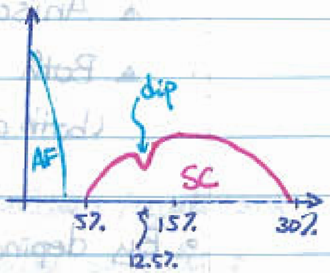
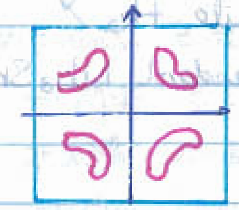
STM on high-T_c superconductor [Yandazi]

- Result: pairing in Cuprate is highly local

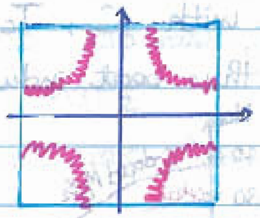


- All cuprates come with Cu–O plane.

- From photoemission, for $T > T_c$



underdop



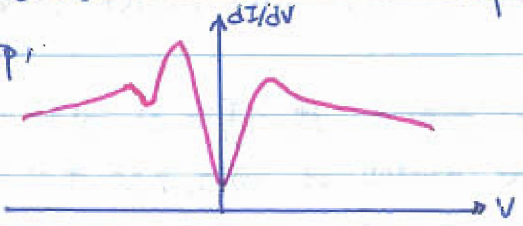
overdop

- Theoretically, Hubbard (to lesser degree t-J) model is thought to be good description of physics
  - ▲ Proposed state is Anderson's RVB. — shown to gives d-wave.
  - ▲ Not clear if an electron-boson coupling picture is reasonable a not.

- Big question: when (at what T) does Cooper pairs form?

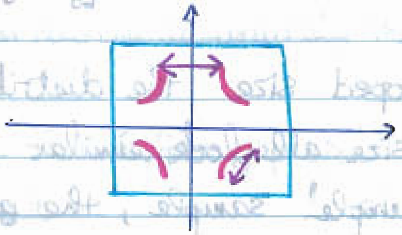
- d-wave is very sensitive to surface quality

- Consider $Bi_2Sr_2CaCu_2O_{8+d}$ (easy to cleave)
  - ▲ For overdop, get:

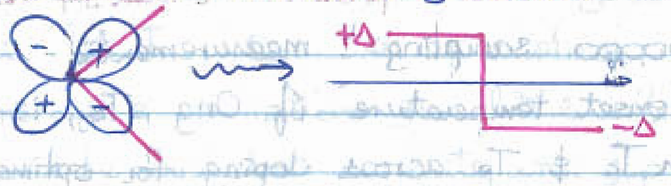


  - ▲ Strong variation of spectrum across space

- This produces inhomogenous gap map.
  - ▲ For large enough samples, gap distribution is highly reproducible.
  - ▲ Length scale of variation ~ 20–30 Å
  - ▲ Typical plot has 256 × 256 pixels, need ~3 days to take.
  - ▲ The conductance map becomes almost uniform as energy approaches $\mathcal{E}_F$ (i.e. towards node).
    $\Longrightarrow$ quasiparticles at nodes are not scattered.
  - ▲ Fourier transform gives interference peaks:



    - ▶ Intrepret as coming from scattering at end of arcs (highest density of state).
  - ▲ There are 2-dimensional zero-mode on surface of sample



    $\Longrightarrow$ Andreev bound state

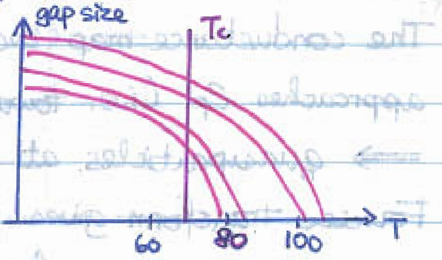
    $\Longrightarrow$ zero bias peaks appear.
    - ▶ Similar effect occurs need impurity.

- Consider the inhomogenous gap map, want to know what happens
  - ▲ Sample ~mm. Heating $\Longrightarrow$ μm expansion
    But need nm resolution.
    $\Longrightarrow$ Need atom tracking spectroscopy.
  - ▲ Gaps at different size at low T disappears at different "T_c". (i.e., non-uniform closing of gap).

▲ Repeat heating-cooling reproduces the same gap map. And variation of gap size does not change its length scale as $T \rightarrow T_c$ (c.f. coherence length, which diverges as $T \rightarrow T_c$)

• If we take $[dI/dV]_{sc} / [dI/dV]_N = R$ across different spots, then we see:

$\Longrightarrow$ different region has different local T_c.



▲ On the overdoped size, the distribution of gaps nomalized to mean gap size all look similar

▲ For optimally doped sample, the gap size distribution changes very slightly across T_c.

▲ Found $\frac{2\Delta}{k_B T_p} = 7.9 \pm 0.2$ on optimal-overdoped side

gap well below T_c

temperature where local gap disappears.

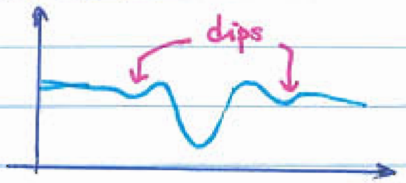
▲ ~ 1000,000 independent measurements.

▲ The "onset temperature" of Ong, T_{Ong}, is about 50% between T_c & T_p across doping for optimal-overdop side of phase diagram.

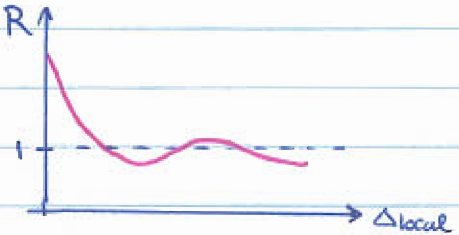
• On underdop side, the spectra becomes bizzare (doesn't fit well to conventional d-wave)

• In underdop samples there are also energy-independent interference peaks.

- Recall that $R = [dI/dV]_{sc}/[dI/dV]_N$ shows dips left & right of gap
  - ▲ May indicate some e^-—boson coupling.



  - ▲



  - ▲ Found no significant correlation between possible electron—boson coupling & gap size
    - $\Longrightarrow$ e^-—boson pairing is unlikely the cause of local gap inhomogenity

- Possible effects that affect gap size (correlation weak)
  - ▲ structural features
  - ▲ Dopants/impurities. ($C_r \sim -0.2$)

- dI/dV at ϵ_F for $T > T_c$ correlate negatively with the gap map at low T ($C_r \sim -0.7$) on optimal-overdop side
  - ▲ Turns out e^- excitations give little information while hole-like excitation correlate with gap size.
    - $\Longrightarrow$ electron-hole asymmetry.
    - (results of Mott physics?)

- Across T_c, the only noticable change is that at low energy the quasiparticles are no longer "ignorant" about local inhomogenity