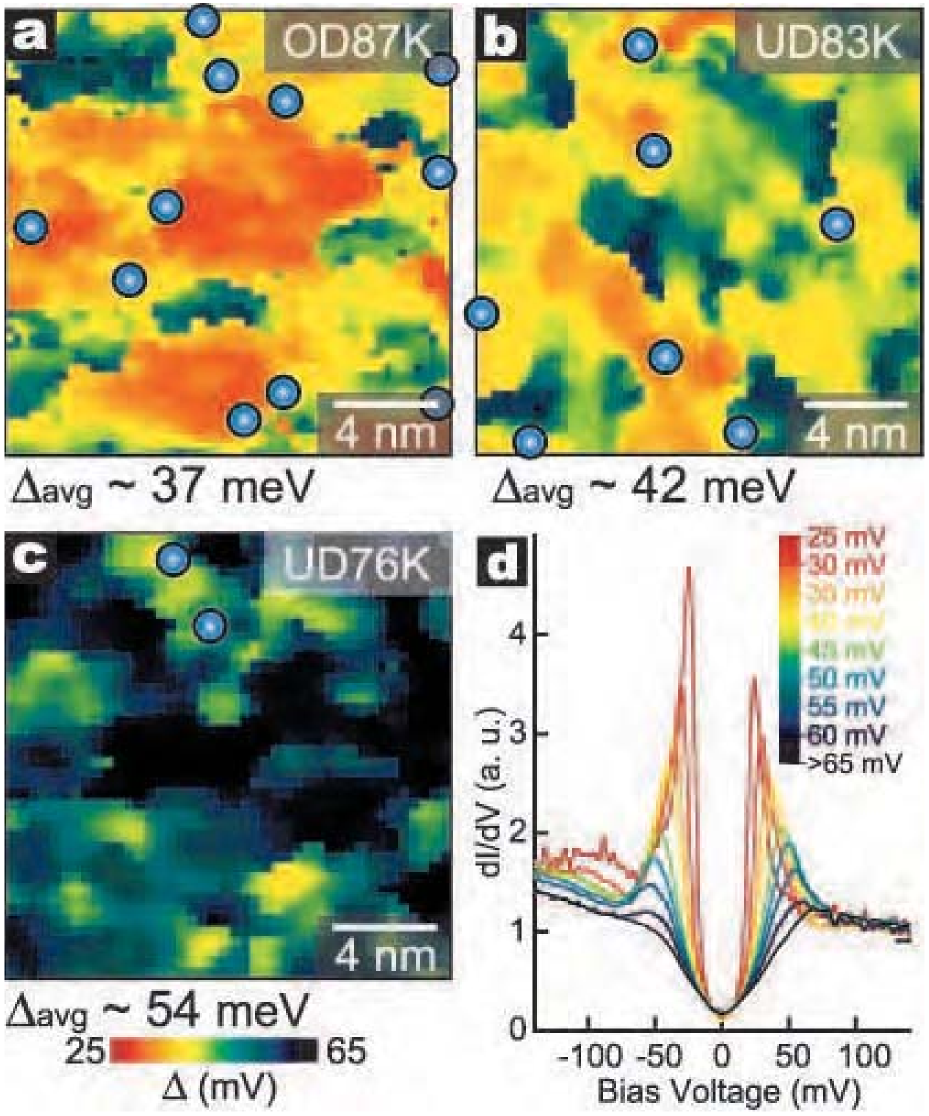
Spatial inhomogeneities

Relation with other impurities

- Like Ni impurities, Zn impurities are not detected in large-gap regions



Bi-2212



Machida *et al.* (2010)

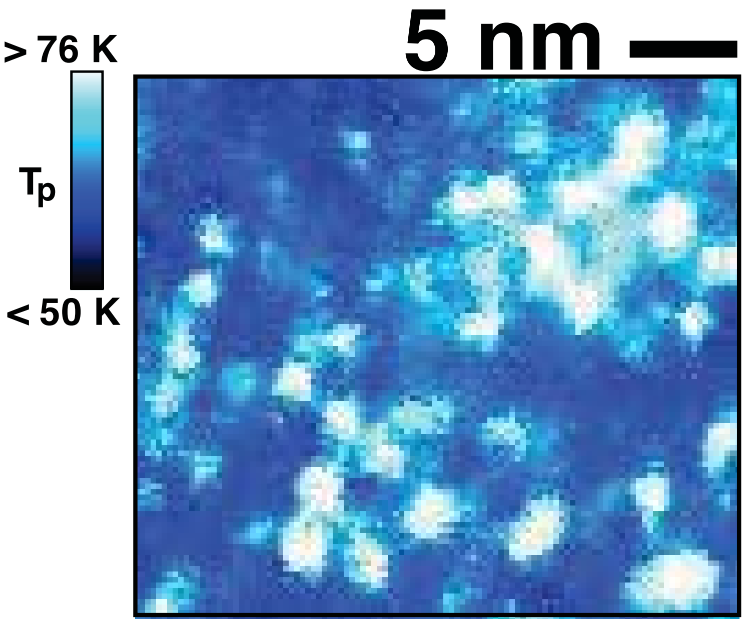
Spatial inhomogeneities

Back to the phase diagram

- Doping is probably inhomogeneous, but cannot (yet) be measured locally

- T^* is also inhomogeneous

Overdoped Bi-2212 (65K)

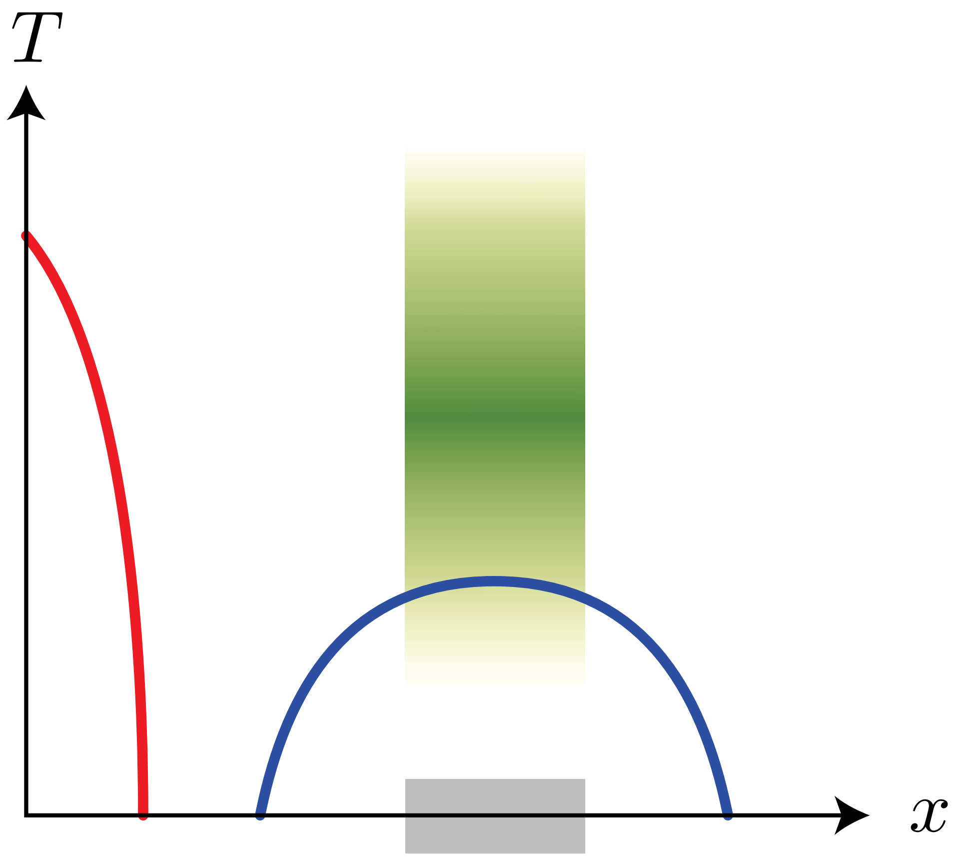


Parker *et al.* (2010)

Gomes *et al.* (2007)

Phase diagram

The problem of inhomogeneity...



What is the meaning of *x* if the material is inhomogeneous?

How to define T^* ?

Phase diagram

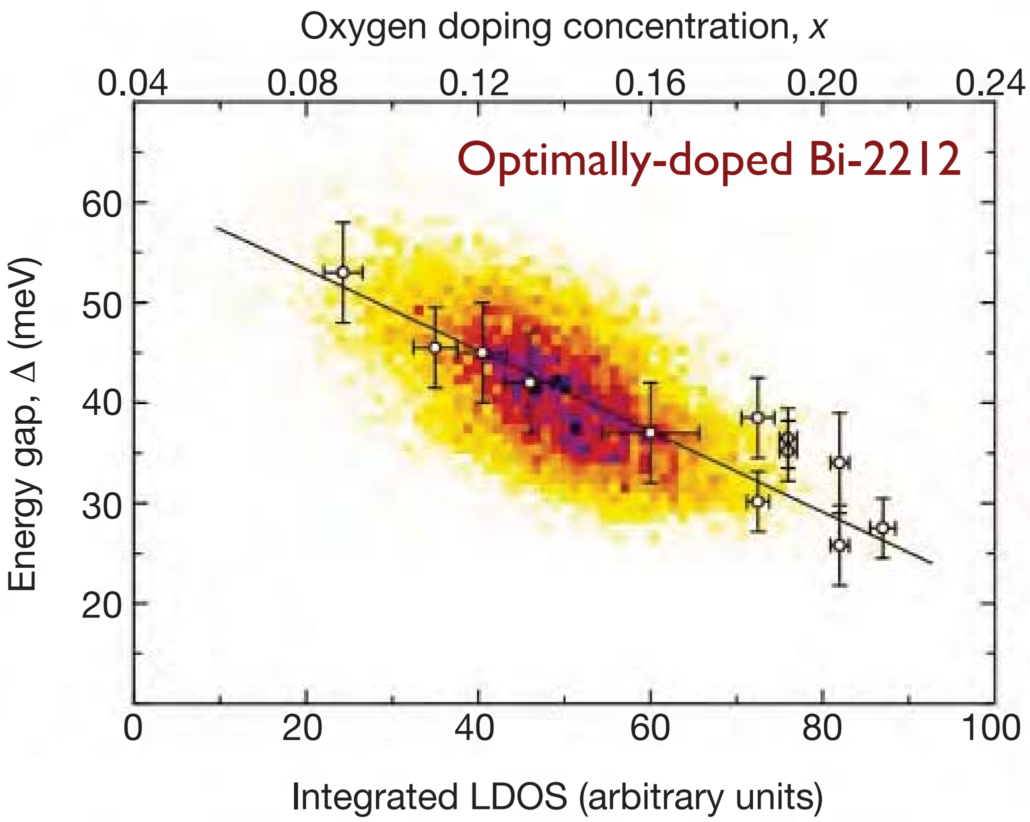
Summary

- Different materials can have the same T_c but very different T^*
- There is no evidence for a hidden QCP in the STM data
- Below T^* a temperature-dependent spectral weight is removed at E_F over a temperature-independent energy scale Δ_p
- The vision entailed by the traditional representation of the (x,T) phase diagram may be too simple

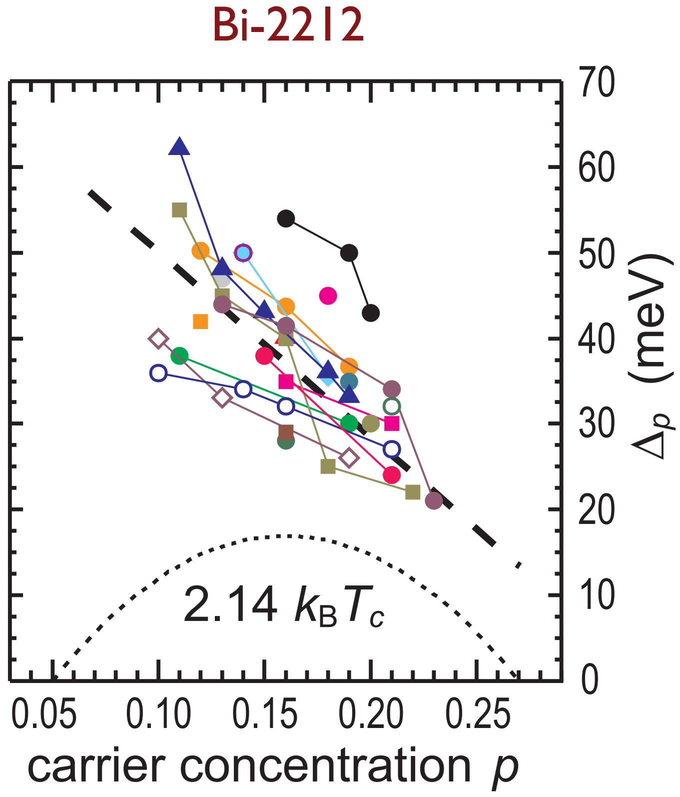
Spatial inhomogeneities

Inhomogeneity is also a chance

Doping-dependent studies can be done on one single sample



Pan *et al.* (2001)

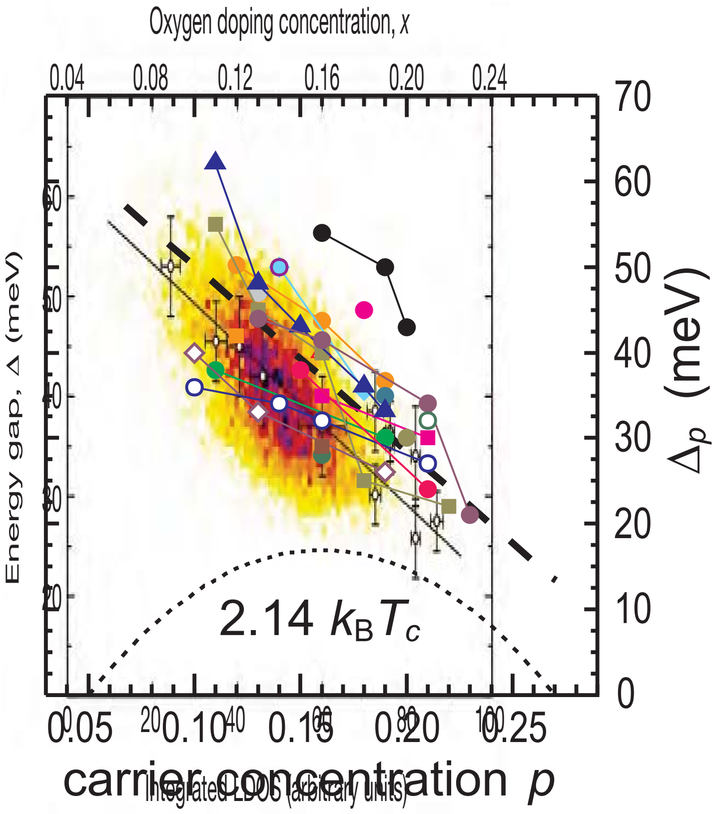


Fischer *et al.* (2007)

Spatial inhomogeneities

Inhomogeneity is also a chance

Doping-dependent studies can be done on one single sample

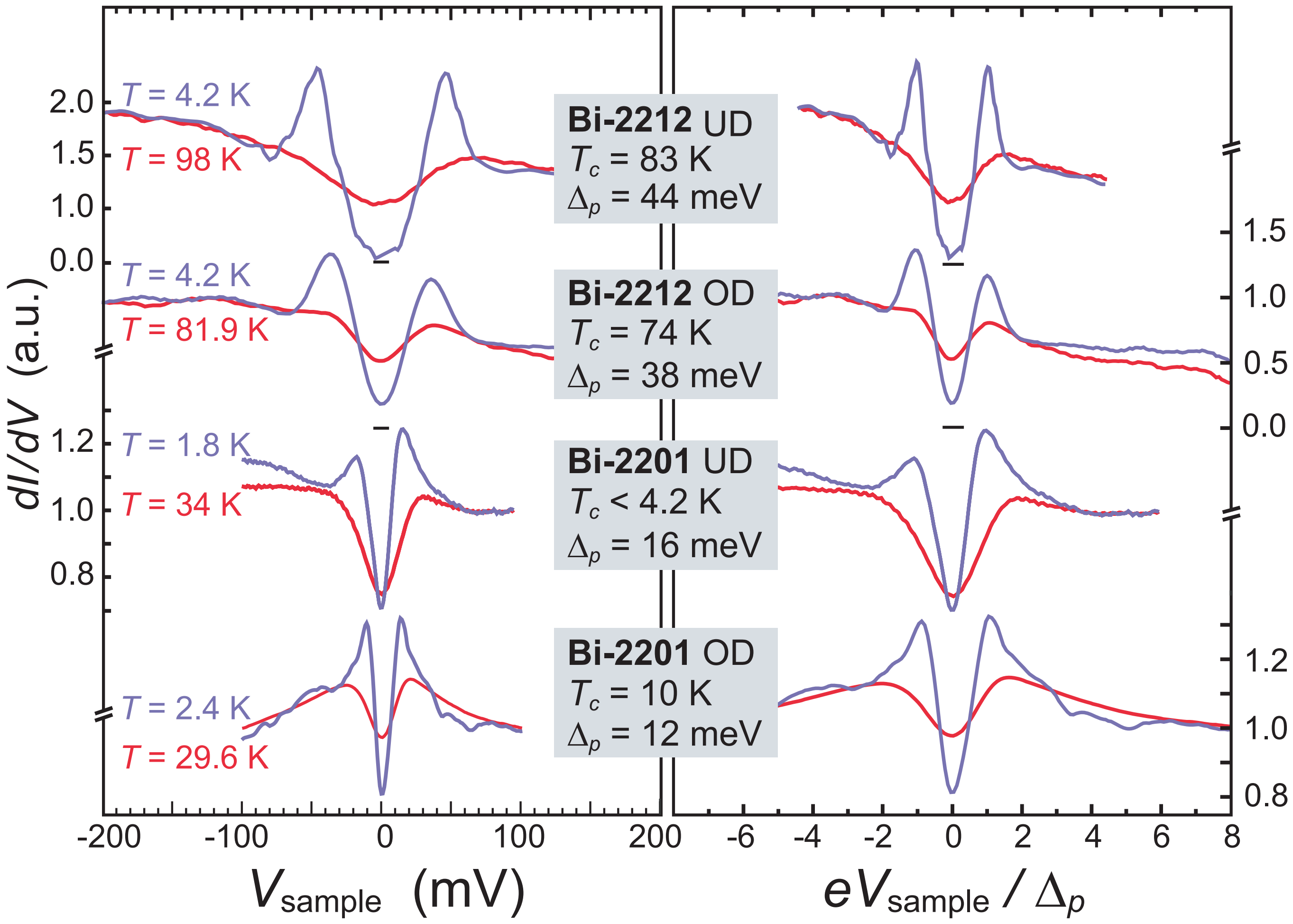


Furthermore inhomogeneity reveals quasi-particle interference phenomena

The spectral signature of the pseudogap observed at $T < T_c$

Characteristics of the pseudogap

$T > T_c$



Fischer *et al.* (2007)

- The pseudogap has the same magnitude as the gap at $T < T_c$

- The coherence peak and dip-hump are suppressed at negative bias

- A small peak slightly shifted to higher energy remains at positive bias

Pseudogap at low temperature

The spectral signature of the pseudogap observed at $T < T_c$

1) On structurally disordered or damaged surfaces

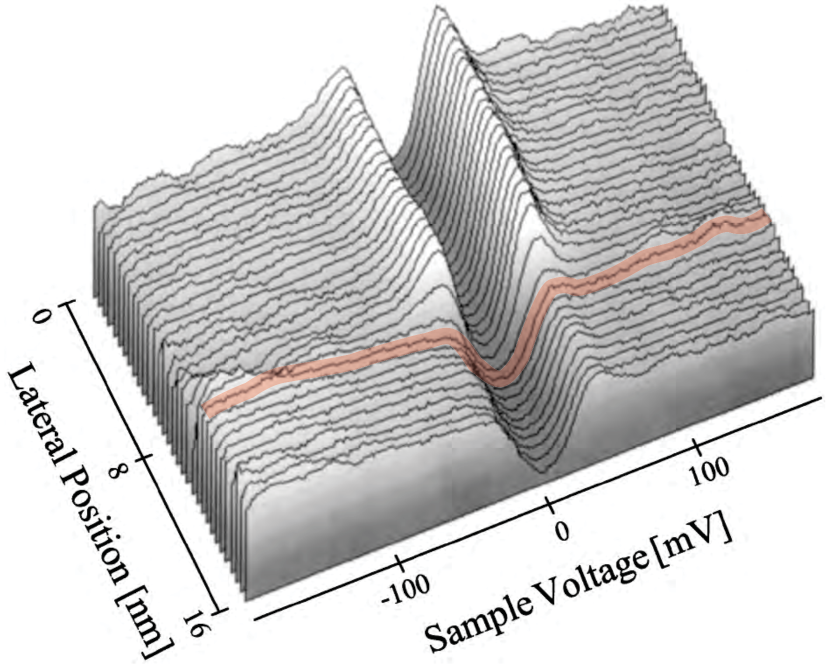
2) Inside vortices

3) In very underdoped and inhomogeneous samples

Pseudogap at low temperature

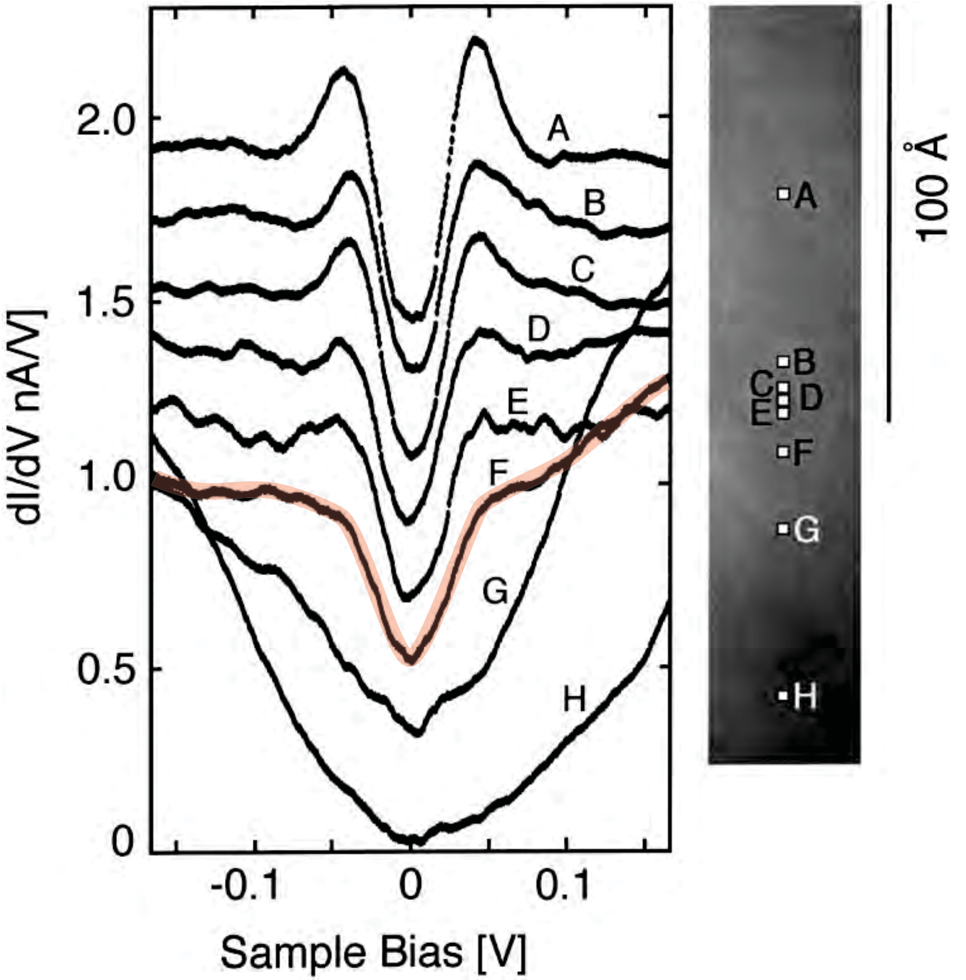
On structurally disordered or damaged surfaces

Bi-2212 films



Cren *et al.* (2000)

Underdoped Bi-2212 (80K)



Howald *et al.* (2001)

On disordered surfaces one observes sharp transitions to regions with pseudogap-like spectra over the scale of the coherence length (~10 Å)

Pseudogap at low temperature

The spectral signature of the pseudogap observed at $T < T_c$

1) On structurally disordered or damaged surfaces

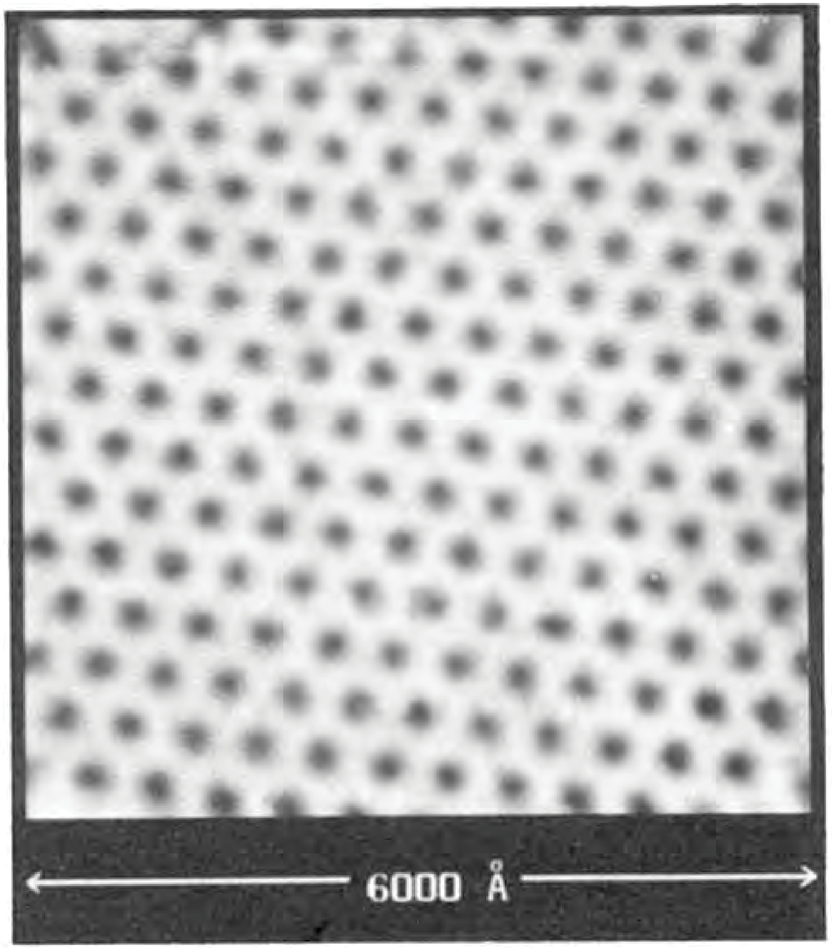
2) Inside vortices

3) In very underdoped and inhomogeneous samples

Pseudogap at low temperature

Vortices imaged by STM

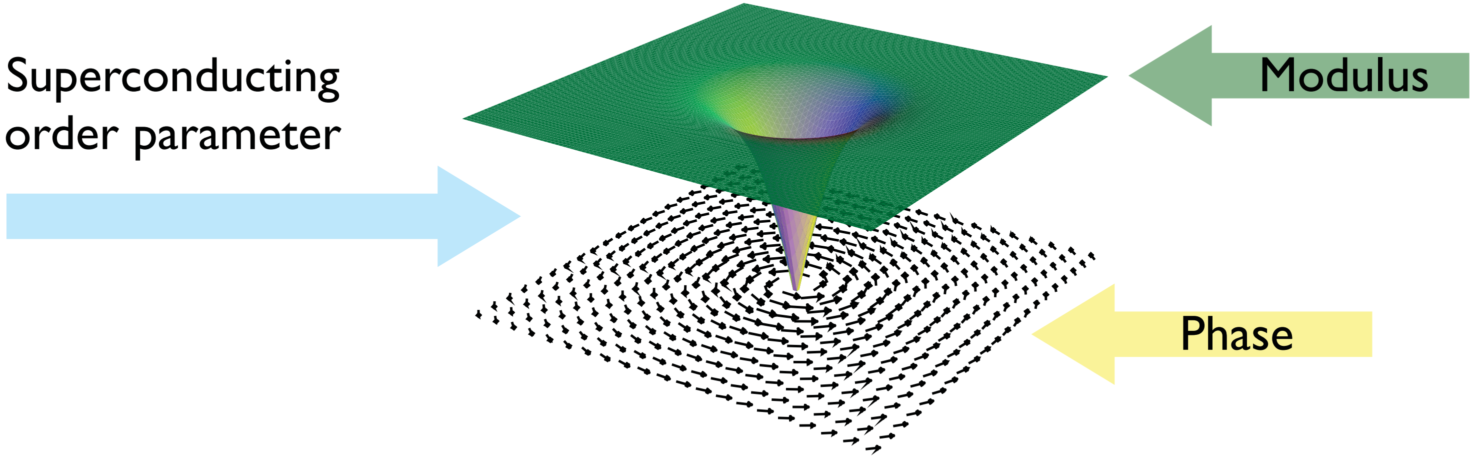
$NbSe_2$



Hess *et al.* (1989)

Pseudogap at low temperature

What is a vortex?

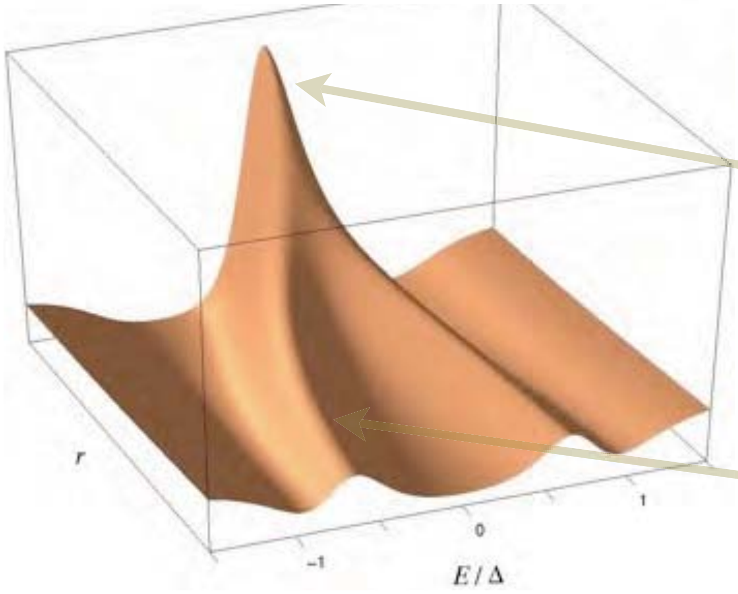


Superconducting order parameter

Modulus

Phase

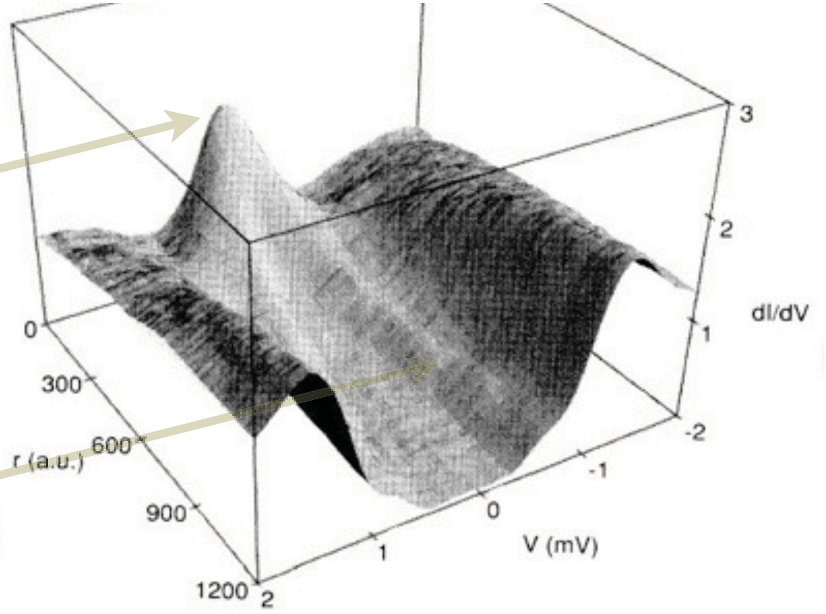
BCS prediction for LDOS



Vortex-core bound-states

Dispersion

STM observation in NbSe$_2$



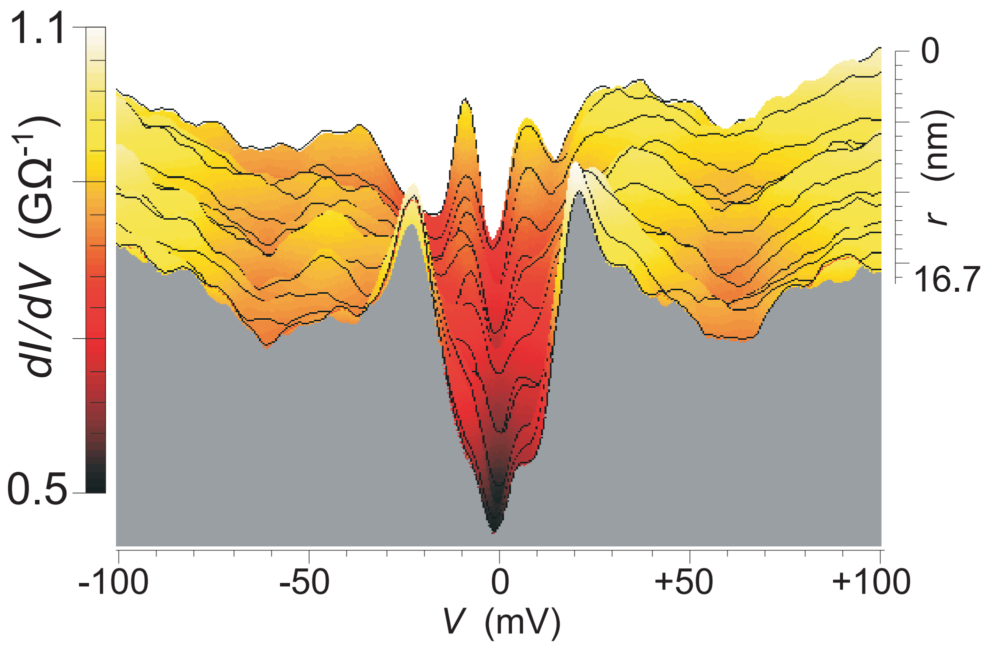
Caroli *et al.* (1964) Gygi *et al.* (1991)

Hess *et al.* (1989)

Pseudogap at low temperature

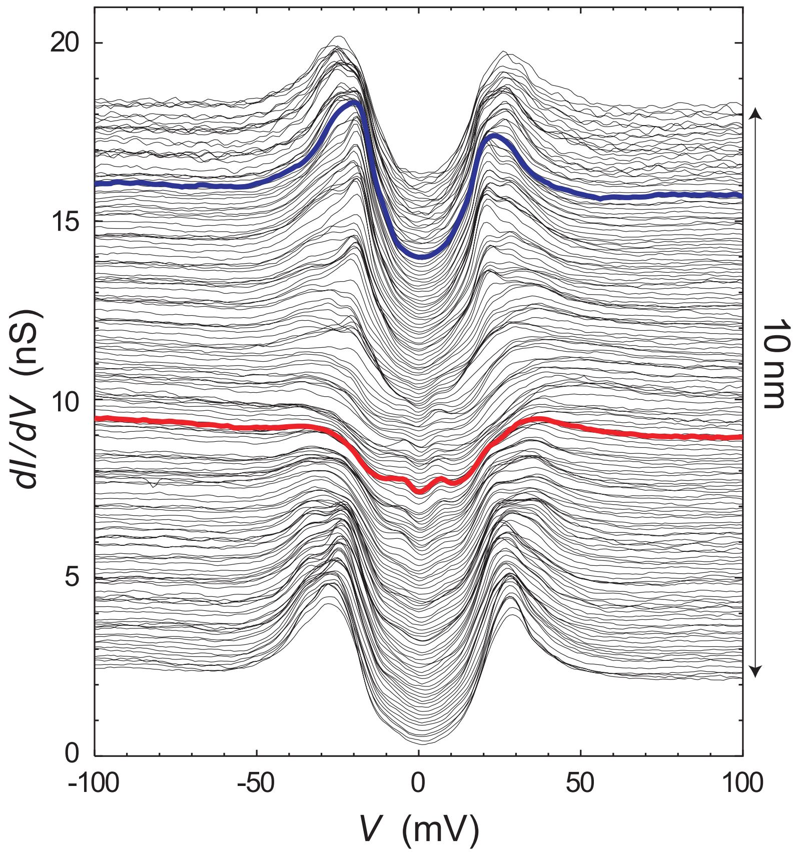
Phenomenology for the cuprates

Optimally-doped Y-123 (91K)



Maggio-Aprile *et al.* (1995)

Overdoped Bi-2212



Levy *et al.* (2005)

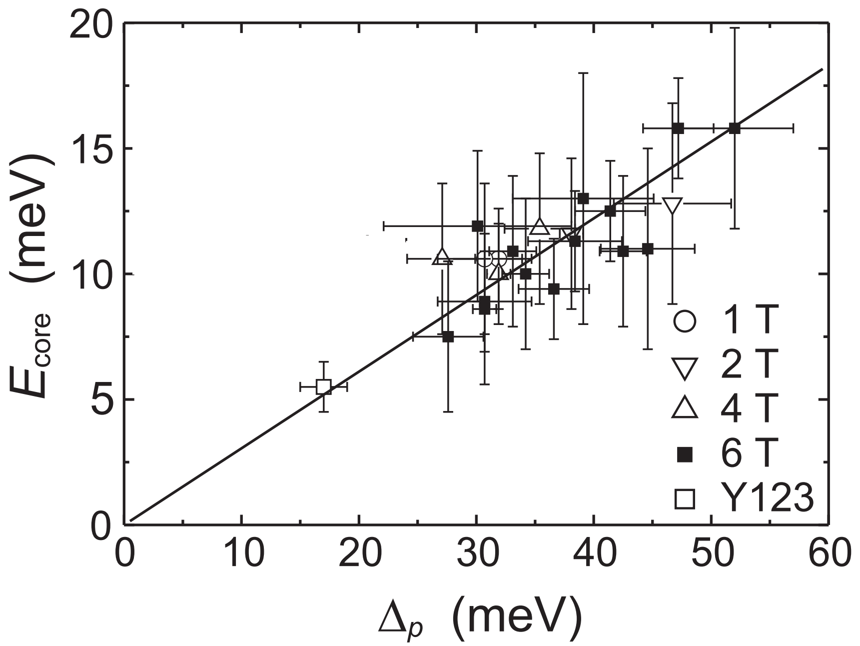
See also Renner *et al.* (1998)
Shibata *et al.* (2003)

See also Hoogenboom *et al.* (2000)
Pan *et al.* (2000)
Matsuba *et al.* (2003)

Pseudogap at low temperature

Vortex cores do not follow the BCS theory in the cuprates

- No zero-bias peak at the center of the core
- No spatial dispersion of the core-states peaks
- Linear rather than quadratic dependence of the core-state energy on Δ_p



Hoogenboom *et al.* (2001)

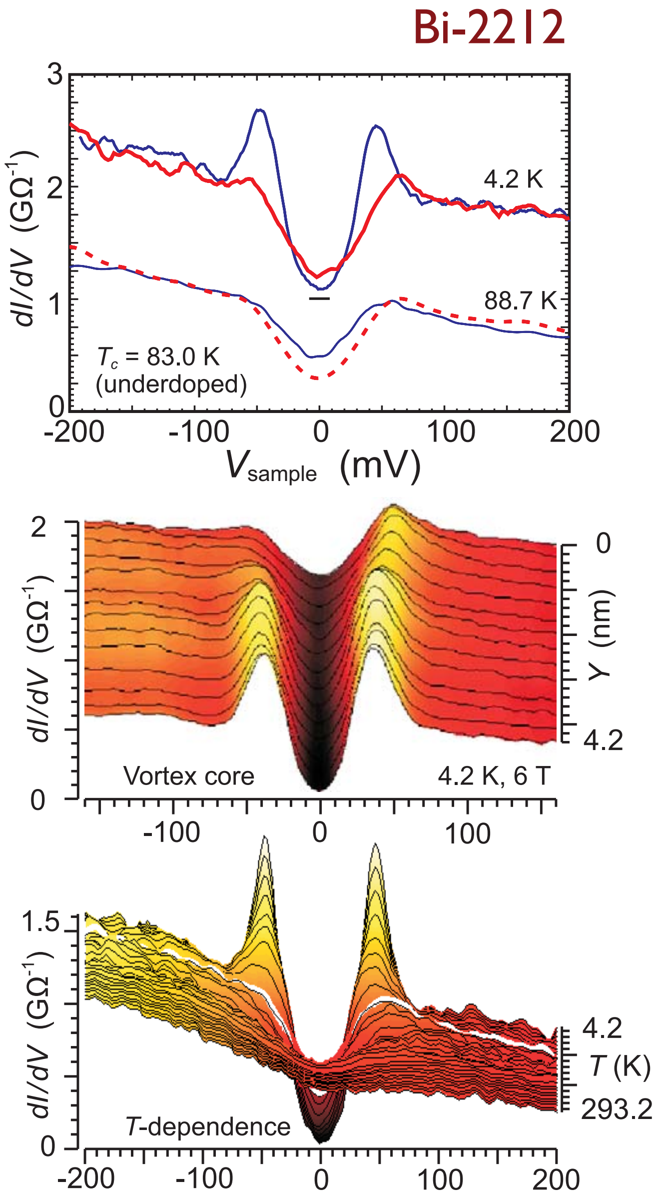
BCS *s*-wave vortex-core states: $E \propto \dfrac{\Delta^2}{E_F}$

Pseudogap at low temperature

A window on the pseudogap in the ground state?

- The vortex-core spectrum is very similar to the spectrum measured just above T_c

- The evolution of spectra when moving out of the vortex is similar to the evolution with increasing temperature



See also Beyer *et al.* (2009)

Renner *et al.* (1998)

Pseudogap at low temperature

The spectral signature of the pseudogap observed at $T < T_c$

1) On structurally disordered or damaged surfaces

2) Inside vortices

3) In very underdoped and inhomogeneous samples

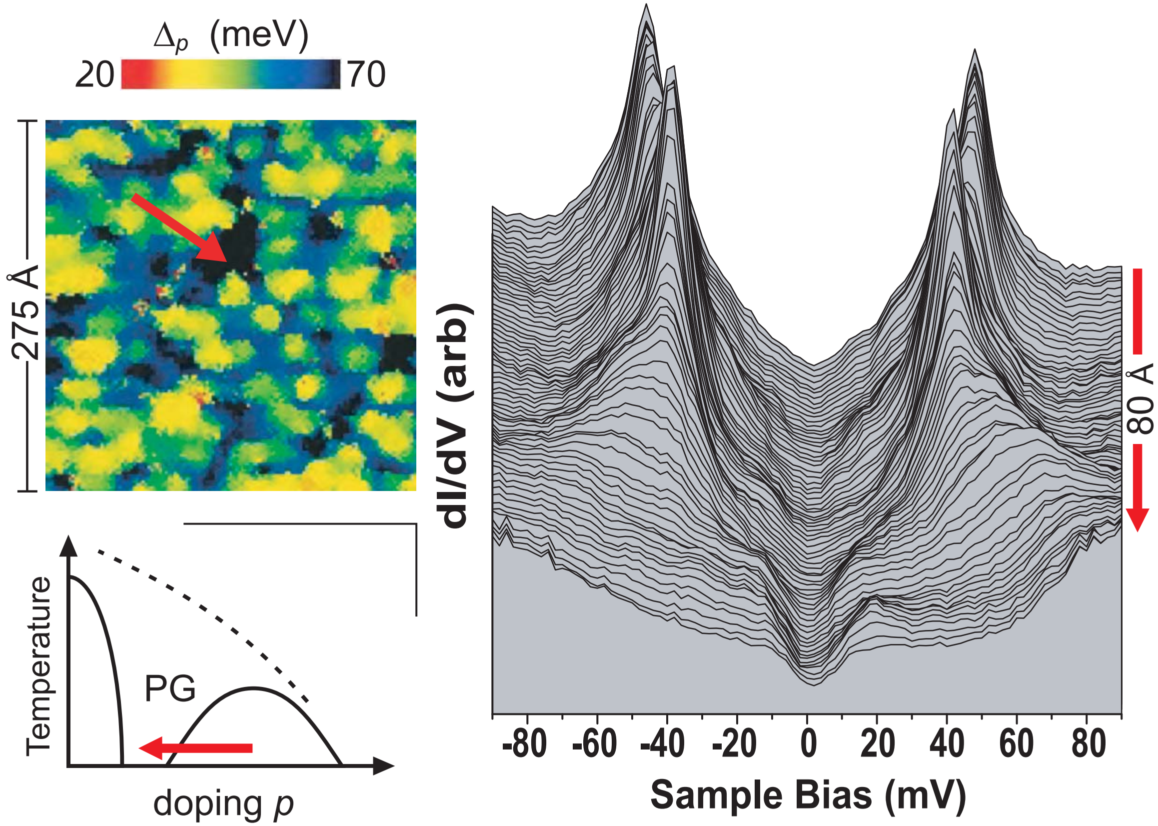
Pseudogap at low temperature

In heavily underdoped samples

In heavily underdoped Bi-2212 one can observe the transition from regions with smaller gap and coherence peaks to regions with larger gap and no coherence peaks.

Since the with of the gap changes, these transitions are suggestive of local variations of doping.

Underdoped Bi-2212



McElroy *et al.* (2004)

See also Hanaguri *et al.* (2004) ($Ca_{2-x}Na_xCuO_2Cl_2$)

Pseudogap at low temperature

Summary

- Spectra different from the typical superconducting ones can be observed close to $T = 0$
- On damaged surfaces and in vortex cores these spectra are similar to the pseudogap spectrum *at the same doping*
- In inhomogeneous Bi-2212, spectra with very large gaps (~80 meV) could be a signature of the heavily underdoped and non-superconducting phase

Contrasts between real-space and reciprocal-space phenomena

Real- and reciprocal-space physics

r space ↔ ***k*** space / high energy ↔ low energy / anti-nodal ↔ nodal

- Phenomenology suggestive of quasi-particles in ***k***-space
  1) Homogeneity of low-energy (nodal) excitations
  2) Quasi-particle interference patterns
  3) Strong-coupling effects

- Phenomenology suggestive of localization in ***r***-space
  1) Inhomogeneity of high-energy excitations
  2) Non-dispersive (energy-independent) 4 × 4 modulation
  3) Modulation in the vortex core
  4) Asymmetry of background conductance, and possible breaking of spatial symmetries

Real- and reciprocal-space physics

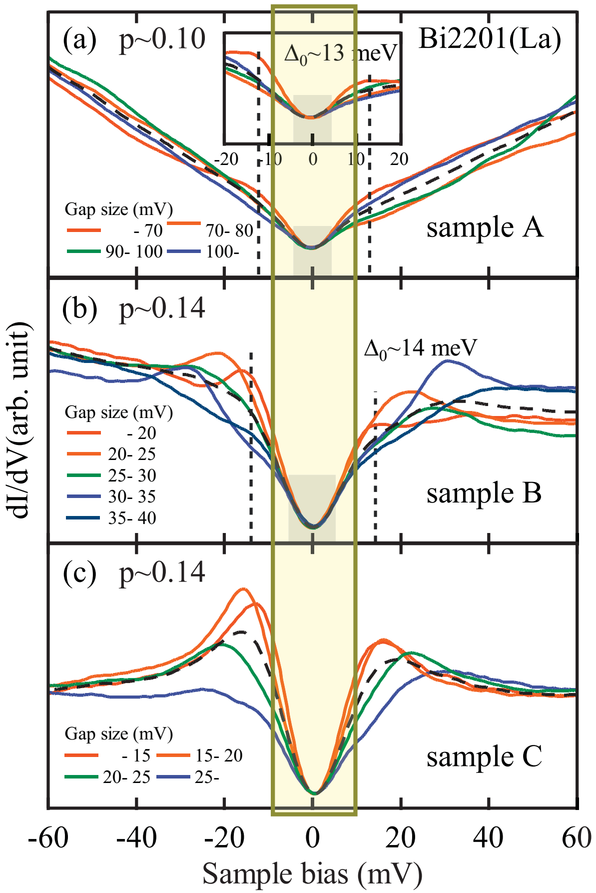
r space ↔ ***k*** space / high energy ↔ low energy / anti-nodal ↔ nodal

- Phenomenology suggestive of quasi-particles in ***k***-space
  1) Homogeneity of low-energy (nodal) excitations

Quasi-particles in ***k***-space

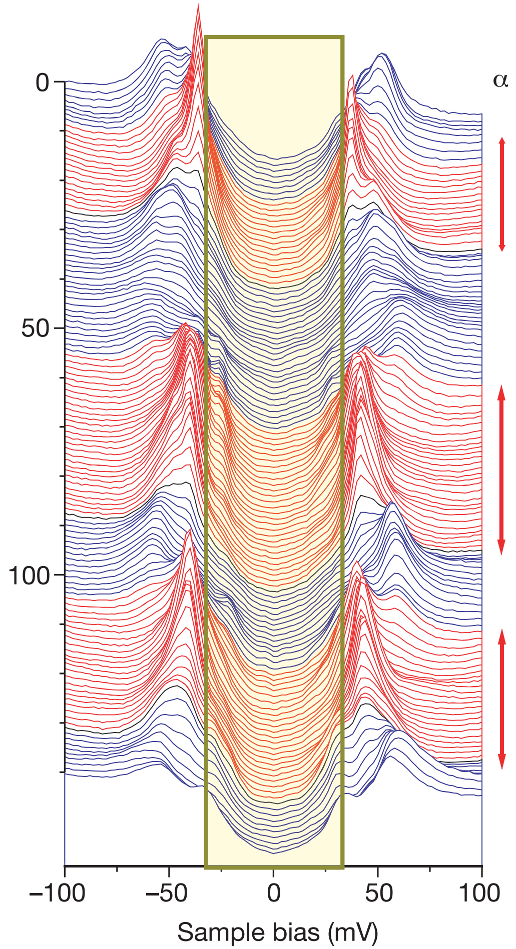
The cuprates are less inhomogeneous at low energy

Bi-2201



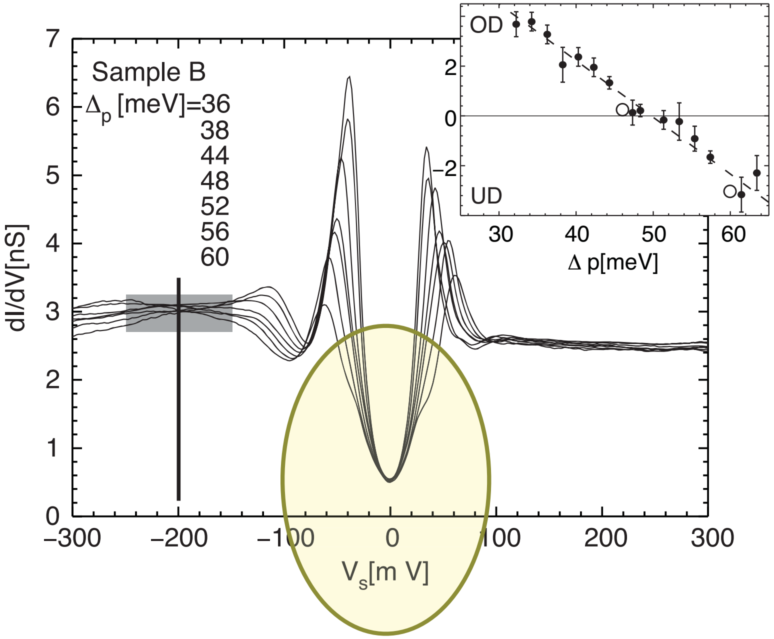
Kurosawa *et al.* (2010)

Bi-2212 (79K)



Lang *et al.* (2002)

Bi-2223



Kugler *et al.* (2006)

The low-energy (nodal) excitations are homogeneous

Real- and reciprocal-space physics

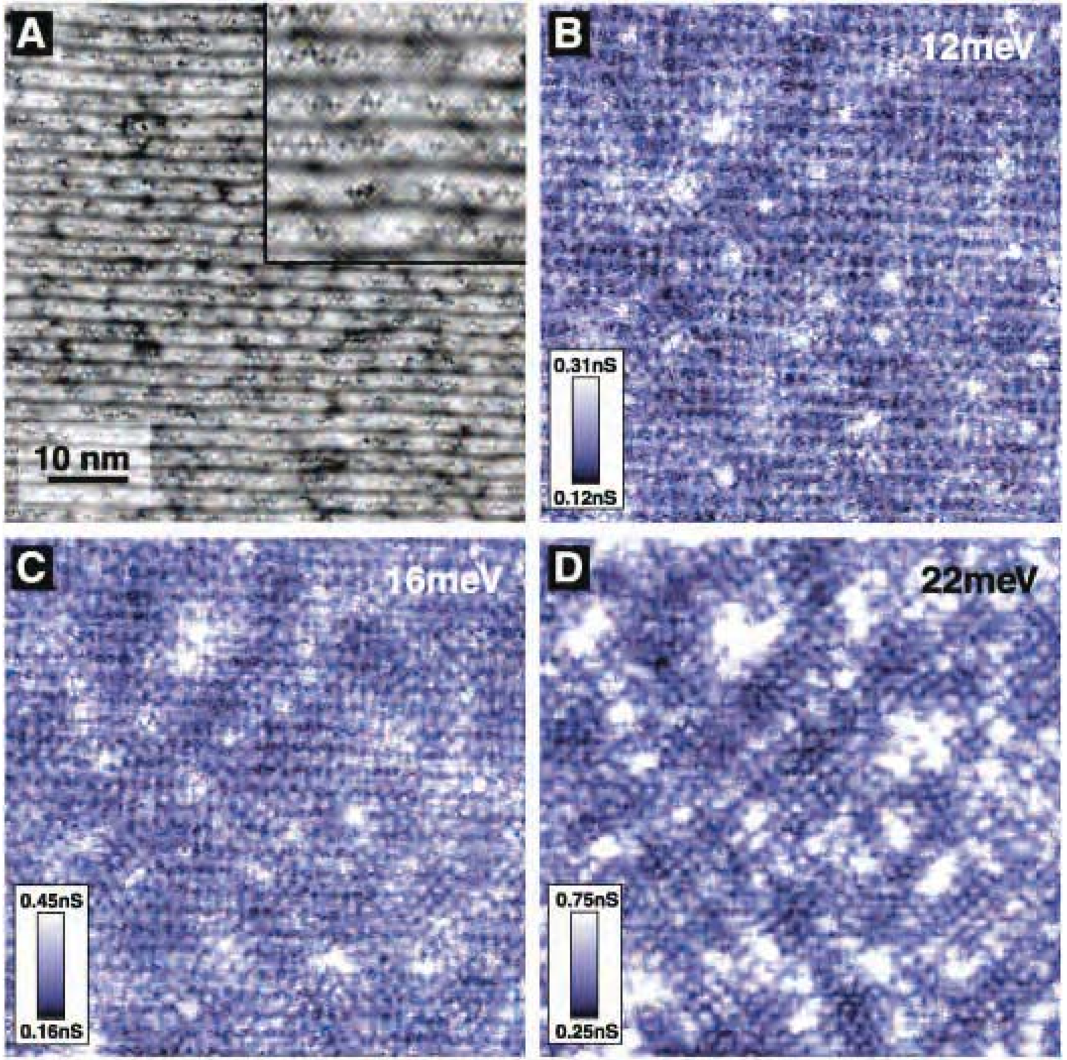
r space ↔ ***k*** space / high energy ↔ low energy / anti-nodal ↔ nodal

- Phenomenology suggestive of quasi-particles in ***k***-space
  1) Homogeneity of low-energy (nodal) excitations
  2) Quasi-particle interference patterns

Quasi-particles in ***k***-space

Quasi-particle interference patterns

Underdoped Bi-2212 (78K)



Hoffman *et al.* (2002)

Quasi-particles in *k*-space

Interpretation of interference patterns

Fourier transform of LDOS in case of weak impurity scattering

Peak at $\omega = E_{\boldsymbol{k}}$

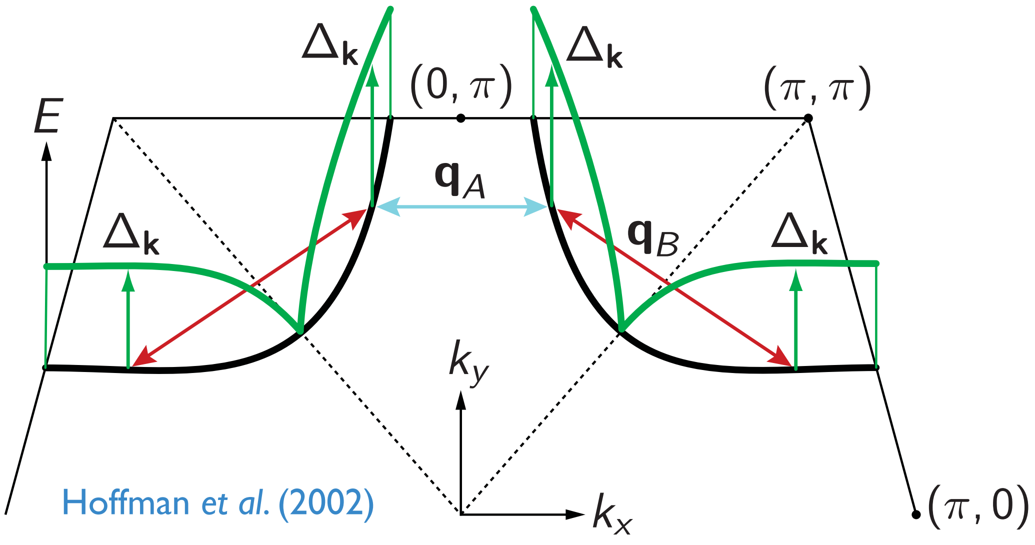
Peak at $\omega = E_{\boldsymbol{k}-\boldsymbol{q}}$

$$\delta N(\boldsymbol{q},\omega) \propto \sum_{\boldsymbol{k}} G(\boldsymbol{k},\omega)\, G(\boldsymbol{k}-\boldsymbol{q},\omega)$$

Peak at

$$\omega = E_{\boldsymbol{k}} = E_{\boldsymbol{k}-\boldsymbol{q}}$$

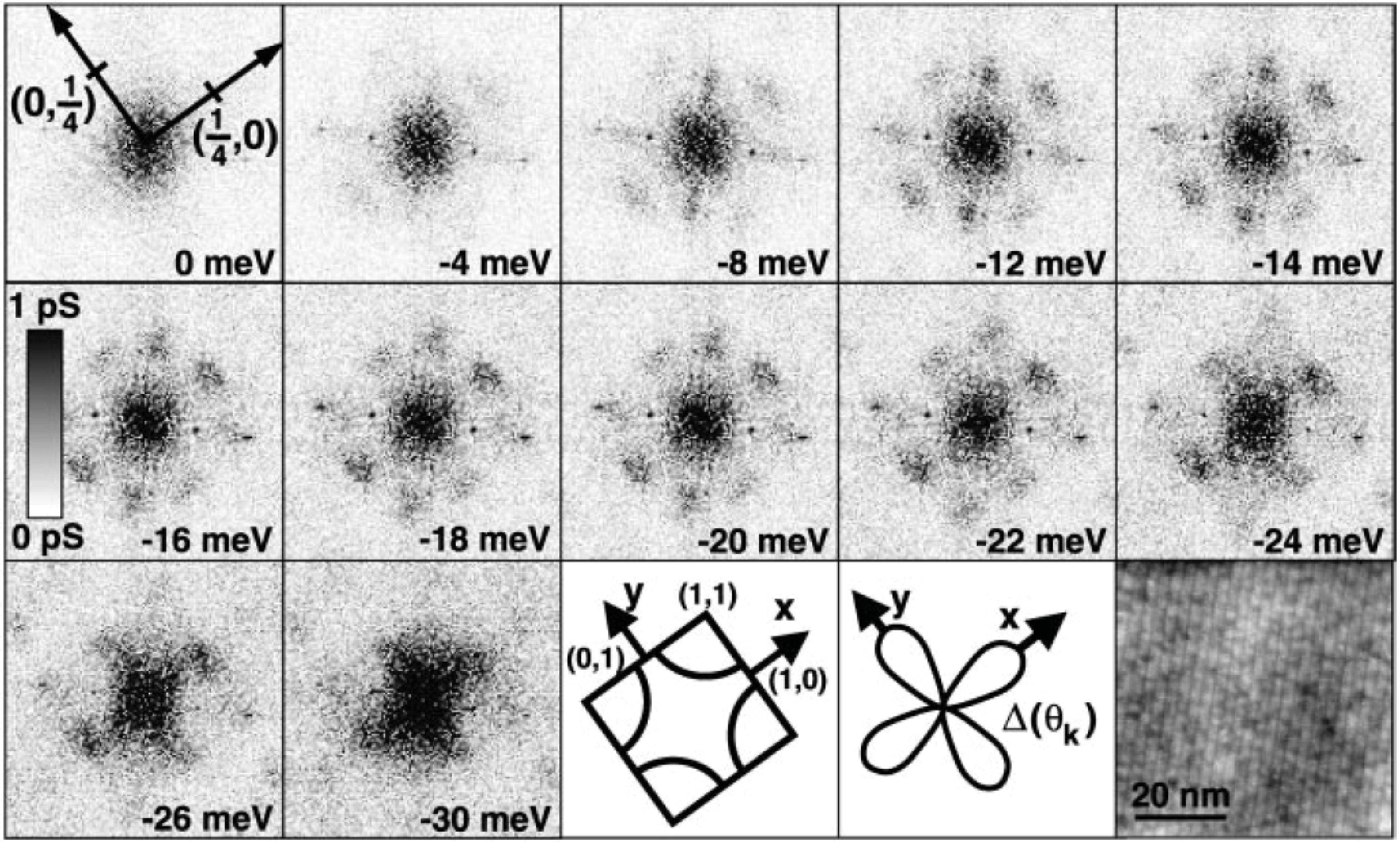
BCS: $E_{\boldsymbol{k}} = \sqrt{\xi_{\boldsymbol{k}}^2 + \Delta_{\boldsymbol{k}}^2}$



Hoffman *et al.* (2002)

Quasi-particles in ***k***-space

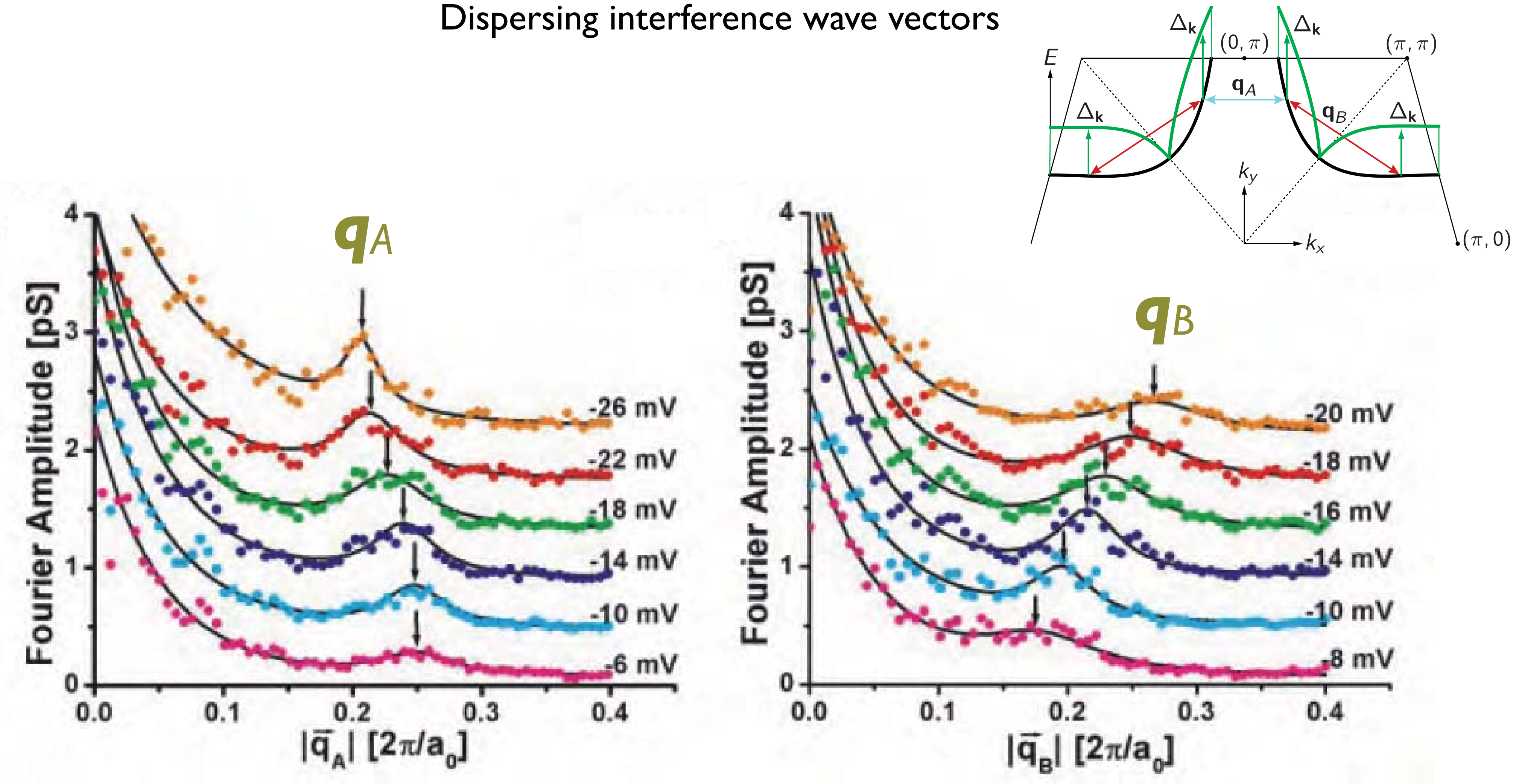
Fourier transform of conductance maps



Hoffman *et al.* (2002)

Quasi-particles in ***k***-space

Dispersing interference wave vectors

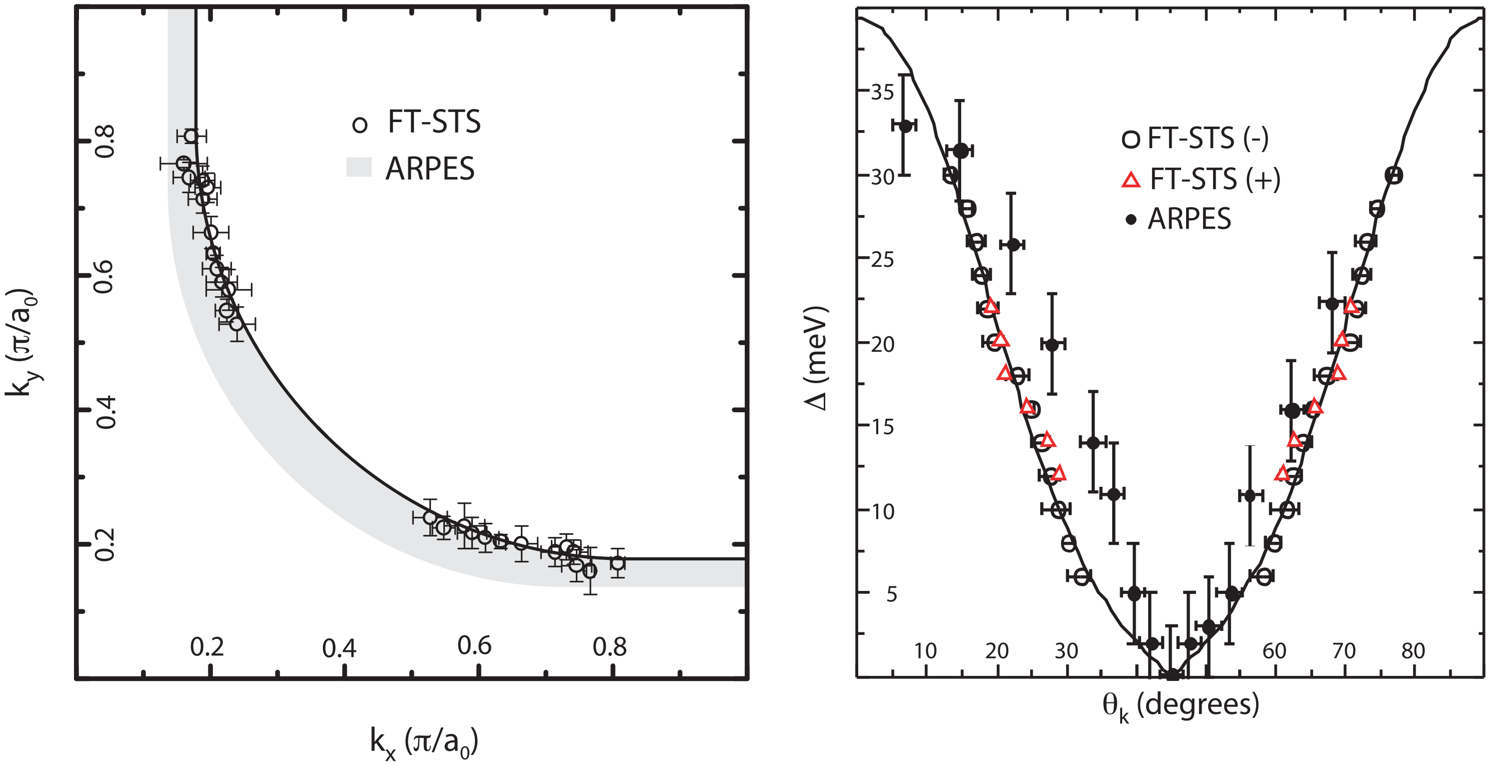


Hoffman *et al.* (2002)

The peaks in the Fourier transformed conductance maps disperse with energy as expected

Quasi-particles in ***k***-space

Reciprocal-space properties recovered from real-space spectroscopy



McElroy *et al.* (2003)

The Fermi surface and the gap function $\Delta_{\boldsymbol{k}}$ can be reconstructed from dispersing interferences, and agree with photoemission data

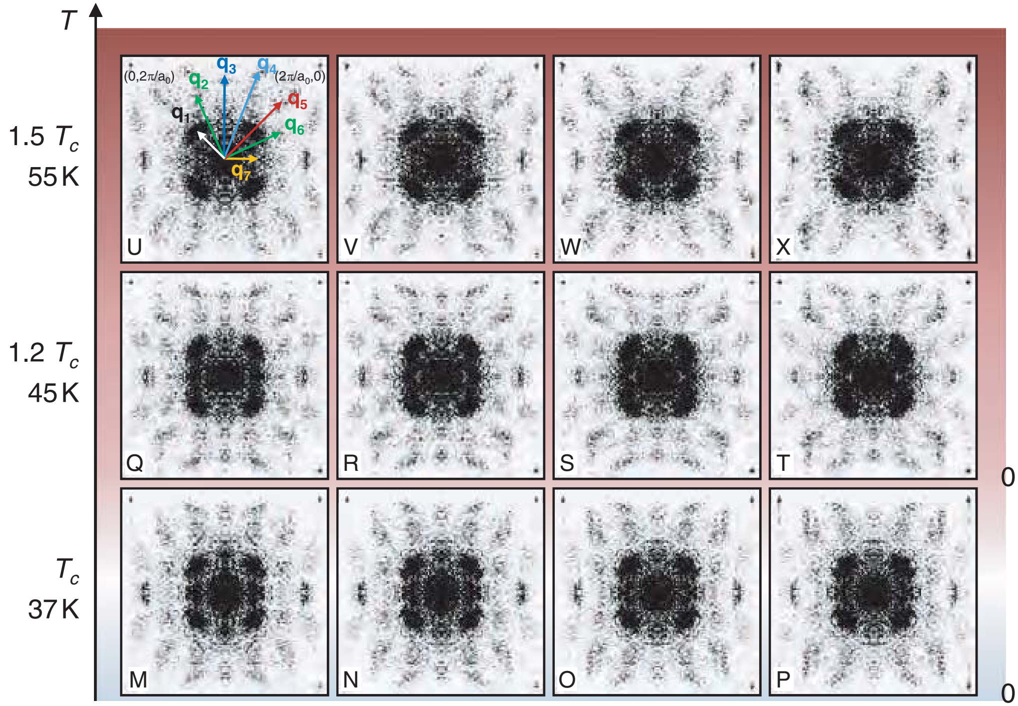
Also seen in $Ca_{2-x}Na_xCuO_2Cl_2$

Hanaguri *et al.* (2007)

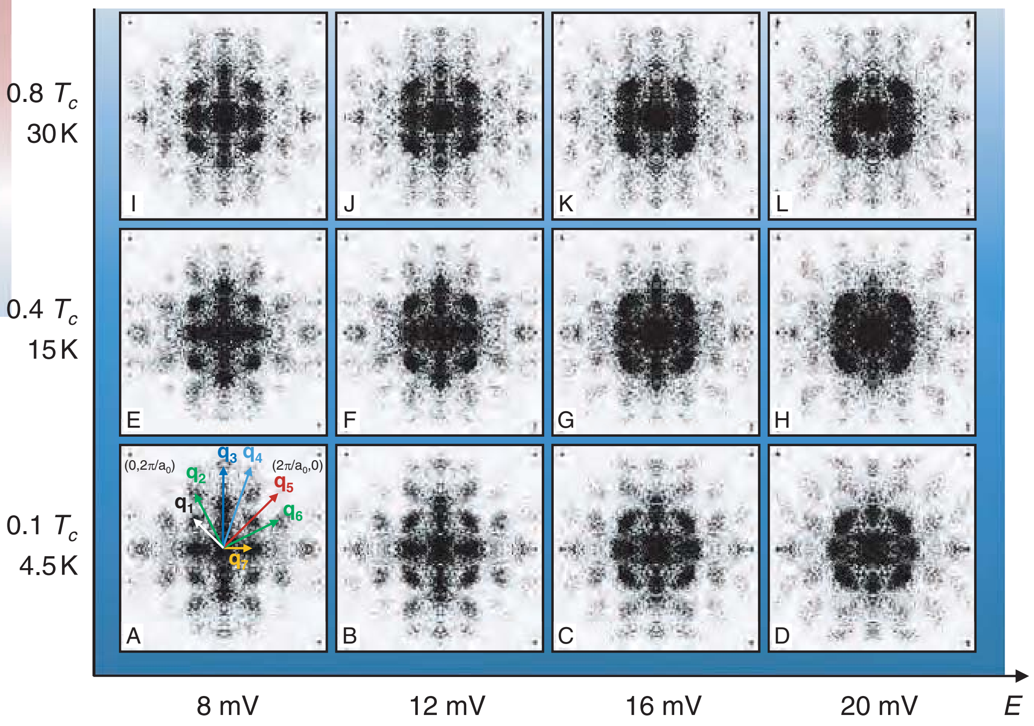
Quasi-particles in ***k***-space

Also present above T_c

Underdoped Bi-2212 (37K)



Lee *et al.* (2009)

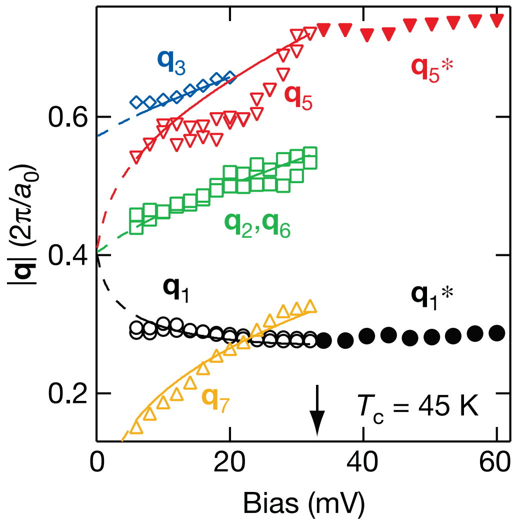


No qualitative change is observed in the quasi-particle interference patterns on crossing T_c

Quasi-particles in ***k***-space

Additional observations

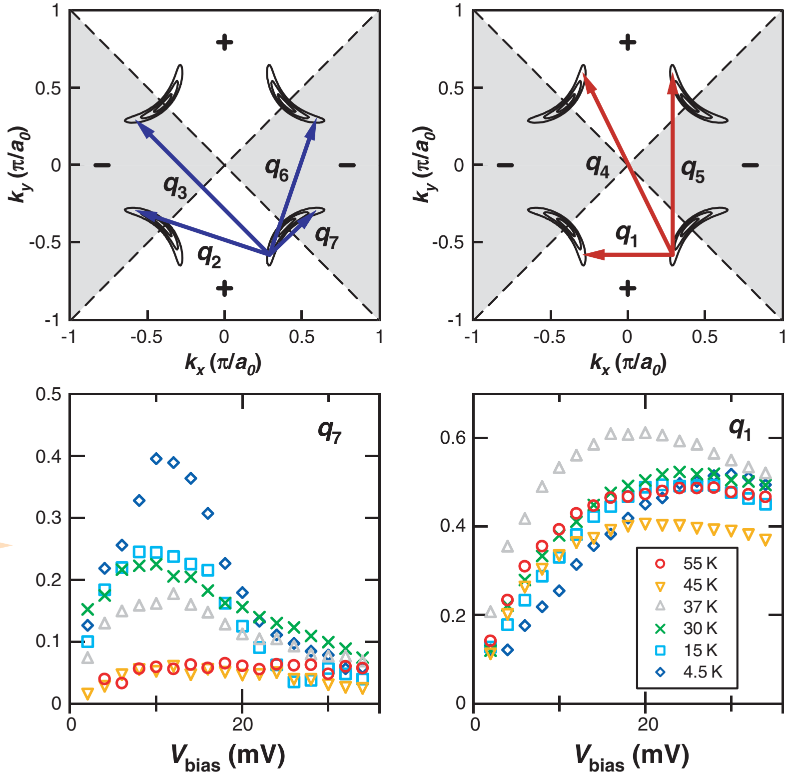
- The dispersing interferences are not observed at energies where the LDOS is inhomogeneous



Kohsaka *et al.* (2008)

- The intensity has a maximum at low energy

- The amplitude for scattering between momenta with equal or opposite sign of the gap have different *T*-dependencies



Lee *et al.* (2009)

Real- and reciprocal-space physics

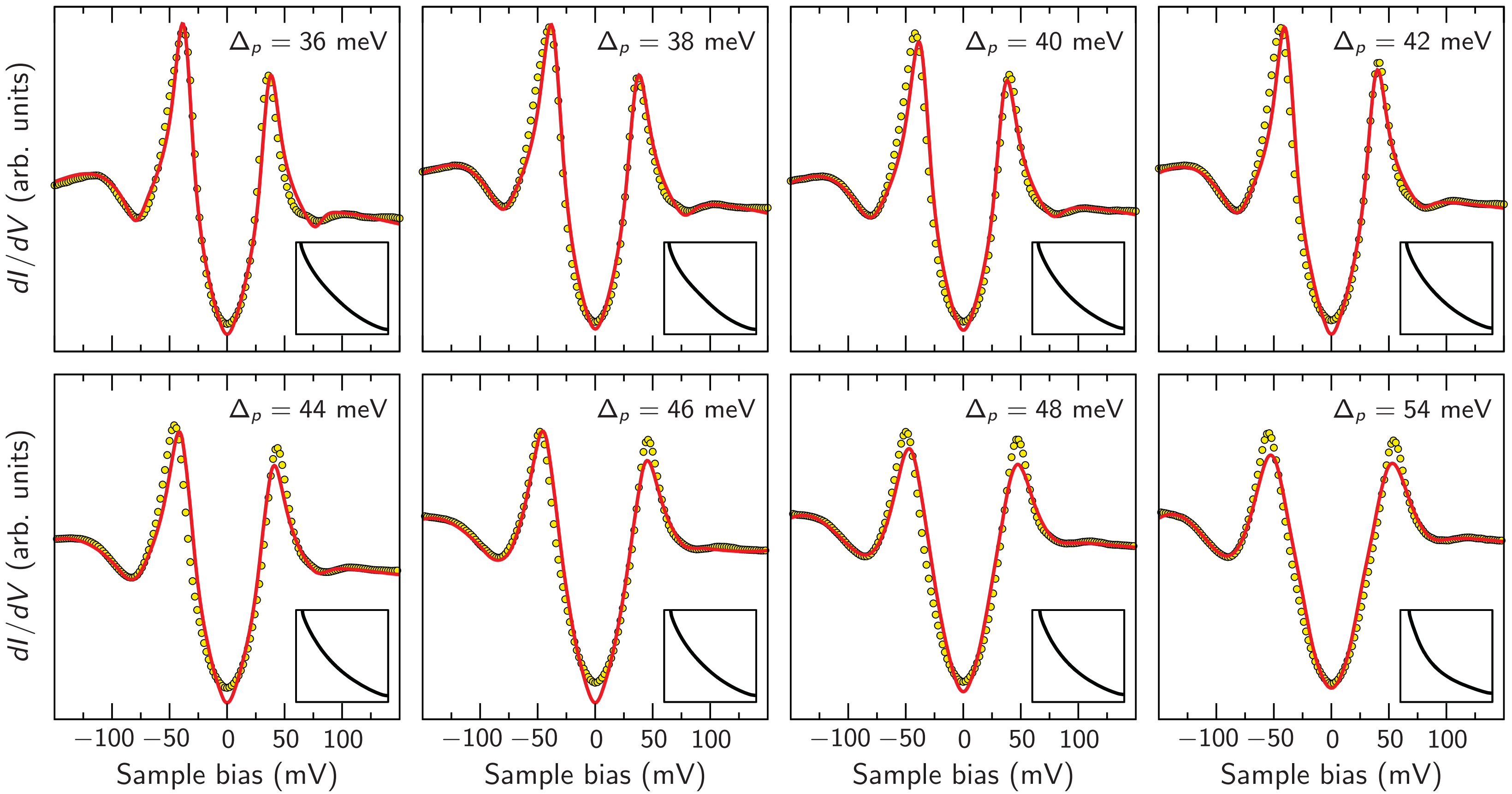
r space ↔ ***k*** space / high energy ↔ low energy / anti-nodal ↔ nodal

- Phenomenology suggestive of quasi-particles in ***k***-space
    1) Homogeneity of low-energy (nodal) excitations
    2) Quasi-particle interference patterns
    3) Strong-coupling effects

Quasi-particles in ***k***-space

The dip feature can be explained by the interaction with the (π, π) resonance

Optimally-doped Bi-2223 (111K)



Fasano *et al.* (to be published)

Model

5-parameters band structure
+
BCS *d*-wave gap
+
Coupling to spin resonance

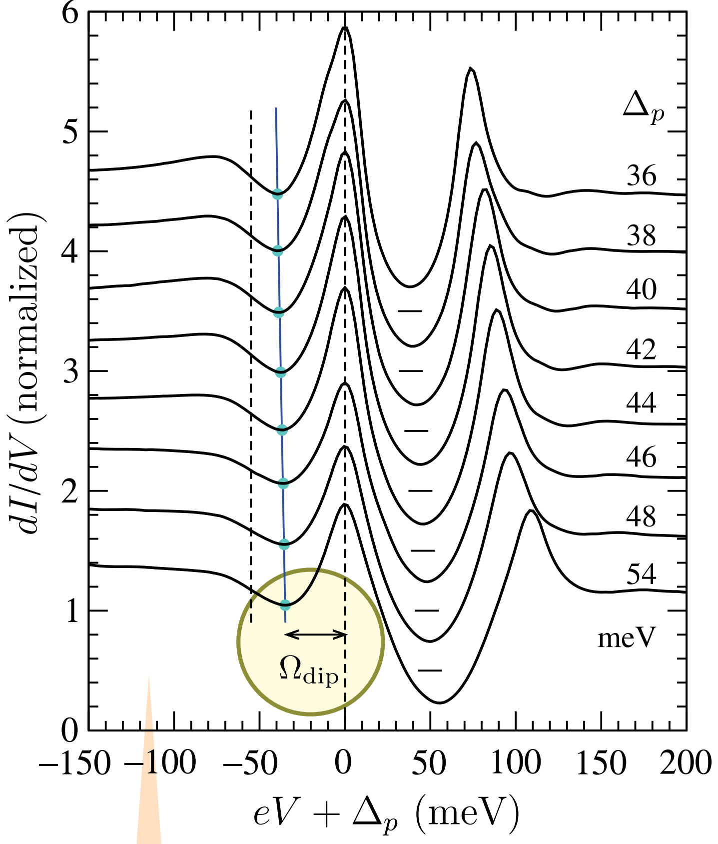
Eschrig *et al.* (2000)

○○○○○○○○ STM data
— Model
— Fermi surface

Quasi-particles in ***k***-space

The dip feature and the gap Δ_p

Optimally-doped Bi-2223 (111K)

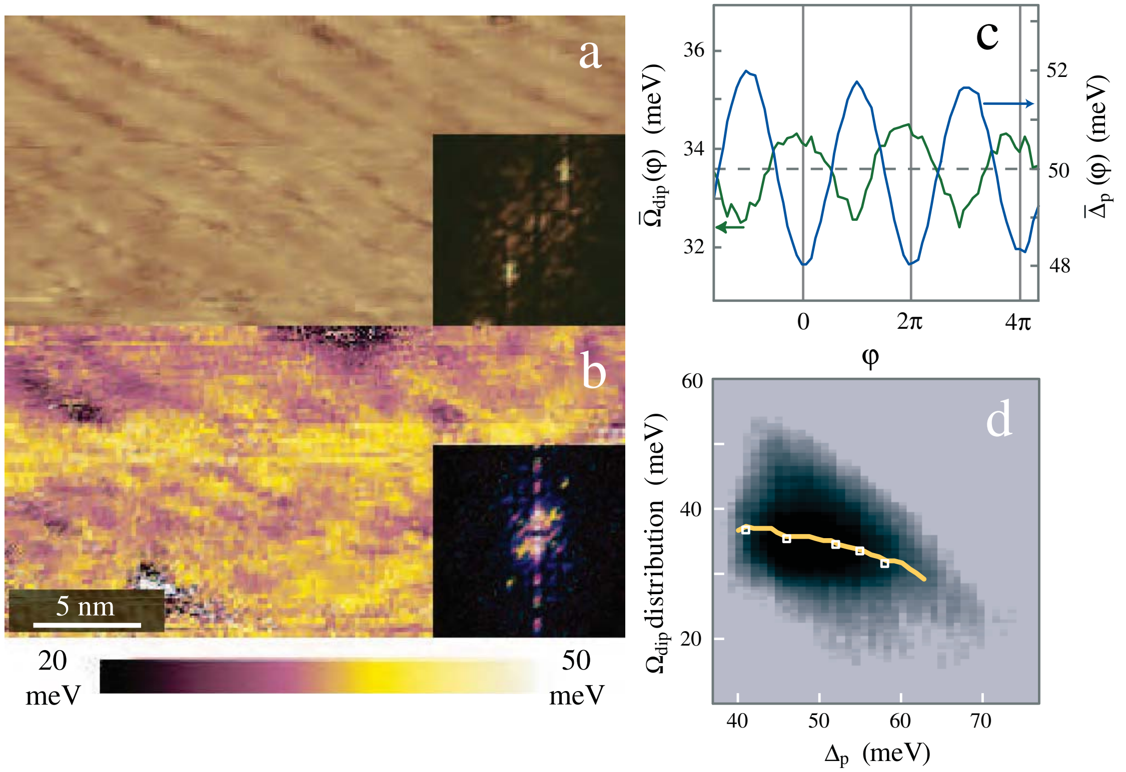


Levy *et al.* (2008)

- The characteristic energy of the dip feature decreases as Δ_p increases

- This anti-correlation is also verified *locally*

Optimally-doped Bi-2223 (111K)



Jenkins *et al.* (2009)

Real- and reciprocal-space physics

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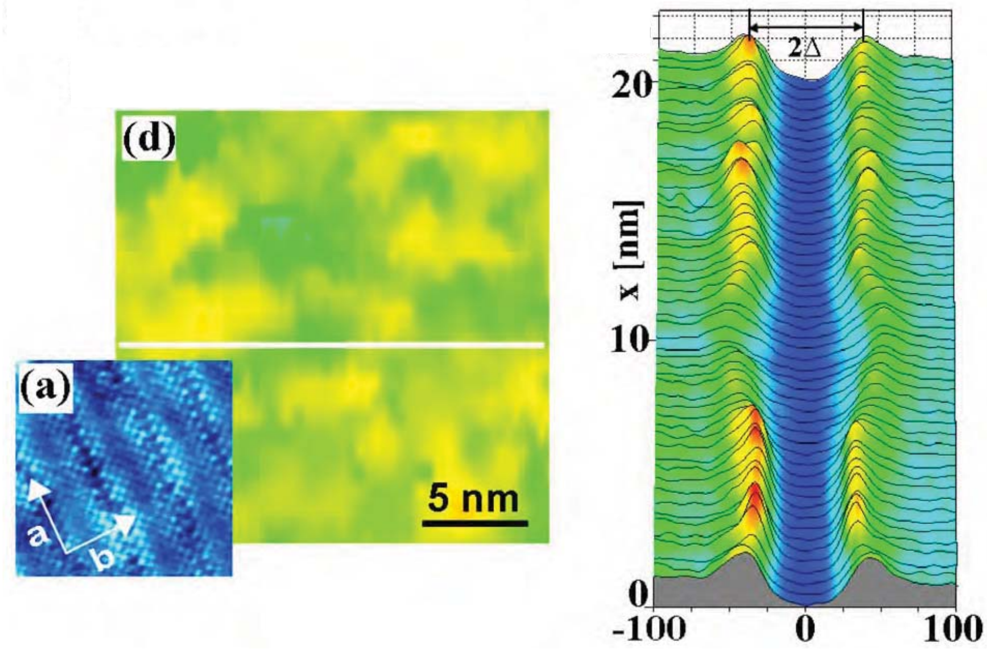
- Phenomenology suggestive of quasi-particles in ***k***-space
  1) Homogeneity of low-energy (nodal) excitations
  2) Quasi-particle interference patterns
  3) Strong-coupling effects
- Phenomenology suggestive of localization in ***r***-space
  1) Inhomogeneity of high-energy excitations

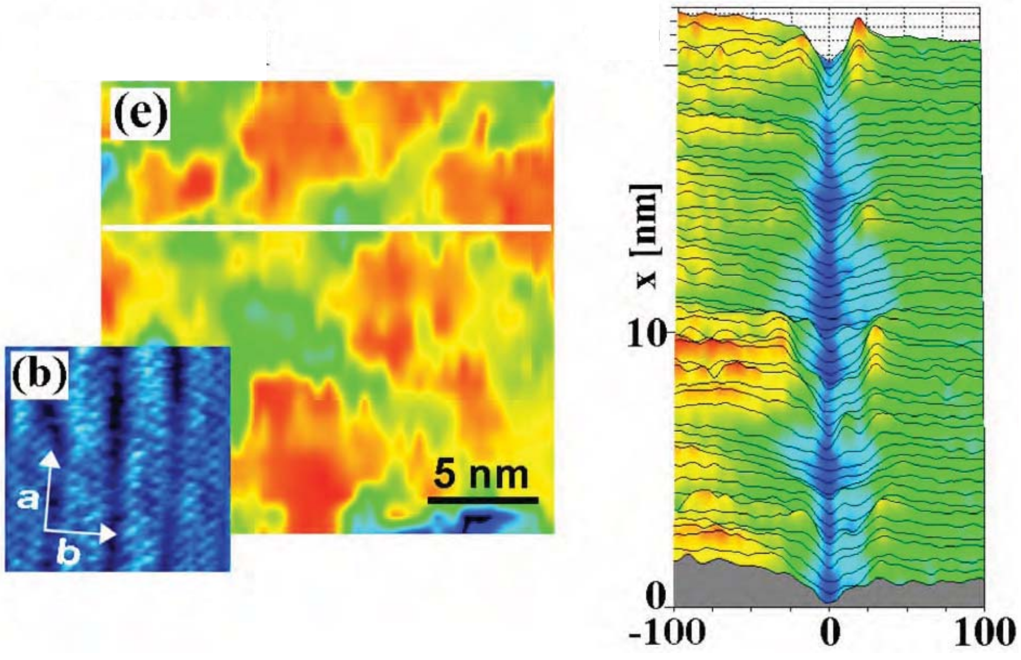
Localization in ***r***-space

Inhomogeneity at the energy-gap scale

Optimally-doped Bi-2212 (93K)



La-doped Bi-2201 (34K)



Sugimoto *et al.* (2006)

Real- and reciprocal-space physics

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  2) Quasi-particle interference patterns
  3) Strong-coupling effects

- Phenomenology suggestive of localization in ***r***-space
  1) Inhomogeneity of high-energy excitations
  2) Non-dispersive (energy-independent) 4 × 4 modulation

Localization in ***r***-space

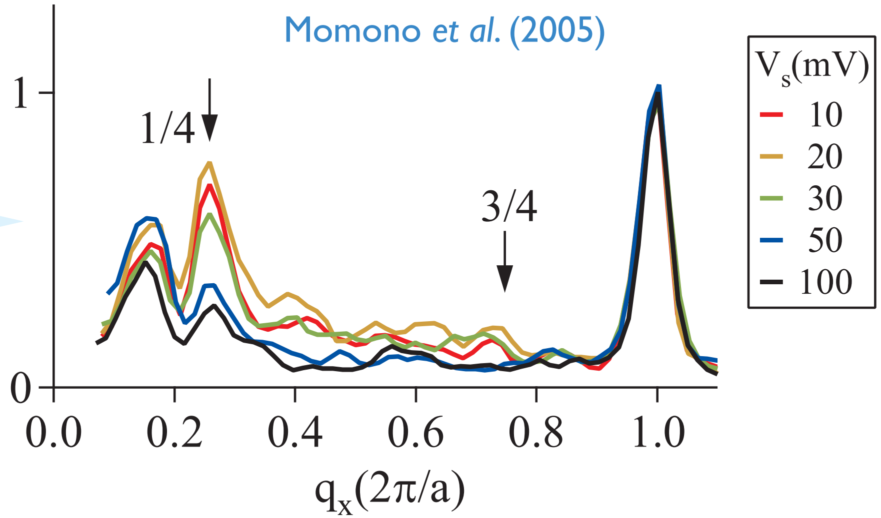
Non-dispersive modulation with ~4*a* period

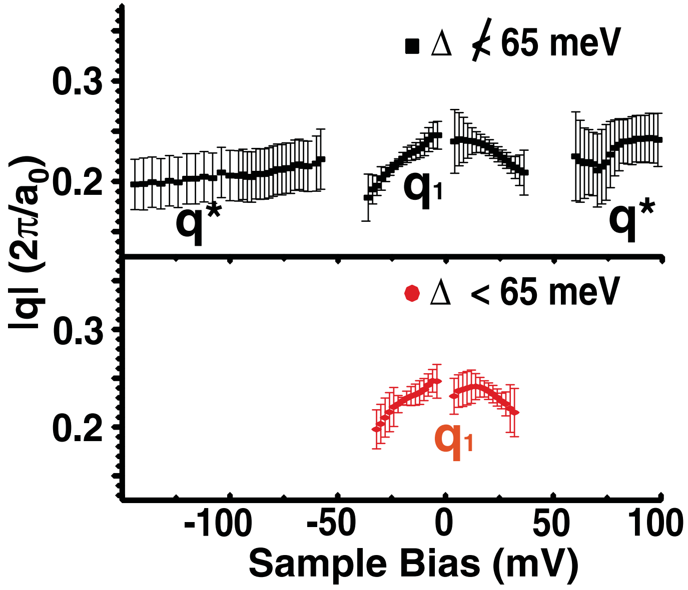
- A non-dispersing 4 × 4 modulation is also observed, different from the quasi-particle interferences

- It is strongest in spatial regions having a large gap

- It becomes more intense with decreasing doping   Hashimoto *et al.* (2006)

Underdoped Bi-2212 (72K)





See also   Howald *et al.* (2003)

McElroy *et al.* (2005)

Localization in ***r*-space**

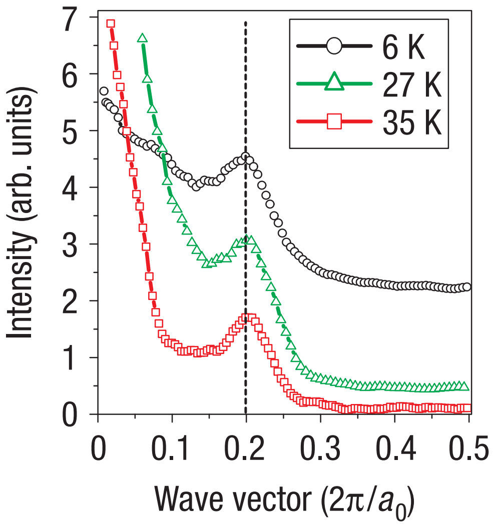
Non-dispersive modulation with ~4*a* period

- The modulation is present above T_c

Vershinin *et al.* (2004)

- The modulation period is temperature independent

Underdoped Bi-2201 (32K)

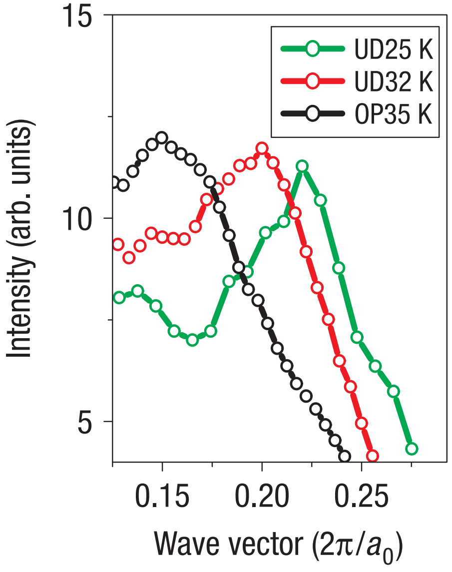


Wise *et al.* (2008)

- The period appears doping dependent in Bi-2201…

- …but not in Bi-2212

Takeyama *et al.* (2007)



Real- and reciprocal-space physics

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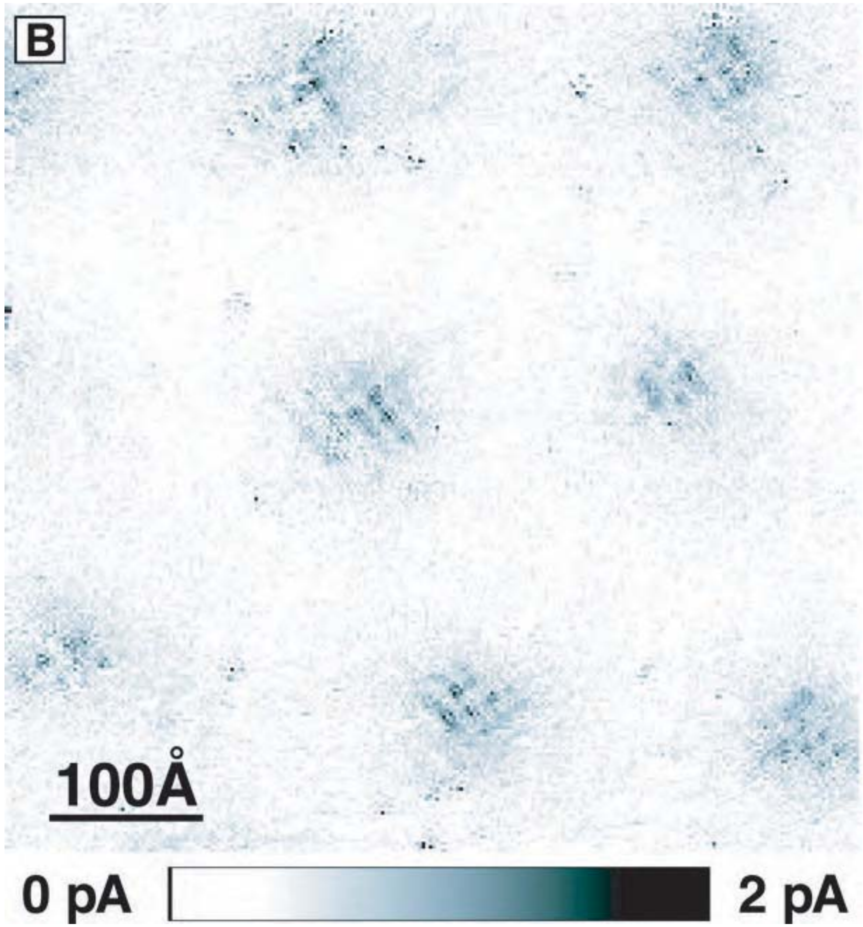
    3) Strong-coupling effects
- Phenomenology suggestive of localization in ***r***-space
    1) Inhomogeneity of high-energy excitations
    2) Non-dispersive (energy-independent) 4 × 4 modulation
    3) Modulation in the vortex core

Localization in ***r***-space

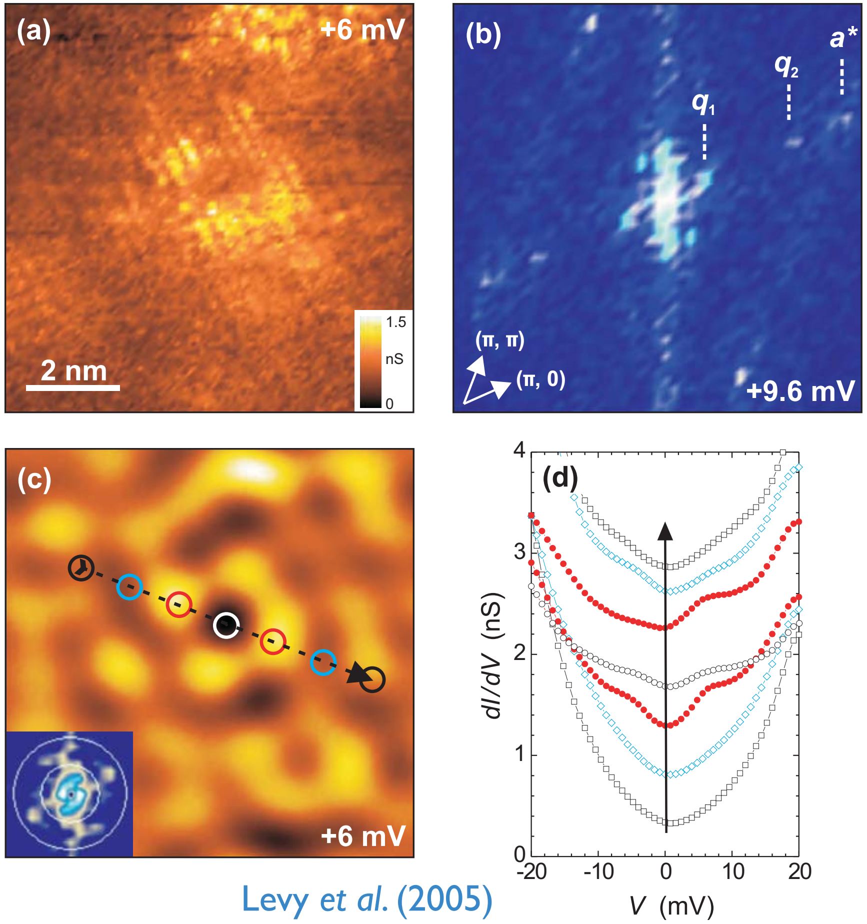
The non-dispersive ~4*a* modulation is enhanced in vortex cores

Overdoped Bi-2212 (89K)

Overdoped Bi-2212 (88K)



Hoffman *et al.* (2002)



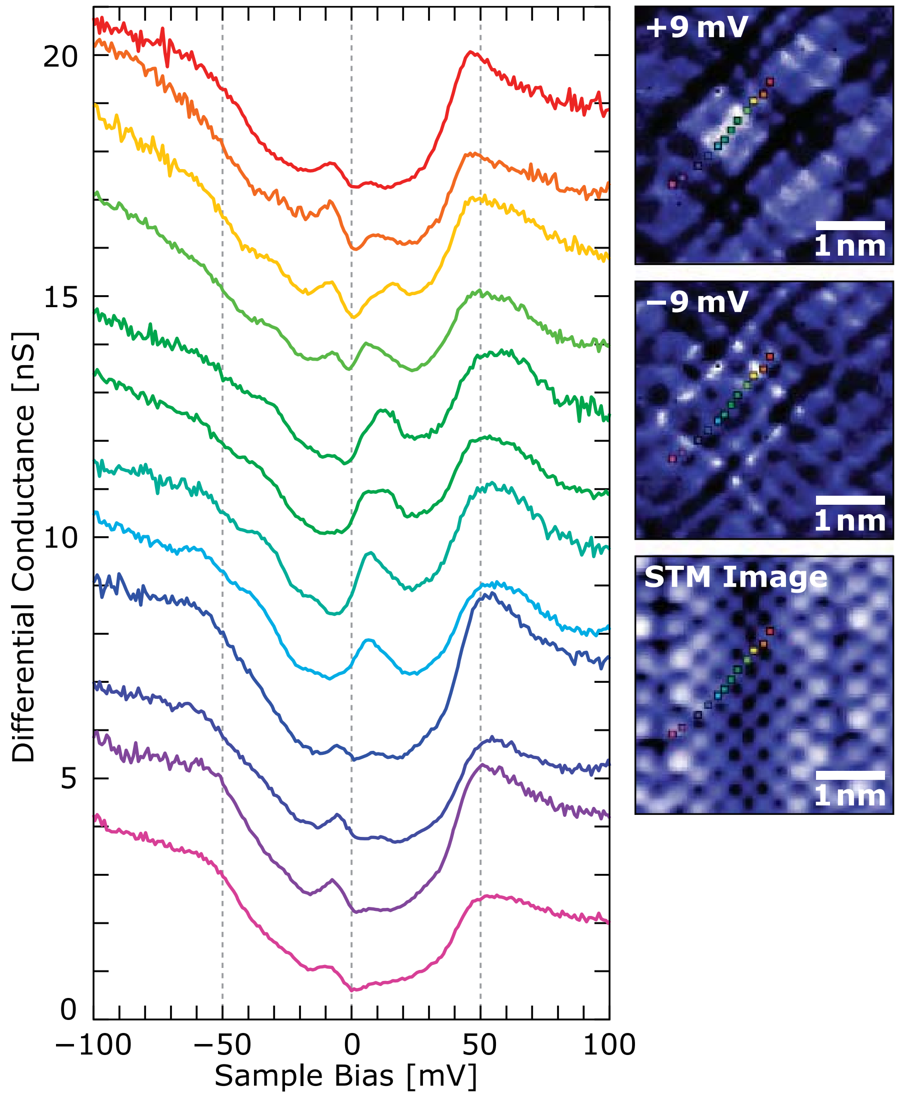
Levy *et al.* (2005)

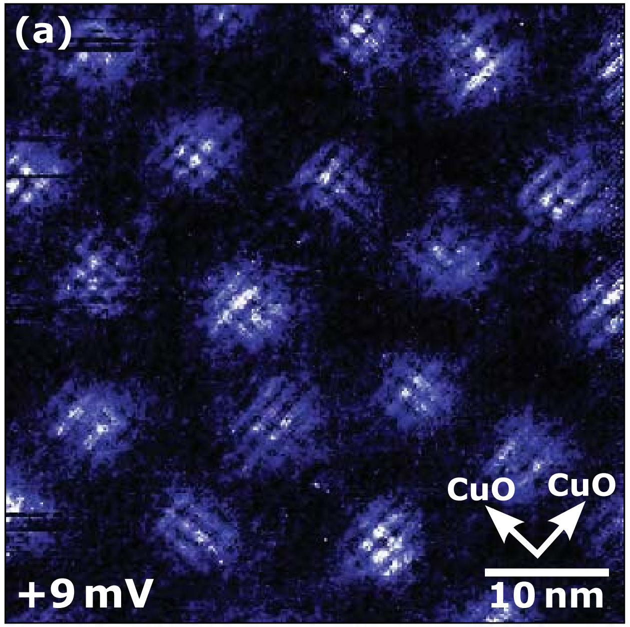
The modulation corresponds spatially and energetically to the vortex-core states

Localization in ***r***-space

4 × 4 modulation in the vortex core: there is more...

Overdoped Bi-2212 (86K)





Matsuba *et al.* (2007)

The particle-hole symmetry and the four-fold lattice symmetry might be broken in the vortex core

See also Beyer *et al.* (2009)

Real- and reciprocal-space physics

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  3) Strong-coupling effects
- Phenomenology suggestive of localization in ***r***-space
  1) Inhomogeneity of high-energy excitations
  2) Non-dispersive (energy-independent) 4 × 4 modulation
  3) Modulation in the vortex core
  4) Asymmetry of background conductance, and possible breaking of spatial symmetries

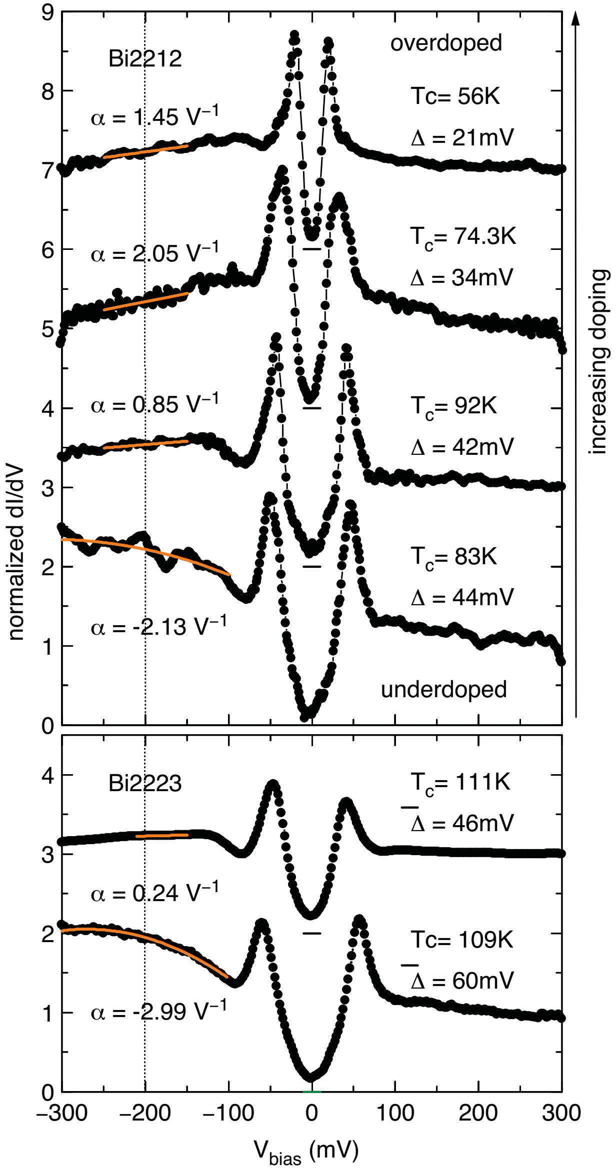
Electron-hole asymmetry

The background conductance is not particle-hole symmetric

- There is a general tendency for the background conductance to be more asymmetric when the gap is larger

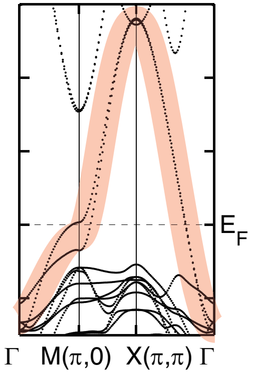
- The asymmetry is (almost) always in favor of negative bias (occupied states)

Kugler *et al.* (2006)



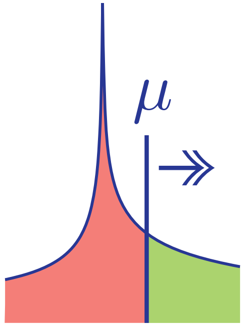
Electron-hole asymmetry

Possible interpretations of the background-conductance asymmetry



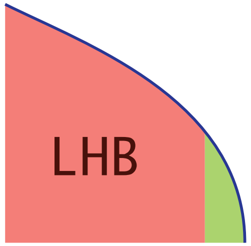
- Weakly non-local tunneling matrix element
  (more weight given to zone-center states)

How to explain the gap dependence?



- Spectral weight of the Van Hove singularity
  (larger gap ⇔ less hole doping ⇔ higher μ)

Real effect, but likely not sufficient



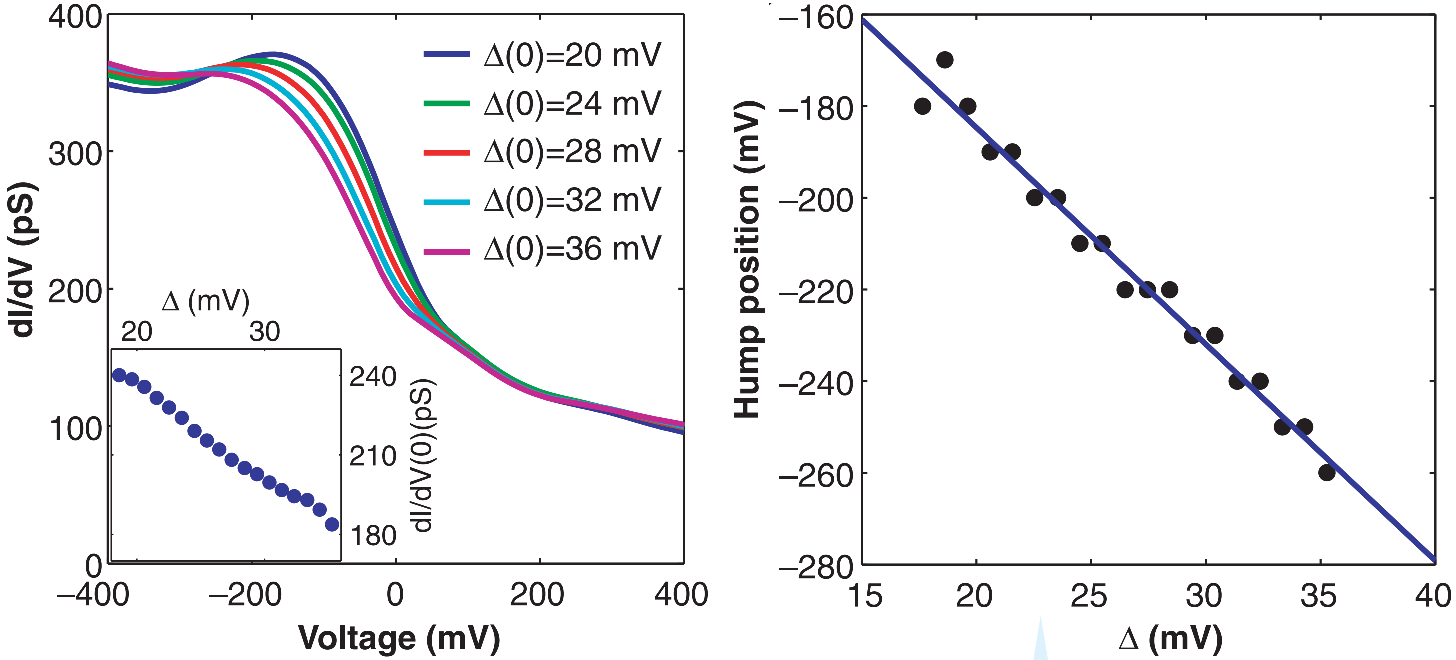
- Electron correlations due to the proximity of the Mott insulating phase
  (background ⇔ top of lower Hubbard band)

Why not inverted in electron-doped?

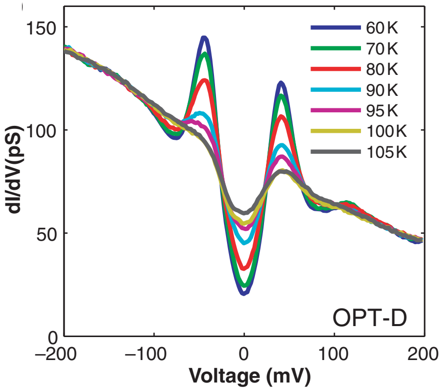
Electron-hole asymmetry

Used to measure the pairing strength

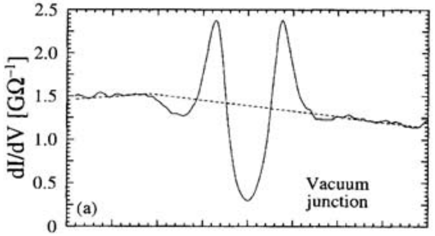
Optimally-doped Bi-2212 (93K)



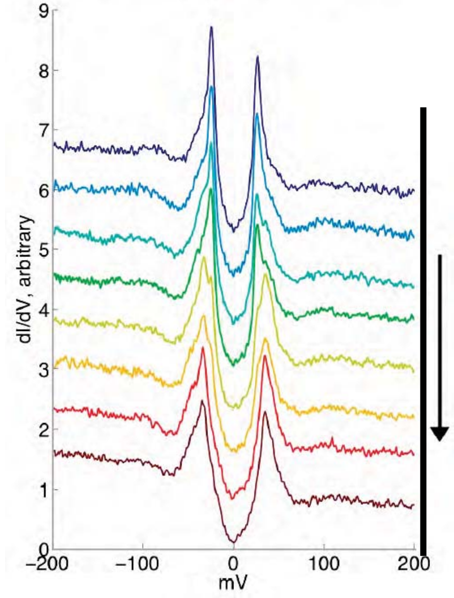
Pasupathy *et al.* (2008)



Pasupathy *et al.* (2008)



Renner *et al.* (1995)



Fang *et al.* (2006)

- The pairing strength has been related to a feature (hump) in the background

- However a large uncertainty remains about the background

Electron-hole asymmetry

A way to measure the local doping ?

- A sum rule relates the LDOS to the hole density (Hubbard model)

Upper cutoff

$t \ll \Omega_L \ll U$

LDOS

hole density

$$\frac{\int_0^{\Omega_L} d\omega\, g(\mathbf{r};\omega)}{\int_{-\infty}^{0} d\omega\, g(\mathbf{r};\omega)} = \frac{2x(\mathbf{r})}{[1-x(\mathbf{r})]} + \dots.$$

~10%

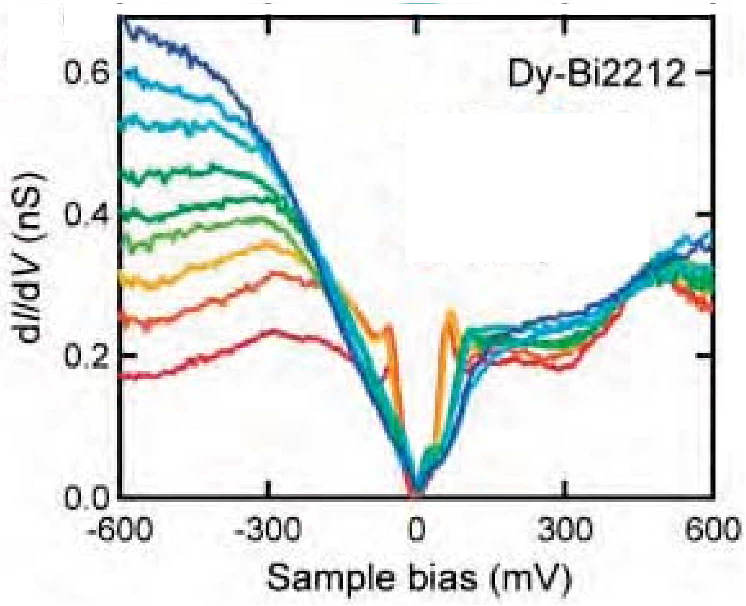
Randeria *et al.* (2005)

- If the matrix elements cancel, and if the STM measures the exact LDOS, this relation allows to determine the local hole density

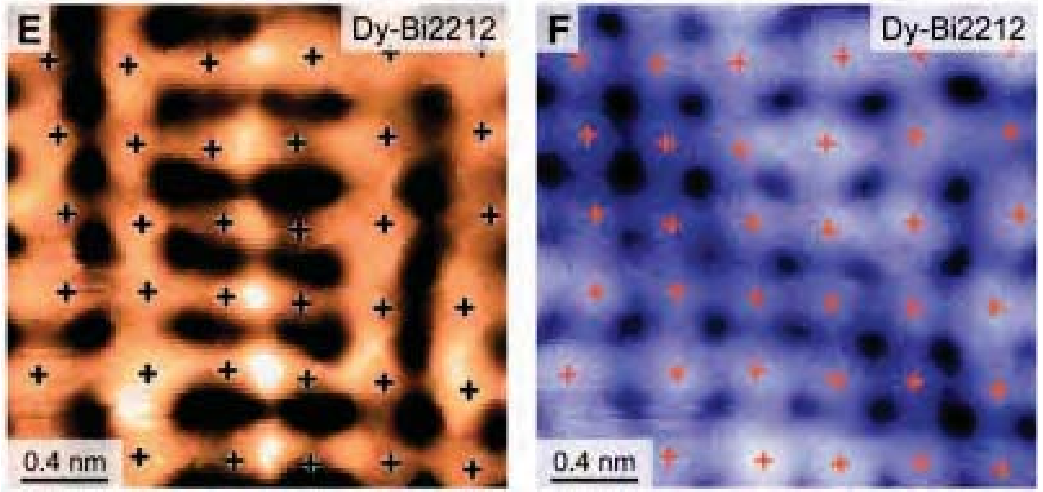
Electron-hole asymmetry

Breaks spatial symmetries

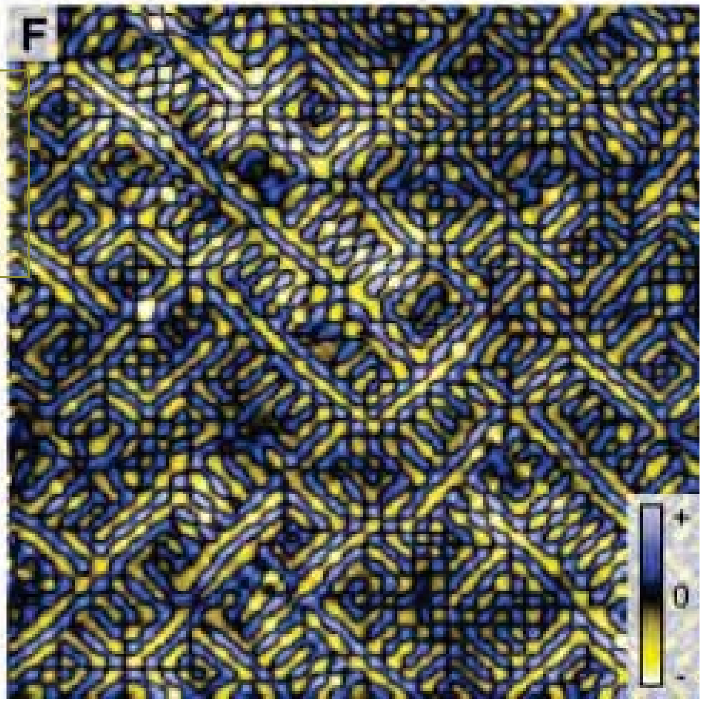
Underdoped Bi-2212 (45K)



Kohsaka *et al.* (2007)



$$\nabla^2 \left[\frac{I(\boldsymbol{r},+V)}{I(\boldsymbol{r},-V)}\right]_{V=150\ \mathrm{mV}}$$



The conductance asymmetry reveals a breaking of C_4 symmetry, in addition to the 4*a* modulation

See also Lawler *et al.* (2010)

Conclusion

No strong conclusion yet...

Precursor pairing

- Common energy scale for gap and pseudogap
- $2\Delta_p / k_B T^* = 4.3$
- Pseudogap opening at the Fermi energy
- Pseudogap with *d*-wave symmetry

?

Competing order

- Non-universality of phase diagram
- Existence of real-space order with broken symmetry
- Pseudogap spectrum present in vortex cores