The Yellow Brick Road* to Room Temperature Superconductivity

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Orlando, Florida, USA

*with apologies to L. Frank Baum, Noel Langley, and MGM

Forward

I agree with Chandra Varma*

*To reach the emerald city, one requires an s-wave order parameter (but there are also other requirements and/or restrictions)

I agree with Richard Feynmann*

*``When a new effect is discovered, and a highly exotic, exciting explanation and a very boring, ordinary one are both provided, the very boring, ordinary explanation is always correct.''

Principal Characters

Dorothy, the sincere, young experimenter (our hero)

D-waves: The Wicked Witch of the West

Distractions and addictions: The "p-word" Poppy Fields

Bob Schrieffer, also known as Glinda, the Good Witch of the North

The shoes of John Bardeen, also known as The ruby slippers

Competing orderings: The flying monkeys

The Ghost of John Bardeen: The Wizard

"PHONONS!"

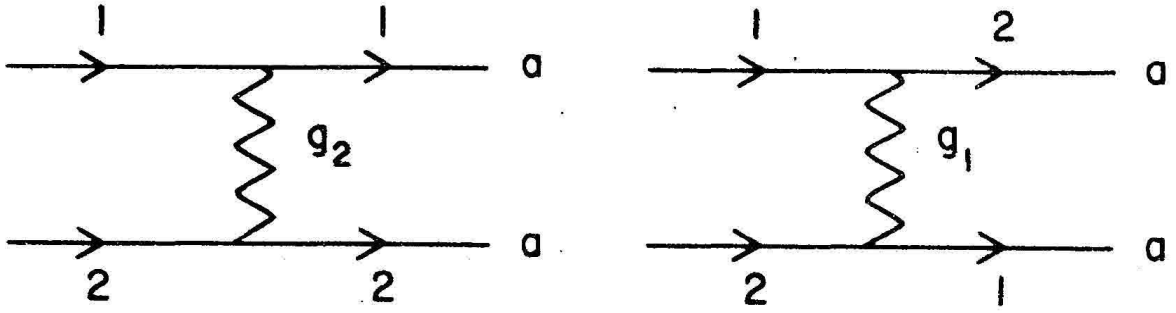
Room Temperature Superconductivity: the emerald city

The Tempest: the discovery of superconductivity

Toto, I've got a feeling we're not in Kansas anymore

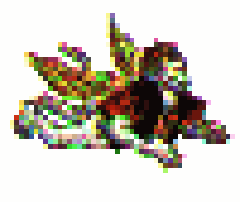
Ding, Dong, the witch is dead! The BCS Theory of Superconductivity

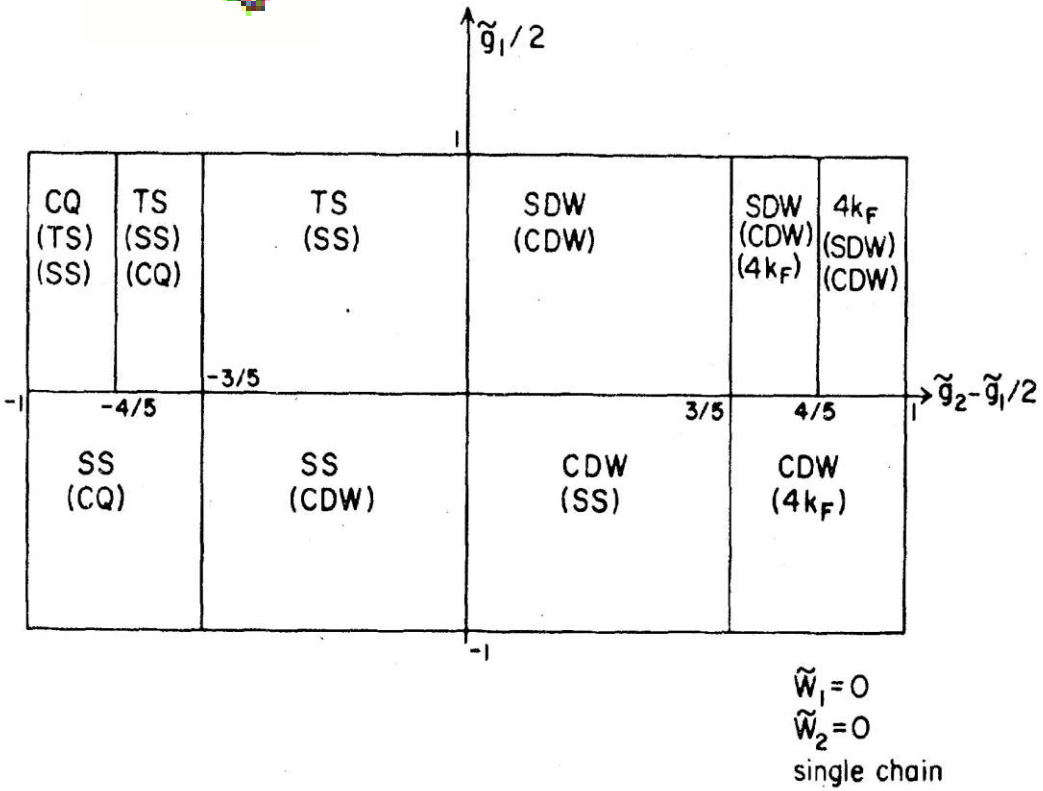
Munchkinland: One dimension



Follow the yellow brick road!

Are you a good witch or a bad witch?

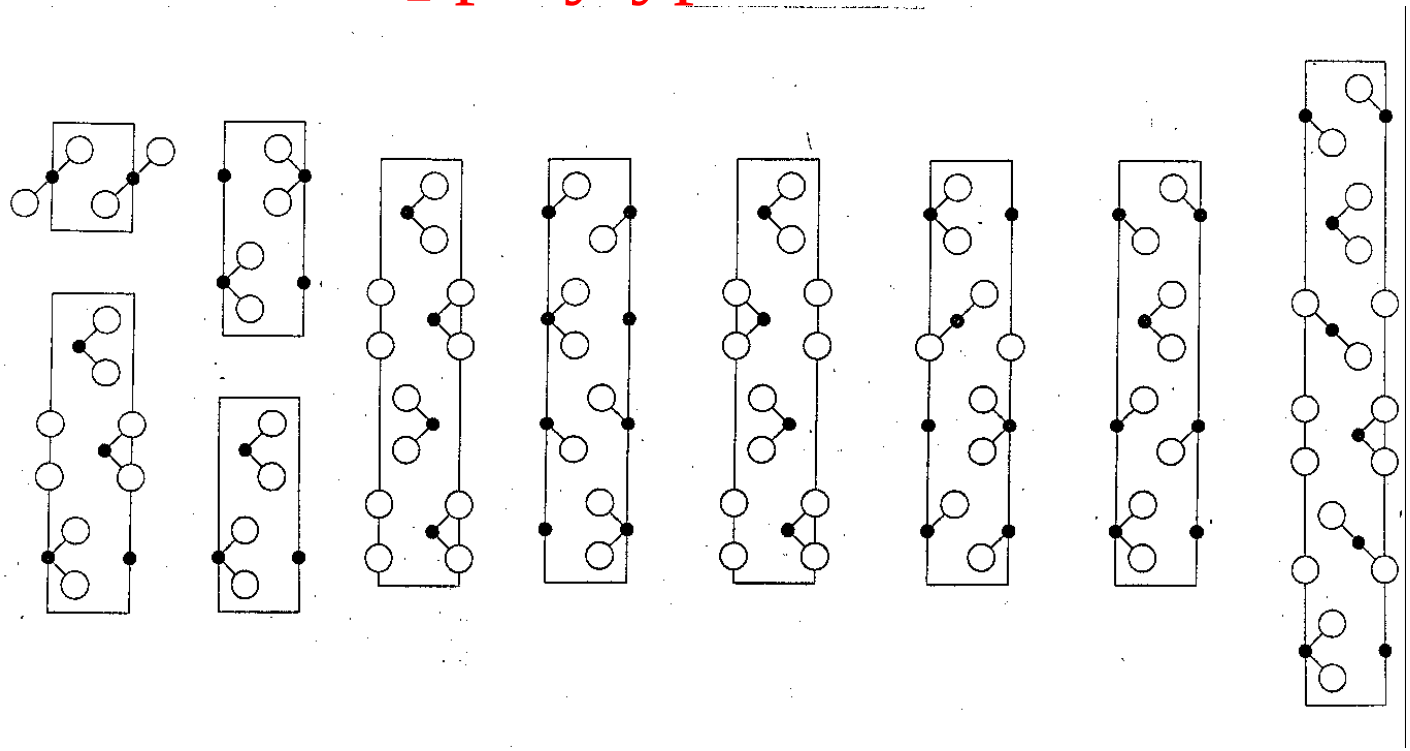




CDW and SS compete

The plains of Munchkinland: two dimensions, the plot thickens…

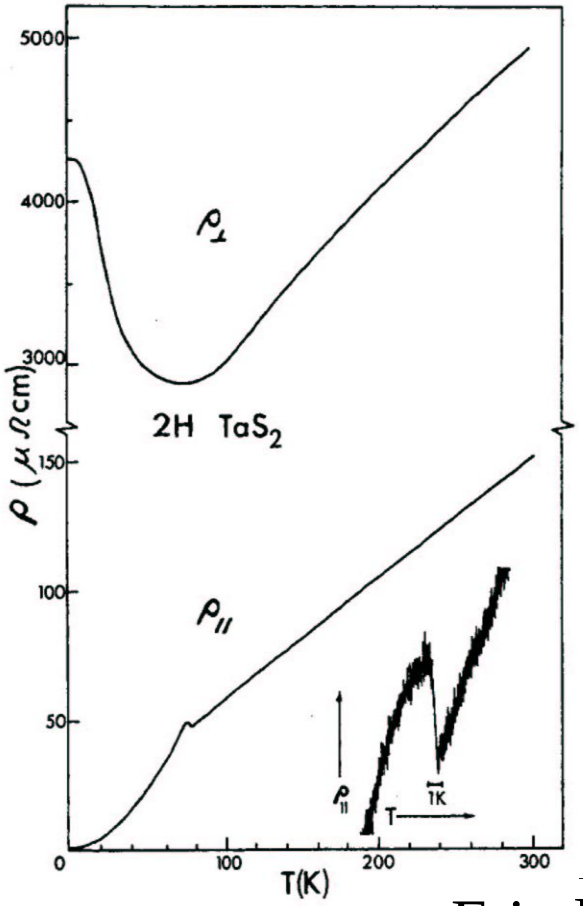
TaS_2 polytypes

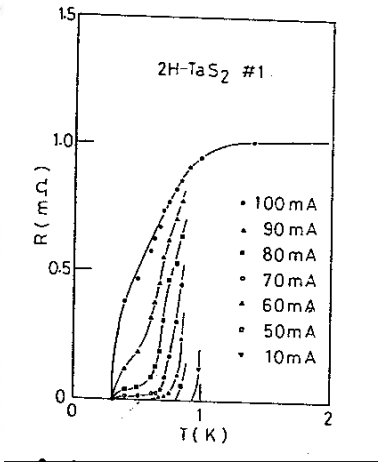


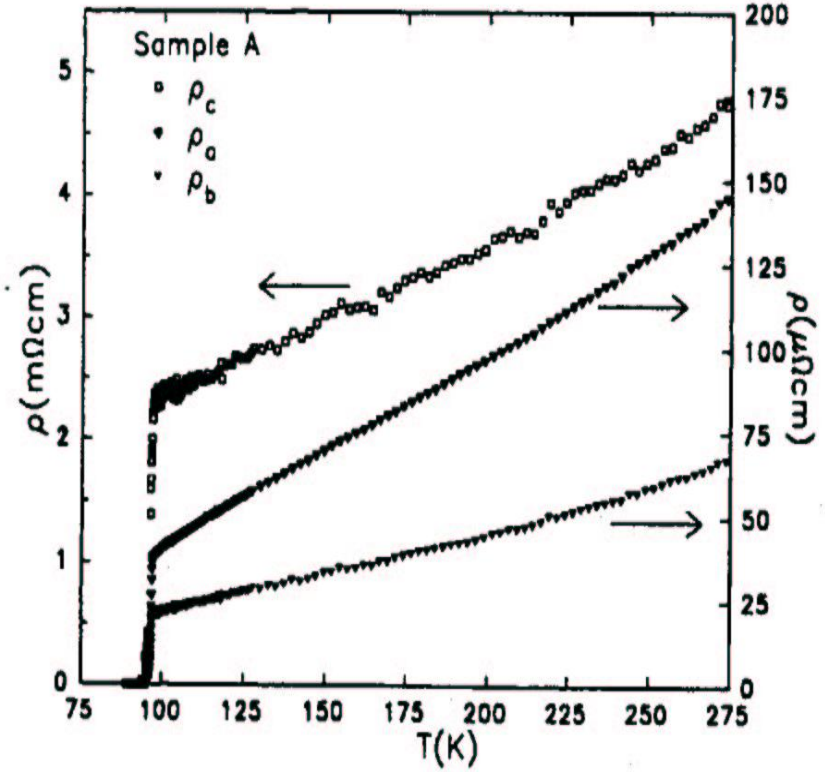
Resistivity: 2*H*-TaS_2 vs. YBCO

2*H*-TaS_2 T_c=0.6K

YBCO
T_c = 93K

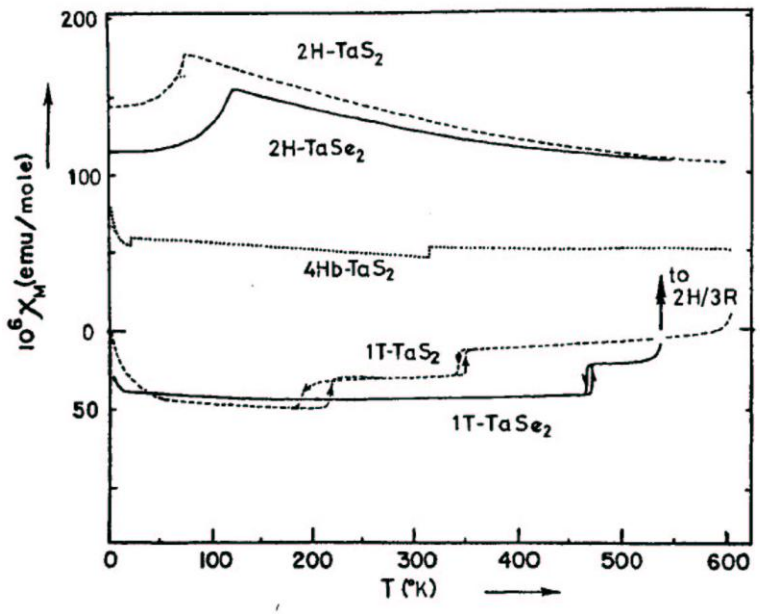




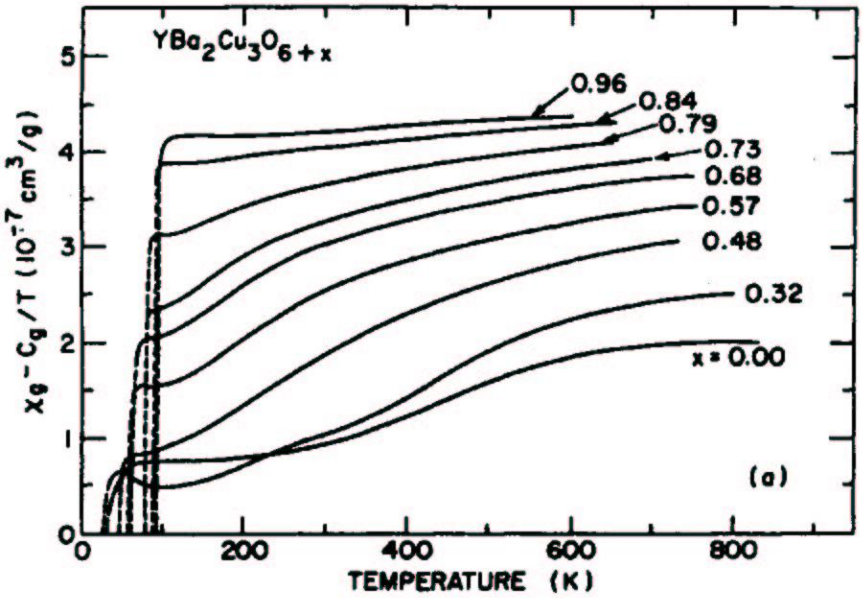


Frindt

Magnetic susceptibility



Wilson, DiSavlo, Mahajan

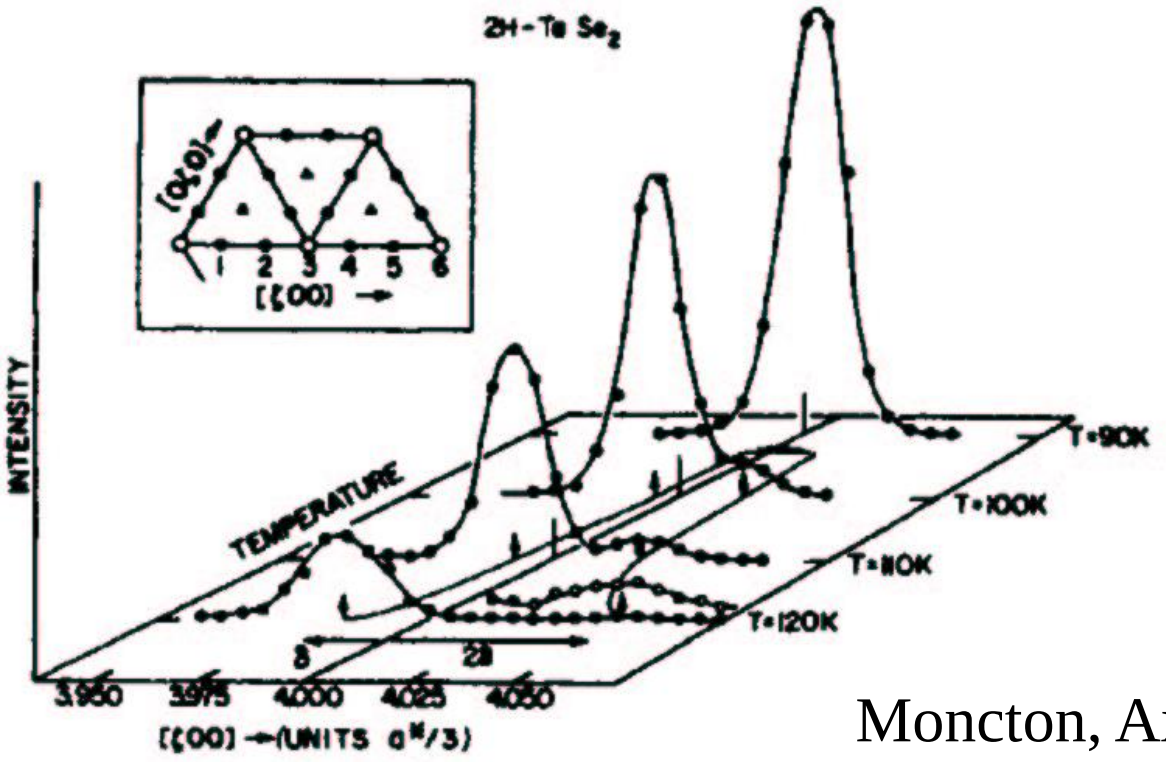


D. Johnston

Properties at 300K

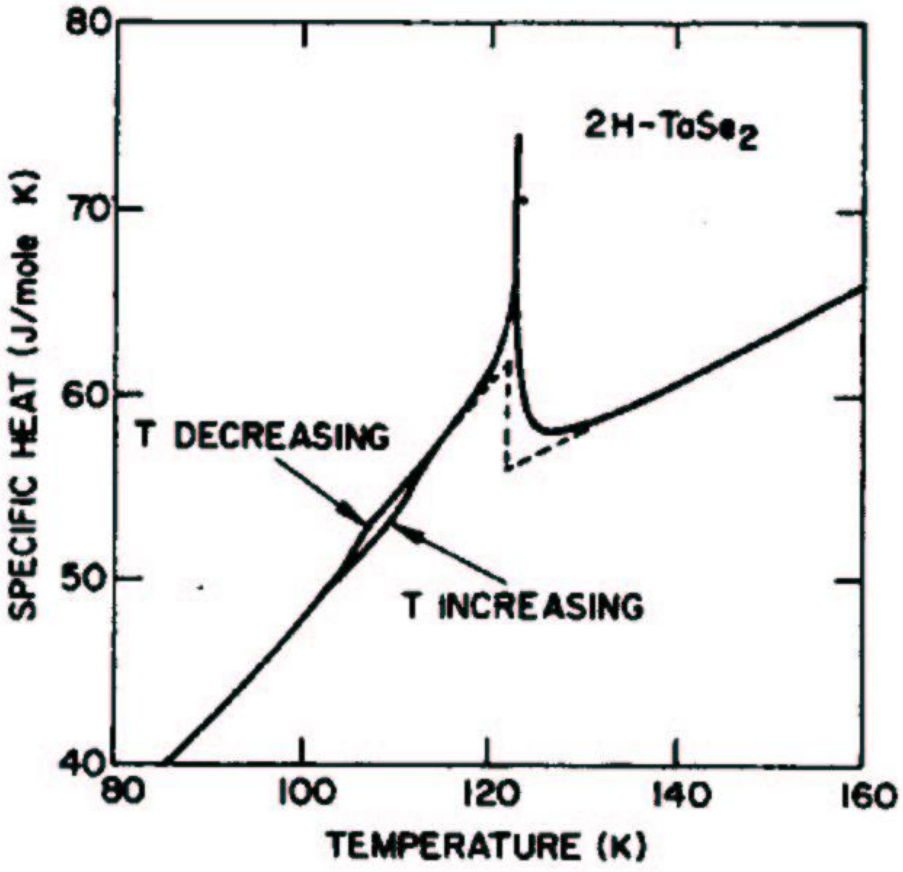
Compound	$\rho_{\parallel}$	$\rho_{\perp}$	$\chi_{\perp}$	$R_{H,\perp}$
	$10^{-4}\,\Omega\,cm$	$10^{-3}\,\Omega\,cm$	10^{-7} cm^3/gm	10^{-4} cm^3/C
2*H*-TaS_2	1.2-1.5	4.8	5.7	2.2
2*H*-$TaSe_2$	1.3		4.1	1.8
YBCO	0.7-1.5	4.8	4.2	4.0

Charge-Density Waves



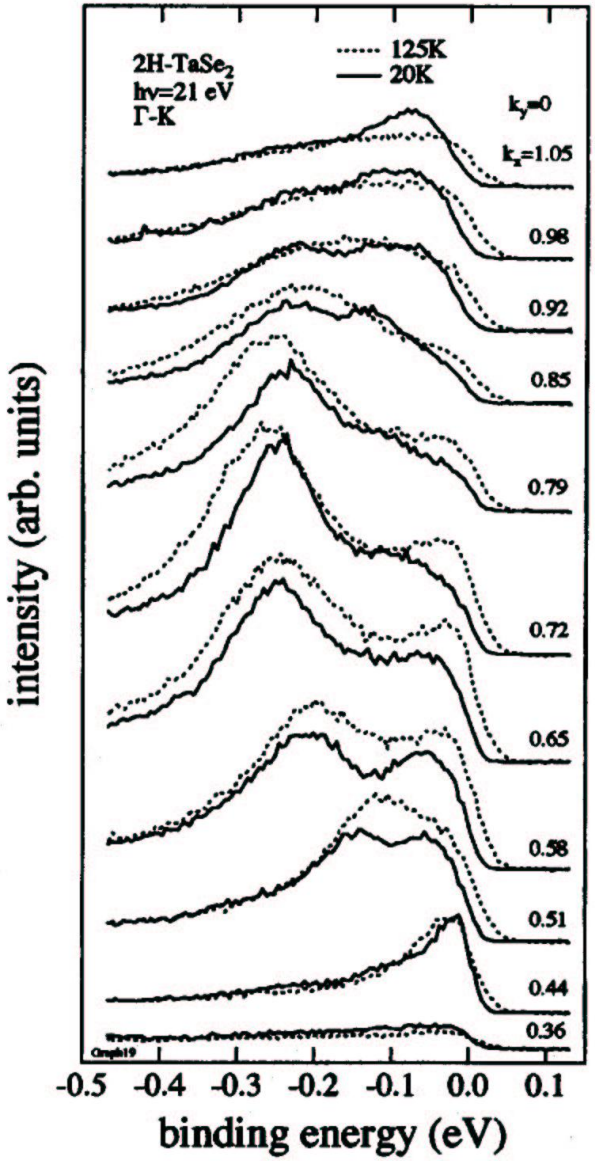
Moncton, Axe, DiSalvo

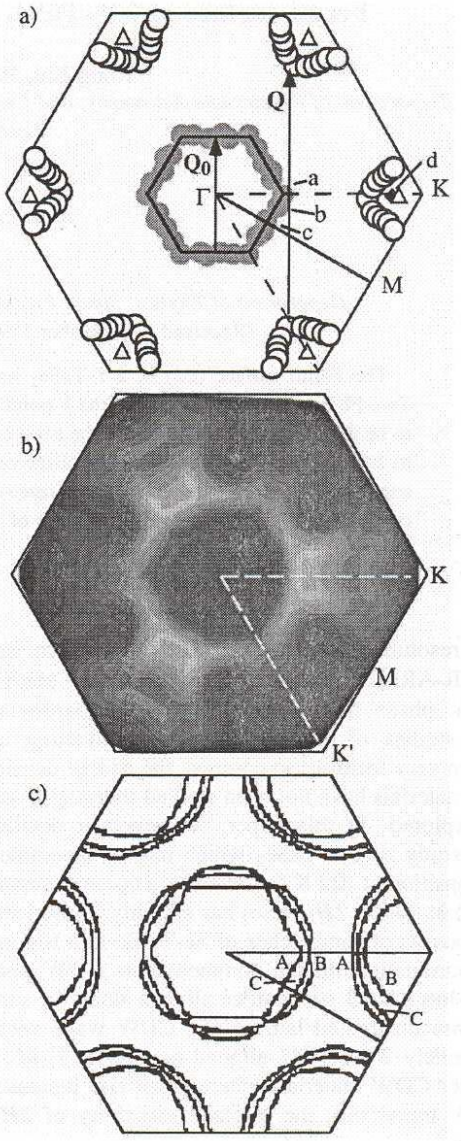
Incommensurate and commensurate CDW's



R. Craven

CDW has a gap with a node





Rong Liu

Saddle bands (extended van Hove singularities) in 2*H*-$TaSe_2$

Also quasi-circular Fermi surface

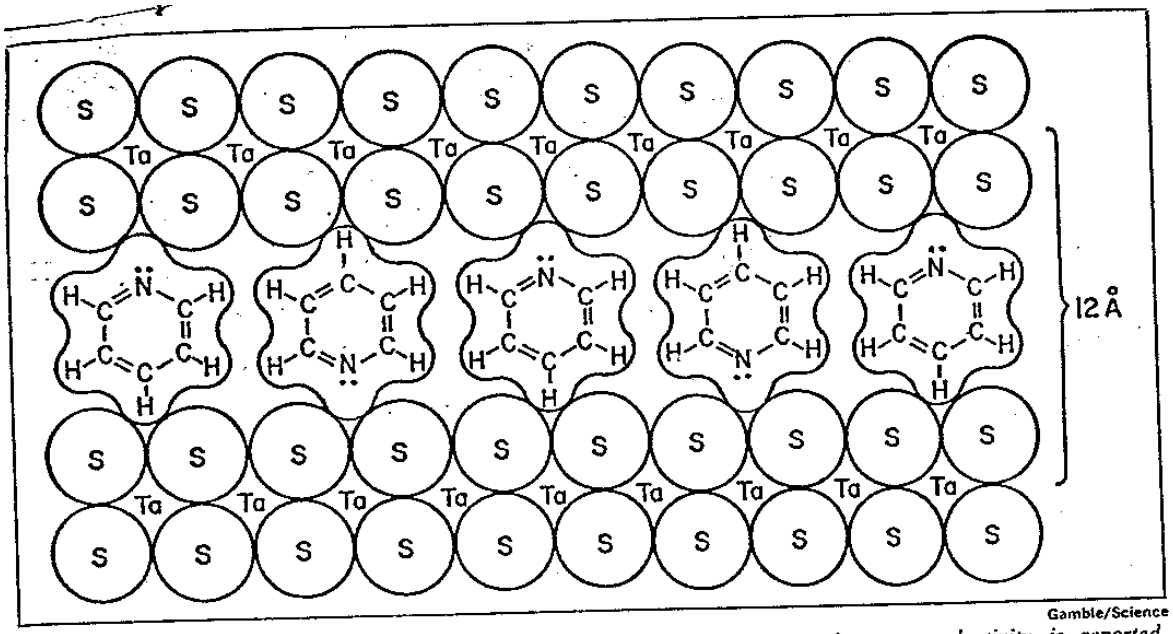
CDW forms at 125K on saddle bands, with six nodes touching the circular FS (commensurate at 90K)

SS forms at 0.2K on the remaining circular FS

Intercalation!

$2H\text{-}TaS_2$ +  = ?

$2H$-$TaS_2(pyridine)_{1/2}$



Gamble/Science

Tantalum disulfide and pyridine sandwich: Either two-dimensional or organic superconductivity is reported.

F. R. DiSalvo,
F. R. Gamble
R. A. Klemm

Synvar

Stanford Univ.

Geballe: Meissner effect no criterion.

T. H. Geballe

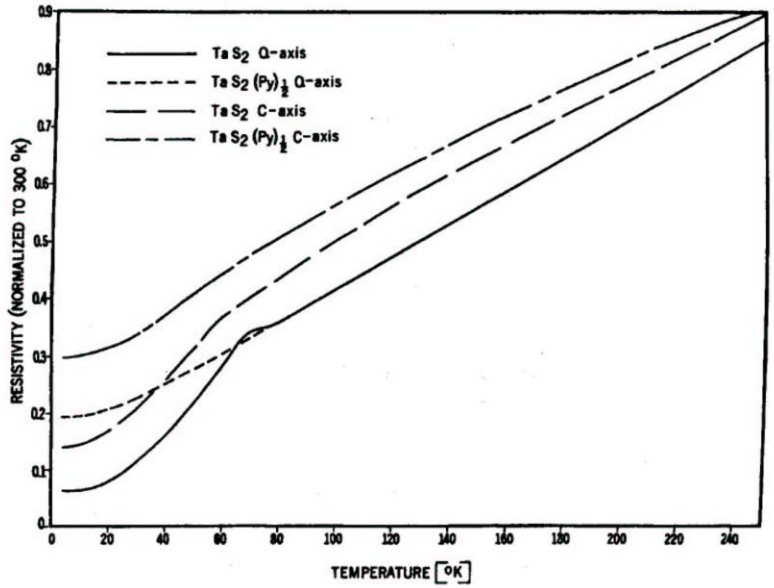
1970

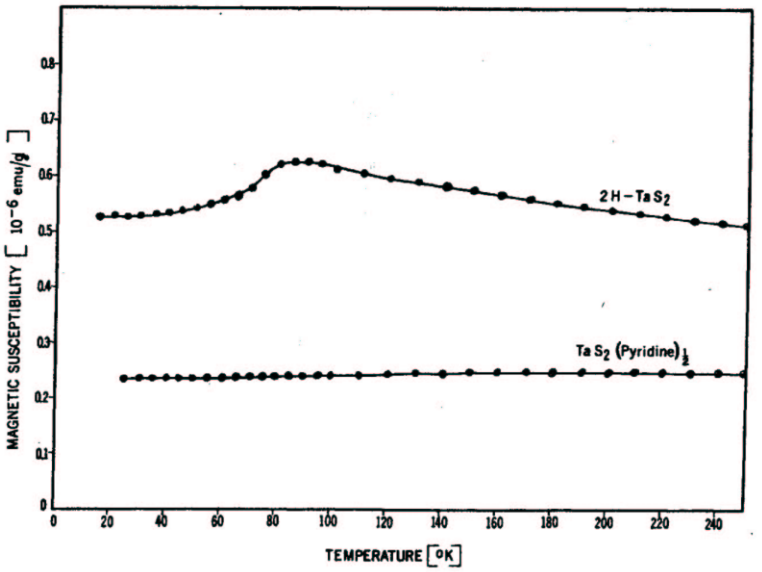
Bernd Matthias:

``Two-dimensional superconductivity is the snake-oil of superconductivity''

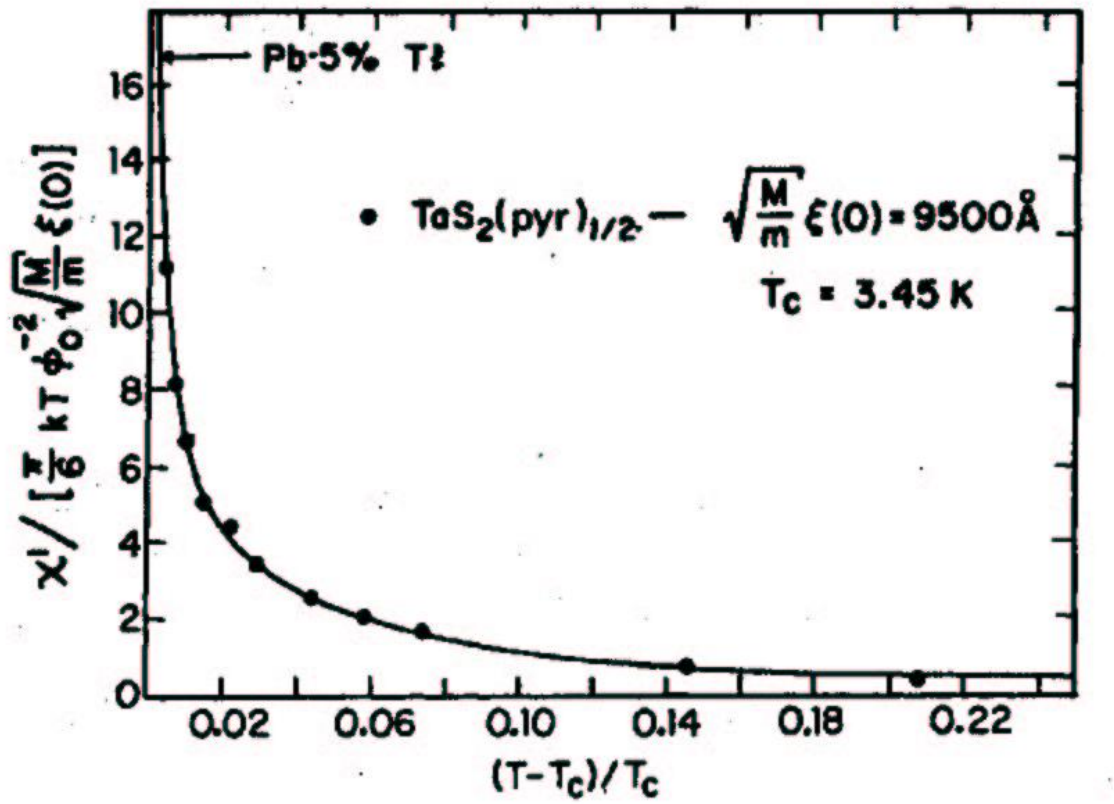
Science News, 1970

CDW removed! (poof!)

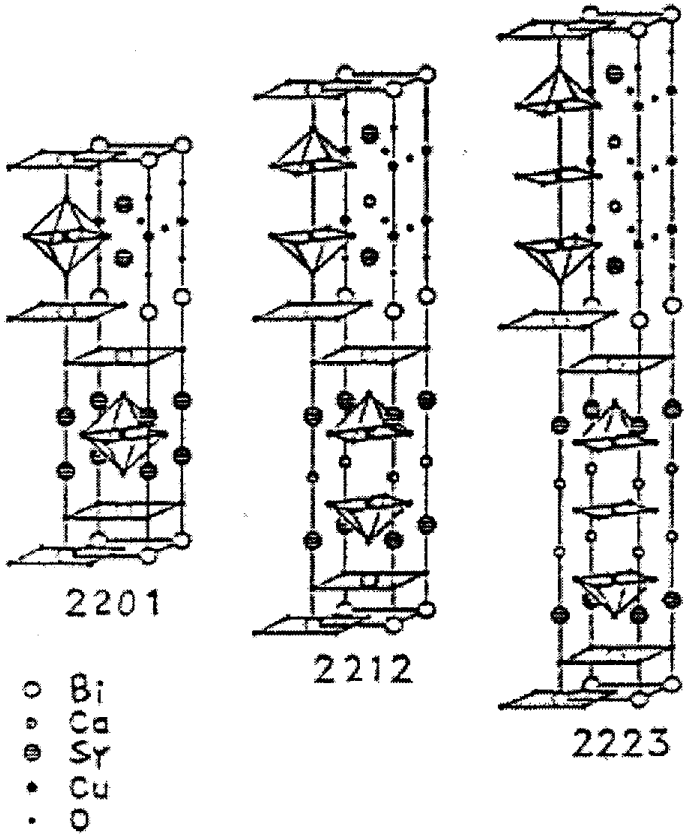




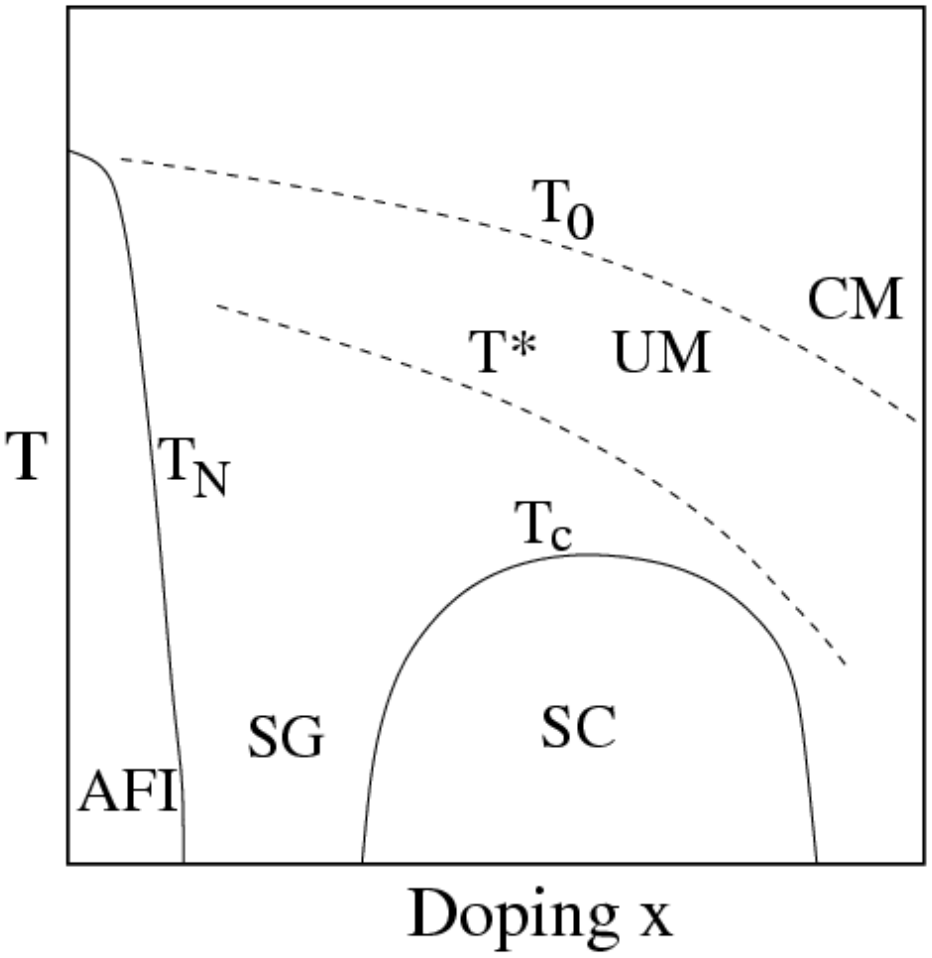
$T_c \rightarrow 3.45K!$

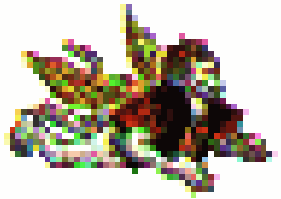


Structures of Bi2201, Bi2212, Bi2223



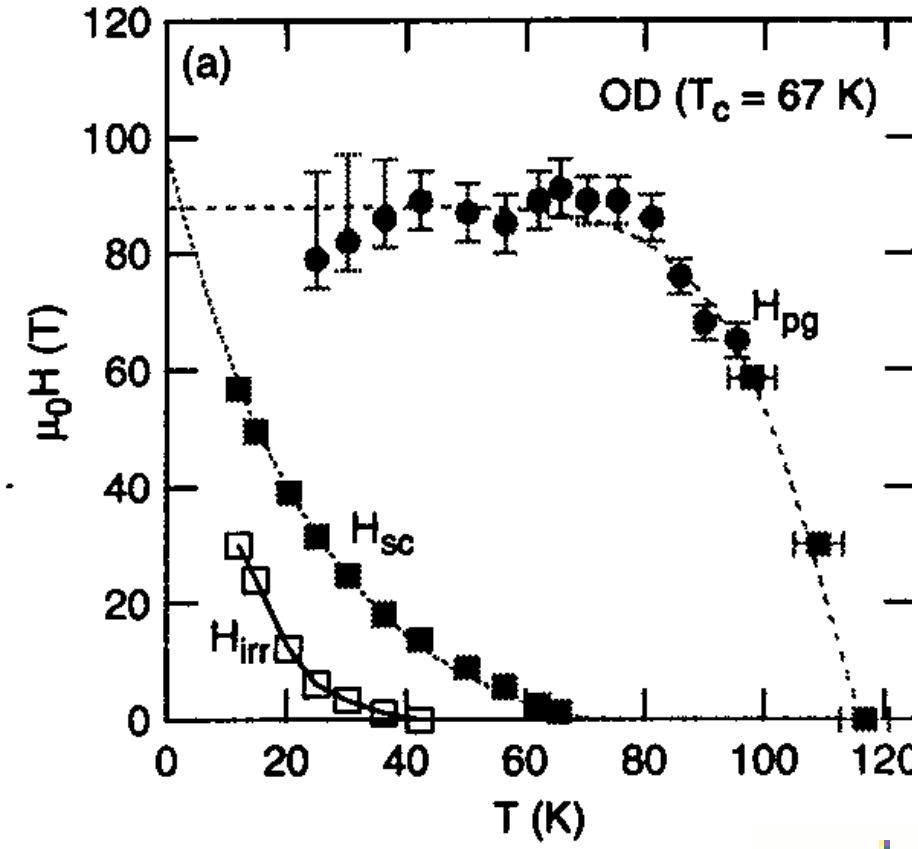
``Exciting'' side



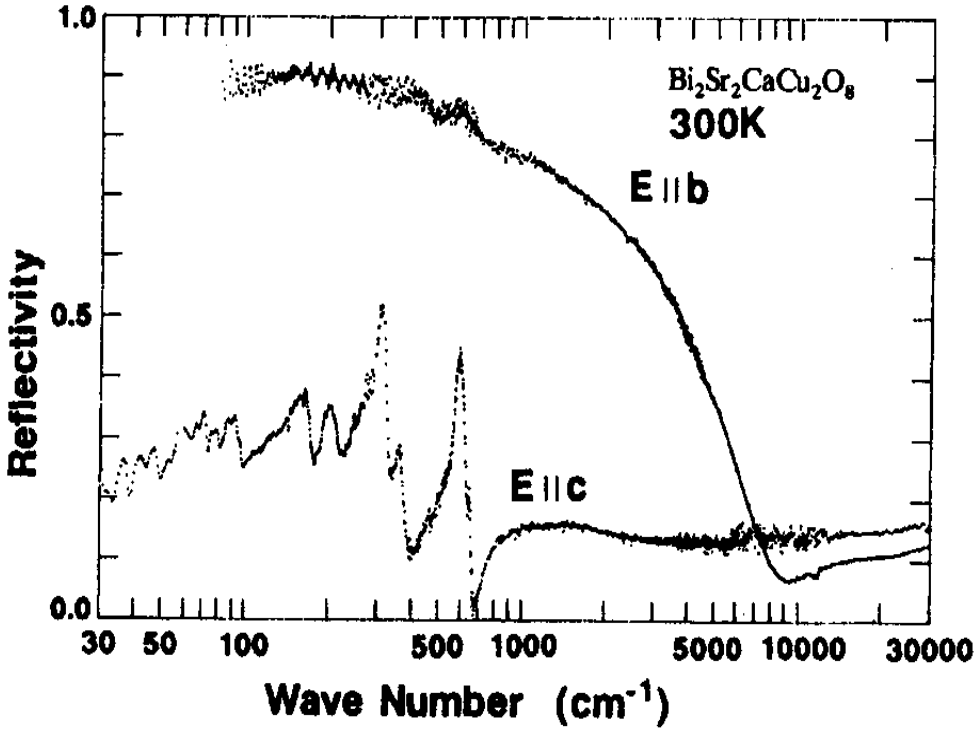


``Boring'' side

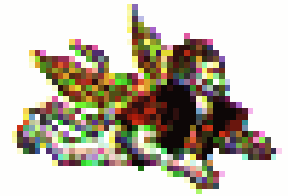
Pseudogap & infrared reflectance



Shibauchi



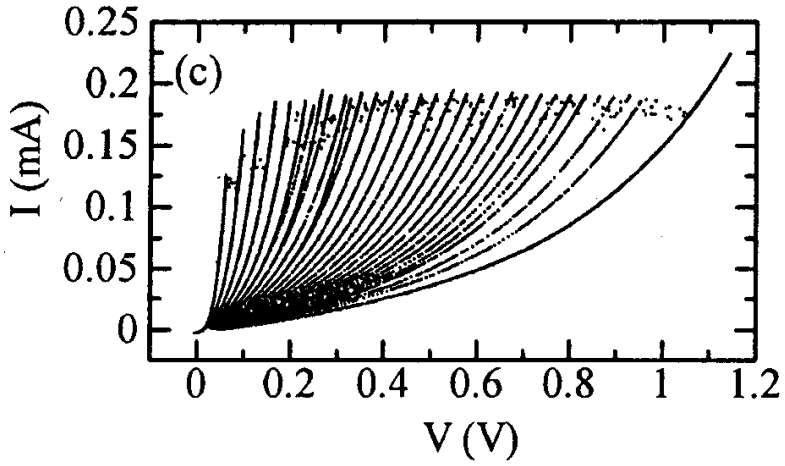
S. Tajima

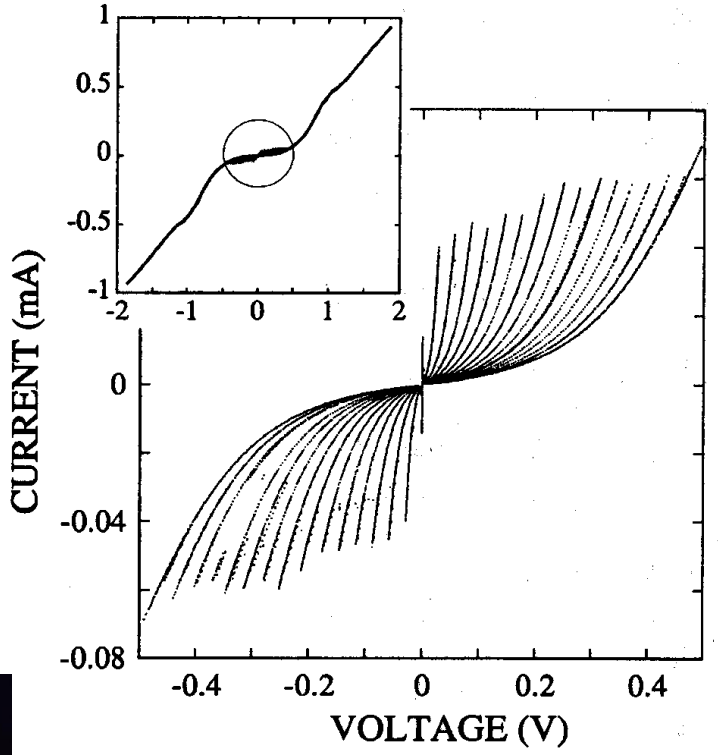


Layered Superconductor: Bi2212

(Irie) and $(HgBr_2)$Bi2212 (Yurgens)

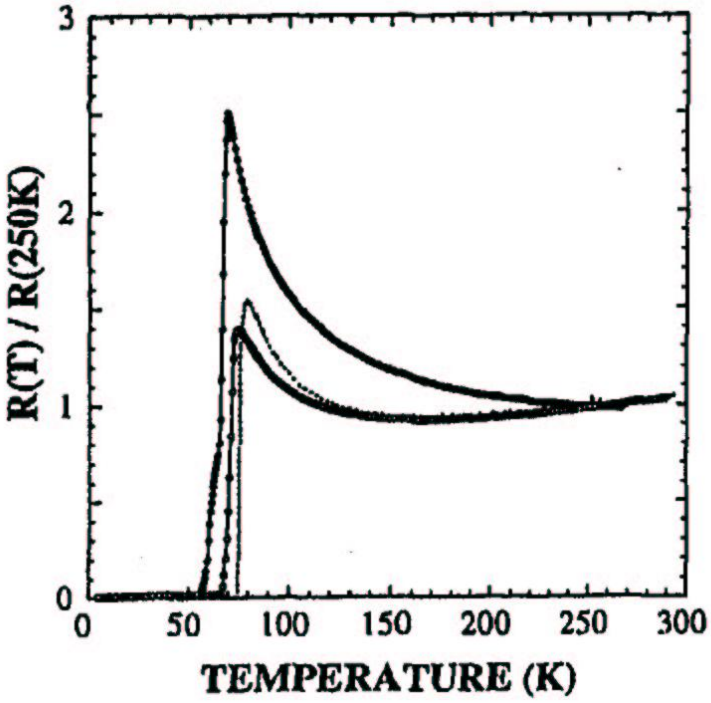
Stack of Josephson junctions

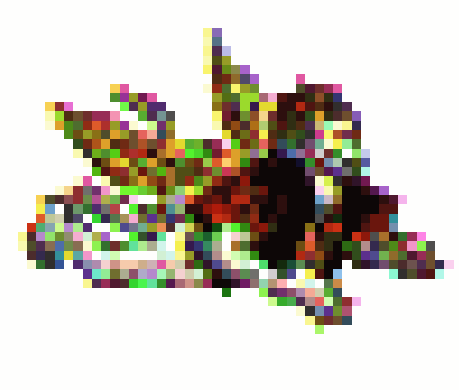




I_cR_n=20% of I_cR_n AB

Intercalation only increases anisotropy

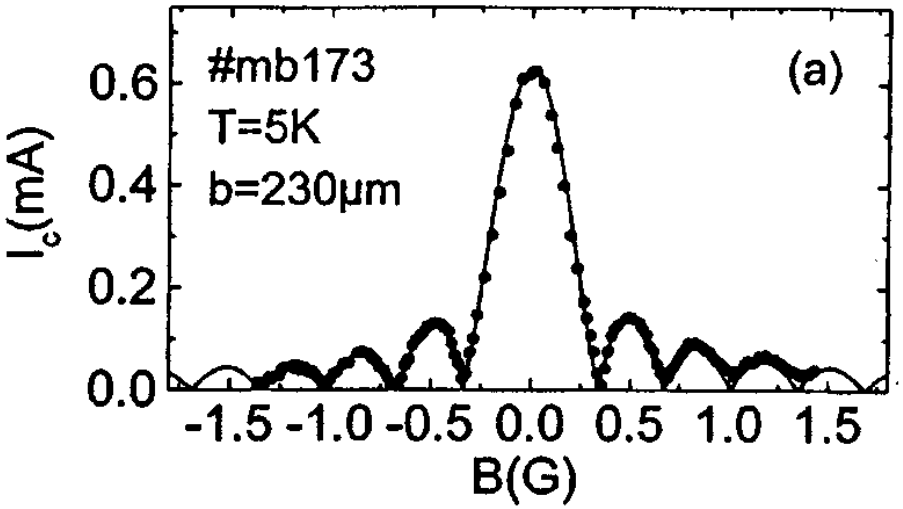


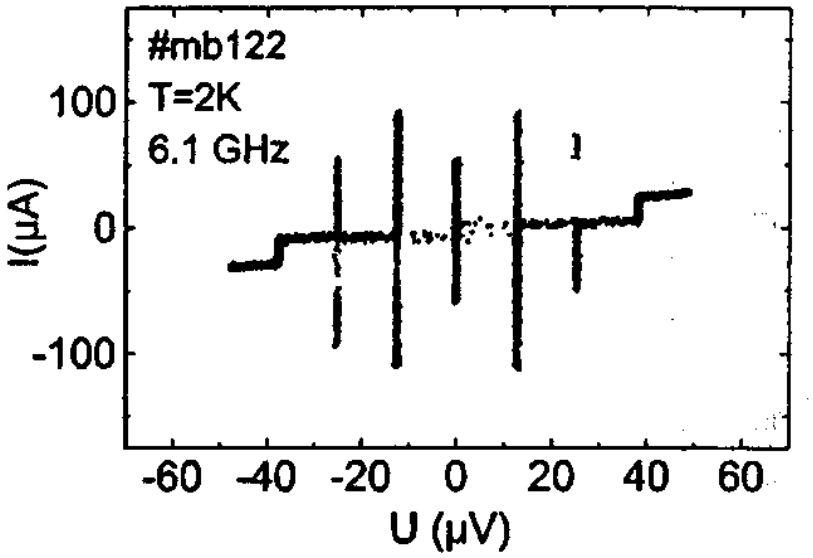


Yurgens

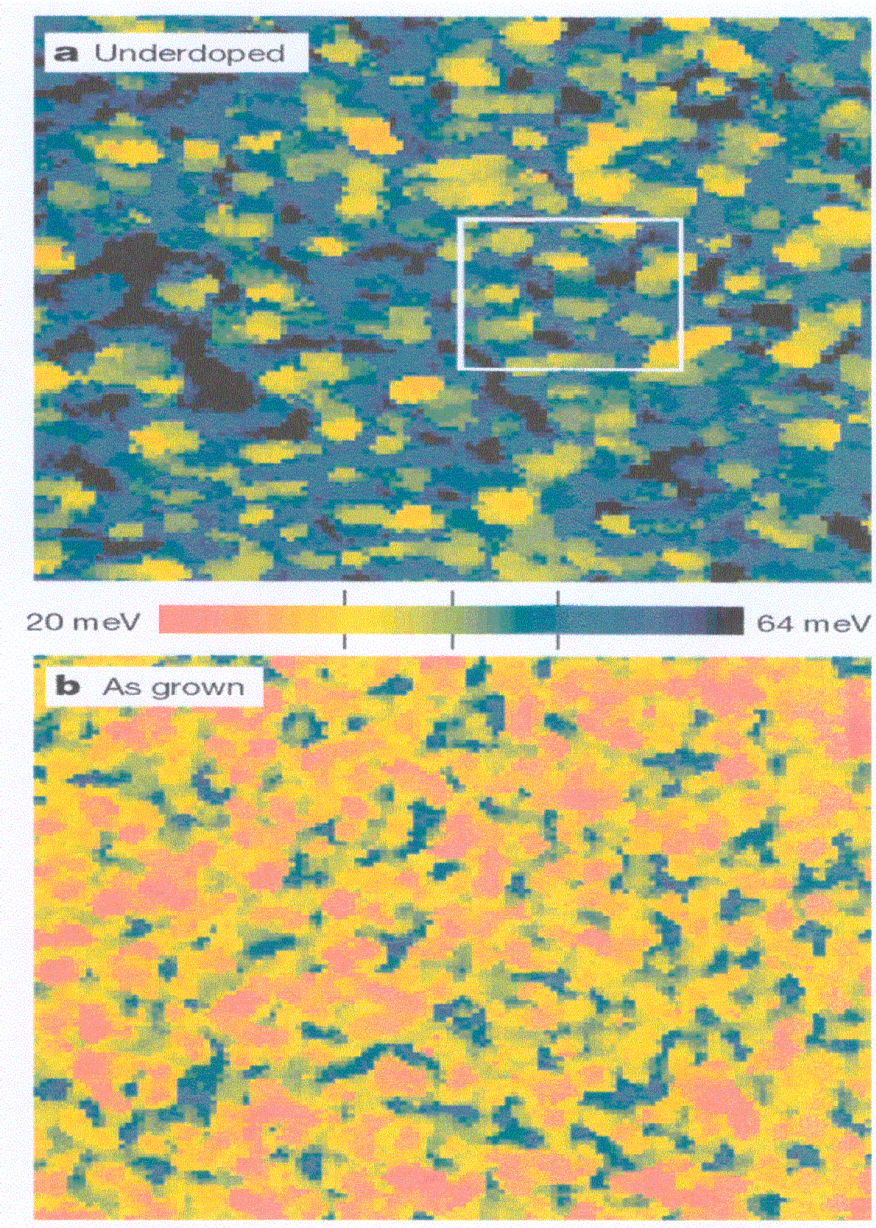
Pb/Bi2212 c-axis Josephson junctions (Möβle & Kleiner, 1999)

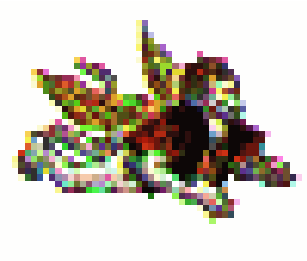
Fraunhofer, Shapiro analyses I_cR_n~8μV





K. M. Lang *et al*. Nature **415**, 412 (2002).





Average stoichiometry

$Bi_{2.15}Sr_{1.92}Ca_{0.75}Cu_2O_{8+\delta}$ Petricek *et al.* 90

$Bi_{2.12\pm0.1}Sr_{1.79\pm0.1}Ca_{0.92\pm0.05}Cu_2O_{8+\delta}$ Gao *et al.* 93

$Bi_{2.05\pm0.03}Sr_{1.98\pm0.01}Ca_{0.75\pm0.03}Cu_{2\pm0.04}O_{8+\delta}$ Kan & Moss 92

$Bi_{2.1\pm0.1}Sr_{1.9\pm0.1}Ca_{1.0\pm0.1}Cu_2O_{8+\delta}$ Grebille *et al.* 96

6% of Bi^{+3} ions replace Sr^{+2} and Ca^{+2} ion site vacancies; O^{-2} ions likely move in to balance charge

$Bi_{2+x}Sr_{2-x}CaCu_2O_{8+\delta}$ Eisaki *et al.*, PRB **69**, 064512 (2004). $82.4K \leq T_c(x) \leq 94K$ with $0.2 \geq x \geq 0$. Doping by O_2 annealing. Many compositions listed in Ref. 9.

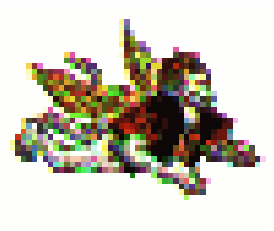
$Bi_{2.22}Sr_{1.55}Ca_{1.17}Cu_{2.01}O_{8+\delta}$ Vedeneev & Maude PRB **72**, 144519 (2005). T_c=84K Quadratic or flat DOS in break-junction tunneling. No O_2 annealing. Excess Bi $\Rightarrow$UD.

Bulk, static nanodomain disorder

Neutron, electron, x-ray diffraction

P. A. Miles *et al.*, Physica C **294**, 275 (1998).

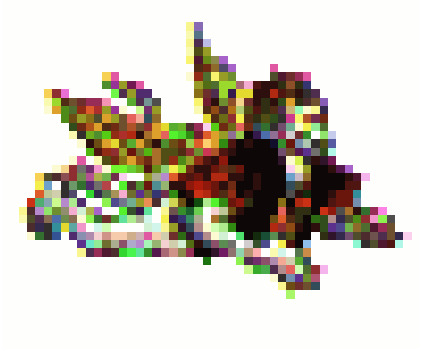
Y. Zhu *et al.*, Microsc. Microanal. **9**, 442 (2003).



Too dirty for d-waves, scarecrow!

Nanoscale chemical and ordering disorder (CDW & SC)

CDW and superconducting orderings are in distinct nanoregions in real space, probably determined by the local chemical composition.

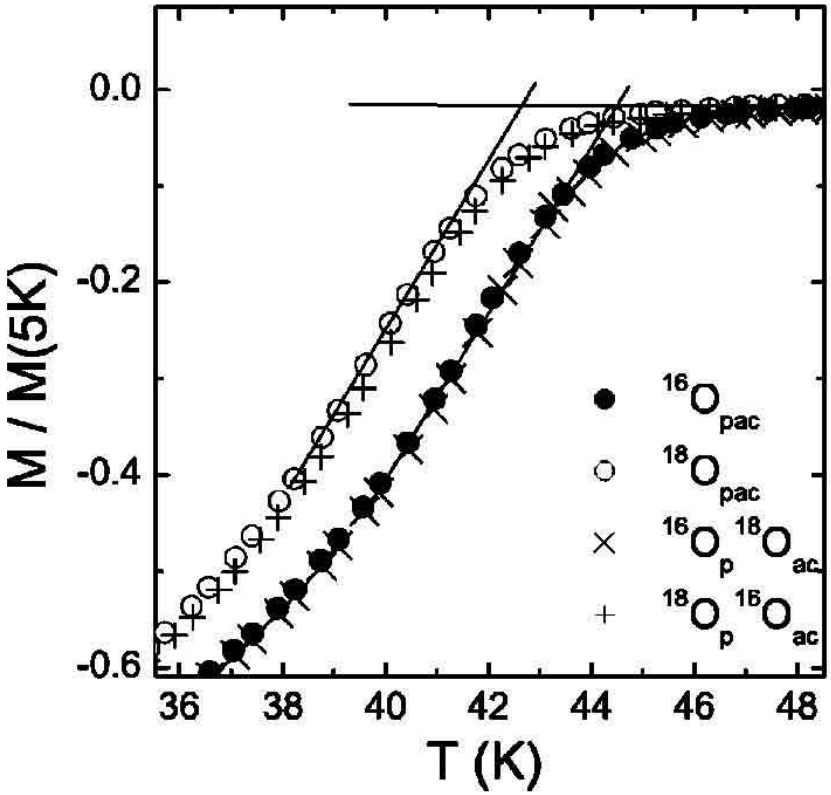


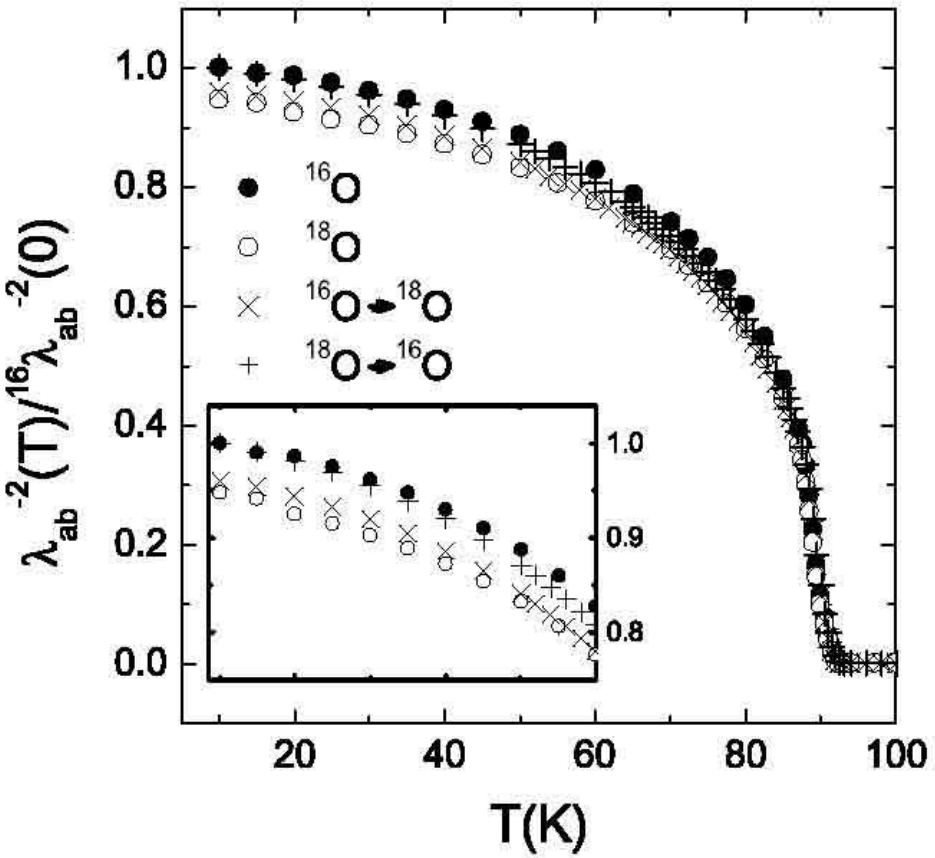
The “p-word”

(If you say “phonons”),
I’ll get you my pretty!

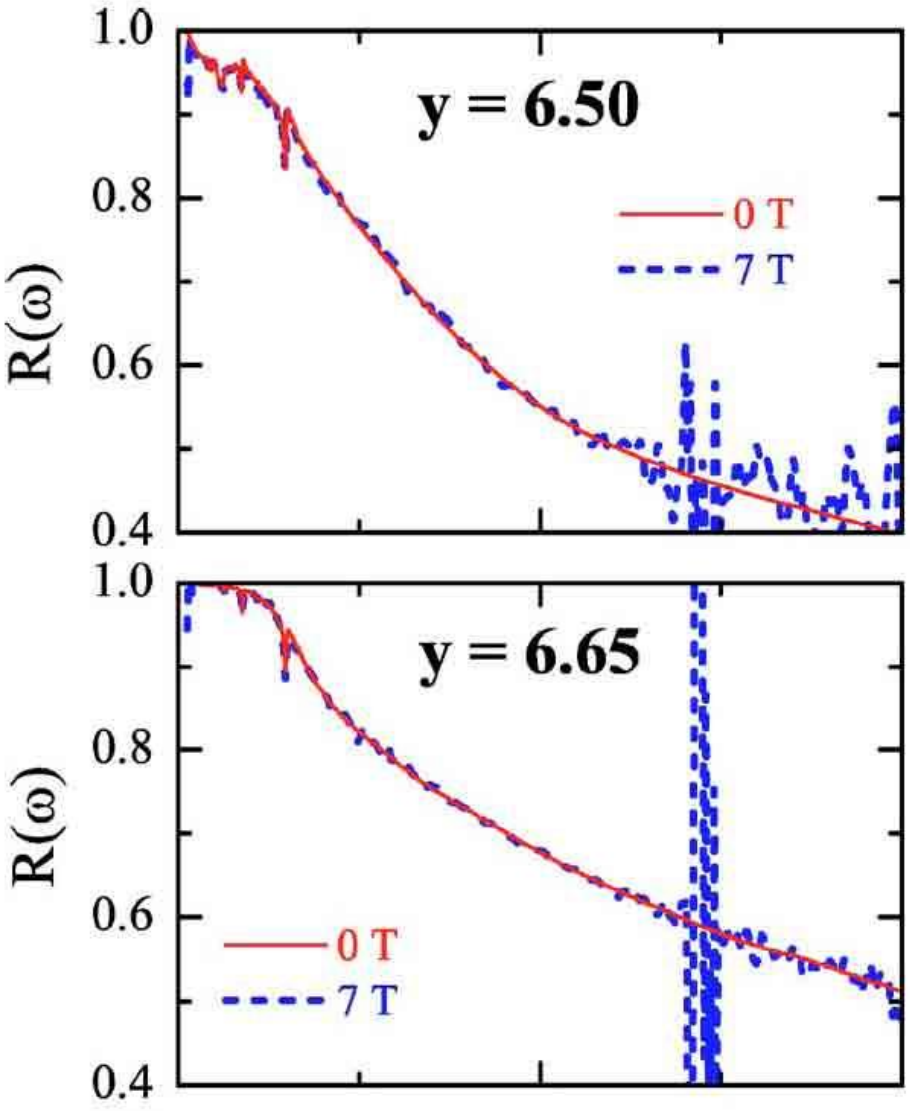
R. Khasanov *et al.*, PRB **68**, 220506 (2003); PRL **92**, 057602 (2004).

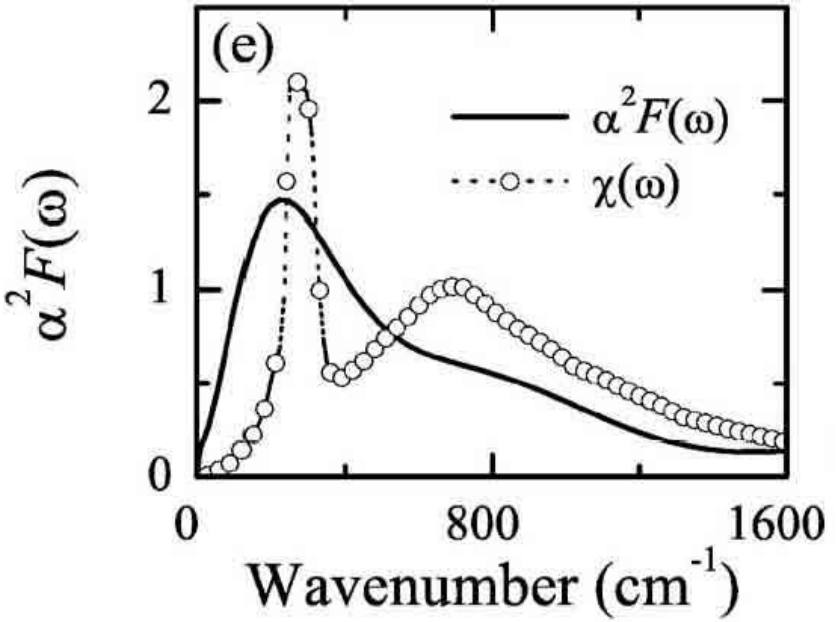
[$Y_{0.6}Pr_{0.4}Ba_2Cu_3O_{7-\delta}$; $YBa_2Cu_3O_{7-\delta}$]





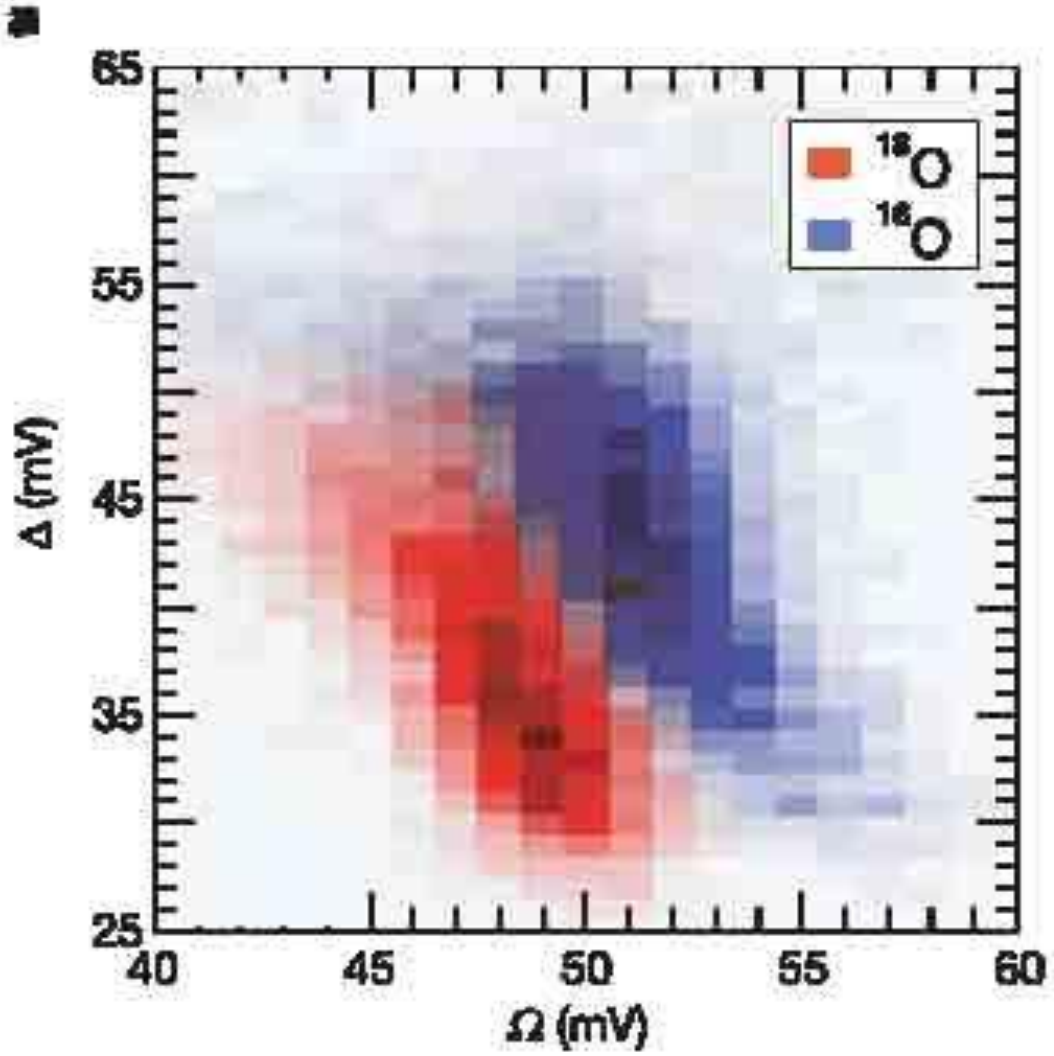
Y. S. Lee *et al.*, Phys. Rev. B **72**, 172511 (2005). [YBCO]





J. Lee *et al.*, Nature **442**, 546 (2006).

Ω from d^2I/dV^2 with STM

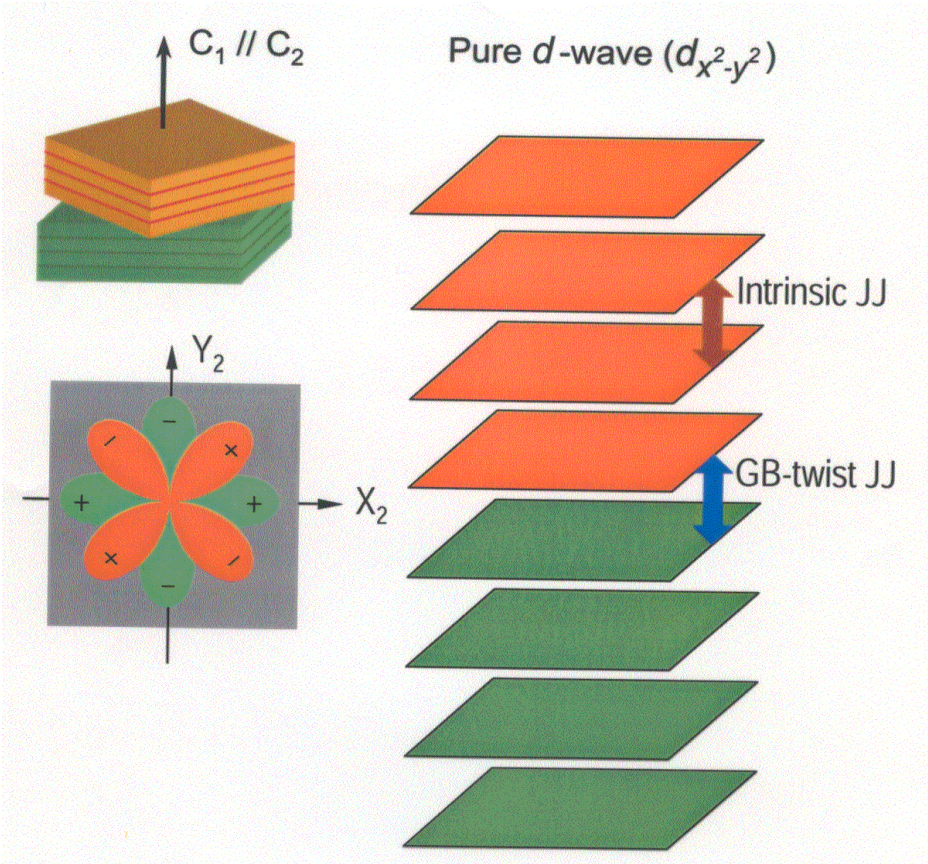


$Bi_2Sr_2CaCu_2O_{8+\delta}$ c-axis twist Josephson junctions

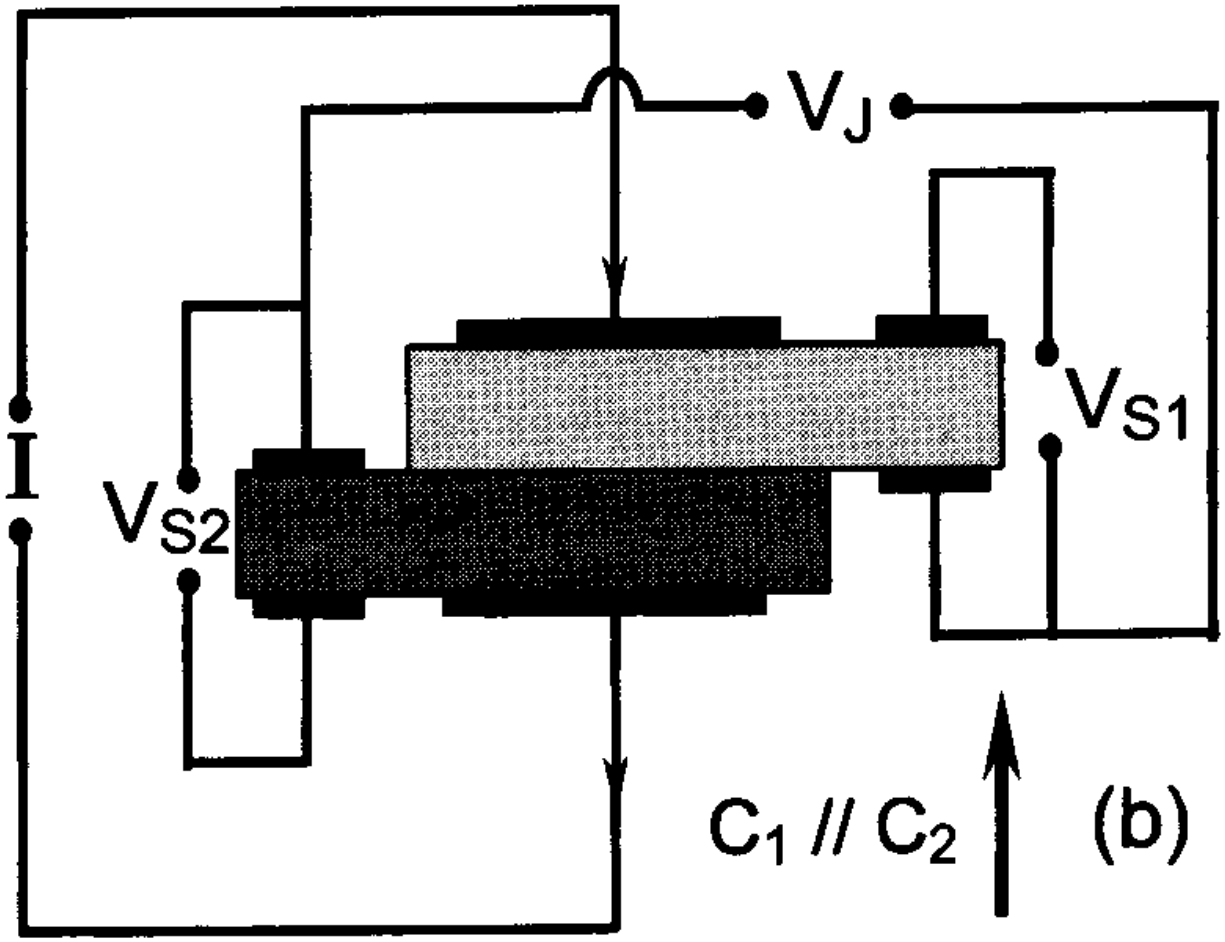
Qiang Li *et al.*, Phys. Rev. Lett. **83**, 4160 (1999).

Review article of the three twist experiments:
RAK, Phil. Mag. **85**, 801 (2005).

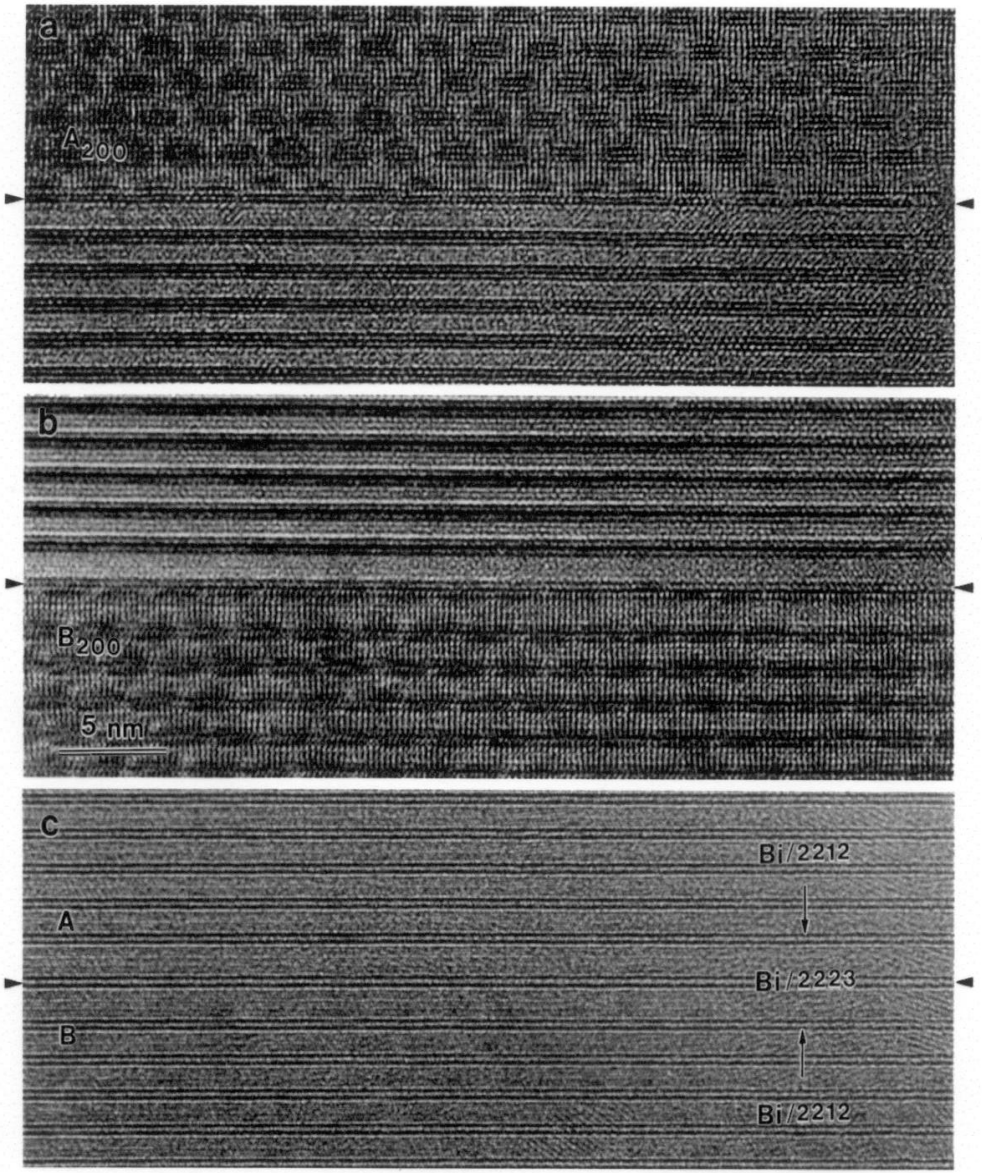
C-axis twist junctions



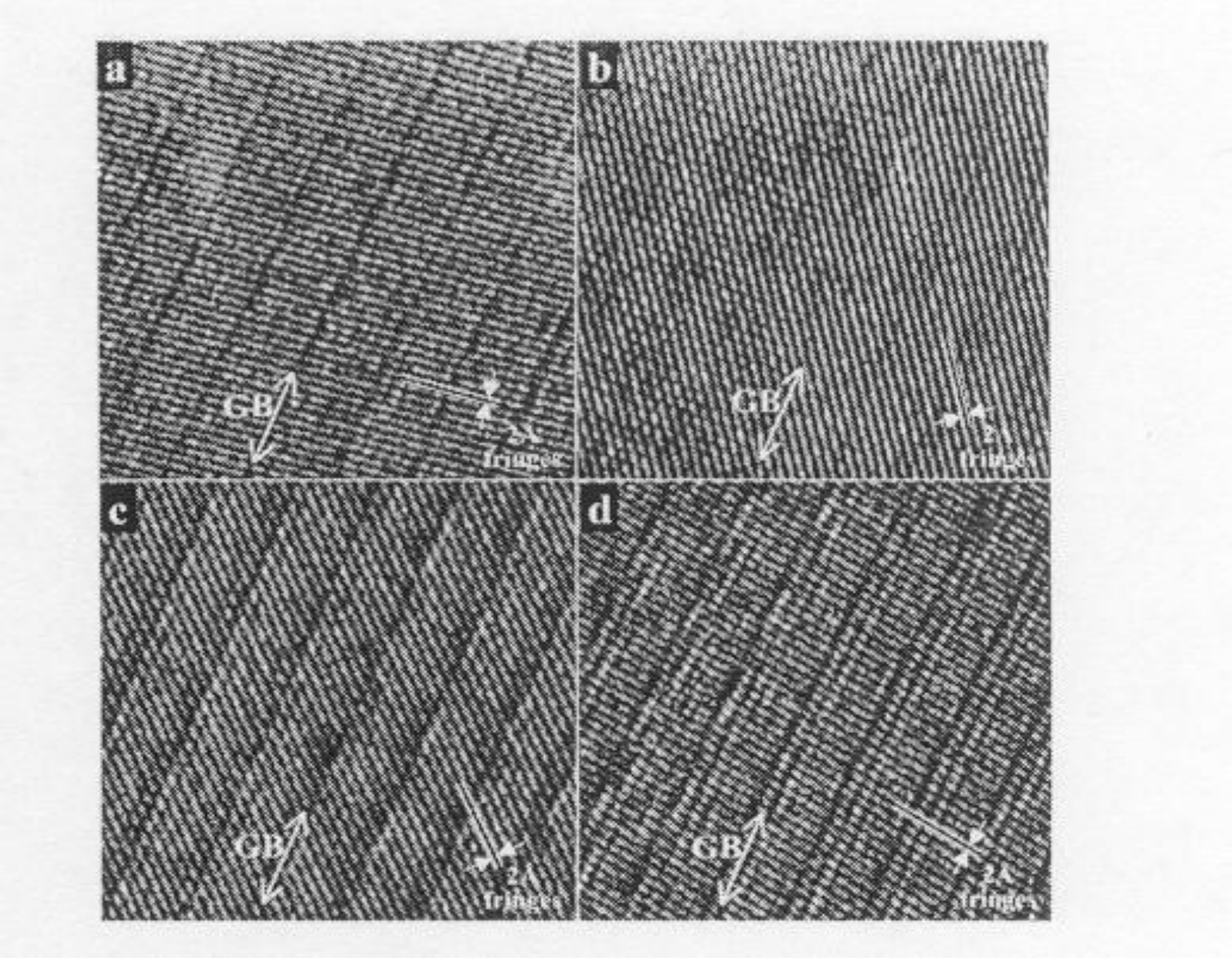
Measurements of I_c



Y. Zhu et al. Phys. Rev. B **57**, 8601 (1998)



M. A. Schofield et al., Phys. Rev. B **67**, 224512 (2003)

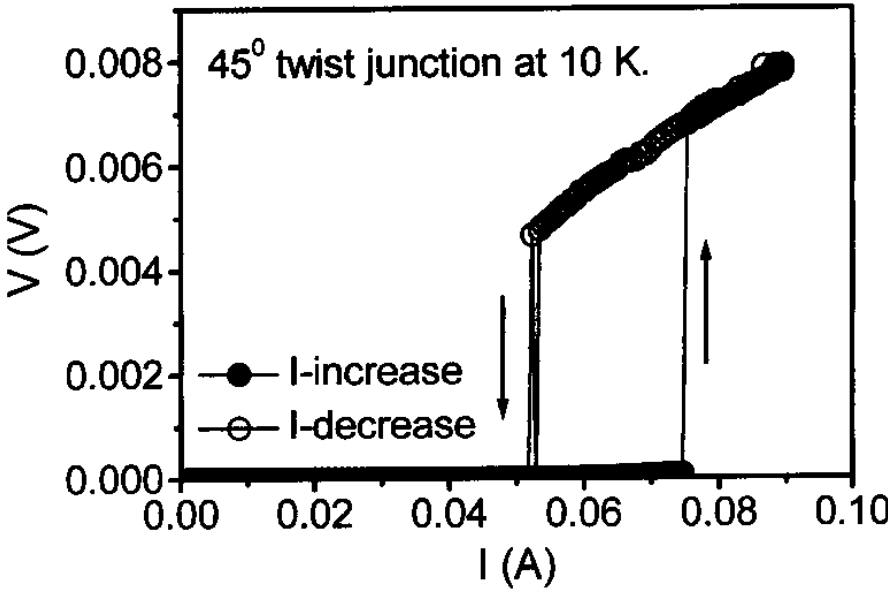


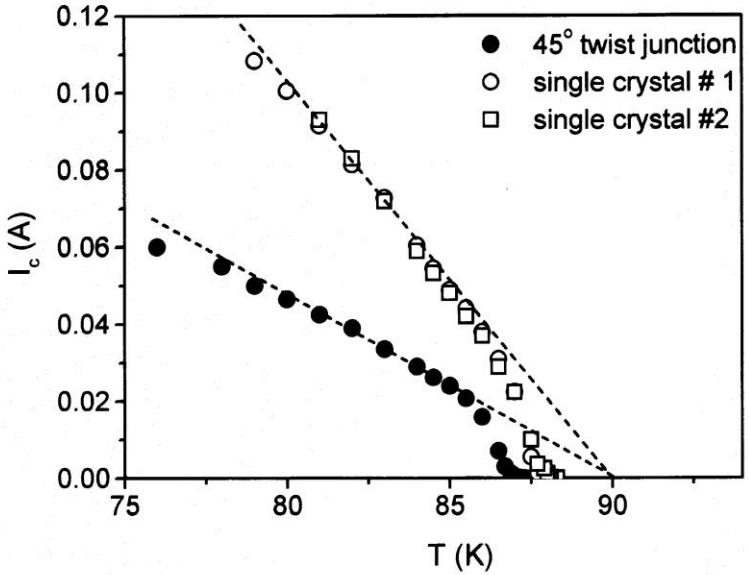
Relative Junction Quality:

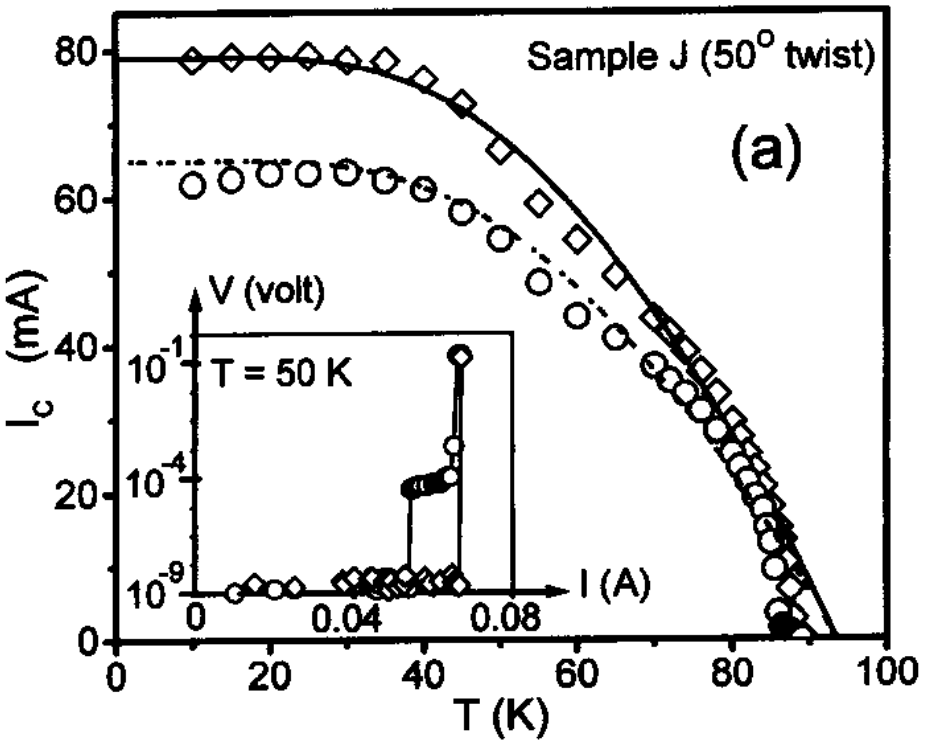
At least 10,000 times superior to all HTSC/HTSC in-plane junctions (Van Harlingen, Tsuei-Kirtley, Mannhart, Claeson, etc.)*

*see the review article by Mannhart and Hilgenkamp

Measurements of I_c^S & I_c^J

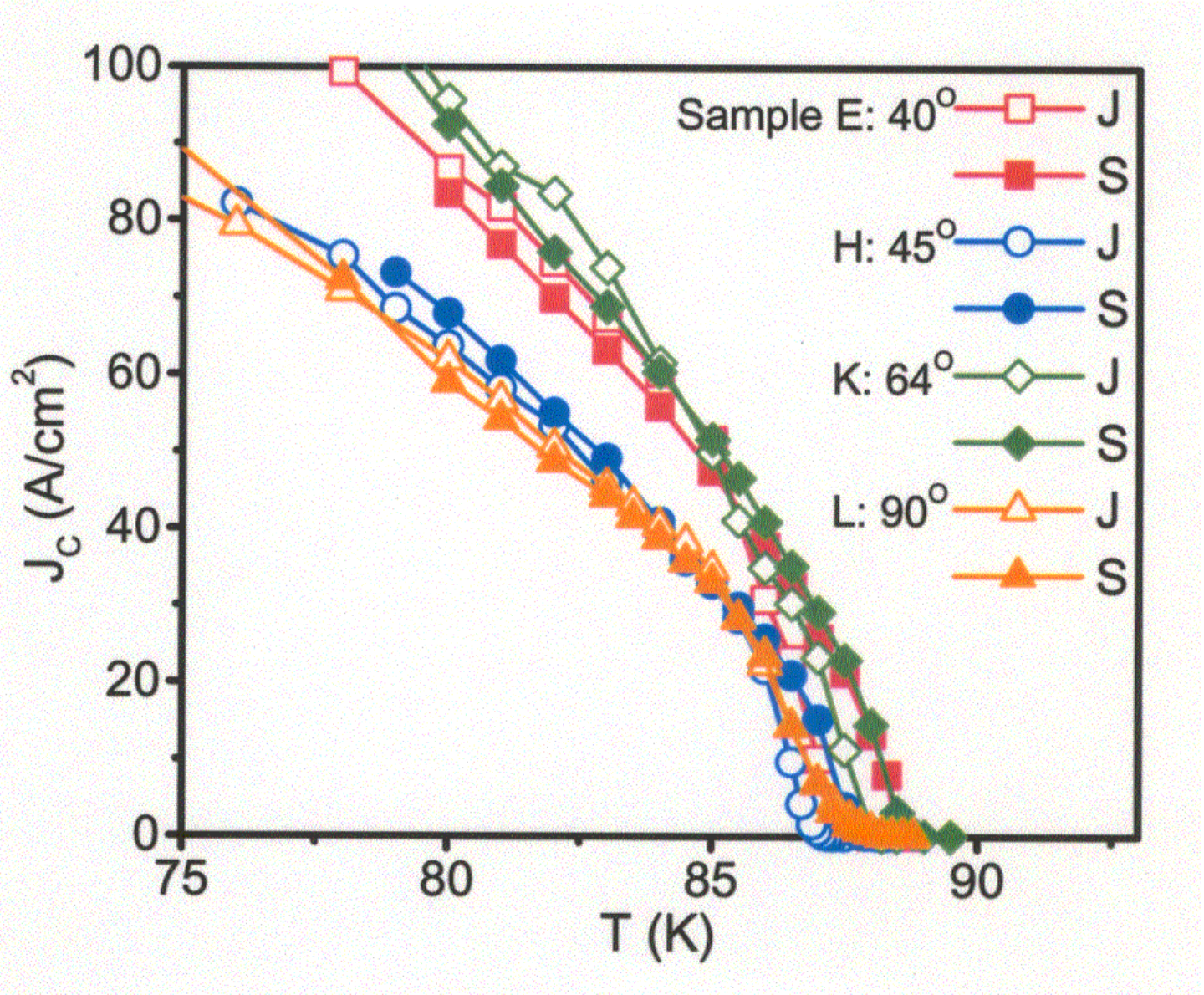




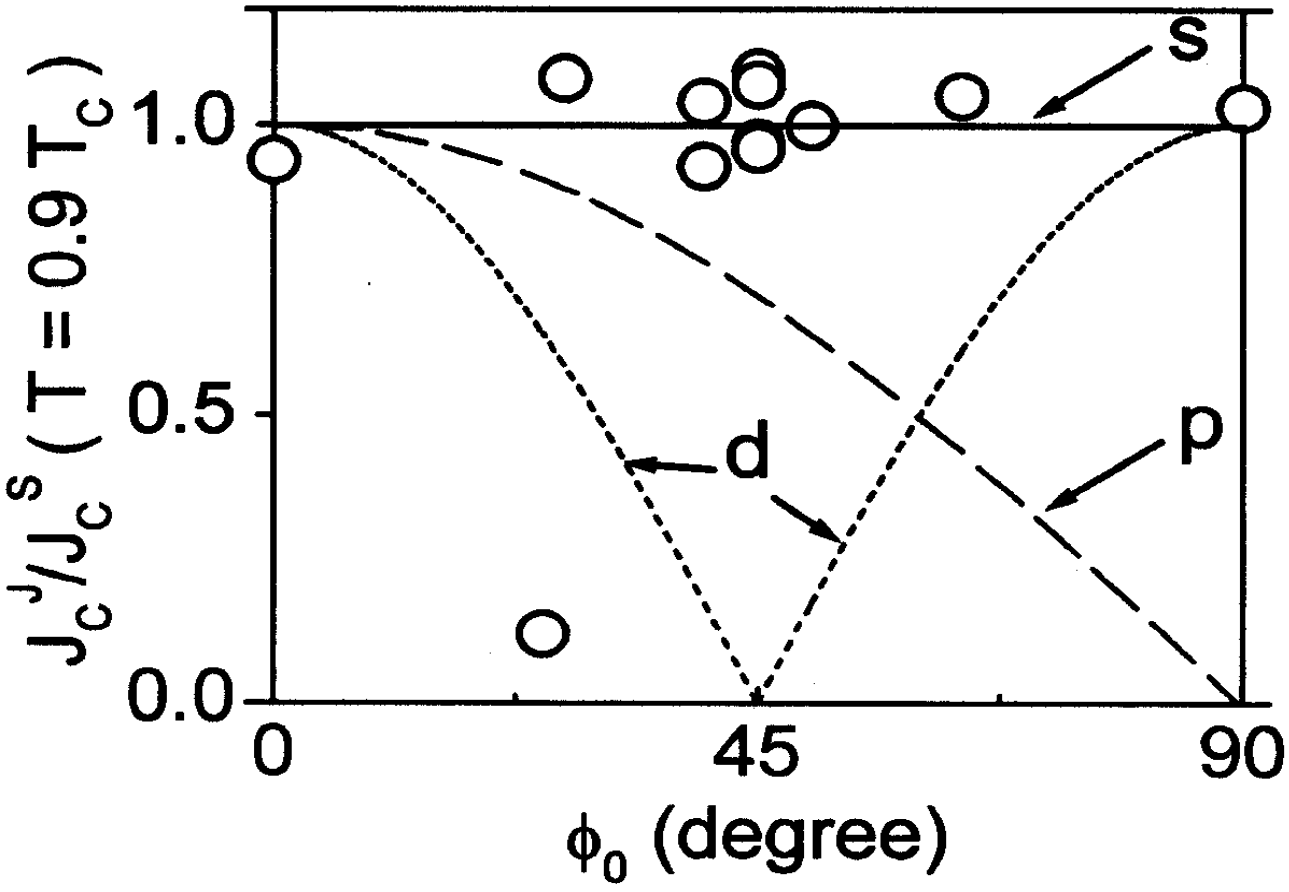


Fluctuations depress T_c by 1-3 K

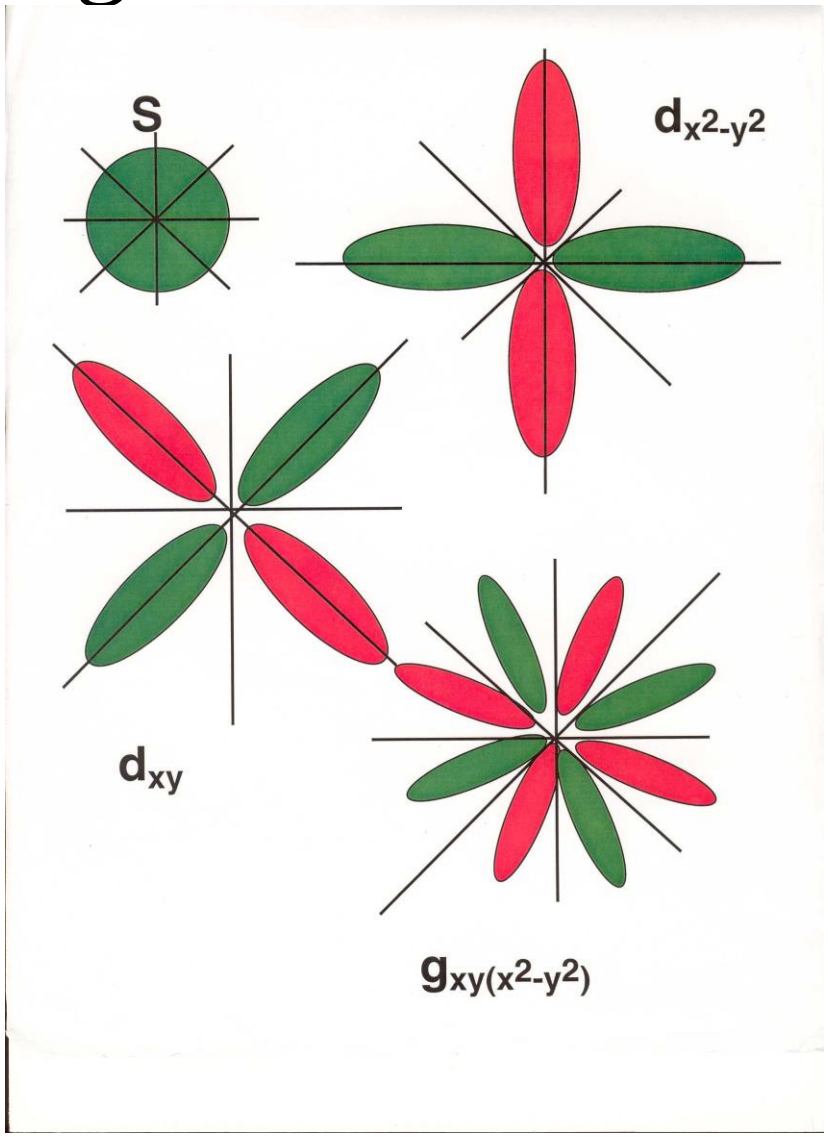
Bicrystal $J_c(T)$



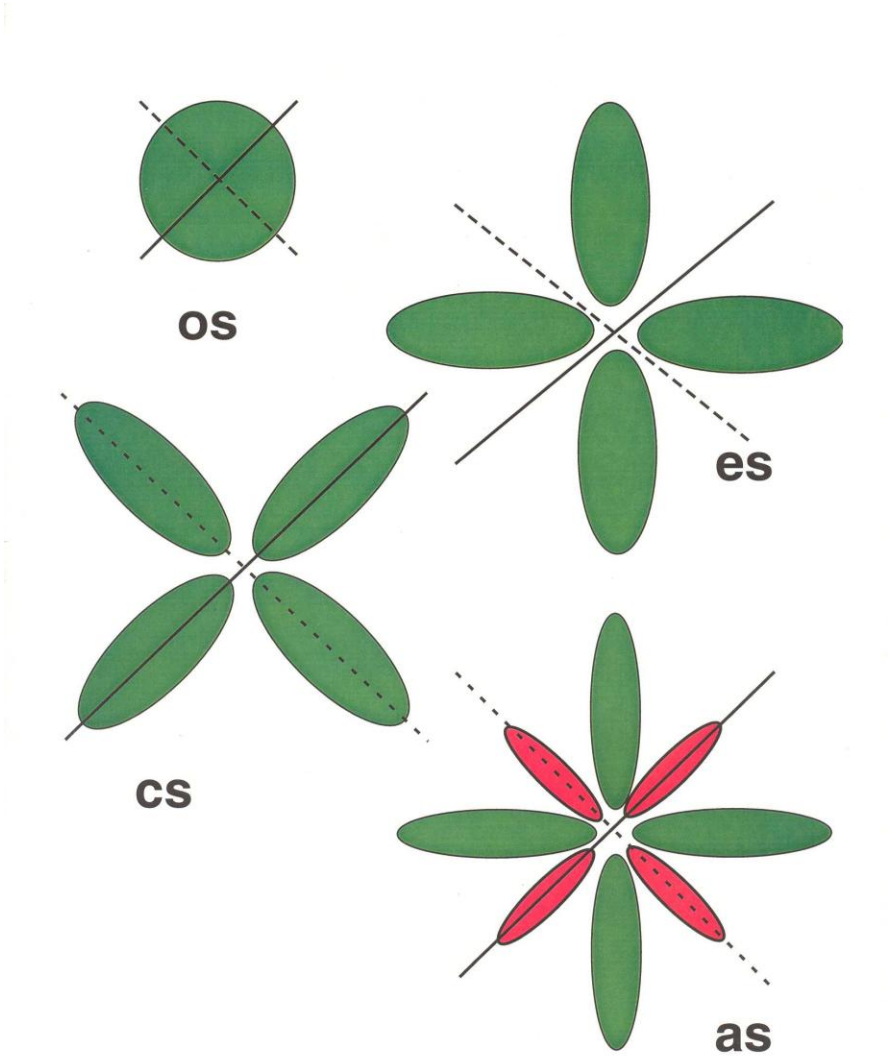
Q. Li et al., Phys. Rev. Lett. **83**, 4160 (1999).

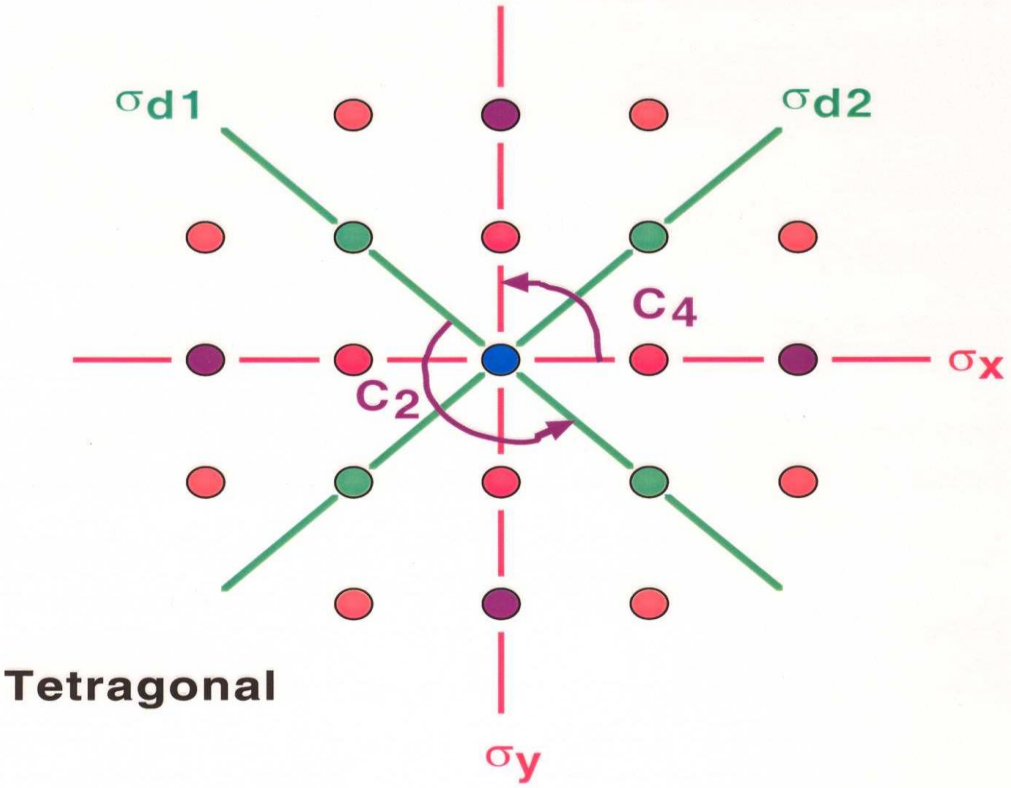


Tetragonal Order Parameters



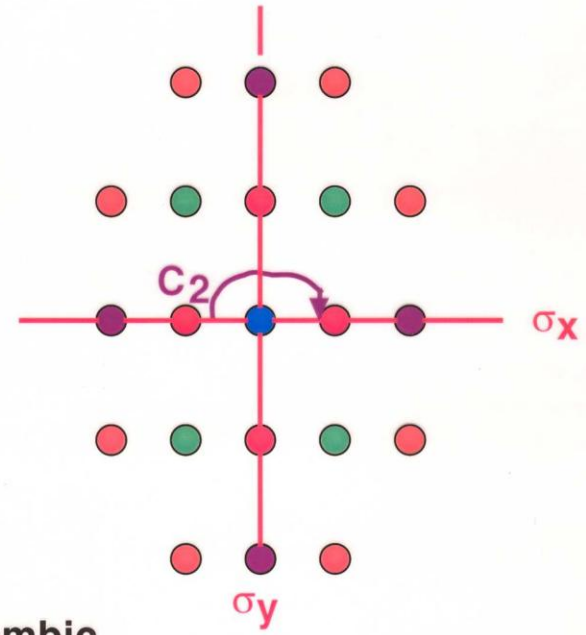
S-wave tetragonal OP's





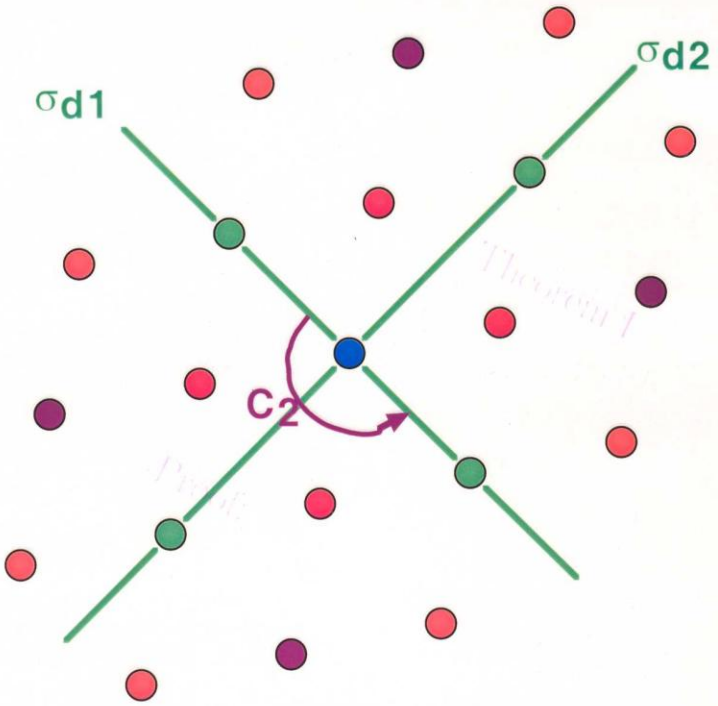
Tetragonal

GT	OP Eigenf.	σ_x σ_y	σ_{d1} σ_{d2}	C_4 C_4^{-1}	C_2
A_1	$\|s\rangle$	+1	+1	+1	+1
B_1	$\|d_{x^2-y^2}\rangle$	+1	-1	-1	+1
B_2	$\|d_{xy}\rangle$	-1	+1	-1	+1
A_2	$\|g_{xy(x^2-y^2)}\rangle$	-1	-1	+1	+1



YBCO orthorhombic

GT OP Eigenf.		σ_x / σ_y	C_2
A_1	$\|s\rangle$ + $\|d_{x^2-y^2}\rangle$	+1	+1
A_2	$\|d_{xy}\rangle$ + $\|g_{xy(x^2-y^2)}\rangle$	-1	+1

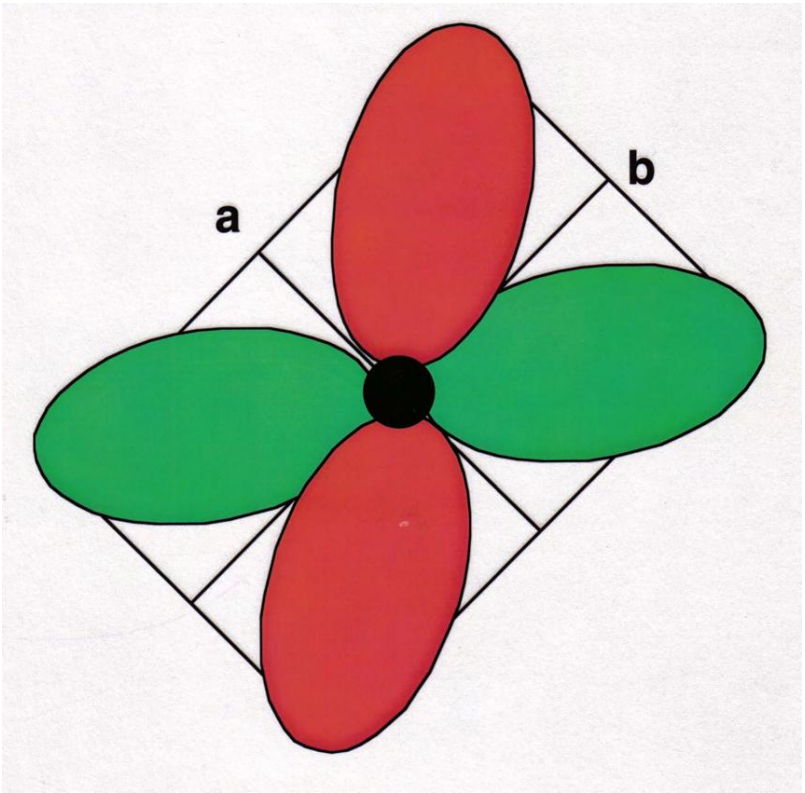


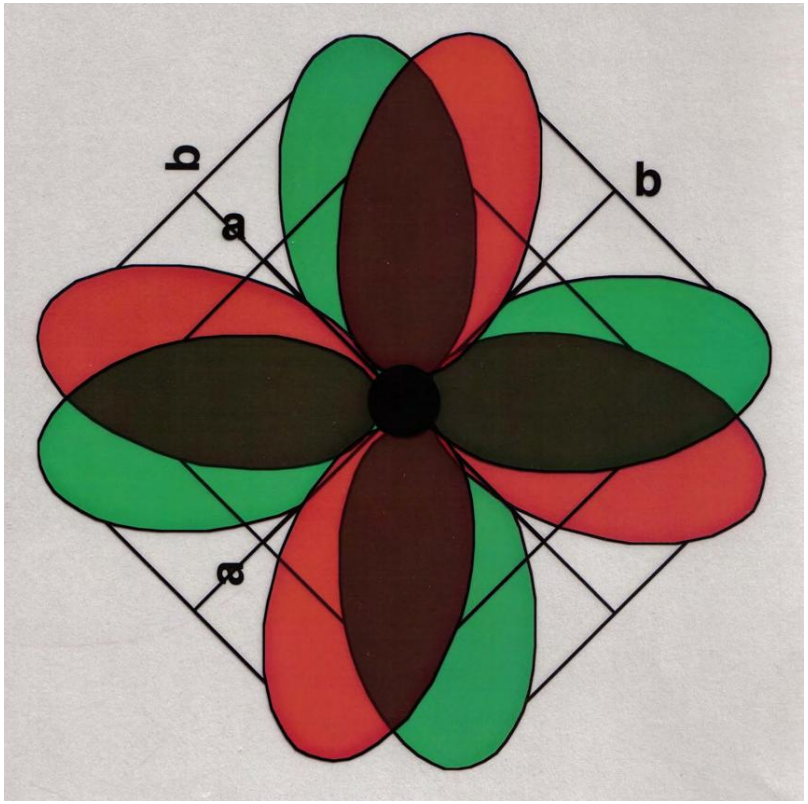
BSCCO orthorhombic

GT	OP Eigenf.	σ_{d1} σ_{d2}	C_2
A_1	$\|s\rangle+\|d_{xy}\rangle$	+1	+1
A_2	$\|d_{x^2-y^2}\rangle$ $+\|g_{xy(x^2-y^2)}\rangle$	-1	+1

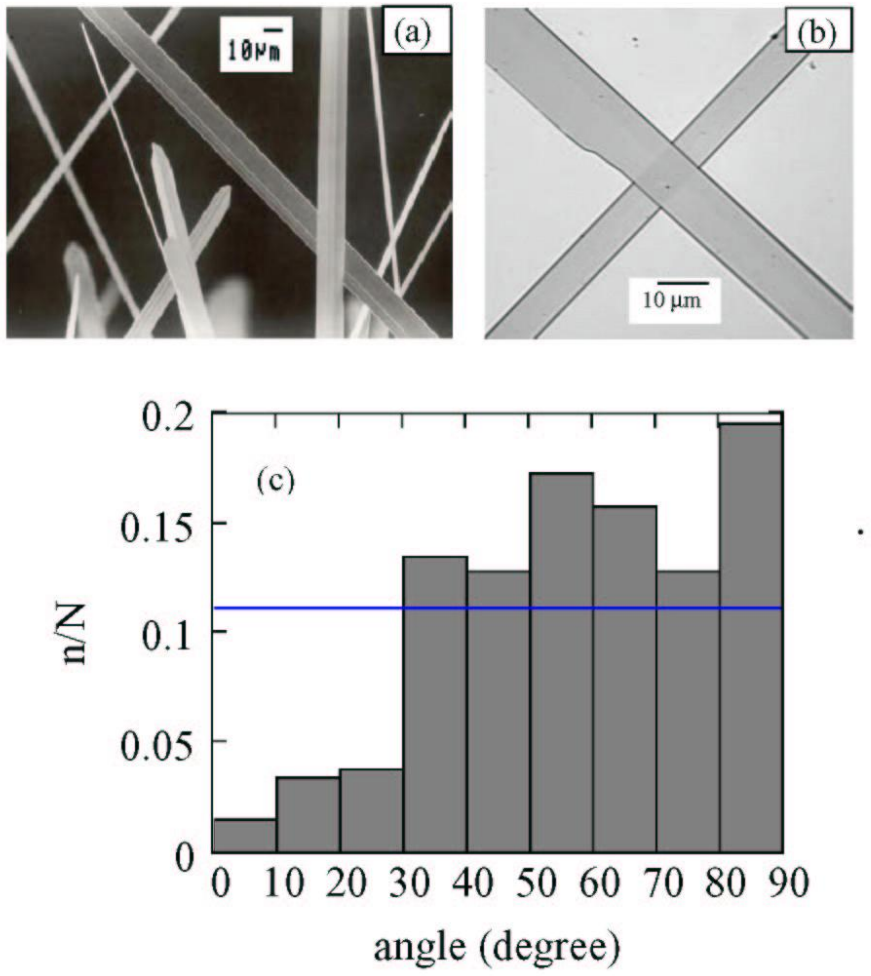
Orthorhombic OP's: $d_{x^2-y^2}$

$\phi_0=0^o$, $I_c>0$; $\phi_0=90^o$, $I_c<0$

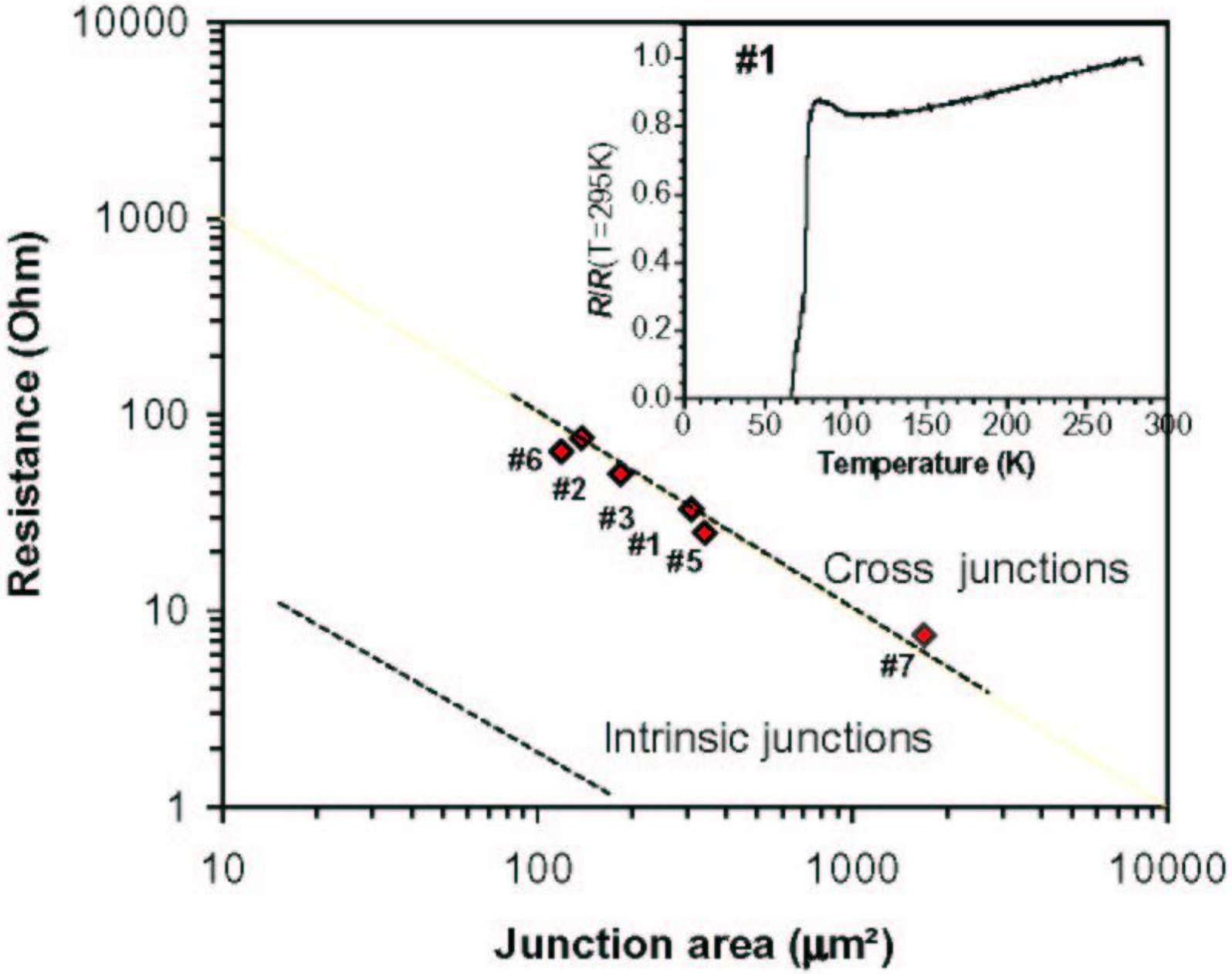


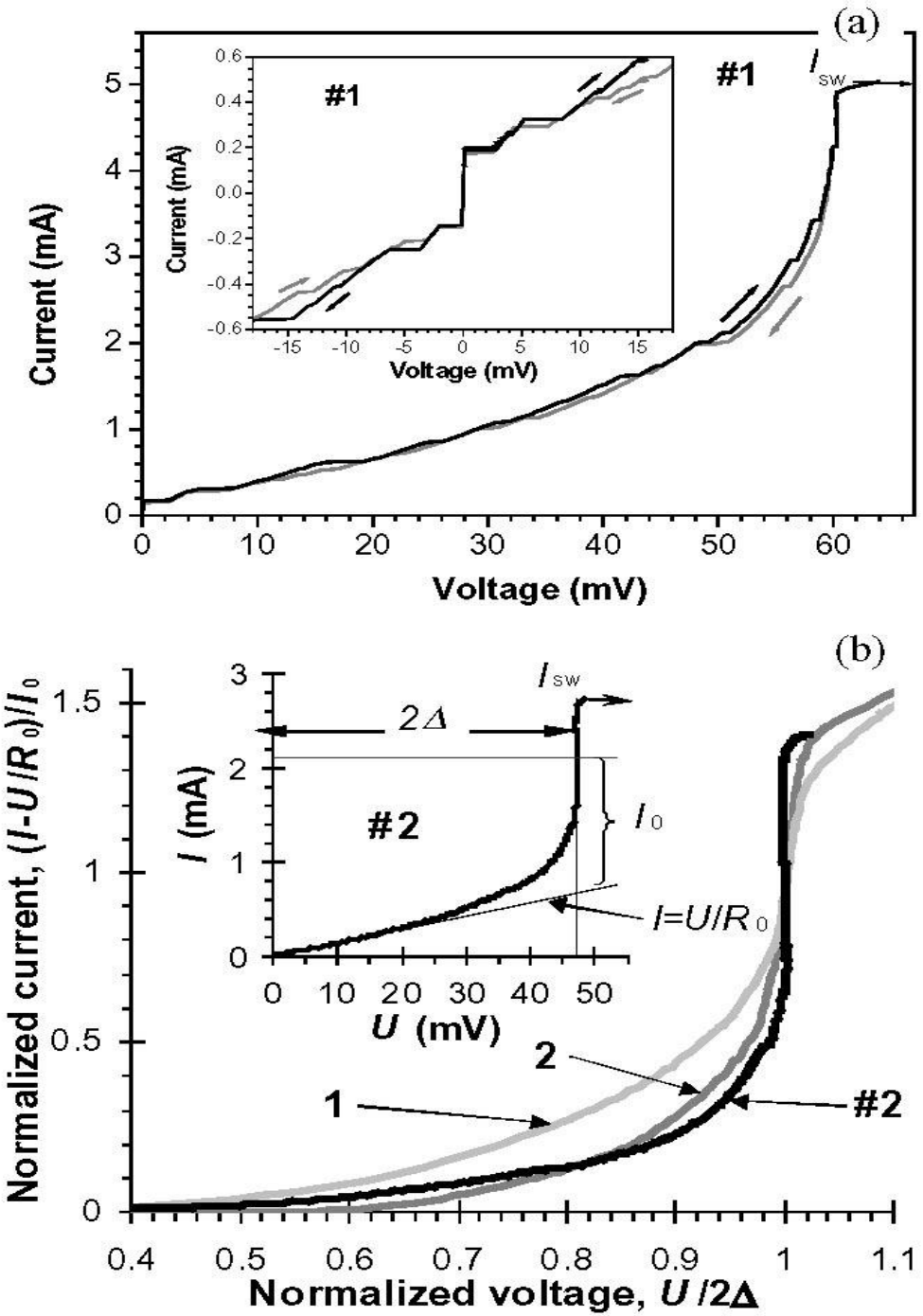


Latyshev *et al.* natural cross whiskers

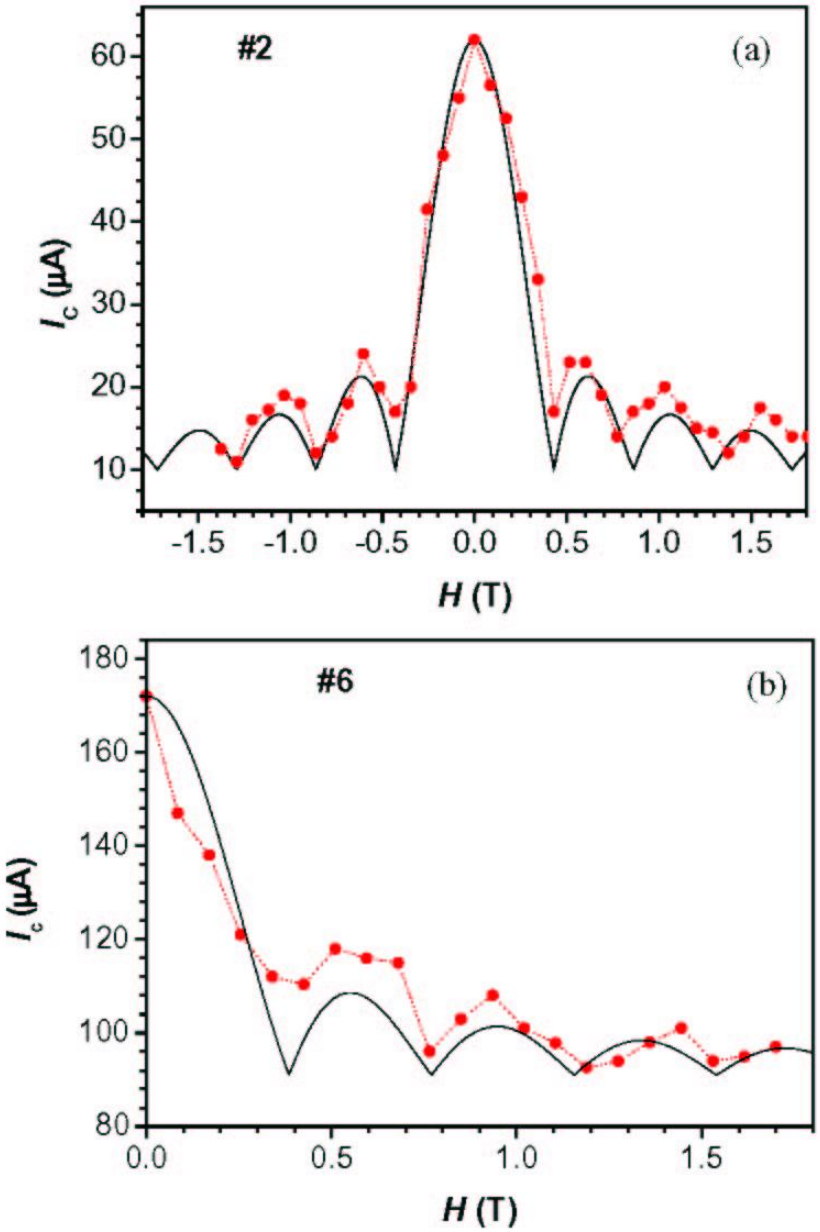


Yu. I. Latyshev *et al.*, Phys. Rev. B **70**, 094517 (2004).

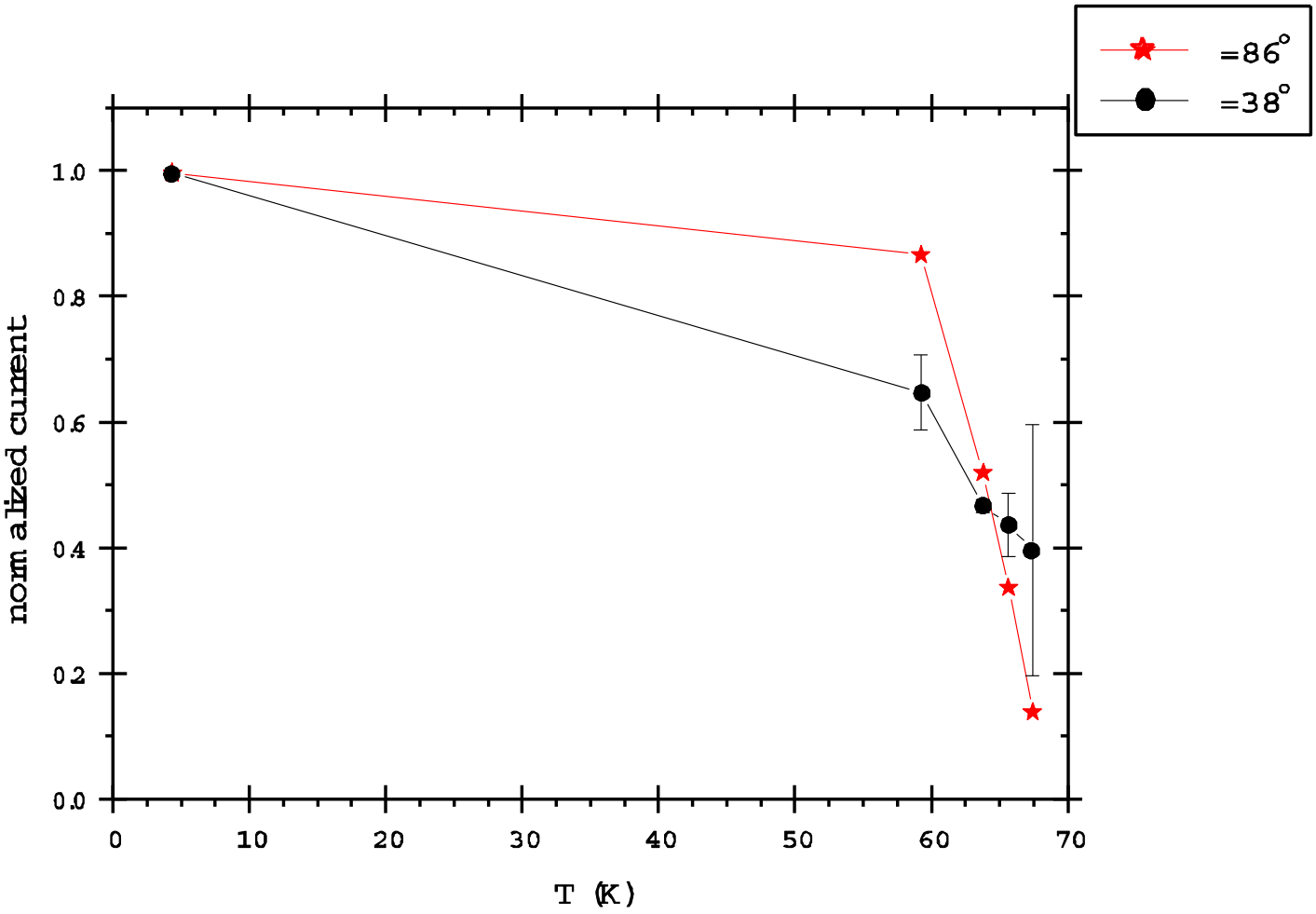

10000
1000
100
10
1
Resistance (Ohm)
10
100
1000
10000
Junction area (μm²)
#6
#2
#3
#1
#5
#7
Cross junctions
Intrinsic junctions
#1
R/R(T=295K)
1.0
0.8
0.6
0.4
0.2
0.0
0
50
100
150
200
250
300
Temperature (K)


(a)
#1
I_{sw}
Current (mA)
Voltage (mV)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-15
-10
-5
0
5
10
15
0
1
2
3
4
5
0
10
20
30
40
50
60
(b)
I_{sw}
2Δ
#2
I (mA)
I_0
$I=U/R_0$
U (mV)
1
2
#2
Normalized current, $(I-U/R_0)/I_0$
Normalized voltage, $U/2\Delta$
0
0.5
1
1.5
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

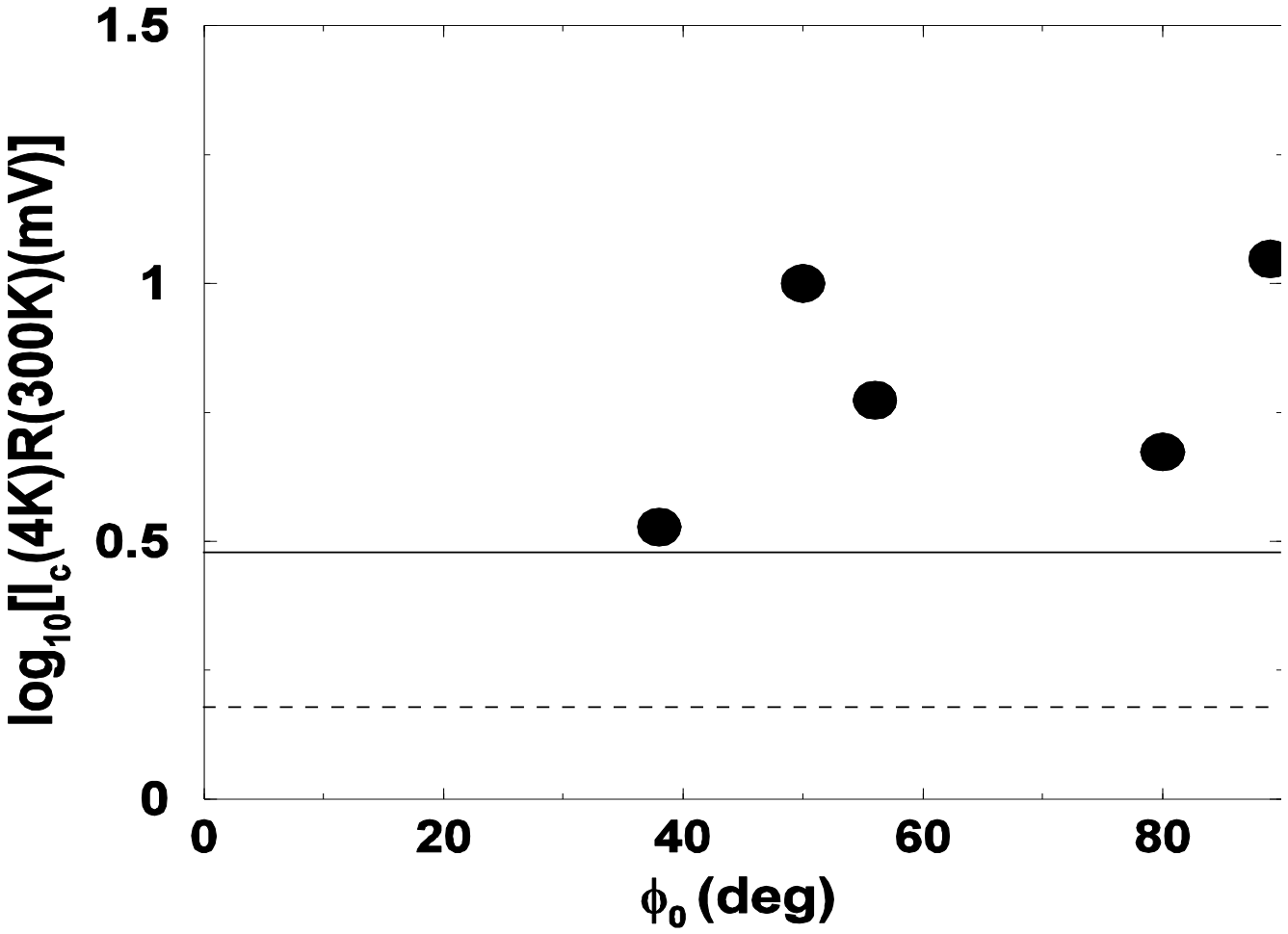
80º, 89º natural cross whiskers



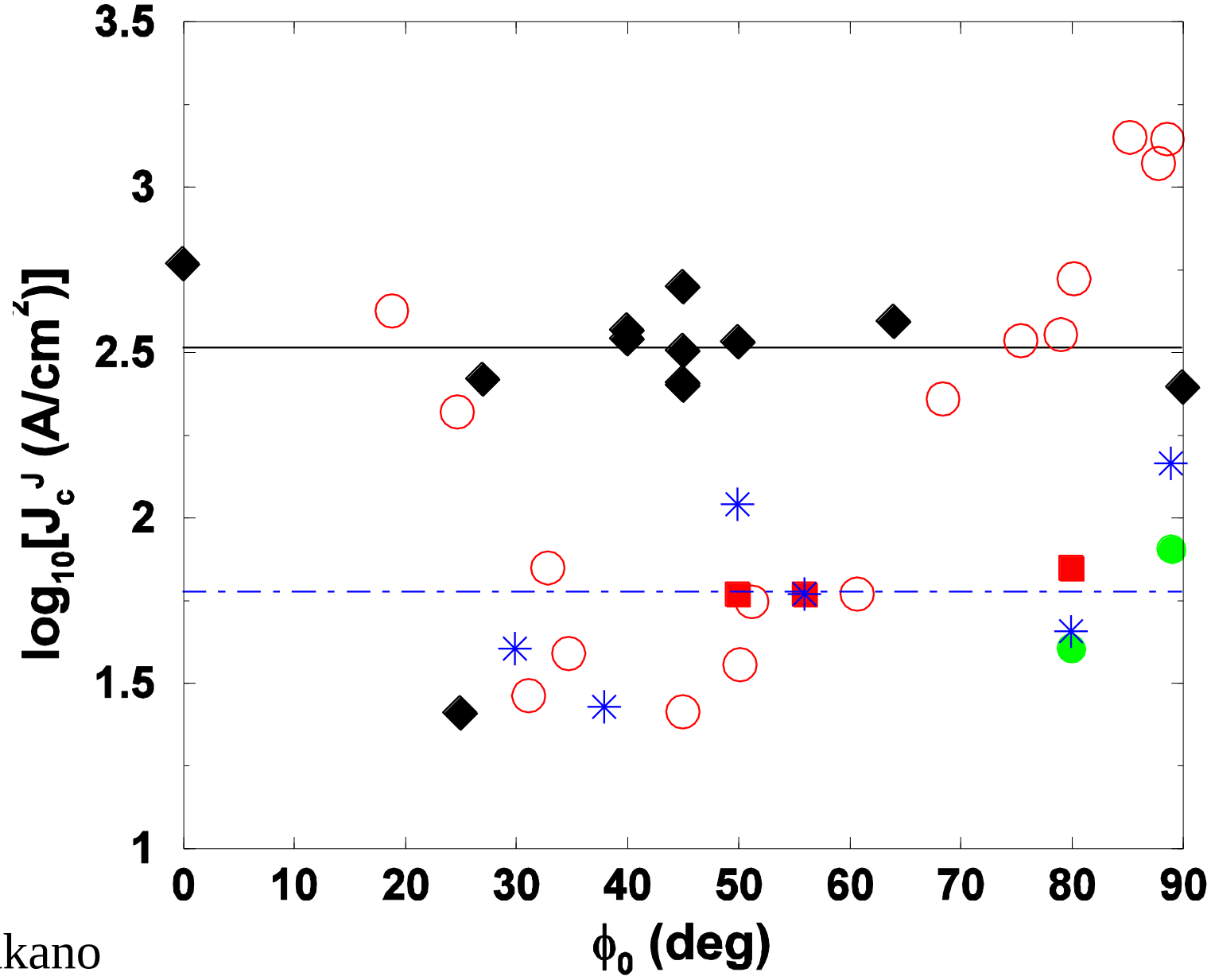
Natural cross whisker T dependence



I_cR of natural cross whiskers
Mean I_cR=7 mV (20% of I_cR_n AB)



Bicrystal, natural & artificial cross whiskers



Y. Takano

Conclusions of the three twist experiments

At least 20% s-wave at T_c
(could be 100%)

Incoherent c-axis tunneling

All c-axis tunneling in the s-wave channel

Require attractive interaction

I'm melting!

Are we in back in Kansas yet?

Which good witches?

Optical phonons (high energy)

Anharmonic phonons (the half-breathing mode?)

High DOS (saddle bands*)

Disorder (removes flying monkeys: CDW', SDW's, magnetism, etc.)

*without compensating interaction renormalizations—M. L. Cohen

Which bad witches?

CDW’s

SDW’s

Magnetism

D-waves

Big U

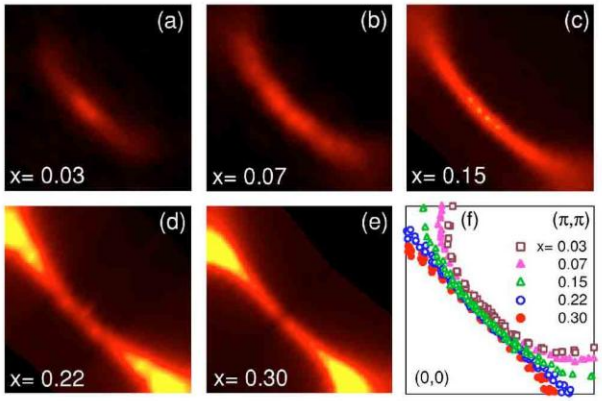
All other exotic theories*

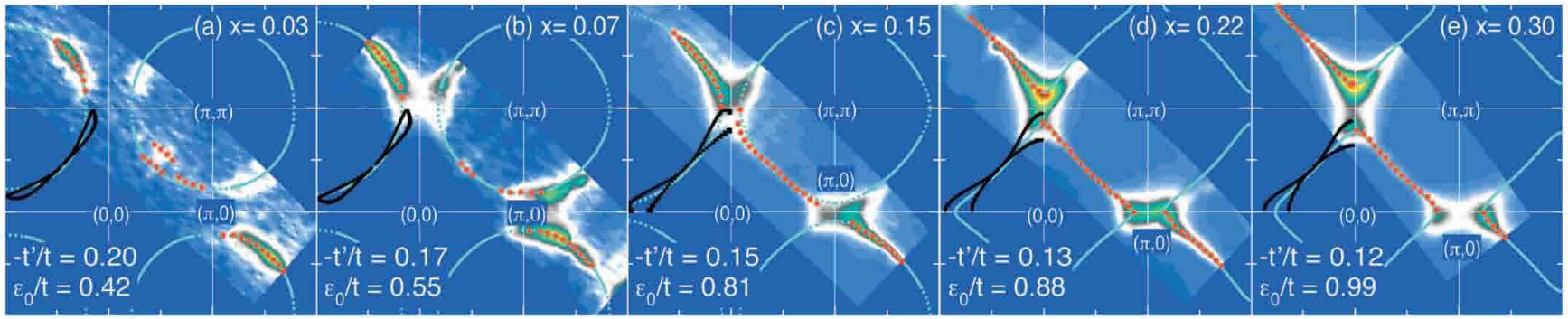
*Feynmann’s axum

High Density of States

Fermi Surface!

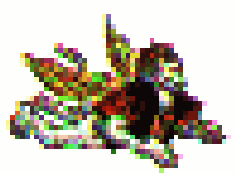
Extended Van Hove singularities





T. Yoshida *et al*., Phys. Rev. B **74**, 224510 (2006).

Hence, on the yellow brick road to the emerald city:



- Avoid the flying monkeys
- Water the d-witches
- Avoid the poppy fields
- Think s-wave!
- Remember what the wizard said: phonons!
- Let the good witch Glinda be your guide
- Wear the ruby slippers

``We're off to see the wizard, the wonderful wizard of oz…''

Follow the Yellow Brick Road. Follow the Yellow Brick Road.

Follow, follow, follow, follow,

Follow the Yellow Brick Road.

Follow the Yellow Brick, Follow the Yellow Brick,

Follow the Yellow Brick Road.

We're off to see the Wizard, The Wonderful Wizard of Oz.

You'll find he is a whiz of a Wiz! If ever a Wiz! there was.

If ever oh ever a Wiz! there was The Wizard of Oz is one becoz,

Becoz, becoz, becoz, becoz, becoz.

Becoz of the wonderful things he does.