DIP meeting report – Technion , March 2013

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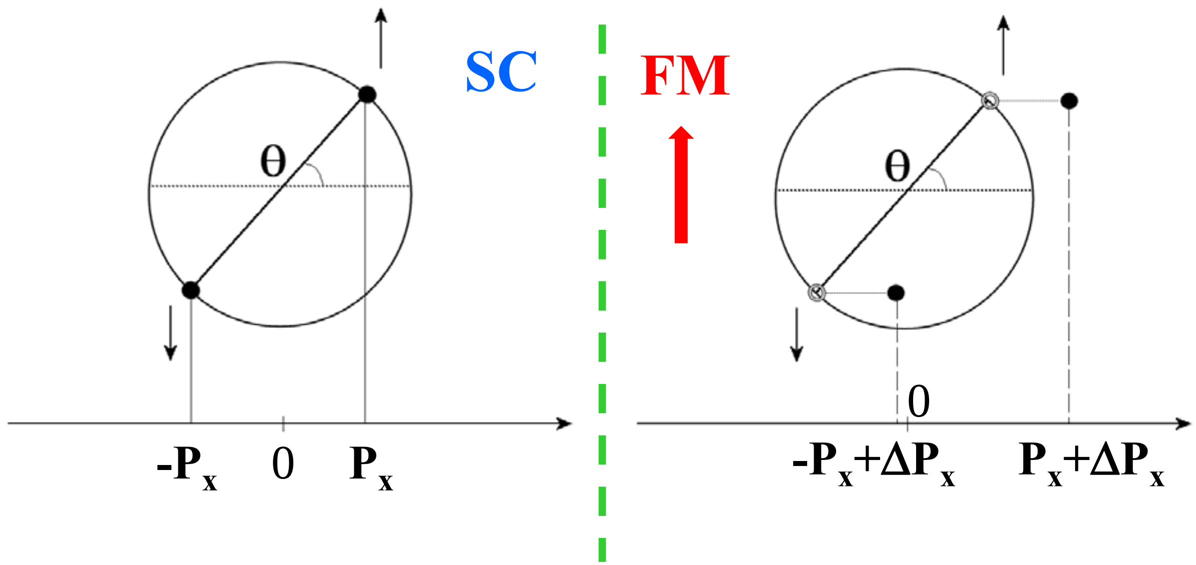
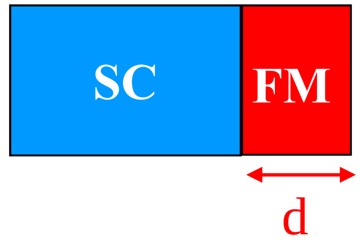
Est. 1925

PE in SC-F junctions: the FFLO mechanism





$$\Delta P_x = \frac{E_{ex}}{v_F \cos\theta}$$

Clean limit: Order parameter ~ $\sin(d/\xi_F)/(d/\xi_F)$; $\xi_F = \hbar v_F / 2E_{ex}$

Dirty limit: Order parameter ~ $\exp(-d/\xi_F)\cos(d/\xi_F)$; $\zeta_F = (\hbar D/2E_{ex})^{1/2}$

ξ_F ~ nm (typically)

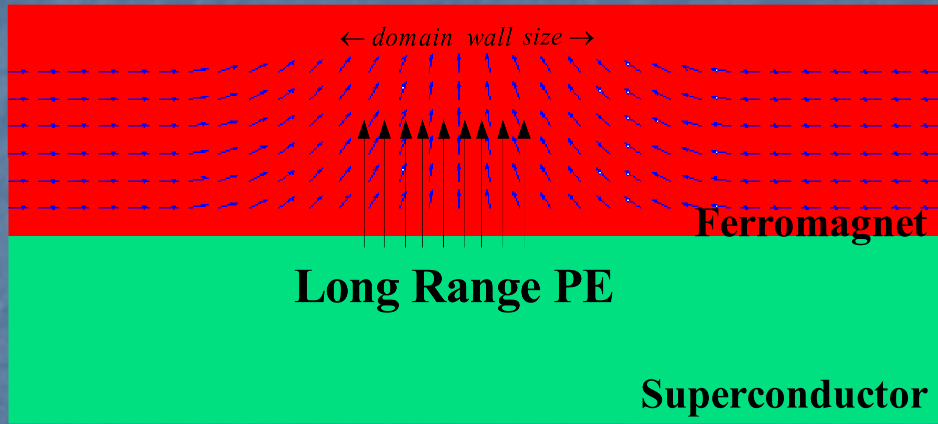
Oscillations and decay of SC properties observed in many cases

Long-ranged PE in S-F bilayers: 1. Crossed Andreev reflections at DWs?
2. Proximity induced triplet pairing.

Proximity induced triplet-pairing at F-S interfaces

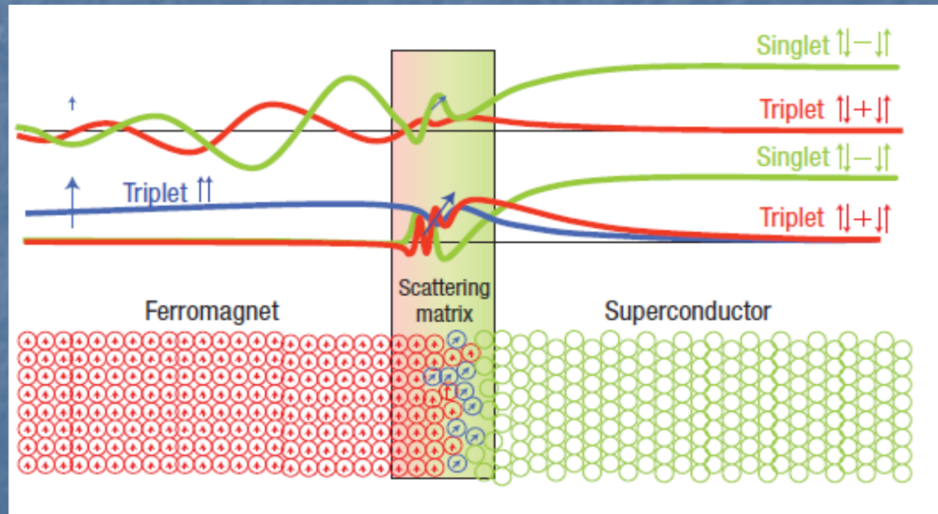
- Magnetic inhomogeneity may cause triplet pairing (e.g., DWs).

A. F. Volkov and K. B. Efetov, Phys. Rev. Lett. 102 (2009)

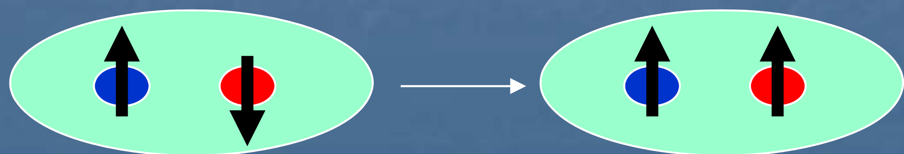


- Spin active interface + interface magnetization different than in the bulk.

M. Eschrig et al., Phys. Rev. Lett. 90, 137003 (2003)



Triplet pairing:



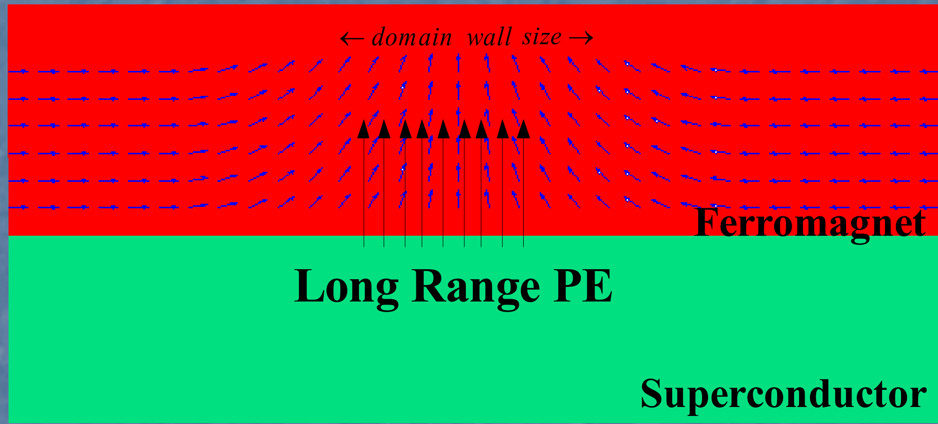
The symmetry of the induced triplet order parameter

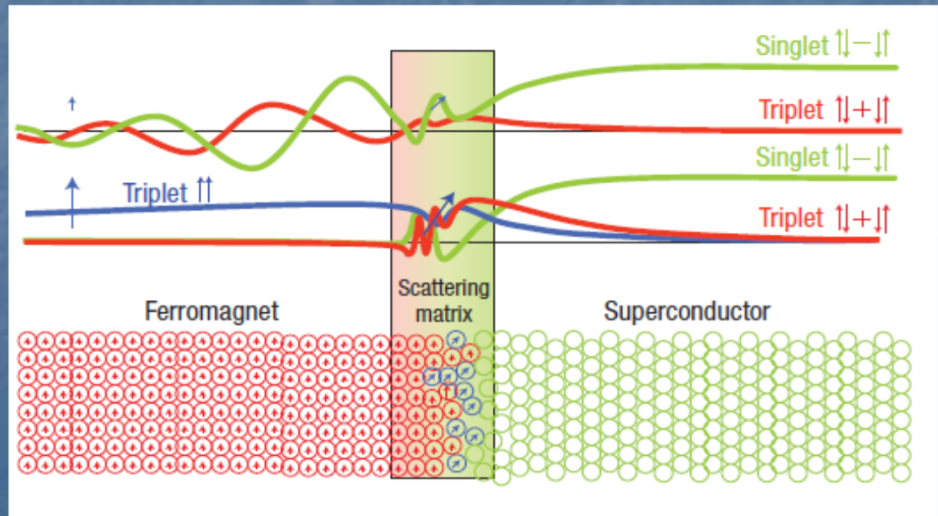
Odd-frequency triplet: *s*- or *d*-wave

Even-frequency triplet: *p*-wave

Note:

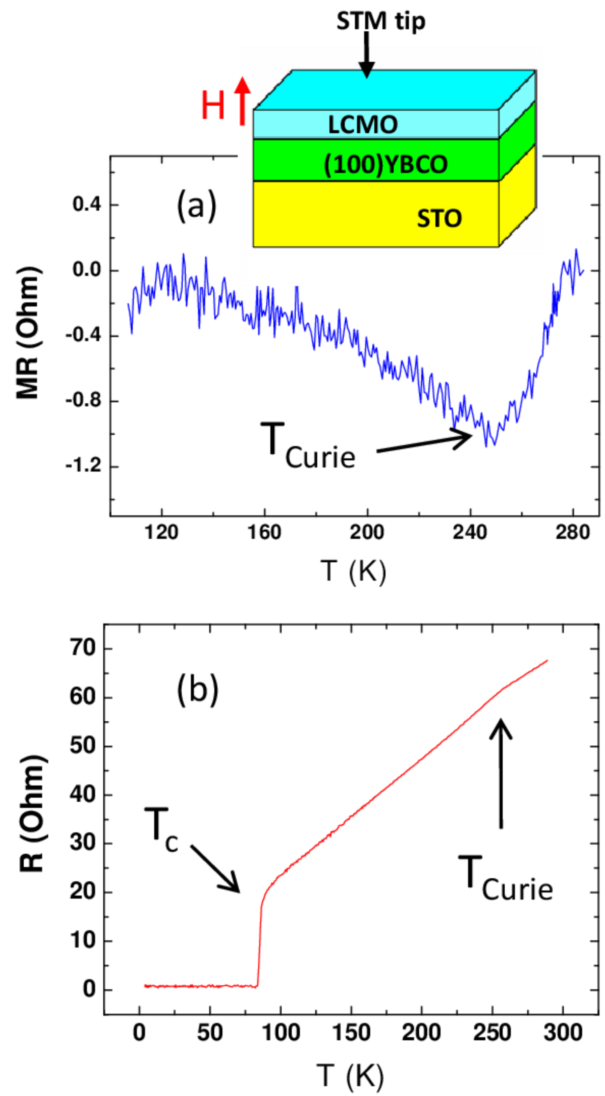
Anisotropic order parameters are sensitive to disorder.





$La_{2/3}Ca_{1/3}MnO_3$ (LCMO)/(100)YBCO bilayers

- LCMO:
- Domain walls of ~20nm at 4.2K ($\gg \xi_S$~2nm in YBCO).
  ➔ CARE suppressed.
- Good lattice matching between LCMO and YBCO
  ➔ high interface transparency.
- Our samples: Epitaxially grown (15-50nm) LCMO layers on 135nm (100)YBCO.



Y. Kalcheim, et al., Phys. Rev. B 83, 064510 (2011)

Overview of spectral features

Non superconducting:

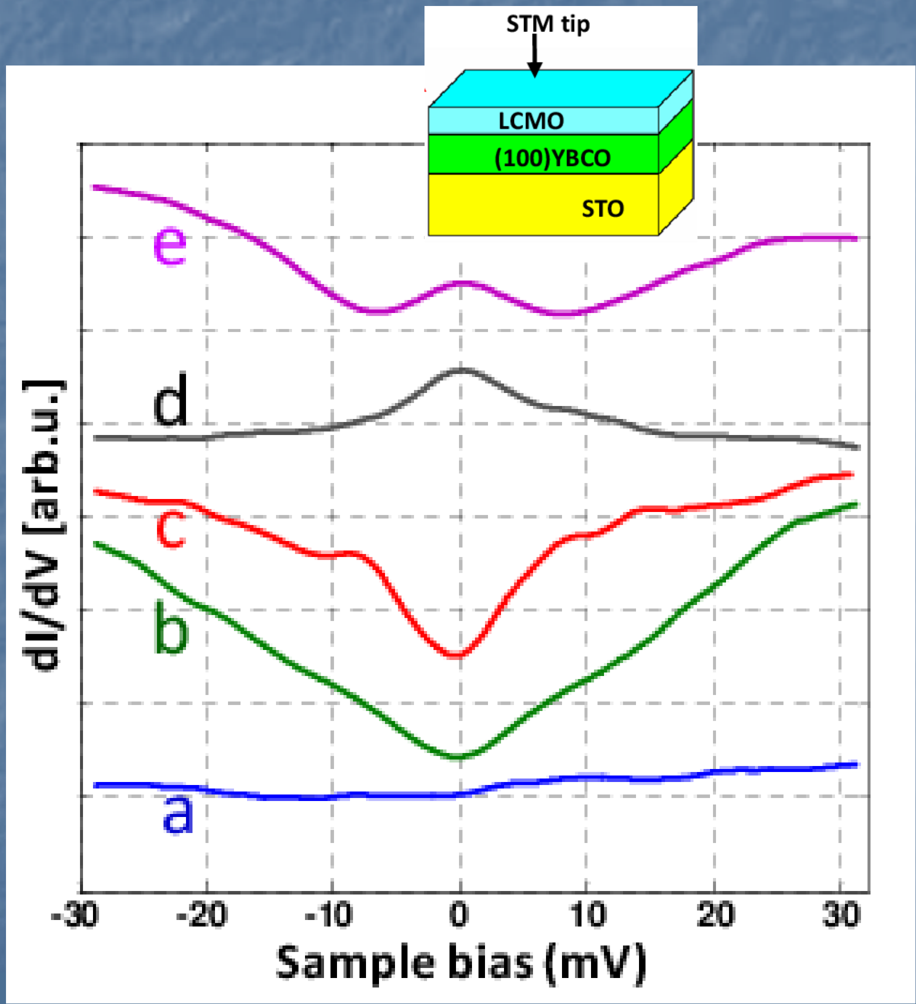
- a) metallic-like spectra.
- b) insulator-like wide gaps.

  S. Chen et al., APL. 82, 1242 (2003).

Induced superconductivity:

- c) proximity induced superconducting gap.
- d) and e) – zero bias conductance peaks - hallmark of a sign changing order parameter.

• Penetration depth much larger than the expected $\zeta_F = (\hbar D/2E_{ex})^{1/2}$

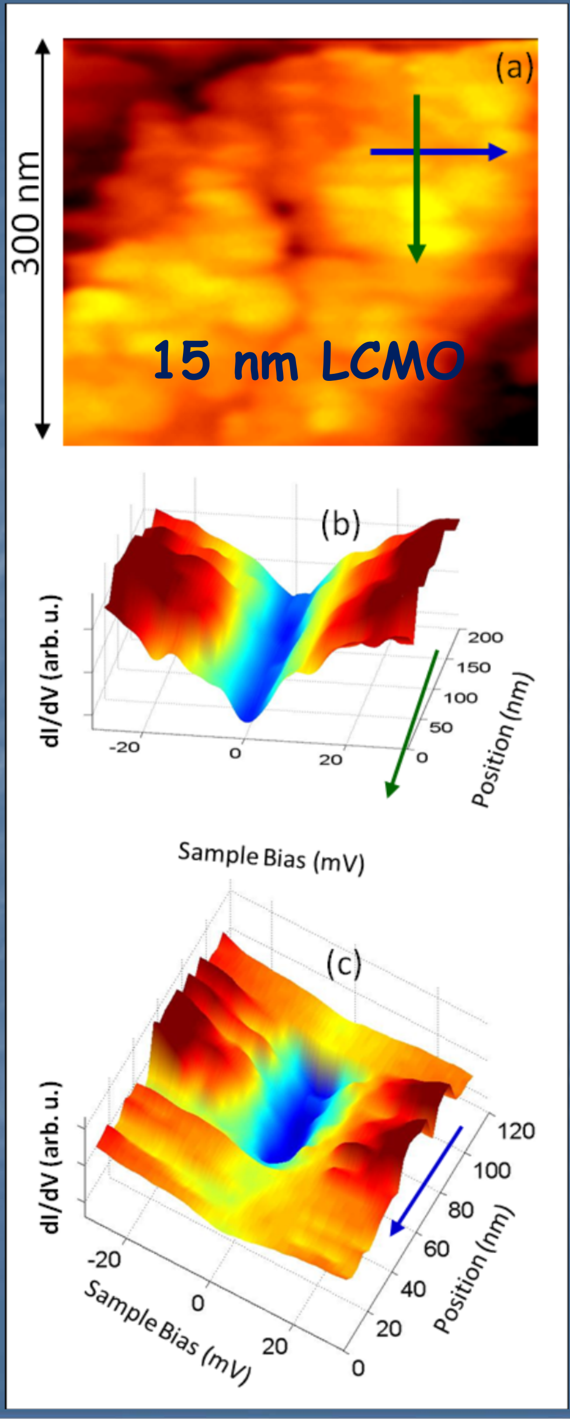


[a-d] - 17nm LCMO, [e] – 30nm LCMO

Localized gaps – domain walls?

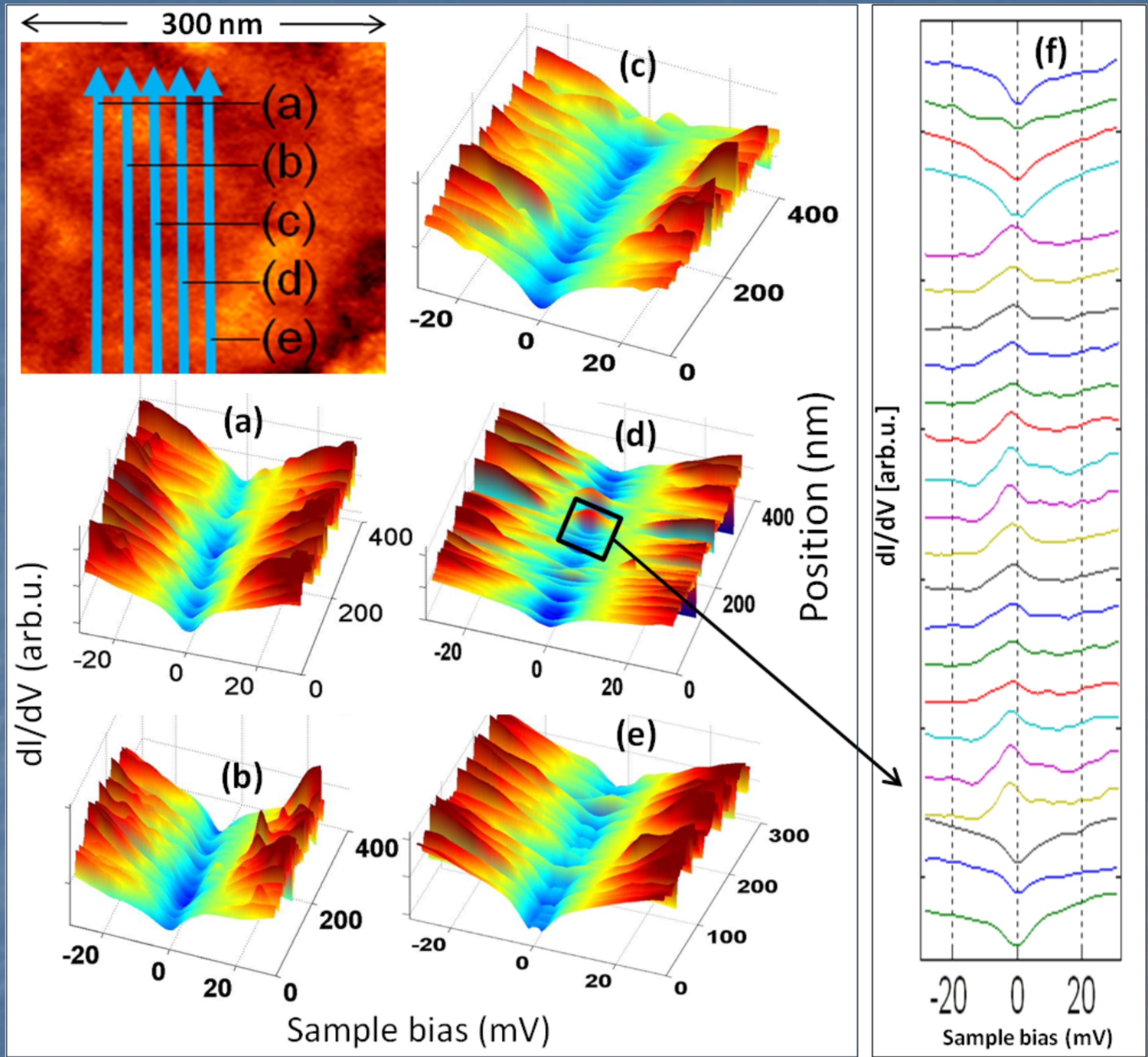
- On few occasions gaps appeared along well defined lines of a width on the order of the LCMO domain walls.
- CARE cannot account for gaps in regions 20 times larger than YBCO's coherence length.

Triplet SC via Efetov & Volkov?



Non-localized SC-like spectral features

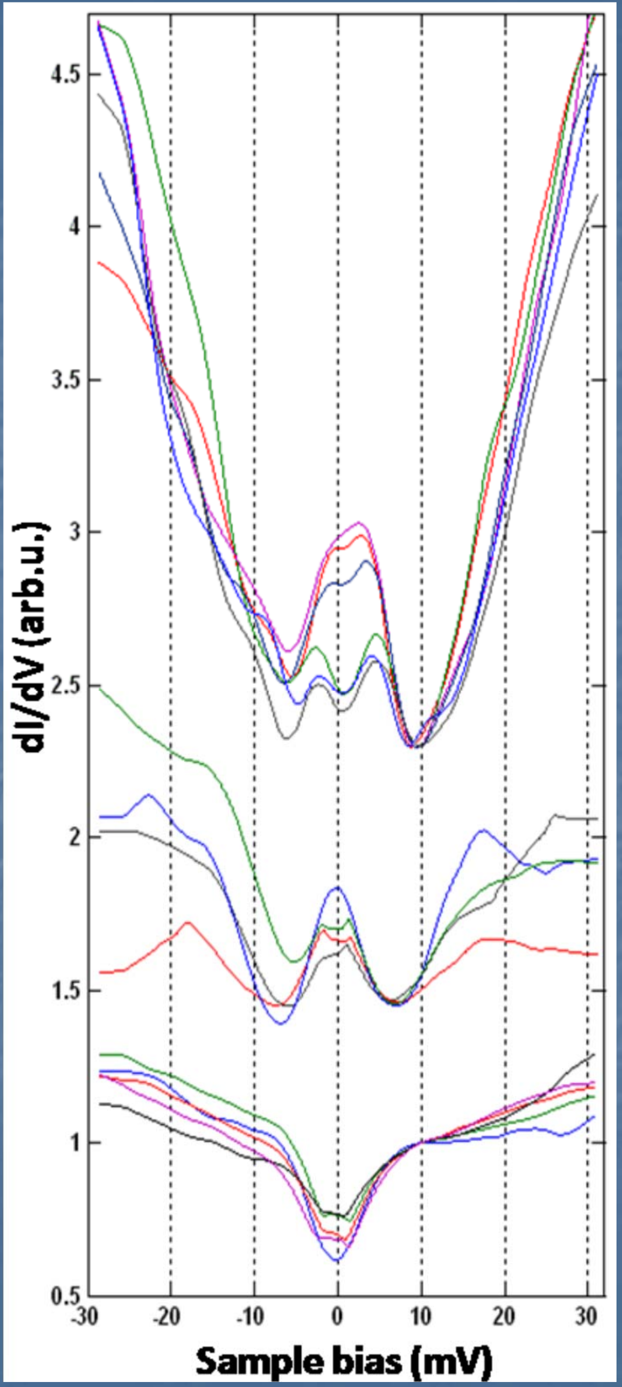
17 nm LCMO



- Not confined to DWs – evidence for Eschrig's model.
- ZBCPs – evidence for *p*- or *d*-wave order parameter.

Zero bias conductance peaks

- ZBCPs were commonly found embedded within gaps.
- ZBCP splitting was also observed.
- No correlation with topography.

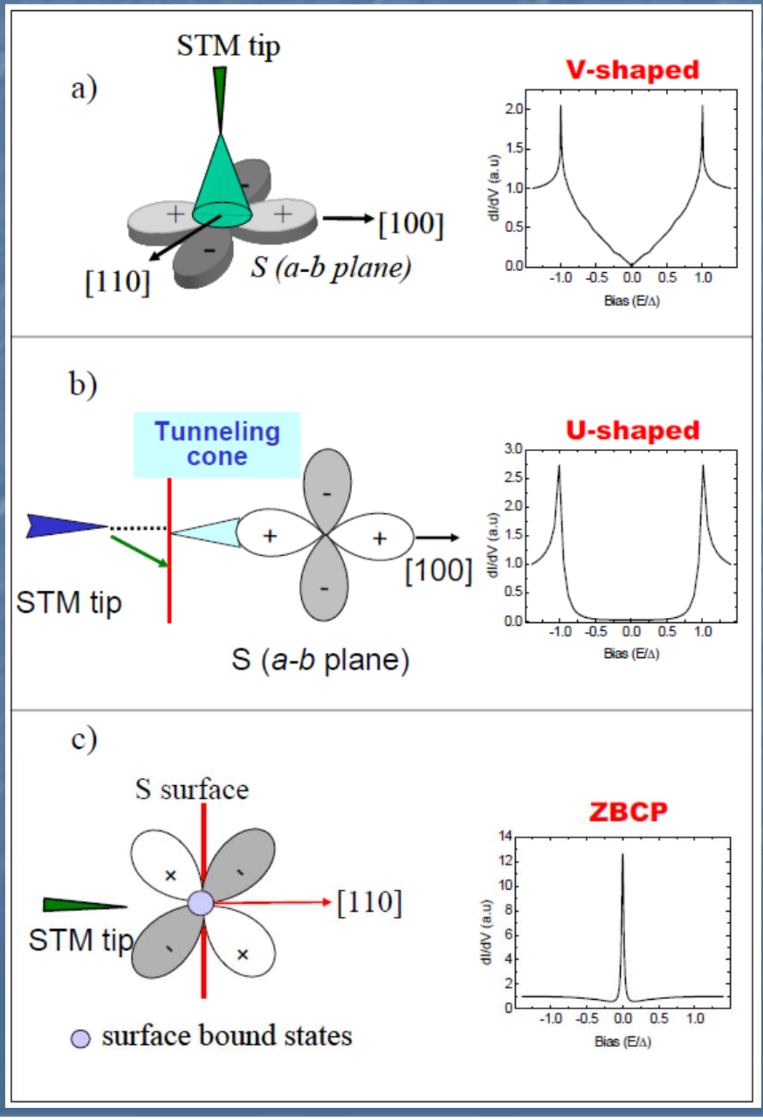


Y. Kalcheim, et al., Phys. Rev. B 83, 064510 (2011)

Possible symmetry of the order parameter

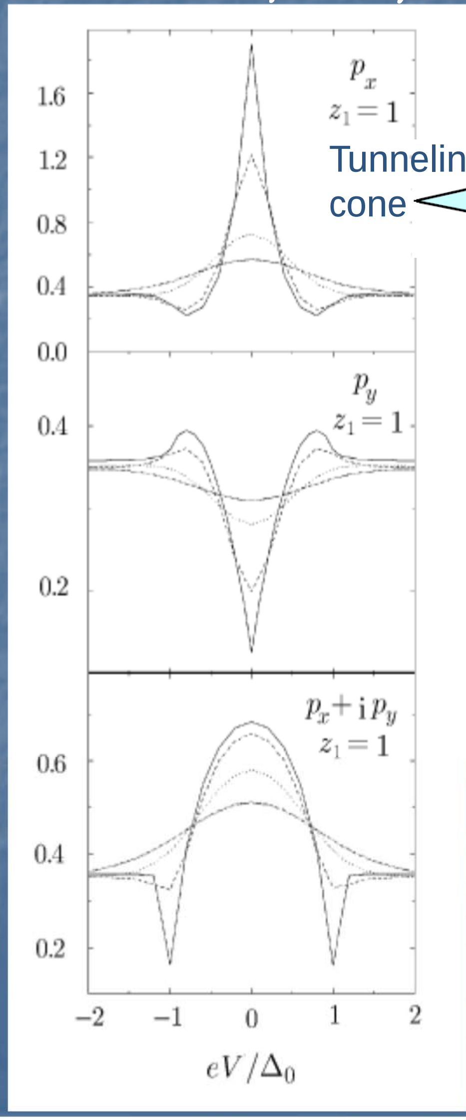
d-wave

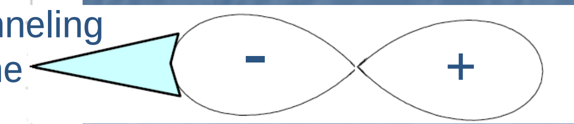
(odd frequency)



p-wave

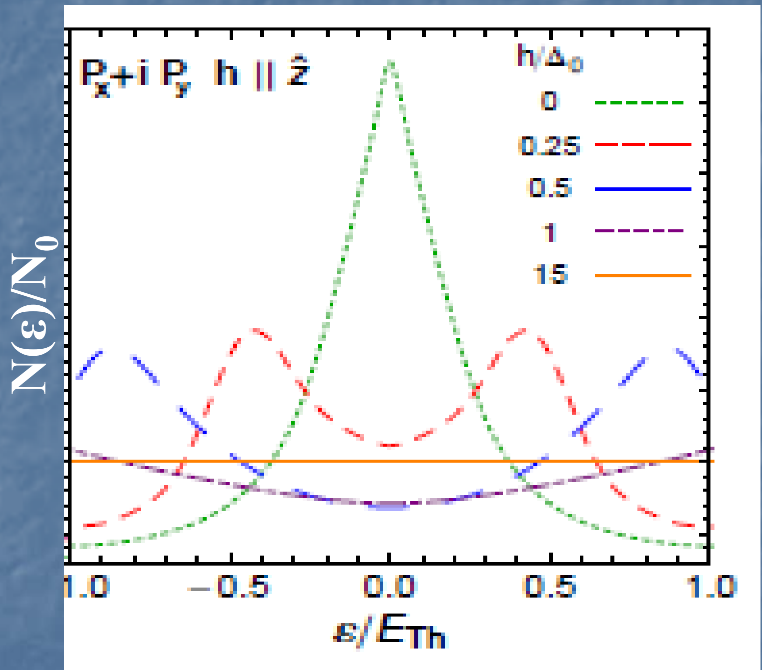
(even frequency)



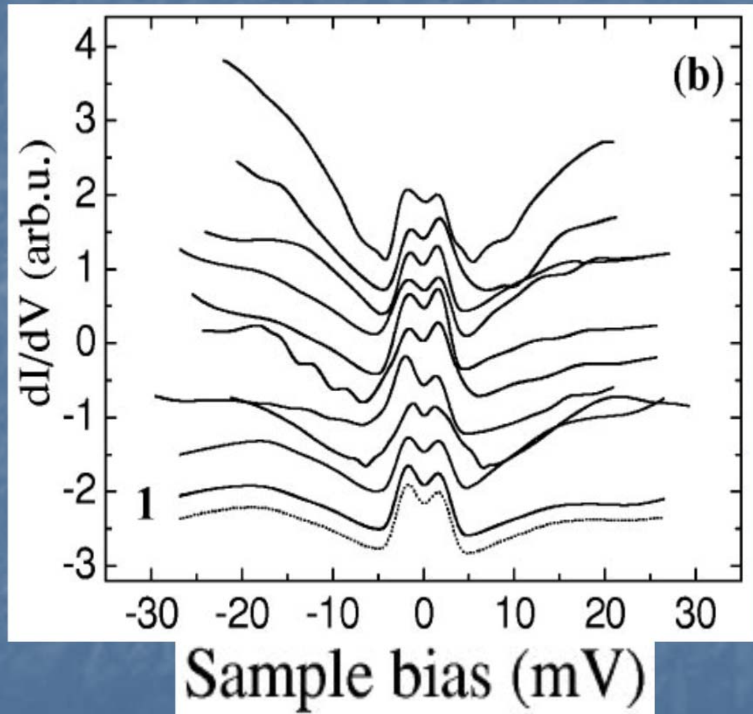


ZBCP splitting

$P_x + iP_y$



$d_{x2-y2}+id_{xy}$ or $d+is$



G. Annunziata, M. Cuoco, C. Noce, A. Sudbo, and J. Linder, arXiv:1009.3014 (2010).

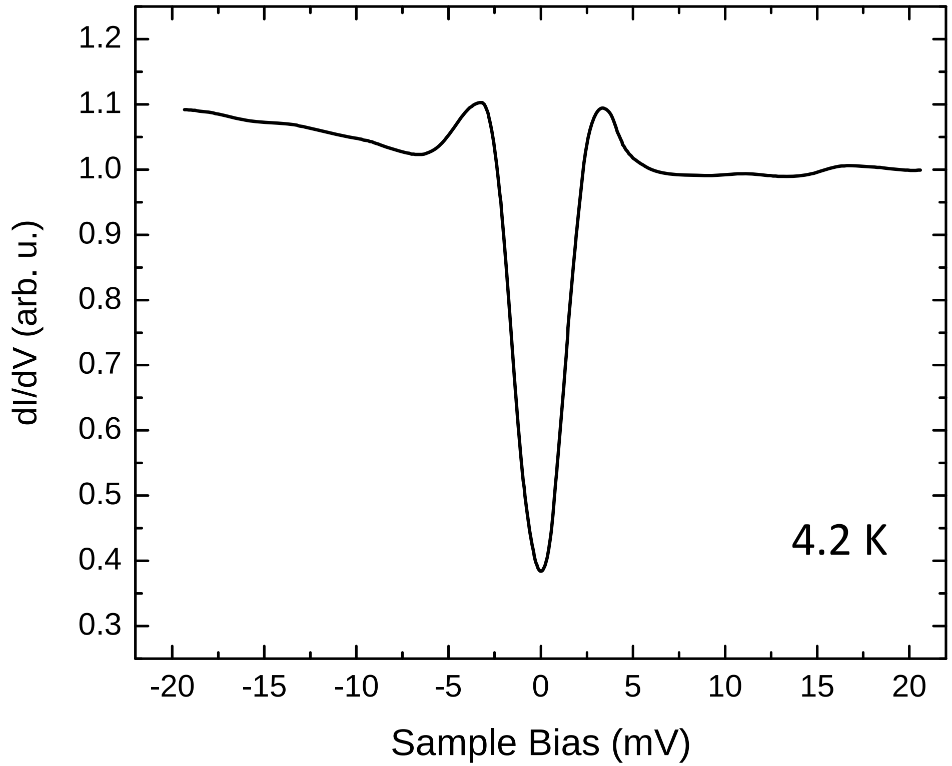
Sharoni et al., Phys. Rev. B, 65, 134526 (2002)

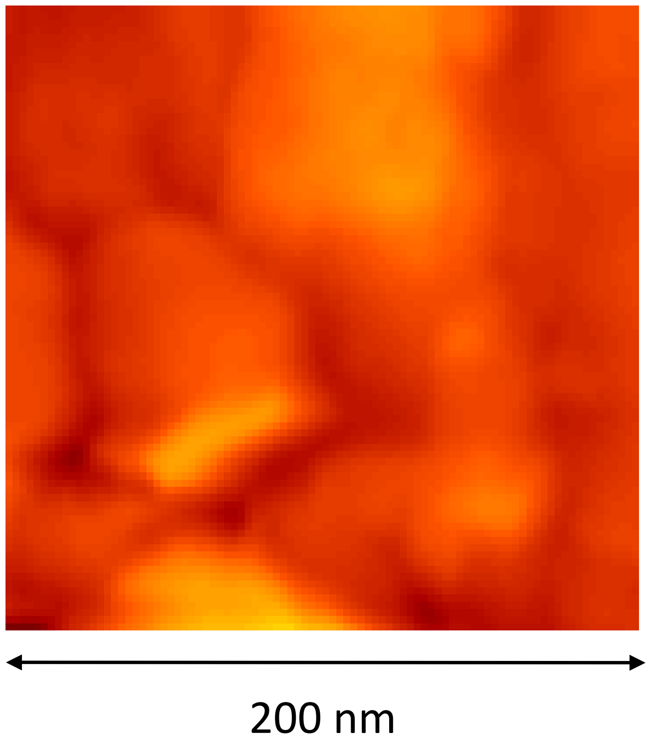
Do the ZBCP features reflect the underlying d-wave symmetry of the YBCO or do they reflect the genuine symmetry of the induced order parameter?

Is the induced order parameter intrinsically anisotropic (*d*-wave or *p*-wave)?

Study bilayers with the e-doped $Pr_{1.85}Ce_{0.15}CuO_4$ (PCCO) HTSC (d-wave SC that does not show ZBCPs)

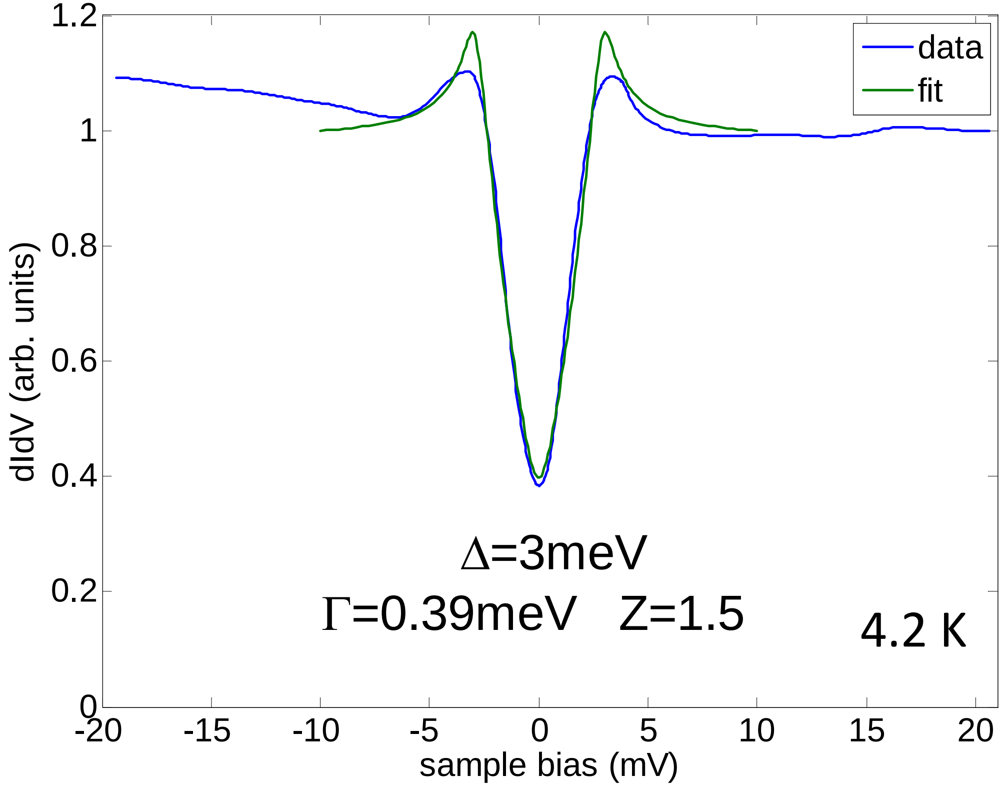
Spectrum measured on the bare PCCO film

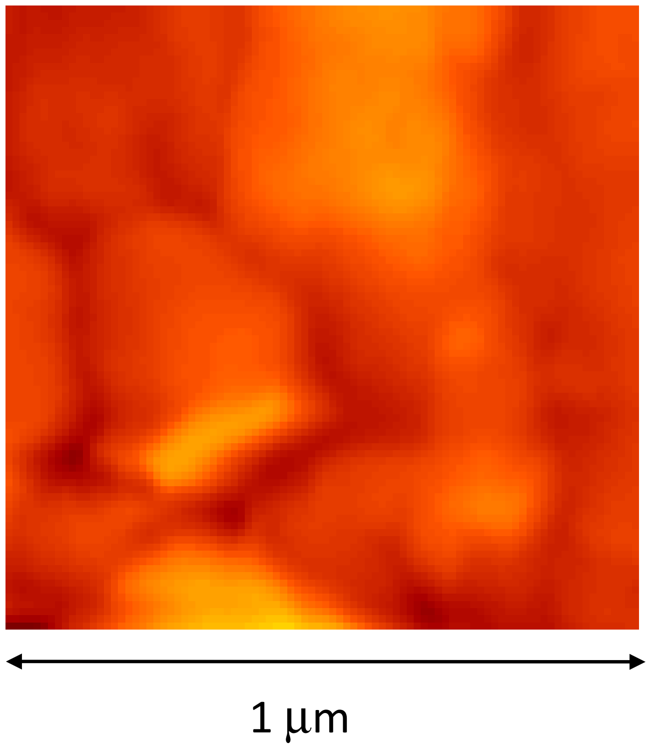




- Only gaps, $\Delta \sim 3$ meV.
- No ZBCPs observed ; not on top of crystallites nor on facets

Fits to tunneling model into a *d*-wave SC

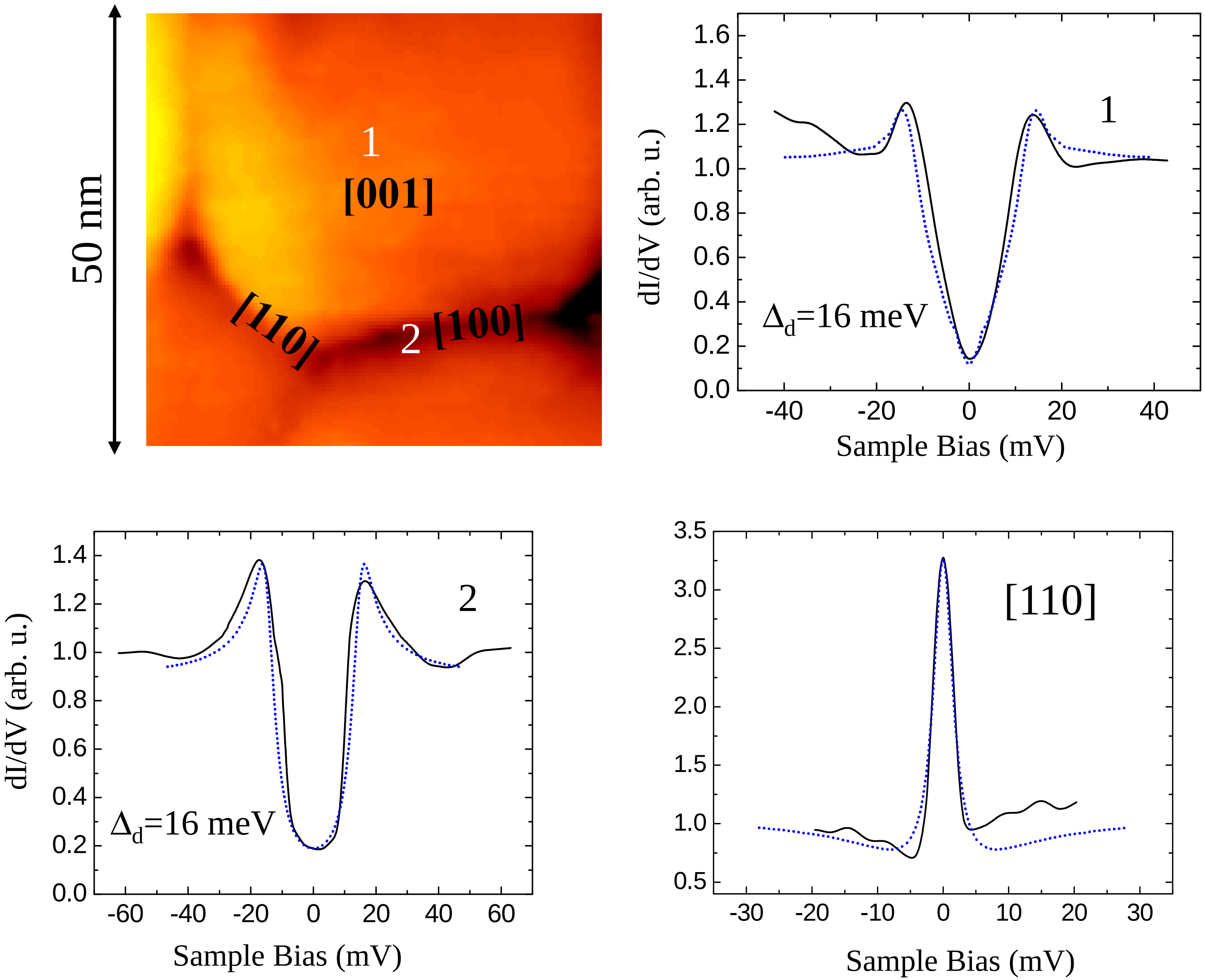




- Only gaps, $\Delta \sim 3$ meV.
- No ZBCPs observed ; not on top of crystallites nor on facets

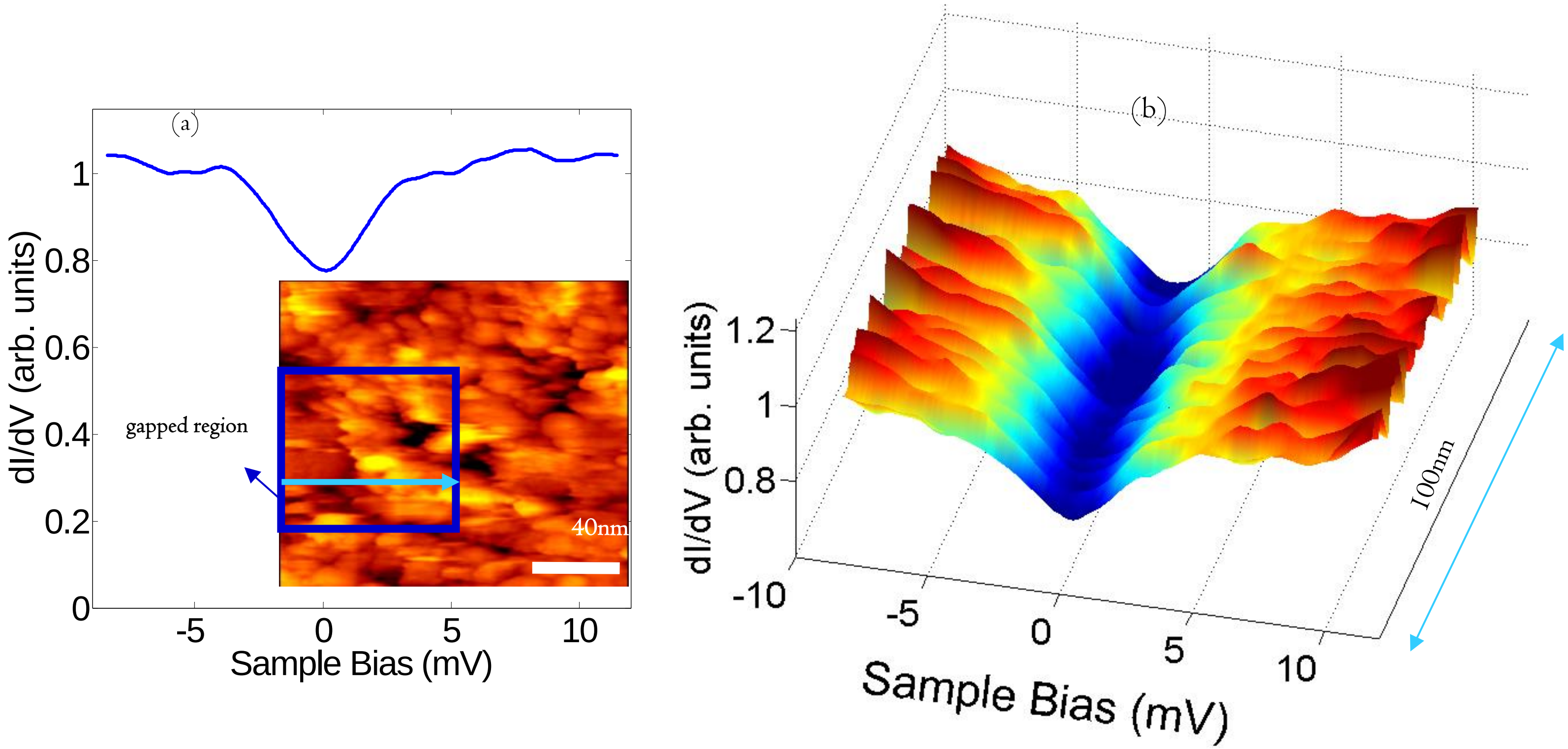
Correlation between spectra and surface morphology (*c*-axis)

YBCO



A. Sharoni *et. al., Europhys. Lett.*, **54**, 675 (2001).

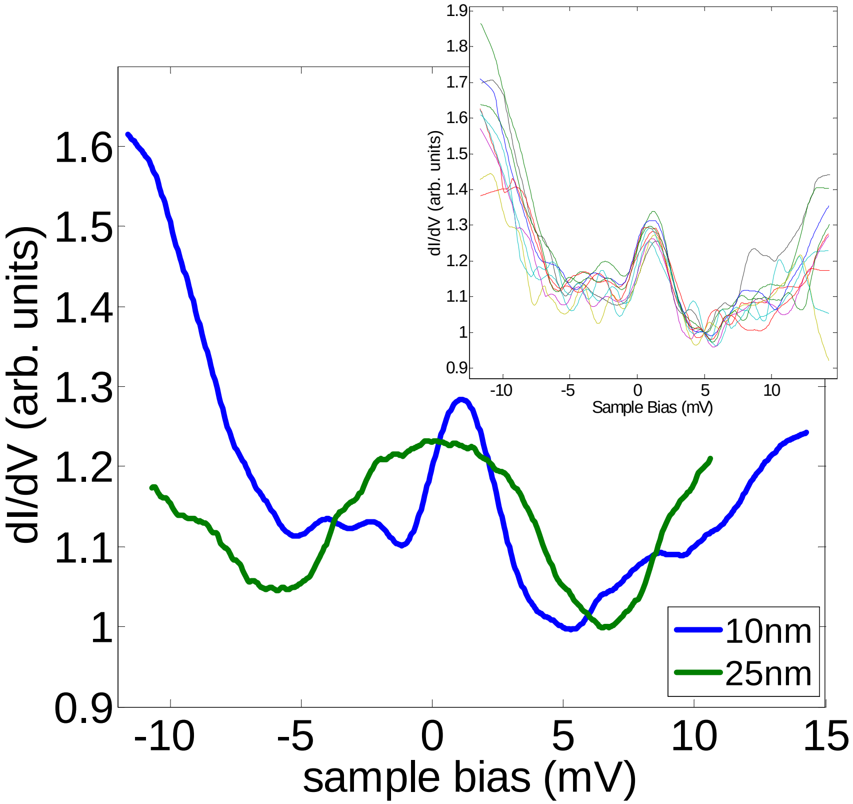
STS on 15 nm LCMO on PCCO bilayer

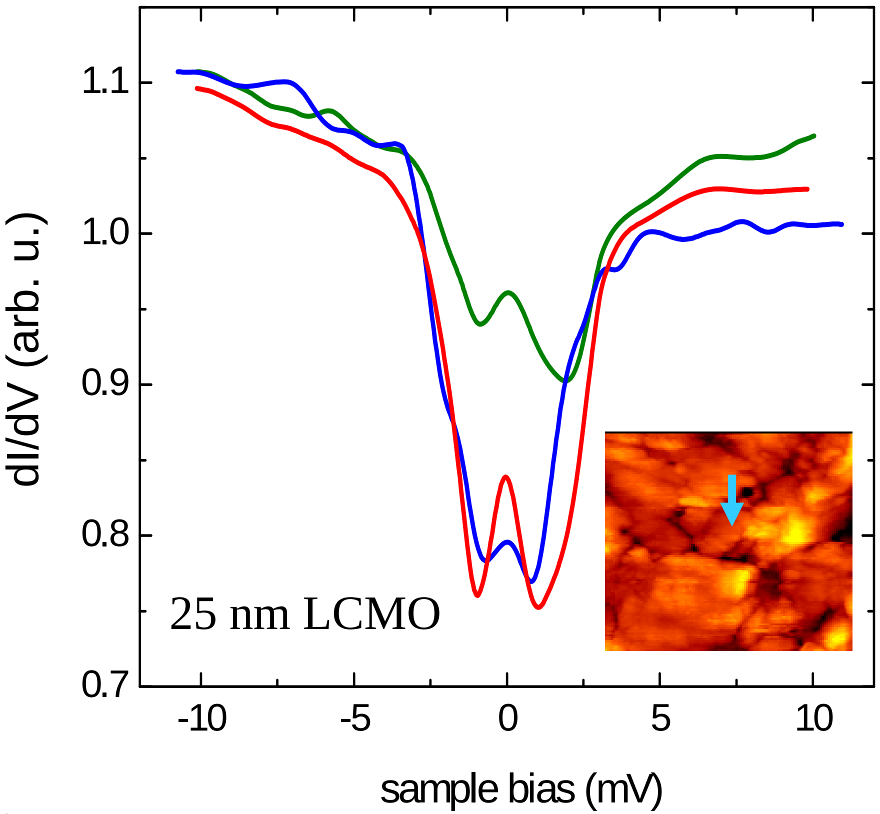


- Most typically: gapped regions within metallic regions.
- Gaps found up to LCMO thicknesses of 25 nm.

Y. Kalcheim, J. Robinson, M. Eglimez, O. Millo, PRB 85, 104504 (2012)

Observation of zero bias conductance peaks





- Appeared less abundantly compared to the gaps
- ZBCP in an intrinsic property of the induced OP.

⇒ The induced OP can be intrinsically anisotropic

Y. Kalcheim, J. Robinson, M. Eglimez, O. Millo, PRB 85, 104504 (2012)

So far:

• Localized long-range proximity effects in LCMO/YBCO and LCMO/PCCO bilayres.

• Results on the LCMO/YBCO and LCMO/PCCO bilayres may be explained by the induction of triplet pairing in the LCMO.

• ZBCPs imply that the proximity induced order-parameter has anisotropic orbital symmetry, *p*-wave or *d*-wave, and even a complex OP ($p + ip$).

Y. Kalcheim, T. Kirzhner, G. Koren, O. Millo, Phys. Rev. B 83, 064510 (2011)

Y. Kalcheim, J. Robinson, M. Eglimez, O. Millo, PRB 85, 104504 (2012)

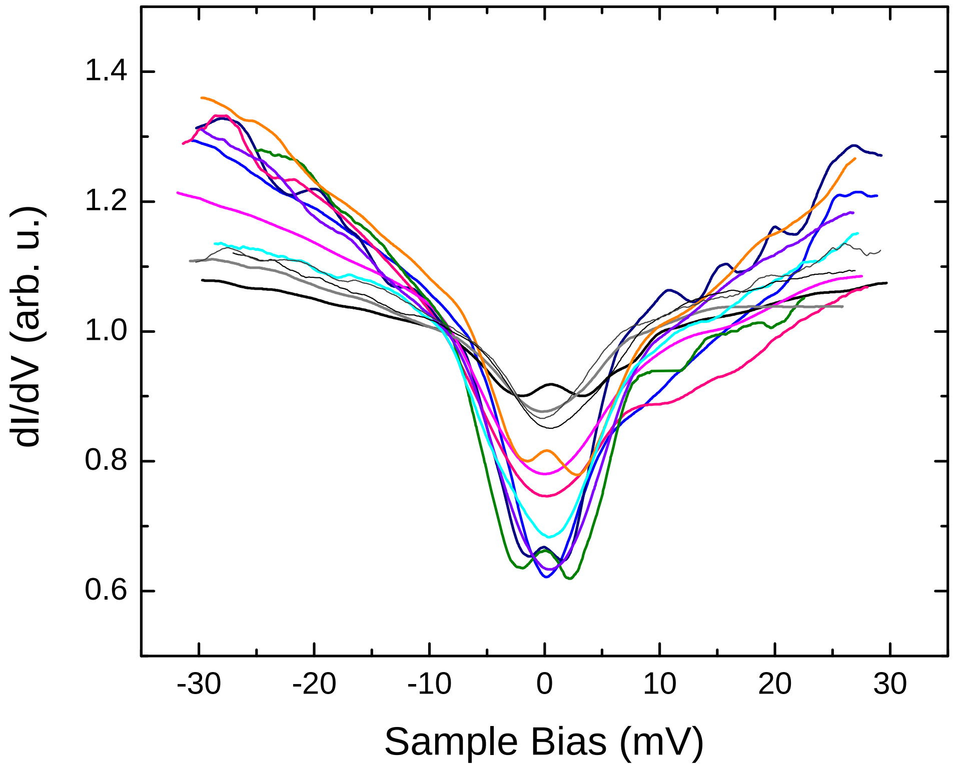
Q?: What is the mechanism leading to triplet-pairing?

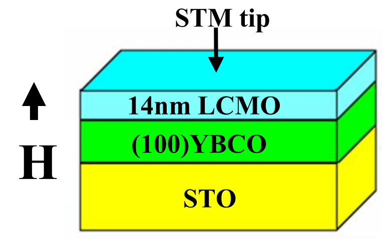
- Look at the effect of magnetic-field application:

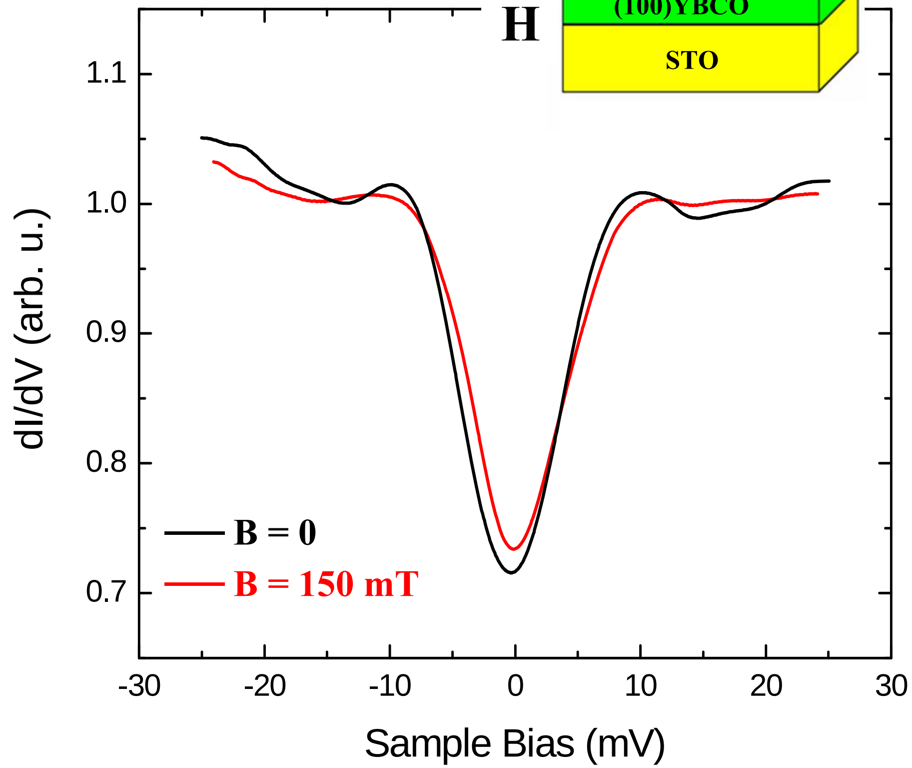
Volkov-Efetov: Proximity effect (triplet-pairing) along DWs – suppressed

Eschrig: Proximity effect (triplet-pairing) – enhanced.

14 LCMO on YBCO



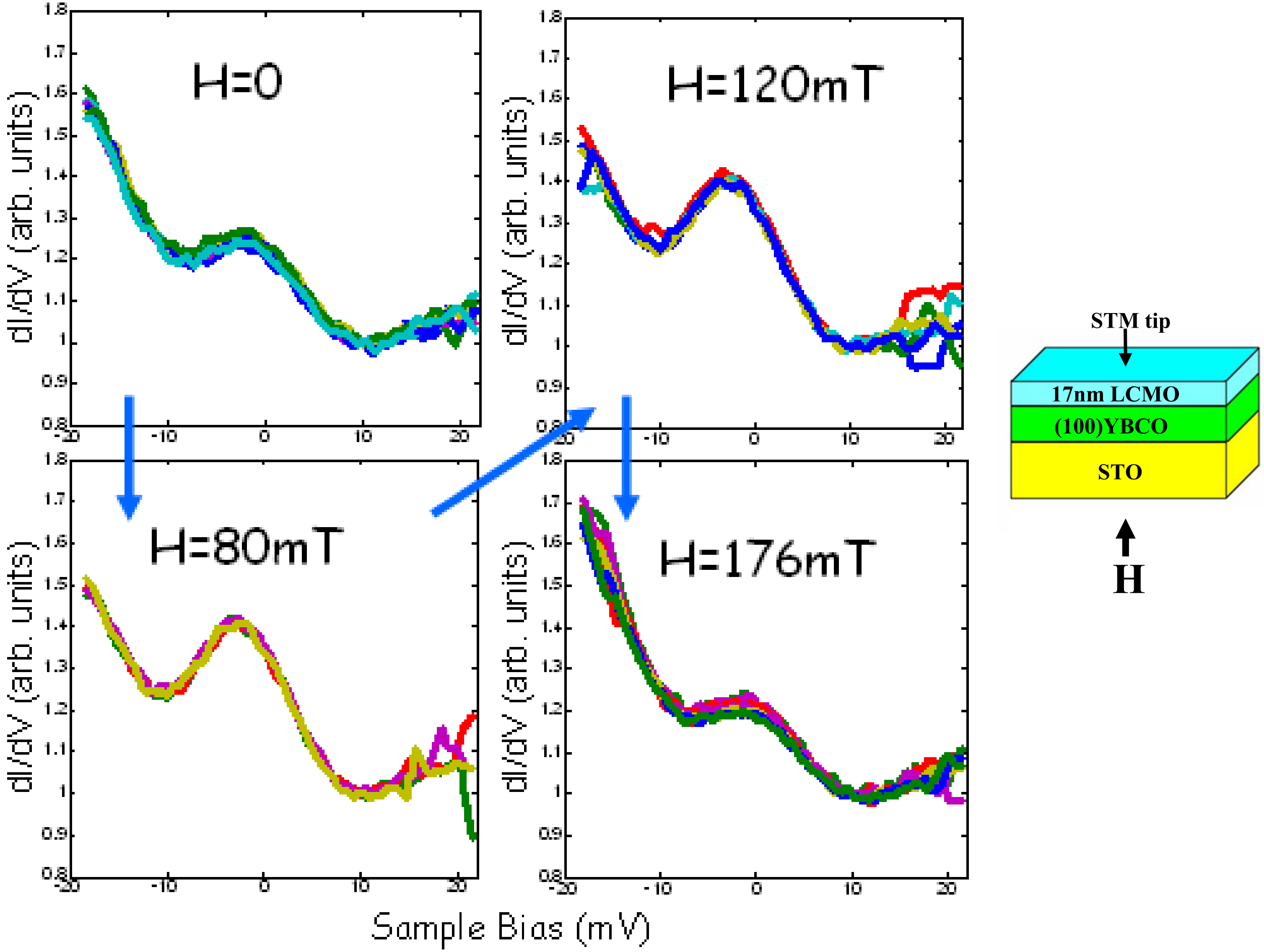




Gray colors – before magnetic field application
"warm" colors – after B = 60 mT
Blue-green colors – after B = 150 mT > B_{sat}

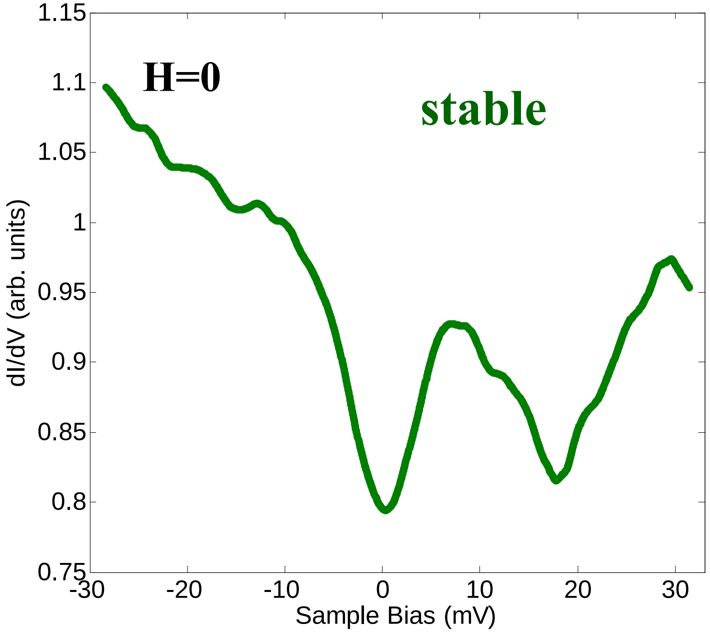
- Application of magnetic field enhances initially (B=0) small gaps, but does not affect much initially large gaps.
- Some ZBCPs appeared, but in this case it seems like that their magnitude and abundance was not affected by the field.

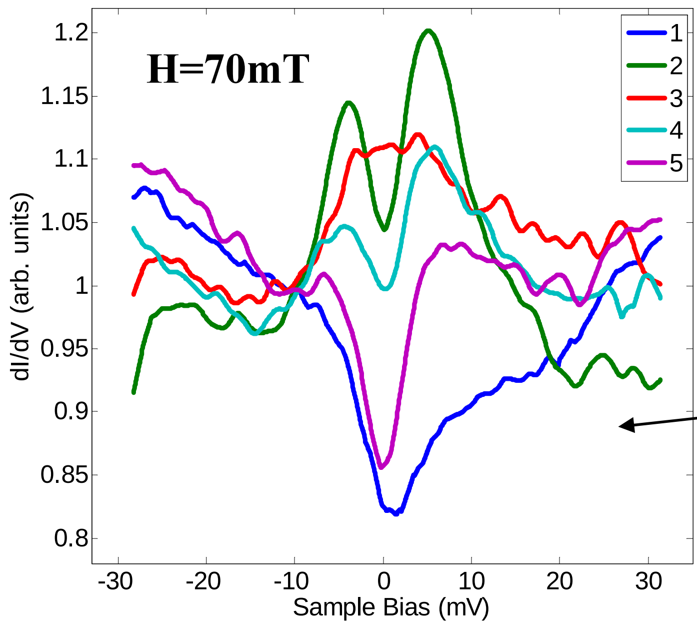
17 LCMO on YBCO

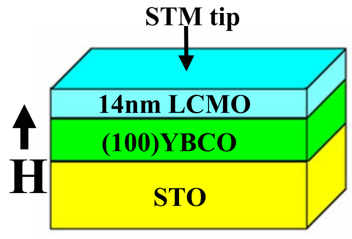


Non-monotonic dependence of the (somewhat shifted) ZBPC on magnetic field. Enhancement up to about the saturation filed and then suppression.

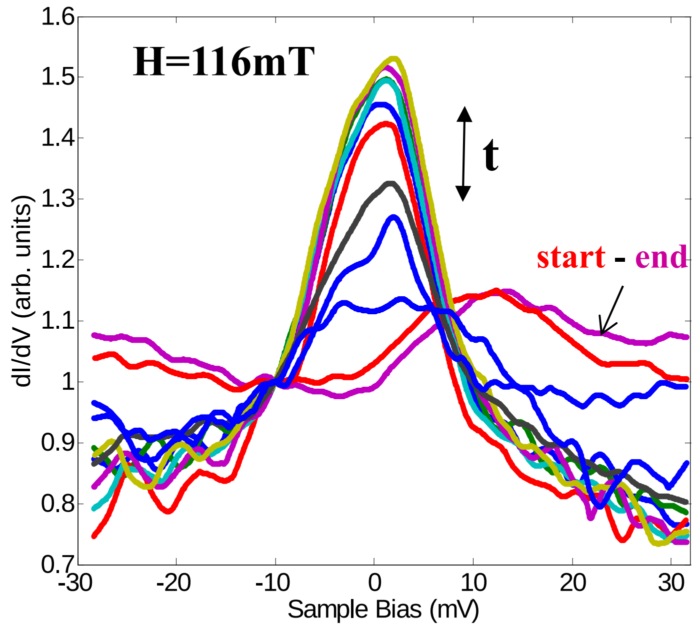
“anomalous” tunneling spectra varying with time under B

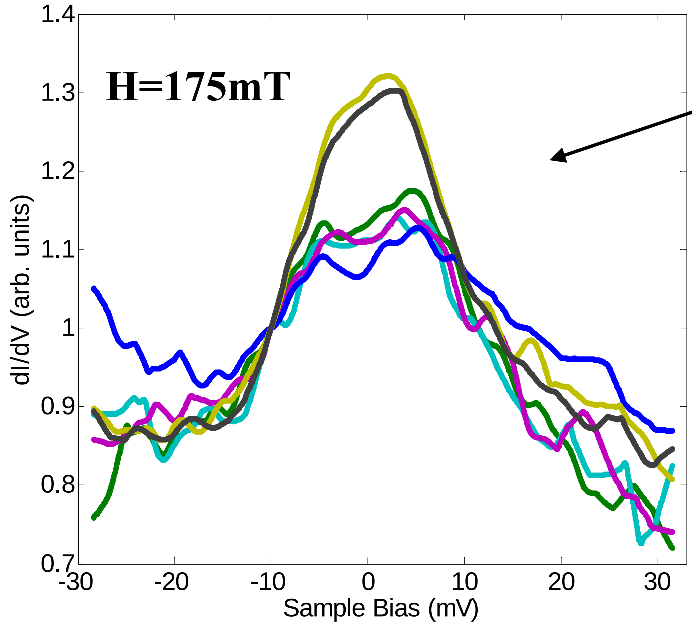






Taken over the course of a few minutes. Each curve represents an average over a set of similar spectra. Delay between each measurement set is tens of seconds/

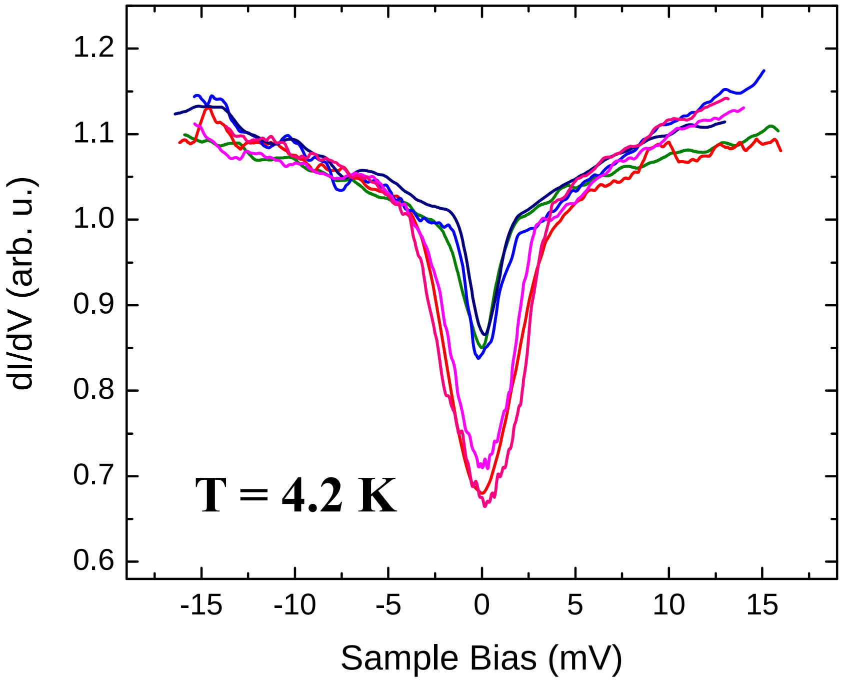


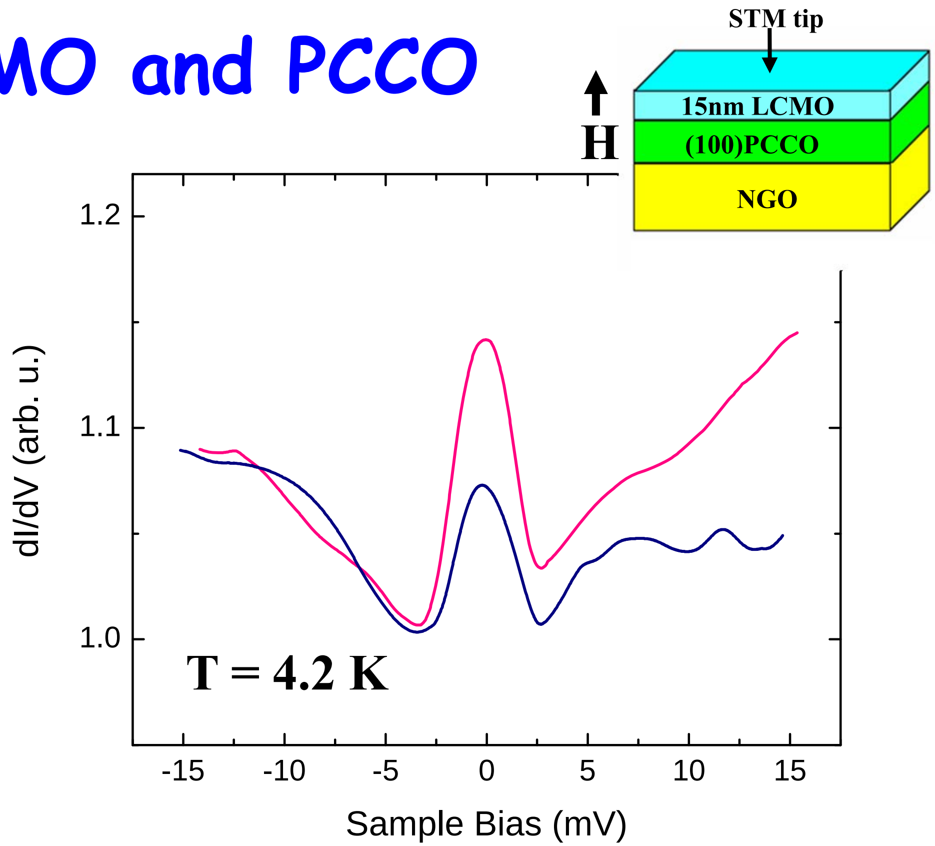


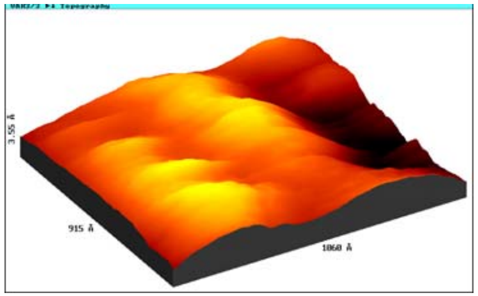
Smaller ZBCPs evolved into the larger ones (green-yellow) within ~ 1 min.

Variations may reflect changes in local magnetization.

15 nm LCMO and PCCO





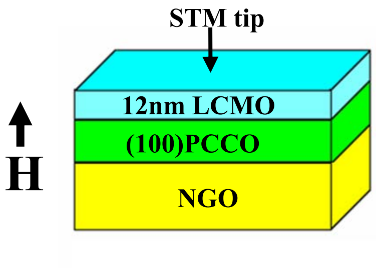


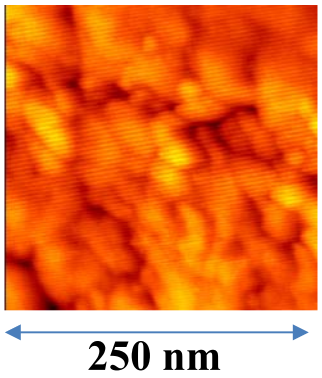
'cold' colors – before application of magnetic field

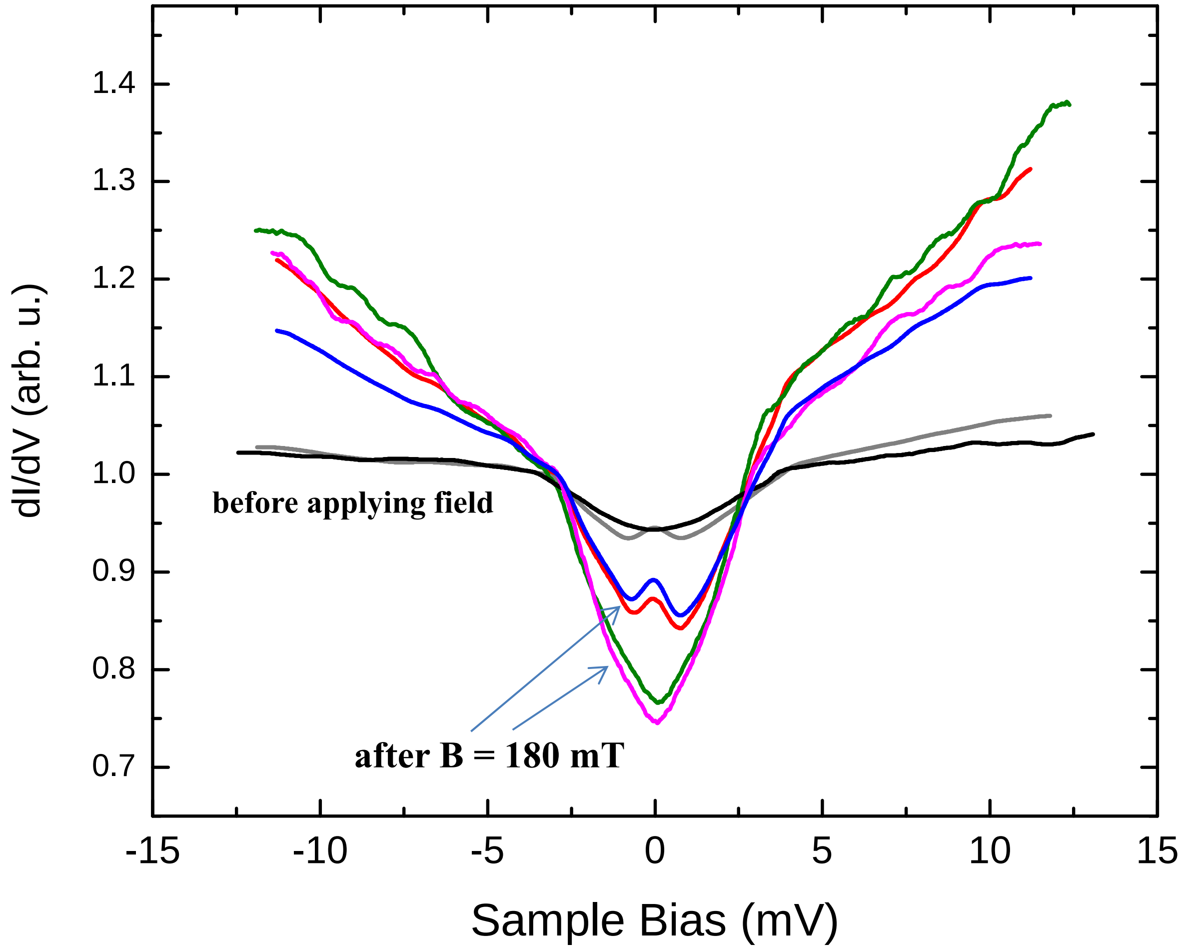
'warm' colors – after application of B = 180 mT

It appears that magnetic field (even after ramping down back to zero) enhances the PE-induced spectral features, both gaps and ZBCPs.

12 nm LCMO and PCCO

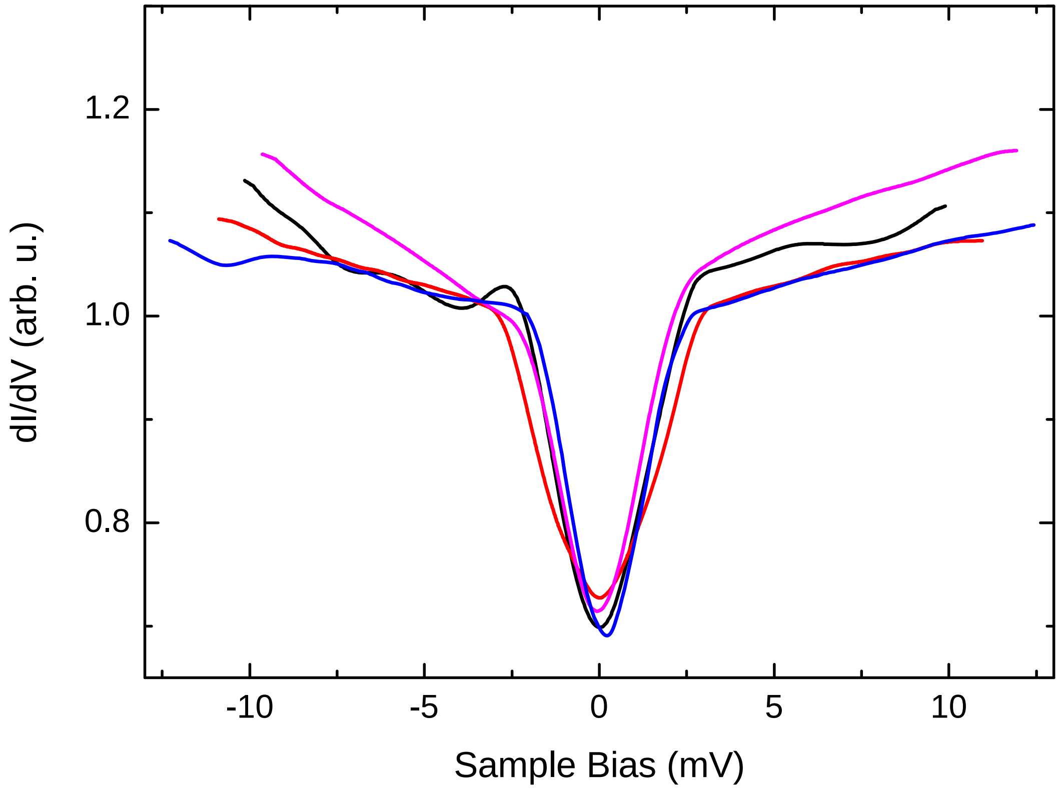


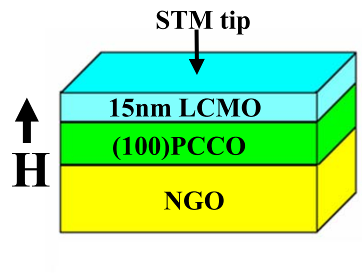




Again, magnetic field enhances gaps and in this case maybe also ZBCPs

15 nm LCMO and PCCO





Black-blue curve – before B application
"warm colored" curves – after B = 150 mT

In regions where the gaps are well developed before B applications, turning on the magnetic field does not change much.

Effect of magnetic field application:

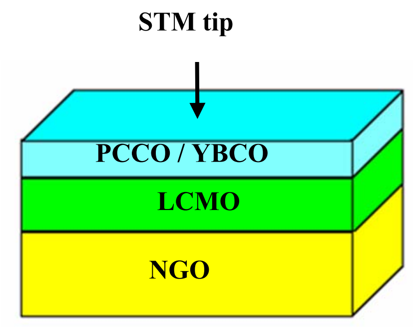
• In general, well developed (large and deep) gaps are not affected much.

• Small gaps usually become more pronounced by the application of magnetic field.

- this effect increases up to the saturation field, after which the gaps may somewhat reduce.
- this was observed also for ZBCPs, but we have less data.

• Variations of spectra with time (non-monotonic) under magnetic field. Changes in local magnetization structure?

Outlook



• Investigate induced triplet pairing in the SC.

- PCCO may be better: ZBCPs will provide more direct (less ambiguous) evidence for induced triplet pairing.

Increased T_C of Nb films upon chemical linking Au dots

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The Hebrew University of Jerusalem

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DIP , DARPA

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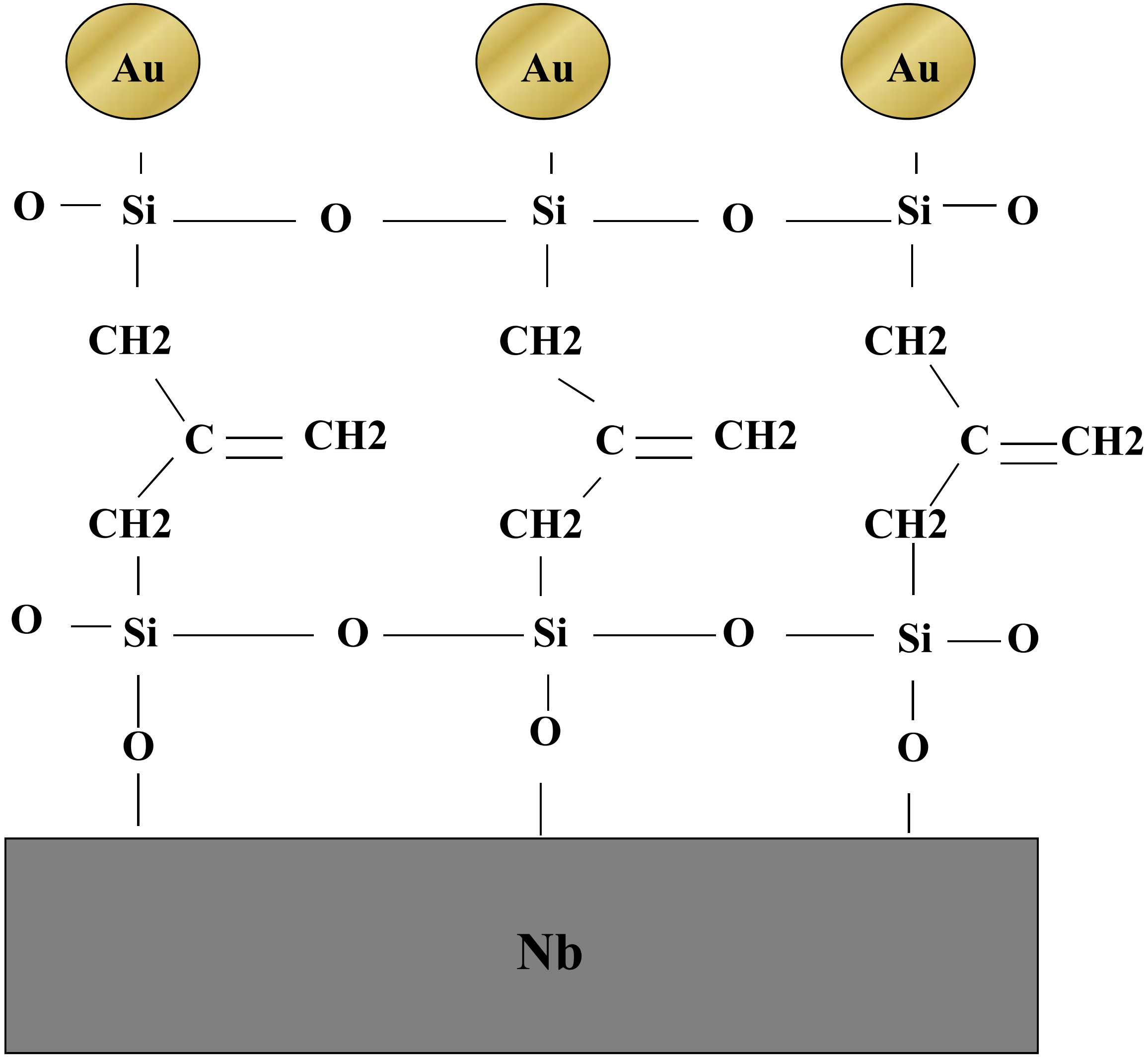
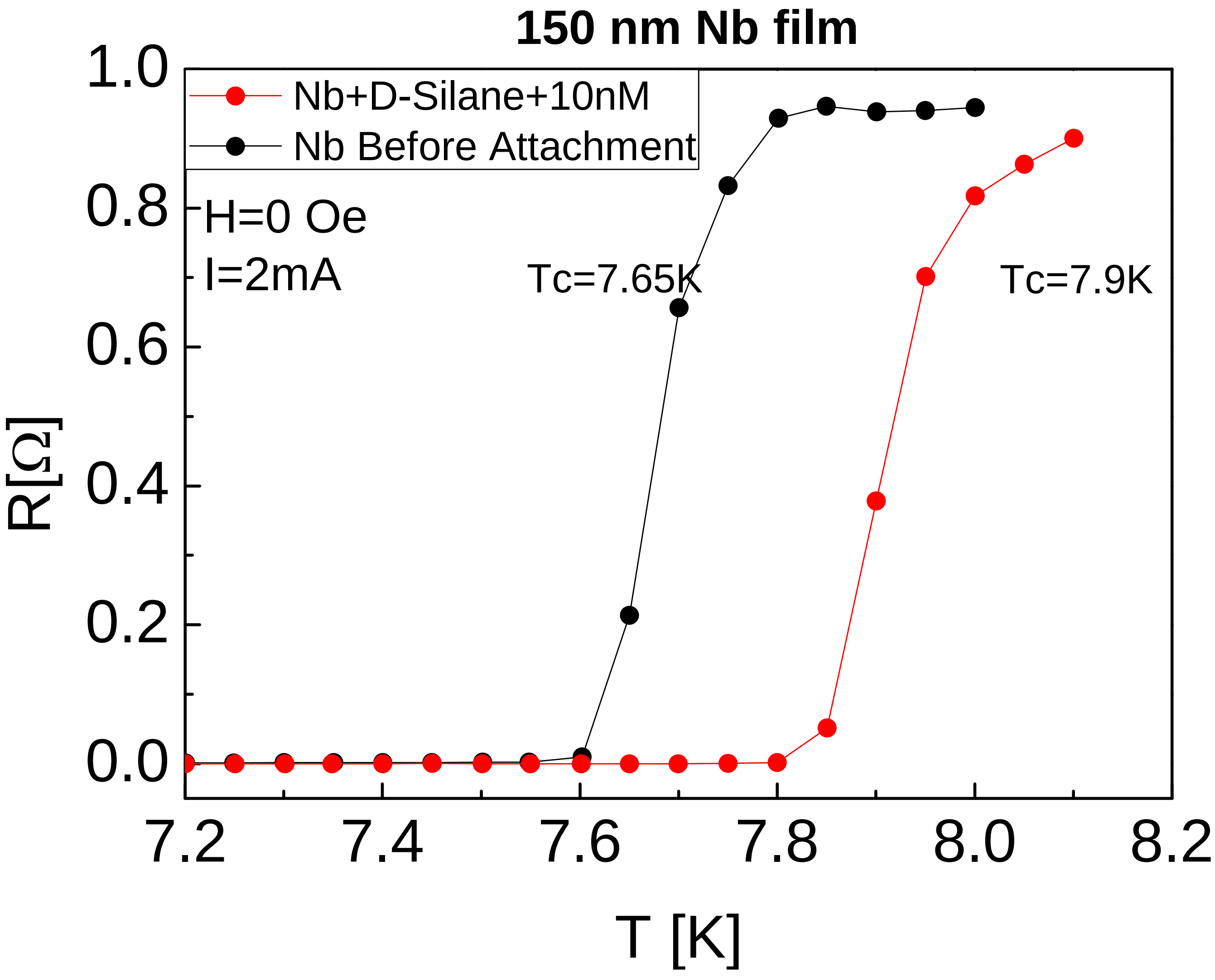
Est. 1925

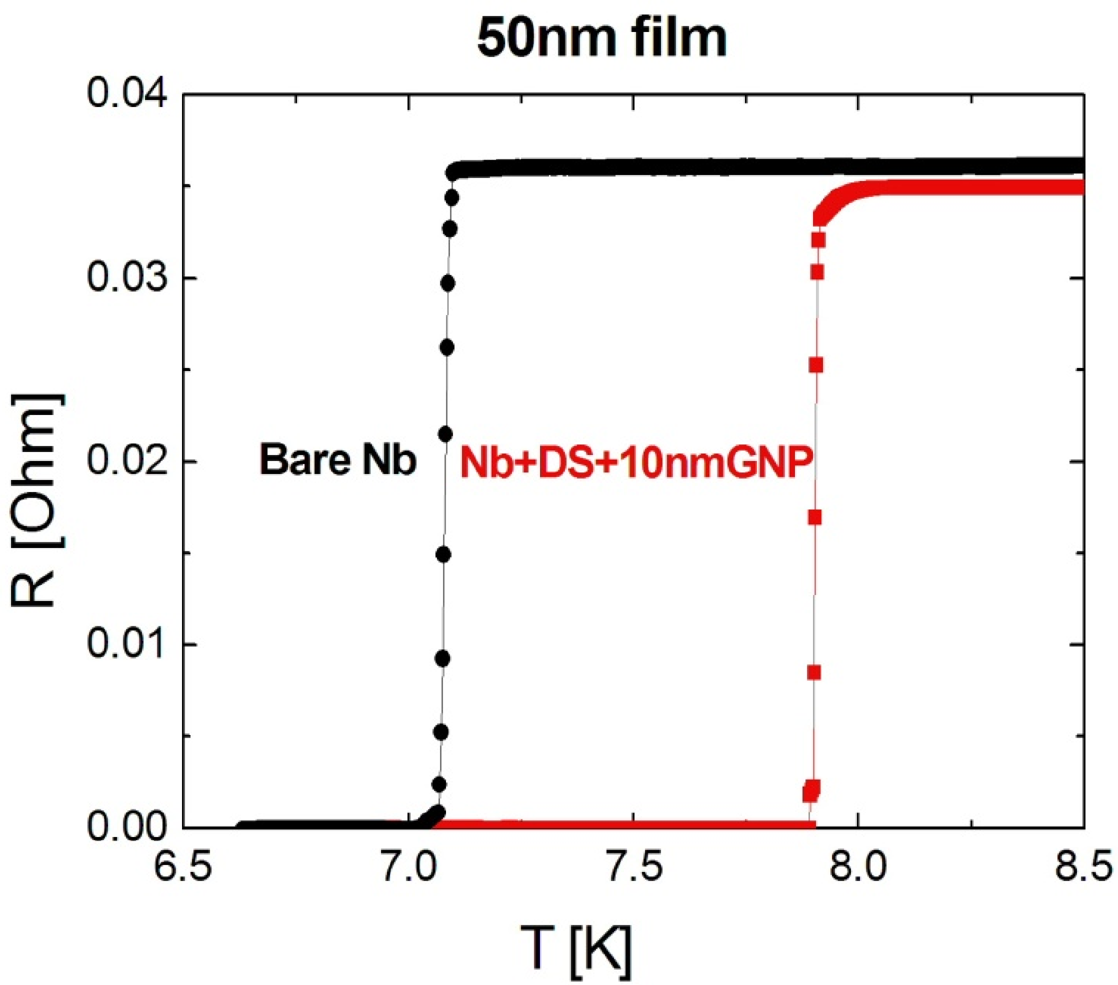
Au nanoparticles attached to Au by di-Silane molecules



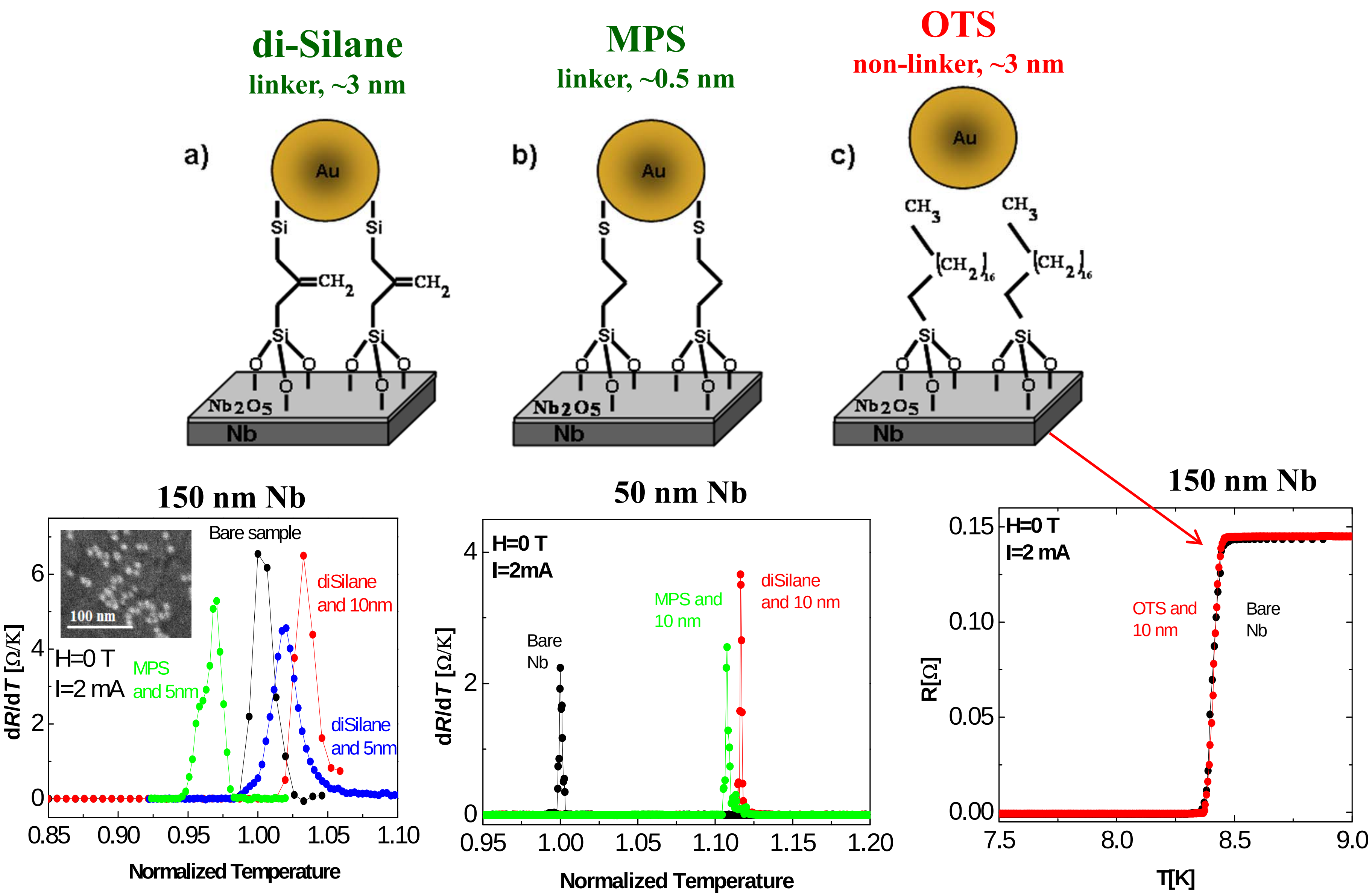
Small but reproducible enhancement of T_c



Small but reproducible enhancement of T_c

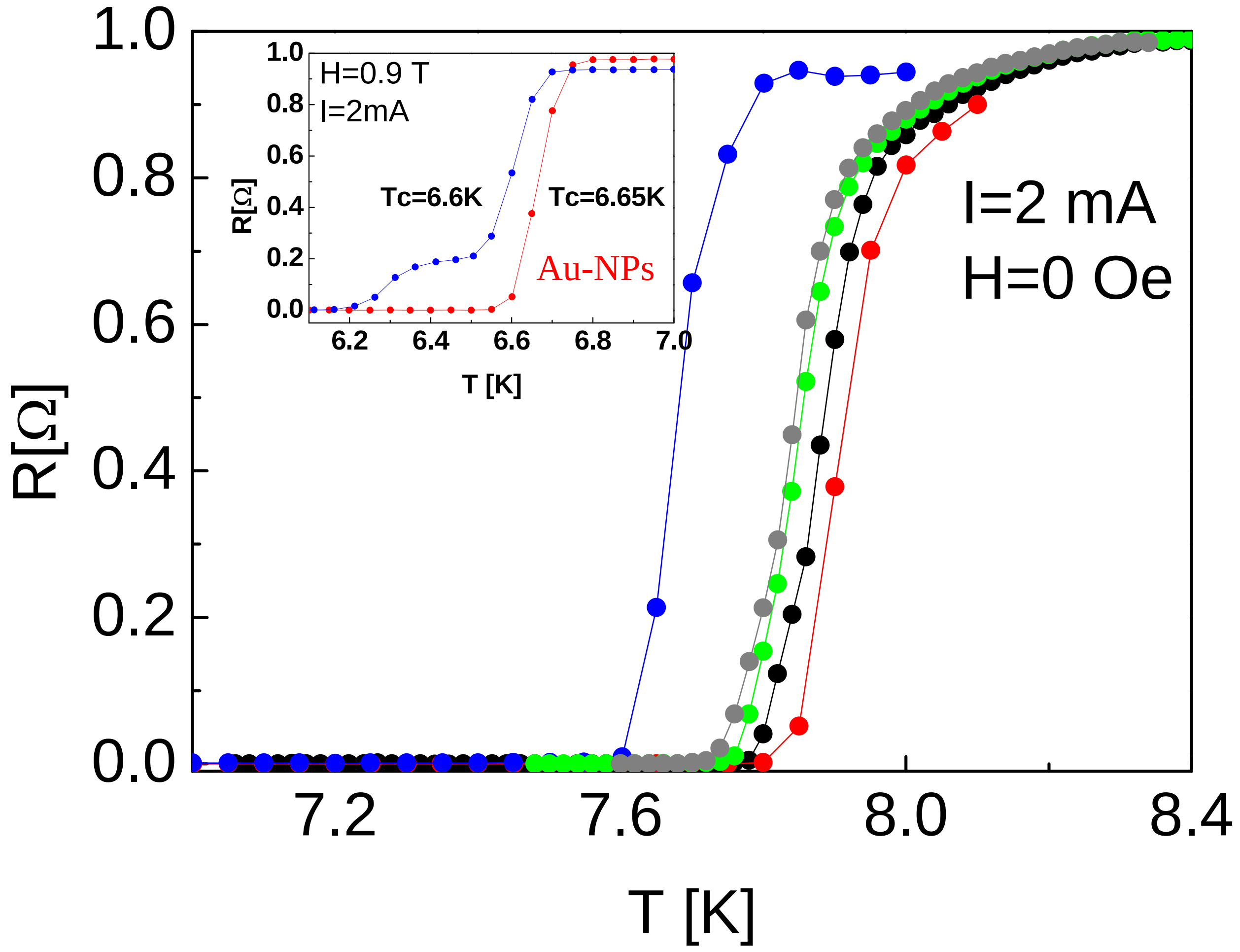


- Relative enhancement increases as the Nb film thickness reduces.



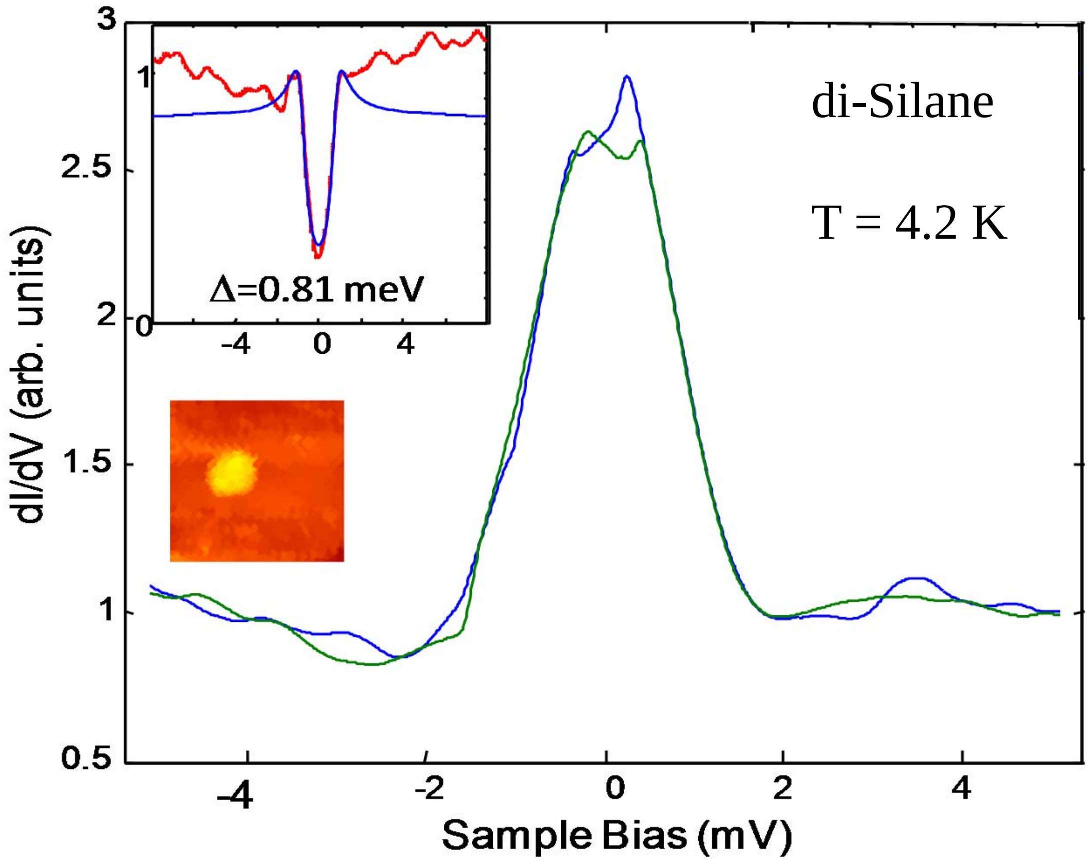
- Chemical linking ⇒ ability for charge transfer is essential
- Not a Coulomb screening effect

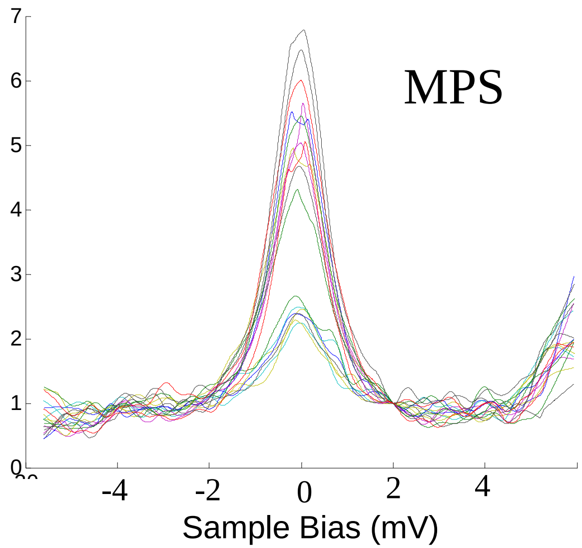
Effect of Au nanoparticles removal



- Tc enhancement effect reduces as NP density reduces.
- Effect much smaller under application of matching magnetic (inset).
  - effect of flux-creep eliminated after linking (inset, red curve).

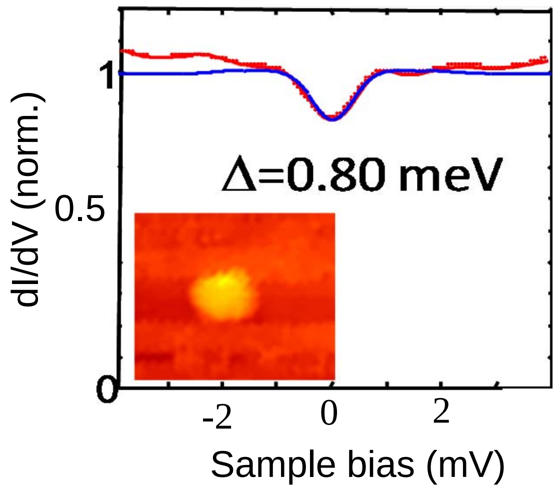
Scanning tunneling spectroscopy - linked dots

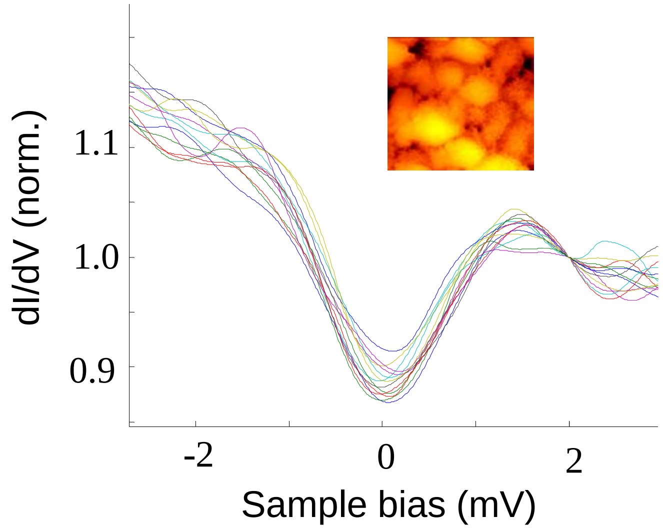


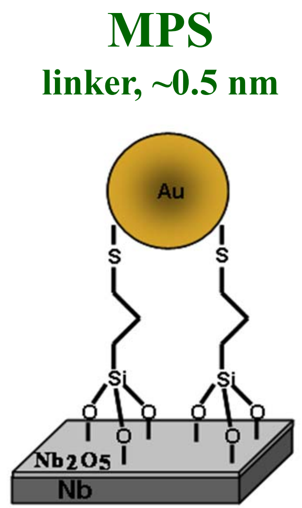


- Enhanced zero-bias conductance on Au dots when T_C increases.
- Far away from Au dots, a reduced Nb SC gap observed.

Scanning tunneling spectroscopy - linked dots



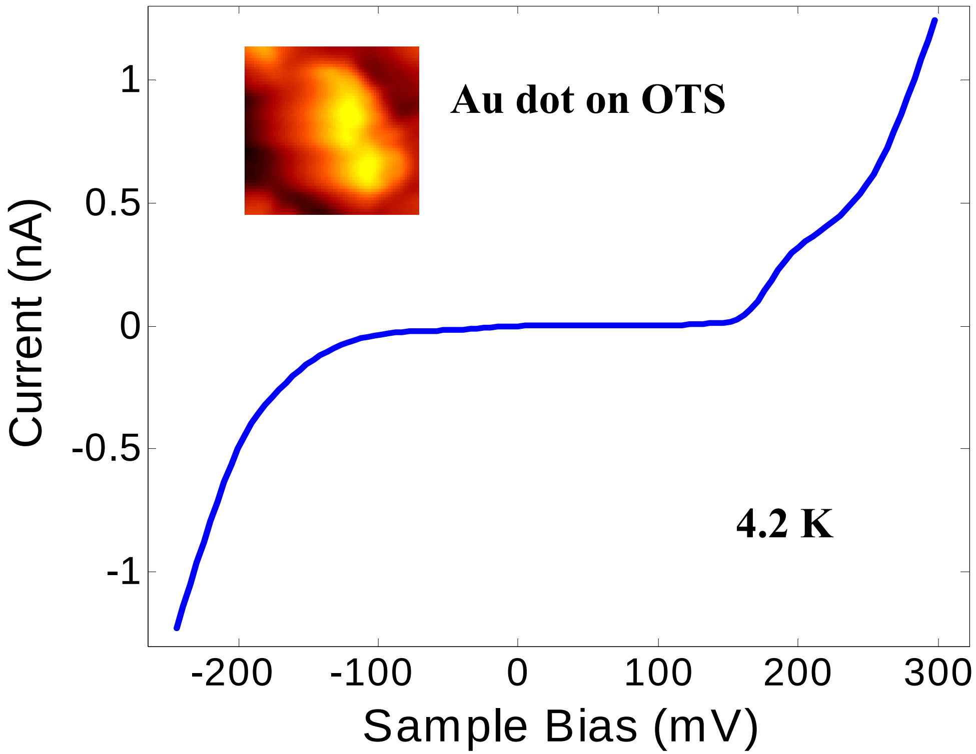




- Proximity-gaps appeared on Au dots when T_C reduced (MPS only).

Andreev reflections through the linker molecules.

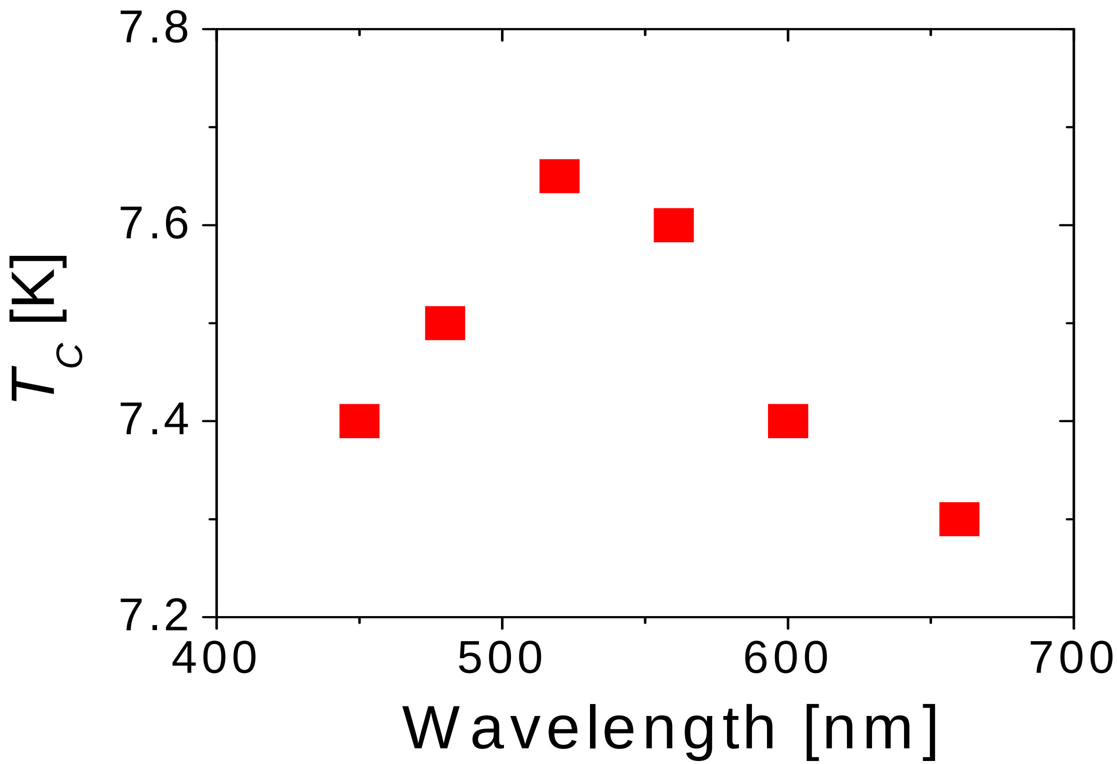
Scanning tunneling spectroscopy - unlinked dots

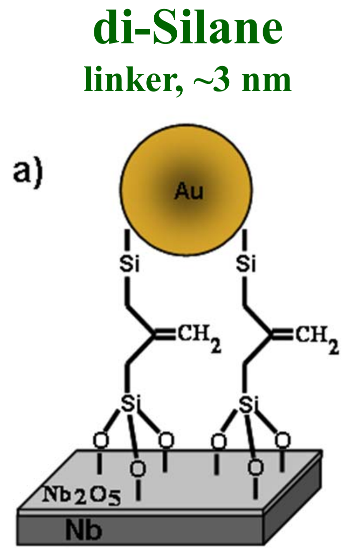


- Coulomb-blocked observed.

  ⇒ Here the tunnel-barrier between the Au-dot an Au-substrate is high.

Effect of illumination wavelength on T_c

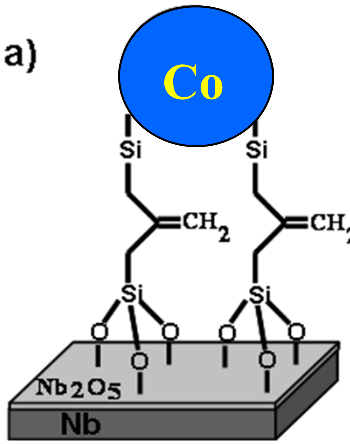




- Plasmon excitation effect on T_c?

Co nanoparticles linked to Nb film.

a)

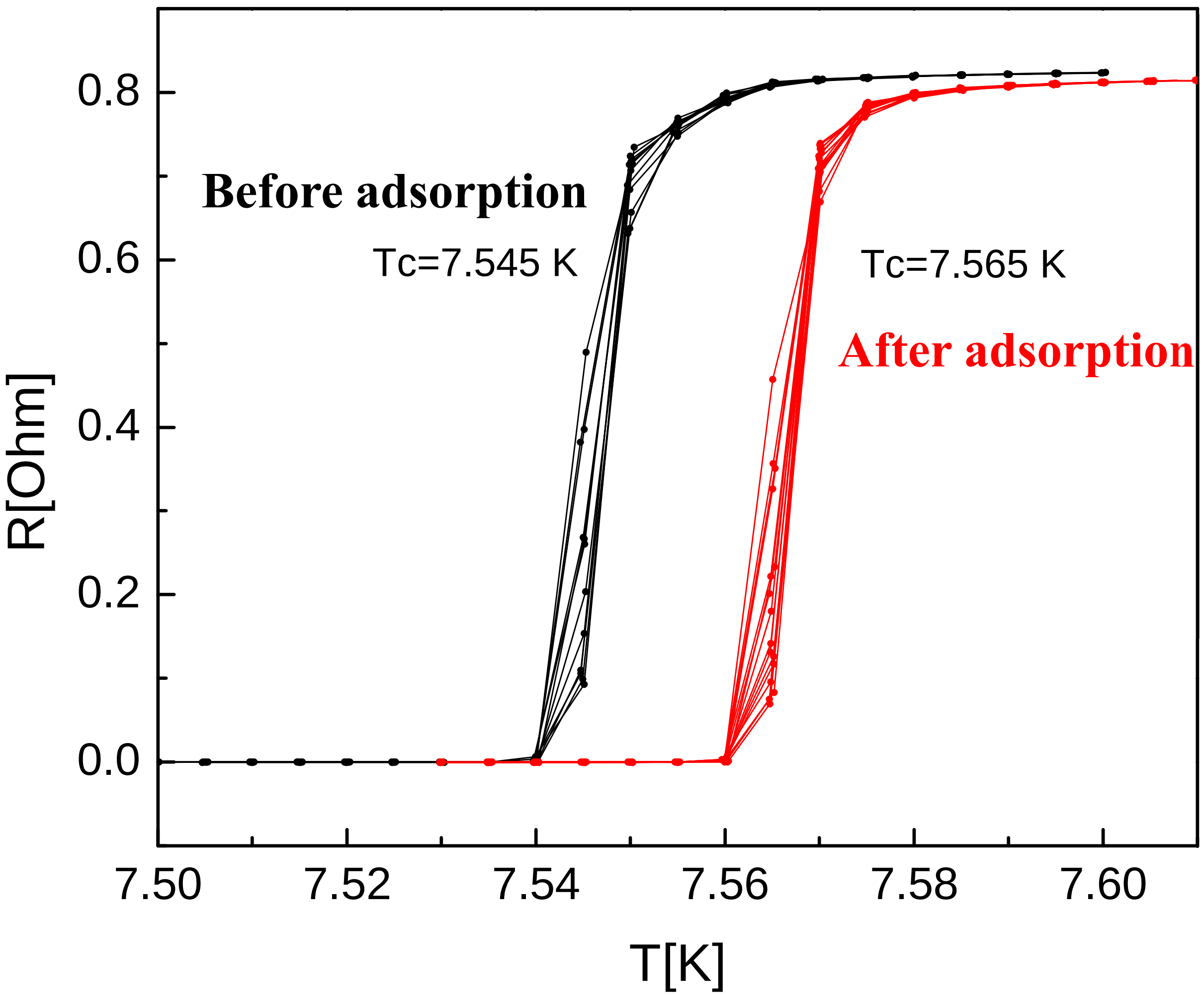


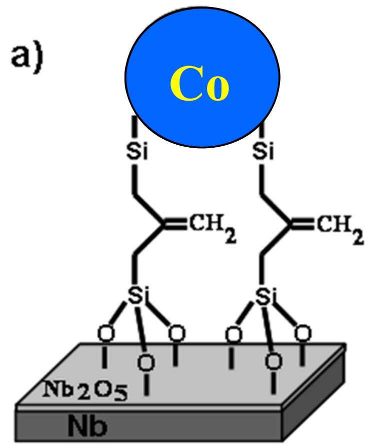
Linking process:

*** Cleaning the surface for 10 min in plasma Argon**
*** di-Silane molecule adsorption.**
*** Co adsorption from Toluene solution: two dips process, each dip for 2 hours, washing with Toluene between the 2 dips.**

Co nanoparticles linked to Nb film.

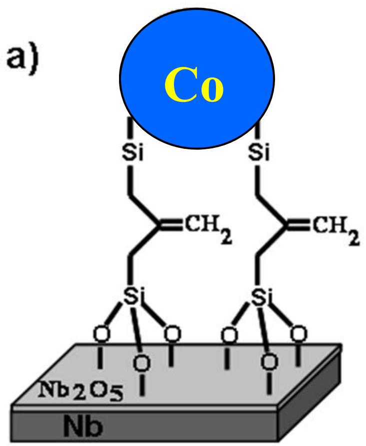
For poor quality of Nb

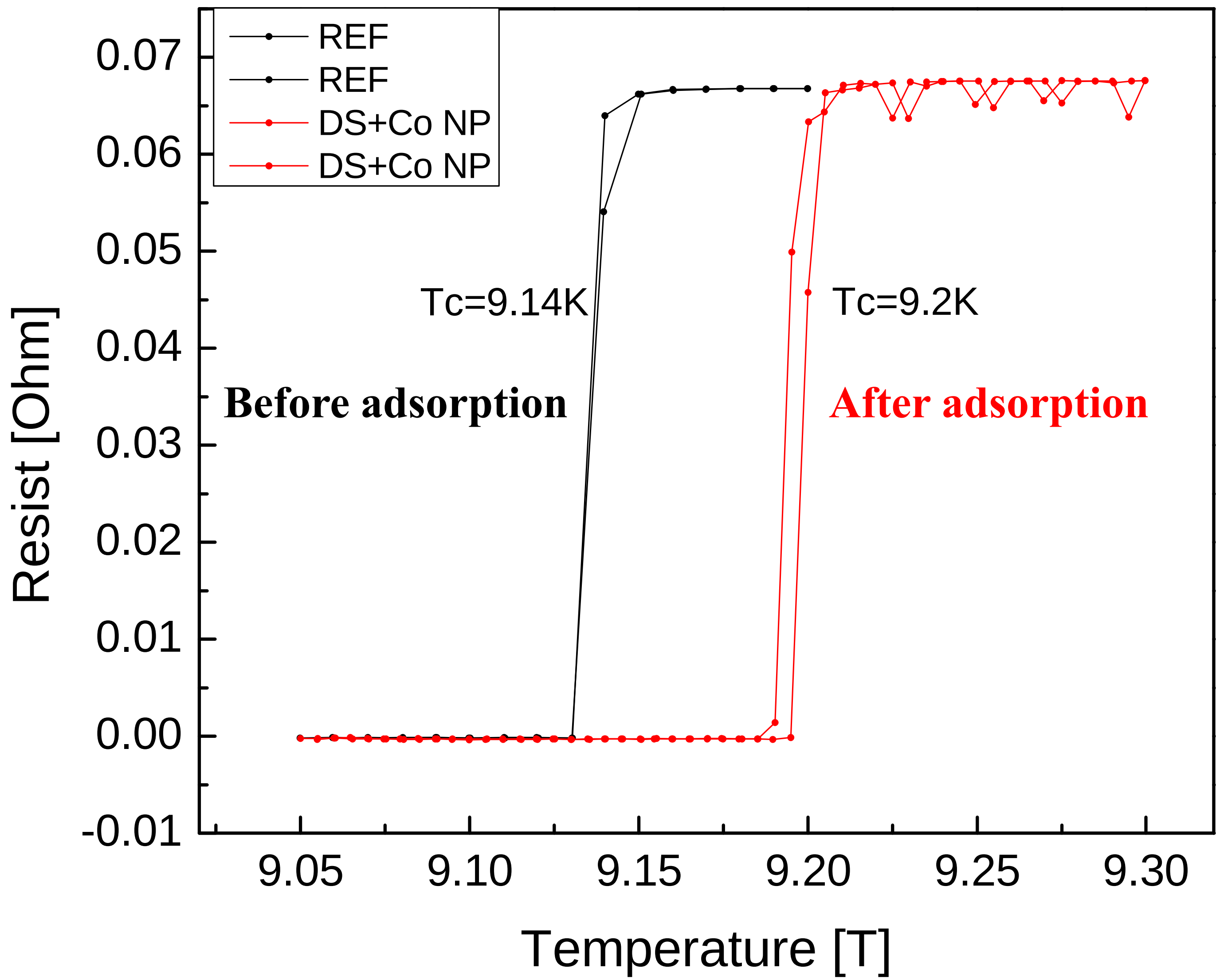




Co nanoparticles linked to Nb film.

High quality Nb film





Summary

• T_C enhancement of Nb films upon chemically linking Au NPs.

• Not a Coulomb screening effect – chemical linking essential.

• Origin not yet understood.

• DOS on the Au-NPs is modified. Either a ZBCP developed, when T_C is enhanced, or induced mini-gap when T_C reduces.

• Small enhancement also upon attaching ferromagnetic Co NPs.