DIP Workshop – Technion (19/03/2013)

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Topics studied in the framework of the DIP project

1. **Superconductivity in HTS nano wires**

   Student in charge: Daniel Levi
   Collaboration: Gad Koren

2. **Quantum effects in HTS/LTS nano-loops**

   Student in charge: Omri Sharon
   Collaboration: Elke Scheer
   Ivan Bozovic'

Magnetoresistance anomalies in ultra-thin granular $YBa_2Cu_3O_{7-\delta}$ wires

Why high-T_c SC?
Why granular?

D-wave pairing symmetry
Josephson π-junctions

Why ultra-thin?
Why nano?

Confinement
Minimizing the available conduction channels

Summary of results

1. Magnetoresistance oscillations
2. Negative magnetoresistance at low fields
3. Negative magnetoresistance slope in the Tesla regime

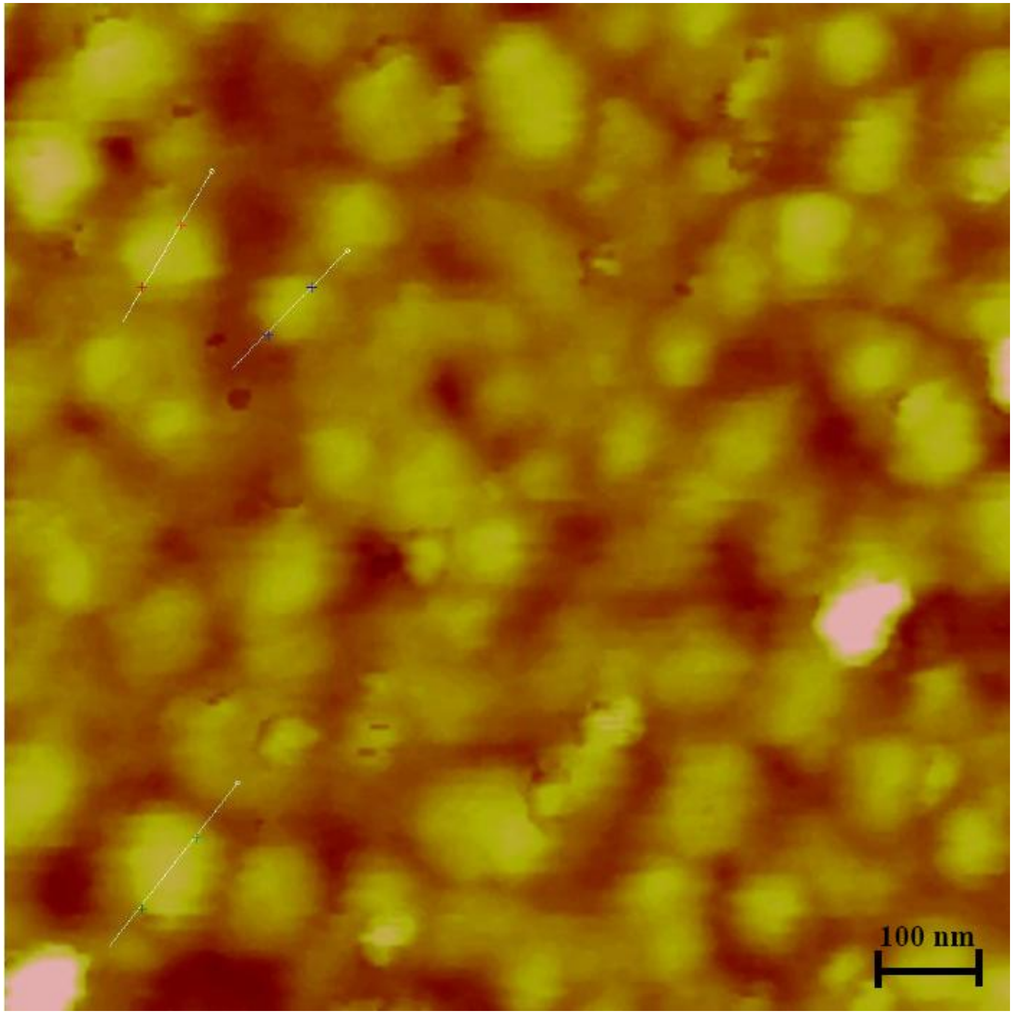
ALL PHENOMENA IN THE SAME SAMPLE

Origin

Granularity
Confinement
D-wave symmetry

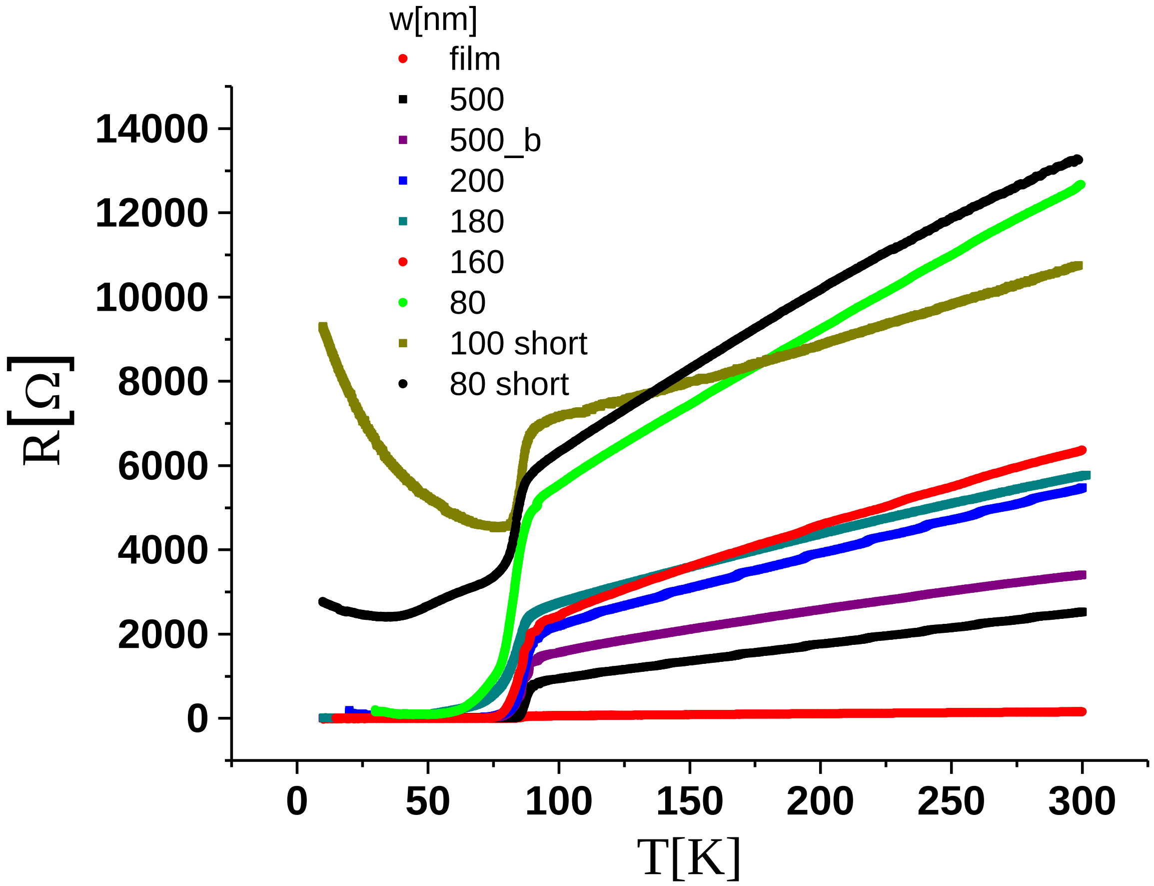
Laser ablated ~**10 nm** thick film

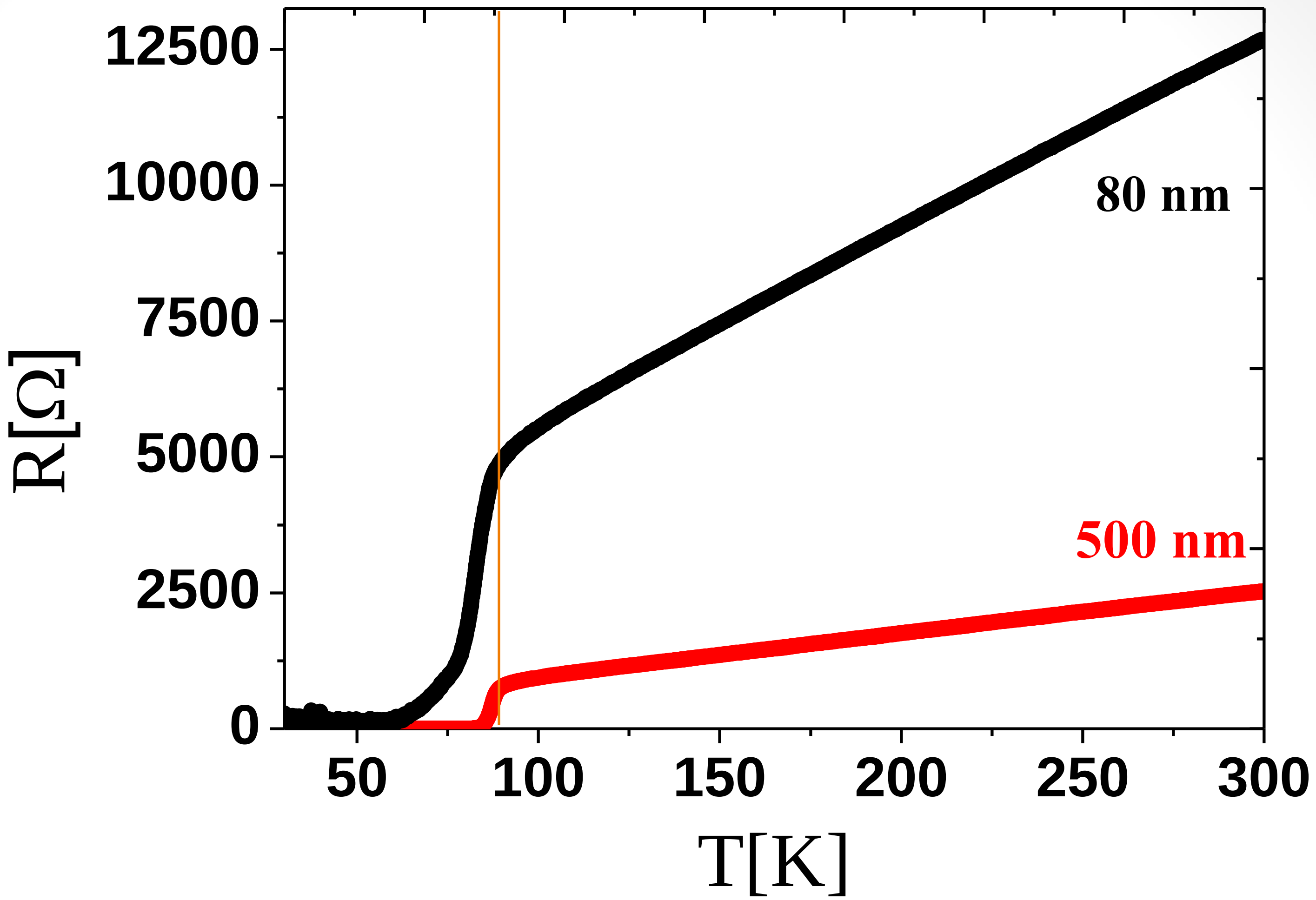
AFM image (1μm x 1μm)



Bridges (L = 400-700 nm, w= 80 – 500 nm) were patterned

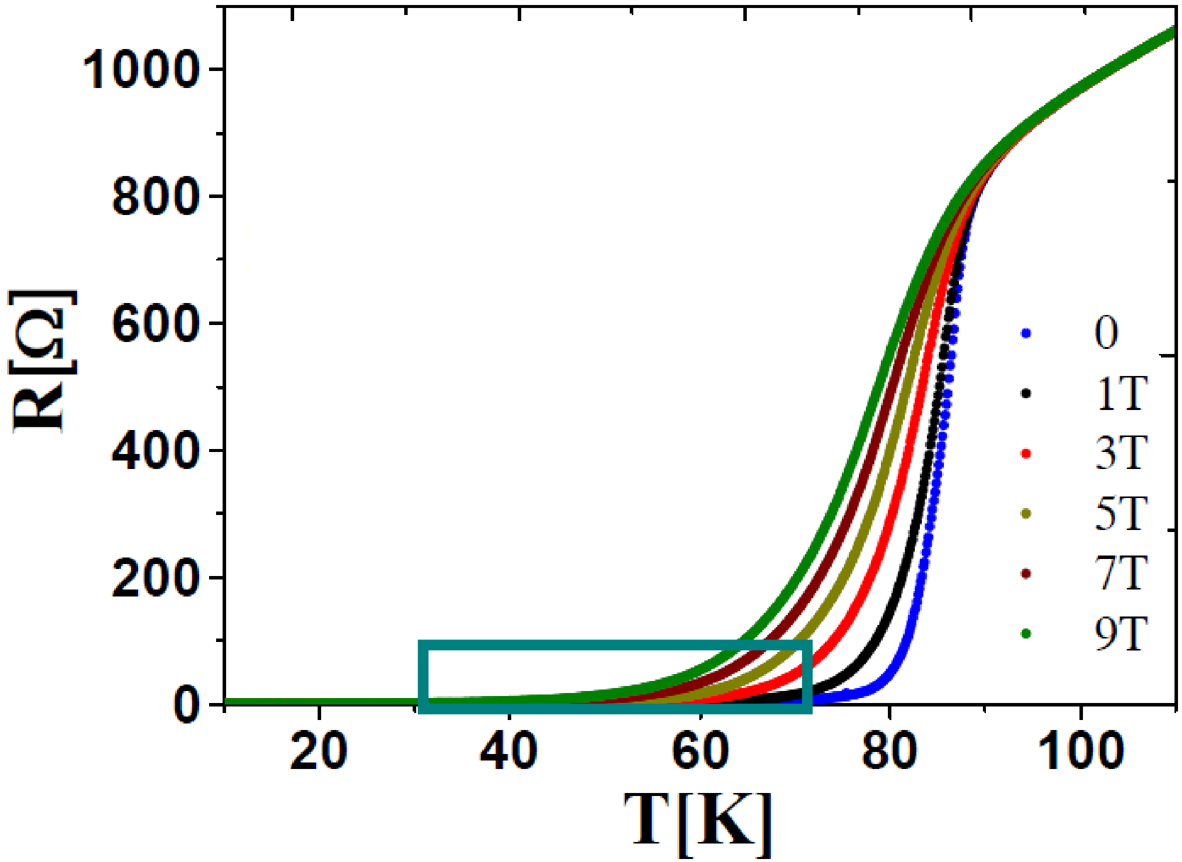
R *vs.* T --- YBCO wires





Similar $T_{onset} = T_c$ (~ 89 K) for all samples

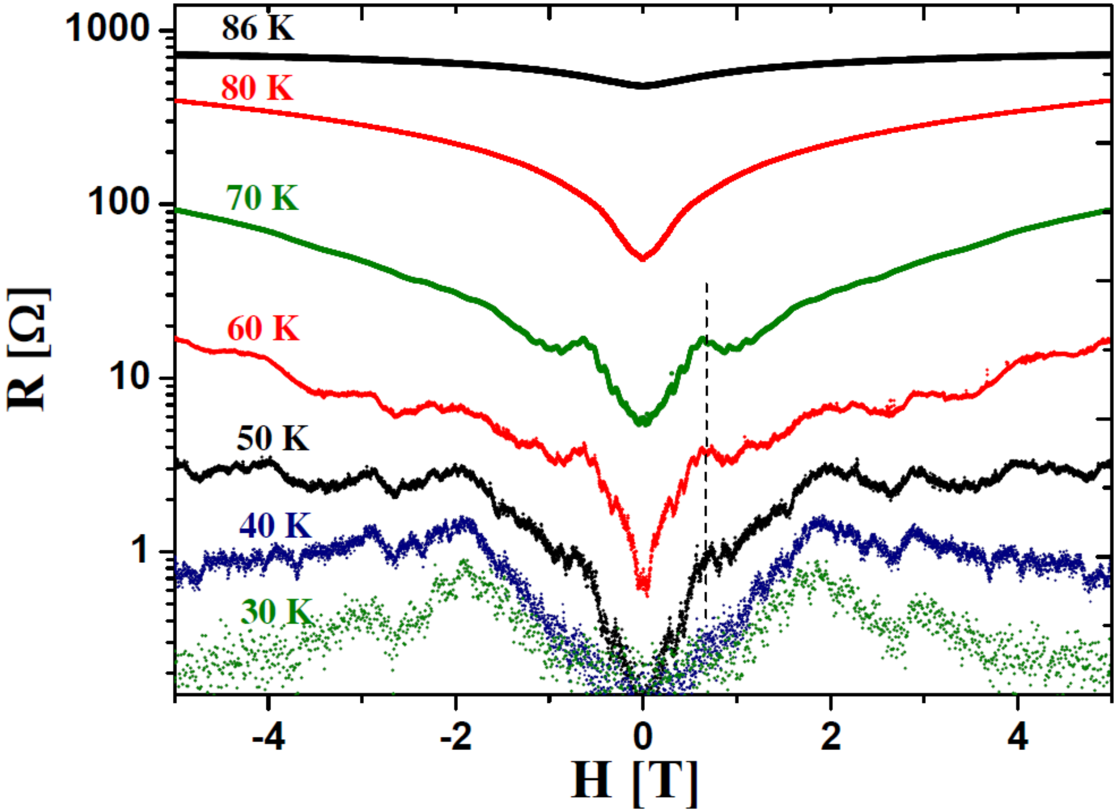
R *vs.* T (500 nm)



- Resistive transition broadening
- R(T) curves cut at low temperature

R *vs. H (500 nm)*

MAGNETORESISTANCE BACKGROUND



a). Strong dependence on H at low fields / Weak dependence at high fields

b). T-independent characteristic field [‘matching’ field]

c). **dR/dT < 0** at low T

Previous observations of dR/dH< 0

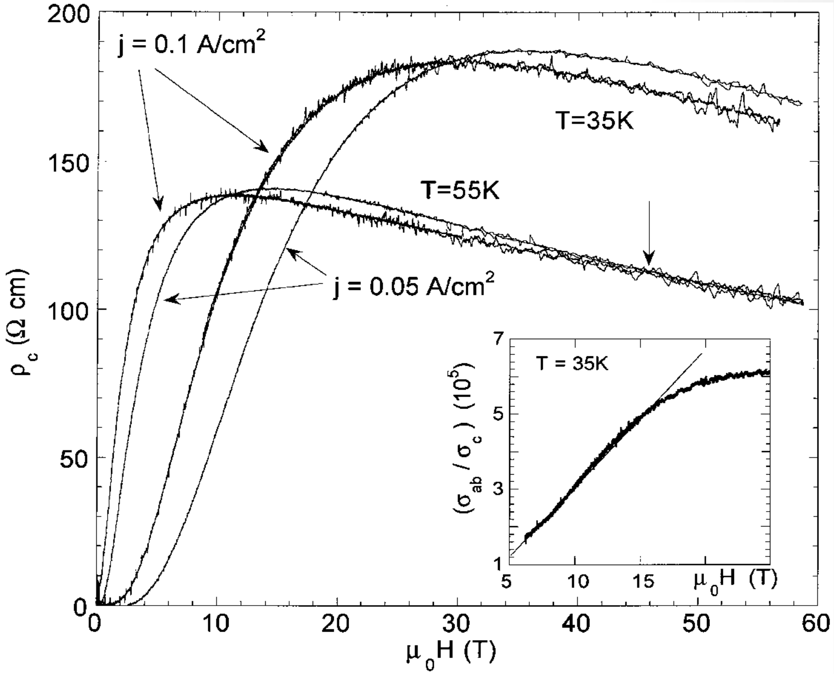
A. *c-axis conductivity in high-T_c crystals*

1/ **$Bi_2Sr_2CaCu_2O_{8+d}$**

Morozov, Krusin-Elbaum, Bulaevskii *et al.* PRL (2000).

2/ **$(LaSe)_{1.14}(NbSe_2)$**

Szabó *et al.* PRL (2001).



c-axis conductivity in a d-wave SC is a parallel, two-channel tunneling process between neighboring layers:

(a) Tunneling of **Cooper pairs**
(**σ ↓ H**).

(b) Tunneling of **quasiparticles** in gapless regions
(**σ ↑ H + c** due to increase in the QP DOS).

Previous observations of $dR/dH < 0$

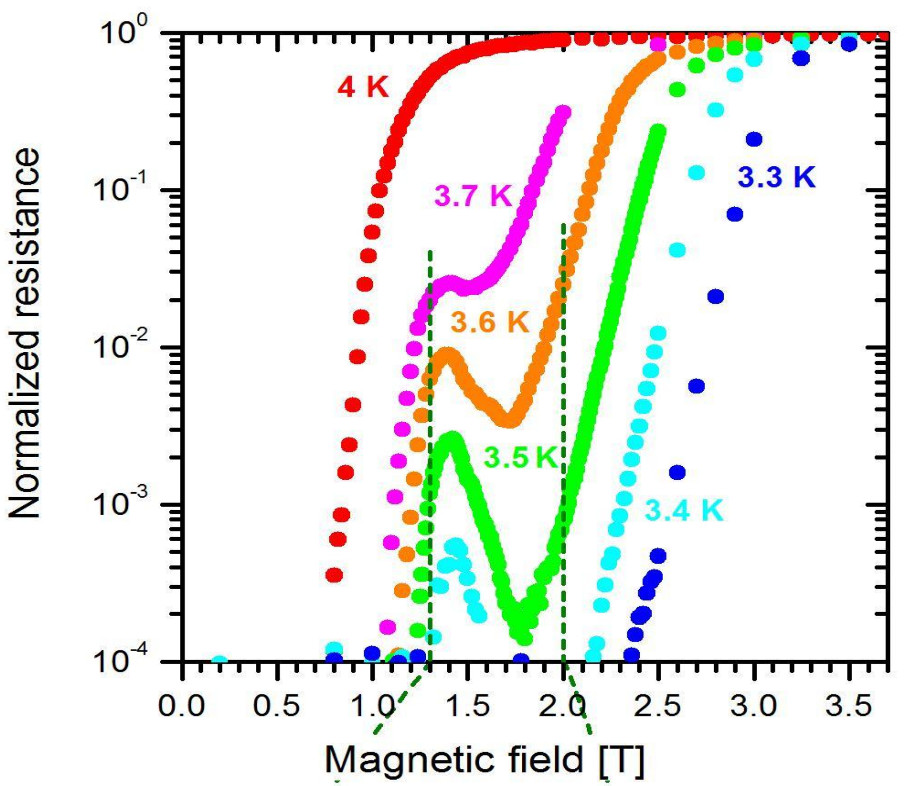
B. *Low-T_c SC -- **confined geometries***

3/ Amorphous **Pb** *ultrathin* films

(Gardner, Xiong, *et al.*, Nature Physics (2011))

4/ **Tungsten**-based *nanowire* and **TiN** networks

(Córdoba, Baturina, Vinokur *et al* Nature Commun (2013))



Surface SC is behind $dR/dT < 0$ (shunting the resistive part at the middle of the sample).

Magnetoresistance background is attributed to three different mechanisms

- **Low fields**: Thermally activated phase slips in weak links

  (‘soft’ component – responsible for low H behavior)

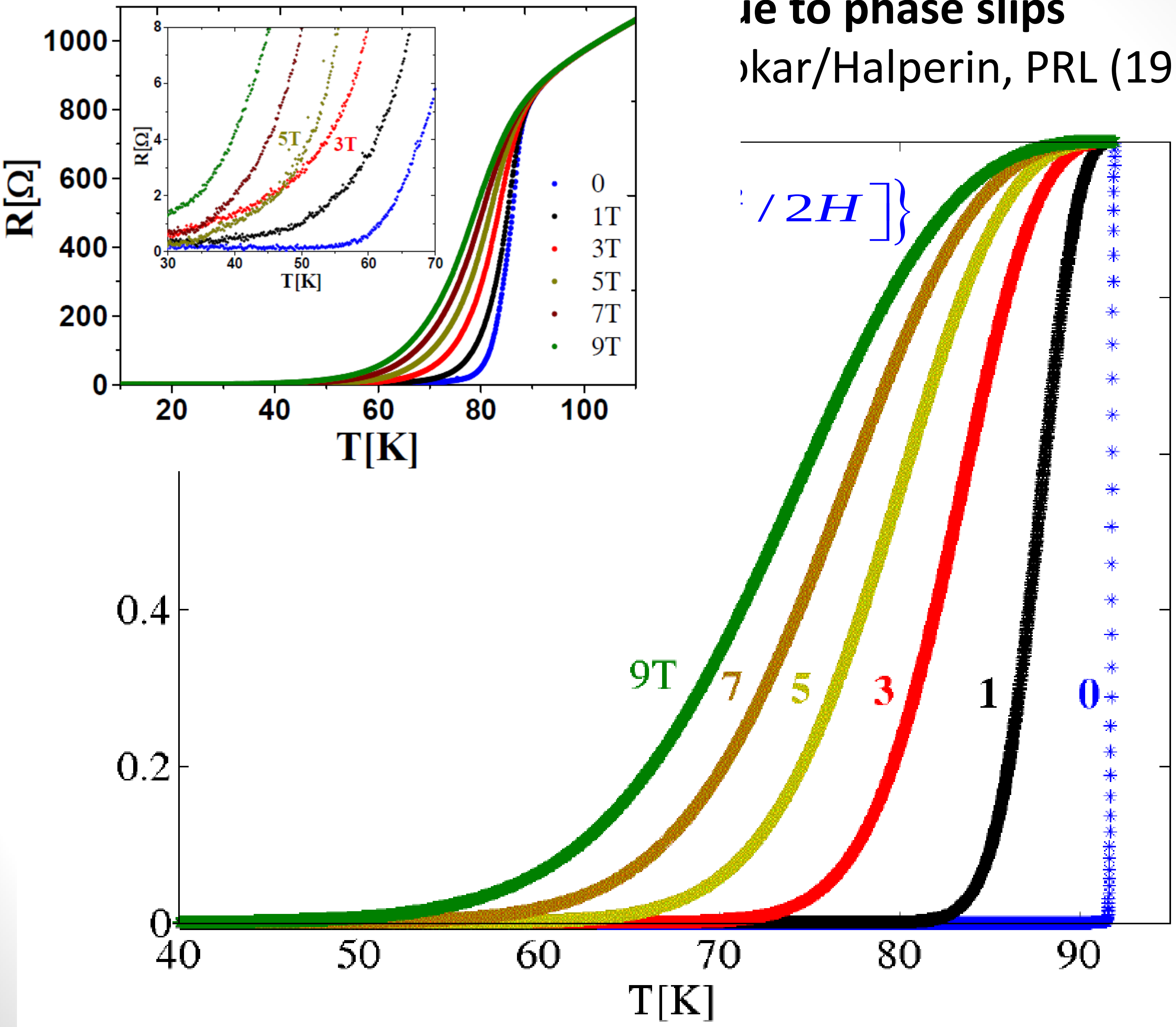
- **High fields**: Thermally activated phase slips in grains

  (‘hard’ component - responsible for high H behavior)

ue to phase slips

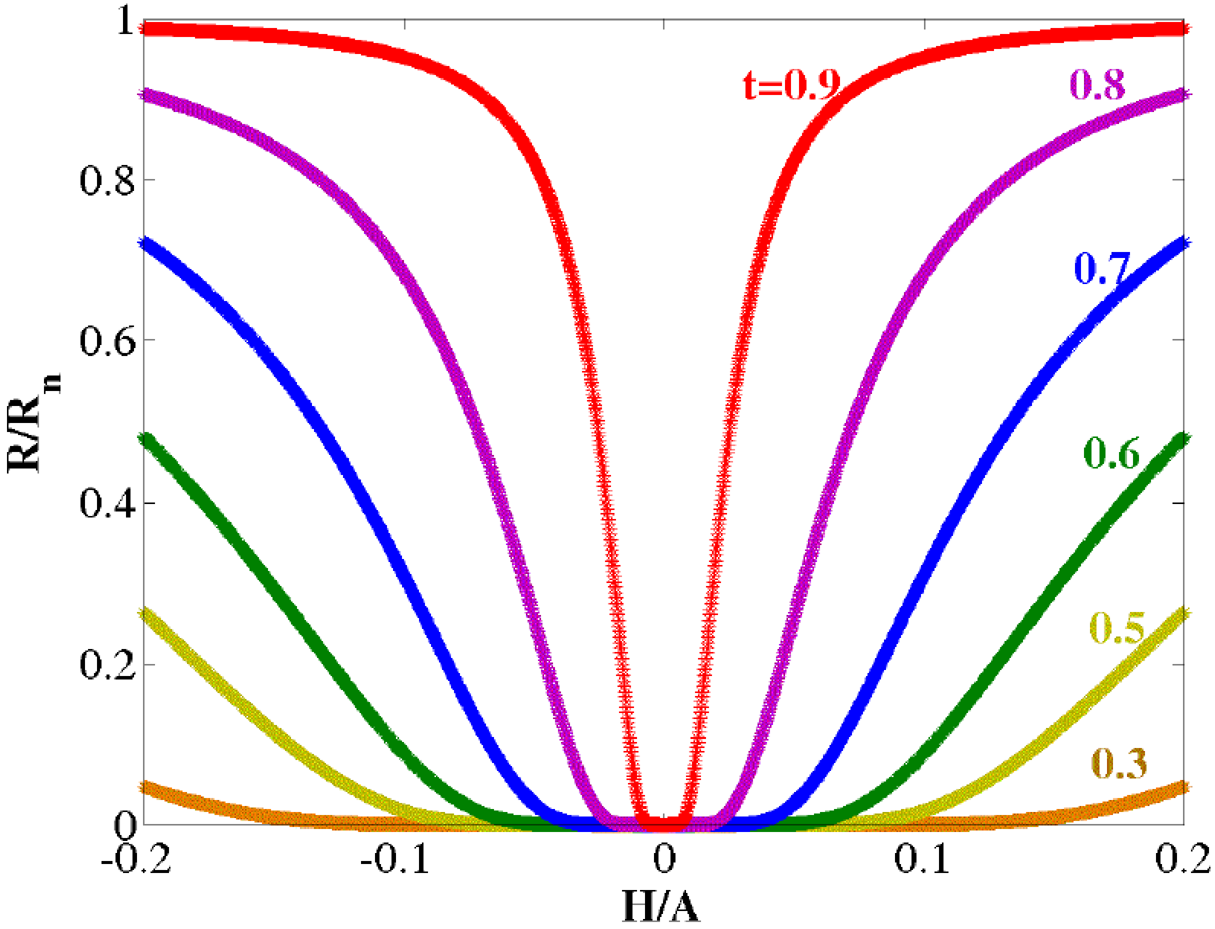
okar/Halperin, PRL (1969)

$/2H]\}$

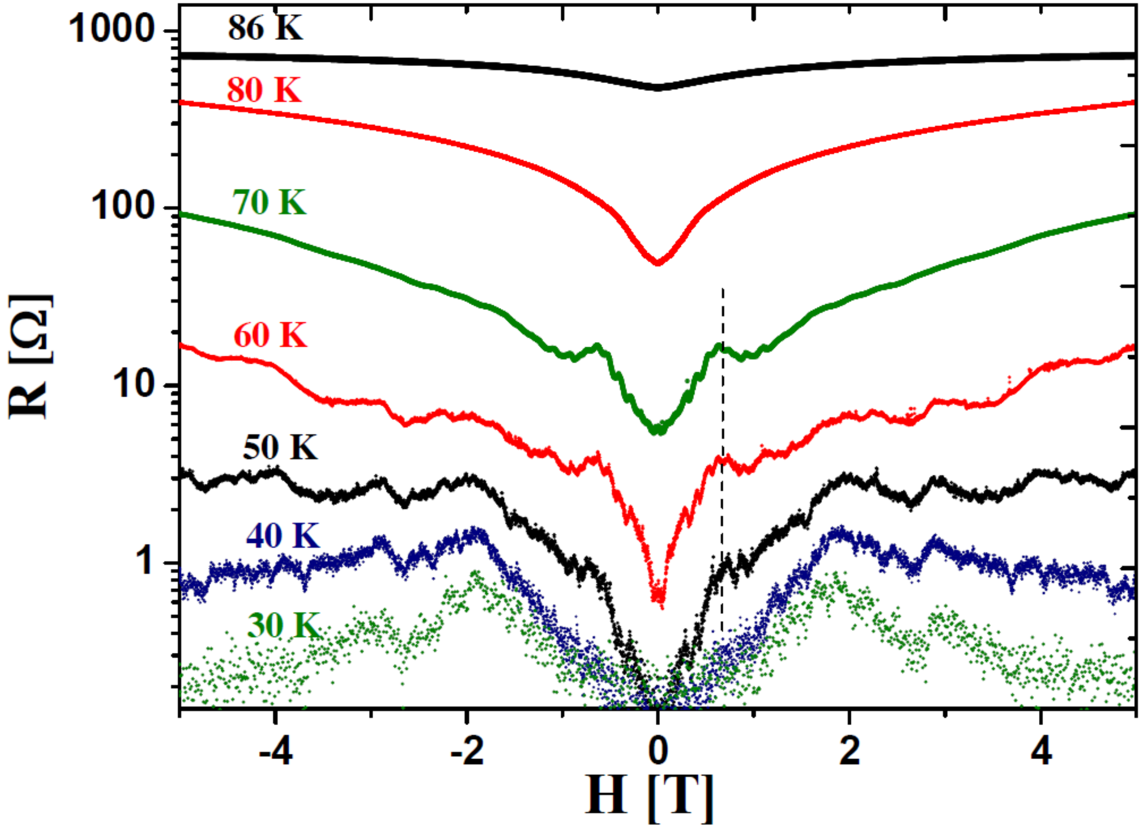


Magnetoresistance at different temperatures

(derived from Tinkham's model)



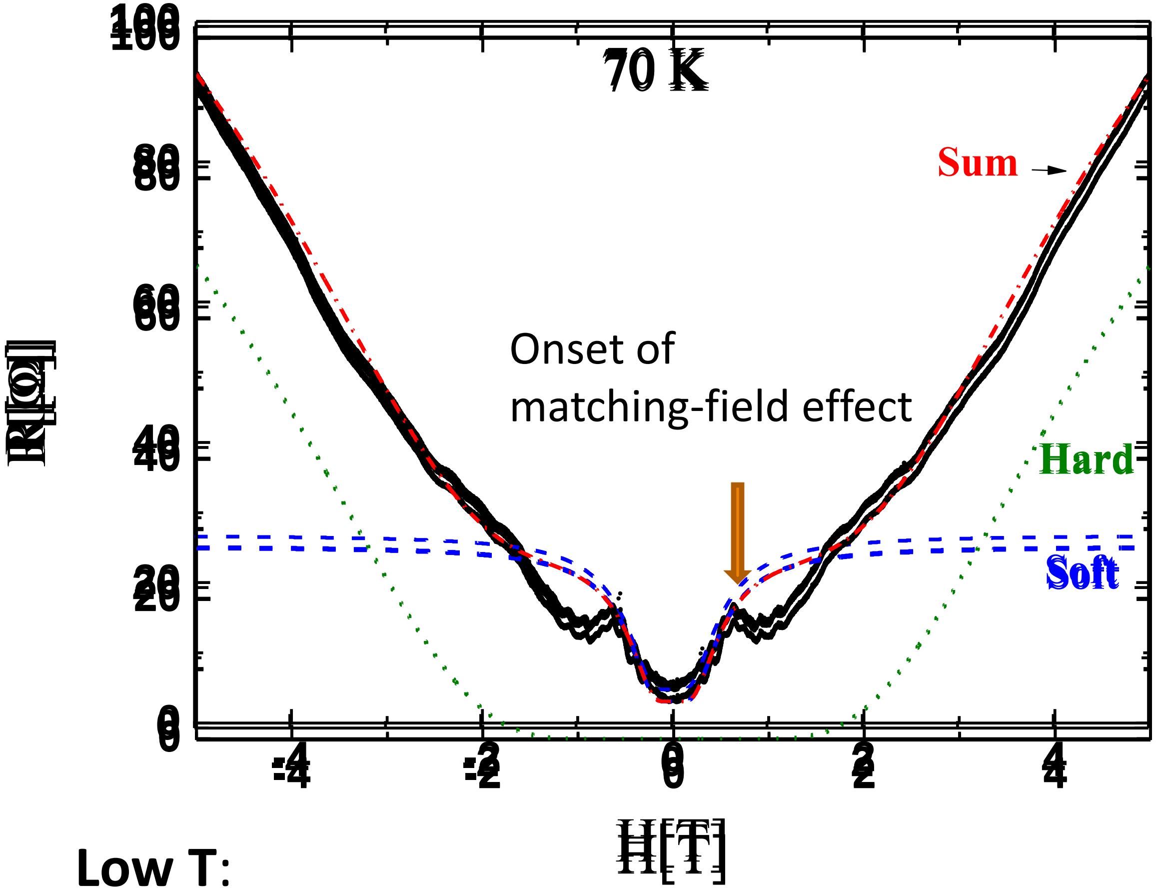
- Flat at "R_n"
- As T decreases onset is pushed to larger fields



Fits to Tinkham's model have been unsuccessful

Data imply TWO contributions:
Weak links / grains ('soft' / 'hard' components)

Illustration of Tinkham's model for MR from soft and hard components



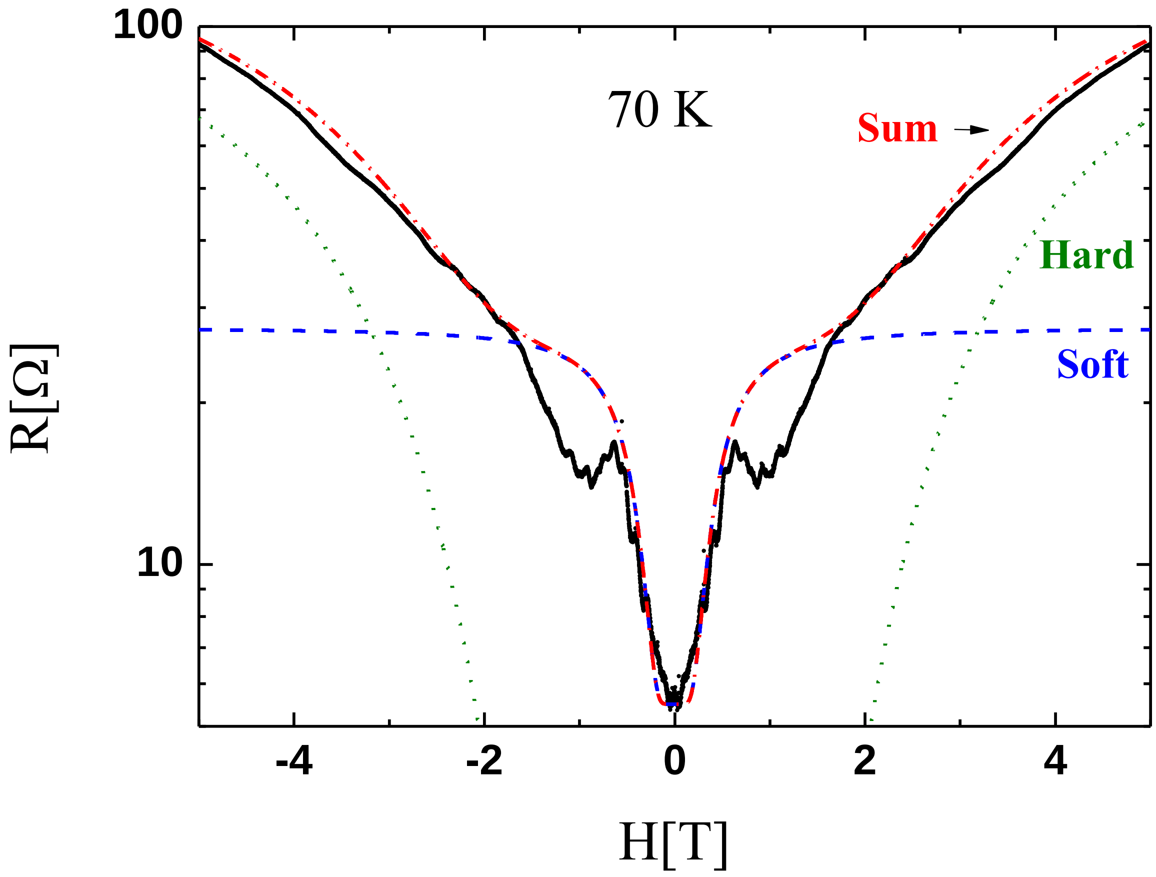
Onset of
matching-field effect

Low T:

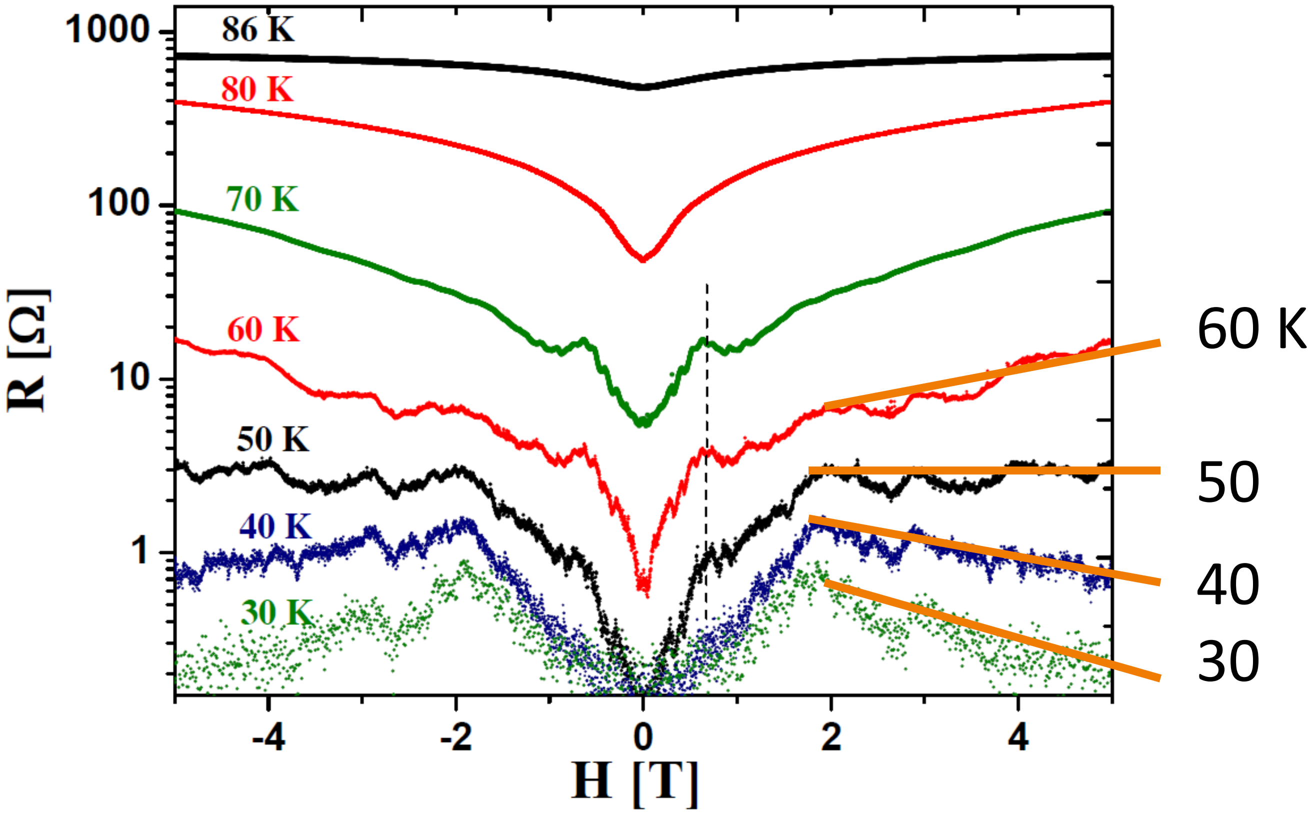
$R_{hard} = 0$

$dR_{soft}/dH \sim 0$

MR log scale



MAGNETORESISTANCE BACKGROUND: dR/dT < 0



dR/dH < 0 at low temperatures

ORIGIN: Quasiparticles tunneling.

(High H: vortices → increased DOS → σ_{qp} H

Mechanism revealed at low T where $\mathbf{R_{hard} = 0}$ **and** $\mathbf{dR_{soft}/dT}$ **small**

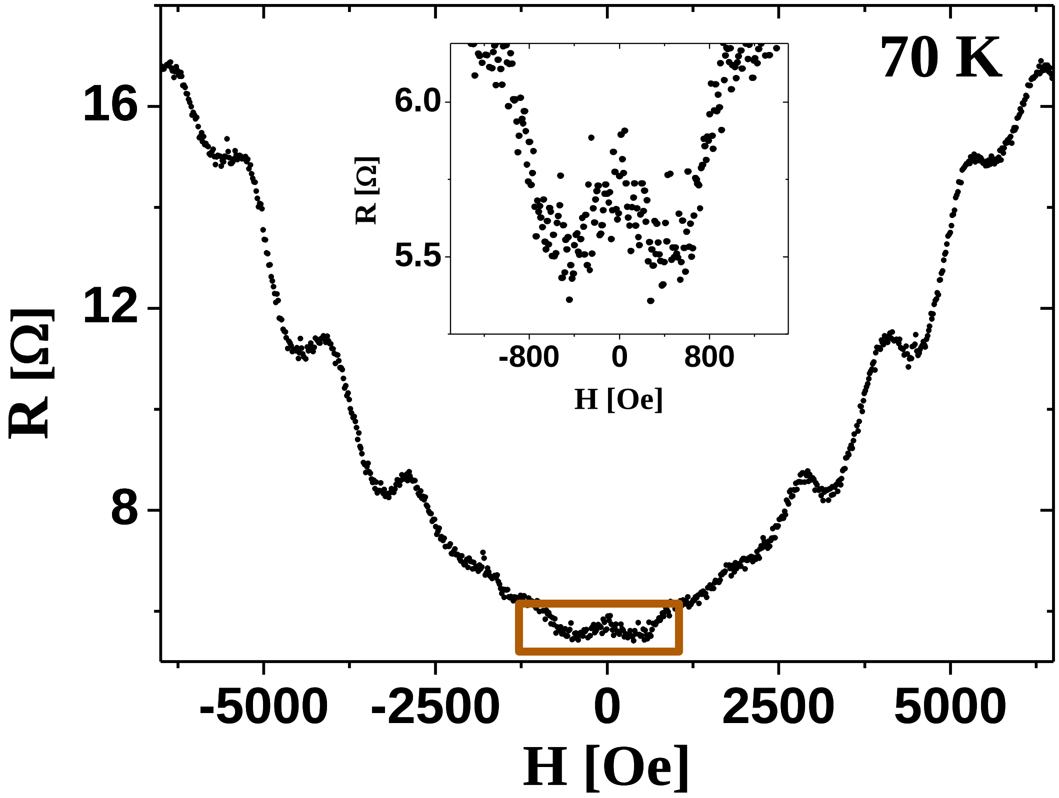
Magnetoresistance background

- **Low fields**: Thermally activated phase slips in weak links
- **High fields**: Thermally activated phase slips in grains
- **Low temperatures - High fields** : Quasiparticles tunneling (High H: vortices → increased DOS → σ_{qp} ↑ H

  Mechanism revealed when $R_{hard} = 0$ and dR_{soft}/dT small

Oscillations and negative magnetoresistance

(500 nm)

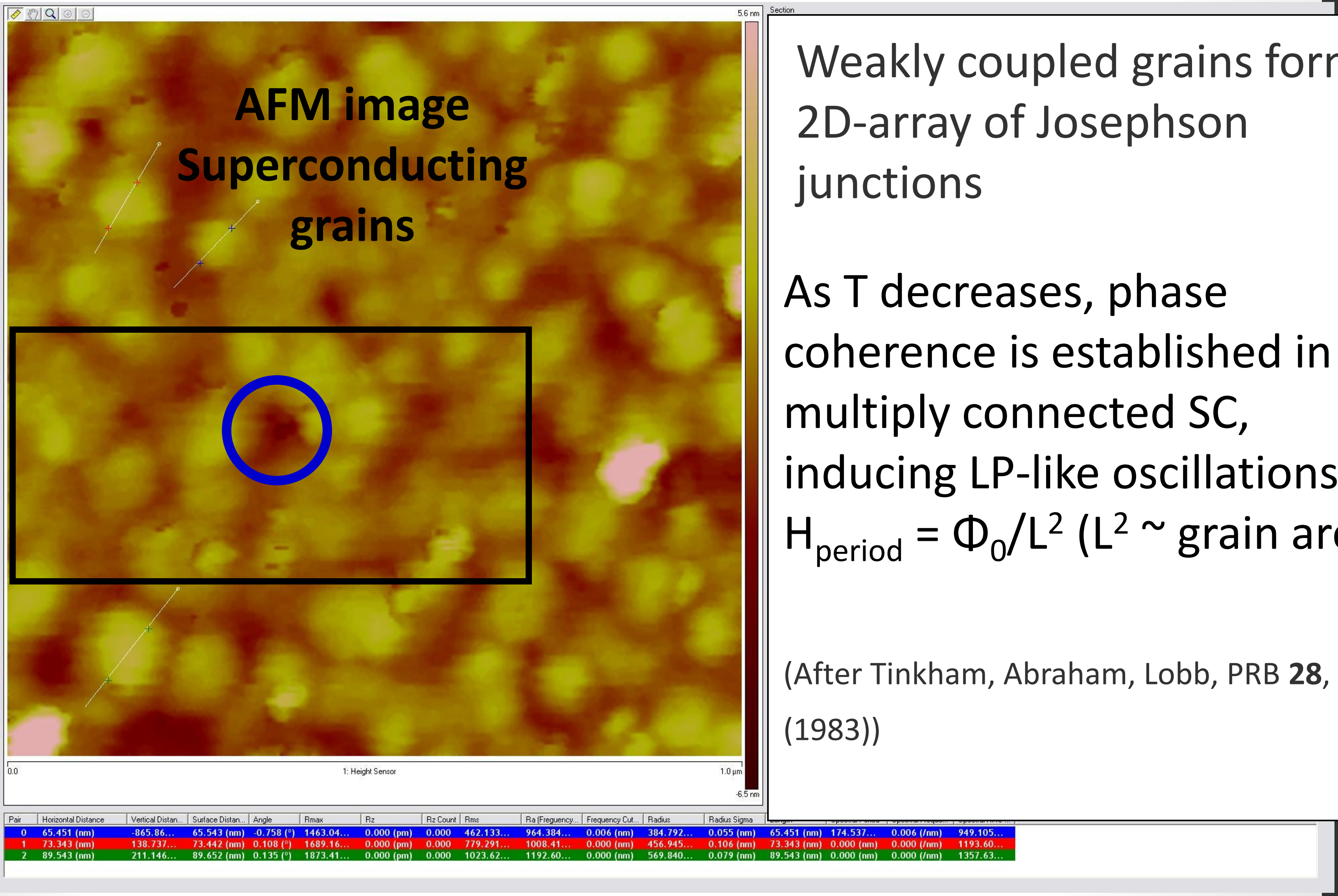


Oscillations

Negative magnetoresistance

Magnetoresistance oscillations

Herzog, Xiong, Dynes, PRB (1998)



AFM image Superconducting grains

Pair	Horizontal Distance	Vertical Distan...	Surface Distan...	Angle	Rmax	Rz	Rz Count	Rms	Ra (Frequency...	Frequency Cut...	Radius	Radius Sigma				
0	65.451 (nm)	-865.86...	65.543 (nm)	-0.758 (°)	1463.04...	0.000 (pm)	0.000	462.133...	964.384...	0.006 (nm)	384.792...	0.055 (nm)	65.451 (nm)	174.537...	0.006 (/nm)	949.105...
1	73.343 (nm)	138.737...	73.442 (nm)	0.108 (°)	1689.16...	0.000 (pm)	0.000	779.291...	1008.41...	0.000 (nm)	456.945...	0.106 (nm)	73.343 (nm)	0.000 (nm)	0.000 (/nm)	1193.60...
2	89.543 (nm)	211.146...	89.652 (nm)	0.135 (°)	1873.41...	0.000 (pm)	0.000	1023.62...	1192.60...	0.000 (nm)	569.840...	0.079 (nm)	89.543 (nm)	0.000 (nm)	0.000 (/nm)	1357.63...

Weakly coupled grains form 2D-array of Josephson junctions

As T decreases, phase coherence is established in multiply connected SC, inducing LP-like oscillations: $H_{period} = \Phi_0/L^2$ (L^2 ~ grain area)

(After Tinkham, Abraham, Lobb, PRB **28**, 6578 (1983))

Explanations proposed for the negative magnetoresistance in low-T_c SC

Pair scattering rate from magnetic impurities is reduced due to spin polarization in the presence of the field

(Simons *et al.* PRB (2012)).
[Origin of magnetic impurities???]

Disorder → Random distribution of negative and positive Josephson critical currents
(Spivak and Kivelson, PRB (1991))

[Relevant near SIT)

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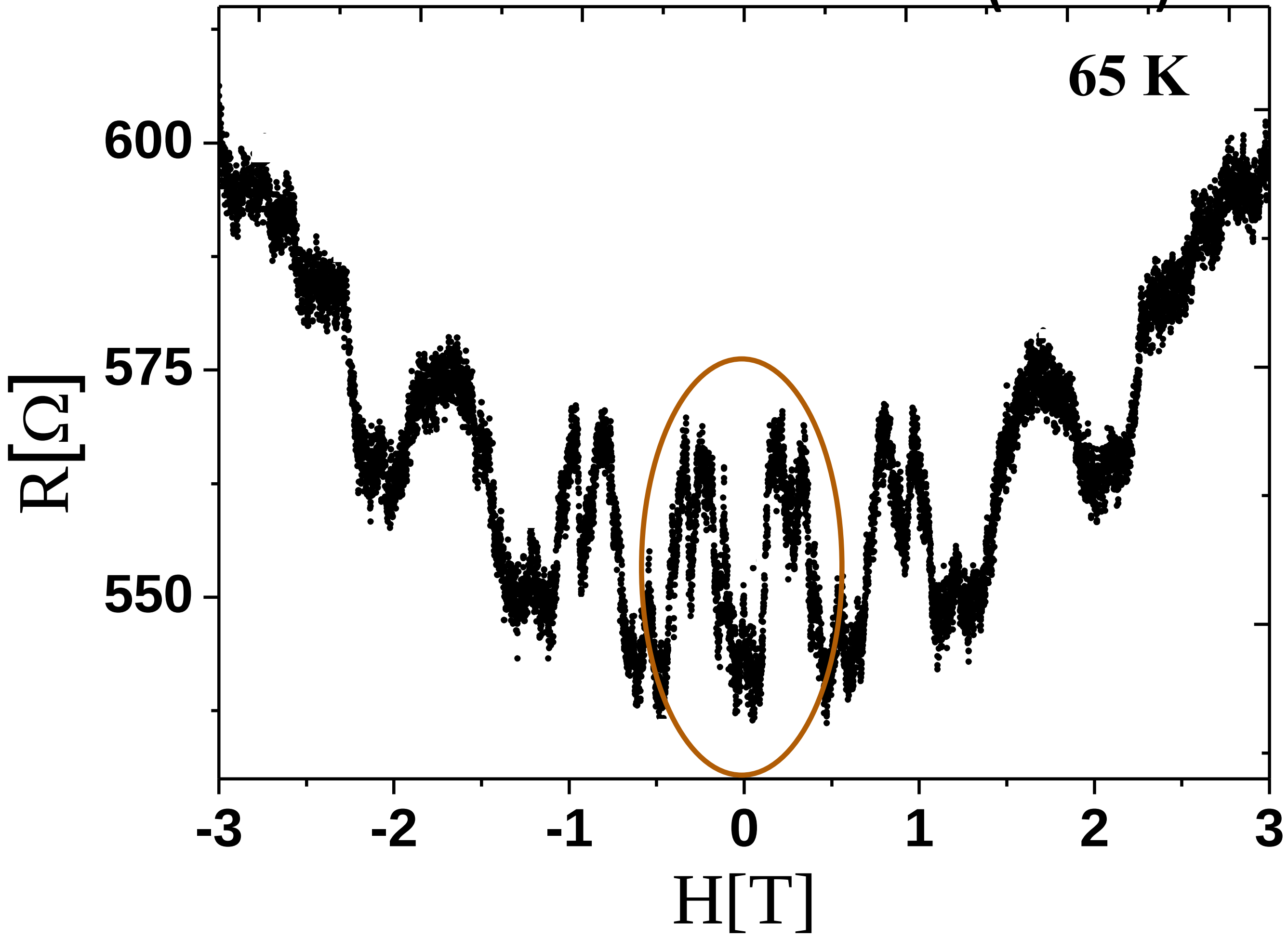
All models concern the initial slope ($dR/dH_{H=0}$)

All models (proposed for the negative MR observed in low-T_c SC concern the initial slope ($dR/dH_{H=0}$)

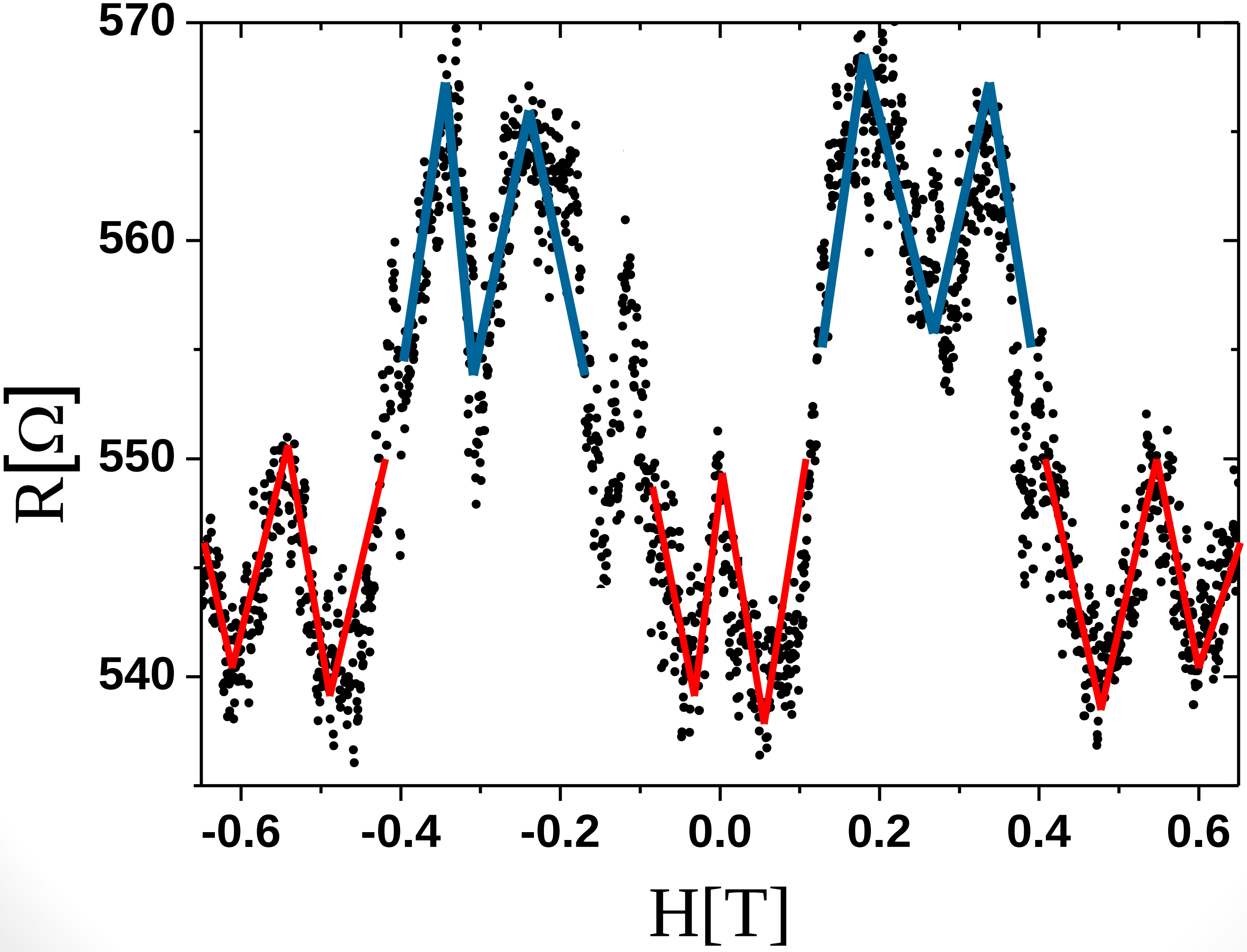
YBCO nano wires:
The **negative magnetoresistance** is part of the **periodic** behavior

80 nm wide wire (65 K)



YBCO nano wire: PERIODIC negative magnetoresistance

(Negative MR is part of the oscillatory behavior)



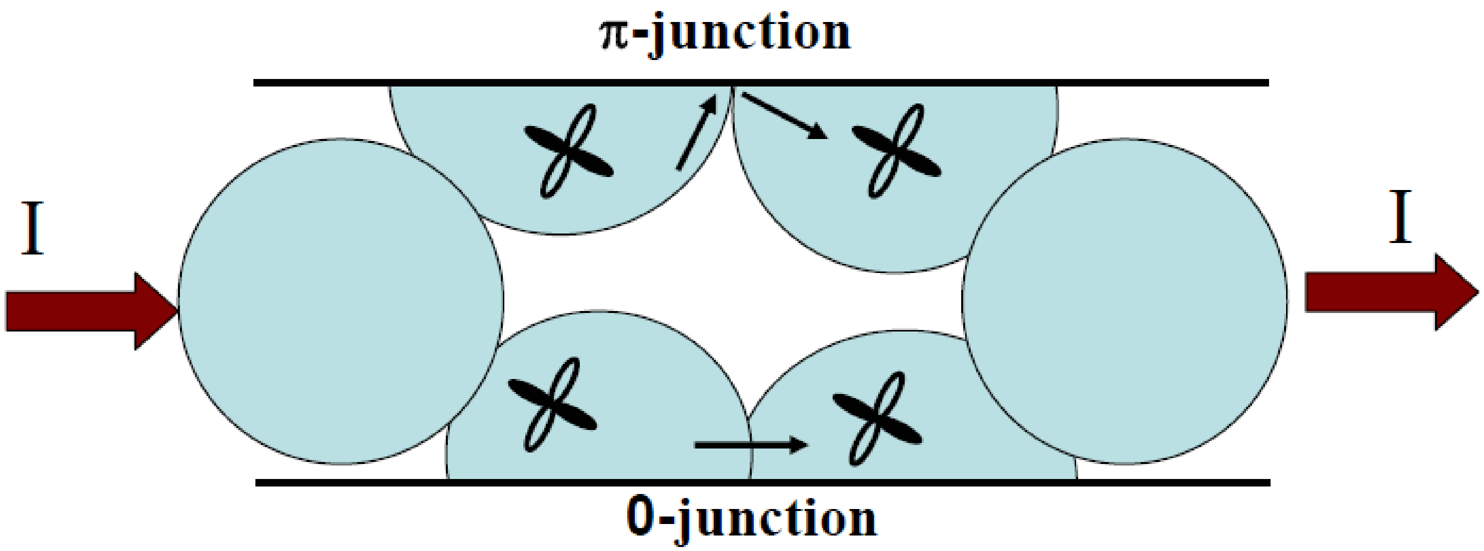
YBCO nano wires:
The **negative magnetoresistance** is part of the **periodic** behavior

Origin

π-junctions included in phase coherent loops induce a π phase shift

Origin for both negative magnetoresistance and oscillations

Origin of negative MR : π-junctions



‘Geometric’ Josephson junctions

Reflected particles at the constriction suffer a sign change of the pairing potential, leading to a π shift.

After Gumann, Iniotakis and Schopohl, *APL* **91** (2007) 192502.

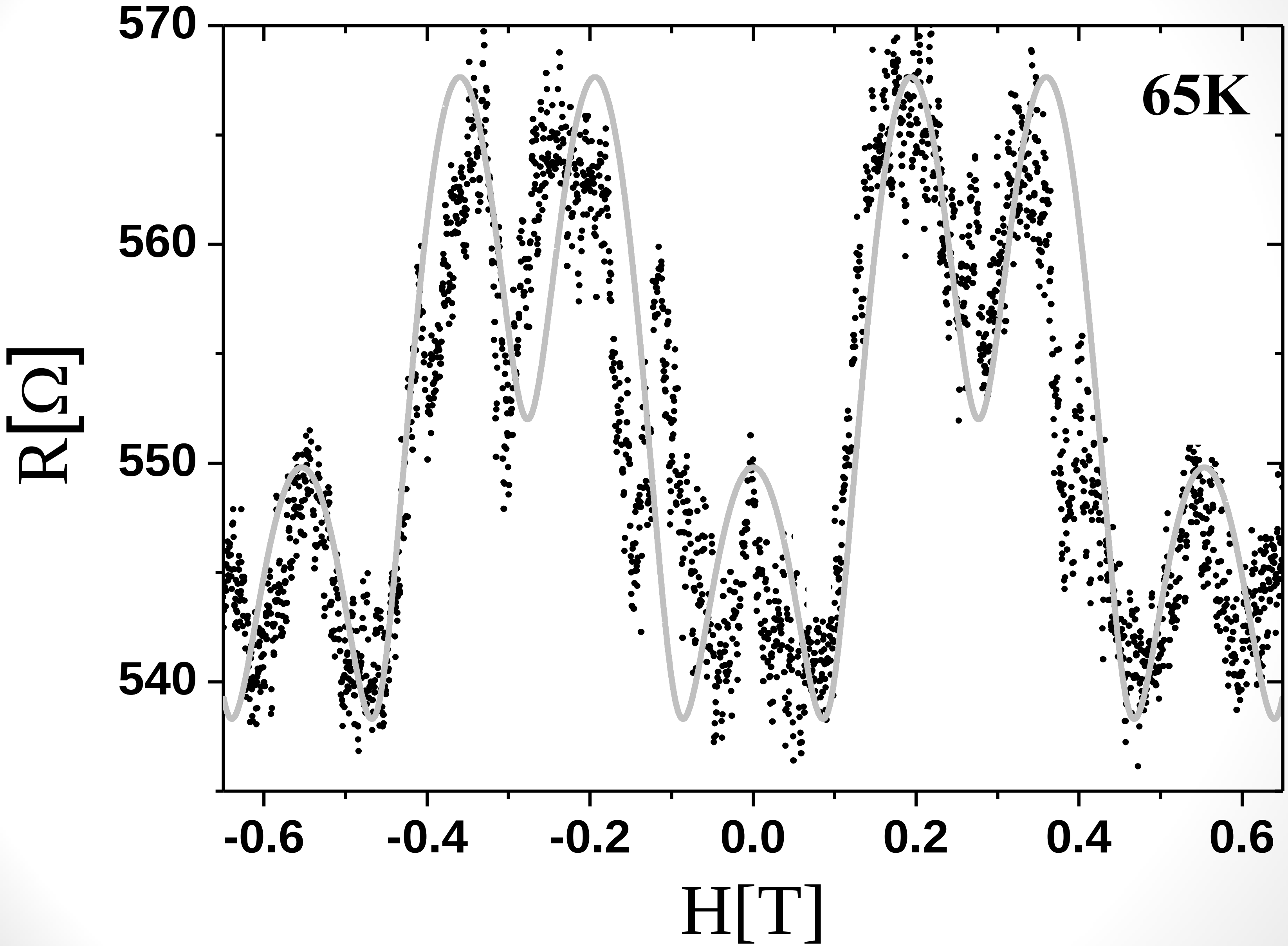
Model: Zero and π-SQUIDs in series

(Negative MR and oscillations have same origin)

- The presence of a SQUID is necessary in order to produce the periodic negative magnetoresistance.
- The two main field-periods (~ 2200 and ~ 6600 Oe) suggests that two SQUIDs with areas differing by a factor of ~ 3 play a role.
- The geometrical constraints of the wires (ratio of the wire width to the grain size of order 1) force these SQUIDs to be connected in series.

Voltage across 0-SQUID and π-SQUID connected in series

$$V=(R_1/2)\sqrt{I^2-\left(2I_{c1}\cos\frac{\pi SH}{\Phi_0}\right)^2}+(R_2/2)\sqrt{I^2-\left(2I_{c2}\sin\frac{\pi(3S)H}{\Phi_0}\right)^2}$$


570
560
550
540
R[Ω]
-0.6
-0.4
-0.2
0.0
0.2
0.4
0.6
H[T]
65K

Summary

Phenomenon	Origin
1. **Background**	
High T low fields MR	Phase slips -weak links
High T high fields MR	Phase slips - grains
Low T – negative slope dR/dT	QP tunneling
2. **Oscillations**	
	Low fields – phase coherent loops
	High fields – matching
3. **Negative MR**	
	Phase coherent loops
	Loops include π- junctions