Quasiparticle interference in the pseudogap phase of cuprate superconductors

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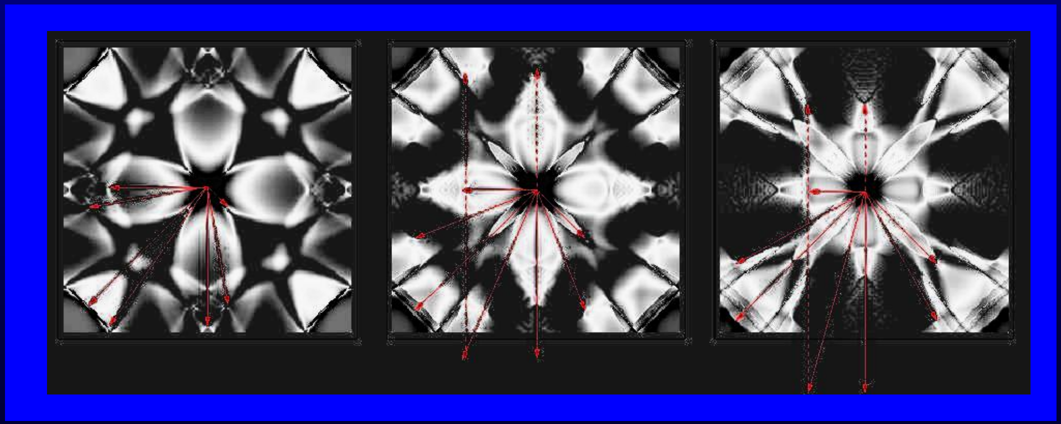

In collaboration with: T. Pereg-Barnea (KITP & UBC)

Pseudogap: the key mystery

Pseudogap is a nonsuperconducting phase intermediate between the AF insulator and d-wave superconductor.

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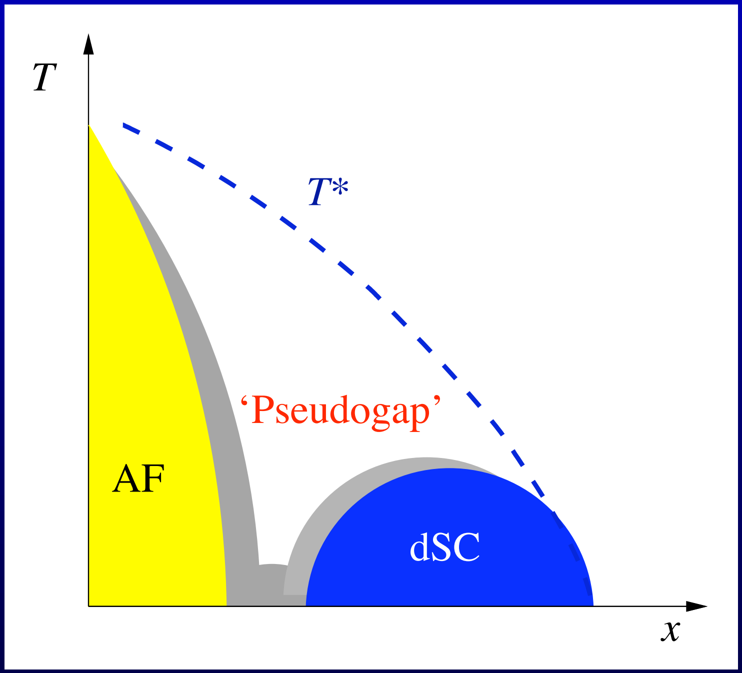

Phase diagram of cuprates. [For exp. review see Timusk and Statt, Rep. Prog. Phys. **62**, 61 (1999).]

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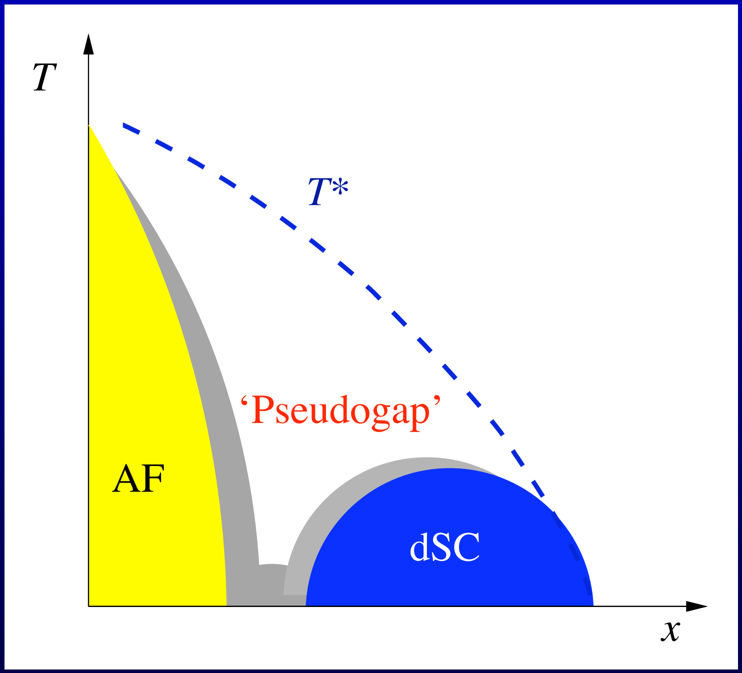

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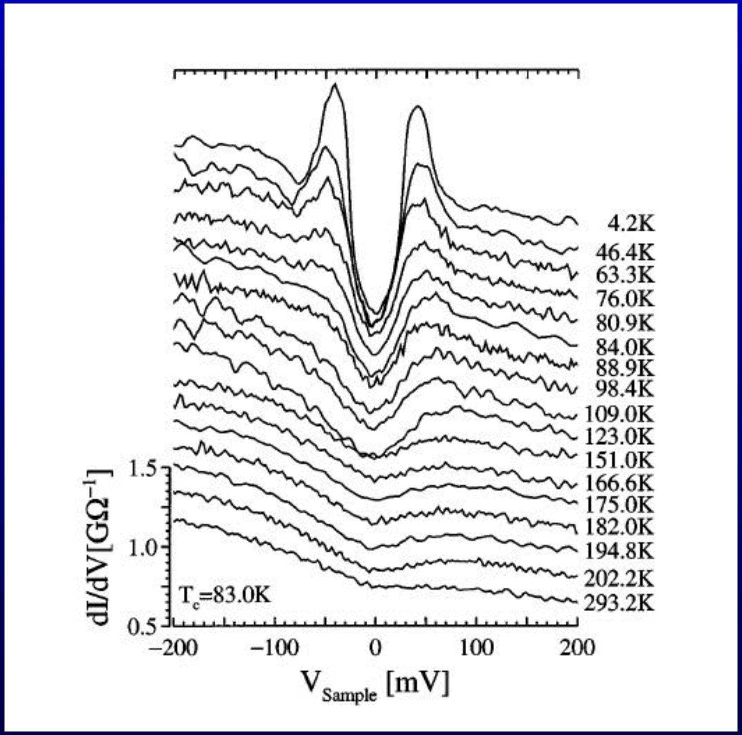

Gap in the single-particle DOS above T_c [tunneling data from Renner *et al.*, PRL **80, 149 (1998)]**

Two schools of thought on the origin of pseudogap

Ascribe the pseudogap phenomenon to:

- Remnants of superconducting order
  - ⋆ Emery and Kivelson, Nature **374**, 434 (1995).
  - ⋆ Franz and Millis, PRB **58**, 14572 (1998)
  - ⋆ Balents, Fisher and Nayak, PRB **60**, 1654 (1999)
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  - ⋆ Laughlin, cond-mat/0209269

- Static or fluctuating competing order in p-h channel (SDW, CDW, DDW, . . .)
  - ⋆ Zhang, Science **275**, 1089 (1997)
  - ⋆ Varma, PRL **83**, 3538 (1999)
  - ⋆ Vojta, Zhang, and Sachdev, PRB **62**, 6721 (2000)
  - ⋆ Chakravarty, Laughlin, Morr, and Nayak, PRB **63**, 094503 (2001)

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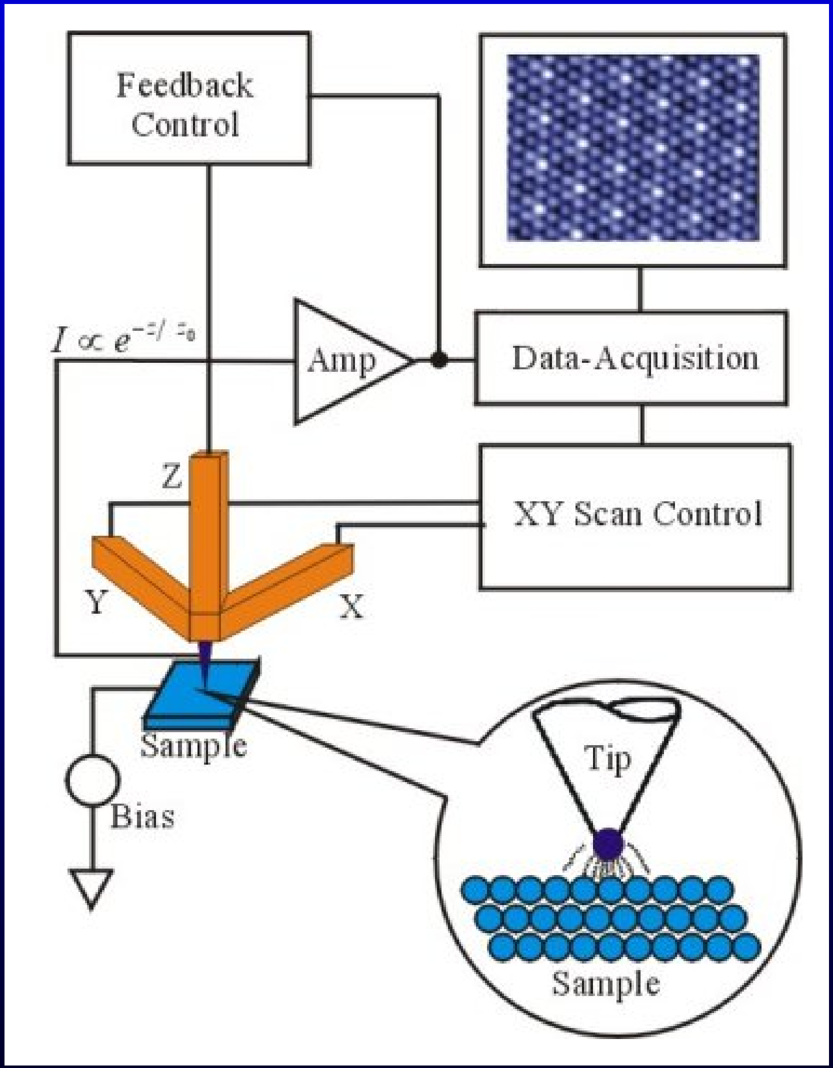
Our proposal: use the recently developed technique of Fourier Transform scanning tunneling spectroscopy (FT-STS).

- Pereg-Barnea and Franz, PRB **68**, 180506(R) (2003)
- Pereg-Barnea and Franz, cond-mat/0401594

STM Basics

[http://people.ccmr.cornell.edu/˜jcdavis/stm]



STM measures differential conductance

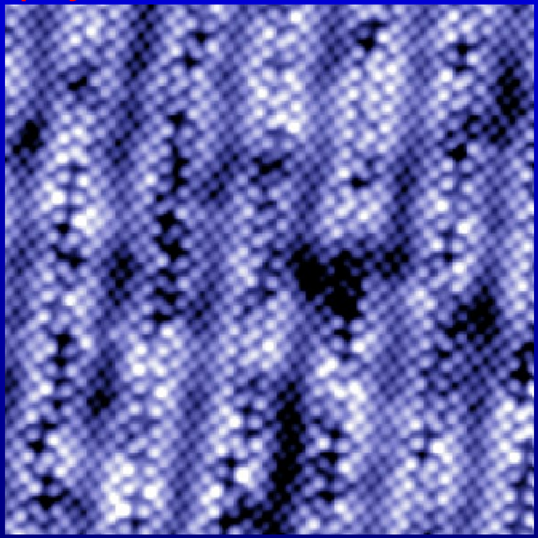
$$n(\mathbf{r},\omega) \simeq \left(\frac{dI(\mathbf{r},eV)}{dV}\right)_{eV=\omega},$$

with potentially atomic resolution.

To reasonable approximation $n(\mathbf{r},\omega)$ is proportional to the Local Density of States (LDOS) of the sample at point $\mathbf{r}$ directly under the STM tip.

Tunneling spectroscopy in cuprates

Topography of BiSCCO:



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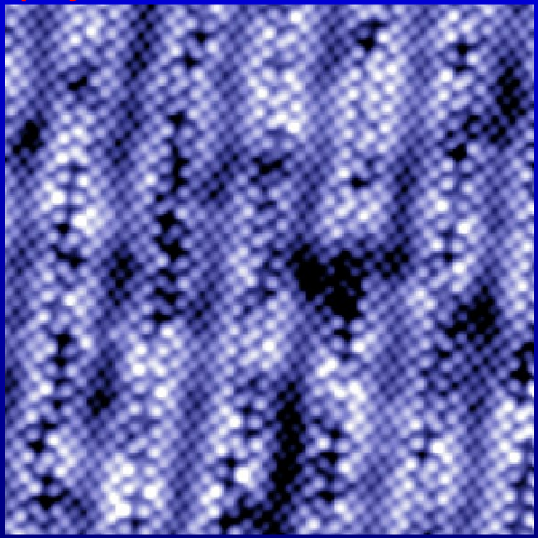
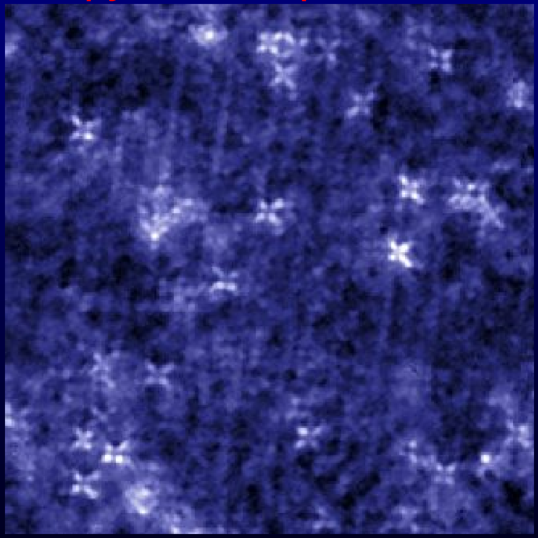


Spectroscopy of Ni impurities:



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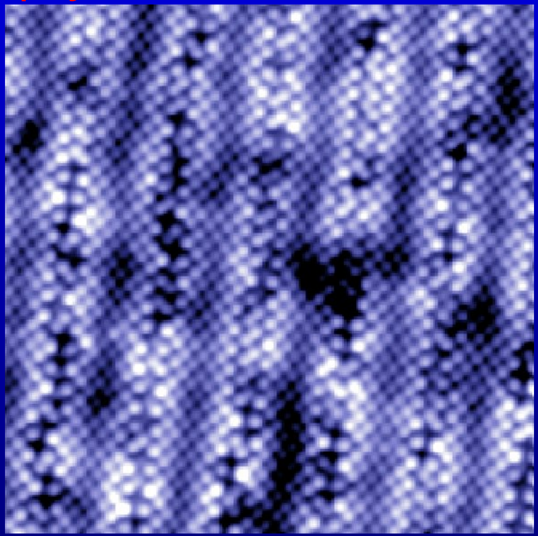

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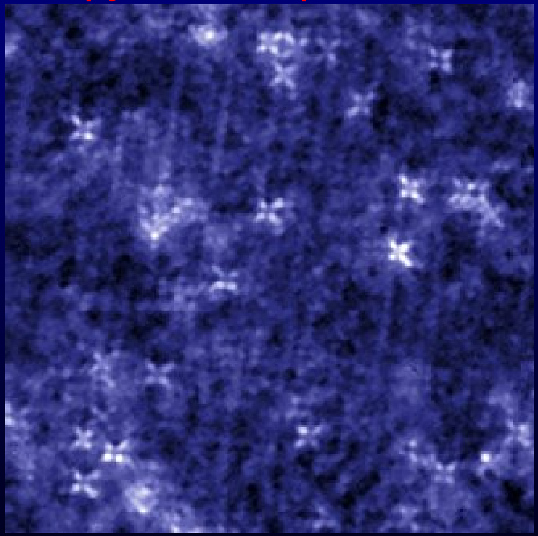
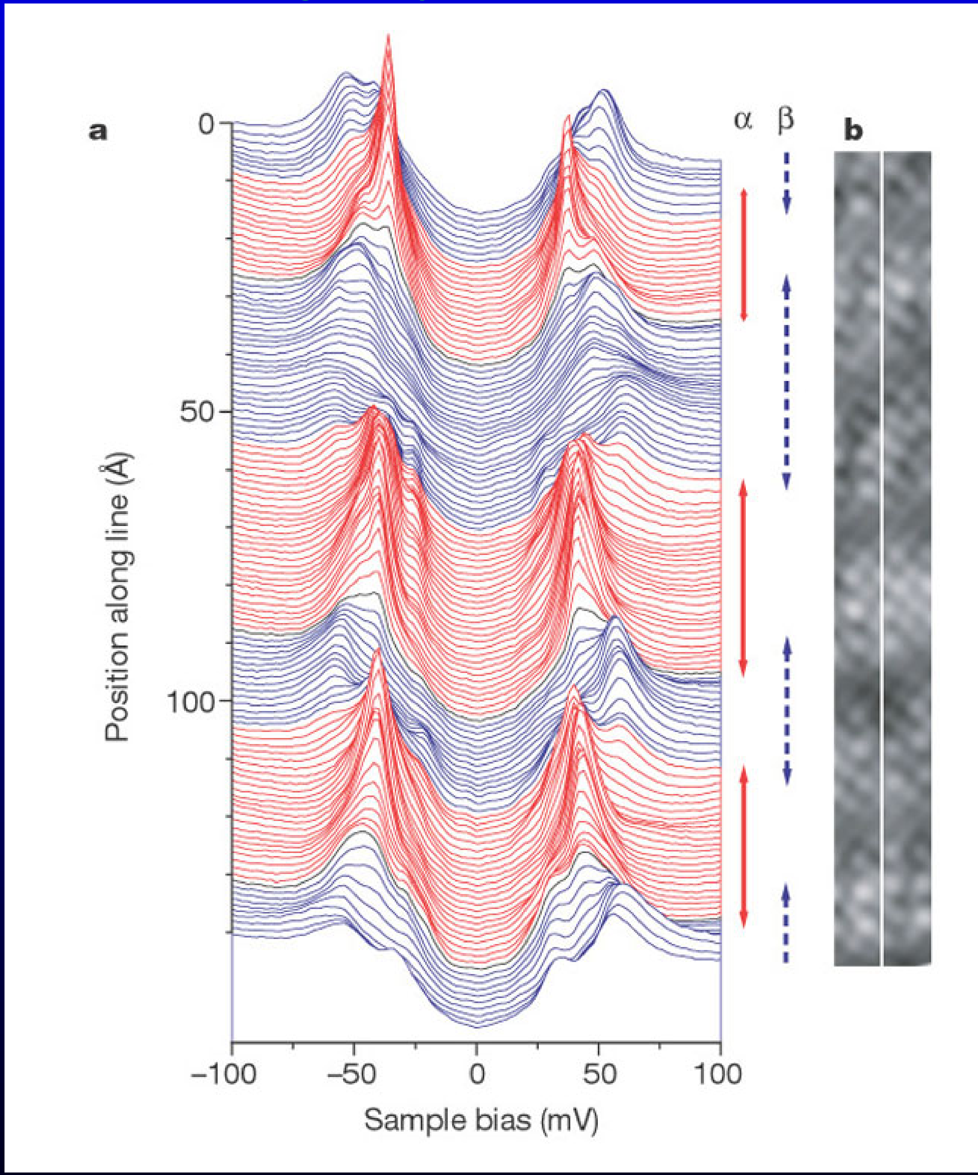
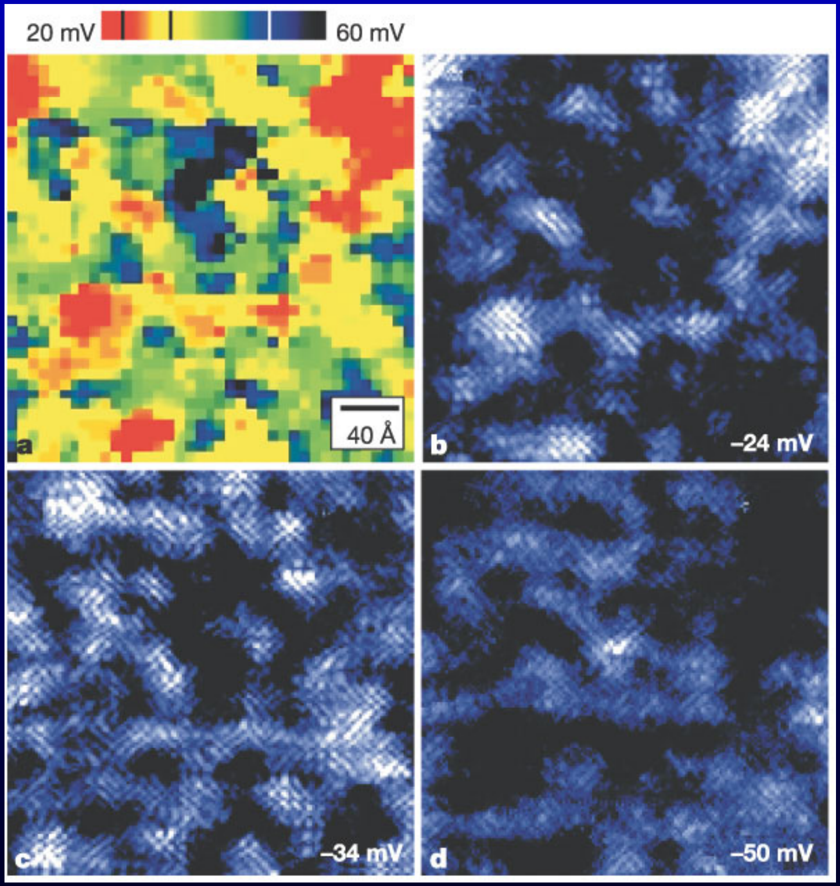


LDOS inhomogeneity:



FT-STS: "Fourier Transform Scanning Tunneling Spectroscopy"

Periodic patterns in LDOS at fixed energy are sometimes observed:



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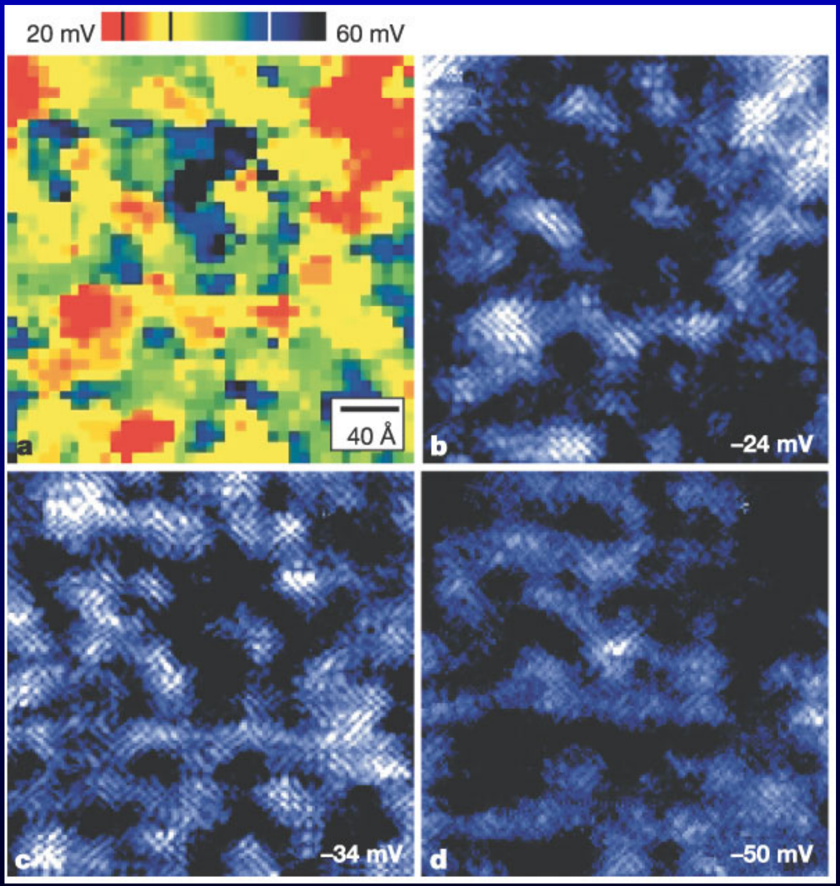
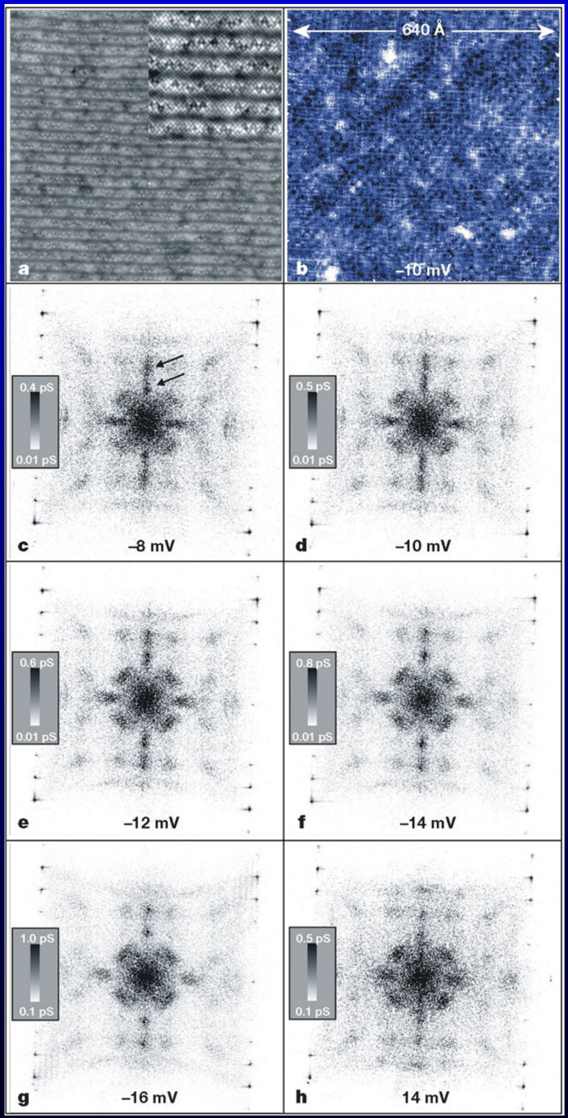
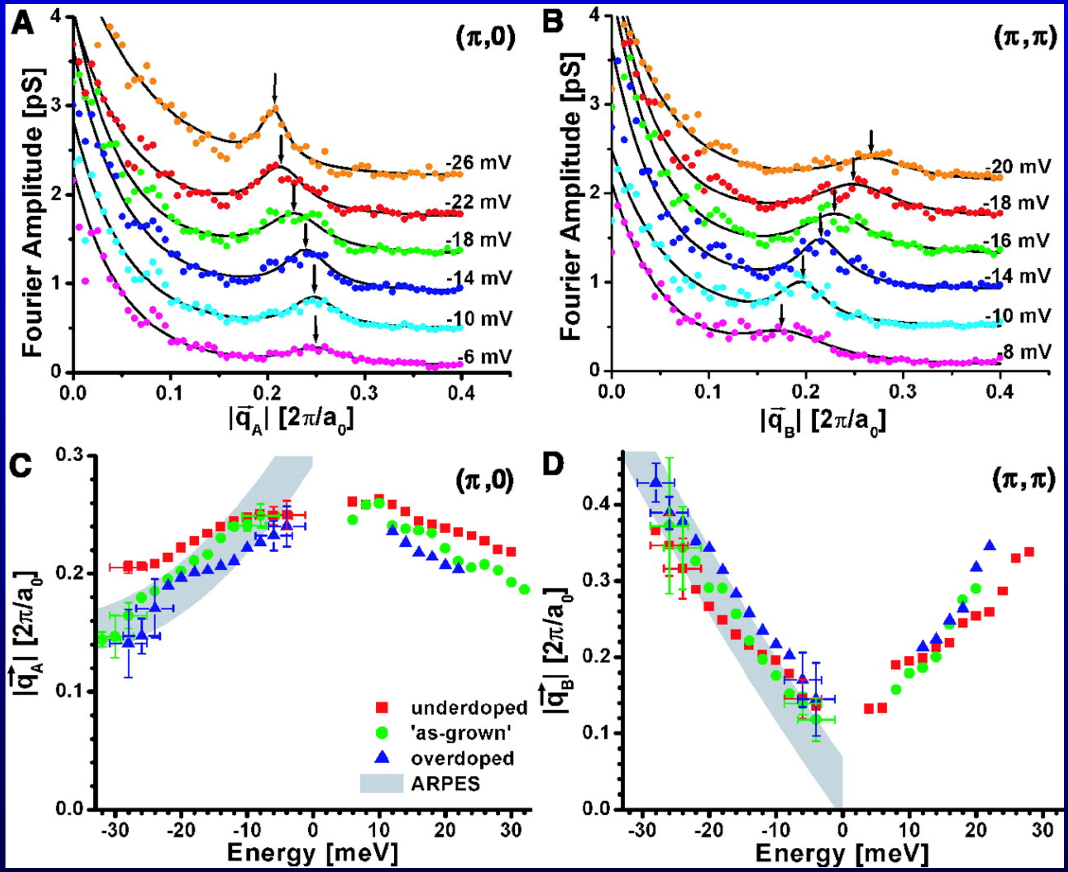


$\longrightarrow$ FT



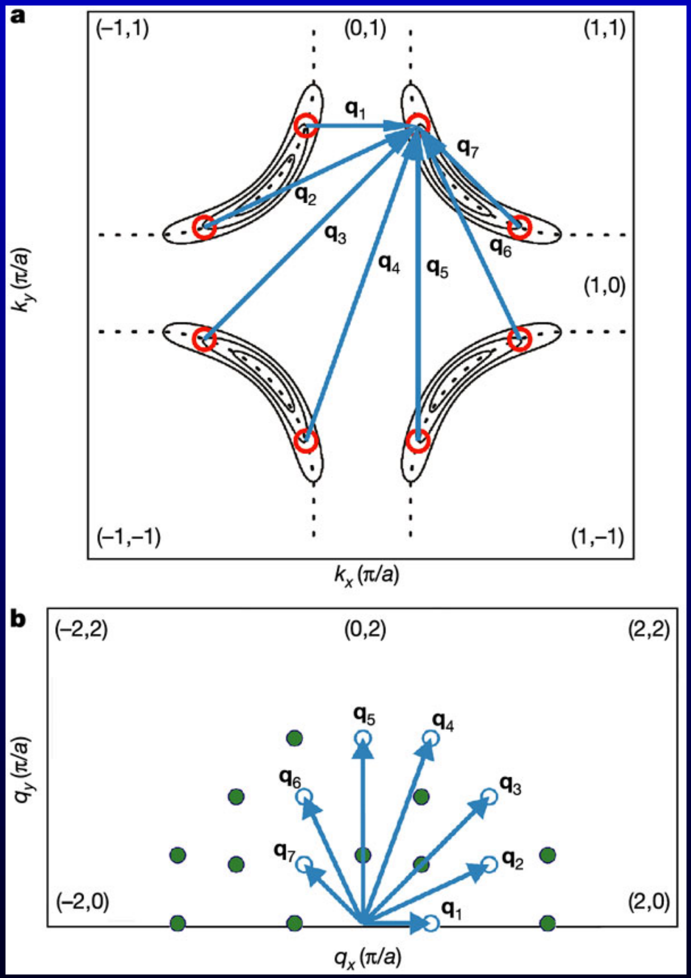
FT-STS peaks disperse as a function of applied bias



- K. McElroy *et al.*, Nature **422**, 592 (2003).
- J.E. Hoffman *et al.*, Science **297**, 1148 (2002).

The "Octet Model"

The octet model asserts that the peaks in FT-STS are due to quasiparticle scattering between the regions of high DOS.



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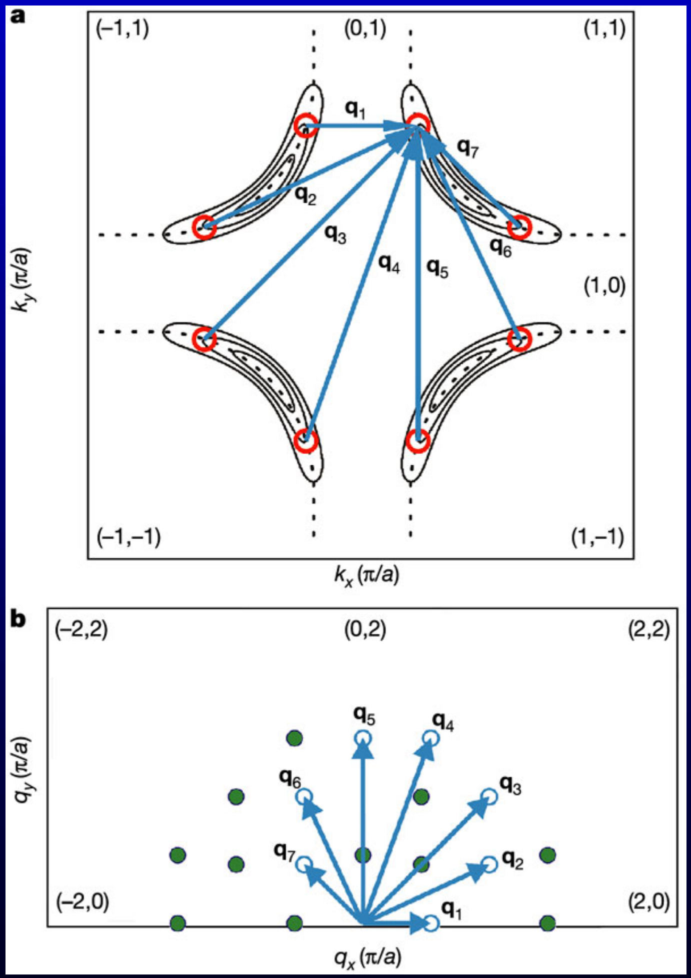
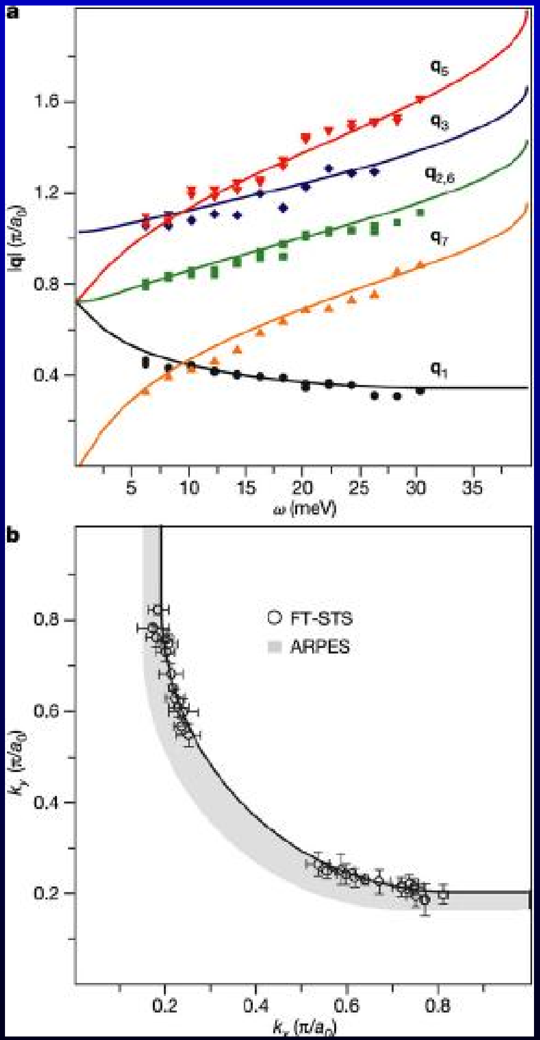
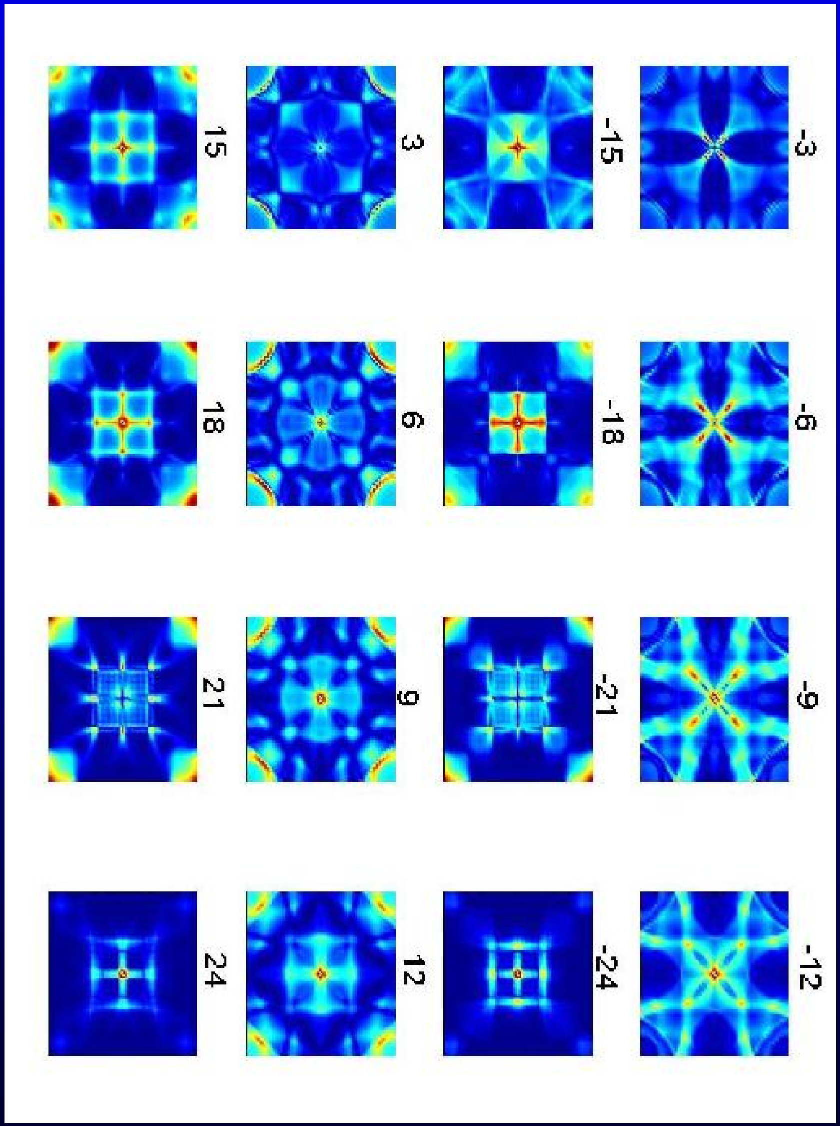
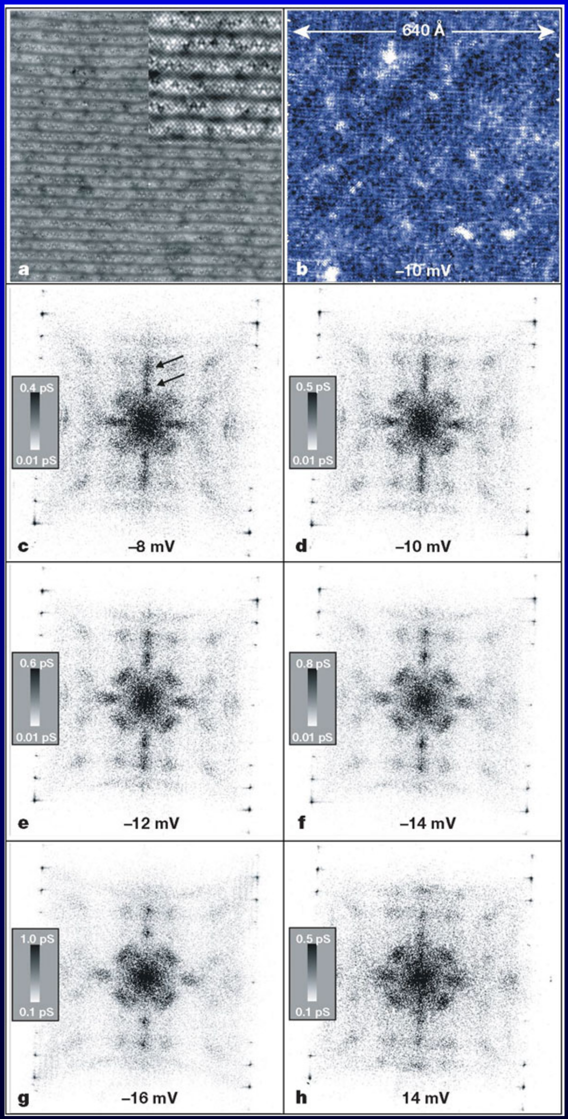




Theory vs. Experiment





T-matrix calculation [Wang and Lee, PRB **67**, 020511(R) (2003)]

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$\longrightarrow$ IDENTIFICATION OF PSEUDOGAP ORDER

Theory of FT-STS

STM measures the quantity

$$n(\mathbf{r},\omega) = -\frac{1}{\pi}\mathrm{Im}[G_{11}(\mathbf{r},\mathbf{r},\omega) + G_{22}(\mathbf{r},\mathbf{r},-\omega)],$$

where $G(\mathbf{r},\mathbf{r}',\omega)$ is a full electron propagator. In the presence of disorder potential V we can write

$$G(\mathbf{k},\mathbf{k}',\omega) = G^0(\mathbf{k},\omega)\delta_{\mathbf{k},\mathbf{k}'} + G^0(\mathbf{k},\omega)\hat{T}_{\mathbf{k}\mathbf{k}'}(\omega)G^0(\mathbf{k}',\omega),$$

with $G^0(\mathbf{k},\omega) = [\omega - \sigma_3\epsilon_{\mathbf{k}} - \sigma_1\Delta_{\mathbf{k}}]^{-1}$ the bare Green's function and $\hat{T}_{\mathbf{k}\mathbf{k}'}(\omega)$ the T-matrix that satisfies the Lippman-Schwinger equation

$$\hat{T}_{\mathbf{k}\mathbf{k}'}(\omega) = \hat{V}_{\mathbf{k}\mathbf{k}'} + \sum_{\mathbf{q}}\hat{V}_{\mathbf{k}\mathbf{q}}G^0(\mathbf{q},\omega)\hat{T}_{\mathbf{q}\mathbf{k}'}(\omega).$$

FT-STS measures $n(\mathbf{q},\omega)$, a spatial Fourier transform of $n(\mathbf{r},\omega)$.

It is useful to consider a limit of weak disorder (i.e. Born limit) in which one can express the non-uniform part $\delta n(\mathbf{q},\omega)$

$$\delta n(\mathbf{q},\omega) = -\frac{1}{\pi}|V_{\mathbf{q}}|\mathrm{Im}\left[\Lambda_{11}(\mathbf{q},\omega) + \Lambda_{22}(\mathbf{q},-\omega)\right],$$

where, for scattering in the charge channel,

$$\Lambda(\mathbf{q},\omega) = \sum_{\mathbf{k}} G^0(\mathbf{k},\omega)\sigma_3 G^0(\mathbf{k}-\mathbf{q},\omega).$$

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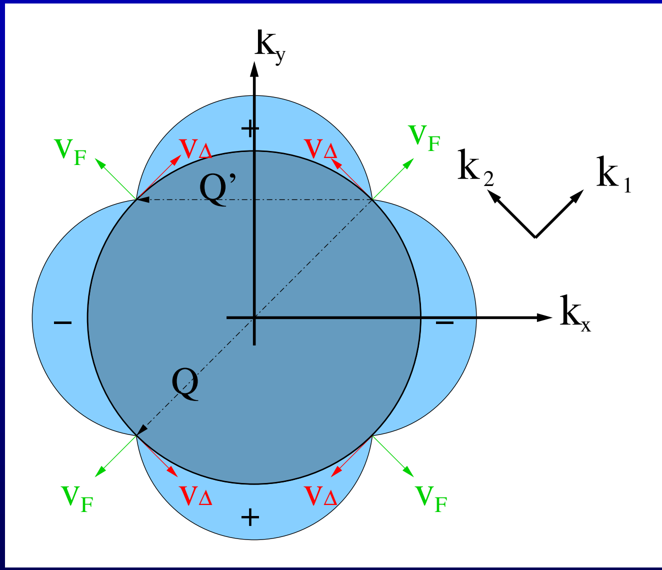
For weak disorder FT-STS provides information about the underlying electron order

Nodal approximation: importance of coherence factors

One finds

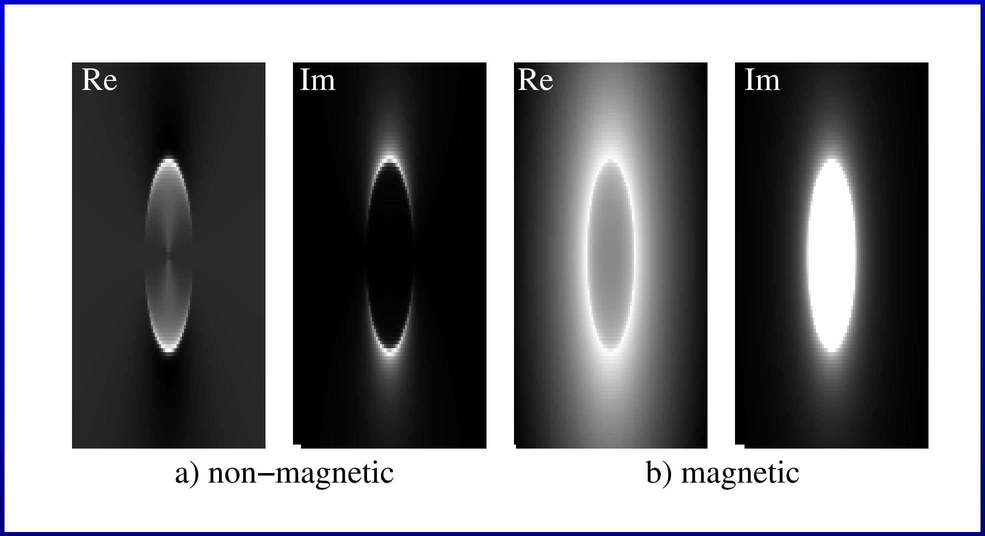
$$\Lambda(\mathbf{q}, i\omega) = \frac{1}{L^2} \sum_{\mathbf{k}} \frac{(i\omega + \epsilon_+)(i\omega + \epsilon_-) - \Delta_+ \Delta_-}{(\omega^2 + E_+^2)(\omega^2 + E_-^2)},$$

with $\epsilon_\pm = \epsilon_{\mathbf{k}\pm\mathbf{q}/2}$, $\Delta_\pm = \Delta_{\mathbf{k}\pm\mathbf{q}/2}$ and $E_\pm = \sqrt{\epsilon_\pm^2 + \Delta_\pm^2}$. Linearize near the nodes to obtain



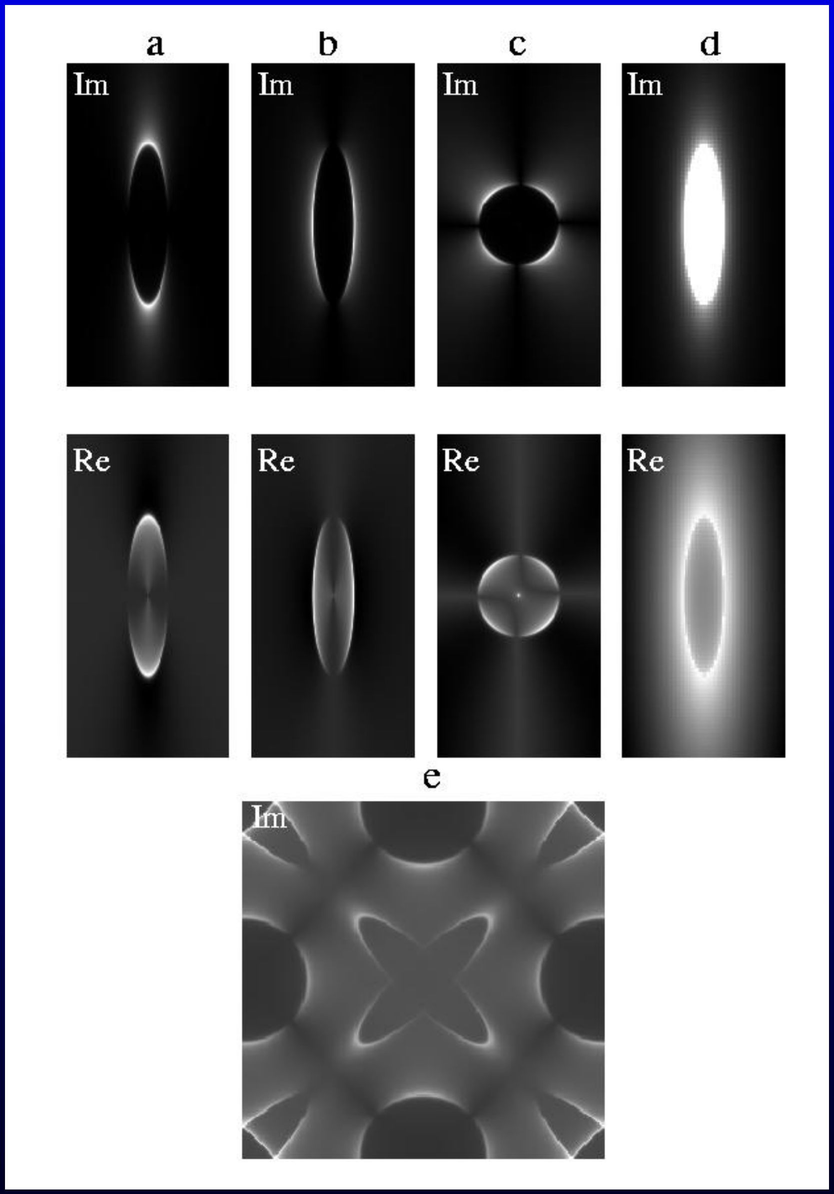
$$\Lambda_{\text{lin}} = \frac{1}{v_F v_\Delta} \int \frac{d^2k}{(2\pi)^2} \frac{-\omega^2 + (k_1^2 - k_2^2) - (\tilde{q}_1^2 - \tilde{q}_2^2)}{[\omega^2 + (\mathbf{k} + \tilde{\mathbf{q}})^2][\omega^2 + (\mathbf{k} - \tilde{\mathbf{q}})^2]}.$$

For intranodal scattering we thus get



Magnetic and non-magnetic scattering differ only in the coherence factors, DOS is exactly the same. Yet, the FT-STS patterns are *qualitatively different!*.

The full picture



One can analyze various intra-node processes similarly in the linearized approximation to obtain the full picture.

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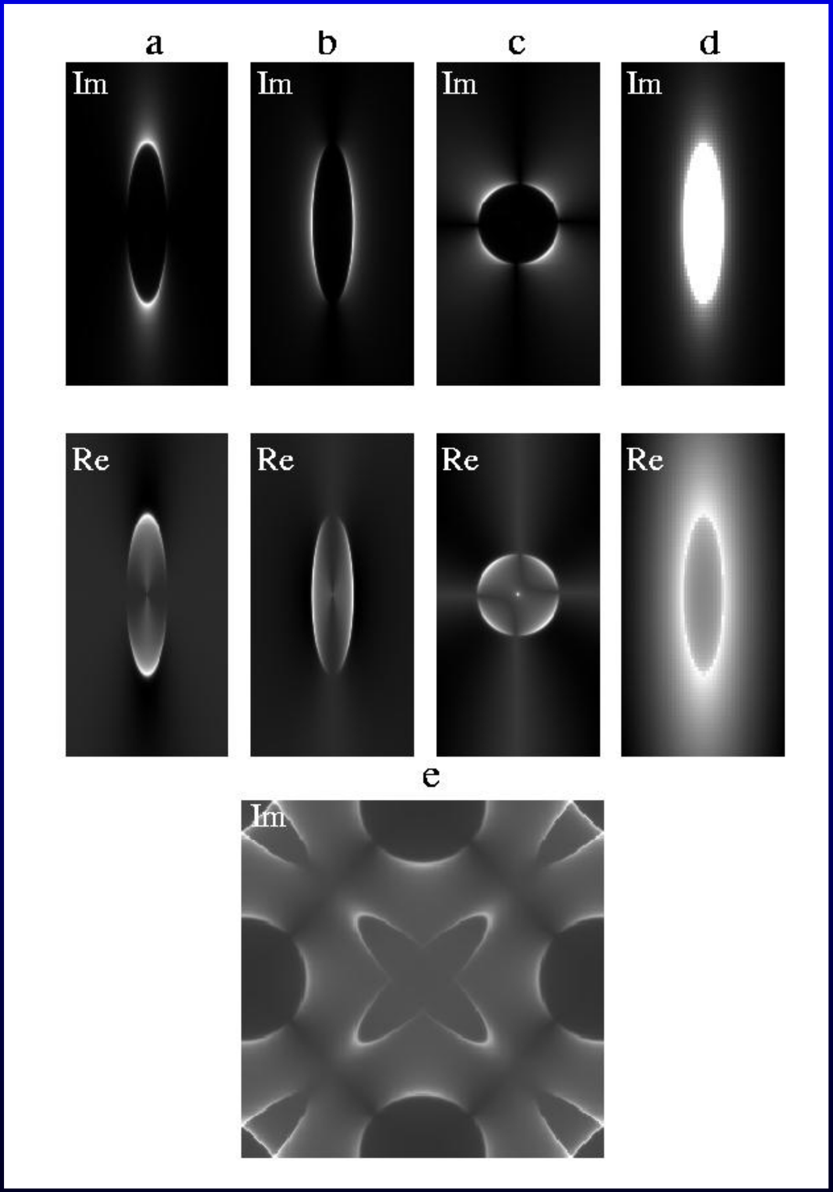

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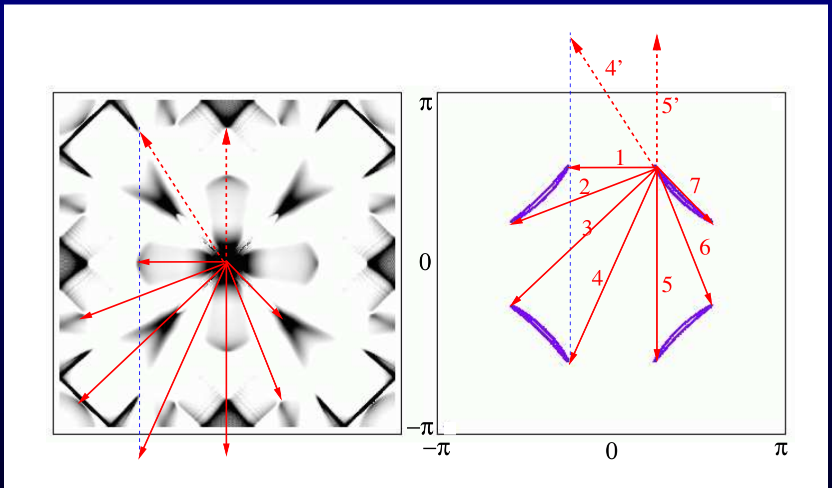
Alternately, one can evaluate $\Lambda(\mathbf{q},\omega)$ exactly using numerical techniques:



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- If the pseudogap is dominated by SC fluctuations then the FT-STS patterns above T_c should be qualitatively similar to those below T_c.
- If the pseudogap is primarily due to some p-h order the we expect a fundamentally different patterns above T_c.
- In the following we illustrate this general thesis on the comparison between QED_3 theory of phase disordered dSC and d-density wave (DDW) scenario for pseudogap.

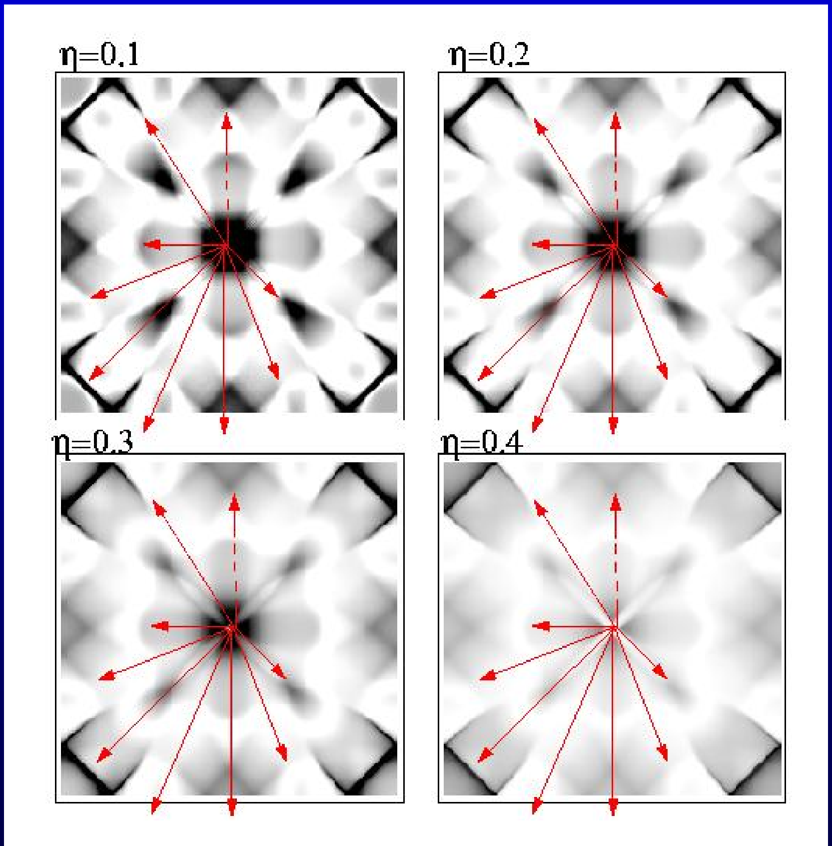
QED$_3$

[Franz and Tešanović, PRL **87**, 257003 (2001)]

This theory describes fermionic excitations in a phase-disordered d-wave superconductor. The electron propagator reads

$$G^0(\mathbf{k}, i\omega) = \lambda^{-\eta} \frac{i\omega + \epsilon_{\mathbf{k}}\sigma_3}{[\omega^2 + \epsilon_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2]^{1-\eta/2}},$$

where λ is a high energy cutoff and η is the anomalous dimension exponent which encodes the physics of phase fluctuations. η is a small positive number, whose precise value is still under debate.



DDW

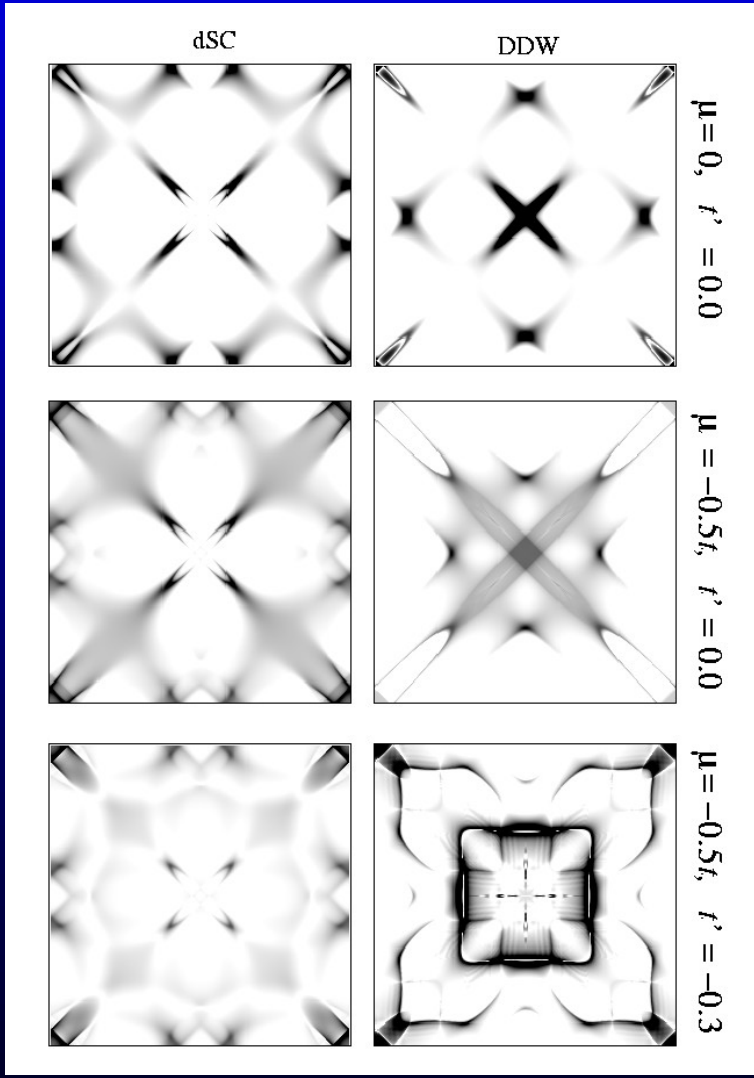
[Chakravarty, Laughlin, Morr, and Nayak PRB **63**, 094503 (2001)]

Also known as the "flux phase", this theory describes the pseudogap as a mean-field state with staggered pattern of currents, breaking the translational symmetry of the square lattice. We have

$$G^0(\mathbf{k}, i\omega) = [(i\omega - \epsilon'_{\mathbf{k}}) - \epsilon''_{\mathbf{k}}\sigma_3 - D_{\mathbf{k}}\sigma_2]^{-1},$$

with $\epsilon'_{\mathbf{k}} = \frac{1}{2}(\epsilon_{\mathbf{k}} + \epsilon_{\mathbf{k}+\mathbf{Q}})$, $\epsilon''_{\mathbf{k}} = \frac{1}{2}(\epsilon_{\mathbf{k}} - \epsilon_{\mathbf{k}+\mathbf{Q}})$, and the DDW gap $D_{\mathbf{k}} = \frac{1}{2}D_0(\cos k_x - \cos k_y)$.

At half filling $(\mu = 0)$ and with nn dispersion $(t' = 0)$ DDW has the same DOS as the dSC.



Conclusions

- By analyzing the quasiparticle interference patterns in the nodal approximation we gained some crucial insights into FT-STS in the superconducting state.
- FT-STS is sensitive to both the quasiparticle DOS and the coherence factors.
- This sensitivity can be used to determine the nature of the condensate responsible for the pseudogap phenomenon in the cuprates.
- Several experimental groups are now actively pursuing this goal.