Magnetic order in lightly hole doped cuprates

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Order and disorder in condensed matter: from solitons to glasses
Ben-Gurion Univ. Beer-Sheva Jan. 25-26 2007
Symposium celebrating Baruch Horovitz's 60th birthday

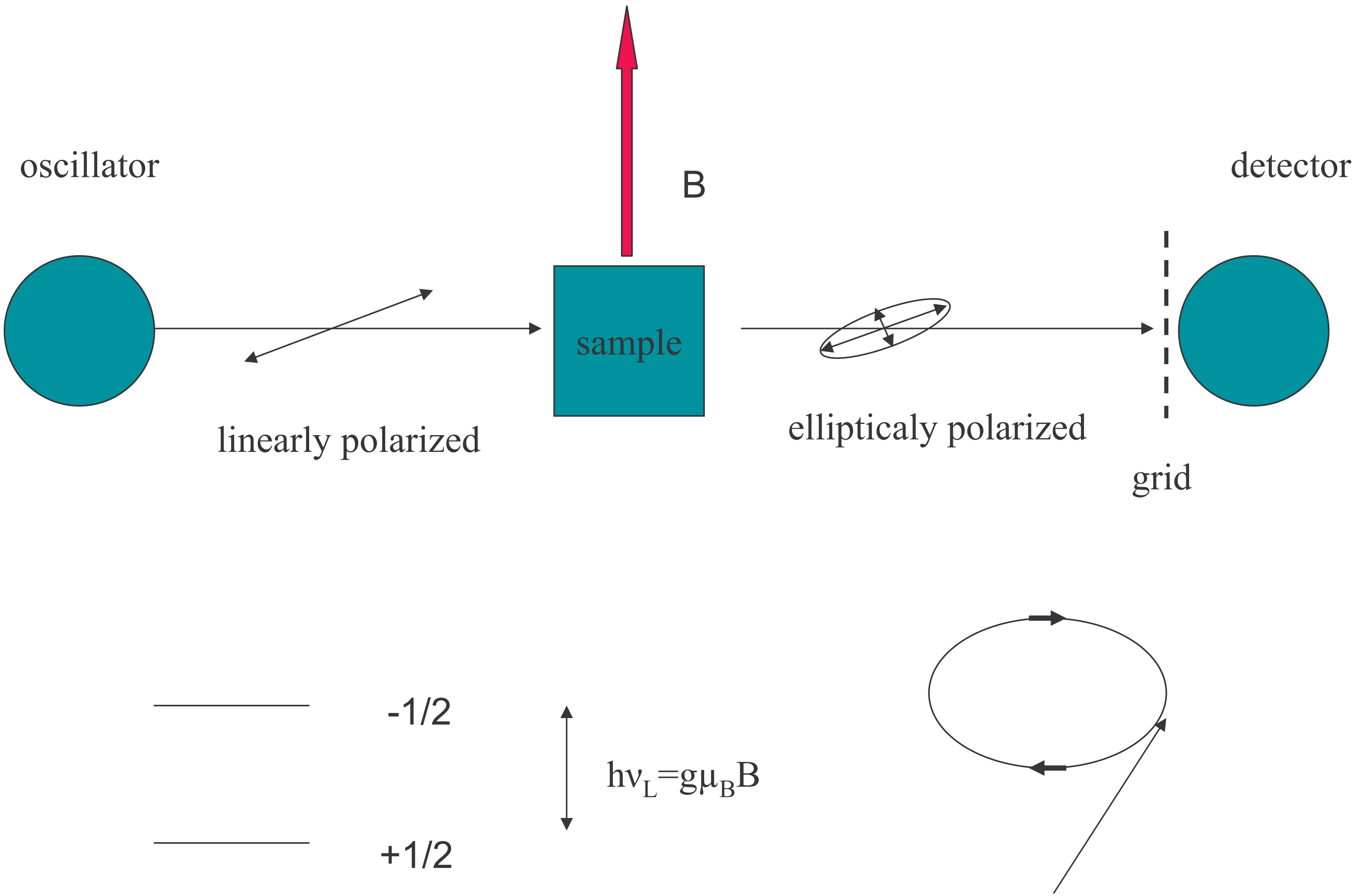
Mihaly Karaszi | Dario Quintavalle | Titusz Feher | Kalman Nagy | A.J.

Baruch,
Many happy
returns!

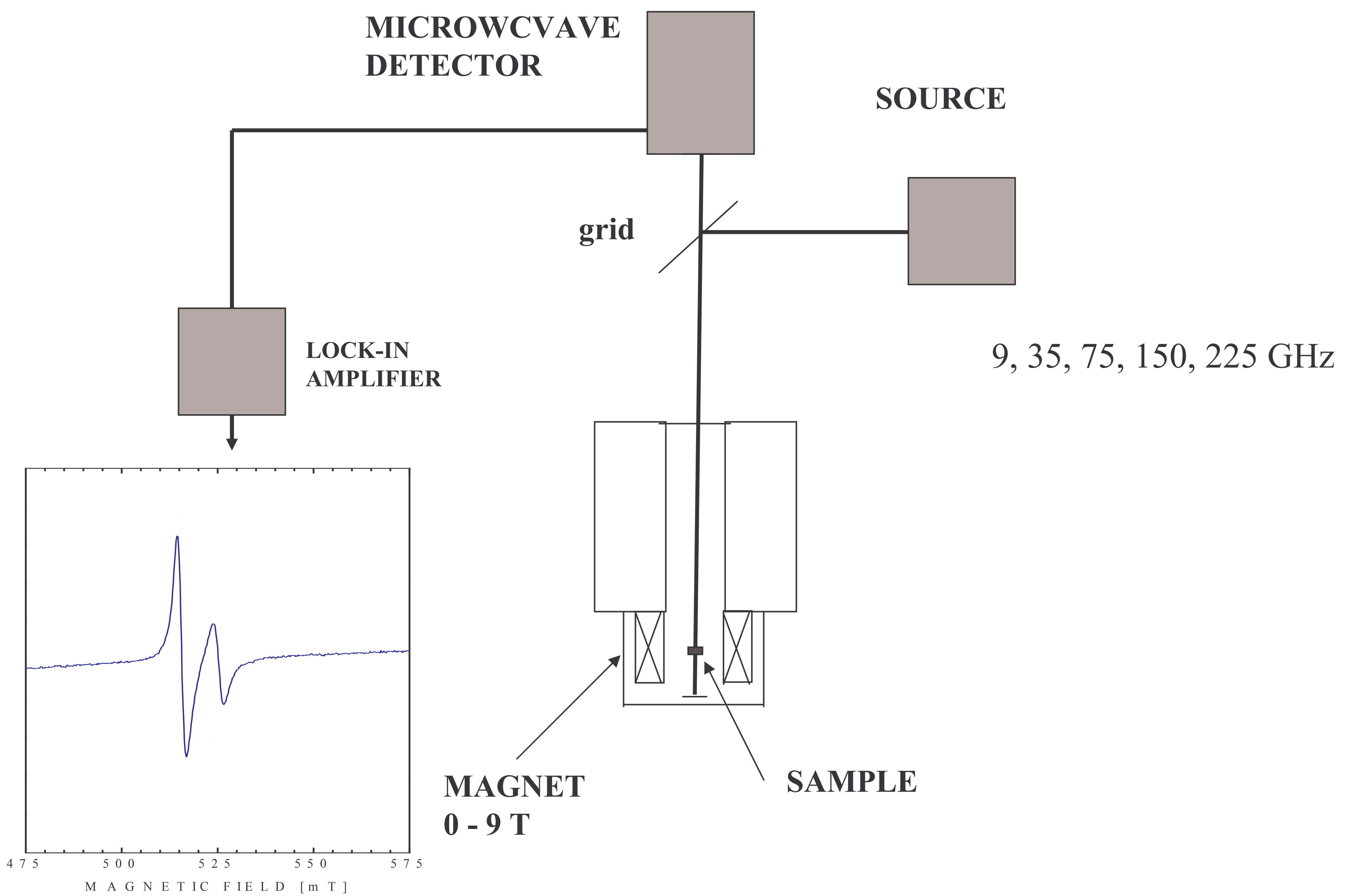
Sorry,
I could not come,
I am supervising
the construction of
the new ESR
day and night !

Fred Zawadowski

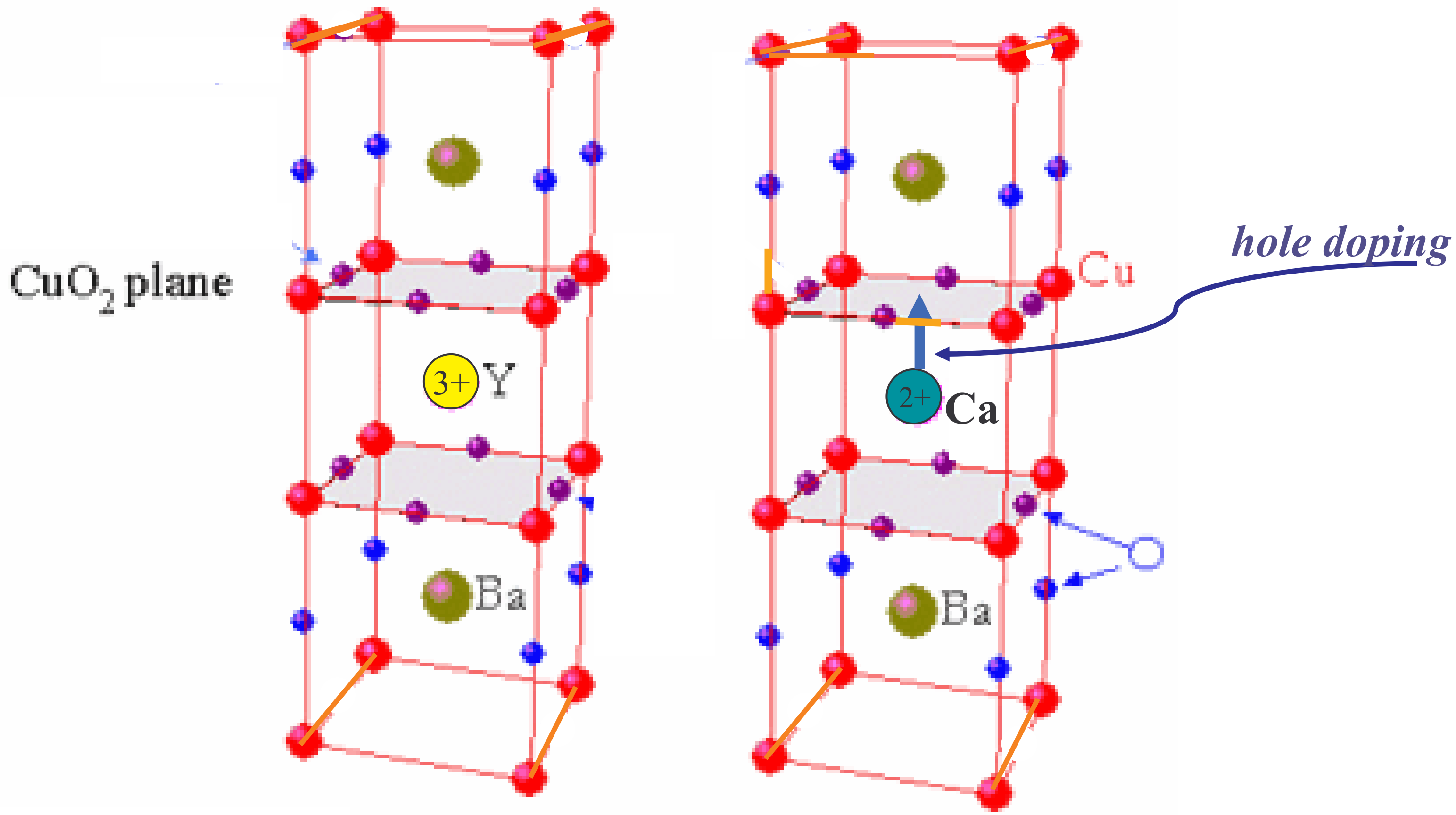
ESR spectrometer



ESR spectrometer

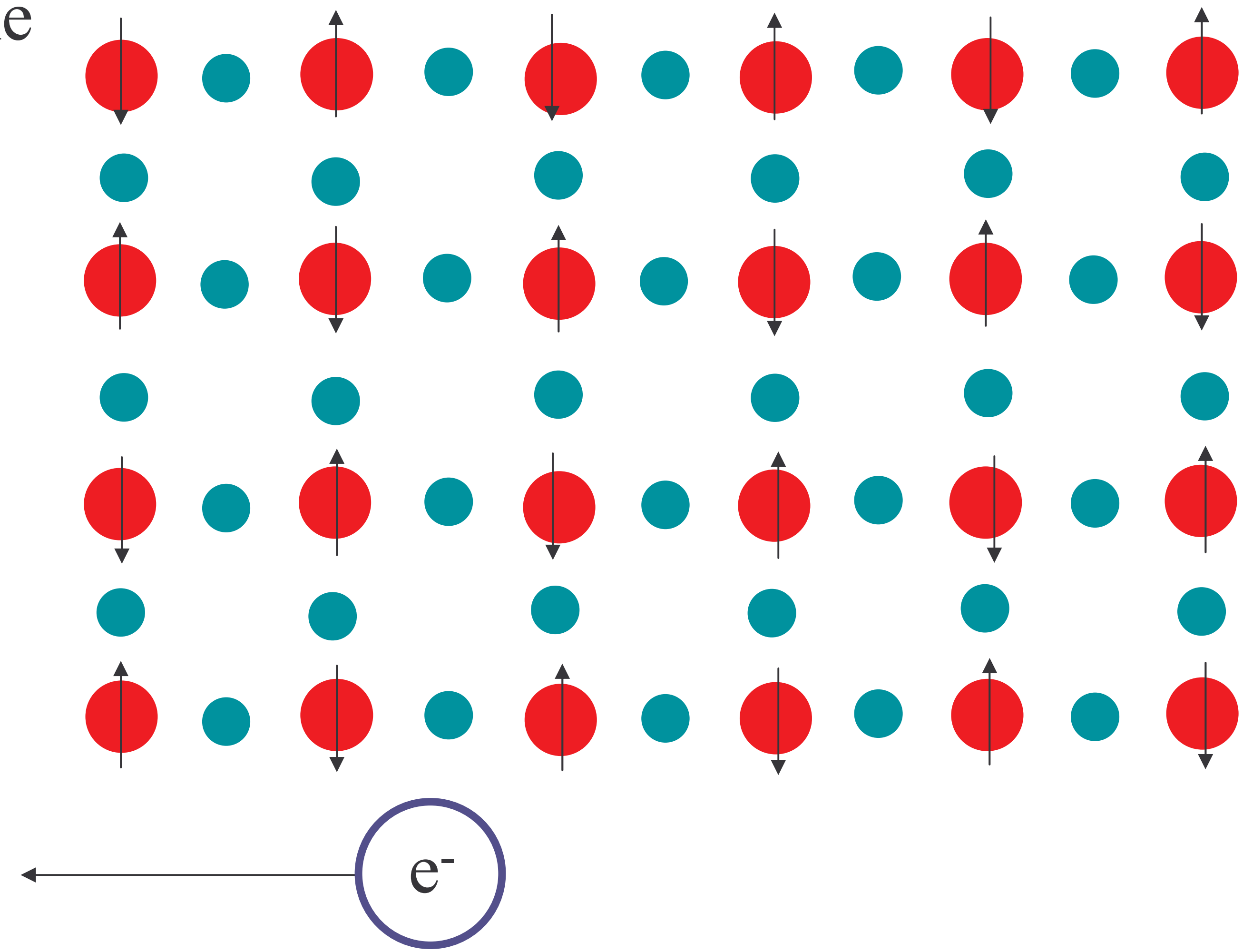


Structure of $Ca_x Y_{1-x} Ba_2Cu_3O_6$

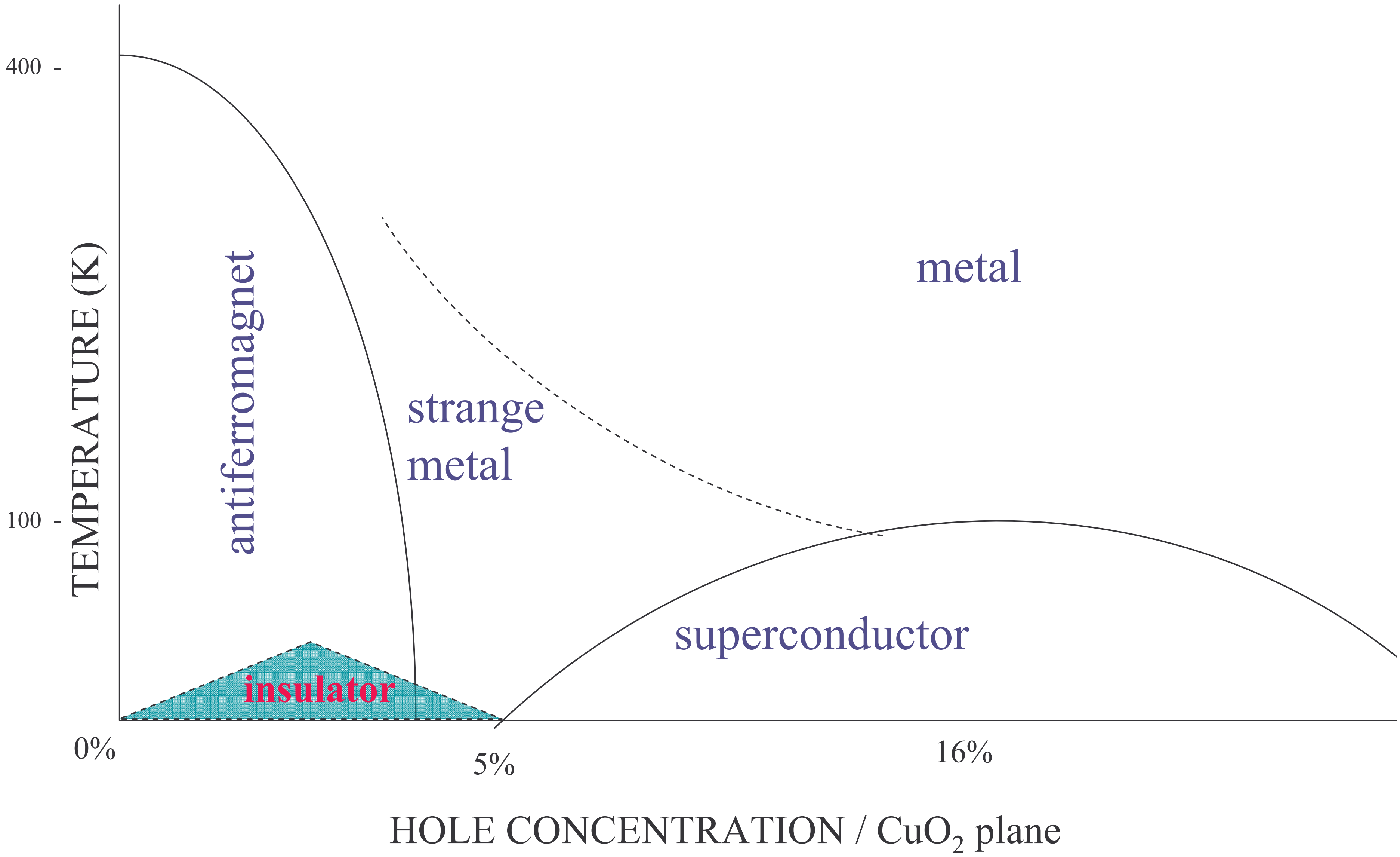


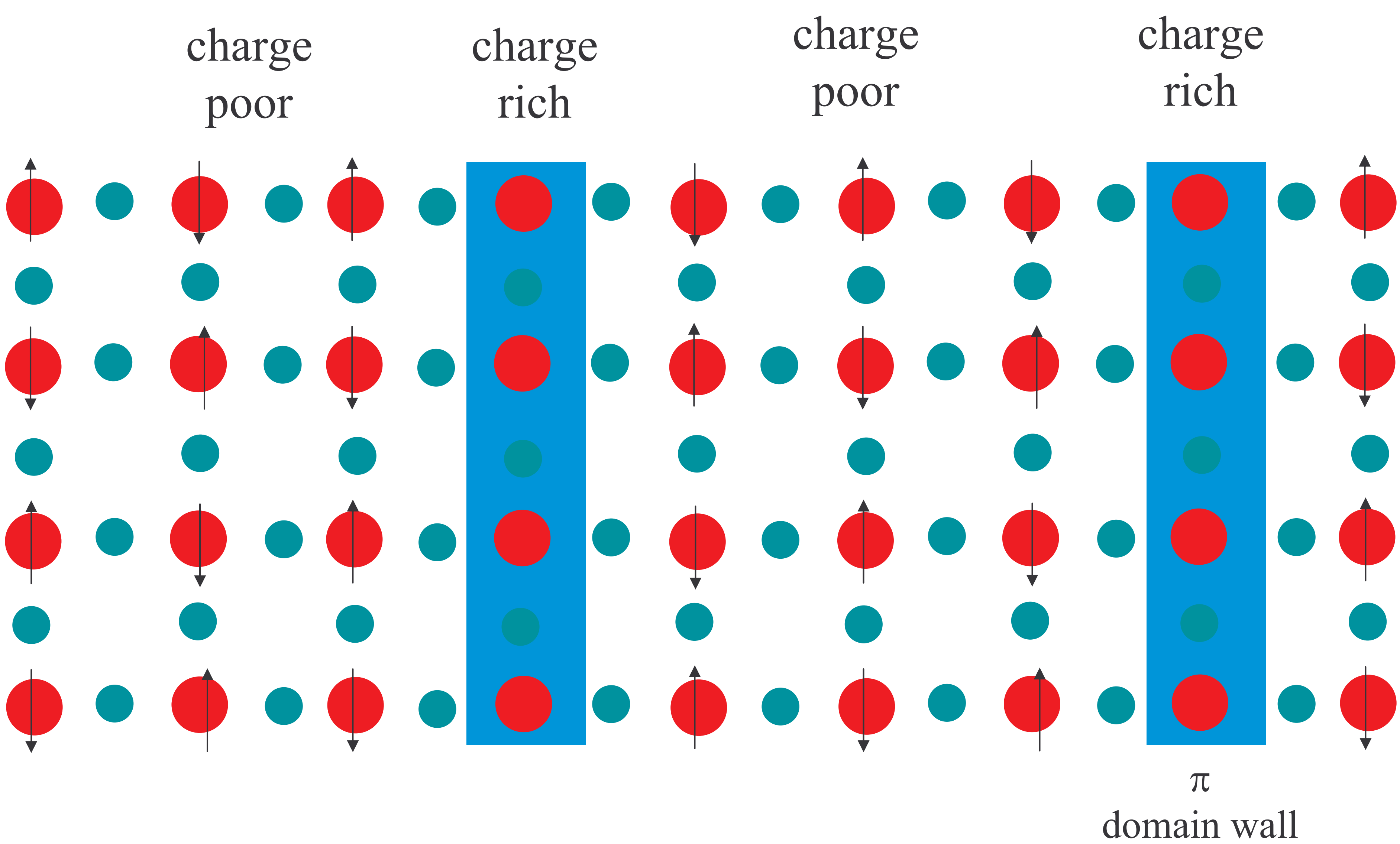
YBCO undoped

CuO_2 plane



Phase diagram of cuprates

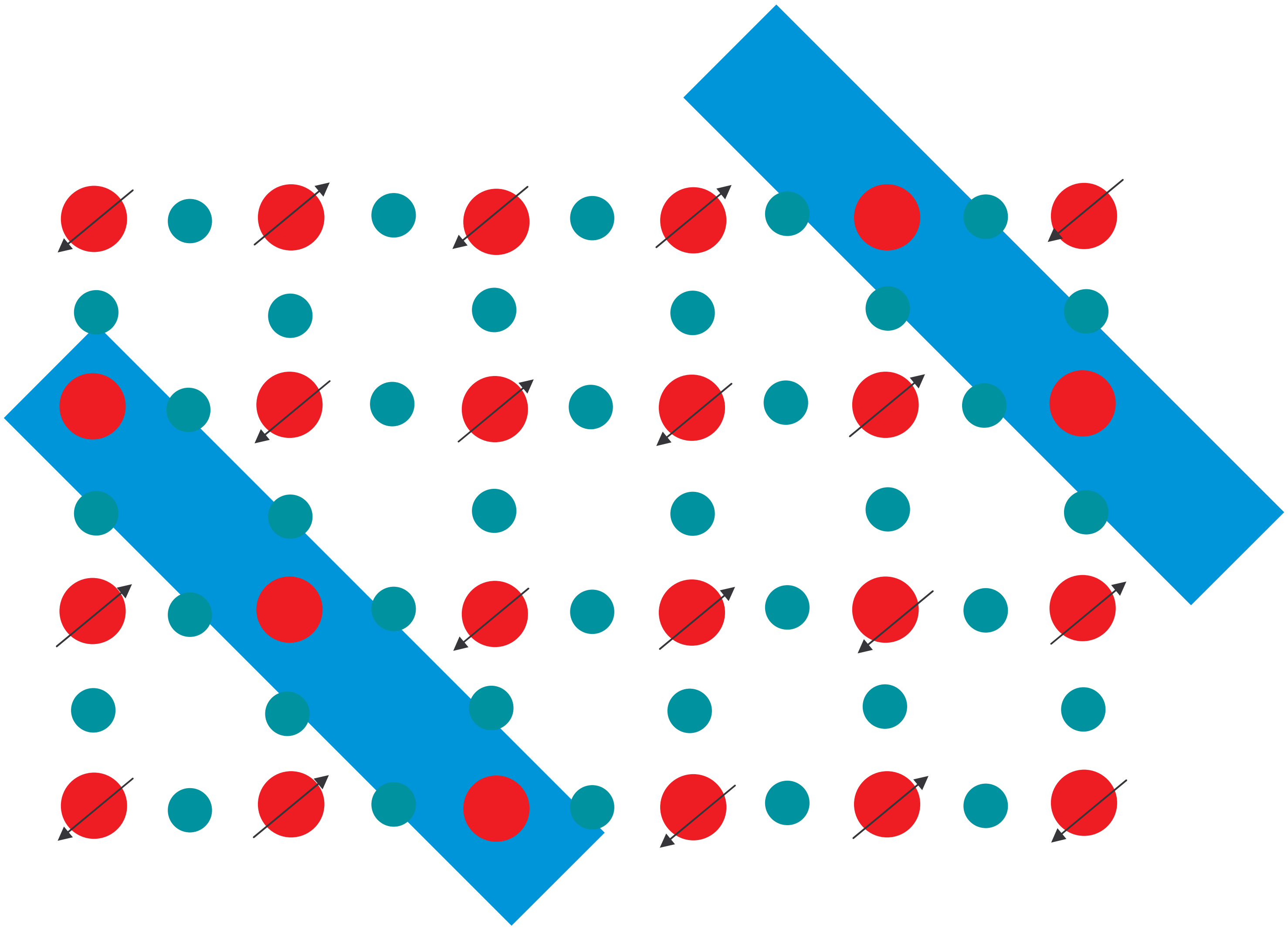




> 0.055 holes / Cu :

collinear incommensurate spin and charge modulation

dynamic, superconductor at low temperatures



0.01- 0.05 holes / Cu :

diagonal incommensurate spin modulation

static at low T (insulator), dynamic at high T (metal)

Neutron diffraction

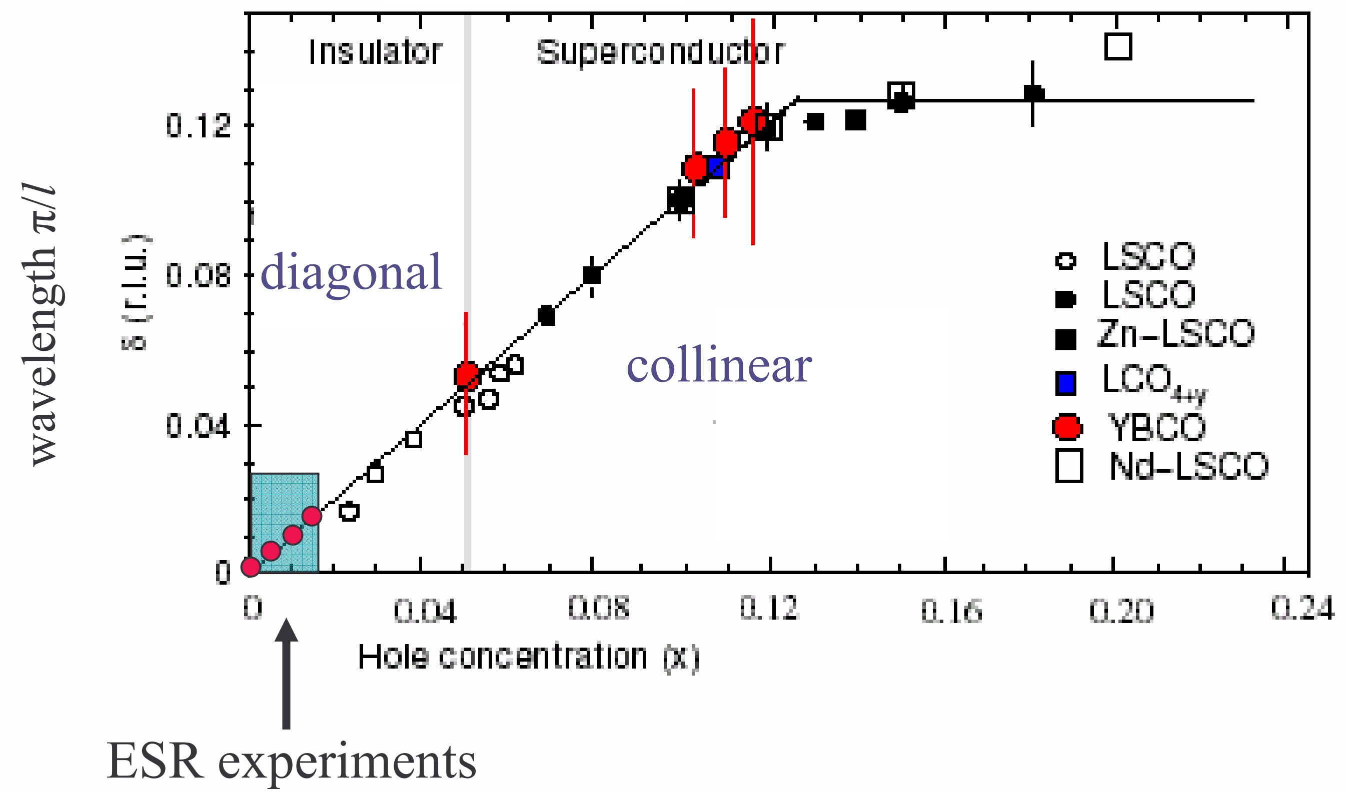
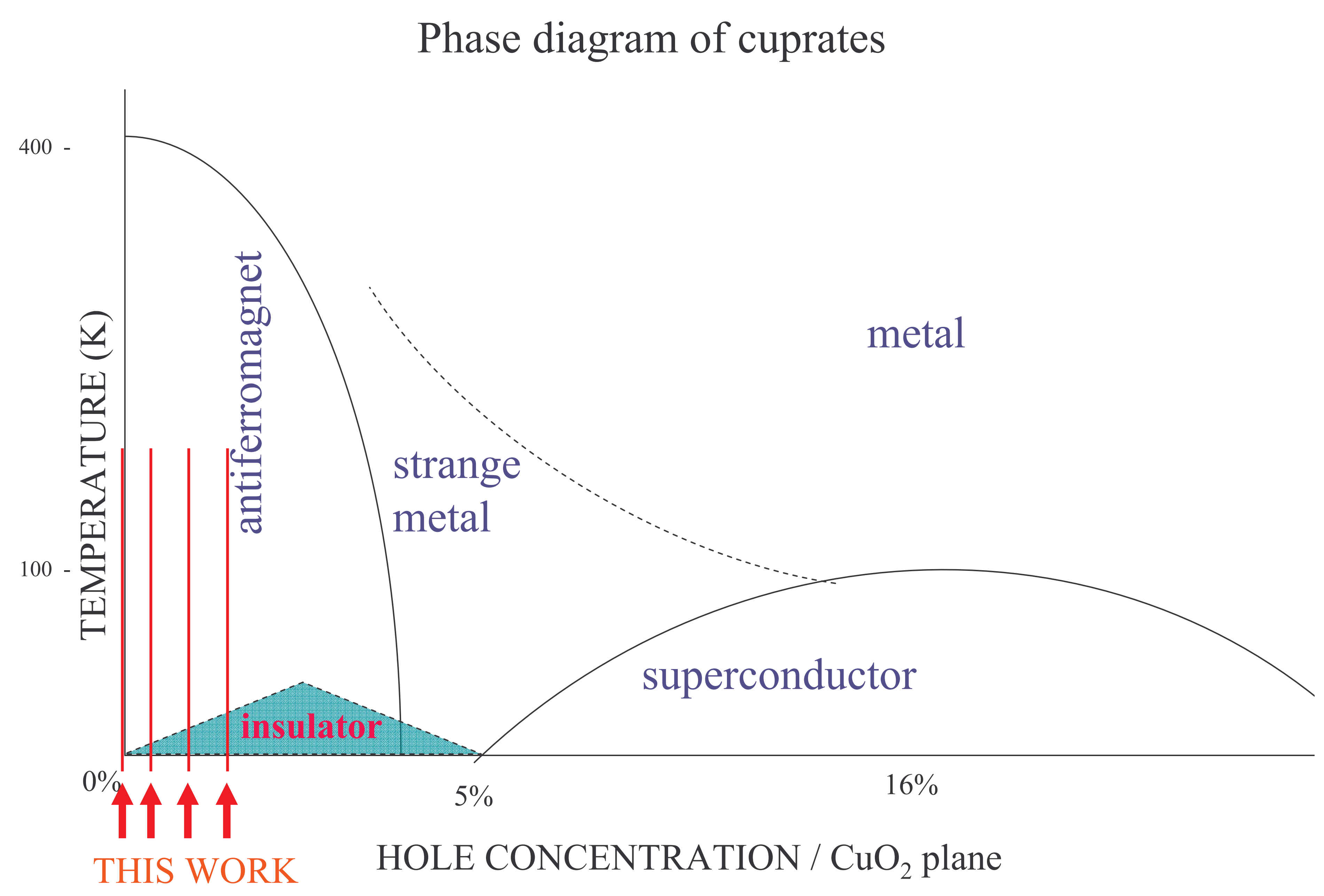
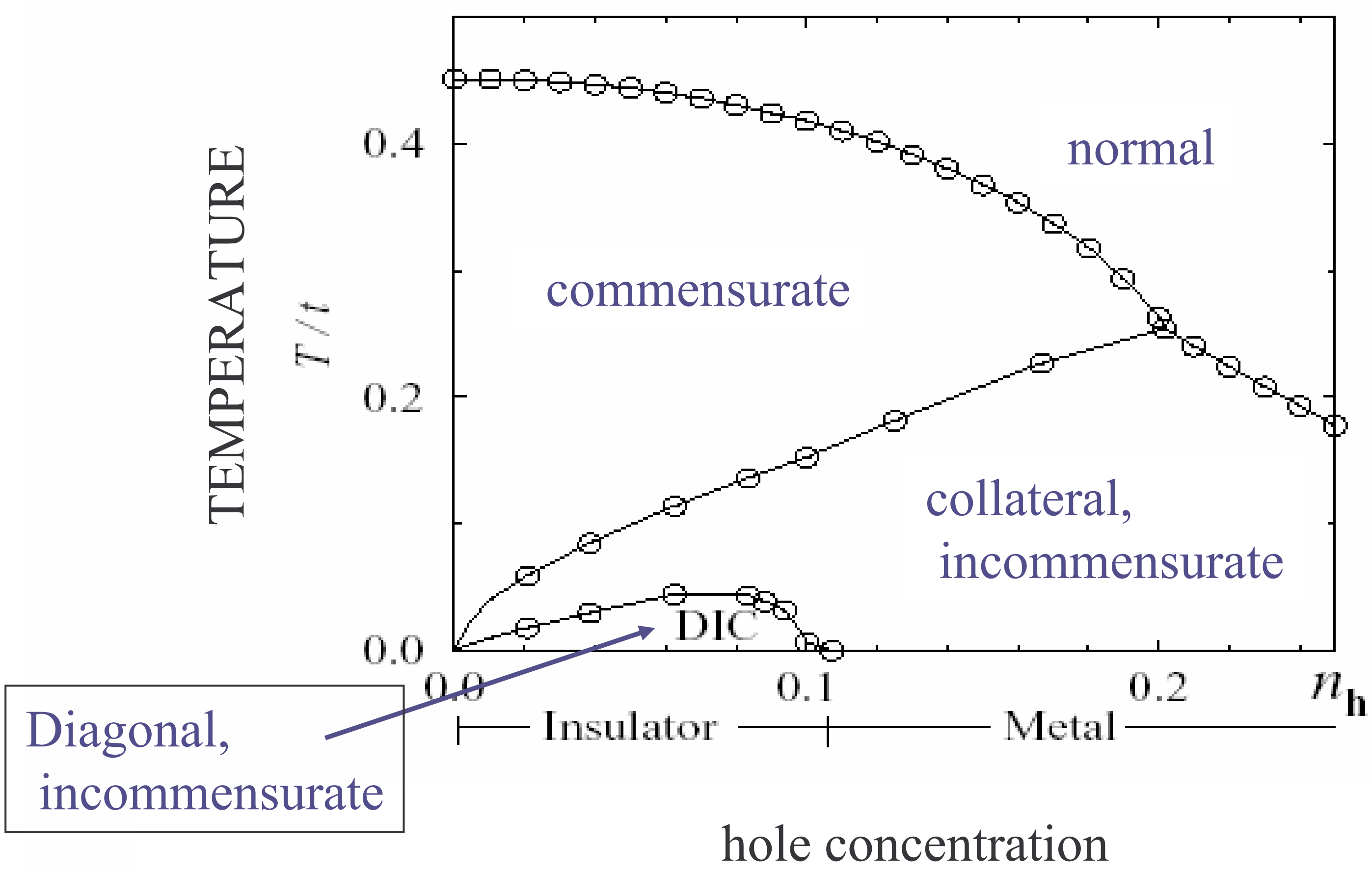


Figure 1.4. Summary of data concerning incommensurability $\delta = \pi/\ell$ as a function of doping concentration x. Data were obtained from neutron-scattering measurements by several groups:


Phase diagram of cuprates
400 -
100 -
TEMPERATURE (K)
antiferromagnet
strange
metal
metal
superconductor
insulator
0%
5%
16%
THIS WORK
HOLE CONCENTRATION / CuO_2 plane

Charge- spin phase separation



STRIPES

Predictions: J. Zaanen, O. Gunnarsson, 1989

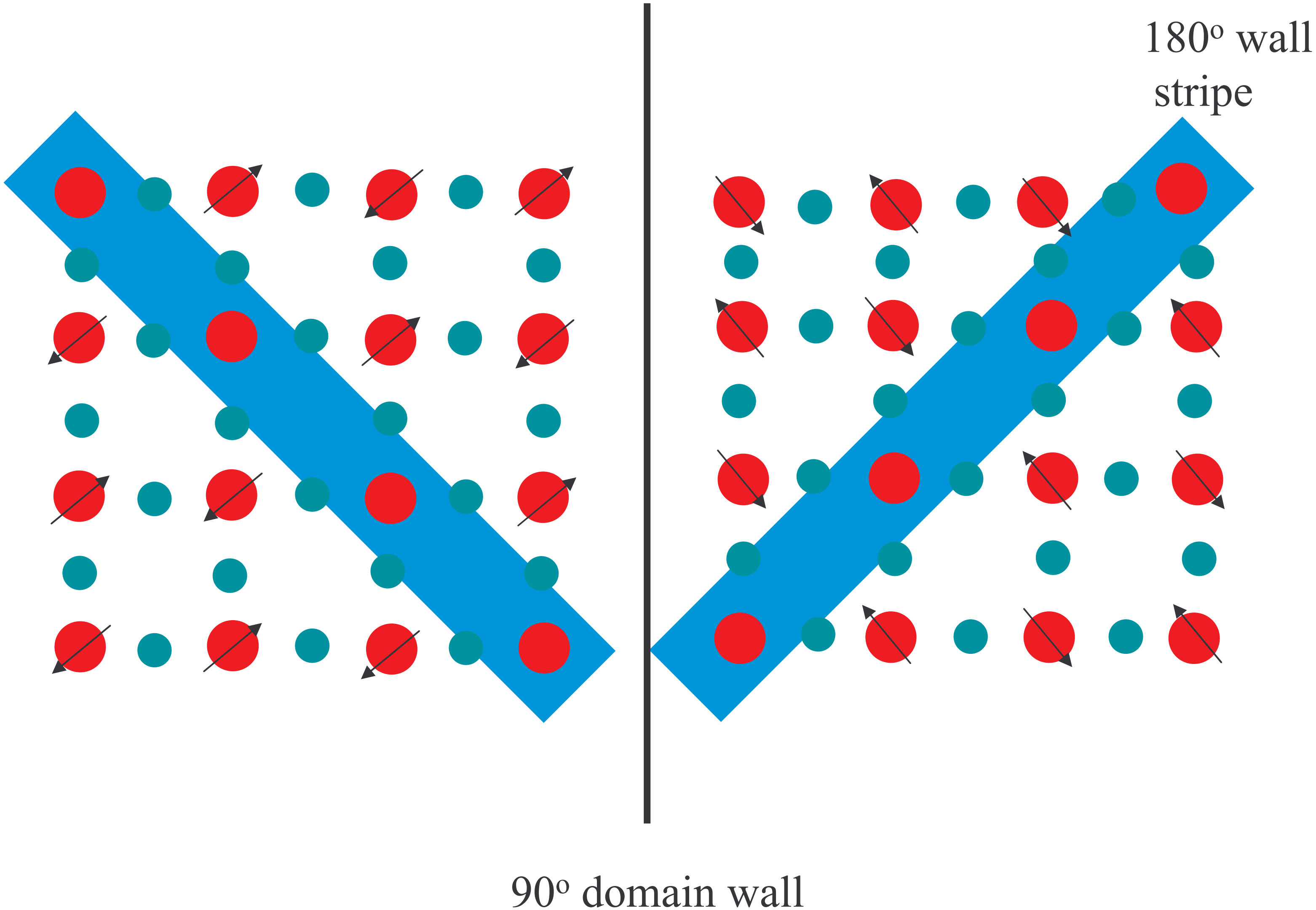
H.J. Schultz 1990

K. Machida 1989

First experiment: J. Tranquada, 1995

Hubbard model. Mean field.

K. Machida, M. Ichioka J. Phys. Soc. Jpn. 68 2168 1999.


180° wall
stripe
90° domain wall

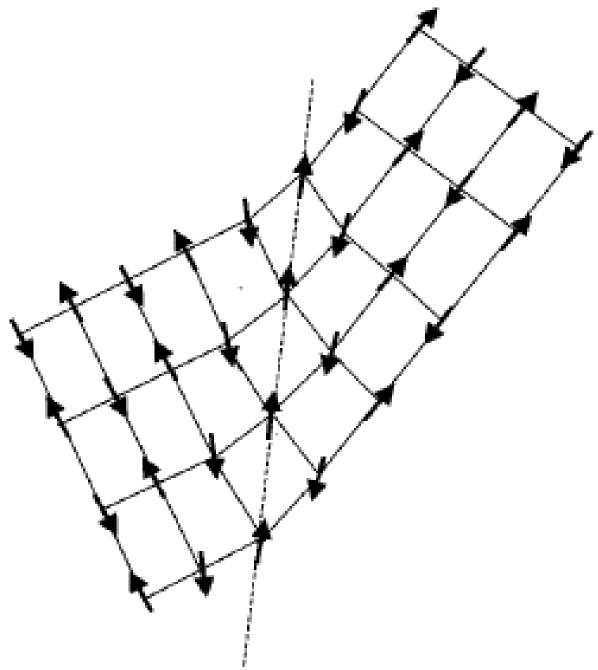


FIG. 1. Twin boundary with spin polarizations (arrows) exhibiting an AF domain wall. The dashed line is in a (110) plane and is

Outline

Gd^{3+} ESR probe

Localisation of holes

Orientation of stripes

Search for conductivity anisotropy

Interactions:
Zeeman + exchange + "crystal field"

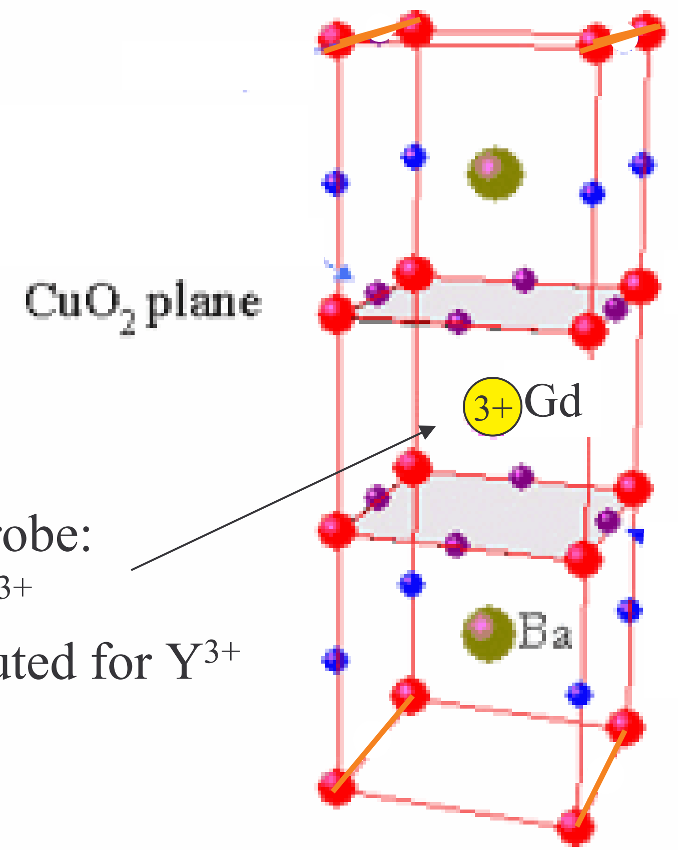
Gd^{3+} ESR measures:

spin susceptibility (ESR Knight shift)

and

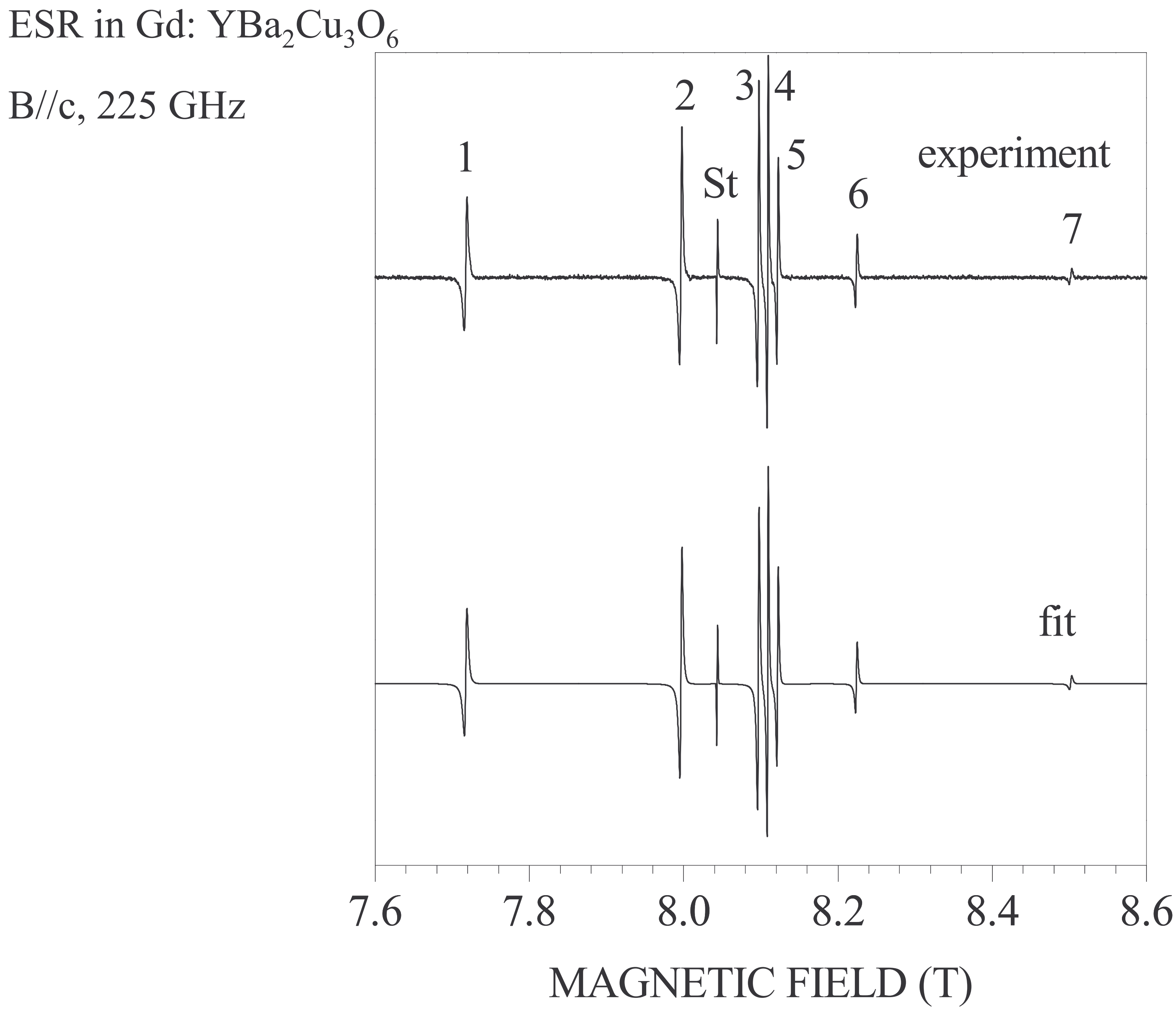
lattice distortion or charge redistribution
(J=7/2 fine structure)

in CuO_2 planes

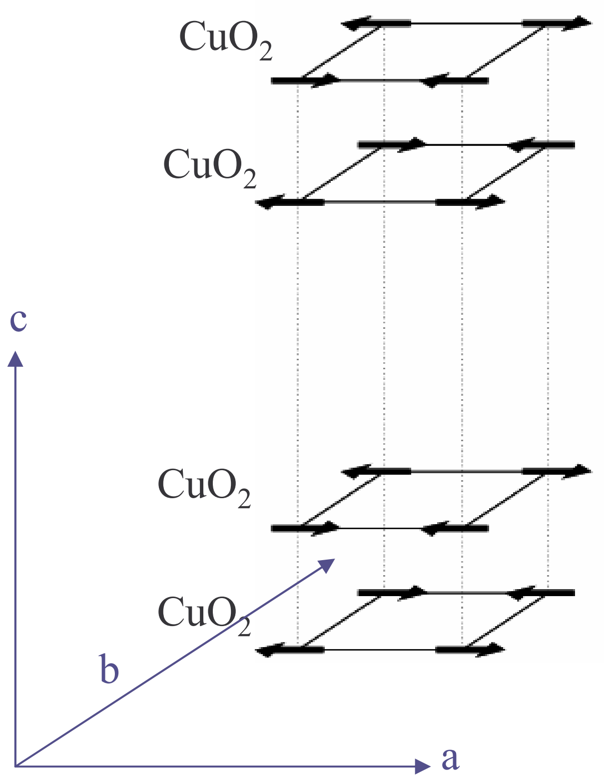


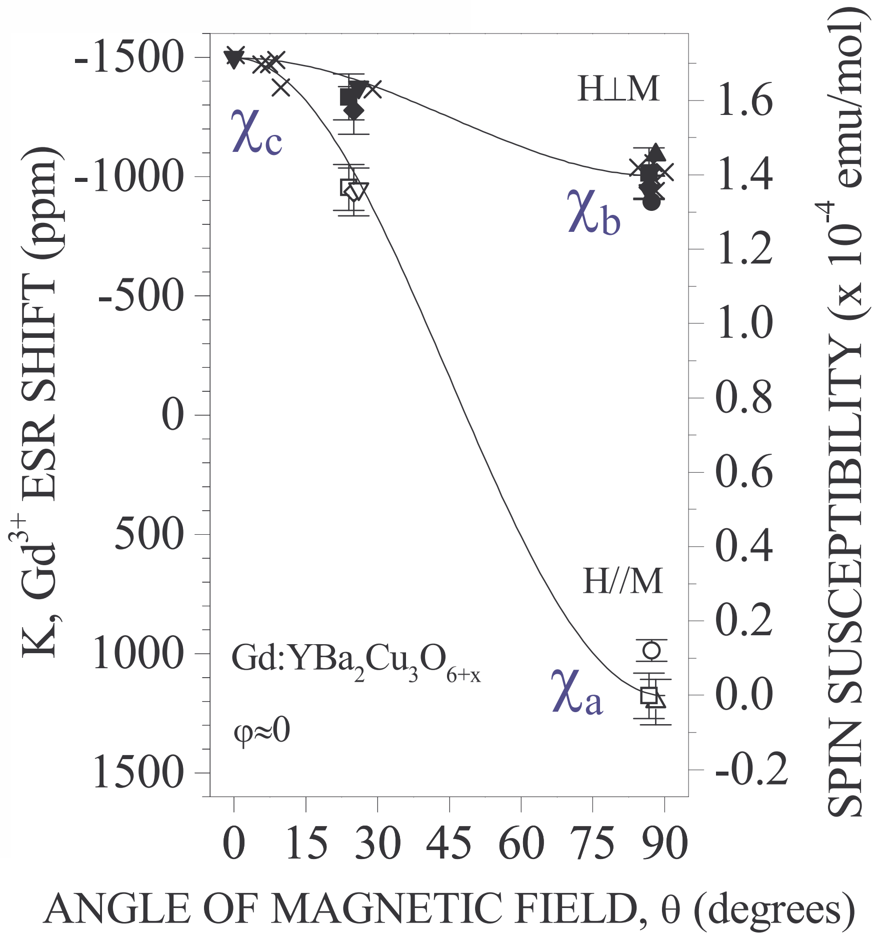
ESR probe:
1% Gd^{3+}
substituted for Y^{3+}


Zeeman splitting
ESR Knight shift
spin susceptibility
fine structure
charge redistribution
hν_L
free ion
Gd3+- CuO2 exchange
"crystal field"
J = 7/2


ESR in Gd: YBa2Cu3O6
B//c, 225 GHz
1
2
St
3
4
5
6
7
experiment
fit
7.6
7.8
8.0
8.2
8.4
8.6
MAGNETIC FIELD (T)

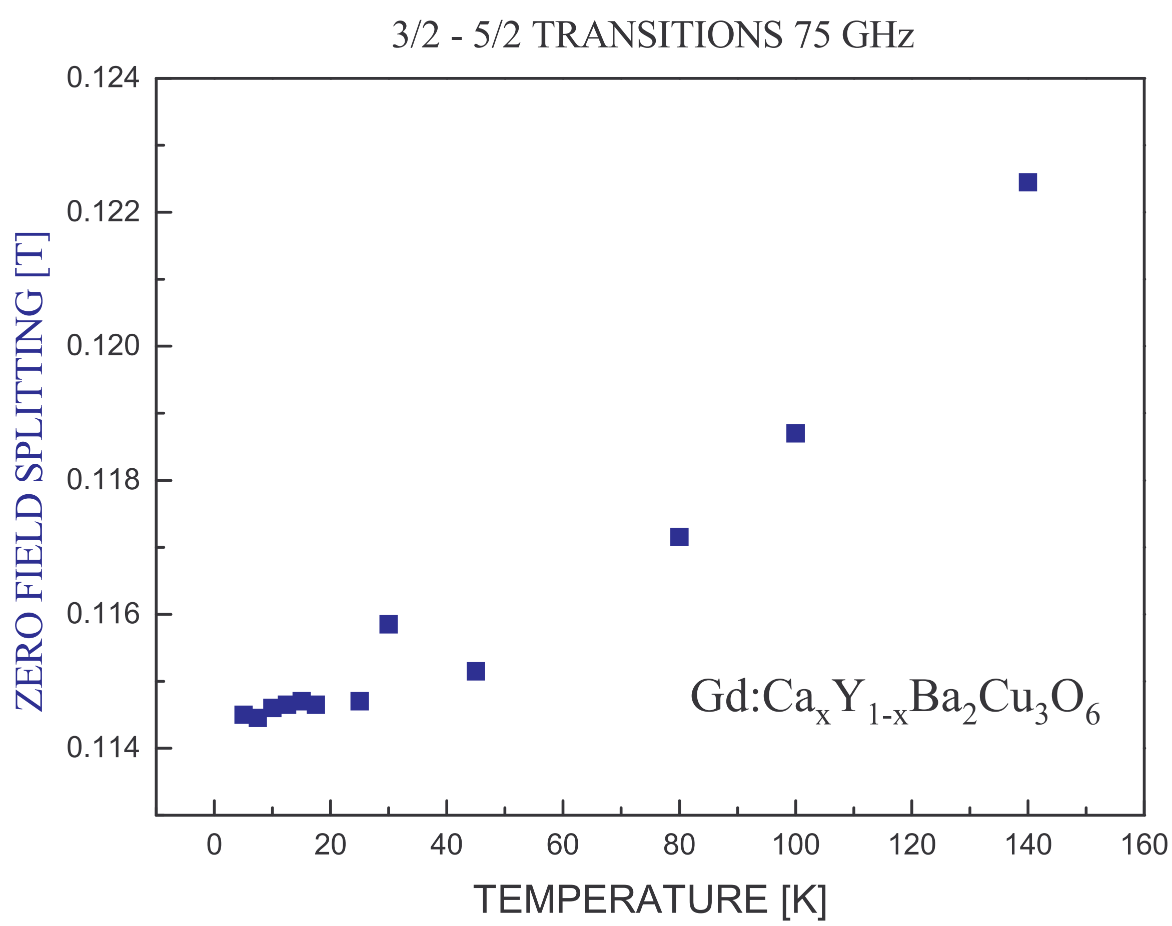
Spin susceptibility in undoped $YBa_2Cu_3O_6$





F. Simon et al Phys. Rev. **B 59** 12072 (1999)

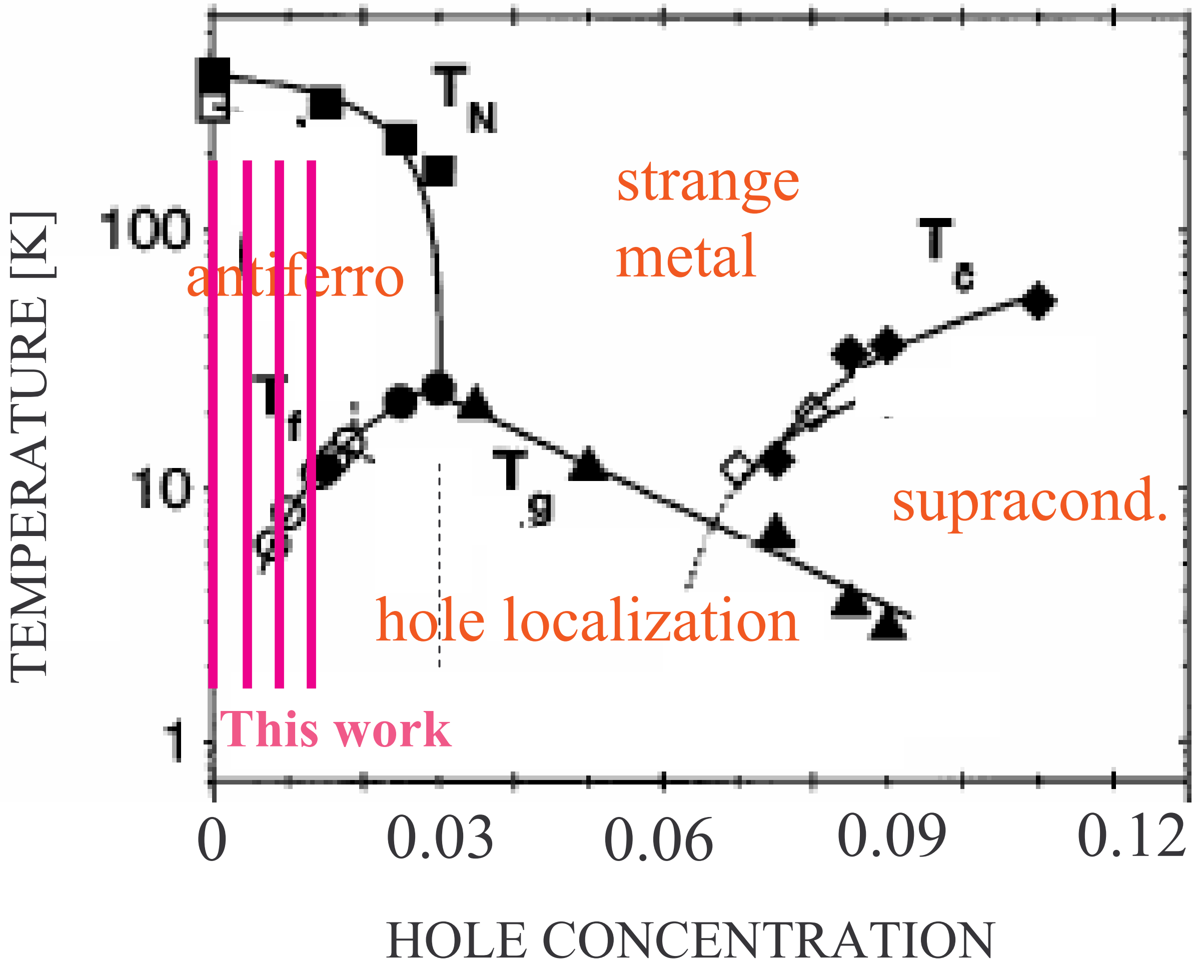
Lattice expansion



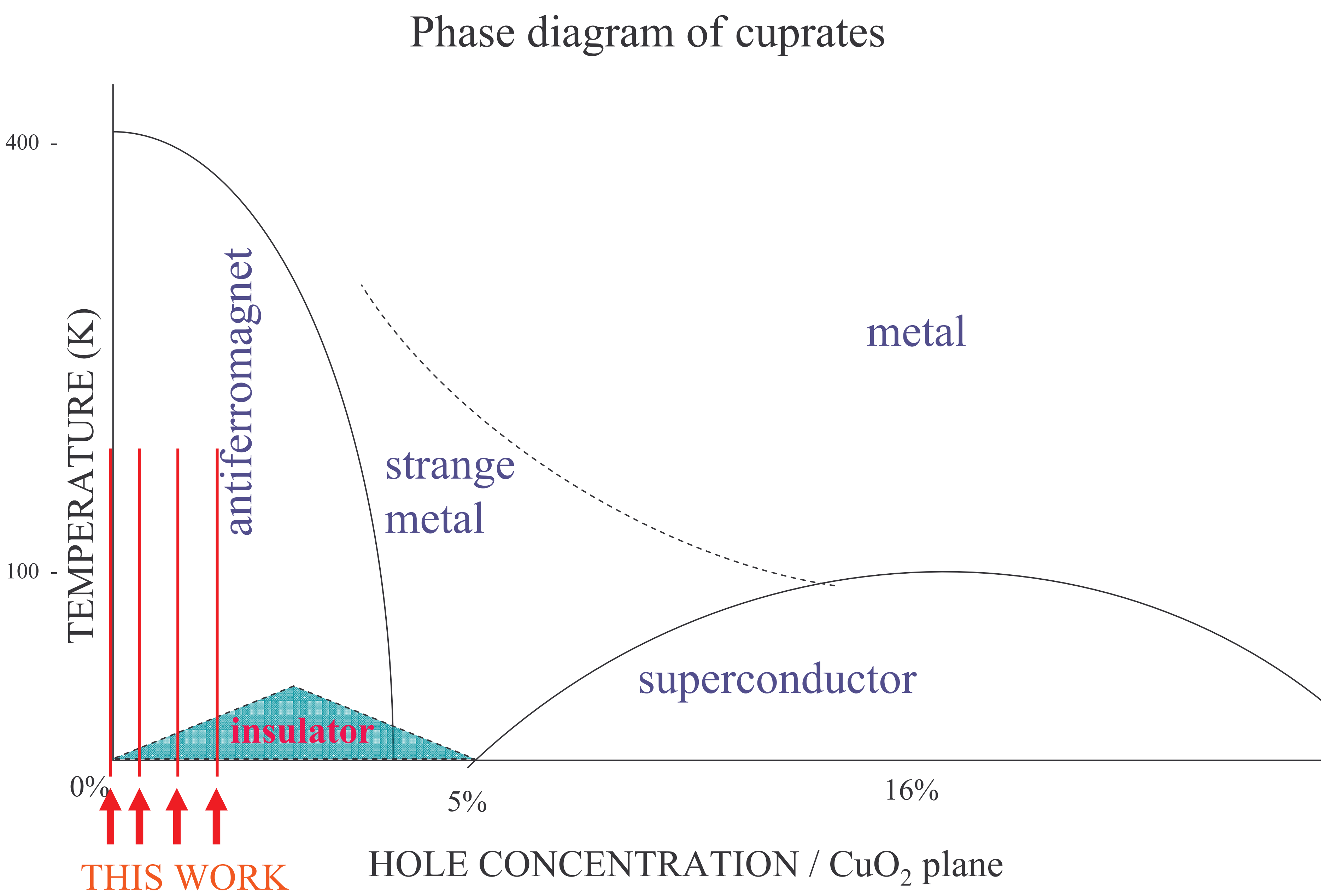
Localisation of holes

Are holes localised around Ca^{2+} ions at low T ?

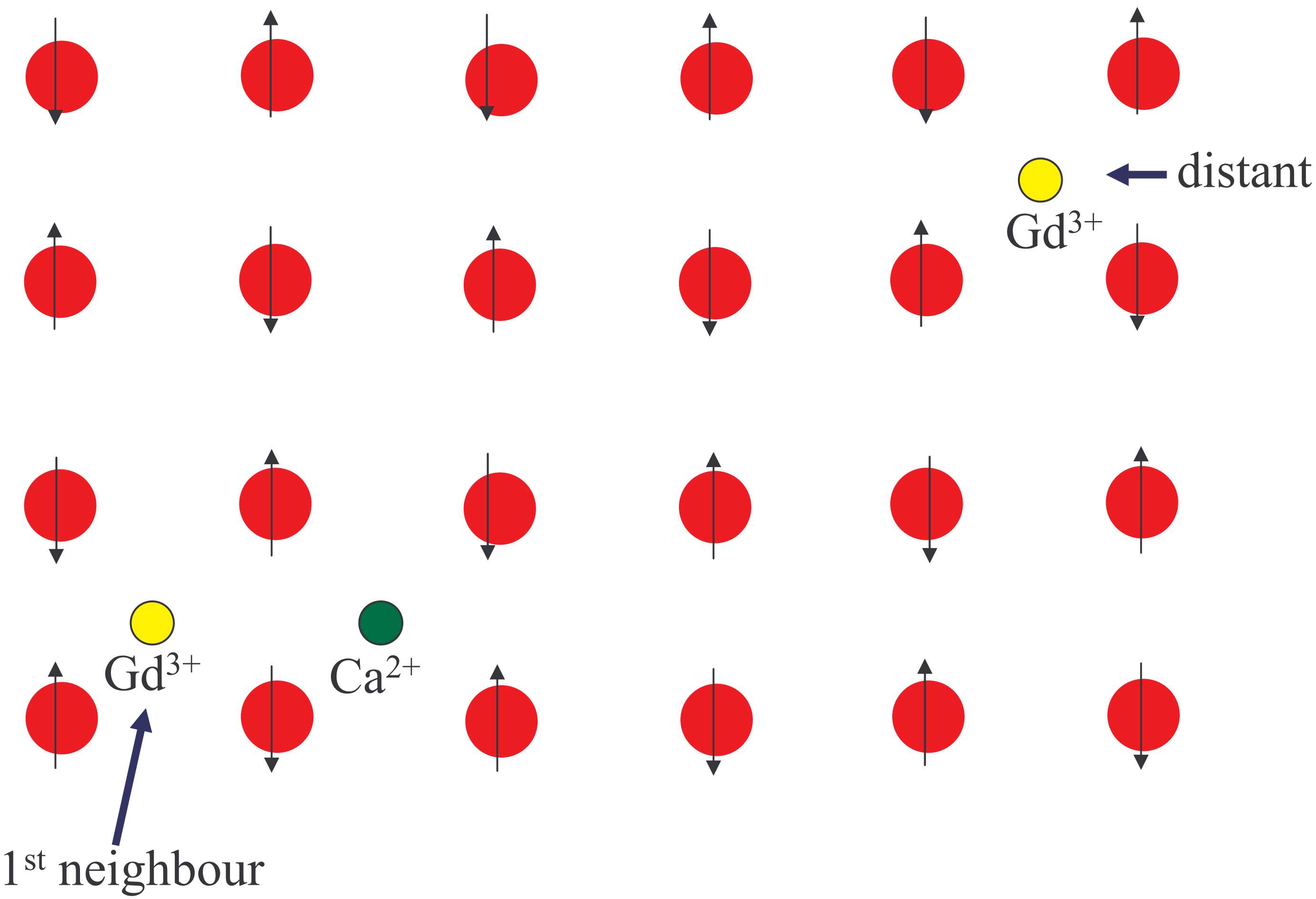
Ca doped $YBa_2Cu_3O_6$ phase diagram



Ch. Niedermayer, C. Bernhard, T. Blasius, A. Golnik, A. Moodenbaugh, and J. I. Budnick
Phys. Rev. Lett.80 (1998) 3843

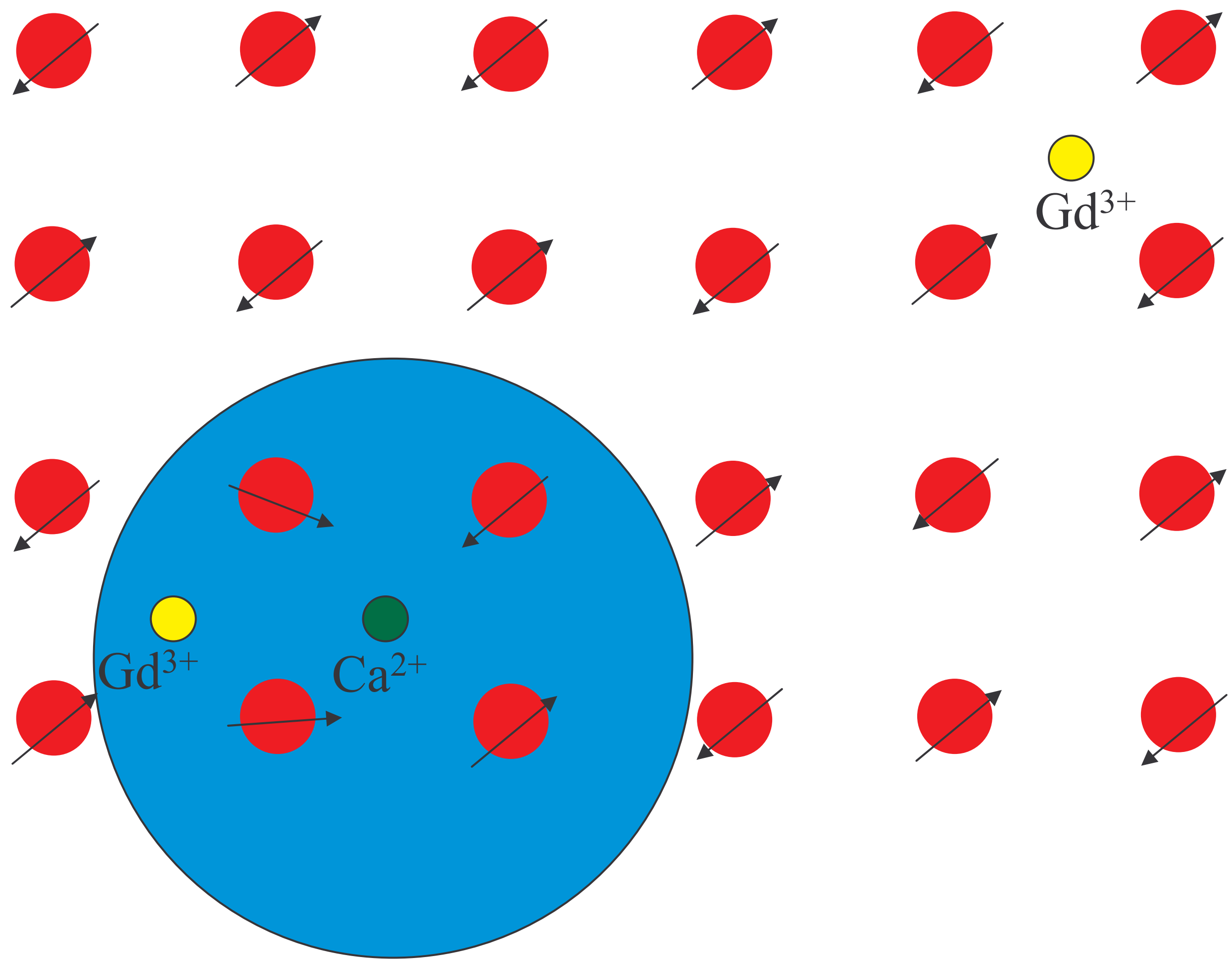

Phase diagram of cuprates
400 -
100 -
TEMPERATURE (K)
antiferromagnet
insulator
strange
metal
metal
superconductor
0%
5%
16%
HOLE CONCENTRATION / CuO2 plane
THIS WORK

High T:
delocalized holes



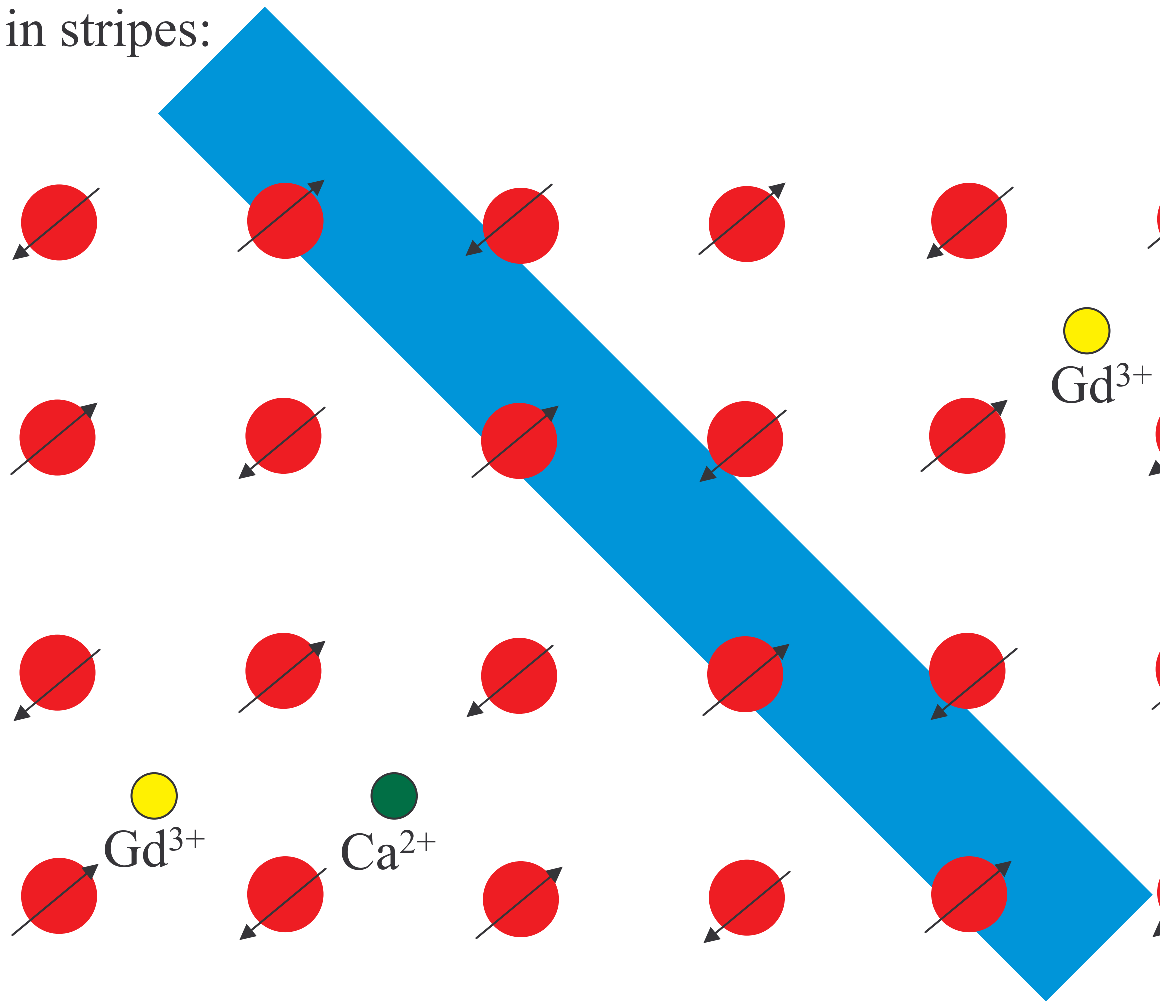
low T

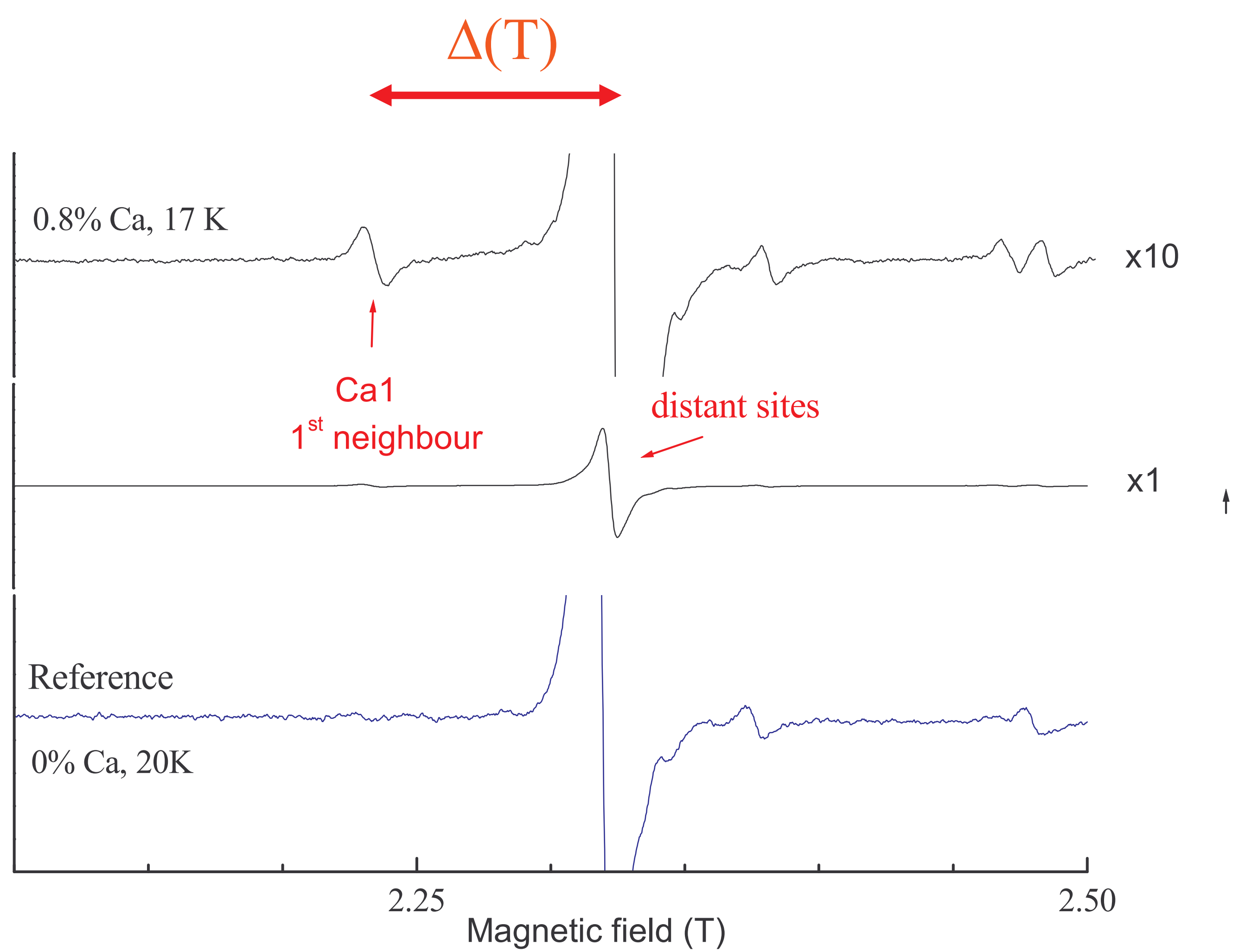
if holes were localized near Ca:



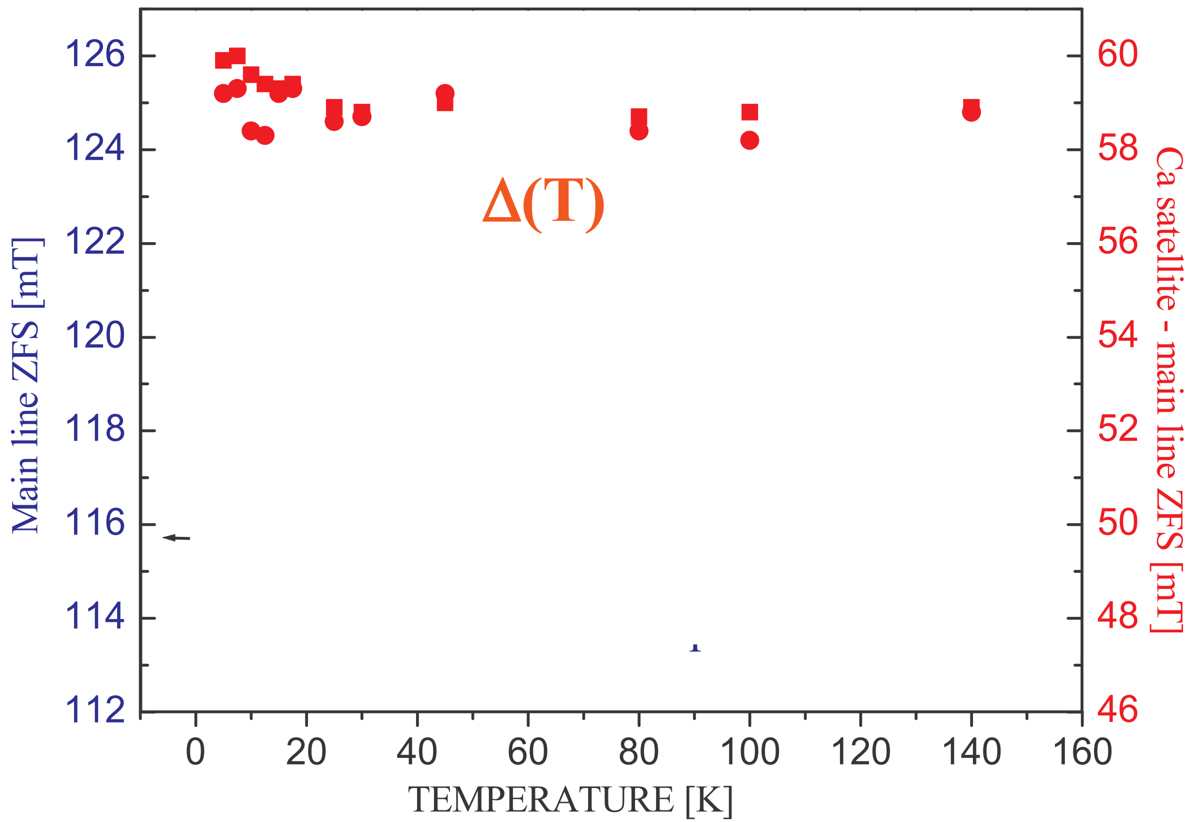
low T

holes ordered in stripes:



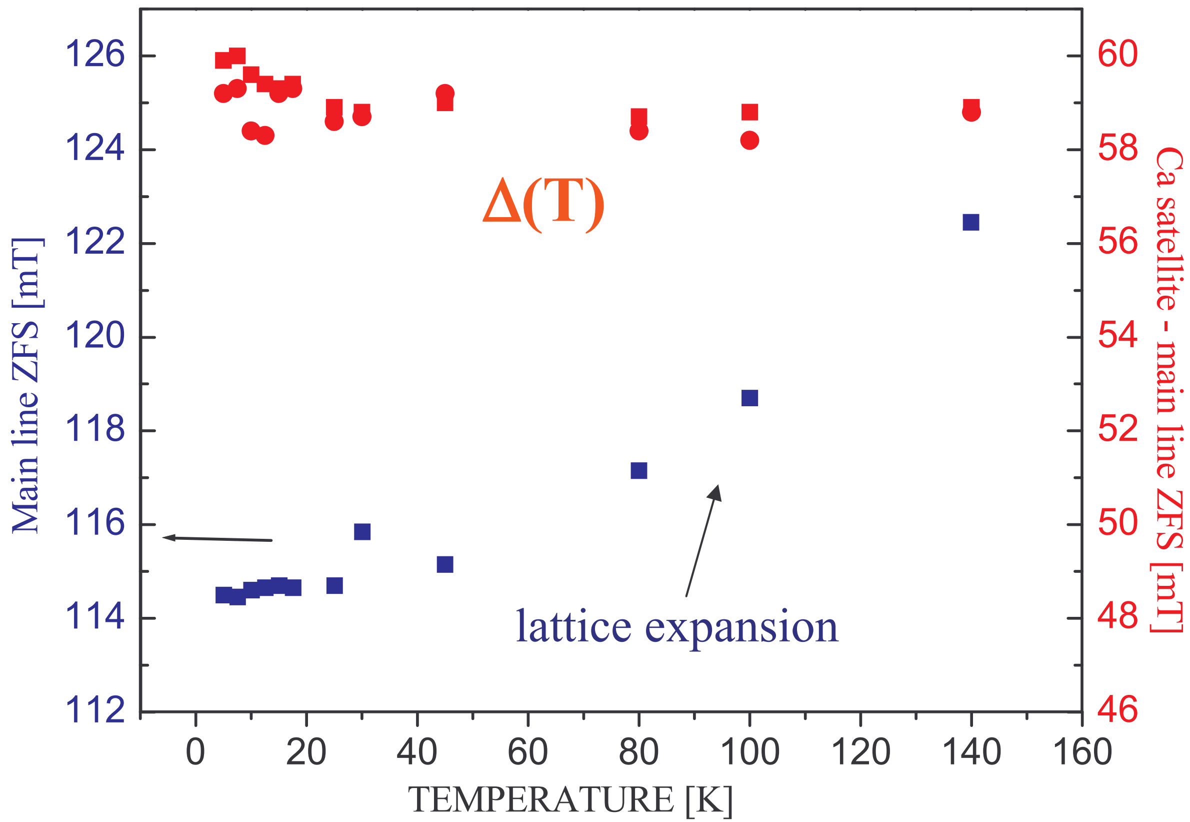

Δ(T)
0.8% Ca, 17 K
x10
Ca1
1st neighbour
distant sites
x1
Reference
0% Ca, 20K
2.25
2.50
Magnetic field (T)

Holes do not localize at the Ca^{2+} sites



$-5/2\rangle \Leftrightarrow |-3/2\rangle$ and $|3/2\rangle \Leftrightarrow |5/2\rangle$ 75 GHz, B//c

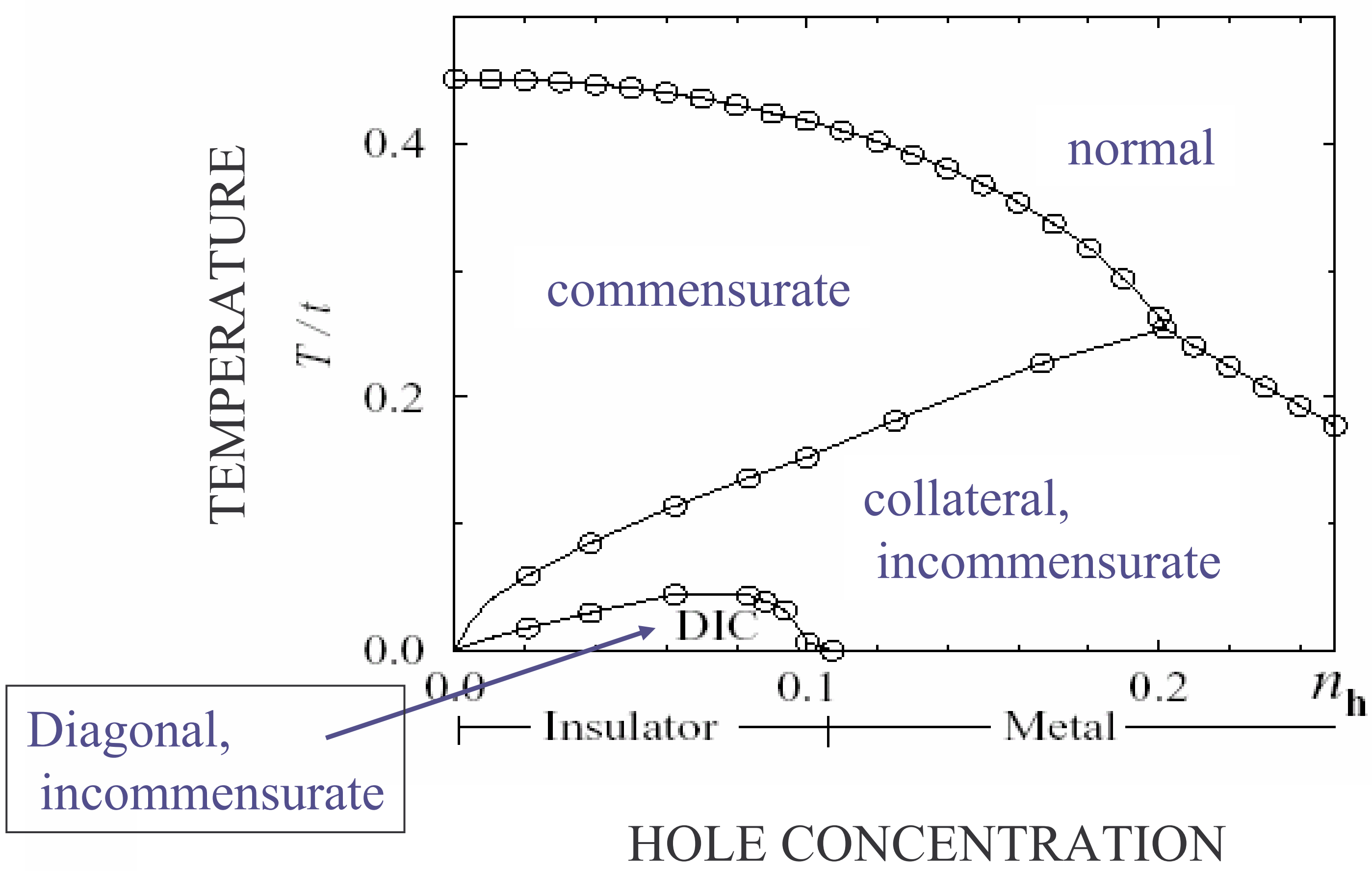
Holes do not localize at the Ca^{2+} sites



–5/2> ⇔ |-3/2> and |3/2> ⇔ |5/2>   75 GHz, B//c

Orientation of spins

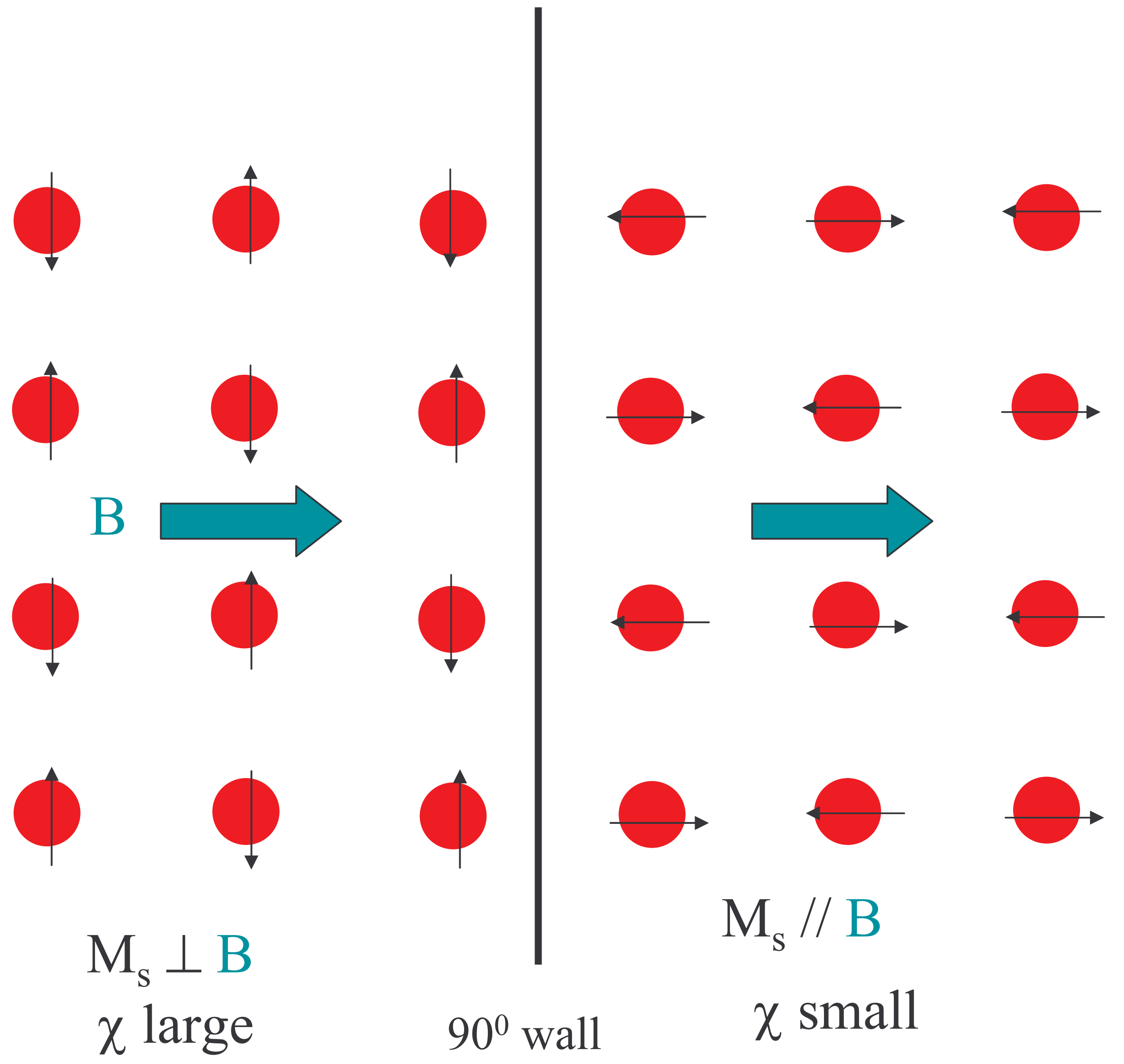
Charge- spin phase separation



Hubbard model. Mean field.

K. Machida, M. Ichioka J. Phys. Soc. Jpn. 68 2168 1999.

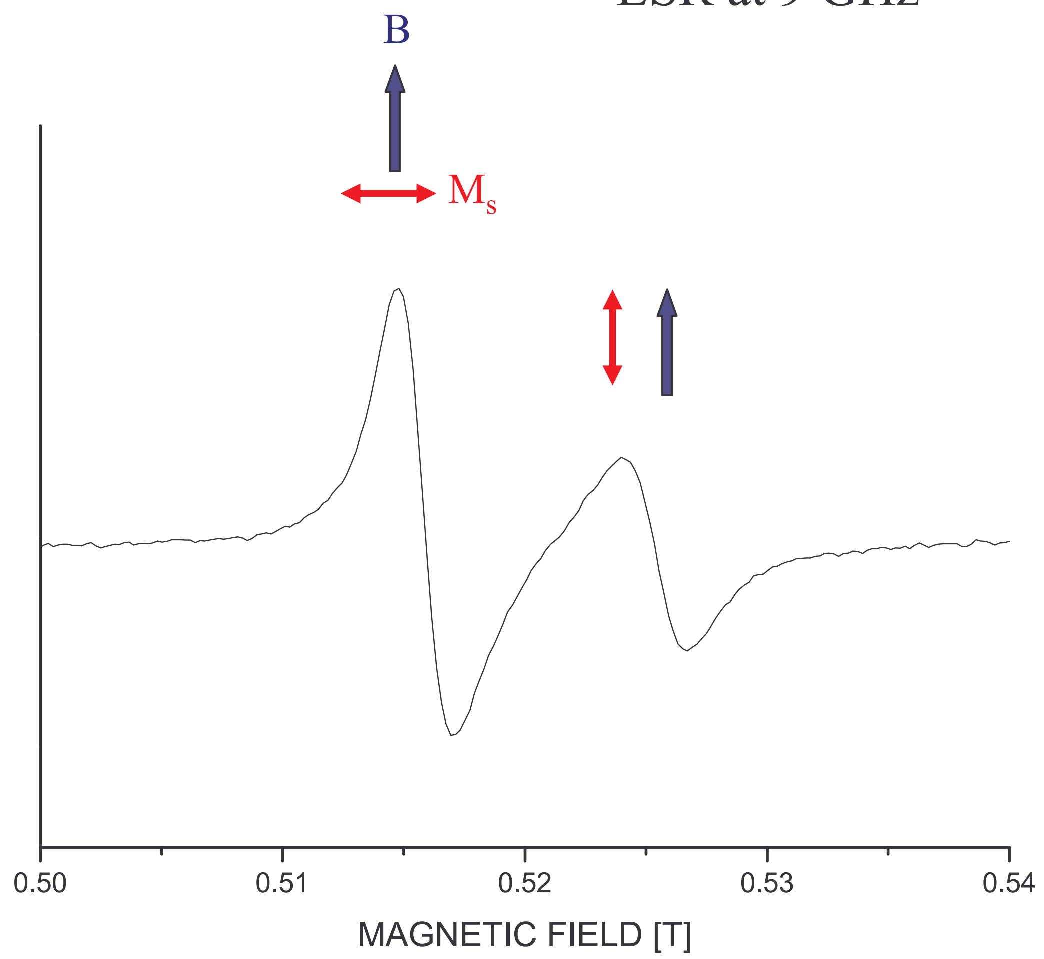
undoped



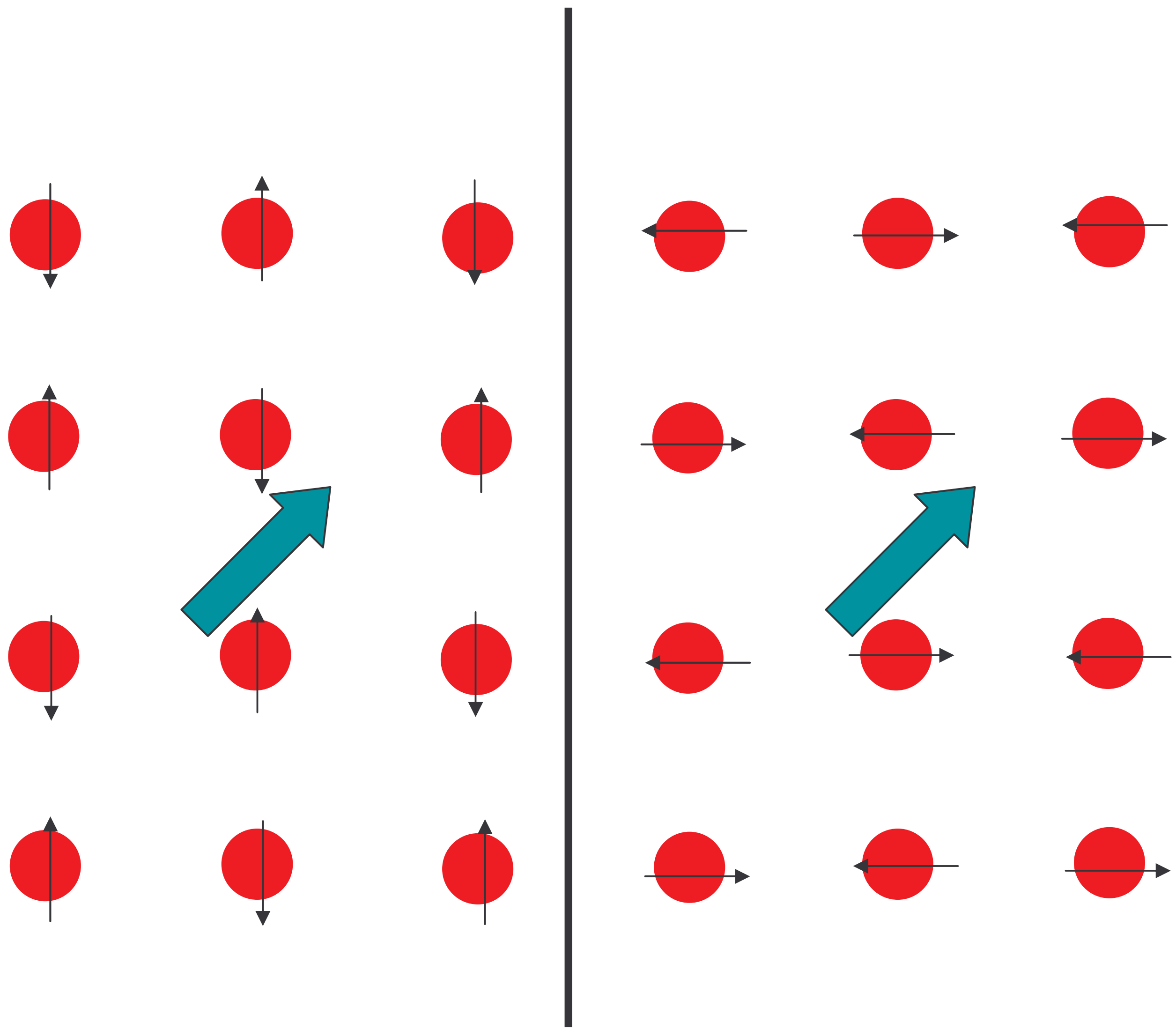
B: magnetic field

undoped

antiferromagnetic domains in $YBaCu_3O_6$
ESR at 9 GHz

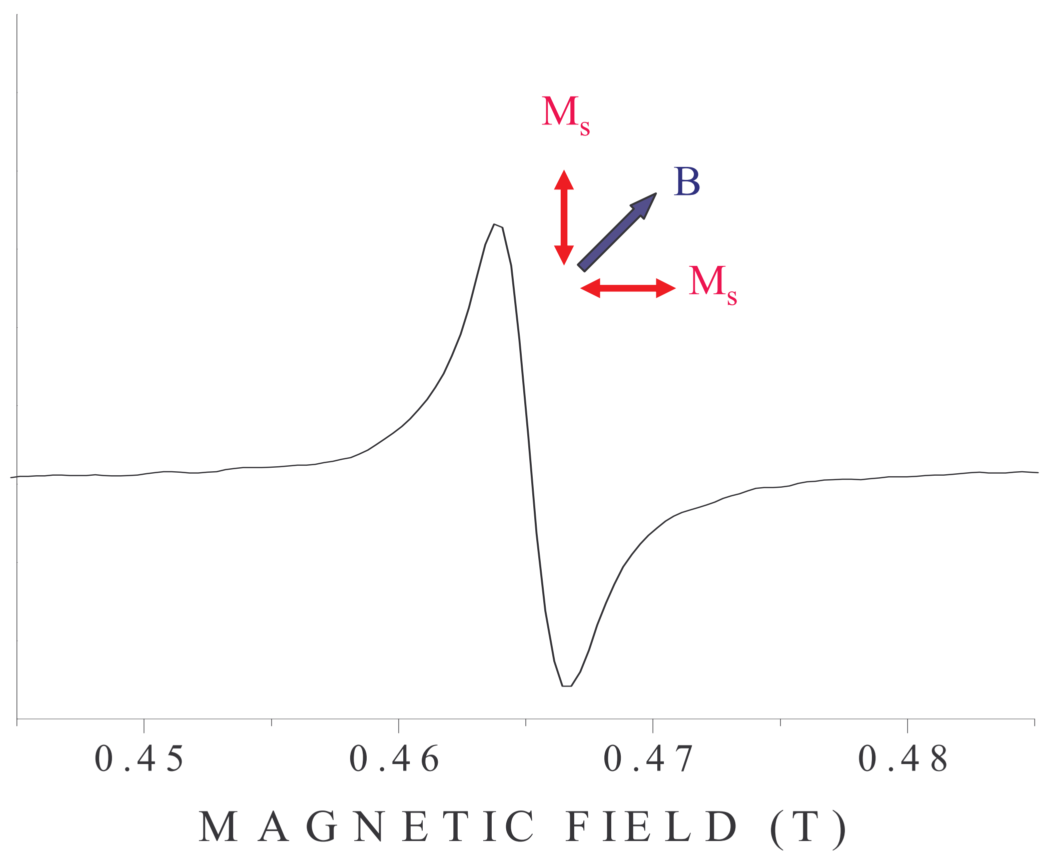


undoped

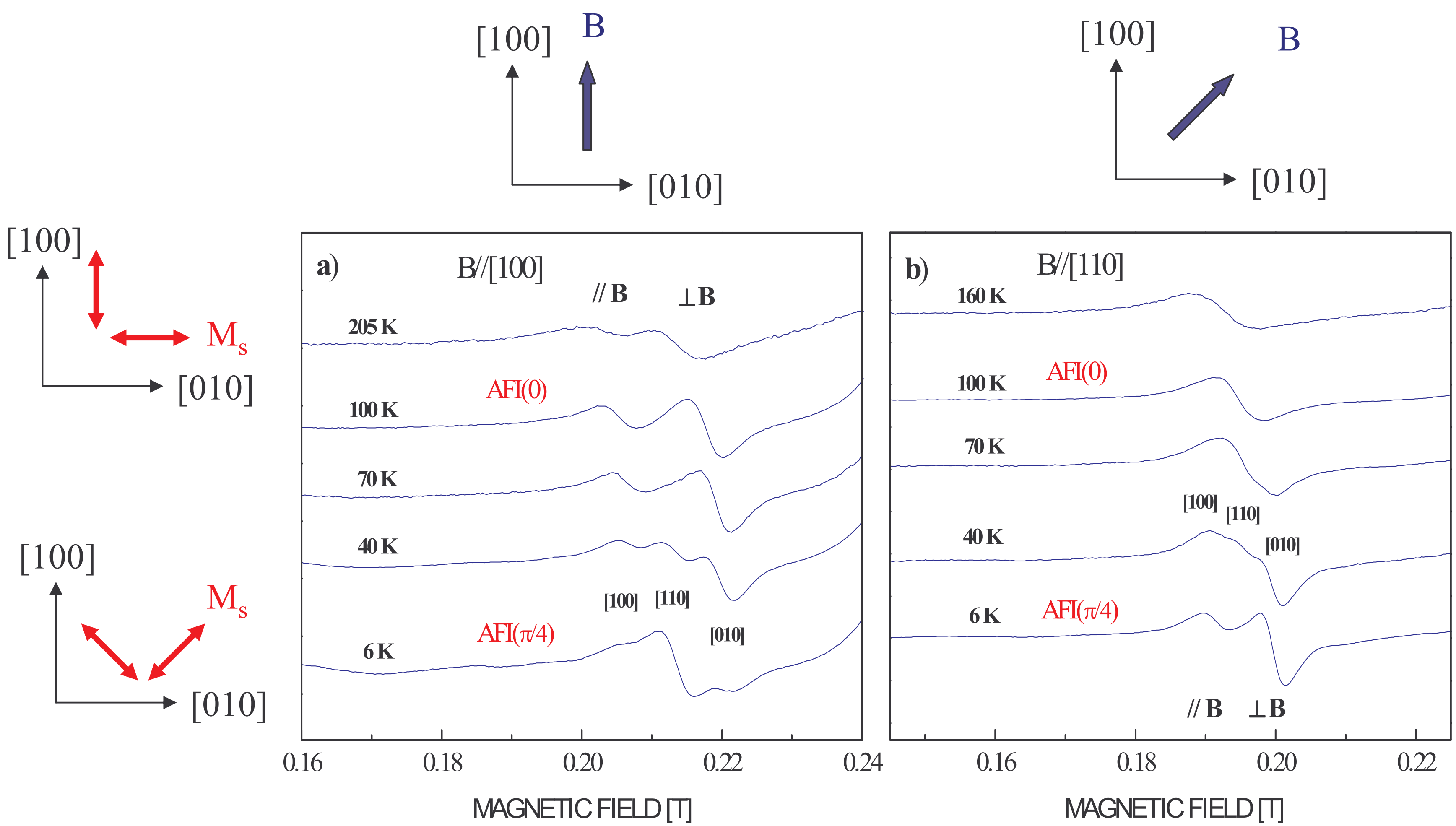


B: magnetic field

undoped

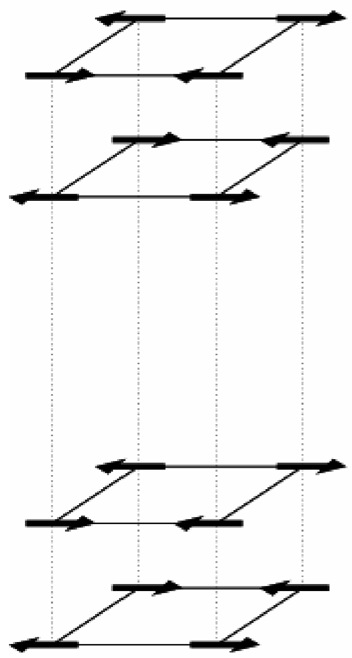


Reorientation of M_s in Ca:YBCO 0.8% Ca



undoped

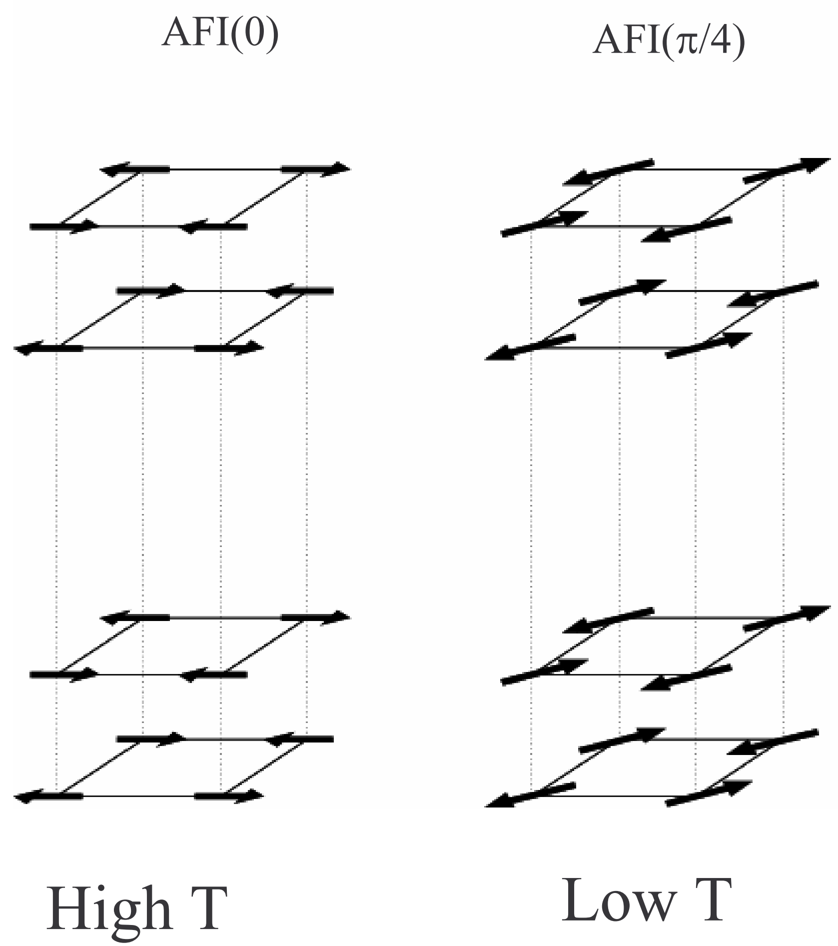
AFI(0)



all T

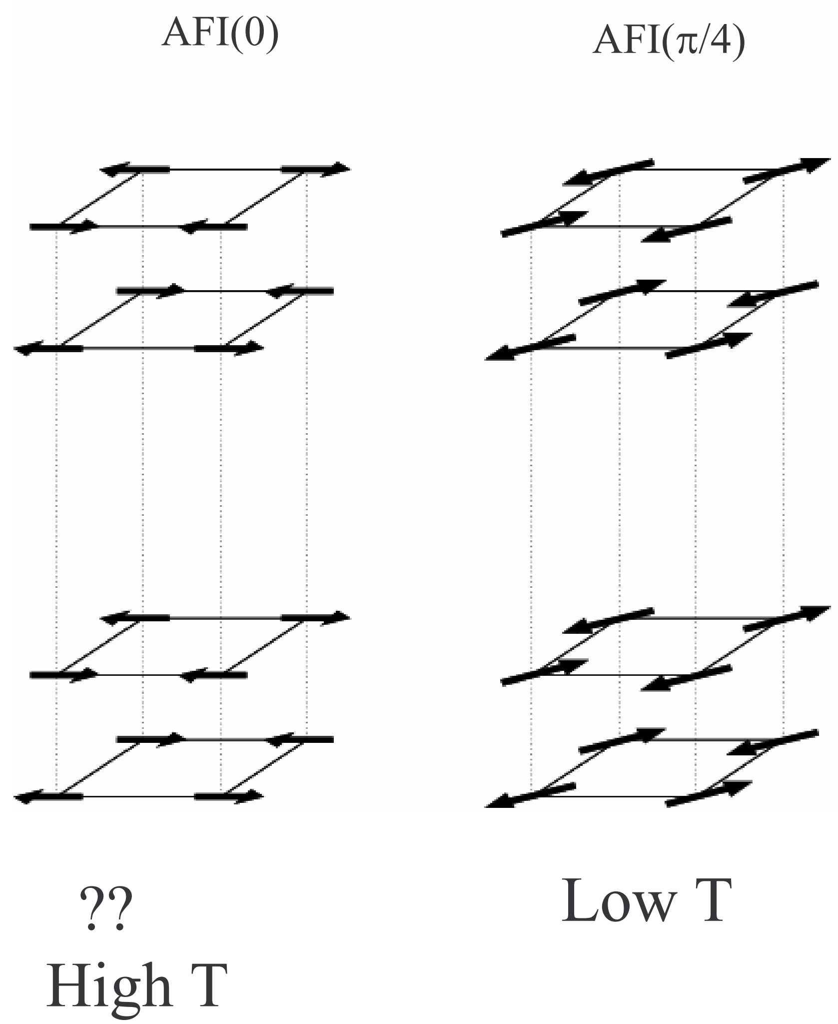
magnetic reorientation in Ca doped $YBa_2Cu_3O_6$

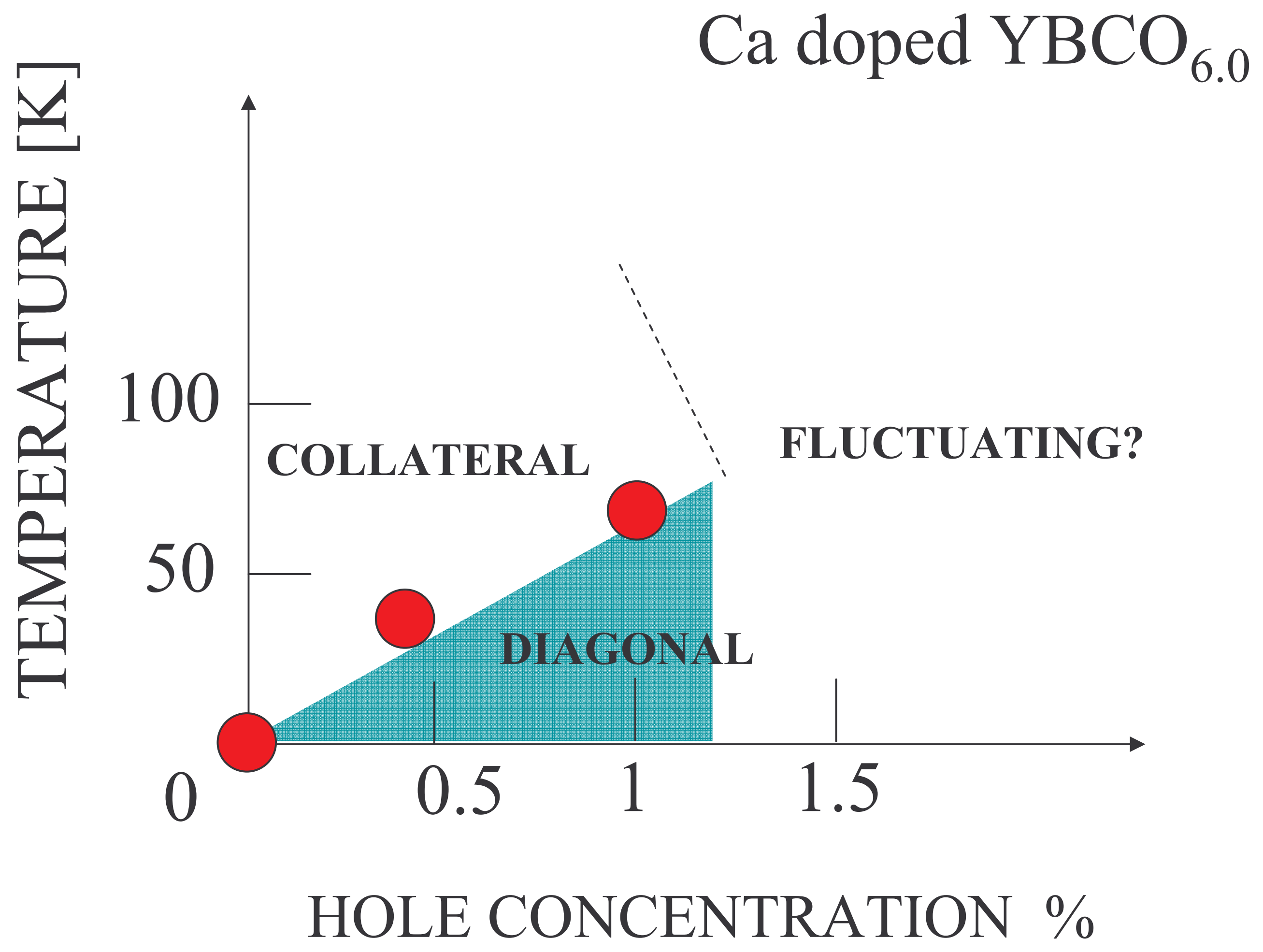
0.8 % Ca



magnetic reorientation in Ca doped $YBa_2Cu_3O_6$

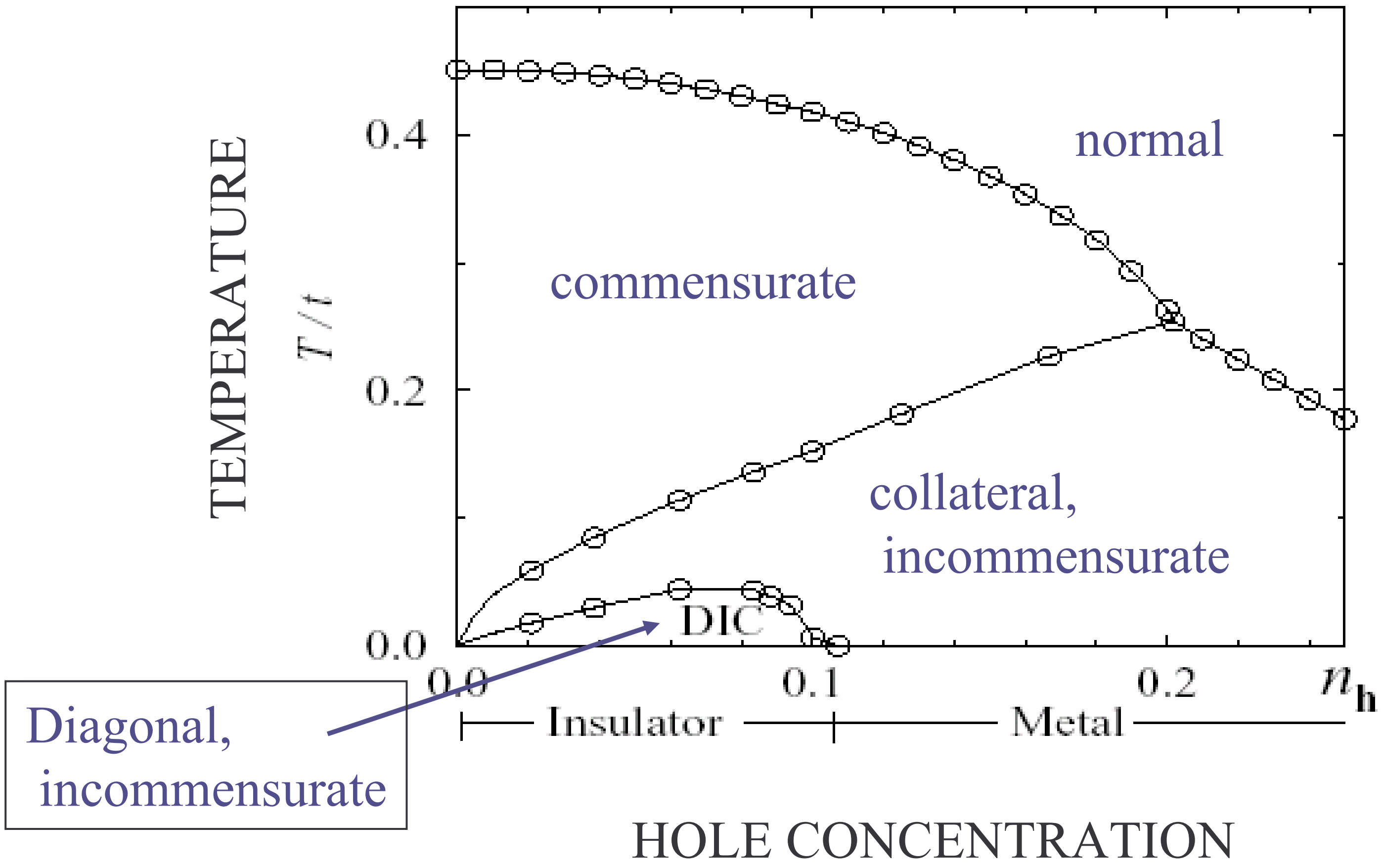
2 % Ca





Ca doped $YBCO_{6.0}$
TEMPERATURE [K]
100
50
0
COLLATERAL
FLUCTUATING?
DIAGONAL
0.5
1
1.5
HOLE CONCENTRATION %

Charge- spin phase separation

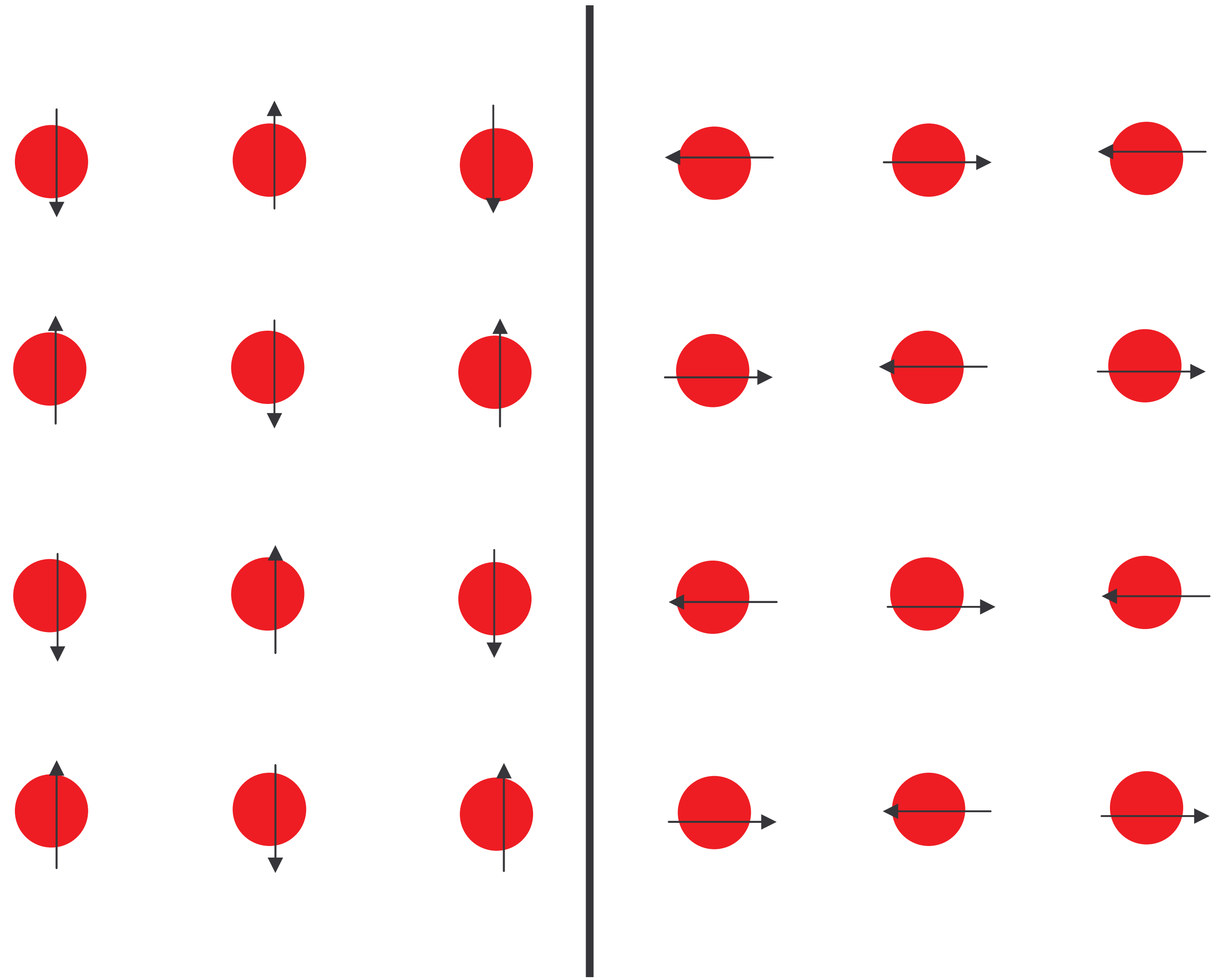


Hubbard model. Mean field.

K. Machida, M. Ichioka J. Phys. Soc. Jpn. 68 2168 1999.

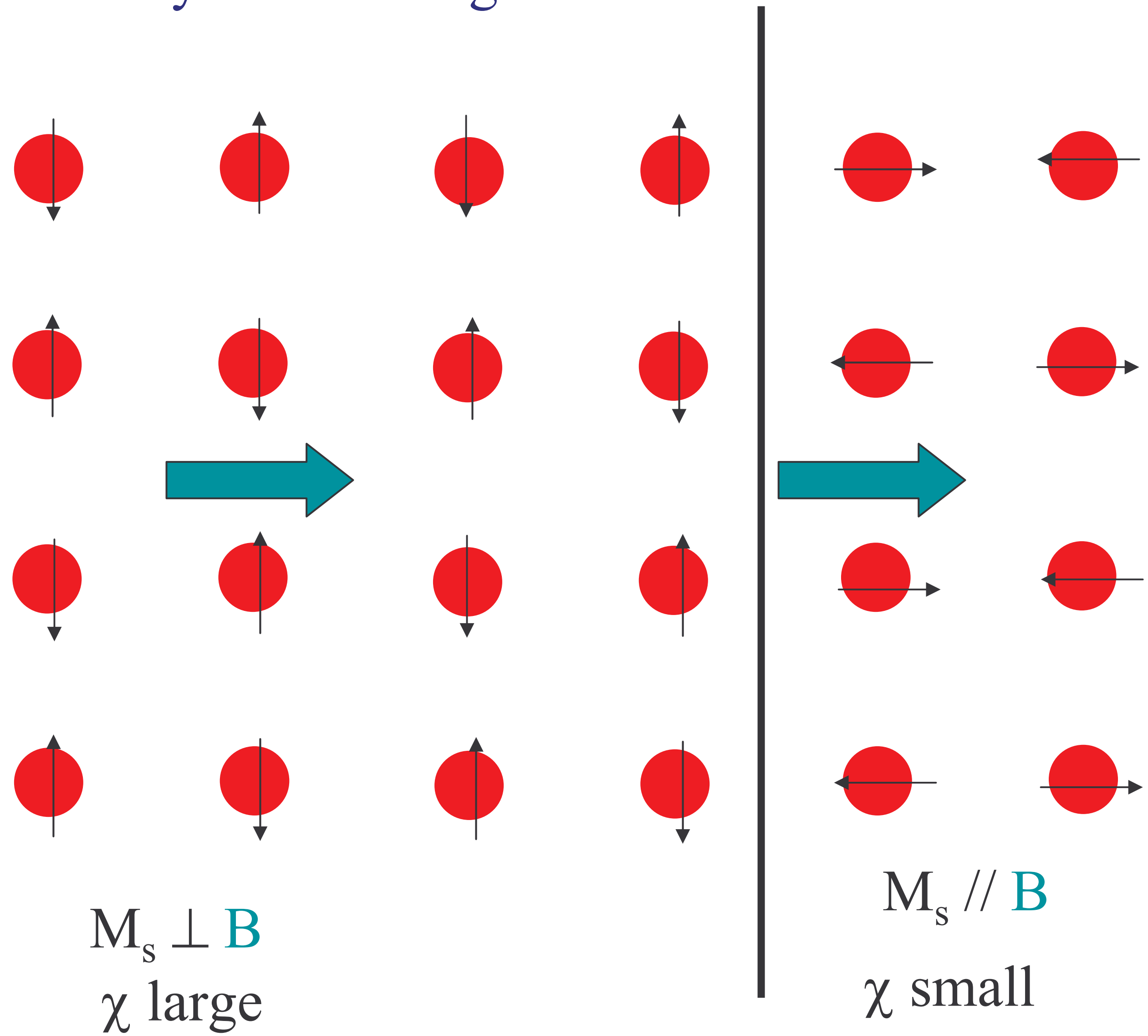
Change of domain structure with magnetic field

Magnetic fields turn crystal into single domain



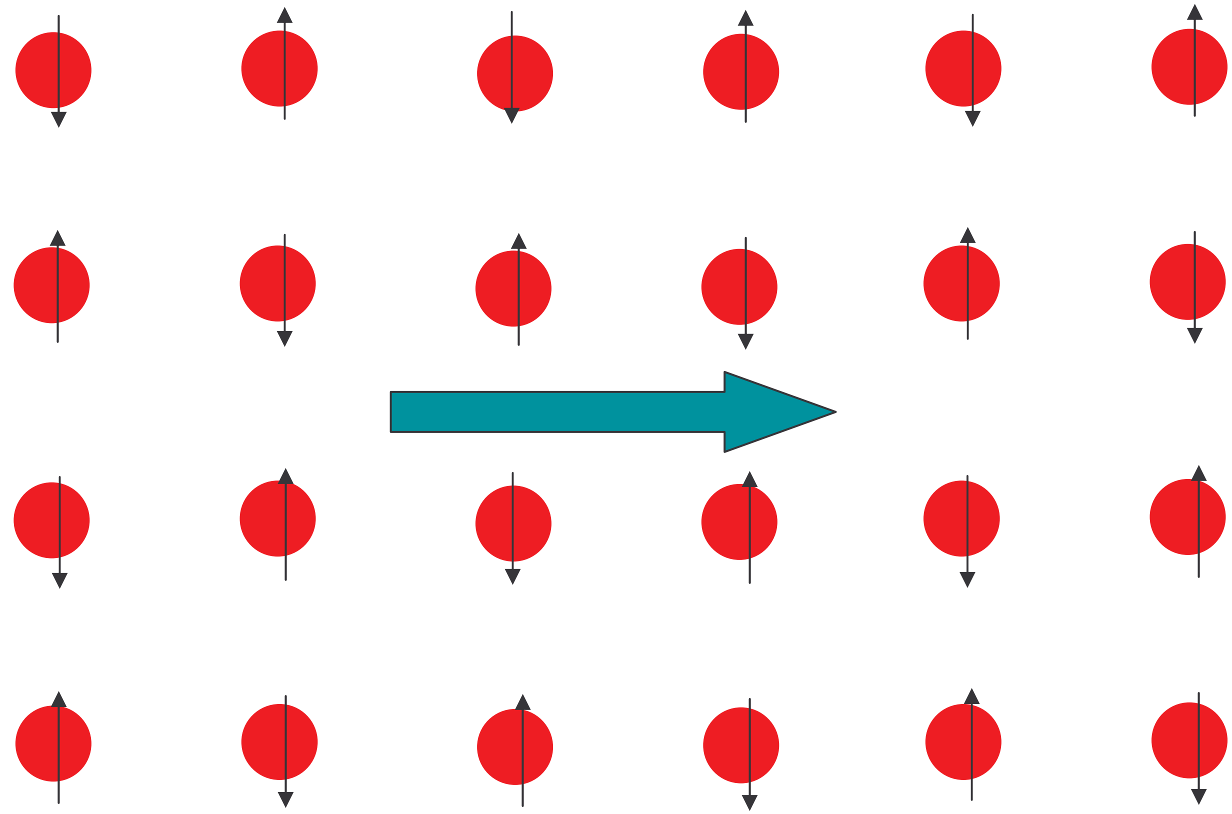
zero magnetic field

Magnetic fields turn crystal into single domain



intermediate magnetic field

Magnetic fields turn crystal into single domain

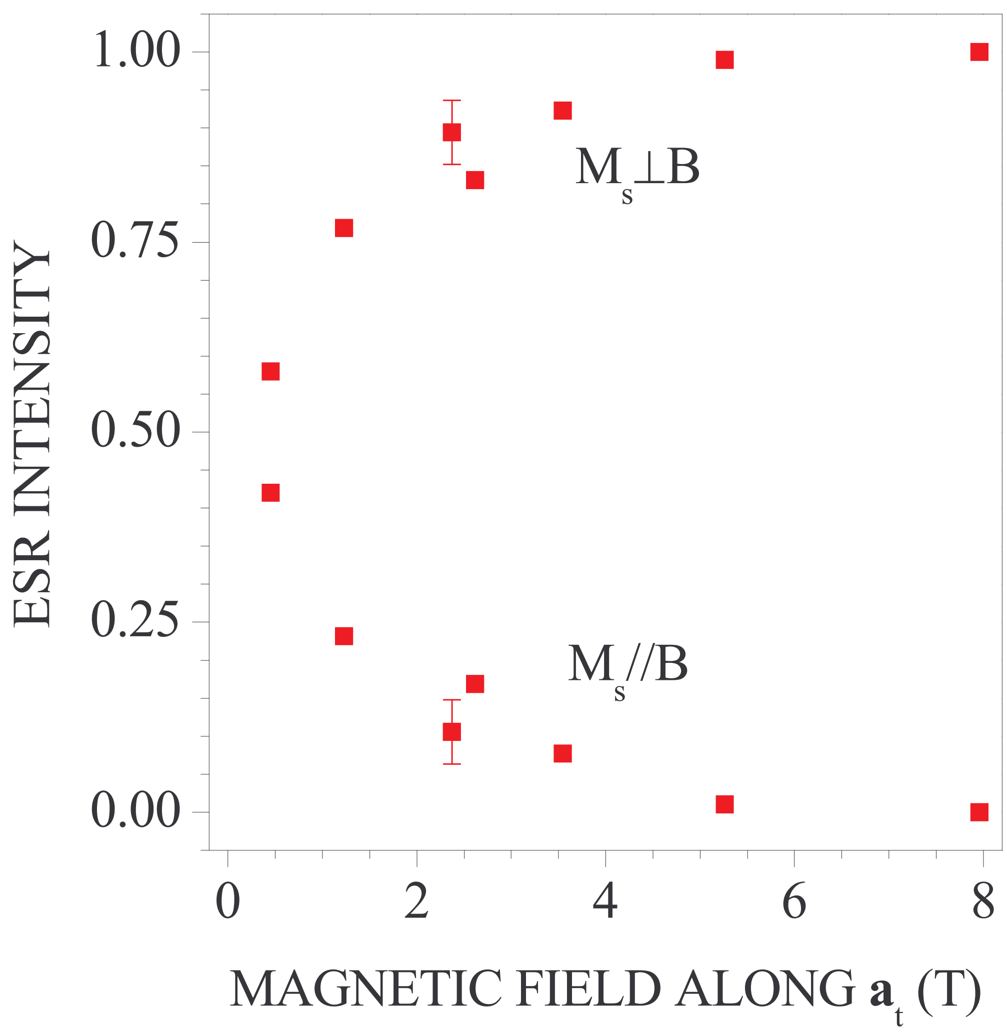


$M_s \perp \mathbf{B}$

χ large

large magnetic field: magnetically single domain

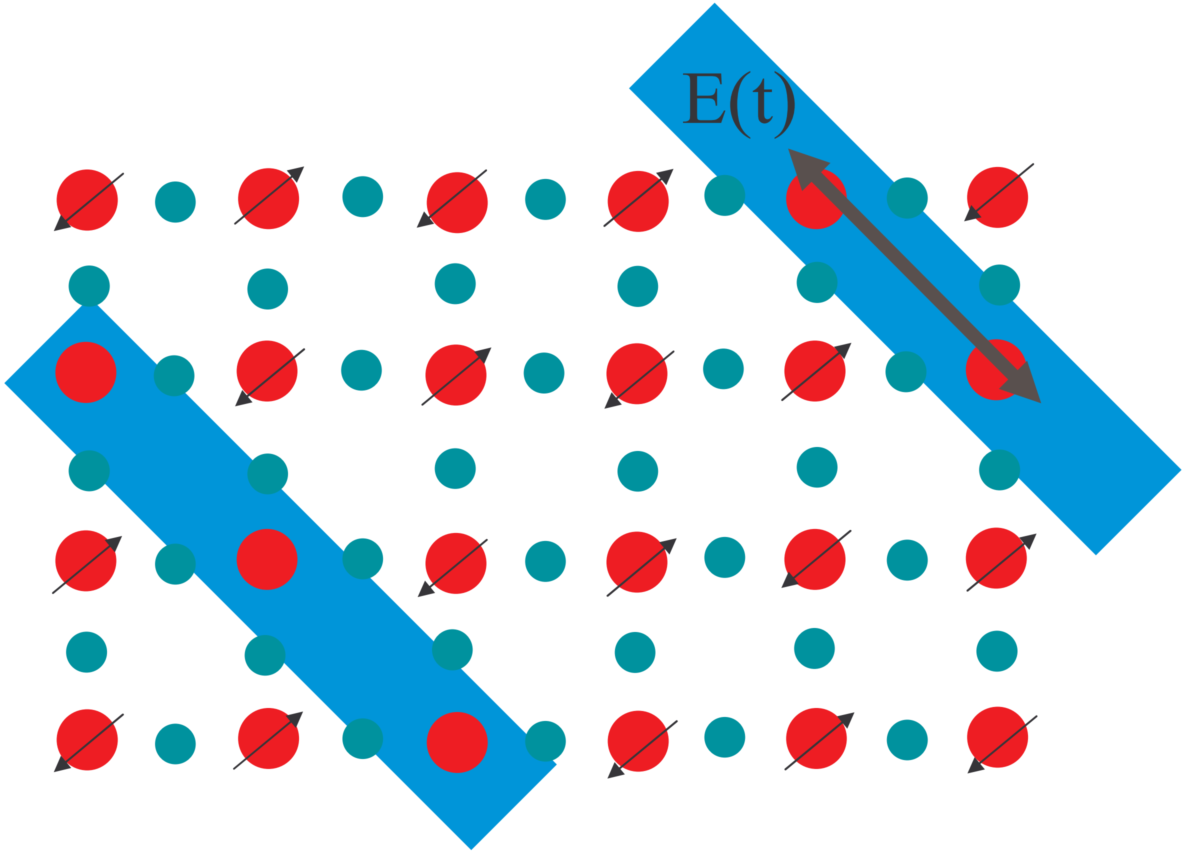
Magnetic fields turn crystal into single domain
Experiment: undoped



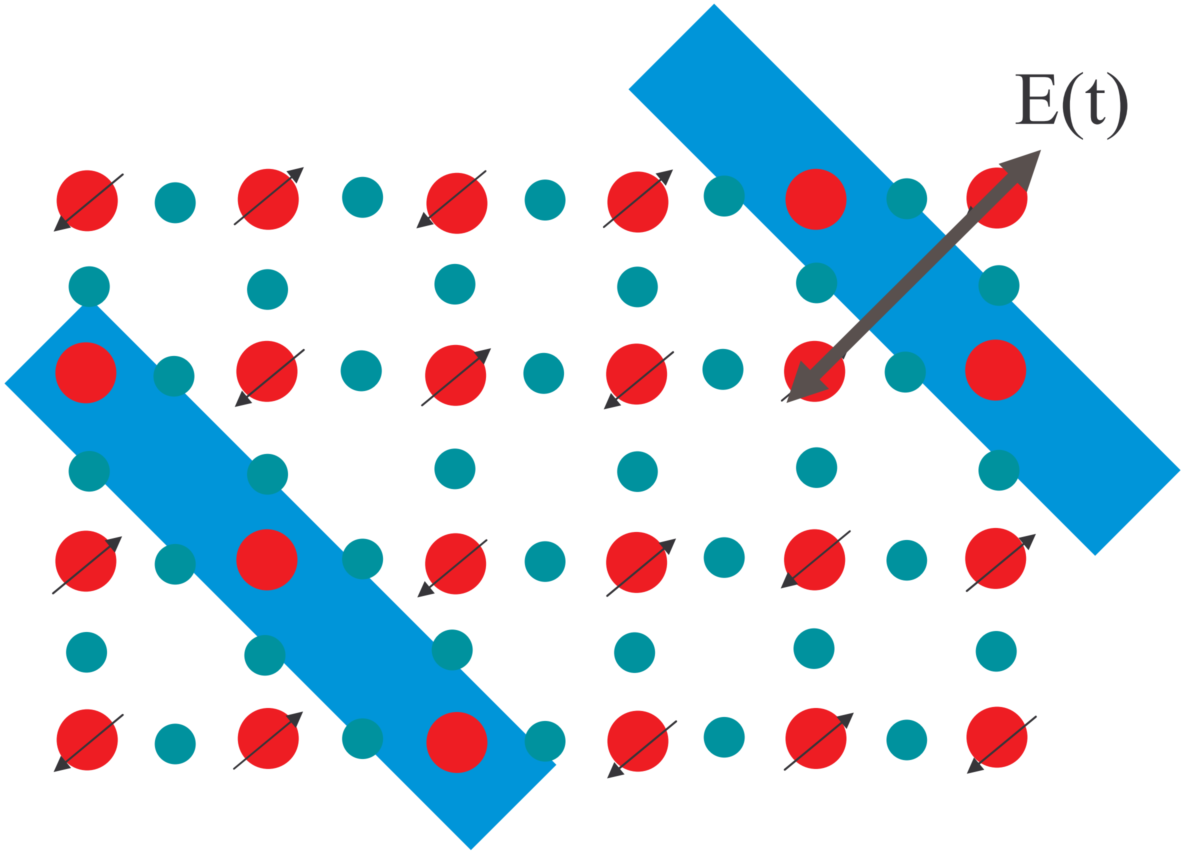
Search for anisotropic conductivity of stripes

1. Raman scattering (R. Hackl et al)
2. D.C. conductivity (Y. Ando et al)
3. IR response

anisotropic conductivity



anisotropic conductivity



Raman scattering

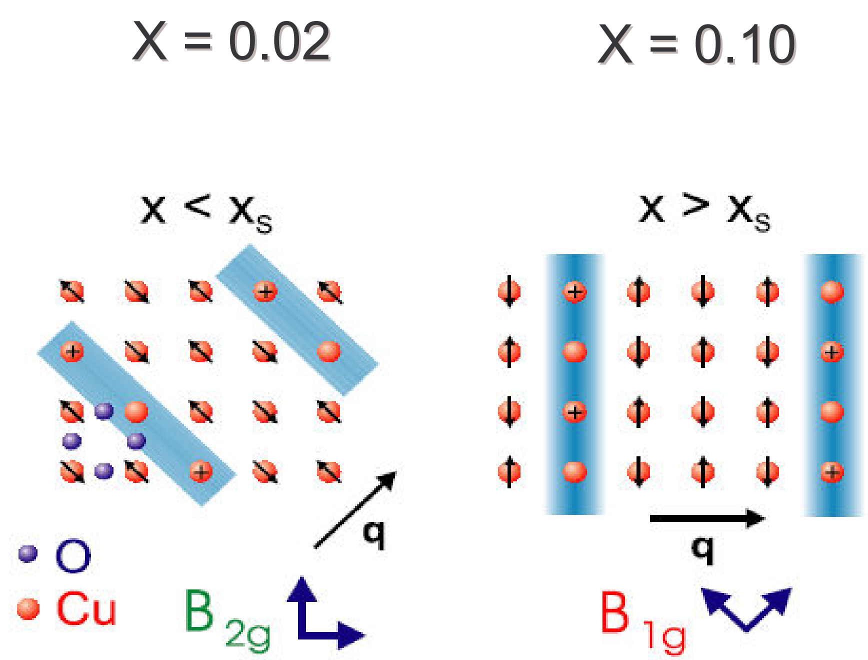


Fig. 1. Sketch of spin-charge-ordered states in the copper–oxygen plane

The response can only be observed if both incoming and outgoing photons have a finite projection on the direction of the stripes or perpendicular to them.

R. Hackl, L. Tassini et al
Journal of Physics and Chemistry of Solids xx (2005) 1–5

Raman scattering, $Ca_xY_{1-x}Ba_2Cu_3O_6$

2 and 3% Ca
Response in B_{2g}:
diagonal

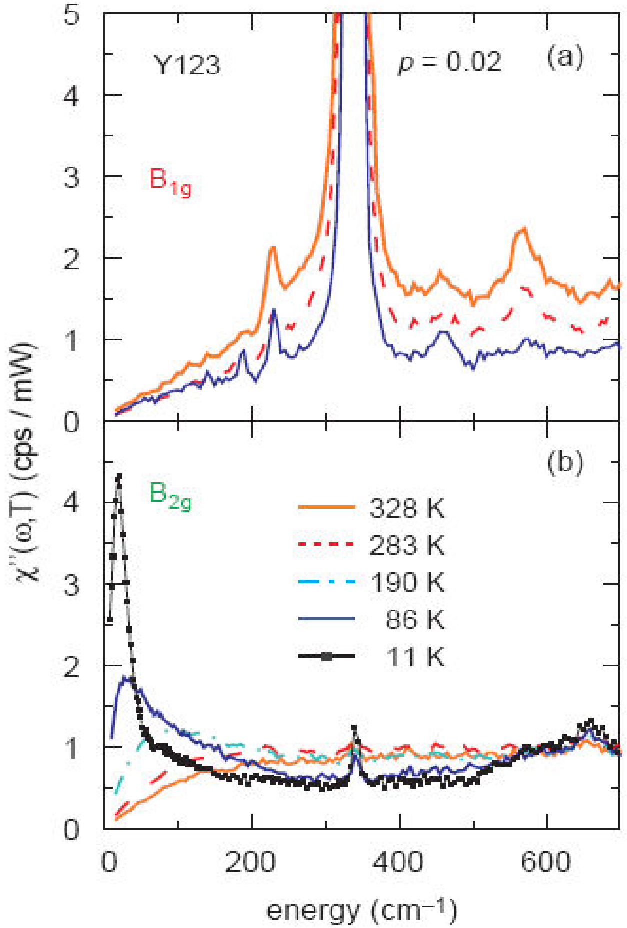
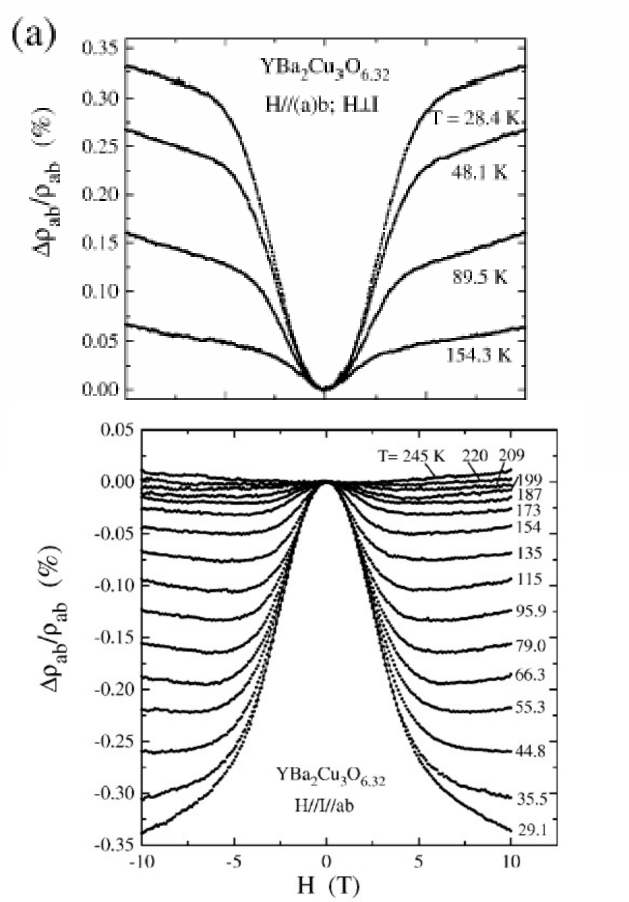


Fig. 7. Raman response $X''_{\mu(w,T)}$ of $(Y_{1.97}Ca_{0.03})Ba_2Cu_3O_{6.05}$ in B_{1g} (a) and B_{2g} (b) symmetry. The doping level is close to $p=0.02$.

R. Hackl, L. Tassini et al
Journal of Physics and Chemistry of Solids xx (2005) 1–5

D.C. resistance in magnetic field

Magneto resistance



H ⊥ I

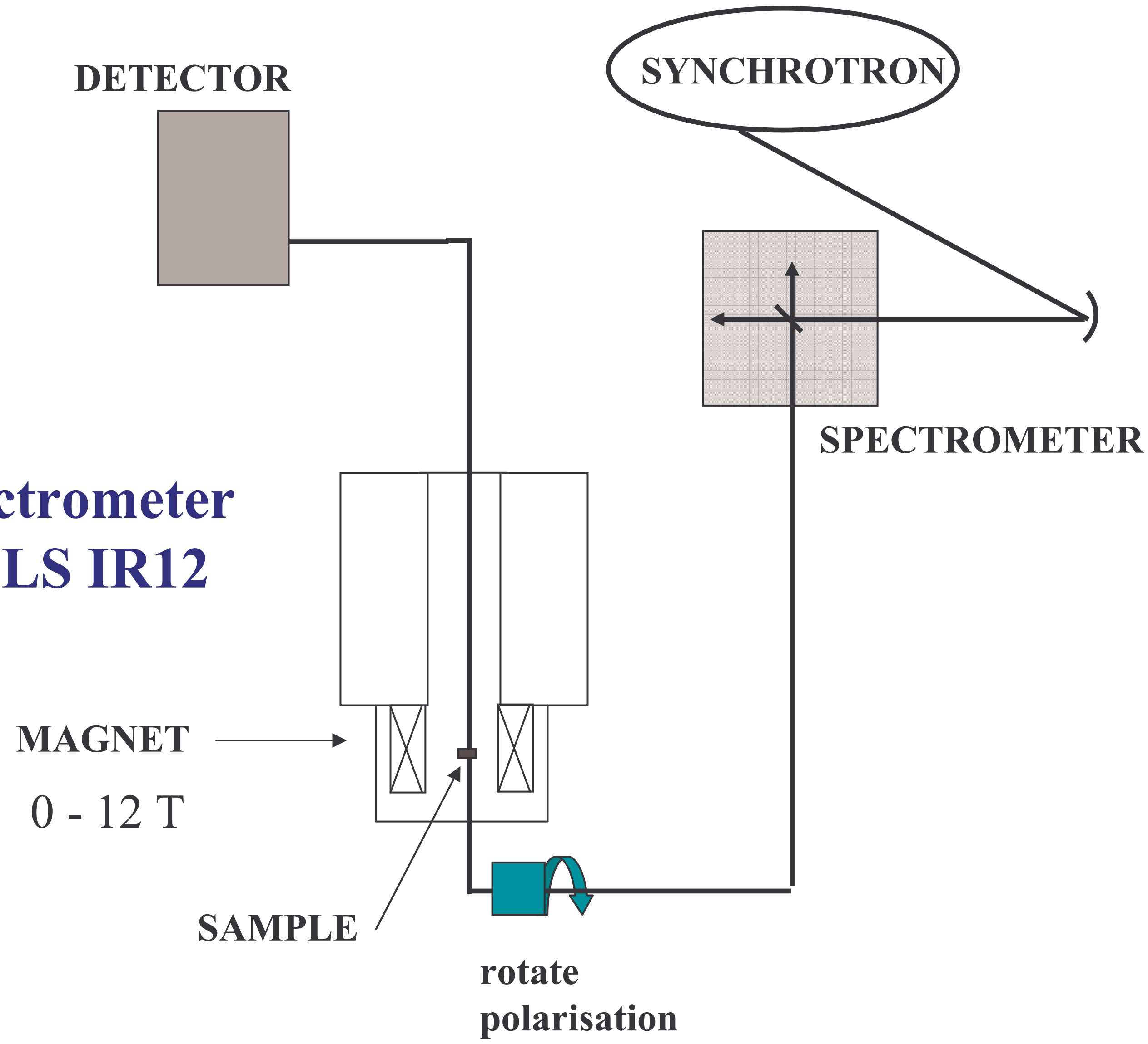
H // I

magnetostriction ?

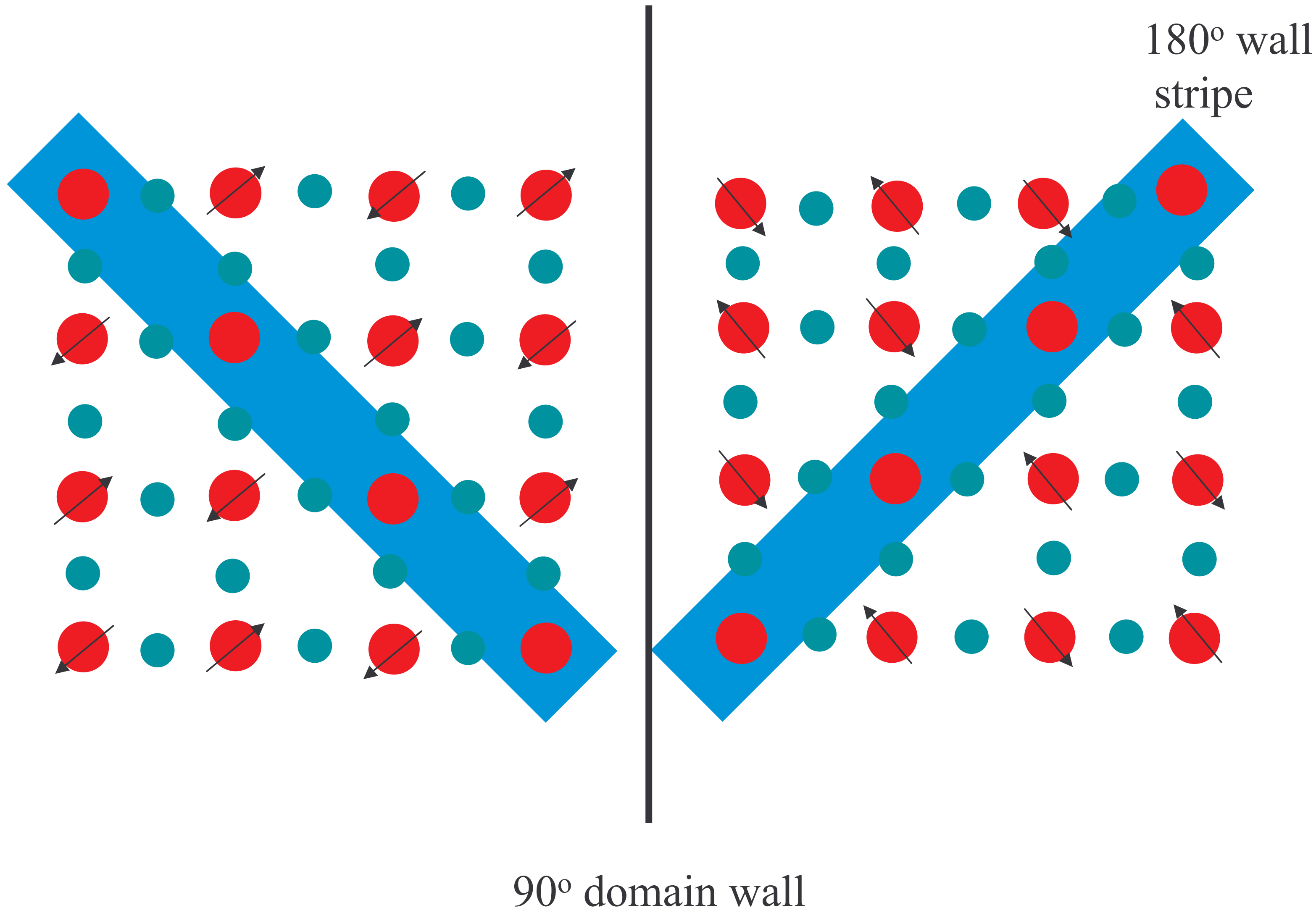
Y. Ando, A. N. Lavrov, and K. Segawa, Phys. Rev. Lett. **83**, 2813 (1999).

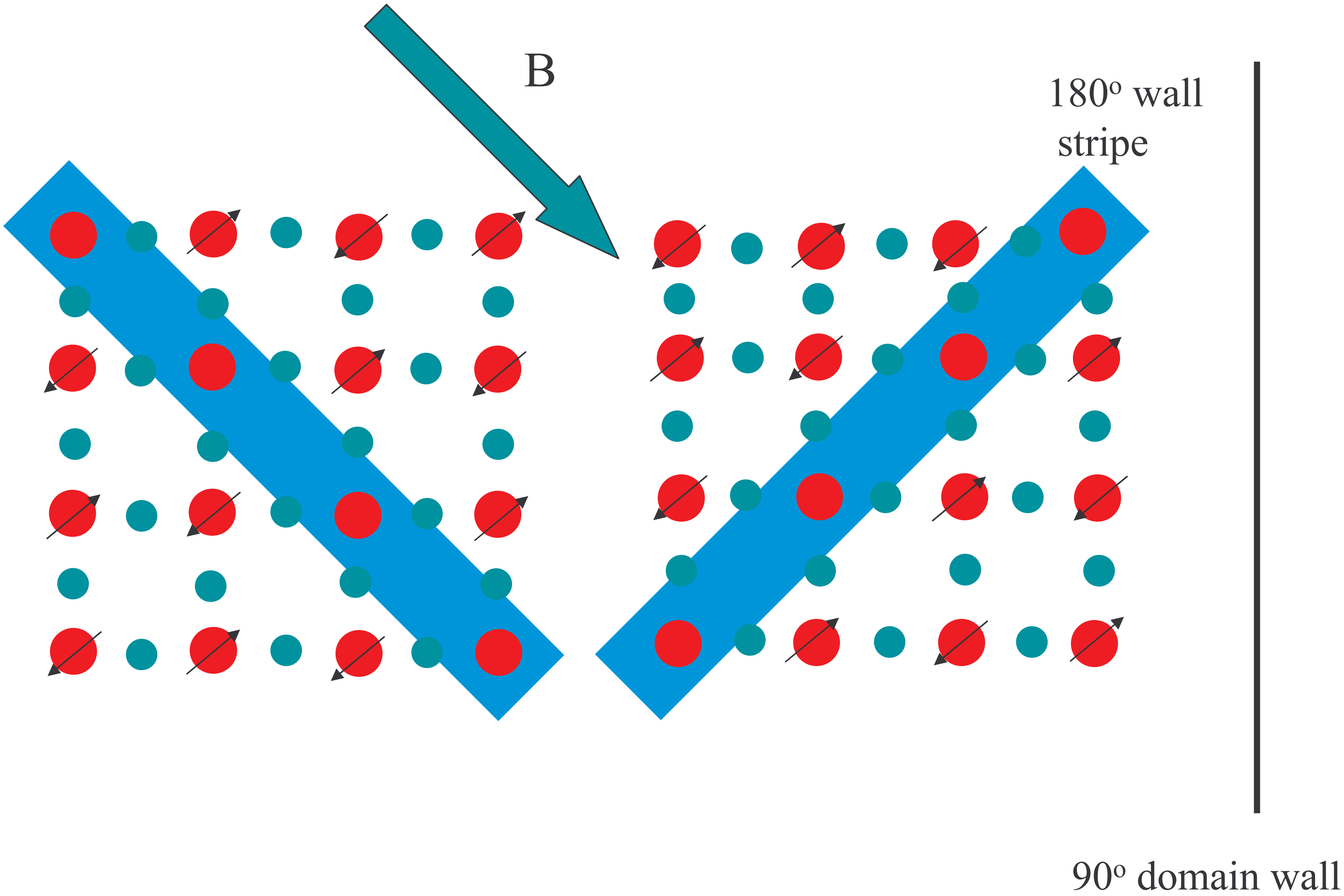
IR transmission in magnetic field

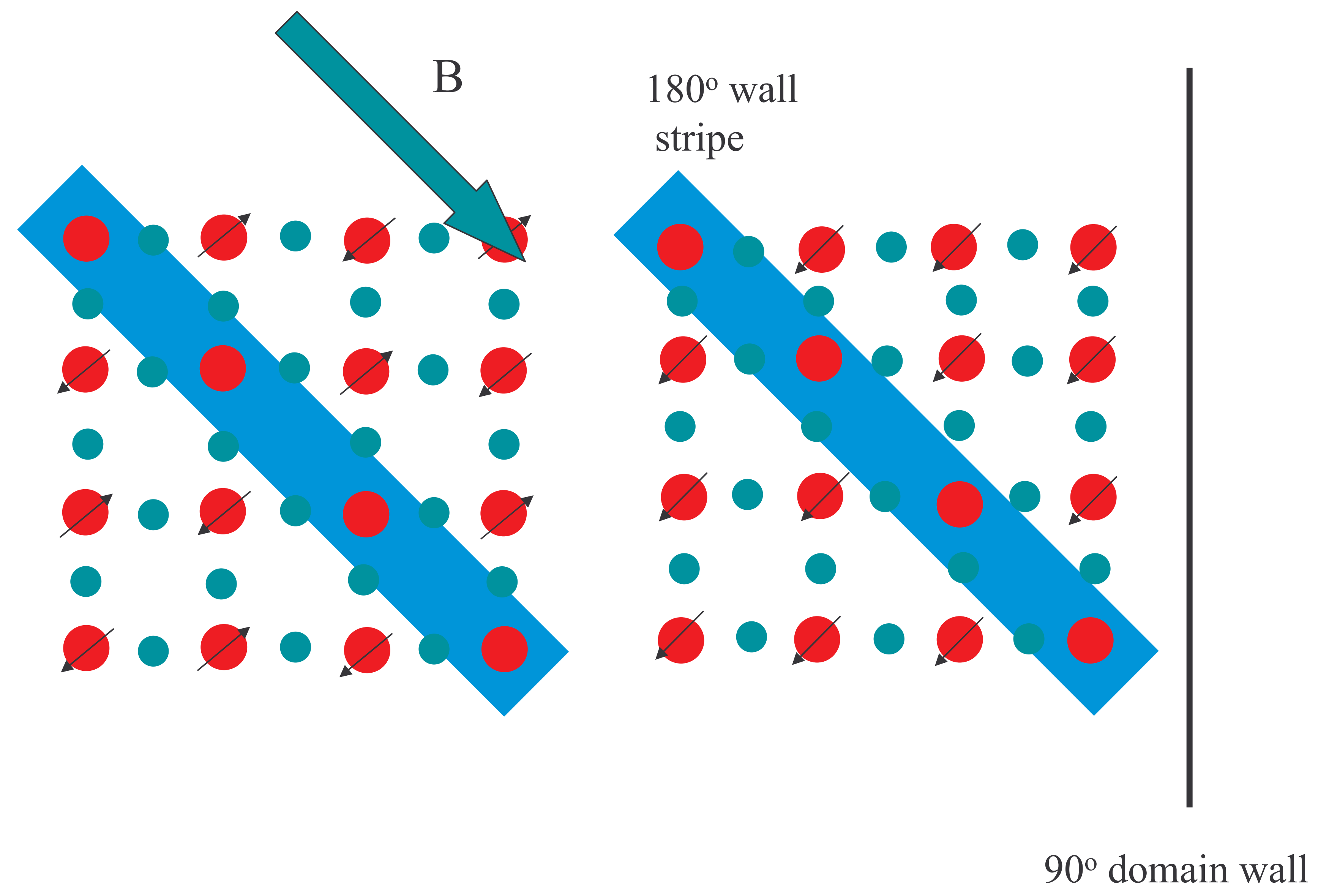
FT-IR ESR spectrometer
Brookhaven NSLS IR12

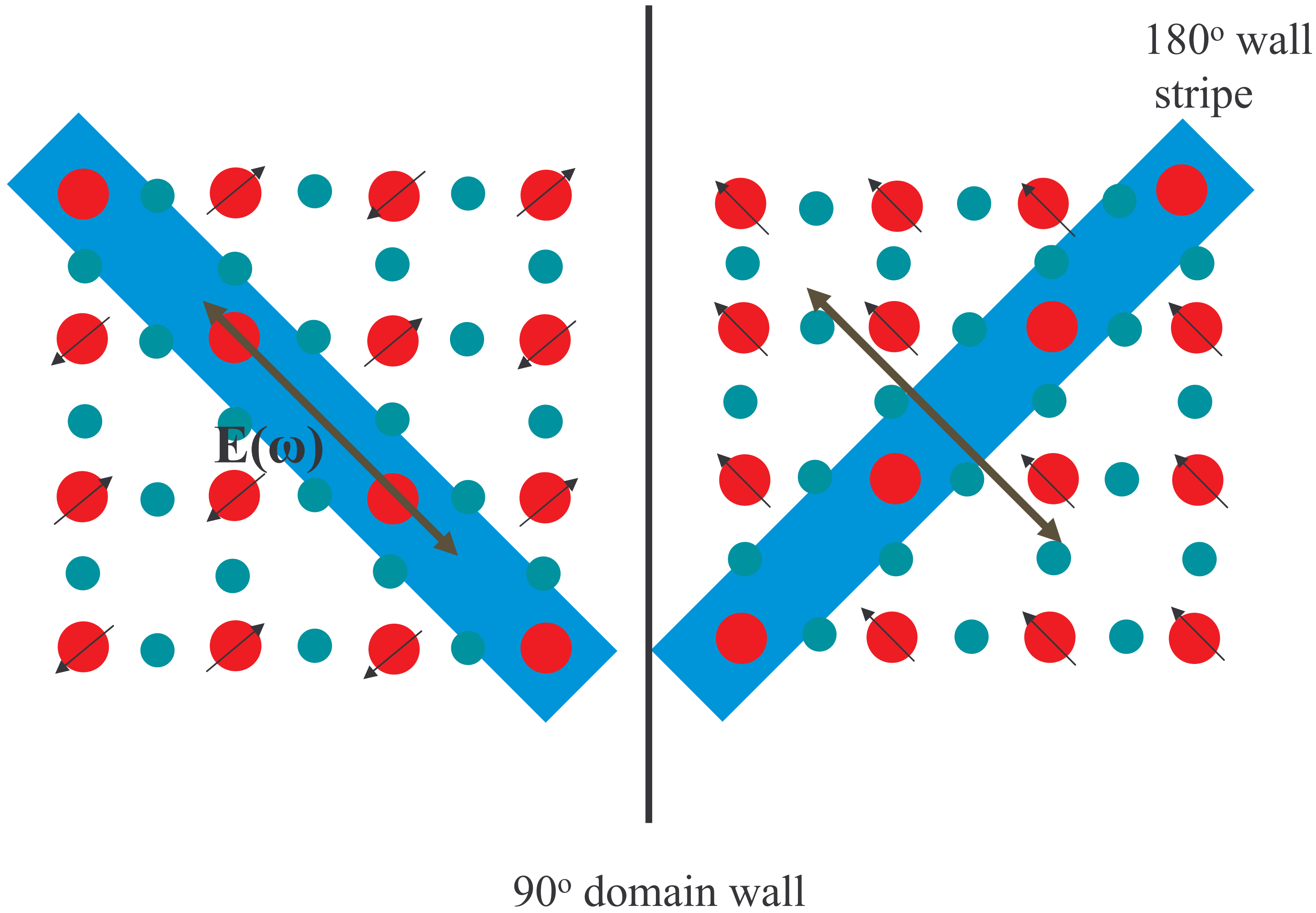


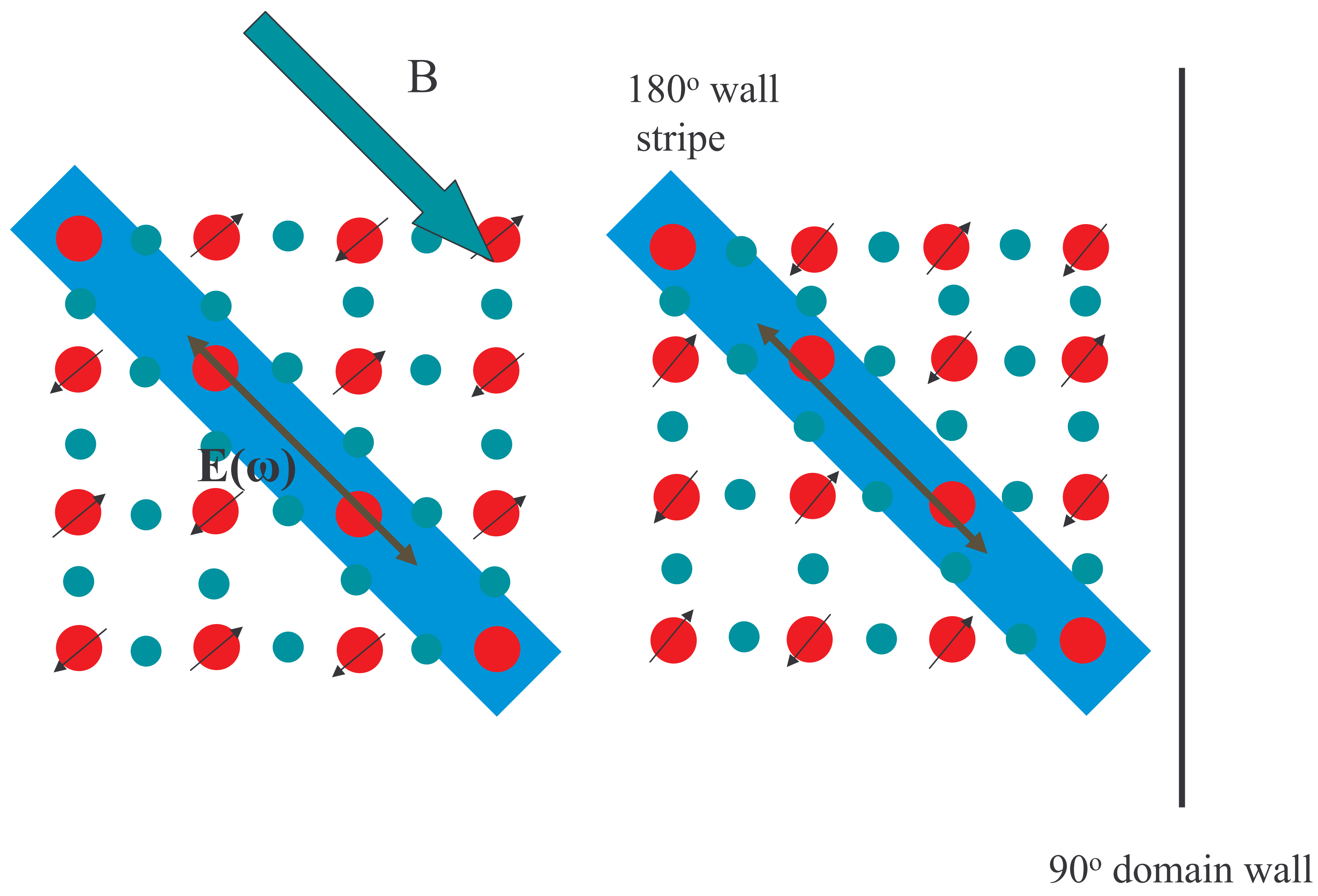
A. Janossy et al Phys.Rev.B 2007


180° wall
stripe
90° domain wall


B
180° wall
stripe
90° domain wall


B
180° wall
stripe
90° domain wall


180° wall
stripe
E(ω)
90° domain wall


B
180° wall
stripe
E(ω)
90° domain wall

2% Ca YBCO in 8 T field:

magnetically single domain
for all orientations

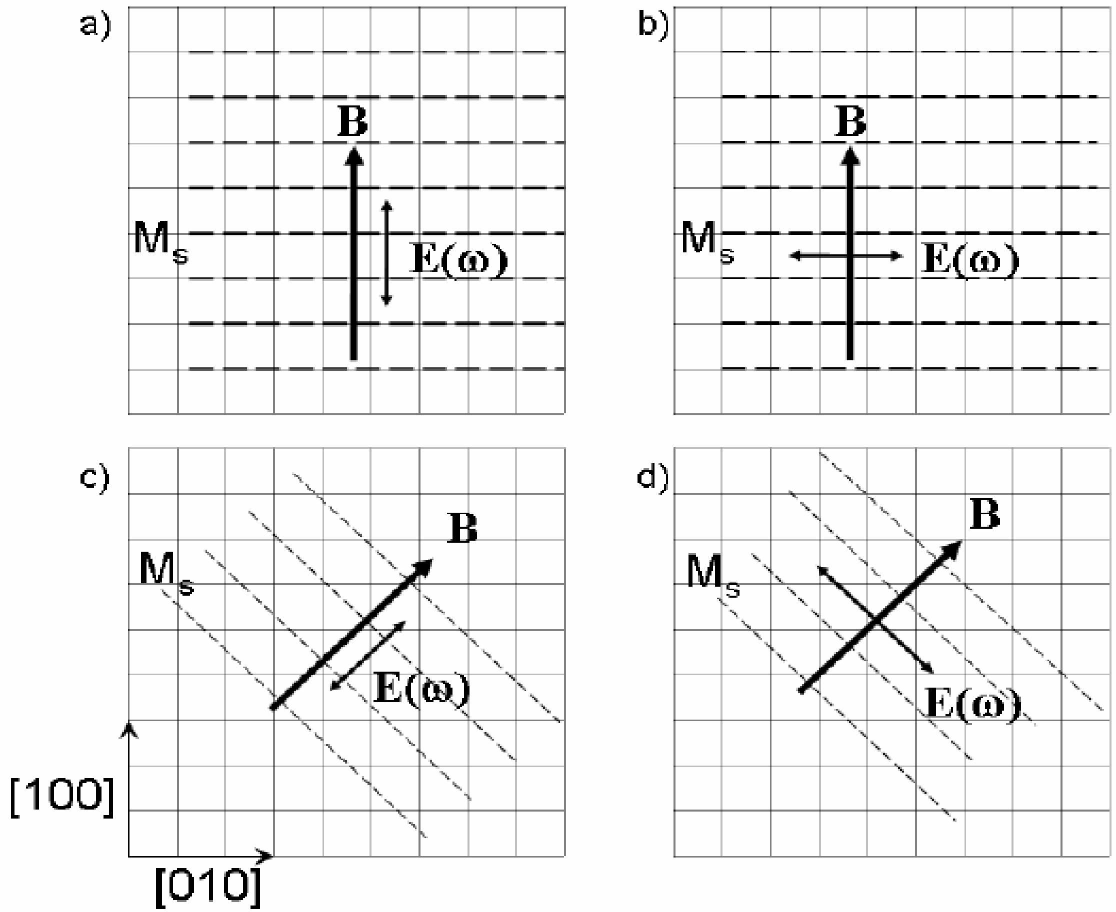


Figure 9. Geometrical arrangements of the infrared (IR) transmission experiments.

IR transmission in magnetic field

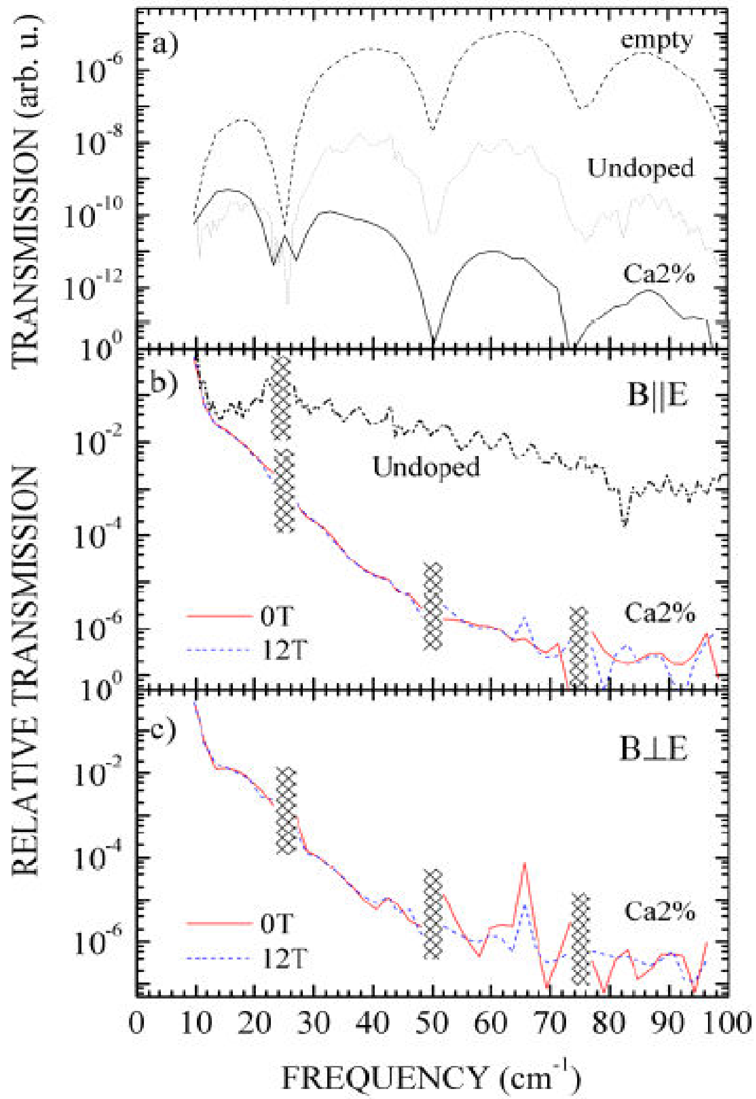
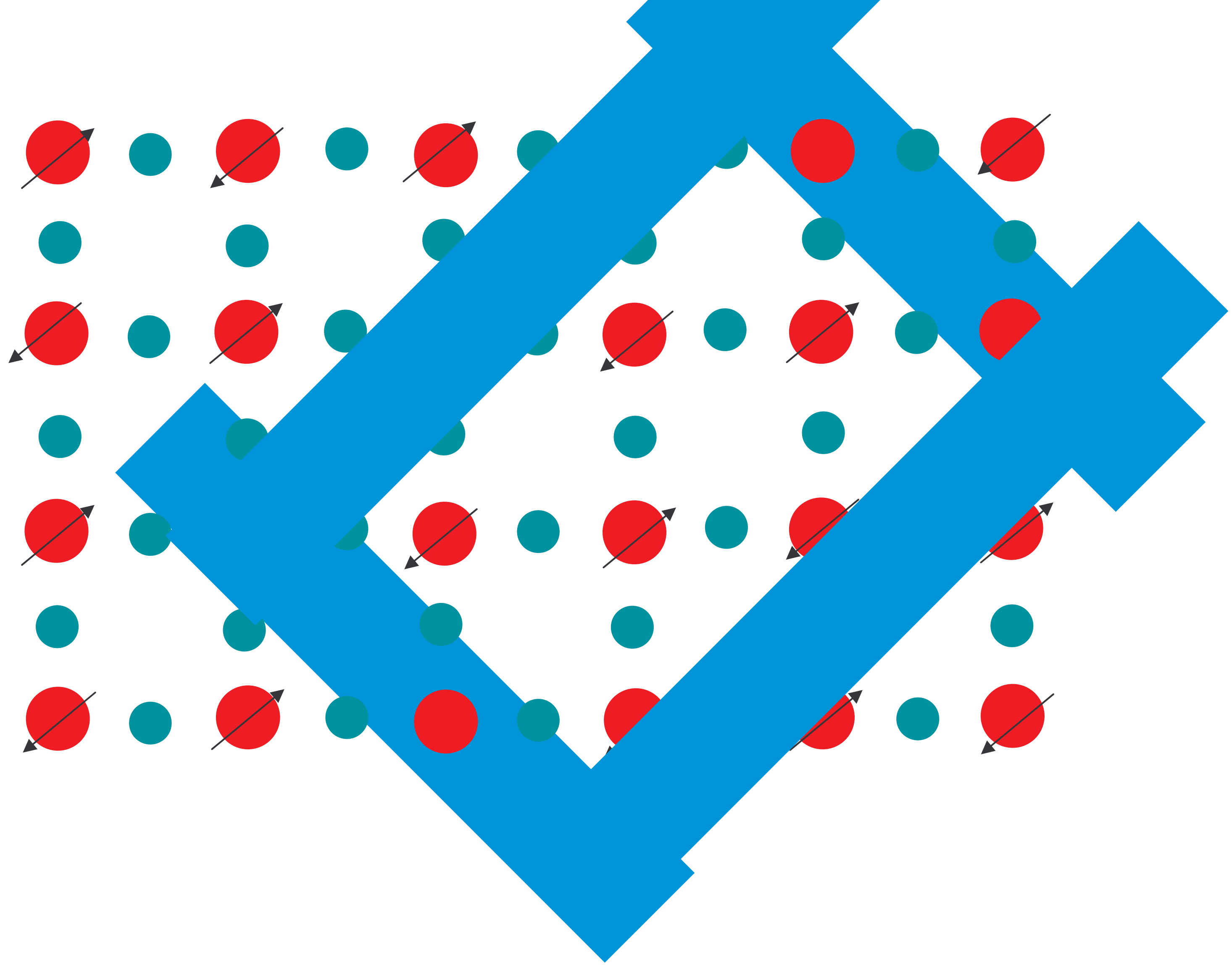


Figure 10. IR transmission through the Ca2% single crystal.

Pinning of spins to lattice

experiment: both 2 and 4-fold anisotropies, 4 fold stronger



Conclusions:

In lightly hole doped Ca:YBCO
at low temperatures:

-Holes are not localized around Ca
-AF magnetization is diagonal => stripes diagonal
-AF domain structure is static

AF magnetization is weakly pinned to stripes

No anisotropy in $\sigma(\omega)$ below ~70 cm^{-1}
=> No sign of conducting stripes

Charged "stripes" are strongly pinned to lattice