Magnetism in correlated-electron materials

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focus on delocalized electrons in metals and superconductors

localized electrons: Hinkov talk

outline

1. introduction
2. interplay between magnetism and unconventional superconductivity
3. oxide heterostructures

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What are correlated electrons?

electron-electron Coulomb interactions + quantum mechanics

very weak → independent electrons: **ordinary metal**

very strong → electron crystal: **Mott insulator**

“strongly correlated electrons” in d- or f-electron metals:

- prone to crystallization
- transport dominated by electron-electron interactions, very different from ordinary metals
- new theory of metals?

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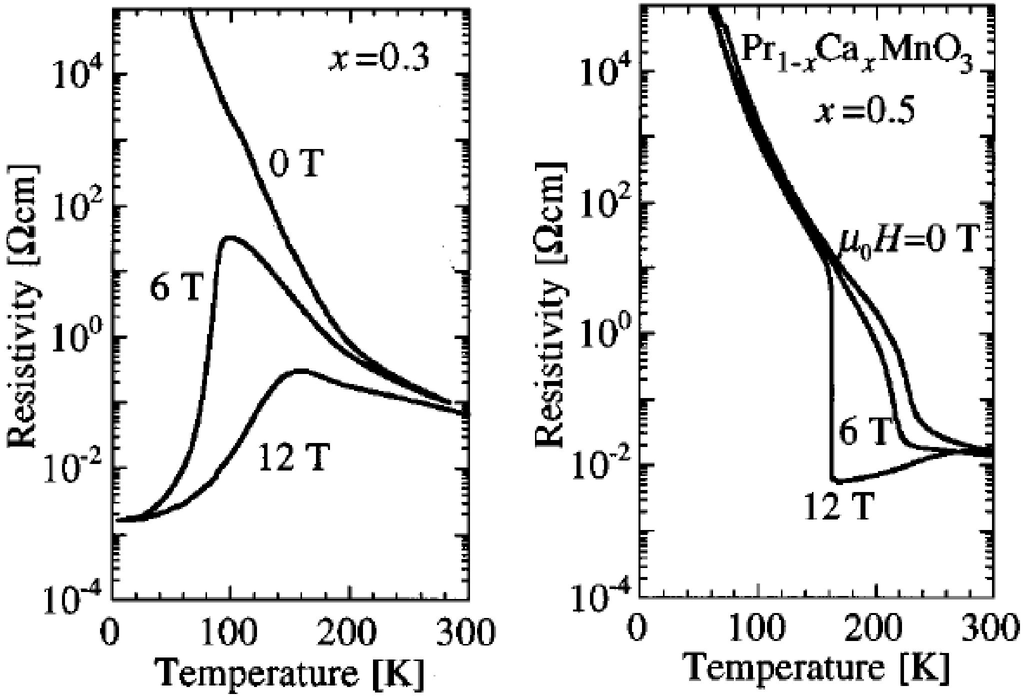
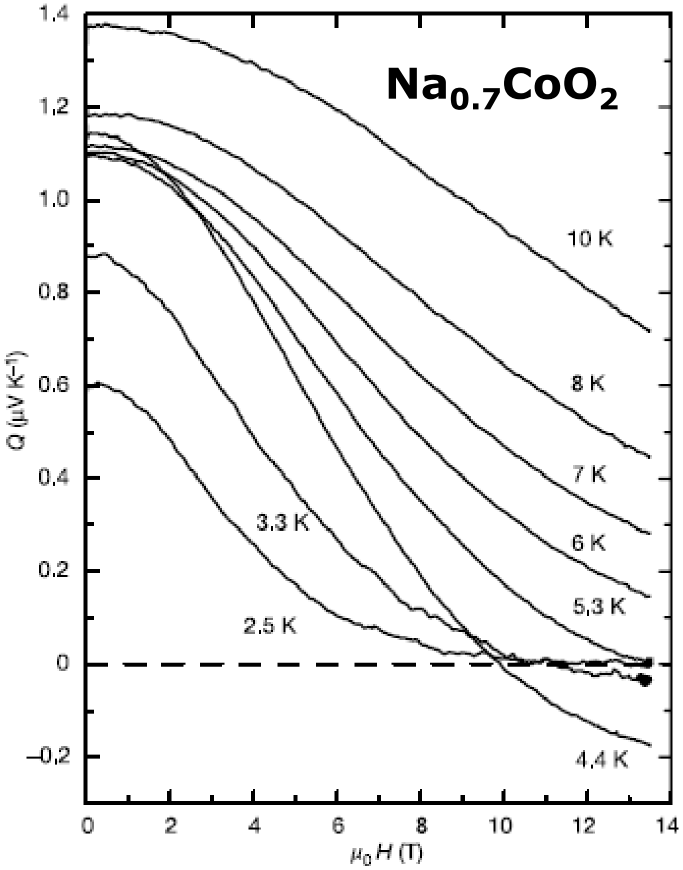
Bulk complex oxides: “colossal” response

example: colossal magnetoresistance

in manganese oxides



Tomioka et al., PRB 1996



example: colossal thermopower

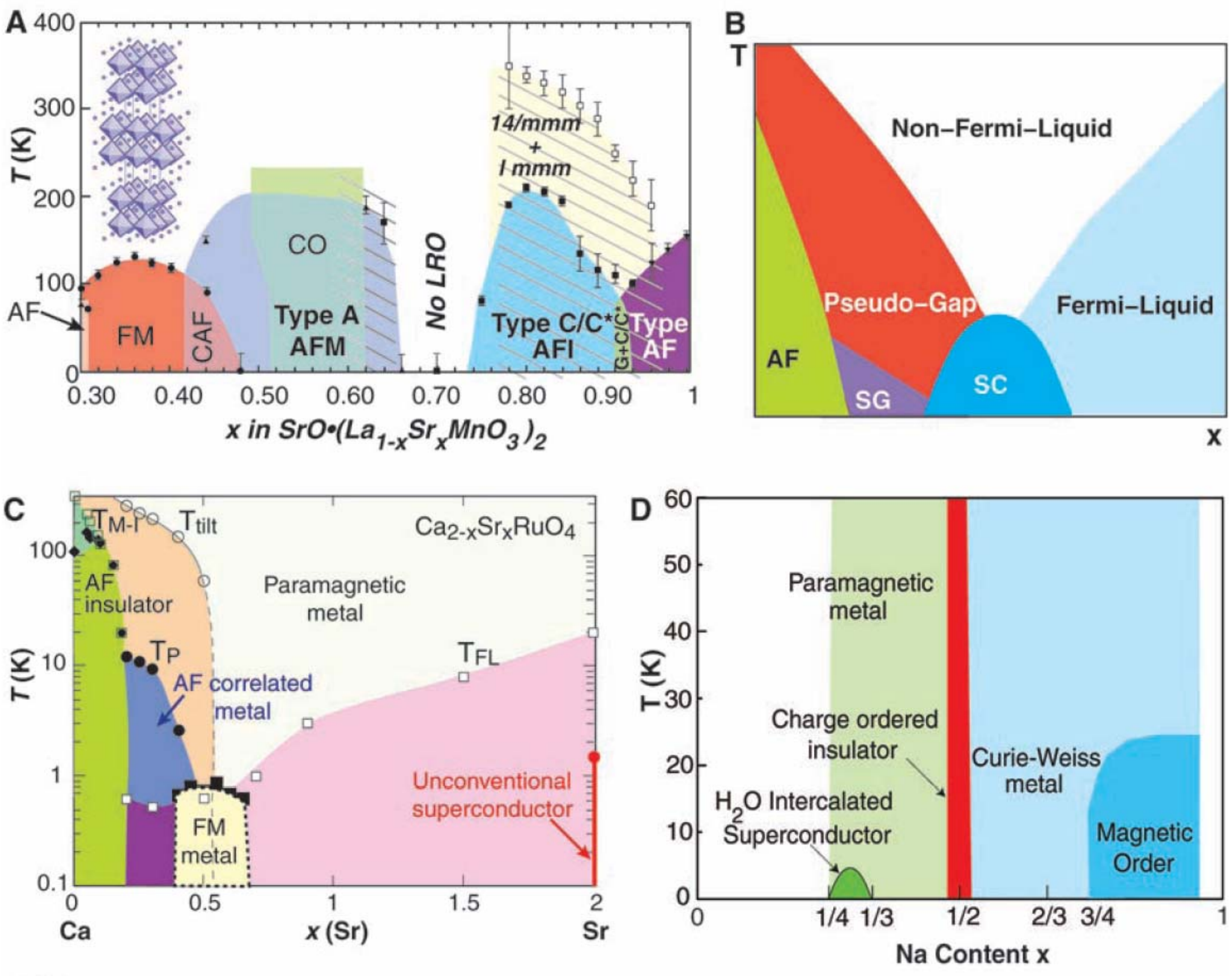
in cobalt oxides

Wang et al., Nature 2003

Competing phases

manganates

cuprates



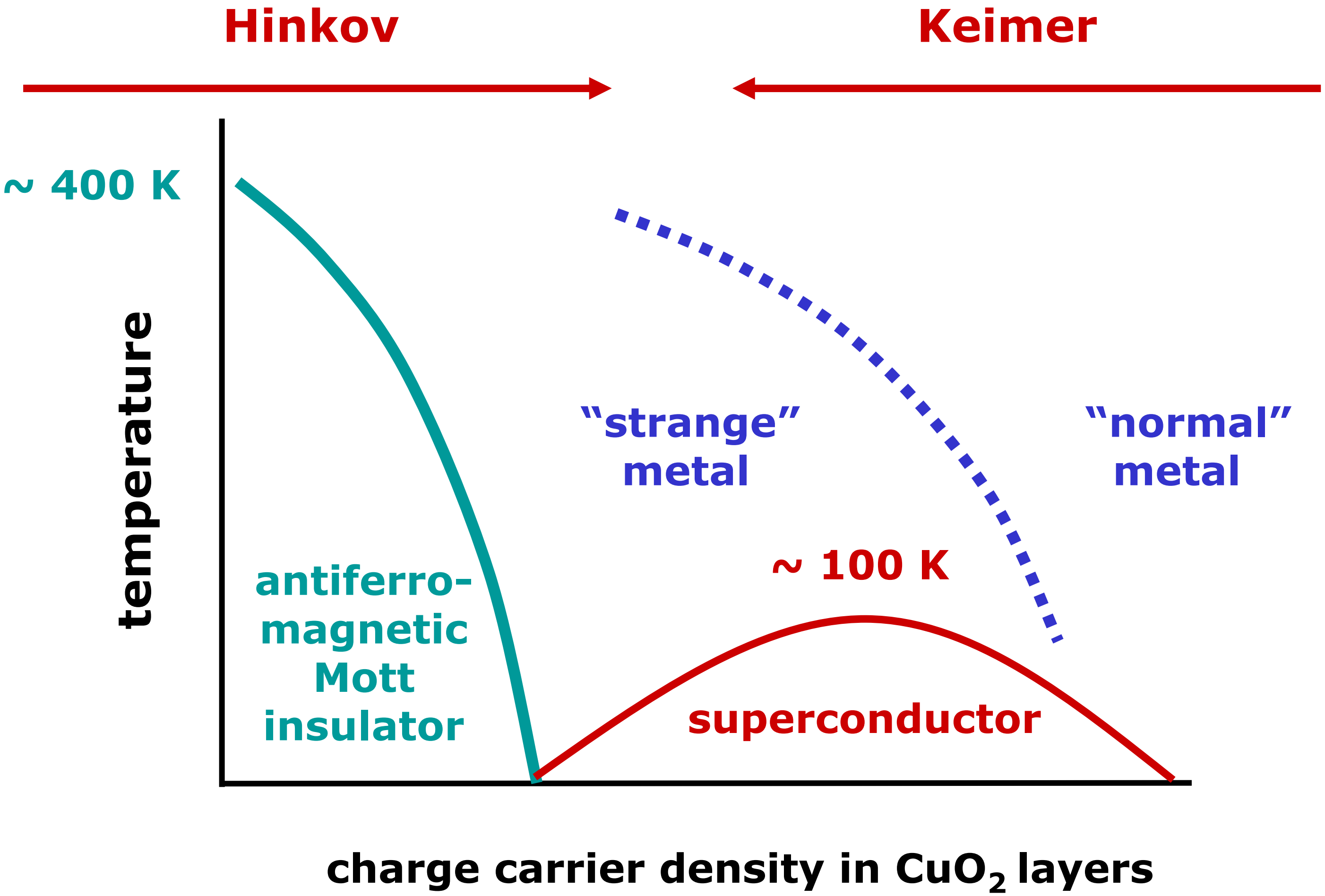
ruthenates

cobaltates

Dagotto, Science 2005

extreme variety of macroscopic properties, microscopic structures

High temperature superconductivity



metallicity and superconductivity in **doped Mott insulator**

electron correlations key to microscopic description

superconductivity driven by repulsive Coulomb interactions?

Cooper-Pairs

quantum-mechanical wave function

analogous to hydrogen atom

$$\Psi_{\text{electron}} = \varphi(r)\,|s\rangle \qquad |s\rangle = \left|\pm\tfrac{1}{2}\right\rangle \equiv |\uparrow\rangle, |\downarrow\rangle$$

$$\Psi_{\text{Cooper}} = \varphi_{\text{central}}(\vec{r}_1 + \vec{r}_2)\,\varphi_{\text{relative}}(\vec{r}_1 - \vec{r}_2)\,|S\rangle$$

quantum numbers relative angular momentum l = 0, 1, 2, ... (s, p, d, ...)

total spin S = 0, 1

$$|S=0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right); \qquad |S=1\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\right), \quad |\uparrow\uparrow\rangle, \quad |\downarrow\downarrow\rangle$$

electrons are identical particles → antisymmetry of wave function

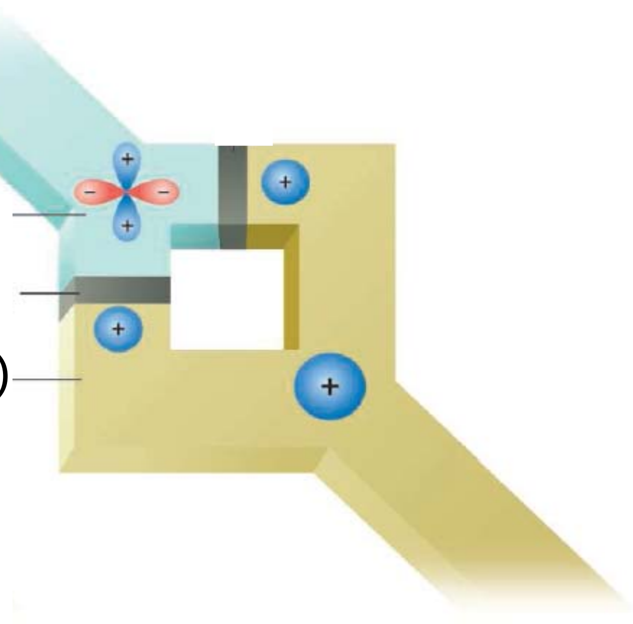
e.g. $l = 0 \rightarrow \varphi_{\text{relative}}$ symmetric → $|S\rangle$ antisymmetric

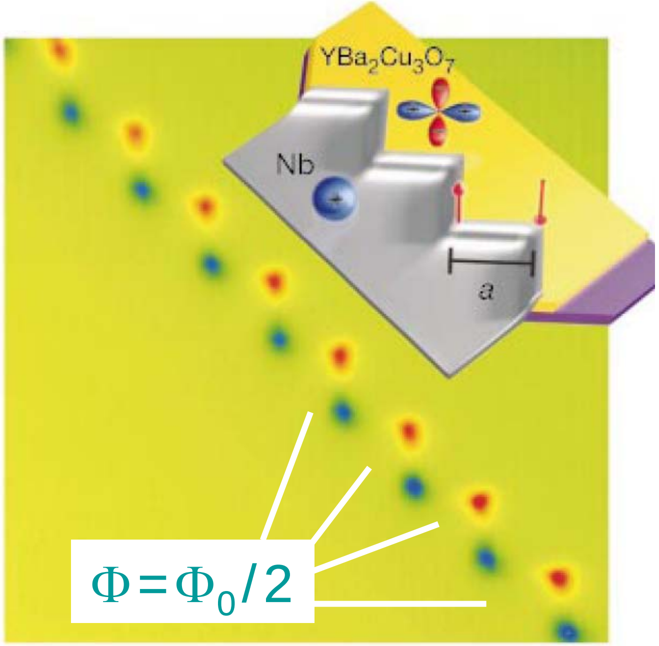
l	S	
0	0	Hg, Pb, Al, MgB_2, ...
1	1	Sr_2RuO_4 ⟵
2	0	high-T_c superconductors ⟵

signature of strong correlations, electronically driven superconductivity

d-wave superconductivity

experimental confirmation: **π-loop**



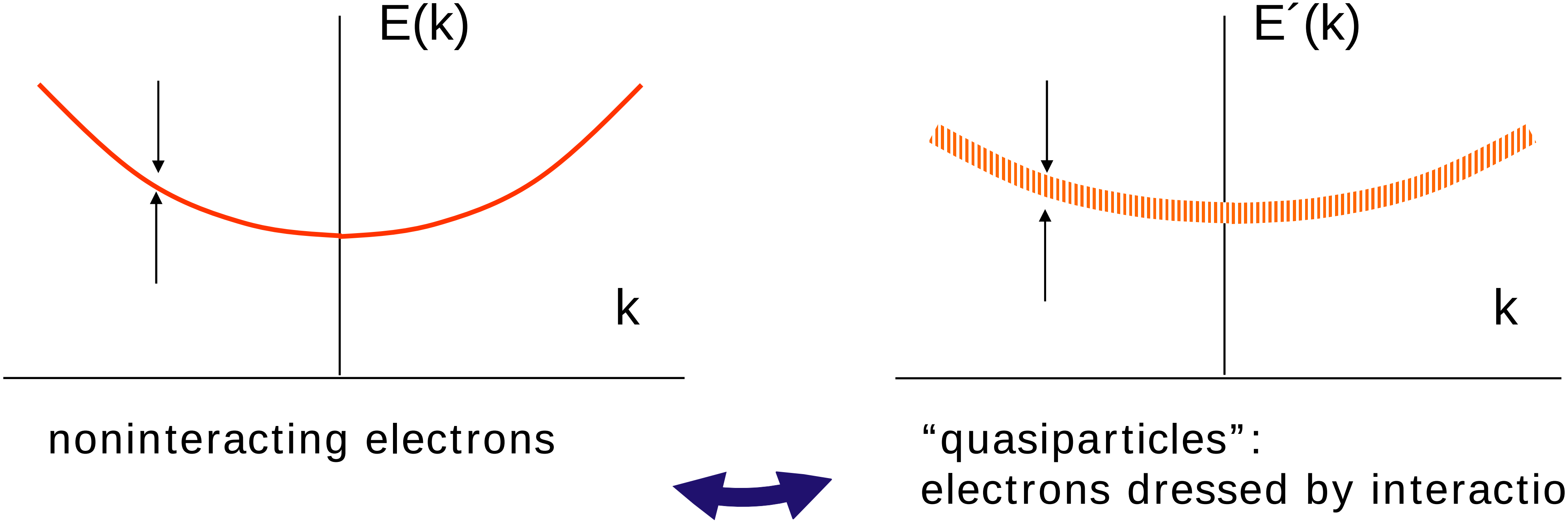


Hilgenkamp et al., Nature 2003

flux quantization: $$\frac{2e\Phi}{\hbar c} = 2\pi n + \pi \rightarrow \Phi = (n+\tfrac{1}{2})\frac{\pi\hbar c}{e} = (n+\tfrac{1}{2})\Phi_0$$

→ **half-integer flux quanta**

Fermi-liquid theory



lifetime = ∞

line width = 0

narrower bands

linewidth ≠ 0 unless E´ → E_F´

noninteracting electrons

“quasiparticles”:
electrons dressed by interactions

adiabatic continuity

Is Fermi liquid theory valid in strongly correlated metals?

Experimental methods: spectroscopy

experimental determination of dynamics and excited states

	q-averaged	**q-resolved**
electron spin	muons NMR	neutrons
↕		
electron charge	optics tunneling	photoemission electrons x-rays
↕		
crystal lattice		neutrons (nuclei) x-rays (core electrons)

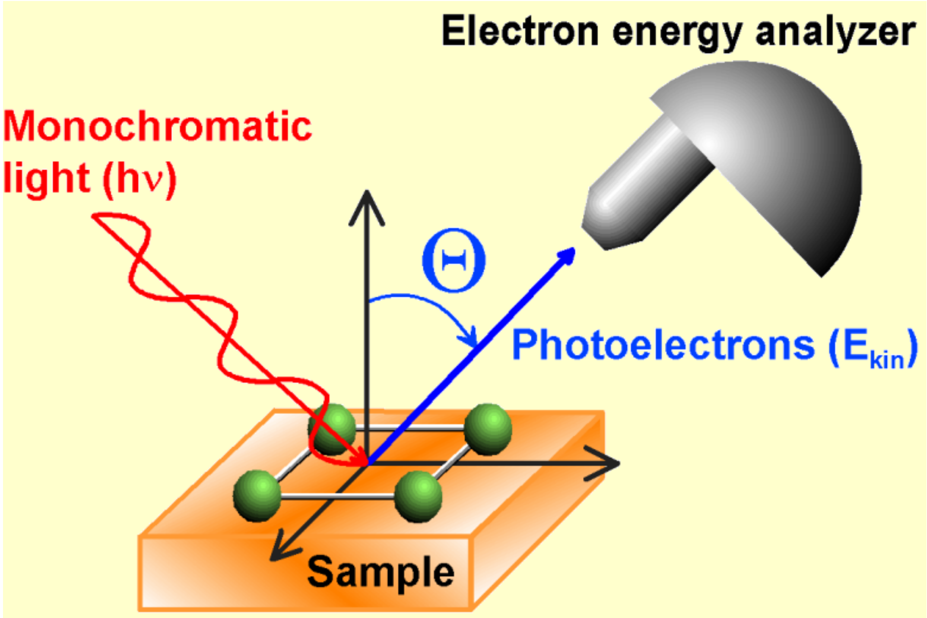
Experimental methods: spectroscopy

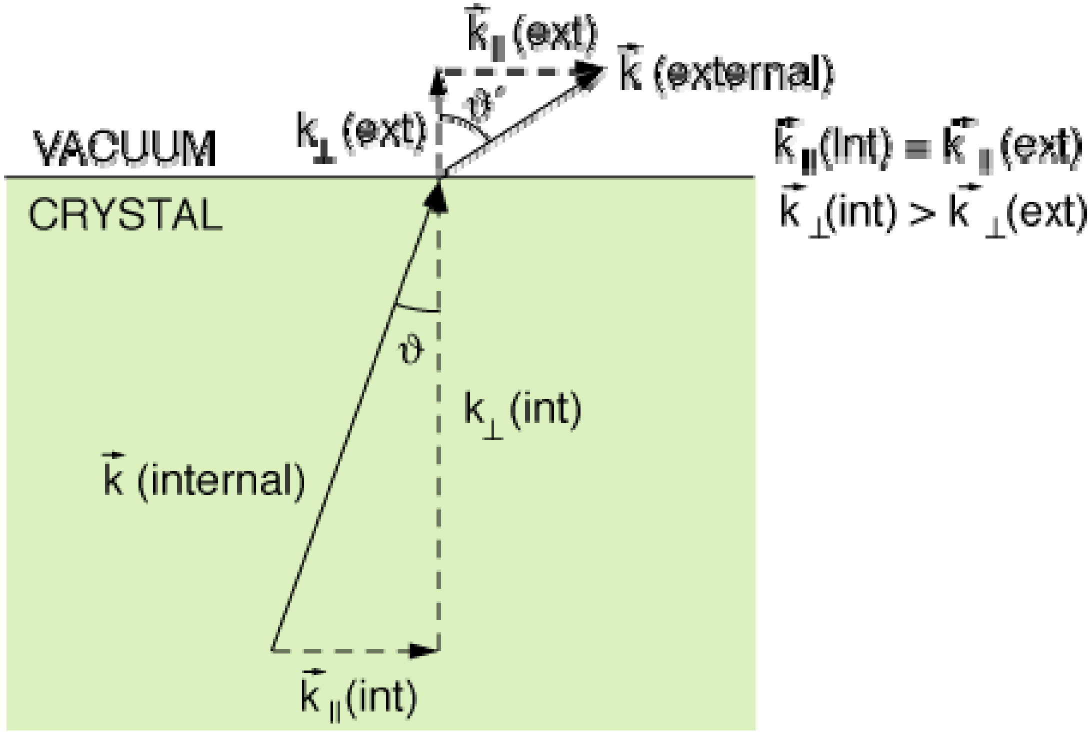
experimental determination of dynamics and excited states

	q-averaged	**q-resolved**
electron spin	muons NMR	neutrons (→ Ronnow talk)
↕		
electron charge	optics tunneling	photoemission electrons x-rays
↕		
crystal lattice		neutrons (nuclei) x-rays (core electrons)

Angle-resolved photoemission spectroscopy

angle-resolved measurement of photoelectric effect





$$k_{\| i} = k_{\| f} = \sin\Theta\sqrt{\frac{2m}{\hbar^2}}\sqrt{E_{kin}} = \sin\Theta\sqrt{\frac{2m}{\hbar^2}}\sqrt{h\nu - E_{band} - e\Phi}$$

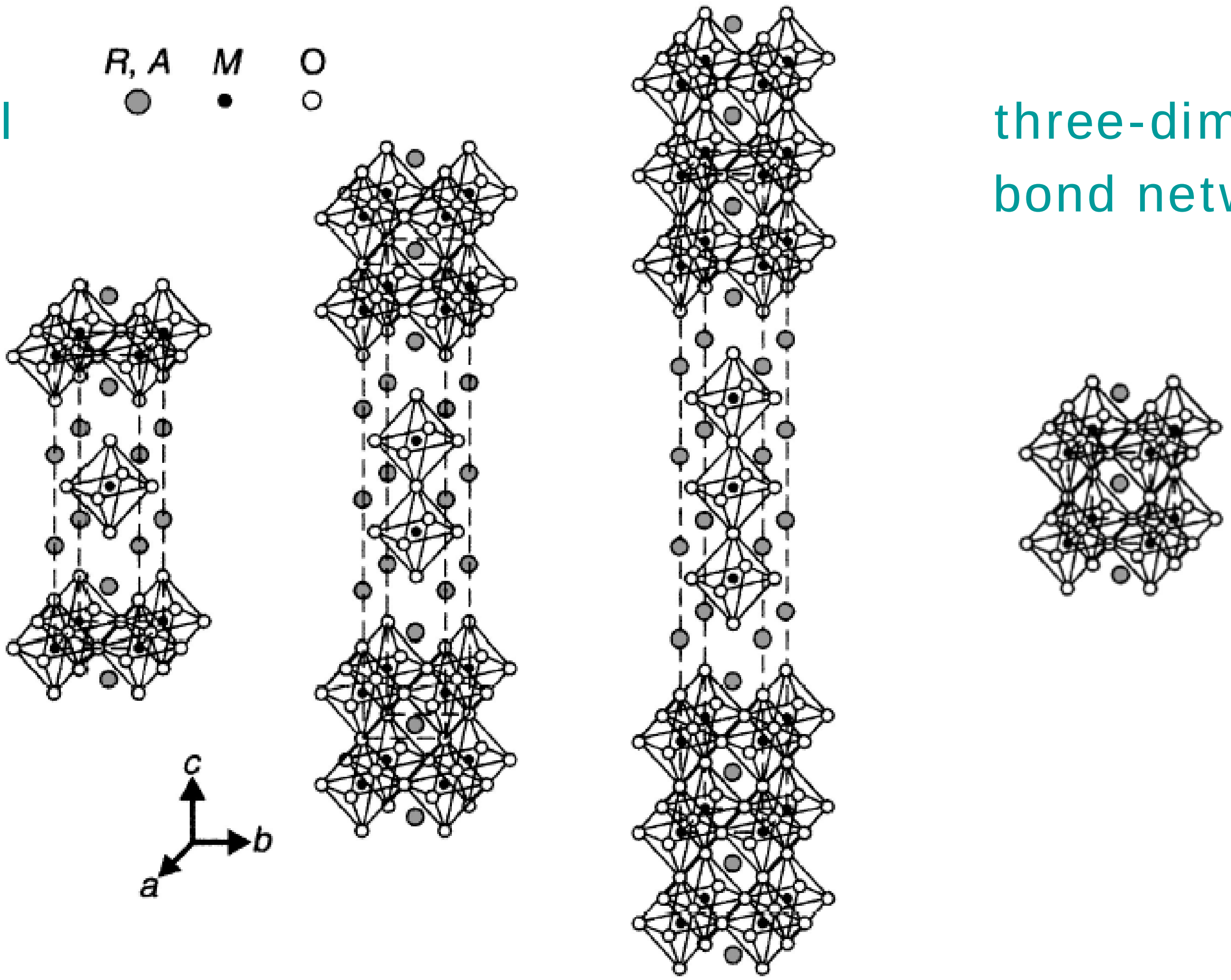
for layered materials with **quasi-two-dimensional electronic structure**

reconstruct electron bands from E_{kin}, emission angle θ of photoelectron

Materials: Ruddlesden-Popper series

two-dimensional bond network

three-dimensional bond network



n=1 $(R,A)_2MO_4$

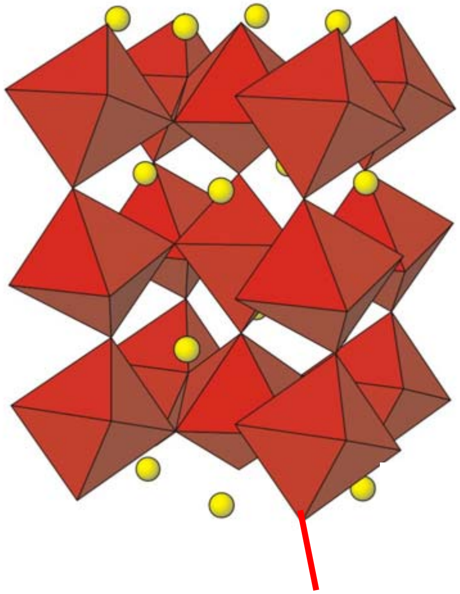
n=2 $(R,A)_3M_2O_7$

n=3 $(R,A)_4M_3O_{10}$

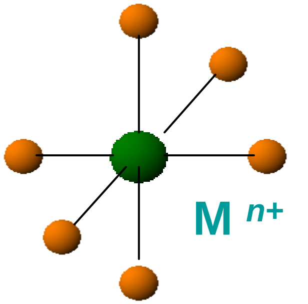
n=∞ $(R,A)MO_3$

Electronic structure

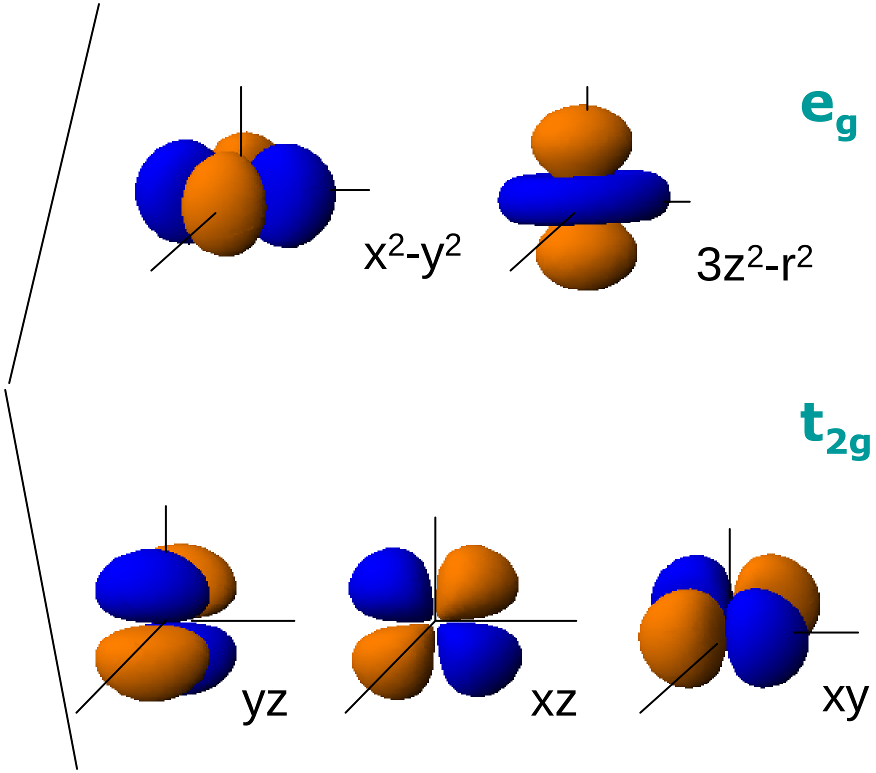
lattice structure



MO$_6$ octahedra



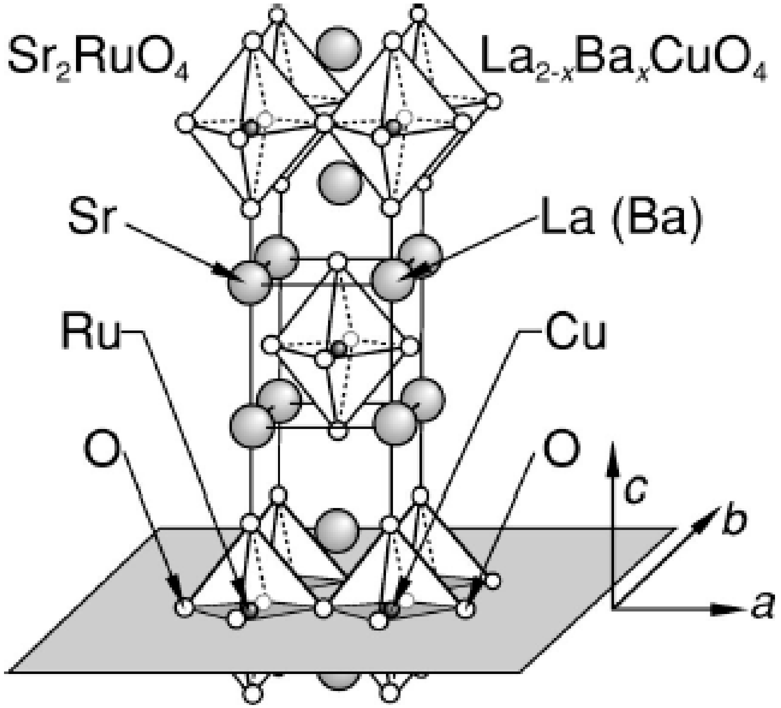
electronic structure



Example Sr_2RuO_4

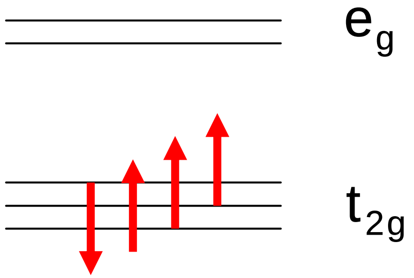
layered structure

isostructural to layered cuprates

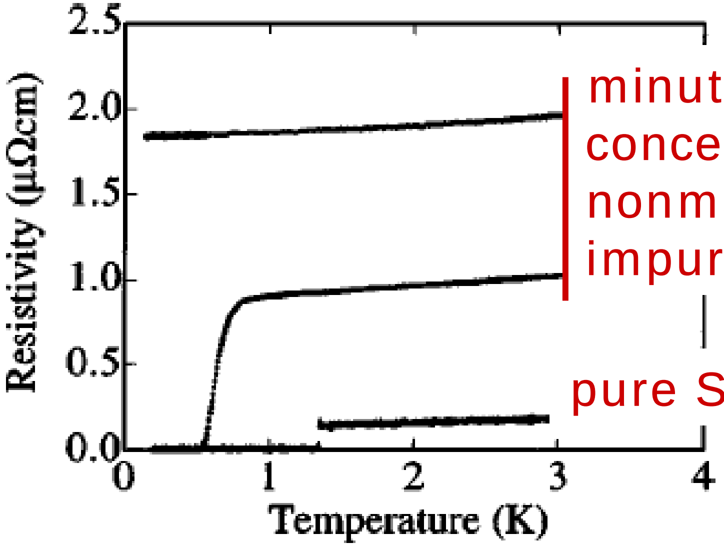


McKenzie & Maeno, RMP 2003

electron configuration $3d^4$



superconductivity



minute concentration of nonmagnetic impurities

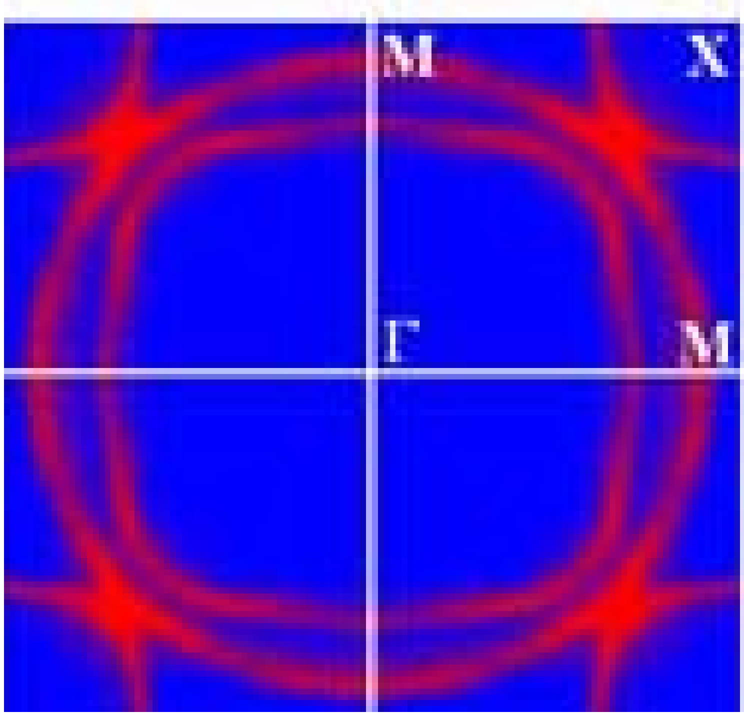
pure Sr_2RuO_4

Sr_2RuO_4 charge excitations

ARPES

- sharp quasiparticles everywhere
- Fermi surface agrees with band structure calculations

Fermi liquid theory valid

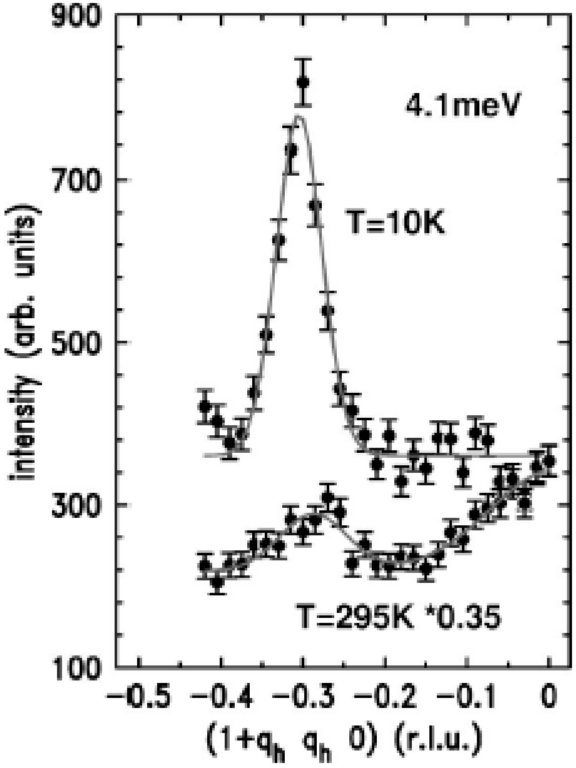


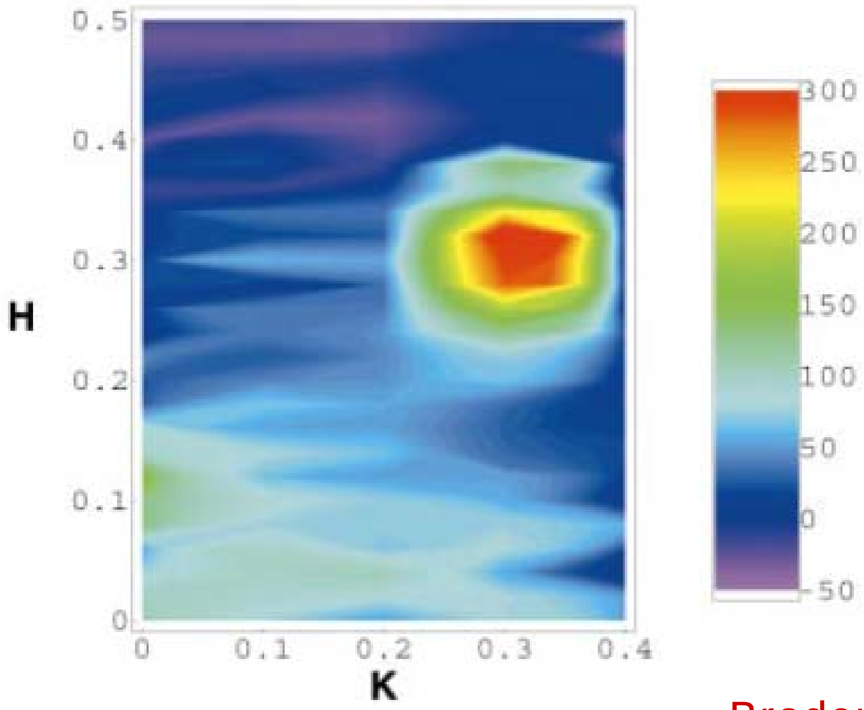
Damascelli et al.,
PRL 2000

Sr_2RuO_4 spin excitations

p-wave pairing by ferromagnetic spin fluctuations?

inelastic magnetic neutron scattering





Braden et al., PRB 2002

no pronounced ferromagnetic fluctuations

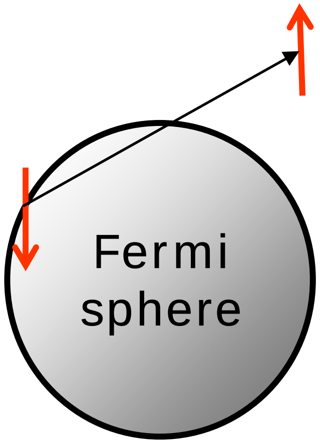
inelastic scattering signal peaked at incommensurate q

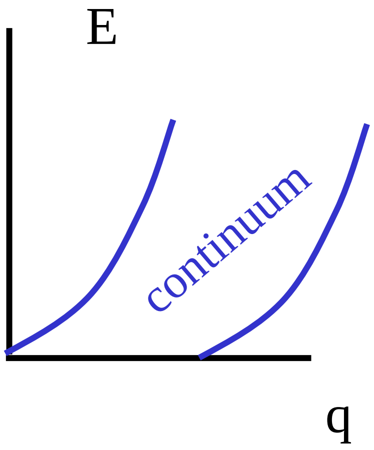
origin of incommensurate excitations?

Spin excitations: Stoner model

susceptibility of electron band

$$\chi_0(q,\omega) = \sum_k \frac{f(E_{k+q\uparrow}) - f(E_{k\downarrow})}{\hbar\omega - (E_{k+q} - E_k - \Delta) + i\varepsilon}$$

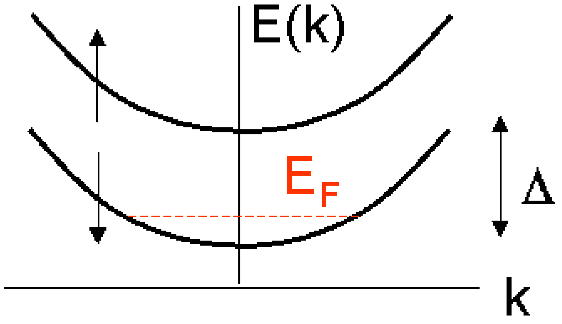


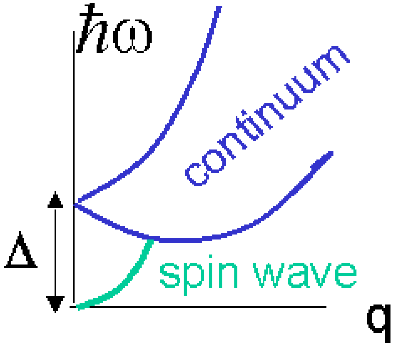


enhanced by electronic correlations

$$\chi(q,\omega) = \frac{\chi_0(q,\omega)}{1 - J(q)\chi_0(q,\omega)}$$

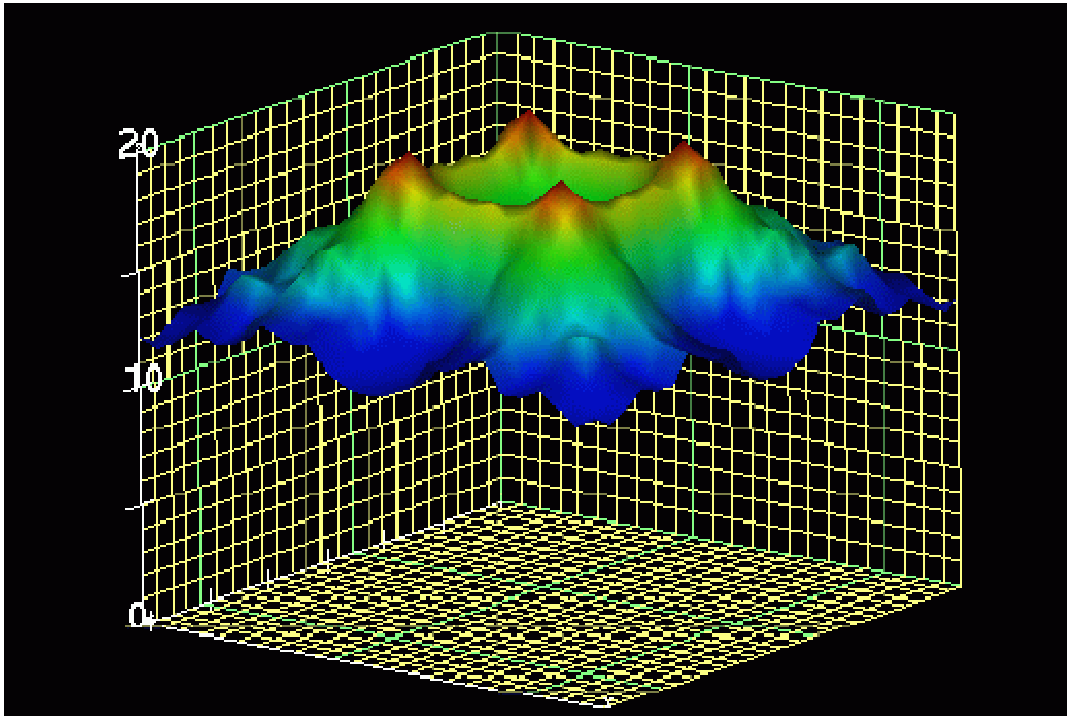
J(q) peaked at q=0, sufficiently strong → ferromagnetism (e.g. Fe, Ni)



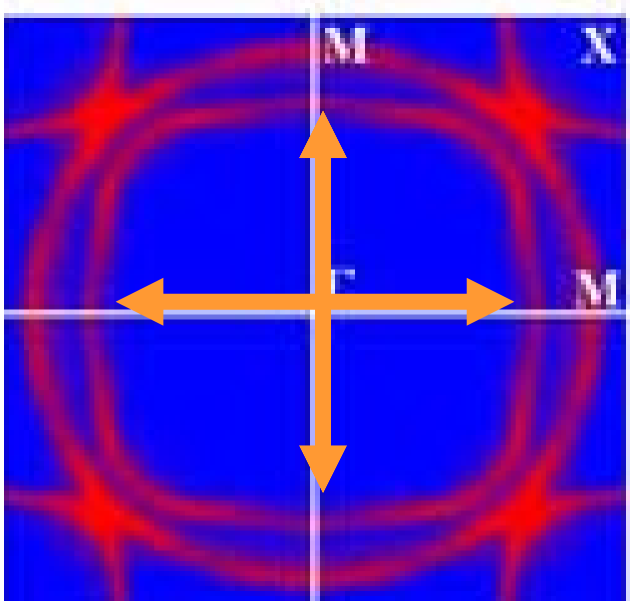


Sr_2RuO_4 spin excitations

band susceptibility of Sr_2RuO_4



incommensurate peaks due to Fermi surface nesting



Mazin et al., PRL 1999

explains incommensurate spin excitations in neutron scattering data

no apparent role in driving p-wave superconductivity

pairing mechanism still elusive

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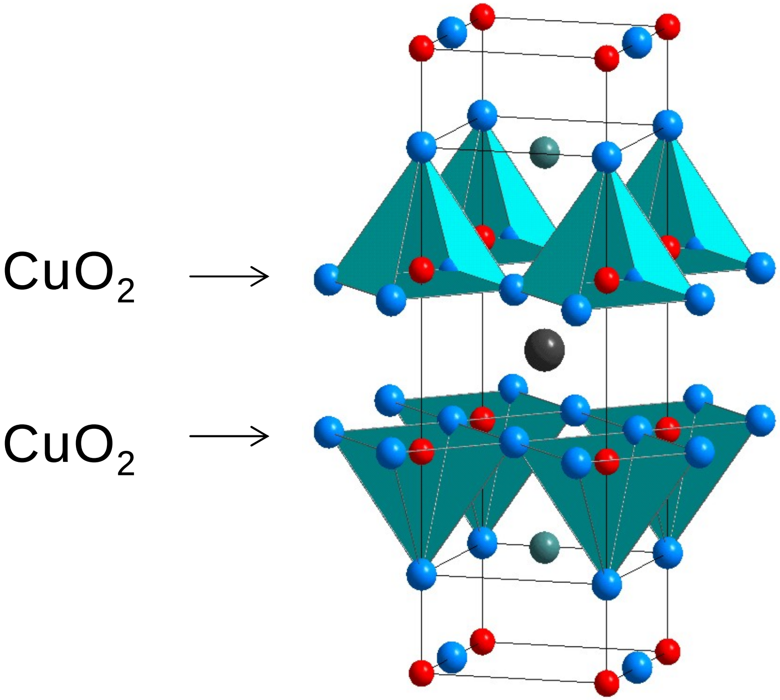
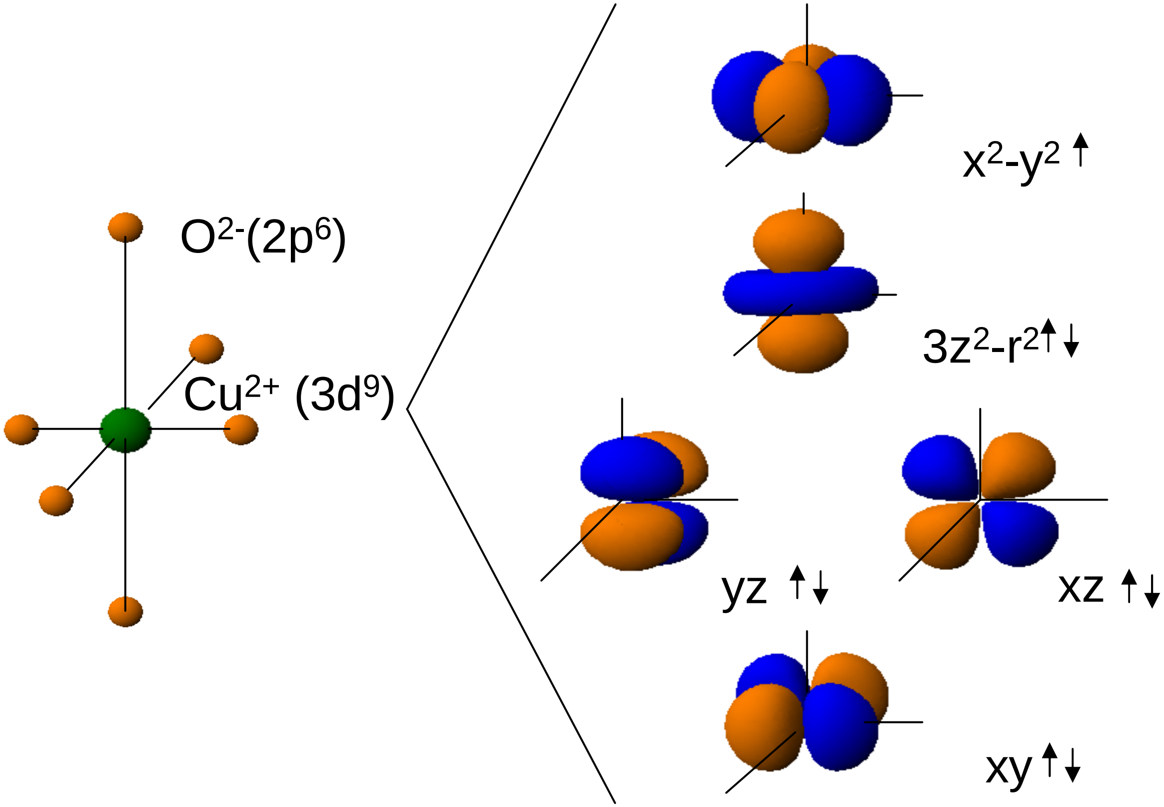
High temperature superconductivity

example: $YBa_2Cu_3O_{6+x}$

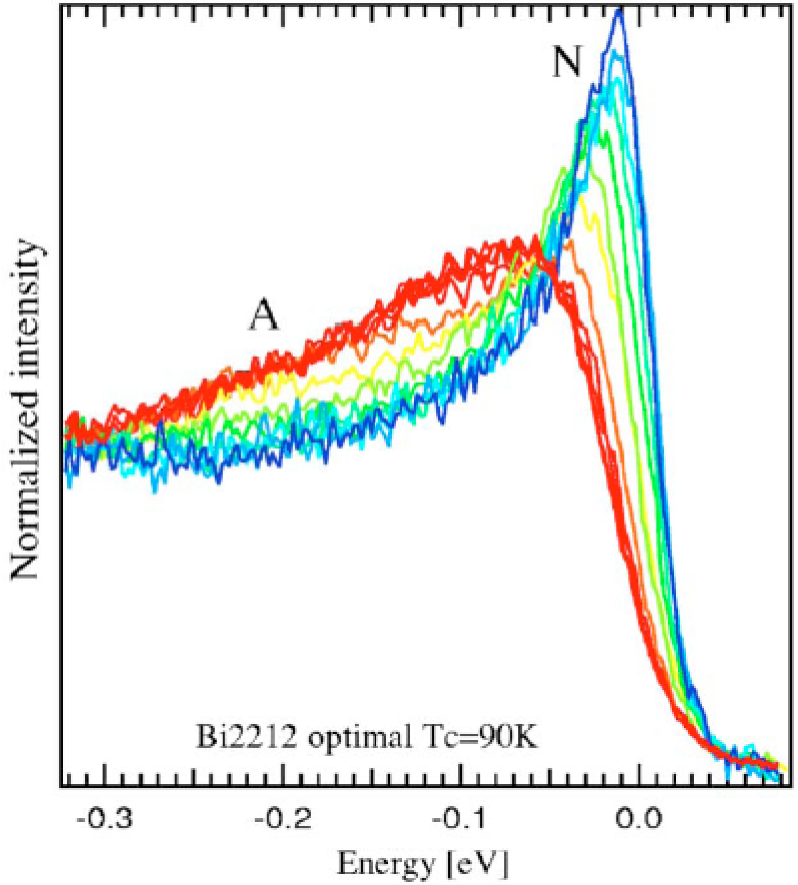


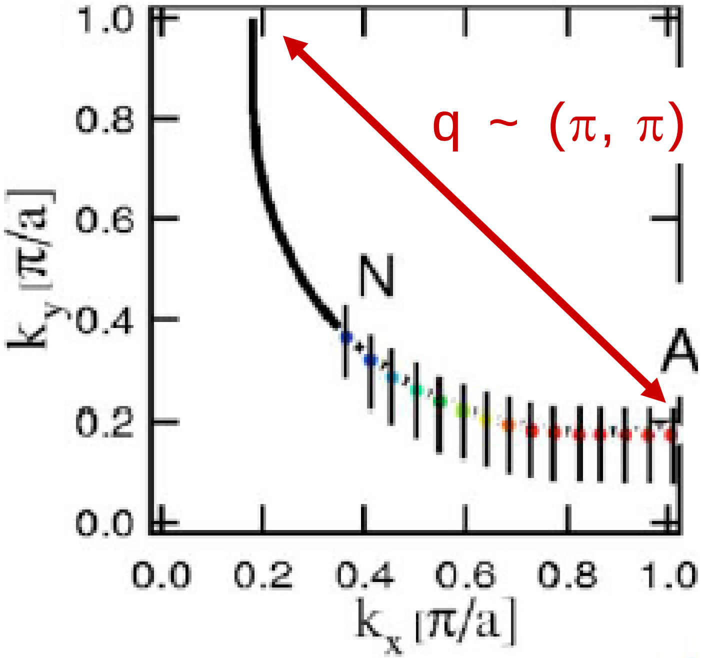


- **two-dimensional electronic structure**
- **single band, no orbital degeneracy**

Charge excitations in high-T_c superconductors

ARPES spectra





segments with broad spectra
connected by wave vector q ~ (π, π)
→ **interaction with spin excitations ?**

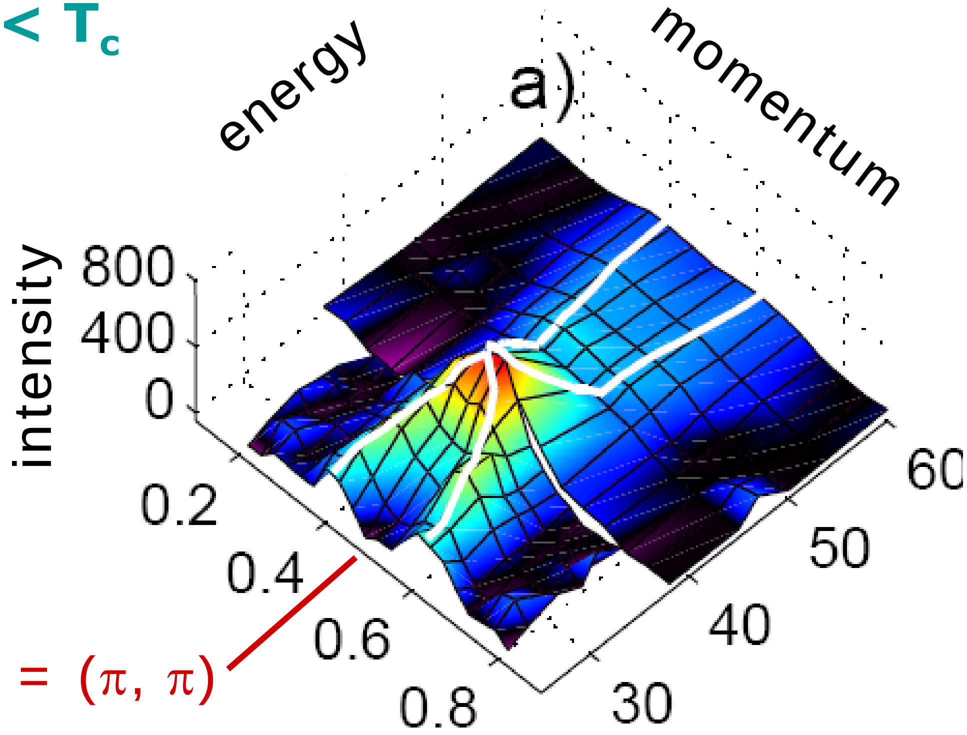
Fermi-liquid quasiparticles only in some segments of momentum space
→ **Fermi-liquid theory insufficient**

Kaminski et al., PRB 2005

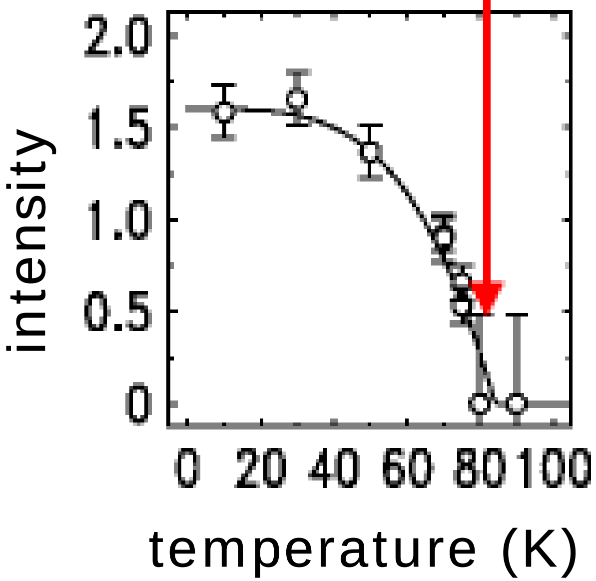
Spin excitations in high-T_c superconductors

$YBa_2Cu_3O_{6+x}$

$T < T_c$



$q = (\pi, \pi)$



T_c=93K

sharp magnetic excitations in superconducting state

unusual “hour glass” dispersion

strongly coupled

to superconducting electrons

short-range magnetic order, spin-fluctuation driven Cooper pairing

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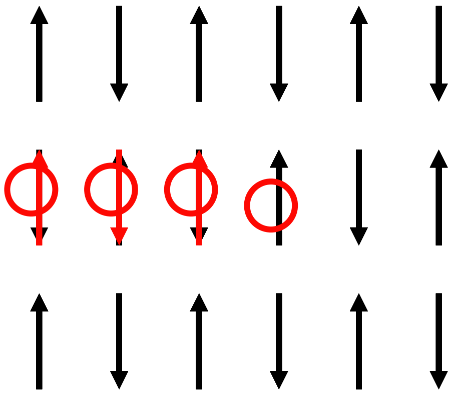
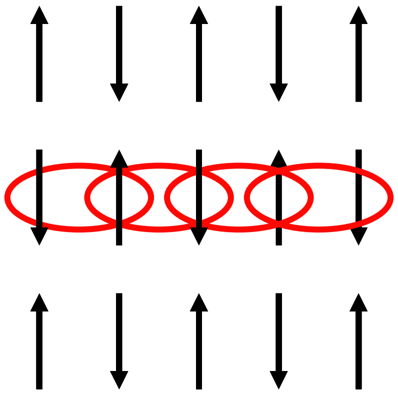
Magnetically driven Cooper pairing

assumption: short-range antiferromagnetic order



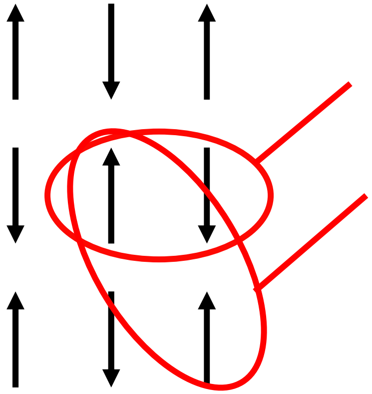


single electron

generates string of broken bonds

S=0 Cooper pair

does not disrupt magnetic order

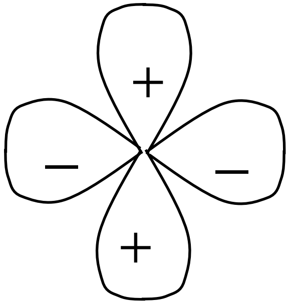


nearest neighbors favorable for Cooper pair formation

next-nearest-neighbors unfavorable

d-wave symmetry of pair wave function

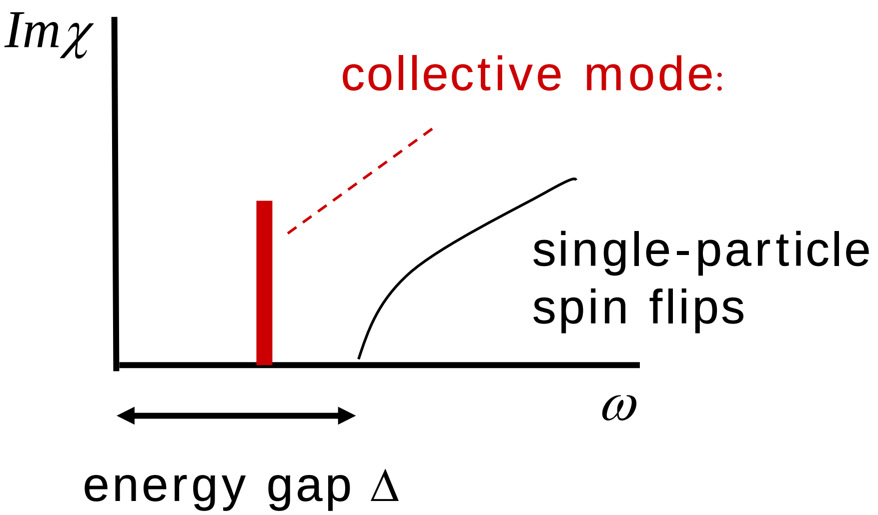
optimal binding energy for Cooper pair



Microscopic model: spin excitons

simplest formalism: Stoner model

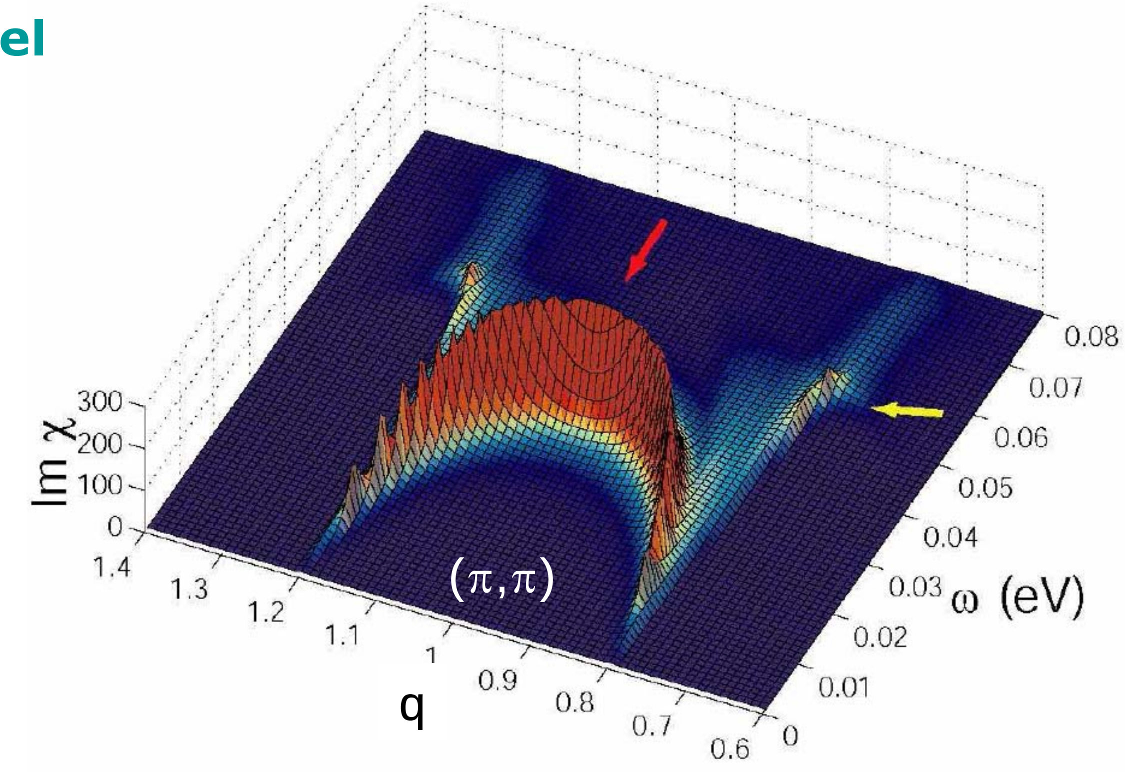
$$\chi(\mathrm{q},\omega)=\frac{\chi_0(\mathrm{q},\omega)}{1-\mathrm{J(q)}\ \chi_0(\mathrm{q},\omega)}$$



collective mode:

single-particle spin flips

energy gap Δ

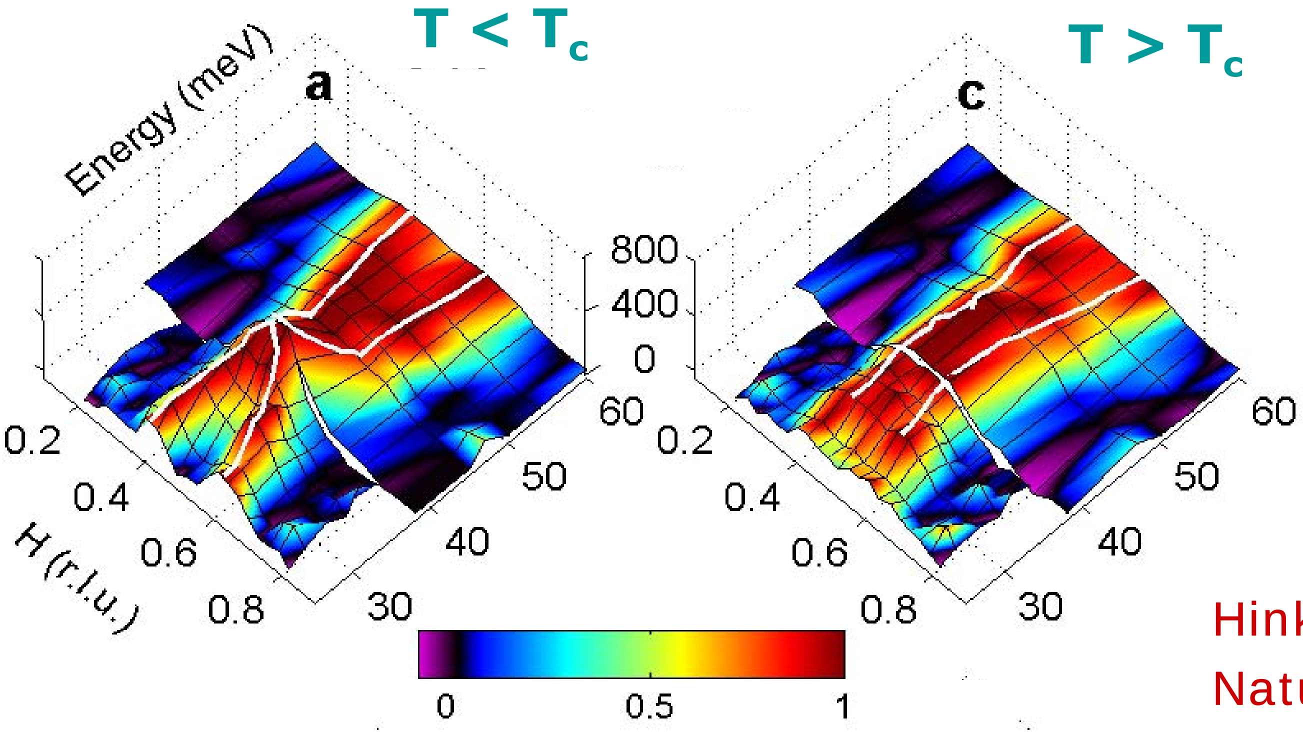


Eremin et al., PRL 2005

explains “hour glass” dispersion

as consequence of d-wave anisotropy of energy gap

Current frontier: “strange metal” state above T_c



Hinkov et al.,
Nature Phys. 2007

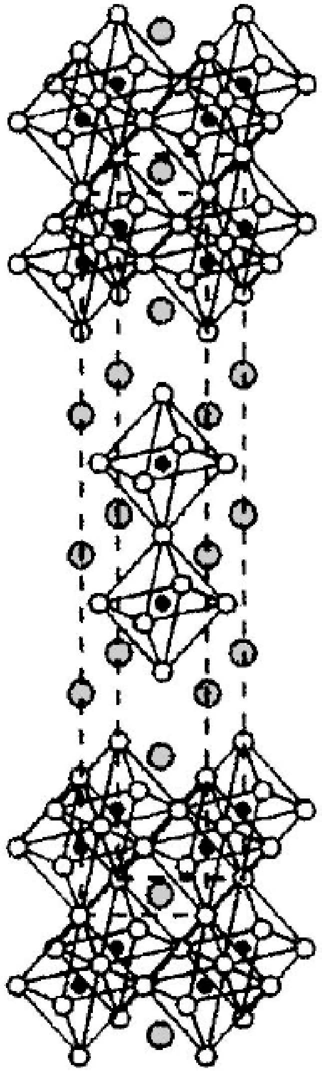
“hour glass” dispersion replaced by “vertical” dispersion

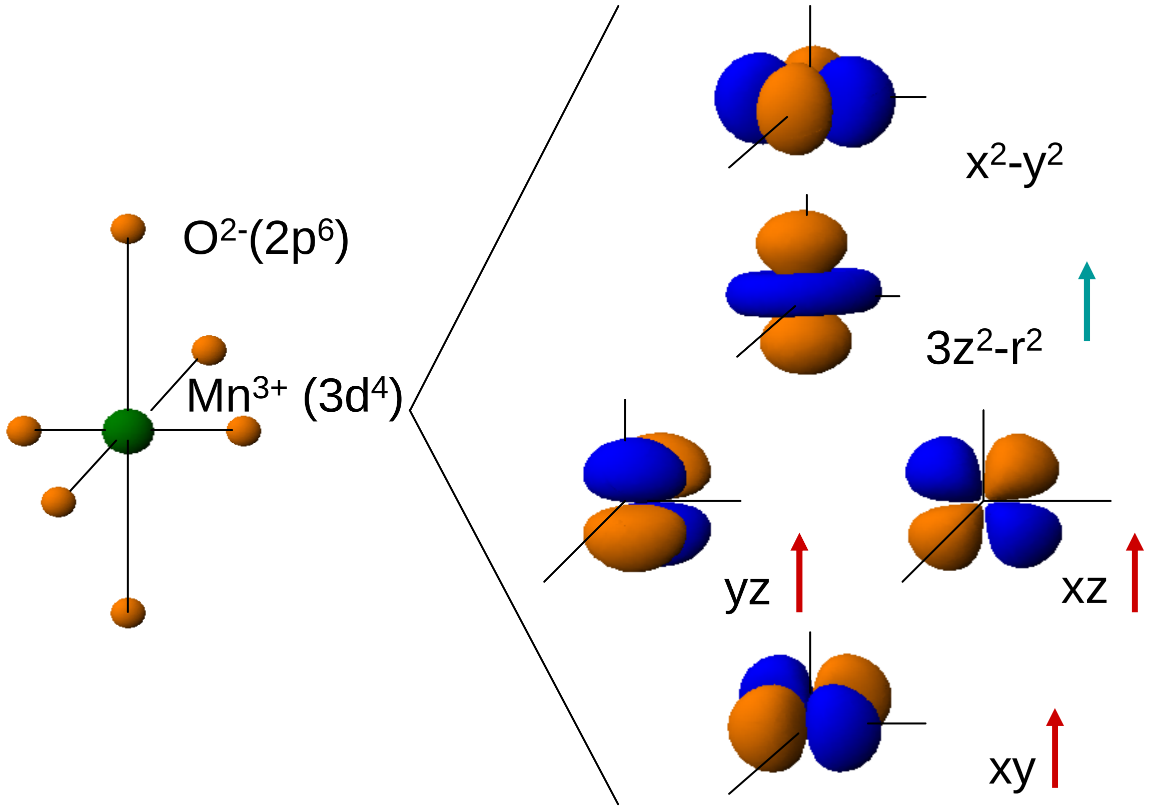
not explained by any microscopic model

→ **Hinkov talk**

Metallic manganates

$La_{2-2x}Sr_{1+2x}Mn_2O_7$





↑ conduction electron

↑ localized “core spin”

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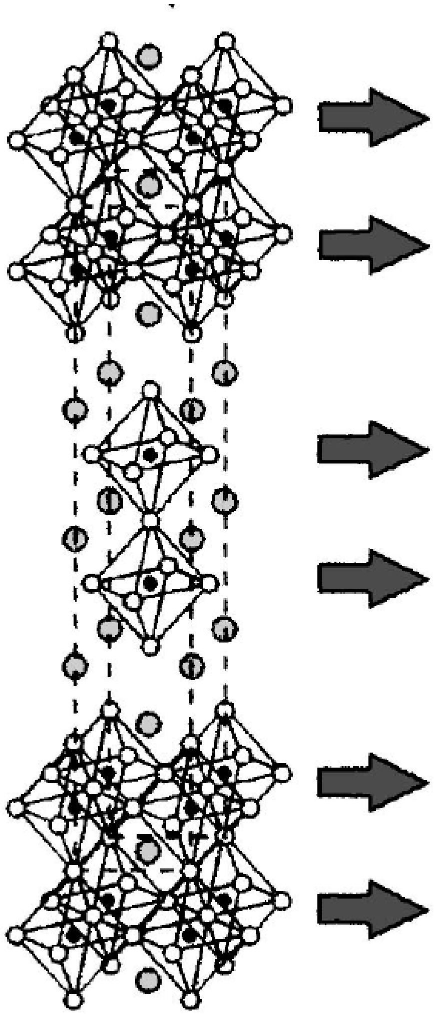
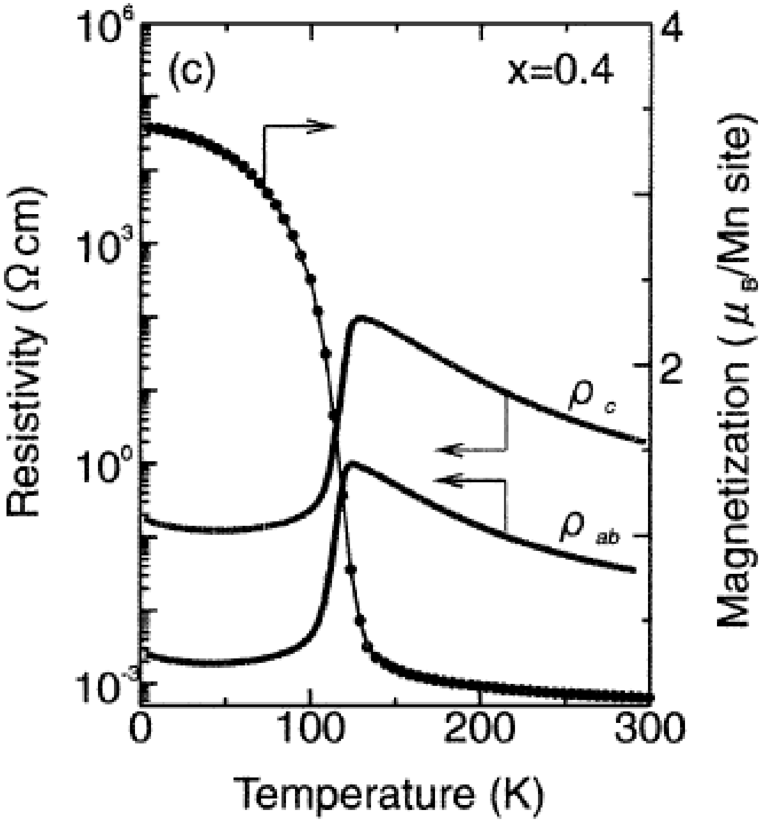
Metallic manganates

$La_{1.2}Sr_{1.8}Mn_2O_7$



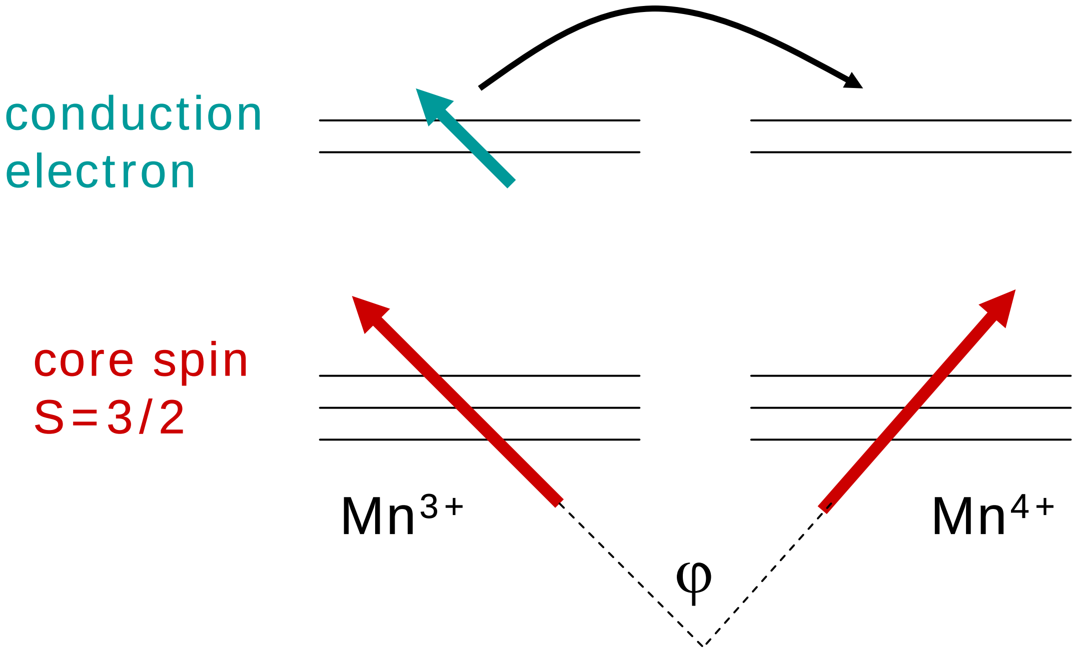


Tokura et al.
Ann Rev. Mat. Sci.
2000

ferromagnetic transition at T_c ~ 130K
resistivity decreases below T_c

Double exchange interaction

effective hopping amplitude $t_{eff} \sim \cos \varphi/2$

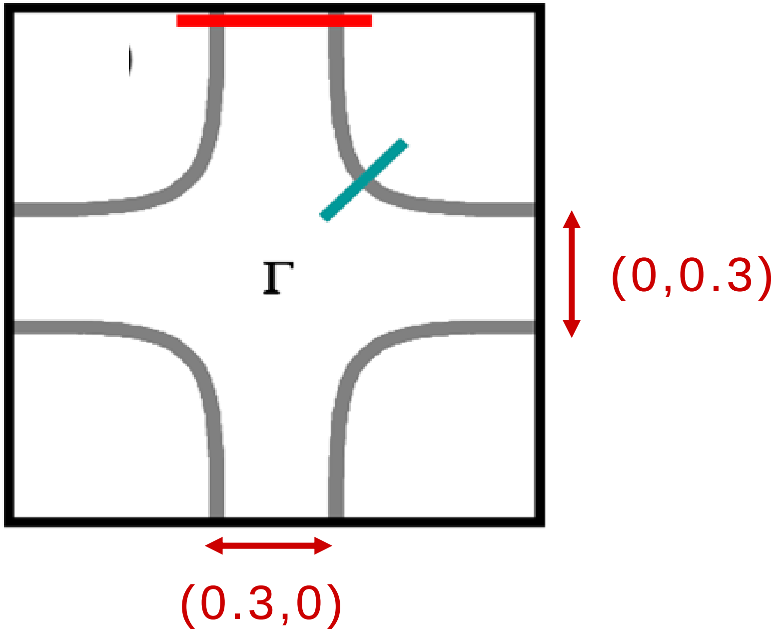


kinetic energy of conduction electrons minimized for parallel core spins

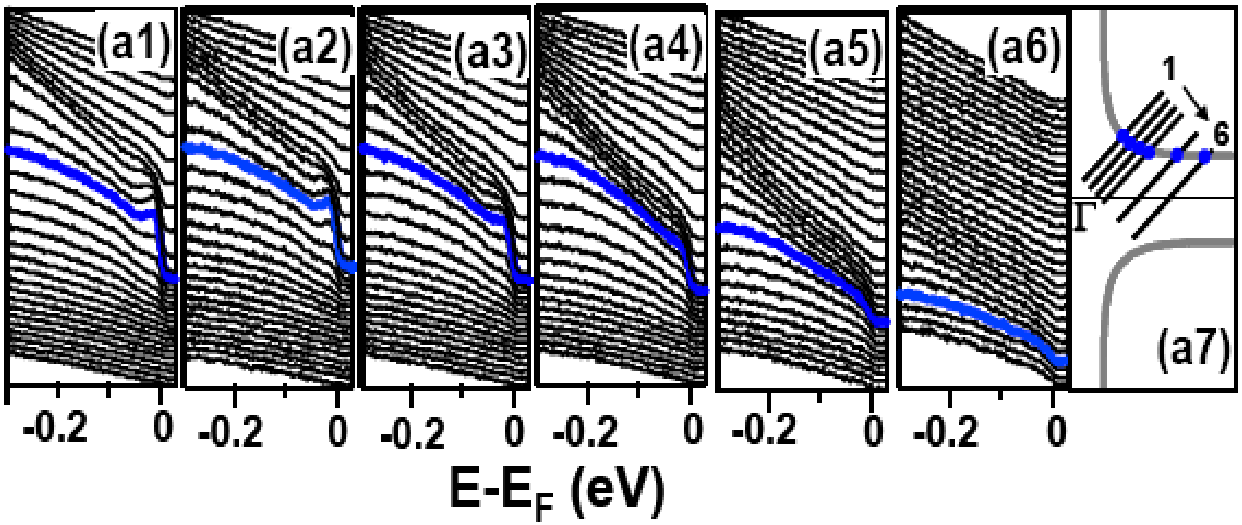
→ drives ferromagnetic transition

Metallic manganates

$La_{1.2}Sr_{1.8}Mn_2O_7$
Fermi surface



ARPES spectra for $T < T_c$



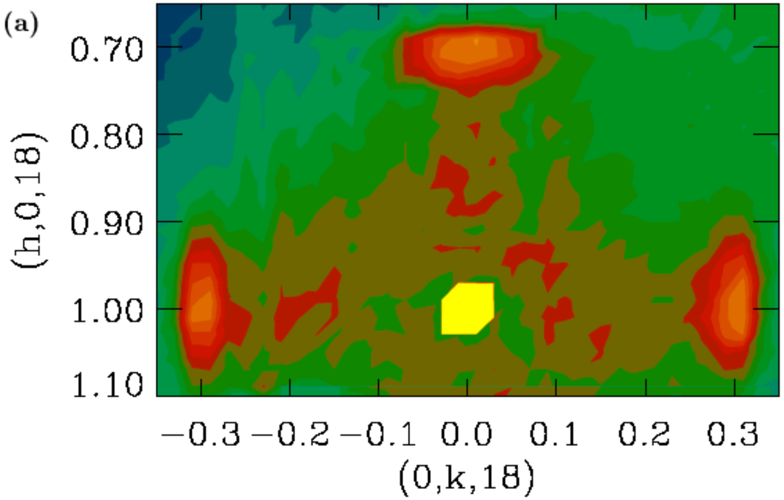
Mannella et al., Nature 2006

quasiparticle peak **only along diagonal directions**

no quasiparticles for Fermi surface segments connected by (0.3,0) and (0,0.3)

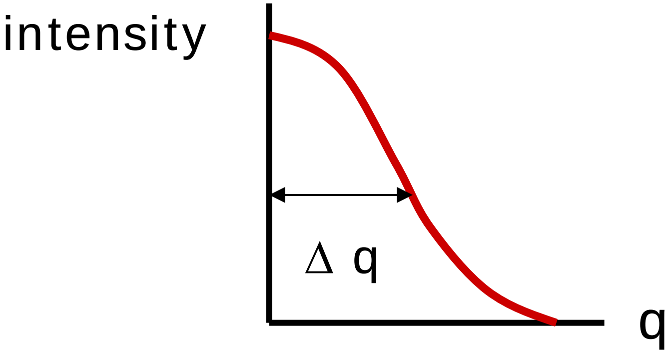
Metallic manganates

x-ray, elastic nuclear neutron scattering



broad features from lattice distortions with in-plane wave vectors $(q_x, q_y) \sim (0.3, 0)$ and $(0, 0.3)$

Vasiliu-Doloc et al., PRL 2000



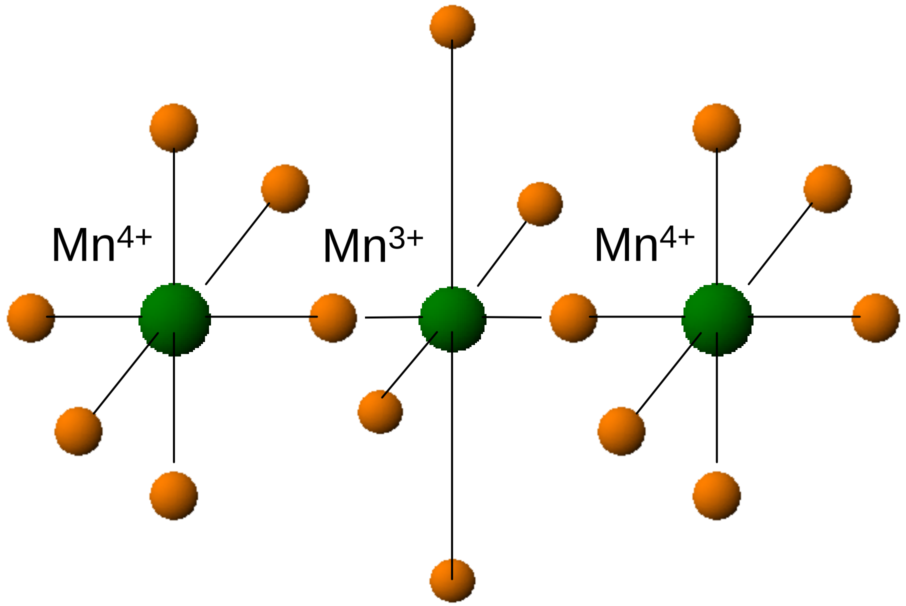
$\Delta q \sim 1/\xi$

ξ = correlation length in real space

short-range lattice distortions

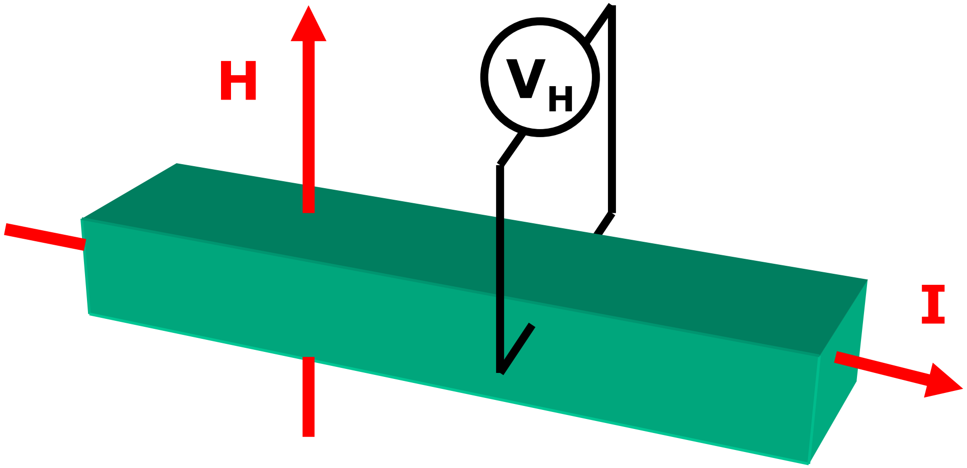
Metallic manganates

possible origin of large scattering: orbital/lattice polarons

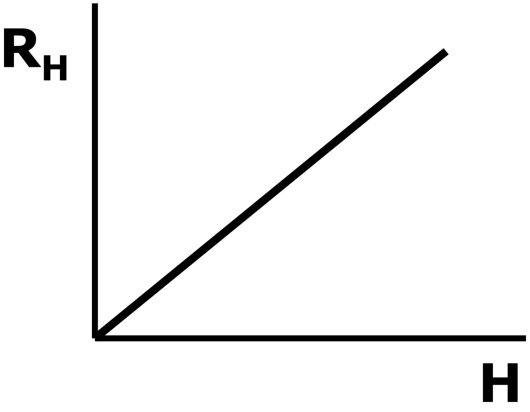


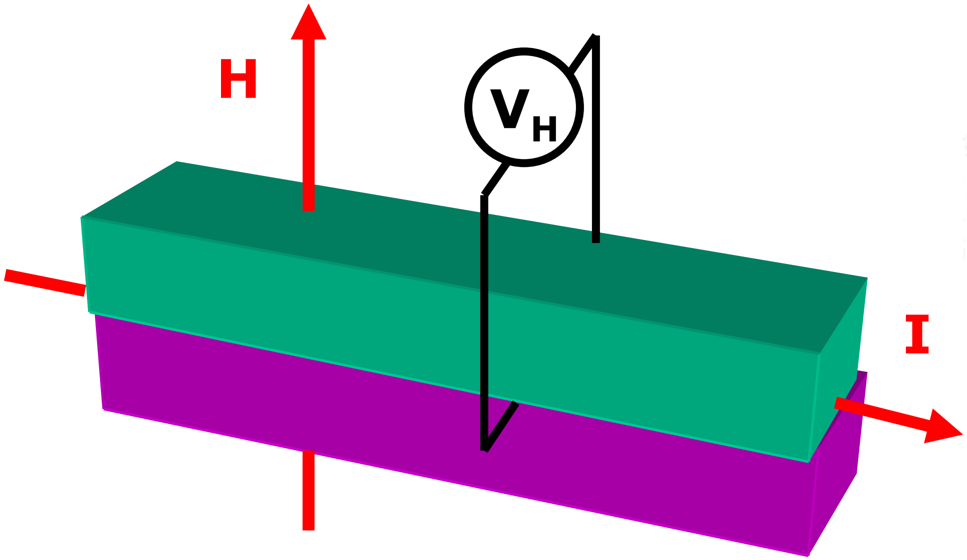
local lattice distortion around moving electron

New physics at interfaces

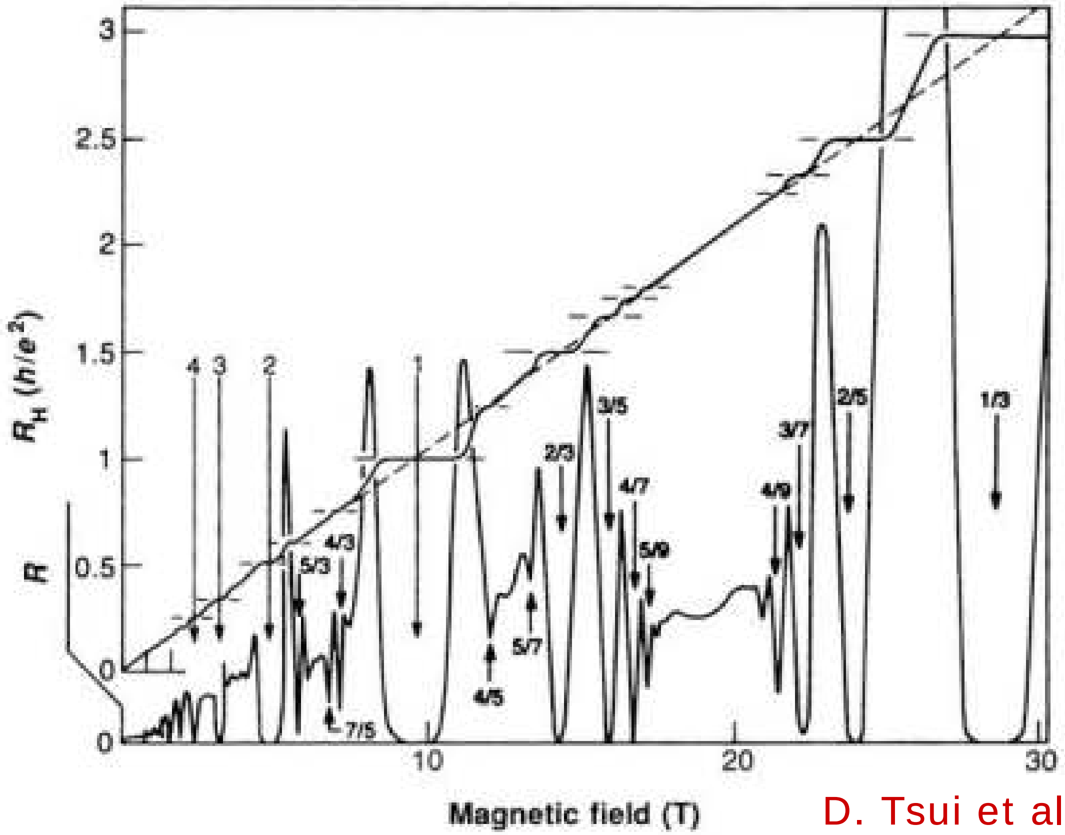


doped semiconductor



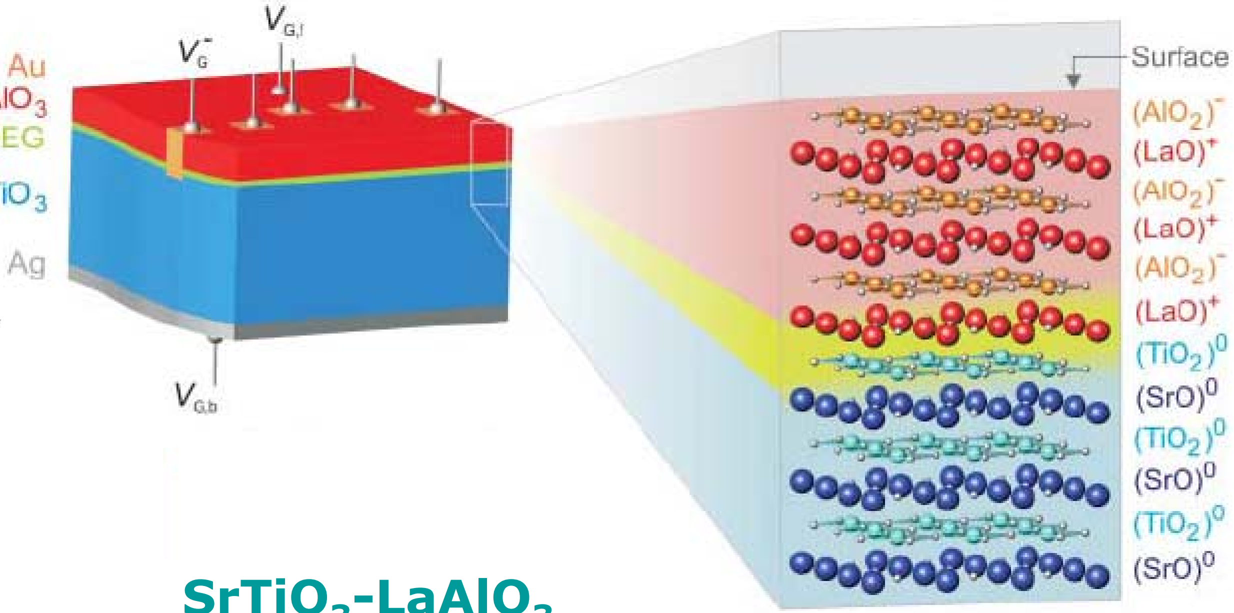


semiconductor heterostructure



D. Tsui et al.

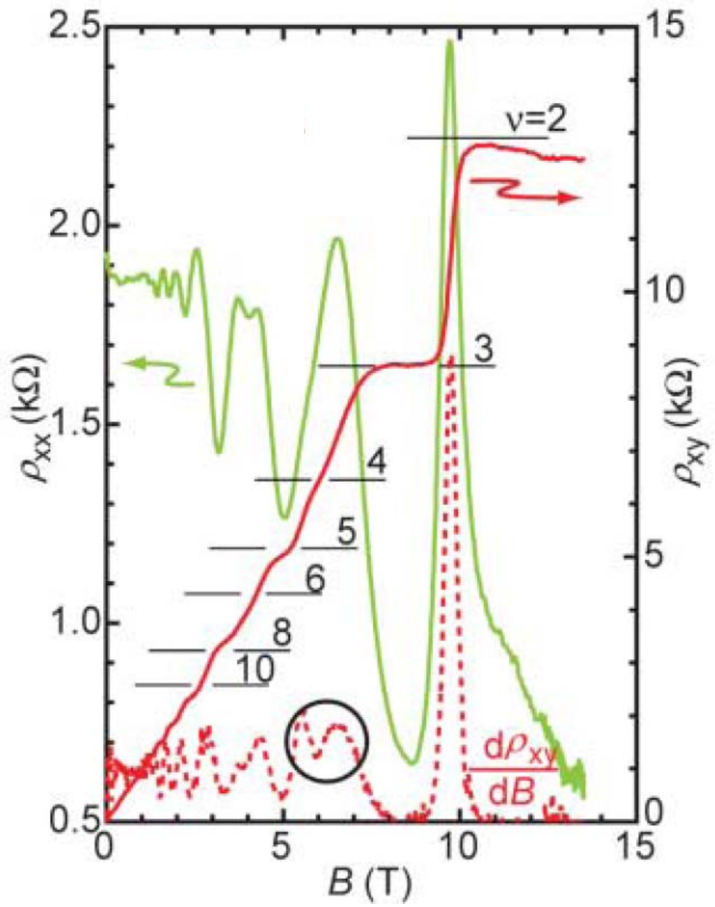
Oxide heterostructures



$SrTiO_3$-$LaAlO_3$

field effect transistor

Thiel et al., Science 2006



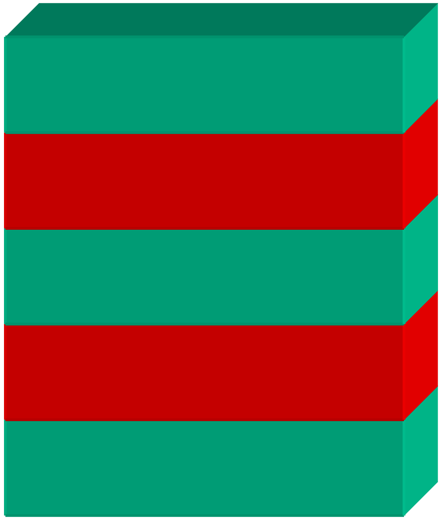
ZnO-$Mg_{1-x}Zn_xO$

quantum Hall effect

Tsukazaki et al., Science 2007

YBCO-LCMO superlattices

ferromagnetic and superconducting oxides

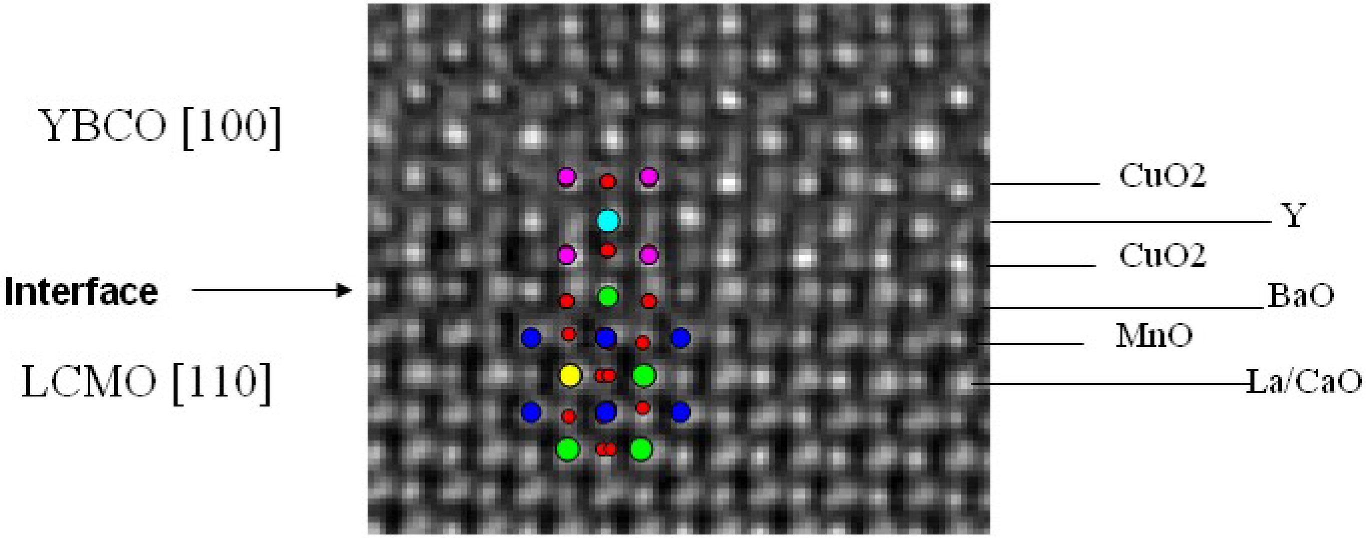


$YBa_2Cu_3O_7$ (YBCO): high-T_c superconducor

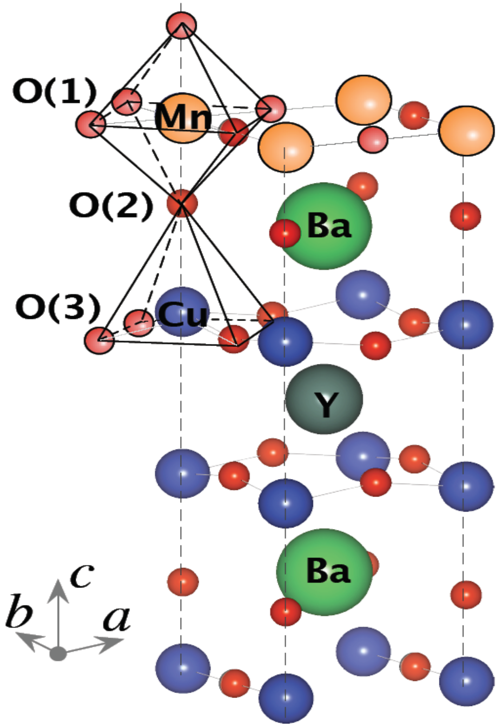
$La_{0.7}Ca_{0.3}MnO_3$ (LCMO): metallic ferromagnet

antagonistic order parameters at interface

YBCO-LCMO superlattices



U. Kaiser et al.

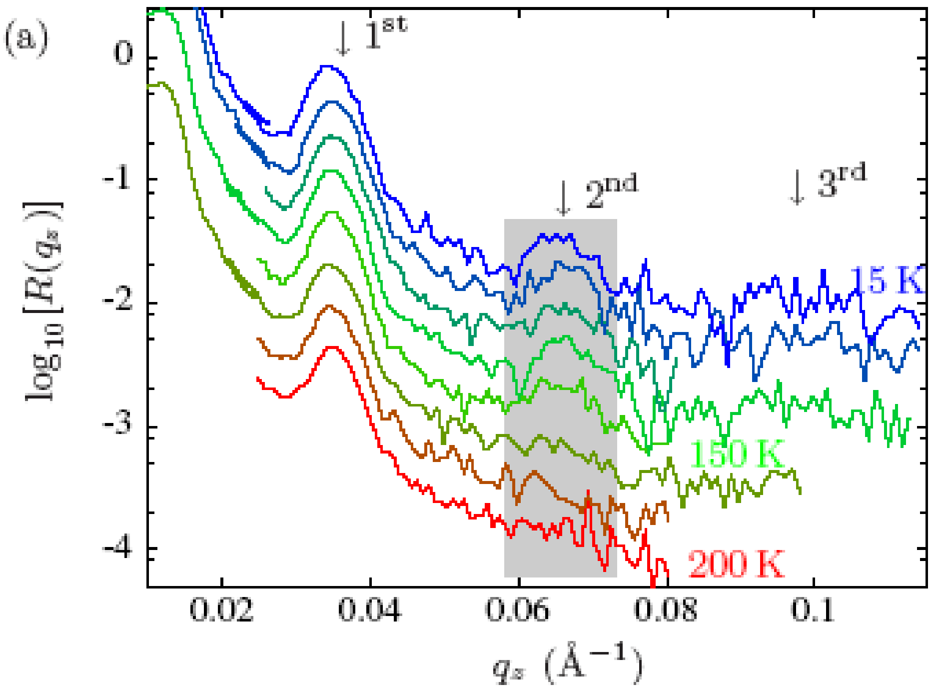


- different magnetic environment
- different valence state
- different crystal field
- different covalent bonding

YBCO-LCMO superlattices

neutron reflectivity

→ Bragg reflections due to structural and magnetic periodicity

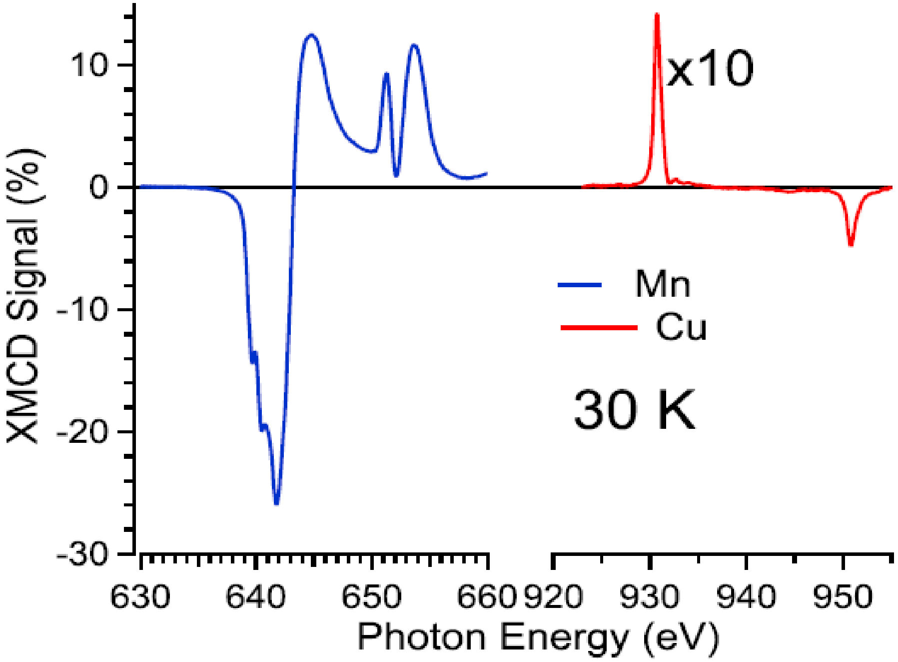


Stahn et al., PRB 2005

magnetic circular dichroism

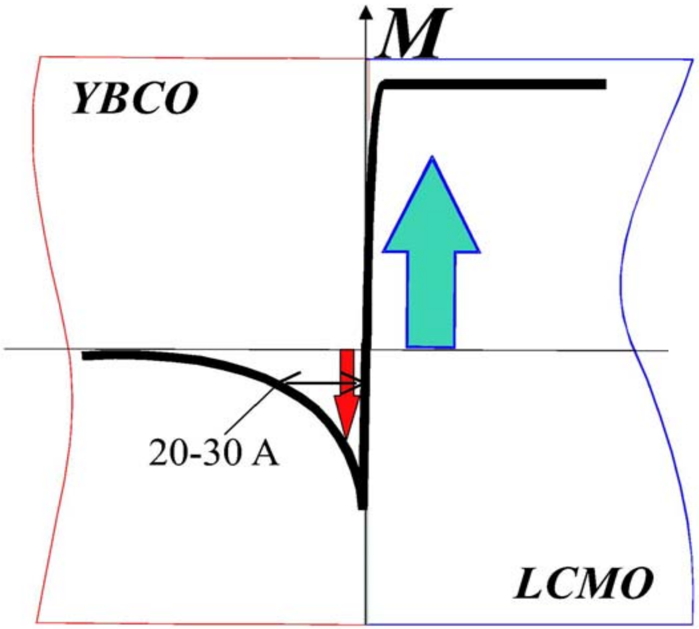
at L- absorption edges

→ element-specific magnetization



- ferromagnetic polarization of Cu in YBCO superconductor
- direction antiparallel to Mn

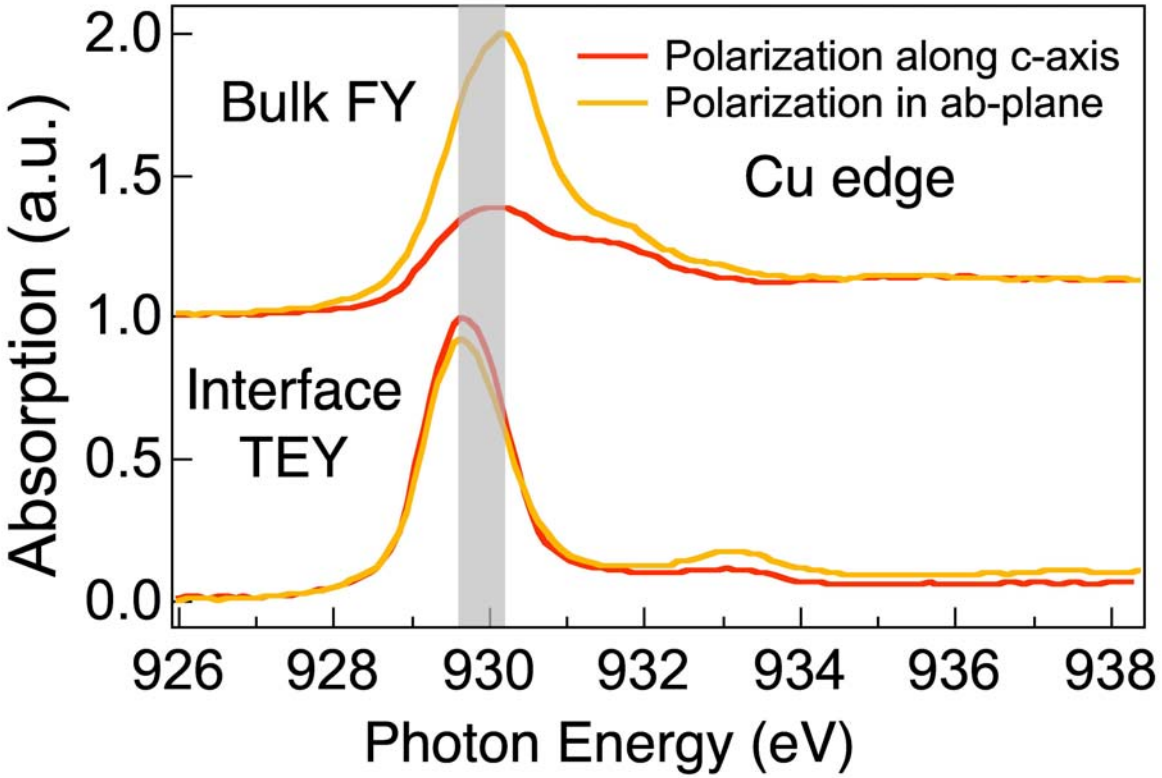
Magnetic reconstruction at interface



Chakhalian et al.,
Nature Phys. 2006

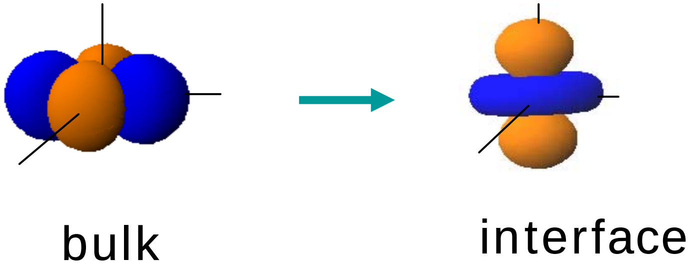
magnetization profile

Orbital reconstruction at interface



Chakhalian et al.
Science 2007

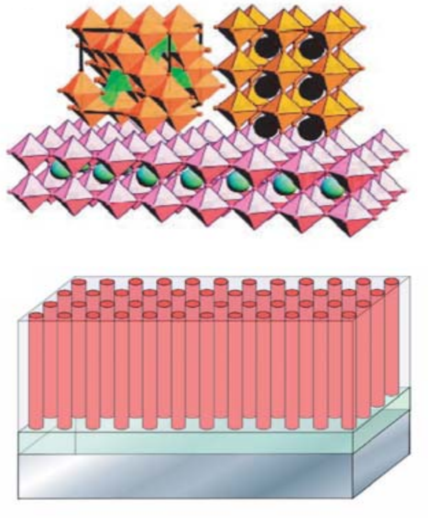
valence electron orbital



completely different transport & magnetic properties at interface

Oxide heterostructure research program

- understand and manipulate orbital and spin polarization at interfaces
- create dense correlated-electron systems with **controlled** interactions
- new quantum phases? ↔ FQHE in semiconductors
- lateral (nano)-structuring



$CoFe_2O_4$ nanopillars in $BaTiO_3$ matrix
Zheng et al., Science 2004