Unconventional(nematic) Metamagnetism in the t_{2g}-orbital System of $Sr_3Ru_2O_7$

Congjun Wu, UCSD

Collaborators: Wei-Cheng Lee, Daniel Arovas, UCSD

Ref: W. C. Lee, C. Wu, PRB 80, 104438 (2009);

W. C. Lee, C. Wu, PRL 103, 176101 (2009);

W. C. Lee, D. Arovas, and C. Wu, PRB 81, 184403 (2010);

W. C. Lee, C. Wu, arXiv:1008.2486.

Related past work on unconventional magnetism with S. C. Zhang (Stanford), E. Fradkin (UIUC).

C. Wu, S. C. Zhang, PRL 93, 36403 (2004); C. Wu, K. Sun, E. Fradkin, and S. C. Zhang, Phys. Rev. B 75, 115103 (2007).

Acknowledgments: J. C. Davis, J. Hirsch, S. Kivelson, A. Mackenzie.

March 3, 2010, UT- Austin

Outline

- **Introduction to unconventional magnetism (Pomeranchuk instabilities with spin):**

  anisotropic states: nematic electron liquids with spin;
  isotropic states: spontaneous generation of spin-orbit coupling.

  C. Wu, S. C. Zhang, PRL 93, 36403 (2004); C. Wu, K. Sun, E. Fradkin, and S. C. Zhang, Phys. Rev. B 75, 115103 (2007).

- Experimental results: nematic meta-magnetism in the t_{2g} orbital system of $Sr_3Ru_2O_7$.

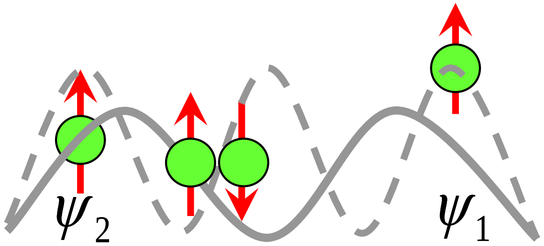
- Microscopic theory with quasi-1D bands of d_{xz} and d_{yz}. Orbital degree of freedom facilitates unconventional meta-magnetism exhibiting orbital ordering.

- STM quasi-particle interference as a test of orbital ordering.

Ferromagnetism: many-body collective effect

E. C. Stoner

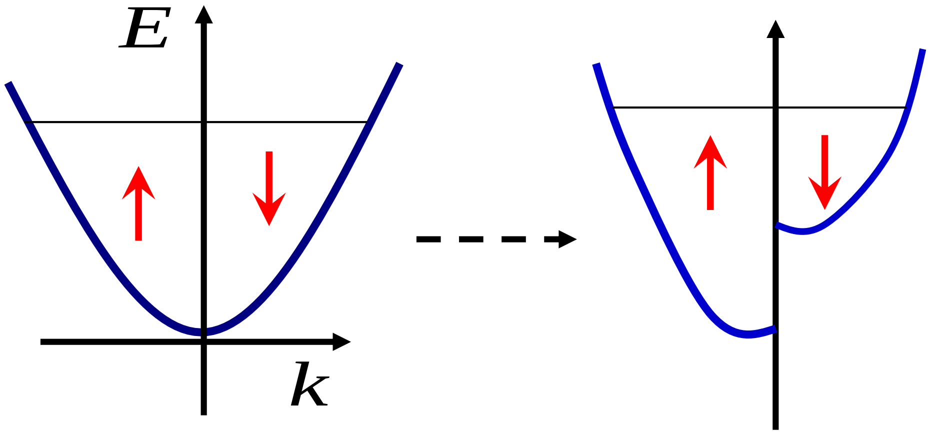
- Driving force: **exchange interaction among electrons**.



$$E_{\uparrow\uparrow} < E_{\uparrow\downarrow}$$

- Stoner criterion:

$$UN_0 > 1$$



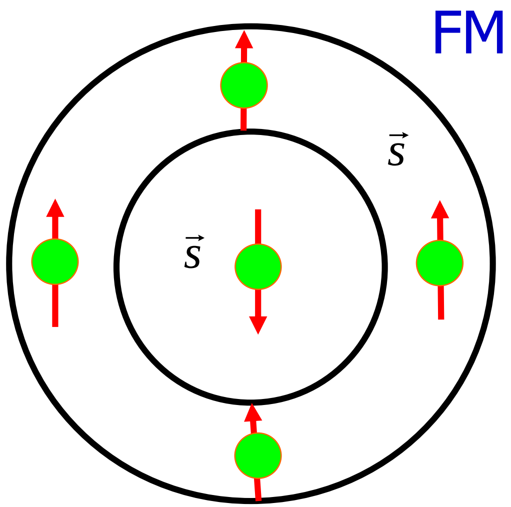
U – average interaction strength; N_0 – density of states at the Fermi level

Fe	Co	Ni

Ferromagnetism: ***s*-wave** magnetism

- Spin rotational symmetry is broken.

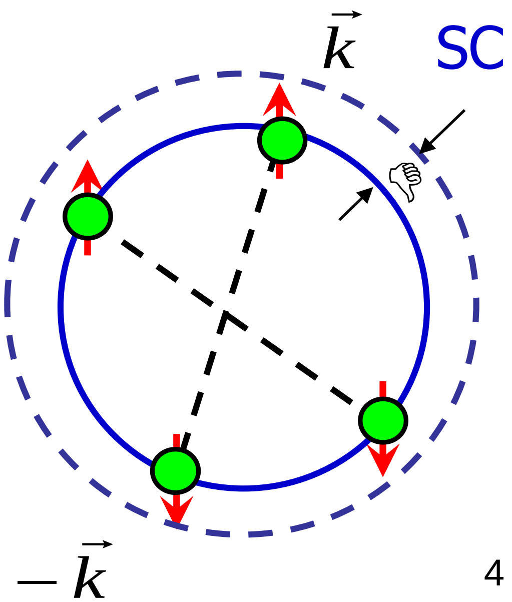
- Orbital rotational symmetry is **NOT** broken: spin polarizes along **a fixed direction** on the Fermi surface.



- *cf.* conventional superconductivity.

Cooper pairing between electrons with opposite momenta.

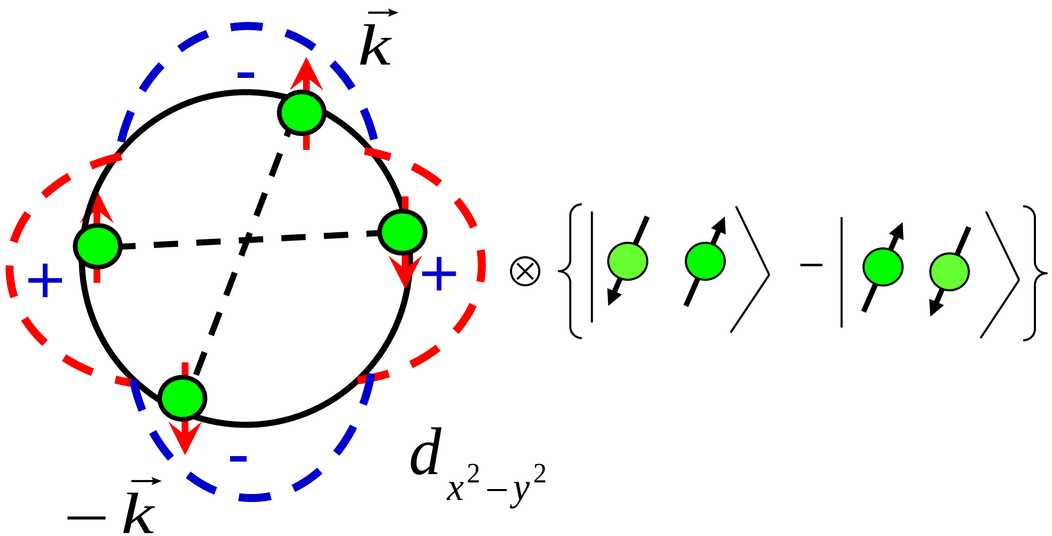
s-wave: pairing amplitude does not change over the Fermi surface.

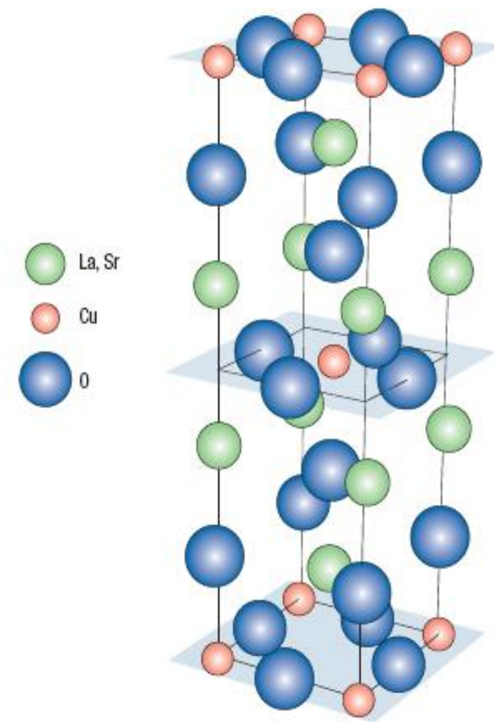


cf. Unconventional superconductivity

• High partial wave channel Cooper pairings (e.g. *p*, *d*-wave …).

• *d*-wave: high T_c cuprates. Paring amplitude changes sign in the Fermi surface.





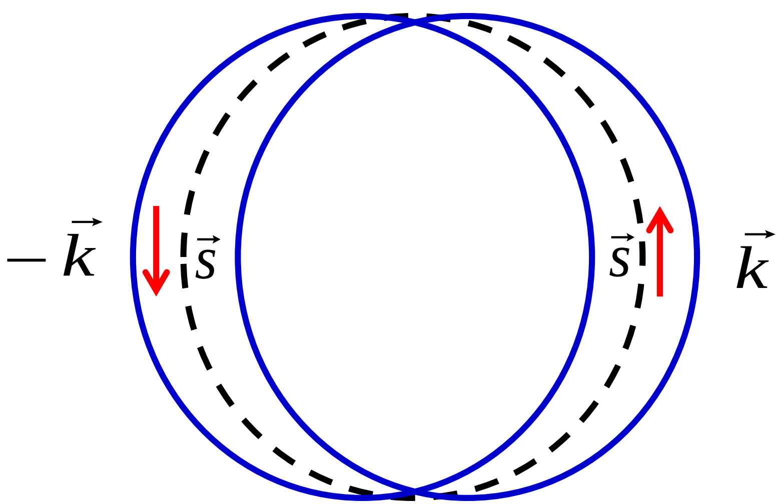
• *p*-wave: Sr_2RuO_4, ^{3}He-A and B.

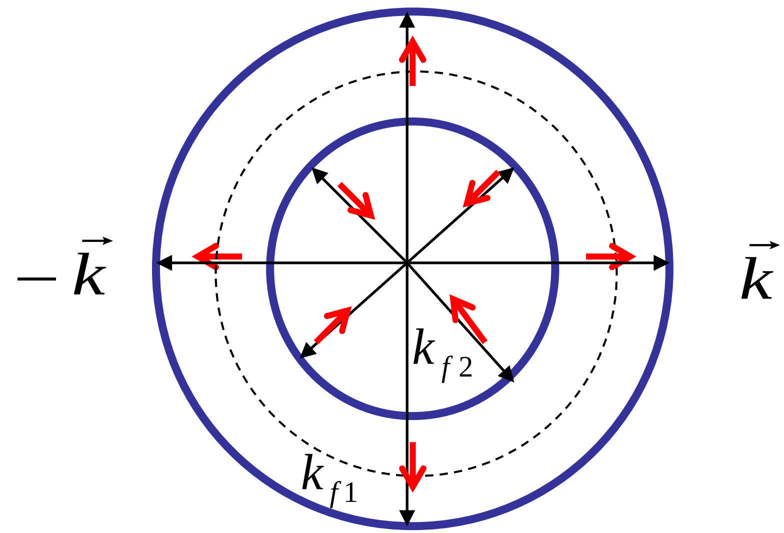
D. J. Van Harlingen, Rev. Mod. Phys. 67, 515 (1995); C. C. Tsuei et al., Rev. Mod. Phys. 72, 969 (2000).

New states of matter: **unconventional magnetism**!

- High partial wave channel generalizations of FM (e.g. *p, d-wave*…) as spin-dependent **Pomeranchuk** instabilities.

- Spin polarization varies over the Fermi surface.





anisotropic (♋) *p*-wave magnetic state

isotropic (♌) *p*-wave magnetic state

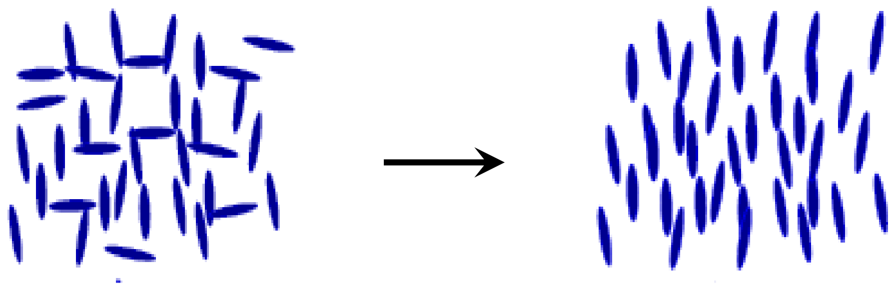
spin flips the sign as $\vec{k} \rightarrow -\vec{k}$.

Anisotropy: liquid crystalline order

- Classic liquid crystal.

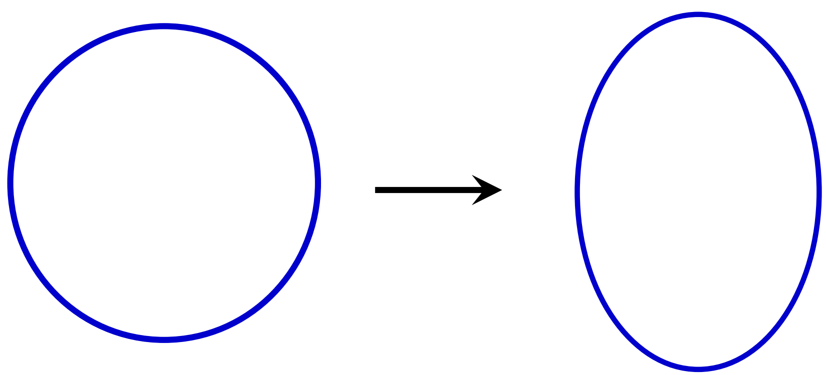
  Nematic phase: rotational anisotropic but translational invariant.

isotropic phase



nematic phase

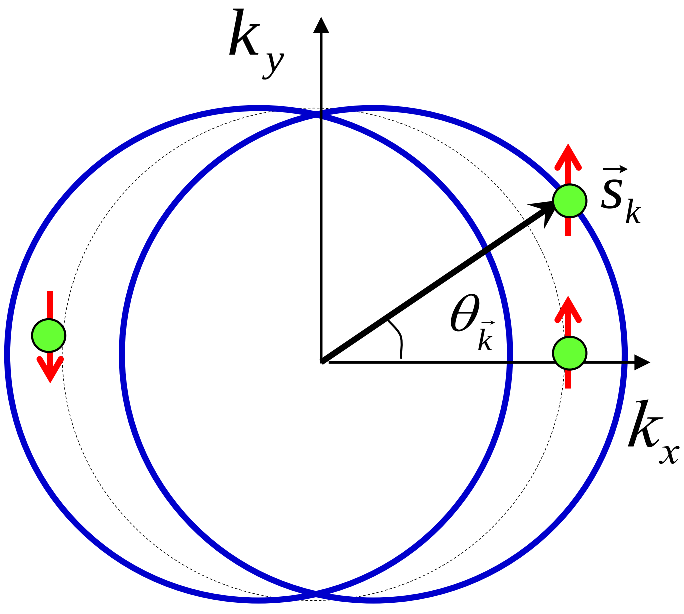
- Quantum version of liquid crystal: **nematic electron liquid**.



Fermi surface anisotropic distortions

S. Kivelson, et al, Nature 393, 550 (1998); V. Oganesyan, et al., PRB 64,195109 (2001).

Anisotropic unconventional (♋) magnetism: electron liquid crystal phases with **spin**!



anisotropic *p*-wave magnetic phase

- *p*-wave distortion of the Fermi surface.
- No net spin-moment: $\vec{S} = \sum_{\vec{k}} \vec{s}_k = 0$
- Spin dipole moment in momentum space (not in coordinate space).

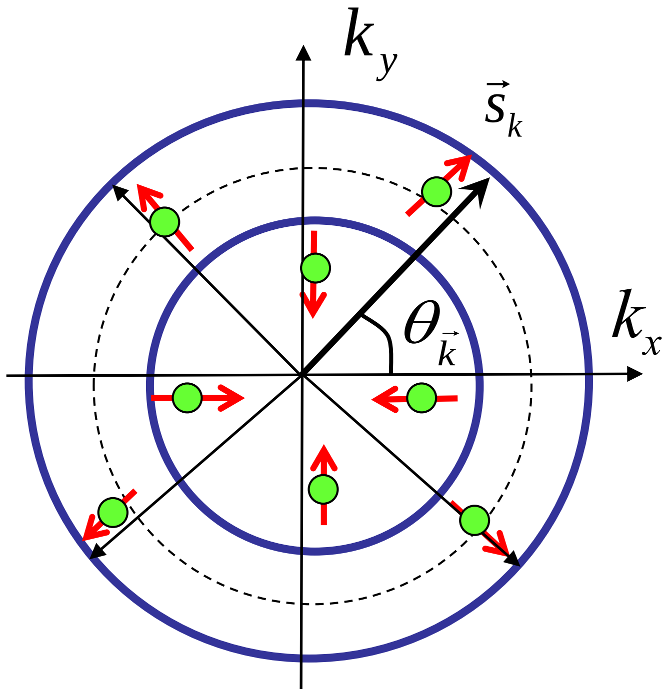
$$\vec{n}_1 = \sum_{\vec{k}} \vec{s}_k \cos\theta_k \neq 0$$

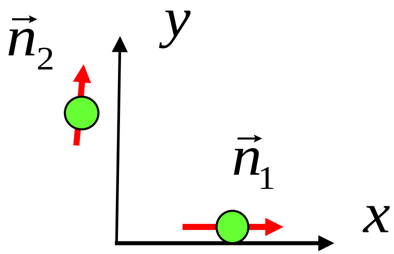
- Both orbital and spin rotational symmetries are broken.

spin-split state by J. E. Hirsch, PRB 41, 6820 (1990); PRB 41, 6828 (1990).

V. Oganesyan, et al., PRB 64,195109 (2001). C. Wu et al., PRL 93, 36403 (2004); Varma et al., Phys. Rev. Lett. 96, 036405 (2006)

The isotropic (♌➂ *p*-wave magnetic phase





- Spin is not conserved; helicity $\vec{\sigma} \cdot \vec{k}$ is a good quantum number.

- No net spin-moment; spin dipole moment in momentum space.

$$\vec{n}_1 = \sum_{\vec{k}} \vec{s}_k \cos\theta_k, \quad \vec{n}_2 = \sum_{\vec{k}} \vec{s}_k \sin\theta_k$$

- **Relative spin-orbit symmetry breaking.** Spontaneous generation of spin-orbit coupling without relativity!

$$H_{MF} = H_0 + \bar{n} \sum_k \psi^+_\alpha \vec{\sigma}_{\alpha\beta} \cdot \vec{k} \psi_\beta$$

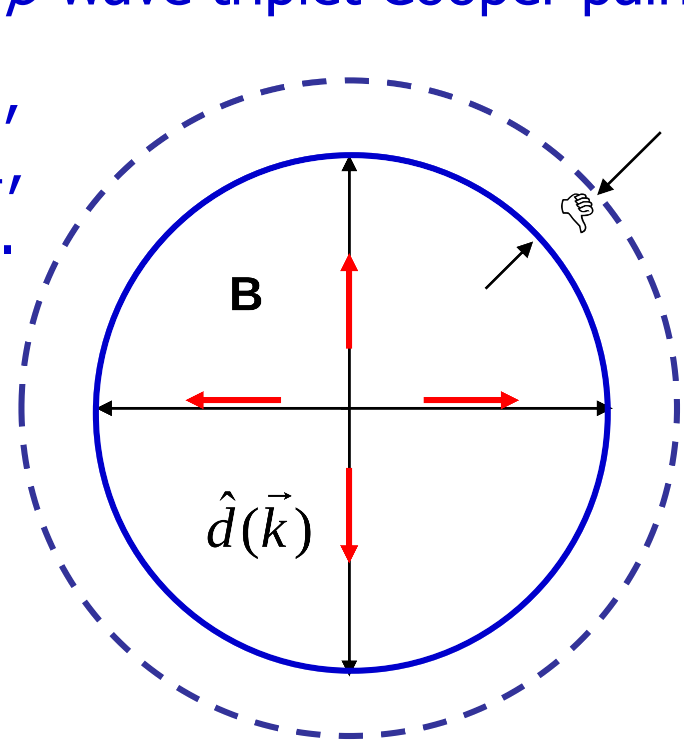
$$\bar{n} = |\vec{n}_1| = |\vec{n}_2|$$

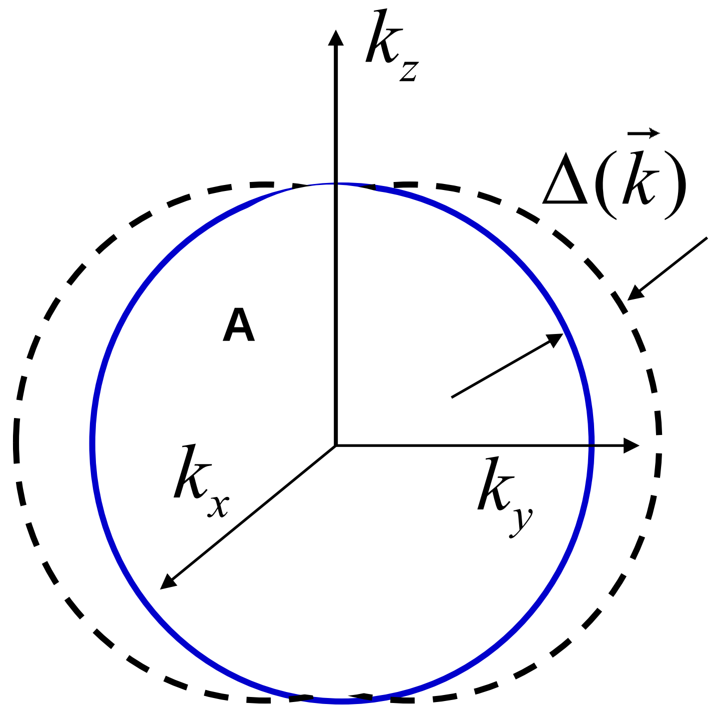
C. Wu et al., PRL 93, 36403 (2004);
C. Wu et al., PRB 75, 115103(2007).

cf. p-wave pairing Superfluid ^{3}He-B, A phases

- *p*-wave triplet Cooper pairing.

L=1,
S=1,
J=0.





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

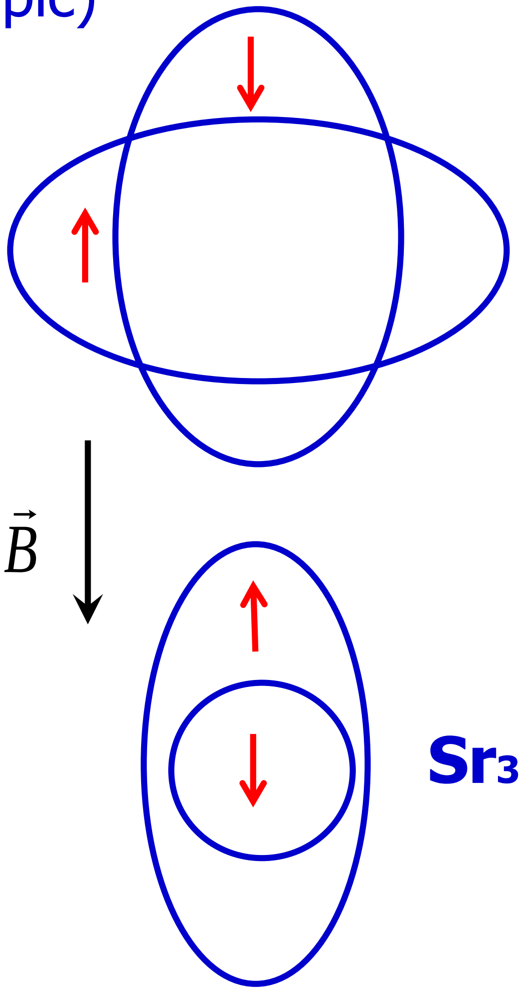
$$\vec{\Delta}(\vec{k}) = \Delta\hat{d}(\hat{k}_x + i\hat{k}_y)$$

- ^{3}He-B (isotropic) phase.
- ^{3}He-A (anisotropic) phase.

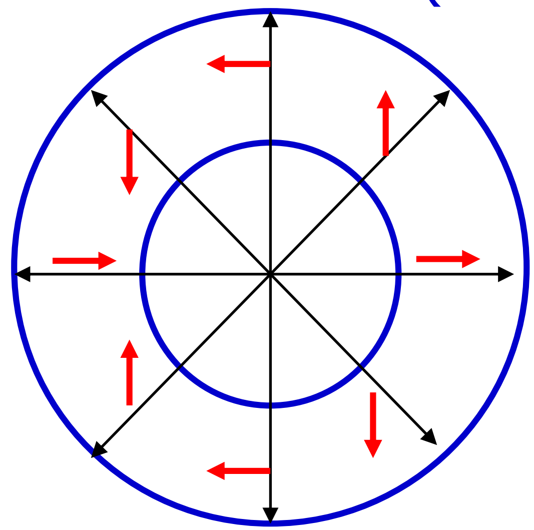
A. J. Leggett, Rev. Mod. Phys 47, 331 (1975)

2D *d*-wave α and β-phases

α-phase
(anisotropic)



β-phase
(isotropic): w=2



$Sr_3Ru_2O_7$

Outline

- Introduction to unconventional magnetism (Pomeranchuk instabilities with spin):

- **Experiments: nematic meta-magnetism in the t_{2g} orbital system of $Sr_3Ru_2O_7$.** -- A. P. Mackenzie's group.

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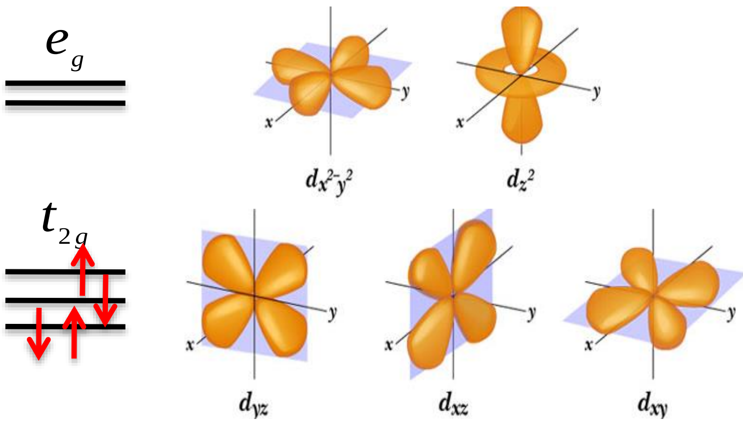
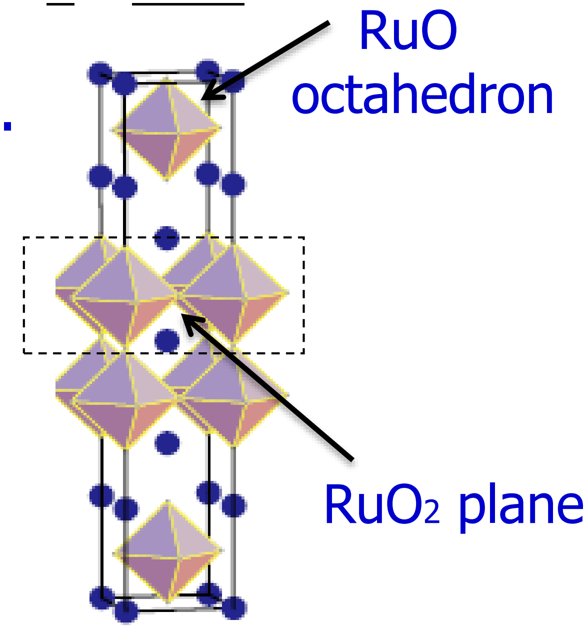
Strontium Ruthenates $Sr_{n+1}Ru_nO_{3n+1}$

- 4d shell; t_{2g} active; 4 electrons per Ru site.





- n=1: Sr_2RuO_4 p-wave superconductor with T_c=1.5K.

- n=2: $Sr_3Ru_2O_7$. No superconductivity. Paramagnet at B=0; **meta-magnetism** at finite B-fields.

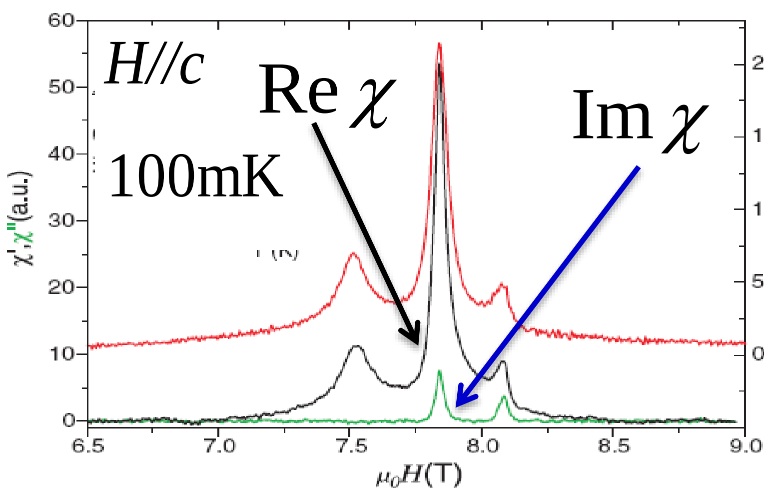
- n>=3: ferromagnet. As $n \to \infty$ ($SrRuO_3$), T_c=165 K.

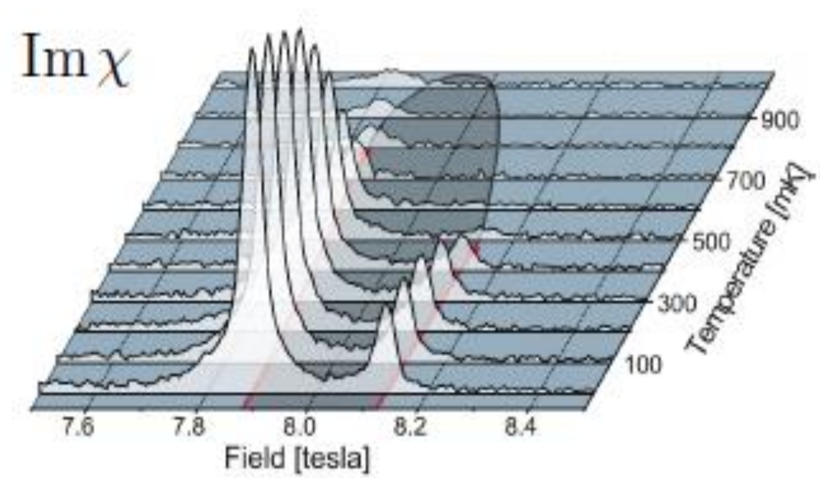
Metamagnetism in $Sr_3Ru_2O_7$

- Metamagnetism: a superlinear relation between magnetization and the B field. Analogy of FM at finite fields, but no symmetry breaking.

- Very pure samples $\rho \sim 0.4 \mu\Omega\,\mathrm{cm}$: two consecutive metamagnetic transitions at 7.8 and 8.1T from AC magnetic susceptibility (17Hz).

- Dissipative peaks in $\mathrm{Im}\,\chi$ mean first order phase transitions (hysteresis).





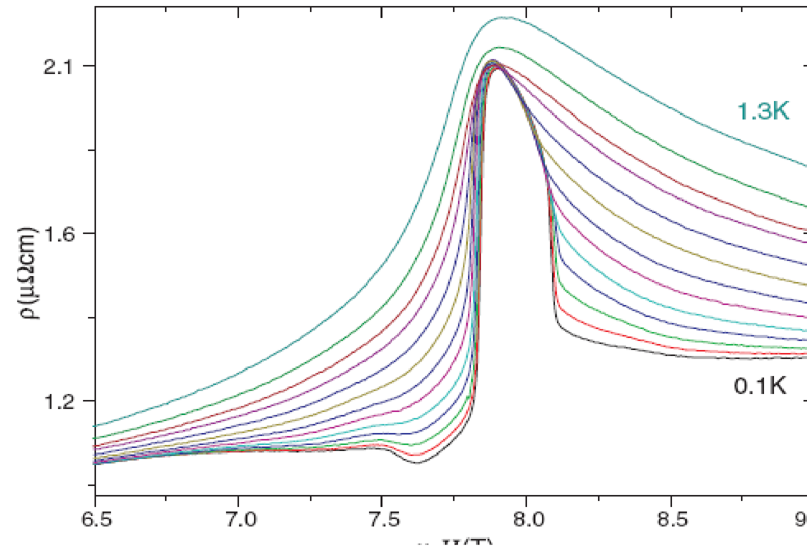
Grigera et. al., Science 306, 1154 (2004)

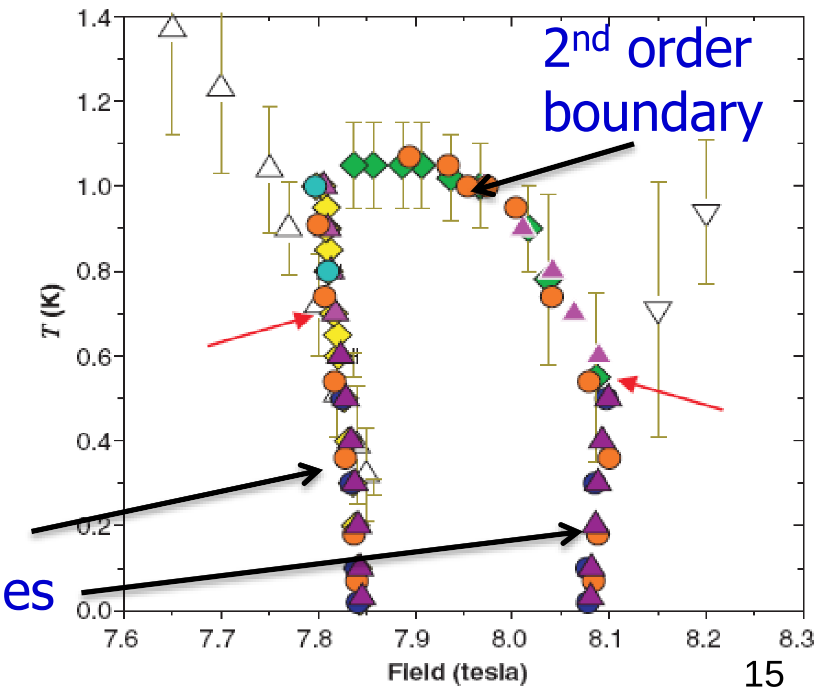
Resistance anomaly

- Between two metamagnetic transitions (T<1K), the resistivity measurement shows enhanced electron scattering.

- Many measurements mark the phase boundary.

- resistivity $\partial_H \rho$ ◆ $\partial_T^2 \rho$ ◆
- ac susceptibility ▲
- magnetostriction ●
- thermal expansion △ ▽
- dc magnetization ●





1st order boundaries

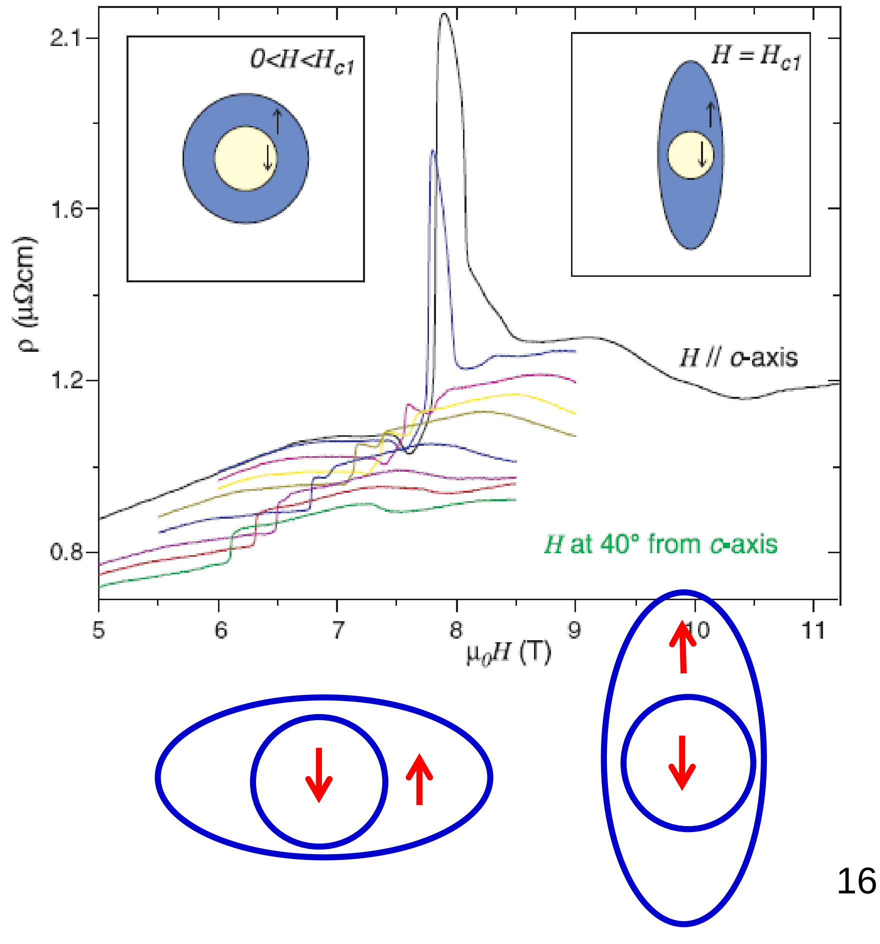
Grigera et. al., Science 306, 1154 (2004)

A new phase: Pomeranchuk instability!

• Spin-dependent Fermi surface anisotropic distortion -- partly d-wave anisotropic unconventional magnetism.

• Resistivity anomaly arises from the **domain formation** due to two different patterns of the nematic states.

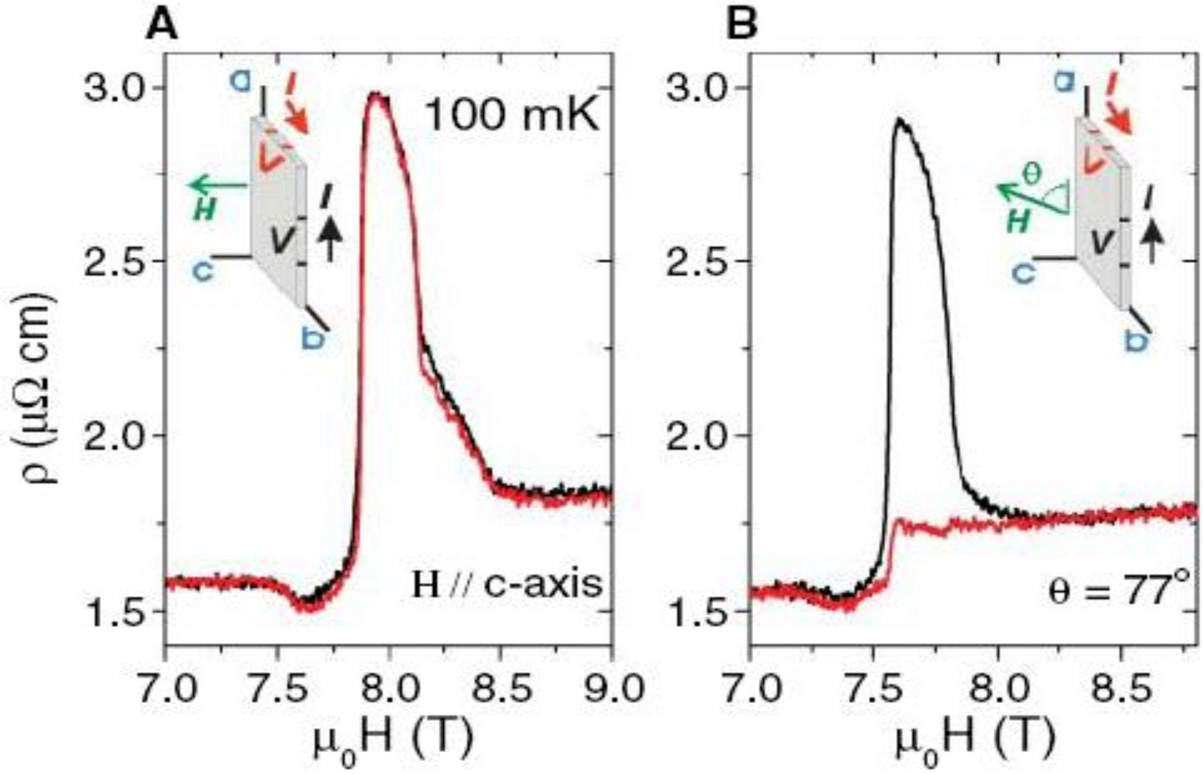
• Resistivity anomaly disappears as B titles from the c-axis, i.e., it is sensitive to the orientation of B-field.



Grigera et. al., Science 306, 1154 (2004)

Further evidence: anisotropic electron liquid

• As the B-field is tilted away from c-axis, large resistivity anisotropy is observed in the anomalous region for the in-plane transport.



Borzi et. al., Science 315, 214 (2007)

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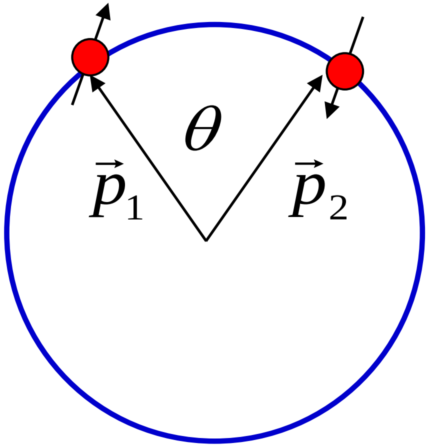
W. C. Lee and C. Wu, PRB 80, 104438 (2009). C. Wu, K. Sun, E. Fradkin, and S. C. Zhang, PRB 75, 115103 (2007).

• STM quasi-particle interference as a test of orbital ordering.

Landau Fermi liquid (FL) theory

L. Landau



- The existence of Fermi surface. Electrons close to Fermi surfaces are important → renormalized into quasi-particles.

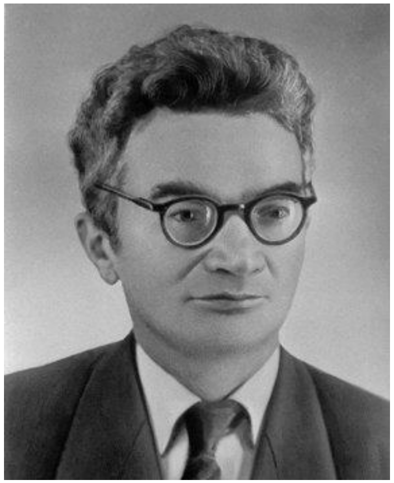
- Interaction functions (no SO coupling):

$$f_{\alpha\beta,\gamma\delta}(\hat{p}_1,\hat{p}_2)=f^{s}(\hat{p}_1,\hat{p}_2) \quad \text{density}$$
$$+f^{a}(\hat{p}_1,\hat{p}_2)\vec{\sigma}_{\alpha\beta}\cdot\vec{\sigma}_{\gamma\delta} \quad \text{spin}$$

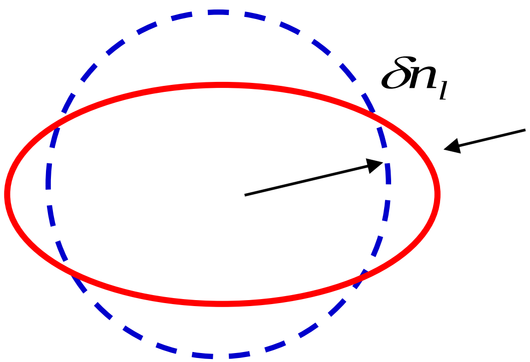
- Landau parameter in the *l*-th partial wave channel:

$$F_l^{s,a}=N_0 f_l^{s,a} \qquad N_0: \mathrm{DOS}$$

Pomeranchuk instability criterion



I. Pomeranchuk



- Fermi surface: elastic membrane.
- Stability:

$$\Delta E_K \propto (\delta n_l^{s,a})^2$$

$$\Delta E_{\text{int}} \propto \frac{F_l^{s,a}}{2l+1}(\delta n_l^{s,a})^2$$

- Surface tension vanishes at:

$$F_l^{s,a} < -(2l+1)$$

- Ferromagnetism: the F_0^a channel.
- Nematic electron liquid: the F_2^s channel.

- Unconventional magnetism: $F_l^a \ (l \geq 1)$

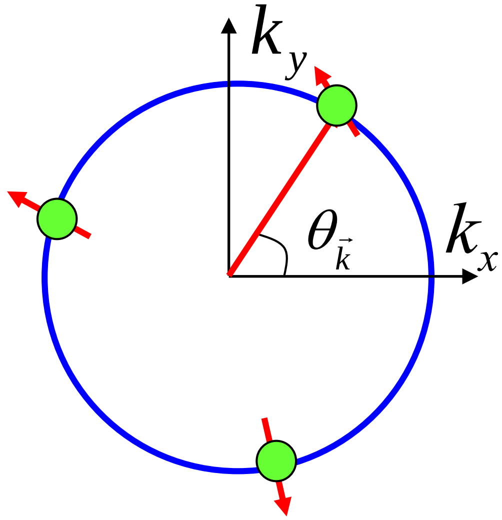
The order parameters: the 2D *d*-wave channel

- F_2^a : spin quadrupole moments in **momentum space**.

C. Wu, K. Sun, E. Fradkin, and S. C. Zhang, Phys. Rev. B 75, 115103 (2007).

$$\vec{n}_{x^2-y^2} = \sum_{\vec{k}} \psi_k^+ \vec{\sigma} \psi_k \cos 2\theta_k$$

$$\vec{n}_{xy} = \sum_{\vec{k}} \psi_k^+ \vec{\sigma} \psi_k \sin 2\theta_k$$



- *cf*. Ferromagnetic order (s-wave): $\vec{s} = \sum_{\vec{k}} \psi_k^+ \vec{\sigma} \psi_k$

- Arbitrary partial wave channels: spin-multipole moments.

$$F_l^a : \cos 2\theta_k \rightarrow \cos l\theta_k ; \;\; \sin 2\theta_k \rightarrow \sin l\theta_k$$

Mean field theory and Ginzburg-Landau free energy

- The d-wave spin exchange interaction:

F_2^a

$$H_{\text{int}} = \sum_q f_2^a(\vec{q})\{\vec{n}_{x^2-y^2}(\vec{q})\cdot\vec{n}_{x^2-y^2}(\vec{q}) + \vec{n}_{xy}(\vec{q})\cdot\vec{n}_{xy}(\vec{q})\}$$

$$H_{MF} = \sum_k \psi^+(k)[\varepsilon(k) - \mu - (\vec{n}_{x^2-y^2}\cos 2\theta_k + \vec{n}_{xy}\sin 2\theta_k)\cdot\vec{\sigma}]\psi(k)$$

- Symmetry constraints: rotation (spin, orbital), parity, time-reversal.

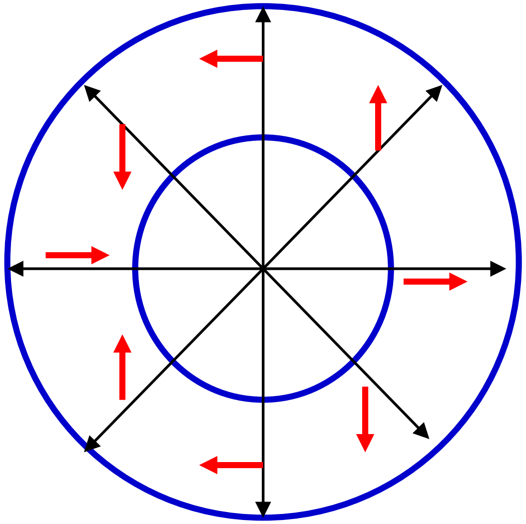
$$F = r(|\vec{n}_{x^2-y^2}|^2 + |\vec{n}_{xy}|^2) + v_1(|\vec{n}_{x^2-y^2}|^2 + |\vec{n}_{xy}|^2)^2 + v_2|\vec{n}_{x^2-y^2}\times\vec{n}_{xy}|^2$$

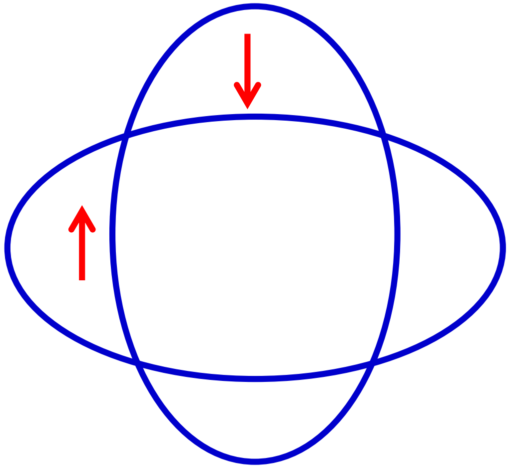
$$r = \frac{N_0}{2}\frac{1+F_2^a/2}{|F_2^a|}$$

$F_2^a < -2$ → instability!

β and α-phases (*d*-wave)

F_2^a





$v_2 < 0 : \beta - \text{phase}$

$v_2 > 0 : \alpha - \text{phase}$

$\vec{n}_{x^2-y^2} \perp \vec{n}_{xy}$ and $|\vec{n}_{x^2-y^2}| = |\vec{n}_{xy}|$

$\vec{n}_{x^2-y^2} // \vec{n}_{xy}; |\vec{n}_{x^2-y^2}| / |\vec{n}_{xy}|$ arbitary

$$H_{MF,\beta} = \sum_k \psi^+(k)[\varepsilon(k) - \mu - \bar{n}(\sigma_x \cos 2\theta_k + \sigma_y \sin 2\theta_k)]\psi(k)$$

$$H_{MF,\alpha} = \sum_k \psi^+(k)[\varepsilon(k) - \mu - \bar{n}\sigma_z \cos 2\theta_k]\psi(k)$$

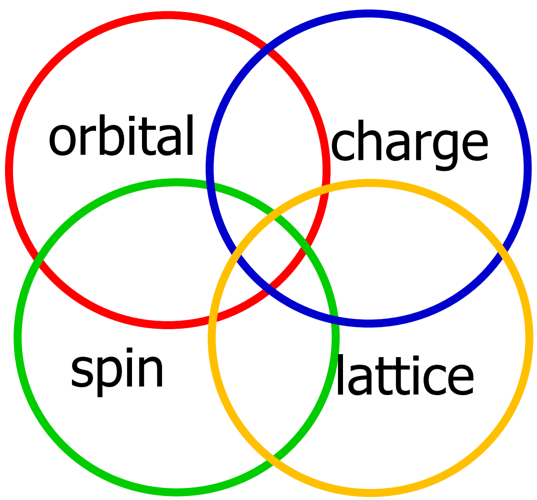
Ref: C. Wu, K. Sun, E. Fradkin, and S. C. Zhang, PRB 75, 115103 (2007).

New ingredients of $Sr_3Ru_2O_7$: t_{2g}-orbitals

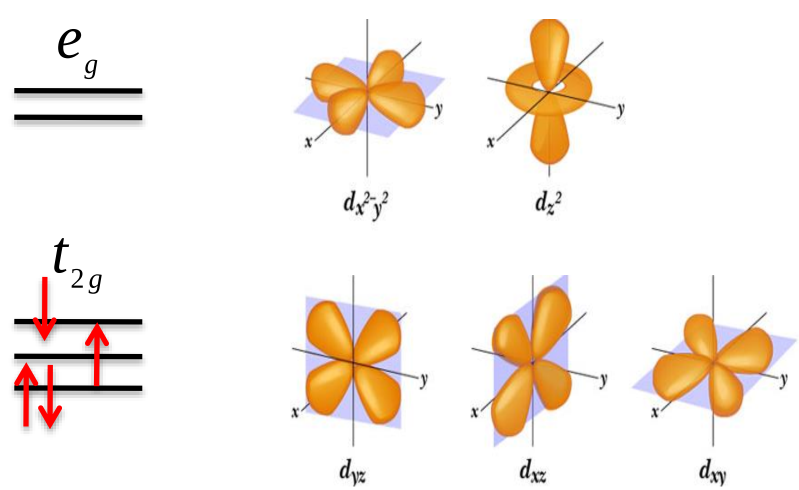
- Itinerant metallic bilayer 4d-system with active t_{2g}-bands (d_{xy}, d_{xz}, d_{yz}).

- Orbitals play important roles in magnetism, superconductivity, and transport properties in transitional metal oxides.

- Orbital degeneracy and spatial anisotropy.

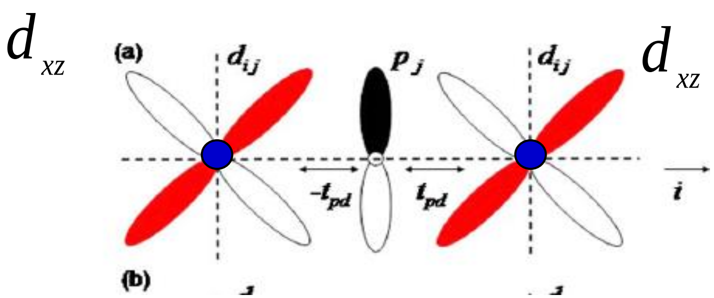


d-orbitals: $d_{x^2-y^2}, d_{r^2-3z^2}, d_{xy}, d_{yz}, d_{xz}$

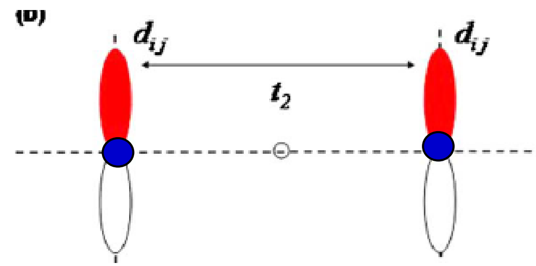


Anisotropic bondings: 2D v.s. quasi 1D bands

- Longitudinal bonding: hopping assisted by oxygen; strong.
- Transverse bonding: direct overlap; weak.

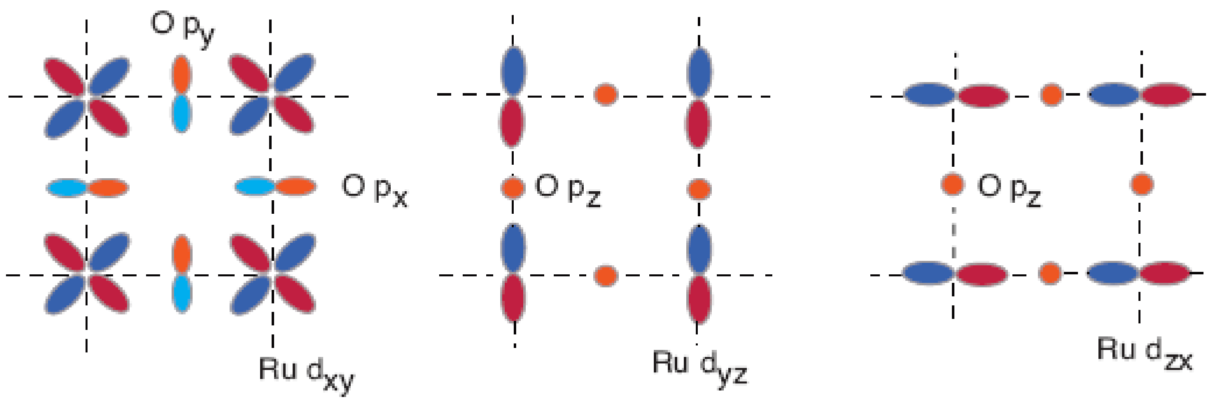


Ru O Ru



Ru O Ru

- In-plane bonding. d_{xy}-band: 2D band; d_{xz} and d_{yz}: quasi-1D bands.



Questions and Observations

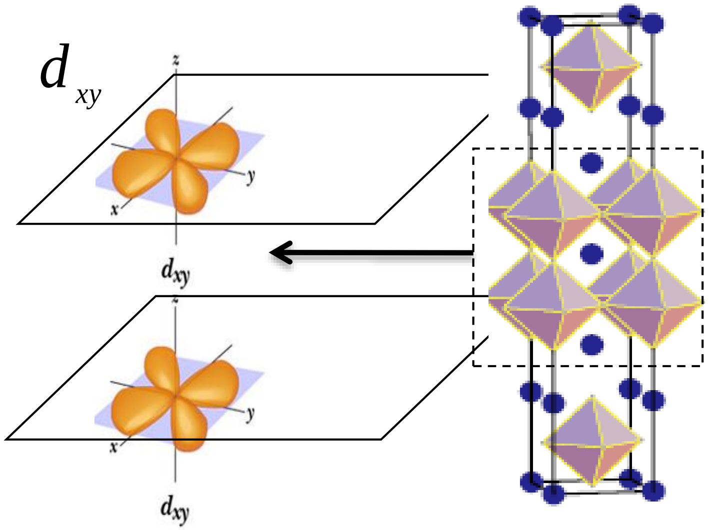
• Q1: Generalize the unconventional magnetic states to orbital systems. Which orbital bands are responsible in Sr327?

• Q2: Landau parameters in high partial wave channels are usually not large. How to enhance the d-wave channel interactions?

• Unconventional (nematic) meta-magnetic transitions in $Sr_3Ru_2O_7$ are NOT observed in the monolayer compound Sr_2RuO_4.

• The bilayer splitting of the d_{xy}-band is very small. No oxygen p-orbitals are involved.

• The d_{xy}-band structures in $Sr_3Ru_2O_7$ and Sr_2RuO_4 are similar.



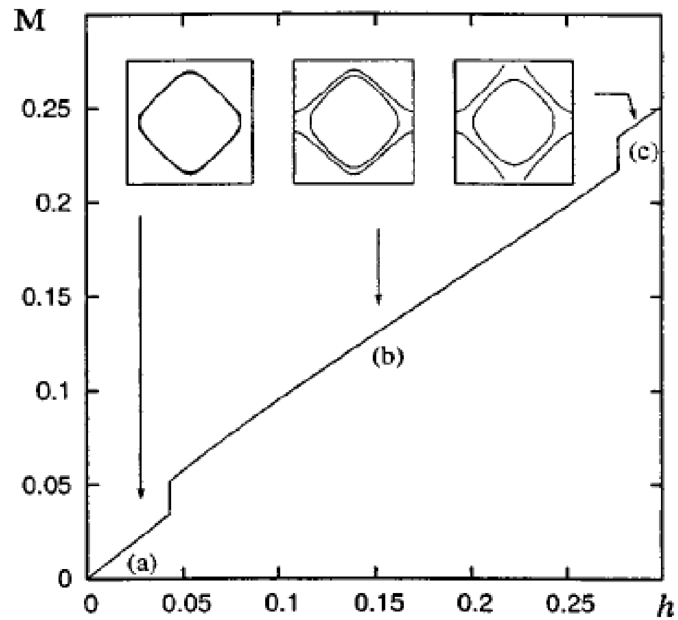
Previous theory based on the d_{xy}-band by Kee et al.

• As the B-field increases, the Fermi surface (FS) of the majority spin expands and approaches the van Hove singularity.

• The 1st meta-magnetic transition: the FS of the majority spin is distorted to cover one of vHs along the x and y directions.

• The 2nd transition: four-fold rotational symmetry is restored.

• Drawback: an artificial d-wave channel inter-site interaction is involved.

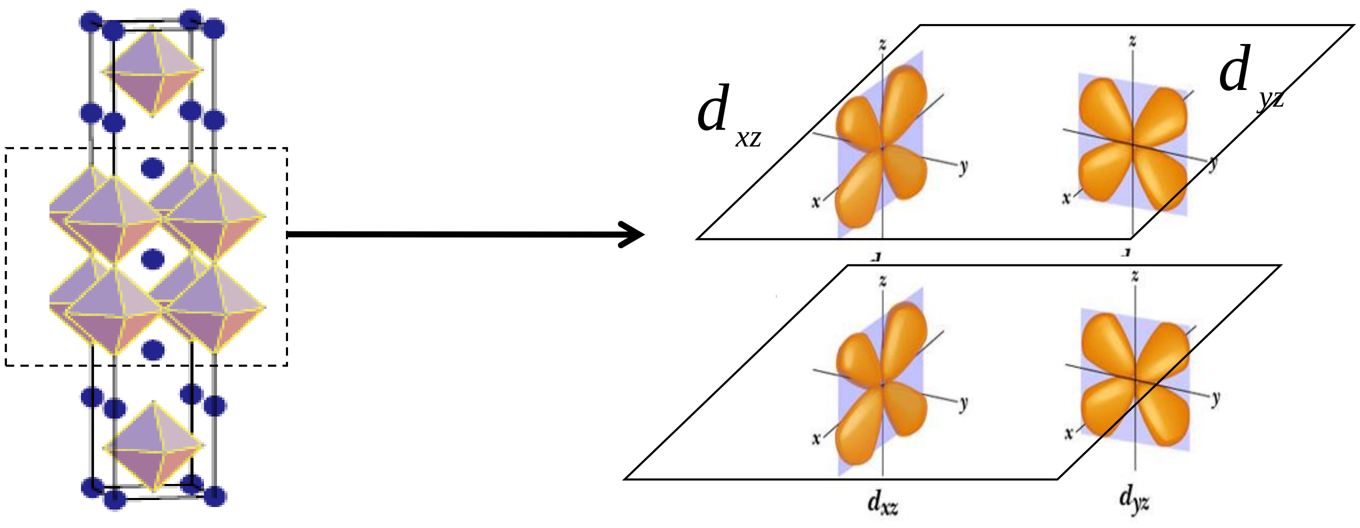


H.-Y. Kee and Y.B. Kim, Phys. Rev. B 71, 184402 (2005); Yamase and Katanin, J. Phys. Soc. Jpn 76, 073706 (2007); C. Puetter et. al., Phys. Rev. B 76, 235112 (2007).

Our proposed solution: quasi-1D d_{xz} and d_{yz}

- The major difference between $Sr_3Ru_2O_7$ and Sr_2RuO_4 is the large bilayer splitting of d_{xz}/d_{yz} bands.

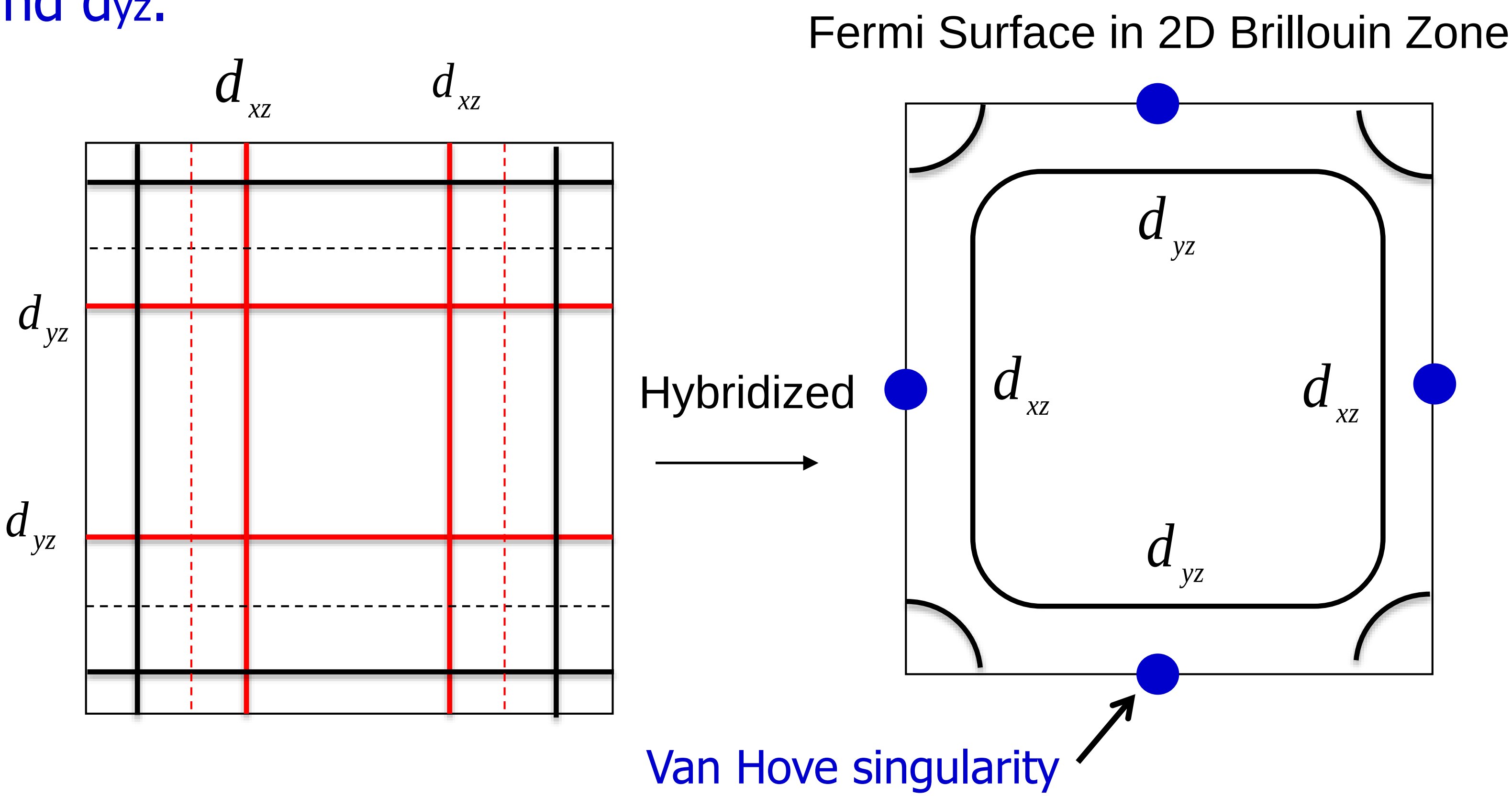
- We will see that orbital band hybridization naturally enhances the *d*-wave channel exchange interaction.



- Similar proposal has also been made by S. Raghu, S. Kivelson *et al.*, Phys. Rev. B 79, 214402(2009).

d_{xz} / d_{yz} orbital band structures and hybridizations

- For simplicity, we only keep the bilayer bonding bands of d_{xz} and d_{yz}.

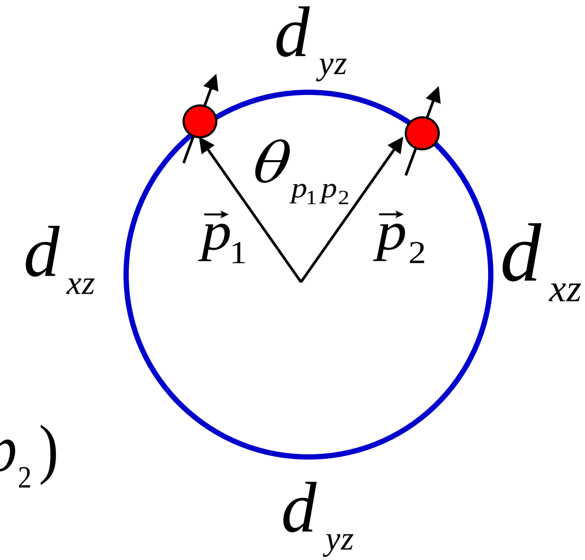


- Eigen-basis has internal *d*-wave like form factors of the orbital configurations.

Band hybridization enhanced Landau interaction in high partial-wave channels

- A heuristic argument: a hybridized band Bloch wavefunction with internal orbital configuration as

$$\left|\Psi_\sigma(p)\right\rangle = e^{ipr}(\cos\phi_p \left|d_{xz}\right\rangle + \sin\phi_p \left|d_{yz}\right\rangle) \otimes \chi_\sigma$$



- The Landau interaction acquires a d-wave angular form factor as.

$$f_{\uparrow\uparrow}(\vec{p}_1, \vec{p}_2) = V(q=0) - \tfrac{1}{2}[1+\cos 2\theta_{p_1 p_2}]V(p_1 - p_2)$$

$$f_{\uparrow\downarrow}(\vec{p}_1, \vec{p}_2) = V(q=0)$$

- Even $V(p_1-p_2)$ is dominated by the *s*-wave component, the angular form factor shifts a significant part of the spectra weight into the *d*-wave channel.

Microscopic Model

- Band Hamiltonian: σ-bonding $t_{//}$, π-bonding $t_{\perp}$, next-nearest-neighbour hoppings t', t''

$$H_{band} = \sum_{k,\sigma} \varepsilon_x(k) d^+_{xz,k\sigma} d_{xz,k\sigma} + \varepsilon_y(k) d^+_{yz,k\sigma} d_{yz,k\sigma} + \lambda(k)\left(d^+_{xz,k\sigma} d_{yz,k\sigma} + h.c.\right)$$

$$\varepsilon_x(k) = -2t_{//}\cos k_x - 2t_{\perp}\cos k_y - 4t'\cos k_x \cos k_y$$

$$\varepsilon_y(k) = -2t_{\perp}\cos k_y - 2t_{//}\cos k_x - 4t'\cos k_x \cos k_y$$

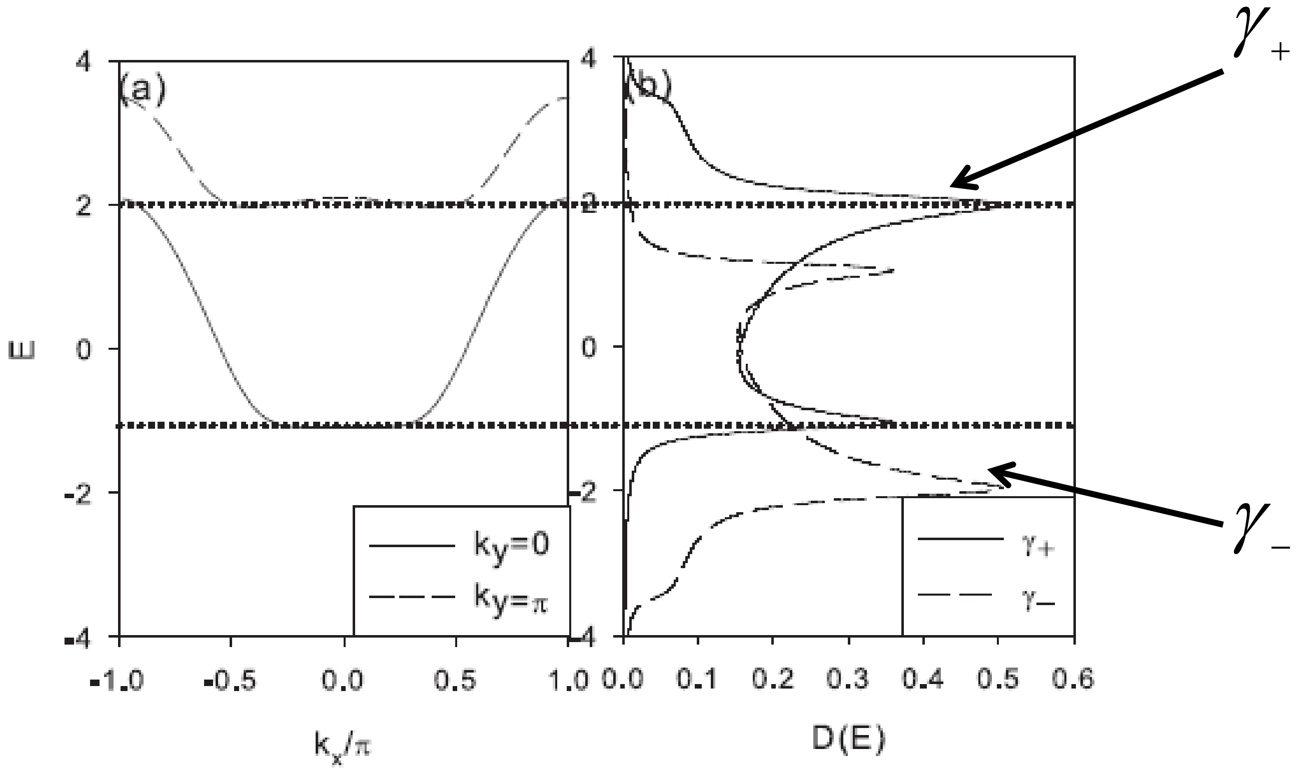
$$\lambda(k) = 4t''\cos k_x \cos k_y$$

- Hybridized eigen-basis.

$$\begin{pmatrix} \gamma_{+,k\sigma} \\ \gamma_{-,k\sigma} \end{pmatrix} = \begin{pmatrix} \cos\phi_k & \sin\phi_k \\ -\sin\phi_k & \cos\phi_k \end{pmatrix} \begin{pmatrix} d_{xz,k\sigma} \\ d_{yz,k\sigma} \end{pmatrix}, \quad \tan 2\phi_k = \frac{-4t''}{t_{//} - t_{\perp}} \frac{\cos k_x \cos k_y}{(\cos k_x - \cos k_y)}$$

$$E^{\pm}(k) = \frac{1}{2}\left(\varepsilon_x(k) + \varepsilon_y(k) \pm \sqrt{(\varepsilon_x(k) - \varepsilon_y(k))^2 + 4\lambda^2(k)}\right)$$

van Hove Singularity of density of states



$$(t_{//}, t_{\perp}, t', t'') = (1.0, 0.145, 0.0, 0.3)$$

Mean-Field Solution based on the multiband Hubbard model

$$H_{\mathrm{int}} + H_{zeeman} = U \sum_{i,a=xz,yz} n_{a\uparrow}(i) n_{a\downarrow}(i) + V \sum_i n_{xz}(i) n_{yz}(i) - J \sum_i \{ S_{xz}(i) \cdot S_{yz}(i) - \tfrac{1}{4} n_{xz}(i) n_{yz}(\mathrm{i}) \}$$

$$+ \Delta \sum_i d^+_{xz\uparrow}(i) d^+_{xz\downarrow}(i) d_{yz\downarrow}(i) d_{yz\uparrow}(i) + h.c. - h \sum_{a=xz,yz\sigma} \sigma d^+_{a\sigma} d_{a\sigma}$$

- Competing orders: magnetization(m), charge (n_c) /spin quadrupolar (n_{sp}) orders near the van Hove singularity.

$$m = \sum_{a=xz,yz} \langle S_a(z) \rangle, \quad n_c = \tfrac{1}{2} \{ \langle n_{xz} \rangle - \langle n_{yz} \rangle \}, \quad n_{sp} = \langle S_{xz}(z) \rangle - \langle S_{yz}(z) \rangle$$

$$H_{mf} = \sum_{k\sigma,\alpha=\pm} \xi_{\alpha\sigma} \gamma^+_{\alpha k\sigma} \gamma_{\alpha k\sigma} + V_m m^2 + V_c n_c^2 + V_{sp} n_{sp}^2$$

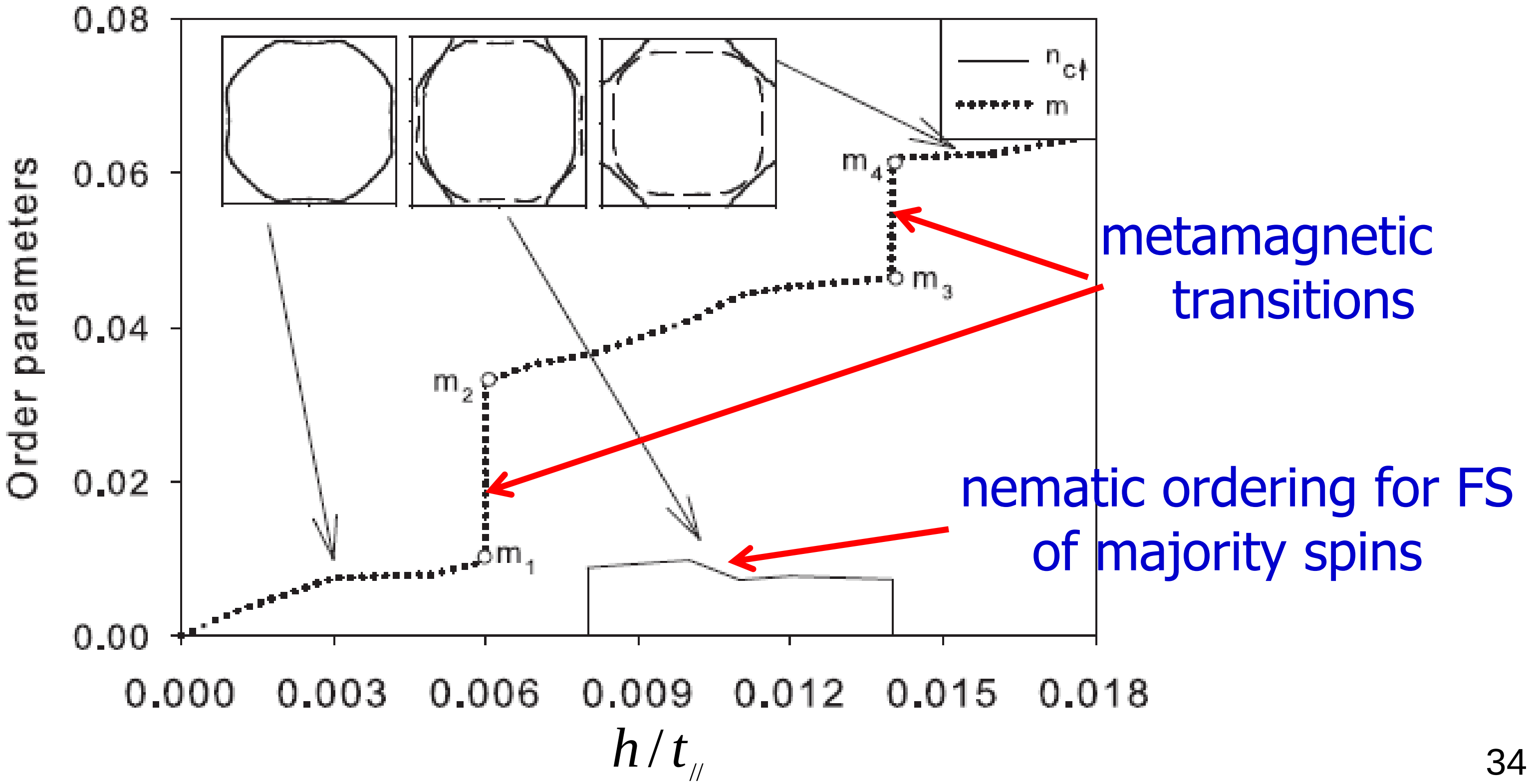
$$\xi_{\alpha\sigma} = E^{\alpha}(k) - \mu - \sigma V_m m - \alpha \left(V_c n_c + \sigma V_{sp} n_{sp} \right) \cos 2\phi_k$$

$$V_m = \frac{U}{2} + \frac{J}{4} \quad , \quad V_c = V + \frac{J}{4} - \frac{U}{2} \quad , \quad V_{sp} = \frac{U}{2} - \frac{J}{4}$$

Phase diagram v.s. the B-field

- **Unconventional** metamagnetism from the **conventional** Hubbard interactions at the mean-field level.

- Nematic ordering as orbital ordering: different occupations between d_{xz} and d_{yz} orbitals.



Outline

- Introduction to unconventional magnetism.

- Experimental results: unconventional (nematic) meta-magnetism in the t_{2g} system of $Sr_3Ru_2O_7$ (bilayer).

- Pomeranchuk instability of Fermi liquids.

- Microscopic theory with quasi-1D bands of d_{xz} and d_{yz}: unconventional metamagnetism with orbital ordering.

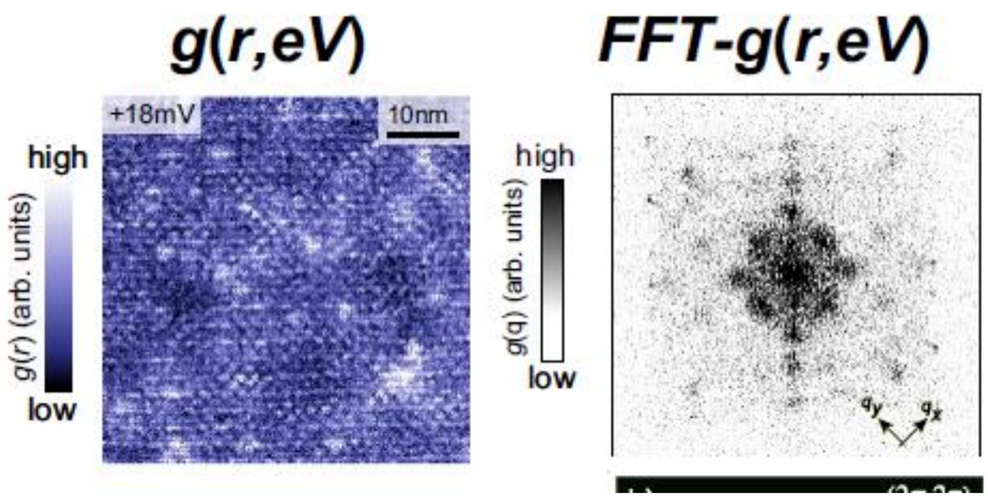
- **STM quasi-particle interference as a test of orbital ordering.**

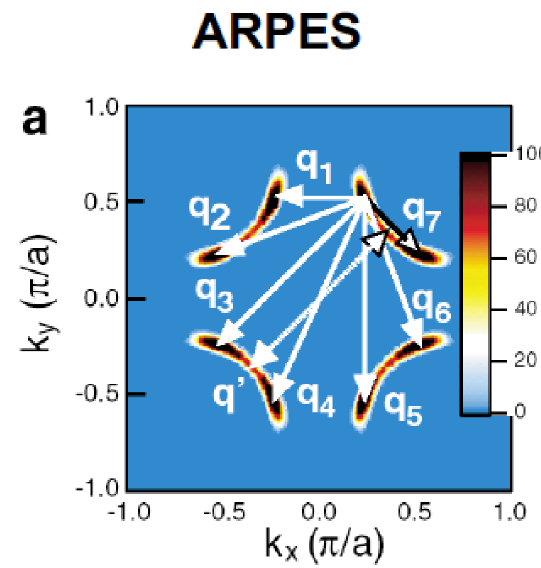
W. C. Lee and C. Wu, Phys. Rev. Lett. 103, 176101 (2009);

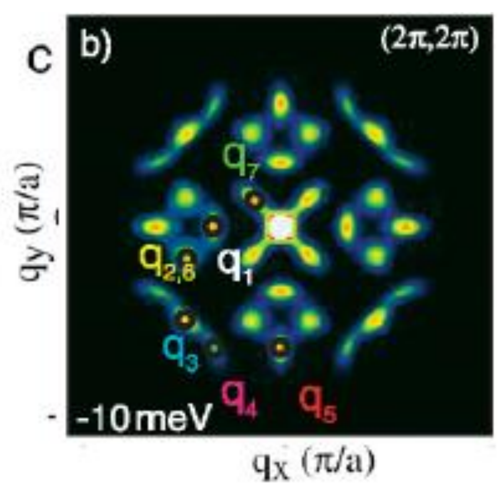
W. C. Lee, D. Arovas, and C. Wu, Phys. Rev. B 81, 184403 (2010).

Spectroscopic Imaging STM quasi-particle interference

- Real space spectroscopy reveals Fermi surface structure. Widely used in high T_c cuprate systems.





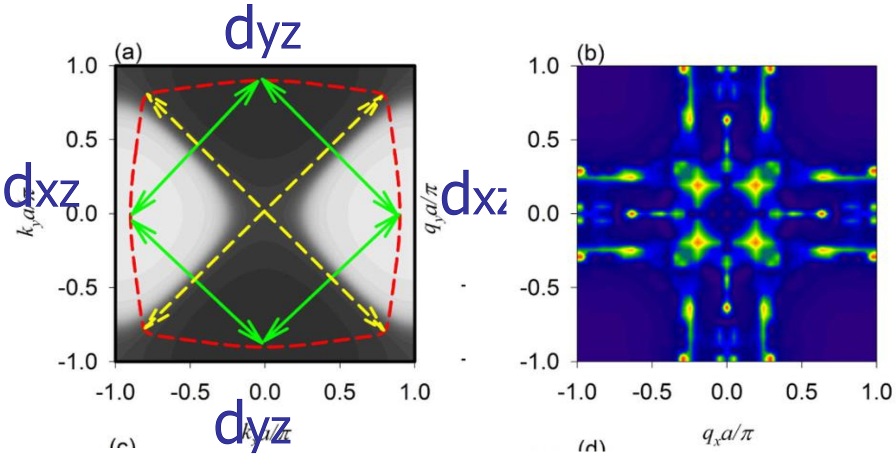


Y. Kohsaka et al., Nature (London) 454, 1072 (2008).
Q.-H. Wang and D.-H. Lee, Phys. Rev. B 67, 020511 (2003).

A toy model calculation: QPI of quasi-1D dxz/dyz bands

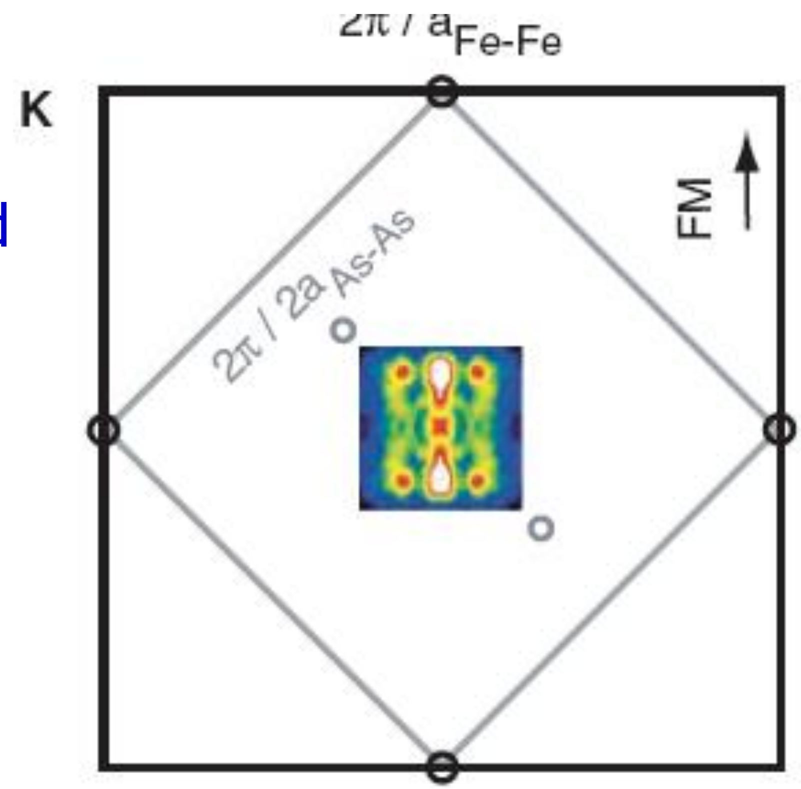
- Quasi 1D orbital band structure.

W. C. Lee and C. Wu, PRL 103, 176101(2009).

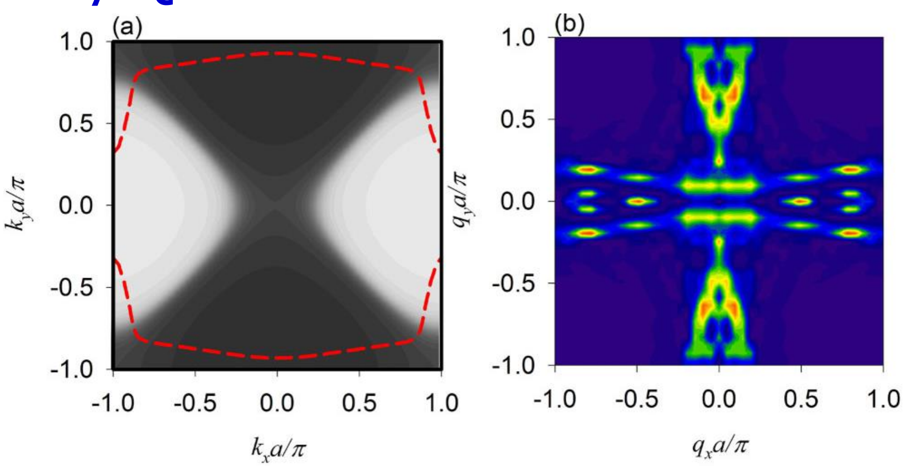


- c.f. $Ca(Fe_{1-x}Co_x)_2As_2$: QPI shows nematic ordering.

Chuang et al, Science 327, 181 (2010).

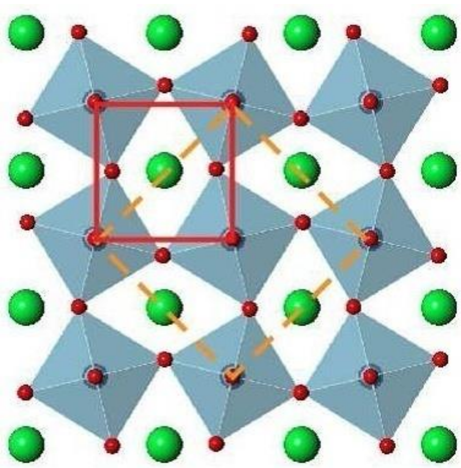


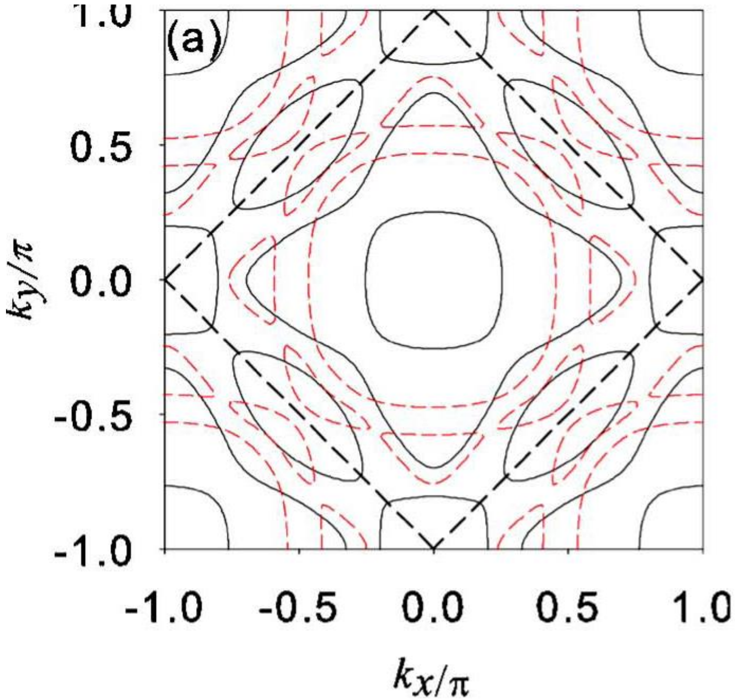
- Orbital ordering can be detected by QPI.



Band structures of $Sr_3Ru_2O_7$

- Complication from the orbital structure, the staggered rotation of RuO octahedra; bilayer splitting, and spin-orbit coupling.
- Fermi surfaces from the tight-binding model.
- Reduced Brillouin zone.
- Bilayer bonding (black) and anti-bonding (red) bands.



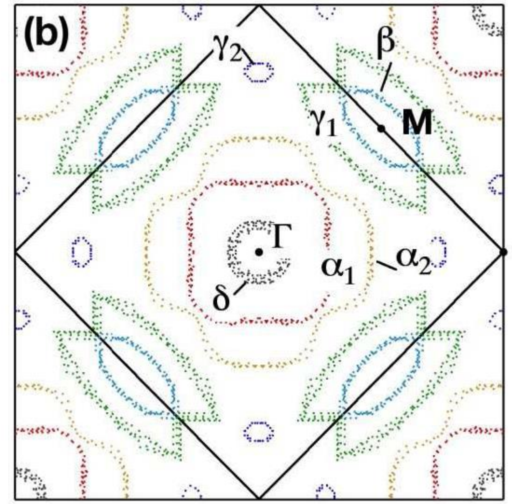


W. C. Lee, D. Arovas, and C. Wu, Phys. Rev. B 81, 184403 (2010).

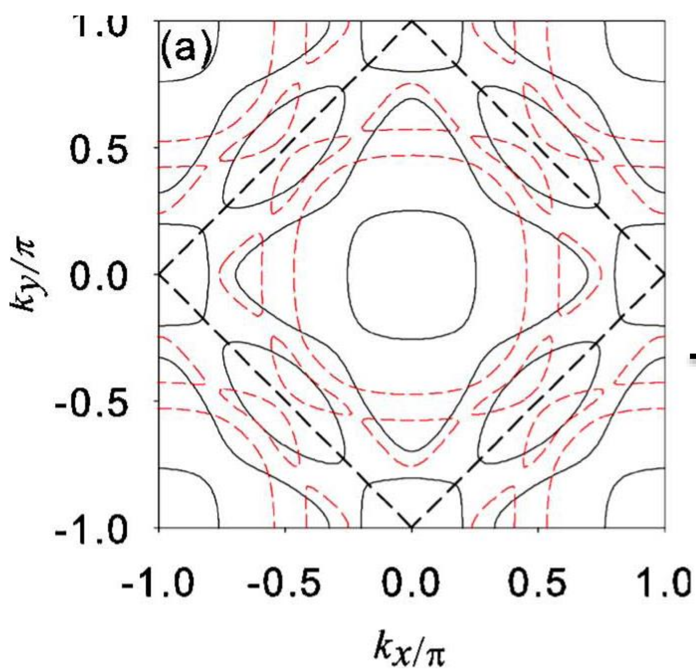
Band structures of $Sr_3Ru_2O_7$ at surface

- Fermi surfaces measured by ARPES. Bilayer bias due to the surface effect.

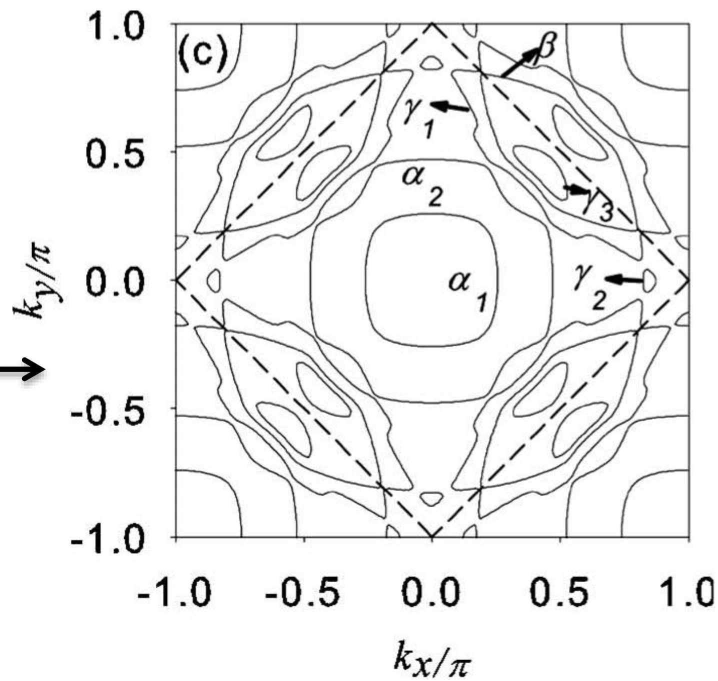
A. Tamai, et al, Phys. Rev. Lett. 101, 026407 (2008)



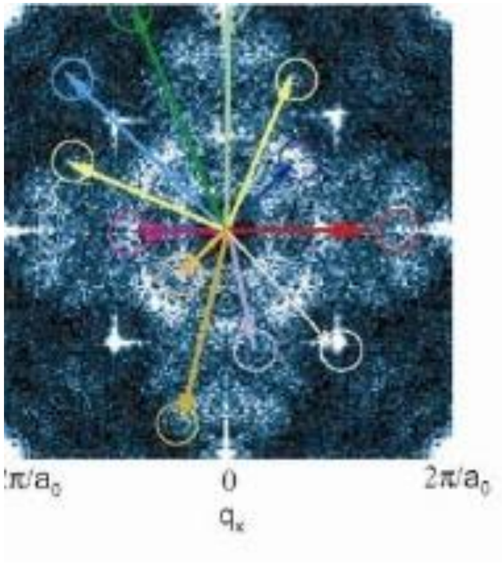
- Tight-binding fit with V_{bias}=10% band width of d_{xz} and d_{yz}. Band crossings avoided.



V_{bias} →



STM QPI at zero field (B=0) in $Sr_3Ru_2O_7$

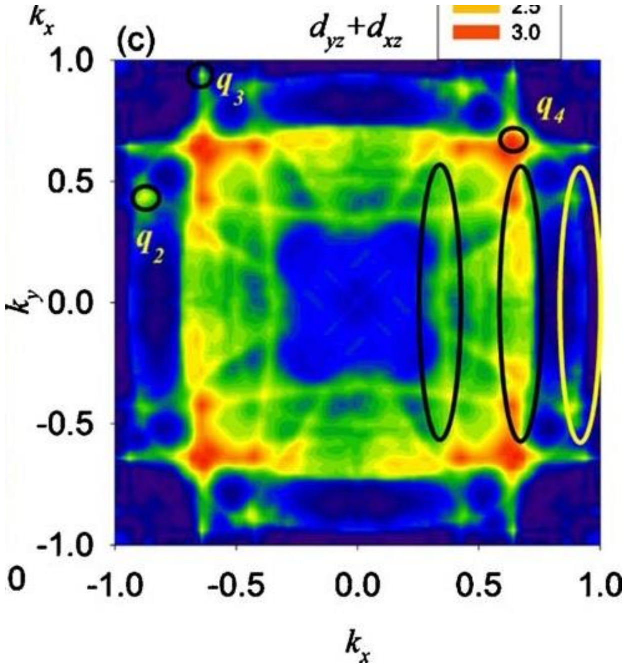


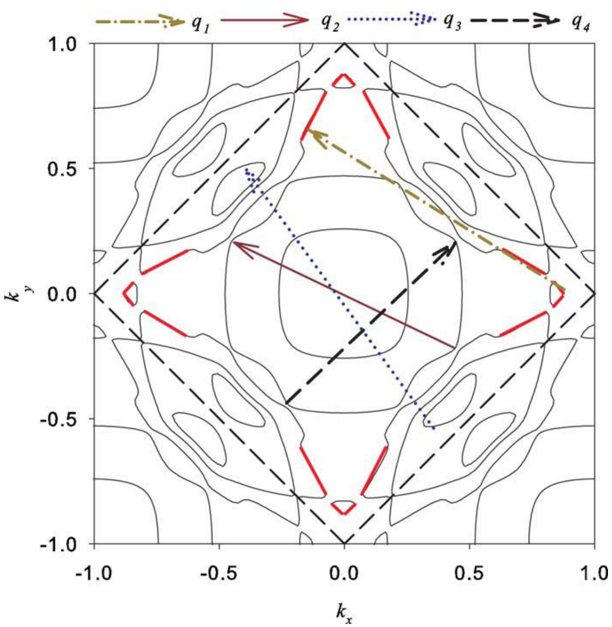
- Quasi-1D band structures have been seen experimentally.

J. H. Lee, et al., Nature Physics 5, 800 (2009)

- T-matrix calculation. Ring structure from quasi-1D orbital scatterings.

W. C. Lee, D. Arovas, and C. Wu, Phys. Rev. B 81, 184403 (2010).





Summary

- Unconventional magnetism is a class of exotic states of matter.
- Quasi-1D orbital bands provide a natural explanation for the unconventional metamagnetic state observed in $Sr_3Ru_2O_7$ as orbital ordering.
- STM quasi particle interference provides a probe to orbital ordering.