Inelastic Tunneling Spectroscopy in Unconventional Superconductors

- ***Molecular Vibration and Single Spin Detection***
- ***Effects of Magnetic Collective Mode***

LA-UR 038196 by

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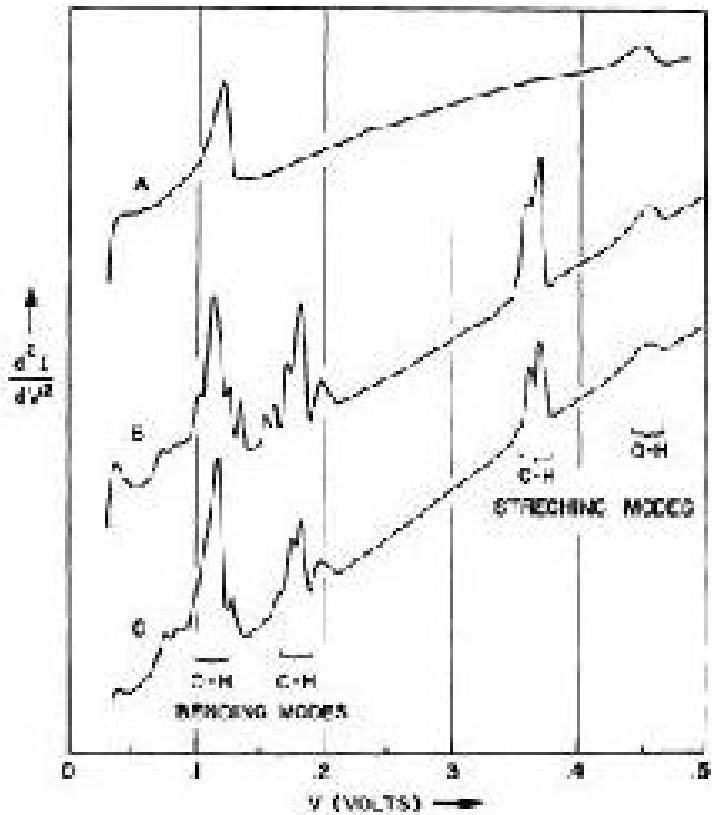
Old Results

R.C. Jaklevic and J. Lambe,

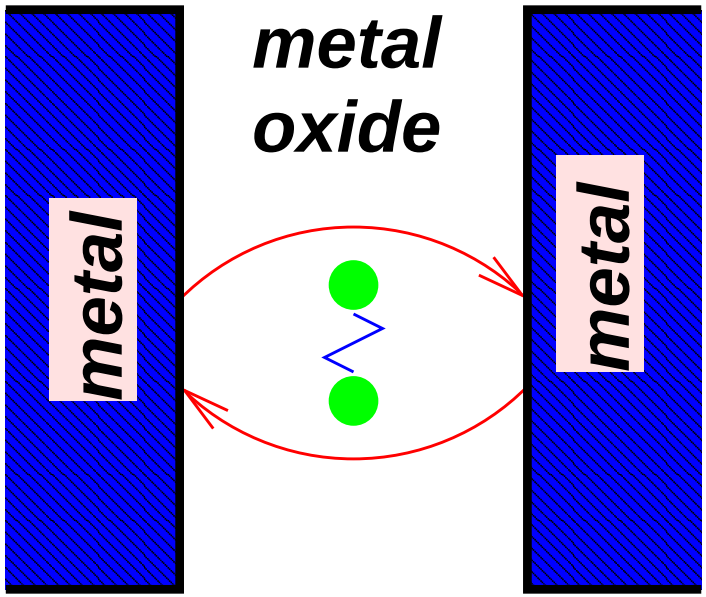
Phys. Rev. Lett. **17**, 1139-1140 (1966)



The conductance of metal–metal oxide–metal tunneling junctions

D.J. Scalapino and S.M. Marcus,

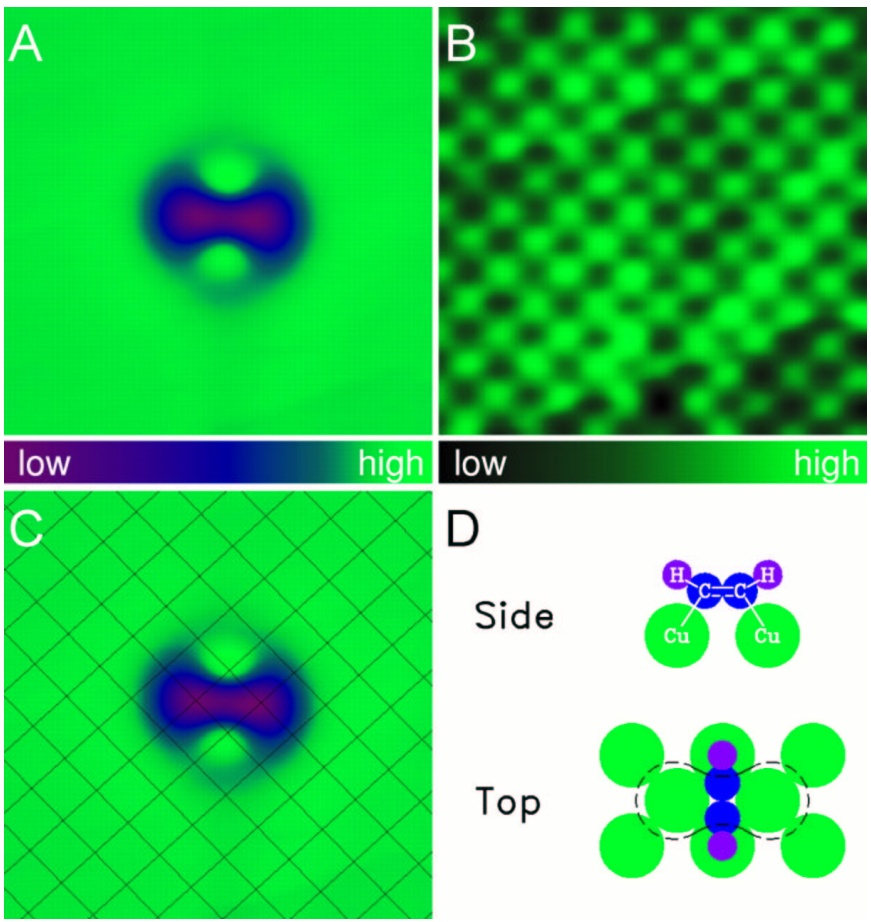
Phys. Rev. Lett. **18**, 459-461 (1967)

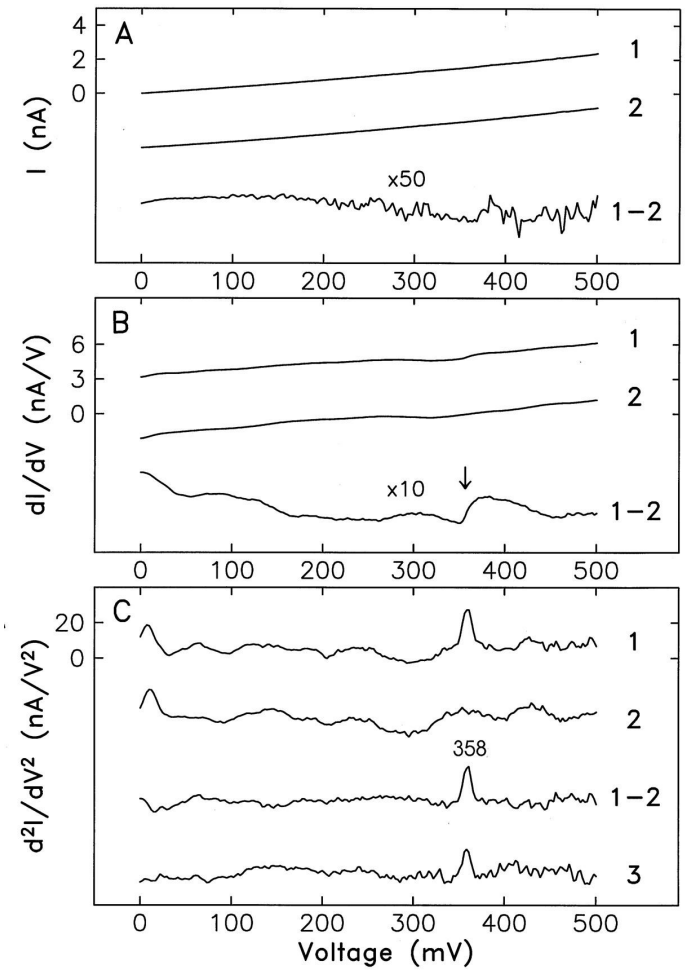


- $H_t = c_L^\dagger c_R T(x) + h.c.$
- $T(x) = t_0(1 + \alpha x)$
- x – Vibrational mode

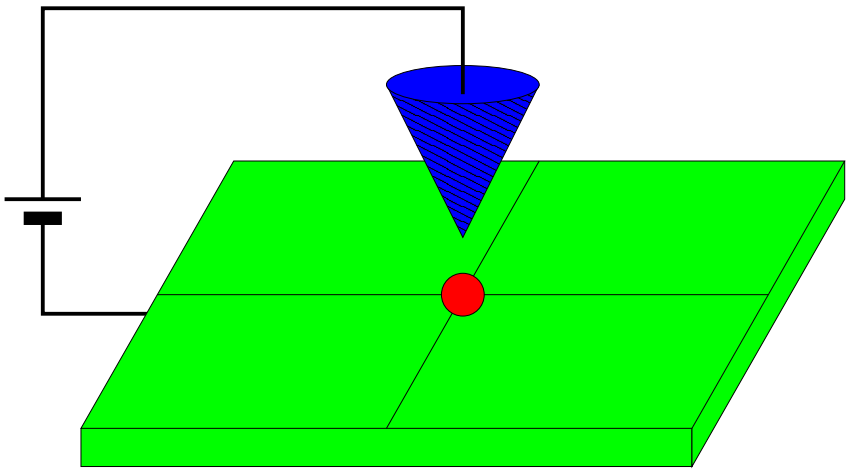
STM observation of local inelastic mode

B.C. Stipe, M.A Rezaei, and W. Ho, Science **280**, 1732 (1998)

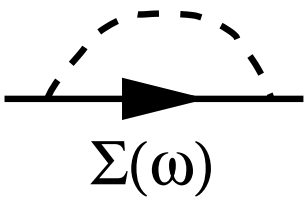




Inelastic STM

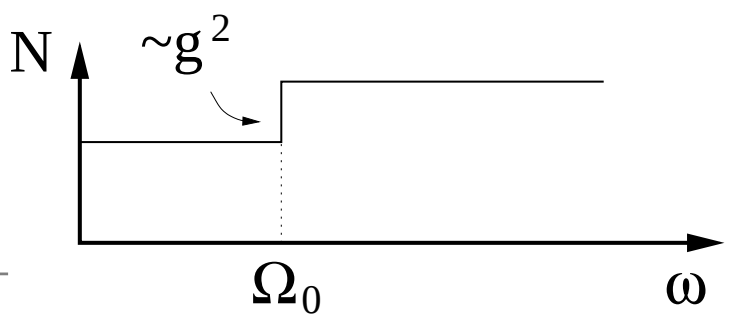


- STM measures local DOS
- $H = H_e + H_v + H_i$
- $H_v = \frac{kx^2}{2}$ – vibrational mode
- $H_i = g c_\sigma^\dagger(\mathbf{r}=0) c_\sigma(\mathbf{r}=0) x$

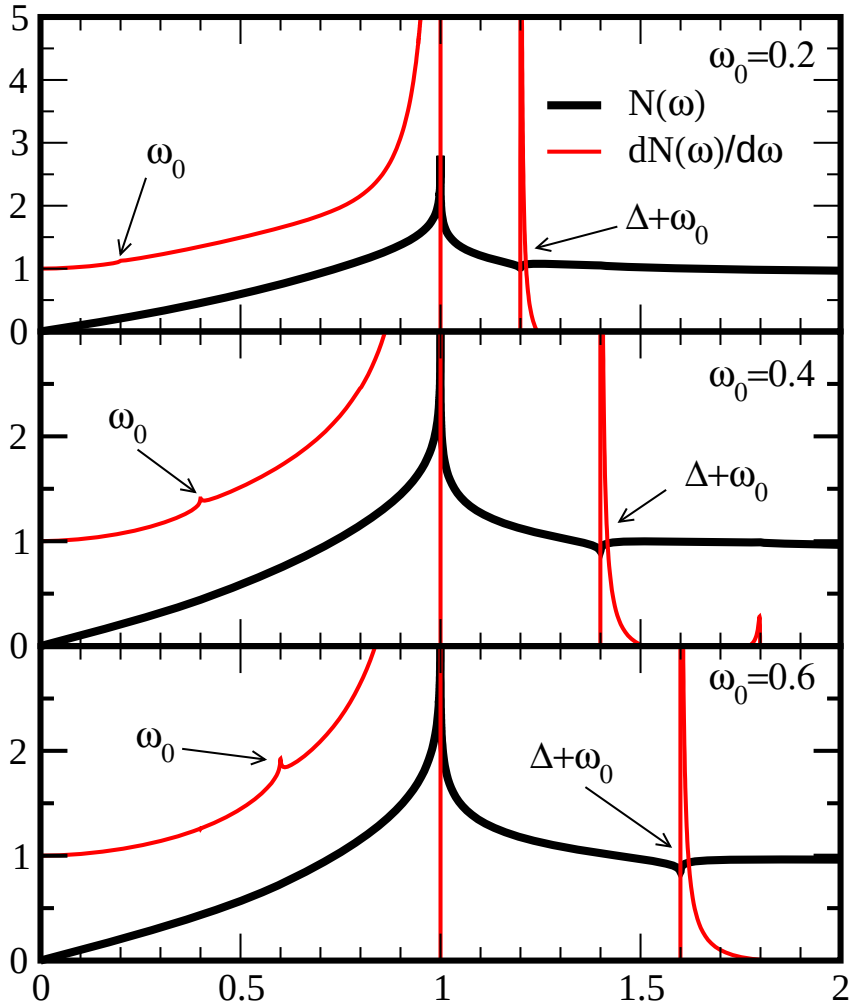


$$\delta N(\omega) = \frac{1}{\pi}\mathrm{Im}\left[G^0(\mathbf{r},\omega)\Sigma(\omega)G^0(\mathbf{r},\omega)\right]$$

For normal metal: $\boxed{\delta N(\omega) \sim g^2 N_0(\omega - \Omega_0)\theta(\omega - \Omega_0)}$



d-wave superconductor



- Black line – DOS
- Red line – DOS derivative
- "Holstein" Features
- For $N_0 \sim 1/eV$, $JN_0 = 0.14$,

$$\frac{\delta N}{N_0} \sim (JN_0)^2 \frac{\omega - \Omega_0}{\Delta_0}$$

The relative change is of the order of few percent

- At 2nd order Spin $\leftrightarrow$ vibration mode

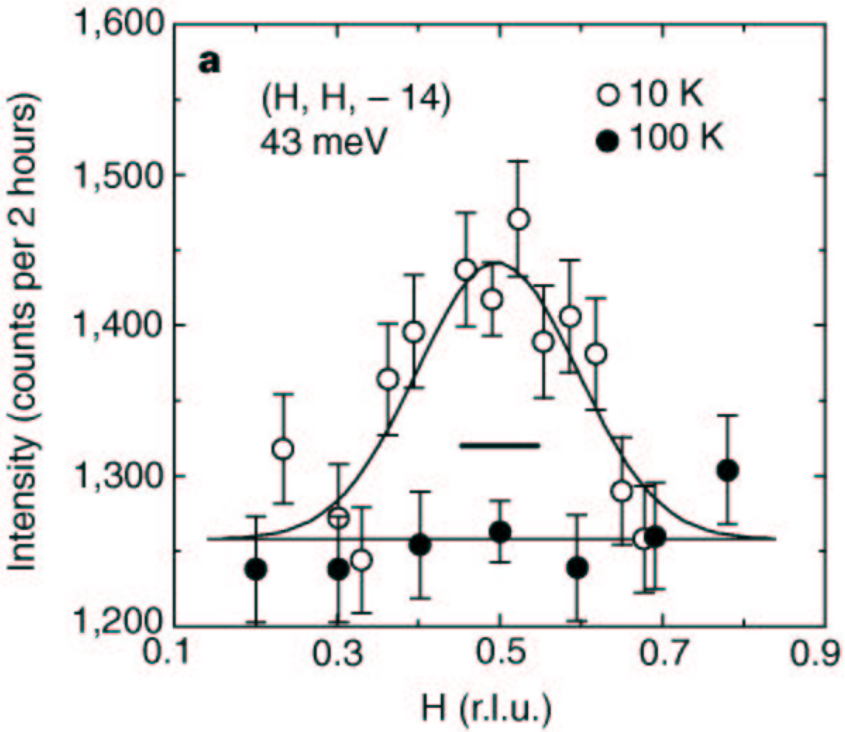
Intermediate Conclusions

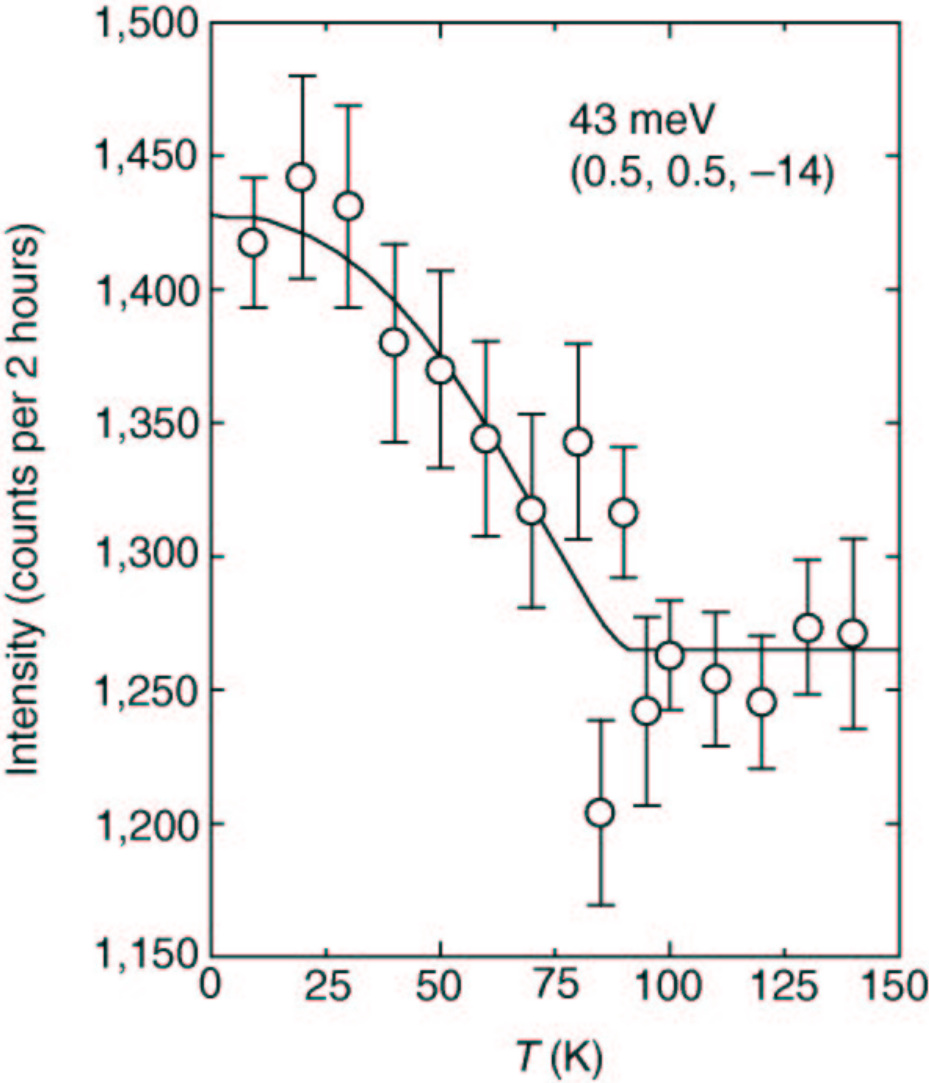
- Vibrational modes of a single molecule was detected by STM
- Single Spin will have the analogous features in STM
- Single Spin detection is possible in STM
- d-wave superconductor gives more options
- The energy of the features depends on magnetic field.
- To avoid Kondo effect either temperature or magnetic field should be larger then T_K

Magnetic Collective Mode

Fong *et al*, Nature, **398**, 588 - 591 (1999), $YBa_2Cu_3O_{6+x}$

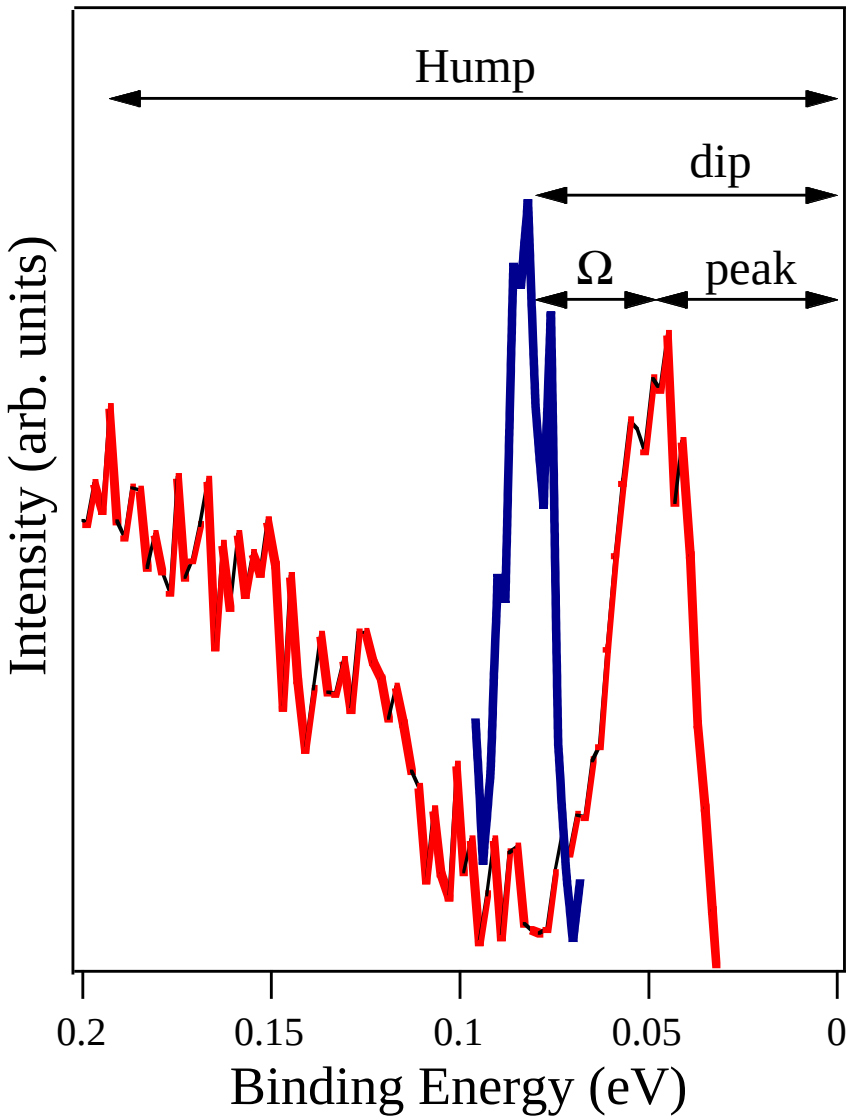
Inelastic neutron scattering
Magnetic mode bellow T_c
Peaked at $Q = (\pi, \pi)$, Ω_0



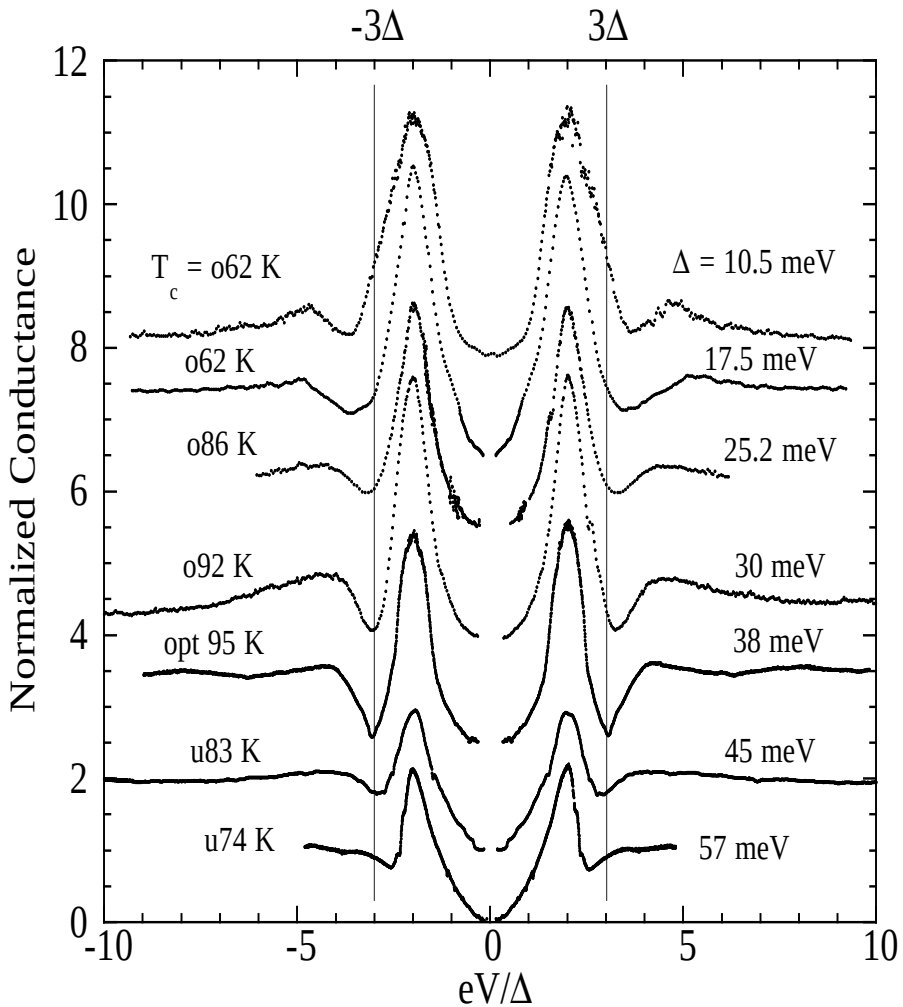


Effect on Electrons

M. Norman *et al*, PRL., **79**, 3506 (1997)



J. Zasadzinski *et al*, PRL **87**, 067005 (2001)

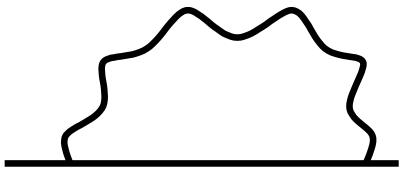


Strategy

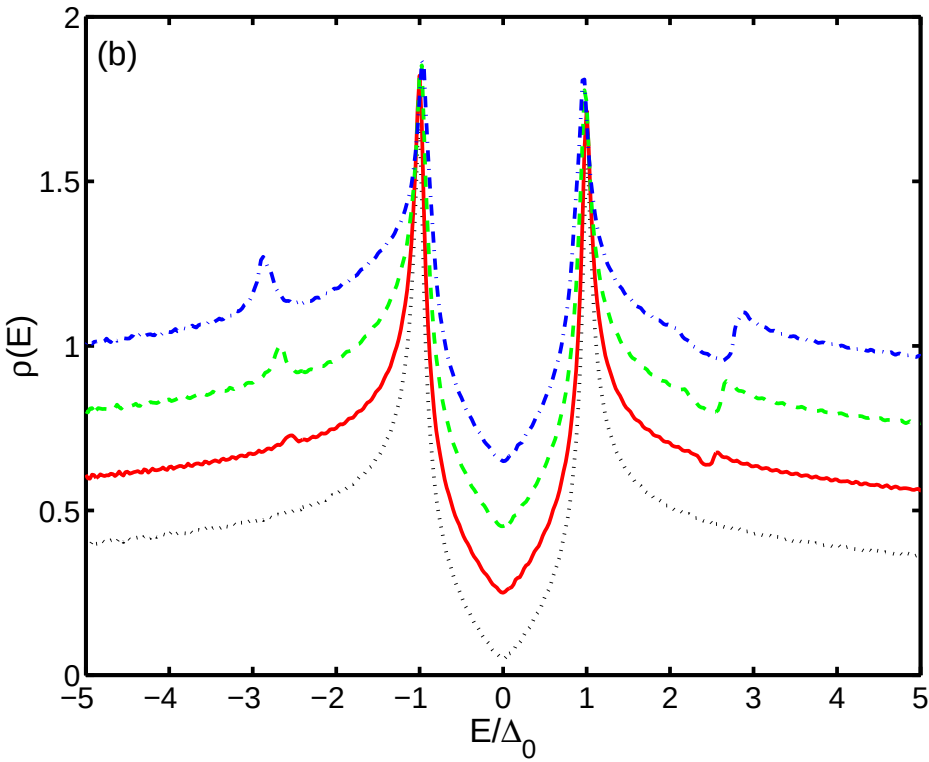
- Calculate corrections to the Green's function due to magnetic mode
- Reproduce the DOS measured by tunneling
- Calculate T matrix due to scattering off impurity
- Calculate the DOS at point $\mathbf{r}$ away from impurity
- Calculate real space Fourier transform of the DOS($\mathbf{r}$)

Correction to DOS due to MM

$$g = 0, \Delta, 2\Delta, 3\Delta$$

$\Sigma(\omega,k)=$ 

$$\hat{\mathbf{G}}^{-1} = \hat{\mathbf{G}}_0^{-1} - \hat{\mathbf{\Sigma}}$$

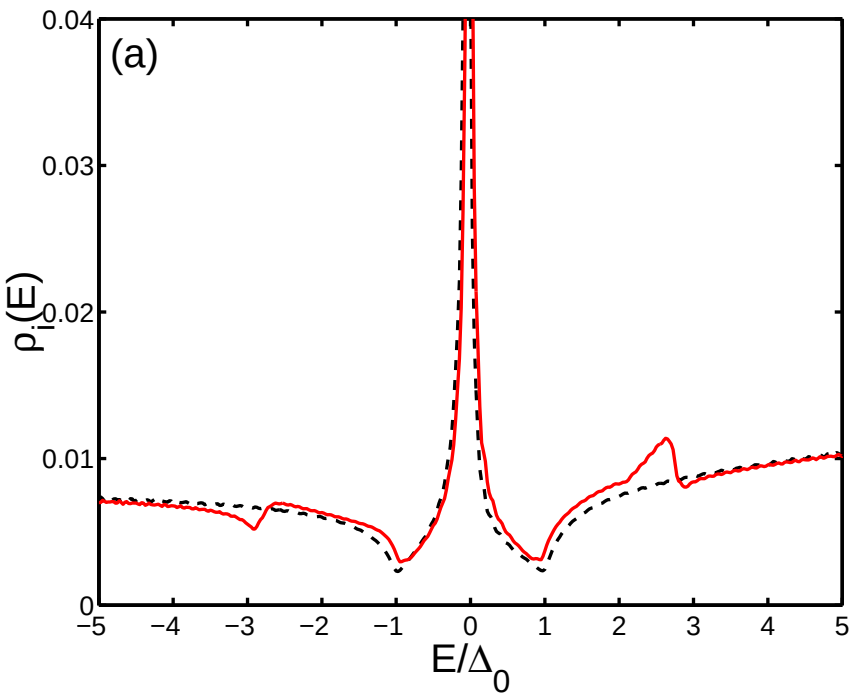


$t = 1.0,\ t' = -0.2,\ \Delta = 0.1,$
$\Omega_0 = 1.5\Delta$

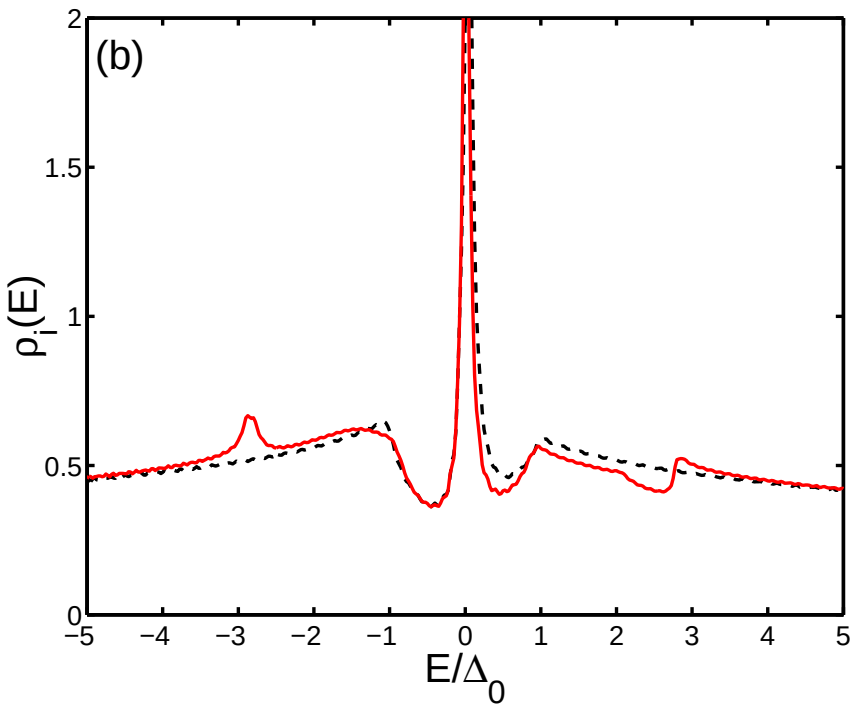
Features at $\pm(\Delta + \Omega_0)$

Local density of states

$$U_0 = 100\Delta,\ g = 3\Delta_0$$



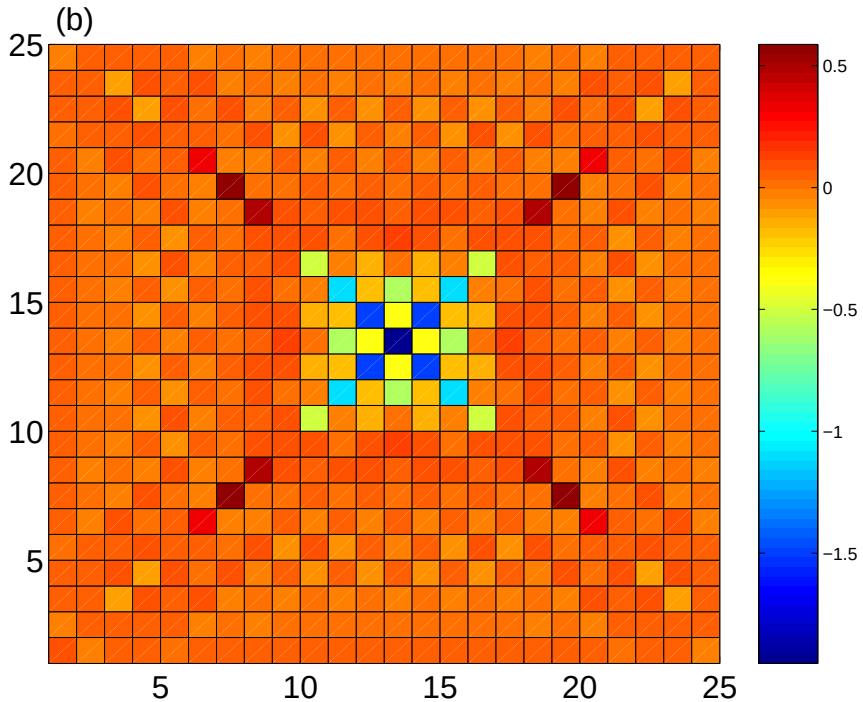
$$\mathbf{r} = (0, 0)$$



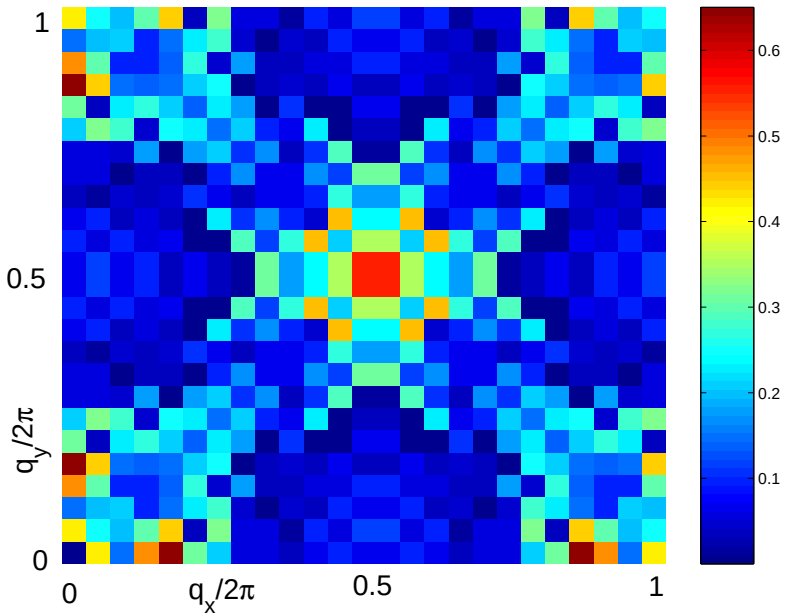
$$\mathbf{r} = (1, 0)$$

LDOS at $E = -\Delta - \Omega_0$

Difference of LDOS for $g = 3\Delta$ and $g = 0$
$N = 1000$



Fourier transform of LDOS
Peak at $\mathbf{Q} = (\pi, \pi)$



Conclusions

- Inelastic STM spectroscopy can be used to detect the collective modes in the Strongly Correlated Systems
- It can be used to extract both energy and momentum of the modes
- In High T_c it can be used as a probe complimentary to INS
- A collective mode can be found without a priori knowledge of the nature of the mode