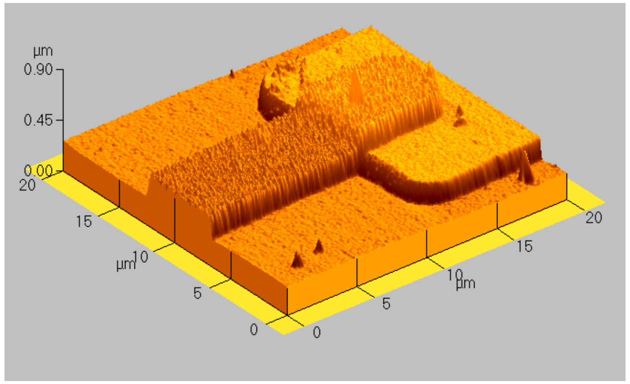

SFS junctions and SF bilayers of YBCO with the metallic ferromagnet $SrRuO_3$: signature of a Crossed Andreev Reflection Effect - CARE

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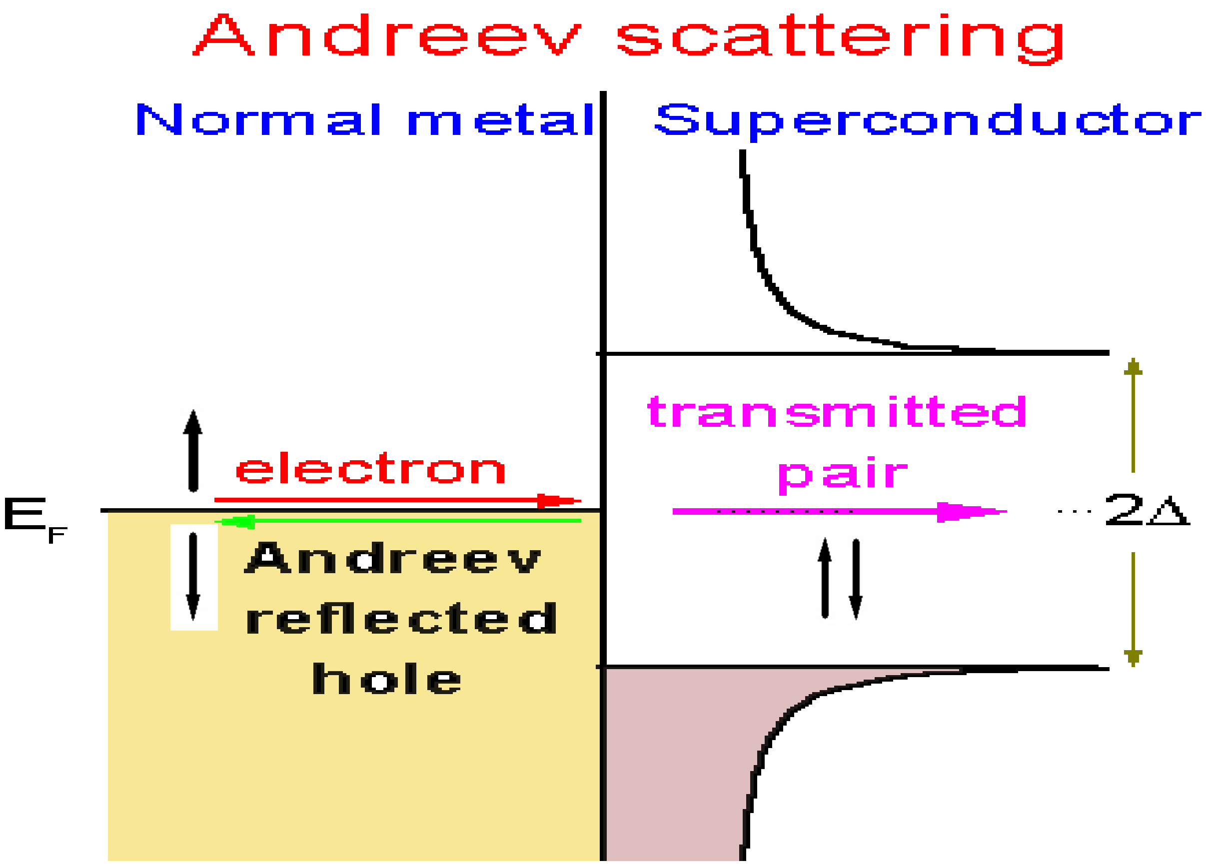
HUJI solid state seminar, May 11, 2006

Previous studies on YBCO/SRO/YBCO ramp junctions

- Many papers by the Conductus and Stanford groups, 1993-1996, (Char, Antognazza, Geballe…)
  - large interface resistance
  - ZBCP – zero bias conductance peak
  - decreasing ZBCP versus magnetic field
- A study by the Juelich group, 1995 (Doemel, Braginski…)
  - Also observed large interface resistance
  - resonant tunneling via one or two localized states

At the time, research was more oriented towards obtaining good Josephson junctions (with large I_cR_N etc.), and not specifically in the magnetic properties of the junctions

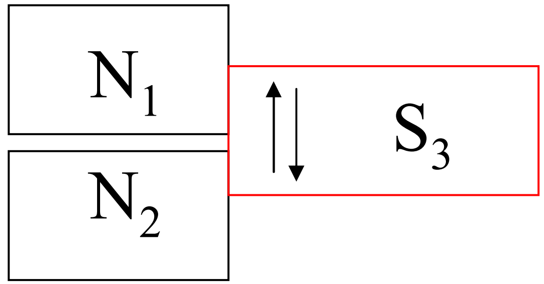
The basic transport process for $E-E_F < \Delta$ in SN junctions is the



Two cases of local and non-local transport in NSN and FSF junctions for $E-E_F<\Delta$:

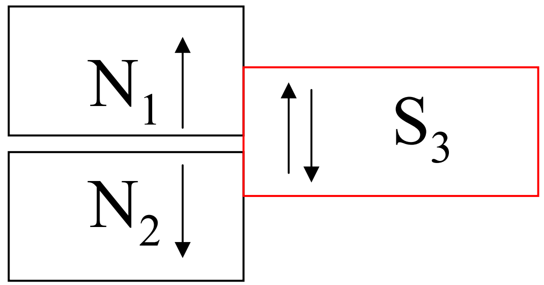
1. Non magnetic metal electrodes (all Andreev channels are possible)

Byers & Platte, PRL 1995



2. Fully spin polarized FM electrodes (only the CARE channel is possible)

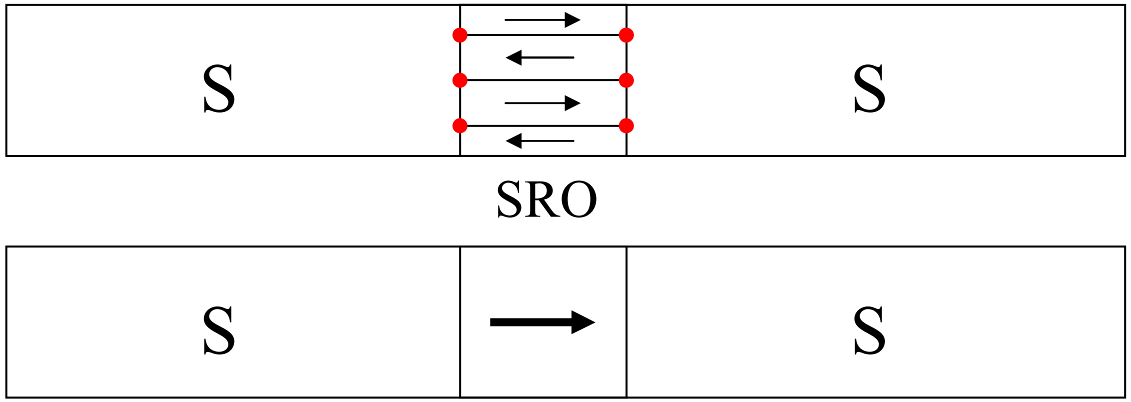
Deutscher & Feinberg, APL 2000



CARE was observed in Al junctions with Fe nano-leads by Beckmann et al., PRL **93**, 197003 (2004) [Karlsruhe]

The basic idea of the present study is:

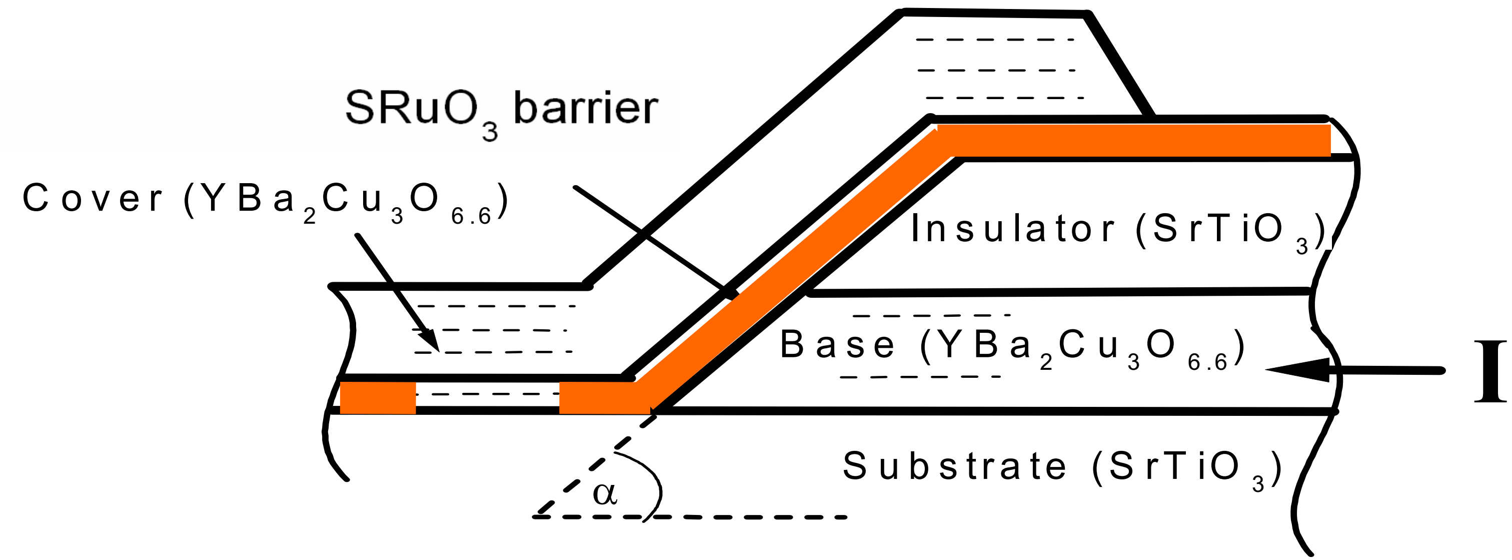
To look for a CARE process in SNS junctions with a ferromagnetic barrier (F). This effect should occur at the intersection of the domain walls with the interfaces



As a FM material for this purpose, we chose $SrRuO_3$ (SRO) since its domain wall width (~3nm) is of the same order of magnitude as the superconducting ξ (~2nm)

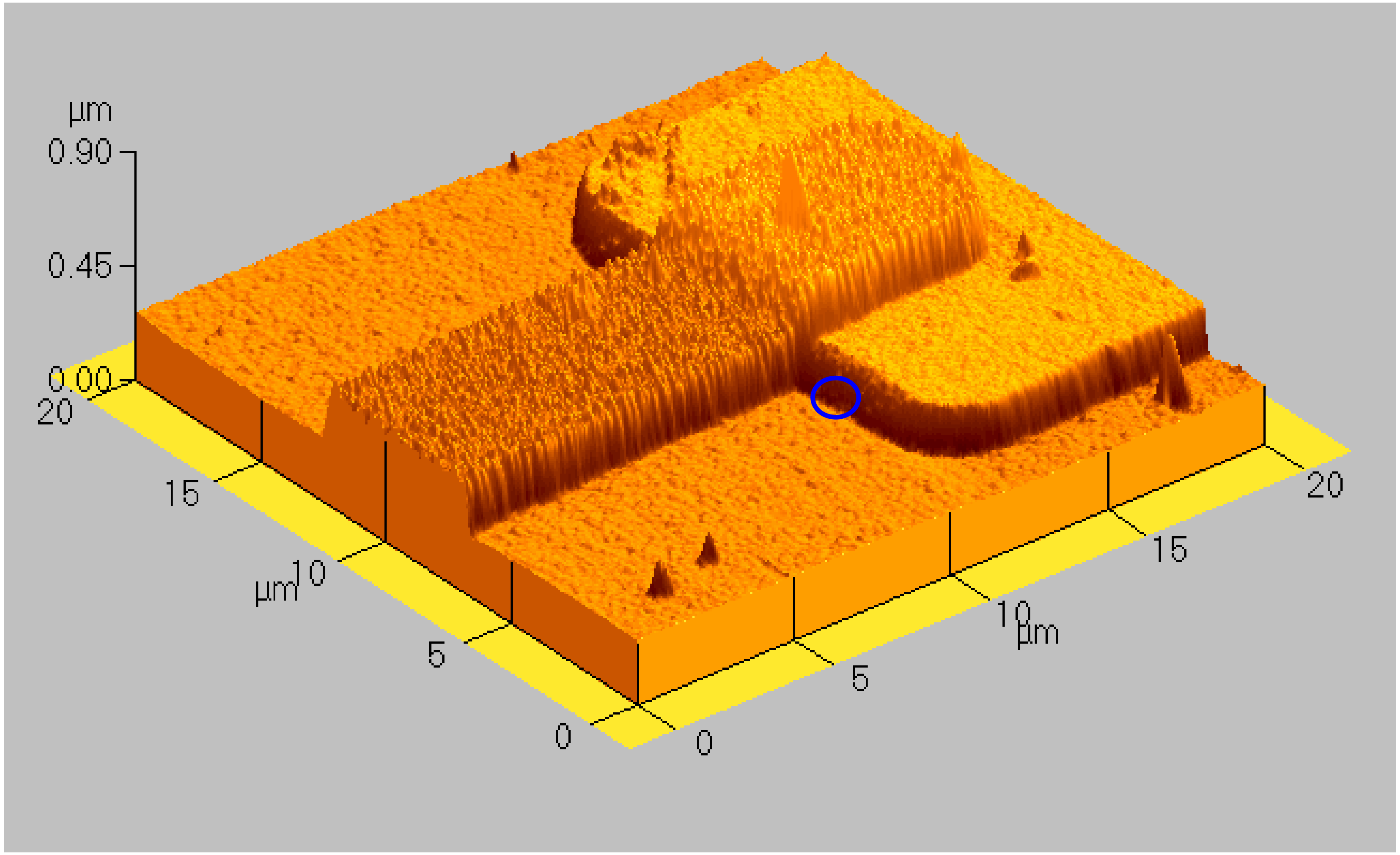
[This is a basic requirement for the CARE process to occur]

Ramp junction cross-section



- All epitaxial structure
  avoids GBJ, and preserves orientation info.
- *a-b* plane coupling
  with the longer coherence length ξ~2nm

AFM of a ramp type junction

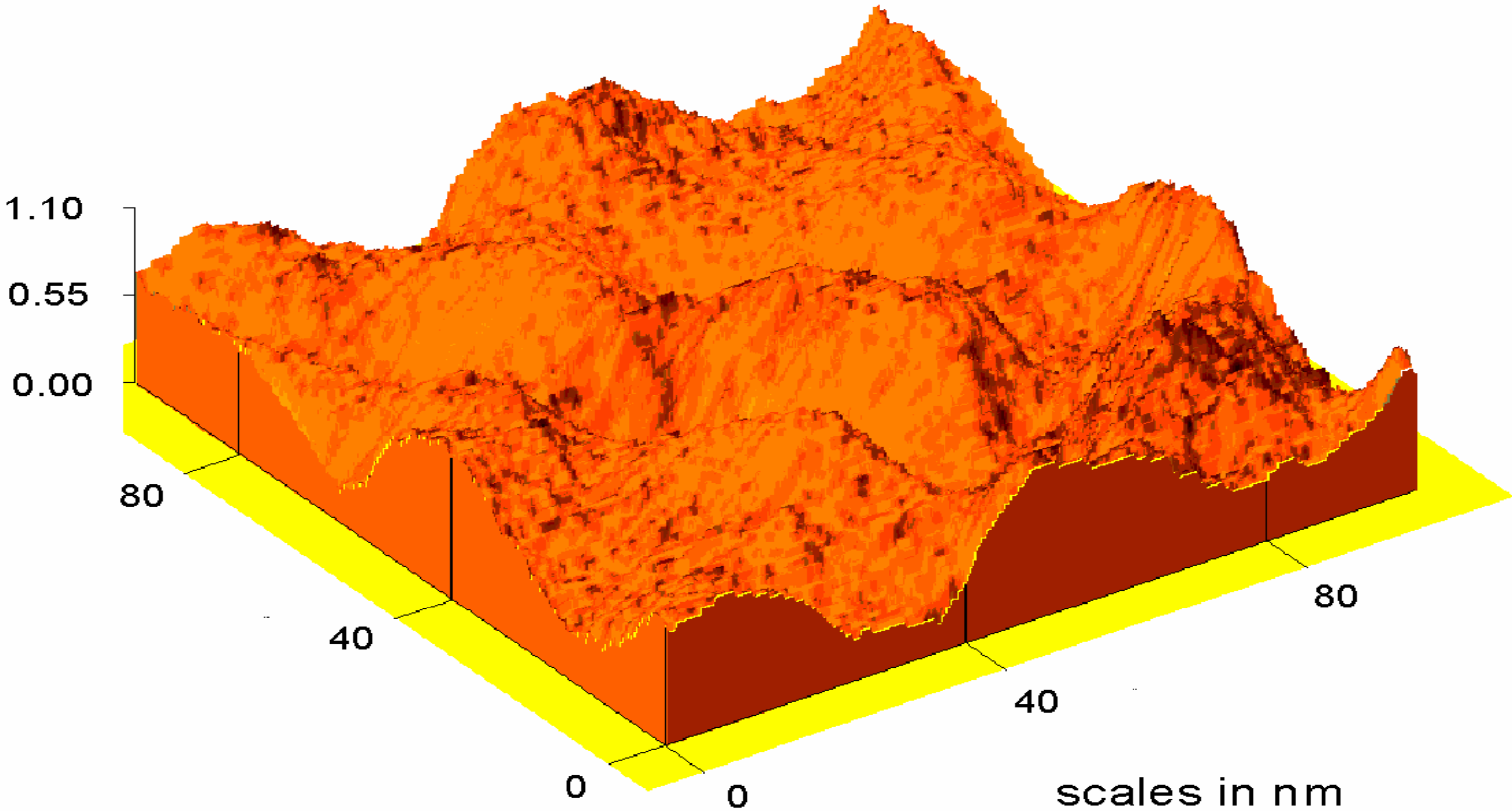


Base electrode: Inuslator (50 nm STO)/80nm YBCO

Cover electrode: gold/80nm YBCO/10-20nm barrier

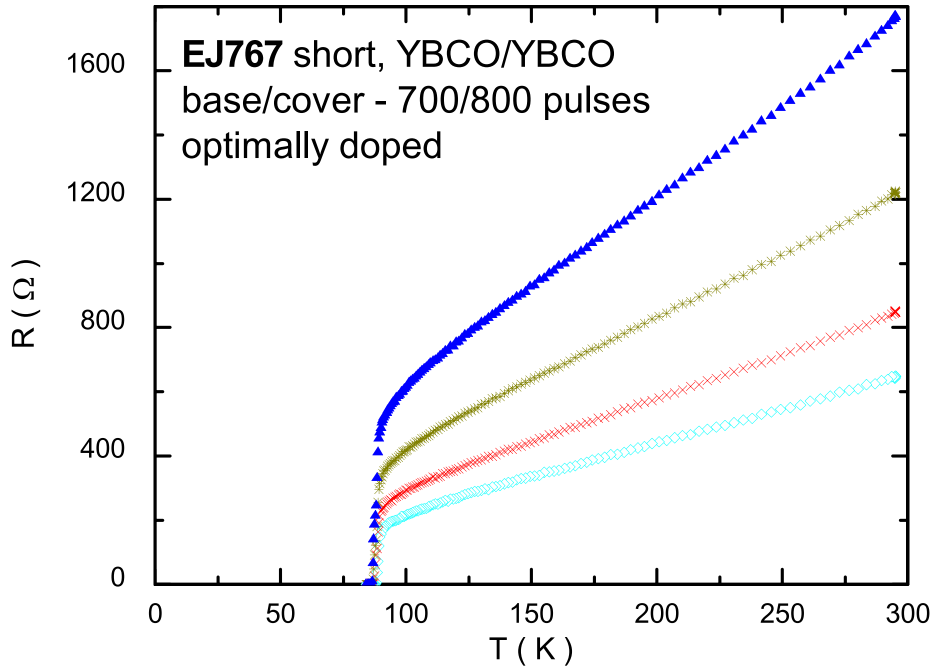
The ramp morphology of the base electrode (the interface) the roughness is less than a coherence length

ξ≈2nm (90K phase) or 3nm (60K phase)

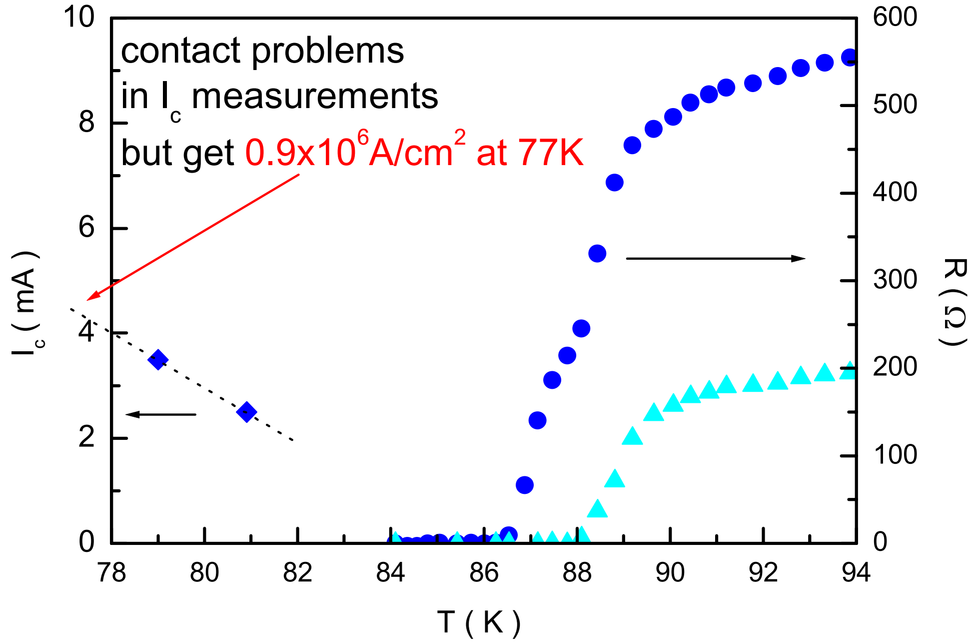


G. Koren & N. Levy, Europhys. Lett. **59**, 121 (2002)

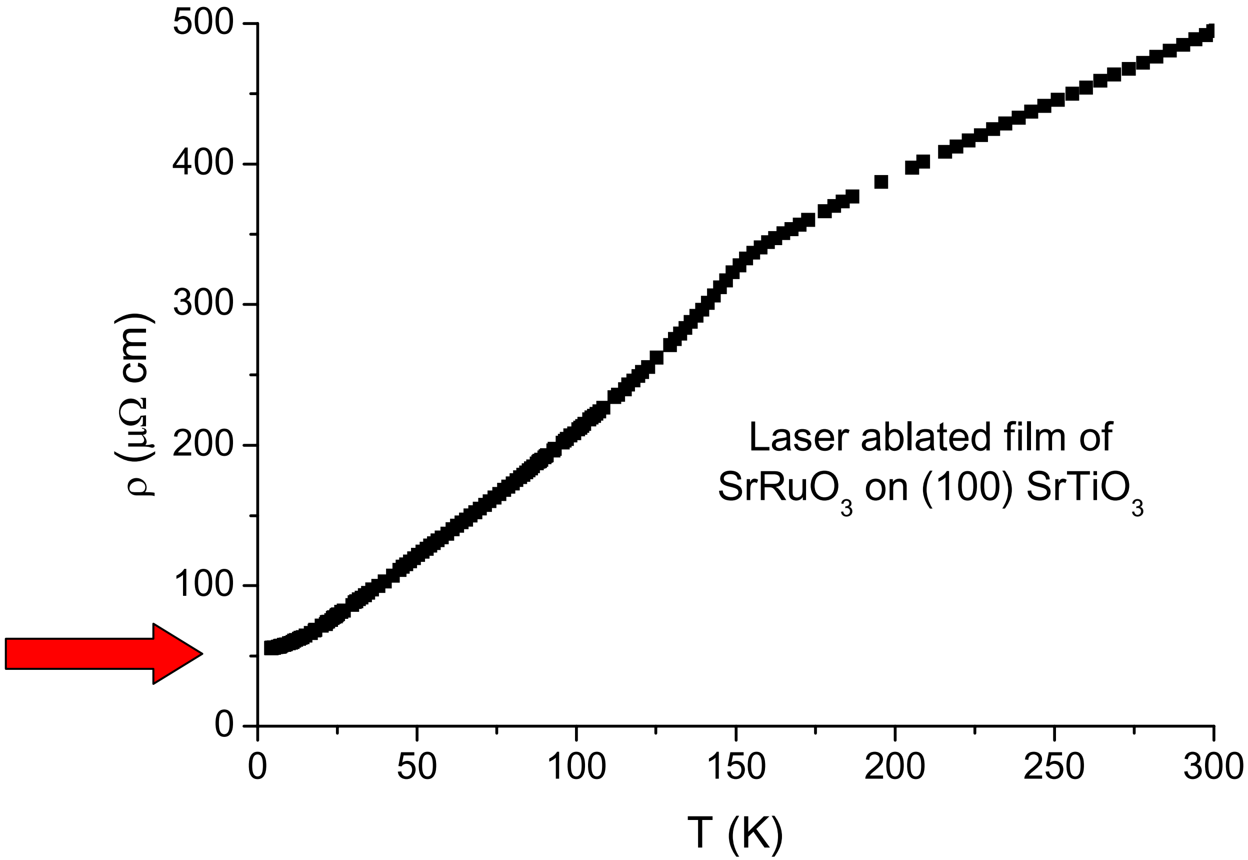
First, in order to check the quality of our fabrication process, we prepared "shorts" – junctions with no barrier



We obtained J_c(77K) of about one million A/cm^2. This is considered satisfactory, in view of the complexity of the multi-step fabrication process

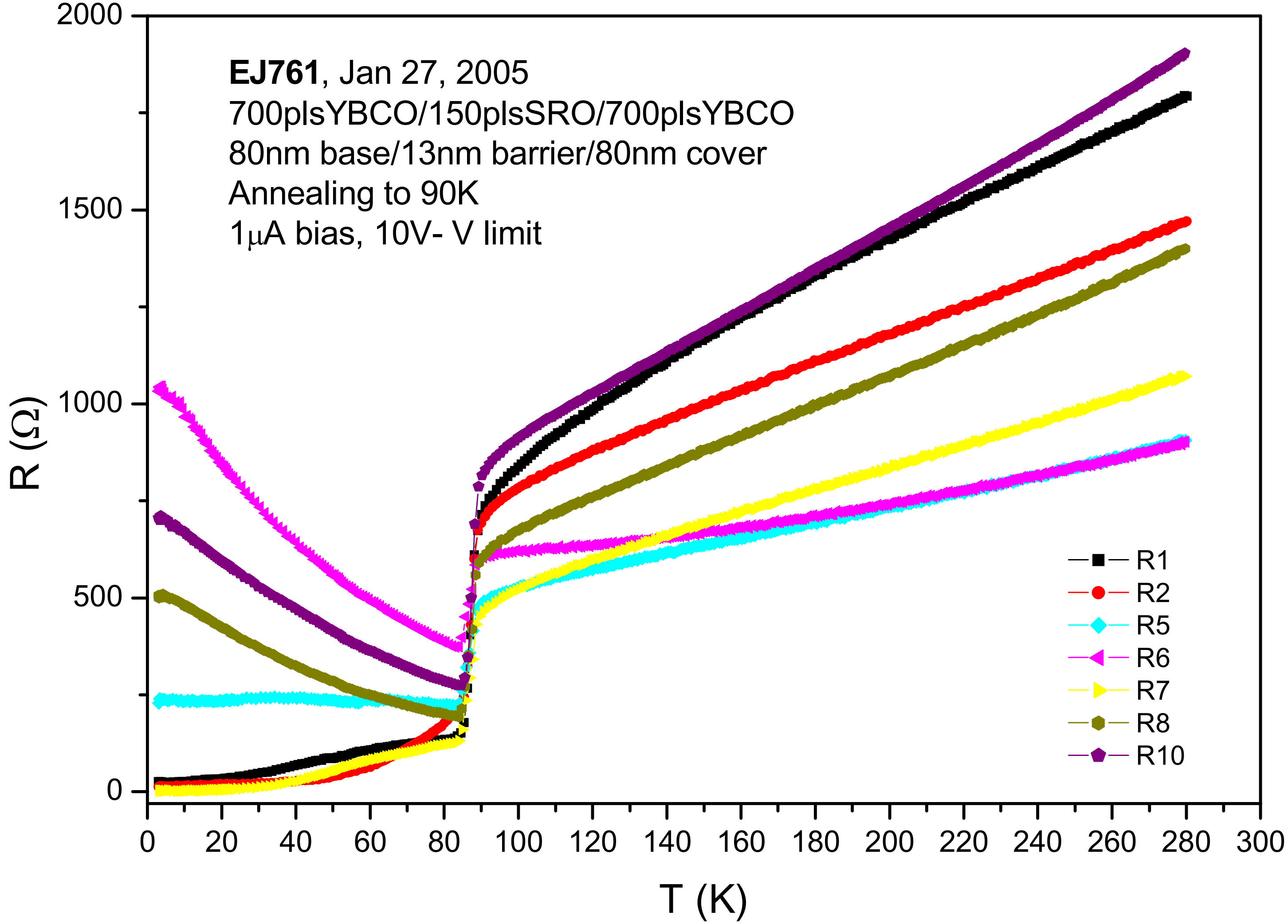


A $SrRuO_3$ film (the barrier)



- Para- to ferromagnetic-transition at a T_c of about 150K
- Similar to the SRO films of Antognazza et al, APL **63**, 1005 (1993)
- The expected Ohmic R_N(4K) of a typical junction ~0.01Ω only!

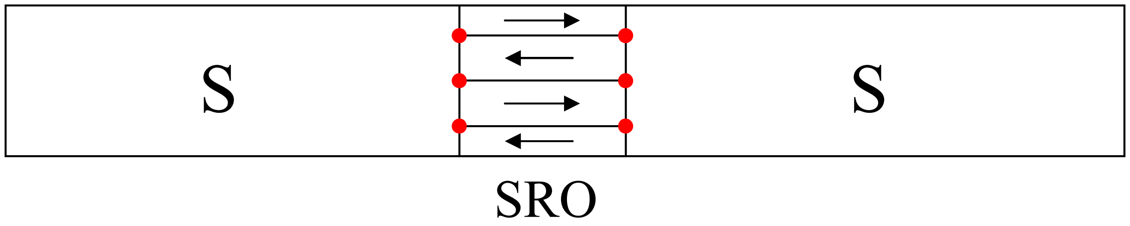
Typical Resistance versus Temperature



The R(4K) values spread over 10-1000Ω -
and this can not be due to the Ohmic resistance of the barrier!

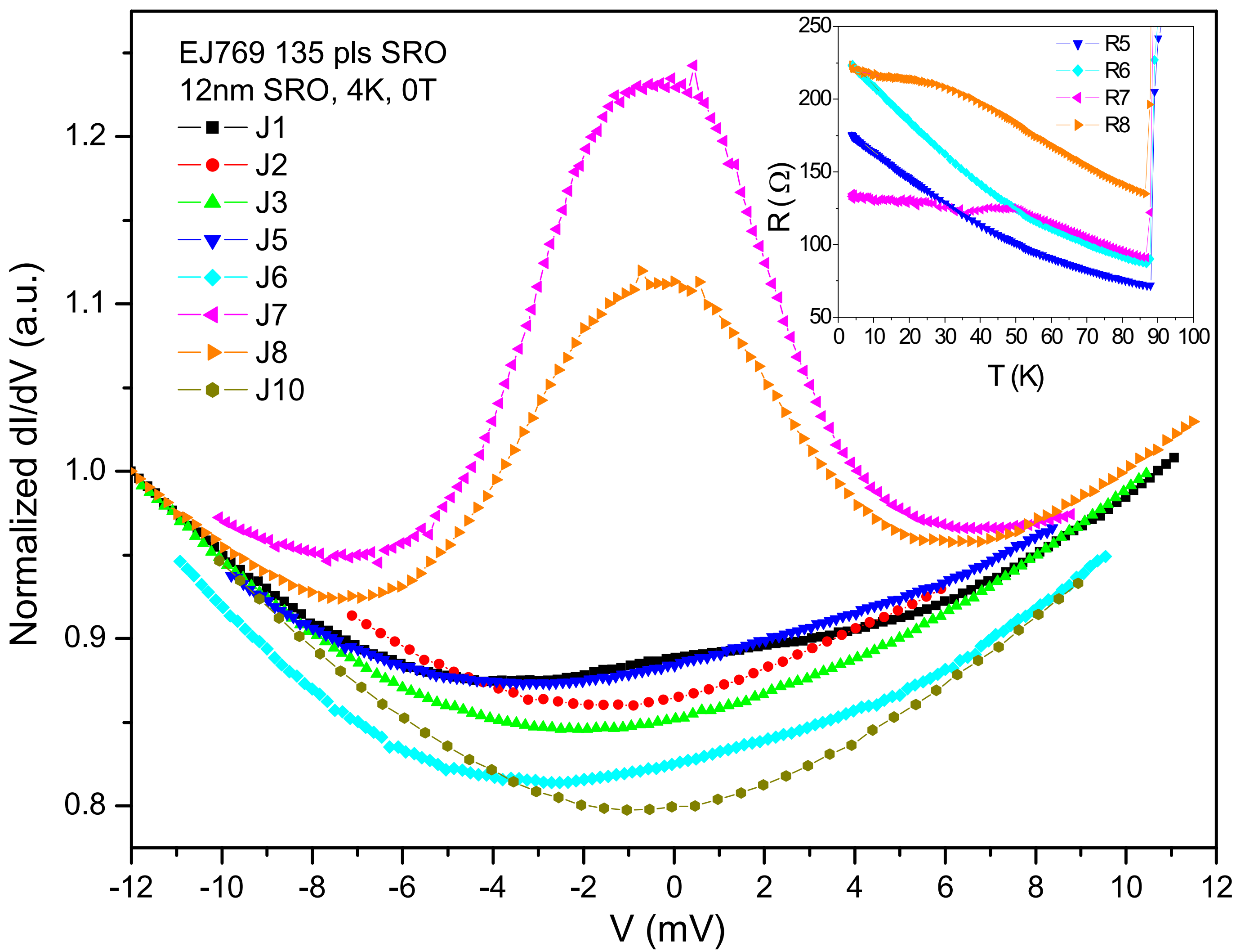
Possible explanations for the large spread and high values of normal resistance in our junctions

- Scattering by magnetic states and pair breaking in the barrier
- Imperfection of the interfaces (defects, resist residues, etc.)
- Spread of the CARE resistances in different junctions due to a different number of magnetic domains in the barrier



Many domains – a low CARE resistance (low R)
A single domain – no Andreev transport (high R)

Spread in the conductance of 8 junctions on a wafer

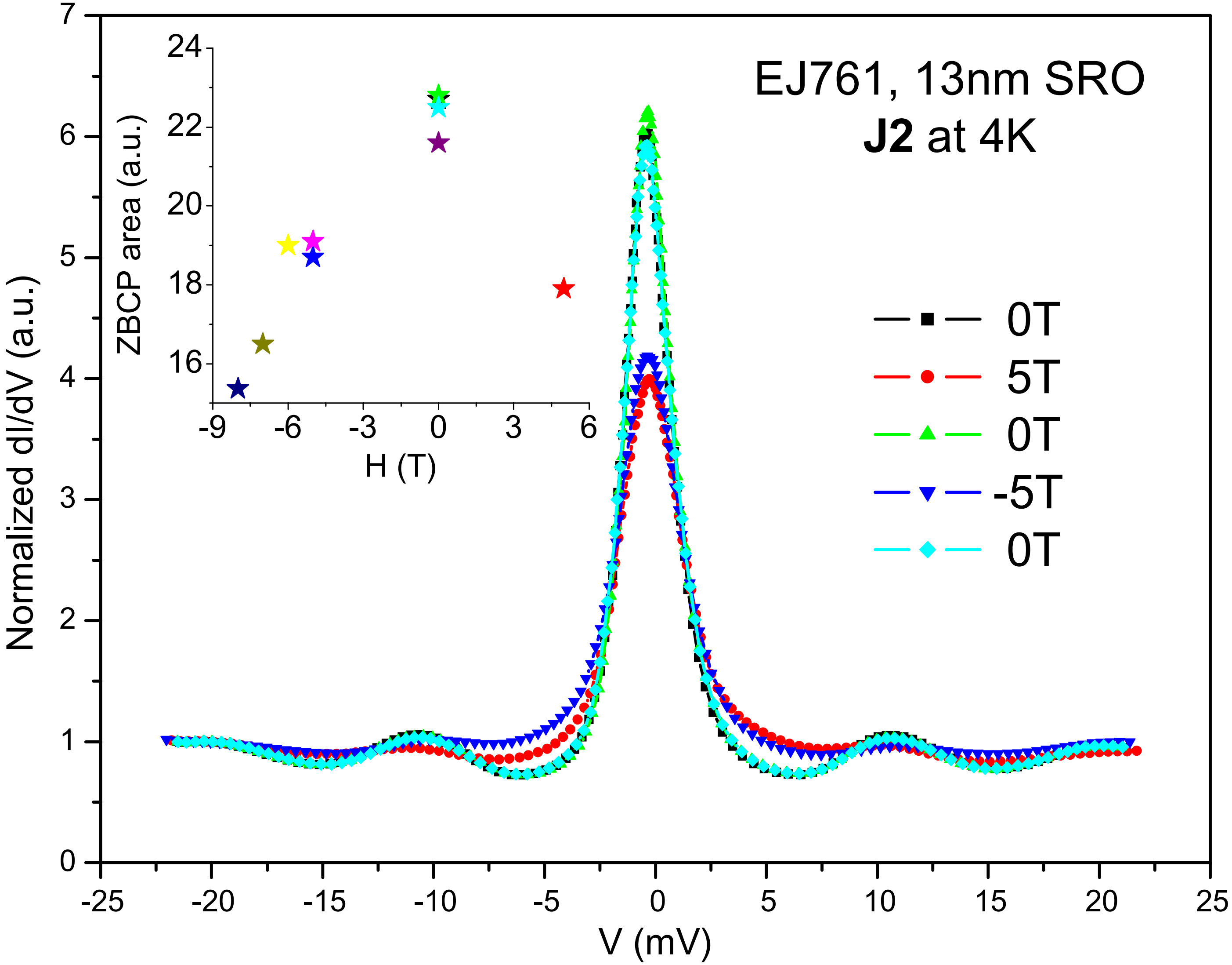


Some ZBCP, some tunneling

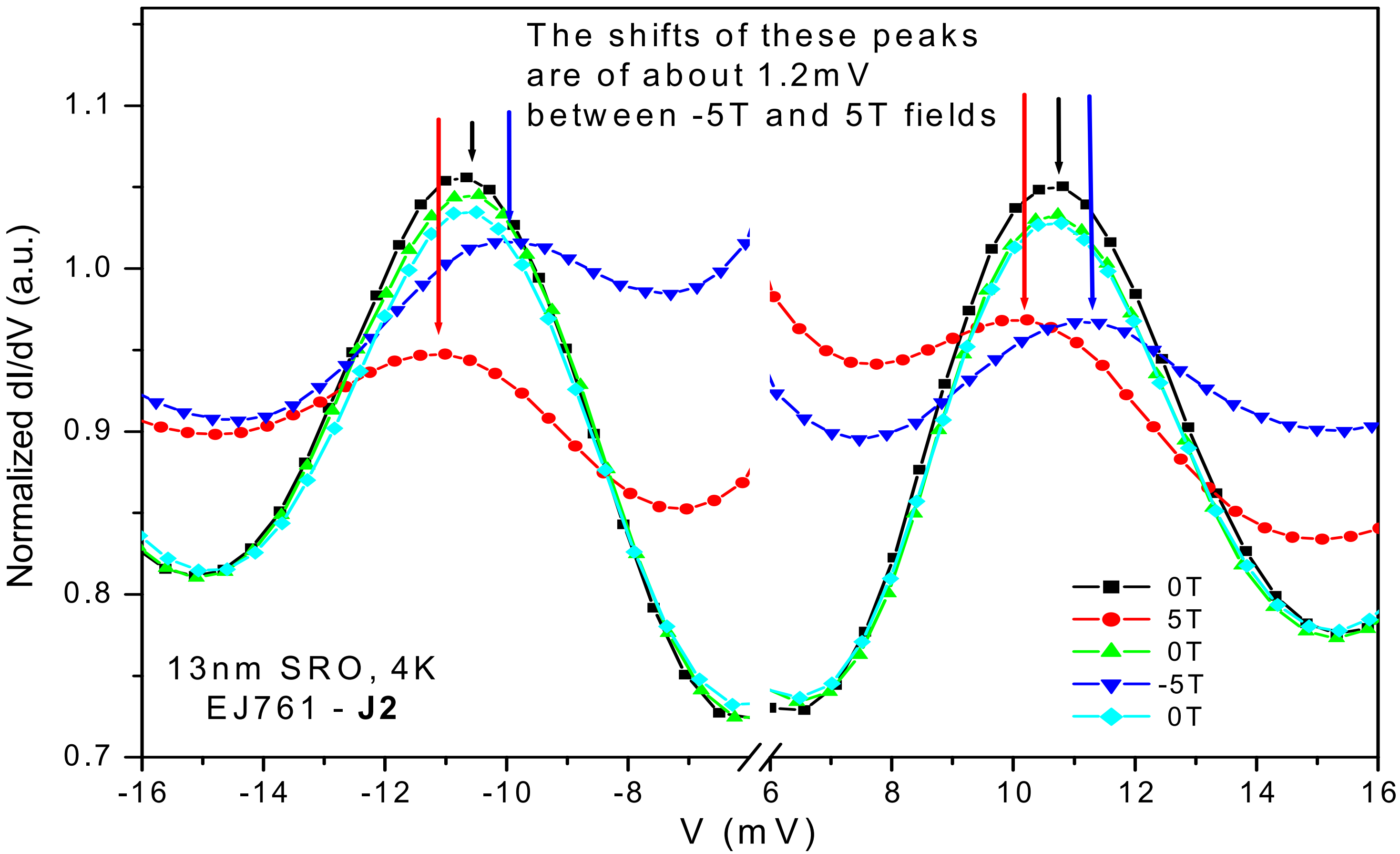
ZBCP when a deviation from VRH occurs in R

Asymmetry in bias – due to a magnetic origin (see next)

Conductance results with ZBCP and bound states



Magnetic field shifting of a bound state



- Shifting of the peaks and the asymmetry in SF junctions were predicted by P. Tedrow and R. Meservey [Phys. Rev. B **7**, 318 (1973)]

- Thus our junctions behave as classical SF junctions

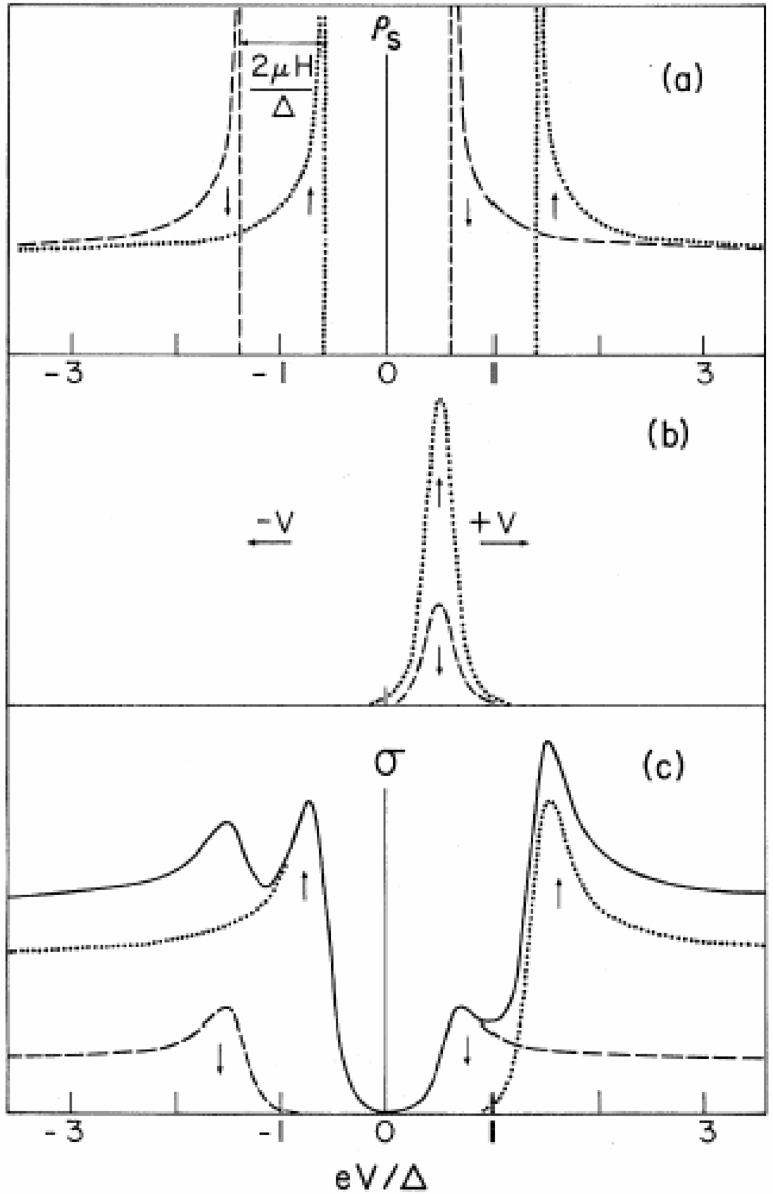
Magnetic field peak splitting in the conductance of SF junctions

P. Tedrow and R. Meservey. Phys. Rev. B **7**, 318 (1973)

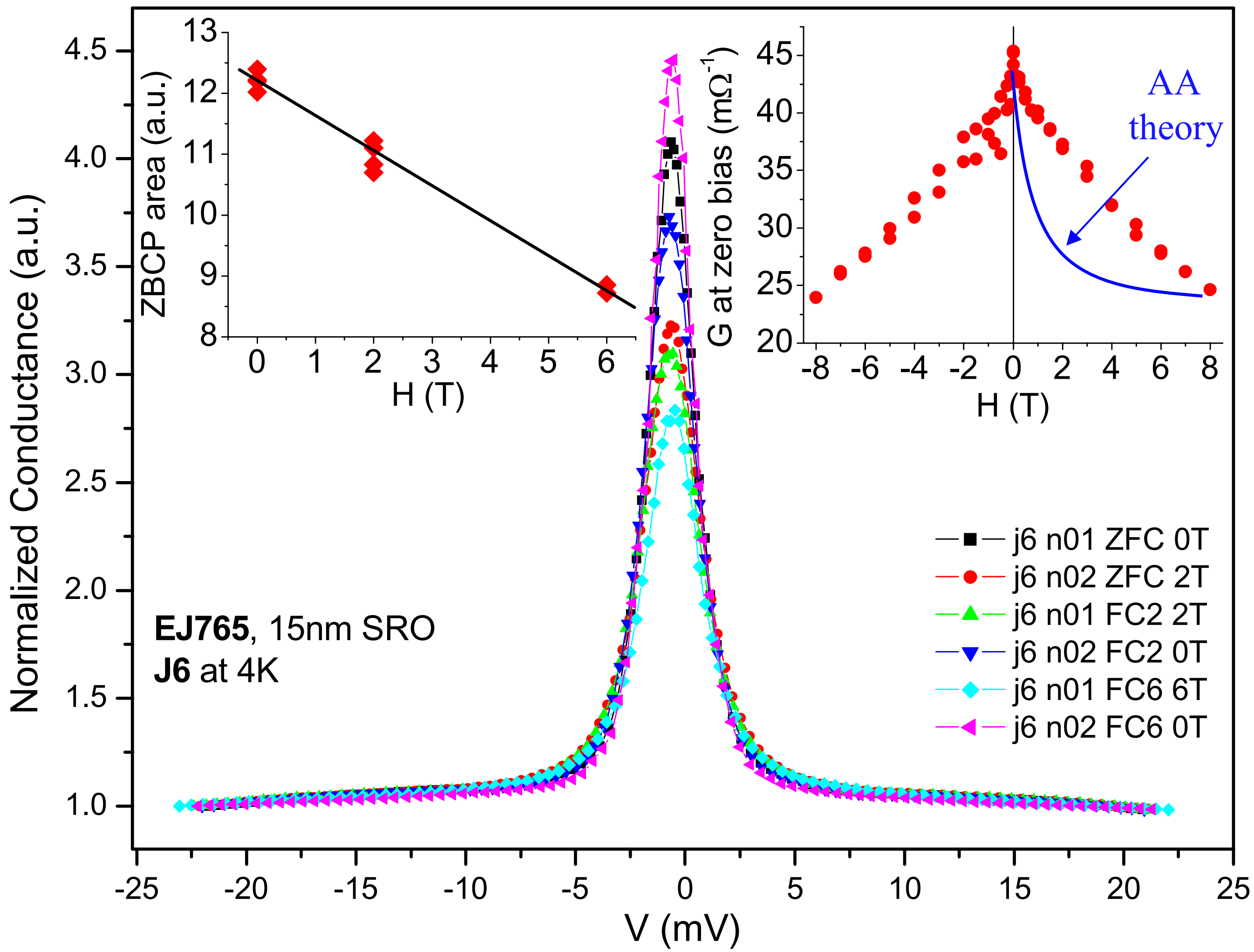
- The expected shift for ±H is $2\mu H/\Delta$ for SF junctions, and $4\mu H/2\Delta$ for SFS junctions.

- We measured a shift of ~1.2mV at ± 5T, where the $4\mu H$ value is 1.28meV. Thus for a bound state energy of Δ_1 and $4\mu H/2\Delta_1$=1.2mV one finds $2\Delta_1 \sim 1$ in units of Δ. This yields $\Delta_1 \sim 0.5\Delta \sim 10$meV, in agreement with our data

- Thus our junctions behave as classical SF junctions



The field dependence of the ZBCP and the G(V=0)



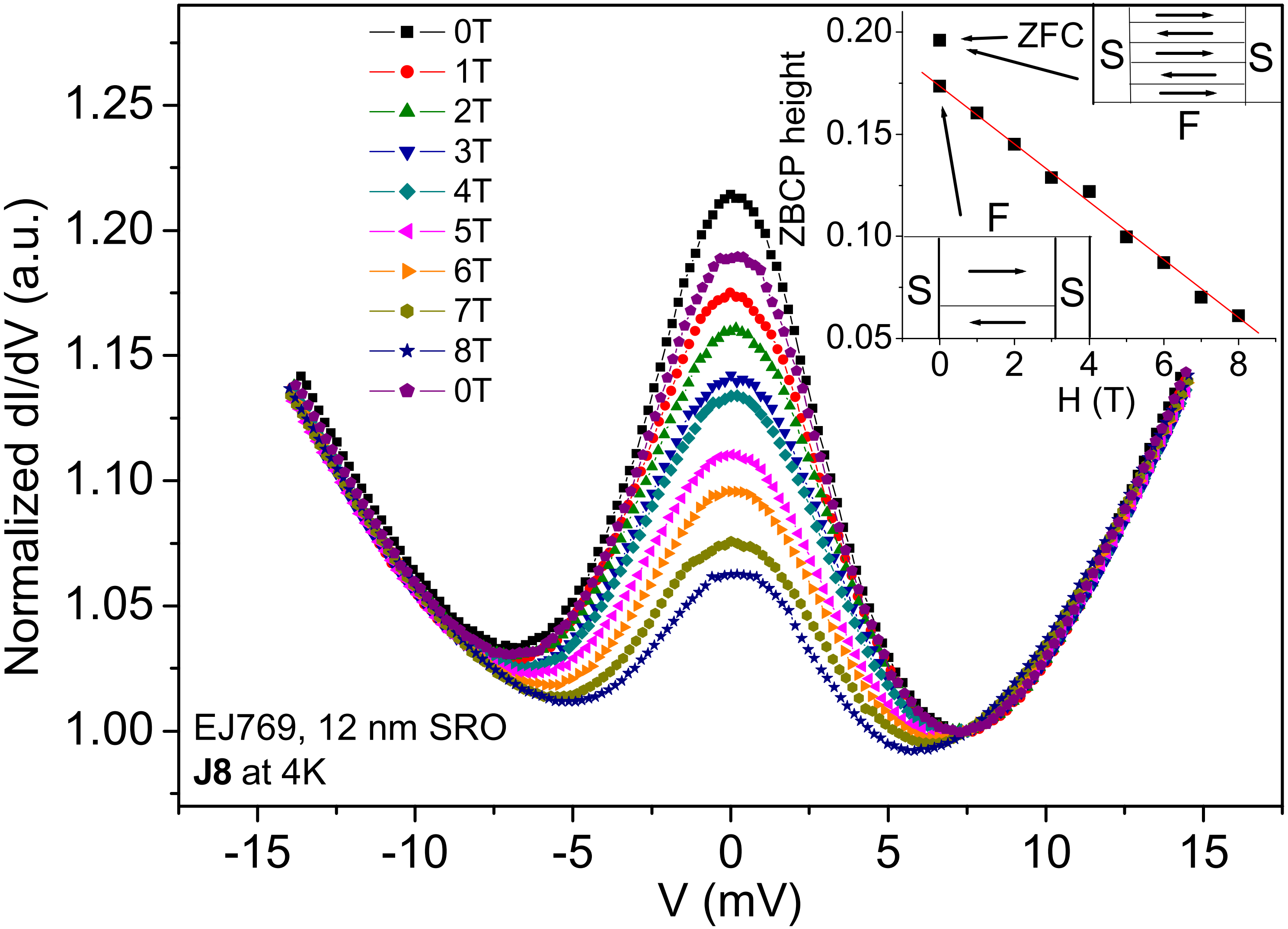
This data is consistent with the CARE mechanism

But not with the detailed results of the Anderson-Appelbaum (AA) theory of scattering by magnetic impurities (PRB **5**, 544 1972)

And more G vs V (H) and ZBCP height vs H

The ZBCP height for ZFC is larger than after field cycling to 8T and back to 0T

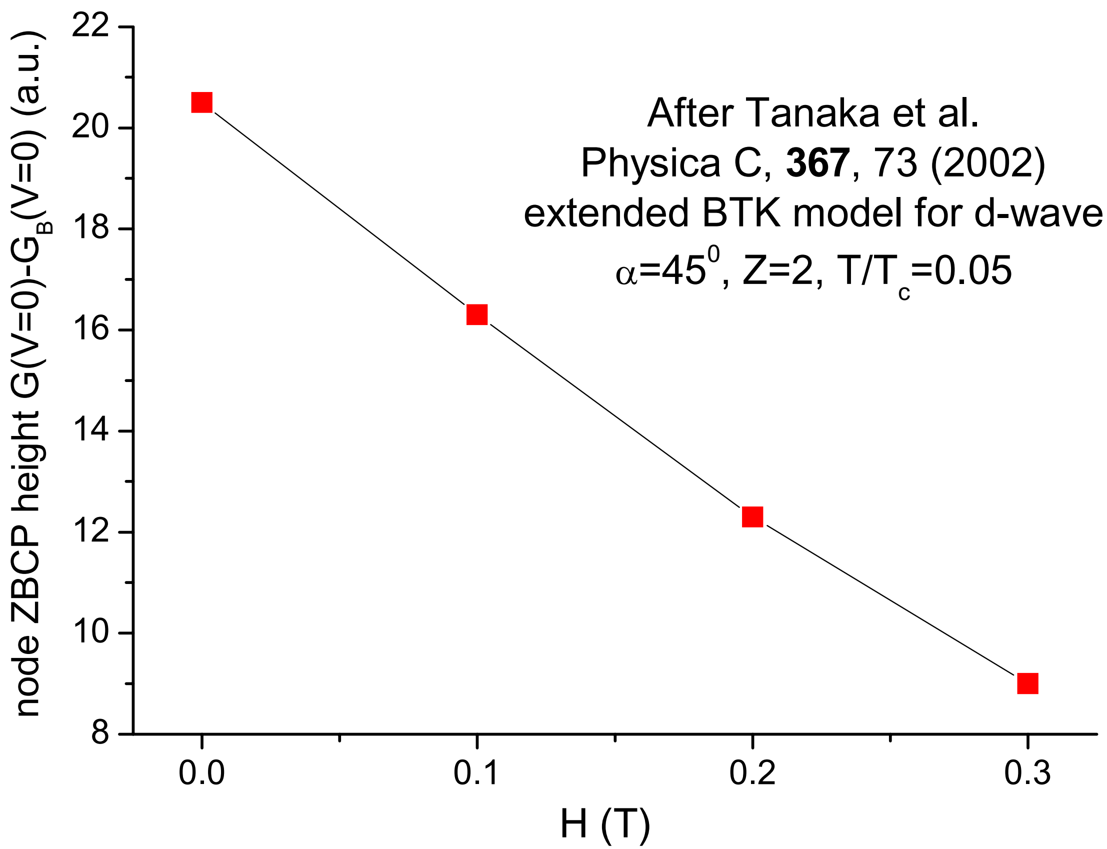
There are more domains at ZFC, thus a higher CARE conductance



What is the expected field dependence of the ZBCP height $[G(V=0)-G_B(V=0)]$ due to CARE ?

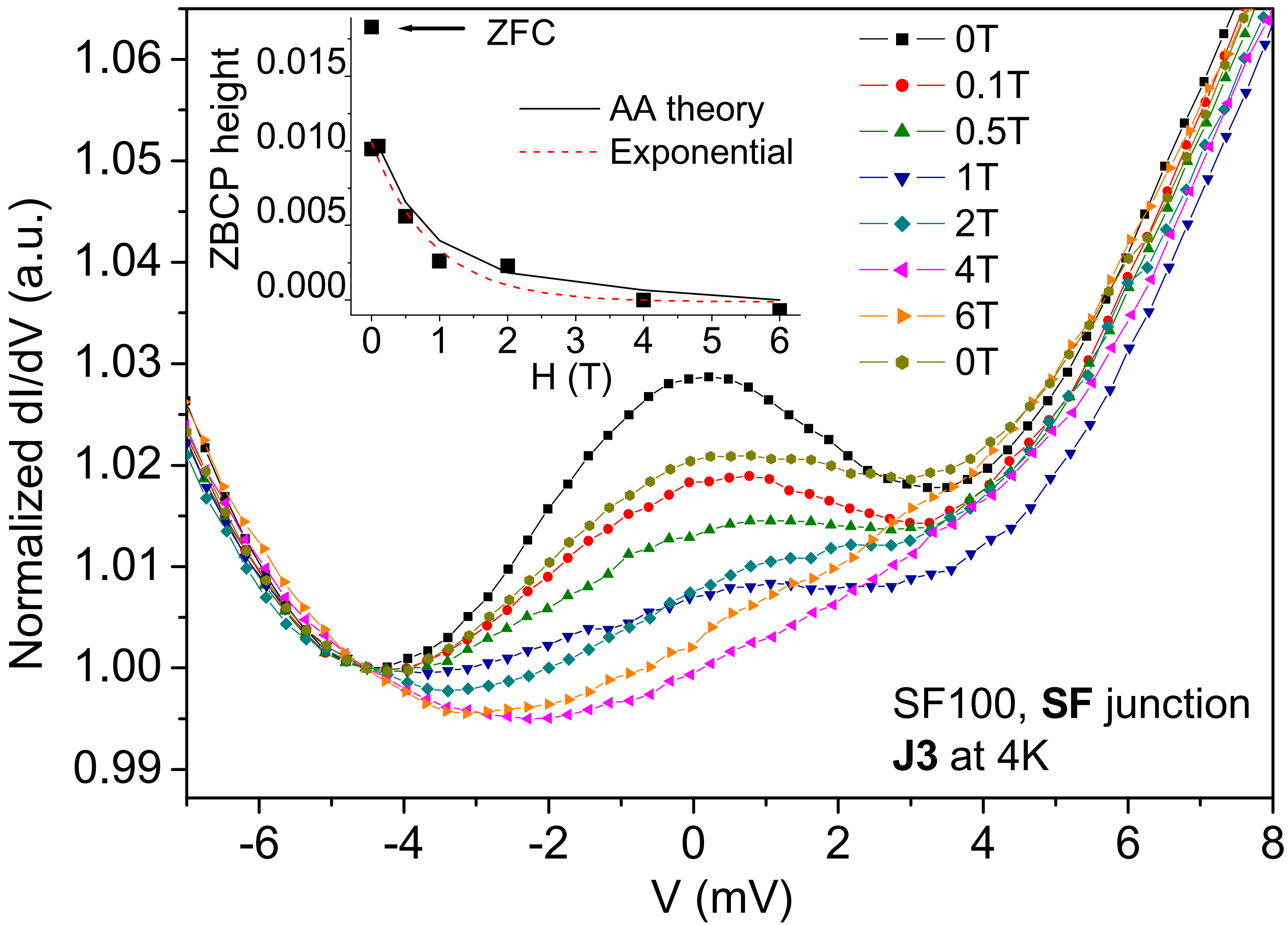
- No CARE calculation is presently available

- The closest we found is of the node ZBCP height by Tanaka *et al*. (simple Andreev in a d-wave HTSC, not specifically CARE)



- ….and this behavior is very similar to our data in SFS junctions maybe because both are due to Andreev scattering
- Atomic roughness of the interface can explain antinode ABS

However, in SF (YBCO/SRO) junctions we find:



The decay vs. H of the ZBCP height is closer to the AA theory (Anderson-Appelbaum) of magnetic scattering

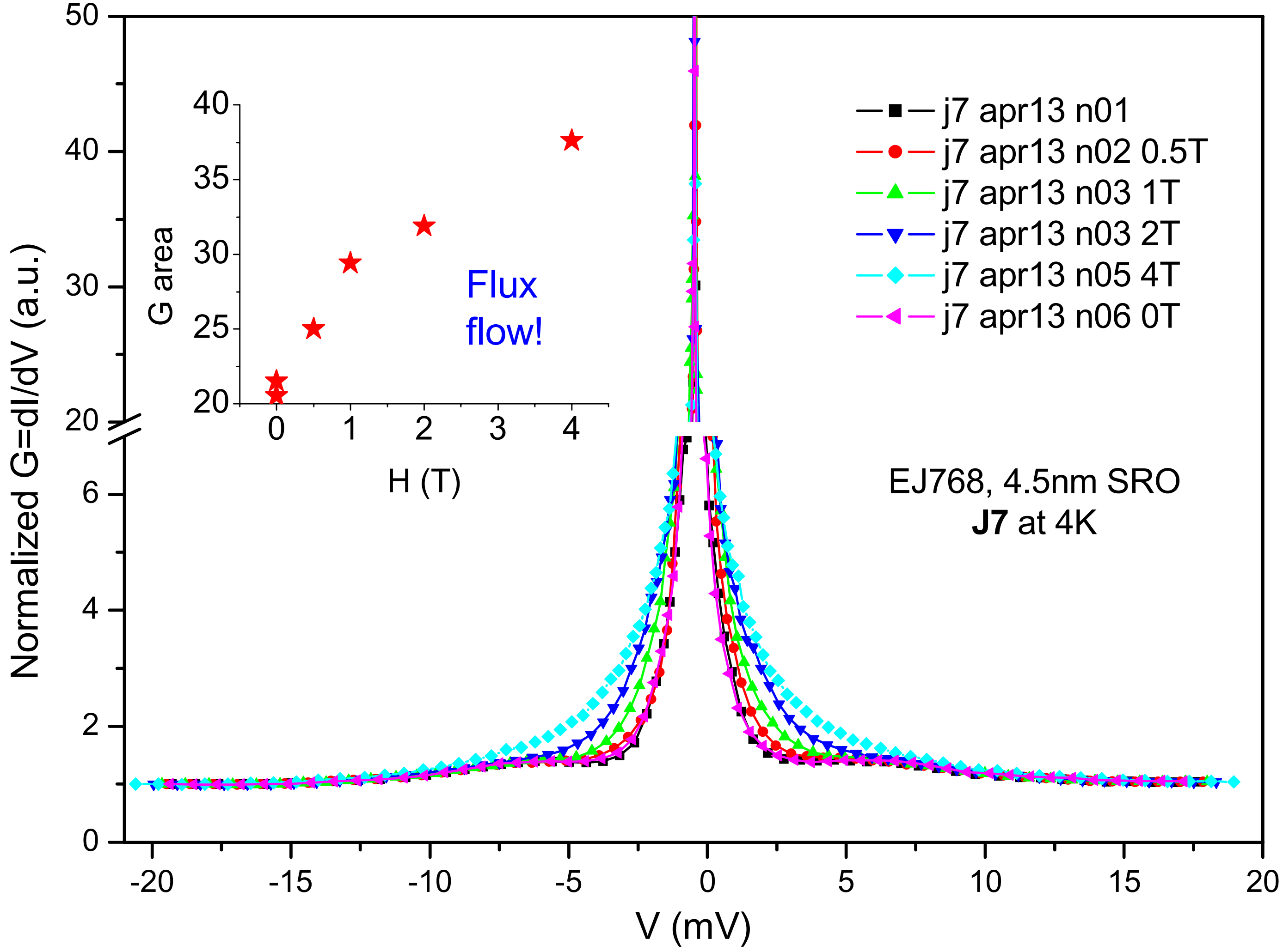
This is possibly due to the larger SRO electrode, which has a higher magnetic order. As a result – more scattering events occur

And a note before the conclusions….

Flux flow effect in junctions with a critical current

Broader I-V curves versus H due to FF

We did not deal with this kind of Junctions here



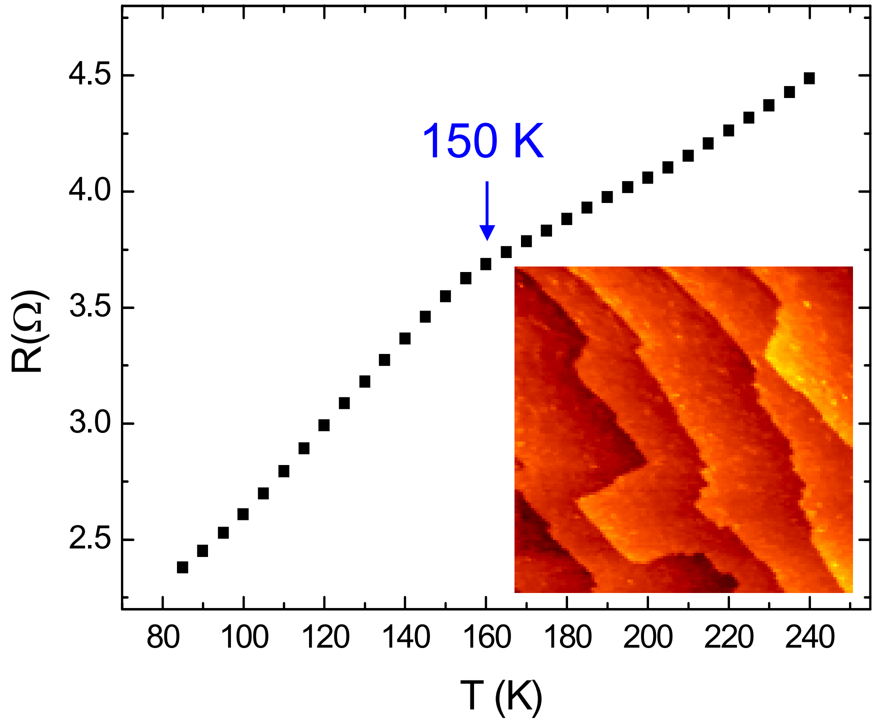
Conclusions

- In many of our SFS junctions a ZBCP was found
- The ZFC ZBCP is higher than the ZBCP after field cycling – indicating a CARE contribution to G
- The ZBCP height was found to decrease linearly with increasing magnetic fields – this is consistent with CARE but not with scattering by magnetic states in the barrier
- Bound states in our junctions were found to shift with magnetic field in agreement with the classical theory of SFS junctions.

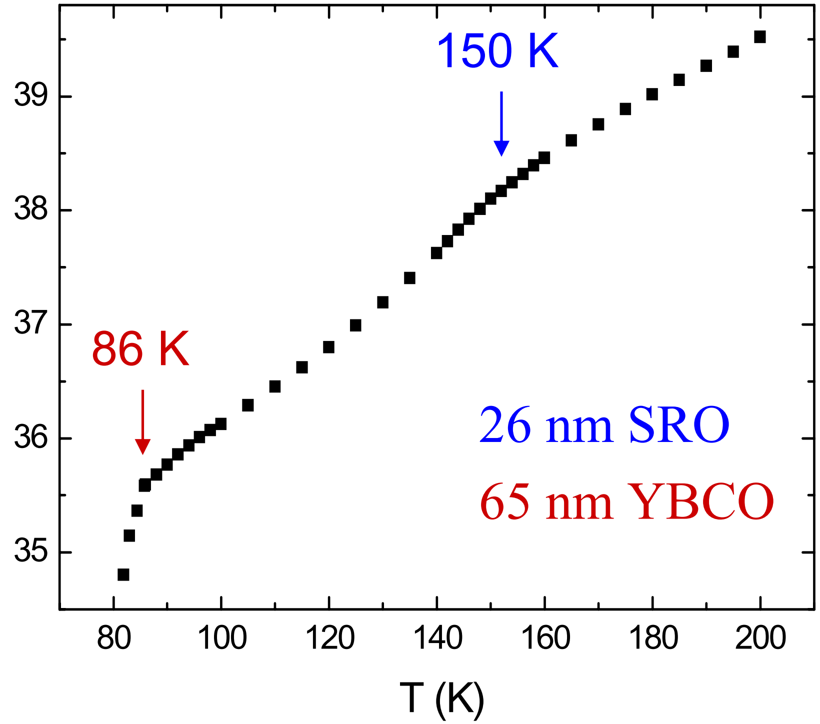
*P. Aronov & G. Koren, Phys. Rev. B **72**, 184515 (2005).

Scanning tunneling spectroscopy in SF bilayers
SRO on a-axis YBCO
(Bilayers prepared at Technion and measured in HUJI)

SRO on STO

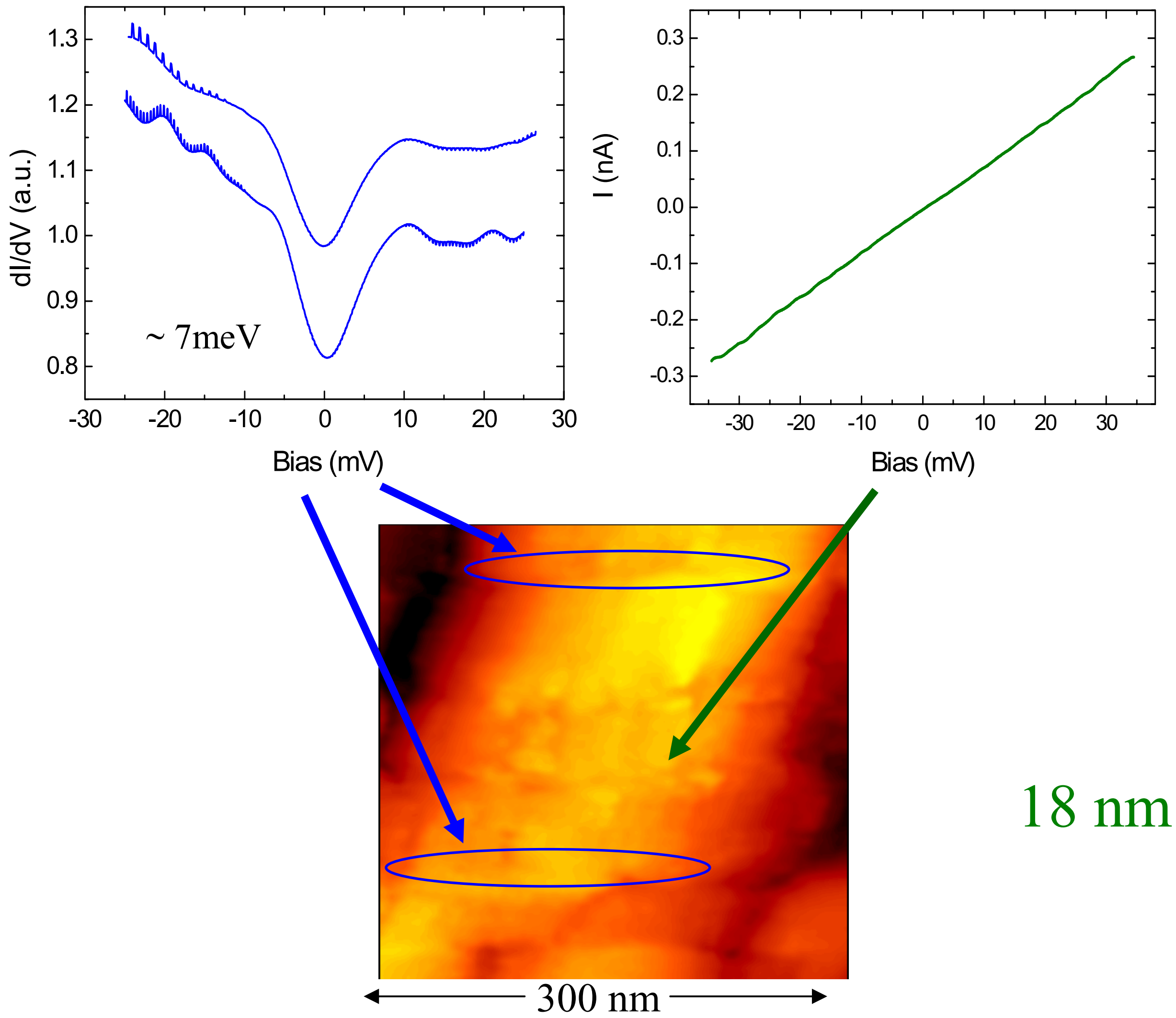


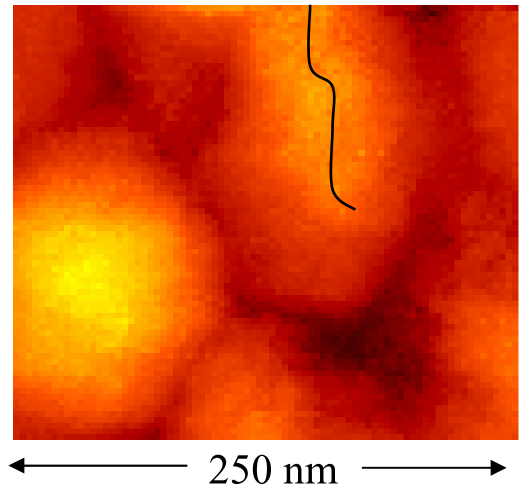
SRO on (100)YBCO



$SrRuO_3$/(100)YBCO proximity bilayer films

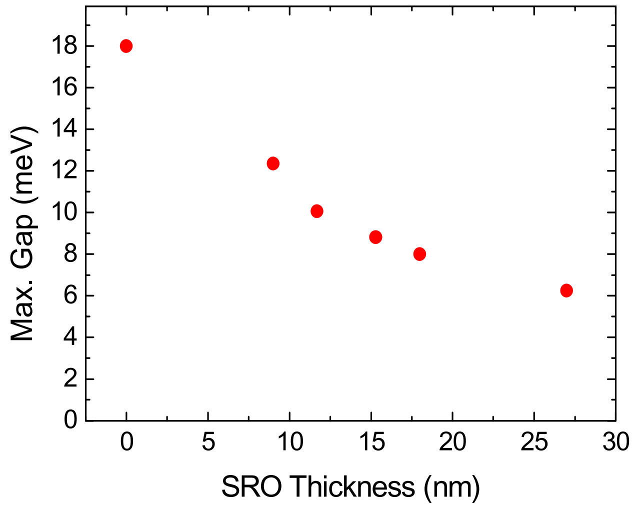
- OP (mini-gaps) induced in F only along narrow elongated areas, a few nm wide.
- On other areas, no induced OP is detected (for SRO layers thicker than 8 nm).



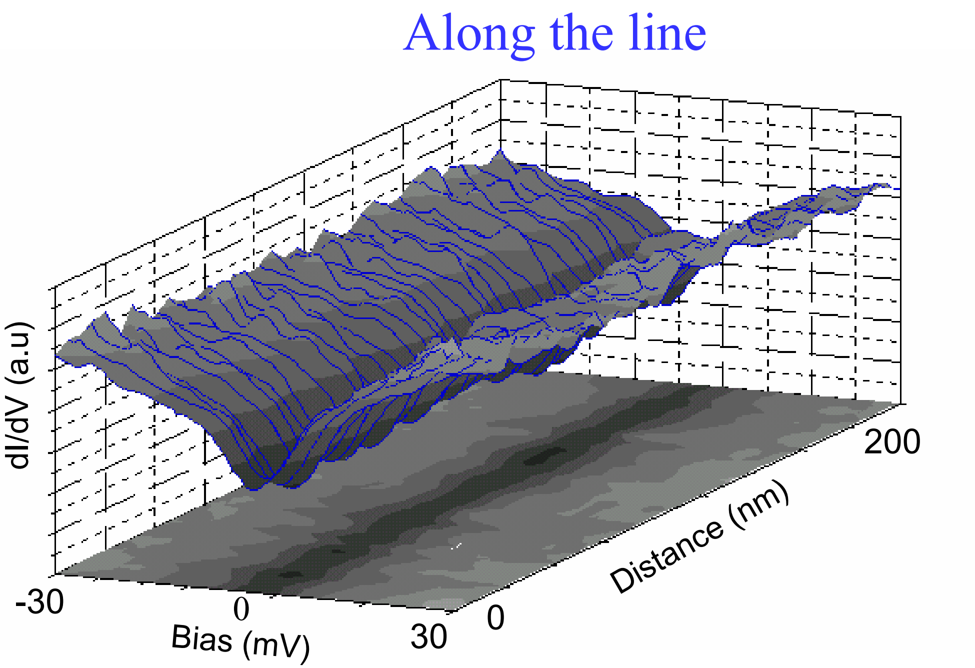


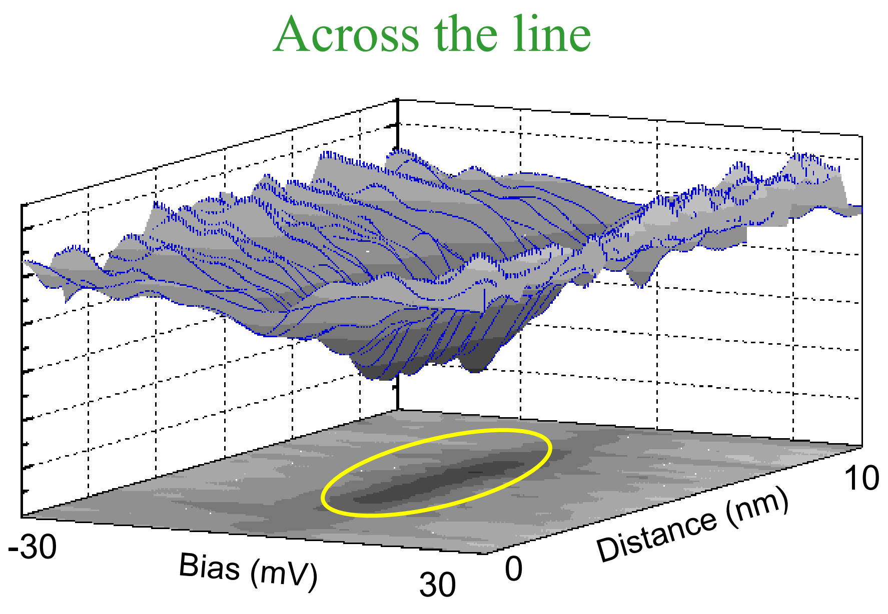
18 nm thick SRO

$SrRuO_3$/(100) YBCO proximity bilayer films



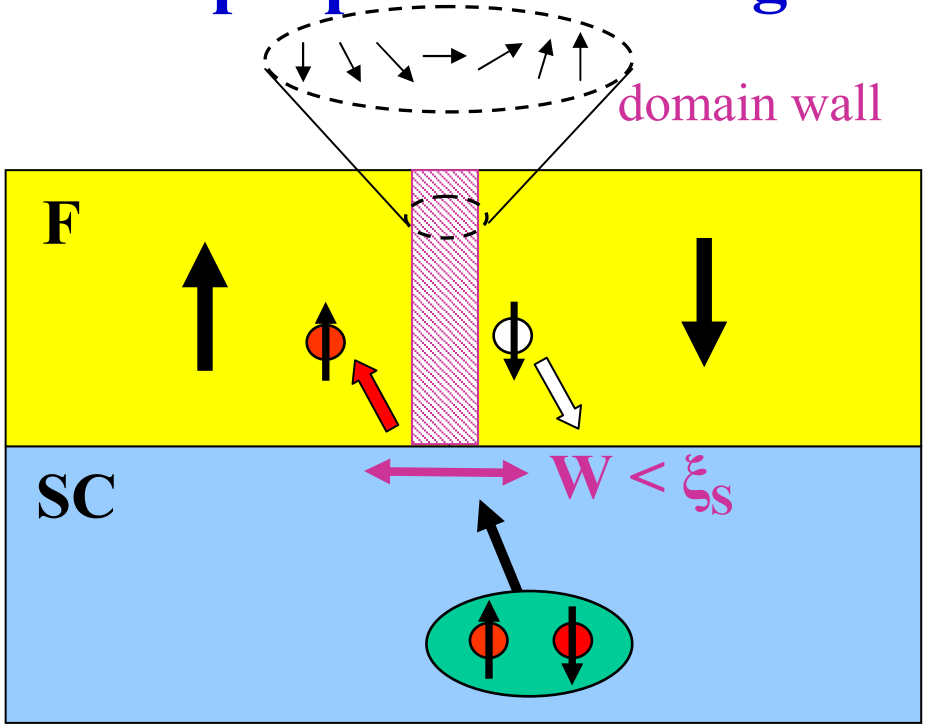
- Constant and continuous gap along the line.
- Width of gapped area less than 8 nm.
- Outside this area – Ohmic characteristics.





What is the origin of the local long-range penetration depth or proximity effect?

We propose CARE again



•The distance between the local gaped regions (the lines in the STM image) corresponds to the magnetic domain structure of the SRO layer

• And this is consistent with **CARE**

• Asulin, Y. Ofer, G. Koren & O. Millo, Phys. Rev. B **74**, 092501 (2006).

Flux flow resistivity anisotropy in the instability regime in the a-b plane of epitaxial YBCO thin films

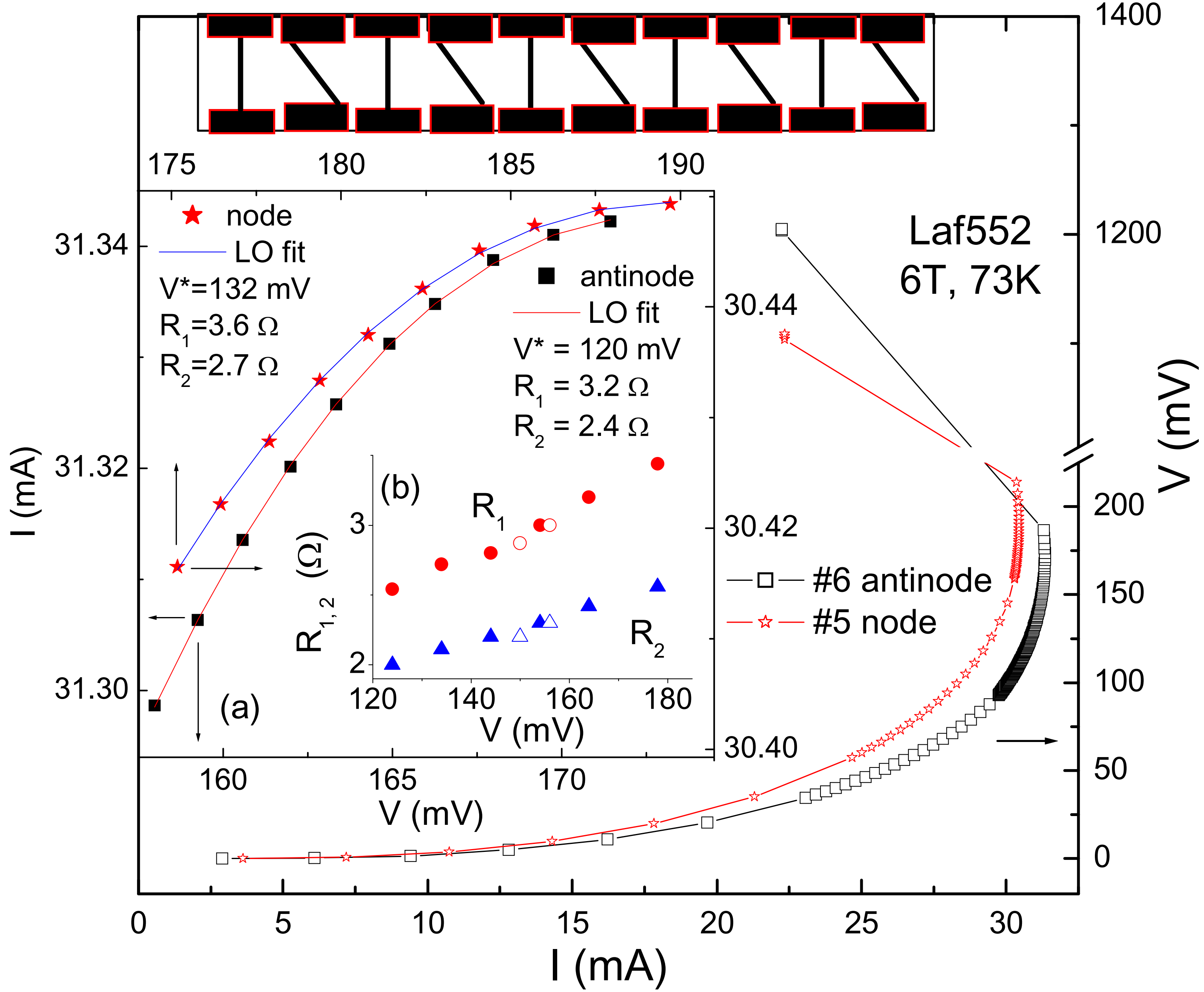
- In the instability regime, flux pinning is negligible.
- Larkin and Ovchinikov found that in this regime:

$$I = \frac{V}{R_1}\left\{1 + \sqrt{1 - \frac{T}{T_c}}\right\} - \frac{V}{R_2}\left(\frac{V}{V^*}\right)^2 \left\{1 + \left(\frac{V}{V^*}\right)^2\right\}^{-1}$$

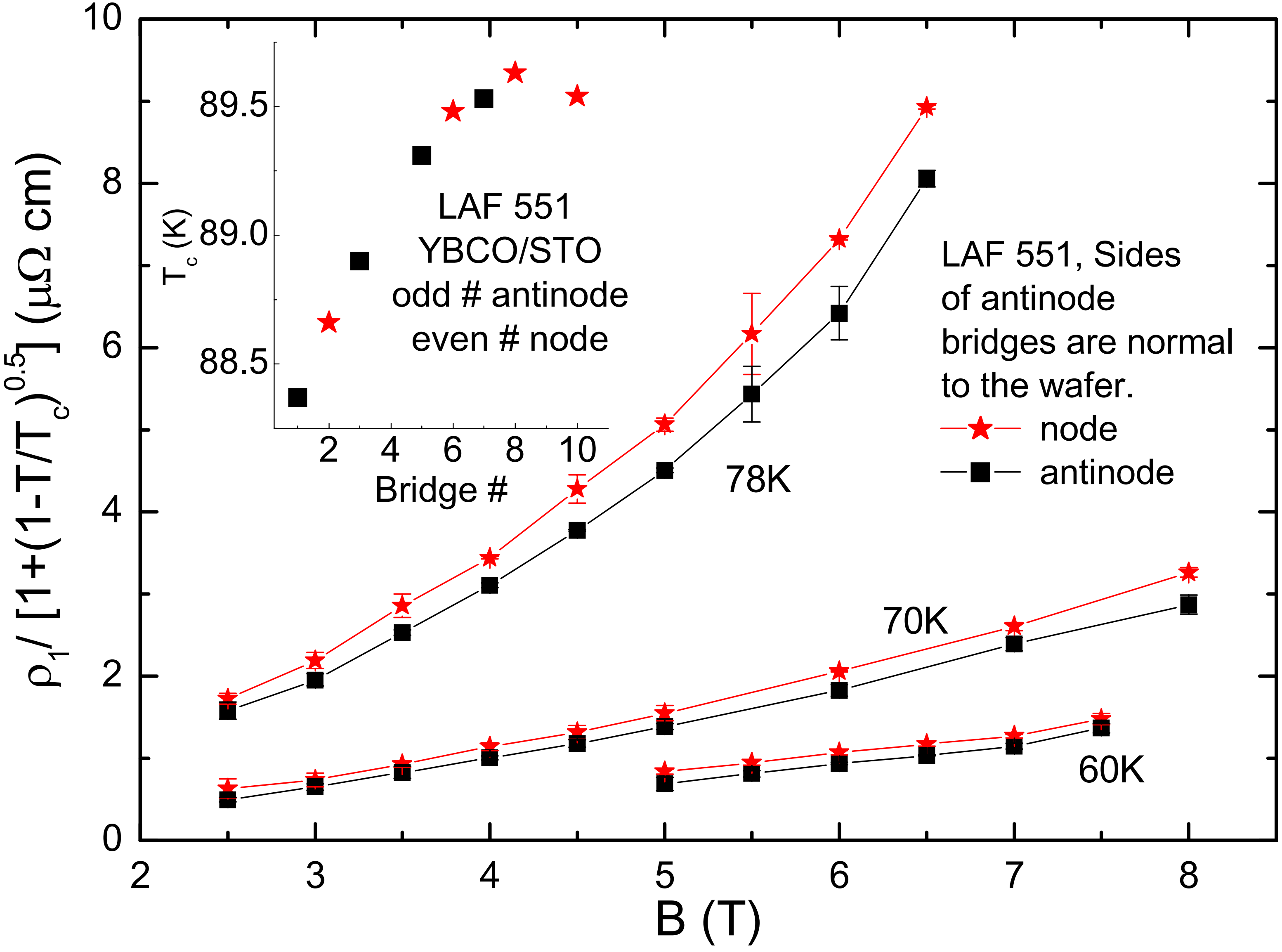
- Where I is the current, V is the voltage,
R_1, and R_2 are the flux flow resistances (FFR),
and V* is a critical voltage.

Due to the d-wave order parameter in the HTSC, the low ex. node quasiparticles density on the FS is higher than that of the antinode.
Thus the FFR should also be anisotropic with larger node values.

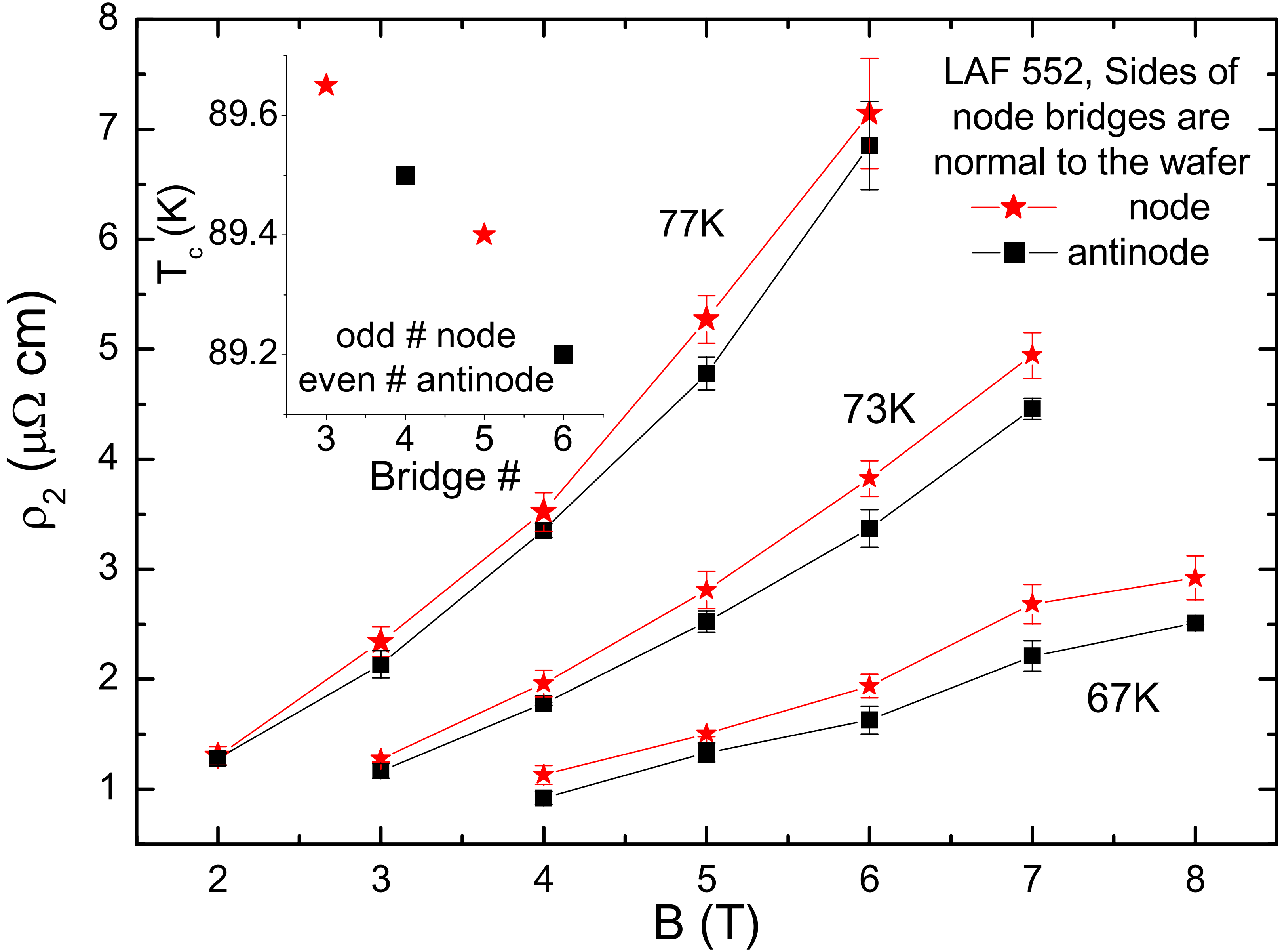
0.12×12×100 μm³ microbridges on wafer & I-V curves



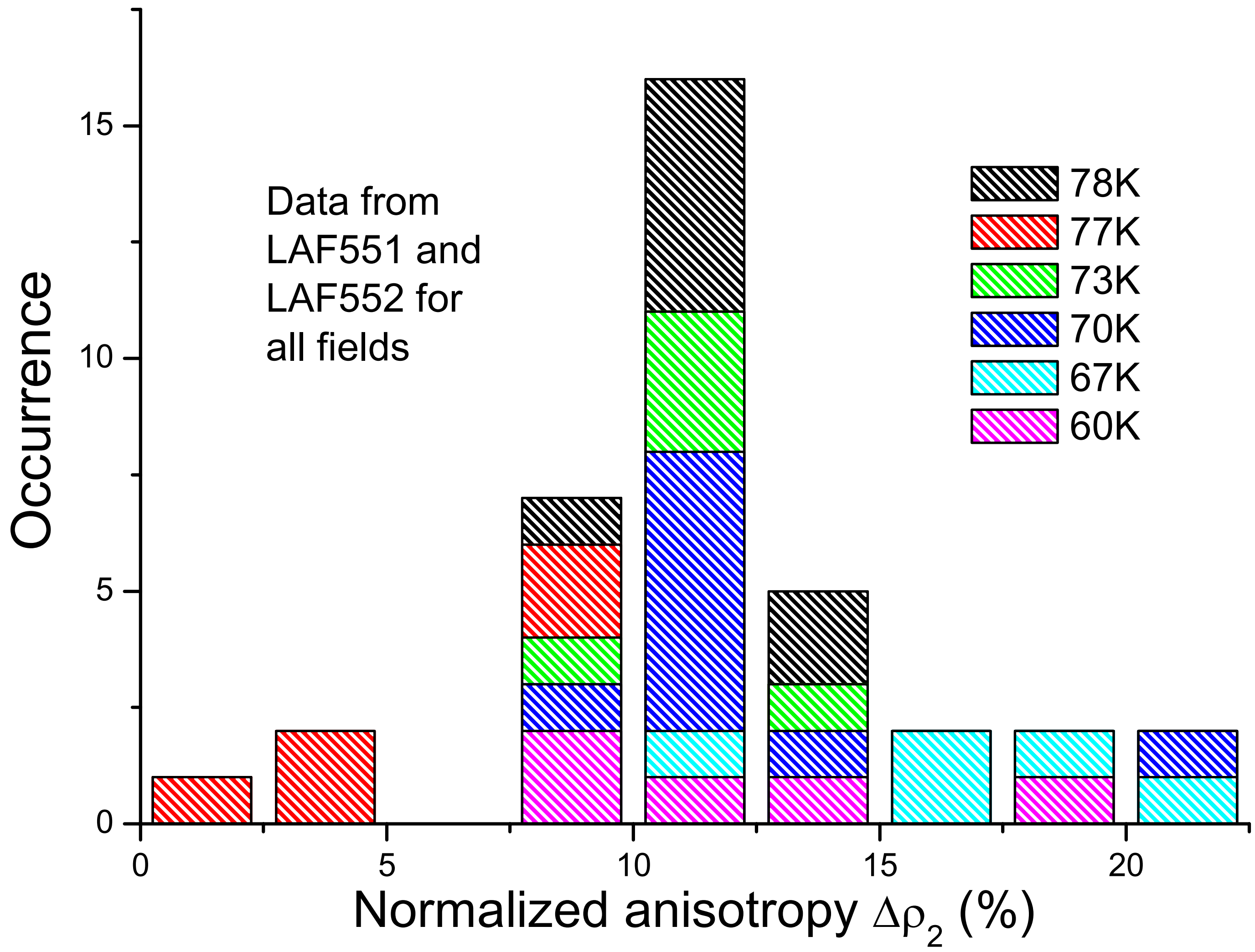
The FFRs versus magnetic field



And another one

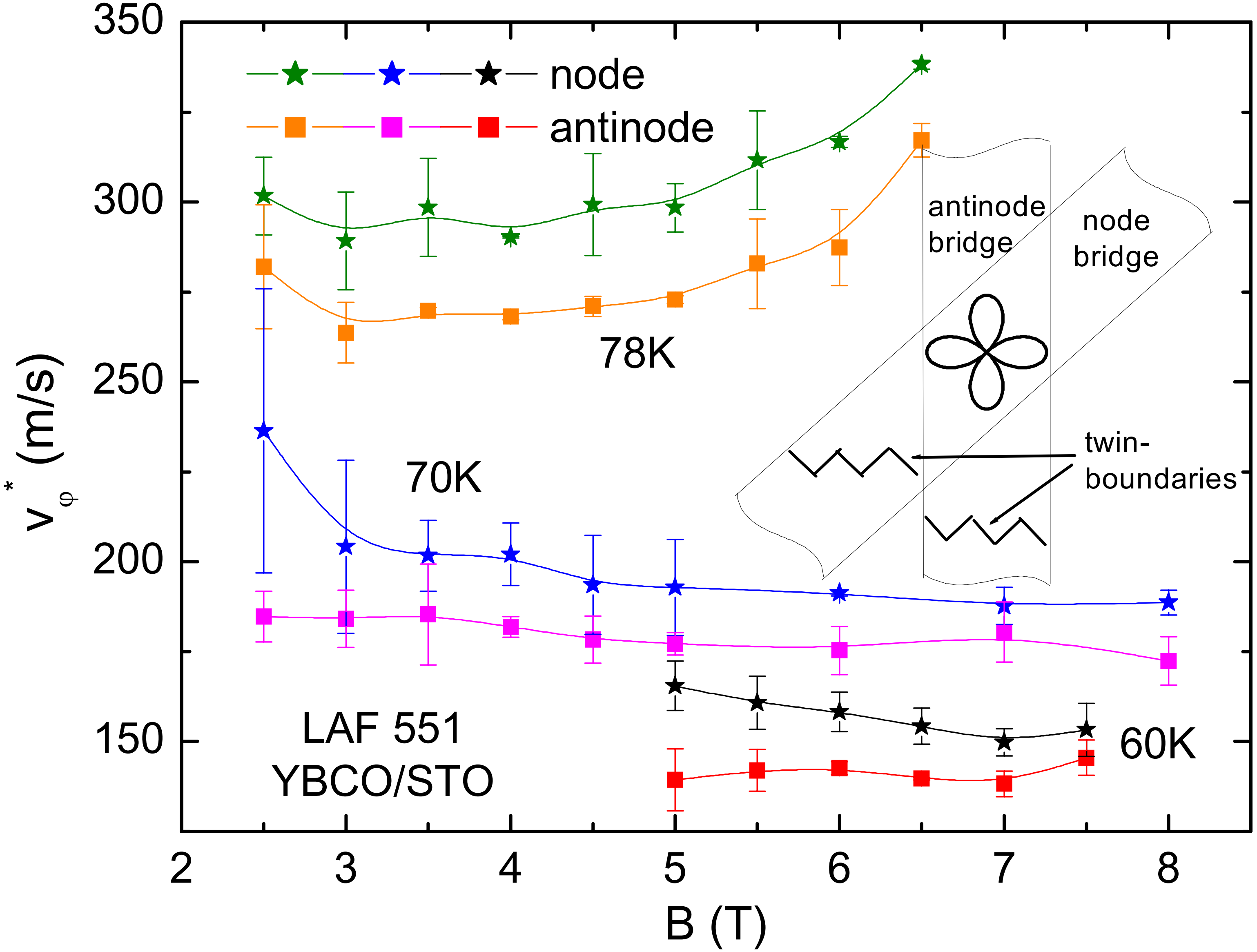


The node - antinode anisotropy
[ρ(node) - ρ(antinode)]/ [ρ(node) + ρ(antinode)]



The critical vortex velocity derived from V*

$$V^* = |\mathbf{v}_\varphi^* \times \mathbf{B}|\, L$$



Conclusions

- A small anisotropy of ~10% is observed in the FFR and v^*_φ between the node and antinode orientations.

- A serious quantitative theoretical model is needed for the description of the observed effect.

- B. Kalisky, P. Aronov, G. Koren, A. Shaulov, Y. Yeshurun and R. P. Huebener, Phys. Rev. Lett. **97** , 067003 (2006)