Multi-Gap Superconductivity of Sr_2RuO_4

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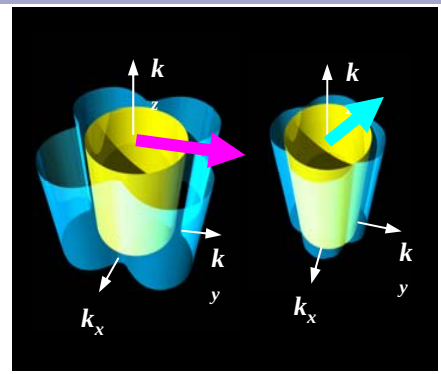


Superconducting gap Structure of Sr_2RuO_4:

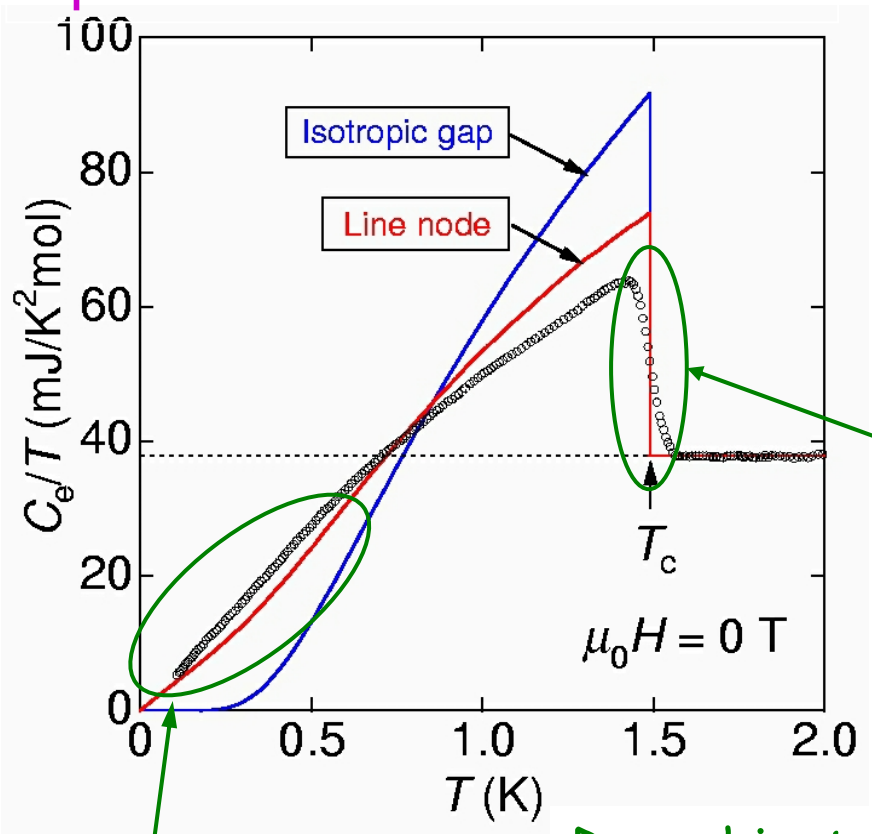
1. **Multi-gap superconductivity** due to two kinds of FSs.

2. The active sc band ("γ-FS") has
   gap minima along the <100> directions.

3. The passive sc bands ("α andβ-FSs") most likely have
   gap ZEROs along the <110> directions
   (or horizontal zeros only on α and β FSs) .

Evidence of Multi-Gap Superconductivity

Specific Heat in zero field



Deguchi *et al.*

A single-band, line-node state is thermodynamically incompatible with the experiment.

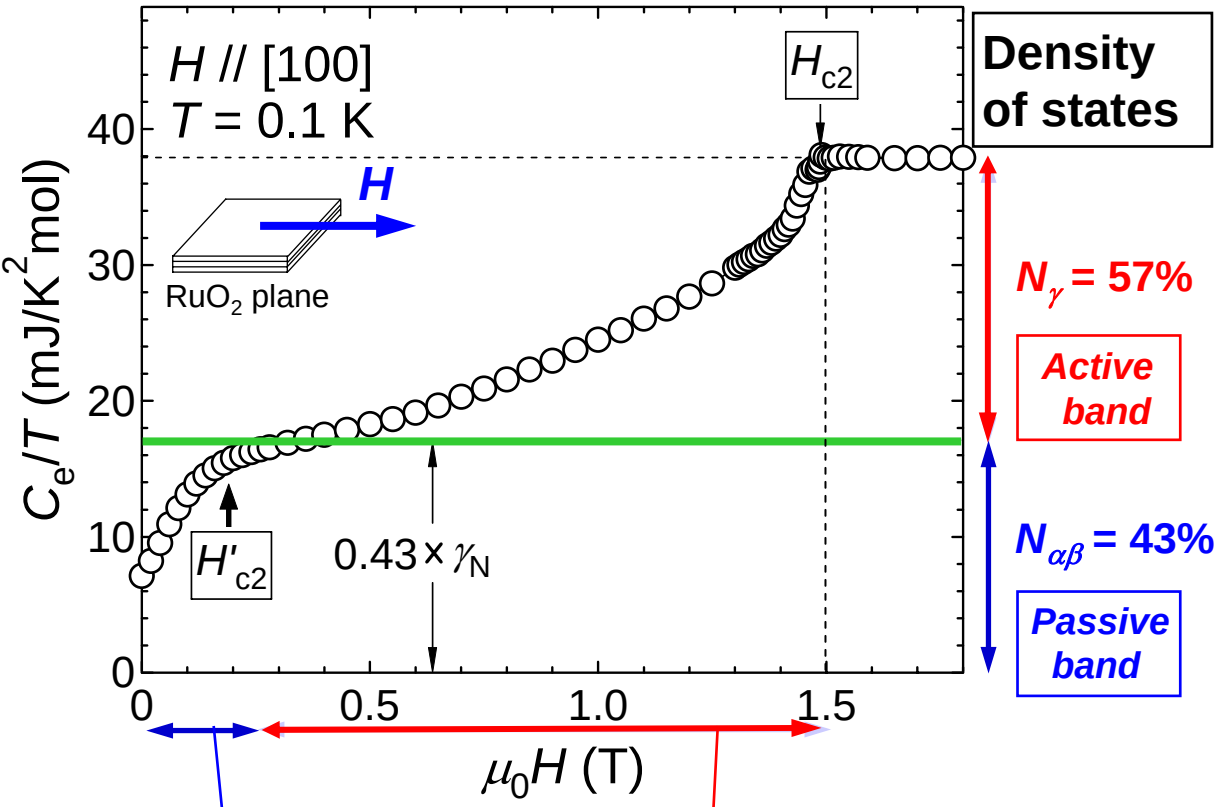
The jump at T_c is smaller than the line-node case.

0.73 (obs.) < 0.95 (line node)

The entropy release at low T exceeds that for a single-band line-node gap.

Evidence of Multi-Gap Superconductivity

Multi-gap structure (with active γ-FS) is consistent with the data.



Density of states

$N_\gamma = 57\%$

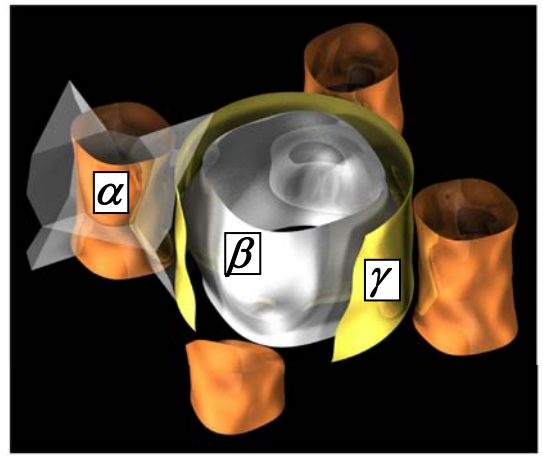
Active band

$N_{\alpha\beta} = 43\%$

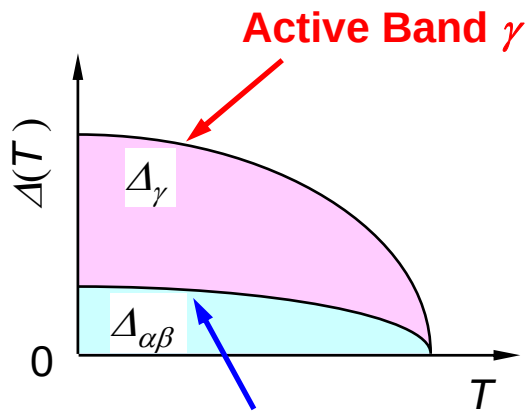
Passive band

Active **SC band is γ**

Passive **SC bands are effective only below 0.3 K and below 0.2 T.**



Gap amplitudes Δ_γ and $\Delta_{\alpha\beta}$ depend on the bands.



Passive Bands α,β

Agterberg, Rice, Sigrist, PRL **78**, 3374 (1997).

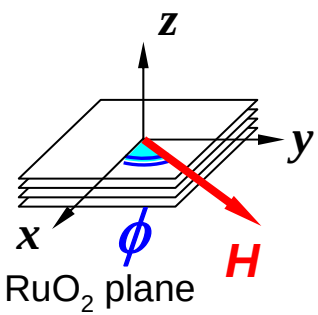
Determination of the Gap Anisotropy

Vector Magnet on a Rotating Stage by Kazuhiko DEGUCHI

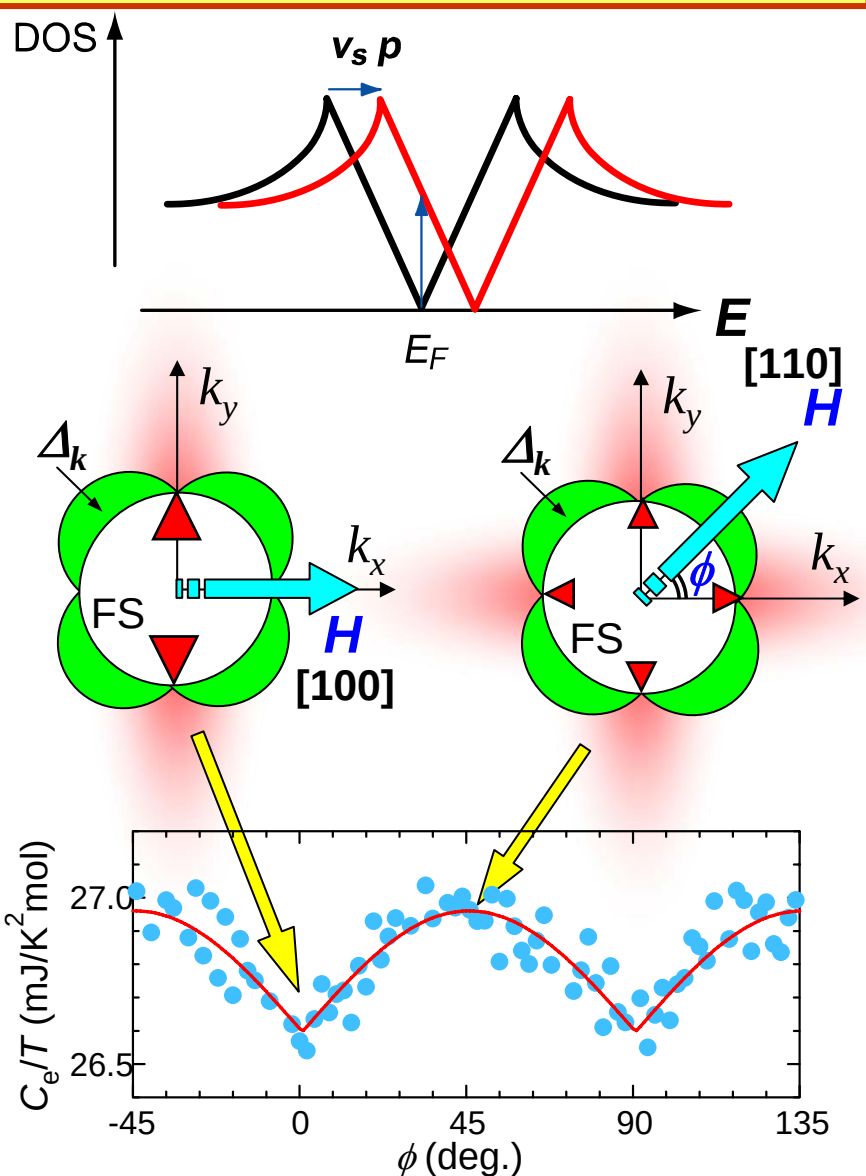
$E'_k > \Delta_{min}$ ⟶ **QP density of states**

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

DOS depends on the field orientation.

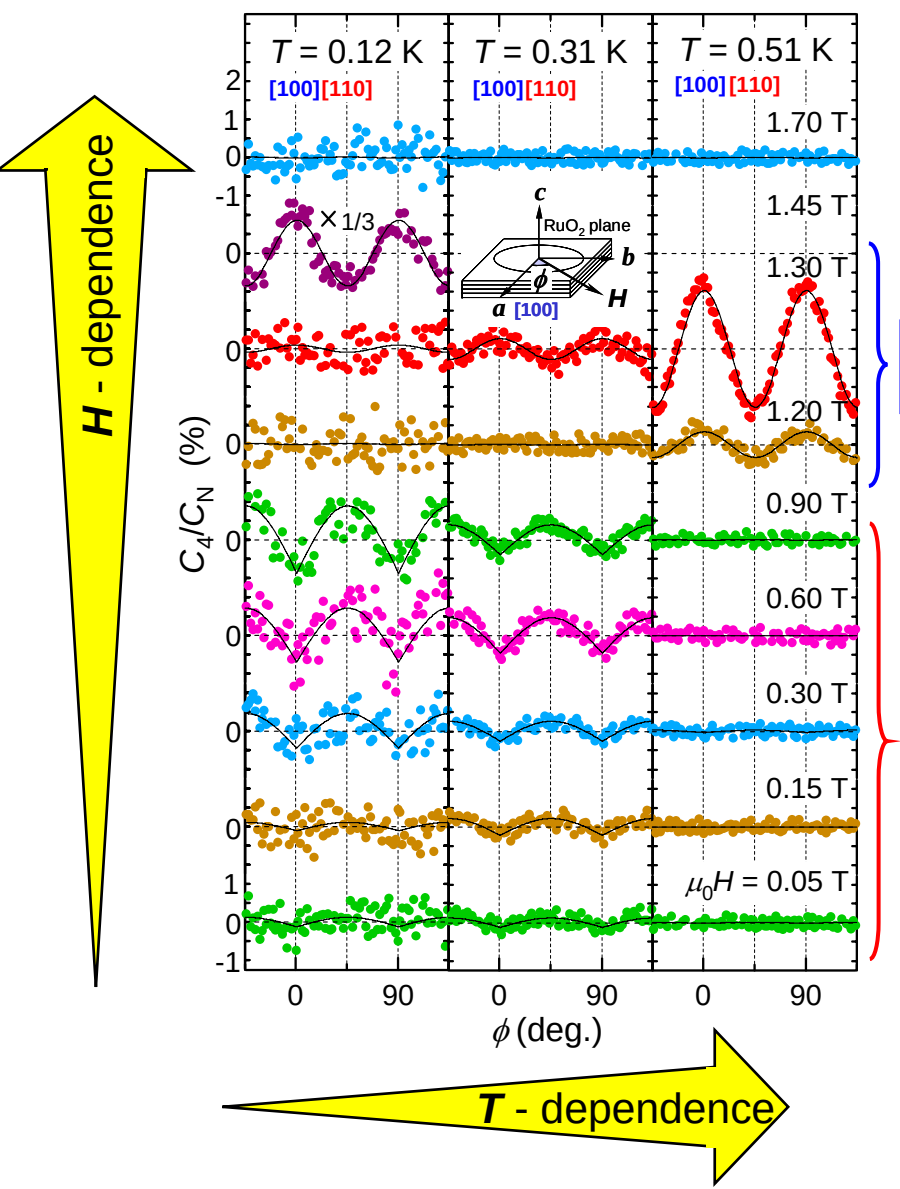


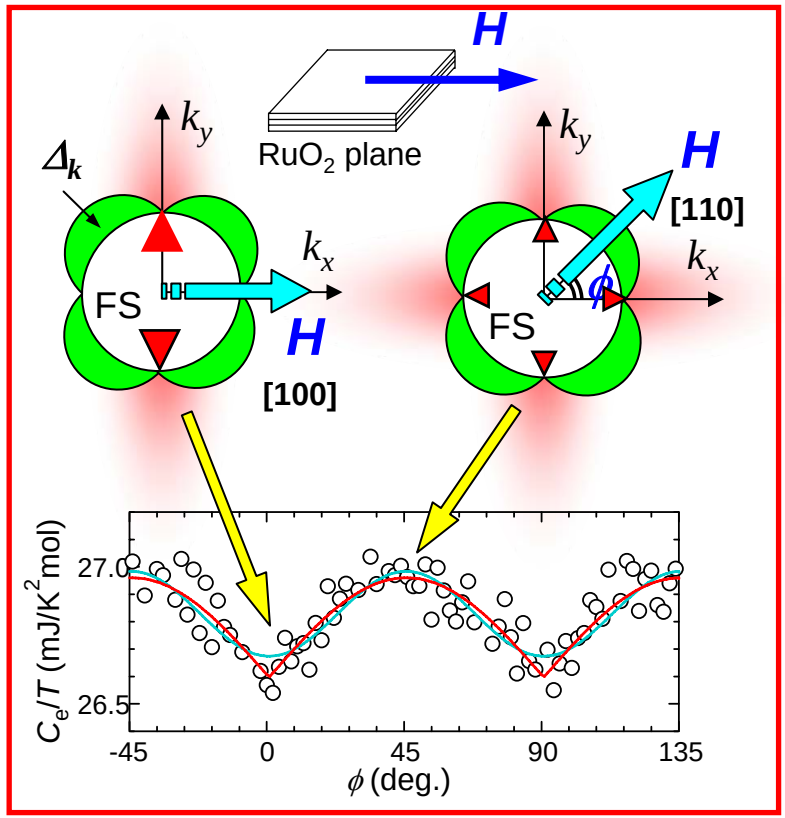
Specific heat under $H(\theta\varphi)$



Field-orientation dependence of the specific heat → gap anisotropy

Deguchi *et al.*, PRL **92**, 047002 (2004).





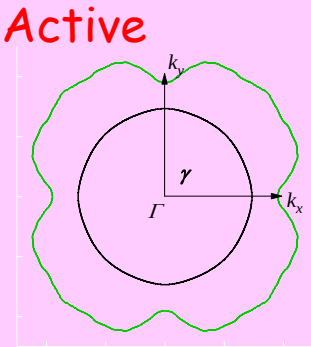
Gap suppression along the <100> **directions**

Gap structure consistent with experiments

1. **Active** band has $\Delta_{min} \neq 0$ along [100].

   DOS is min for H along [100].

   The size of ΔC at T_c suggests $\Delta_{min} \neq 0$.



observation: 0.73 (total)

$\Delta_{min} \neq 0$: $\Delta C/\gamma T_c$ = 1.22-1.07 x 57% = 0.70-0.61 (γ only)

$\Delta_{min} = 0$: $\Delta C/\gamma T_c$ = 0.95 x 57% = 0.54 (γ only)

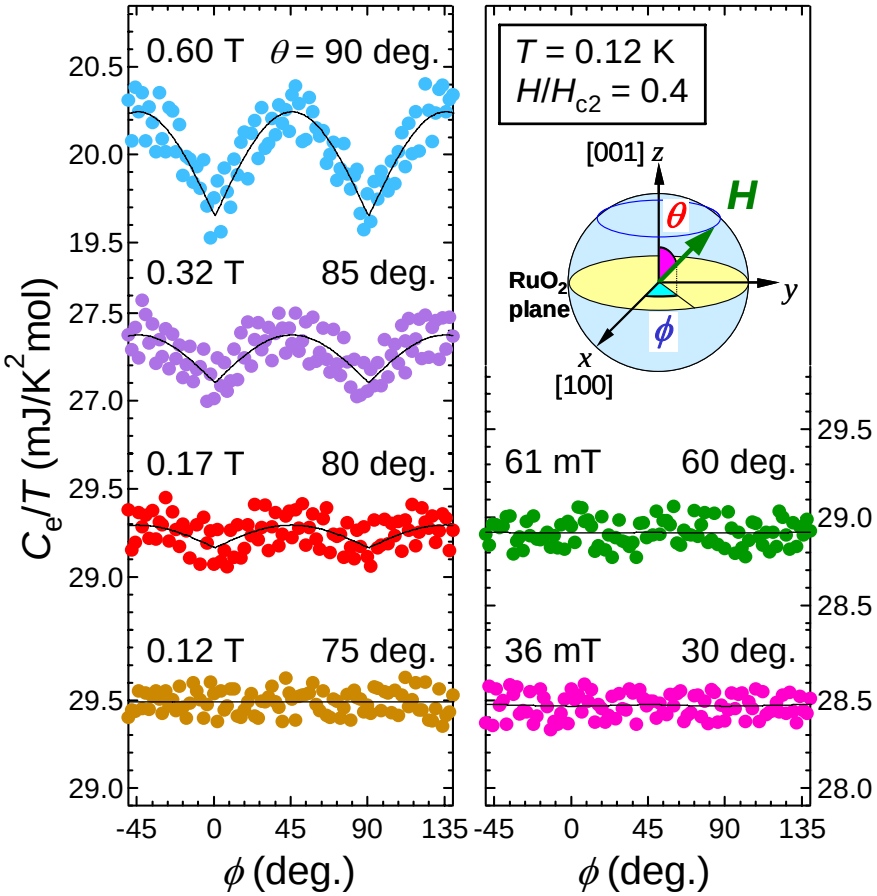
too small

For $\Delta_{min}/\Delta_{max}$ = 1/2 - 1/4

Polar angle θ dependence of $C_e(\varphi)$

– "Horizontal"? or "vertical"? gap zero on the passive FS –

OSC is strong when only γ contributes to the OSC.
OSC is suppressed when all the bands contribute to the OSC.

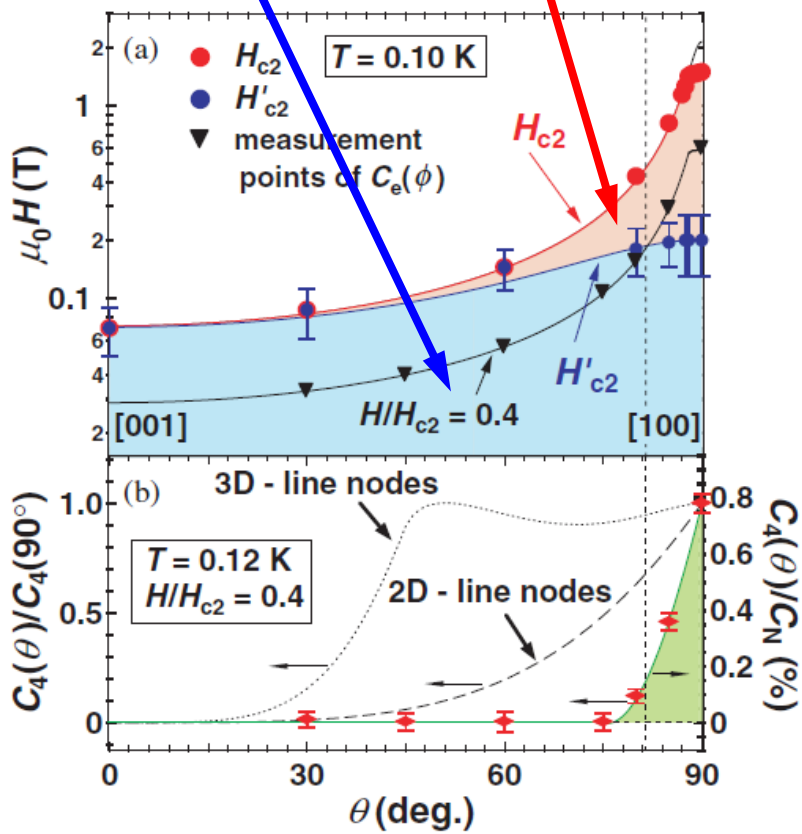


Deguchi *et al.*, JPSJ **73**, 1313-1321 (2004).

Contribution to $C_4(\theta)$

All bands

γ **– band** *only*
(α, β **– bands: QP**)



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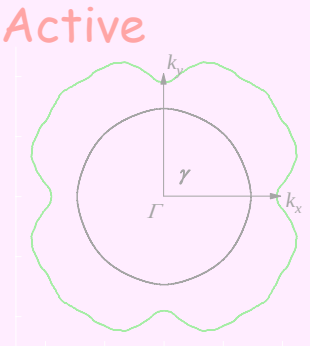

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too small

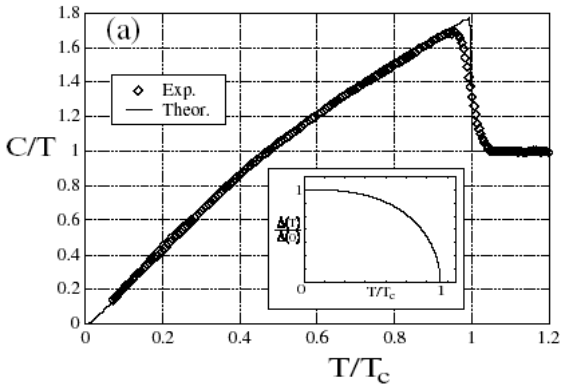
2. Passive band has $\Delta_{min} = 0$ along [110] or horiz. line node.

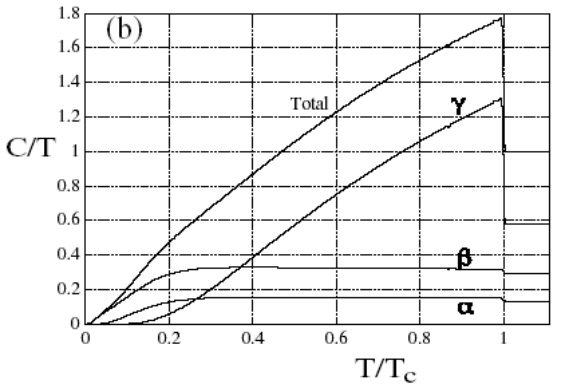
   DOS oscillations disappear at low T and H.

T^2-dependence of C_p suggests $\Delta_{min} = 0$ (gap zero) .

No need to introduce *horizontal* line node.

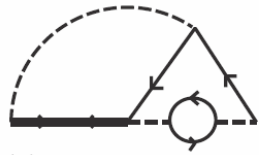
Success of Microscopic Mechanism Theory Based on Realistic Fermi Surfaces



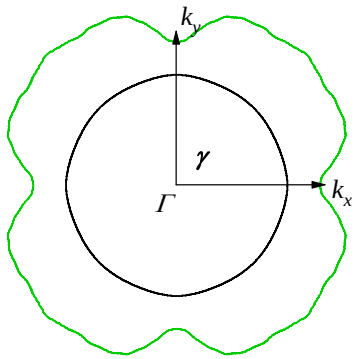


Third-Order Perturbation Theory

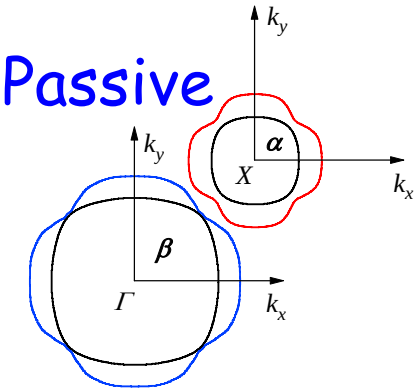
Coulomb repulsion
beyond the spin fluctuations



Active



Passive

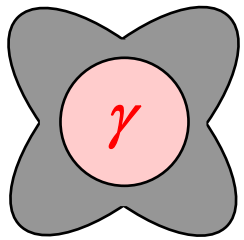
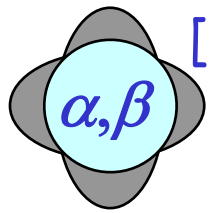


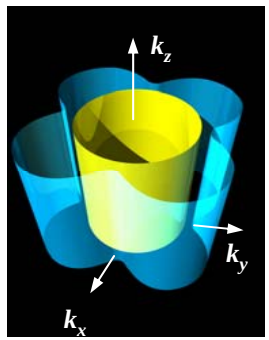
No horizontal line nodes

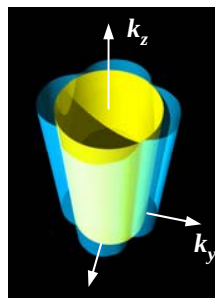
T. Nomura and K. Yamada,
J. Phys. Soc. Jpn. **71**, 404 (2002).

Also by Kuroki, Aoki *et al.*;
Yanase, Ogata *et al.*

Conclusion: Gap structure of Sr_2RuO_4

	γ - band	α, β- bands
Roles in Superconductivity	Active	Passive
Symmetry	$d = z\Delta_0(k_x + ik_y)$	
Gap structure	 Min. along [100].	 Zero along [110].
Physical Origin of Gap Anisotropy	Odd parity and FS proximity to BZ boundary	Incommensurate AF fluctuation





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