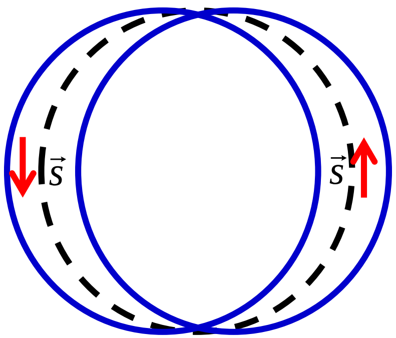
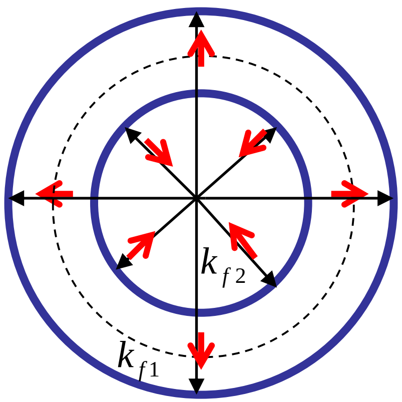
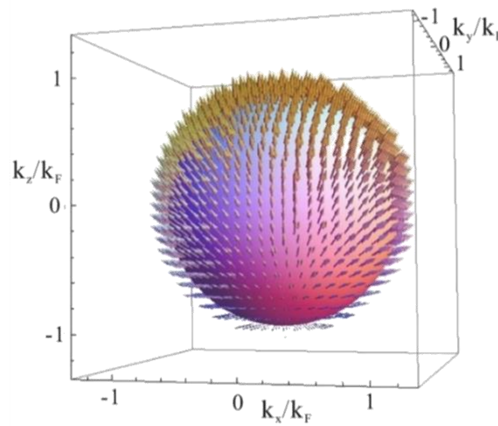
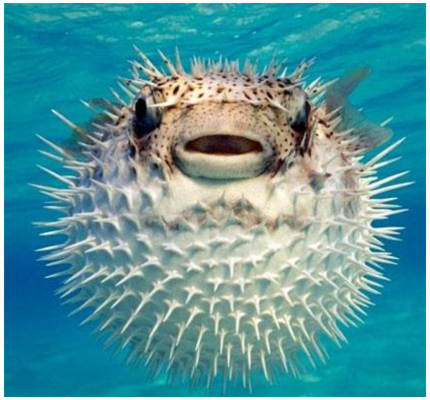
Unconventional magnetism and spontaneous spin-orbit ordering

Congjun Wu (Univ. California, San Diego)









Ref. 1) C. Wu and S. C. Zhang, PRL 93, 36403 (2004);

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

3) Y. Li, C. Wu, PRB 85, 205126 (2012).

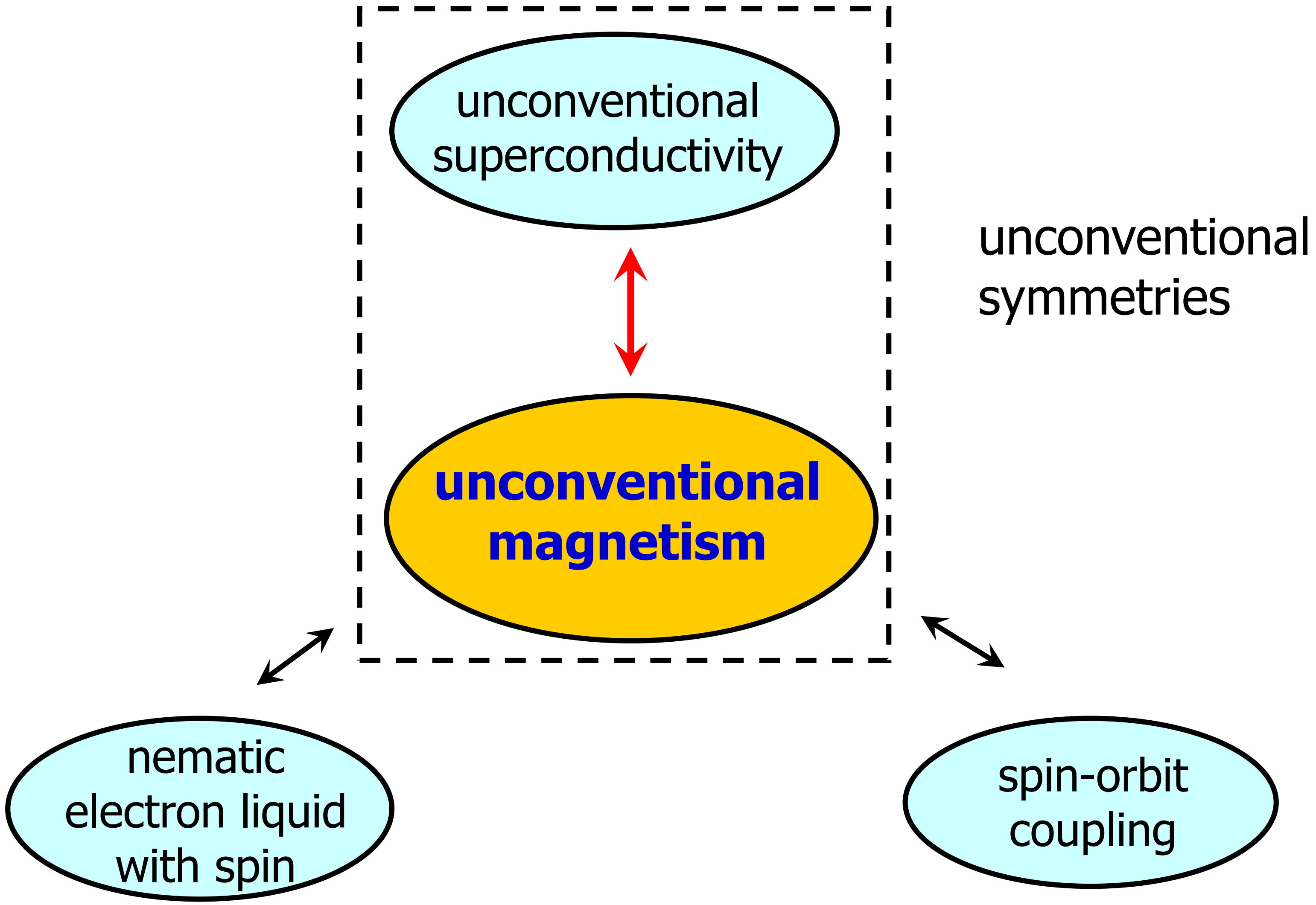
Jan 18, 2017, UCSD

Collaborators

- S. C. Zhang, Stanford.
- E. Fradkin, UIUC.
- D. Arovas, UCSD
- K. Sun, UIUC (now at U. Michigan)
- W. C. Lee, UCSD (now at Binghamton, SUNY)
- Y. Li, UCSD (now at Johns Hopkins)
- C Xu and S. L. Xu, UCSD

Thanks to J. Hirsch, M. Beasley, A. L. Fetter, S. Kivelson, J. Zaanen, S. Das Sarma,, A. J. Leggett, L. Balents for stimulating discussions.

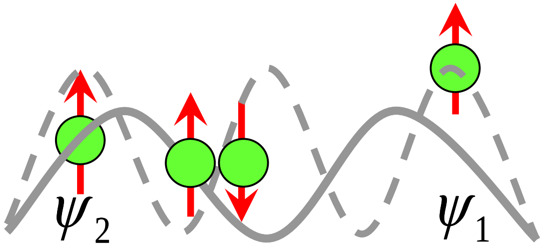
Introduction



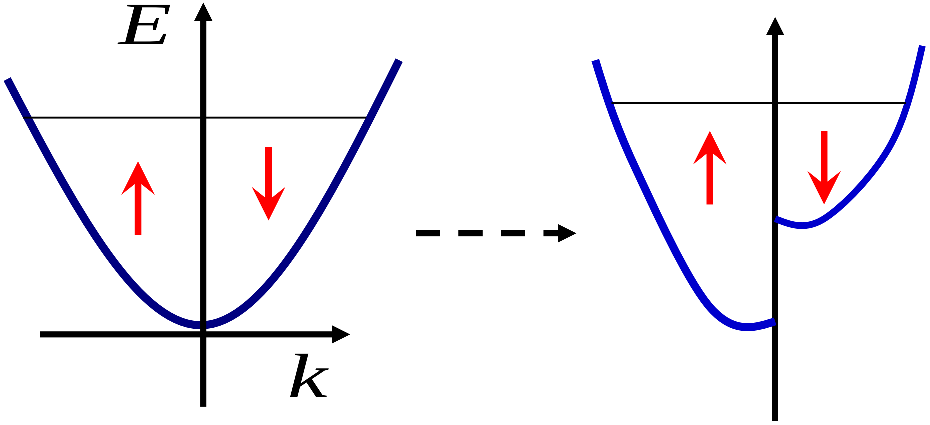
Itinerant FM: Quantum origin!

E. C. Stoner

- Q: How does spin-independent interaction induce spin polarization?
- Electrons with parallel spins avoid each other to reduce repulsion.



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



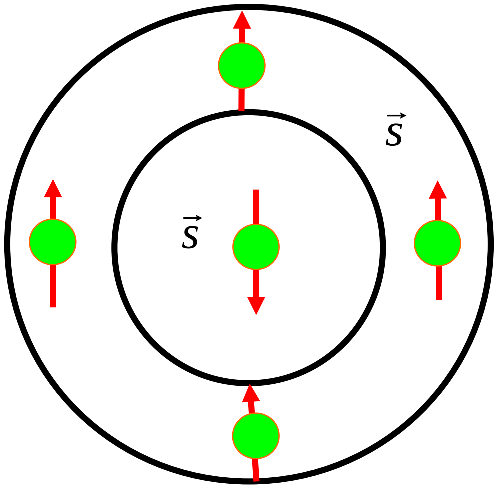
- **Stoner criterion:**

$$UN_0 > 1$$

U: interaction strength

Itinerant ferromagnetism: ***s*-wave**

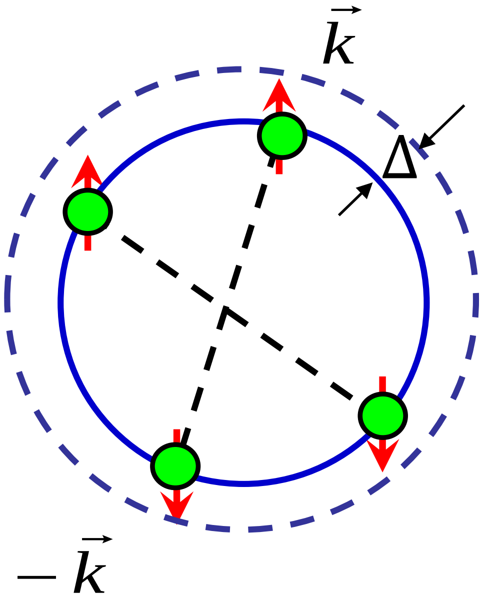
- Spin rotational symmetry is broken.



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

- *cf.* Conventional superconductivity.

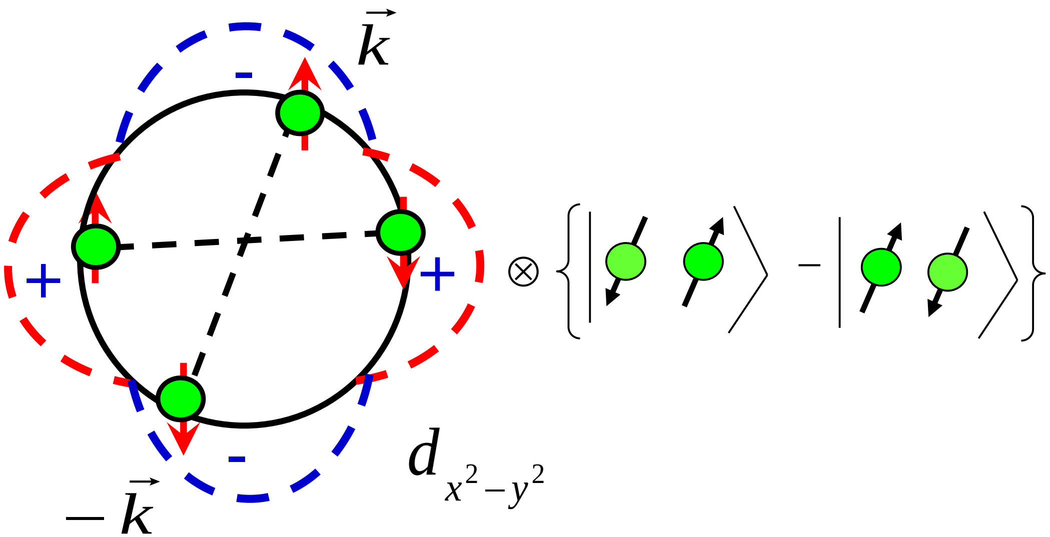
s-wave: gap function invariant over the Fermi surface.

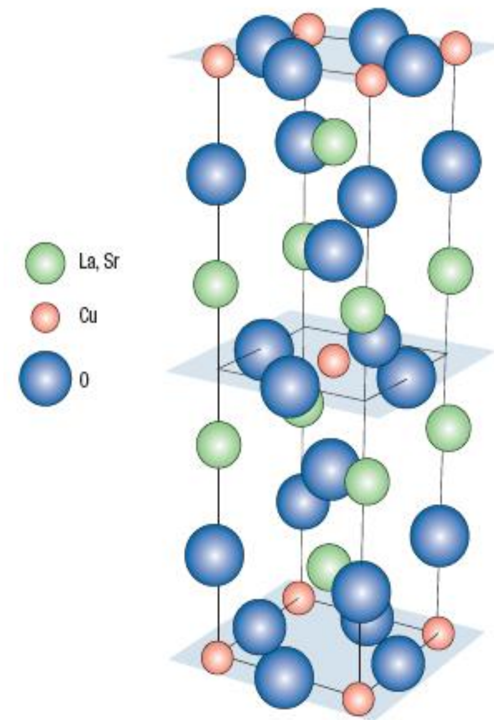


cf. Unconventional superconductivity

- High partial wave pairing symmetries (e.g. *p*, *d*-wave …).

- *d*-wave: high T_c cuprates.





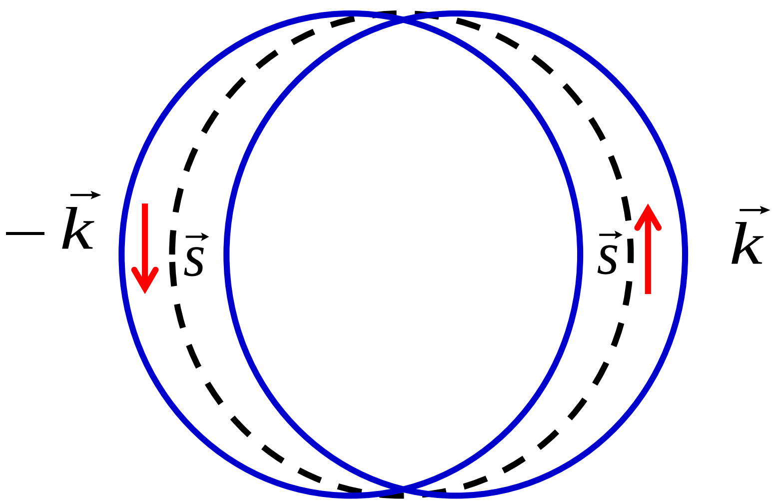
- *p*-wave: Sr_2RuO_4, ^{3}He-A and B.

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

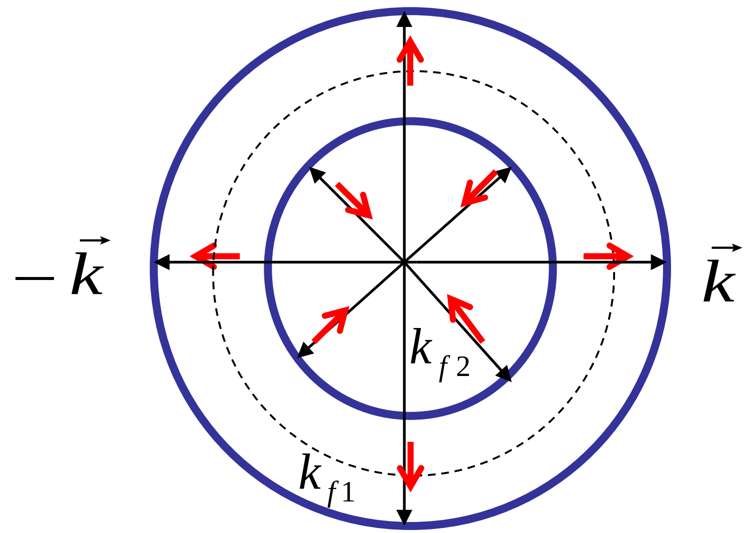
New states of matter: **unconventional magnetism**!

- High partial wave channel magnetism (e.g. *p, d-wave*…) .

- Multi-polar spin distribution over the Fermi surface.



anisotropic *p*-wave state

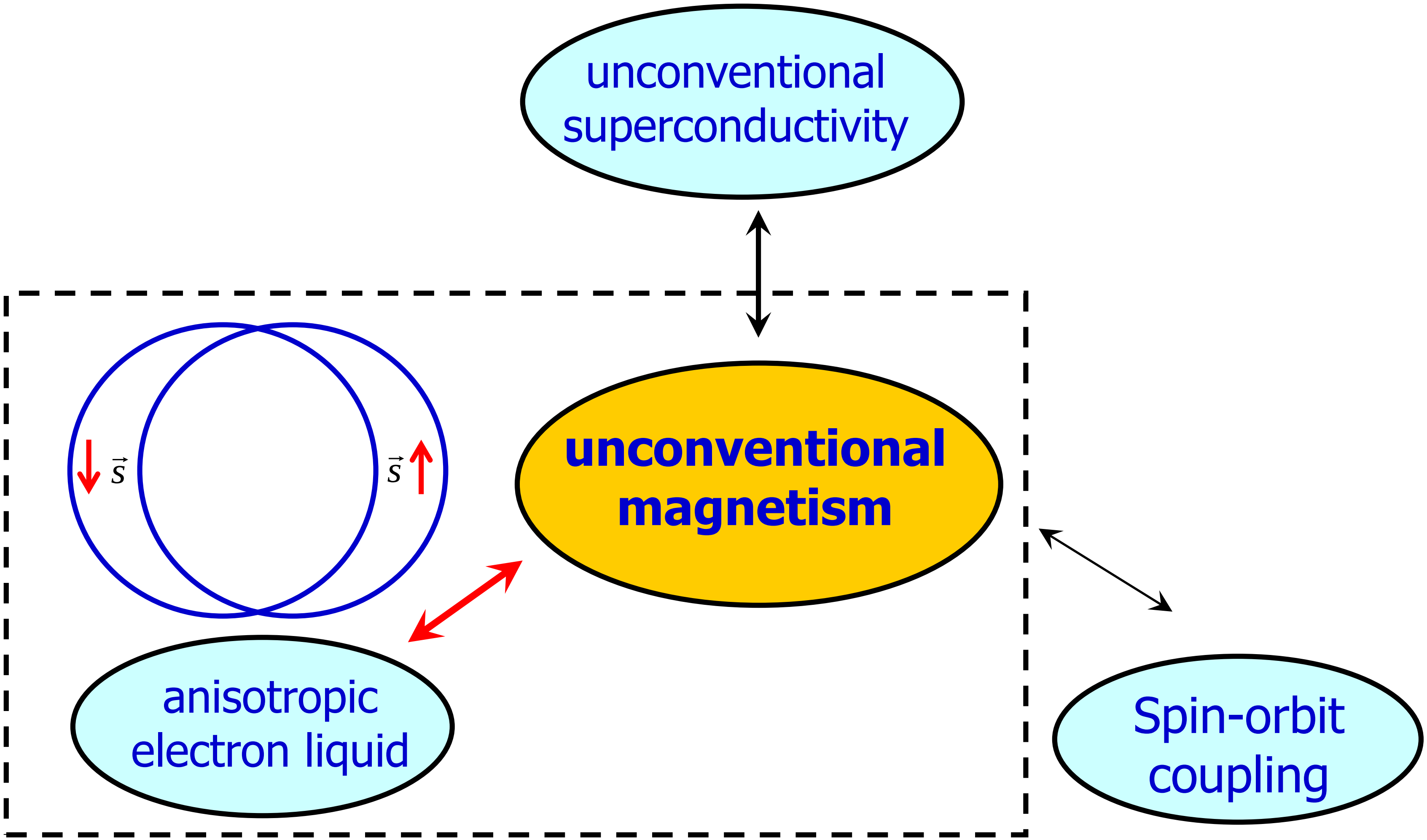


isotropic *p*-wave state

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

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

Introduction: electron spin liquid-crystal

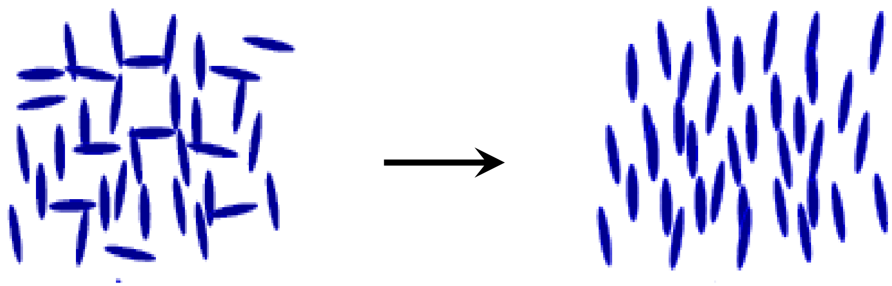


Anisotropy: liquid crystalline order

- Classic liquid crystal.

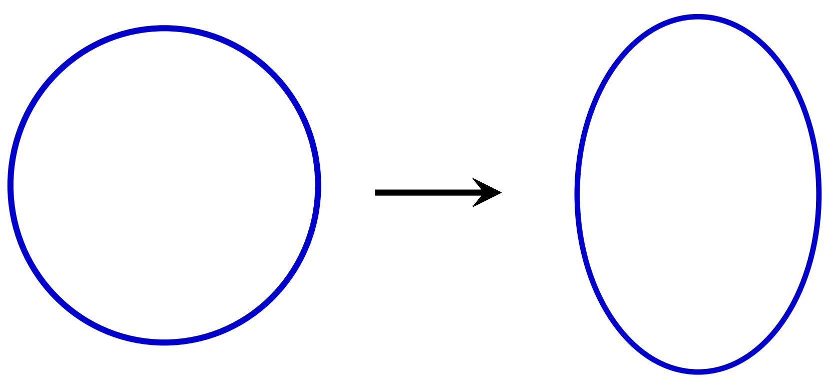
  Nematic phase: rotational anisotropic but translational invariant.

isotropic phase



nematic phase

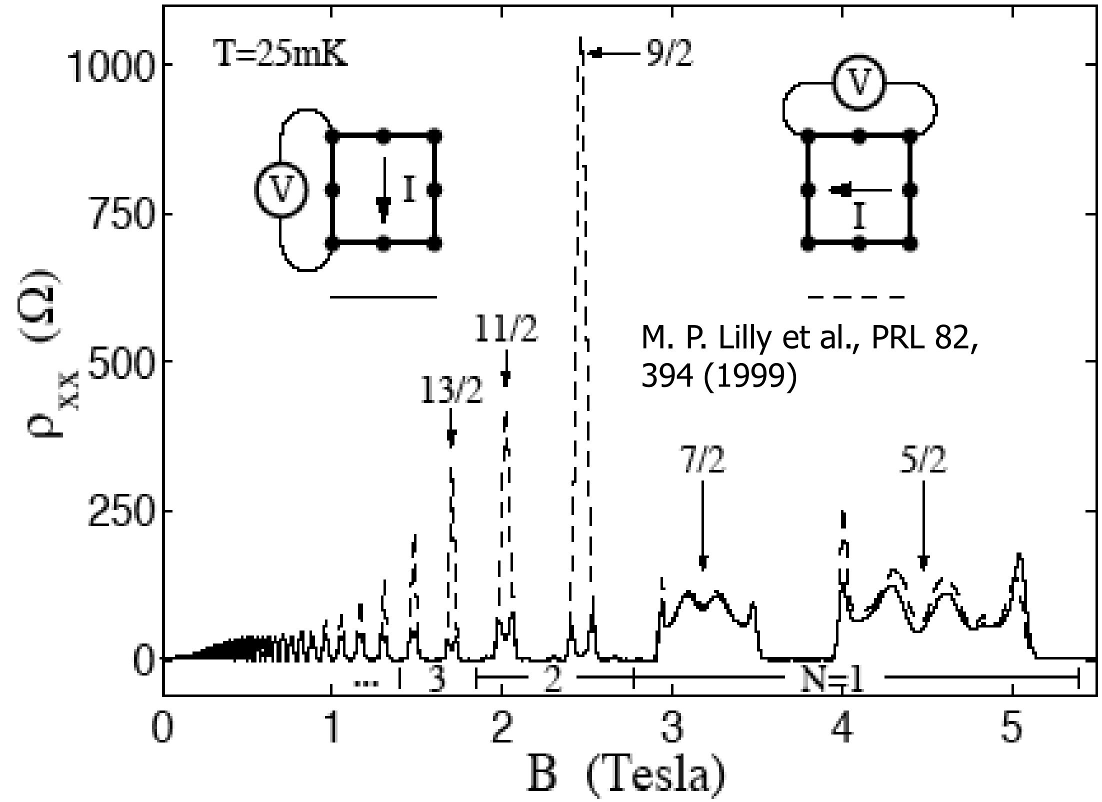
- Quantum version of liquid crystal: **nematic electron liquid**.



Fermi surface anisotropic distortions

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

Nematic electron liquid in 2D GaAs/AlGaAs at high B fields

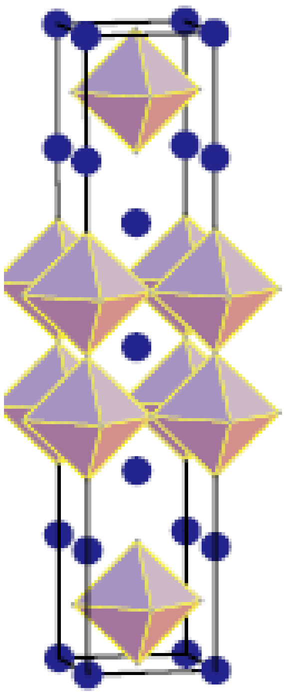


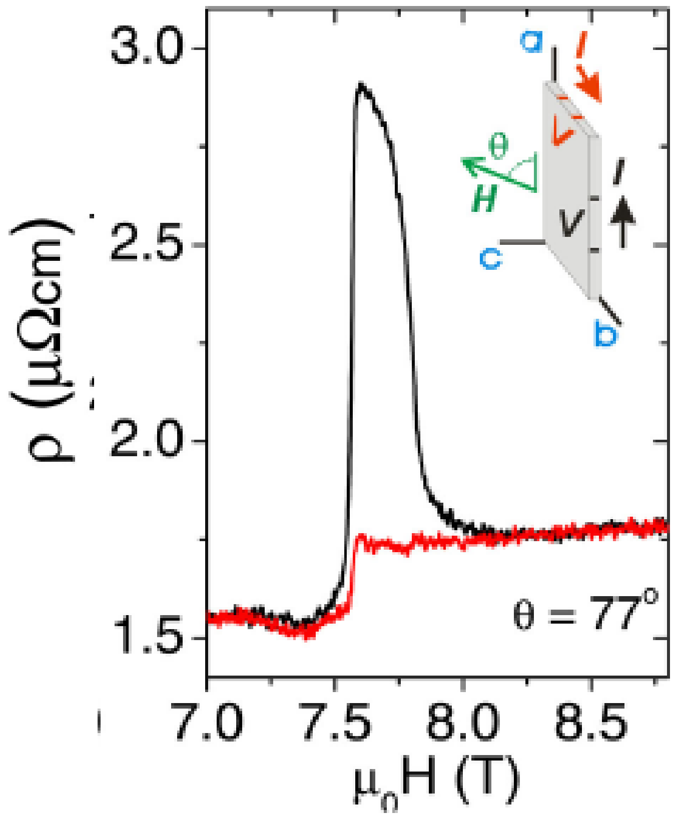
M. P. Lilly et al., PRL 82, 394 (1999)

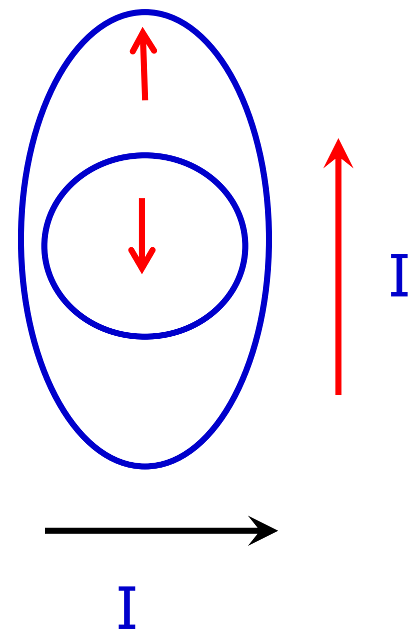
M. M. Fogler, et al, PRL 76 ,499 (1996), PRB 54, 1853 (1996); E. Fradkin et al, PRB 59, 8065 (1999), PRL 84, 1982 (2000).

Nematic electron liquid in $Sr_3Ru_2O_7$ at high B fields

- Quasi-2D system; resistivity **anisotropy** at 7~8 Tesla.
- Fermi surface nematic distortions.

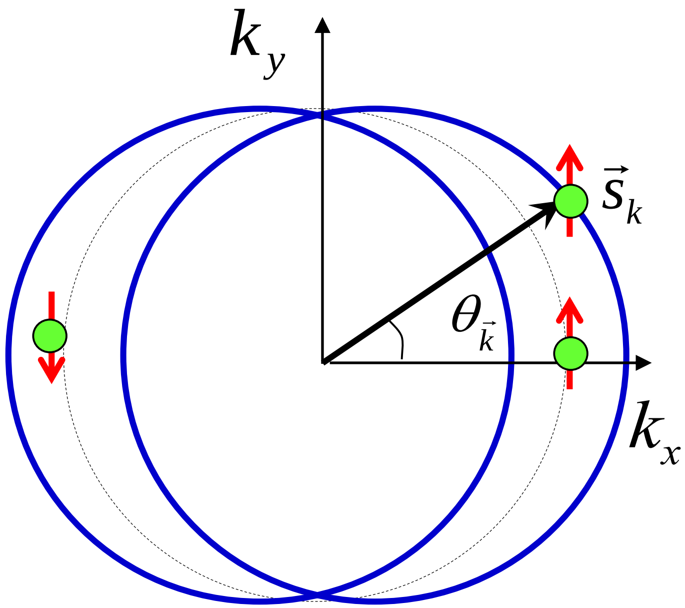






S. A. Grigera et al., Science 306 1154, (2004). R. A. Borzi et al.. Science express (2006).

Anisotropic unconventional magnetism: spin liquid-crystal phases!



anisotropic *p*-wave magnetic phase

- *p*-wave distortion of the Fermi surface.
- Spin dipole moment in momentum space (not in coordinate space).

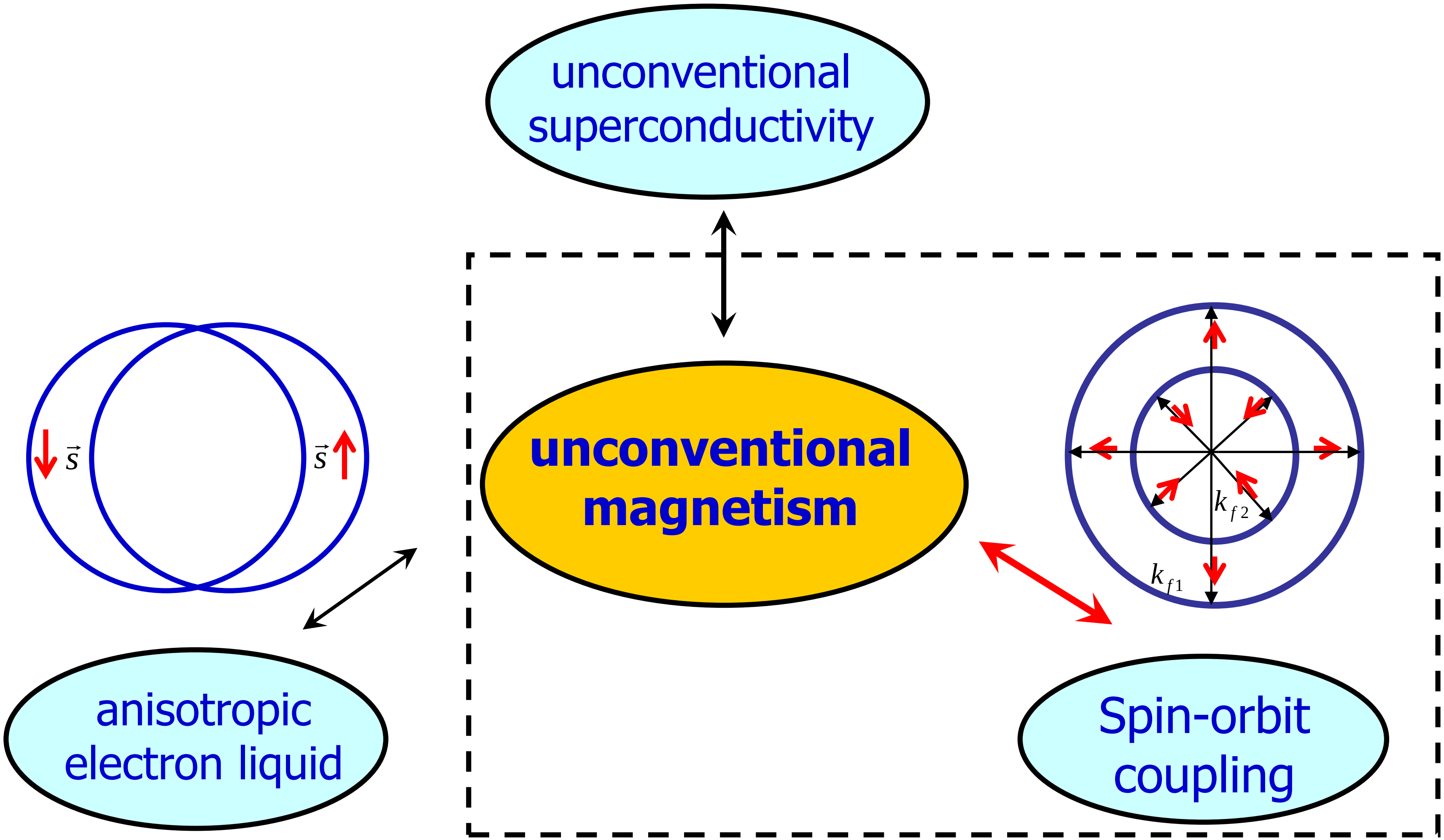
$$\vec{n}_1 = \sum_{\vec{k}} \vec{s}_k \cos\theta_k \neq 0$$

- 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)

Introduction: dynamic generation of spin-orbit coupling



Unconventional magnetism: dynamic generation of spin-orbit (SO) coupling!

- Conventional wisdom**:**

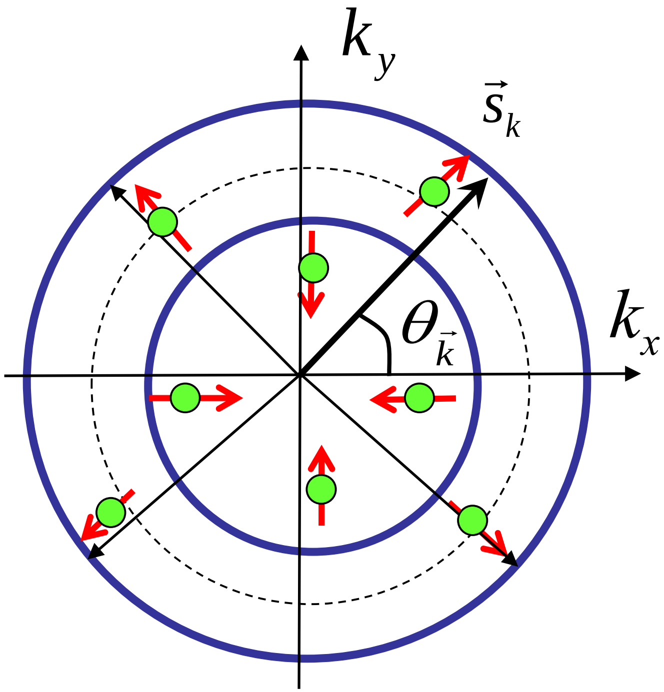
  A **single-body** effect from the Dirac equation

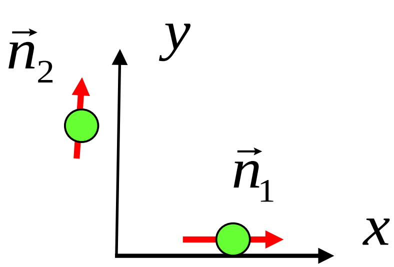
- New mechanism **(many-body collective effect):**

Generate SO coupling through **unconventional magnetic phase transitions.**

- **Advantages**: tunable SO coupling by varying temperatures;
  new types of SO coupling.

The isotropic *p*-wave magnetic phase





- Helicity $\vec{\sigma}\cdot\vec{k}$ is a good quantum number.

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

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

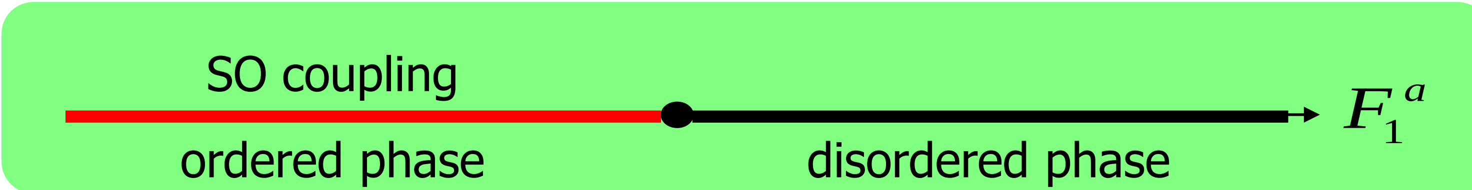
- **Isotropic phase with SO coupling.**

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

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

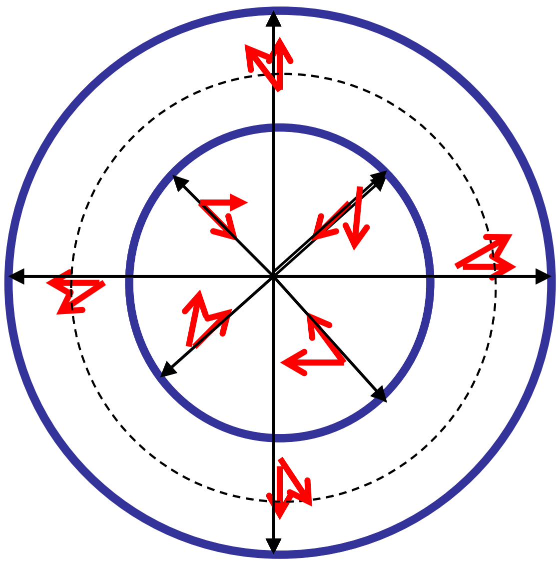
C. Wu et al., PRL 93, 36403 (2004);
C. Wu et al., PRB PRB.75, 115103 (2007). .

The subtle symmetry breaking pattern



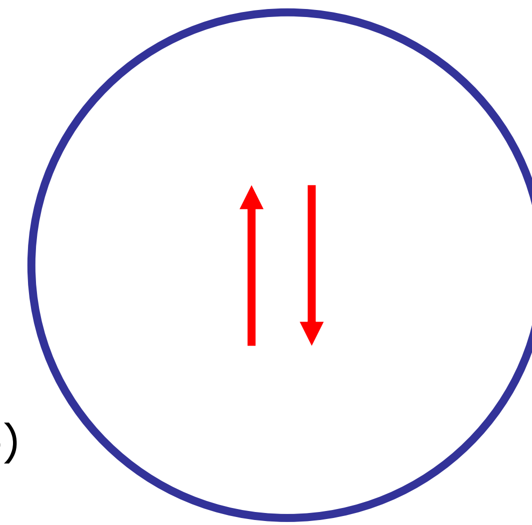
- $\vec{J}$ is conserved , but $\vec{L}, \vec{S}$ are not separately conserved.

- **Independent** orbital and spin rotational symmetries.



$$\vec{J} = \vec{L} + \vec{S}$$

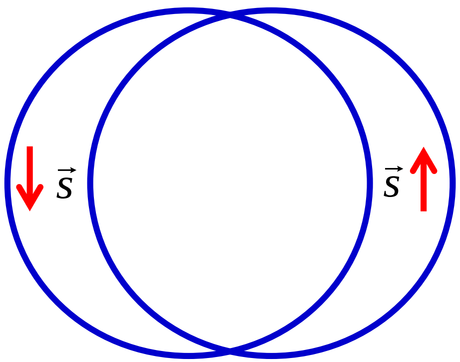
Leggett, Rev. Mod. Phys **47**, 331 (1975)



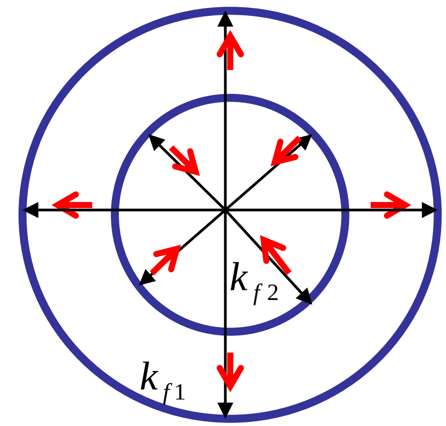
- **Relative spin-orbit** symmetry breaking.

Summary of the introduction

unconventional superconductivity



unconventional magnetism



electron liquid crystal with spin

spin-orbit coupling

Outline

- Introduction.

- **Mechanism for unconventional magnetic phase transitions.**

  - Fermi surface instability of the Pomeranchuk type.

  - Mean field phase structures.

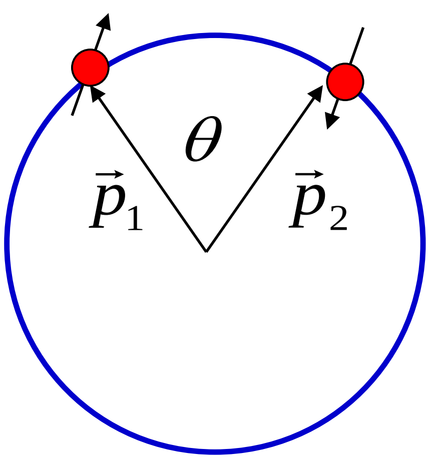
  - Collective modes and neutron spectroscopy.

- Spin-orbit coupled Fermi liquid theory – magnetic dipolar.

- Possible directions of experimental realization and detection methods.

Landau Fermi liquid (FL) theory

L. Landau



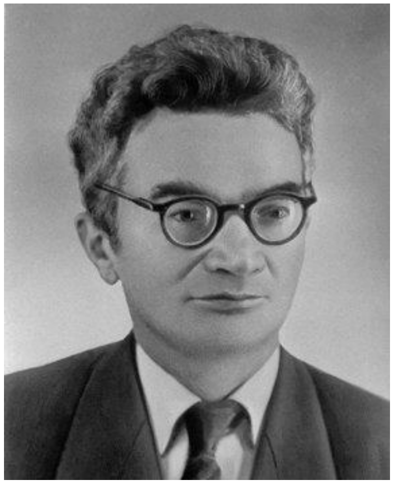
- The existence of Fermi surface.
- Electrons close to Fermi surface are important.
- Interaction functions:

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

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

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

Pomeranchuk instability



I. Pomeranchuk

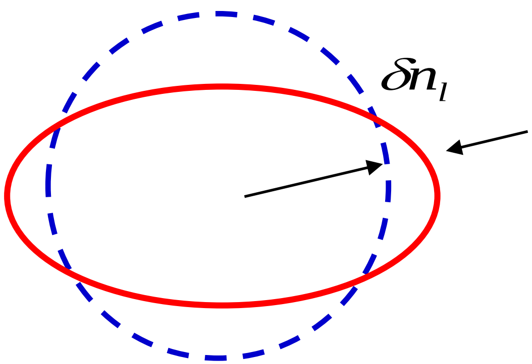
- Fermi surface: elastic membrane.
- Stability:

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

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

- Surface tension vanishes at:

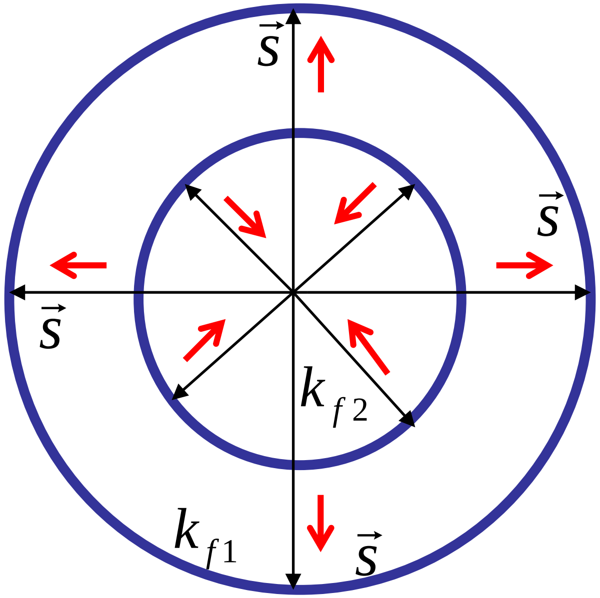
$$F_l^{s,a} < -(2l+1)$$



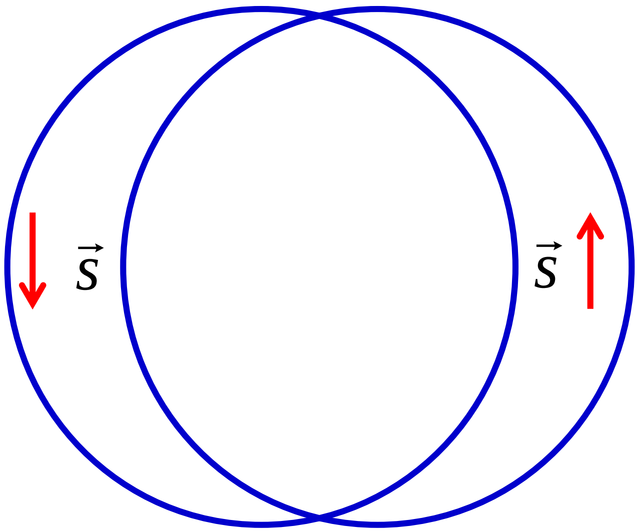
- Ferromagnetism: the F_0^a channel.
- Nematic electron liquid: the F_2^s channel.

Unconventional magnetism: Pomeranchuk instability in the spin channel

F_1^a



$\beta-\text{phase}$

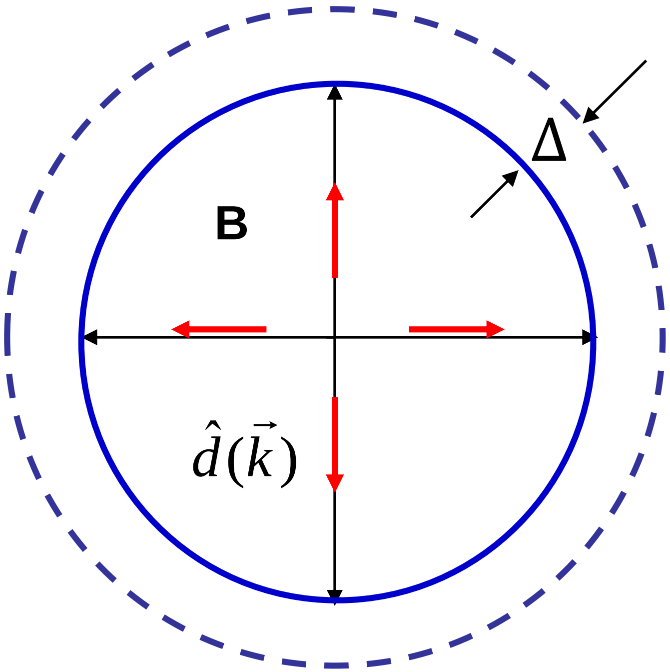


$\alpha-\text{phase}$

- An analogy to superfluid ^{3}He-B (isotropic) and A (anisotropic) phases.

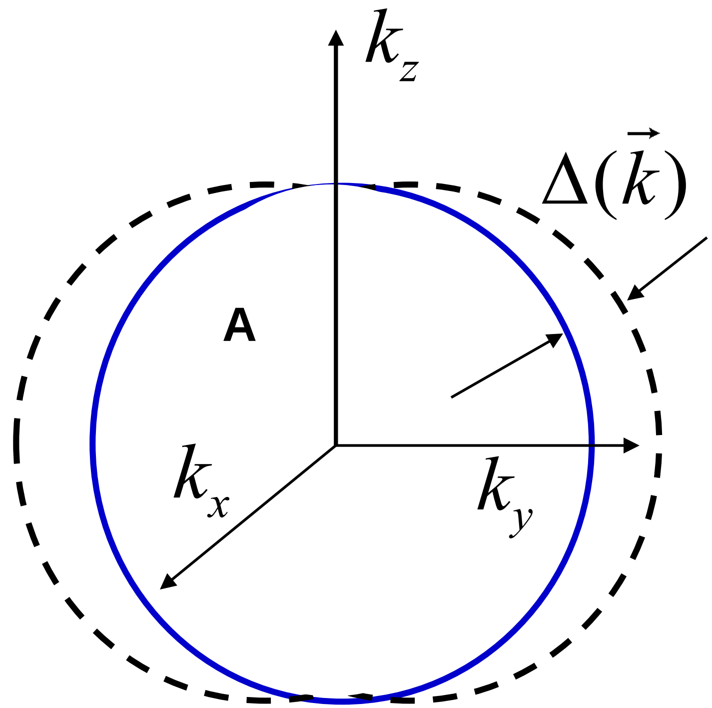
cf. Superfluid ^{3}He-B, A phases

- *p*-wave triplet Cooper pairing.



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

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



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

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

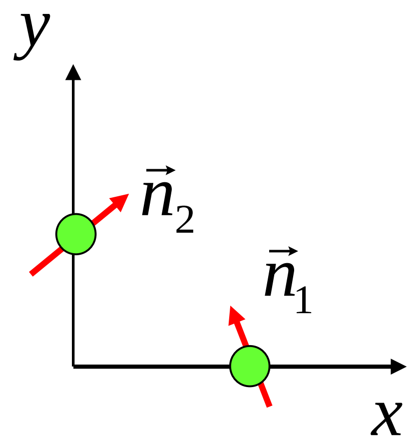
A. J. Leggett, Rev. Mod. Phys 47, 331 (1975)

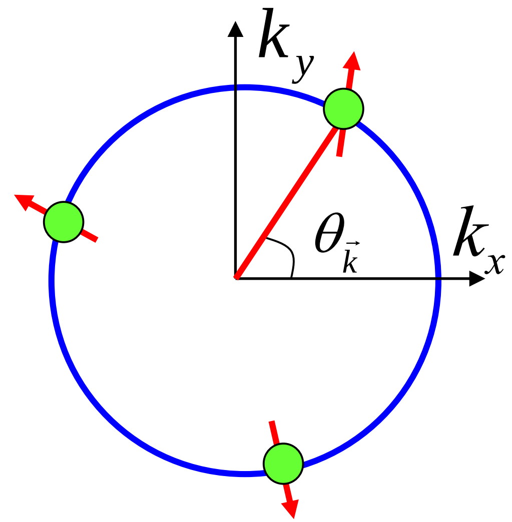
The order parameters: the 2D *p*-wave channel

- F_1^a : Spin currents flowing along x and y-directions, or **spin-dipole moments in momentum space**.

$$\vec{n}_1 = \sum_{\vec{k}} \psi_k^+ \vec{\sigma} \psi_k \cos\theta_k$$

$$\vec{n}_2 = \sum_{\vec{k}} \psi_k^+ \vec{\sigma} \psi_k \sin\theta_k$$





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

- Arbitrary partial wave channels: spin-multipole moments.

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

Mean field theory and Ginzburg-Landau free energy

- The simplest non-*s*-wave exchange interaction:

F_1^a

$$H_{\text{int}} = \sum_q f_1^a(\vec{q})\{\vec{n}_1(\vec{q})\cdot\vec{n}_1(\vec{q}) + \vec{n}_2(\vec{q})\cdot\vec{n}_2(\vec{q})\}$$

$$H_{MF} = \sum_k \psi^+(k)[\varepsilon(k) - \mu - (\vec{n}_1\cos\theta_k + \vec{n}_2\sin\theta_k)\cdot\vec{\sigma}]\psi(k)$$

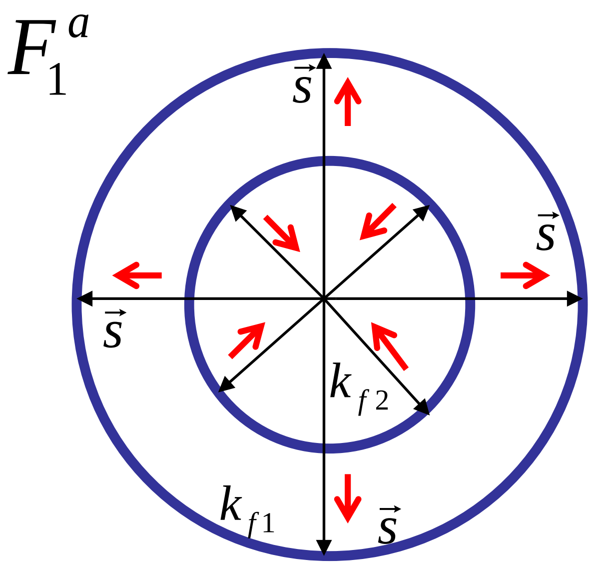
- Symmetry constraints: rotation (spin, orbital), parity, time-reversal.

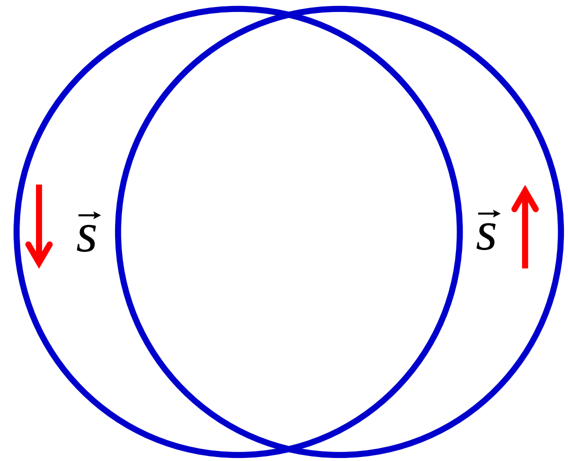
$$F(\vec{n}_1,\vec{n}_2) - F(0) = r(|\vec{n}_1|^2 + |\vec{n}_2|^2) + v_1(|\vec{n}_1|^2 + |\vec{n}_2|^2)^2 + v_2|\vec{n}_1\times\vec{n}_2|^2$$

$$r = \frac{N_0}{2}\frac{1+F_1^a/2}{|F_1^a|}$$

$F_1^a < -2$ → instability!

β and α-phases (*p*-wave)



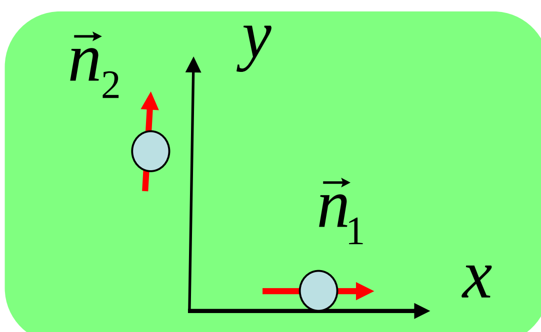


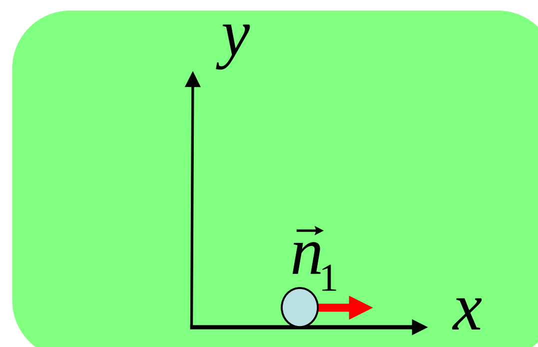
$v_2 < 0 : \beta - \text{phase}$

$\vec{n}_1 \perp \vec{n}_2$ and $|\vec{n}_1| = |\vec{n}_2|$

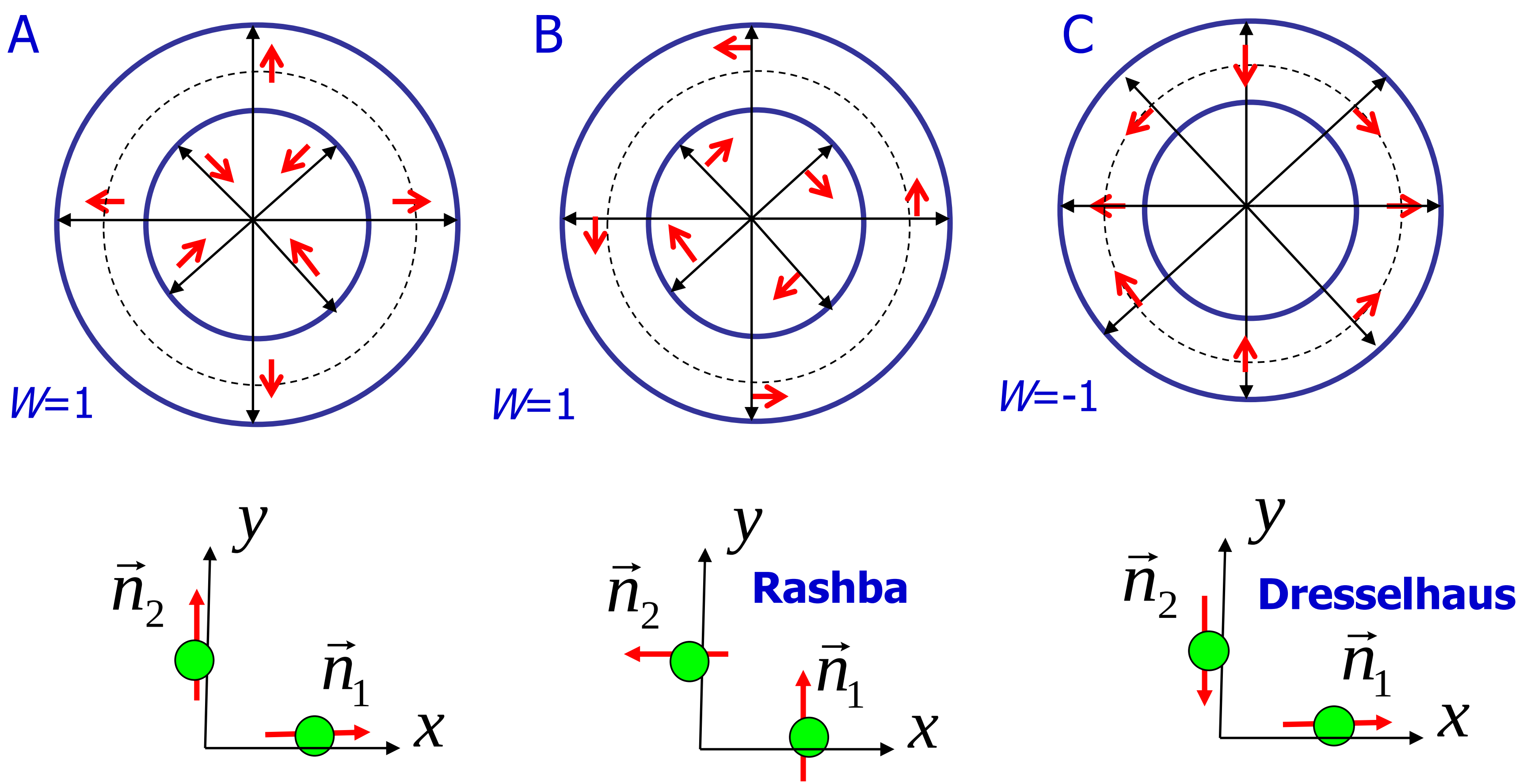
$v_2 > 0 : \alpha - \text{phase}$

$\vec{n}_1 \,//\, \vec{n}_2 ; |\vec{n}_2| / |\vec{n}_1|$ arbitary





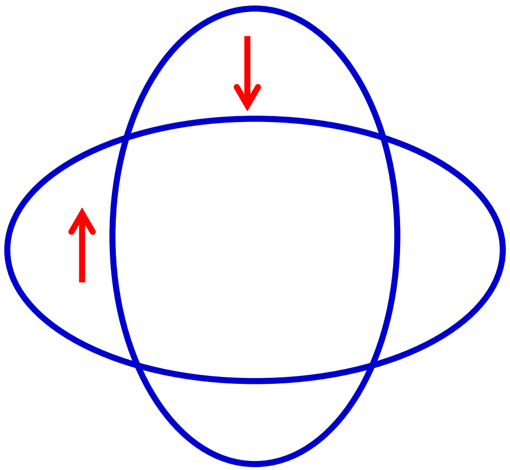
The β-phases: vortices in momentum space



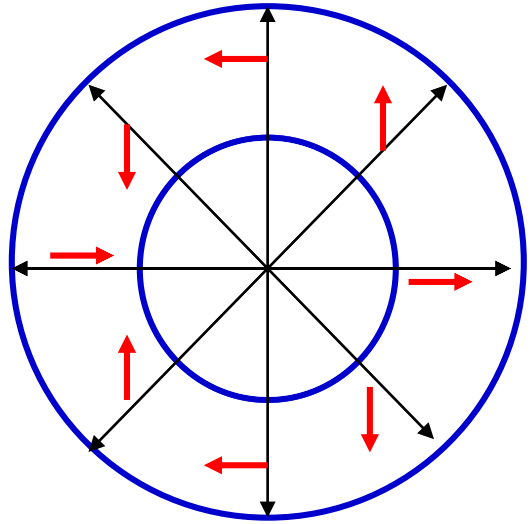
- Perform global spin rotations, A→ B→ C.

L. Fu's(PRL2015): gyro ferroelectric muti-polar

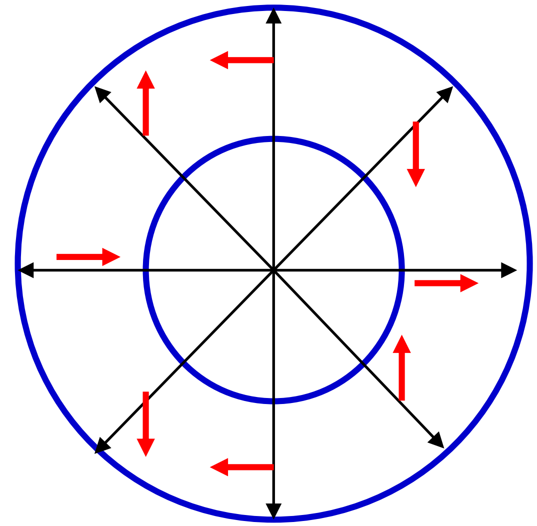
2D *d*-wave α and β-phases



α-phase



β-phase: w=2



β-phase: w=-2

<u>The α-phases: orbital & spin channel Goldstone (GS) modes</u>

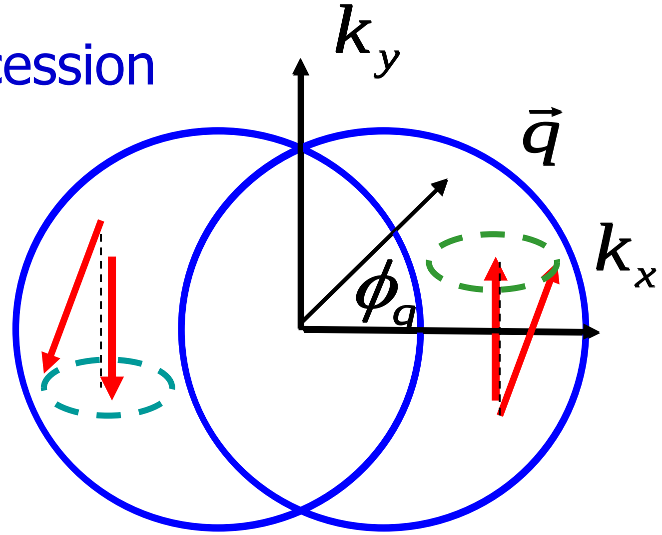
- Orbital channel GS mode: FS oscillations (intra-band transition).

$$L^{\alpha}_{FS}(\vec{q},\omega) = N_0\{\frac{(q\xi)^2}{|F_l^a|} - i\frac{\omega}{2v_f q}(1+\cos 2\phi_q)\}$$

Anisotropic overdamping: The mode is maximally overdamped for q along the x-axis, and underdamped along the y-axis (l=1).

- Spin channel GS mode: "spin dipole" precession (spin flip transition).

$$\omega^2_{x\pm iy} = \frac{\bar{n}^2}{|F_l^a|}(q\xi)^2$$



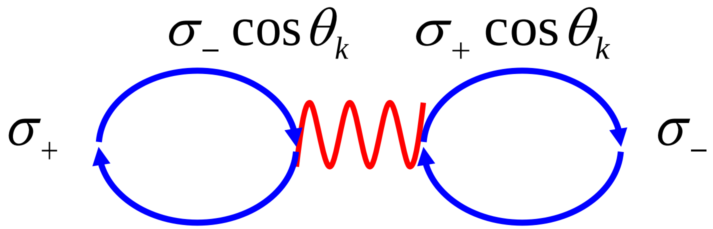
Nearly isotropic, underdamped and linear dispersions at small q.

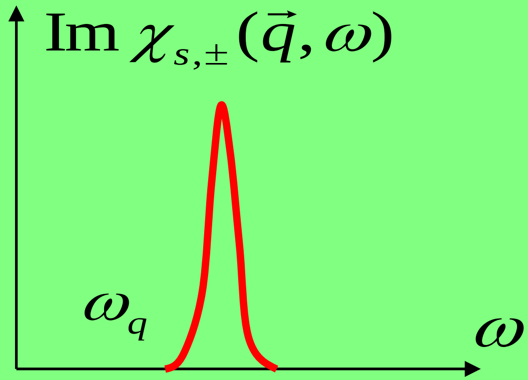
The α-phases: neutron spectra

- No *elastic* Bragg peaks.

- $\vec{n}_{1,2}$ can couple with spin dynamically **at** $T < T_c$ -- coupling between GS modes and spin-waves (spin-flip channel).

$$L = (\vec{n}_1 \times \partial_t \vec{n}_1 + \vec{n}_2 \times \partial_t \vec{n}_2) \cdot \vec{S}$$
$$\rightarrow \bar{n}\,(S_y \partial_t n_{1x} - S_x \partial_t n_{1y})$$

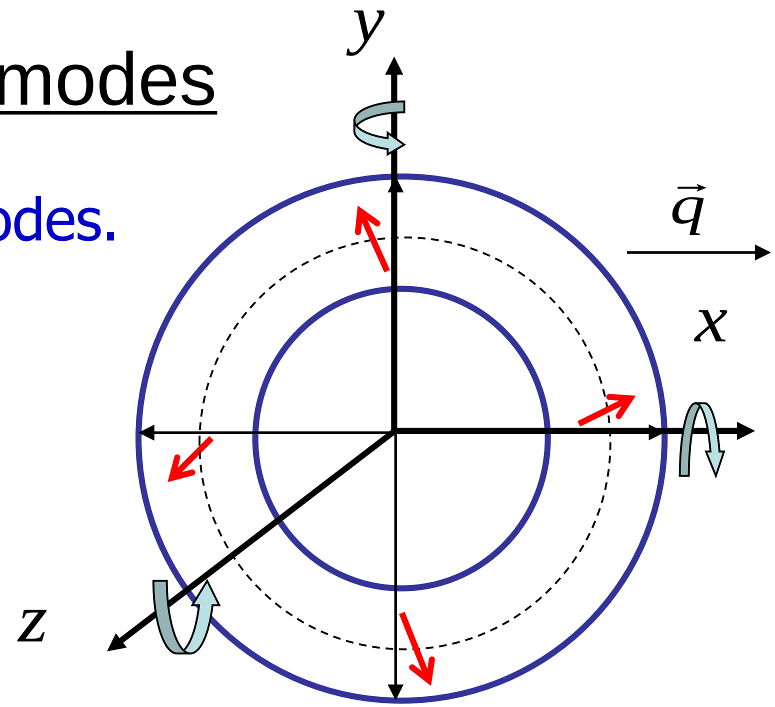




$$\mathrm{Im}\,\chi_{s,\pm}(\vec{q},\omega) \approx N_0 \omega_q^2 \delta(\omega^2 - \omega_q^2)$$

- *In-elastic*: **resonance peaks** develop **at T<T$_c$**.

The β-phases: GS modes



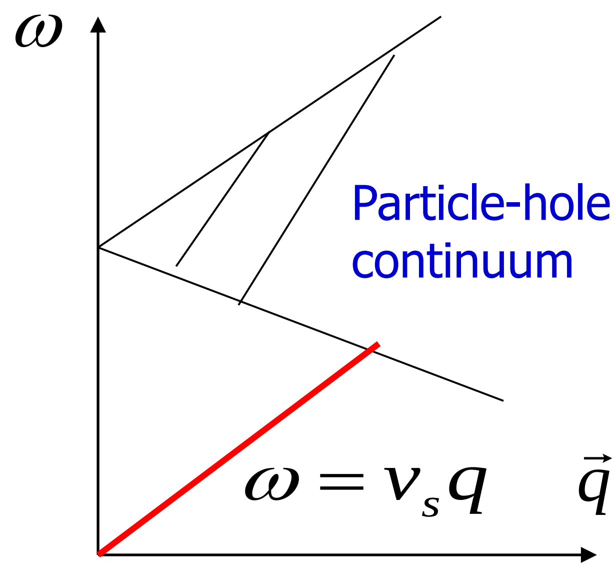
- 3 branches of relative spin-orbit modes.

$$O_z = \frac{1}{\sqrt{2}}(n_2^x - n_1^y);$$

$$O_x = -n_2^z;\ O_y = n_1^z;$$

- For $l \geq 2$, these modes are with linear dispersion relations, and underdamped at small q.

- Inelastic neutron spectra: GS modes also couple to spin-waves, and induce resonance peaks in both spin-flip and non-flip channels.



Outline

- Introduction.

- Mechanism for unconventional magnetic phase transitions.

  - Fermi surface instability of the Pomeranchuk type.

  - Mean field phase structures.

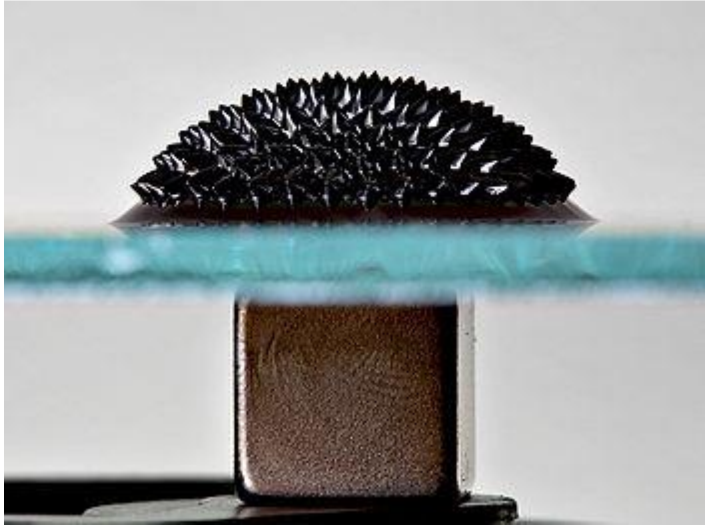
  - Collective modes and neutron spectroscopy.

- **Spin-orbit coupled Fermi liquid theory – magnetic dipolar interaction.**

- Possible directions of experimental realization and detection methods.

Magnetic dipoles: from classic to quantum

- Ferro-fluid: iron powders in oil.



- **In solids, magnetic dipolar interaction ≪ Coulomb interaction.**

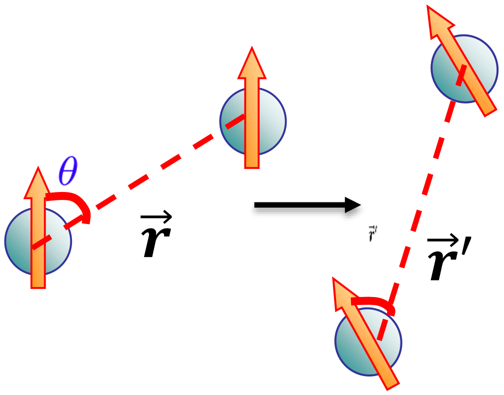
$$r_s = \frac{d}{a_B} \qquad E_m = \frac{\mu_B^2}{d^3} = \frac{\lambda_{cmp}^2}{a_B^2}\frac{Ry}{r_s^3} = \frac{\alpha^2}{r_s^2}E_{el} \approx \frac{1.4}{r_s^3} meV$$

Magnetic dipolar Fermi gases

- Itinerant magnetic dipolar system: $({}^{161}Dy,\ {}^{163}Dy)\ 10\mu_B$

$$n \approx 4\times 10^{13} cm^{-3},\ T_F \approx 300nK \qquad \lambda = \frac{E_d}{E_f} \approx 15\%$$

- SO coupling at the interaction level.



$$V(\vec{r}) = \frac{(g\mu)^2}{r^3}[\vec{F}_1\cdot\vec{F}_2 - 3(\vec{F}_1\cdot\hat{r})(\vec{F}_2\cdot\hat{r})]$$

- SO coupled many-body physics (no Fermi surface splitting):

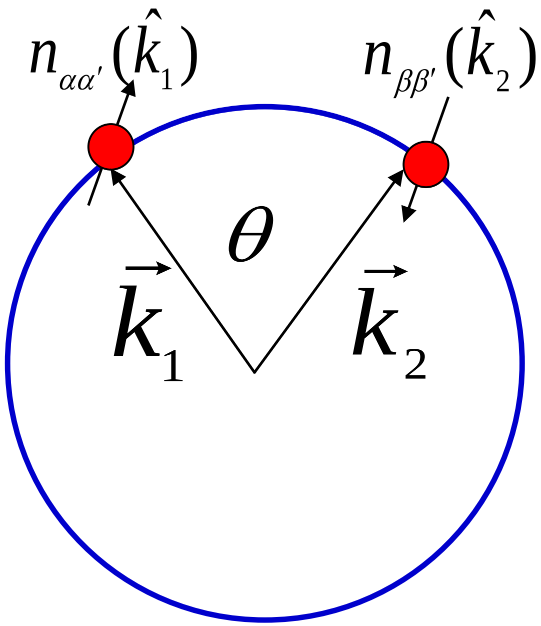
Weyl p-wave triplet pairing (L=S=J=1) Y. Li, C. Wu, Sci. Rep., 2,392 (2012).

SO coupled Fermi liquid: Y. Li, C. Wu, PRB 85, 205126 (2012).

Spin-orbit (SO) coupled Fermi liquid theory

- Landau functions: SO harmonic partial-wave decomposition.

$$\frac{N_0}{4\pi} f_{\alpha\alpha',\beta\beta'}(\hat{k}_1, \hat{k}_2) = \sum_{JJ_zLL'} Y_{JJ_z;LS}(\hat{k}_1, \alpha\alpha') \, F_{JJ_zLS;JJ_zL'S} \, Y^+{}_{JJ_z;L'S}(\hat{k}_2, \beta\beta')$$



- Landau matrices: an eigenvalue <-1 → Pomeranchuk instability

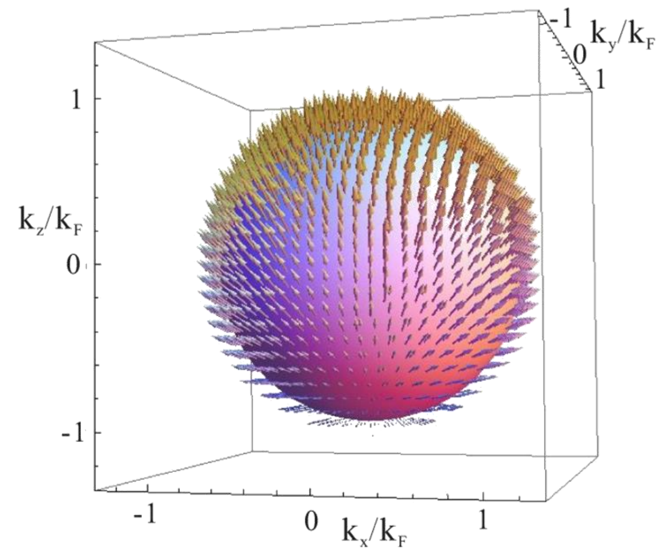
- $J = 1^-$(odd parity), $L = S = 1$.

- Transfer SO coupling to the single particle level (Rashba like).

Y. Li, C. Wu, PRB 85, 205126 (2012).

Topological SO zero sound

- SO coupled Fermi surface oscillations.
  u_0: hedgehog distribution: $J = 0^-$;
  u_1: longitudinal ferro: $J = 1^+$, and $u_0 > u_1$



$$\vec{S}\left(\vec{r}, \vec{k}, t\right) = (u_0 \hat{k} + u_1 \hat{q}) e^{i(\vec{q}\cdot\vec{r} - \omega t)}$$

- Underdamped mode
  $s = \omega/(v_f q) > 1$: sound velocity > Fermi velocity.

$$s_{\lambda \ll 1} \approx 1 + 2e^{-2(1+1/2F_+)} = 1 + 2e^{-2-12/7\pi\lambda}. \qquad s_{\lambda \gg 1} \approx \frac{F_\times}{3} = \frac{\pi}{3\sqrt{3}}\lambda.$$

$$F_+ = F_{10;01} + F_{00;11} \quad F_\times = \sqrt{F_{10;01} F_{00;11}}$$

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A natural generalization of ferromagnetism

• The driving force is still exchange interactions, but in **non-s-wave** channels.

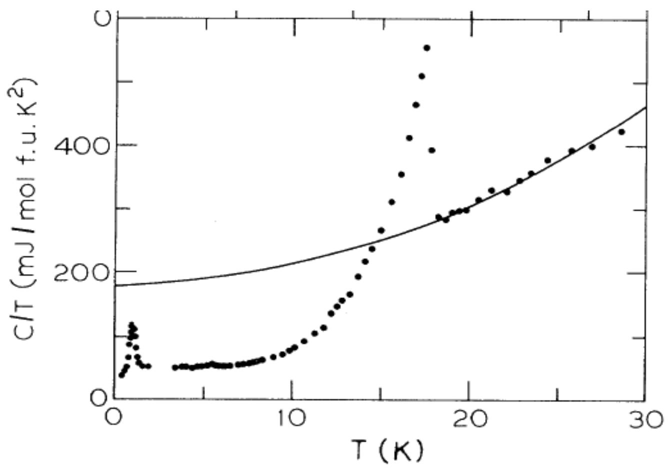
	s-wave	*p*-wave	*d*-wave
SC/SF	Hg, 1911	^{3}He, 1972	high T_c, 1986
magnetism	Fe, ancient time	?	?

• Optimistically, unconventional magnets are probably not rare.

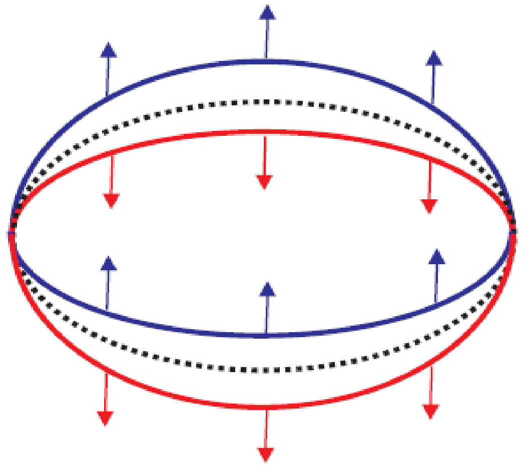
cf. Antiferromagnetic materials are actually very common in transition metal oxides. But they were not well-studied until neutron-scattering spectroscopy was available.

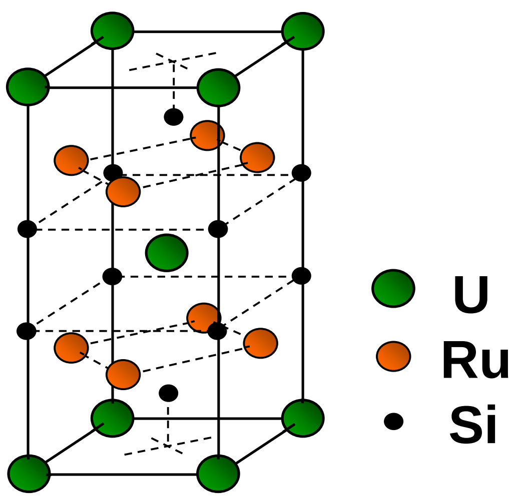
Search for unconventional magnetism (I)

- URu_2Si_2: hidden order behavior below 17.5 K.



T. T. M. Palstra et al., PRL 55, 2727 (1985);
M. B. Maple et al, PRL 56, 185 (1986)



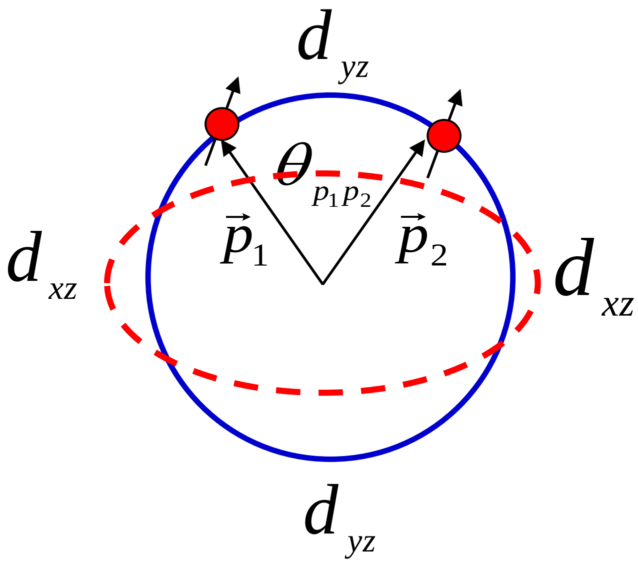


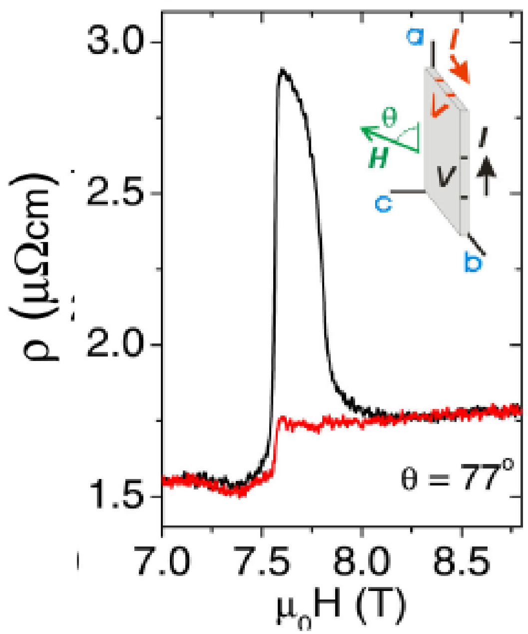
helicity order (the *p*-wave α-phase);

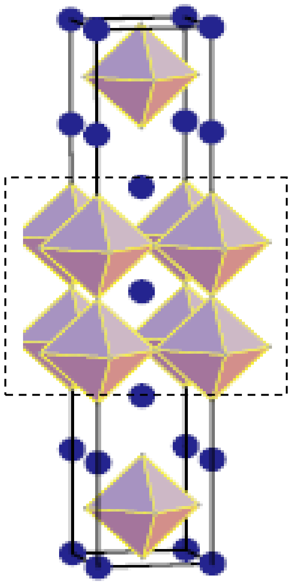
Varma et al., Phys. Rev Lett. 96, 036405 (2006)

Search for unconventional magnetism (II)

• $Sr_3Ru_2O_7$ in the external B field – Orbital-assisted unconventional meta-magnetic state.







$$f_{\uparrow\uparrow}(\vec{p}_1,\vec{p}_2)=V(q=0)-\tfrac{1}{2}[1+\cos 2\theta_{p_1p_2}]V(p_1-p_2)$$

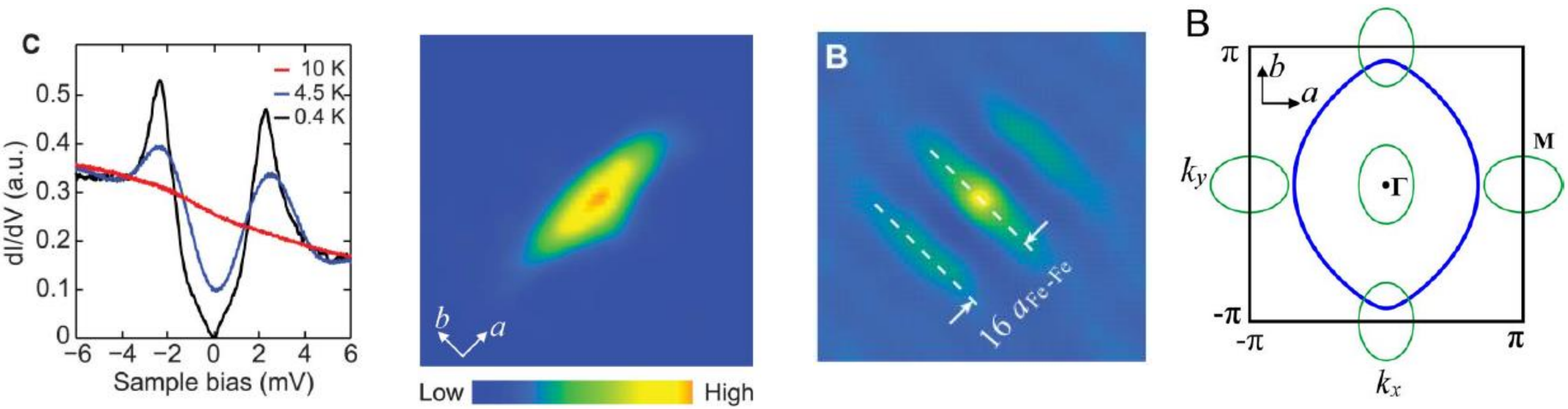
$$f_{\uparrow\downarrow}(\vec{p}_1,\vec{p}_2)=V(q=0)$$

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

Direct Observation of Nodes and Twofold Symmetry in FeSe Superconductor

Can-Li Song,[1,2] Yi-Lin Wang,[2] Peng Cheng,[1] Ye-Ping Jiang,[1,2] Wei Li,[1] Tong Zhang,[1,2] Zhi Li,[2] Ke He,[2] Lili Wang,[2] Jin-Feng Jia,[1] Hsiang-Hsuan Hung,[3] Congjun Wu,[3] Xucun Ma,[2*] Xi Chen,[1*] Qi-Kun Xue[1,2]

Science 332, 1410 (2011)



- Consistent with orbital ordering between dxz/dyz orbitals.

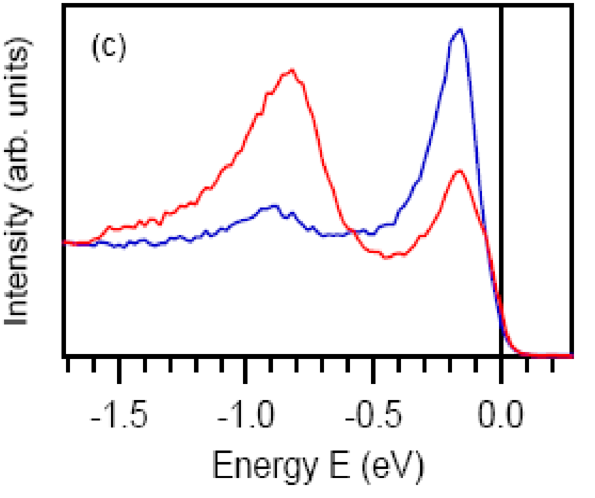
H. H. Hung, C. L. Song, Xi Chen, Xucun Ma, Q. K. Xue, C. Wu, Phys. Rev. B 85, 104510 (2012).

Detection (I): ARPES

- Angular Resolved Photo Emission Spectroscopy (ARPES).

ARPES in spin-orbit coupling systems (Bi/Ag surface), Ast et al., cond-mat/0509509.

band-splitting for two spin configurations.



- α and β-phases (dynamically generated spin-orbit coupling):

The band-splitting is proportional to order parameter, thus is temperature and pressure dependent.

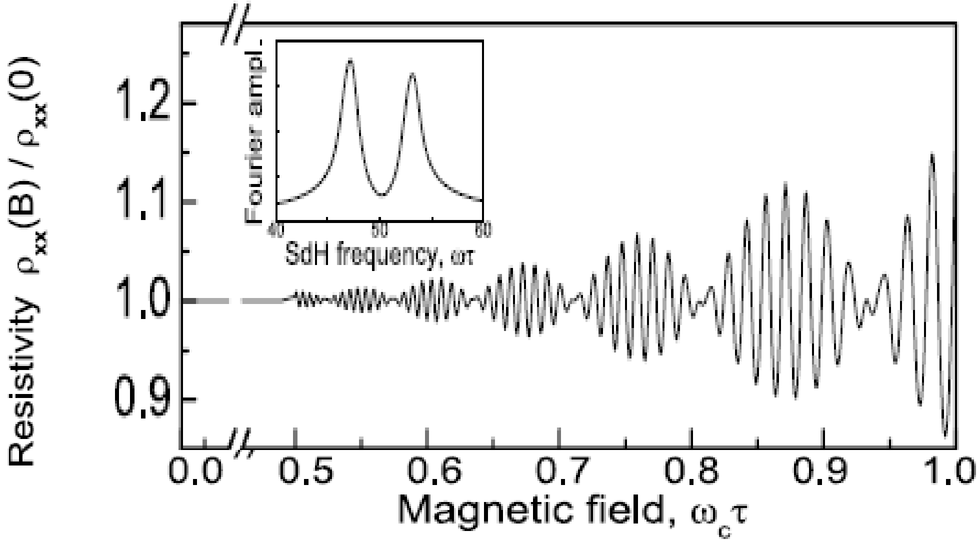
Detection (II): neutron scattering and transport

- Elastic neutron scattering: no Bragg peaks;

Inelastic neutron scattering: resonance peaks below T_c.

- Transport properties.

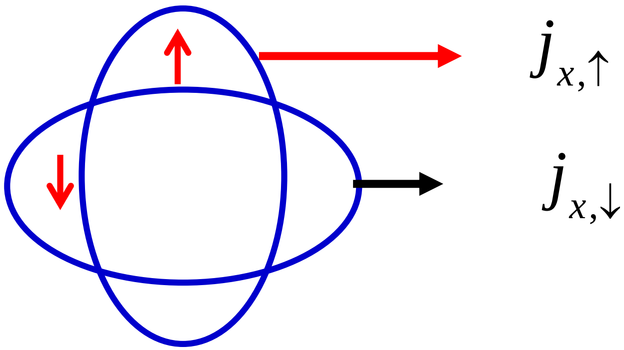
β-phases: Temperate dependent beat pattern in the Shubnikov - de Hass magneto-oscillations of ρ(B).



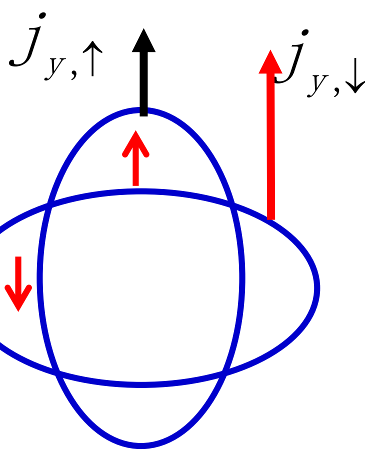
N. S. Averkiev et al., Solid State Comm. 133, 543 (2004).

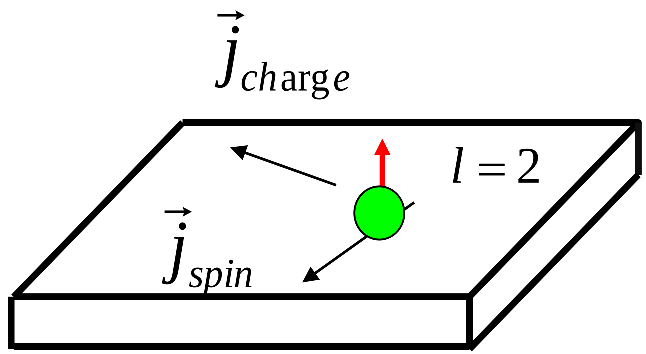
Detection (III): transport properties

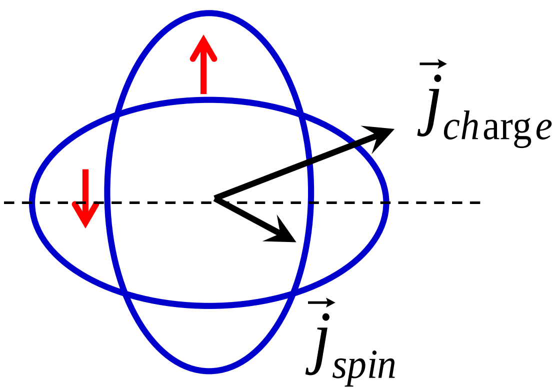
- Spin current induced from charge current (d-wave).
Their directions are symmetric about the x-axis.



$$\begin{pmatrix} j_x^{spin} \\ j_y^{spin} \end{pmatrix} \propto \begin{pmatrix} 1 & \\ & -1 \end{pmatrix} \begin{pmatrix} j_x^{charge} \\ j_y^{charge} \end{pmatrix}$$



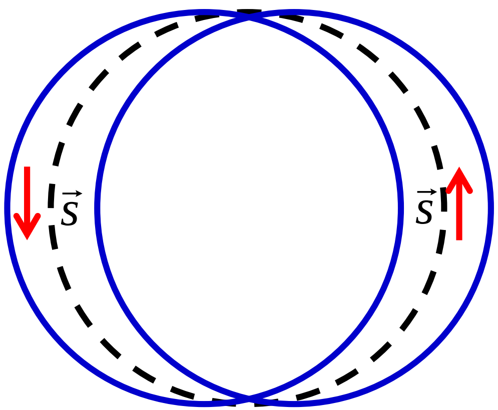




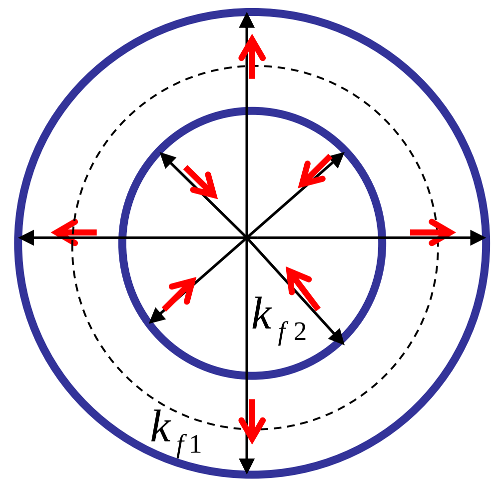
Summary

unconventional superconductivity

α-phase

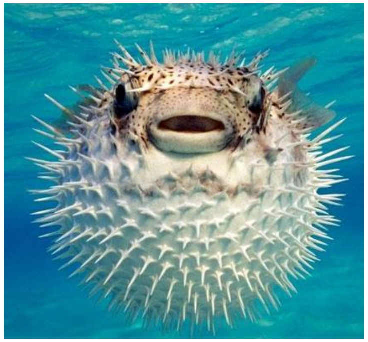


β-phase



unconventional magnetism

electron liquid crystal with spin



spin-orbit coupling