UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

H4.SMR/1001-8

IX TRIESTE WORKSHOP ON
OPEN PROBLEMS IN
STRONGLY CORRELATED SYSTEMS

14 - 25 July 1997

KONDO vs POLARONIC VIEW OF CMR MANGANITES

N. FURUKAWA
University of Tokyo
Institute for Solid State Physics
Minato-Ku, Tokyo
JAPAN

These are preliminary lecture notes, intended only for distribution to participants.

Kondo vs Polaronic View of CMR Manganites

Nobuo Furukawa
Institute for Solid State Physics,
University of Tokyo

ABSTRACT

- Introduction
  - ⋆ Double-Exchange systems (review)
  - ⋆ Recent experimental results
  - ⋆ Recent theoretical proposals
- DMF for the Ferromagnetic Kondo Lattice Model.
- Scaling Relations
- Summary

② $(R,A)MnO_3$ manganites are double-exchange ferromagnets.

- Zener (1951), Anderson-Hasegawa (1955), deGennes (1960), Searle-Wang (1970), Kubo-Ohata (1972)

Zener (1951):
Ferromagnetism in $LaMnO_{3-\delta}$ due to itinerant motion of Mn 3d electrons. $Mn^{3+} = (3d)^4 = (t_{2g})^3(e_g)^1$

Model Hamiltonian
(extended *s*-*d* model, Zener model, Kondo lattice model)

$$\mathcal{H} = -t\sum\left(c^\dagger_{i\sigma}c_{j\sigma} + h.c.\right) - J_\mathrm{H}\sum\vec{S}_i\cdot\vec{\sigma}_i$$

Double-Exchange Interaction between local spins $\vec{S}$.

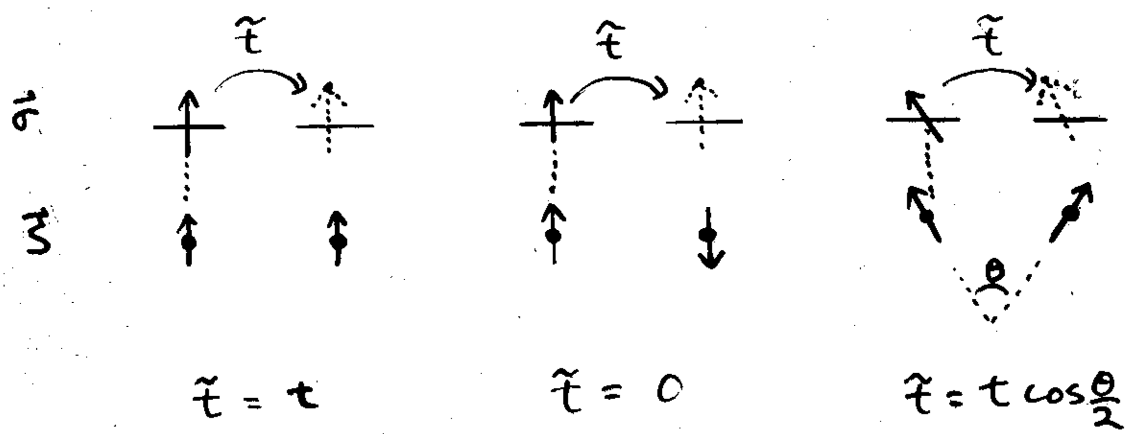
Anderson-Hasegawa (1955):
Effective Hamiltonian in the limit $J_\mathrm{H}\to\infty$:
project out electron's spin component anti-parallel to localized spin $\vec{S}$, i.e.

$$\mathcal{H} = \sum\tilde{t}_{ij}\tilde{c}^\dagger_i\tilde{c}_j + h.c.$$

where hopping matrix element $\tilde{t}_{ij}$ is

$$|\tilde{t}_{ij}| = t\cos(\theta_{ij}/2)$$

and $\tilde{c}_i$ is electron operator with spin parallel to $\vec{S}_i$.



Zener (1951):
Ferromagnetism in $LaMnO_{3-\delta}$ due to itinerant motion of Mn 3d electrons. $\quad Mn^{3+} = (3d)^4 = (t_{2g})^3(e_g)^1$

Model Hamiltonian
(extended *s*-*d* model, Zener model, Kondo lattice model)

$$\mathcal{H} = -t\sum\left(c_{i\sigma}^{\dagger}c_{j\sigma} + h.c.\right) - J_{\mathrm{H}}\sum\vec{S}_i\cdot\vec{\sigma}_i$$

Double-Exchange Interaction between local spins $\vec{S}$.

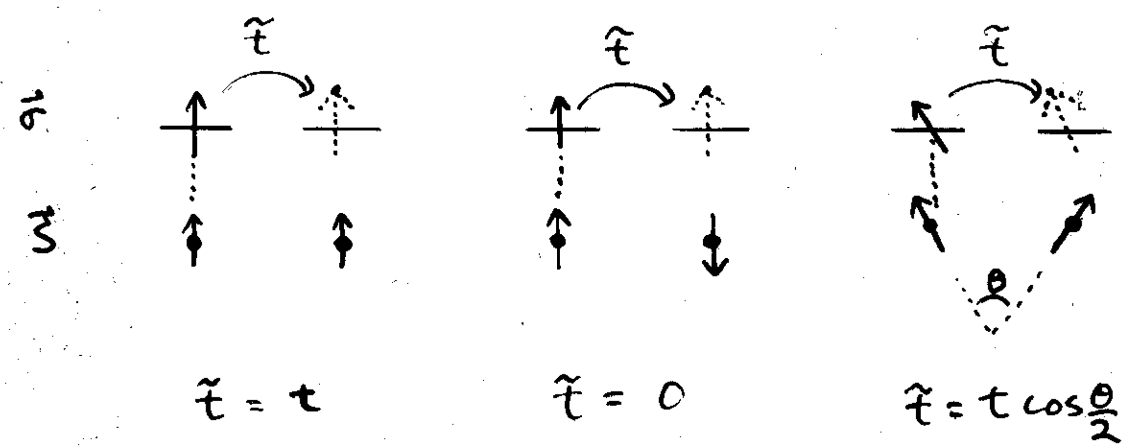
Anderson-Hasegawa (1955):
Effective Hamiltonian in the limit $J_{\mathrm{H}} \to \infty$:
project out electron's spin component anti-parallel to localized spin $\vec{S}$, i.e.

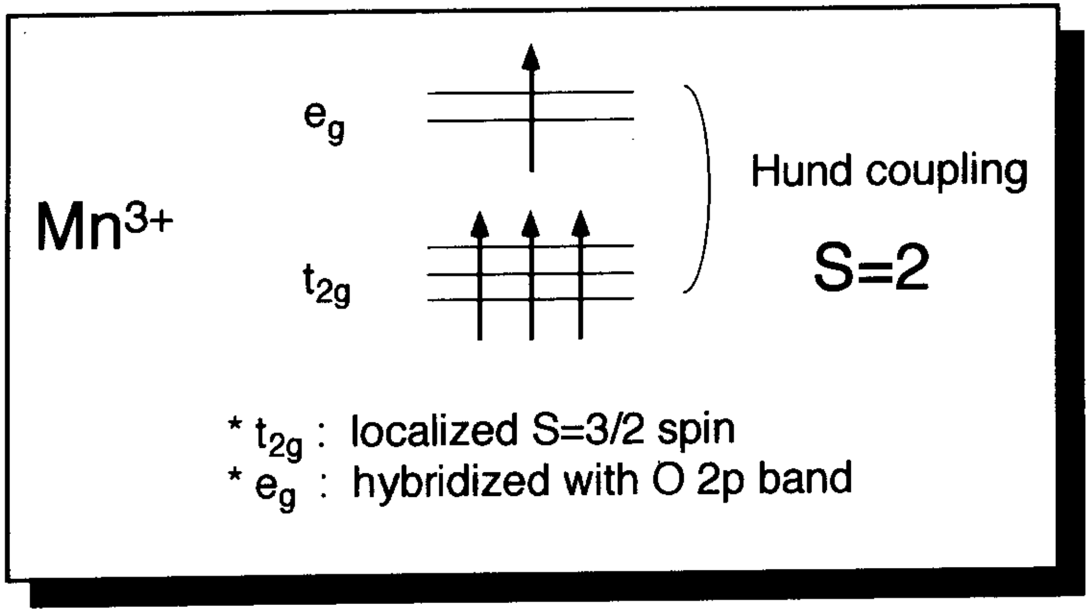
$$\mathcal{H} = \sum\tilde{t}_{ij}\tilde{c}_i^{\dagger}\tilde{c}_j + h.c.$$

where hopping matrix element $\tilde{t}_{ij}$ is

$$|\tilde{t}_{ij}| = t\cos(\theta_{ij}/2)$$

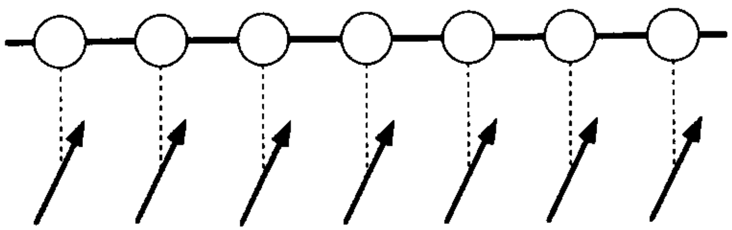
and $\tilde{c}_i$ is electron operator with spin parallel to $\vec{S}_i$.





* t_{2g} : localized S=3/2 spin
* e_g : hybridized with O 2p band

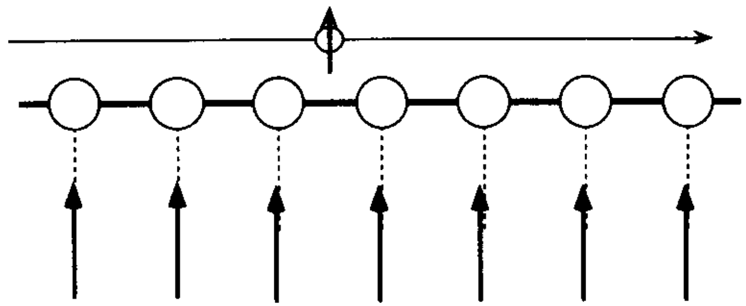
Kondo Lattice Model



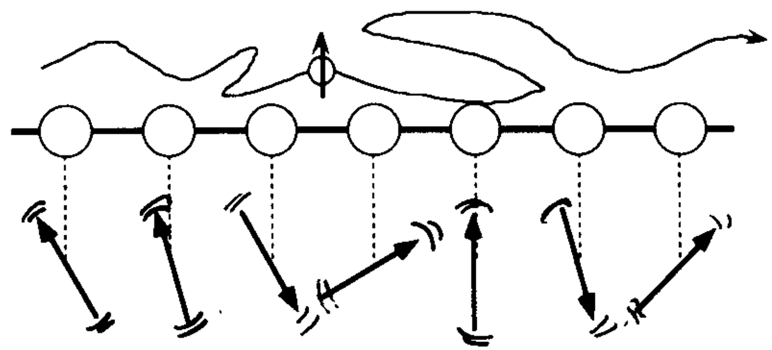
$$H=-\sum_{ij,\sigma} t_{ij}c^{\dagger}_{i\sigma}c_{j\sigma} - J\sum_{i} \vec{S}_i \cdot \vec{\sigma}_i$$

S=3/2
J>0 ferromagnetic

Ferromagnetic state:



paramagnetic state:



spin disorder scattering

Zener, Anderson-Hasegawa, de Gennes, Kubo-Ohat

$(R,A)MnO_3$ manganites are double-exchange ferromagnets.

- Zener (1951), Anderson-Hasegawa (1955), deGennes (1960), Searle-Wang (1970), Kubo-Ohata (1972)

(?) Are $(R,A)MnO_3$ manganites double-exchange ferromagnets?

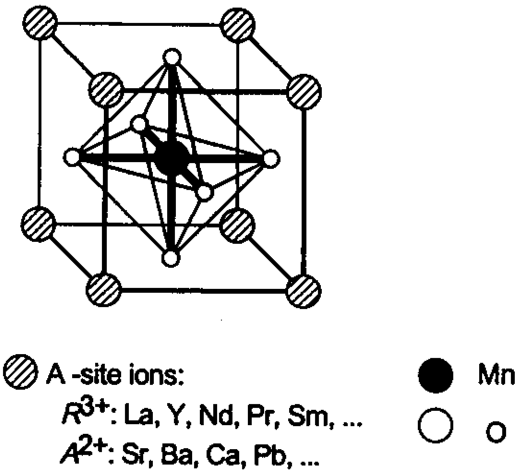
- Experimental Evidences:
  - ⋆ Ferromagnetic-metal in limited region only.
  - ⋆ Relevance of lattice distortion:
    - ∗ A-type AF with collective Jahn-Teller distortion
    - ∗ Oxigen distortion (Debye-Waller, PDF) anomaly near T_c
  - ⋆ Relevance of orbital degree of freedom:
    - ∗ Charge ordered AF insulator with orbital ordering near $x \sim 0.5$.
    - ∗ A-type AF metal
  - ⋆ Intrinsic vs. Extrinsic effects: grain boundaries, etc.

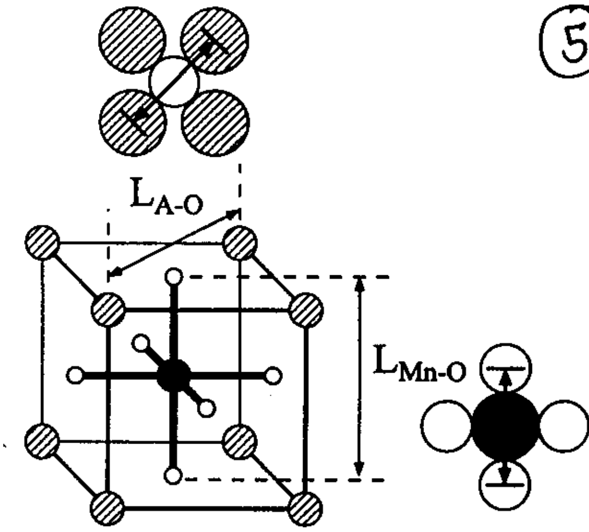
(These are clarified by recent experiments with high quality samples/techniques.

carrier number x vs bandwidth W)

⑤ ④

(R,A)MnO3

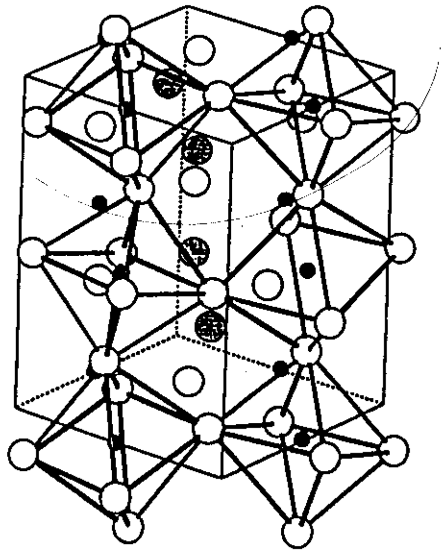




Carrier Doping

$R_{1-x}A_xMnO_3$: Mn $(3d)^{4-x}$

tolerance factor $t = \frac{L_{A-O}}{\sqrt{2} L_{Mn-O}}$



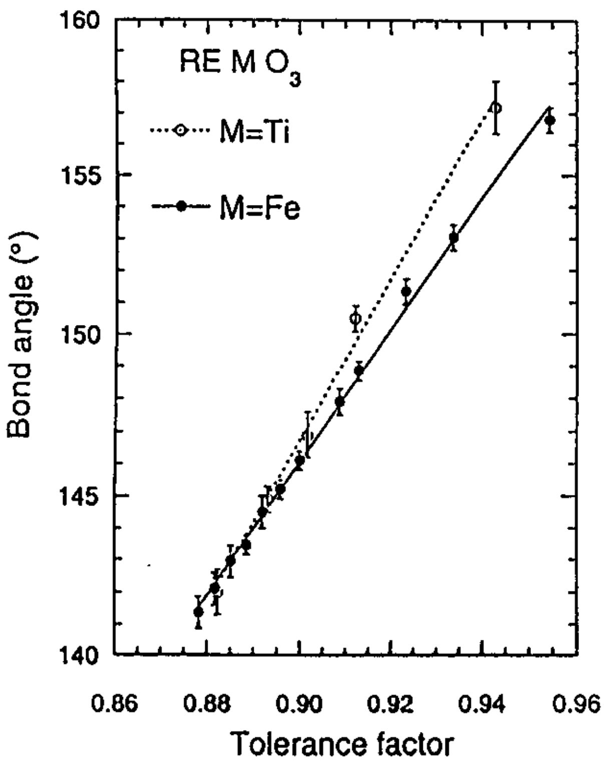
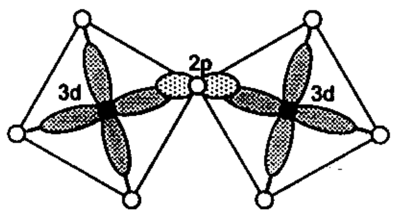


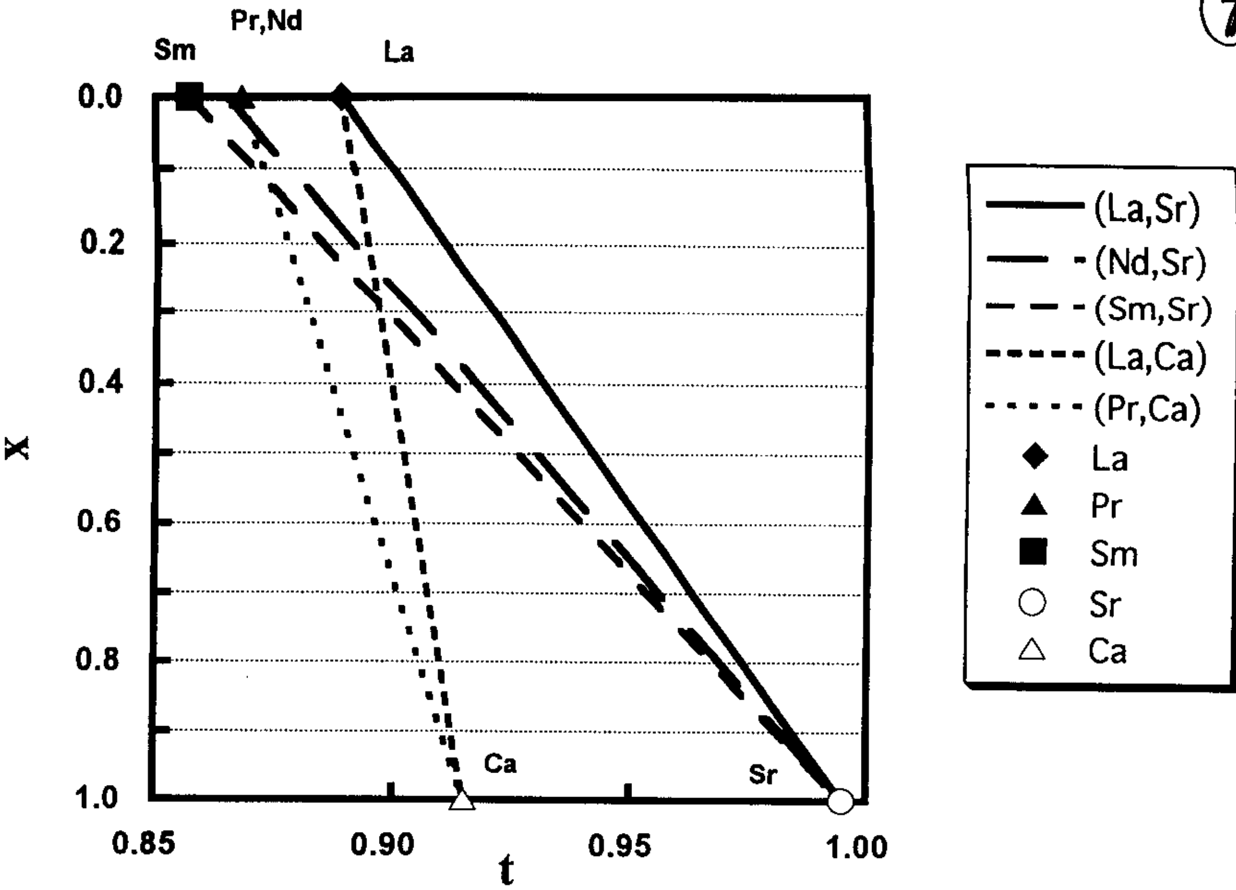
Fig. 66

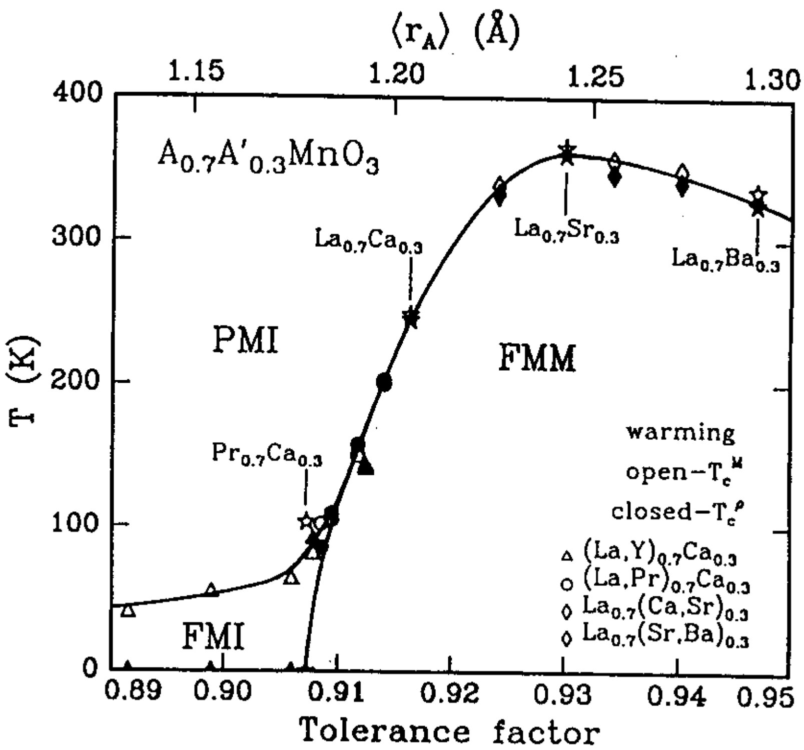
Tilting of octahedra reduces electron hopping.



$t_{dd} \propto (\cos\theta)^2$

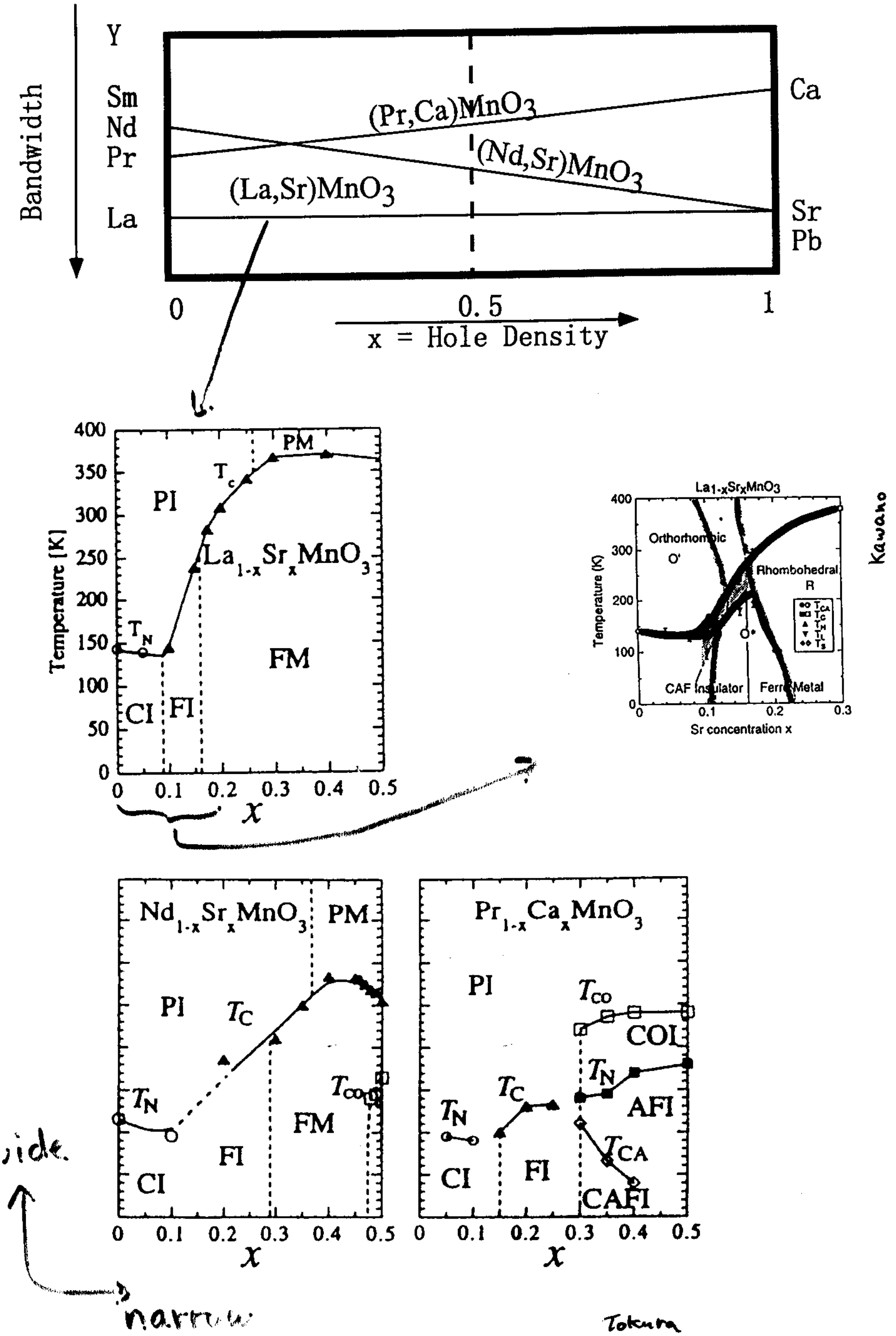
Bandwidth control





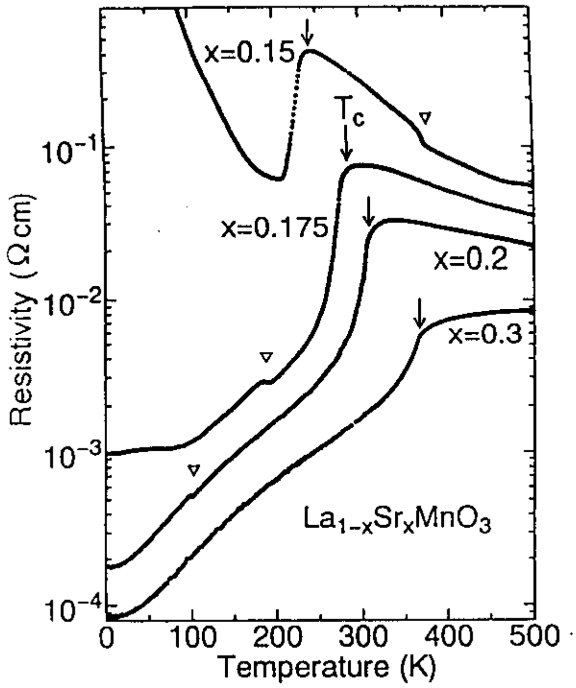
Hwang et al.

"Lattice effect"



Bandwidth
Y
Sm
Nd
Pr
La
Ca
Sr
Pb
(Pr,Ca)MnO3
(Nd,Sr)MnO3
(La,Sr)MnO3
0
0.5
1
x = Hole Density
La1-xSrxMnO3
Temperature [K]
PI
PM
Tc
TN
FM
CI
FI
x
La1-xSrxMnO3
Orthorhombic
O'
Rhombohedral
R
O*
CAF Insulator
Ferro Metal
Temperature (K)
Sr concentration x
Kawano
Nd1-xSrxMnO3
PI
PM
TC
TN
Tco
FM
FI
CI
Pr1-xCaxMnO3
PI
Tco
COI
TN
TC
AFI
TCA
CI
FI
CAFI
wide
narrow
Tokura

CMR in (La, Sr) MnO$_3$



ρ - T

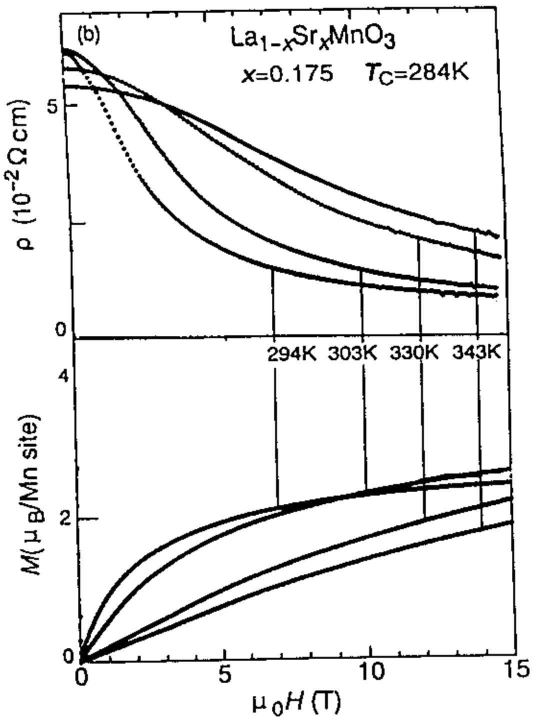
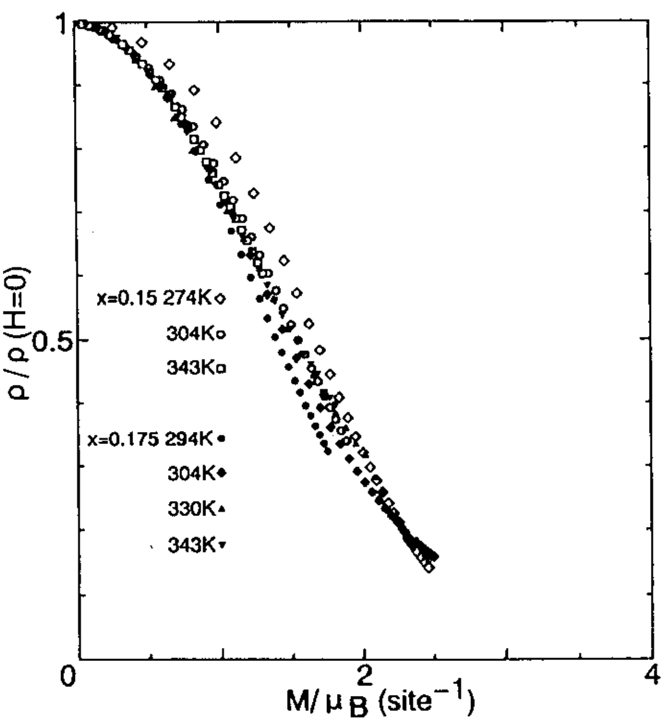


Fig.7(b): Urushibara *et al.*

ρ-H and M-H

Fig.1 Tokura et al.



ρ - M

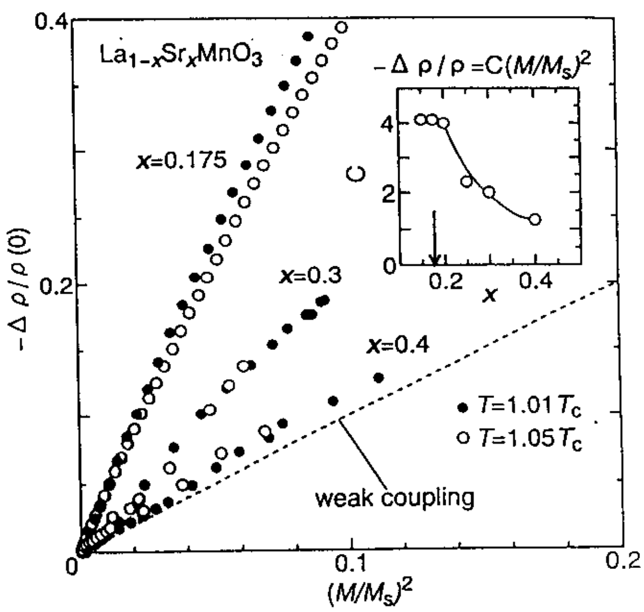
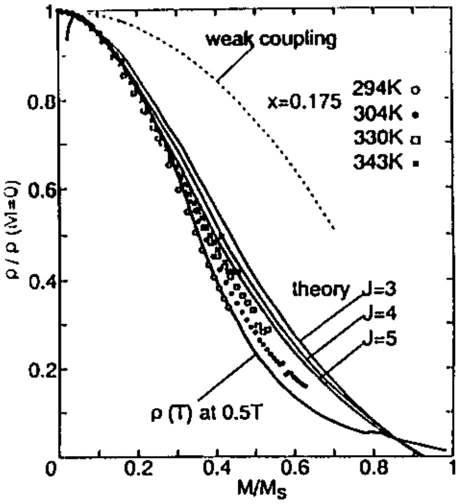


Fig.9: Urushibara *et al.*

C

$La_{1-x}Sr_xMnO_3$ (wide band) — single crystal



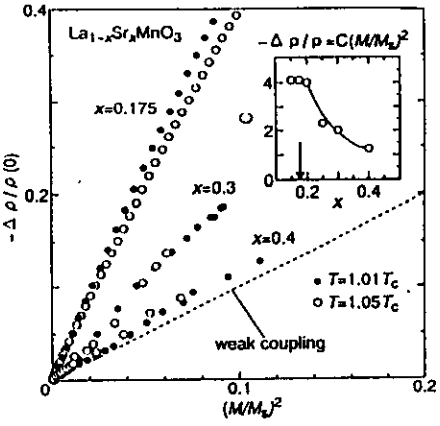
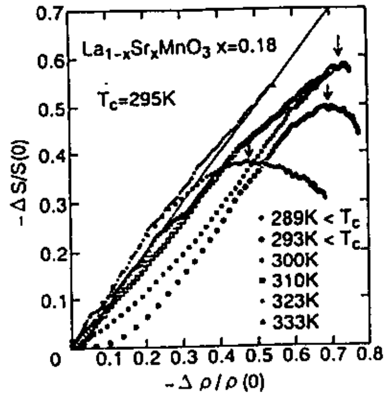


Fig.9: Urushibara *et al.*

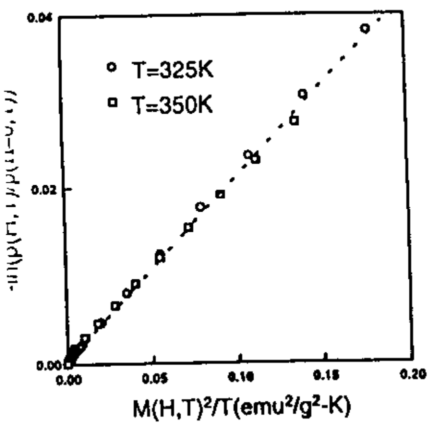


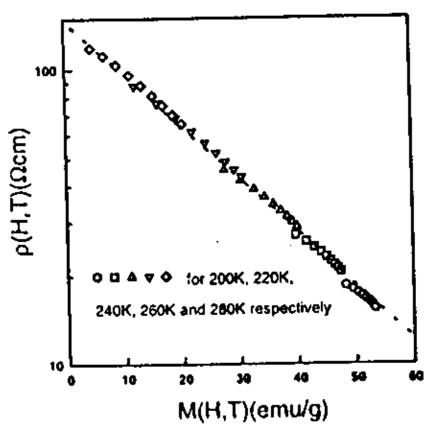
Asamitsu et al.

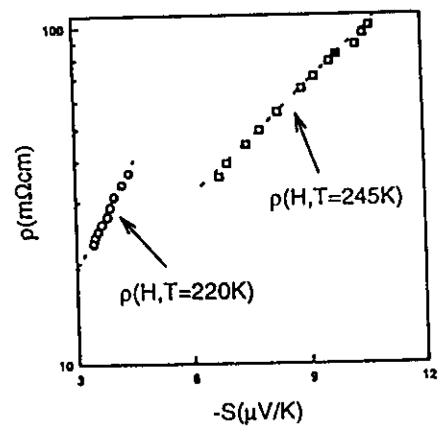
$$-\frac{\Delta\rho}{\rho_0} \propto M^2 \qquad \frac{\Delta S}{S_0} \sim \frac{\Delta\rho}{\rho_0} \propto M^2$$

double-exchange

$La_{1-x}Ca_xMnO_3$ (narrow band) — film





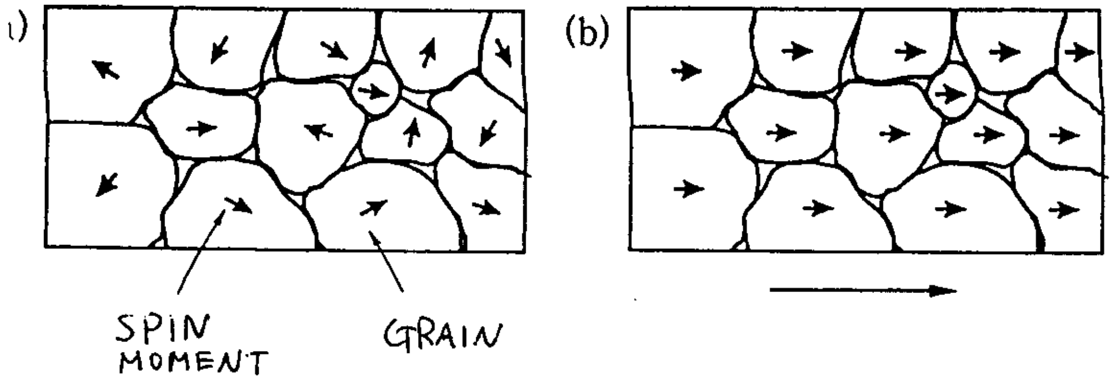


Chen et. al

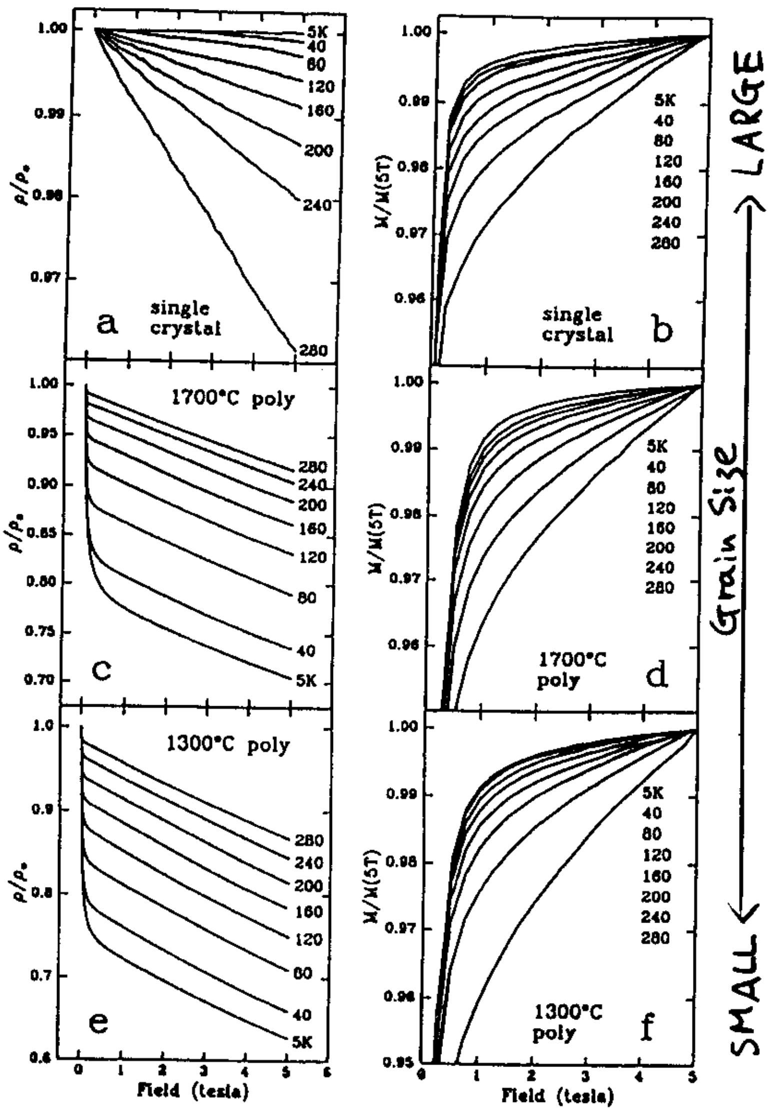
$\rho(H,T) \propto \exp\left(-\frac{\alpha M^2}{T}\right)$ at $T > T_c$ — thermal activation

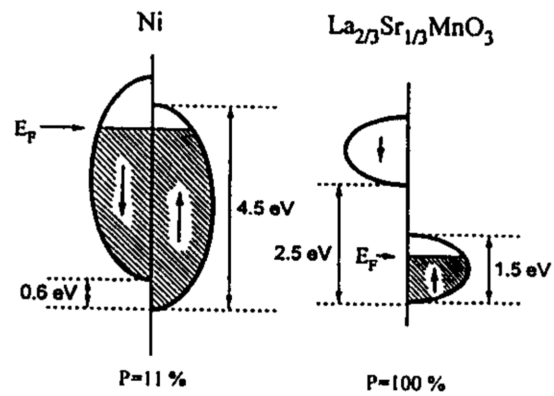
$\rho(H,T) \propto \exp\left(-M(H,T)\right)$ at $T < T_c$ — ???

$S \propto \ln \rho$



Tunneling Magnetoresistance
(Hwang et.al)





Be Careful!
Large Extrinsic Effects are Present!!

$La_{1-x}Sr_xMnO_3$

Phase Diagram:

magnetism & transport

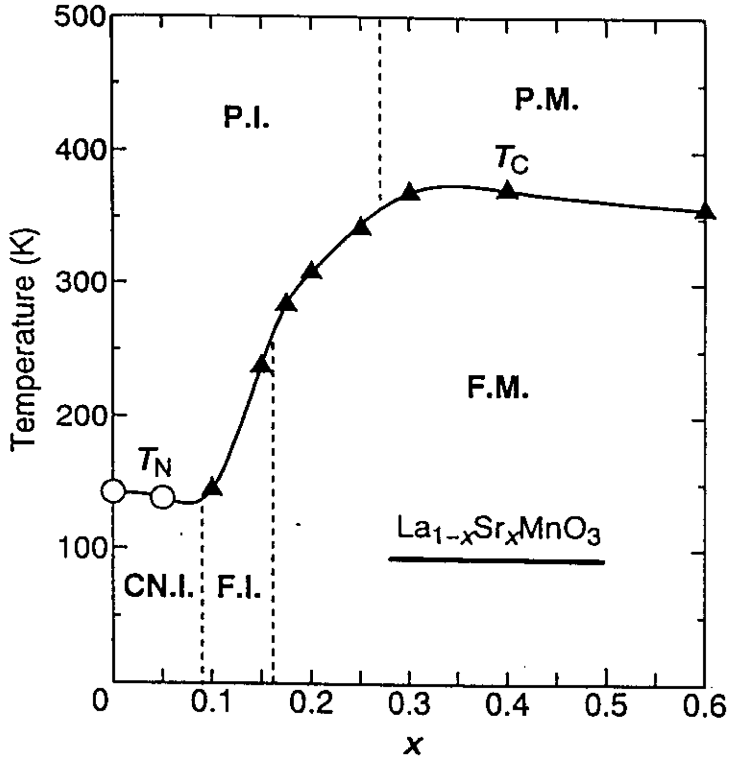
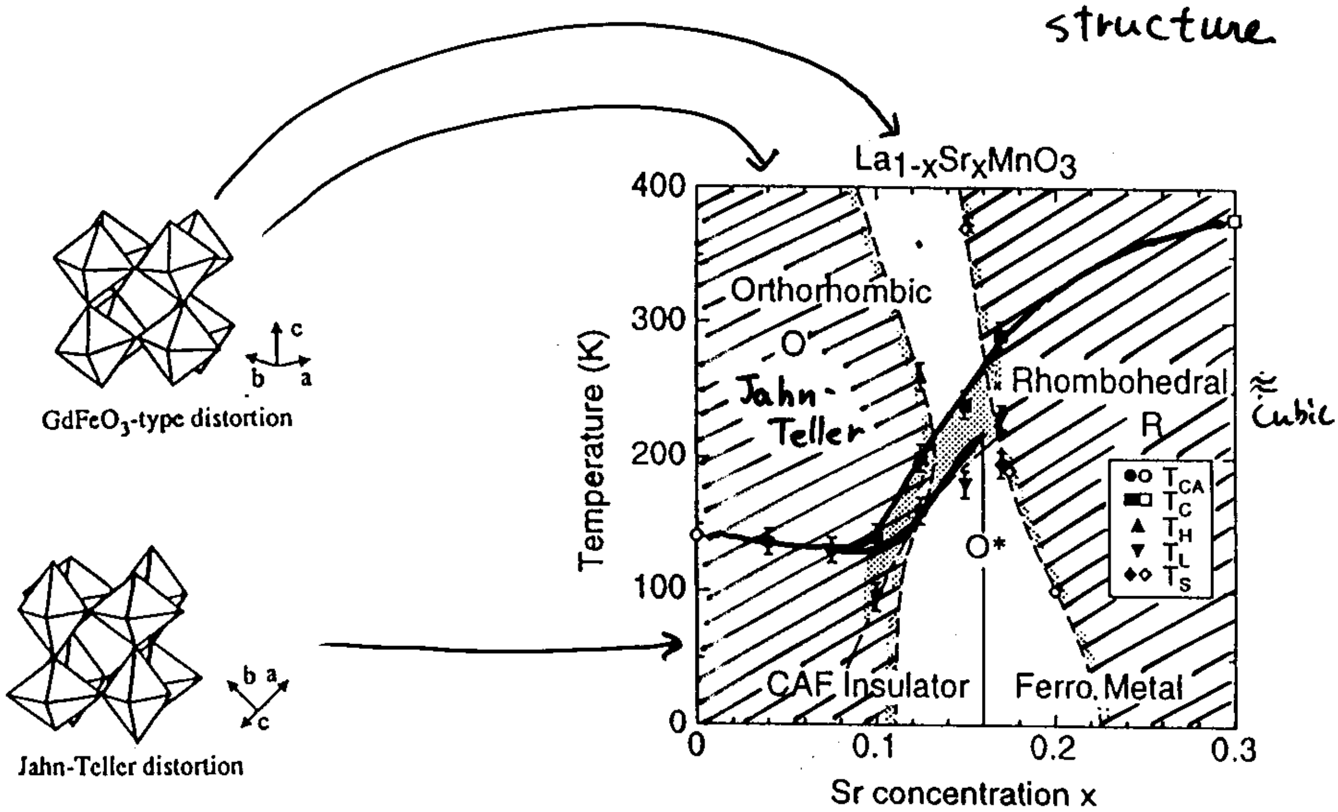
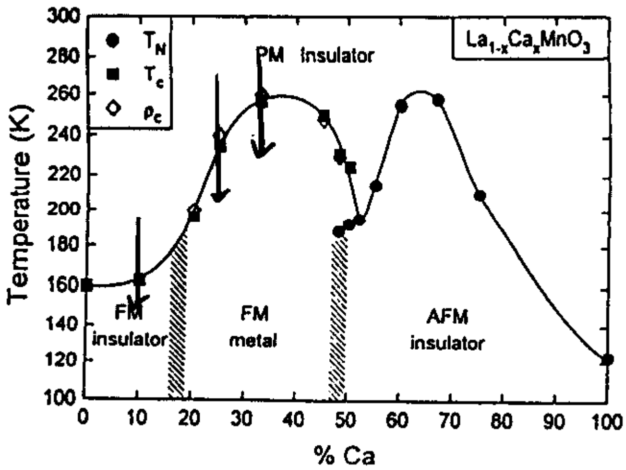


Fig.5: Urushibara *et al.*

Phase Diagram: structure



Kawano

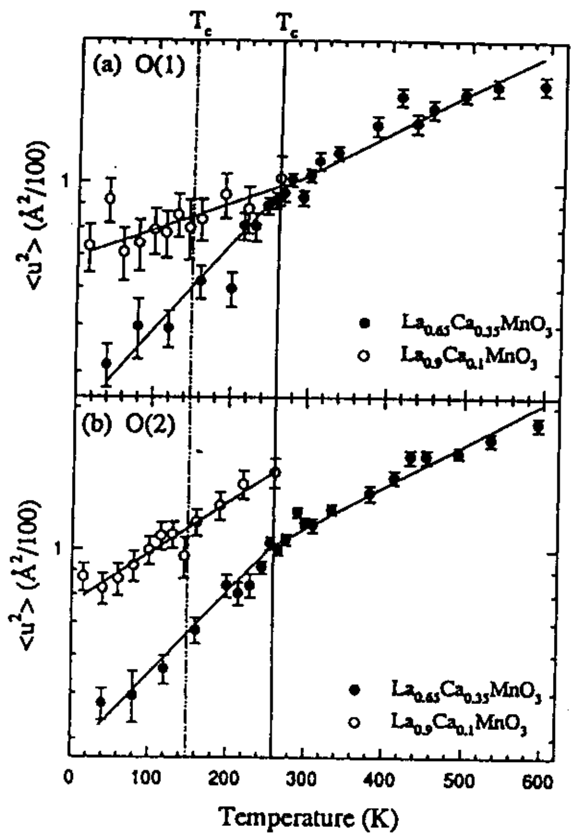


Oxygen distortion

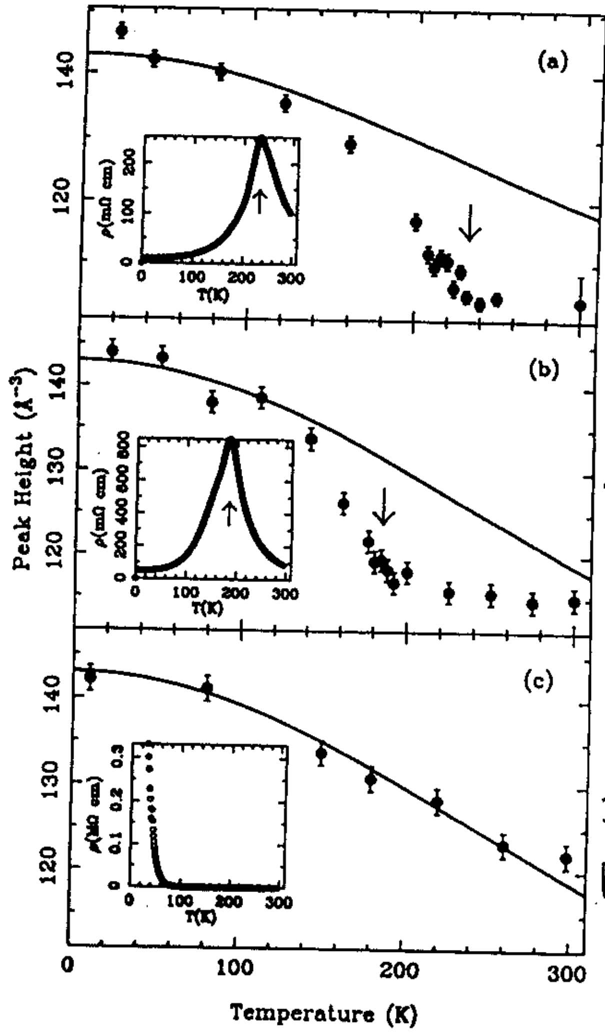
in

(La, Ca) MnO_3

Strong
Electron-Lattice
coupling.



Dai
Debye-Waller factor
for O-atom

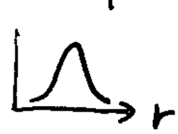


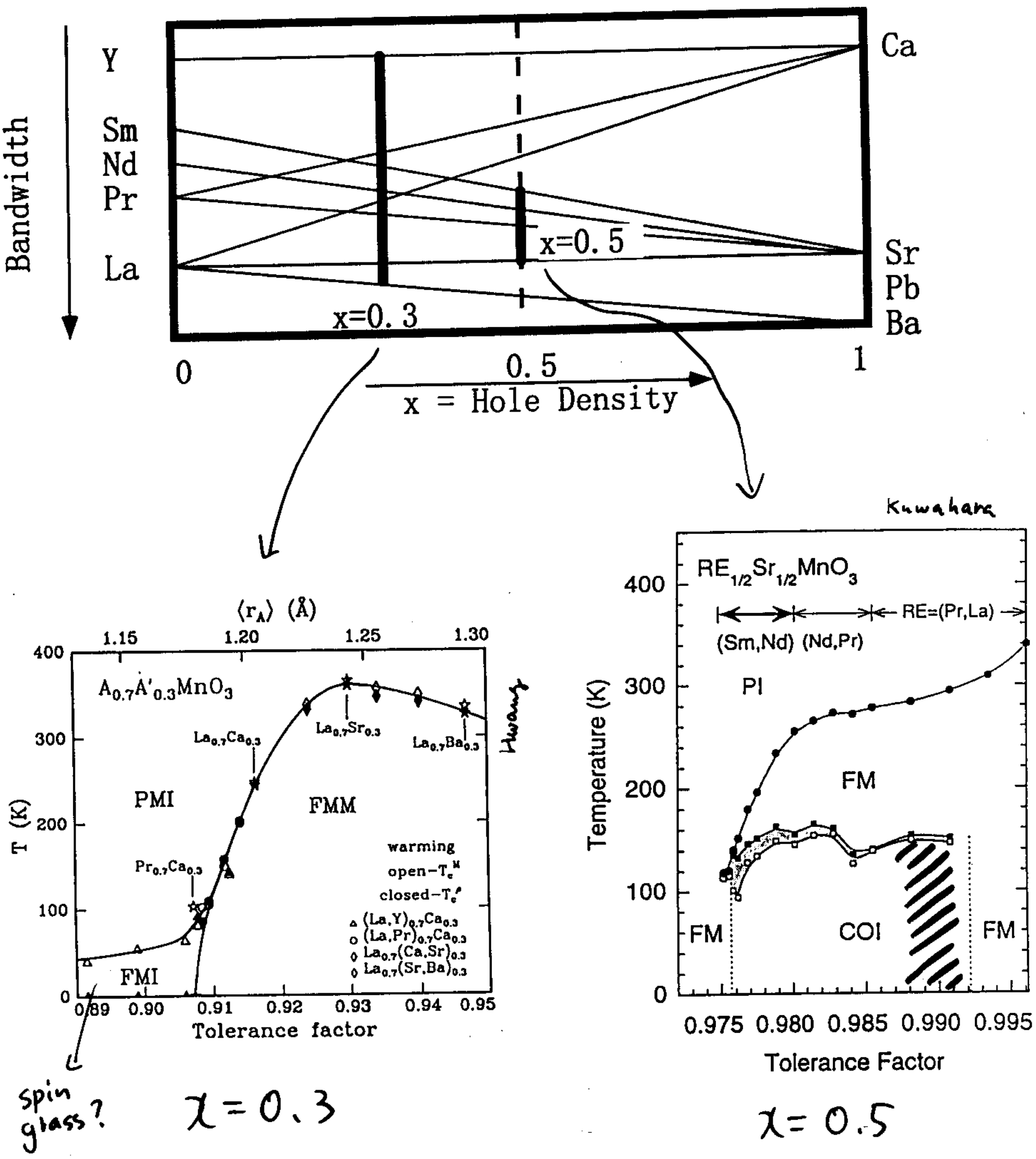
$x = 0.25$
PI → FM

$x = 0.21$
PI → FM

$x = 0.12$
PI → FI

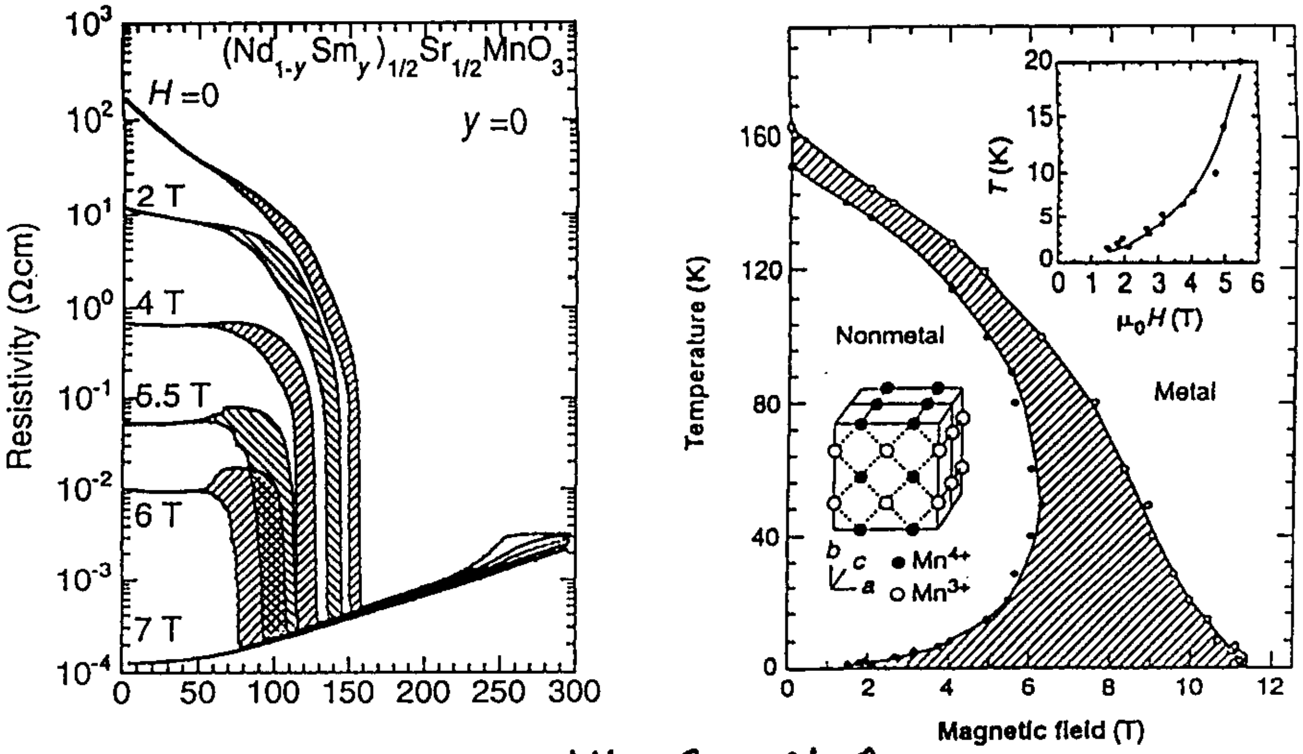
Billinge
O-O pair distribution function



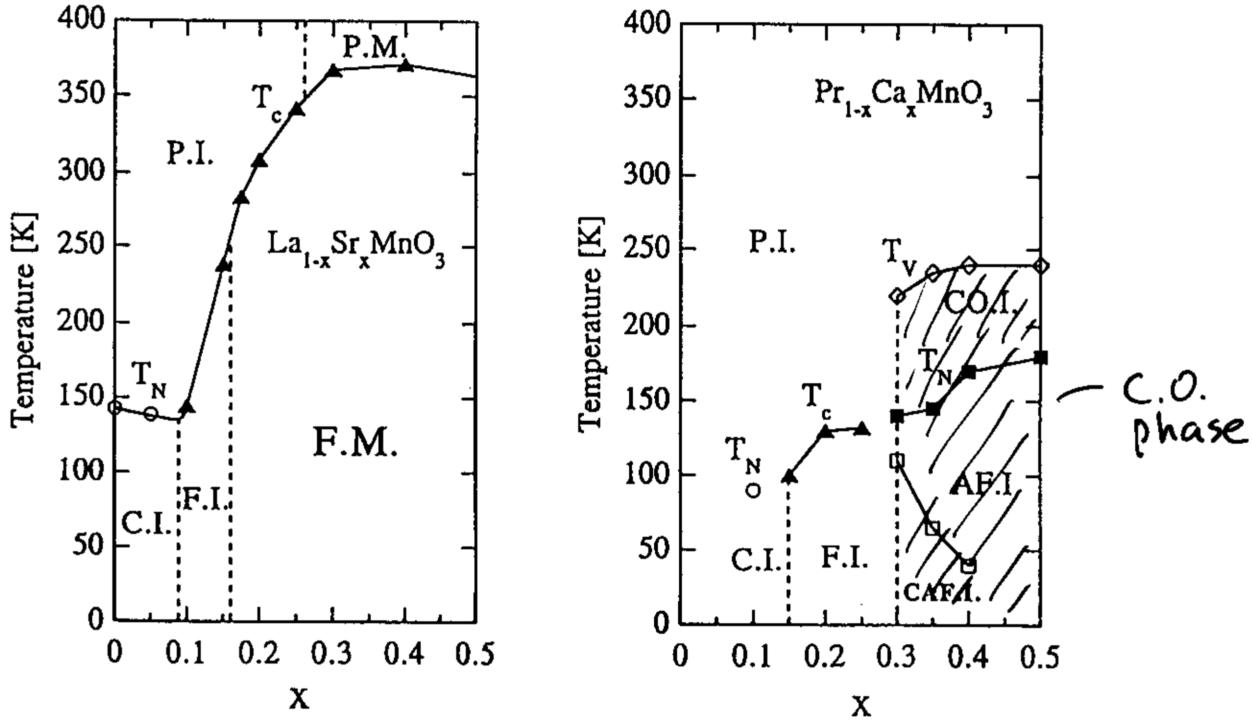


Bandwidth
Y
Sm
Nd
Pr
La
Ca
Sr
Pb
Ba
x=0.3
x=0.5
0
0.5
1
x = Hole Density
⟨r_A⟩ (Å)
1.15
1.20
1.25
1.30
A0.7A'0.3MnO3
PMI
FMM
FMI
La0.7Ca0.3
La0.7Sr0.3
La0.7Ba0.3
Pr0.7Ca0.3
warming
open−Tc^M
closed−Tc^ρ
(La,Y)0.7Ca0.3
(La,Pr)0.7Ca0.3
La0.7(Ca,Sr)0.3
La0.7(Sr,Ba)0.3
T (K)
Tolerance factor
Hwang
spin glass?
x = 0.3
Kuwahara
RE1/2Sr1/2MnO3
(Sm,Nd) (Nd,Pr)
RE=(Pr,La)
PI
FM
COI
Temperature (K)
Tolerance Factor
x = 0.5

Charge Order



Nd 1/2 Sr 1/2 MnO3



No C.O.

Figure 1. Y. Tomioka et al.

$(R,A)MnO_3$ manganites are double-exchange ferromagnets.

- Zener (1951), Anderson-Hasegawa (1955), deGennes (1960), Searle-Wang (1970), Kubo-Ohata (1972)

Are $(R,A)MnO_3$ manganites double-exchange ferromagnets?

- Experimental Evidences:
  - ⋆ Ferromagnetic-metal in limited region only.
  - ⋆ Relevance of lattice distortion:
    - ∗ A-type AF with collective Jahn-Teller distortion
    - ∗ Oxigen distortion (Debye-Waller, PDF) anomaly near T_c
  - ⋆ Relevance of orbital degree of freedom:
    - ∗ Charge ordered AF insulator with orbital ordering near $x \sim 0.5$.
    - ∗ A-type AF metal
  - ⋆ Intrinsic vs. Extrinsic effects: grain boundaries, etc.
- Theoretical approaches / proposals
  - ⋆ Dynamic Jahn-Teller theory (Millis)
  - ⋆ Small polaron (Spin, Lattice) (Bishop, Varma)
  - ⋆ Spin fluctuation (Kataoka)
  - ⋆ Orbital liquid (Nagaosa)

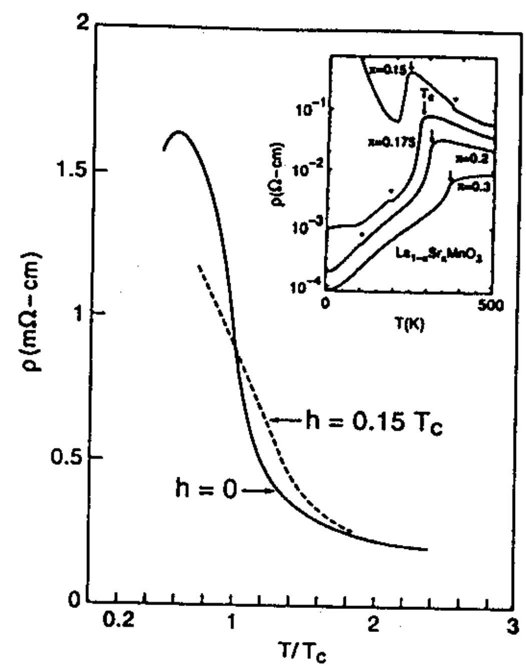
⋮

Millis et al.:

Double Exchage Alone Does Not Explain the Resisivity of $La_{1-x}Sr_xMnO_3$, Phys. Rev. Lett. **74** (1995) 5144.

Double-Exchange Model vs. $La_{1-x}Sr_xMnO_3$

- Curie temperature: Theory ($T_c = 1000 \sim 3000$K) overestimates one order of magnitude.
- Temperature dependence of resistivity ρ:
  $\rho(T)$ completely different at $T < T_c$.
- Absolute value of ρ: Larger values at experiment.

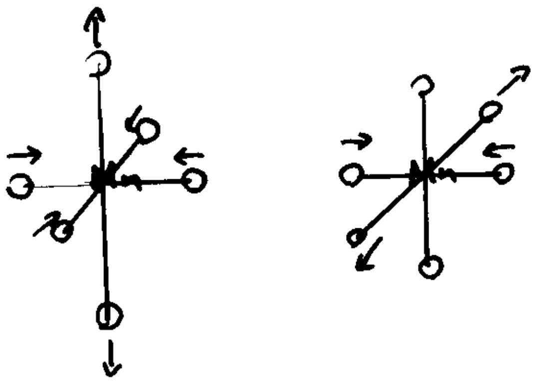


Dynamic Jahn-Teller Mechanism for CMR in $La_{1-x}Sr_xMnO_3$, Phys. Rev. Lett. **77** (1996) 175.

- $\sigma < \sigma_{Mott}$ explained by polaron mechanism.
- Reduced T_c explained by lattice fructuation.

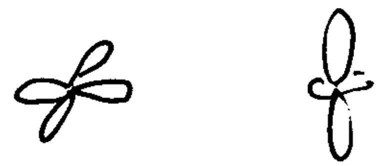
Jahn - Teller Effect

MnO_6



Q_3 $\qquad$ Q_1

$d_{x^2-y^2}$ $\qquad$ $d_{z^2-r^2/3}$



pseudospin

$\tau = +1$ $\qquad$ $\tau = -1$

$$\vec{Q} = (Q_1, 0, Q_3)$$

$$\mathcal{H}_{JT} = \lambda \sum_i \vec{Q}_i \vec{\tau}_i$$

Dynamic Jahn-Teller Hamiltonian $\qquad$ Millis - Mueller - Schraiman

$$\mathcal{H} = \mathcal{H}_{DE} + \mathcal{H}_{JT} + \mathcal{H}_{lattice} ,$$

assume disordered state (no LRO) for lattice distortion $\vec{Q}$

- large electron-lattice coupling λ

  $\Rightarrow$ (small) polaron

- supression of curie temperature T_c

E-mail from the organizer of Trieste Workshop:

```
Some Possible Discussion Topics:
(i) Quantum Critical View of cuprates - Does it
make sense?
(ii) Do we have the right starting model for an
understanding of CMR?
(iii) ...
```

Another question:

Do we have the right understanding of the double-exchange system?

Universalities, qualitative/quantitative behaviors, etc.

Example: Estimate of the Curie temperature

- $T_c = 1000 \sim 3000$K (Millis et al., mean field)
- $T_c = 200 \sim 400$K (Röder et al., high-T expansion)

for bandwidth $W \sim 1$eV.

Difficulties:

- Strong Hund's coupling between spins and electrons.
- Large spin fluctuations near T_c

$$J_H|\Delta S| \gg W$$

- Need to deal with thermodynamics, transport properties, etc.

Double-exchange alone model is already very difficult.

We need to know more about this "simple" model!!

Dynamical mean-field approach for the double-exchange system.

N. Furukawa: J. Phys. Soc. Jpn. **63** (1994) 3214,
ibid **64** (1995) 2754,
ibid **64** (1995) 2734,
ibid **64** (1995) 3164.

Hamiltonian:

$$\mathcal{H} = -t \sum_{<ij>,\sigma} \left(c_{i\sigma}^{\dagger} c_{j\sigma} + h.c. \right) - J_{\mathrm{H}} \sum_i \vec{S}_i \cdot \vec{\sigma}_i$$

- $\vec{S}_i$: Localized t_{2g} spins approximated by classical rotator spins $|\vec{S}| = 1$. (In reality, $S = 3/2$.)
- $\vec{\sigma}_i$: Itinerant e_g electron spins.
- t: Electron hopping matrix element. In $D \to \infty$ limit, we rescale t so that the bandwidth W is finite.

  Hereafter, bandwidth W is the unit of energy.
- J_{H}: Hund's coupling between e_g and t_{2g} electrons.
- x: Carrier number (hole concentration), $x = 1 - n$.

Estimate of W and J_{H} from experiments:
$W = 1 \sim 2\mathrm{eV}$, $J_{\mathrm{H}} = 2 \sim 3\mathrm{eV}$.

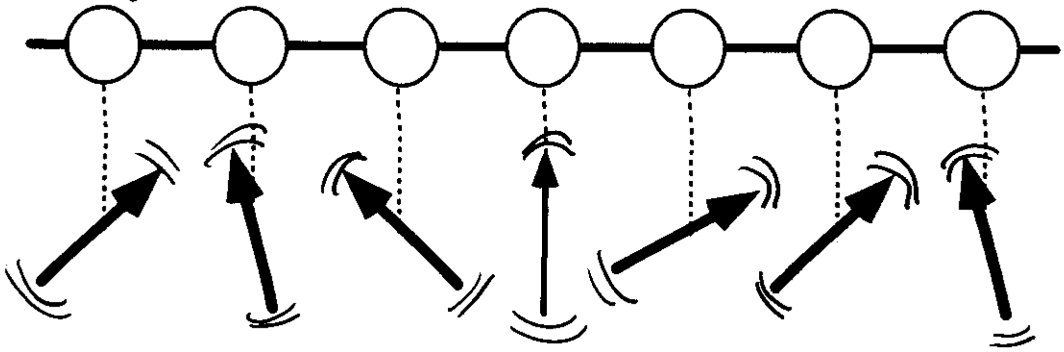
Dynamical Mean-Field Theory:

Infinite dimensional approach $D \to \infty$,
c.f. Georges et al., Rev. Mod. Phys. **68** (1996) 13.

☆ More accurate calculation for this simple model.

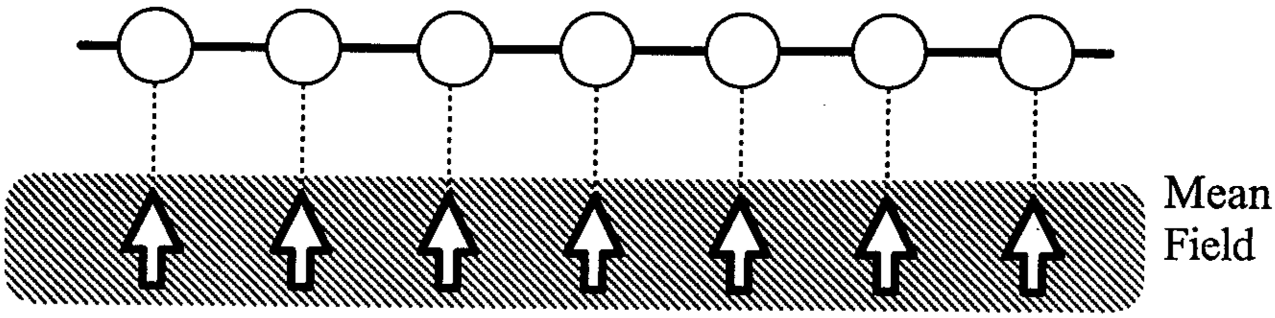
☆ Compare with EXPERIMENTS.
Is this model enough or not?

Thermodynamics:



Thermal average
= average over all possible configurations of each spin.

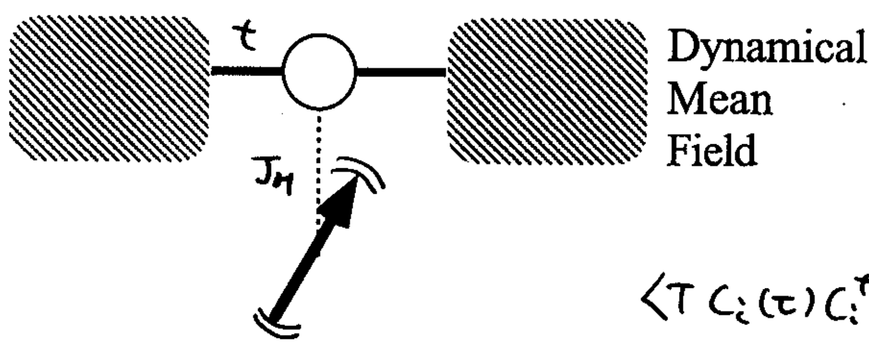
Mean Field Approximation



Replace localized spin by <u>average spin moment</u>
= no spin fluctuation

$h_{MF} = \langle S_i \rangle$

Dynamical Mean Field Approximation



$\langle T c_i(\tau) c_i^{\dagger}(0) \rangle = G(\tau)$

Replace electron dynamics by its <u>average</u>
(one-particle Green's function),
average over all possible spin configurations.

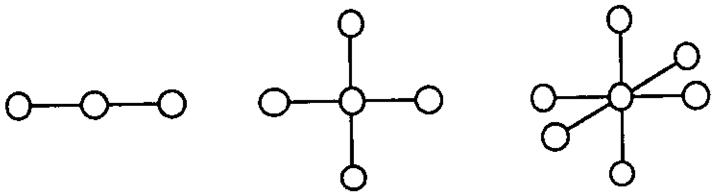
$J_H \gg t.$

Local spin fluctuation is considered non-perturbatively.

Methods:

* Solve the double-exchange model, using the "dynamical mean-field" theory.

D=∞ system
=1 site + dynamical mean field

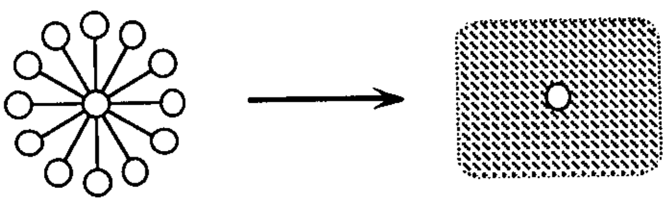


D=1 D=2 D=3

Metzner-Vollhardt,

Georges-Kotliar,

Ohkawa



D>>1

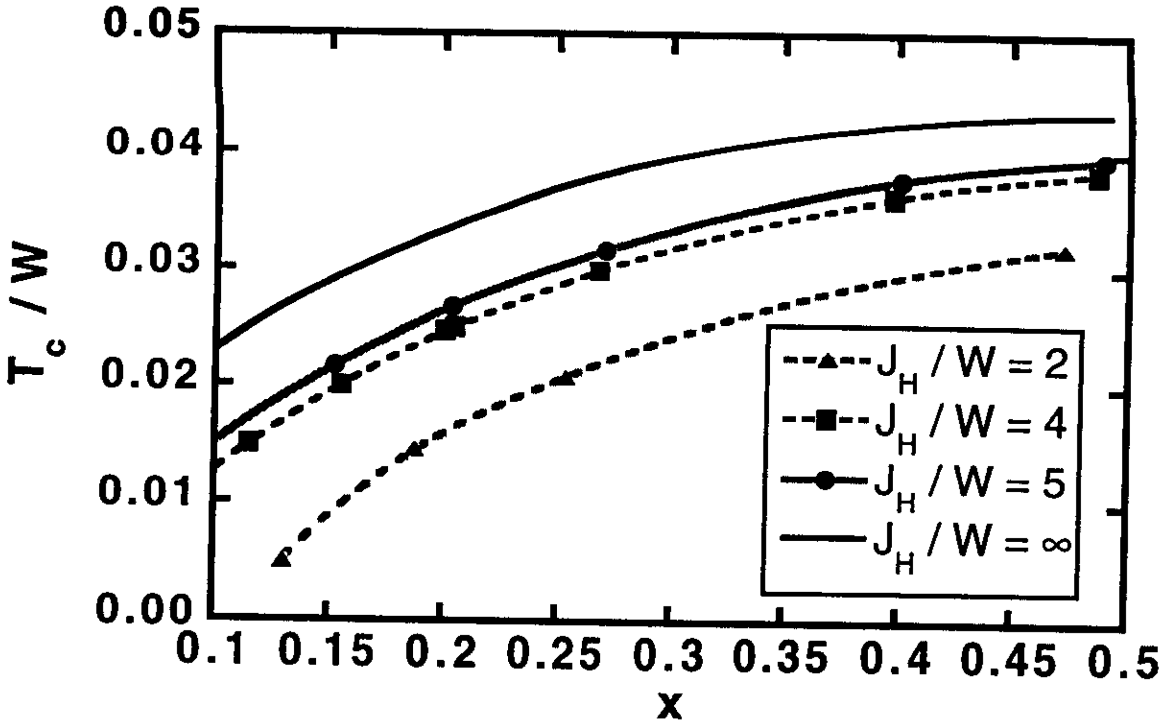
fluctuation in space may be neglected

Georges-Kotliar-Krauth-Rozenberg Rev Mod Phys.

Order Parameter $= \langle T c_i(\tau) c_i^{\dagger}(0) \rangle$

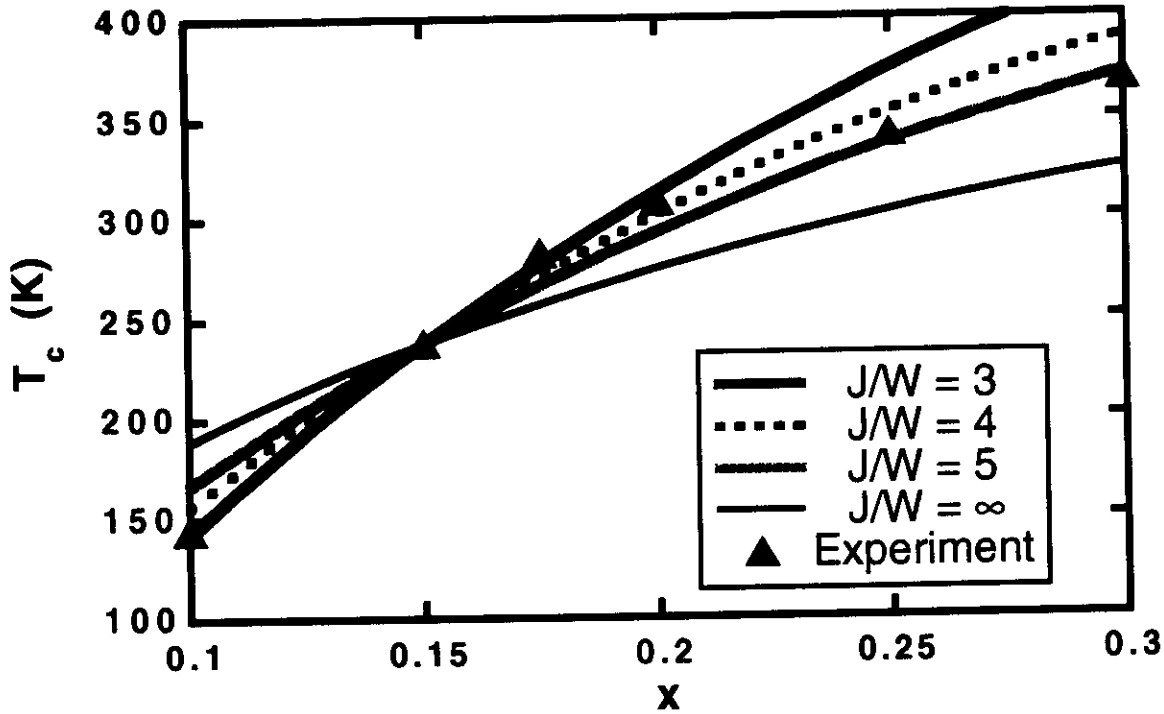
* Strong Hund's coupling region
  = spin exchange is unfavored.

Take the classical spin limit.
Exact solution is available in infinte dimension.



Curie Temperature

at $W \sim 1\,eV$, $T_c \lesssim 400\,K$

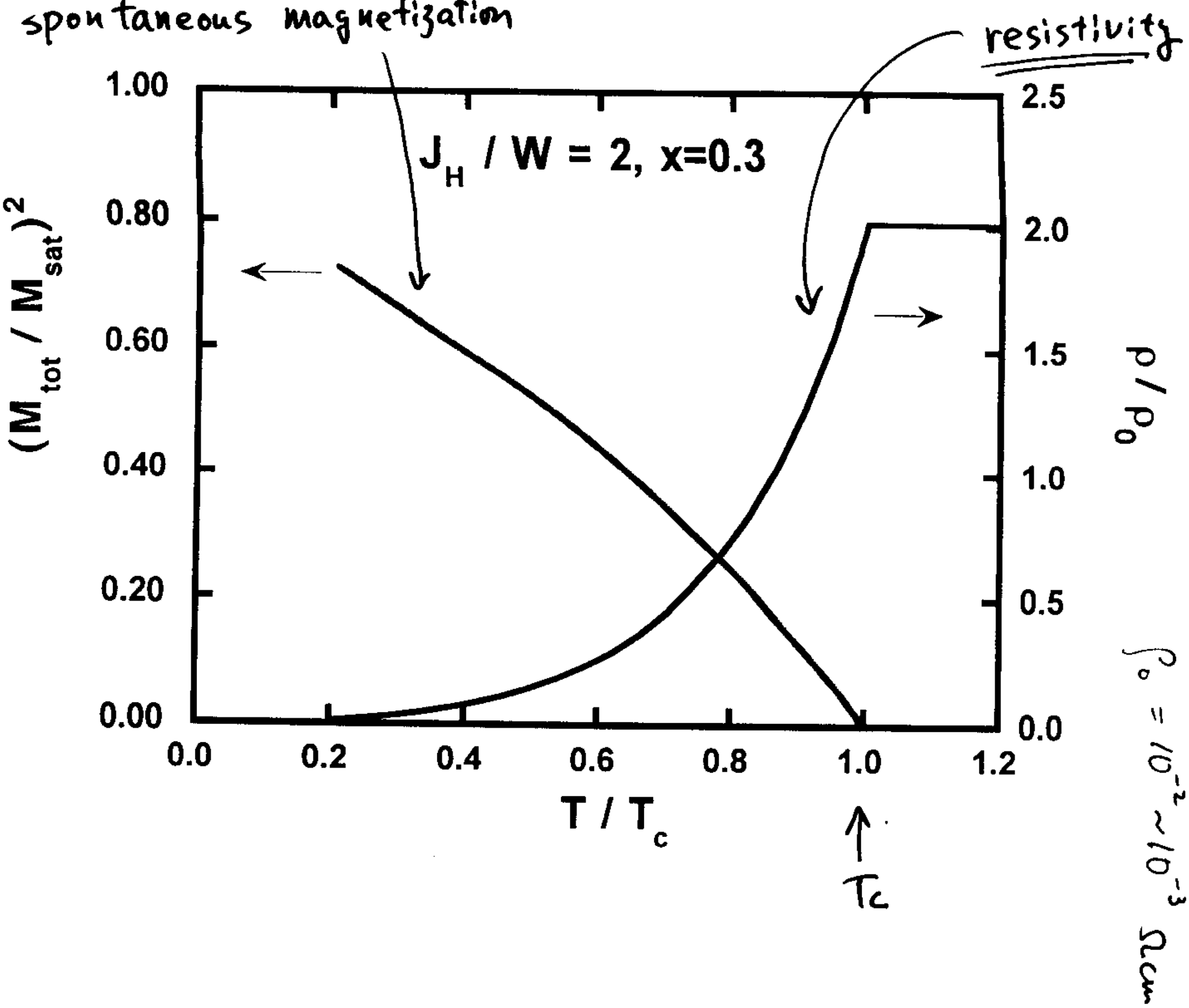


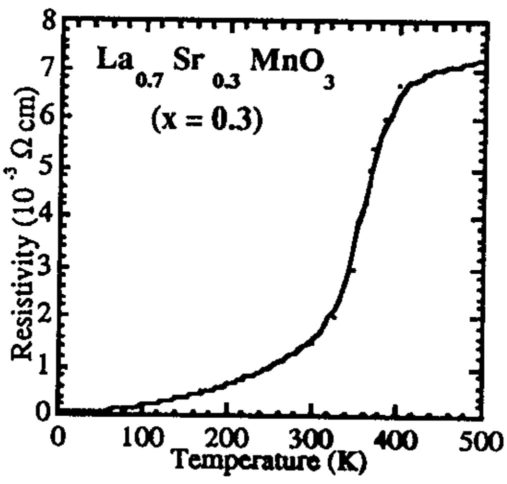
▲ $La_{1-x}Sr_xMnO_3$

For each J_H/W, T_c is scaled so that it reproduces the T_c at $x = 0.15$.

$W \sim 1eV$ and $J_H/W \sim 4$

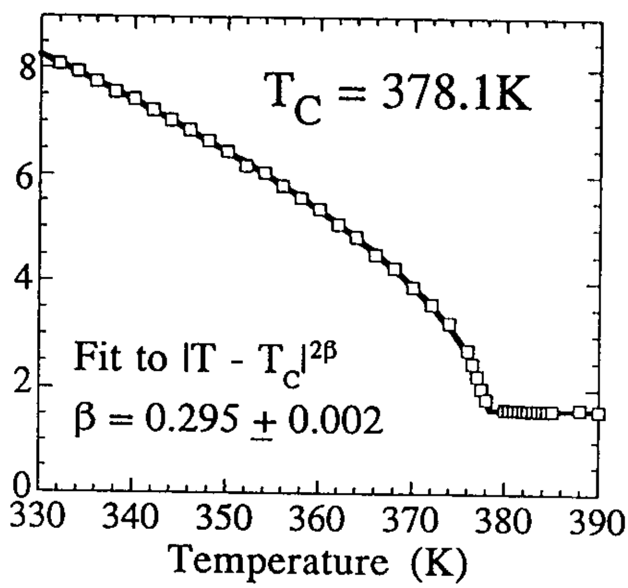
reproduces T_c at $0.1 \lesssim x \lesssim 0.25$





resistivity

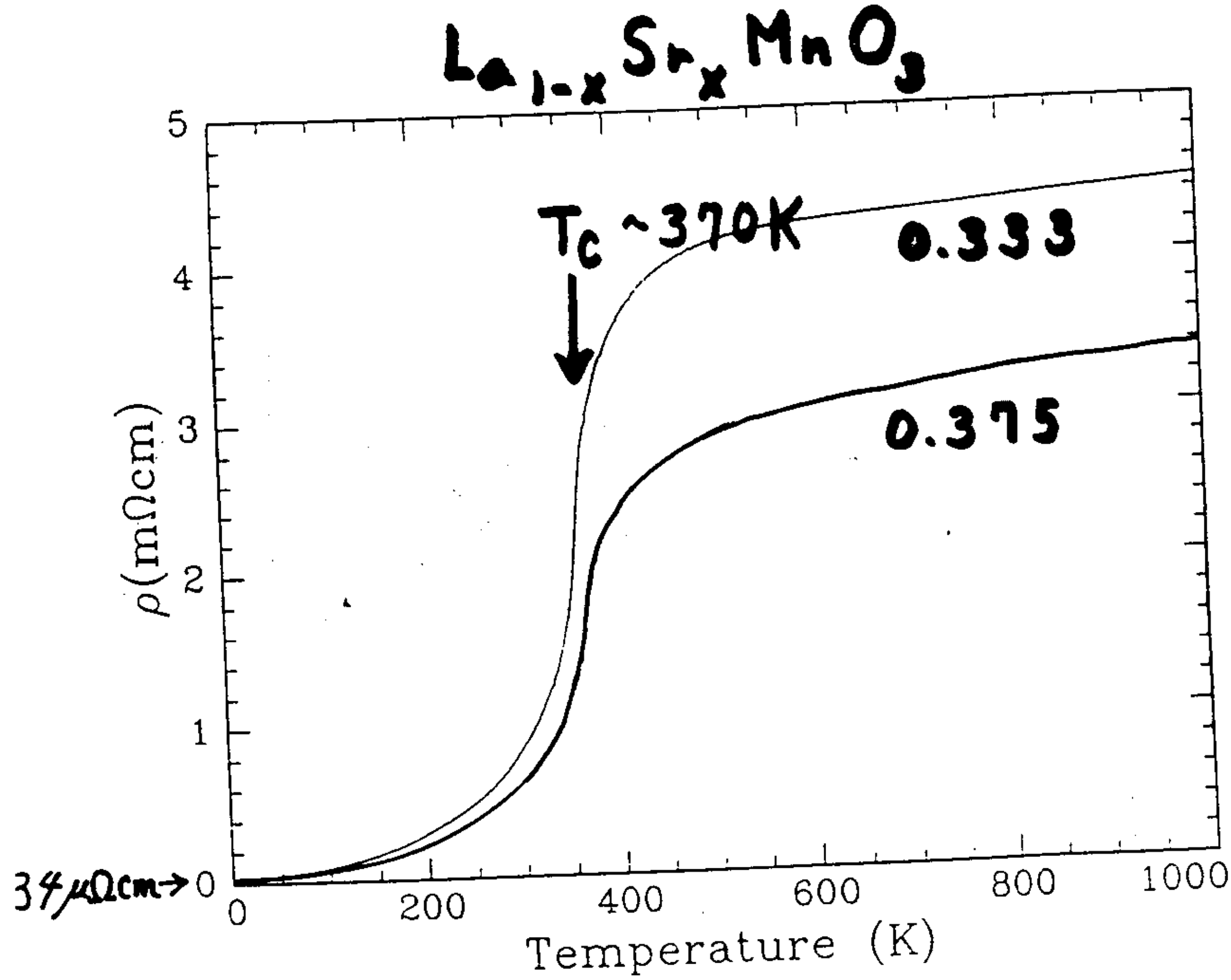
(Tokura et.al)



magnetization

$S(Q)^2 \propto M^2$

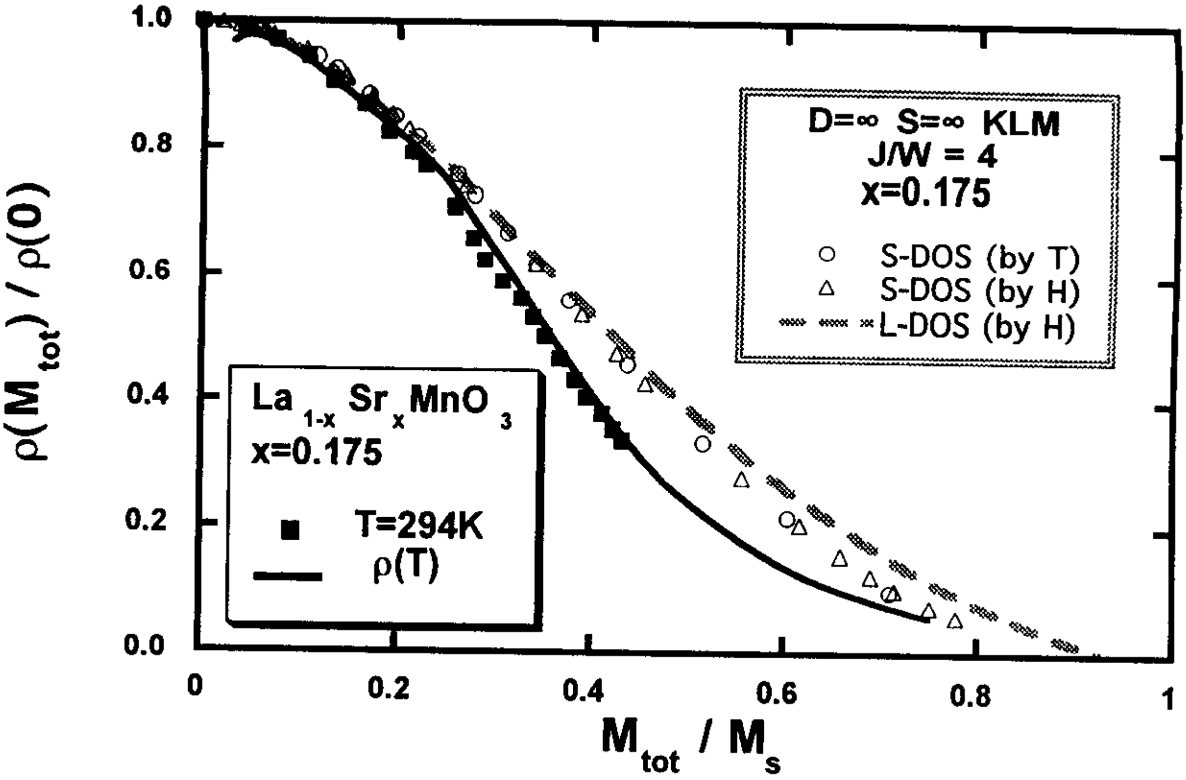
Martins etal.



S.W. Cheong.

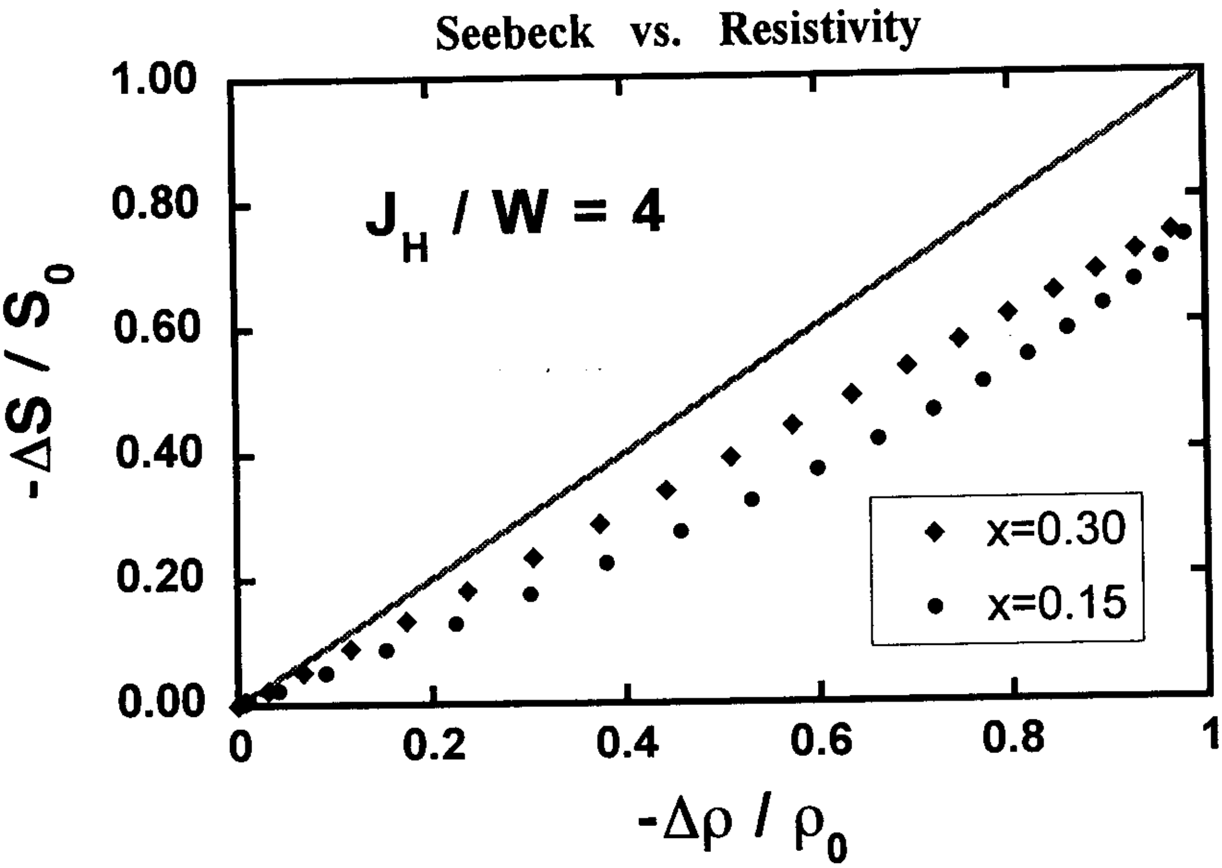
clean Single Crystal

La$_{1-x}$Sr$_x$MnO$_3$ vs. Double Exchange Model
(x=0.175)



$$\frac{\rho}{\rho_0} = 1 - C\left(\frac{M_{tot}}{M_{sat}}\right)^2$$

$$C \sim 4$$



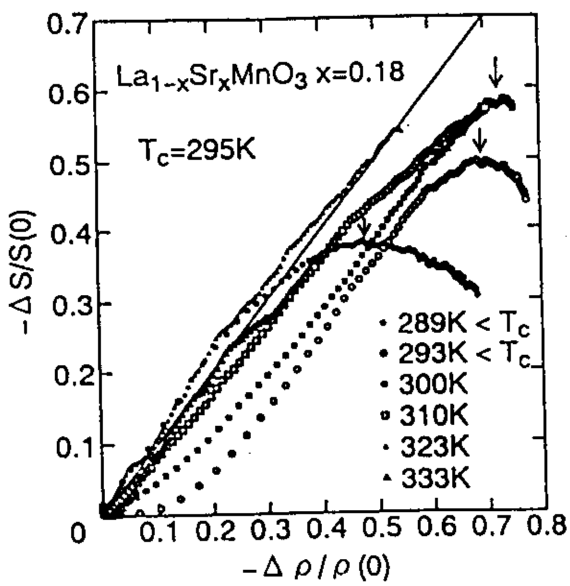
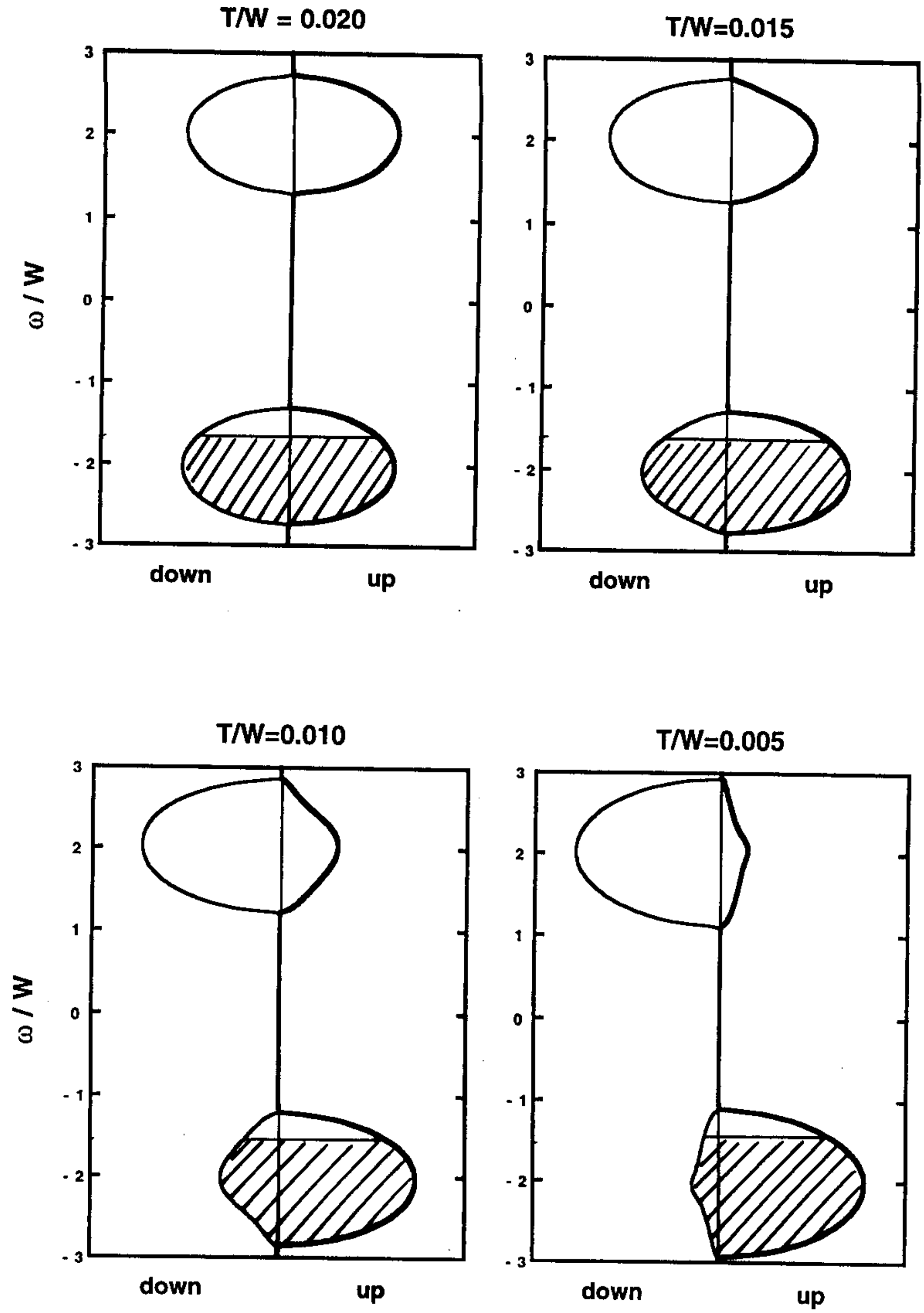


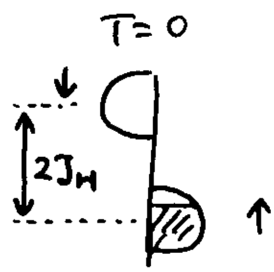
FIG. 2. Correlation between magnetothermoelectric and magnetoresistance effects at various temperatures in the x=0.18 crystal. The change of S in a magnetic-field normalized by the zero-field value $[-\Delta S/S(0)]$ is plotted as a function of the normalized resistivity change $[-\Delta\rho/\rho(0)]$. A solid line represents a linear relation that $-\Delta S/S(0) = -\Delta\rho/\rho(0)$. Arrows indicate maxima of $-\Delta S/S(0)$ (see text).

Asamitsu et al.

Temperature dependence of DOS

by dynamical Mean Field





W : bandwidth

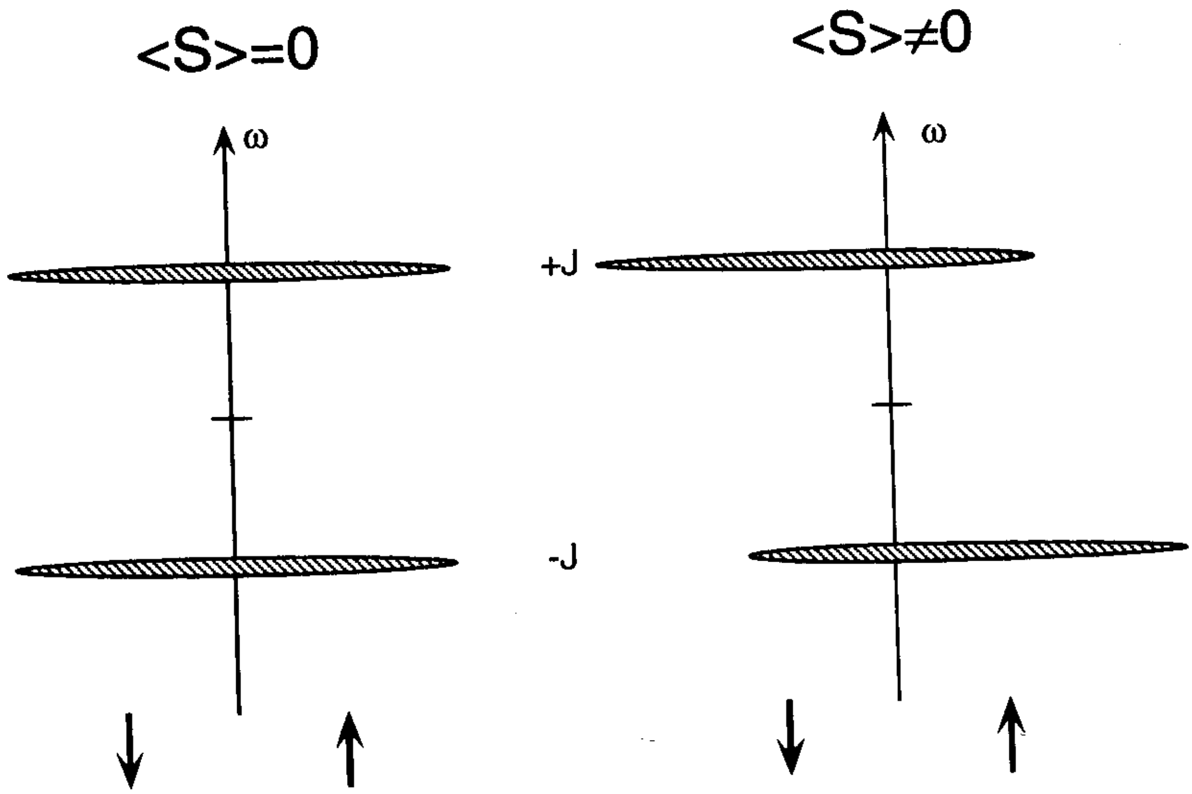
J_H : Hund's coupling

$(J_H/W = 2, \quad x = 0.2)$

Atomic limit

$$H = -J\sum_i \vec{S}_i \cdot \vec{\sigma}_i \longrightarrow \varepsilon = \pm J$$

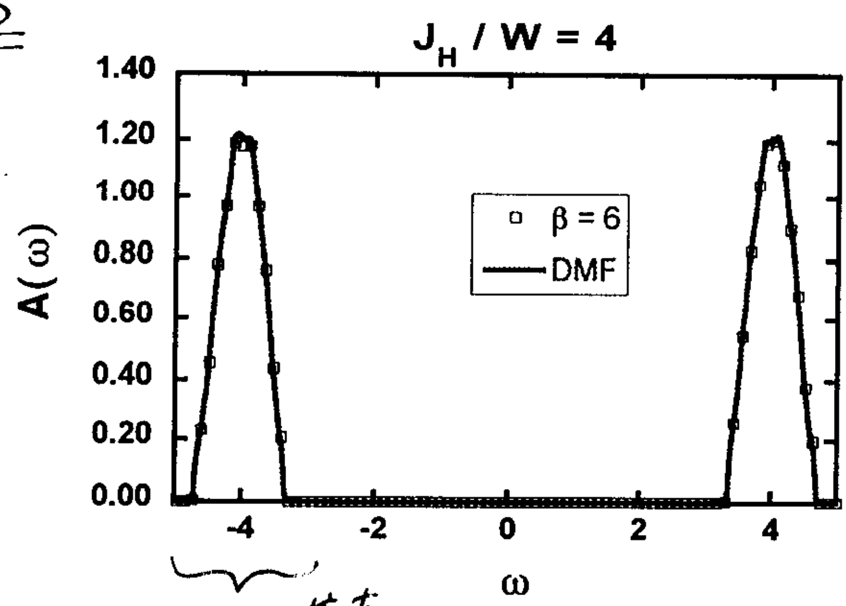
electron DOS



有限サイズ クラスターにおける

Dynamical Mean-Field Approx. と (and) Monte Carlo の比較. (COMPARISON)

DOS

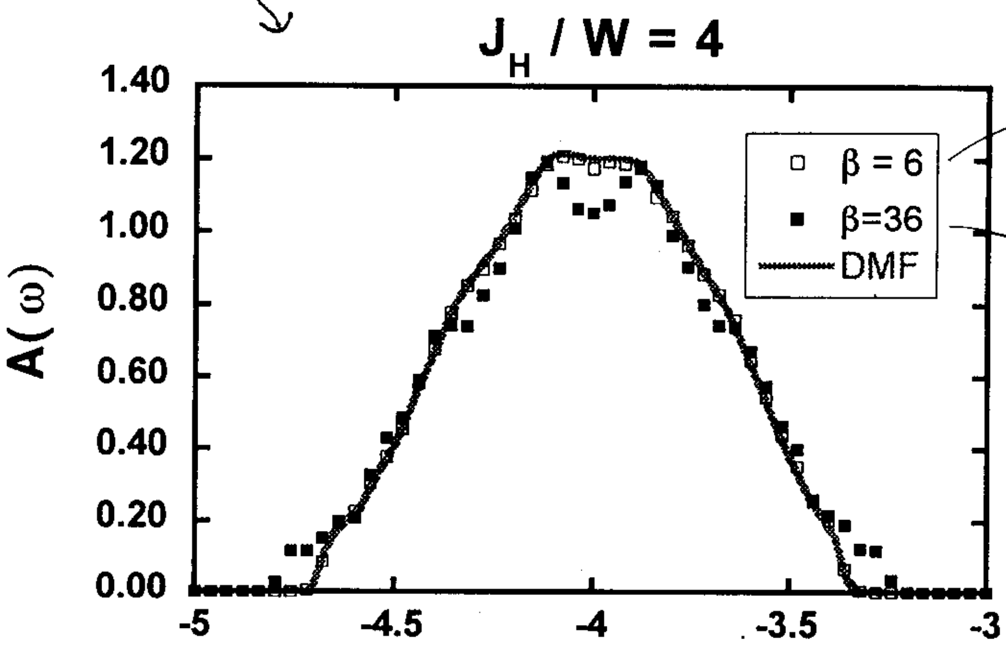


$6 \times 4 \times 4$

$\langle n \rangle \sim 0.5$

$T_c^{MF} \sim W/36$

拡大



$\rightarrow T_c \ll T \ll W$

$\rightarrow T \gtrsim T_c$

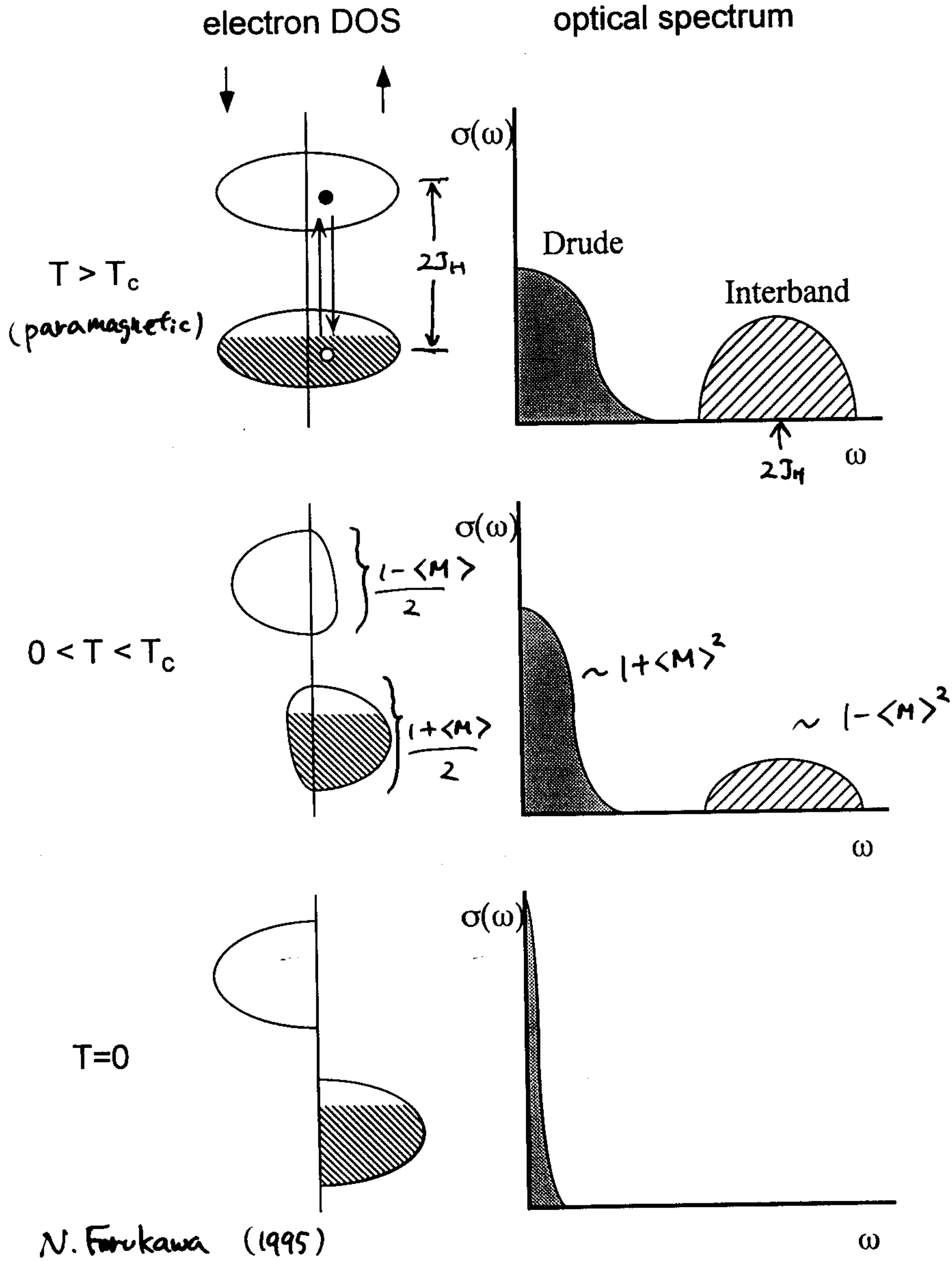
DMF:

$T \rightarrow 0$ で exact, (Ferro. Ground State)

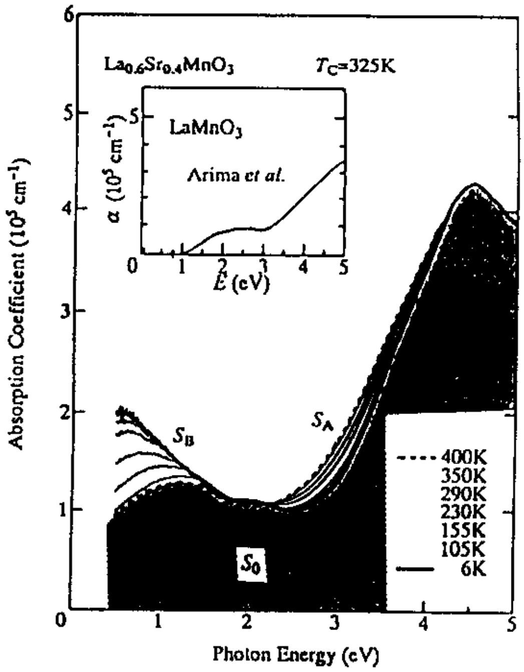
$T \gg T_c$ でも よい (good) 一致 (agreement)

$T \simeq T_c$ で 多少のずれ (スピンの空間的ゆらぎ)
small deviation due to spacial fluctuations of spins

Doublel-Exchange model: Strong Hund's coupling limit



N. Furukawa (1995)



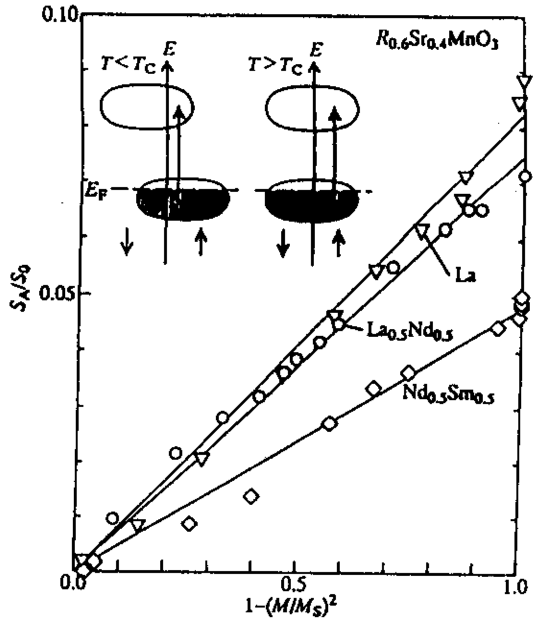
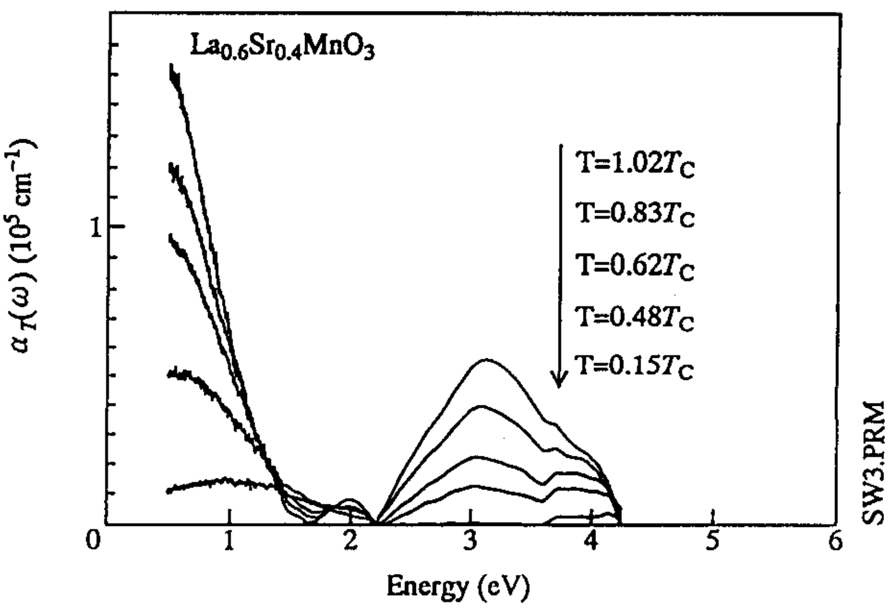
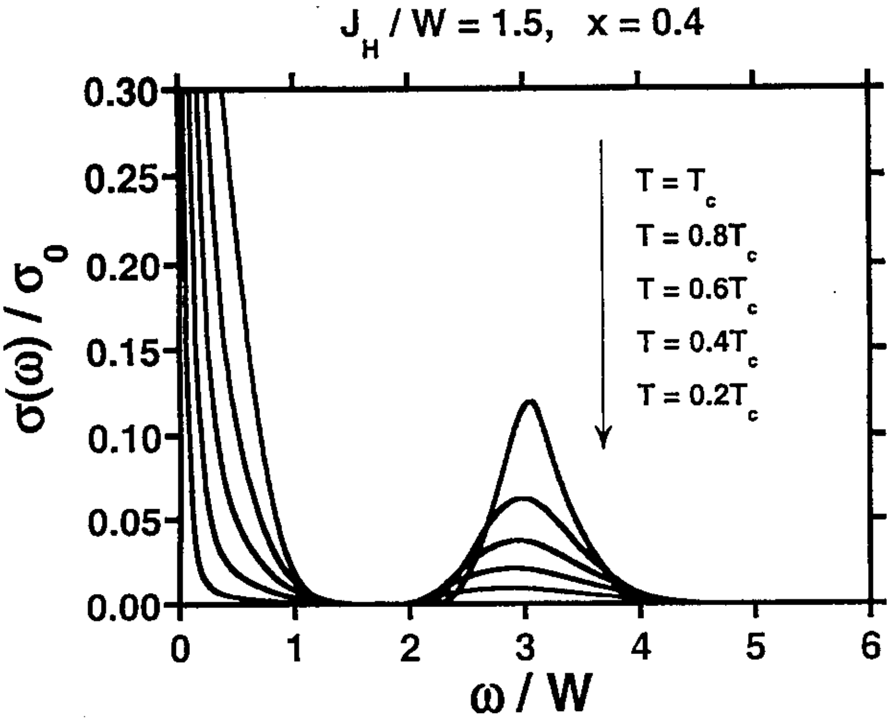
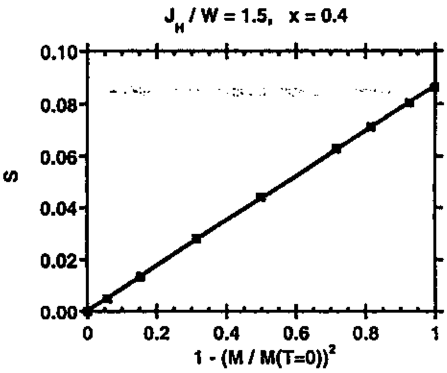


Fig. 4:Y.Moritomo et al.

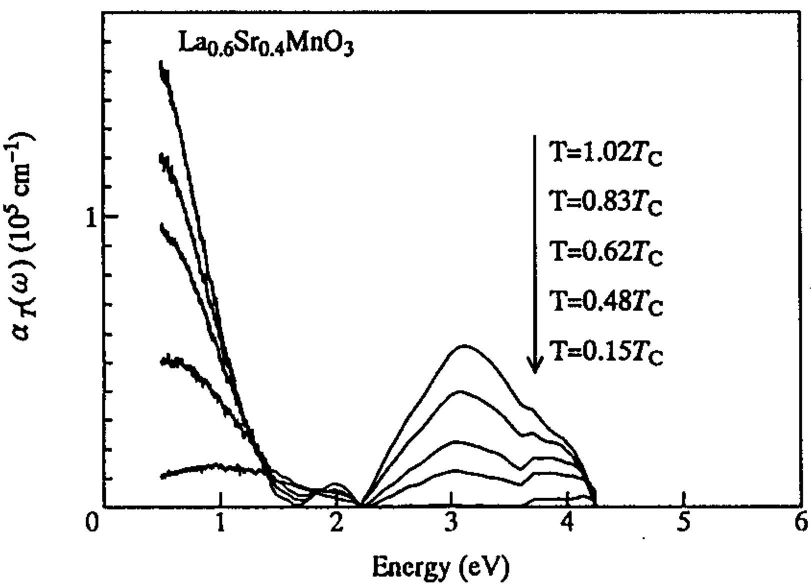


Moritomo ('97)





Theory
vs
Experiment



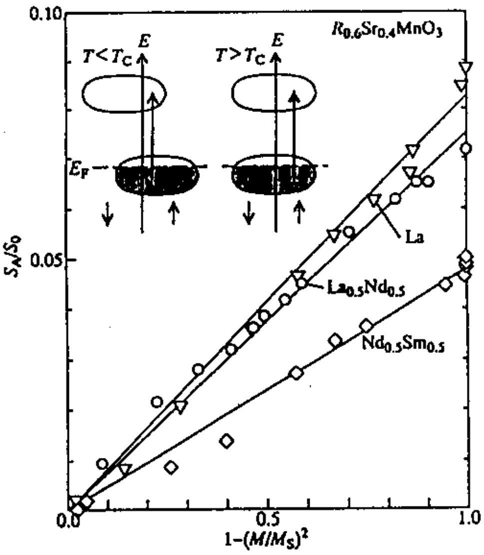
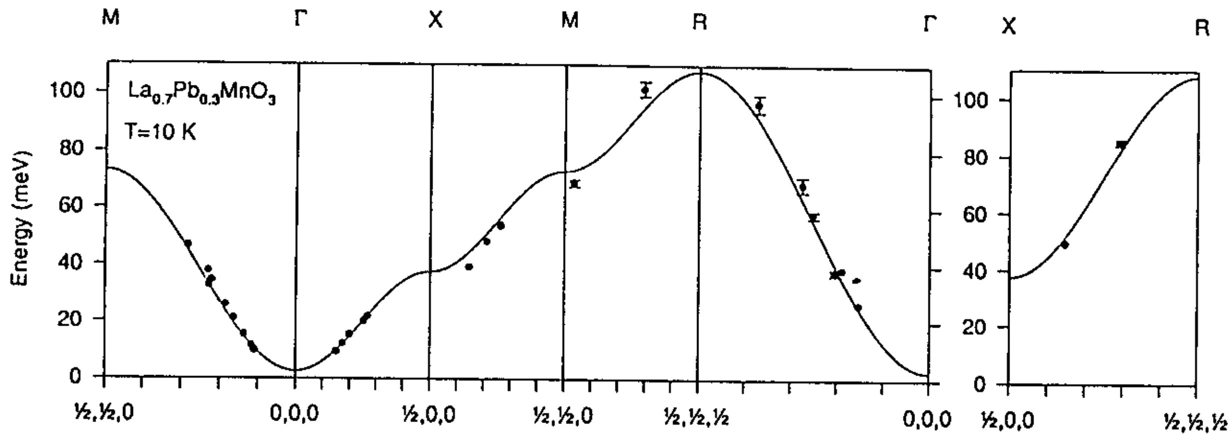
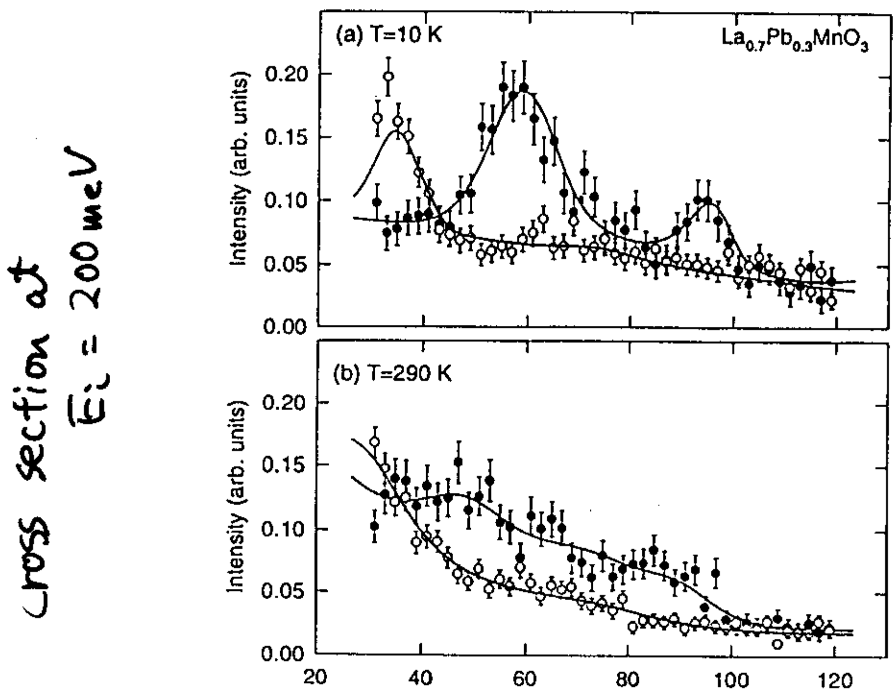


Fig. 4:Y.Moritomo *et al.*

Neutron Inelastic Scattering Experiment of $La_{0.7}Pb_{0.3}MnO_3$. [Perring *et al.*] ISIS



* Well-defined spin-wave dispersion relation is observed.
Dispersion curve reproduced by the Heisenberg model.



* Anomalous Temperature dependence in the life-time of the spin-wave.

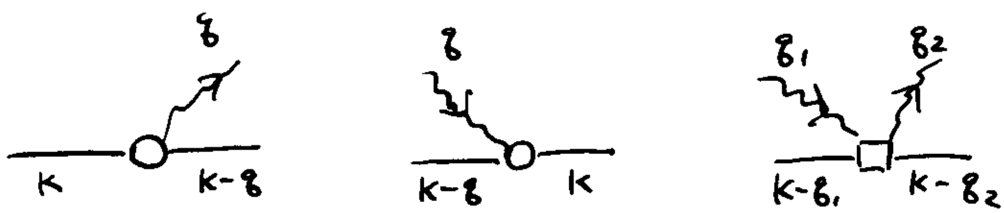
Can the Double-Exchange Model explain these properties?

Spin Wave Approximation

$1/S$ expansion at the ferromagnetic ground state.

$$S_i^+ \simeq \sqrt{2S} a_i, \quad S_i^- \simeq \sqrt{2S} a_i^\dagger, \quad S_i^z = S - a_i^\dagger a_i.$$

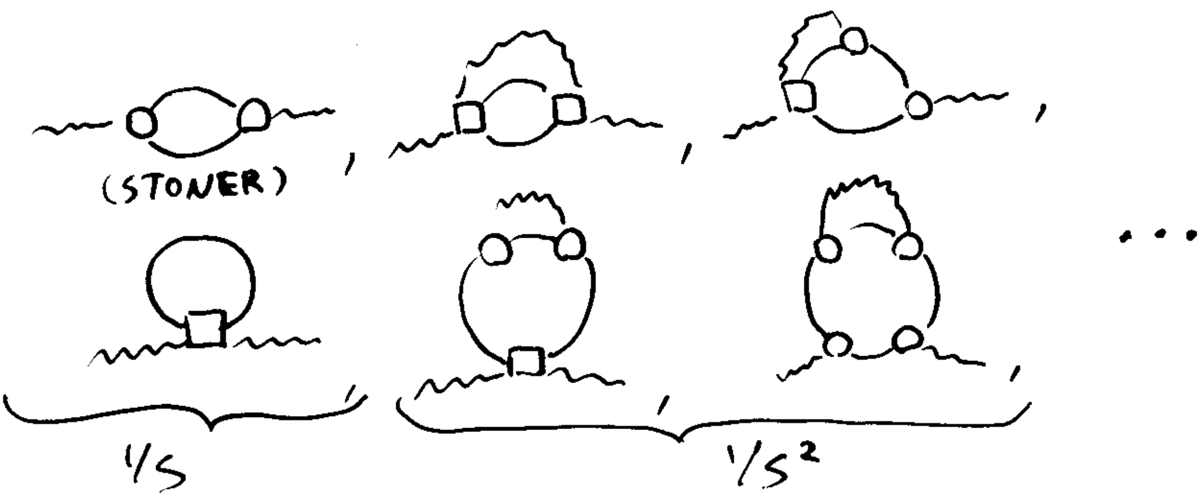
Electron-SpinWave interaction vertices:



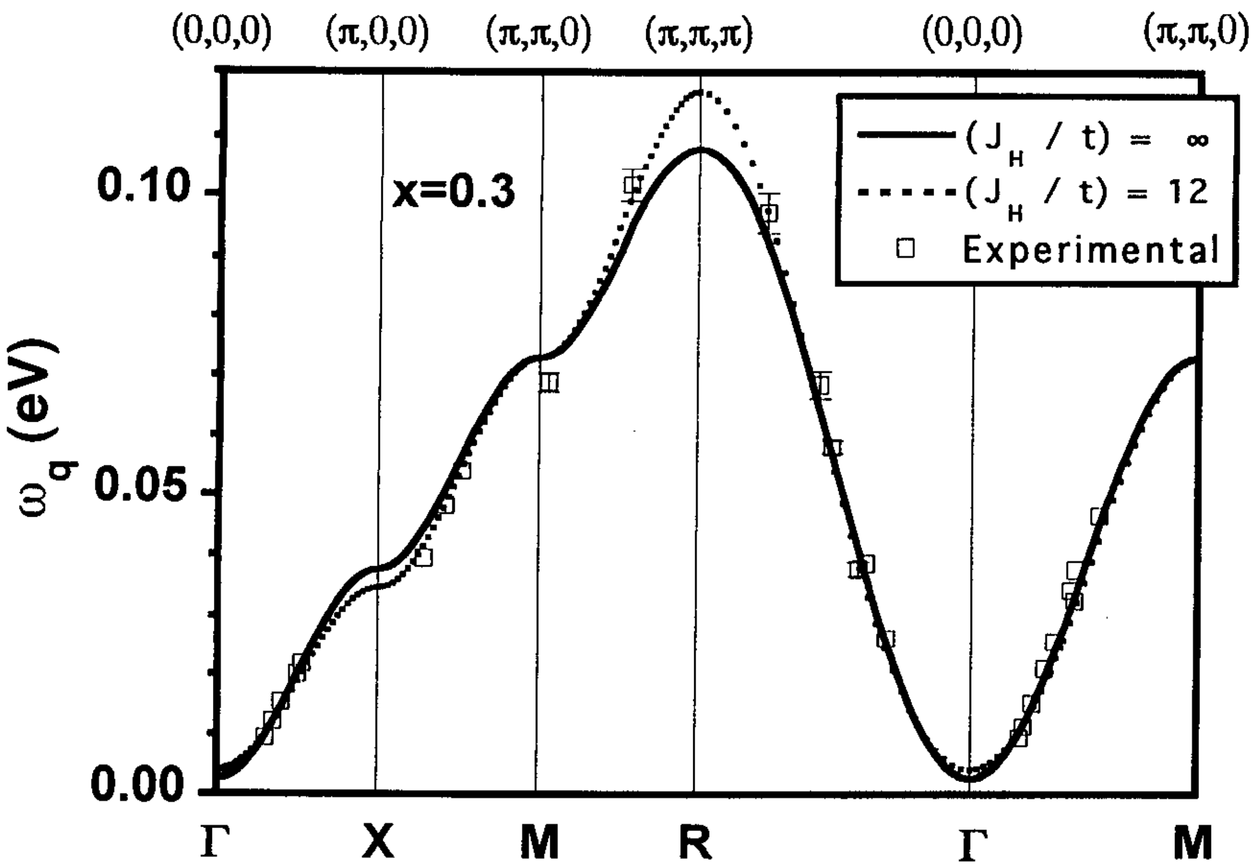
Simple cubic lattice with n.n. hopping.

$$\varepsilon_k = -2t(\cos k_x + \cos k_y + \cos k_z).$$

Calculate the SelfEnergy of the spin wave.
Dispersion relation: $\omega_q = \Pi(q, \omega_q)$.



Double-Exchange Model on a Cubic Lattice (Spin Wave Approx.)



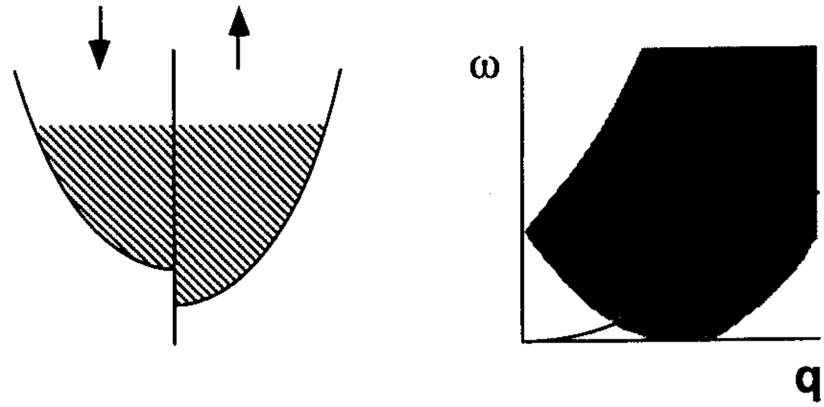
Neutron Inelastic Scattering Experiment in $La_{0.7}Pb_{0.3}MnO_3$ and parameter fittings with effective models.

	experiment	Heisenberg Model	Double-Exchange Model
Spin wave Bandwidth	0.1eV		
fitting parameters		2JS = 8.8 meV	t = 0.2 eV, J = 2.4 eV
Ferromagnetism T_c	355K	(Mean field result) 581K	(D infinity result) 440K

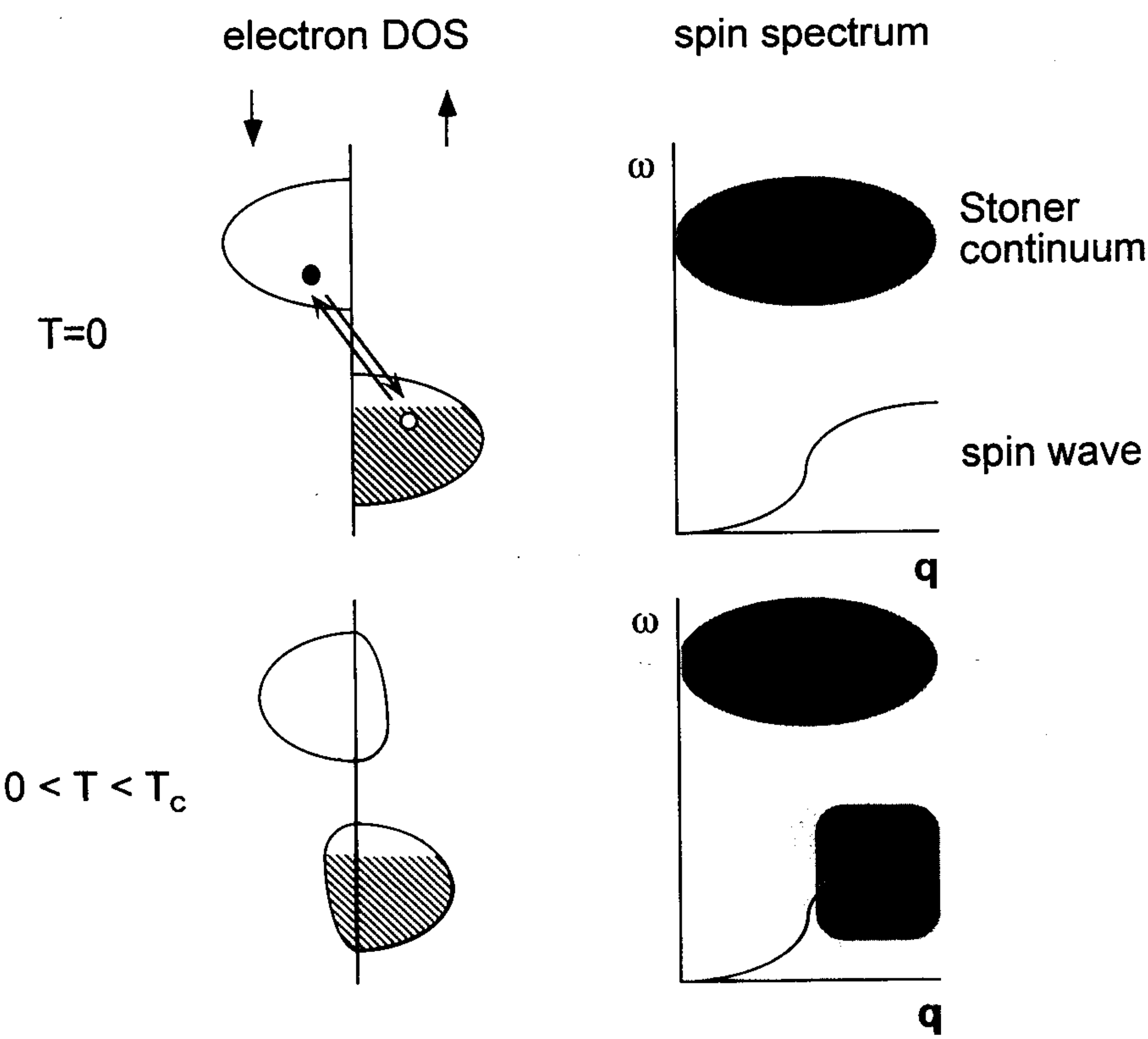
The Double-Exchange model consistently reproduce the spin-wave dispersion relation and T_c.

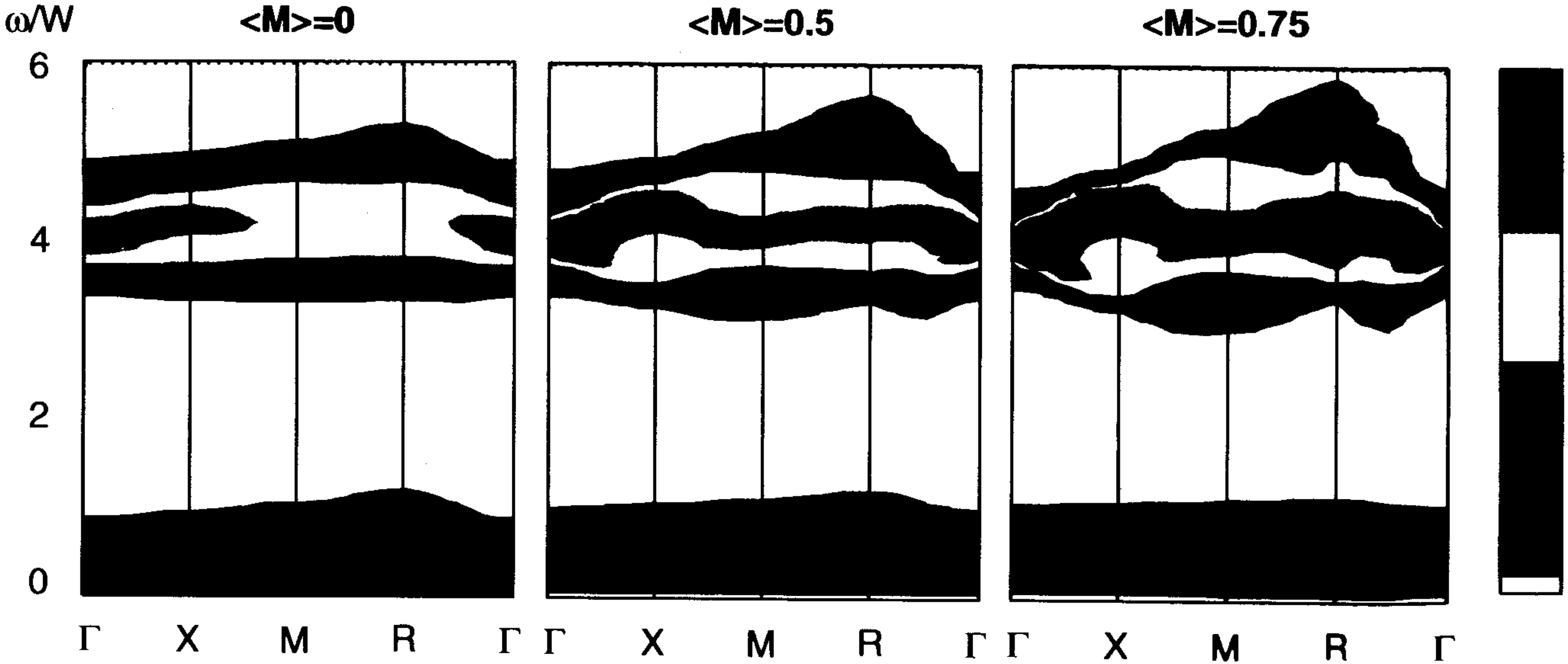
Stoner excitation

(conventional) Weak Ferro-metal



Doublel-Exchange model: Strong Hund's coupling limit

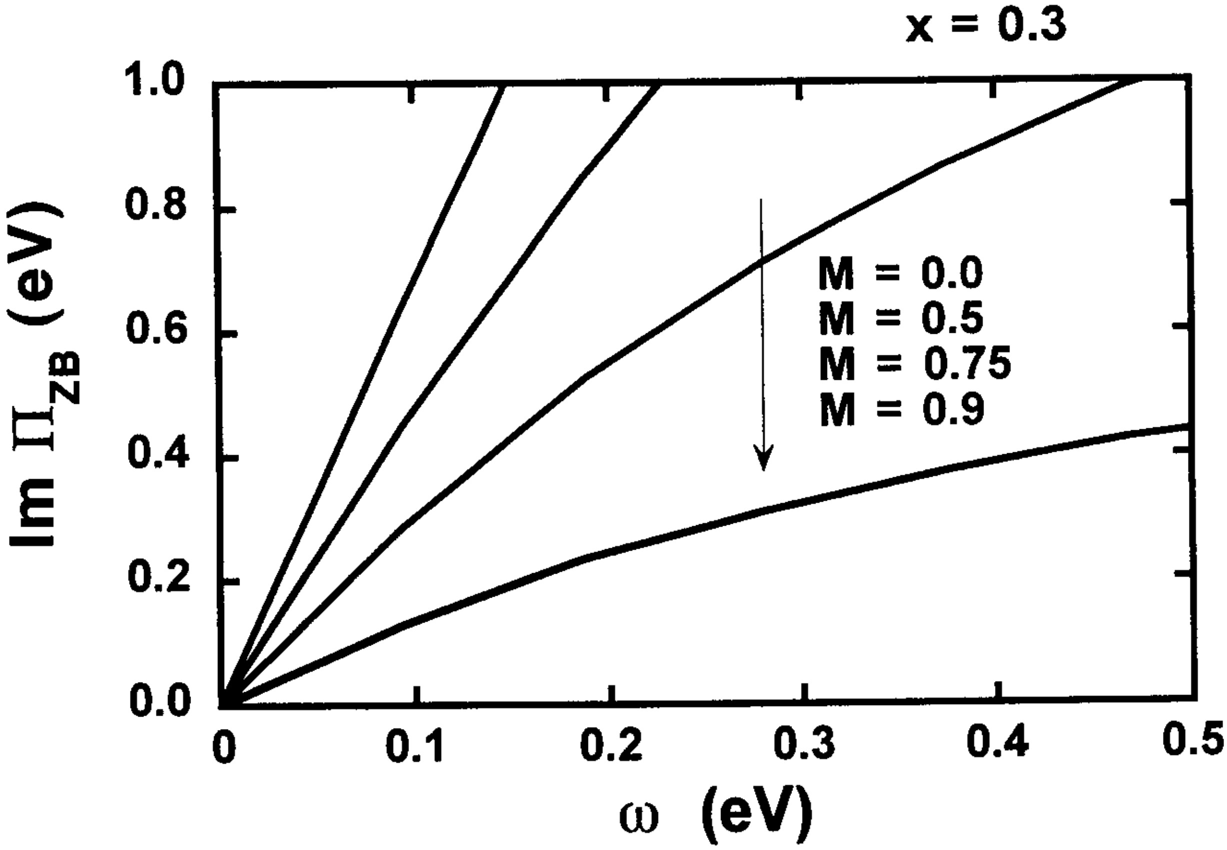




$\mathrm{Im}\,\chi(q,\omega)$

$J_H / W = 2$

$x = 0.3$



Stoner Absorption

$$\Gamma_q = \mathrm{Im}\,\Pi(q, \omega_q)$$

$$\Rightarrow \quad \Gamma_q \cong \alpha\,(1 - M^2)\cdot \omega_q$$

$M = \langle S_z \rangle / S$
moment

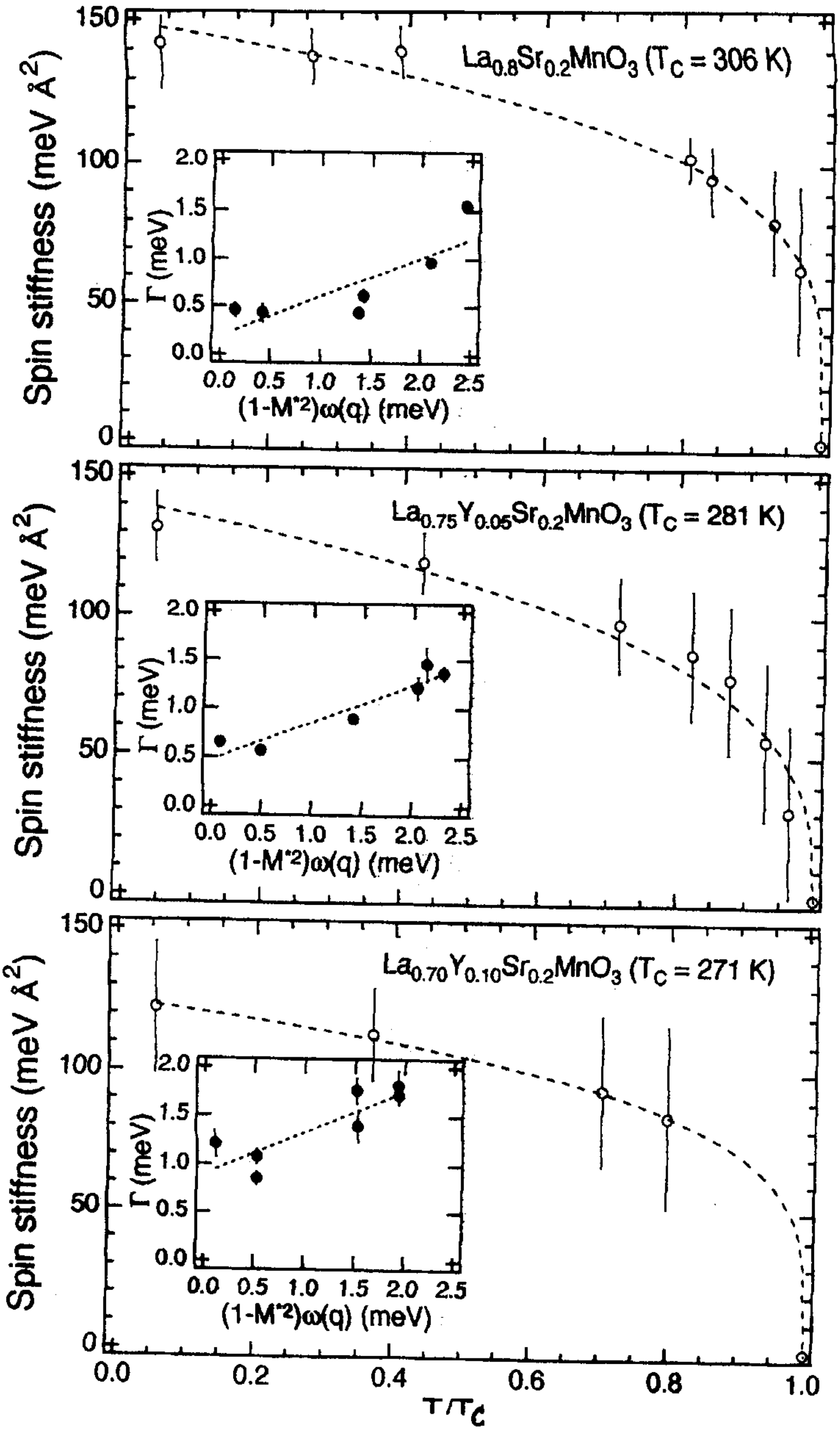
α : dimensionless const. of order 1

Stoner Absorption

$$\mathrm{Im}\,\chi(q, \omega) \sim \alpha_q\,(1 - M^2)\,\omega$$

FIG. 2 - K. Hirota - Reference Number 21

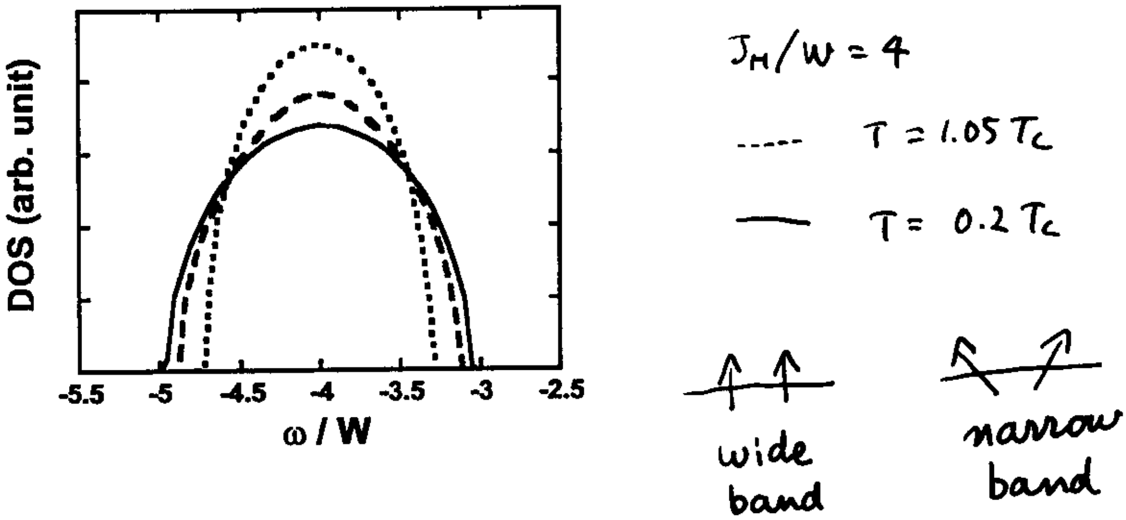
$\Gamma_q = \Gamma_0 + \alpha_q (1-M^2)\,\omega(q)$



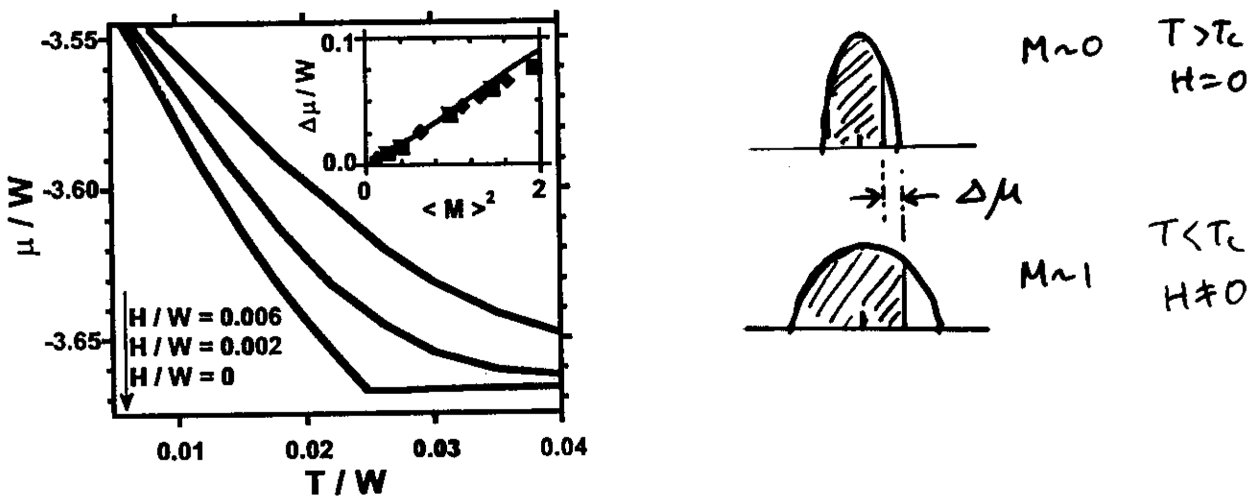
'97 04/14 MON 15:40 [受付番号 6306] 002

Temperature Dependence of DOS Width

Spin fluctuation at high temperature reduces electron hopping.



For fixed band filling,
Change of DOS width cause shift of μ .



Shift of μ can be as large as 0.1eV for $W \sim$ 1eV.

cond-mat/9905176
to be published J.P.S.J.

Scaling Relations

Scaling relations in the double-exchange systems:

- Resistivity

$$-\frac{\Delta\rho}{\rho} \propto M^2$$

- Optical conductivity peak for inter-band absorption

$$\int \sigma(\omega)\mathrm{d}\omega \propto 1 - M^2$$

- Spin wave lifetime due to Stoner absorption

$$\Gamma_q \propto (1 - M^2)\omega_q$$

are consistent with experiments for (La,Sr)MnO_3 (WIDE band).

Many thermodynamical quantities are controlled by the magnetism. Double Exchange System is relevant for LSMO!

For NARROW-band compounds e.g. (La,Ca)MnO_3, deviations from such scaling functions are observed.

- Intrinsic?
- Extrinsic?

Kinetic energy vs. coupling with Lattice/Orbital

W vs. g, $J_{ex}^{orb} \sim \frac{t^2}{U}$, $J_{superexchange}$

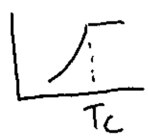
Millis et al.:
Double Exchage Alone Does Not Explain the Resisivity of $La_{1-x}Sr_xMnO_3$, Phys. Rev. Lett. **74** (1995) 5144.

Double-Exchange Model vs. $La_{1-x}Sr_xMnO_3$

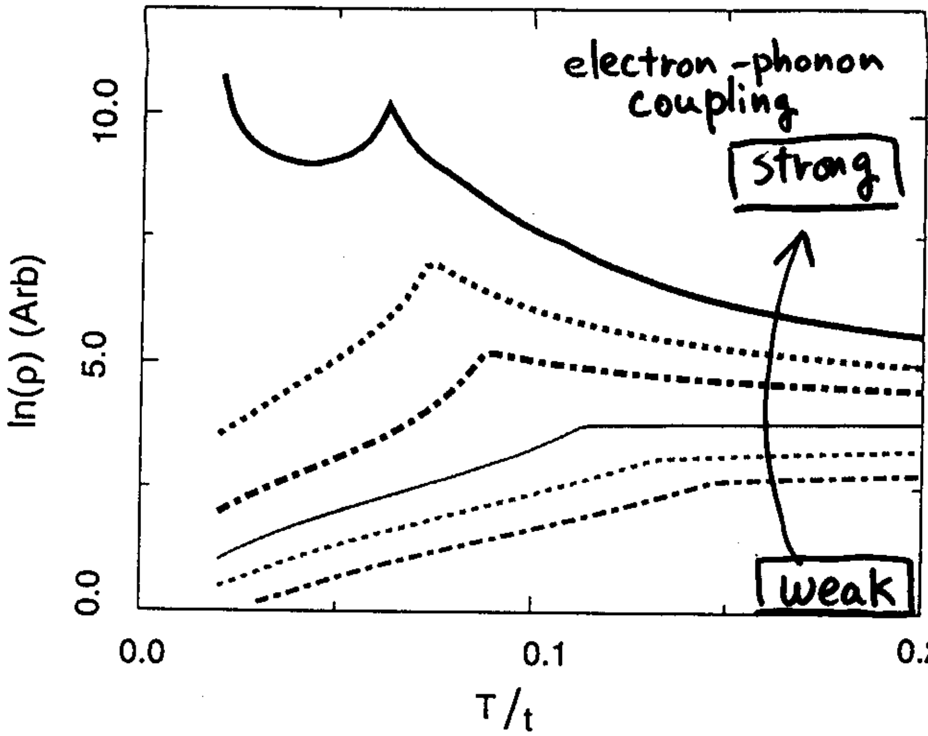
- Curie temperature: Theory ($T_c = 1000 \sim 3000$K) overestimates one order of magnitude.
- Temperature dependence of resistivity ρ:
  $\rho(T)$ completely different at $T < T_c$.
- Absolute value of ρ: Larger values at experiment.

Present Results

- Curie Temperature $T_c \lesssim 400$K
  consistent
- $\rho(T)$ consistent with
  $(LaSr)MnO_3$ $x \sim 0.3$



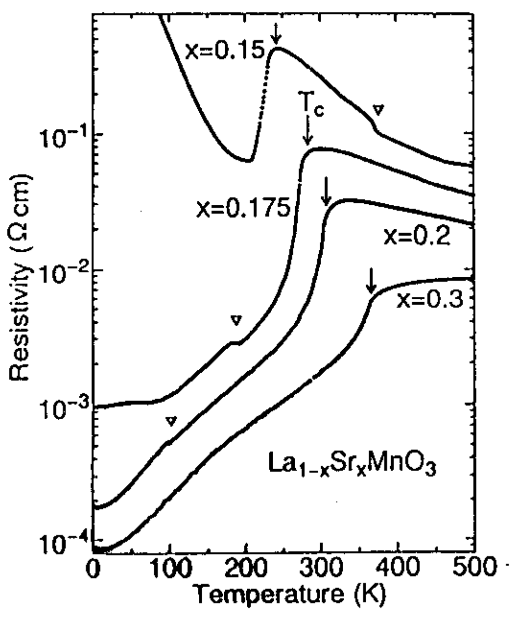
- Absolute value for ρ at $T > T_c$
  $\frac{\rho}{\rho_0} = 1 \sim 10$ $(\rho_0 = 1/\sigma_{Mott})$
  depending on parameter choice
  consistent with $(LaSr)MnO_3$
  $x \gtrsim 0.2$

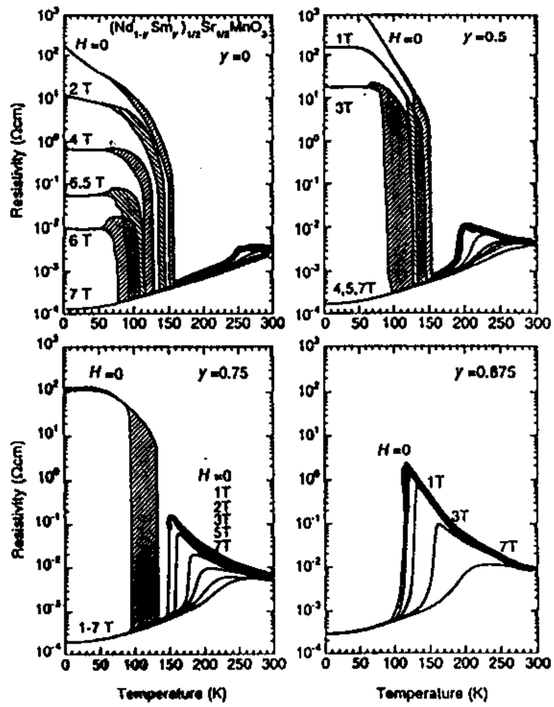


Millis ('96)
Dynamic JT
by
DMF

"crossover"

Tokura et al.





$Nd_{1/2}Sr_{1/2}MnO_3$ wide band

↕

$Sm_{1/2}Sr_{1/2}MnO_3$ narrow band

Phenomenology

Energy scales in Double-Exchange Systems:

e_g electron system:
kinetic energy $W \sim 1$eV

Strong Hund's coupling

t_{2g} spin system:
Ferromagnetic coupling
$\sim T_c \sim 300$K

t_{2g} spin system is influenced by:
$\Delta T \sim 10^2$K, or $H \sim 10^1$T at $T \sim T_c$.

The change in t_{2g} state causes a large change in e_g states,
in the energy scale ~ 1eV.

If $T_c \ll W \sim J_H$, small magnetic field is enough to cause a large change in electronic states.

Origin of the CMR: small T_c and large J_H.

If the ferromagnetic state is a metal and the paramagnetic state is highly resistive (due to any mechanism), weak magnetic field causes a large change in conductivity.

All manganates in metallic region show similar behavior for CMR. But, in detail, ...

SUMMARY

CMR manganites $(R,A)MnO_3$:

- Rich phase diagram by bandwidth and doping control.
- "Double-exchange ferromagnetic metal" appears only in a limited region of the phase diagram.
- Spin-Charge-Lattice-Orbital strongly coupled system: Spin/Charge/Orbital ordering, structure transition, superstructure, ...

Nevertheless, a model with double-exchange alone explains:

- Curie temperature T_c, and its doping dependence.
- Magneto-transport phenomena
  - ⋆ Magnetoresistance universal curve.
  - ⋆ Spectral change in $\sigma(\omega)$.
  - ⋆ Seebek coefficient.
- Spin wave dispersion relation and its lifetime.

in wide-bandwidth compound $(La,Sr)MnO_3$.

Little Polaron Effect in $(La,Sr)MnO_3$

Scaling relations / Universalities.

Open Question:

- Why other interactions are so irrelevant?
- How and what kind of crossover/phase transition occurs when bandwidth becomes narrower?
  Any more exotic phenomena?

Theoretically:
Universalities of double-exchange plus lattice/orbital/etc. system?

something else?

Experiment	Material (chemistry)	Theory

Experiment

☆ High T_c
Wide Band

$\rho(T)$

P ⟷ F
2nd order

↕ To understand the difference in Physics,

☆ Low T_c
Narrow Band

P ⟷ F ⟷ AF ⟷ P

(1st order)
with { lattice, charge, orbital } order

Material (chemistry)

$(La,Sr)MnO_3$
(La, Pb)
(La, Ba)
⋮

$(La,Ca)MnO_3$
(Nd, Sr)
(Pr, Sr)
(Pr, Ca)
⋮

Theory

Double Exchange
(t, J_H)

↑
we need "adiabatic" continuation in chemistry and theory
↓

Double Exchange
+ lattice
+ orbital
+ long range Coulomb
+ disorder
+ ....

+ Extrinsic Effects
(grain, domain, ...