Superconductivity and Magnetism in Ruthenates

Nano'05

M. Sigrist, ETH Zurich

Outline:

1. Spin-triplet superconductivity in Sr_2RuO_4

   special topics: inhomogeneous 3-Kelvin phase

2. Metamagnetism in Sr_3Ru_2O7

   special topics: Condon domain formation

Theory:

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M.E. Zhitomirsky
C. Honerkamp
H. Monien
A. Furusaki
B. Binz
K. Wakabayashi

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J. Goryo
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B. Braun
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T. Morinari
M. Takigawa
K. Machida
T. Nomura
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Experiment:

Y. Maeno
A. Mackenzie
G. Luke
T. Uemura
Y. Liu
A.C. Mota
J. Kirtley

X. Mao
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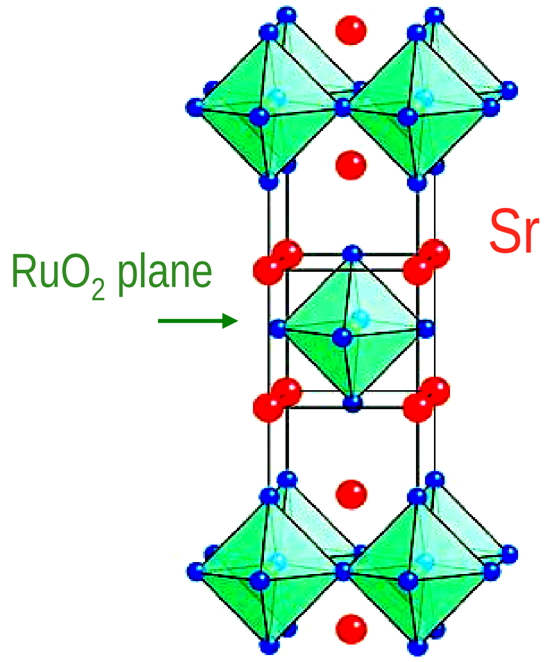
K. Ishida
C. Bergemann
M. Braden
E. Dumont
M. Tanatar

S. Nakatsuji
S. NishiZaki
S. Ikeda
M. Wada
S. Deguchi
E. Forgan
Y. Matsuda

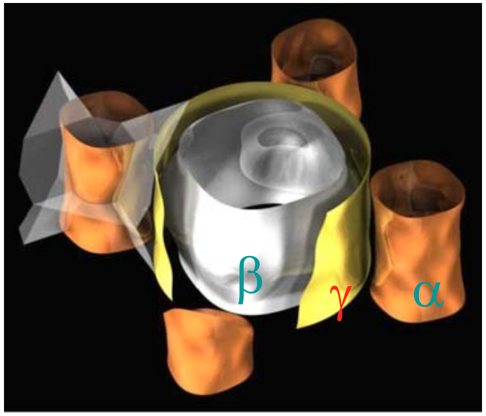
Sr_2RuO_4 - strongly correlated 2D Fermi liquid

Crystal structure: layered perovskite
analog High-T_c cuprates



Quasi-two-dimensional Fermi liquid

3 "cylindrical" bands 3d-t_{2g} - orbitals of Ru



de Haas - van Alphen

Bergemann,

Mackenzie et al.

Correlation effects

mass enhancement $m^*/m_0 \approx 4$

susceptibility enhancement $\chi^*/\chi_0 \approx 5-8$

Superconductivity: T_c = 1.5 K

Maeno, Bednorz et al, (1994)

Analogy to ^{3}He ⇒ p-wave spin-triplet pairing

^{3}He - strongly correlated Fermi liquid

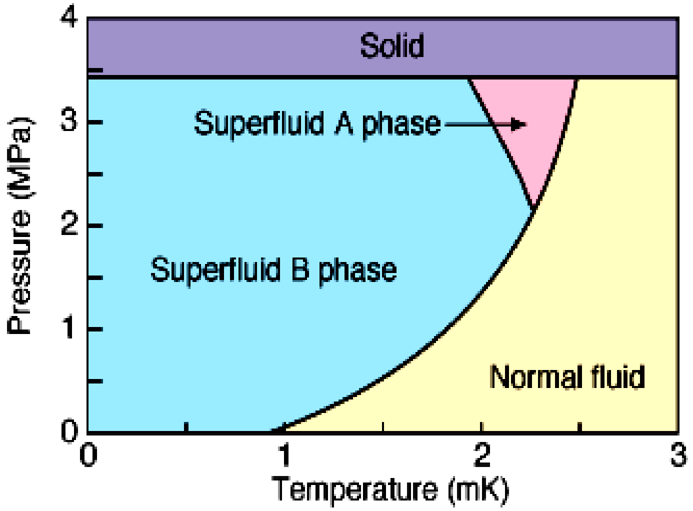
effective mass: $m^*/m \approx 4$

spin susceptibility: $\chi^*/\chi \approx 9$

$\Big\}$ ⟺ strong correlation effects

Superfluidity:

Lee, Osheroff & Richardson (1971)



Cooper pairing:

odd parity spin triplet

$\ell = 1 \qquad S = 1$

p-wave

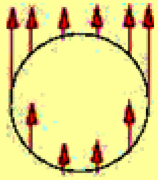
Pair wavefunction

$$F_{ss'}(\vec{k}) = \langle c_{-\vec{k}s} c_{\vec{k}s'} \rangle = \begin{pmatrix} F_{\uparrow\uparrow}(\vec{k}) & F_{\uparrow\downarrow}(\vec{k}) \\ F_{\downarrow\uparrow}(\vec{k}) & F_{\downarrow\downarrow}(\vec{k}) \end{pmatrix}$$

$$= \begin{pmatrix} -d_x(\vec{k}) + i d_y(\vec{k}) & d_z(\vec{k}) \\ d_z(\vec{k}) & d_x(\vec{k}) + i d_y(\vec{k}) \end{pmatrix}$$

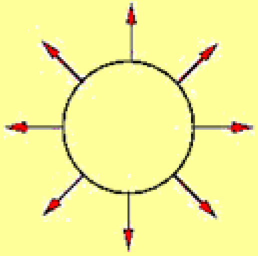
A-phase

$$\vec{d}(\vec{k}) = \hat{z}(k_x \pm i k_y)$$



B-phase

$$\vec{d}(\vec{k}) = \hat{x}k_x + \hat{y}k_y + \hat{z}k_z$$



Superconducting phase

Fundamental p-wave pairing states:

Tetragonal crystal symmetry D_{4h}

Spin-orbit coupling

Γ	$\vec{d}$	
A_{1u}	$\vec{d} = \hat{x}k_x + \hat{y}k_y$	B-phase
A_{2u}	$\vec{d} = \hat{x}k_y - \hat{y}k_x$	
B_{1u}	$\vec{d} = \hat{x}k_x - \hat{y}k_y$	
B_{2u}	$\vec{d} = \hat{x}k_y + \hat{y}k_x$	
E_u	$\vec{d} = \hat{z}(k_x \pm ik_y)$	A-phase

Quasiparticle gap: nodeless

$$\Delta(\vec{k}) = |\vec{d}(\vec{k})| = |\vec{k}|$$

Experimental evidence:

sample purity essential
spin polarizable
intrinsic magnetism
flux line lattice
phase sensitive tests
....

$$\vec{d}(\vec{k}) = \underbrace{\hat{z}}_{\frac{1}{\sqrt{2}}\{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle\}} \quad \underbrace{(k_x \pm ik_y)}_{L_z = \pm 1}$$

degeneracy: 2
chirality: orbital moment

"Chiral p-wave state"

Phase sensitive tests

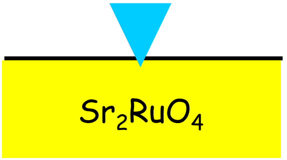
Quasiparticle tunneling:

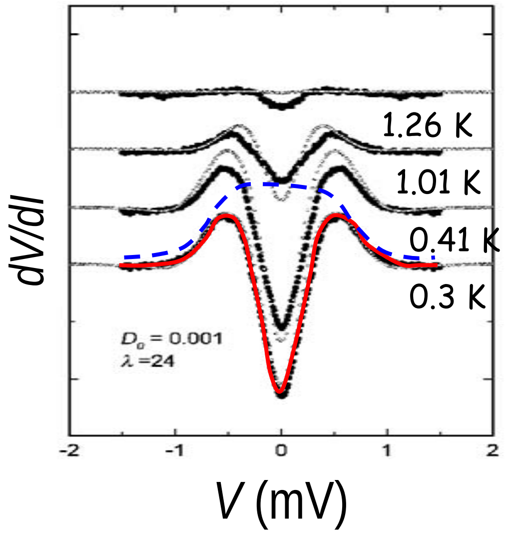
observation of surface boundstates

subgap features in I-V-characteristics

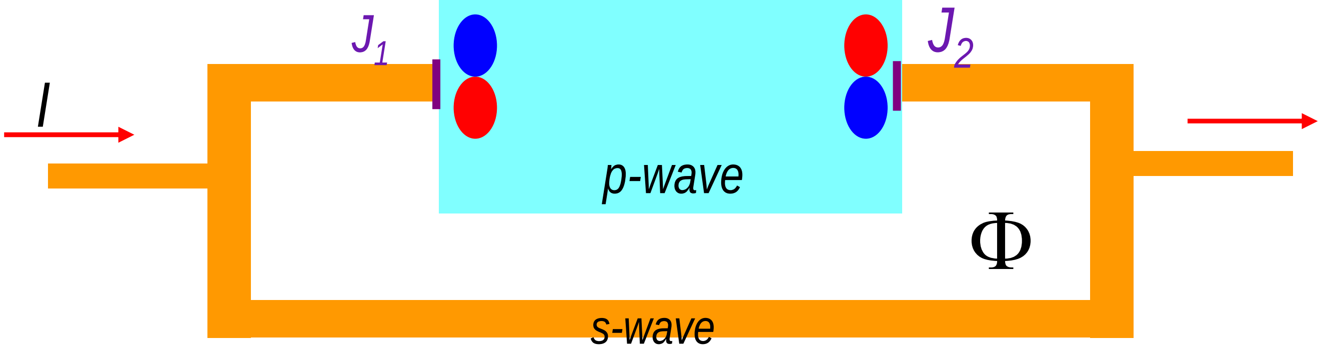
Point contact spectroscopy

Laube, Goll, von Lohneysen et al.





SQUID experiments:



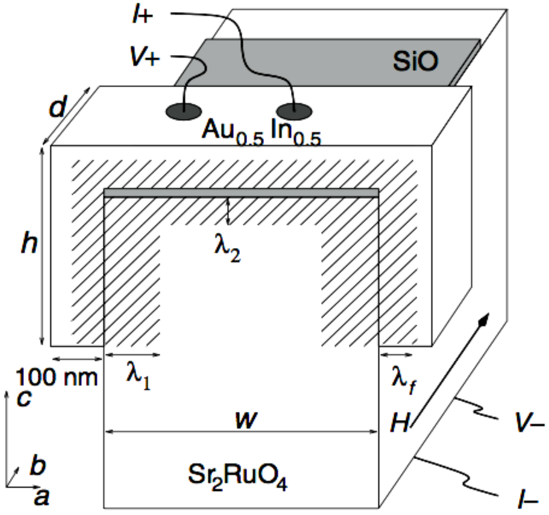
design following Geshkenbein, Larkin and Barone

Phase sensitive tests

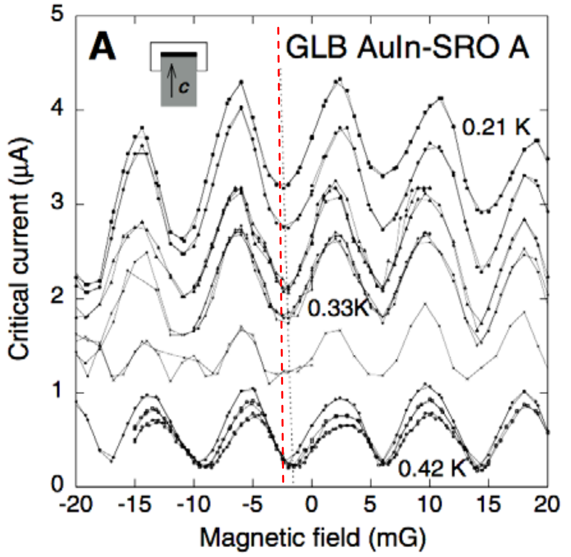
SQUID experiments:

Y. Liu et al., *Science 306 (2004)*

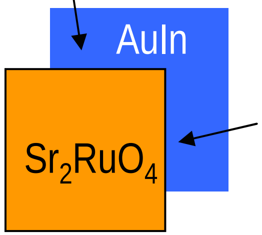
AuIn



bridge SQUID



corner SQUID



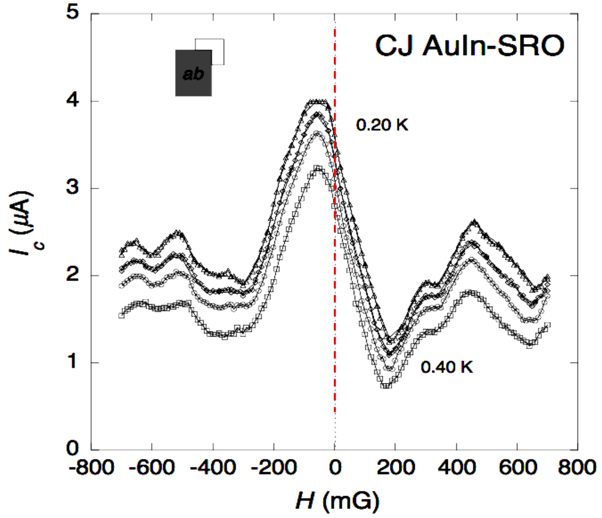
0-phase

AuIn

Sr_2RuO_4

$\pi/2$ *-phase*

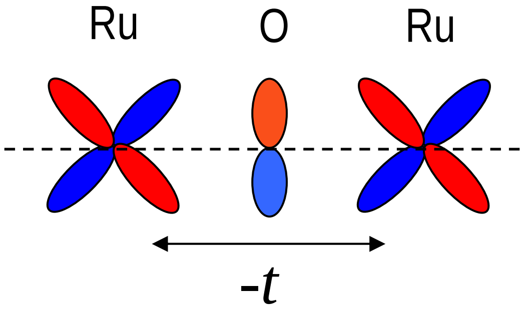
k_x+ik_y



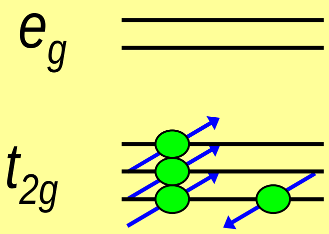
broken time reversal symmetry

Electronic structure of $4d$-t_{2g}-orbitals

π -hybridization Ru - O - Ru



Ru^{4+} 4d

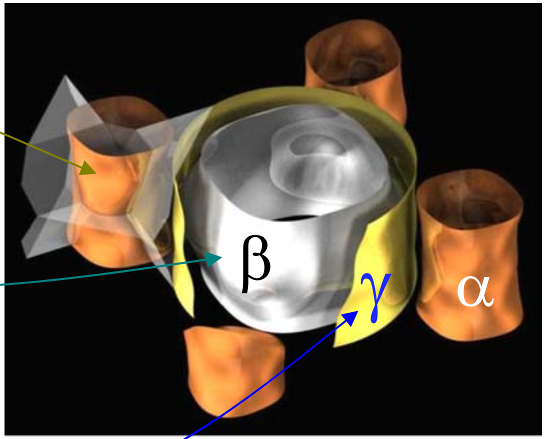


d_{yz} d_{zx} → α β

d_{xy} → γ

three bands crossing Fermi level

de Haas-van Alphen



Bergemann et al.

Degeneracy of p-wave state in 2D

analog to superfluid ^{3}He films

Γ	$\vec{d}$
A_{1u}	$\vec{d} = \hat{x}k_x + \hat{y}k_y$
A_{2u}	$\vec{d} = \hat{x}k_y - \hat{y}k_x$
B_{1u}	$\vec{d} = \hat{x}k_x - \hat{y}k_y$
B_{2u}	$\vec{d} = \hat{x}k_y + \hat{y}k_x$
E_u	$\vec{d} = \hat{z}(k_x \pm i k_y)$

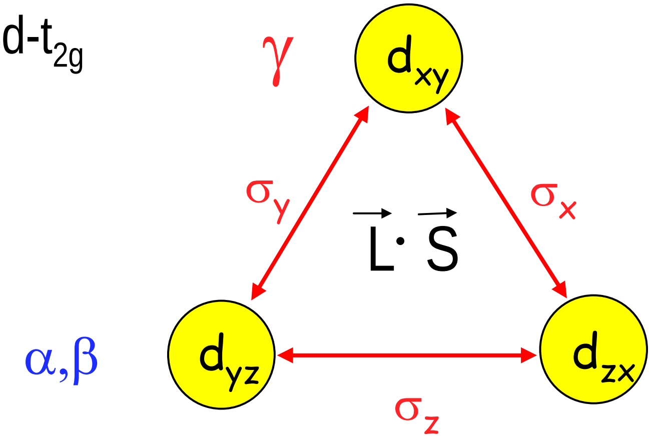
quasiparticle gap identical:

$$\left|\vec{d}\right| = \sqrt{k_x^2 + k_y^2}$$

weak-coupling
condensation energy
degenerate

lift of degeneracy by spin-orbit coupling

Ru-ion 4d-t_{2g}



$$H_{so} = i\alpha \sum_{\vec{k},s,s'} \sum_{l,m,n} \varepsilon_{lmn}\, \sigma^{l}_{ss'}\, c^{+}_{\vec{k}s,m} c_{\vec{k}s',n}$$

$\alpha \approx 10 - 20\%$ band width

Degeneracy of p-wave state in 2D

analog to superfluid ^{3}He films

Γ	$\vec{d}$
A_{1u}	$\vec{d} = \hat{x} k_x + \hat{y} k_y$
A_{2u}	$\vec{d} = \hat{x} k_y - \hat{y} k_x$
B_{1u}	$\vec{d} = \hat{x} k_x - \hat{y} k_y$
B_{2u}	$\vec{d} = \hat{x} k_y + \hat{y} k_x$
E_u	$\vec{d} = \hat{z}(k_x \pm i k_y)$

quasiparticle gap identical:

$$\left|\vec{d}\right| = \sqrt{k_x^2 + k_y^2}$$

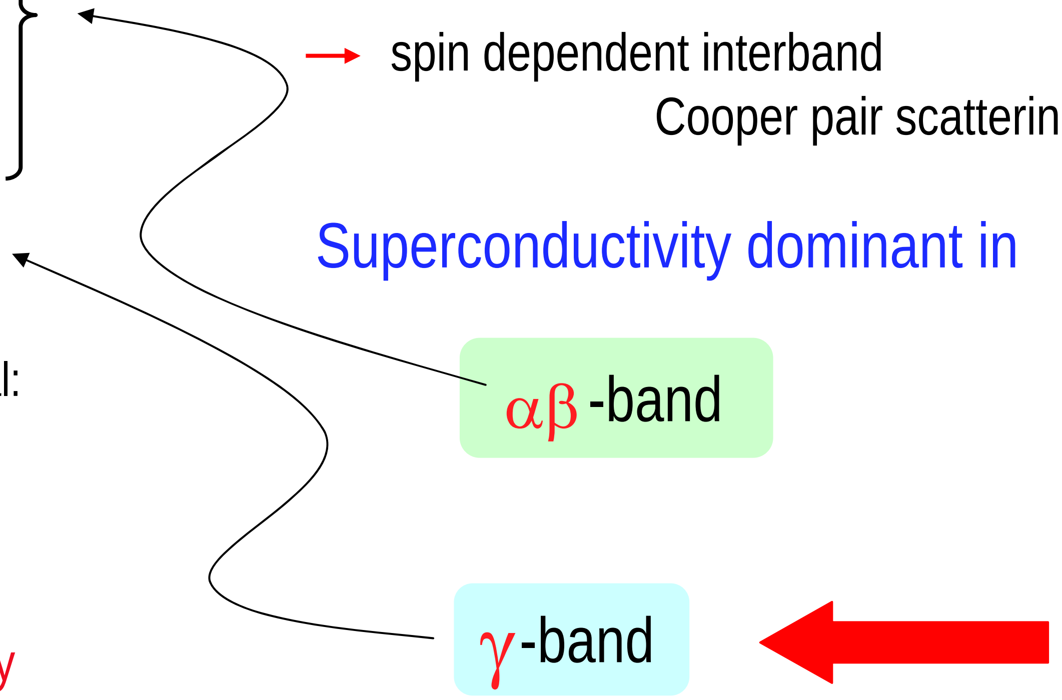
weak-coupling condensation energy degenerate

lift of degeneracy by spin-orbit coupling

Ng & MS, Yanase & Ogata, Eremin et al.

→ FM spin fluctuations inplane polarized

→ spin dependent interband Cooper pair scattering



Superconductivity dominant in

αβ-band

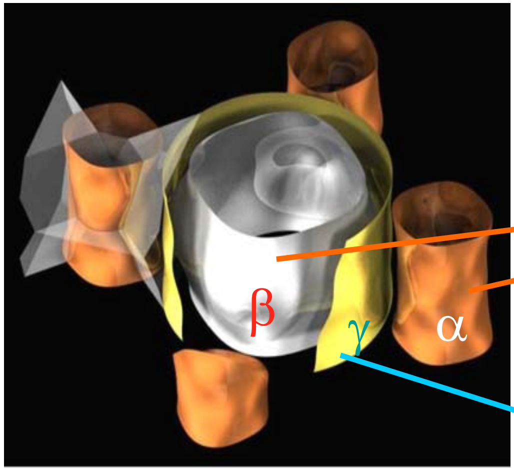
γ-band

Orbital dependent superconductivity

Spin fluctuation exchange involved in pairing mechanism?

NMR-analysis:

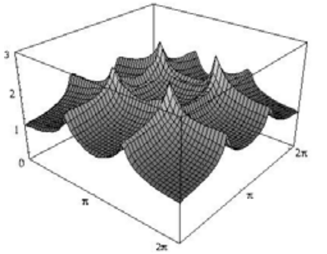
Imai et al.
Mukuda et al.



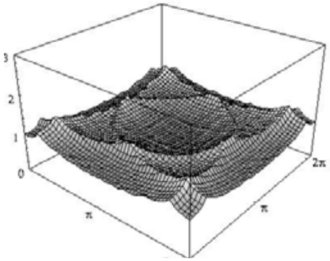
αβ–band:
AF fluctuations

γ–band:
FM fluctuations

static spin susceptibility



K.K. Ng
Mazin &
Singh



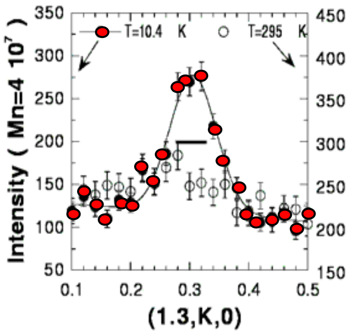
Spin triplet pairing

favored on
γ–band

suppressed on
αβ–bands

Neutron
scattering

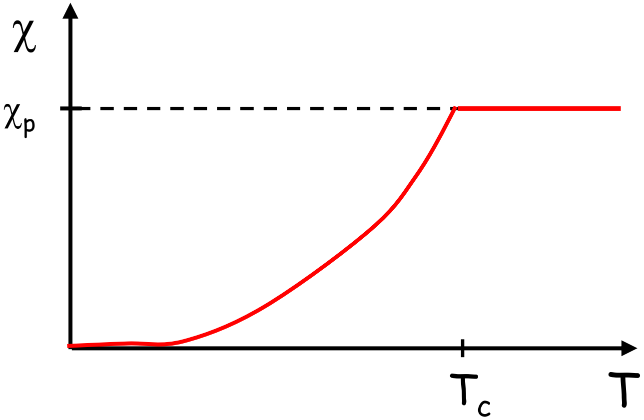
Sidis, Braden et al.



Spin anisotropy

- spin singlet pairing → Yosida behavior of spin susceptibility

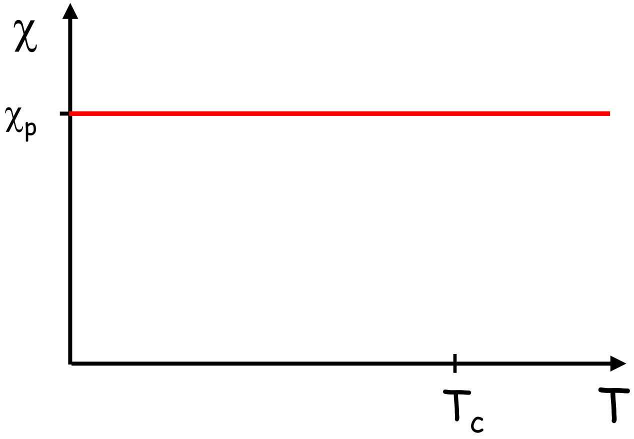
pair breaking
by spin polarization



- spin triplet pairing

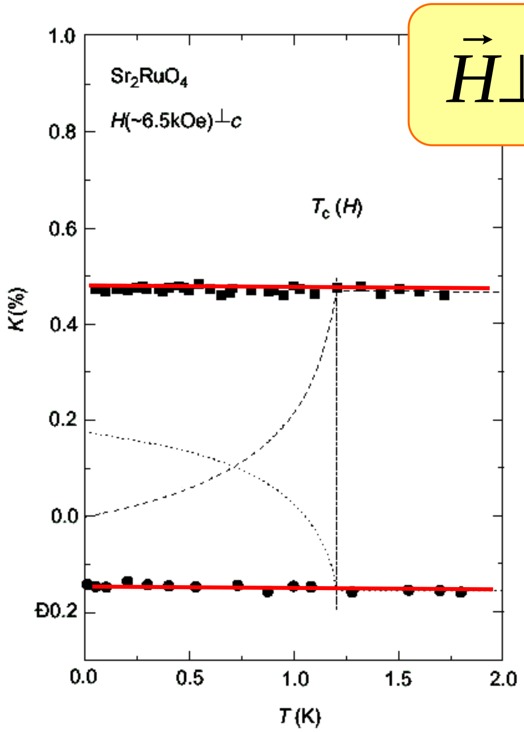
no pair breaking
for equal spin pairing

$\chi =$ const. for $\vec{d}(\vec{k}) \cdot \vec{H} = 0$



Spin anisotropy

^{17}O-Knight shift



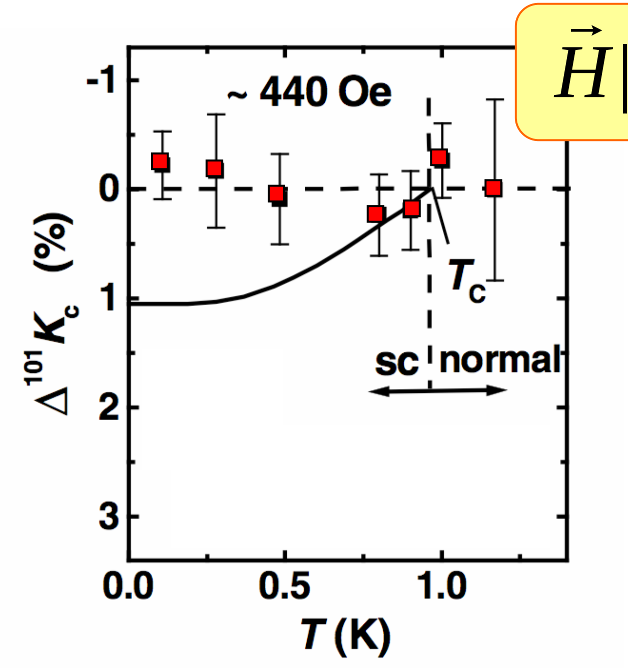
$$\vec{H} \perp c$$

Ishida et al, 1998

consistent with

$$\vec{d} = \hat{z}\left(k_x \pm i k_y\right)$$

^{101}Ru-Knight shift



$$\vec{H} \| c$$

Murakawa et al, 2004

rotation in field → $\vec{d} \cdot \vec{H} = 0$

degeneracy lift small
pinning of *d*-vector weak

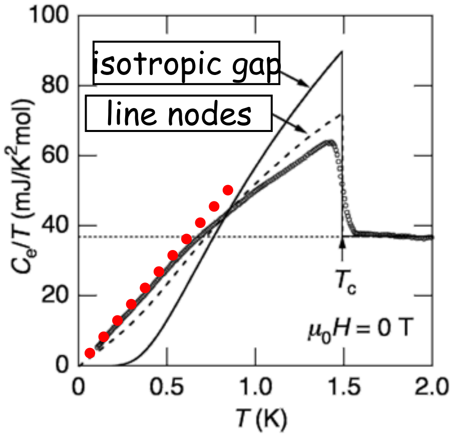
Gap structure and
Low-temperature thermodynamics

Gap structure and low-temperature thermodynamics

Observed "powerlaws"

specific heat

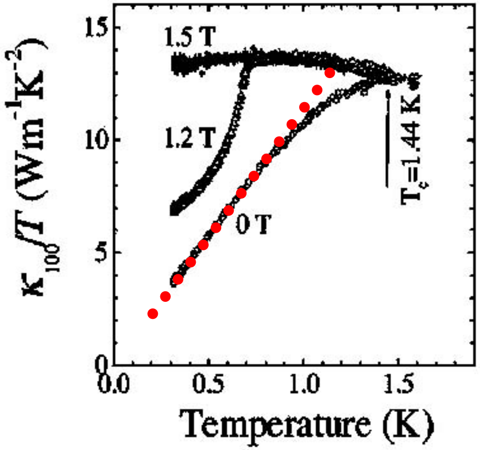
$$\frac{C}{T} \propto T$$



NishiZaki et al.

thermal conductance

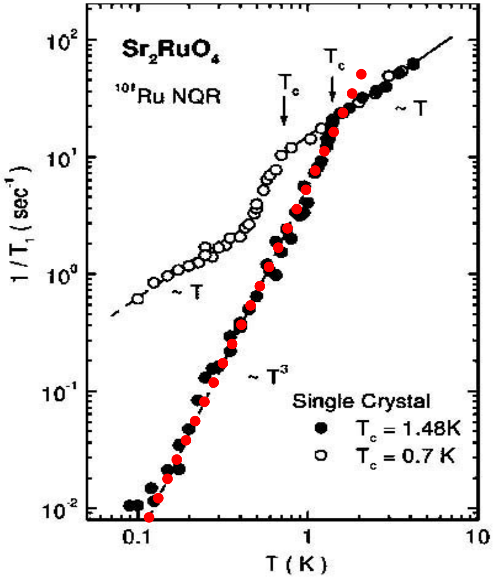
$$\frac{\kappa}{T} \propto T$$



Tanatar et al.

NMR

$$\frac{1}{T_1} \propto T^3$$

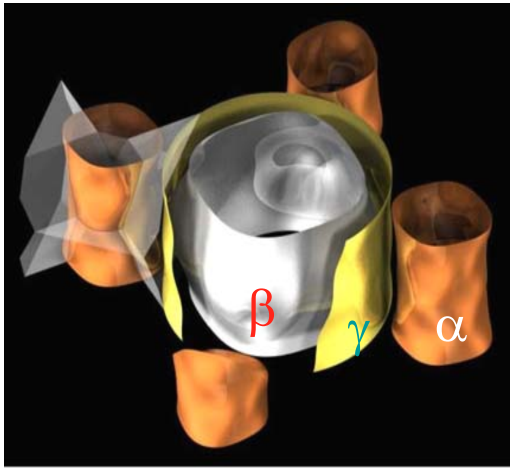


Ishida et al.

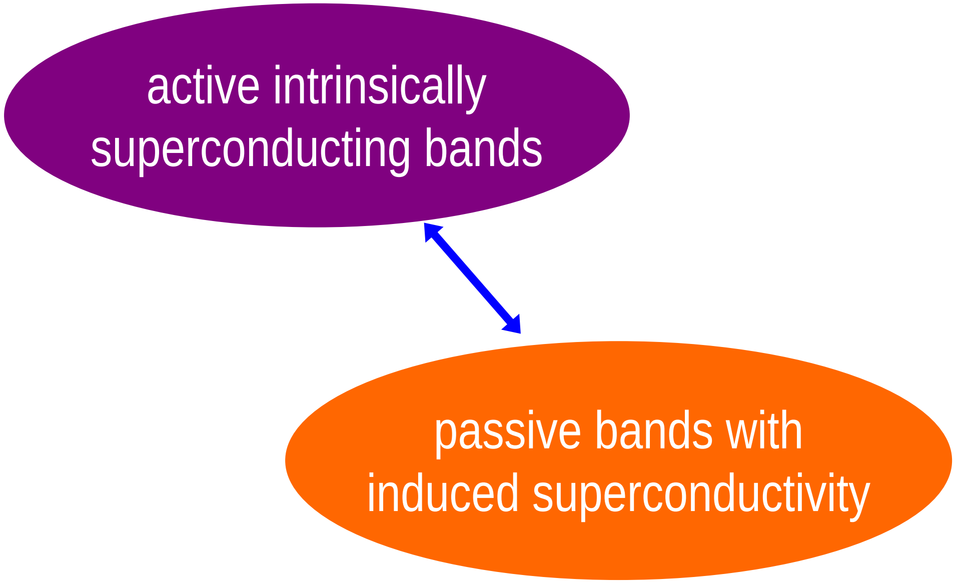
consistent with line nodes

Multiband effects

Three bands:



Multi-band superconductivity:



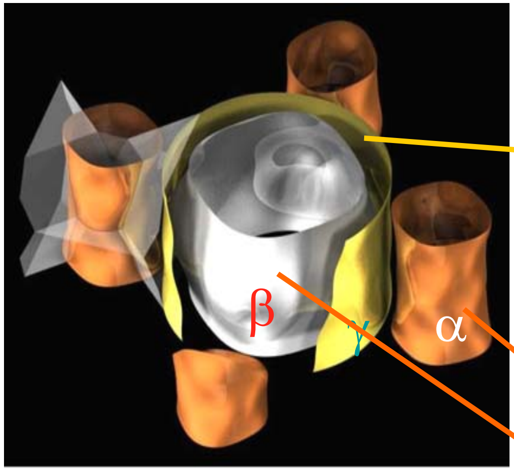
active intrinsically superconducting bands

passive bands with induced superconductivity

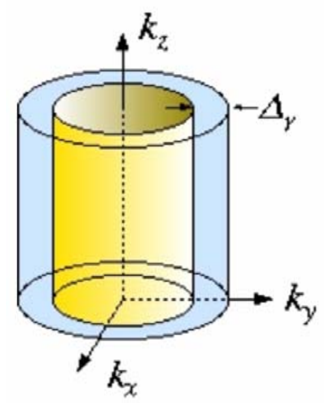
Agterberg, Rice& MS

Multiband effects

Three bands:

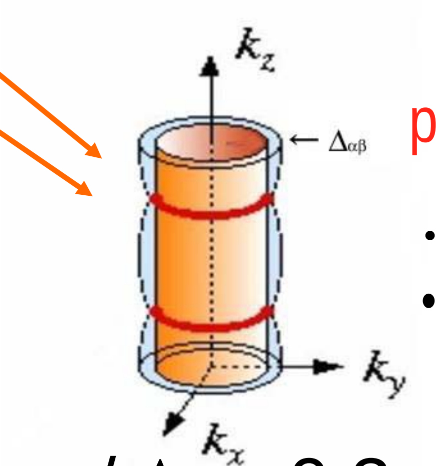


Zhitomirsky & Rice (2001)



active band (γ)

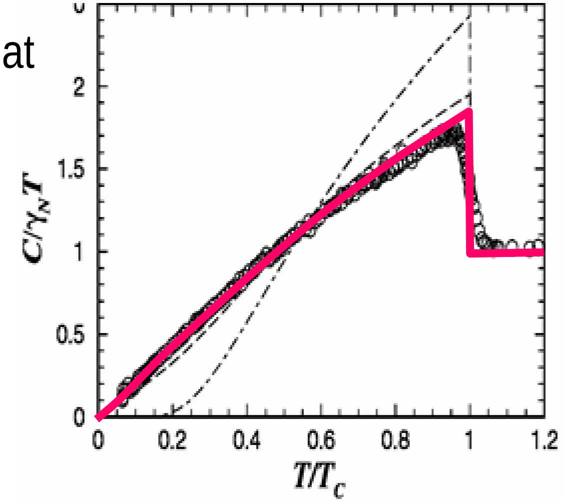
- intrinsic superconducting instability
- large nodeless gap



passive bands ($\alpha\beta$)

- induced superconductivity
- small gap with horizontal line nodes

specific heat fitting



$$\Delta_{\alpha,\beta} / \Delta_\gamma \sim 0.3$$

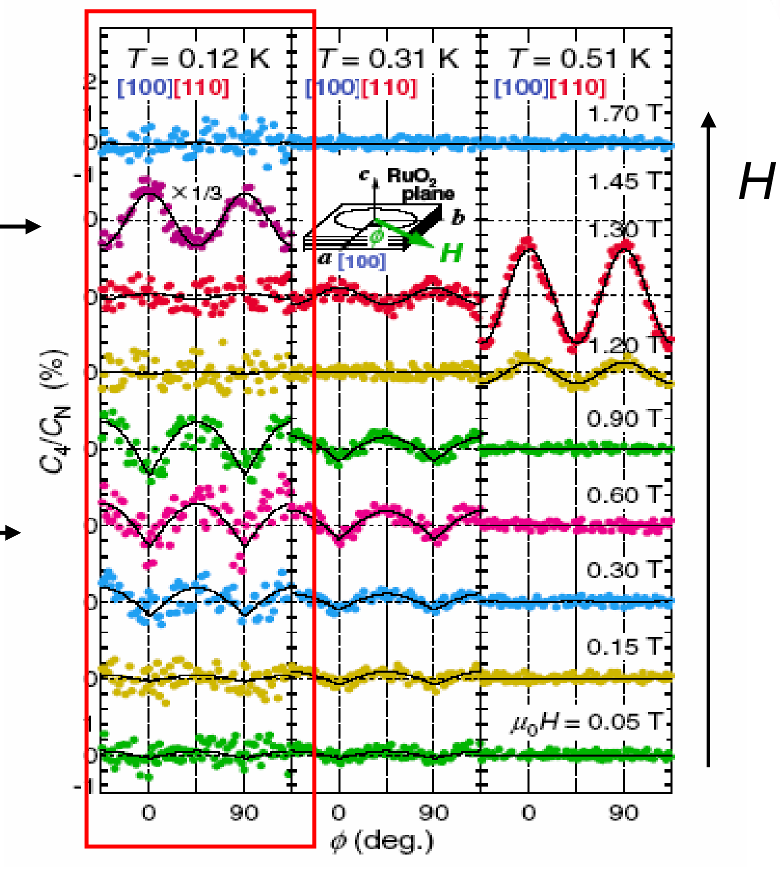
Gap anisotropy - specific heat

Specific heat in inplane magnetic field

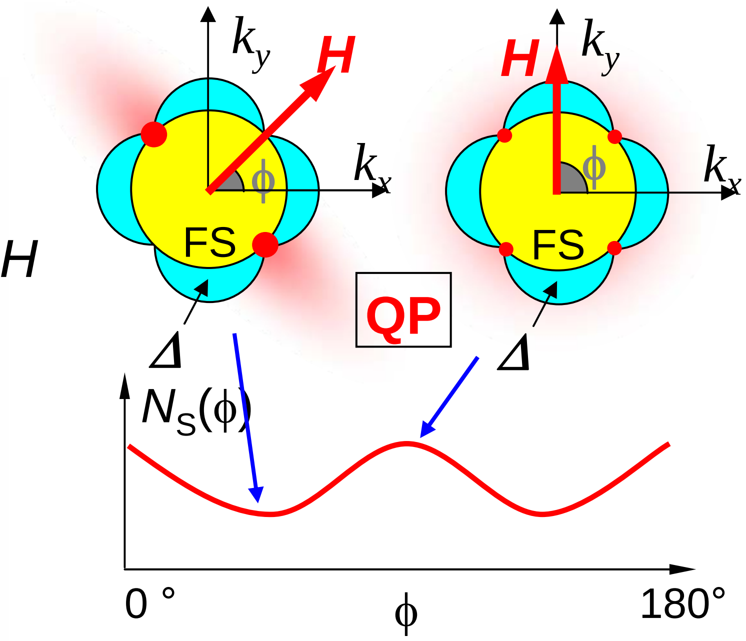
anisotropy

H_{c2}

$\Delta_{\vec{k}}$



Deguchi et al. (2004)



Doppler shift

$E'_k > \Delta_{min} \longrightarrow$ Quasi-particle DOS

$$N_S(\vec{H}) \sim \frac{C_e(\vec{H})}{T}$$

DOS depends on field direction

Vekhter; Maki, Won, Thalmeier. Dahm; Miranovi, Machida, ……

Basic gap nodes

Gap structure within the Brillouin zone:

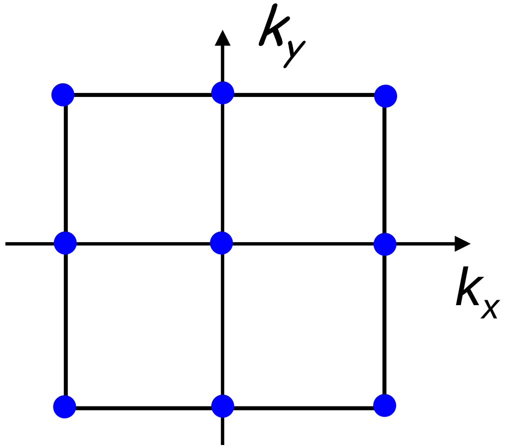
Perodicity: $\Delta_{\vec{k}} = \Delta_{\vec{k}+\vec{G}}$ reciprocial lattice vector $\vec{G}$

Zeros: $\Delta_{-\vec{k}} = -\Delta_{\vec{k}} = \Delta_{-\vec{k}+\vec{G}}$ odd parity

$\Delta_{\vec{k}} = 0$ for $\vec{k} = -\vec{k} + \vec{G} \Rightarrow \vec{k} = \dfrac{\vec{G}}{2}$

Brillouin zone

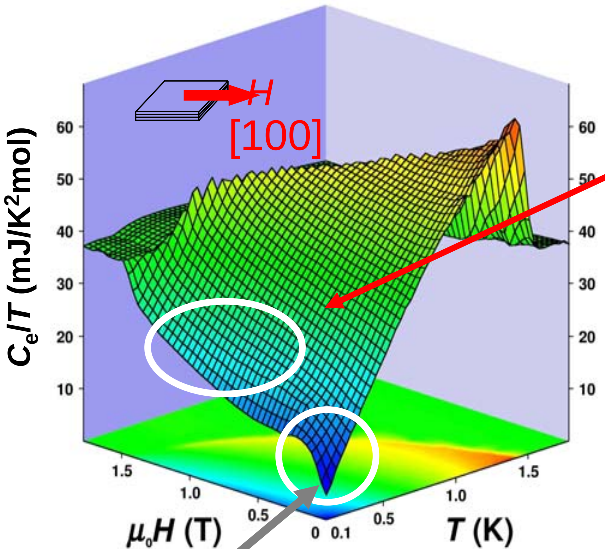
mandatory zeros
on the BZ boundary

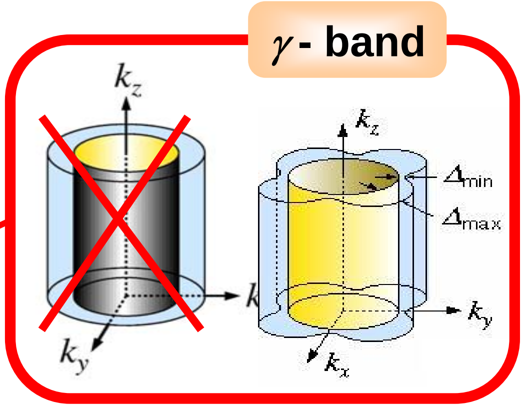


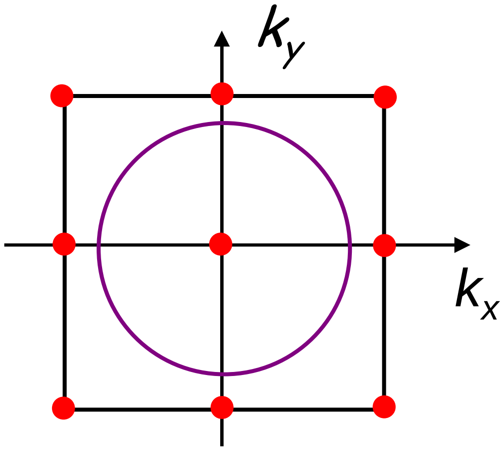
$$\vec{d}(\vec{k}) = \hat{z}(\sin k_x \pm i \sin k_y)$$

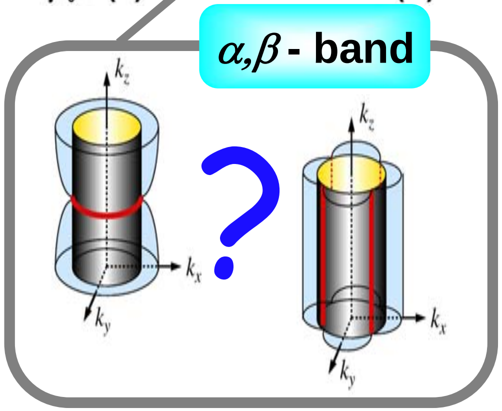
$$|\Delta_{\vec{k}}|^2 = |\vec{d}(\vec{k})|^2$$

Gap anisotropy - summary









γ– band: BZ-zeros

→ gap anisotropy

minimum along [100]

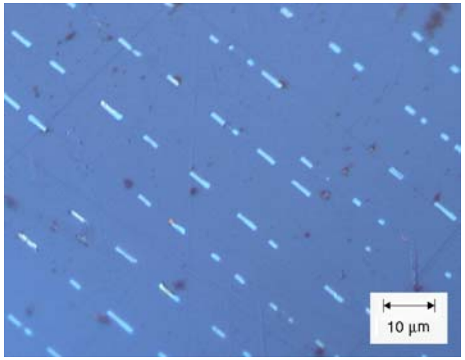
e.g. Narikyo and Miyake (1999)

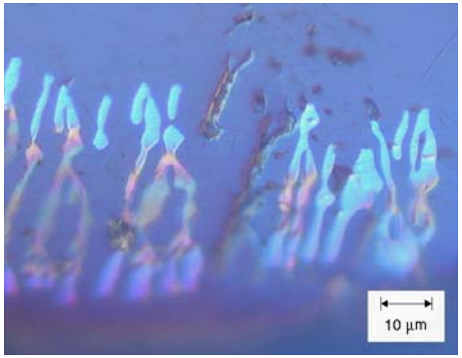
$$\vec{d}\left(\vec{k}\right) = \hat{z}\left\{\sin k_x \pm i \sin k_y\right\}$$

Frustrated inhomogeneous phase

3-Kelvin phase

Sr_2RuO_4 with excess Ru-metal inclusions



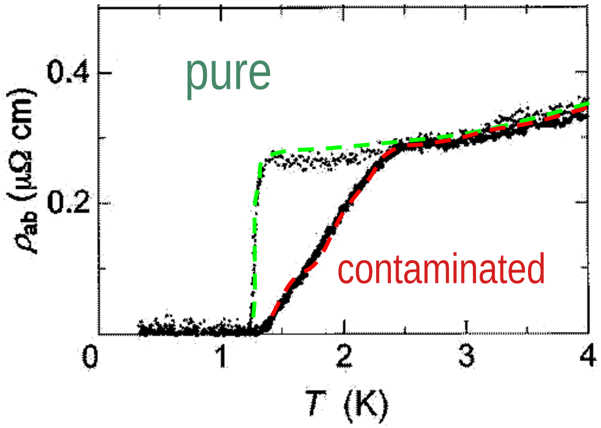


μm-size Ru-inclusions

Maeno et al (1997)

Onset of inhomogeneous superconductivity close to 3 K "3-Kelvin phase"

resistivity

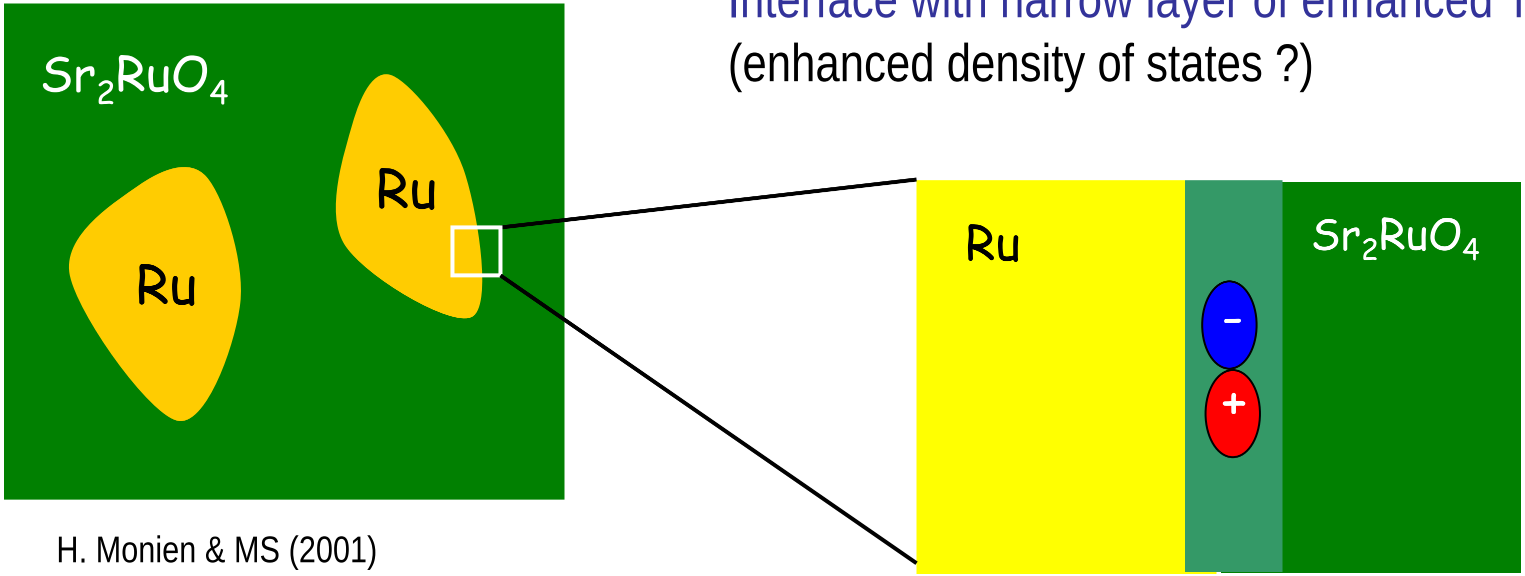


Ru-metal: $T_c = 0.5$ K

Nucleation of superconductivity on the interface between Ru and Sr_2RuO_4?

3-Kelvin phase - nucleation at the interface

Interface with narrow layer of enhanced T_c
(enhanced density of states ?)



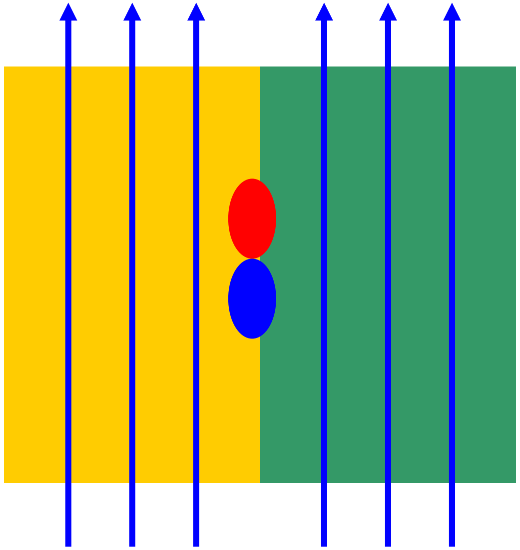
H. Monien & MS (2001)

nucleation of p-wave state parallel to interface

better concentrated in beneficial region

time reversal invariant → symmetry breaking transition

Upper critical field H_{c2}



Highest H_{c2} for fields parallel to interface

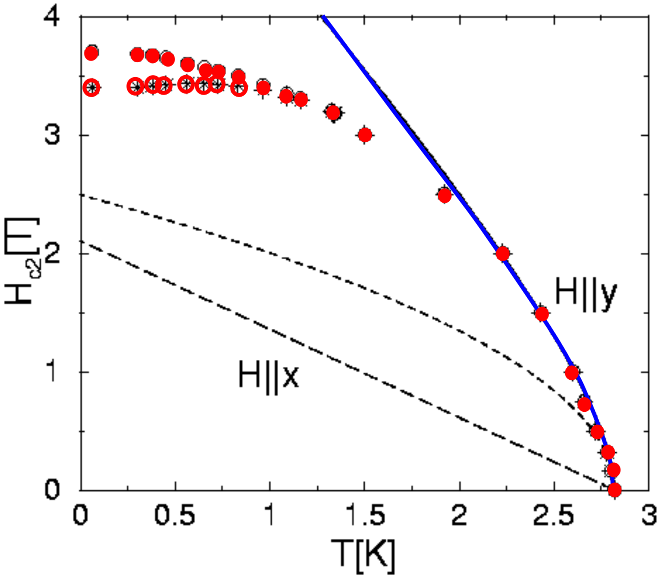
$$H_{c2} \propto \sqrt{T^* - T}$$

Note: in bulk $H_{c2} \propto (T_c - T)$

Correction: shrinking cyclotron radius

$$\eta_{\|} = \eta_0 e^{-|x|/\xi} e^{-\alpha x^2}$$

Matsumoto, Bellardinelli, MS

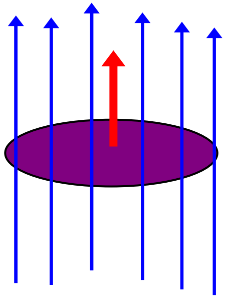


Yaguchi et al

$$H_{c2} \propto \left(T^* - T\right)^{0.7}$$

Upper critical field H_{c2}

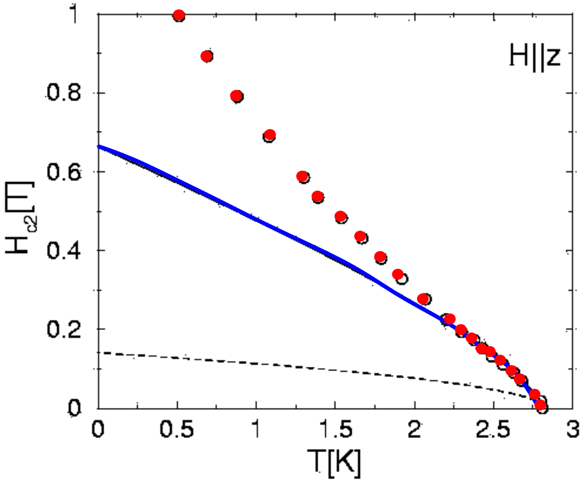
Field parallel to z-axis



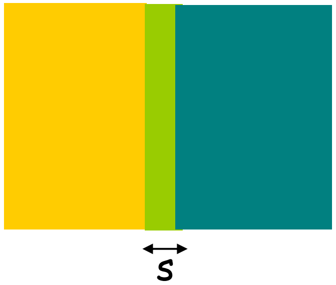
Coupling to the magnetic moment of the Cooper pairs

→ mixing of p_x and p_y (chiral phase)

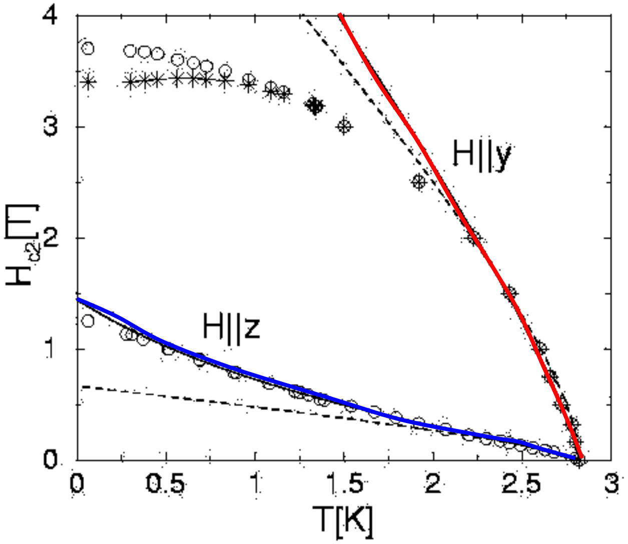
→ enhancement of H_{c2}



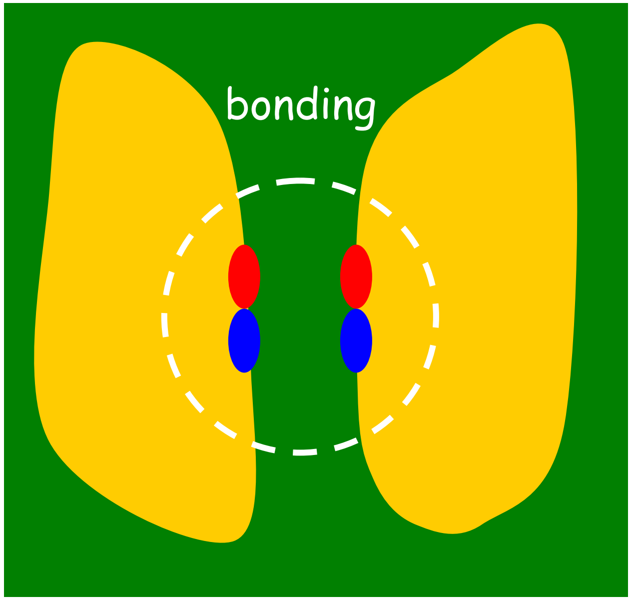
Finite width of interface region

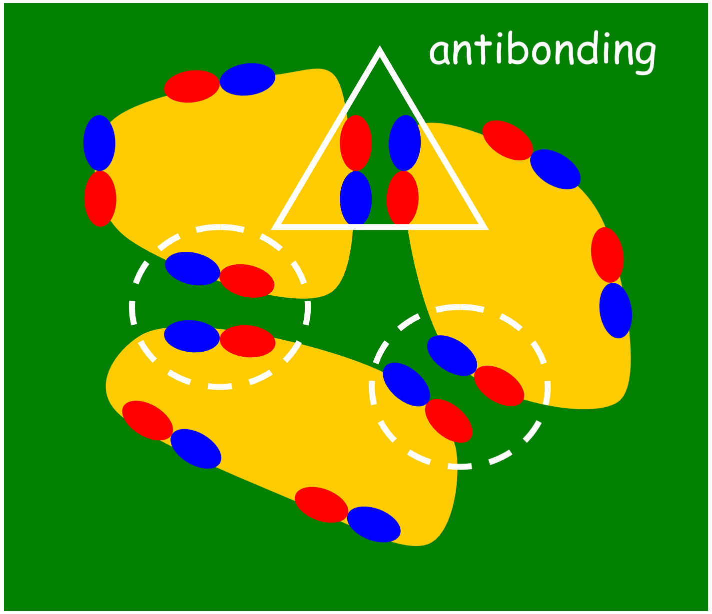


$s \approx 0.3\ \xi_0$ (20 nm)



Capillary and frustration effect





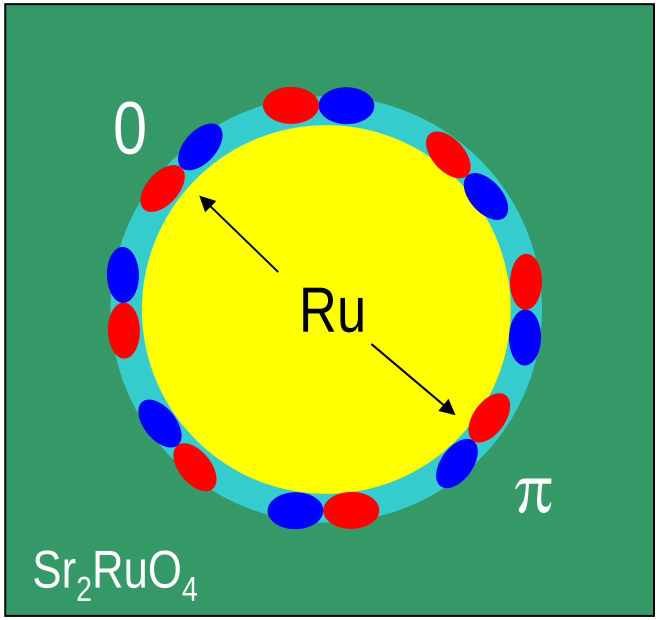
Lowest energy with same phase
Josephson coupling

Frustration due to π-links

Release of frustration by spontaneous currents
possibly visible in ac-susceptibility

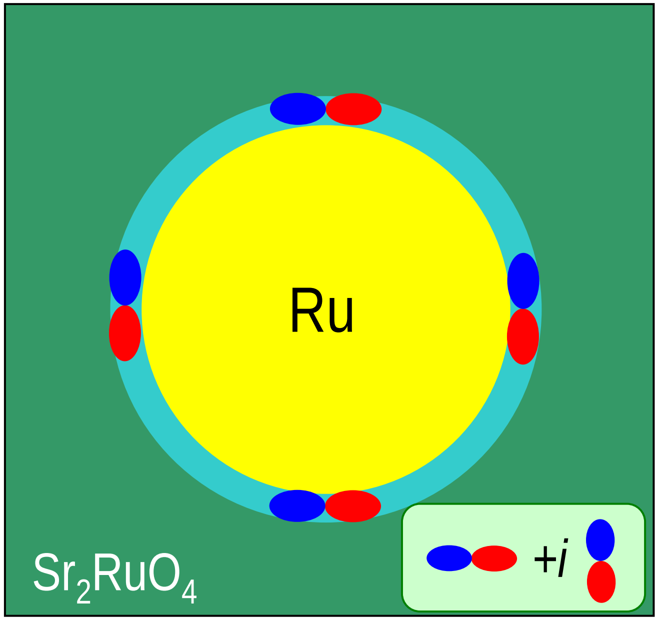
Interface and topological defects

interface nucleate



winding of phase

bulk phase



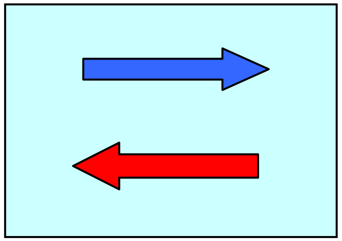
no winding

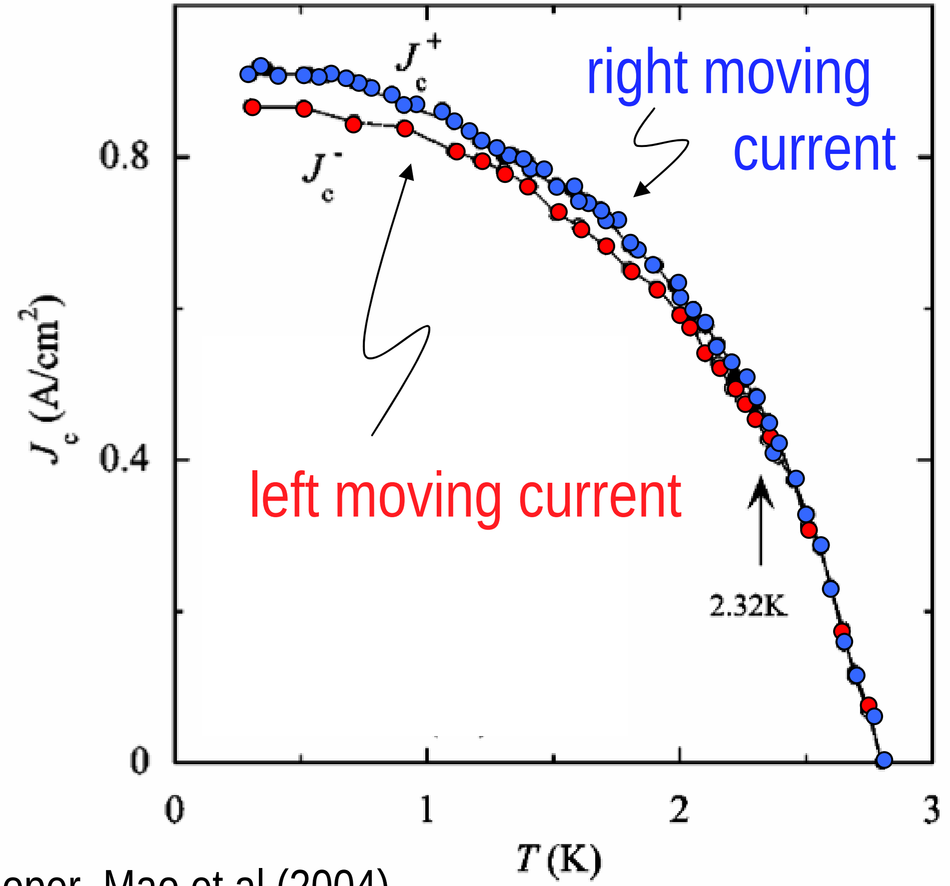
change of topology between inhomogeneous and bulk phase

Signature of frustration effects

Critical current in 3-Kelvin phase

currents in opposite directions





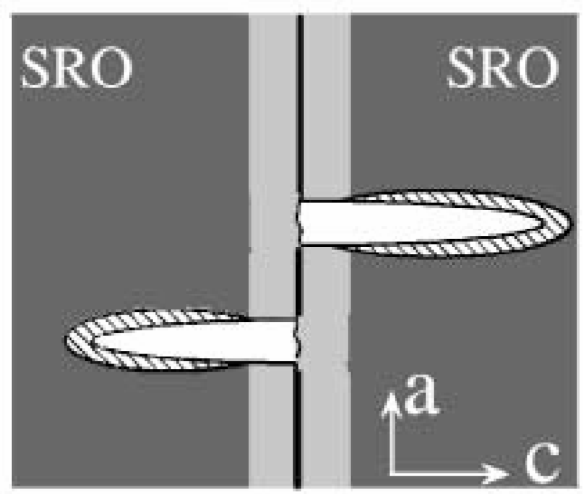
right moving current

left moving current

Hooper, Mao et al (2004)

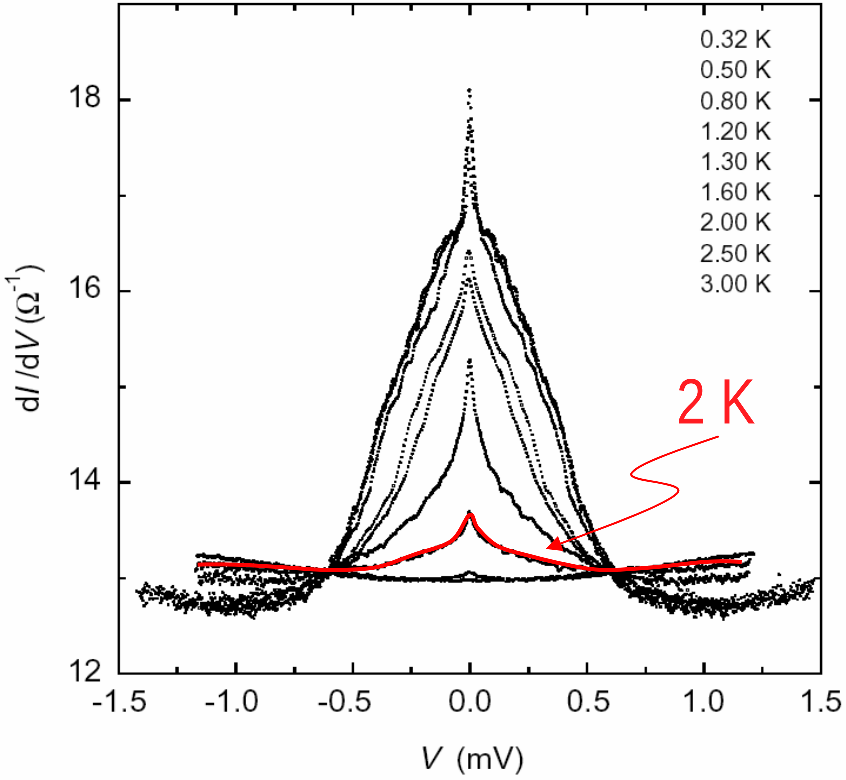
Signature of unconventional pairing

break junction along c-axis



Mao, Liu et al, (2001)

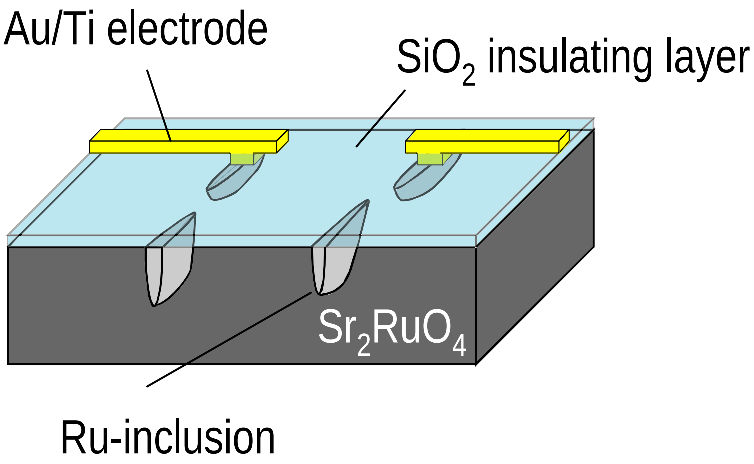
quasiparticle tunneling

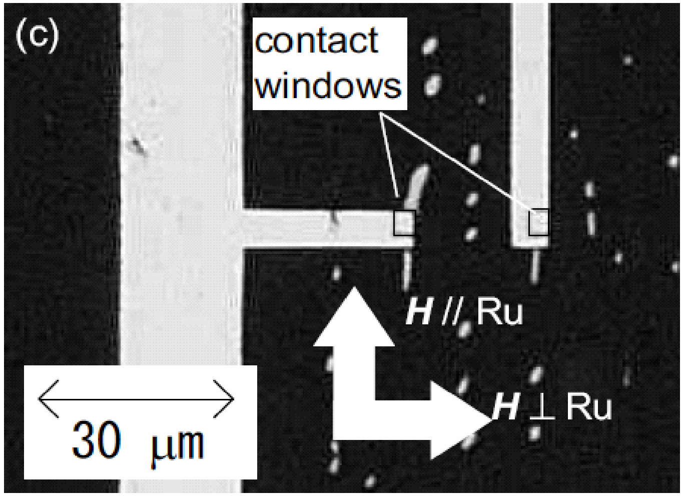


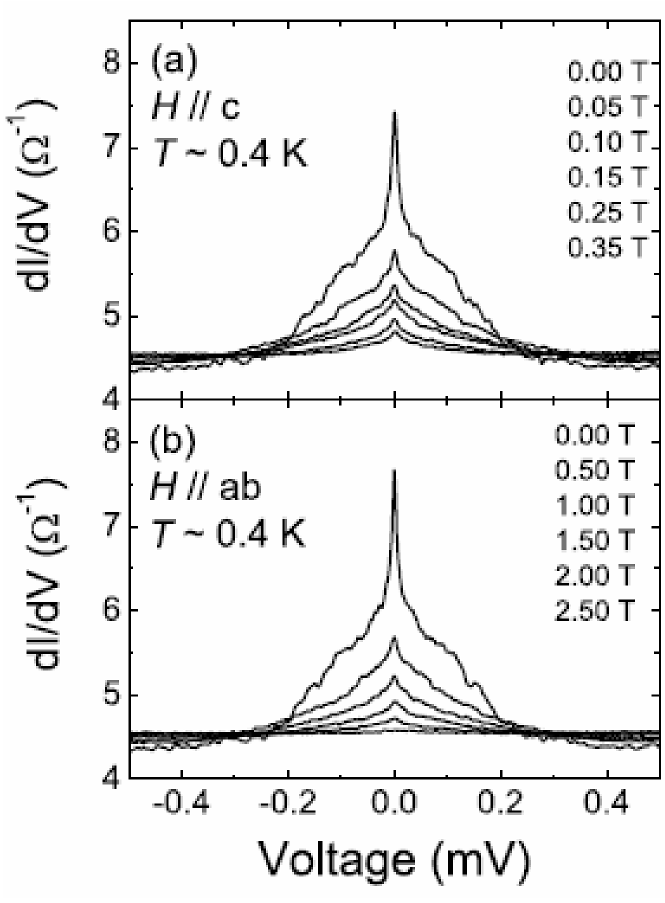
zero-bias anomaly

Signature of unconventional pairing

Contacts to specific Ru-inclusions







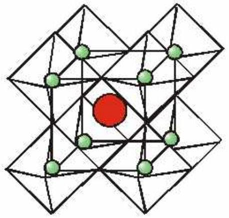
Kawamura, Yaguchi et al,

J.Phys.Soc.Jpn. 74, 531 (2005)

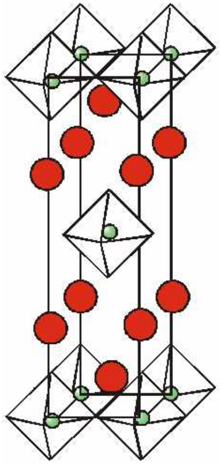
Metamagnetism in $Sr_3Ru_2O_7$

Ruddelson-Popper series: $Sr_{n+1}Ru_nO_{3n+1}$

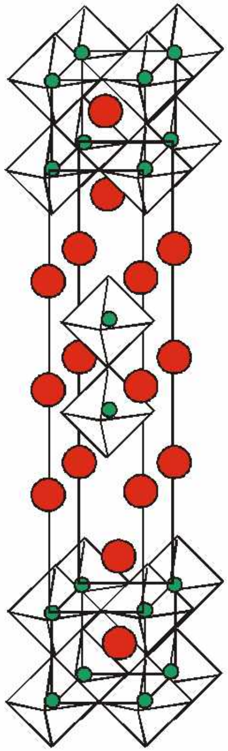
Ferromagnetism



n=∞ $SrRuO_3$

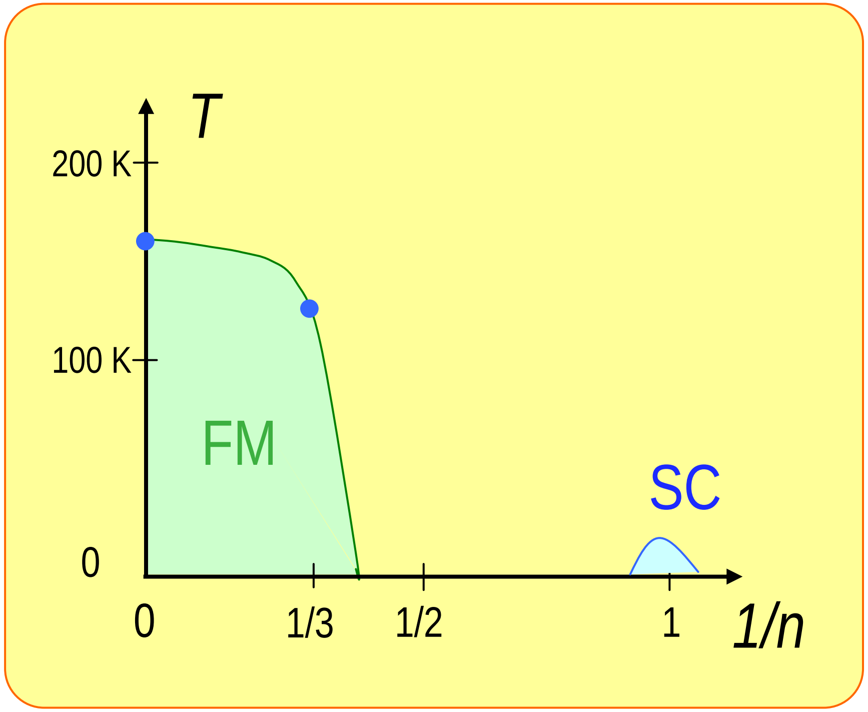


n=1 Sr_2RuO_4



n=2

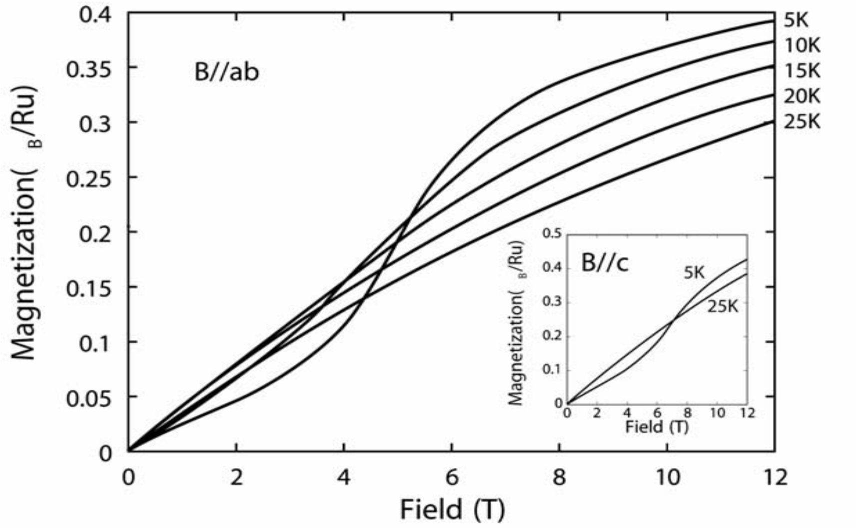
$Sr_3Ru_2O_7$



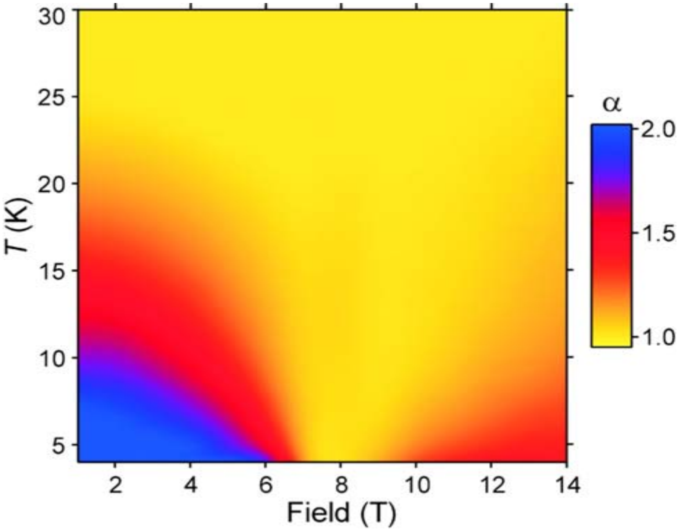
bilayer compound close to
ferromagnetic quantum phase transition

Metamagnetic transition in $Sr_3Ru_2O_7$

Quantum critical behavior at the metamagnetic transition



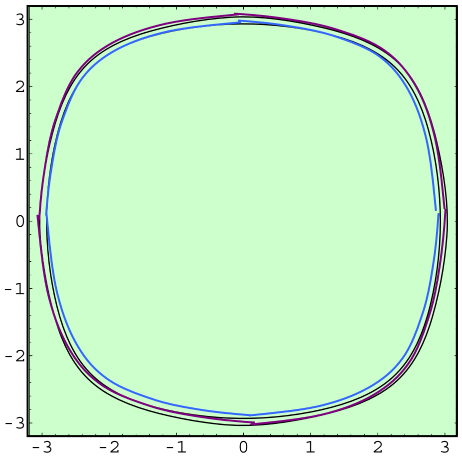
$$\rho(T) = \rho_{res} + AT^{\alpha}$$

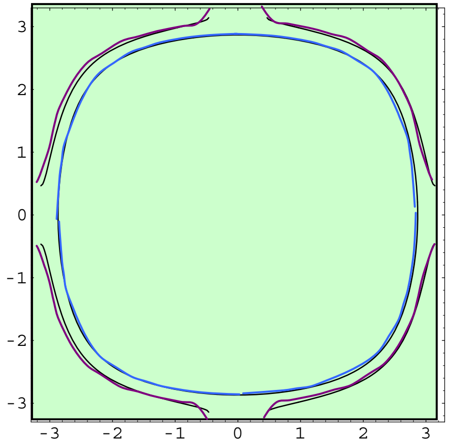


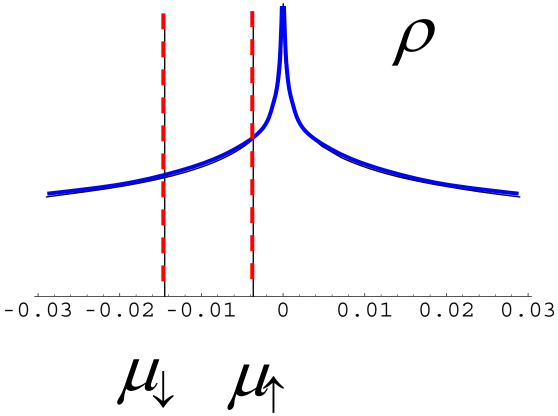
Grigera et al., Science, 294, 329 (2001)

Perry et al., PRL 86, 2661 (2001)

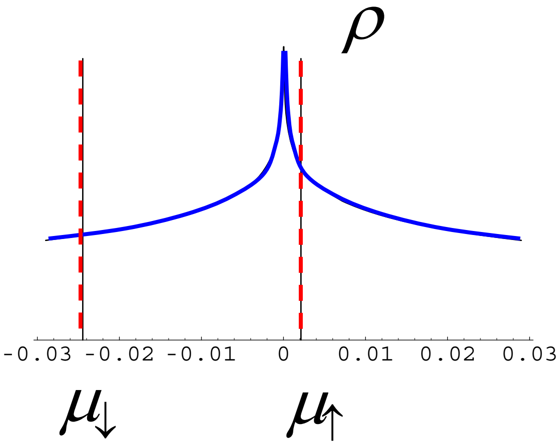
Fermi surface topology change







van Hove
singularity



Binz & MS

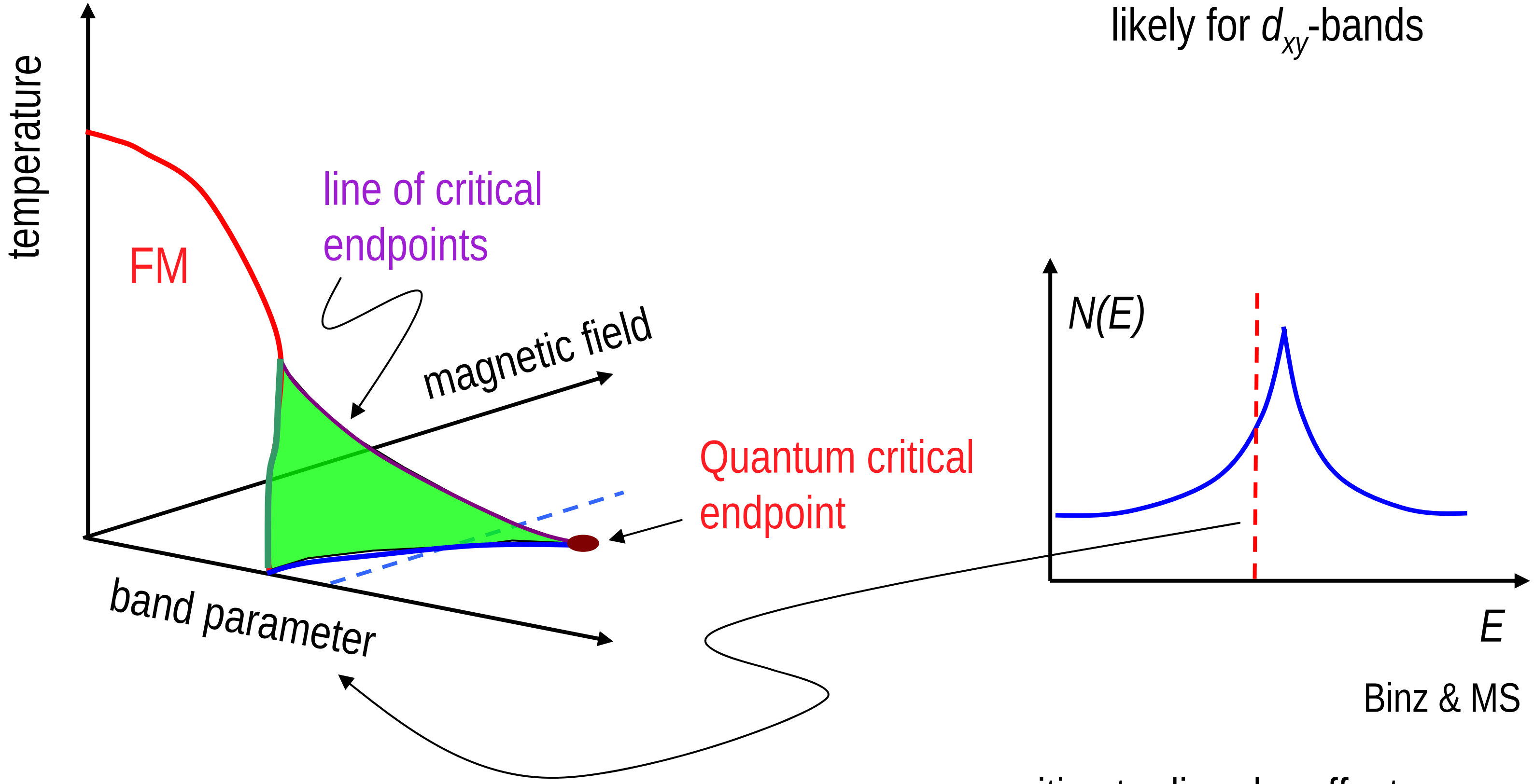
Phase diagram

Metamagnetic transition

and 1st order transition

chemical potential close to
Van Hove singularity

likely for d_{xy}-bands

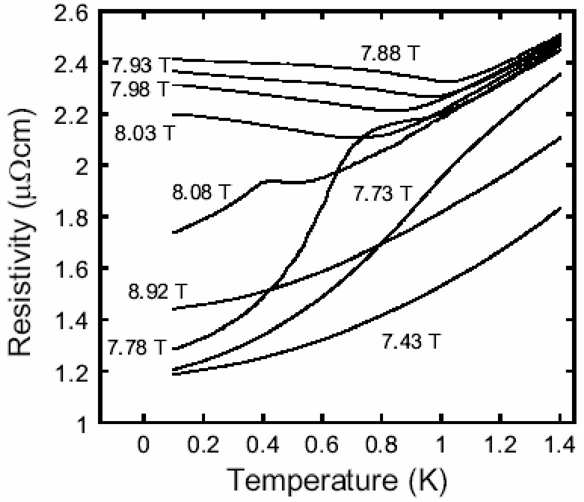


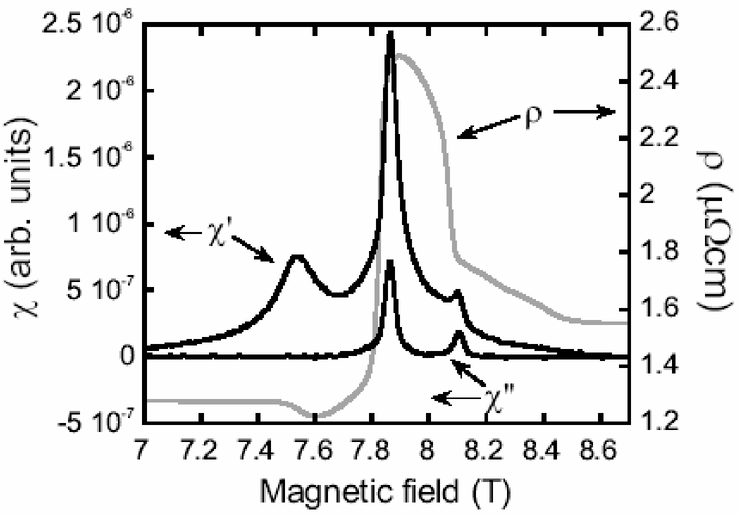
Binz & MS

sensitive to disorder effects

Honerkamp

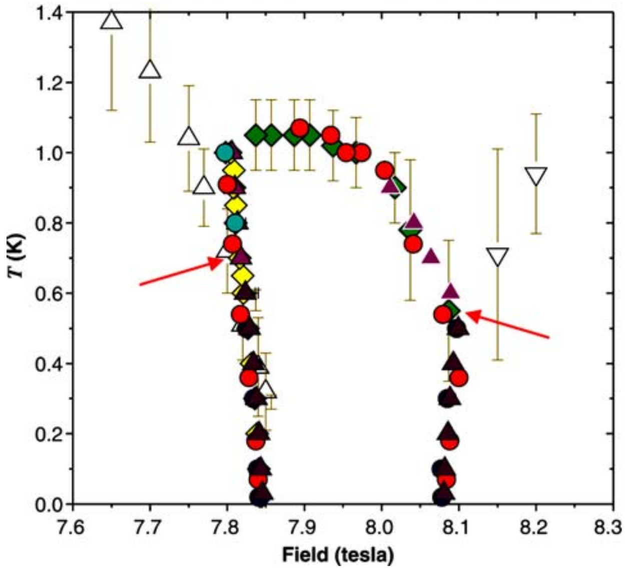
Metamagnetic transition in ultrapure samples





Perry et al. Phys. Rev. Lett. (2004)

new intermediate phase



Grigera et al., Science (2004)

→ Pomeranchuk (Fermi surface) instability ?

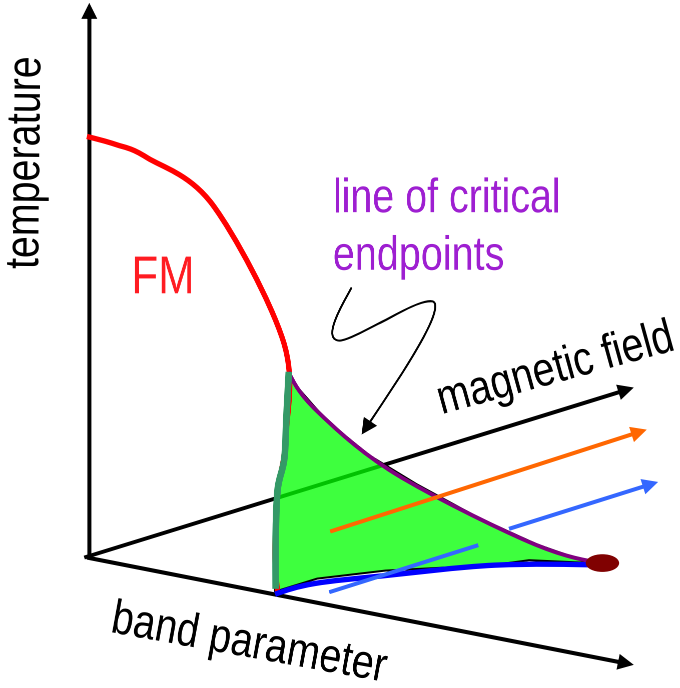
Schofield et al.

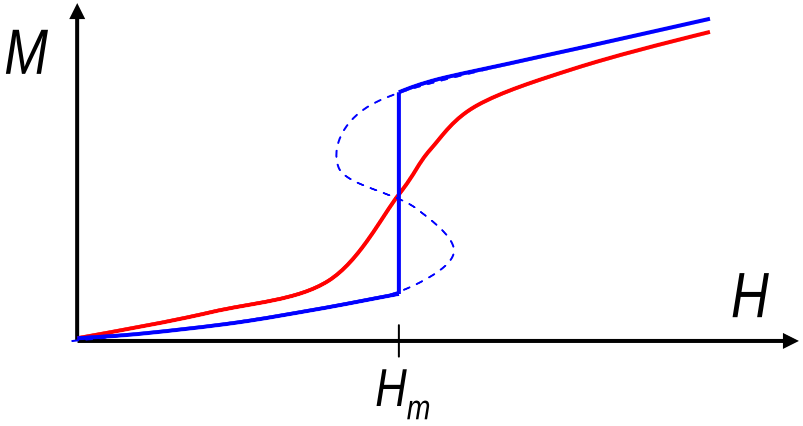
→ orbital charge redistribution?

Honerkamp

Condon domains

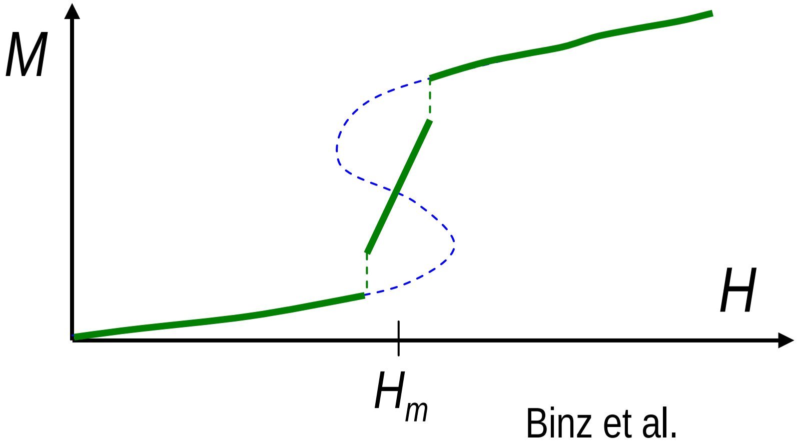
demagnetization effects





stable and metastable states

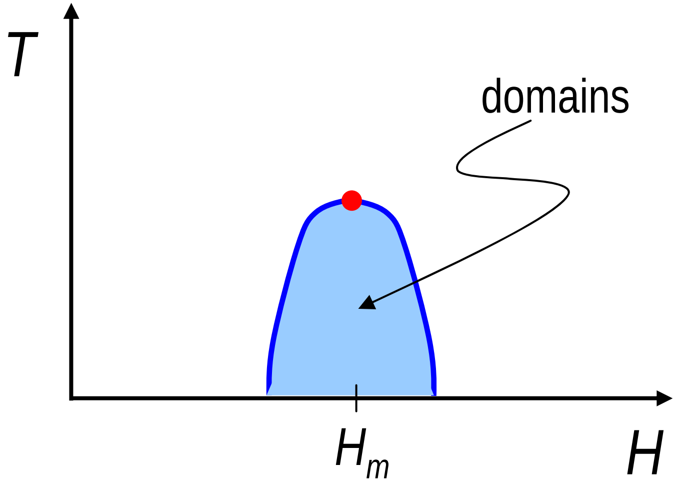
→ Condon domains

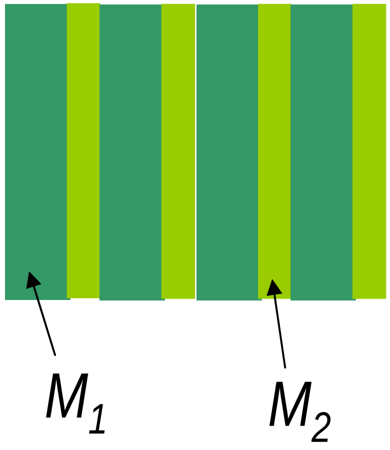


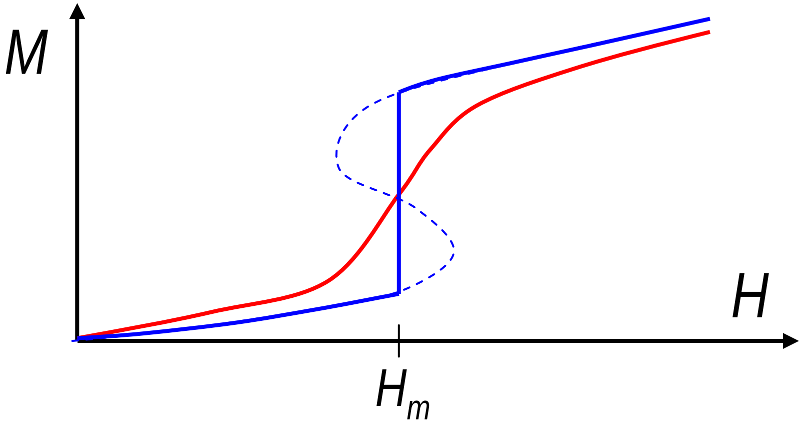
Binz et al.

Condon domains

demagnetization effects

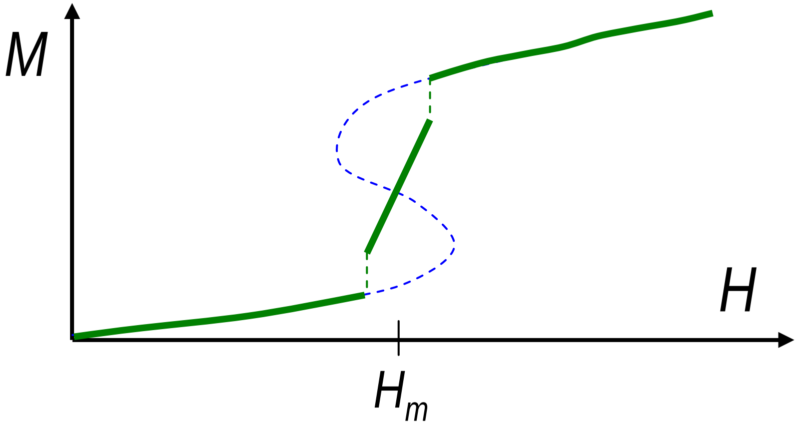






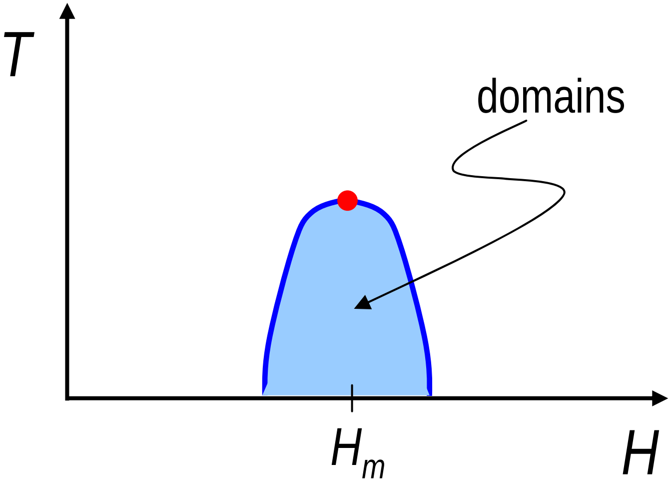
stable and metastable states

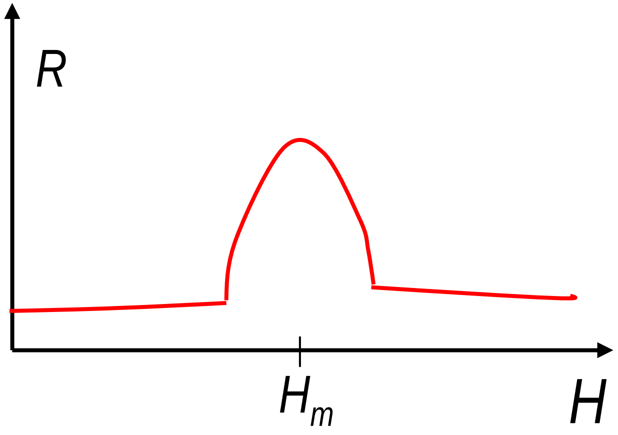
→ Condon domains

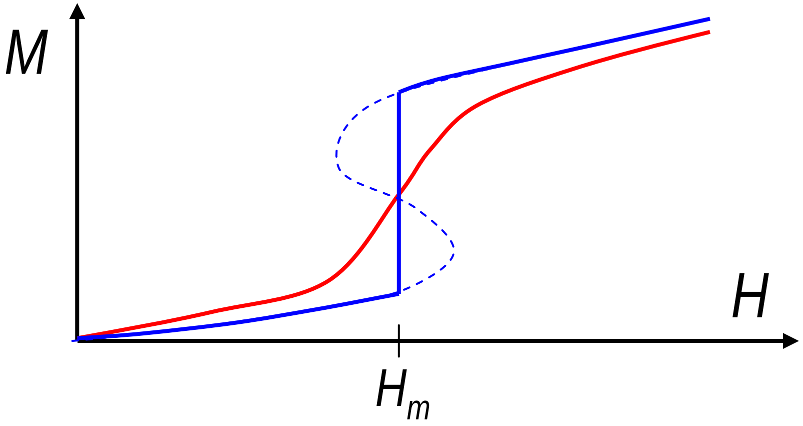


Condon domains

demagnetization effects

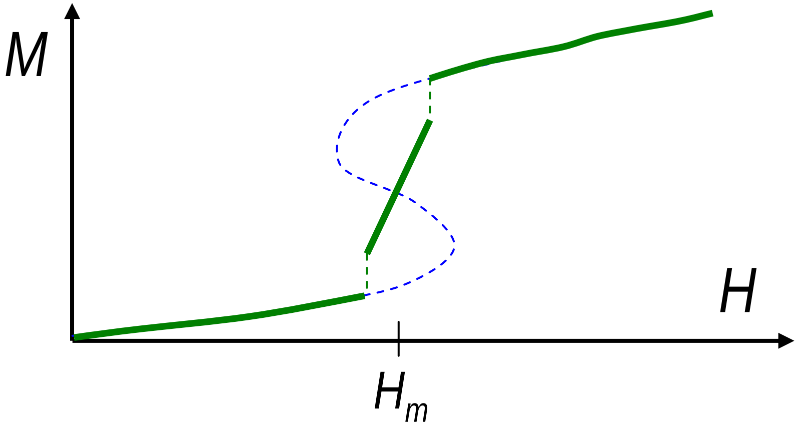






stable and metastable states

→ Condon domains

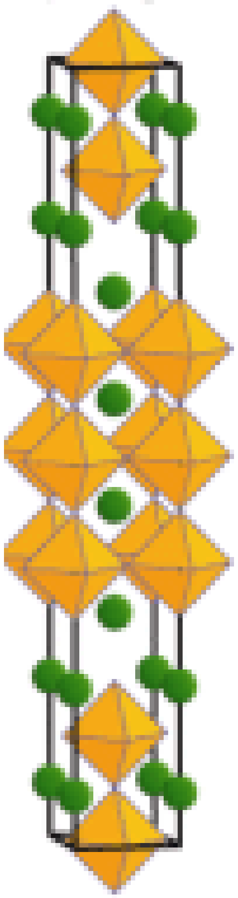


Possible phase separation in triple-layer $Sr_4Ru_3O_{10}$

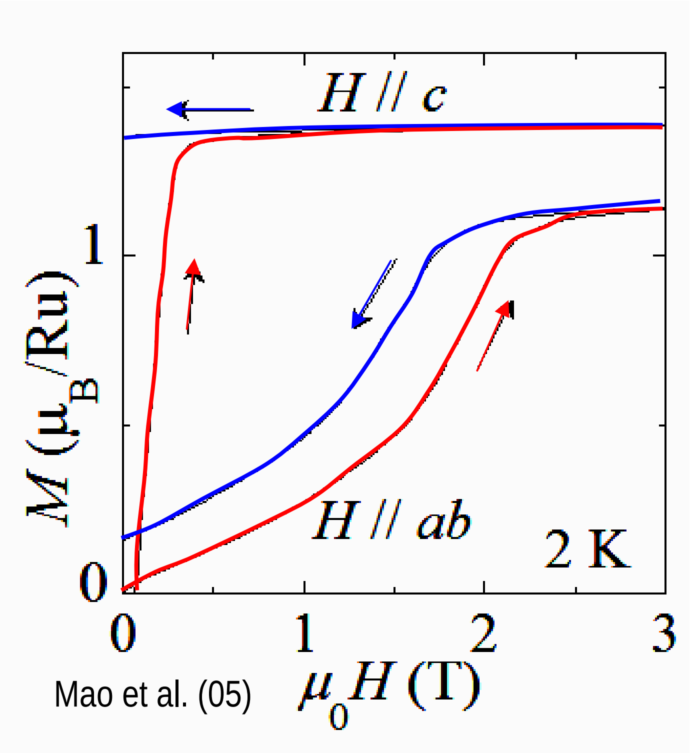
Discontinuous metamagnetic transition

Cao et al., PRB (2003)

Mao et al. cond-mat (2005)



Magnetization process



Mao et al. (05)

- ferromagnetism *H* || *c*
  $T_C = 105\ K$
- 1^{st} order transition *H* || *ab*
  Hysteresis in magnetization

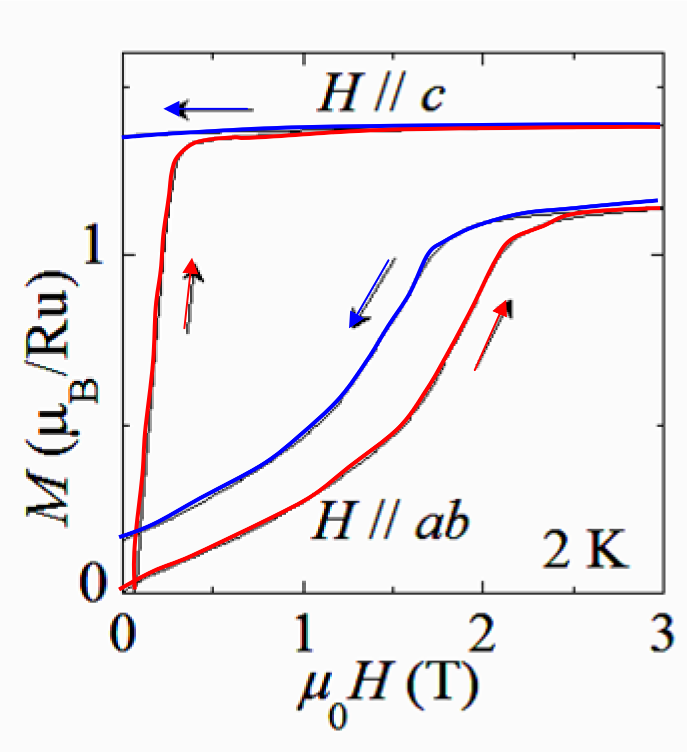
Domain formation ! ?

Visible in transport ?

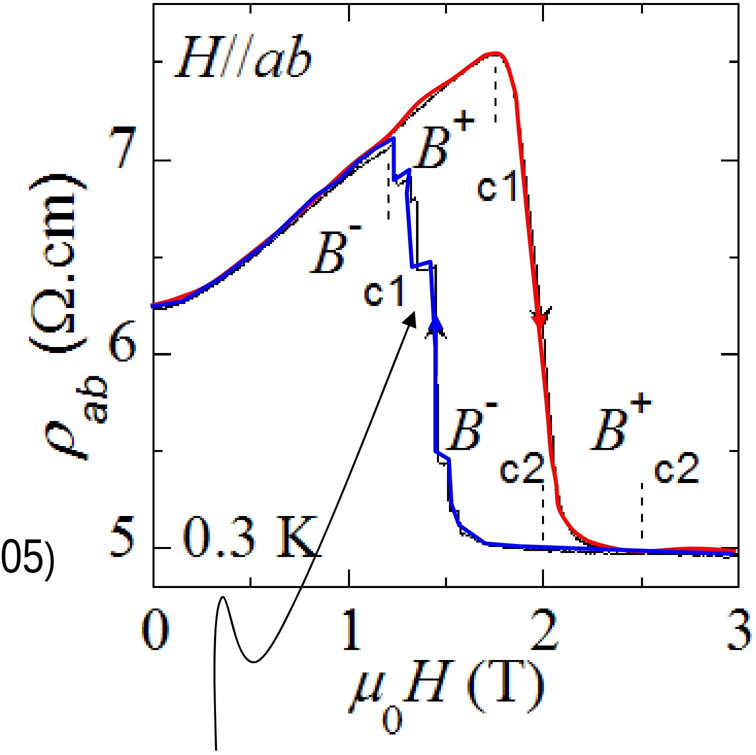
Possible phase separation in triple-layer $Sr_4Ru_3O_{10}$

Discontinuous metamagnetic transition

Magnetization process



Inplane field - inplane resistance



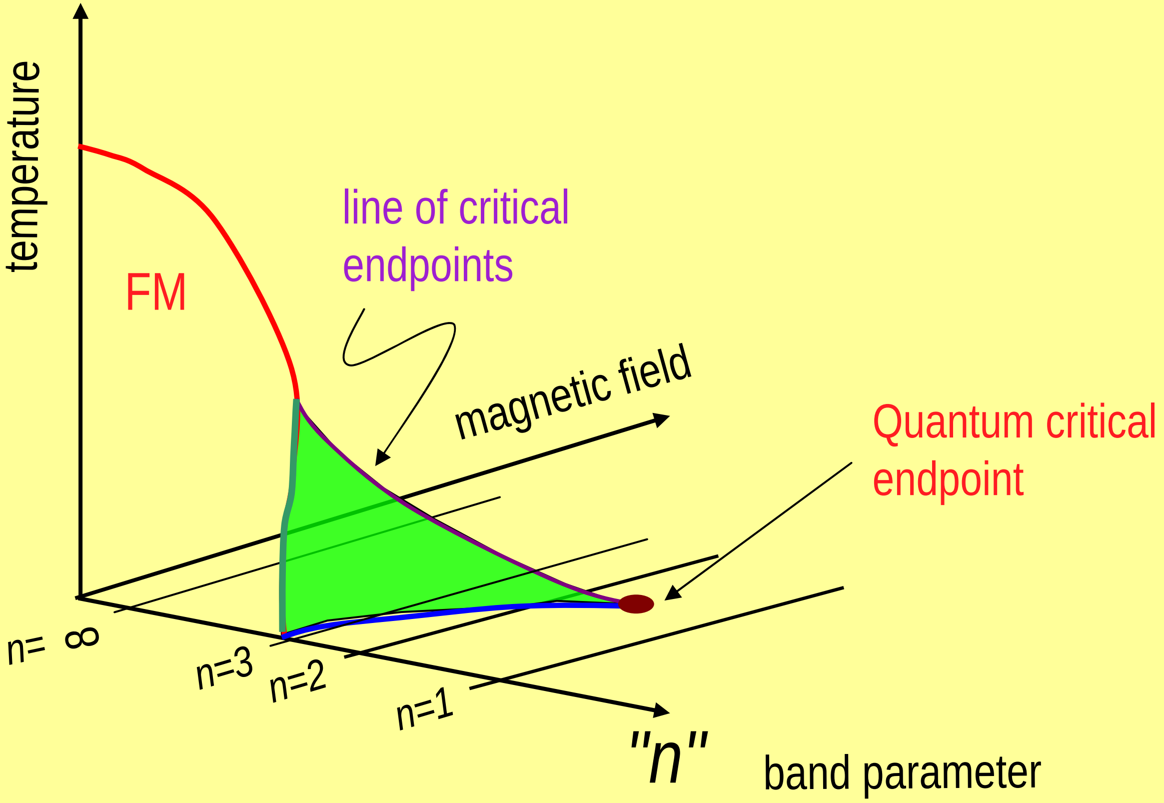
Mao et al. (05)

discontinuous jumps in ρ_{ab}

possibly effects of domains

$Sr_{n+1}Ru_nO_{3n+1}$ - phase diagram

layer number *n* - a scan through phase diagram



Conclusion

Superconducting single layer compound: Sr_2RuO_4

- Unconventional superconductivity out of strongly correlated Fermi liquid
- Understanding of microscopic mechanism still limited
- Phenomenological aspects rather well understood

Exemplary case with many complications, but also many opportunities

Magnetism in multi-layer compounds: $Sr_{n+1}Ru_nO_{3n+1}$

- Itinerant metamagnetism in bilayer compound with puzzling low-temperature phase
- Multi-layer compounds map out a phase diagram: physics of 1st-order QPT
- We do not see yet all the complications here