

# Signatures of unconventional superconductivity in oxide based 2DEG

Daniela Stornaiuolo

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D. Massarotti  
R. Di Capua  
G.P.Pepe  
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M.Salluzzo

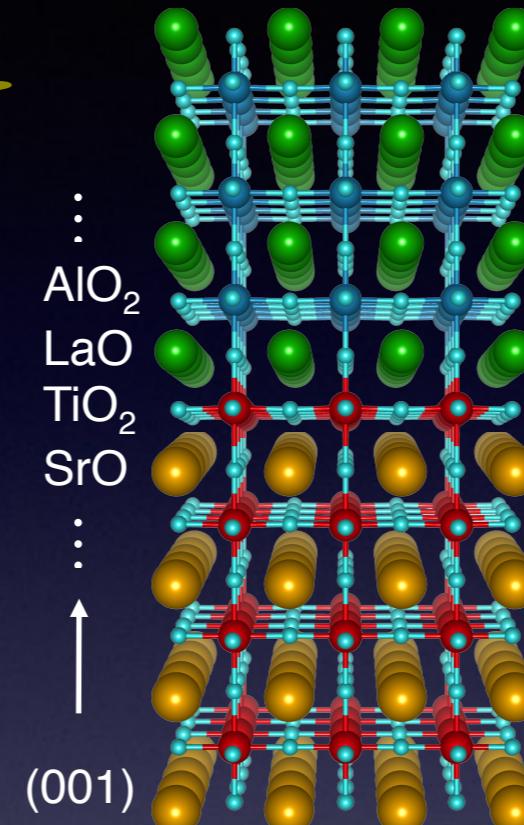
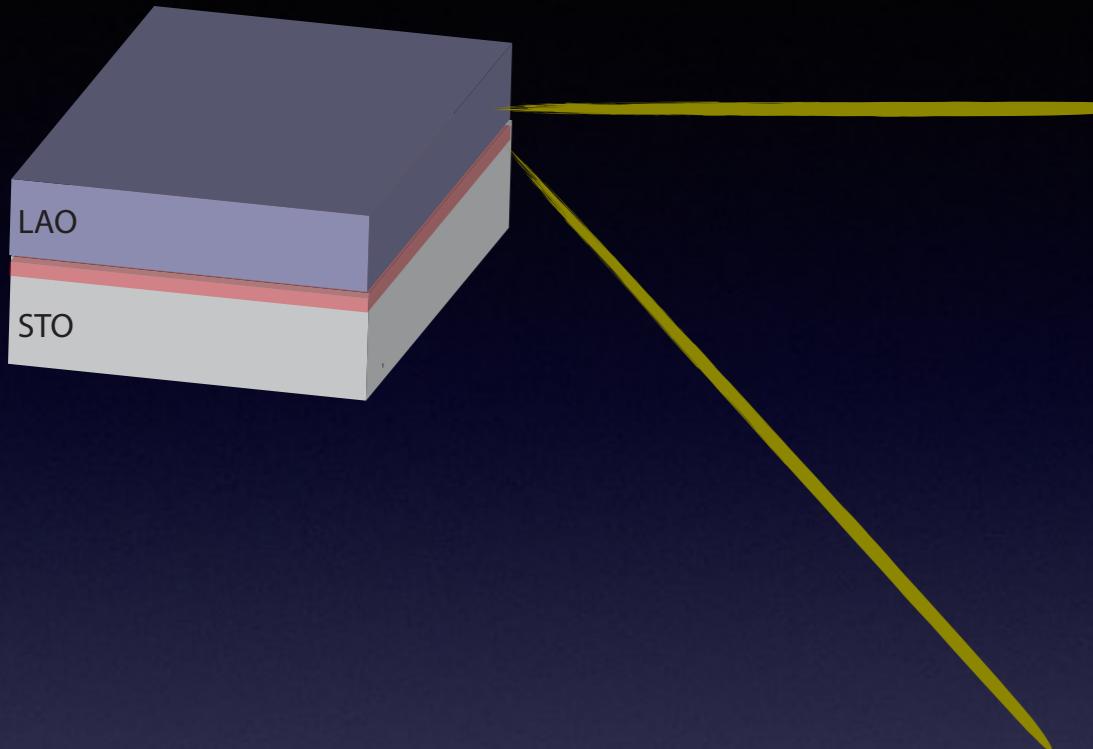


in collaboration with: S.Gariglio, J.-M. Triscone, University of Geneva





# oxide 2DEGs - LAO/STO



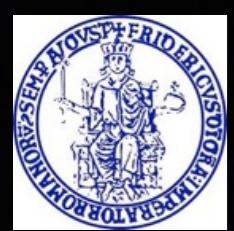
$\text{LaAlO}_3$ :  
band insulator  
 $\Delta = 5.6 \text{ eV}, \kappa = 24$

$\text{SrTiO}_3$ :  
band insulator  
 $\Delta = 3.2 \text{ eV}, \kappa(300 \text{ K}) = 300$   
quantum paraelectric

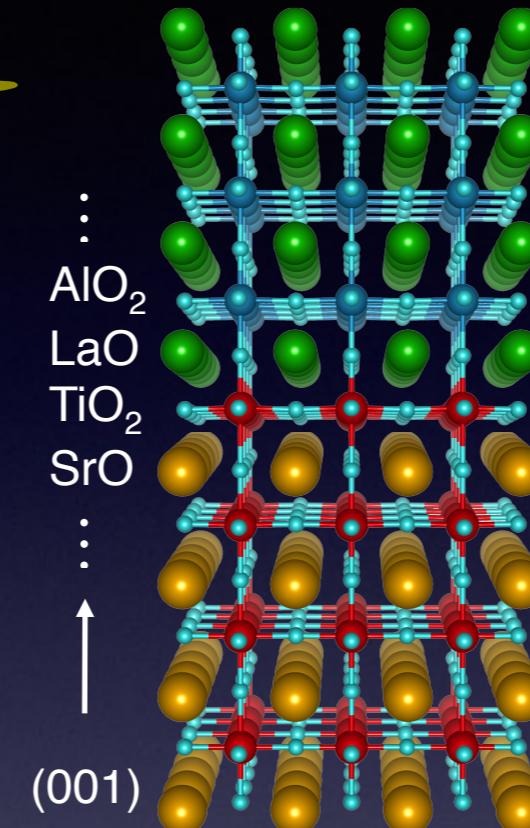
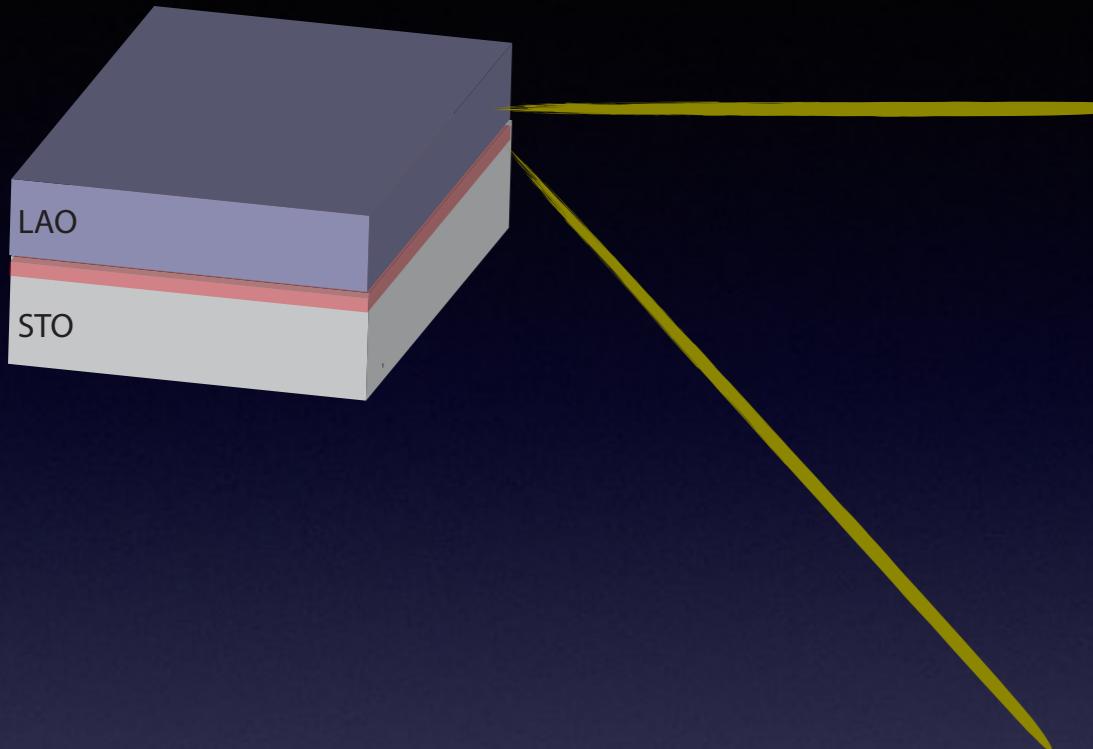
A. Ohtomo, H.Y. Hwang, Nature (2004)

## LAO/STO 2DEG properties

- 2004 interfacial conductivity
- 2006 back-gate induced resistance switching
- 2006 patterned conductivity
- 2007 giant Seebeck coefficient
- 2007 Superconductivity
- 2007 magnetic effects
- 2008 cAFM induced resistance switching
- 2008 field effect tunable superconductivity
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- 2009 Nanodevices fabrication via cAFM
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- 2010 Nanoscale rectification
- 2010 Photodetector
- 2011 control of electronic conduction using polar adsorbates
- 2013 Enhanced photoresponse
- 2014 gas sensing characteristics
- ... ...



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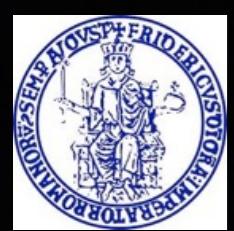
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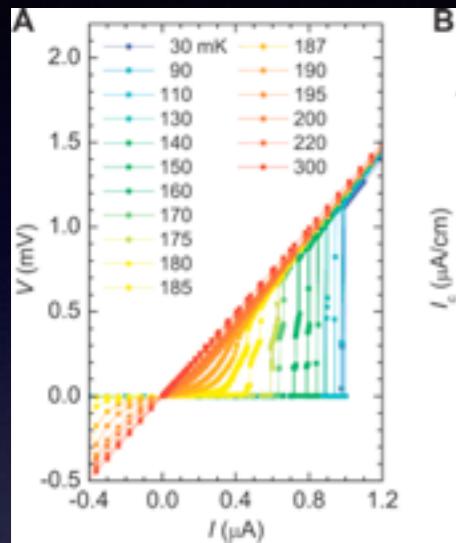
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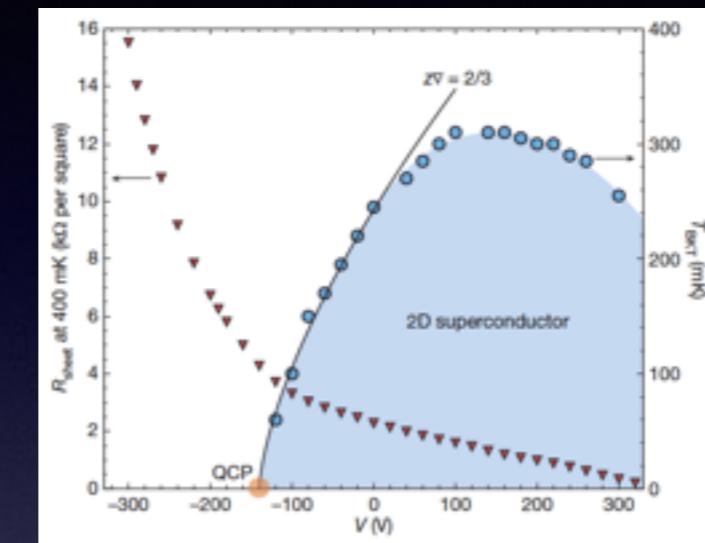
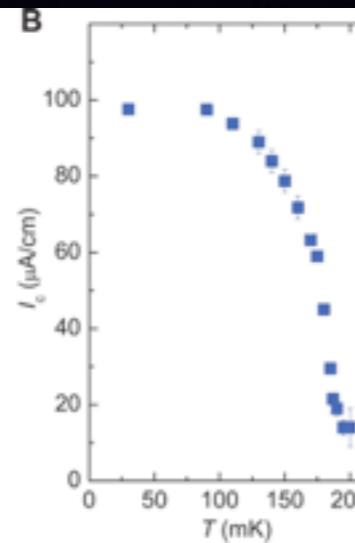


# LAO/STO superconductivity

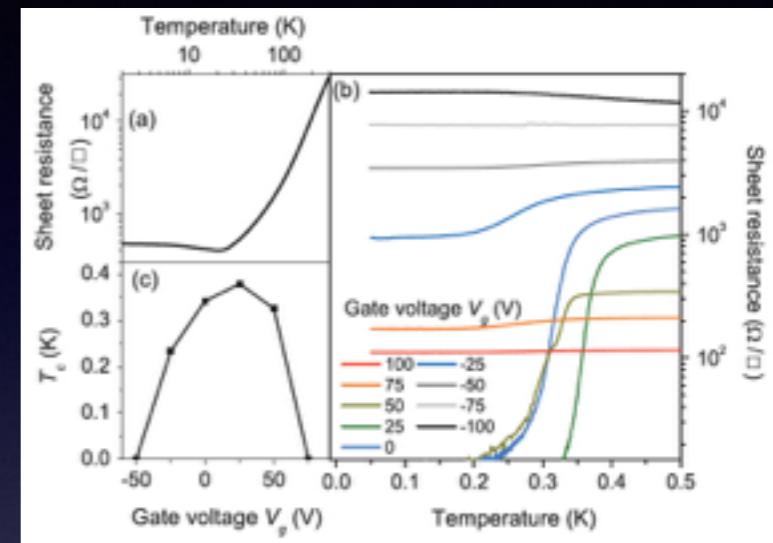
superconductor to insulator transition via electric field effect



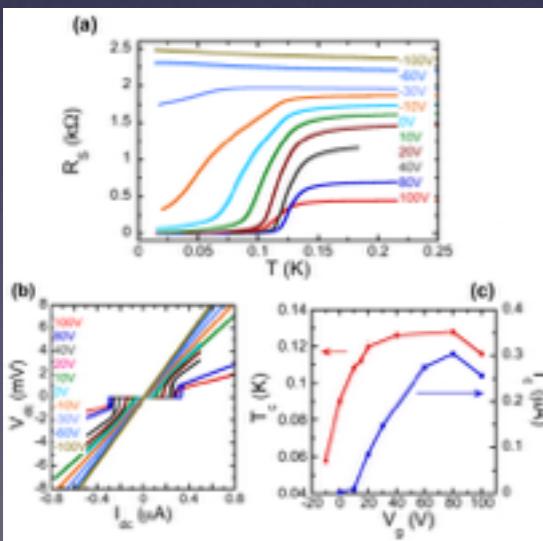
N.Reyren et al. Science (2007)



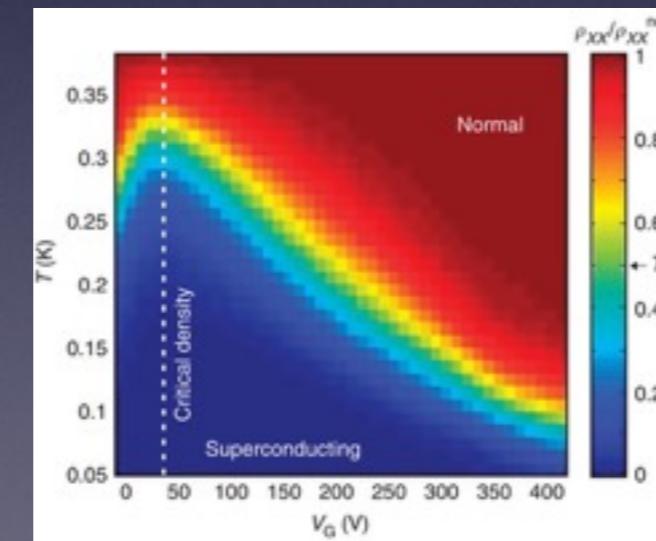
A.D.Caviglia et al. Nature (2008)



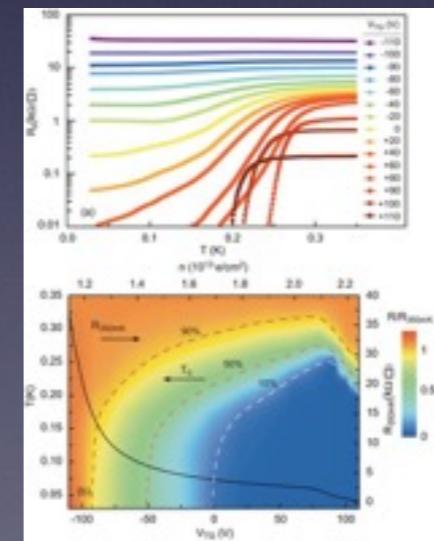
C.Bell et al. PRL 2011



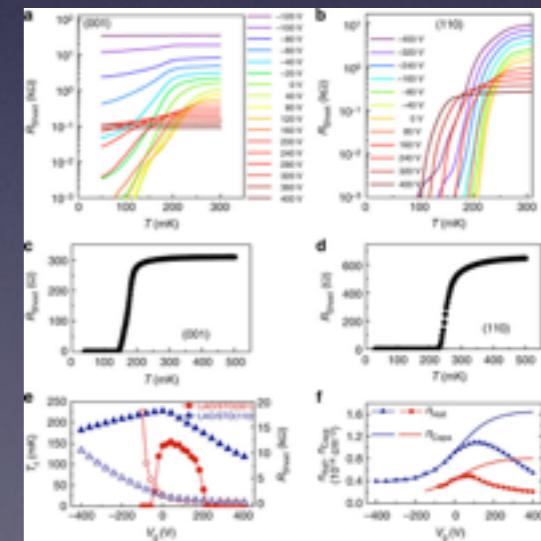
D.A.Dikin et al.,  
PRL. 2011



A.Joshua et al.,  
Nat. Comm. 2012



S.Hurand et al.,  
Nat. Comm. 2015



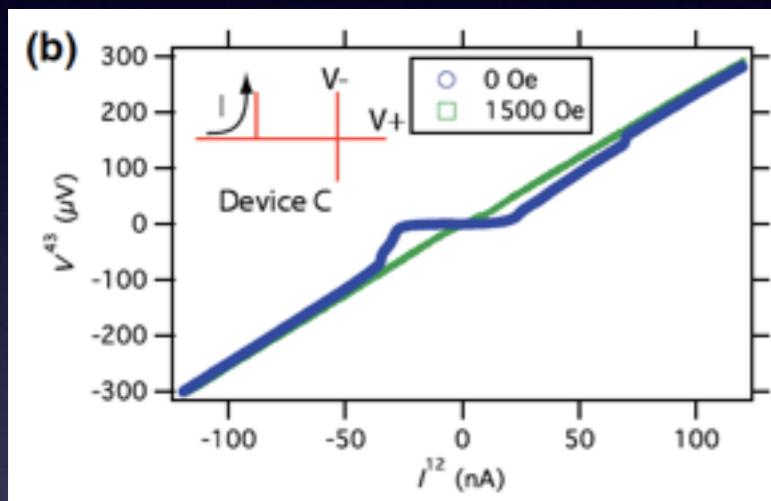
G.Herranz et al.,  
Nat. Comm. 2015



# LAO/STO superconductivity

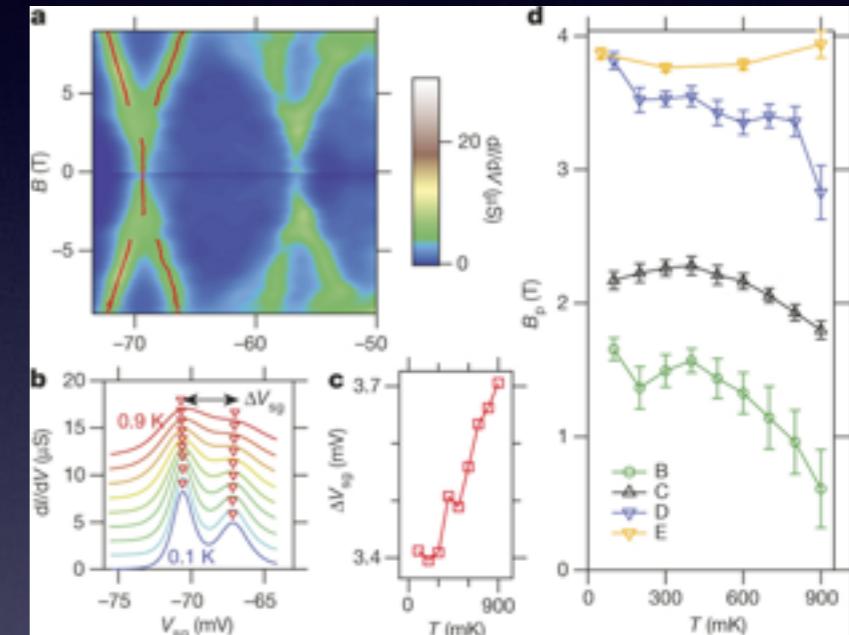
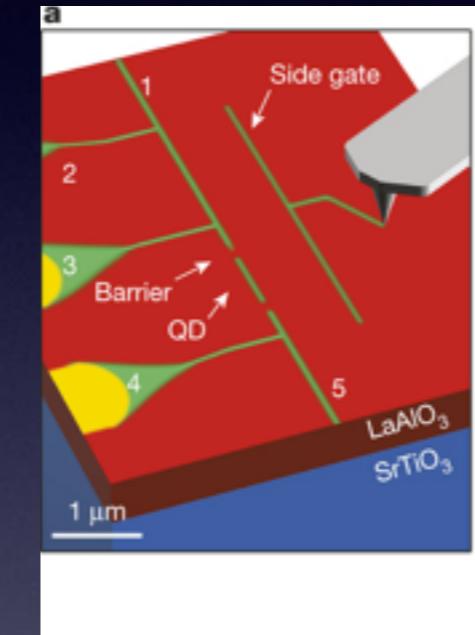
LAO/STO superconducting state is still largely unexplored

non local transport in  
sketched nanostructure



C.Cheng et al., PRX 2013

electron pairing without superconductivity

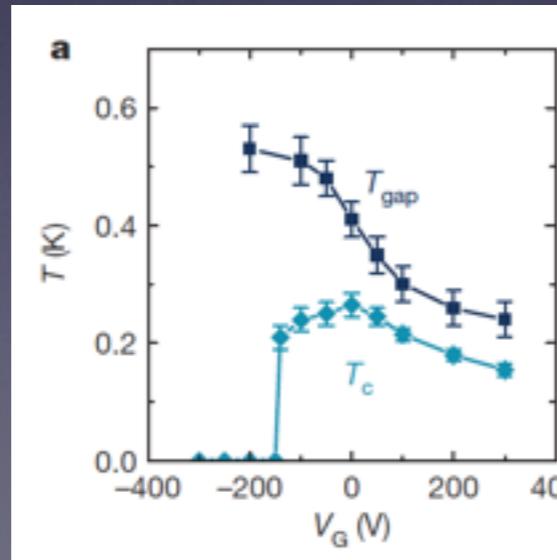
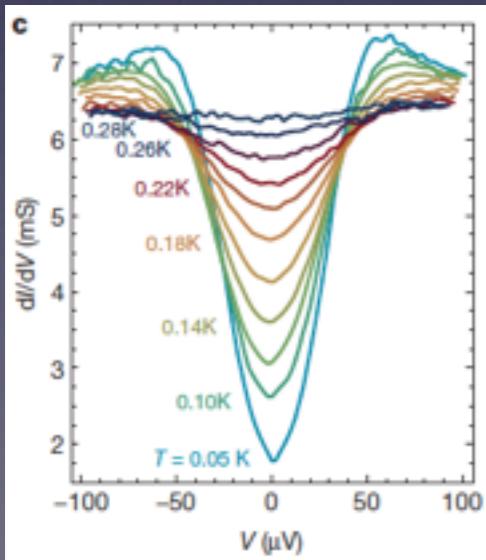


G. Cheng et al., Nature 2015

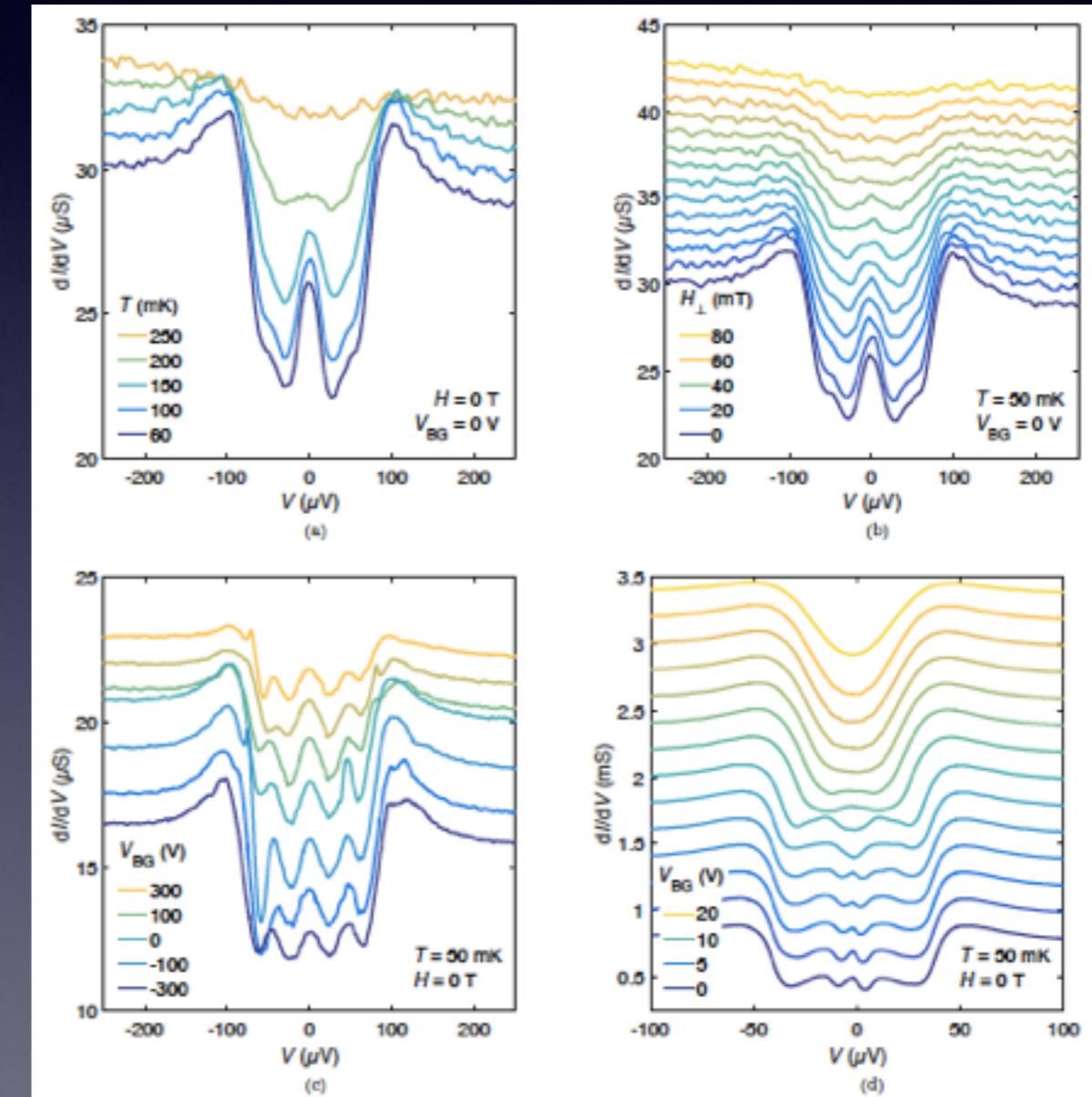


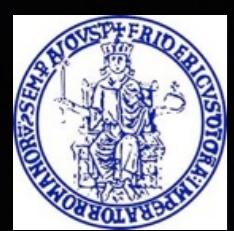
# LAO/STO superconductivity

LAO/STO superconducting state is still largely unexplored



Tunnel spectroscopy



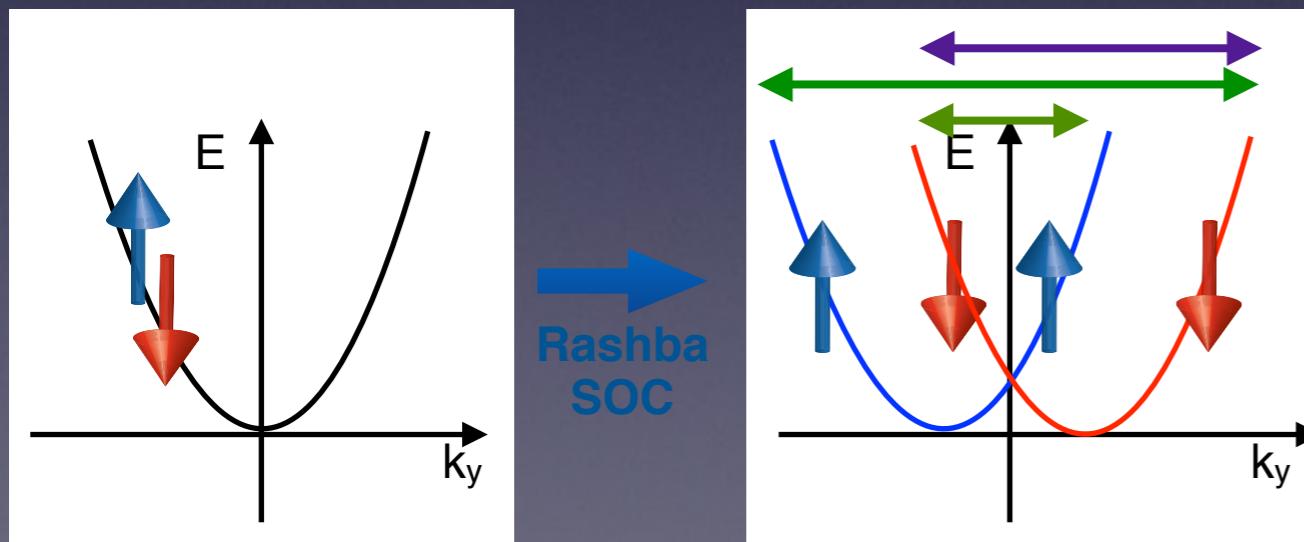


# LAO/STO superconductivity

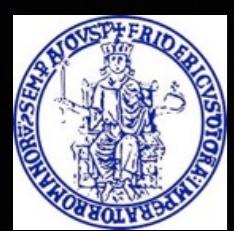
LAO/STO superconducting state is still largely unexplored

- ? order parameter symmetry
- ? mechanism for superconductivity
- ? superconductivity + Rashba SOC
- ? ... ...

L.P. Gor'kov, E.I. Rashba, *Superconducting 2D System with Lifted Spin Degeneracy: Mixed Singlet-Triplet State*, Physical Review Letters 2001

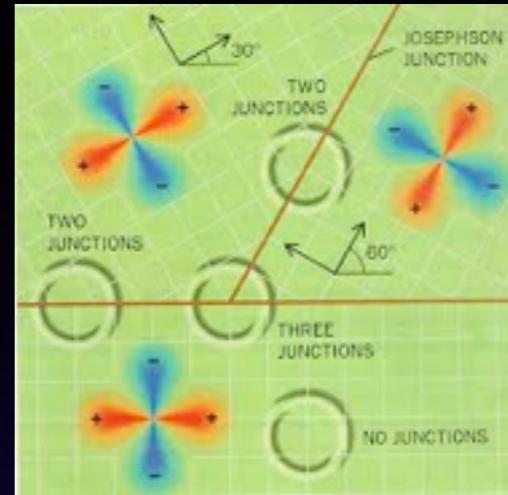


- K. Yada et al, Phys. Rev. B (2009)
- Y. Tanaka et al., Phys. Rev. B (2009)
- L. Fidkowski et al. Phys. Rev. B (2011)
- S. Nakosai et al, Phys. Rev. Lett. (2012)
- R.M. Fernandes, Phys. Rev. B (2013)
- F. Loder, J. Phys.: Condens. Matter (2013)
- N. Mohanta and A. Taraphder, EPL, (2014)
- M. S. Scheurer and J. Schmalian, Nature Comm. (2015)
- V. Kozii and L. Fu, Phys. Rev. Lett. (2015)
- E. Lake et al. Phys. Rev. B (2016)
- K.-C. Weng, and C.D. Hu, Scientific Reports (2016)
- S.B. Chung et al. Scientific Reports (2016)

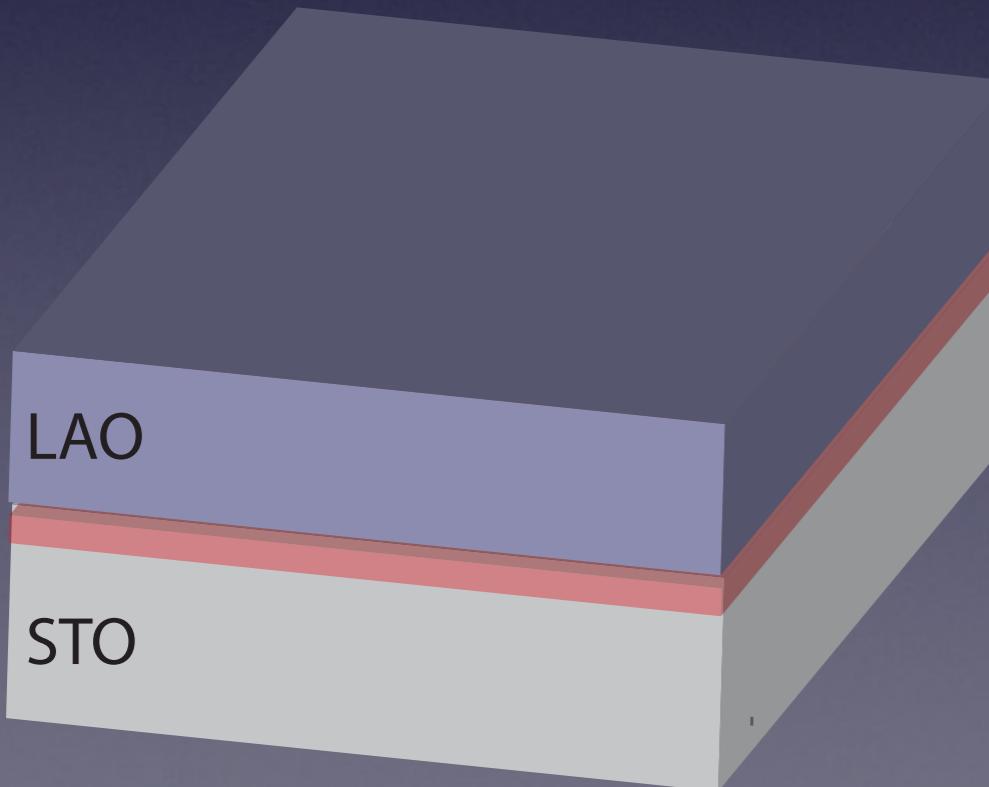


# LAO/STO JJs fabrication

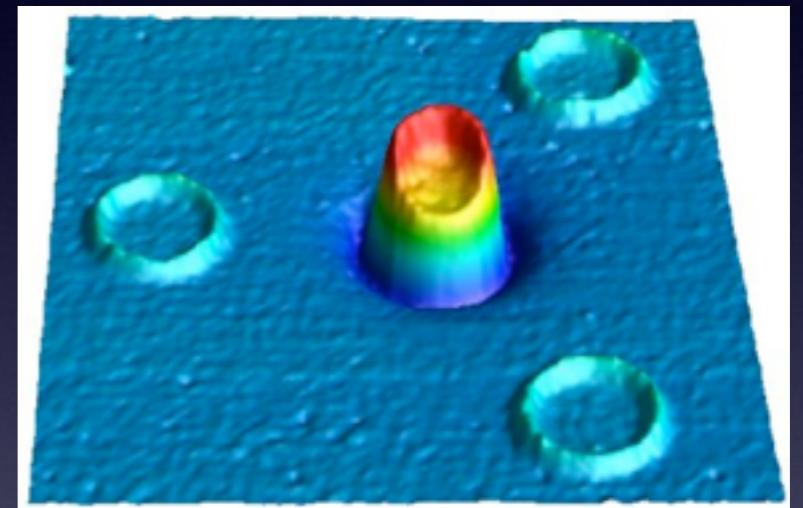
**Josephson junctions** (JJs) are a powerful tool to study the superconducting properties and asymmetries in the OP. The directional dependence of the pair wave function reflects in sign changes of the  $I_c$ .



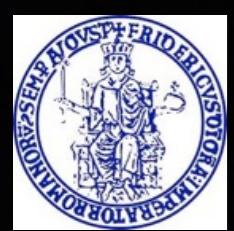
the ability to realize JJs opens the way to many applications



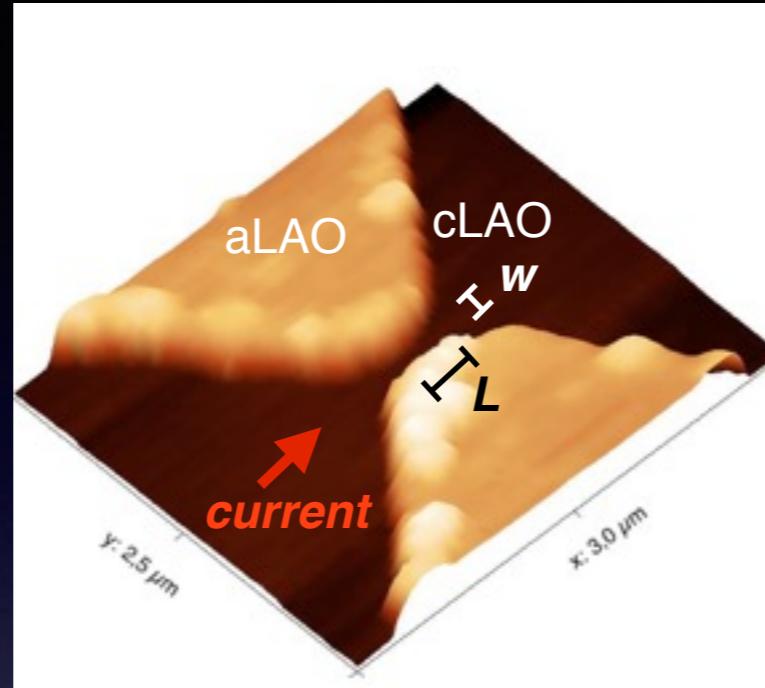
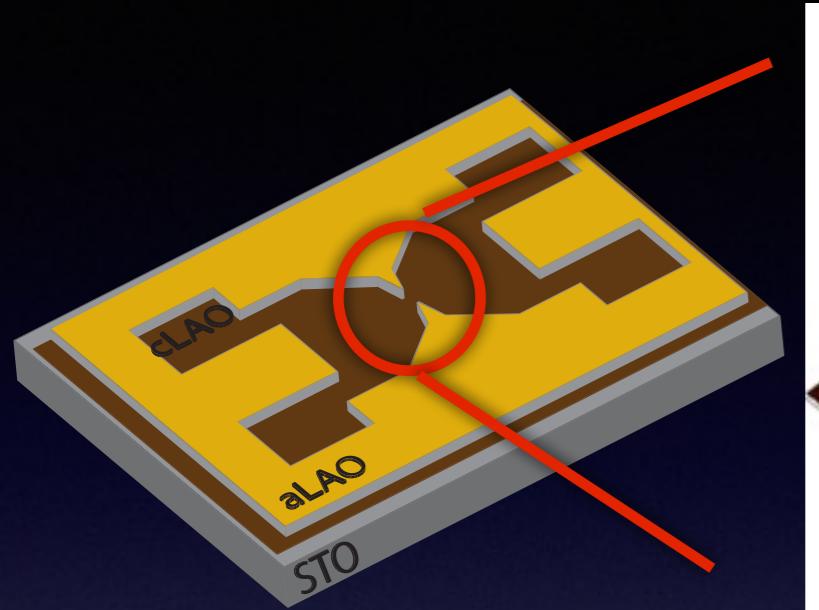
the 2DES is buried under 2-3nm of LAO  $\Rightarrow$  constriction type junctions



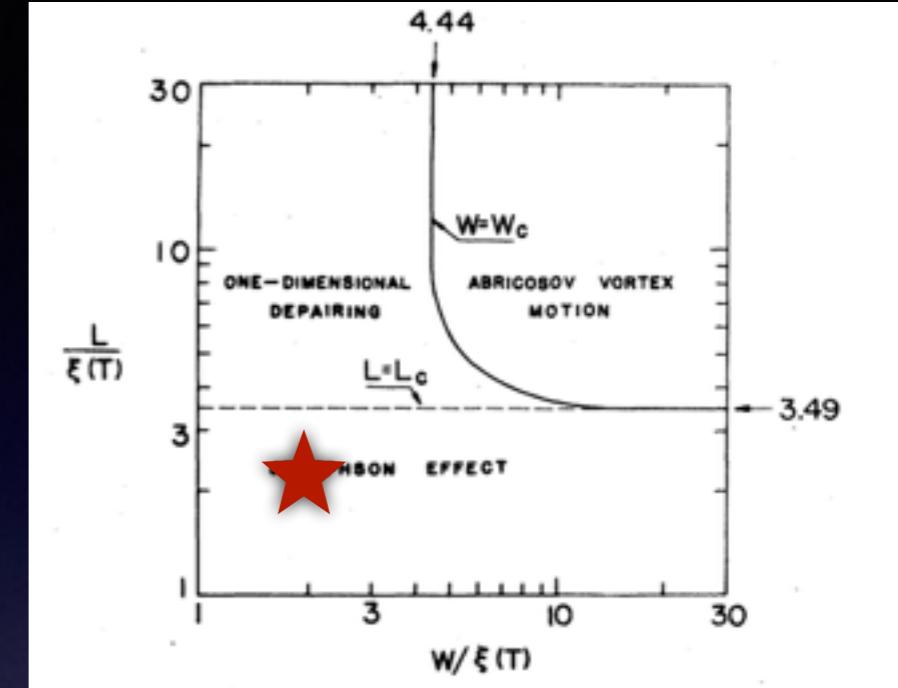
J.R.Kirtley



# LAO/STO JJs

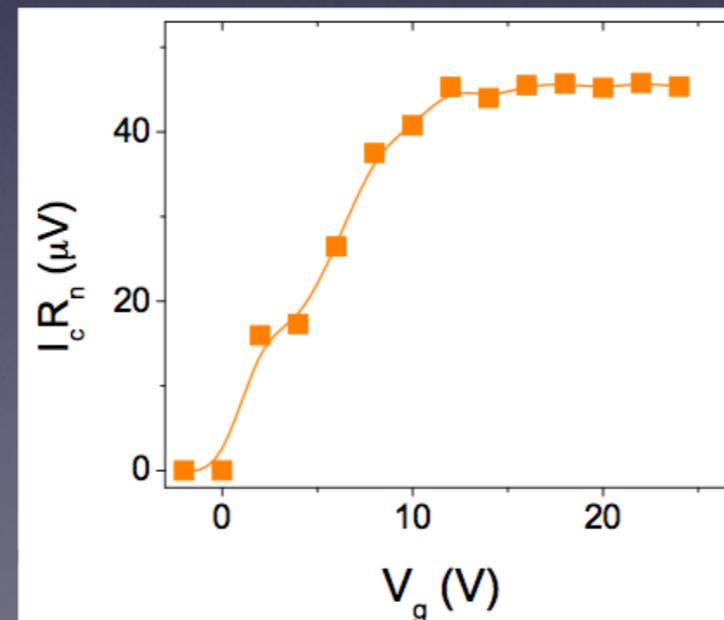
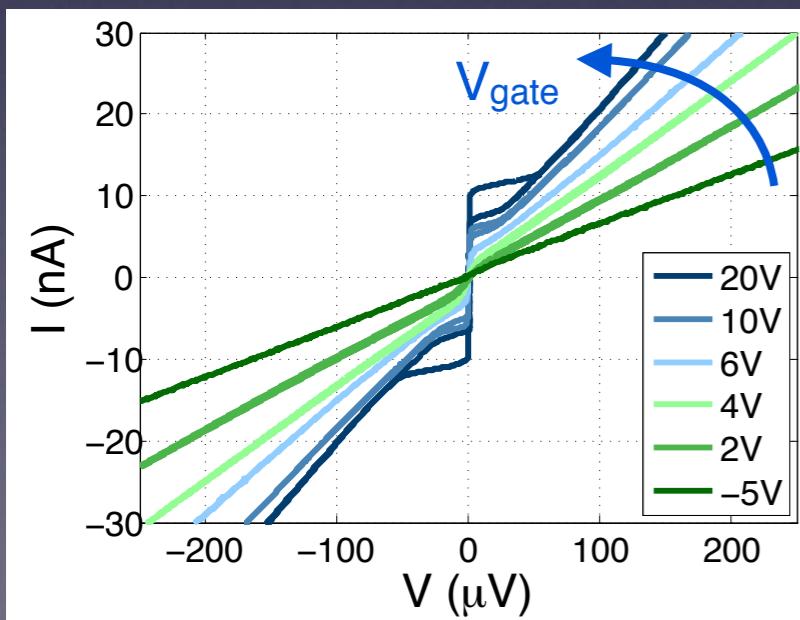


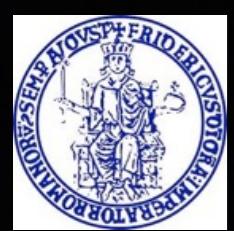
$L, w = 150\text{-}200\text{ nm}$   
 $\xi \approx 50\text{-}70\text{ nm}$



K.K.Likharev  
Review of Modern Physics 1979

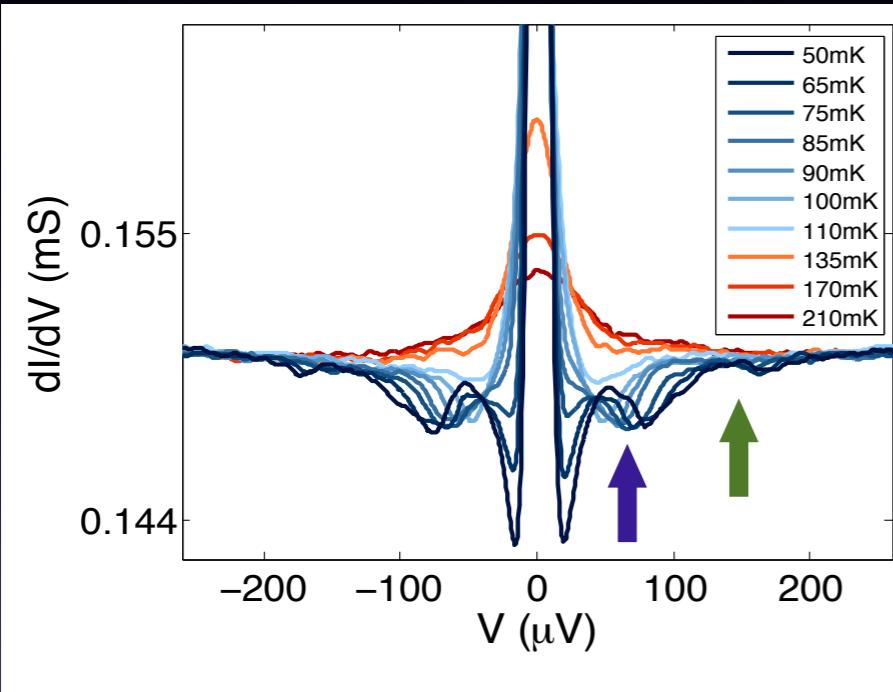
tunability with electric field



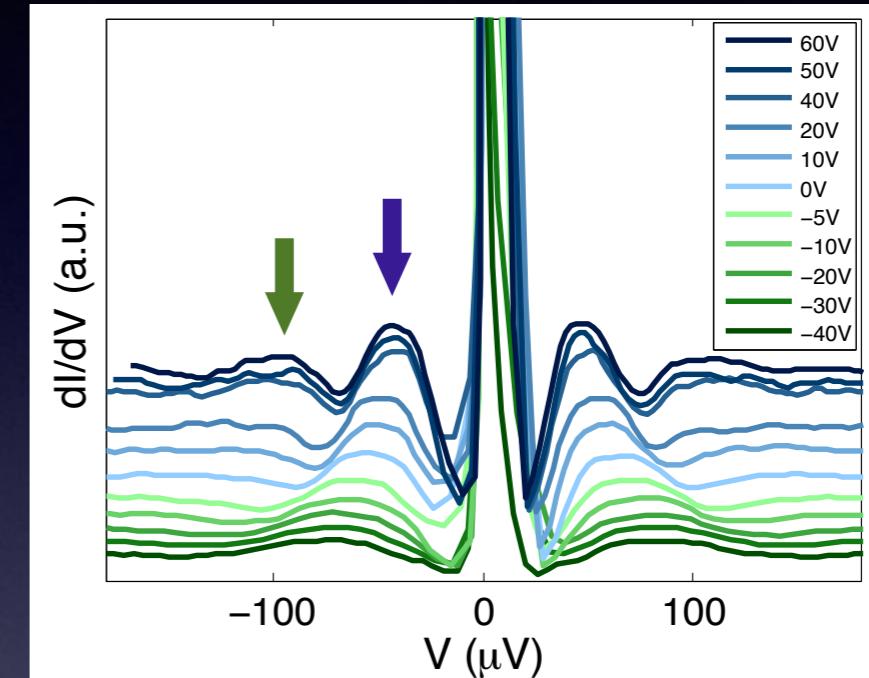


# LAO/STO JJs - $dI/dV$

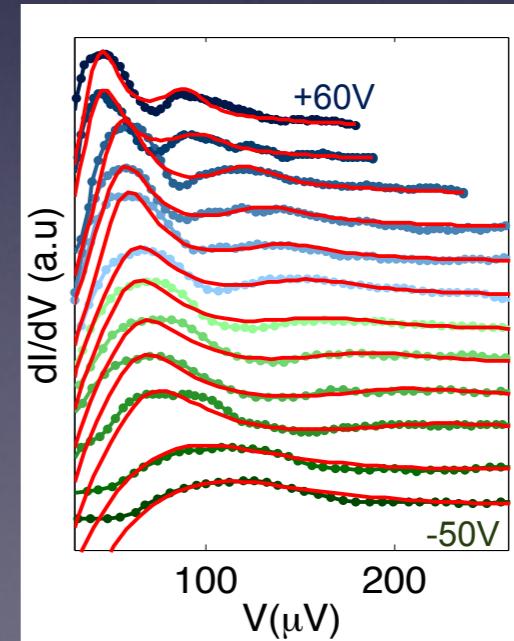
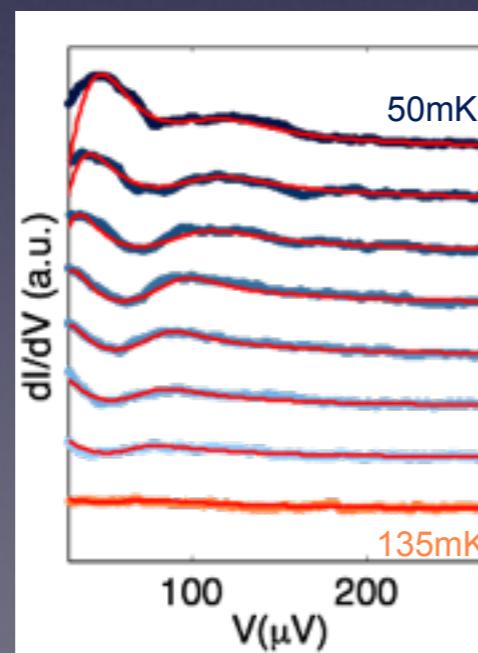
conductance as a function of T  
Device A

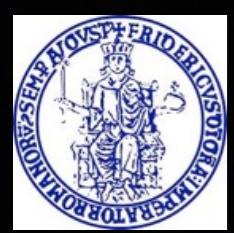


conductance as a function of  $V_g$   
Device B  
 $T=50\text{ mK}$

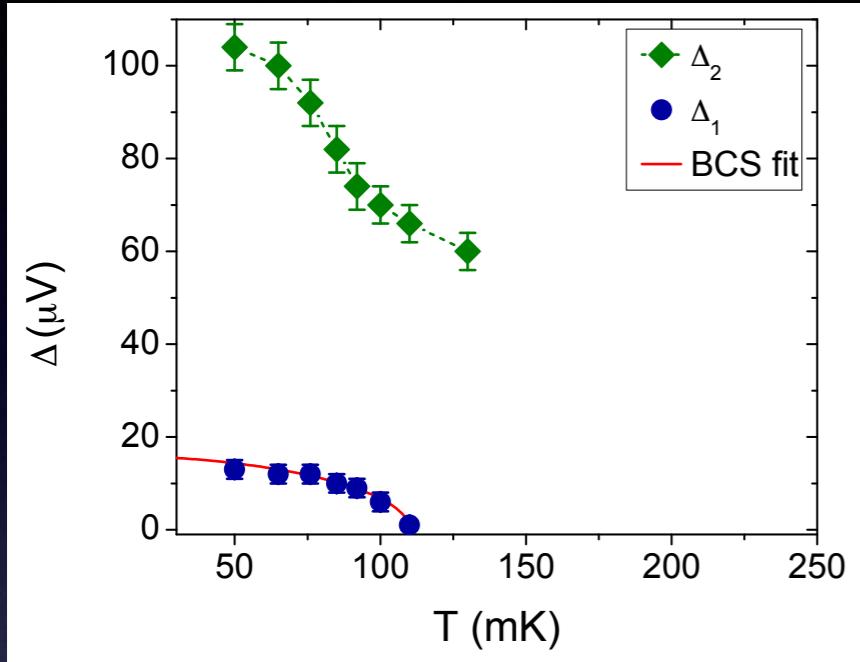


two gap fit  
(v.  $\text{MgB}_2$ )

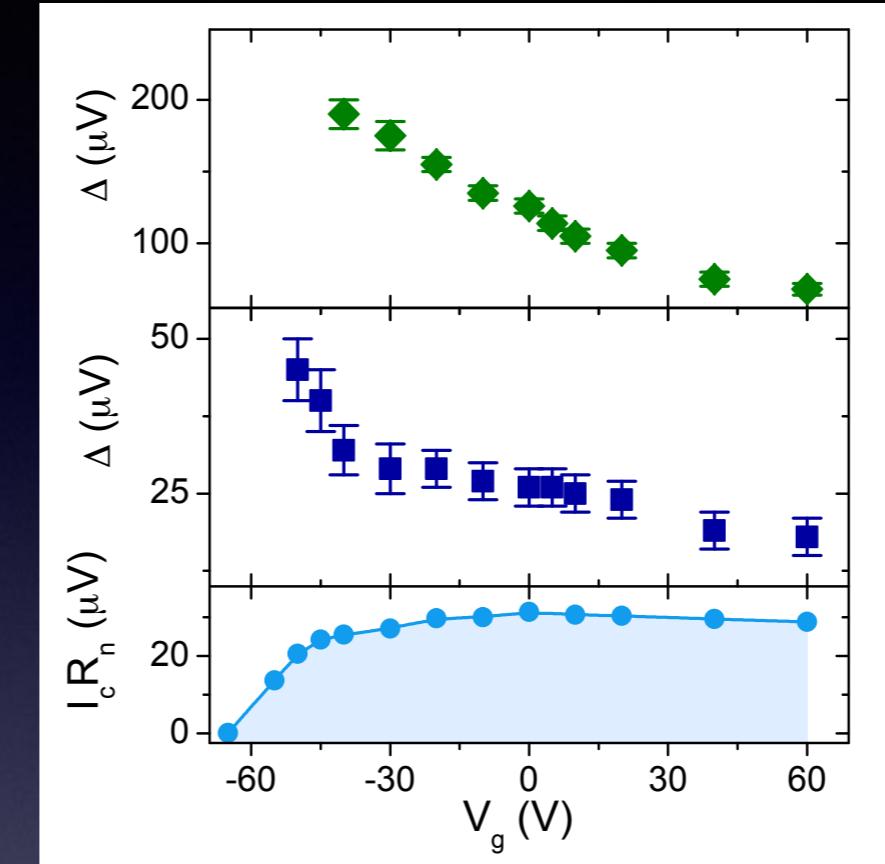




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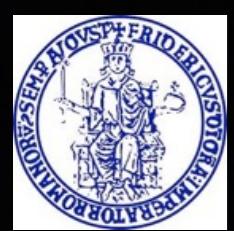


$\Delta_1$  BCS like with  
 $\Delta_0/k_B T \approx 1.7$   $T_c = 110\text{mK}$   
 $\Delta_2$  non BCS

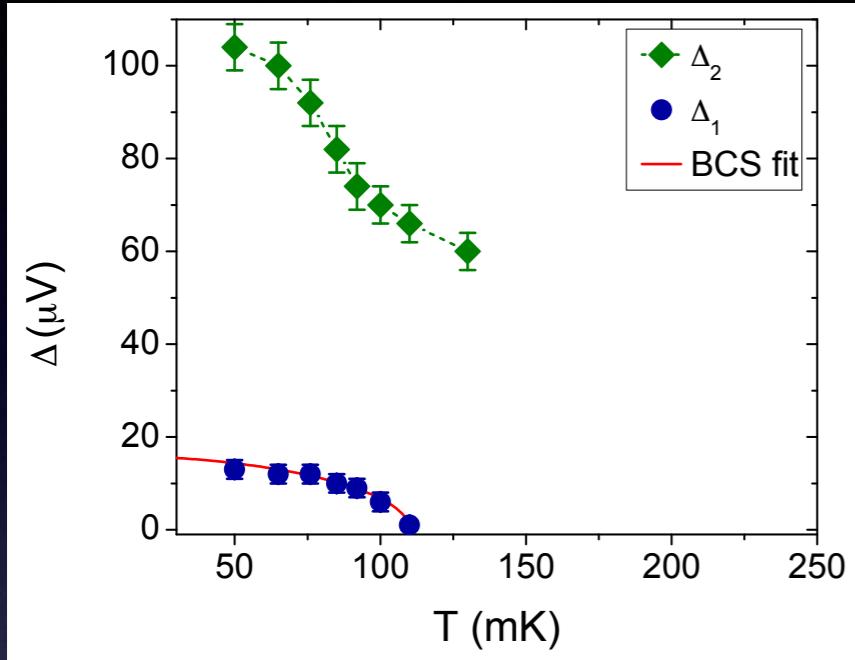


$\Delta_1$  and  $\Delta_2$  increase with decreasing  $V_g$

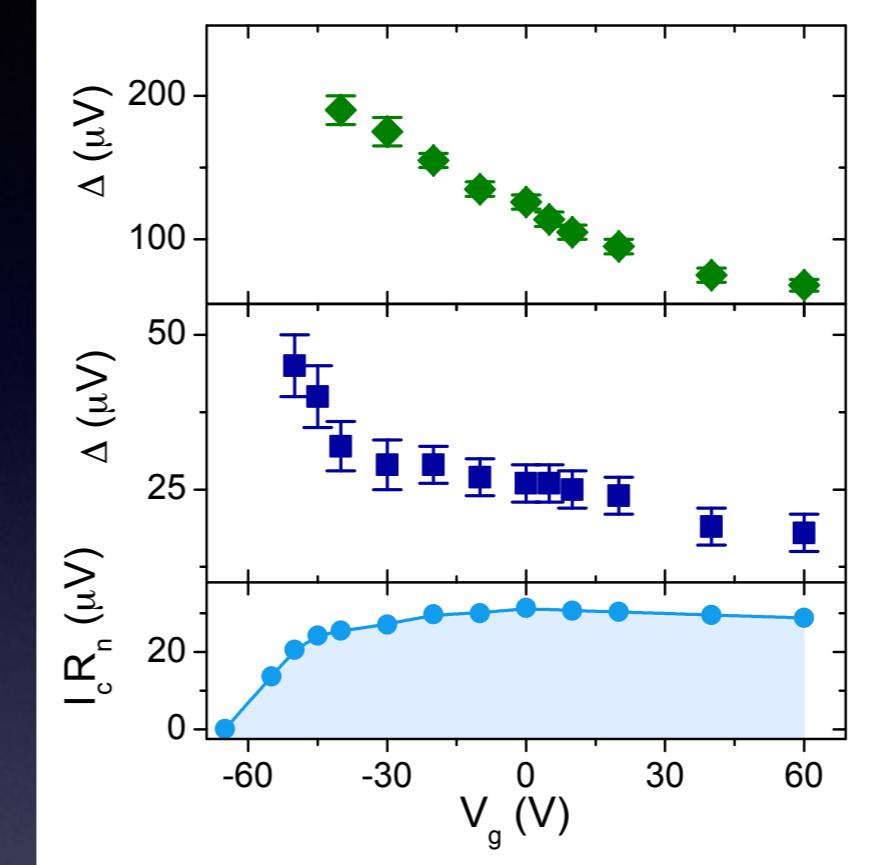
see also C.Richter et al.  
Nature 2013



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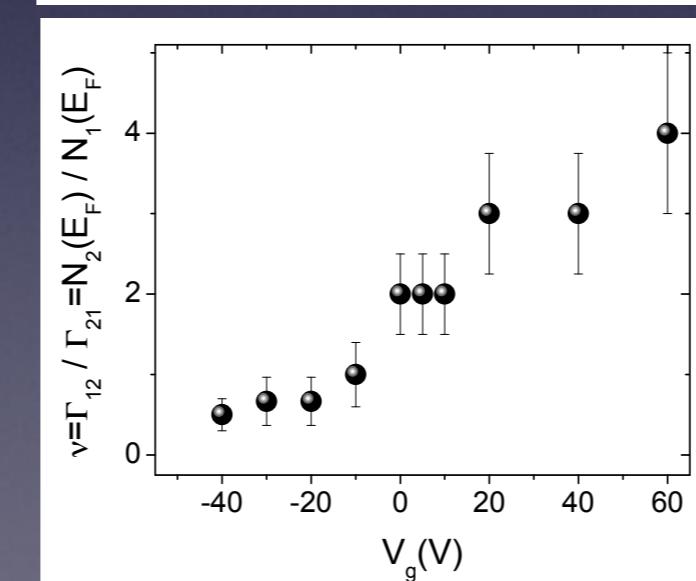


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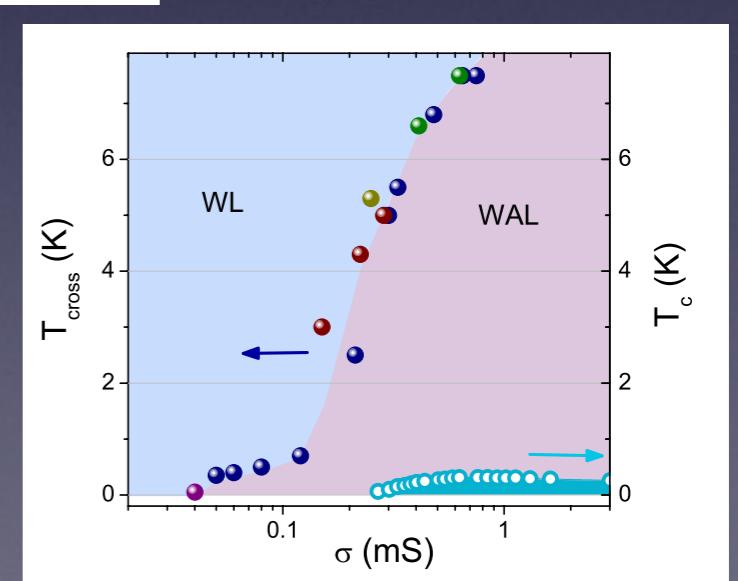


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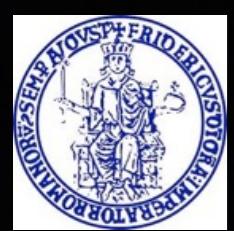
$$\nu = N_2(0)/N_1(0) = \Gamma_{12}/\Gamma_{21}$$



D.Stornaiuolo et al., PRB 2014

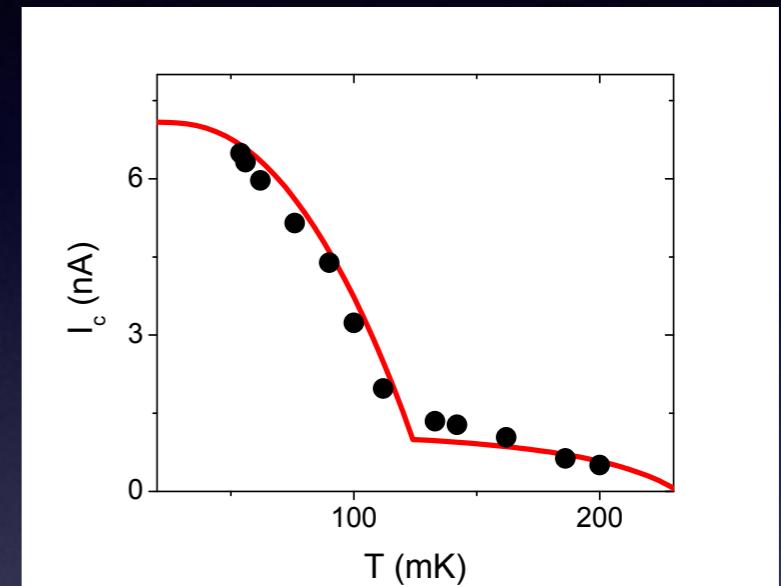
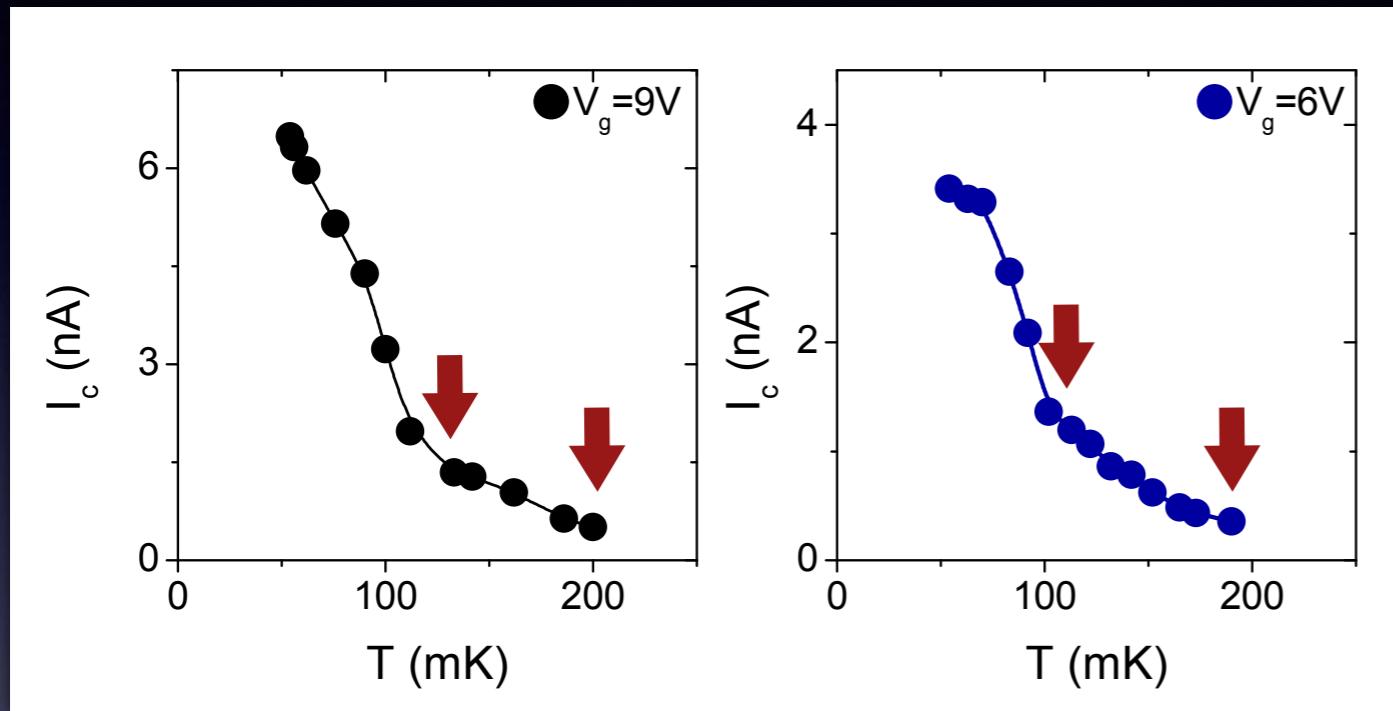
the density of states related to  $\Delta_2$  increases with the gate more than that of  $\Delta_1$

→ link between  $\Delta_2$  and Rashba SOC

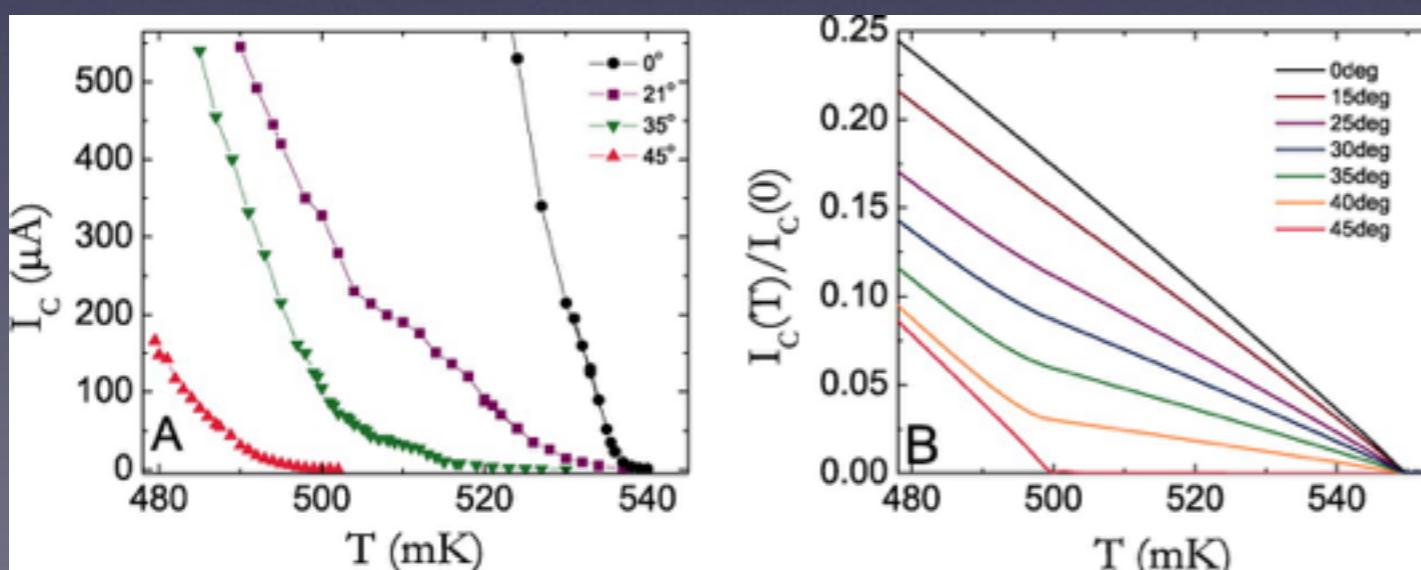


# LAO/STO JJs - $I_c(T)$

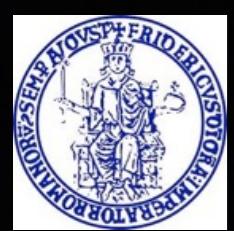
The presence of two **superconducting** energy scales is confirmed by the behavior of  $I_c(T)$



fit performed using a two gap theory



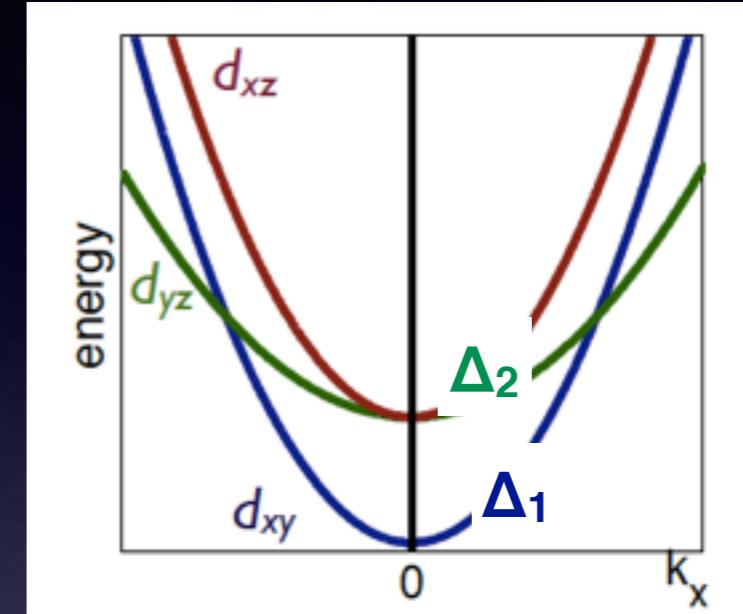
J.D. Strand et al., The Transition Between Real and Complex Superconducting Order Parameter Phases in UPt<sub>3</sub>, Science (2010)

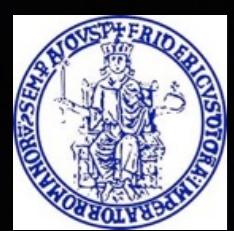


# LAO/STO JJs - $dI/dV$

what about the origin of  $\Delta_1$  and  $\Delta_2$ ?

1.  $\Delta_1$  and  $\Delta_2$  are linked to  $d_{xy}$  and  $d_{xz-yz}$  bands respectively

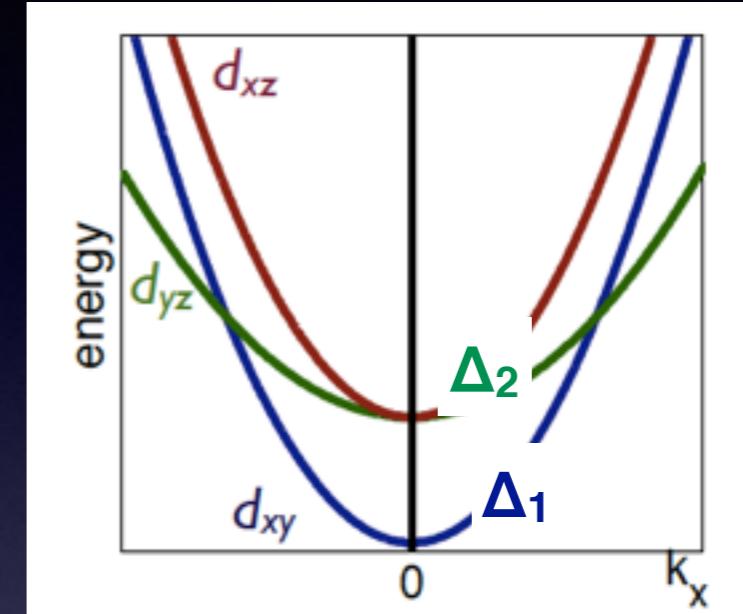




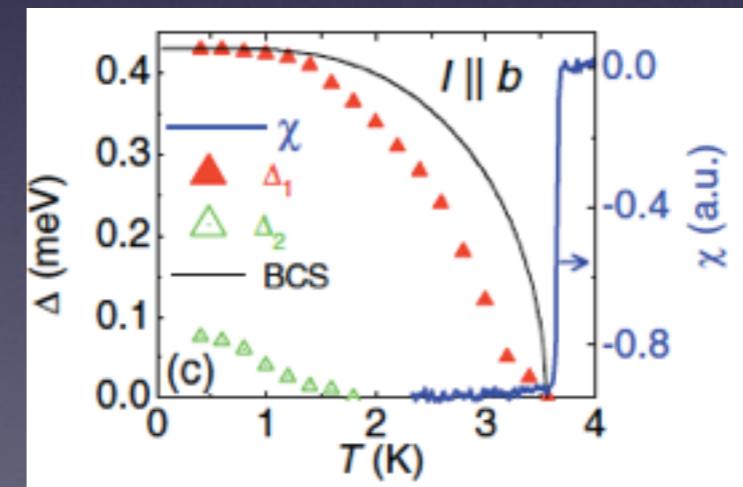
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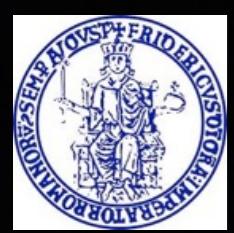
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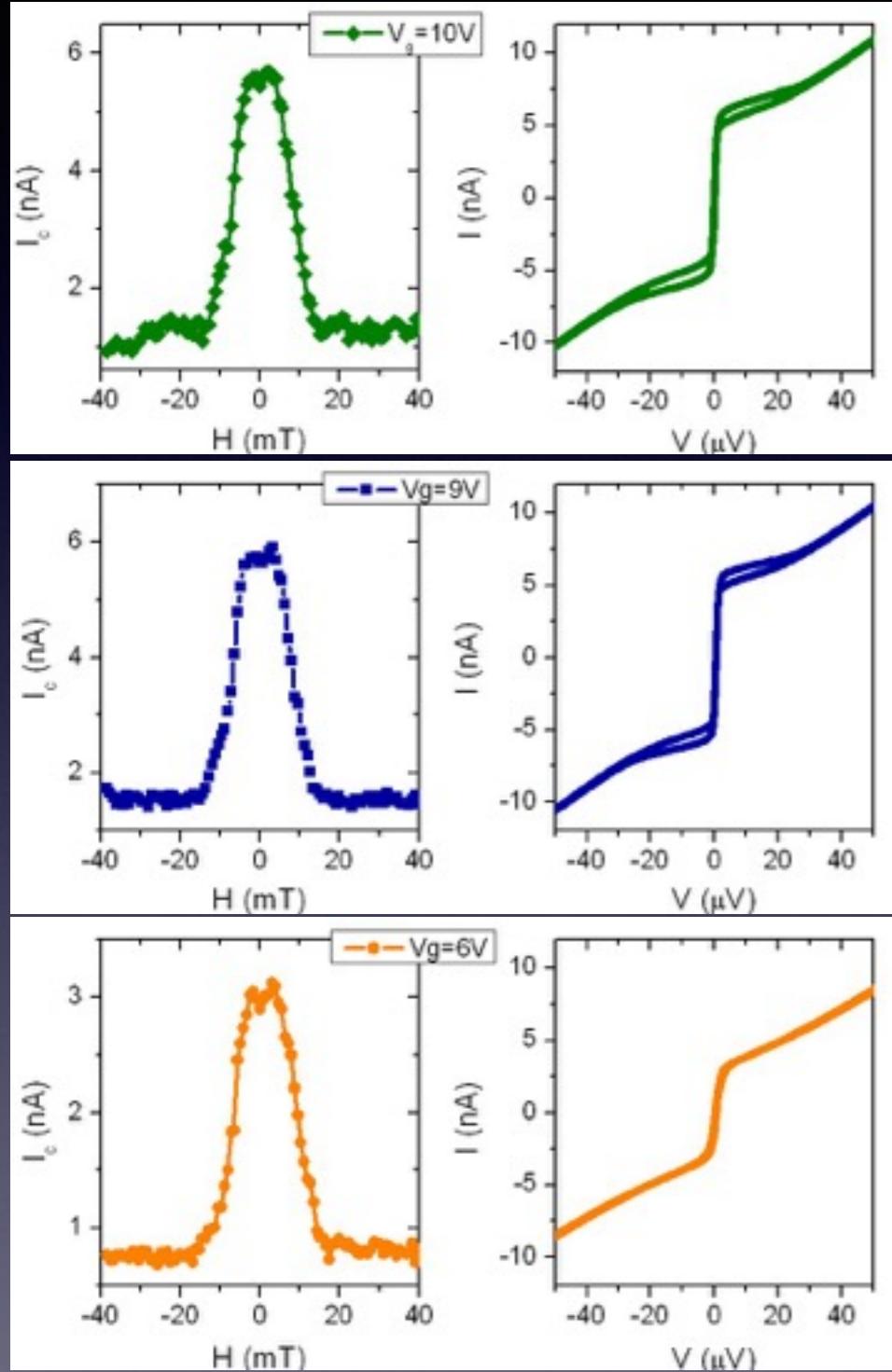
2.  $\Delta_1$  and  $\Delta_2$  are linked to a multi component order parameter of the s+ip type



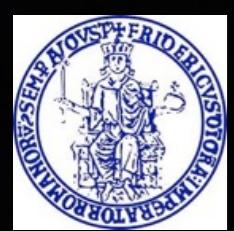
M.Mondal et al., "Andreev bound state and multiple energy gaps in the noncentrosymmetric superconductor BiPd", PRB 2012



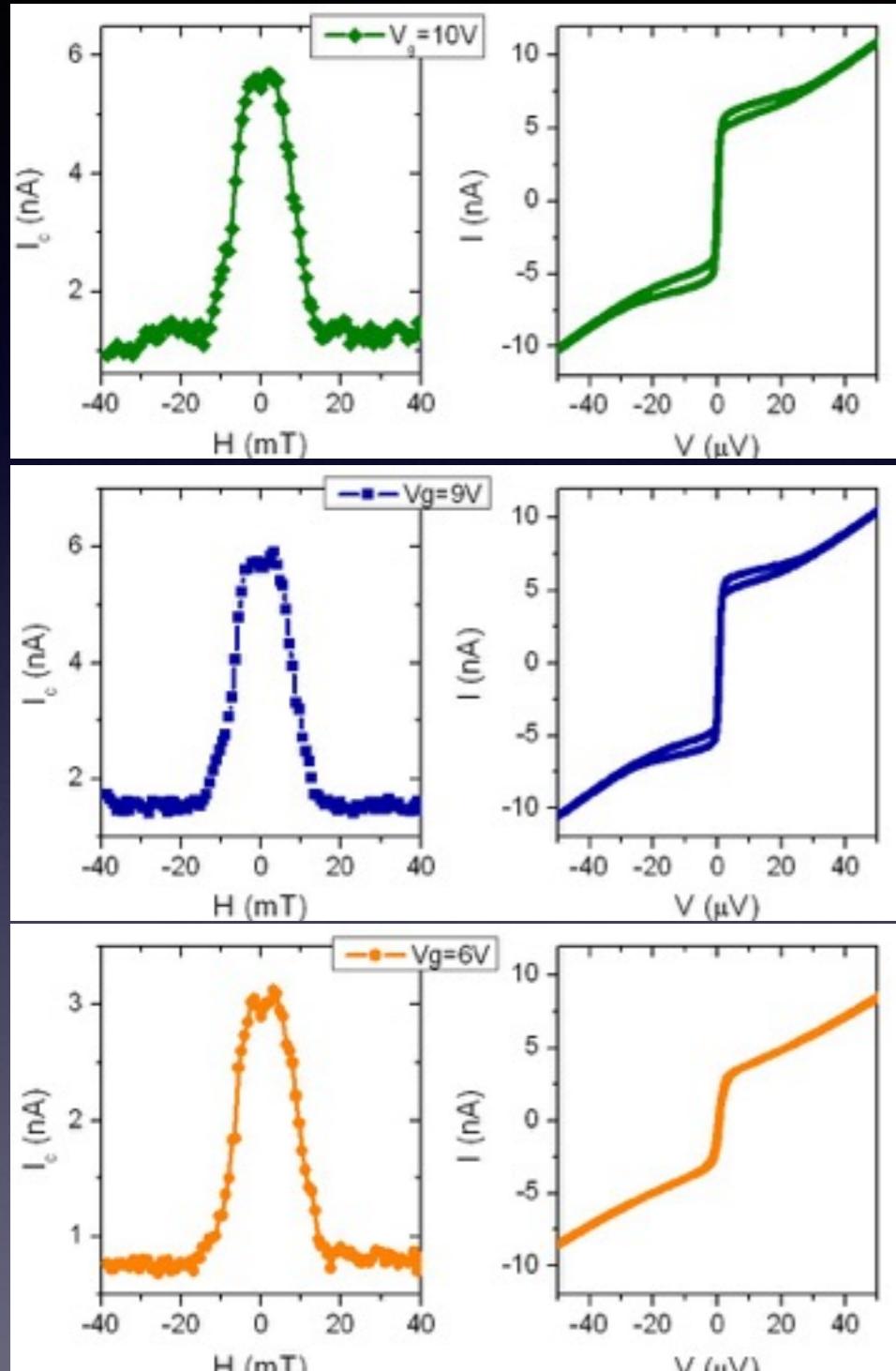
# LAO/STO JJs - $I_c(H)$



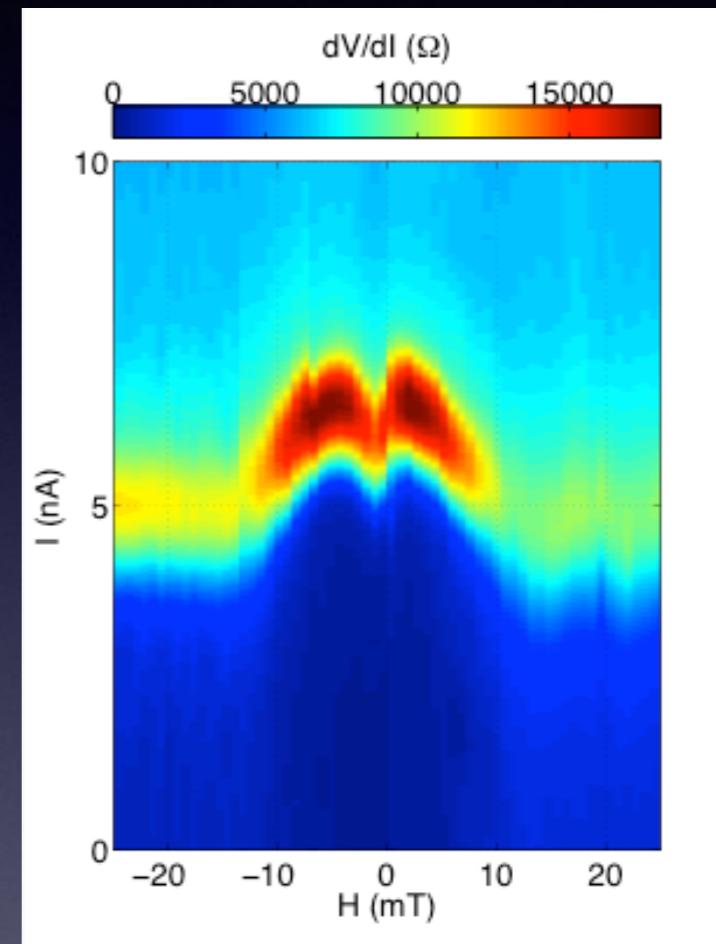
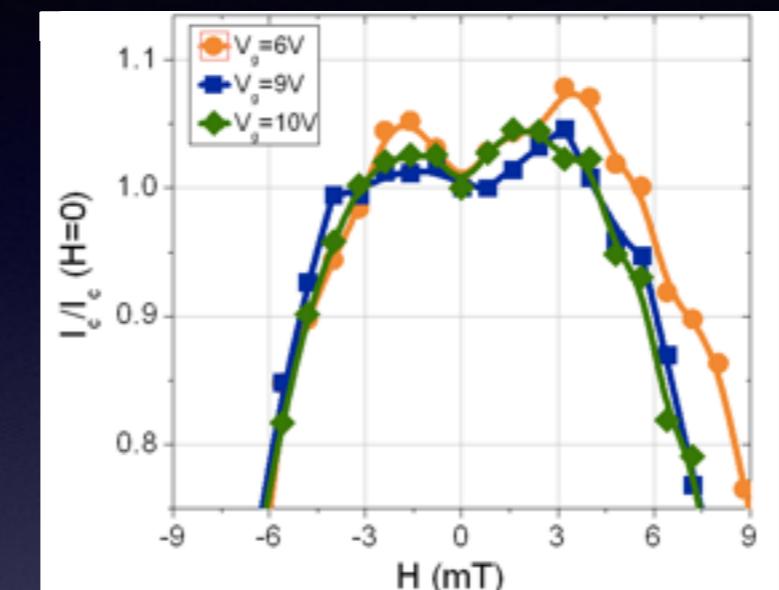
- The pattern periodicity is the same for all the gate voltages



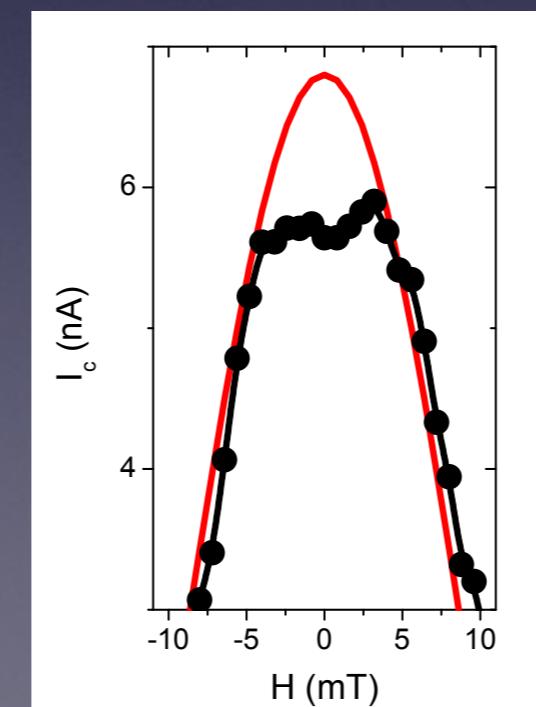
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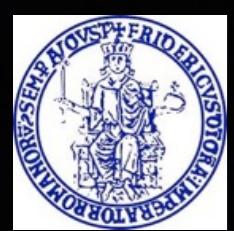
- The pattern periodicity is the same for all the gate voltages
- A dip at zero  $H$  can be seen



$dV/dI$  for  $V_g = 10\text{V}$



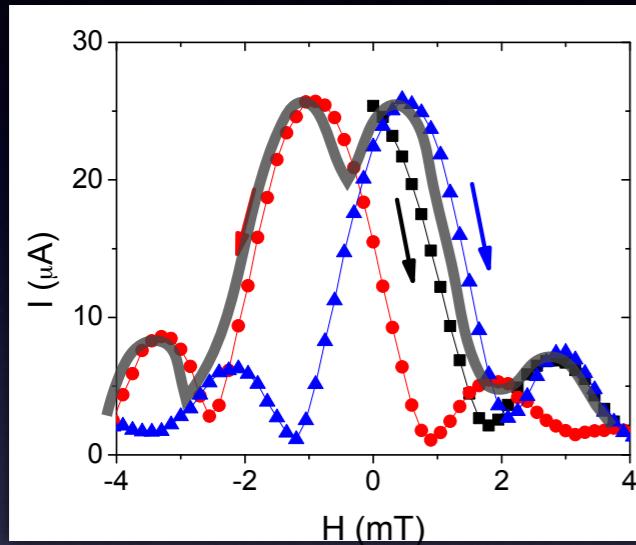
marked deviation from the Fraunhofer behavior around  $H=0$



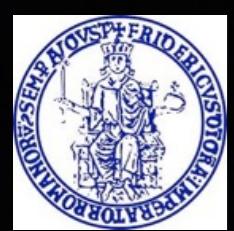
# LAO/STO JJs - $I_c(H)$

zero field dip in the  $I_c(H)$  pattern: origin

1. magnetic effects?



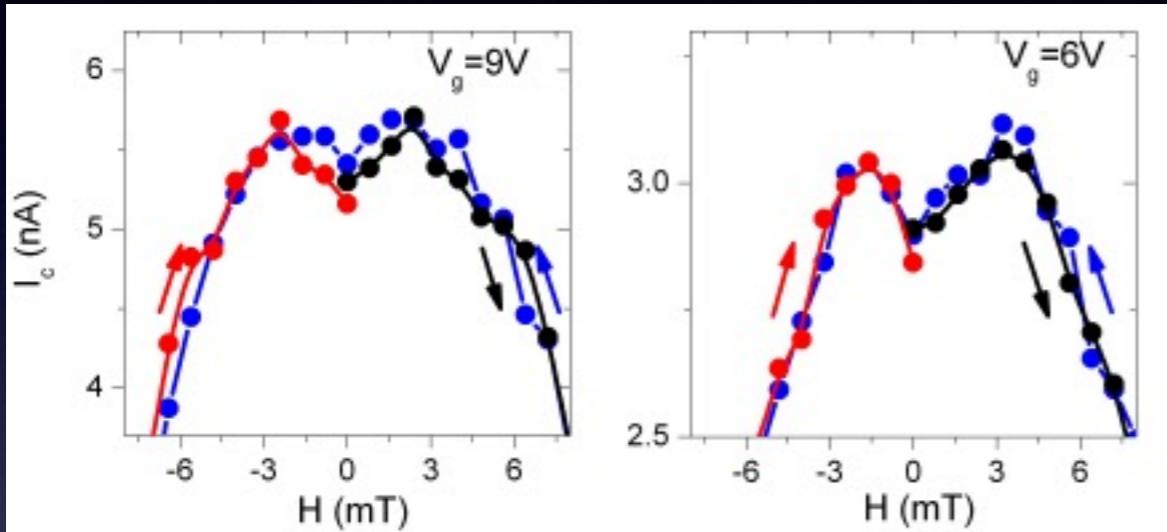
magnetic pattern of an SFS junction



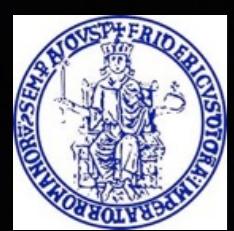
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## 1. ~~magnetic effects?~~



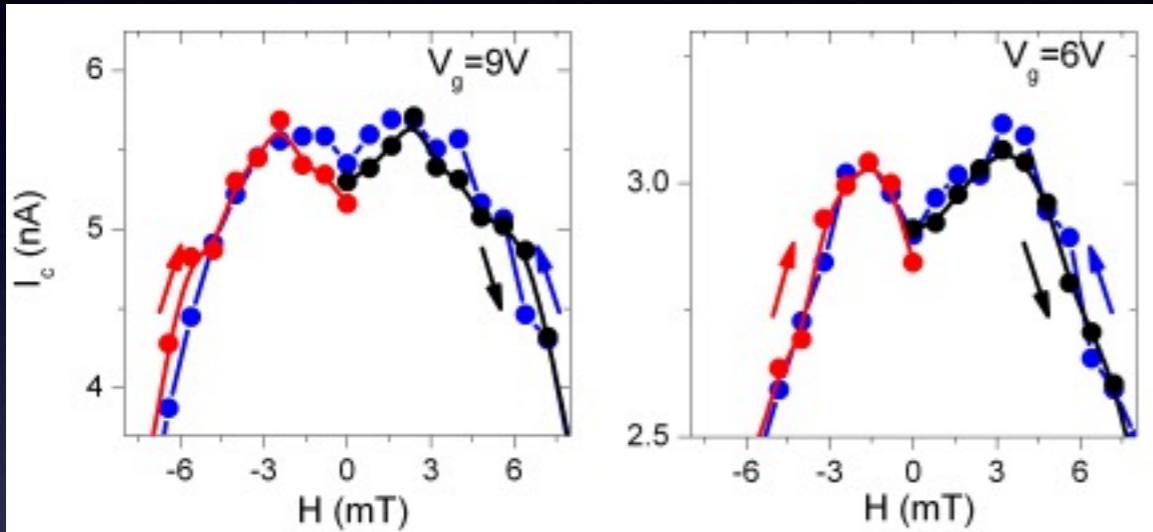
LAO/STO JJ no hysteresis can be seen



# LAO/STO JJs - $I_c(H)$

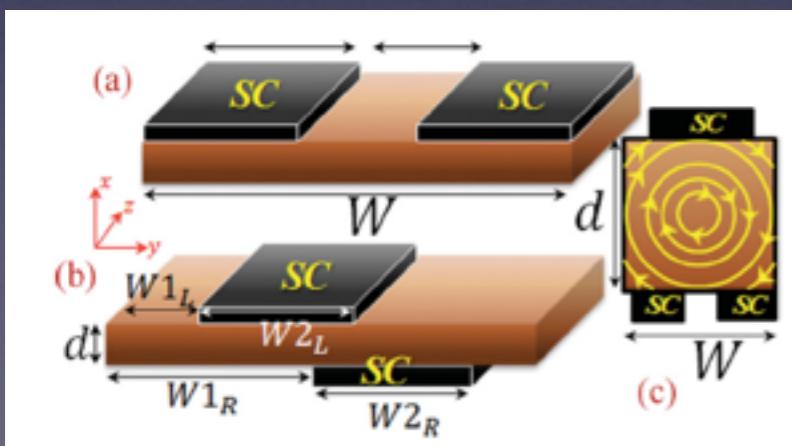
zero field dip in the  $I_c(H)$  pattern: origin

## 1. ~~magnetic effects?~~

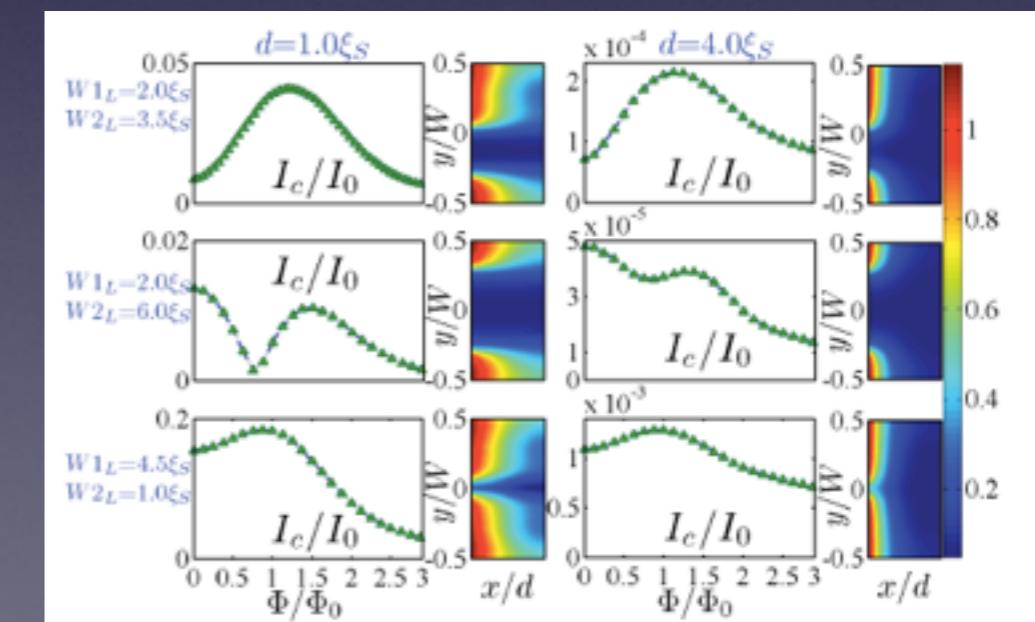


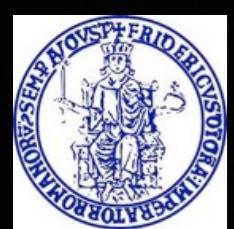
LAO/STO JJ no hysteresis can be seen

## 2. electrodes misalignment?



M. Alidoust and J. Linder,  $\phi$ -state and inverted Fraunhofer pattern in nonaligned Josephson junctions, PRB 2013

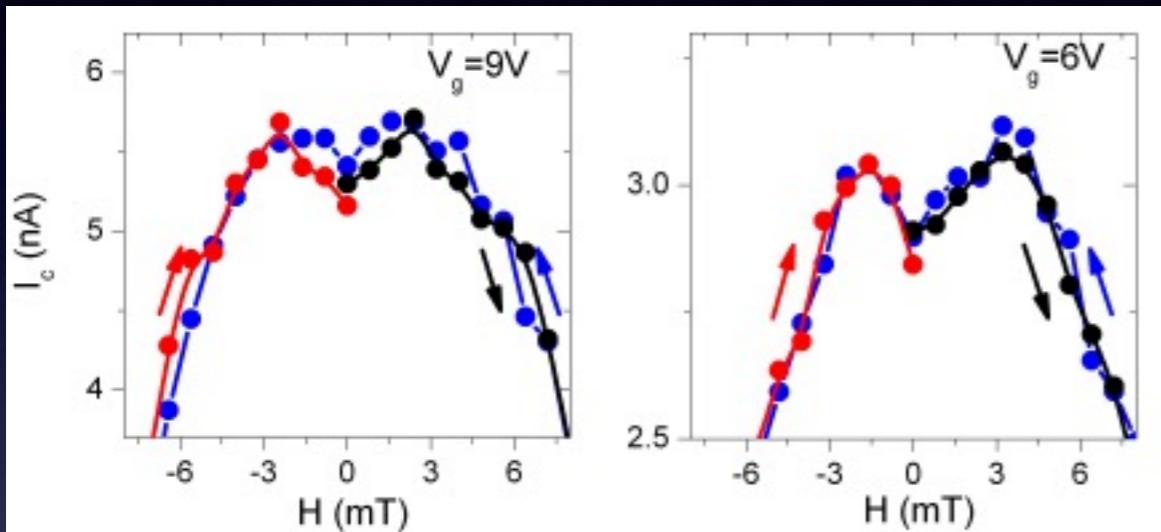




# LAO/STO JJs - $I_c(H)$

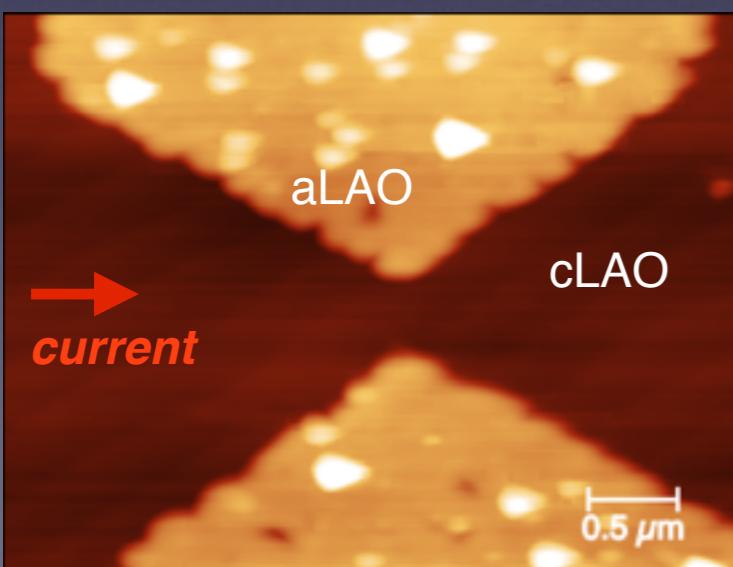
zero field dip in the  $I_c(H)$  pattern: origin

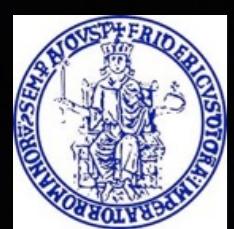
## 1. ~~magnetic effects?~~



LAO/STO JJ no hysteresis can be seen

## 2. ~~electrodes misalignment?~~

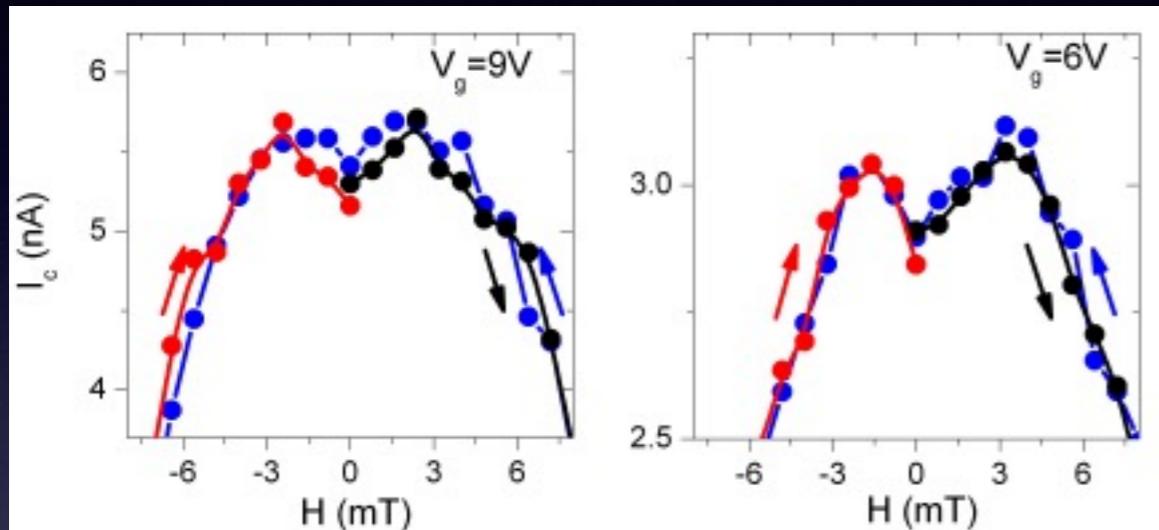




# LAO/STO JJs - $I_c(H)$

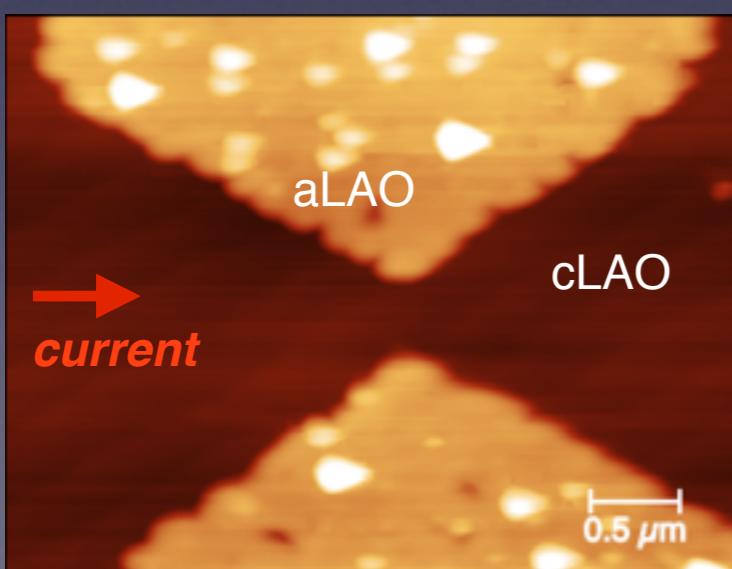
zero field dip in the  $I_c(H)$  pattern: origin

1. ~~magnetic effects?~~

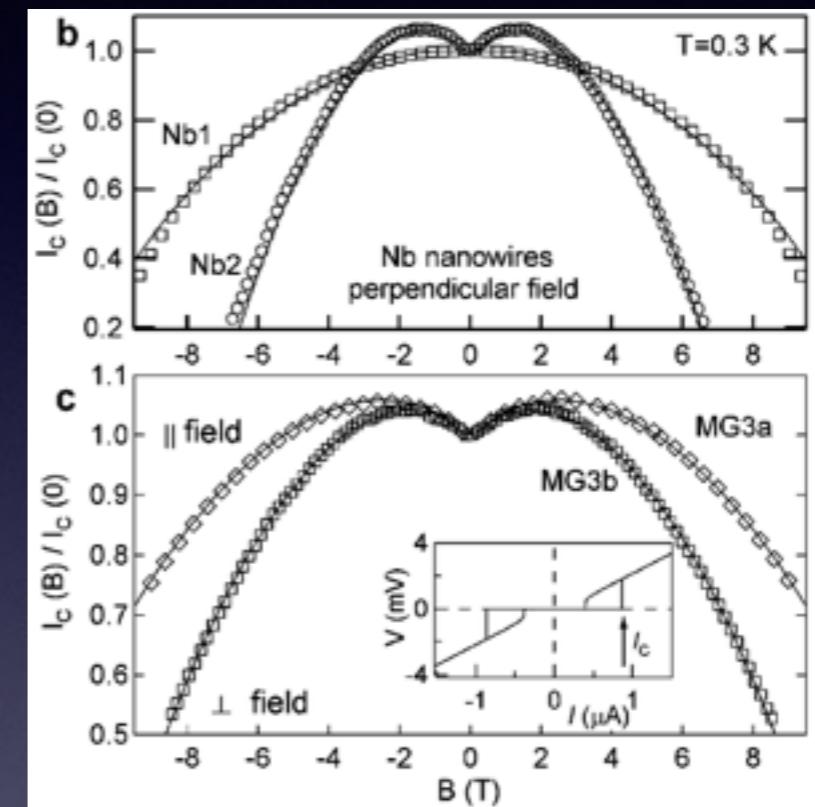


LAO/STO JJ no hysteresis can be seen

2. ~~electrodes misalignment?~~



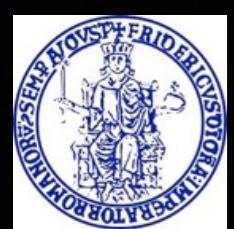
3. scattering from magnetic impurities?



A. Rogachev et al., PRL 2006

phase breaking of Cooper pairs induced by spin flip scattering on magnetic impurities.  
Such spin flip scattering disappears when the magnetic moments are polarized under a magnetic field:

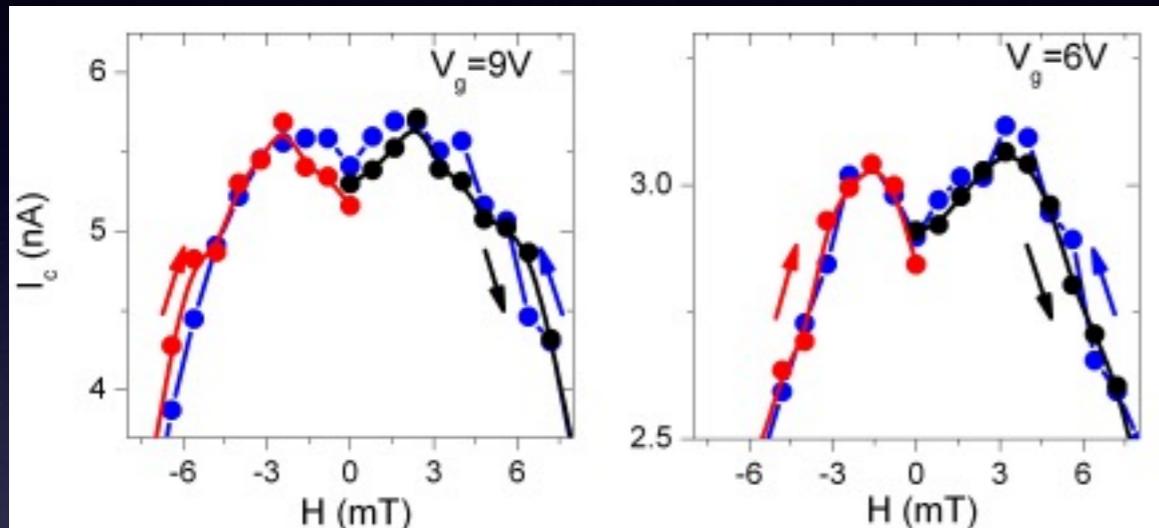
$$\mu_B B = k_B T$$



# LAO/STO JJs - $I_c(H)$

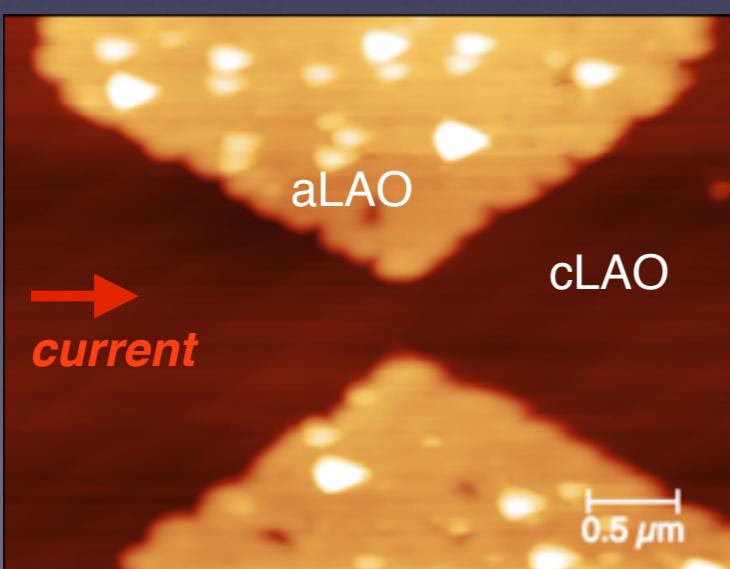
zero field dip in the  $I_c(H)$  pattern: origin

~~1. magnetic effects?~~

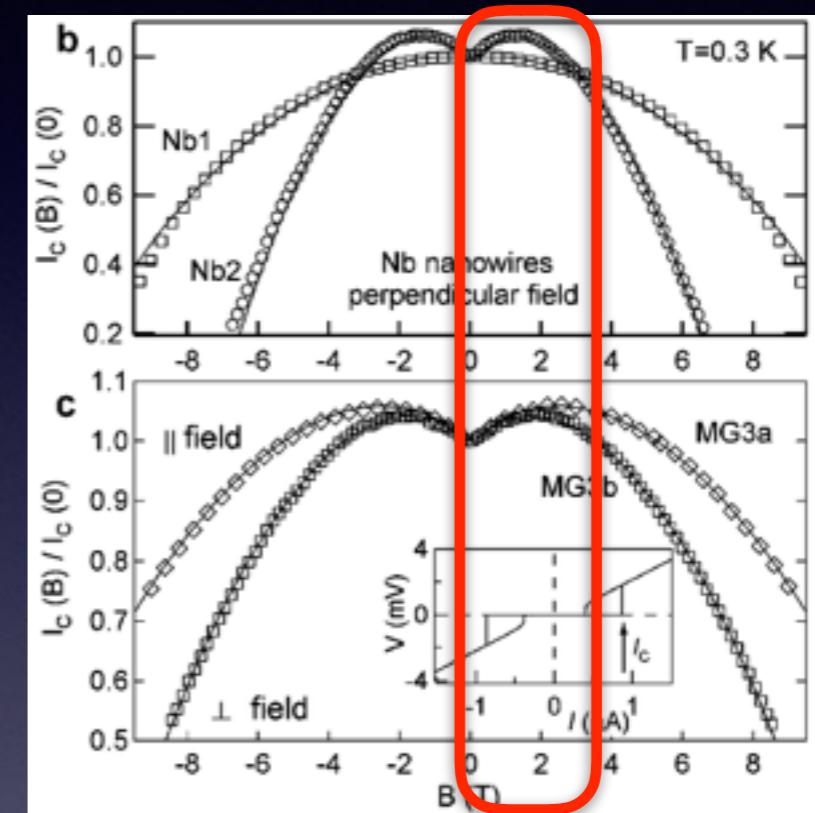


LAO/STO JJ no hysteresis can be seen

~~2. electrodes misalignment?~~



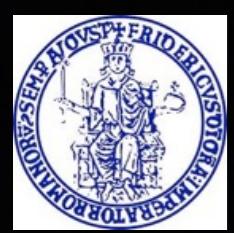
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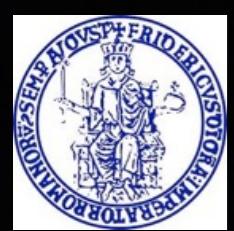


# LAO/STO JJs - $I_c(H)$

zero field dip in the  $I_c(H)$  pattern: origin?  
interference effects between 0 and  $\pi$  sections

standard “0” junction       $I = I_c \sin(\Delta\varphi)$

$\pi$  junction       $I = I_c \sin(\Delta\varphi + \pi)$       shift of  $\pi$  in the  
junction’s phase



# LAO/STO JJs - $I_c(H)$

zero field dip in the  $I_c(H)$  pattern: origin?  
interference effects between 0 and  $\pi$  sections

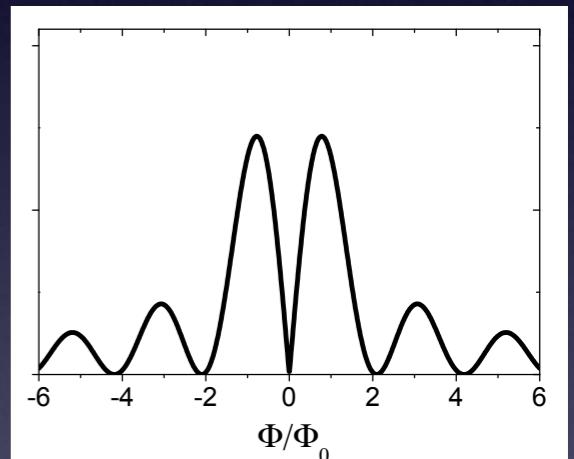
standard “0” junction  $\rightarrow I = I_c \sin(\Delta\varphi)$

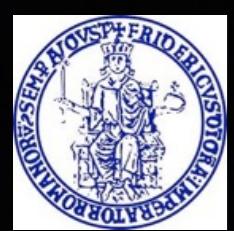
$\pi$  junction  $\rightarrow I = I_c \sin(\Delta\varphi + \pi) = -I_c \sin(\Delta\varphi)$

shift of  $\pi$  in the junction’s phase

see D.A.Wollman  
et al., PRL 1995

$$I_c^{0-\pi}(\Phi) \propto \frac{\sin^2(\pi\Phi/2\Phi_0)}{|\pi\Phi/2\Phi_0|}$$





# LAO/STO JJs - $I_c(H)$

zero field dip in the  $I_c(H)$  pattern: origin?  
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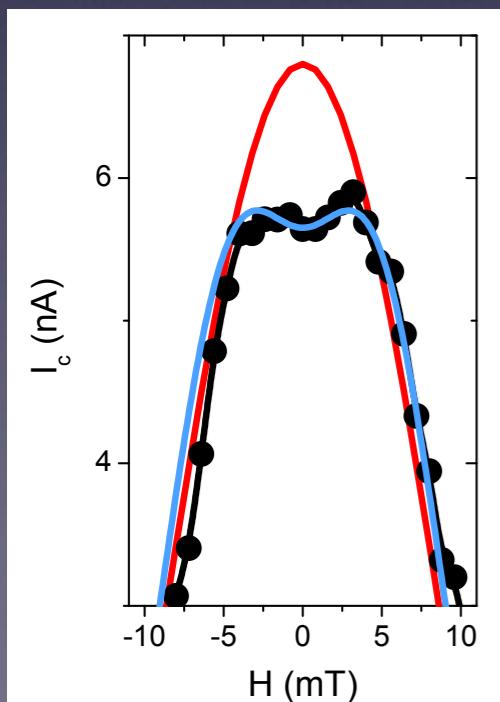
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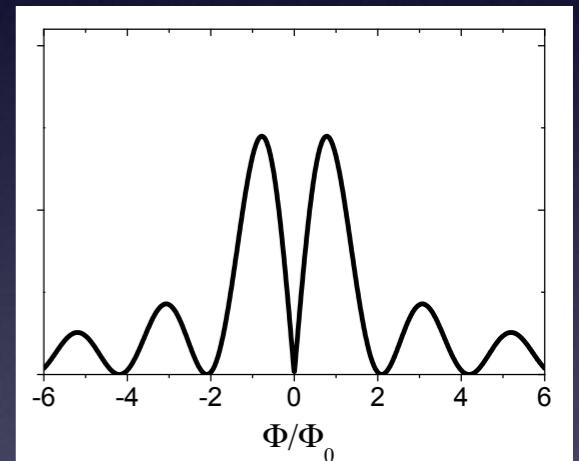
fit of the  $I_c(H)$  pattern assuming a 0 and a  $\pi$  section

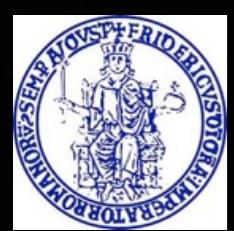
$$I(H, \phi) = J_c^0 L \int_0^{w1} \sin \left( \frac{2e}{\hbar c} L x H + \phi \right) dx + J_c^\pi \int_{w1}^{w1+w2} \sin \left( \frac{2e}{\hbar c} L x H + \phi + \pi \right) dx$$

$$\frac{J_c^0}{J_c^\pi} \sim \frac{1}{0.11}$$

$$\frac{J_c^0}{J_c^\pi} = \frac{R_{11}^{-1} \Delta_1}{R_{22}^{-1} \Delta_2} \sim \frac{1}{0.16}$$

from the  $I_c(T)$  fit  
at  $V_g=10V$





# LAO/STO JJs - $I_c(H)$

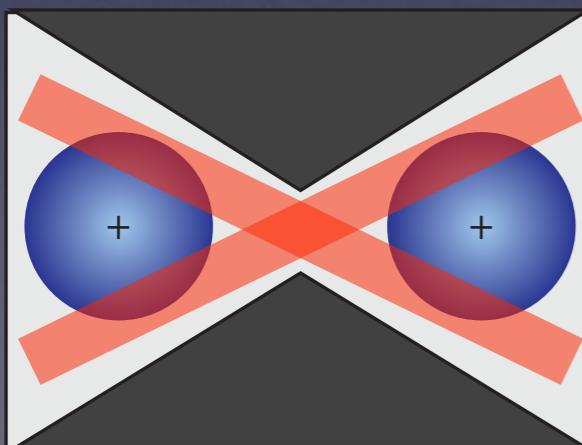
zero field dip in the  $I_c(H)$  pattern: origin?  
interference effects between 0 and  $\pi$  sections

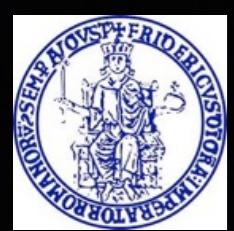
standard “0” junction  $\rightarrow I = I_c \sin(\Delta\varphi)$

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shift of  $\pi$  in the  
junction’s phase

in order to obtain a  $\pi$  section we need an  
unconventional order parameter!





# LAO/STO JJs - $I_c(H)$

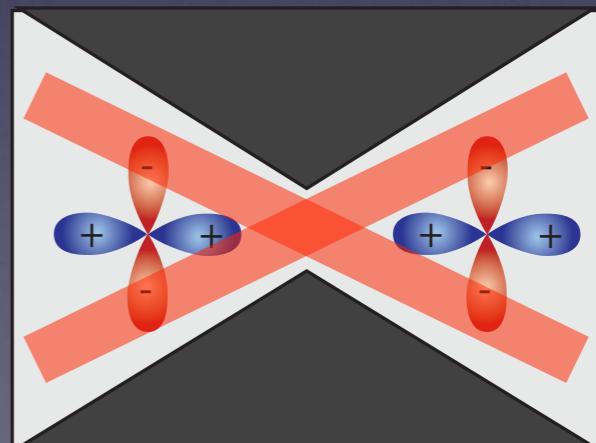
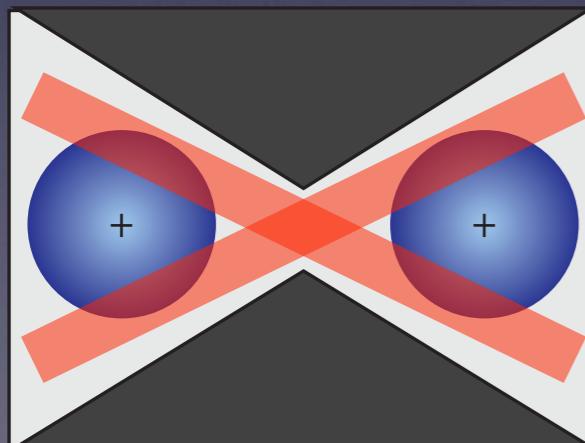
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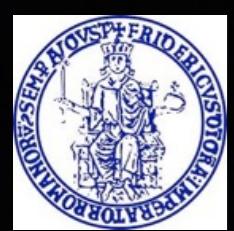
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shift of  $\pi$  in the junction’s phase

in order to obtain a  $\pi$  section we need an unconventional order parameter!



NOTE: d-wave would not work!

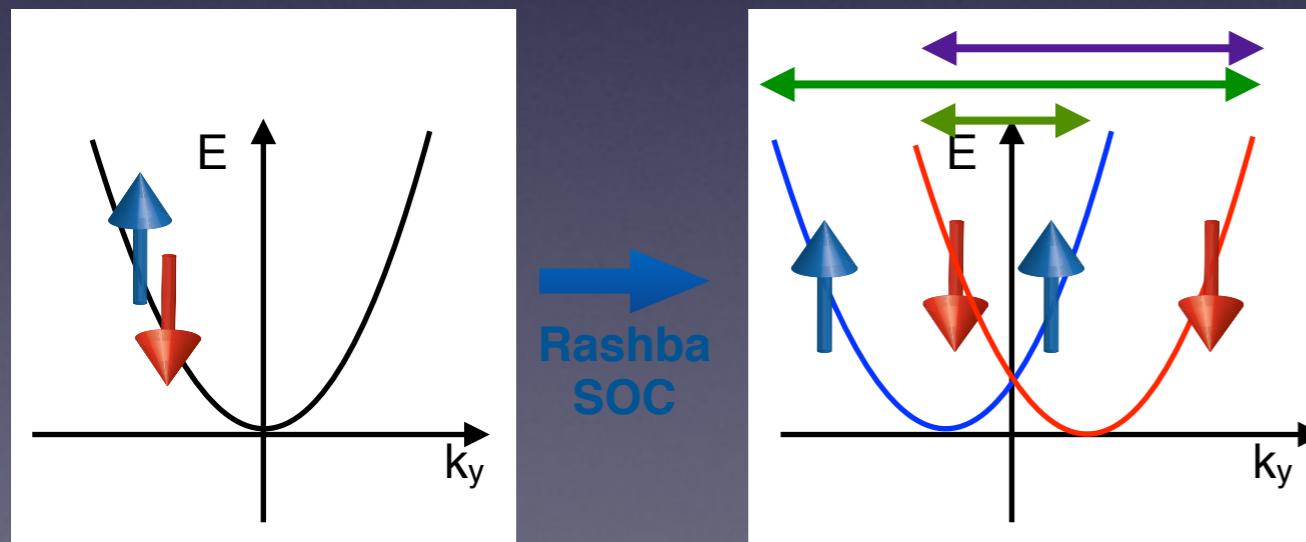


# LAO/STO superconductivity

LAO/STO superconducting state is still largely unexplored

- ? order parameter symmetry
- ? mechanism for superconductivity
- ? superconductivity + Rashba SOC
- ? ... ...

L.P. Gor'kov, E.I. Rashba, *Superconducting 2D System with Lifted Spin Degeneracy: Mixed Singlet-Triplet State*, Physical Review Letters 2001

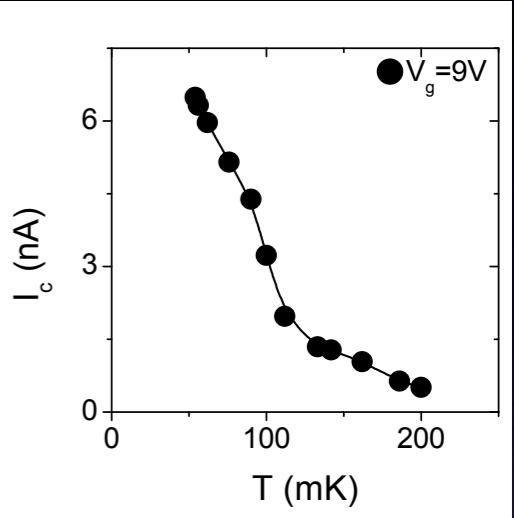
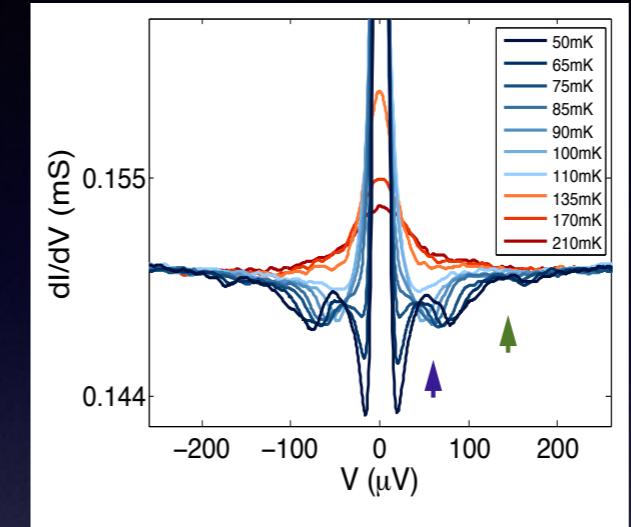


- K. Yada et al, Phys. Rev. B (2009)
- Y. Tanaka et al., Phys. Rev. B (2009)
- L. Fidkowski et al. Phys. Rev. B (2011)
- S. Nakosai et al, Phys. Rev. Lett. (2012)
- R.M. Fernandes, Phys. Rev. B (2013)
- F. Loder, J. Phys.: Condens. Matter (2013)
- N. Mohanta and A. Taraphder, EPL, (2014)
- M. S. Scheurer and J. Schmalian, Nature Comm. (2015)
- V. Kozii and L. Fu, Phys. Rev. Lett. (2015)
- E. Lake et al. Phys. Rev. B (2016)
- K.-C. Weng, and C.D. Hu, Scientific Reports (2016)
- S.B. Chung et al. Scientific Reports (2016)

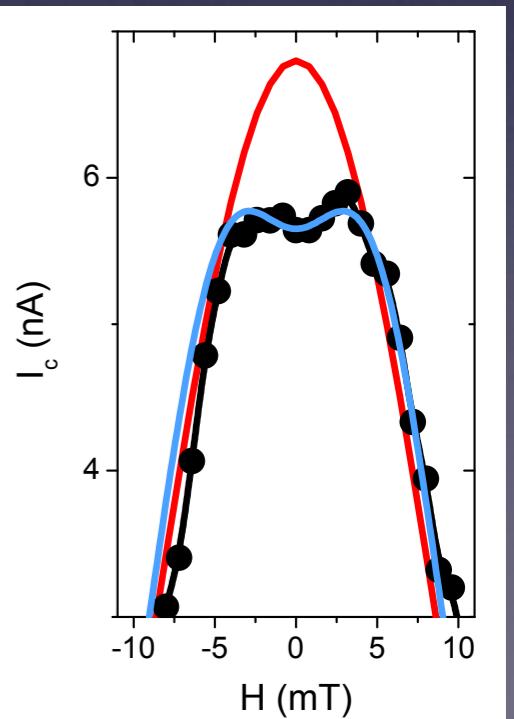


# conclusions

- conductance measurements and  $I_c(T)$  give evidences of **two** superconducting energy scales



- the  $I_c(H)$  pattern can be explained only assuming a  $\pi$  contribution to the transport → unconventional order parameter





thank you for your attention



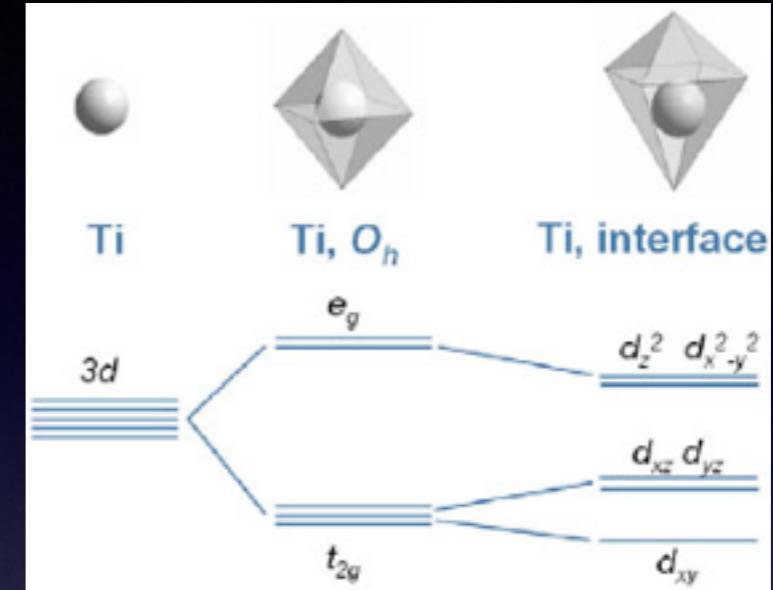
EUCAS 2017 - Geneva, 19/09/2017



# oxide 2DEGs - LAO/STO

conducting electrons come from the Ti 3d bands which are splitted at the interface,  $3d_{xy}$  being the lowest in energy

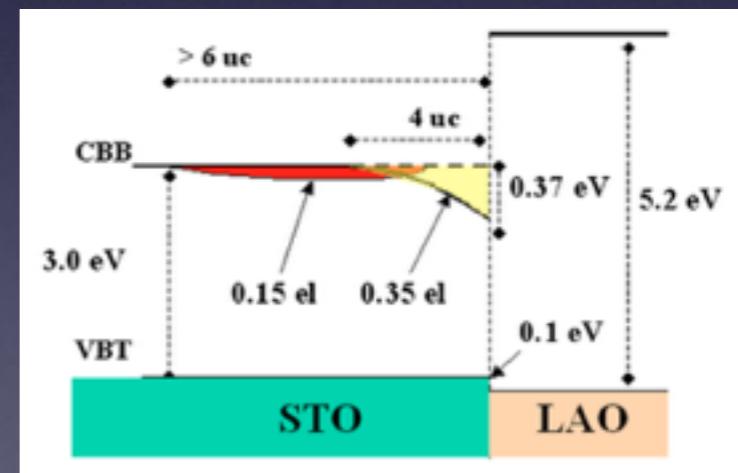
R. Pentcheva and W.E. Pickett, Phys. Rev. B (2006)  
Salluzzo et al. Phys. Rev. Lett 2009



J.-L.Maurice et al. Europhysics Letters

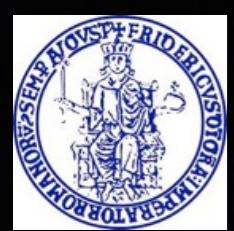
they are confined due to the presence of an electric potential

confined multiband system



P. Delugas et al. Phys. Rev. Lett (2011)

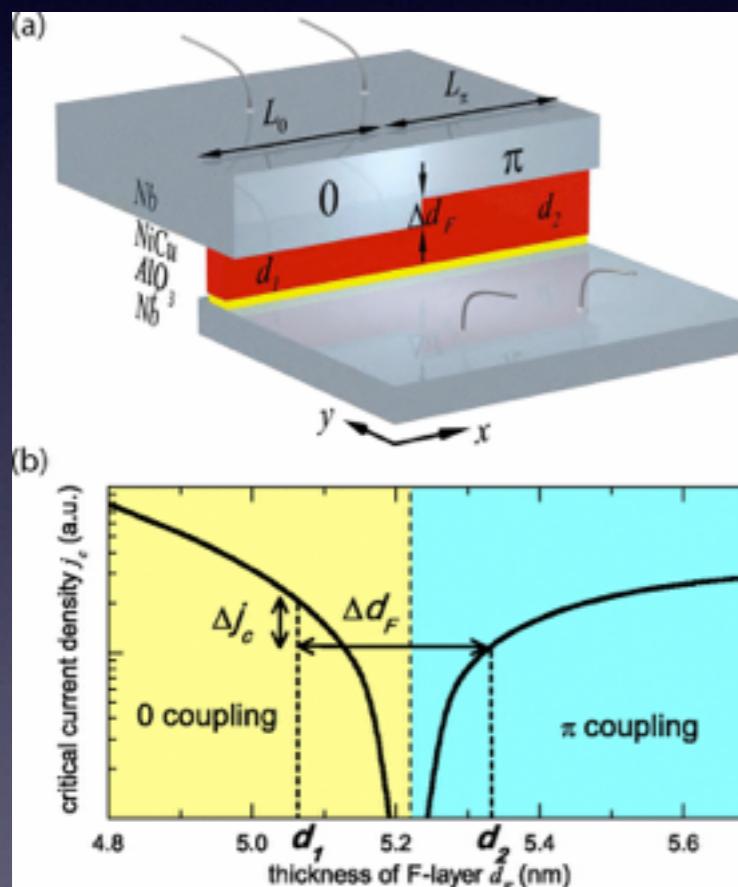
properties are (also) linked to the different filling of the bands, with different effective masses and symmetry



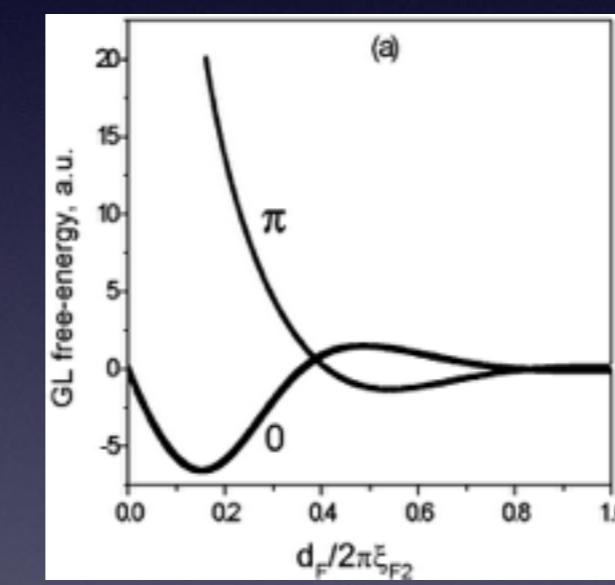
# LAO/STO JJs - $I_c(H)$

zero field dip in the  $I_c(H)$  pattern: origin?  
interference effects between 0 and  $\pi$  sections

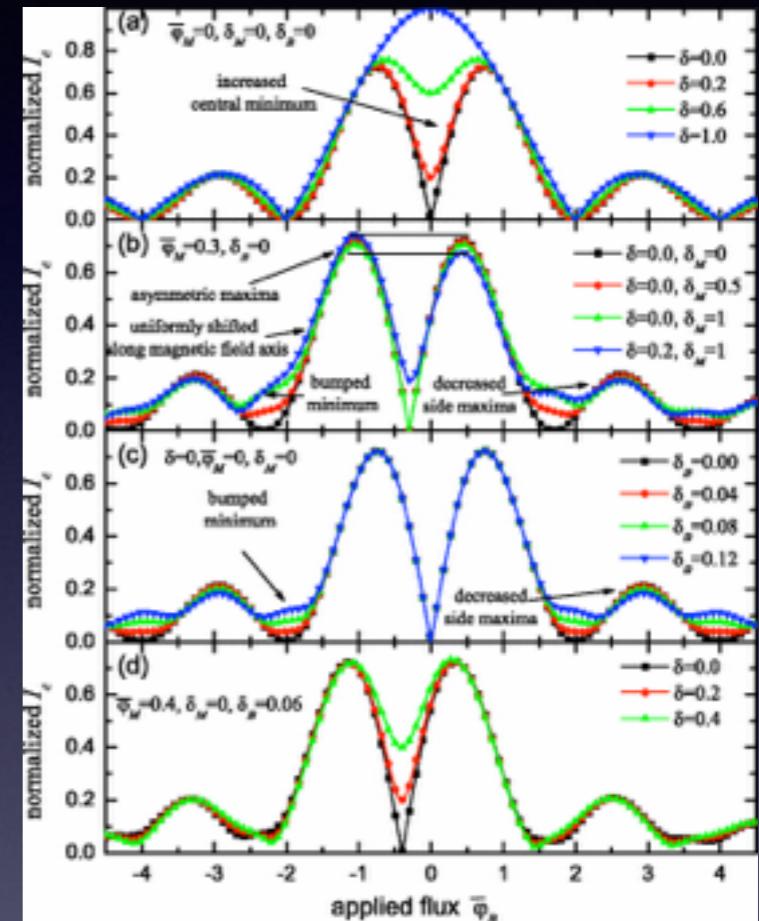
0- $\pi$  SFS junction

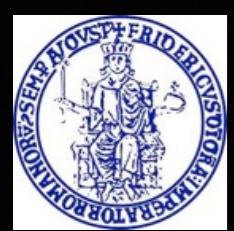


M. Kemmler et al., PRLB 2010



V.V. Ryazanov et al., PRL 2001

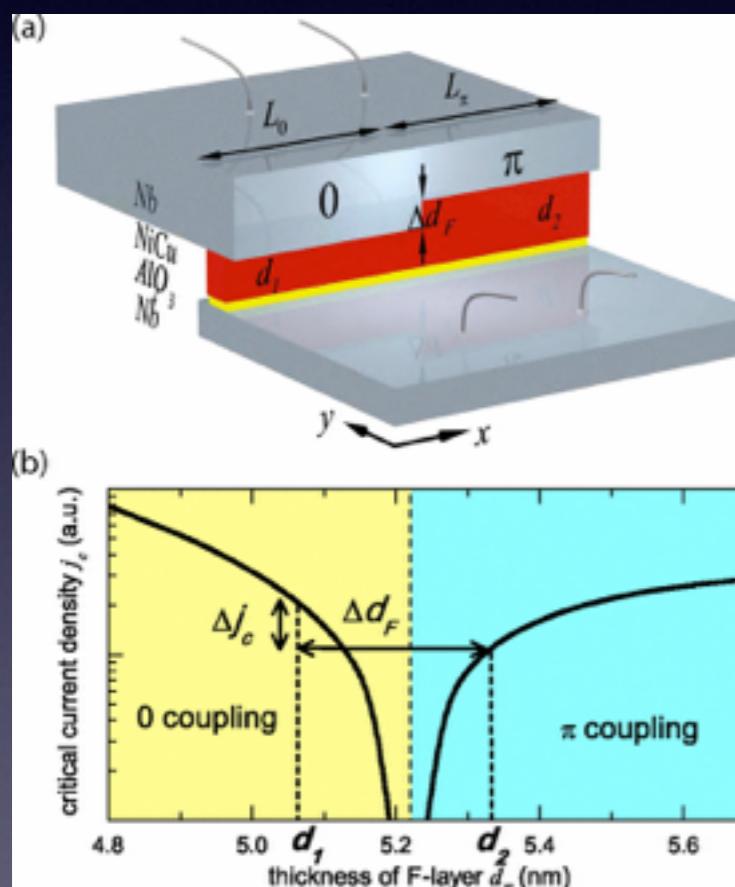




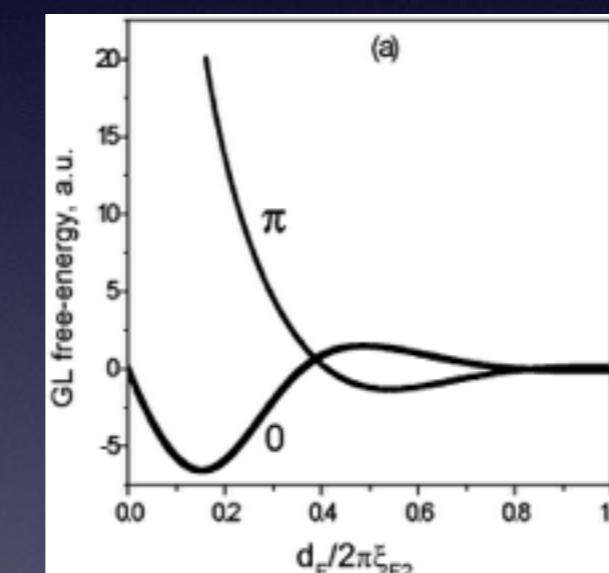
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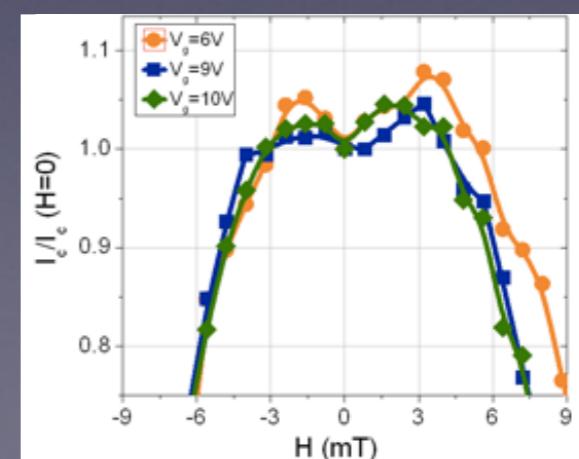
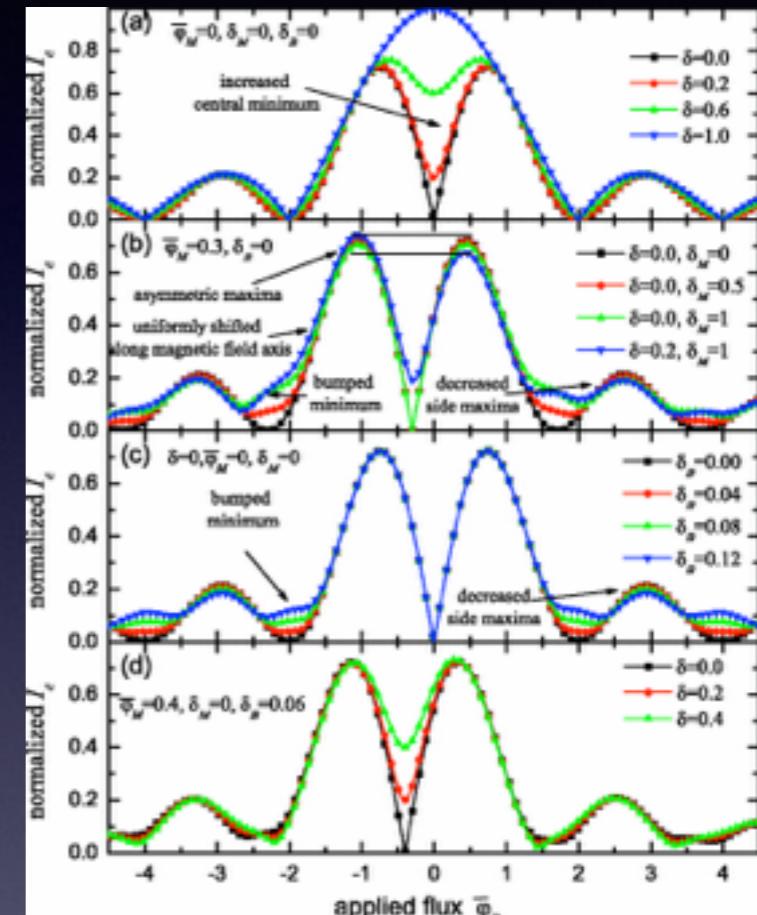
0- $\pi$  SFS junction



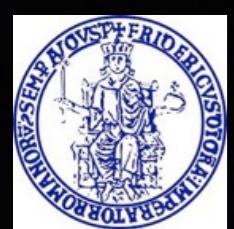
M. Kemmler et al., PRLB 2010



V.V. Ryazanov et al., PRL 2001



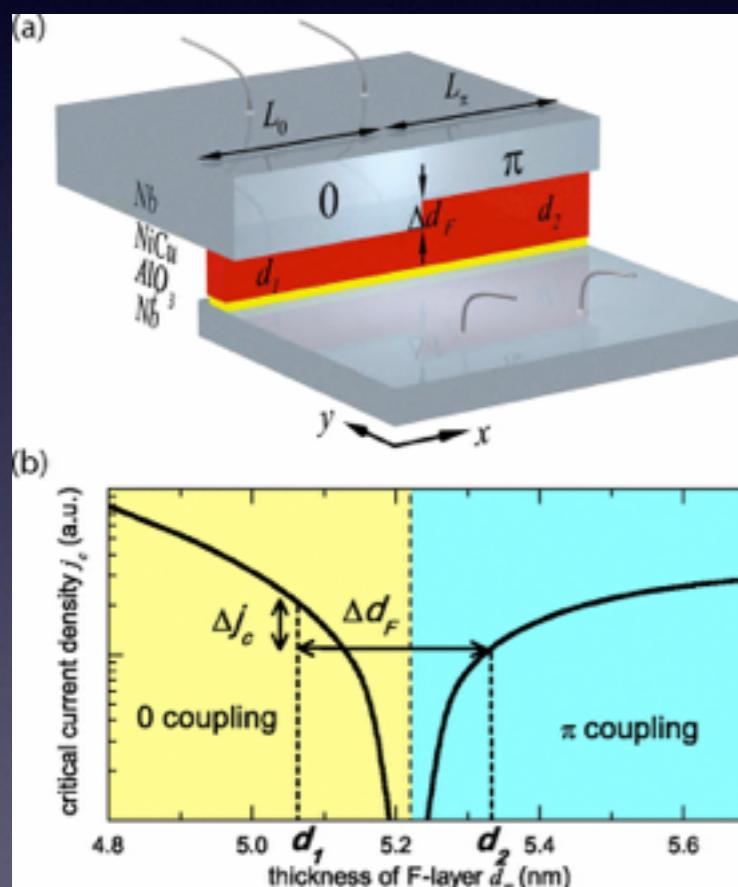
- no shift along the field axis
- the zero field dip is robust with respect to  $V_g$



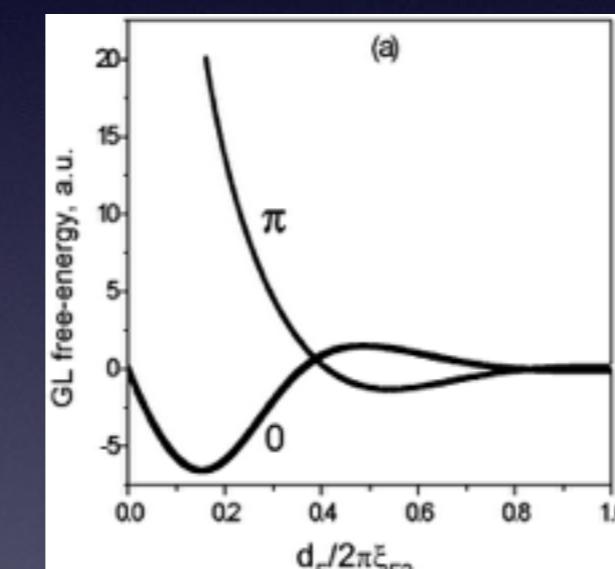
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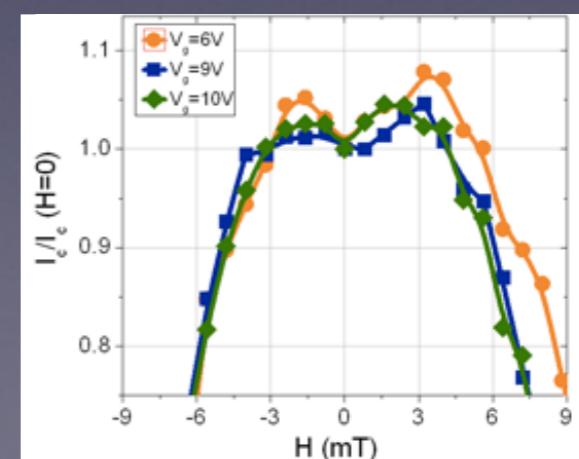
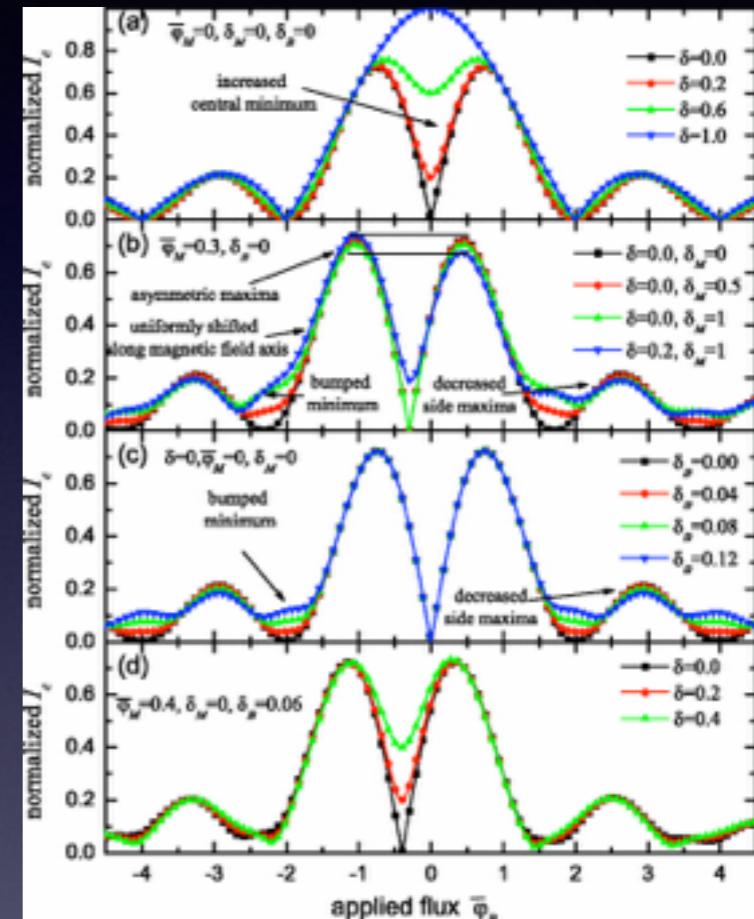
0- $\pi$  SFS junction X



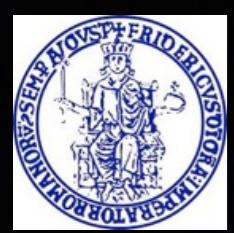
M. Kemmler et al., PRLB 2010



V.V. Ryazanov et al., PRL 2001

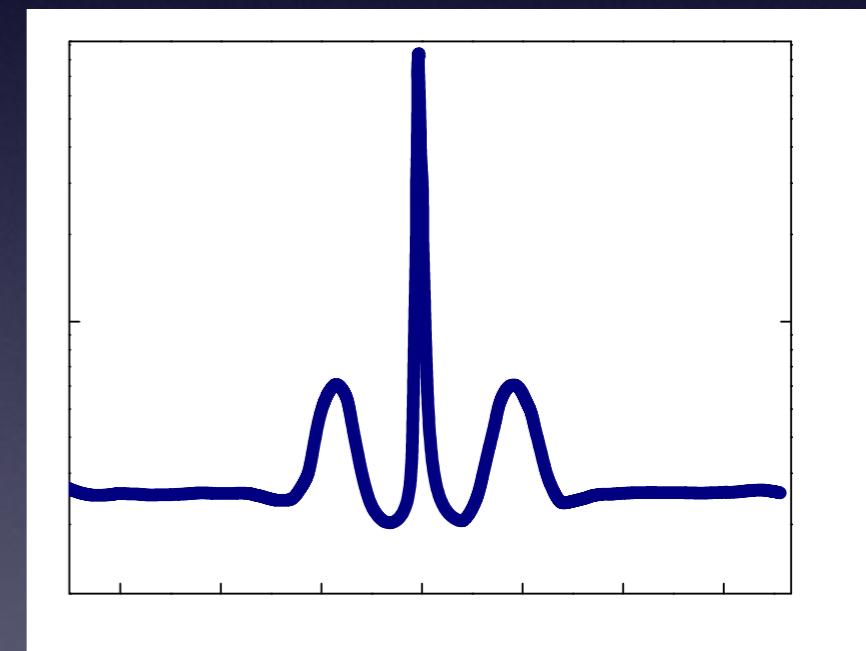
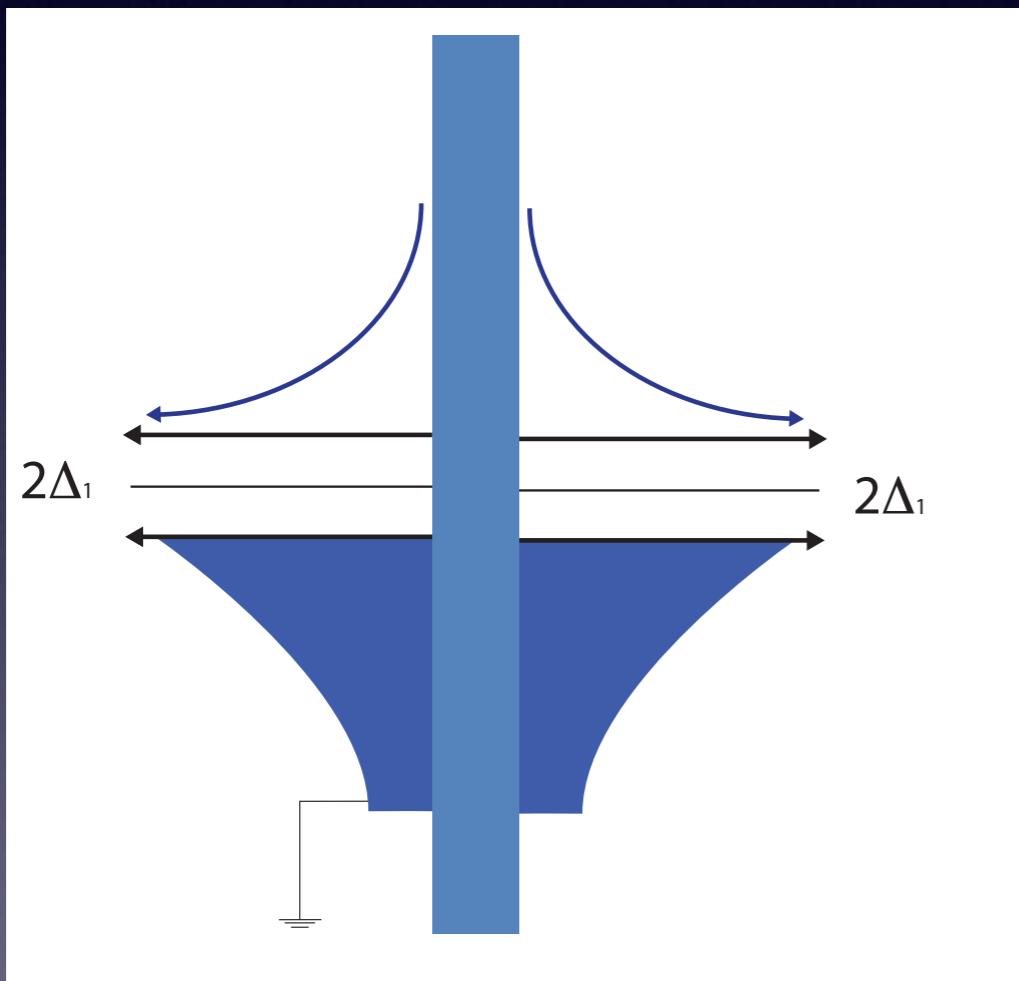


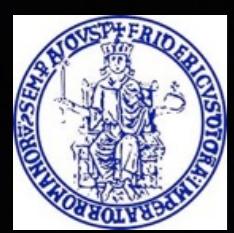
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# LAO/STO JJs - $dI/dV$

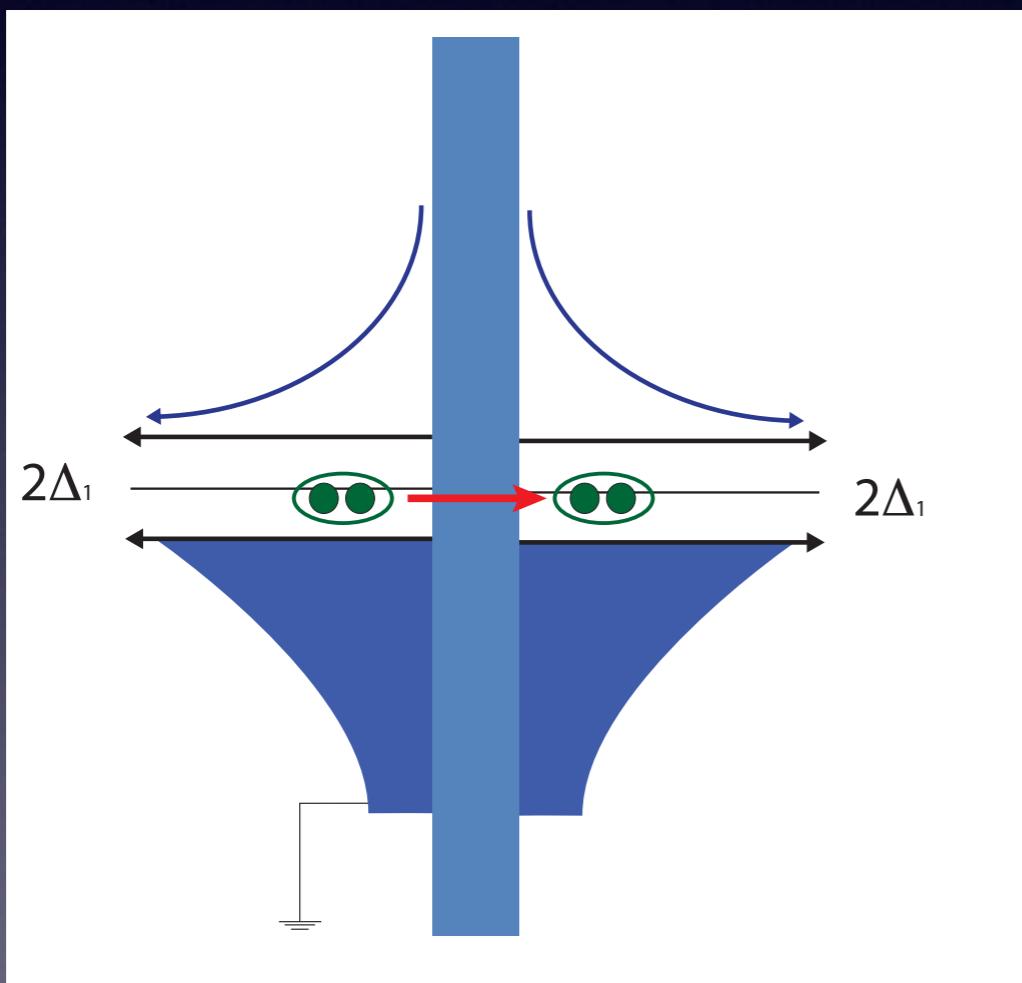
conductance measurement



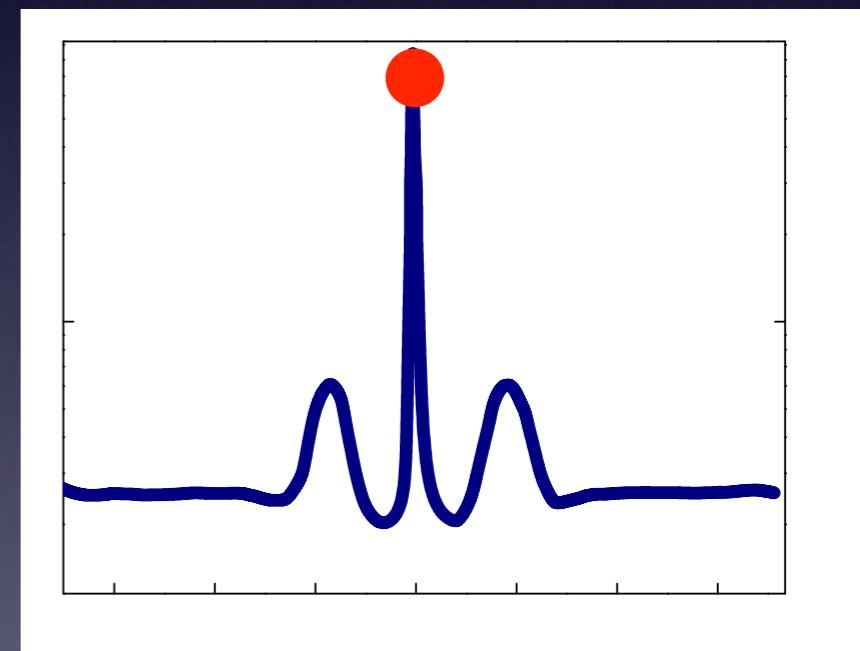


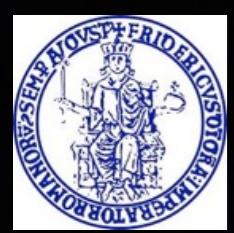
# LAO/STO JJs - $dI/dV$

conductance measurement



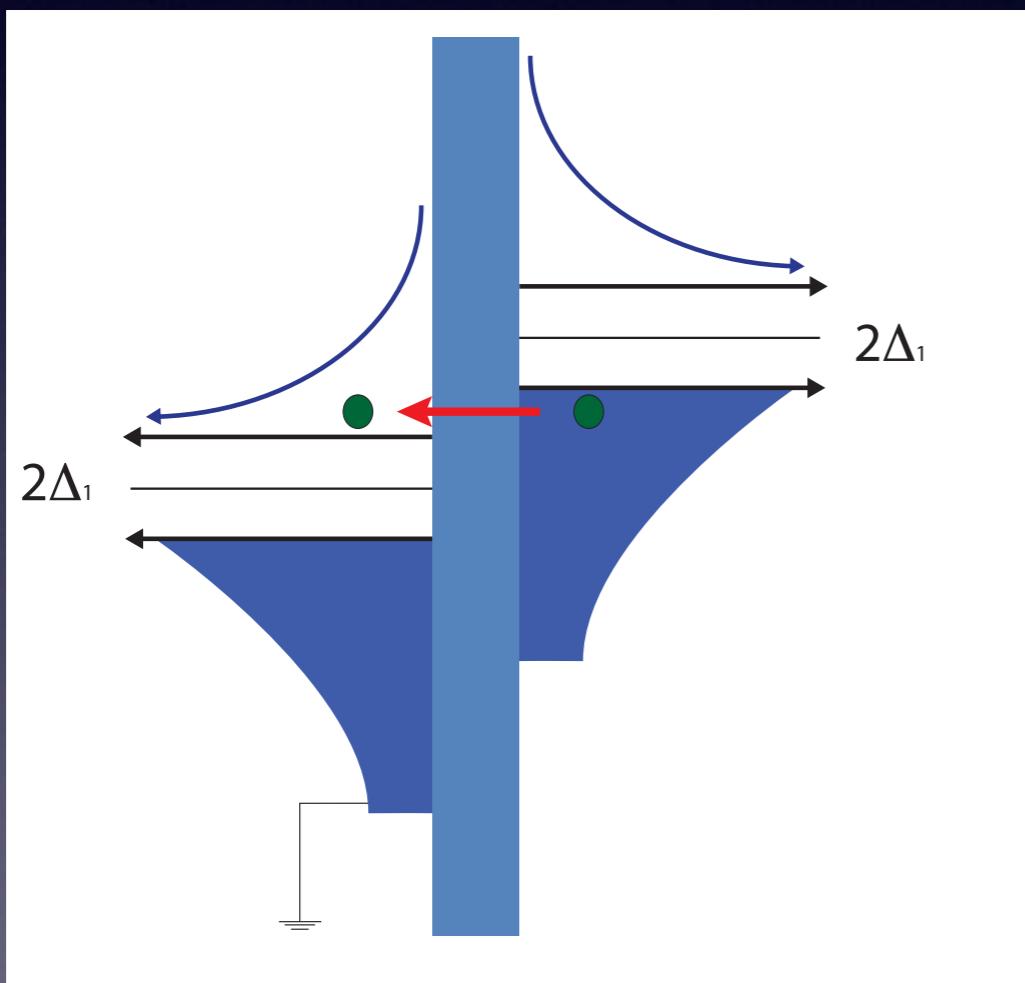
$V=0$





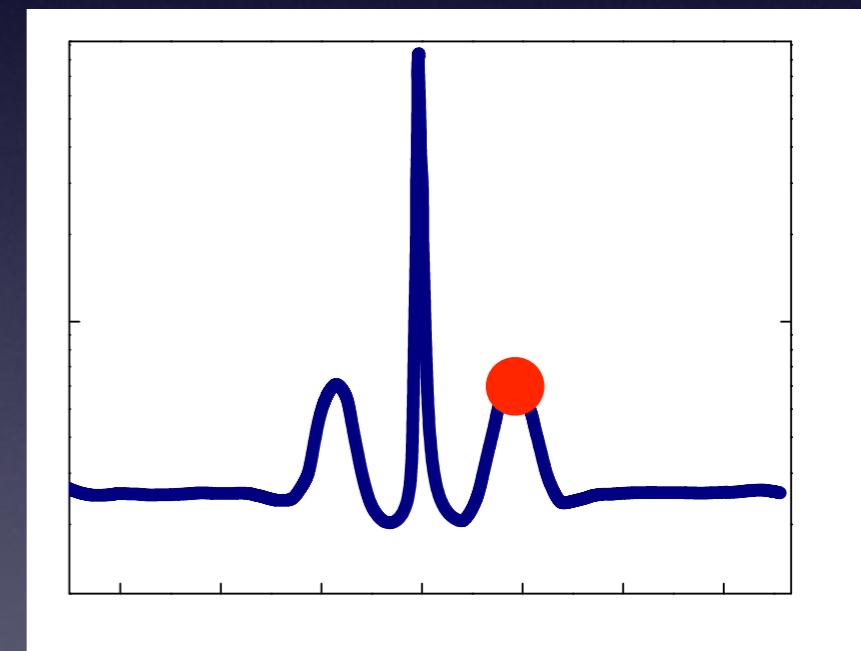
# LAO/STO JJs - $dI/dV$

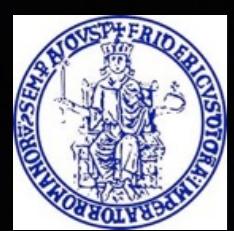
conductance measurement



$V=0$

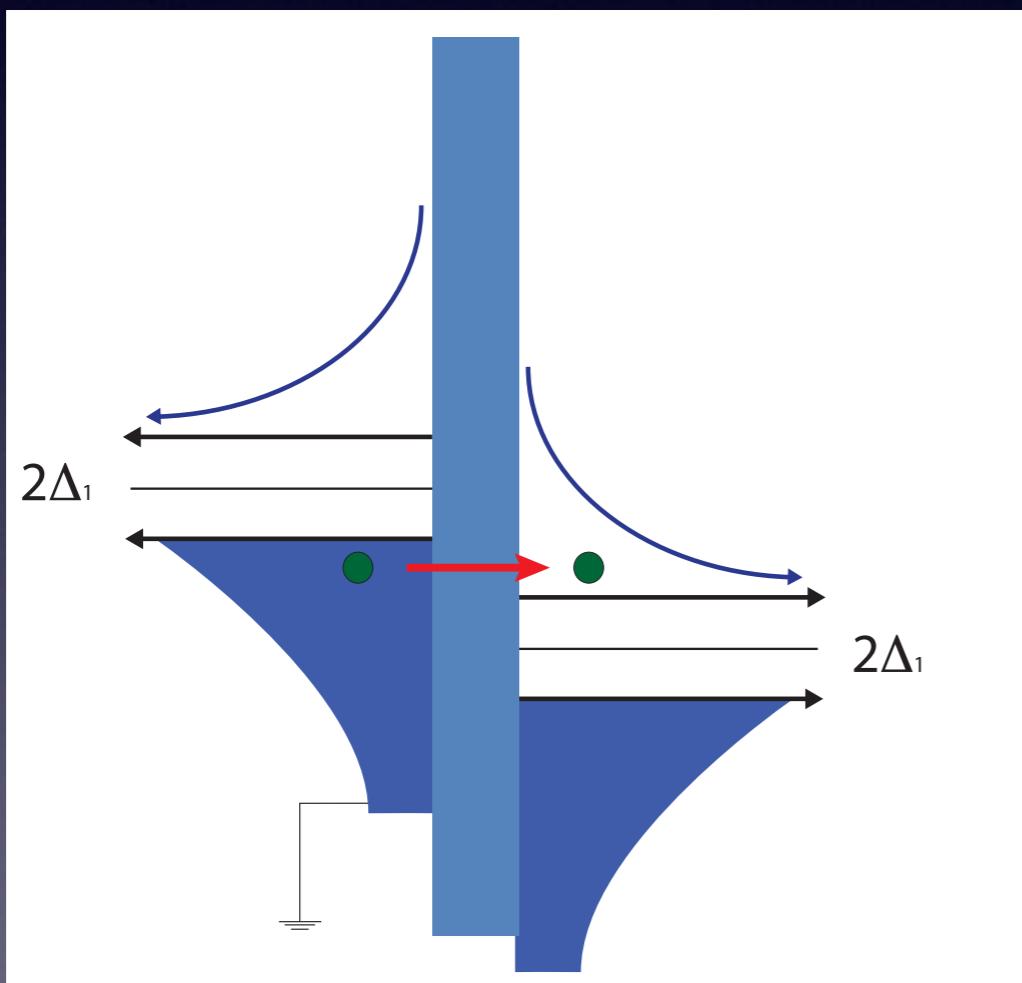
$V=2\Delta$





# LAO/STO JJs - $dI/dV$

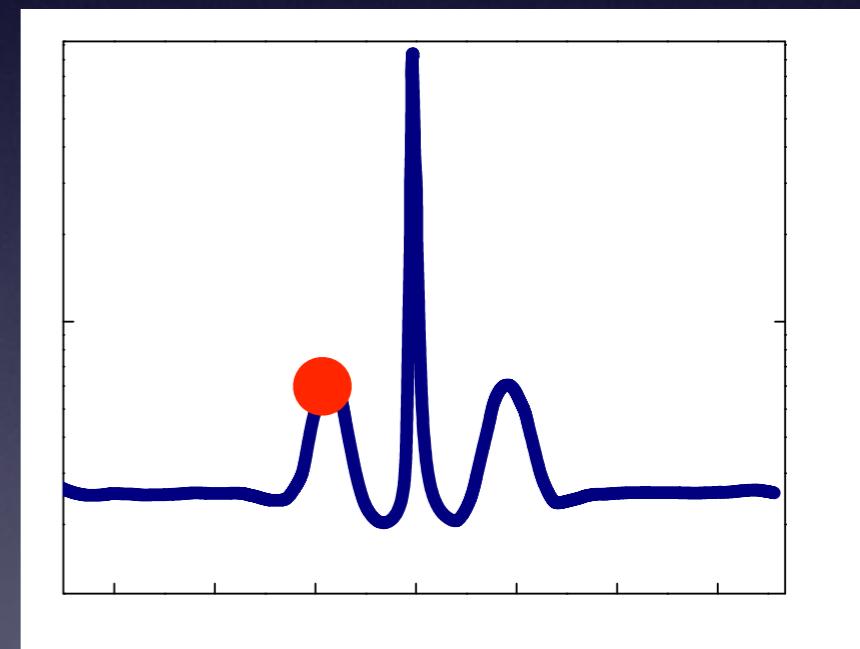
conductance measurement

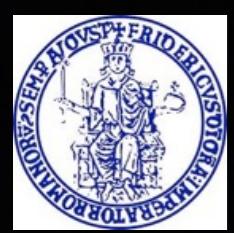


$V=0$

$V=2\Delta$

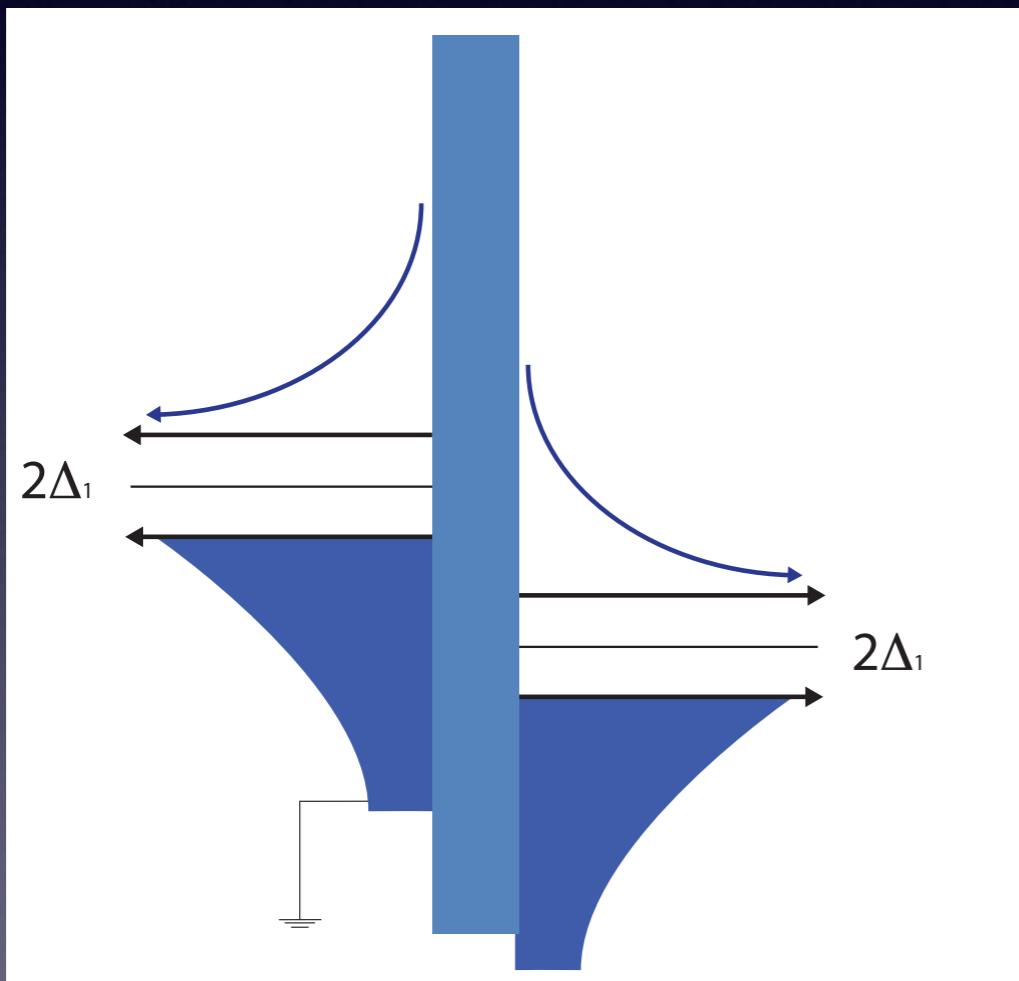
$V=-2\Delta$





# LAO/STO JJs - $dI/dV$

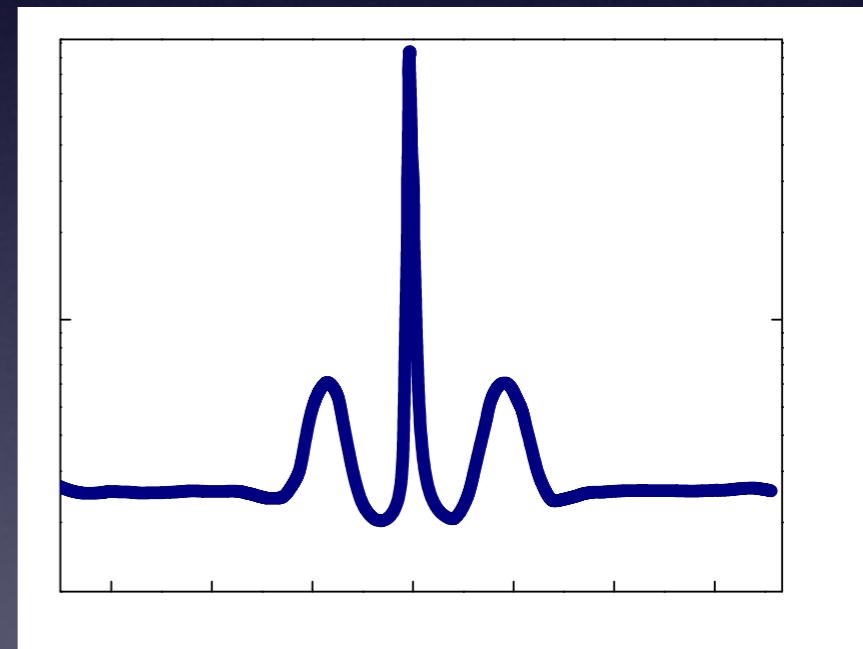
conductance measurement

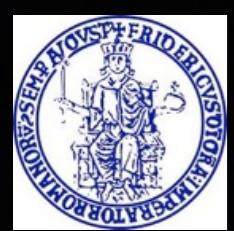


$V=0$

$V=2\Delta$

$V=-2\Delta$





# LAO/STO JJs - $dI/dV$

two gap fit (v. MgB<sub>2</sub>)

total density of states

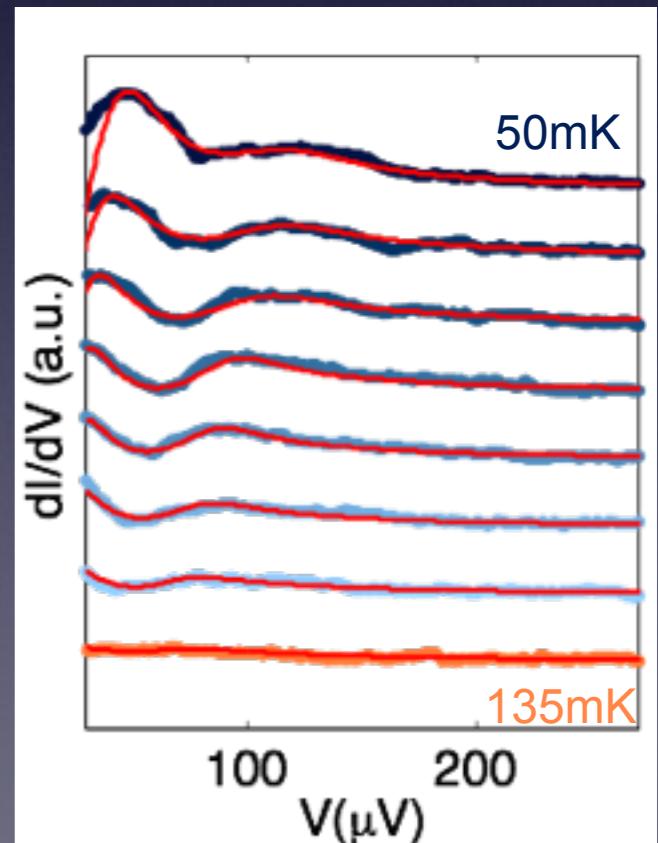
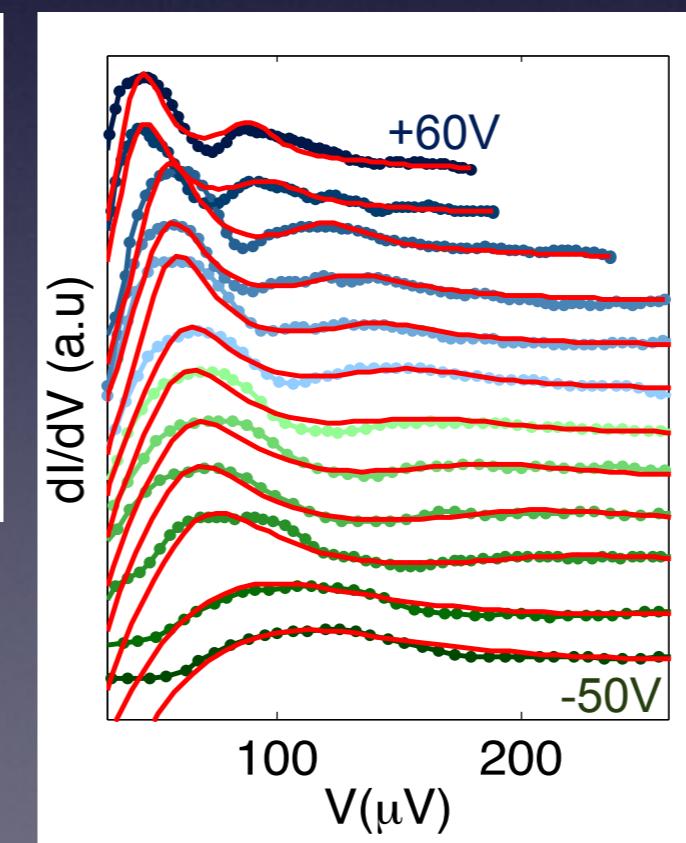
$$N^T(E) = \alpha_1 N_1(e) + \alpha_2 N_2(E)$$

$$\alpha_1 + \alpha_2 = 1$$

$$\frac{N_{1,2}(E)}{N_{1,2}(0)} = \text{Re} \left[ \frac{u_{1,2}^2(E)}{\sqrt{u_{1,2}^2(E) - 1}} \right]$$

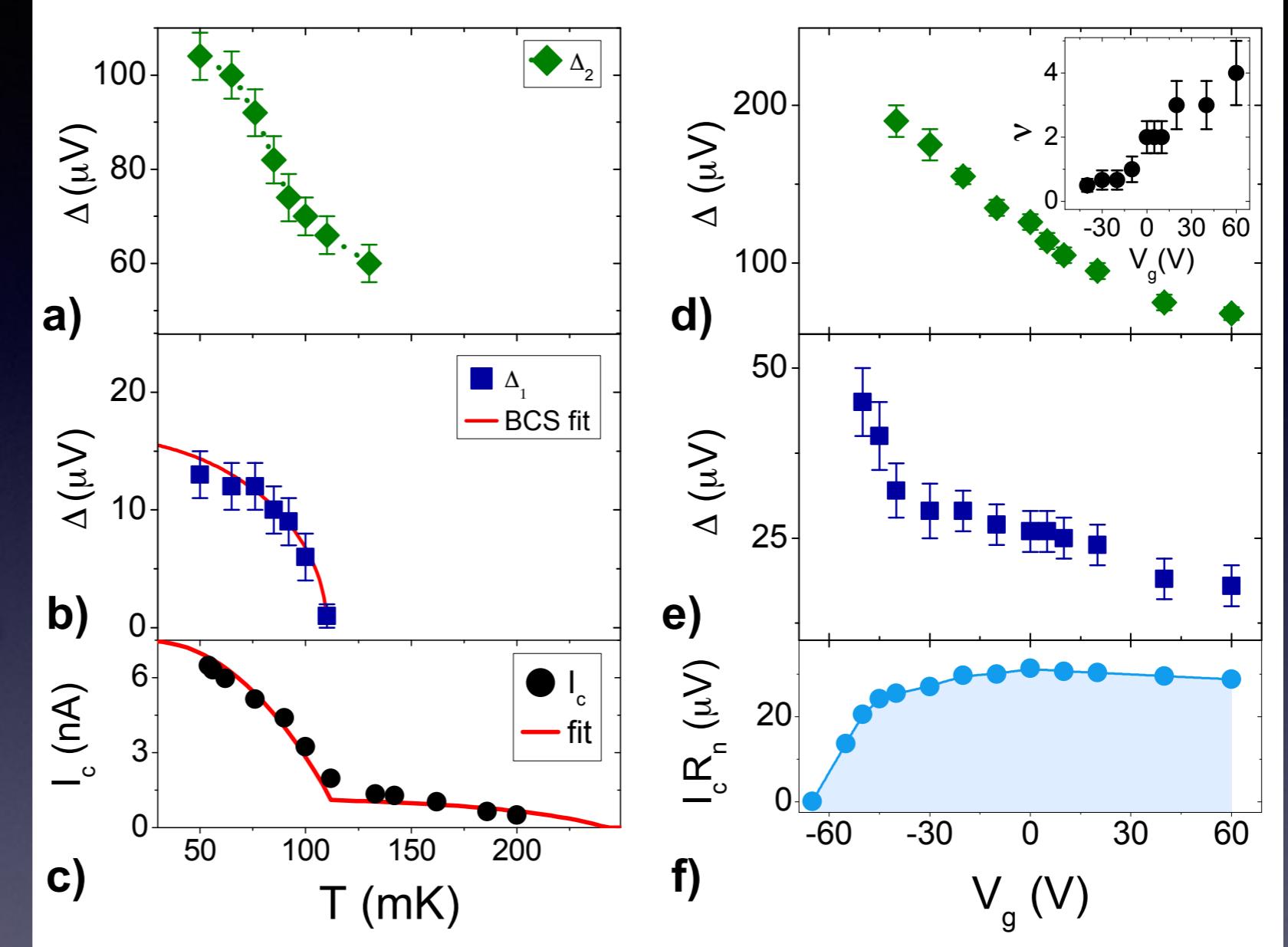
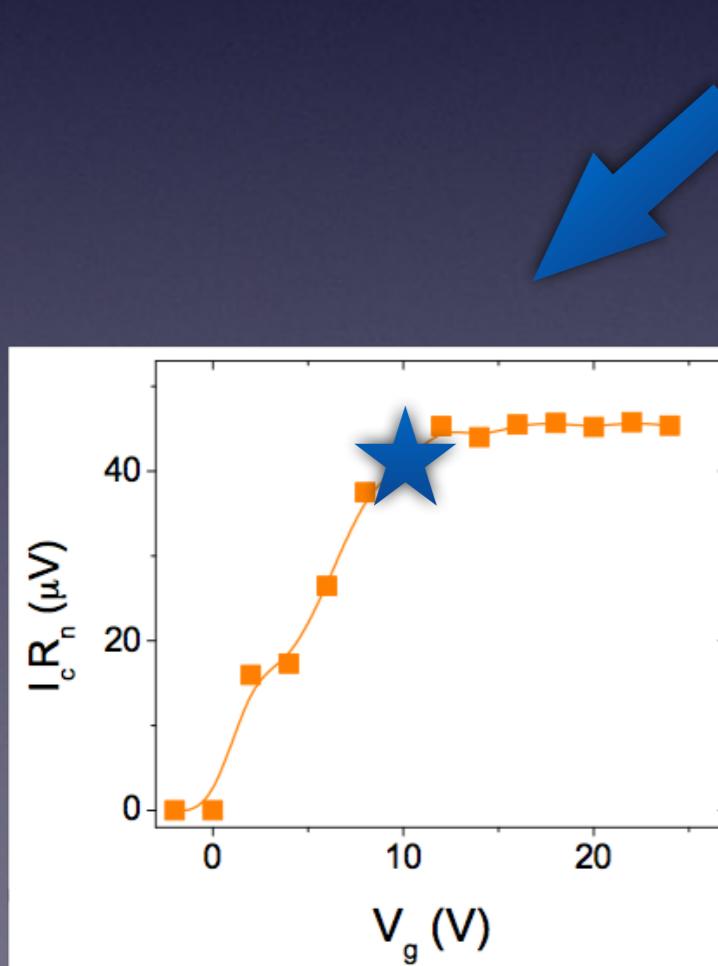
$\Gamma_1, \Gamma_2$  intraband scattering rates  
 $\Gamma_{12}, \Gamma_{21}$  interband scattering rates

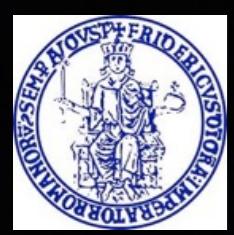
$$u_1(E)\Delta_1 = E + i\Gamma_1 + i\Gamma_{12} \frac{u_2(E) - u_1(E)}{\sqrt{u_2^2(E) - 1}}$$
$$u_2(E)\Delta_2 = E + i\Gamma_2 + i\Gamma_{21} \frac{u_1(E) - u_2(E)}{\sqrt{u_1^2(E) - 1}}$$



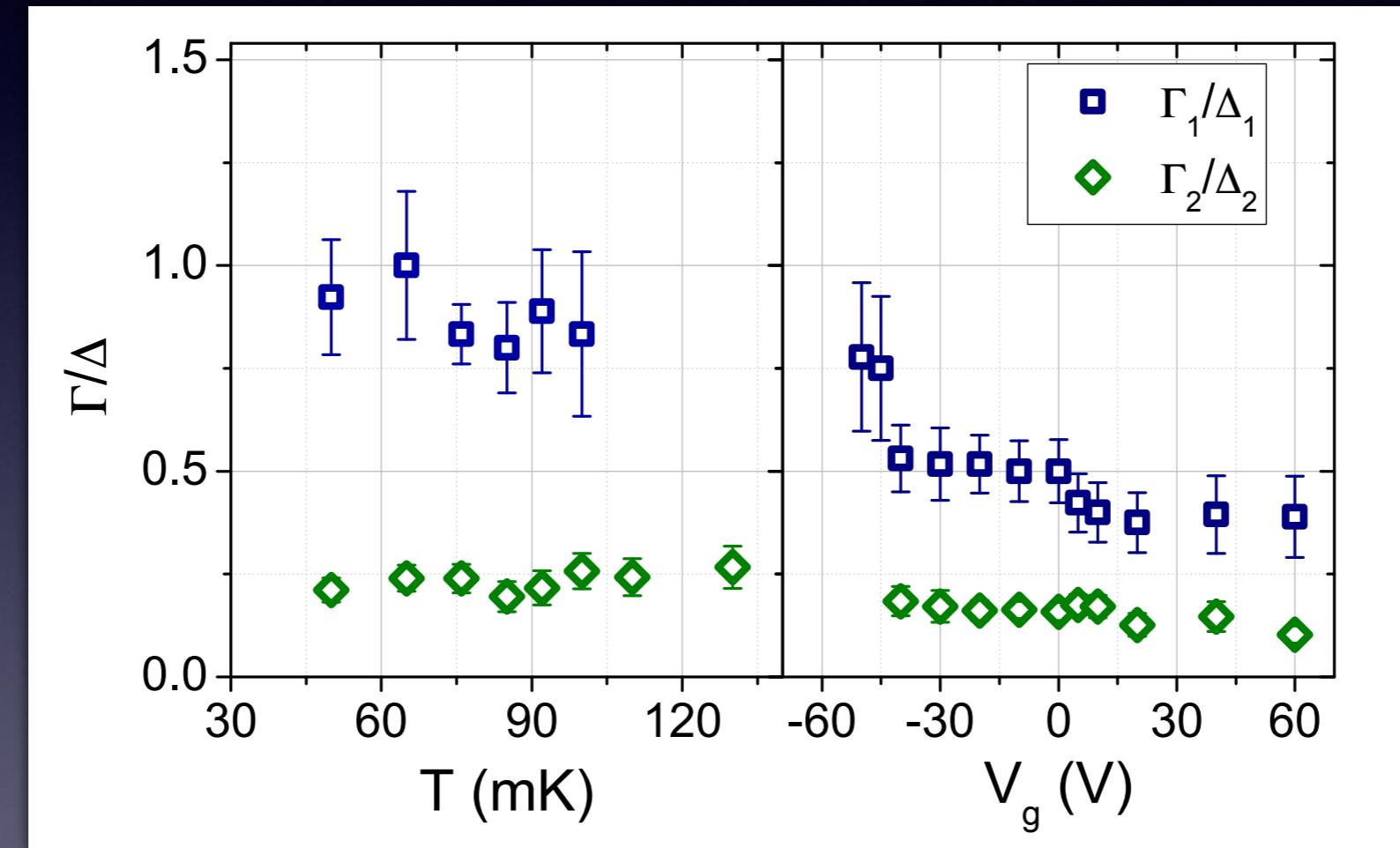


# LAO/STO JJs - $dI/dV$





# scattering parameters





# LAO/STO Josephson junctions - dI/dV



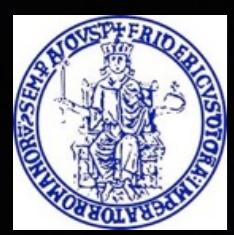
- In SIS with conventional superconductors, if  $\Delta_a$  and  $\Delta_b$  are the gap of the two electrodes, the peaks in  $dI/dV$  will be found at  $|\Delta_a - \Delta_b|$  and  $|\Delta_a + \Delta_b|$ .

In the case the two electrodes are made of the same material, these quantities become 0 and  $2\Delta$ .

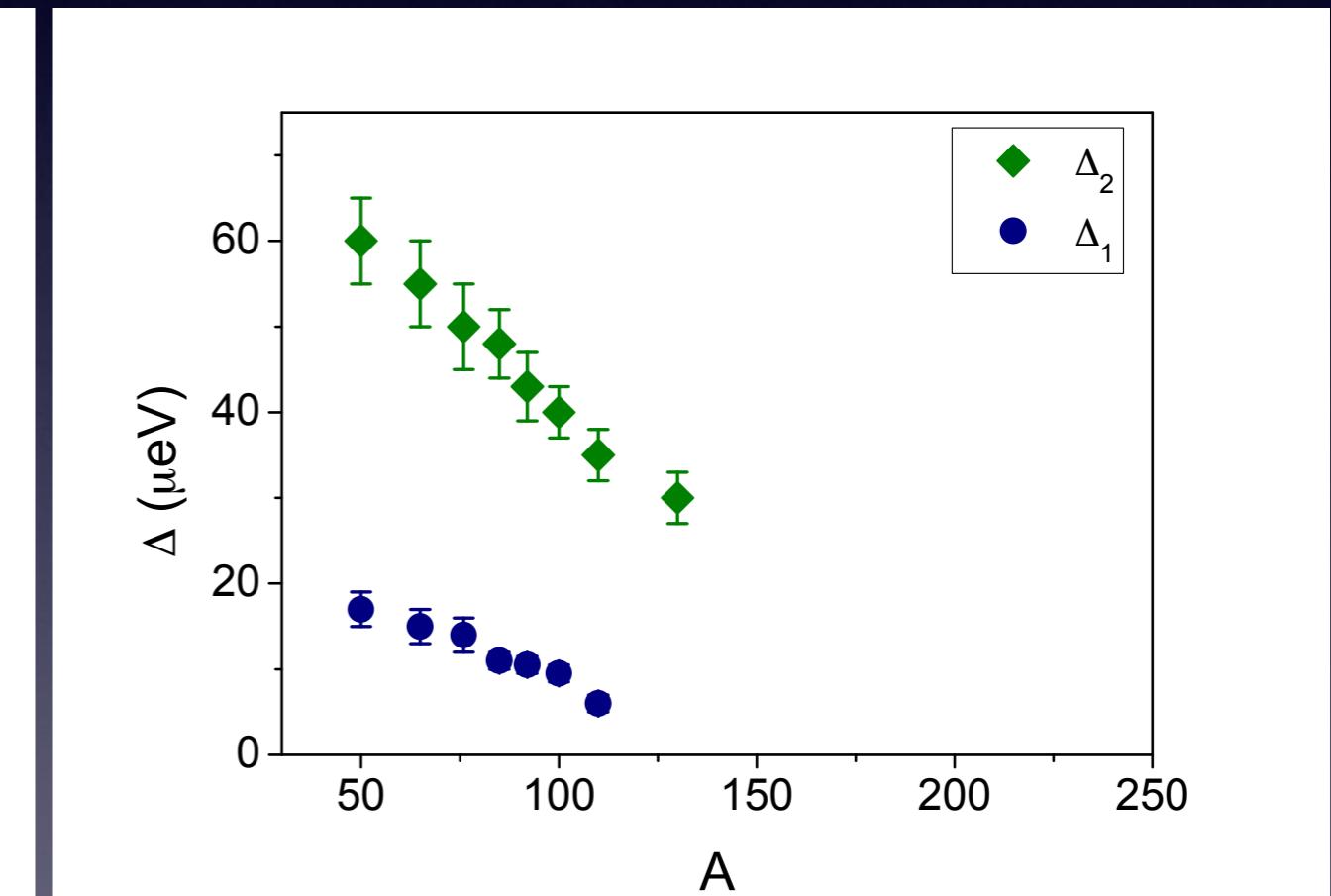
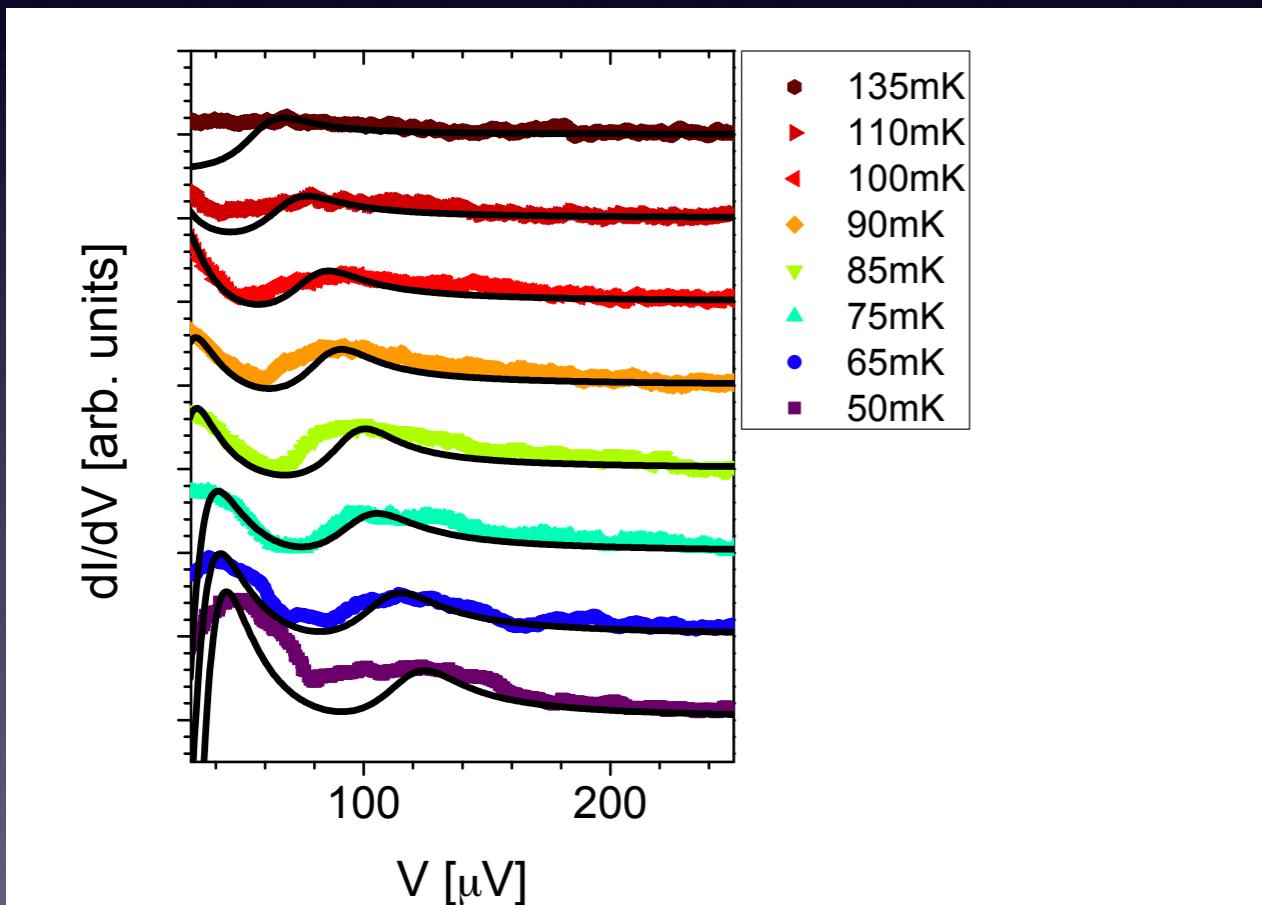
- In SIS with two gap superconductors, if the electrodes are made of the same material and  $\Delta_1$  and  $\Delta_2$  are the two gaps (with  $\Delta_2 > \Delta_1$ ), peaks will be found at:  
0;  $2\Delta_1$ ;  $(\Delta_2 - \Delta_1)$ ;  $(\Delta_2 + \Delta_1)$ ;  $2\Delta_2$
- In the case of two channels, peaks should be found at  $2\Delta_1$  and  $2\Delta_2$ ; this means that the fitted value of  $\Delta_2$  changes a lot.

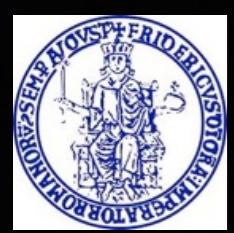
In the two gap scenario we first consider the combination of the DOS and then calculate the current

In the two channels scenario we first consider the currents generated by the DOS and then calculate the parallel combination of these currents.

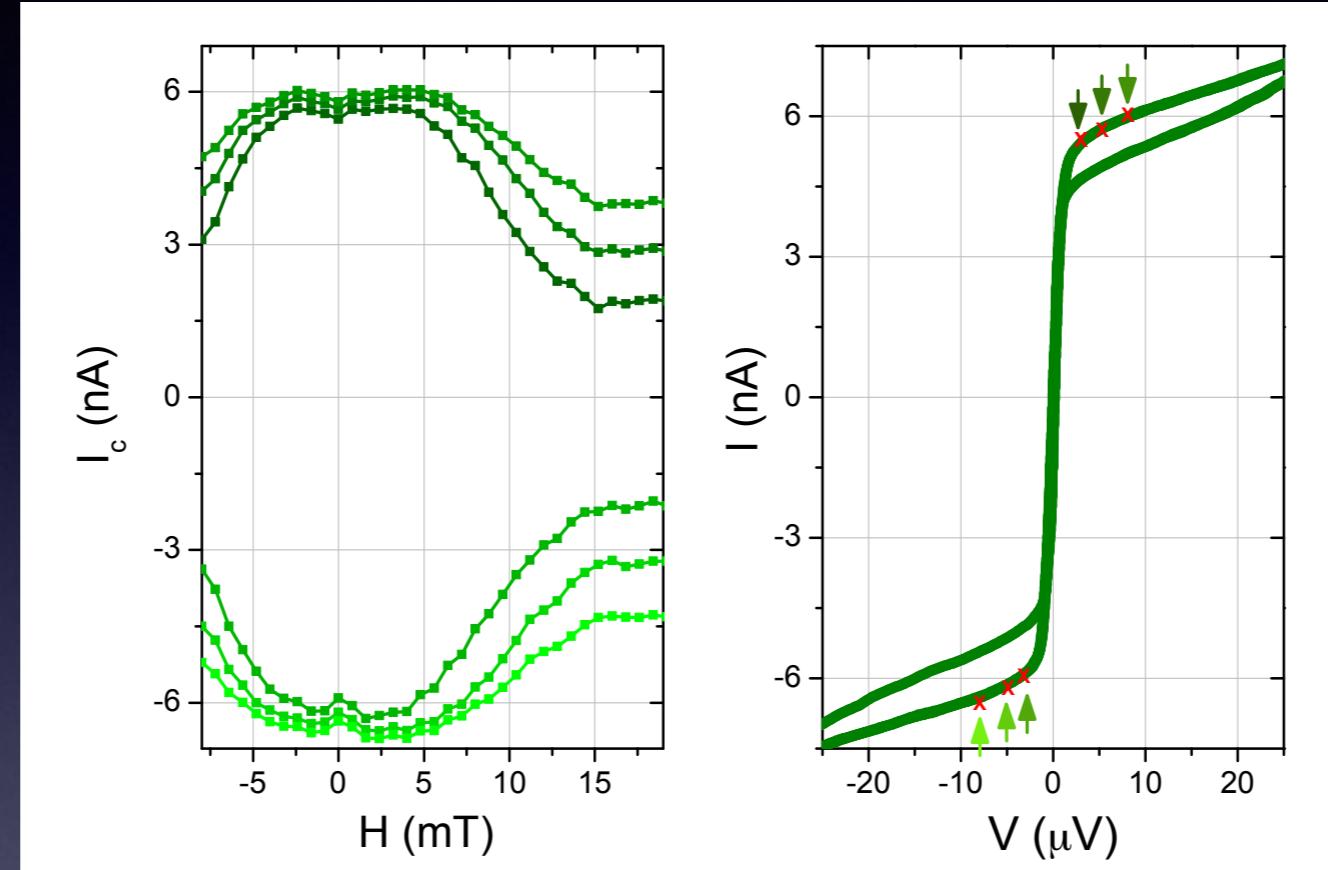


two channels fit

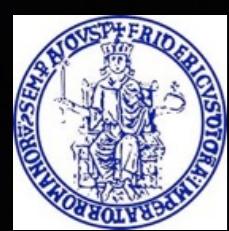




# LAO/STO JJs - $I_c(H)$

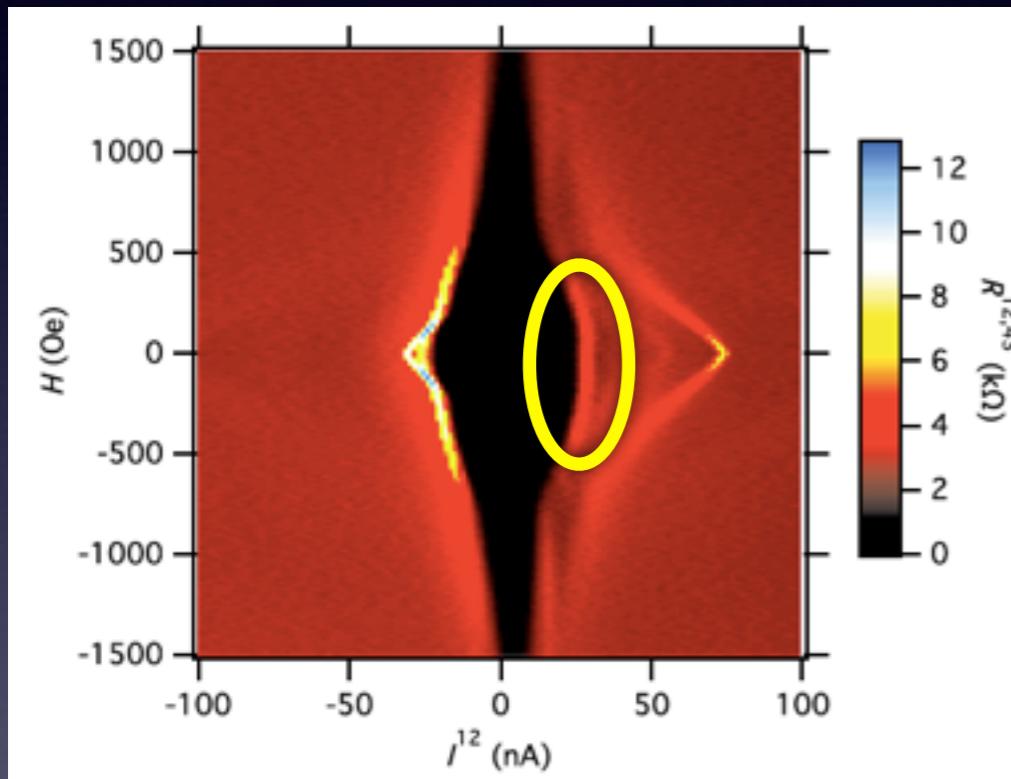


the dip is present for both  $I_{c+}$  and  $I_{c-}$  and does not depend on the  $V$  criterium



# LAO/STO JJs - $I_c(H)$

zero field dip in the  $I_c(H)$  pattern: other evidences in the literature?



C.Cheng et al. Anomalous Transport in Sketched Nanostructures at the LaAlO<sub>3</sub>/SrTiO<sub>3</sub> Interface  
PRX 2013

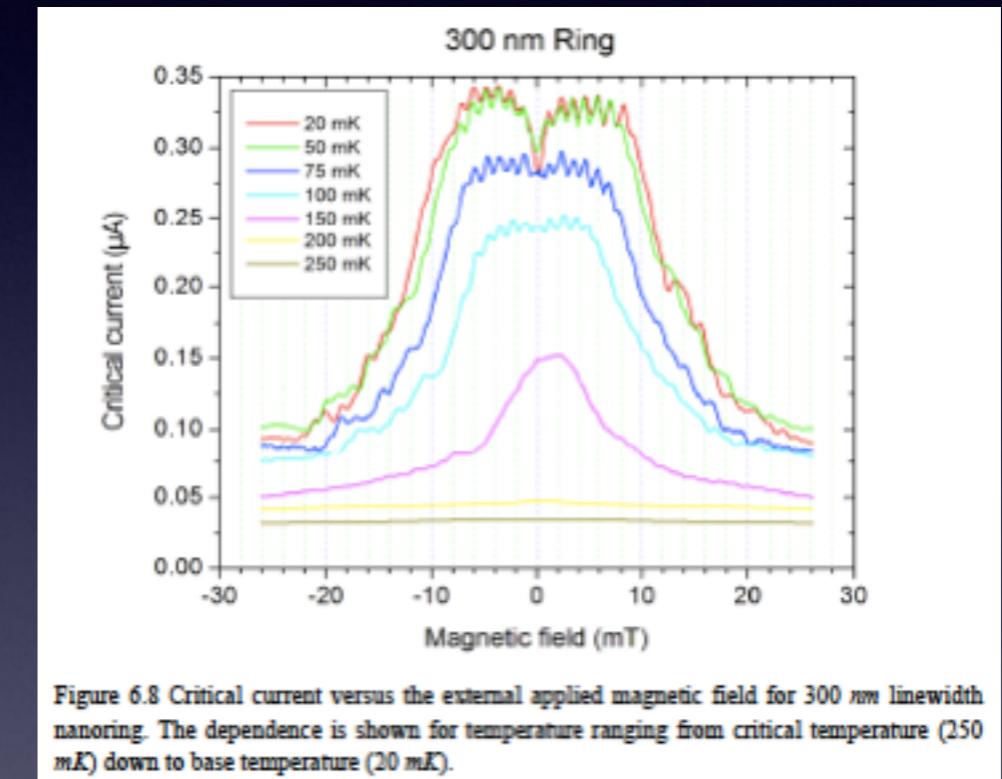
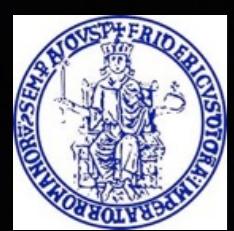


Figure 6.8 Critical current versus the external applied magnetic field for 300 nm linewidth nanoring. The dependence is shown for temperature ranging from critical temperature (250 mK) down to base temperature (20 mK).

P.P Aurino, Ph.D. Thesis, 2016



# LAO/STO JJs - $I_c(H)$

origin of the  $\pi$  channel in LAO/STO junctions

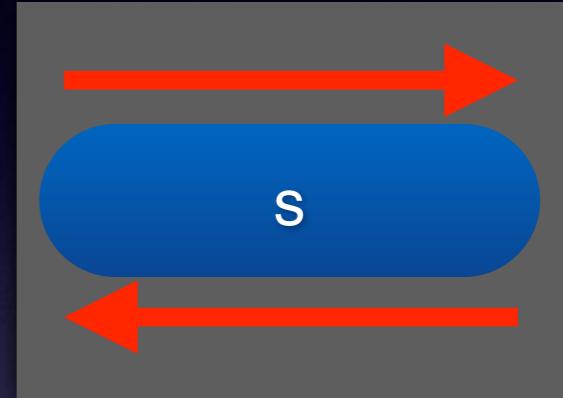
## protected edge states

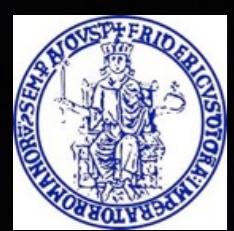
experiments:

- Fete et al., *Rashba induced magnetoconductance oscillations in the LaAlO<sub>3</sub>-SrTiO<sub>3</sub> heterostructure*, PRB 2012
- C.Cheng et al. *Anomalous Transport in Sketched Nanostructures at the LaAlO<sub>3</sub>/SrTiO<sub>3</sub> Interface*, PRX 2013

theories:

- Y. Tanaka,et al., *Theory of topological spin current in noncentrosymmetric superconductors*, PRB 2009
- M. Sato and S. Fujimoto, *Topological phases of noncentrosymmetric superconductors: Edge states, Majorana fermions, and non-Abelian statistics*, PRB 2009
- C-K Lu and S. Yip, *Spin current in topologically trivial and nontrivial noncentrosymmetric superconductors*, PRB 2010
- Y. Asano and S. Yamano, *Josephson effect in noncentrosymmetric superconductor junctions*, PRL 2011
- L.X. Hayden,et al., *Intrinsic spin Hall effect at asymmetric oxide interfaces: Role of transverse wave functions*, PRB 2013
- P. Burset et al., *Transport signatures of superconducting hybrids with mixed singlet and chiral triplet states*, PRB 2014

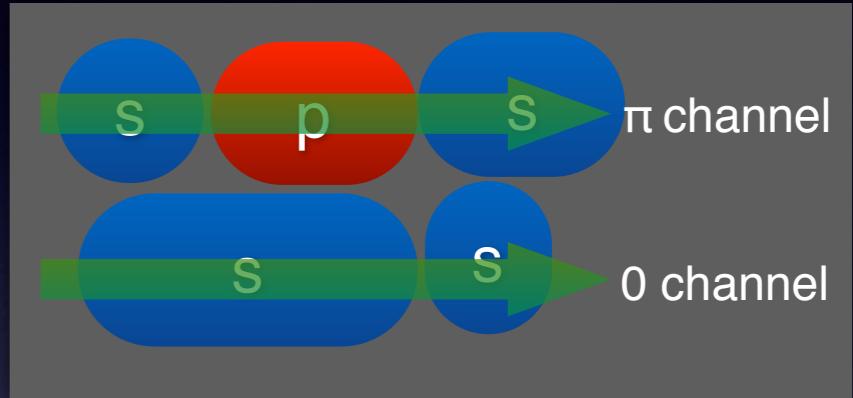




# LAO/STO JJs - origin of the $\pi$ channel

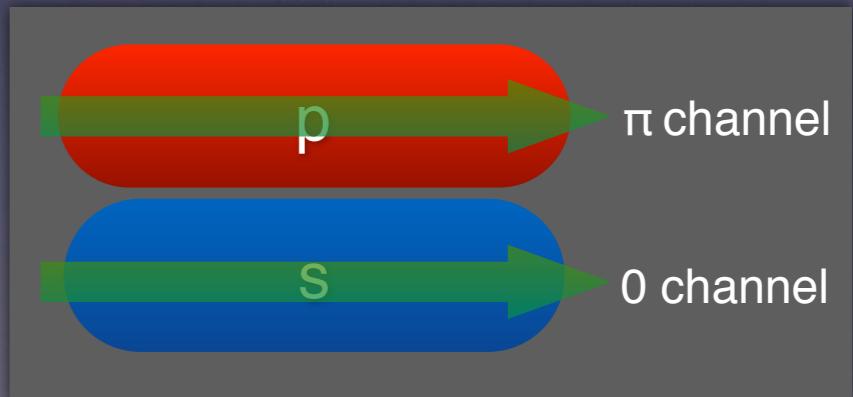
## s-p-s junction

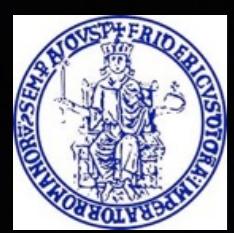
- V.B. Geshkenbein et al. *Vortices with half magnetic flux quanta in “heavy-fermion” superconductors*, PRB 1987
- C. Honerkamp, M. Sigrist, *The competition between the 0 and the pi phase shift in the Pb-Sr<sub>2</sub>Ru<sub>4</sub>-Pb junction*, Progress of Theoretical Physics, 1998
- N. Hayashi et al., *Josephson effect between conventional and Rashba superconductors*, Physica C 2008



## p junction with TRS breaking

- K.Ueda, T.M. Rice, *p-wave superconductivity in cubic metals*, PRB 1985
- M.Sigrist, *Superconductivity with broken time-reversal symmetry*, Physica B, 2000
- T. K.Ng, et al. *Broken time-reversal symmetry in Josephson junction involving two-band superconductors*, EPL 2009
- P.M.R. Brydon et al., *Functional Superconductor Interfaces from Broken Time-Reversal Symmetry*, PRL 2010
- L.Klam et al., *Josephson effect and triplet-singlet ratio of noncentrosymmetric superconductors*, PRB 2014



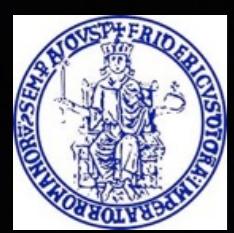


# LAO/STO JJs - $I_c(H)$

zero field dip in the  $I_c(H)$  pattern: origin?  
interference effects between 0 and  $\pi$  sections

standard “0” junction       $I = I_c \sin(\Delta\varphi)$

$\pi$  junction       $I = I_c \sin(\Delta\varphi + \pi)$       shift of  $\pi$  in the junction's phase



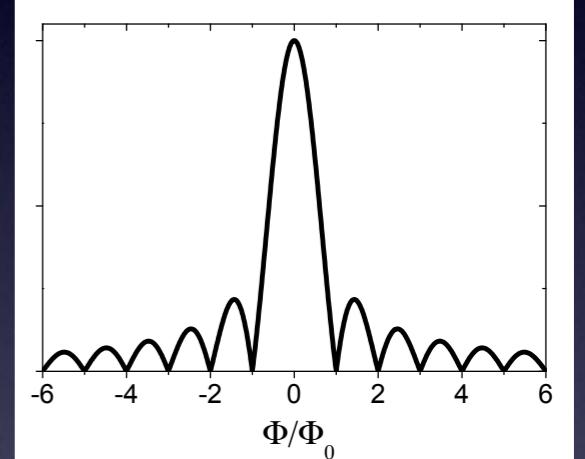
# LAO/STO JJs - $I_c(H)$

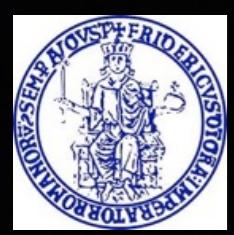
zero field dip in the  $I_c(H)$  pattern: origin?  
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standard “0” junction       $I = I_c \sin(\Delta\varphi)$

$\pi$  junction       $I = I_c \sin(\Delta\varphi + \pi) = I_c \sin(\Delta\phi)$

$$I_c^{0,\pi}(\Phi) \propto \left| \frac{\sin(\pi\Phi/\Phi_0)}{\Phi/\Phi_0} \right|$$



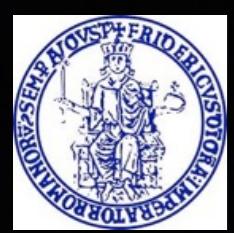


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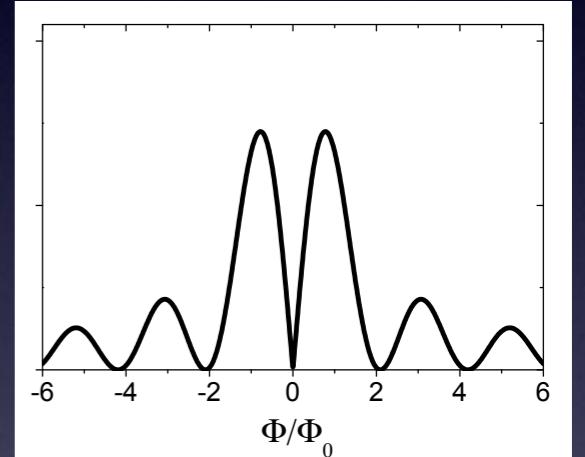
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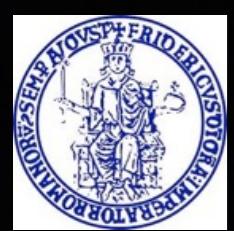
standard “0” junction  $\rightarrow I = I_c \sin(\Delta\varphi)$

$\pi$  junction  $\leftarrow I = I_c \sin(\Delta\varphi + \pi) = -I_c \sin(\Delta\varphi)$

see D.A.Wollman  
et al., PRL 1995

$$I_c^{0-\pi}(\Phi) \propto \frac{\sin^2(\pi\Phi/2\Phi_0)}{|\pi\Phi/2\Phi_0|}$$





# LAO/STO JJs - $I_c(H)$

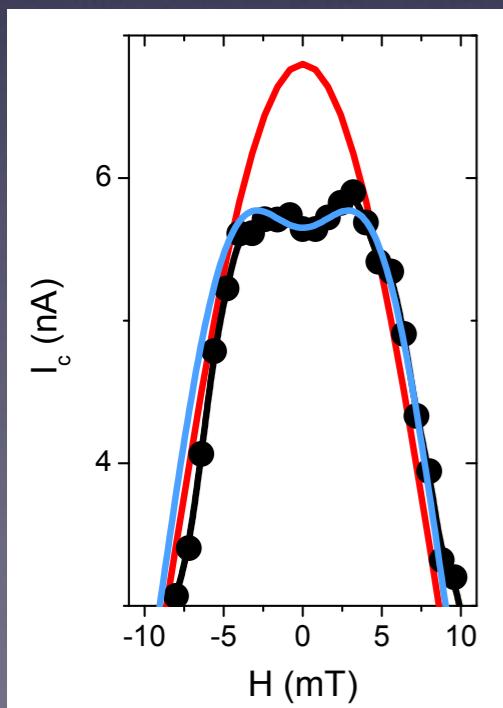
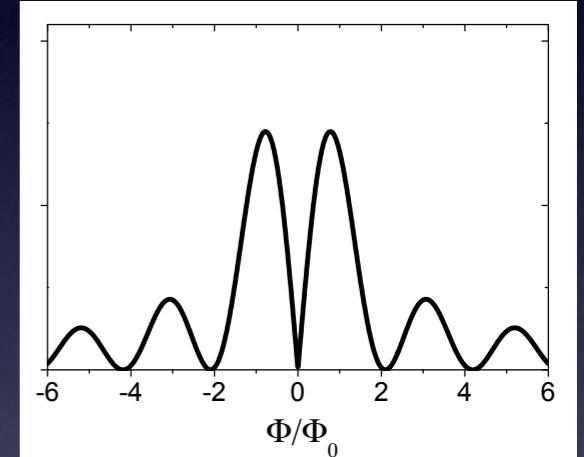
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see D.A.Wollman  
et al., PRL 1995

$$I_c^{0-\pi}(\Phi) \propto \frac{\sin^2(\pi\Phi/2\Phi_0)}{|\pi\Phi/2\Phi_0|}$$



fit of the  $I_c(H)$  pattern assuming a 0 and a  $\pi$  section

$$I(H, \phi) = J_c^0 L \int_0^{w1} \sin \left( \frac{2e}{\hbar c} L x H + \phi \right) dx + J_c^\pi \int_{w1}^{w1+w2} \sin \left( \frac{2e}{\hbar c} L x H + \phi + \pi \right) dx$$

$$\frac{J_c^0}{J_c^\pi} \sim \frac{1}{0.11}$$

$$\frac{J_c^0}{J_c^\pi} = \frac{R_{11}^{-1} \Delta_1}{R_{22}^{-1} \Delta_2} \sim \frac{1}{0.16}$$

from the  $I_c(T)$  fit  
at  $V_g=10V$