LSU
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Department of
Physics & Astronomy

Hysteresis, Avalanches, and Slow Relaxation: Complex non-equilibrium spin dynamics in a Zeeman-limited superconductor

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U.S. DEPARTMENT OF ENERGY | Office of Science

Outline:

1. Superconductivity and magnetic fields
2. The Spin-Paramagnetic phase diagram
3. Tunneling and excess single particle states near the S-P transition
4. Avalanches and FFLO physics
5. Summary

Collaborators:

- Joe Prestigiacomo
- TJ Liu
- Y.M Xiong
- Shane Stadler
- Gianluigi Catelani

Y. L. Loh, N. Trivedi, Y. M. Xiong, P. W. Adams, and G. Catelani, *PRL* **107**, 067003 (2011).

Y.M. Xiong, S. Stadler, P.W. Adams, and G. Catelani, *PRL* **106**, 247001 (2011).

T. J Liu, J. C. Prestigiacomo, Y. M. Xiong, and P. W. Adams, *PRL* **109**, 147207 (2012).

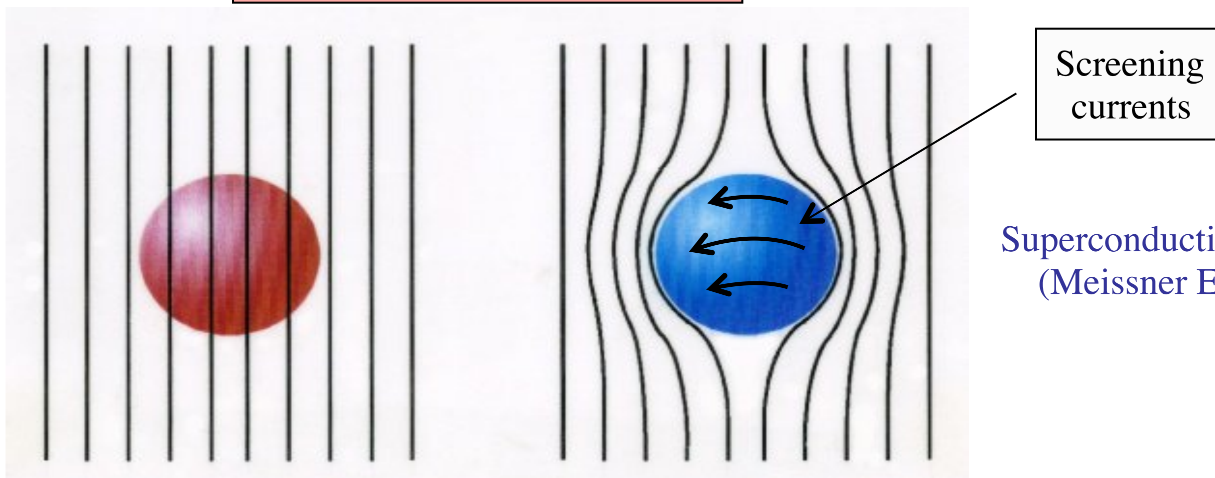
T.J. Liu, J. C. Prestigiacomo, and P.W. Adams, *PRL* **111**, 027207 (2013).

J.C. Prestigiacomo, T.J. Liu, and P.W. Adams, *Phys. Rev. B* **90**, 184519 (2014)

Orbital Response of a Superconductor to a Magnetic Field

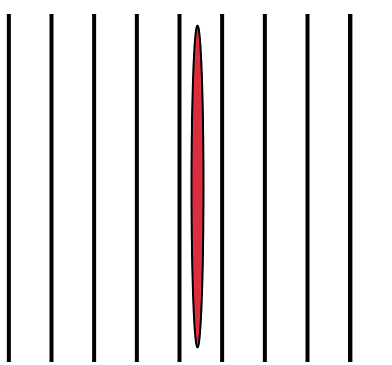
Bulk Superconducting Systems

Normal State

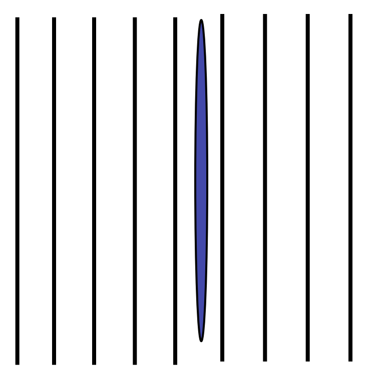


Superconducting State
(Meissner Effect)

Disk with width << ξ in a parallel field



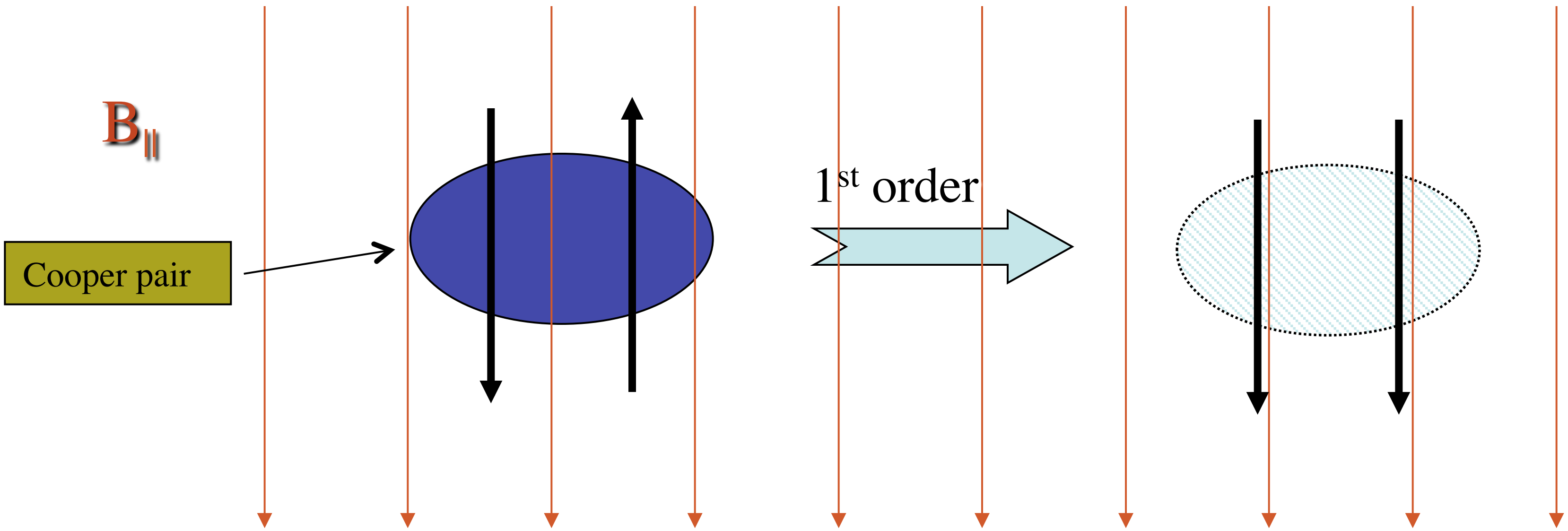
Normal State



Superconducting State
(no screening currents)

Thin Film Superconductivity in High Parallel Magnetic Fields

Assume magnetic field oriented parallel to superconducting film of thickness d < ξ_0 so that there can be no significant orbital response to the applied field.

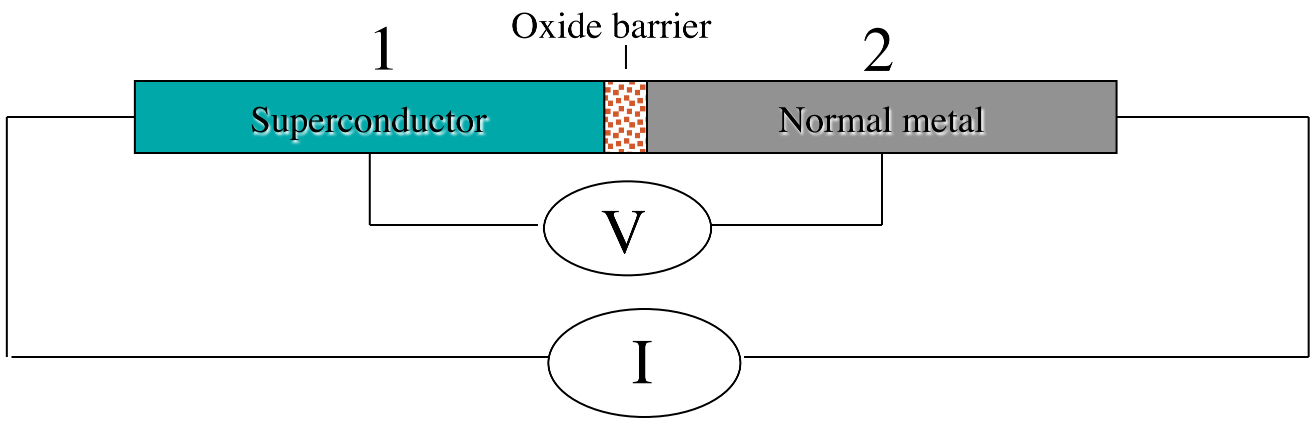


Energy: Δ $2\mu_B B_{\parallel}$

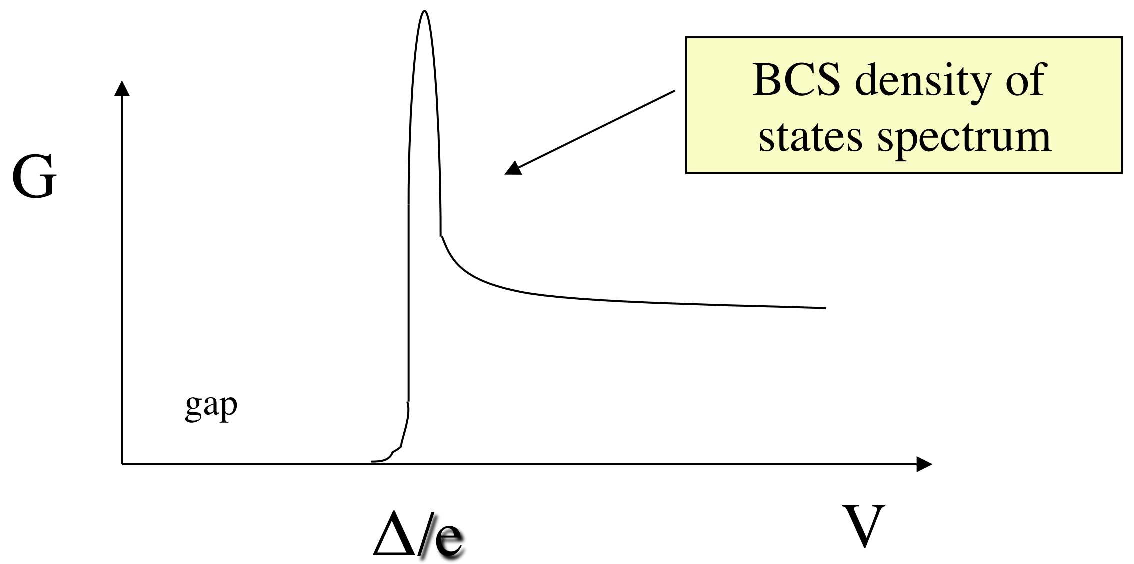
S-P Transition: $B_{c\parallel} \approx \dfrac{\Delta}{\sqrt{2}\mu_B} \sim 1.8$ T/K $(g_L = 2)$

(Spin-Paramagnetic)

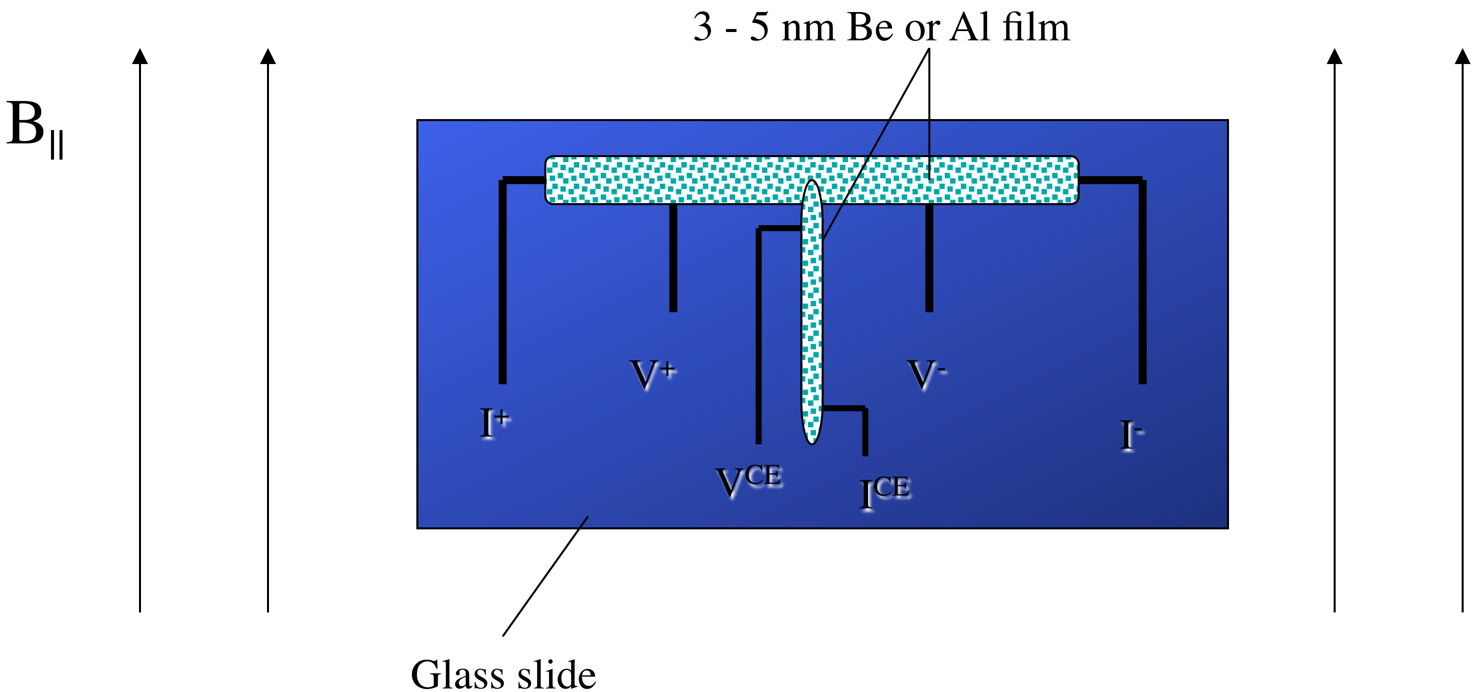
Electron Tunneling and the DOS



Tunneling Conductance: G ~ $N_1 N_2$ (kT << eV, Δ)



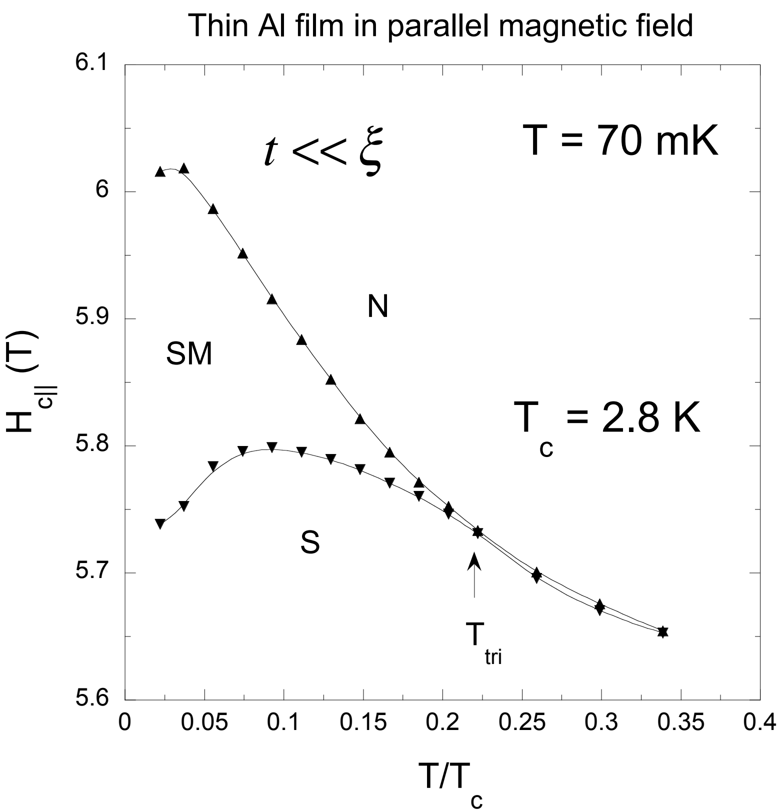
Sample Geometry

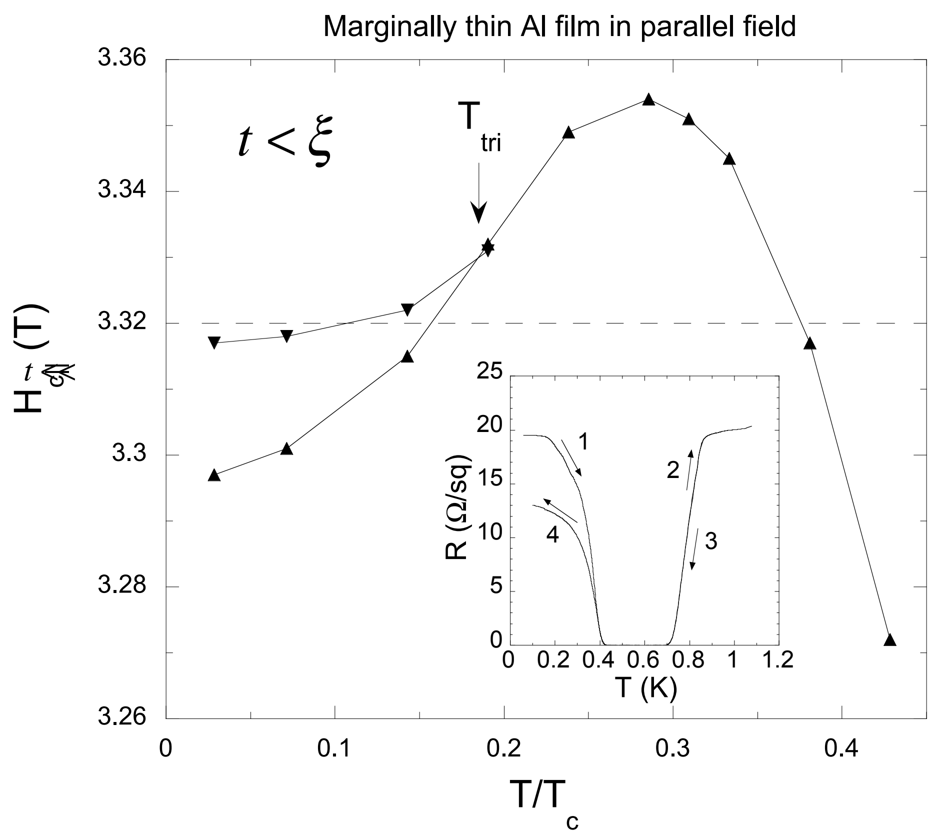


Al:

T_c = 1.1 K (bulk)
T_c = 2.7 K (quenched film)
barrier type oxide Al_2O_3
g-factor ~ 1.8*; $E_z \sim 1.8\mu_B B_{||}$

S-P Phase Diagram of Pristine Al Films

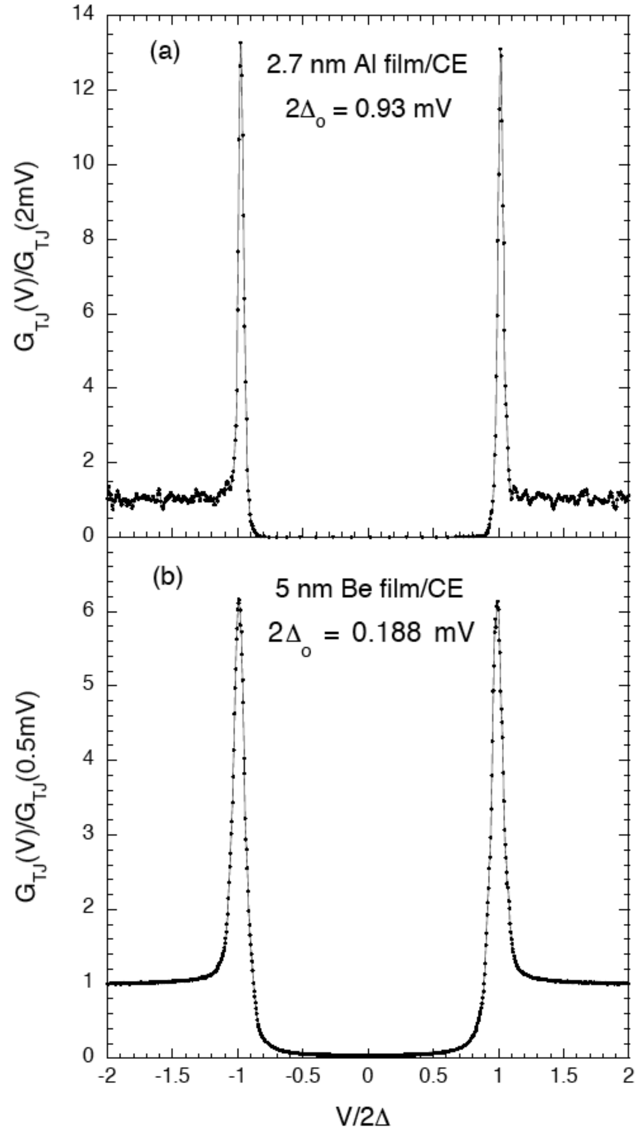




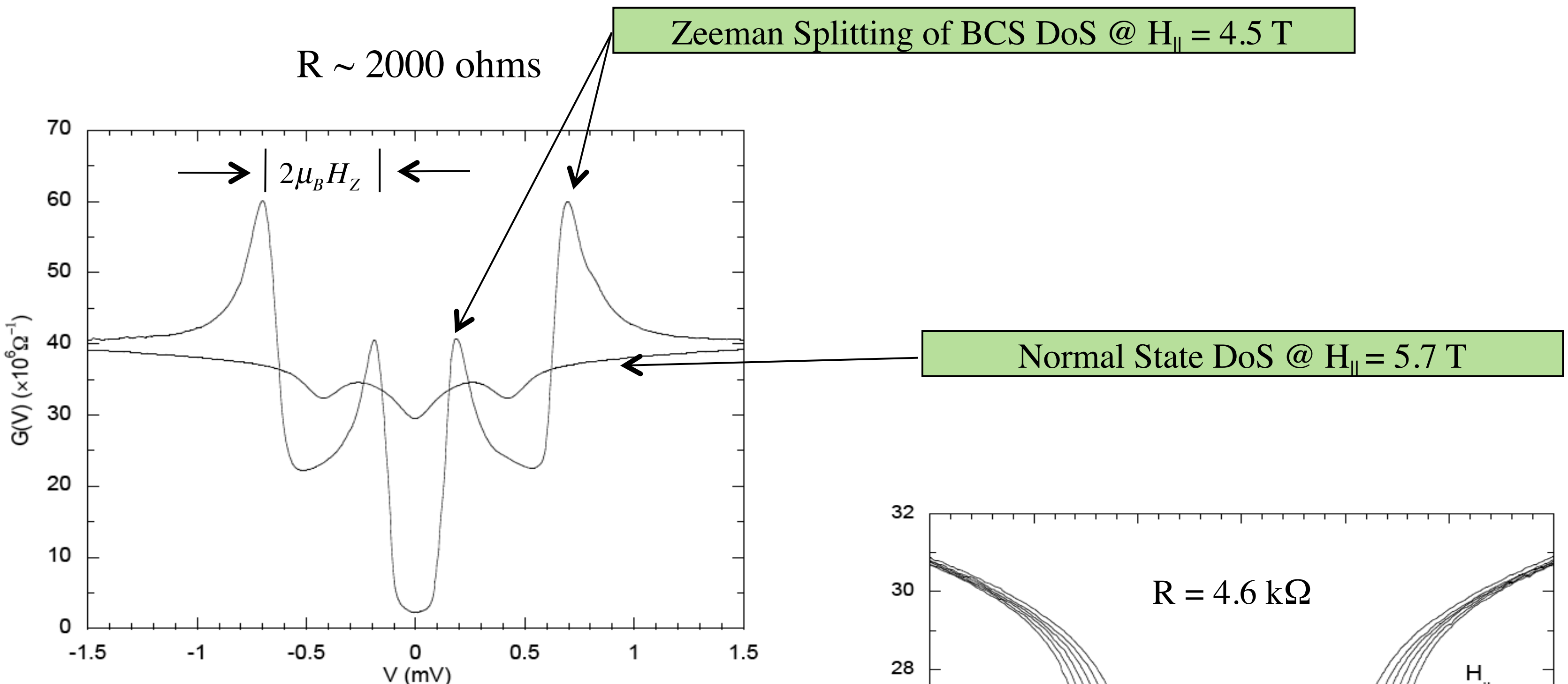
S: superconducting
N: normal state
SM: state memory

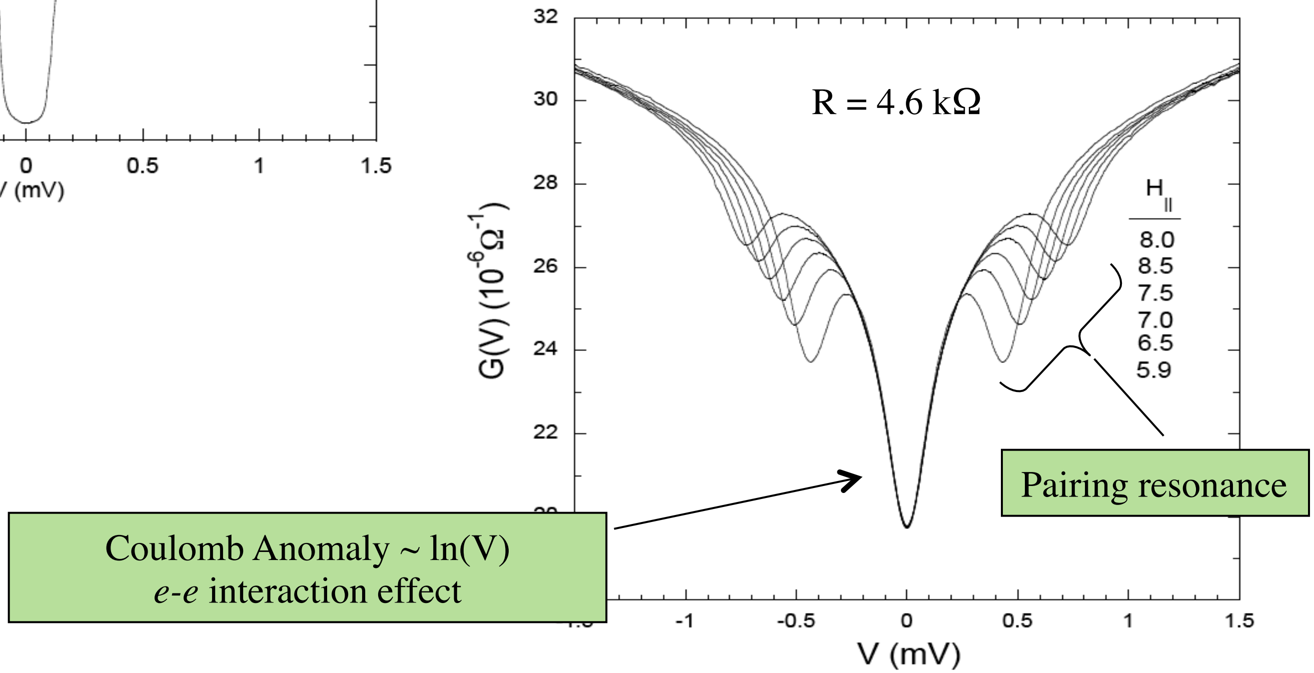
S-I-S Tunneling

T ~ 100 mK

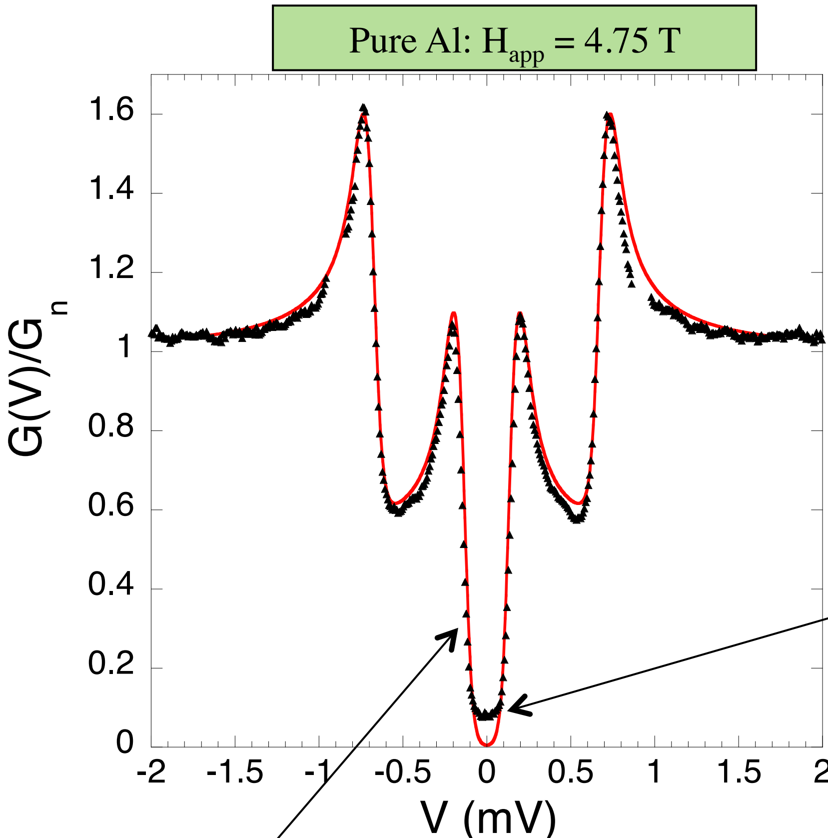


Tunneling Probe of the Zeeman Field





Microscopic Nature of the Zeeman-limited Transition



Tunneling density of states of a 2.5 nm thick Al film in a parallel magnetic at T = 80 mK.

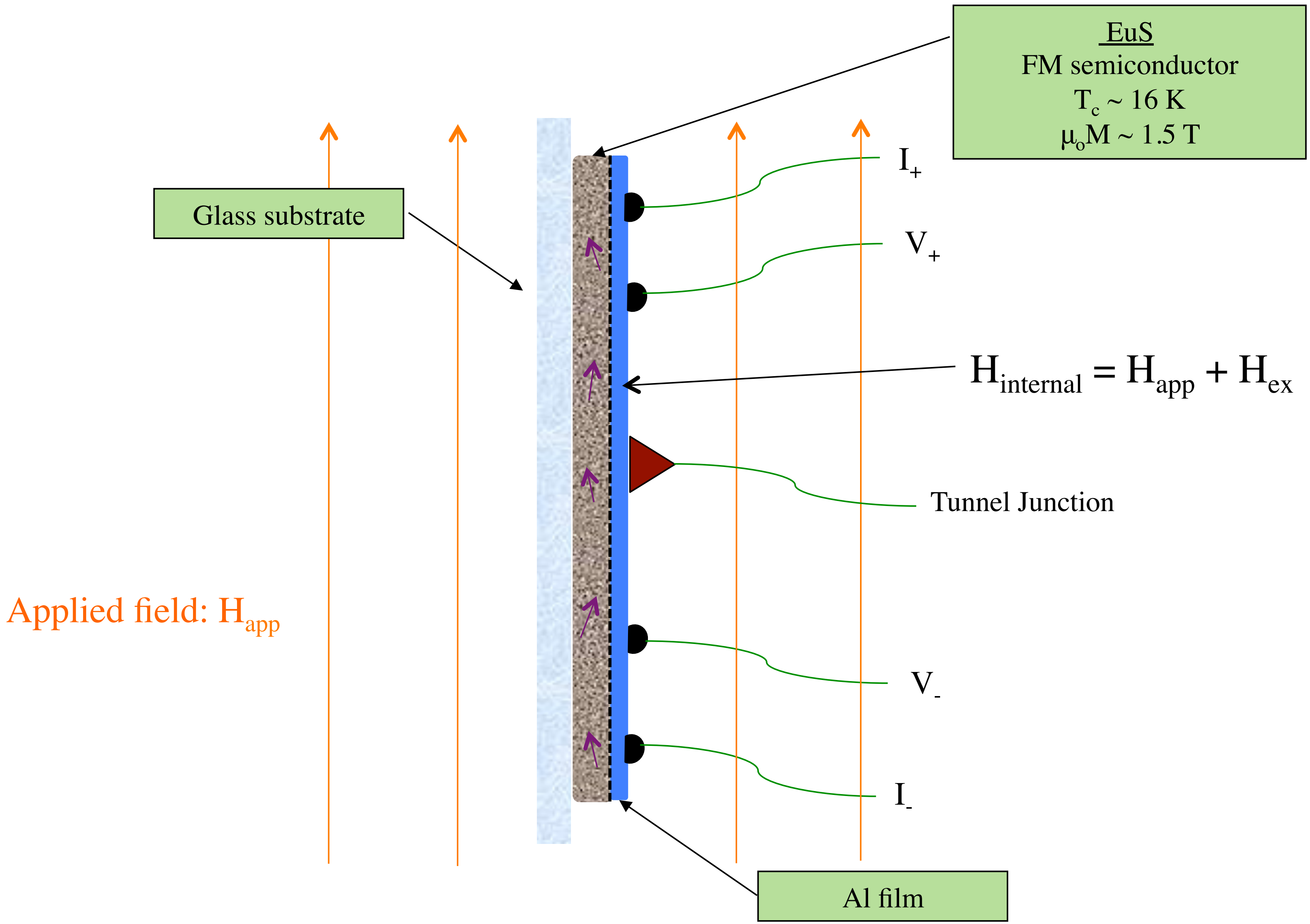
Note excess states at V = 0!

The origin of these excess states has been a mystery for more than 30 years.

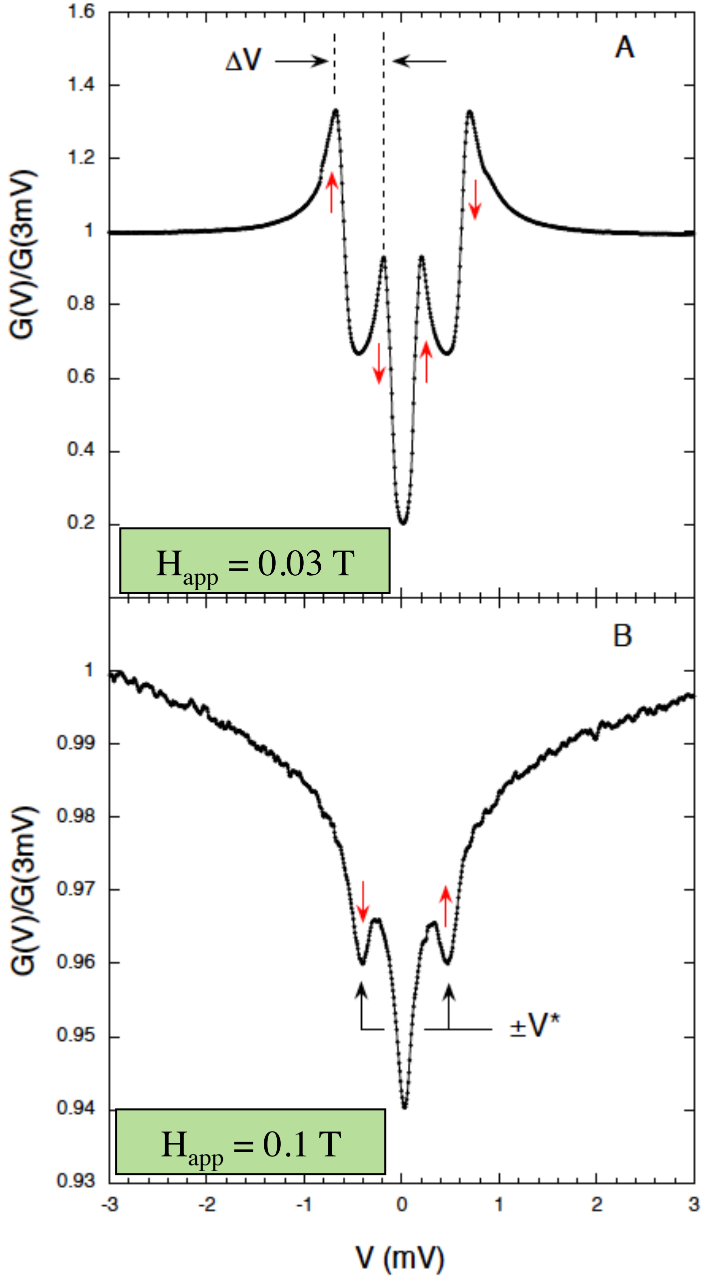
1. Misalignment of ~1 deg
2. Leaky tunnel junction
3. Sample irregularities
4. Instrumentation issues

Red Curve: homogeneous BCS DoS

Inducing Exchange Fields in Al Films



Direct Spectroscopic Evidence of the Exchange Field in Al Films on EuS



$$\Delta V = E_z / e$$

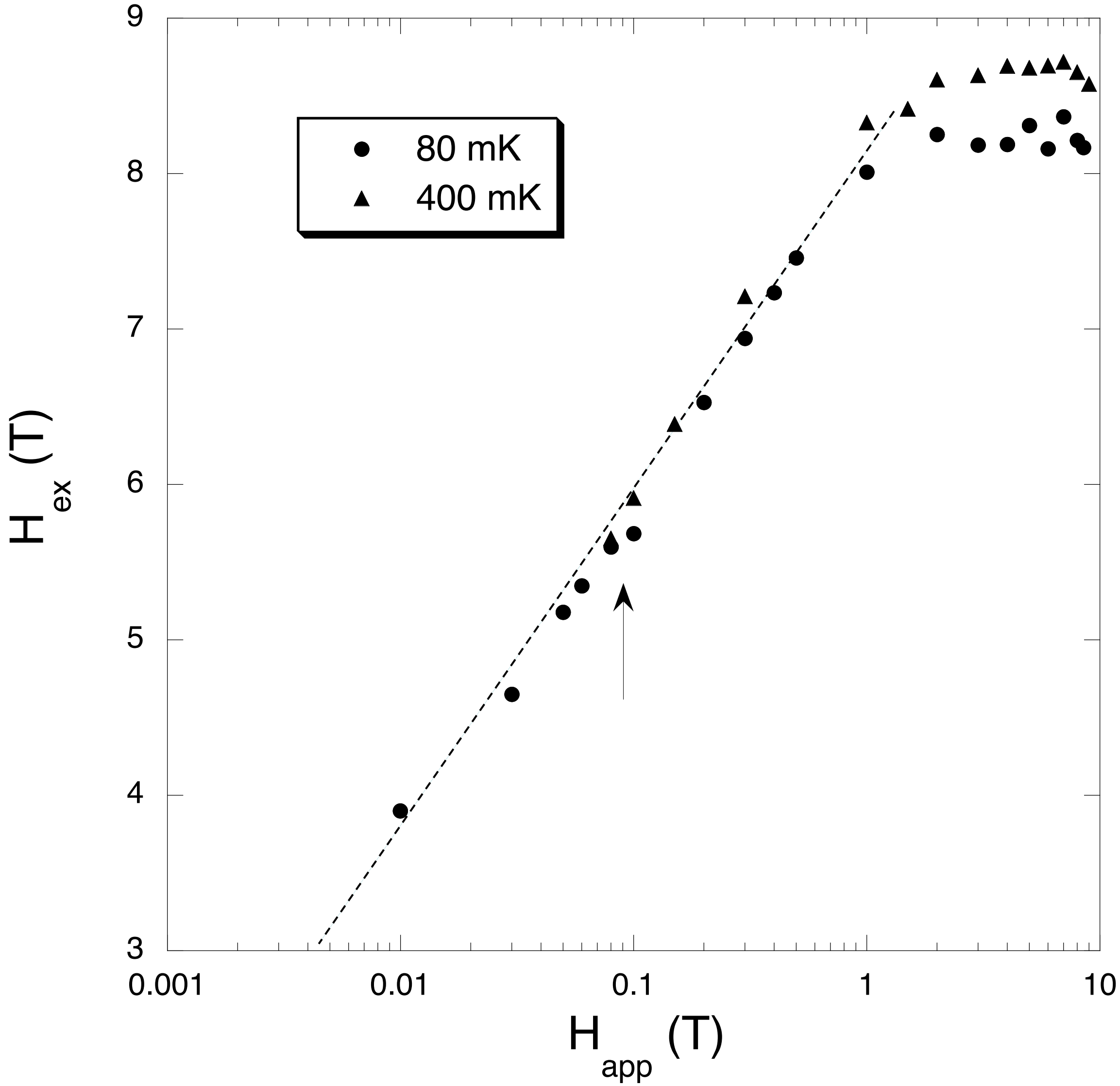
$$E_Z = 2\mu_B H_Z$$

H_{ex} ~ 4 T!

$$eV^* = \frac{1}{2}\left(E_z + \sqrt{E_z^2 - \Delta_o^2}\right)$$

Aleiner and Altshuler, PRL **79**, 4242 (1997)

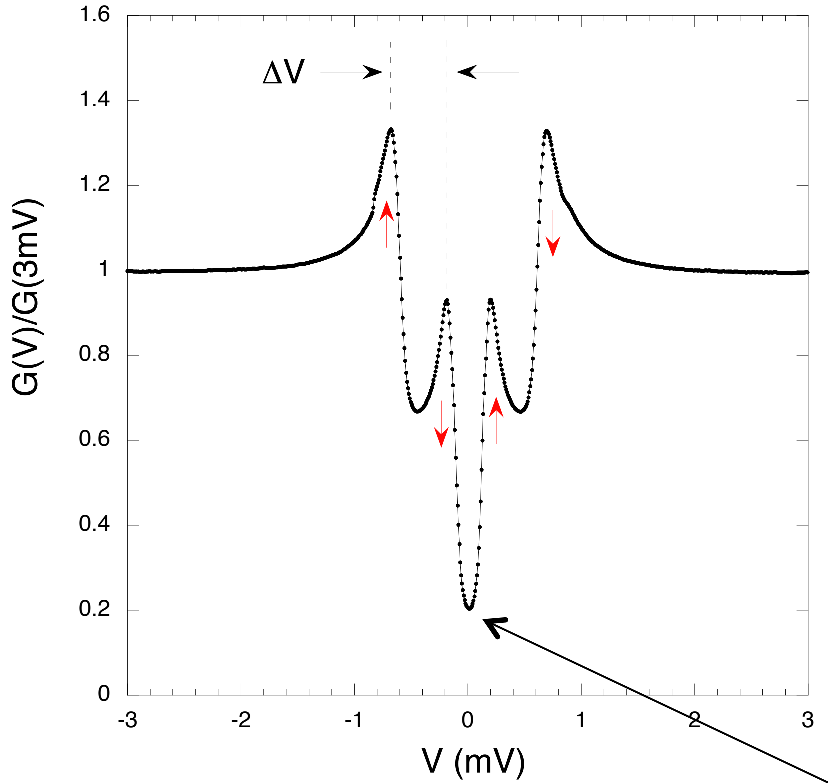
Y.M. Xiong, P.W. Adams, and G. Catelani, PRL ***103,*** 067009 (2009)



9
8
7
6
5
4
3
0.001
0.01
0.1
1
10
80 mK
400 mK
H_ex (T)
H_app (T)

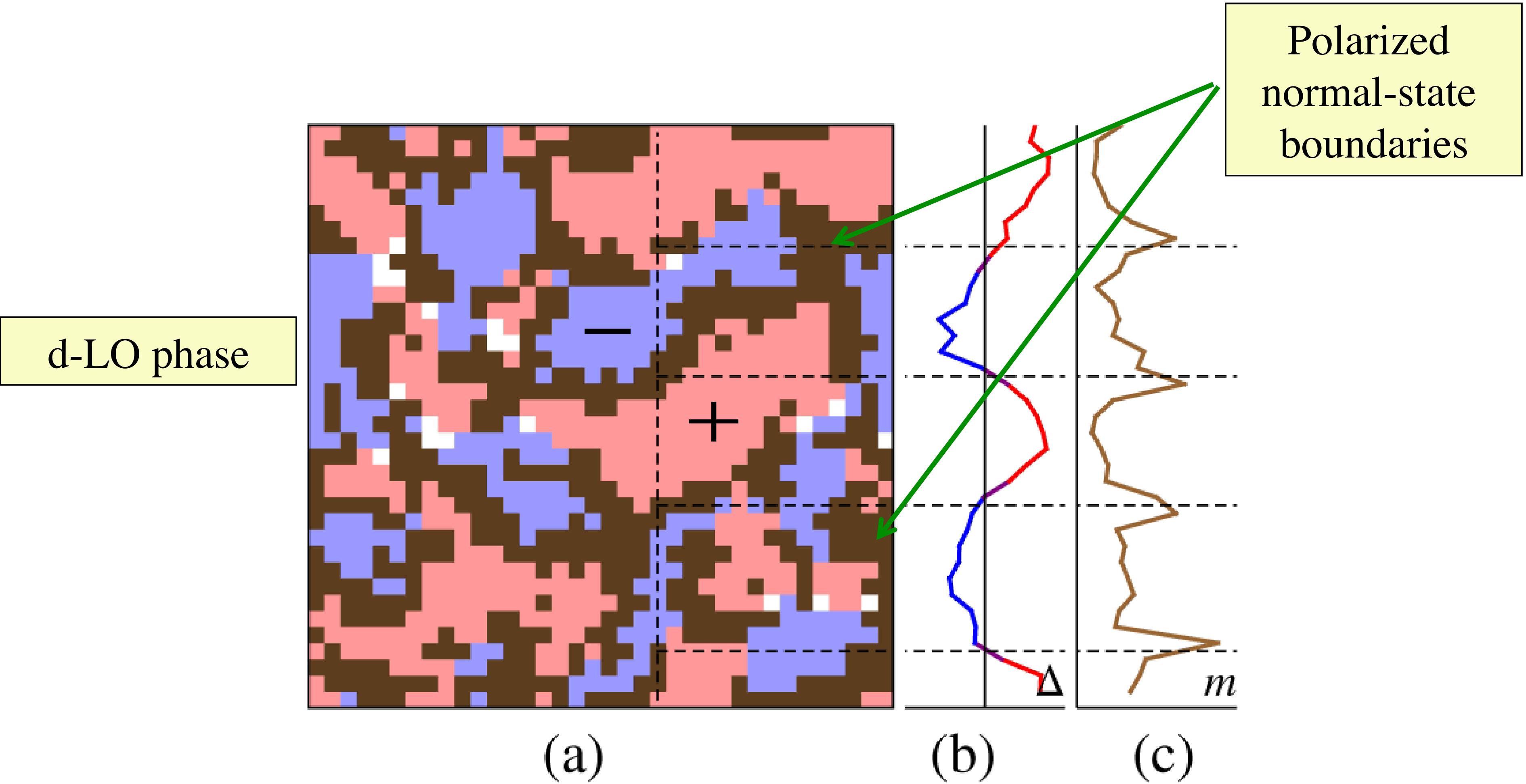
Even with a pure Zeeman interaction, the excess states remain.

Al/EuS: H_{app} = 0.03 T; H_{ex} = 4.3 T



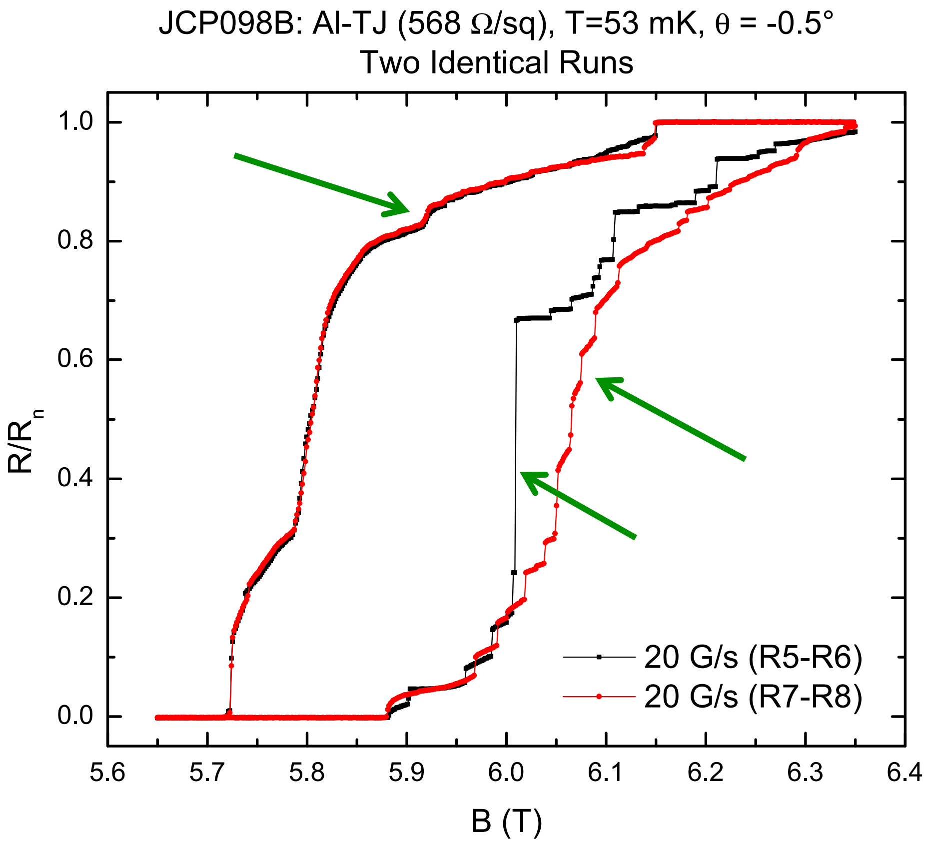
Again, excess states at V = 0!

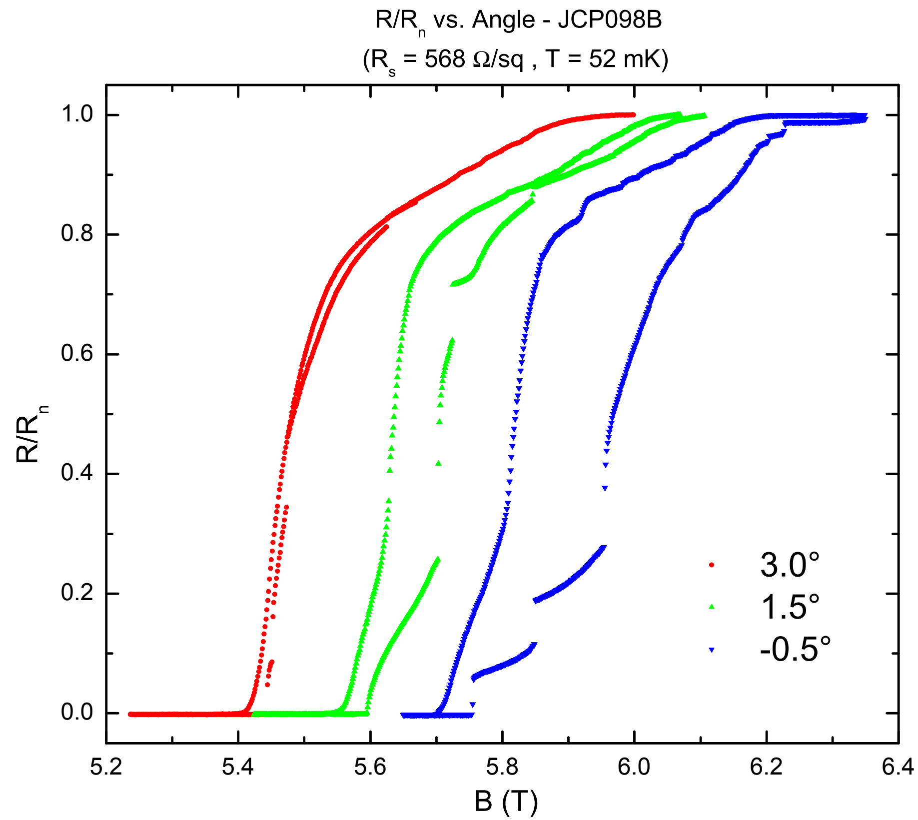
FFLO Modulation of the Order Parameter Near $H_{c||}$



Y.L. Loh, N. Trivedi, Y.M. Xiong, P.W. Adams and G. Catelani, PRL 107, 067003 (2011)

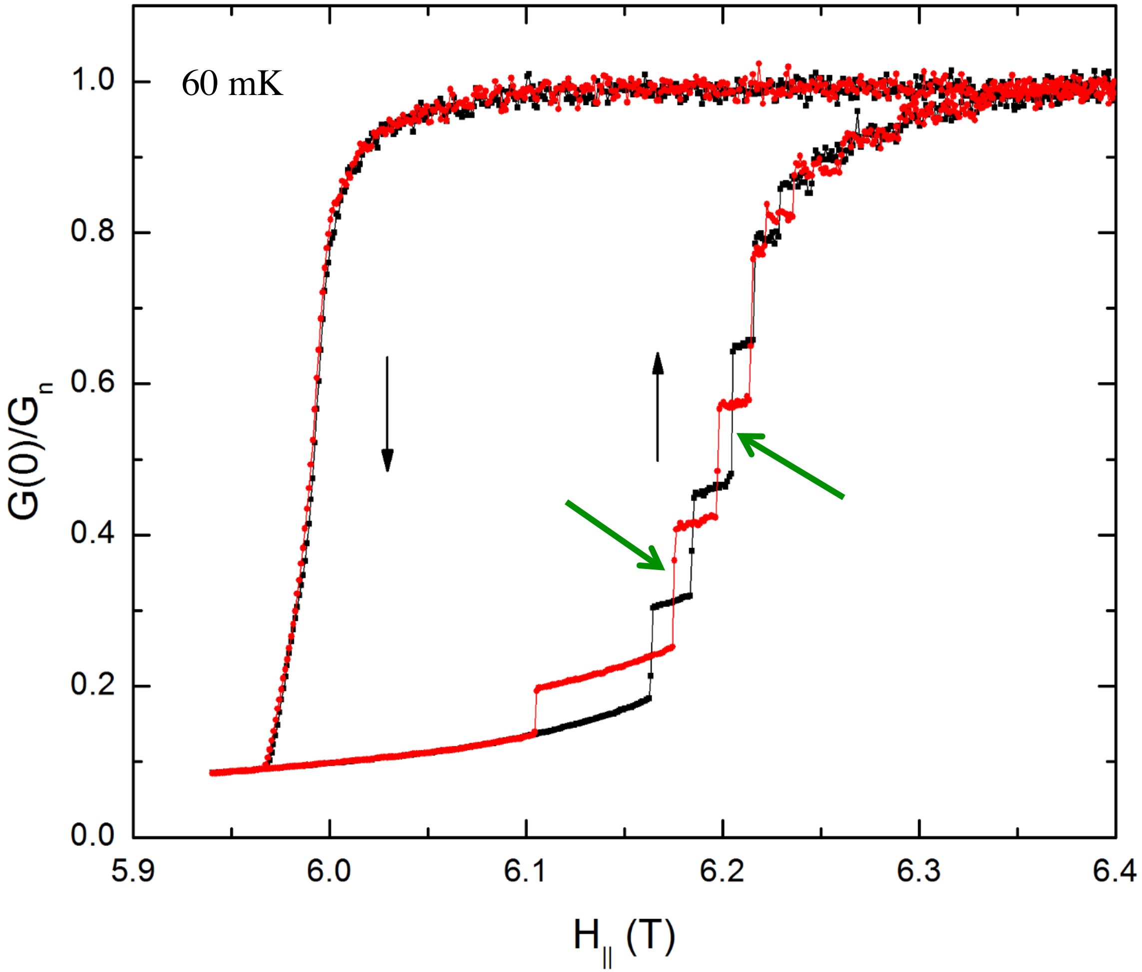
Avalanches and Slow Relaxation Near $H_{c||}$



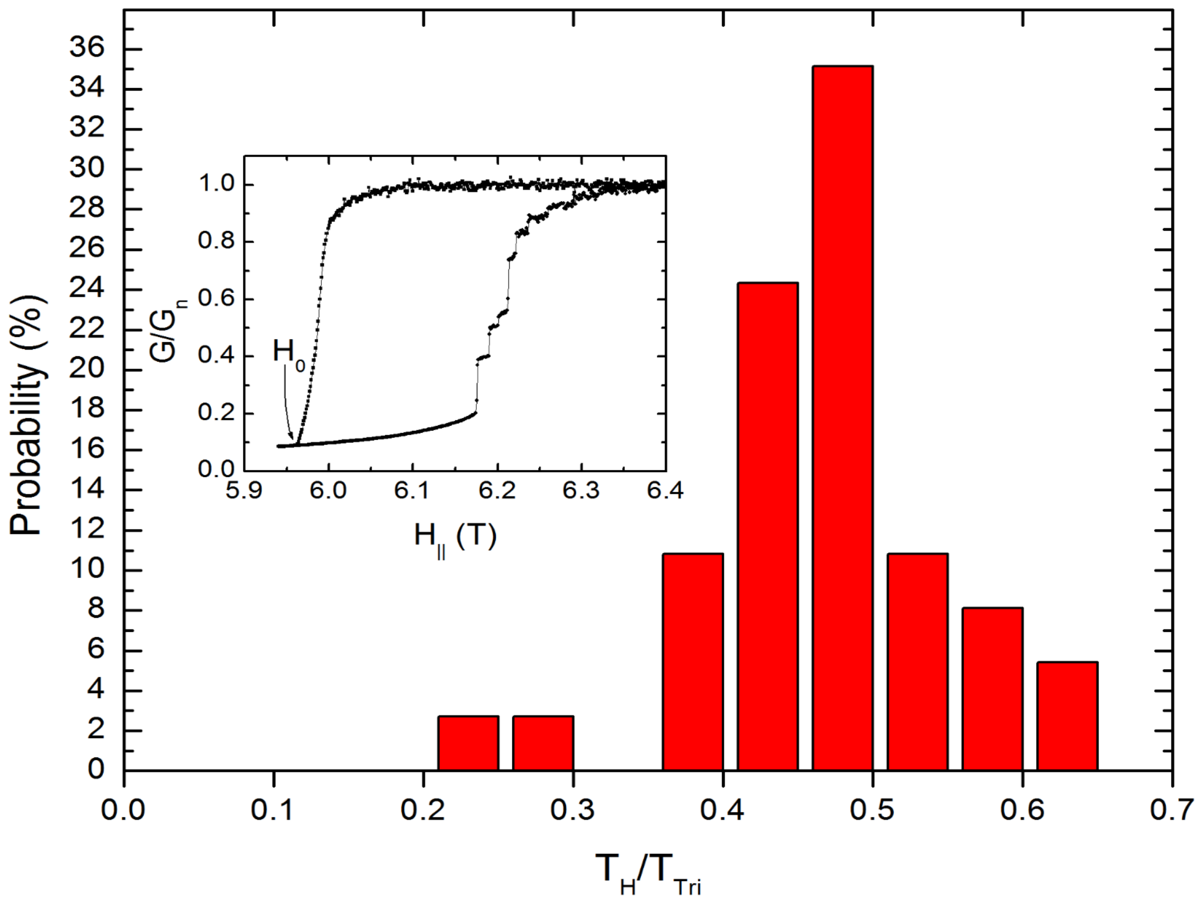


Avalanches in the DOS

Al film: t = 2.5 nm, R = 540 Ohm/sq

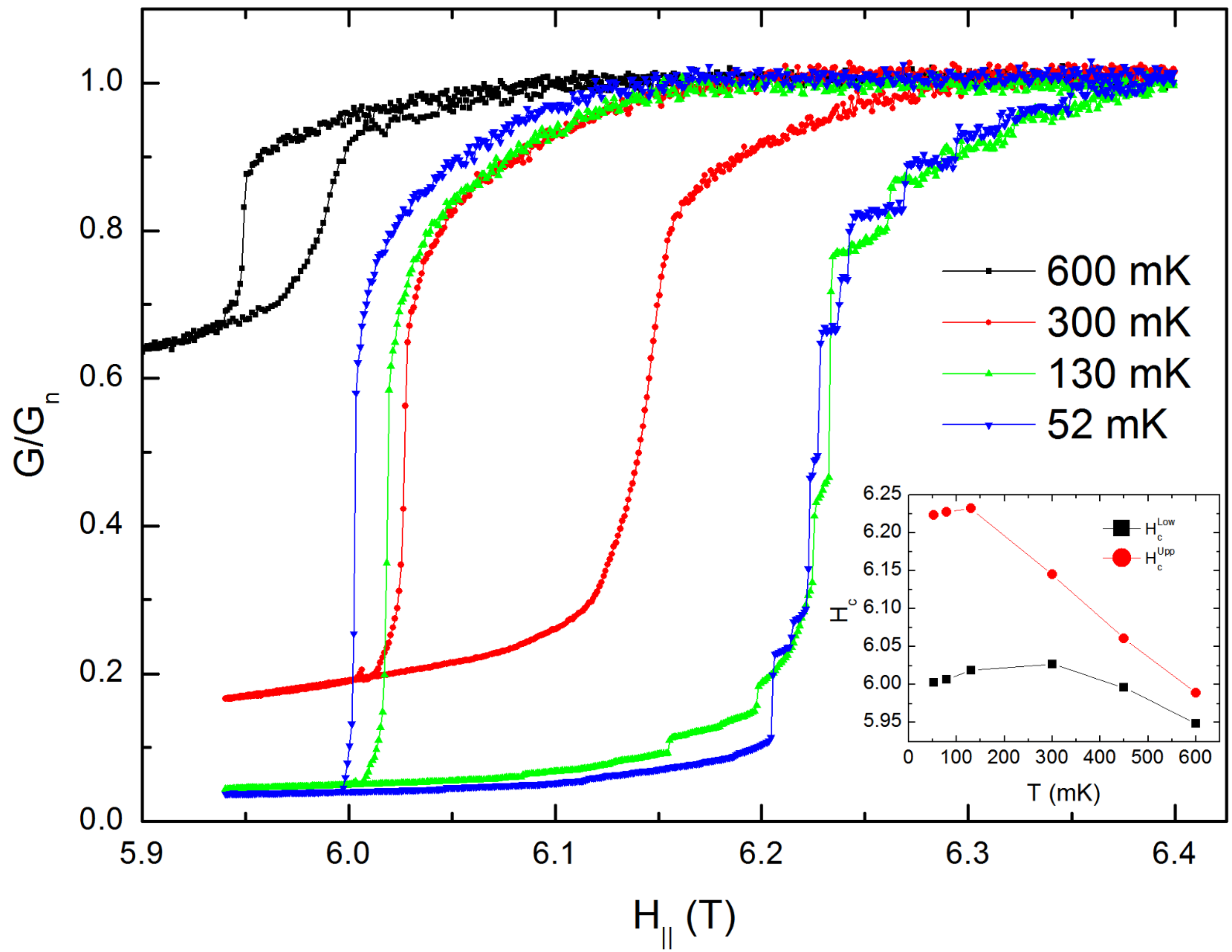


Statistics of the Avalanches



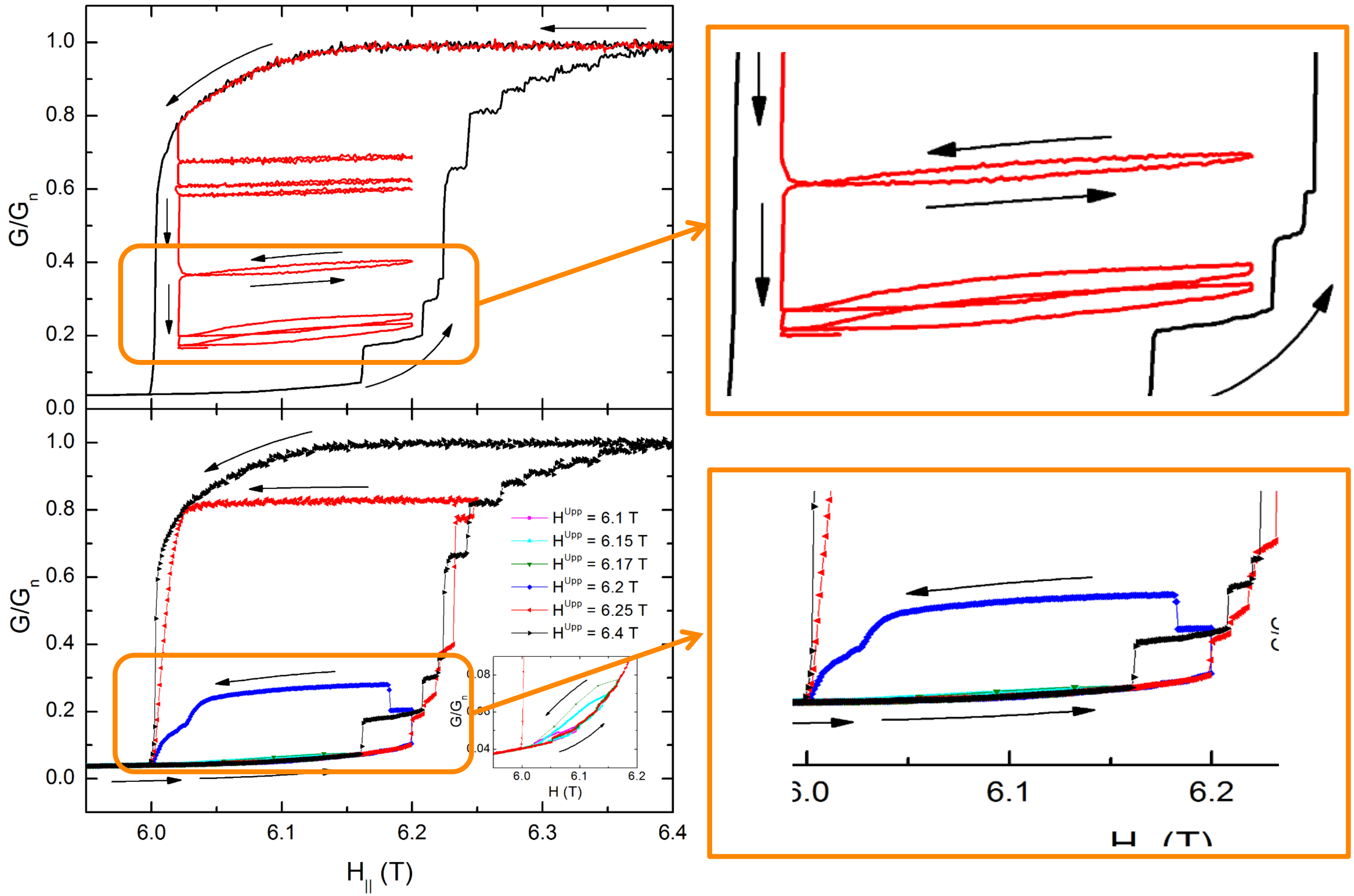
$$T_{\mathrm{Tri}} = 750\ \mathrm{mK}$$

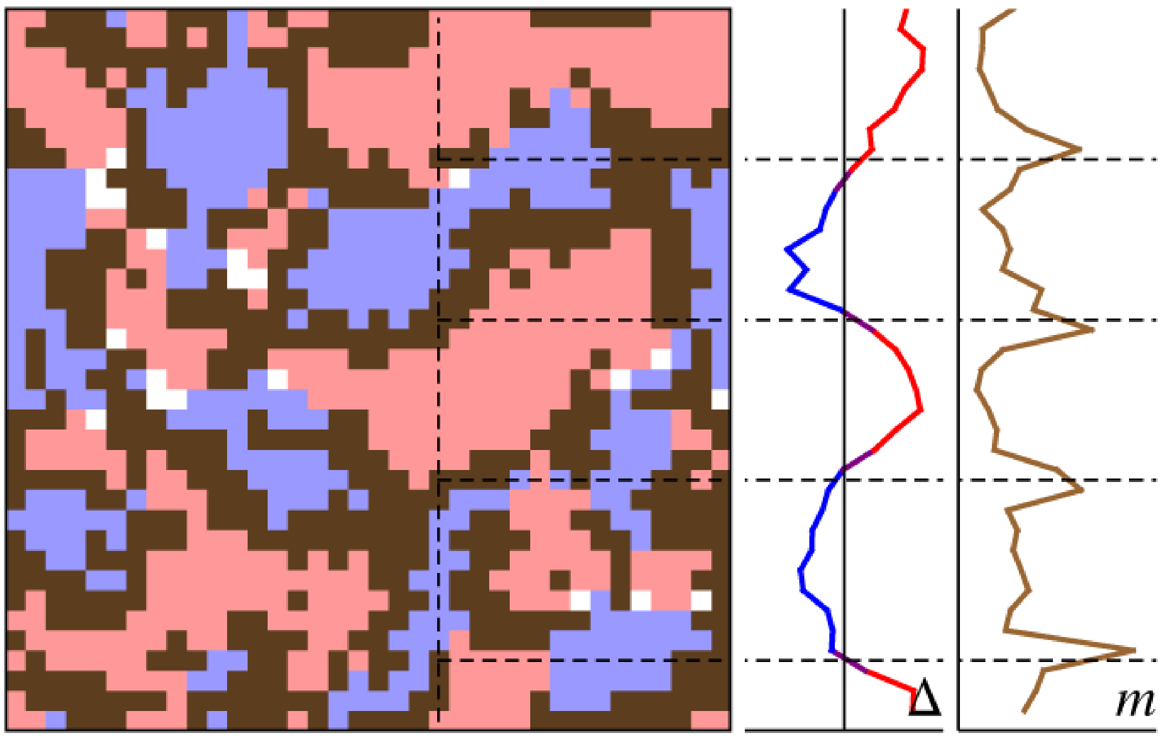
$$T_H = 2\mu_B(H - H_0)/k_B$$



1.0
0.8
0.6
0.4
0.2
0.0
G/G_n
5.9
6.0
6.1
6.2
6.3
6.4
H_|| (T)
600 mK
300 mK
130 mK
52 mK
6.25
6.20
6.15
6.10
6.05
6.00
5.95
H_c
0
100
200
300
400
500
600
T (mK)
H_c^Low
H_c^Upp

Minor Hysteresis Loops





(a) (b) (c)

Summary

- We believe that the SC order parameter is non-trivial in the hysteretic region of the S-P transition.
- Excess states at the Fermi energy may be an indication of a disordered FFLO phase that emerges in a high Zeeman field.
- Tunneling data shows that the avalanche behavior is in the condensate itself.
- The asymmetry of the avalanches is unusual and cannot easily be explained.