Unconventional Magnetism: Dynamic Generation of Spin-orbit Coupling and Electron Liquid Crystal States

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

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

KITP, 05/16/2007

Collaborators

- E. Fradkin, UIUC.

- K. Sun, UIUC.

- S. C. Zhang, Stanford.

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Outline

- **Introduction.**

  - What is unconventional magnetism?

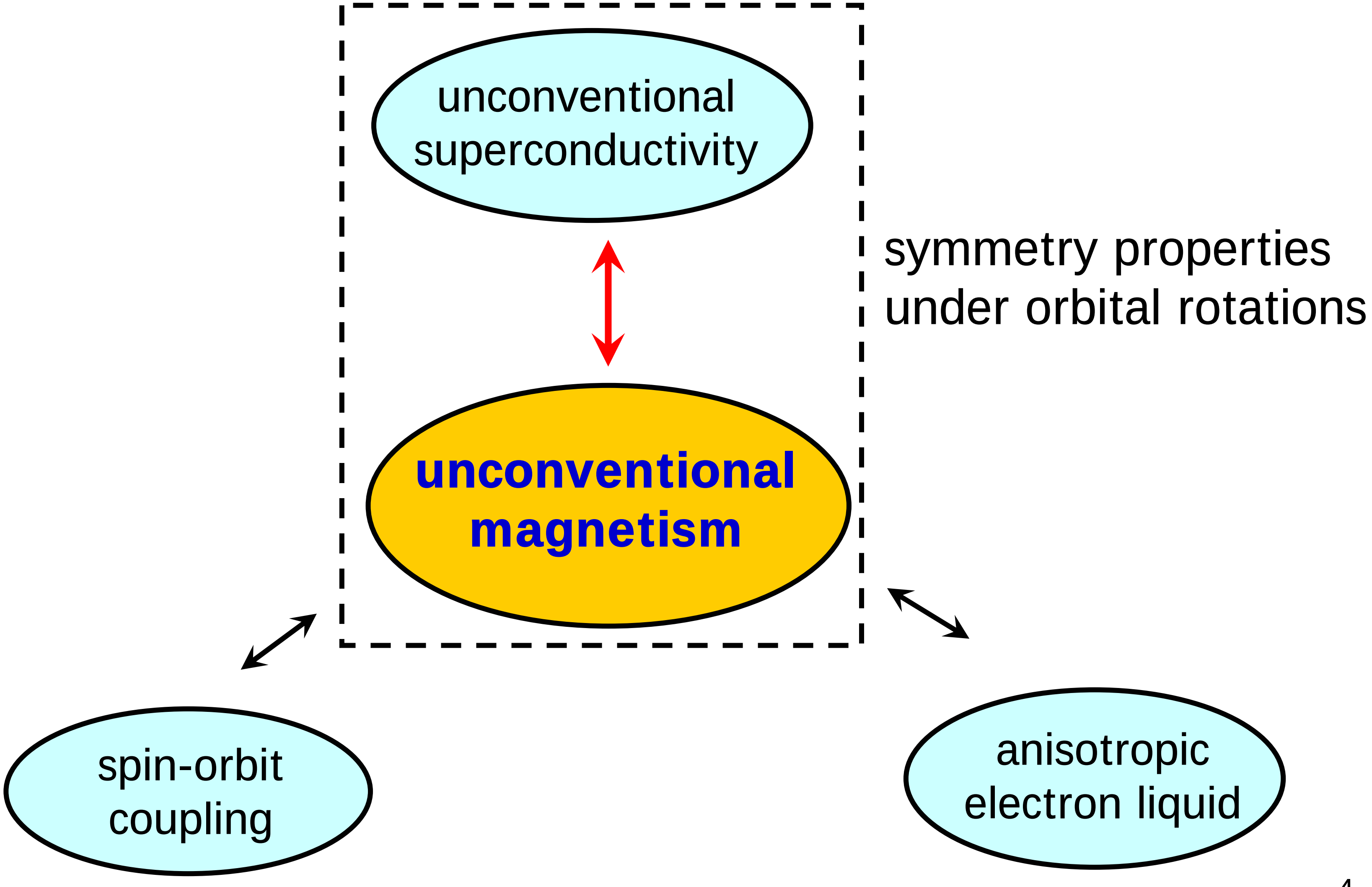
  - Its deep connections to several important research directions in condensed matter physics.

- Mechanism for unconventional magnetic phase transitions.

- Low energy collective modes.

- Possible experimental realization and detection methods.

Introduction



The early age of ferromagnetism

司南

World's first compass:
south-pointer

Thales (624-546 BC) says that a stone (lodestone) has a soul because it causes movement to iron.

----*De Anima*, Aristotle (384-322 BC)

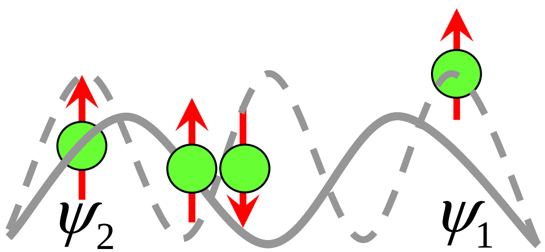
The lodestone attracts iron.

---- *Guiguzi (鬼谷子)* **(4th century BC)**

Ferromagnetism: many-body collective effect

E. C. Stoner

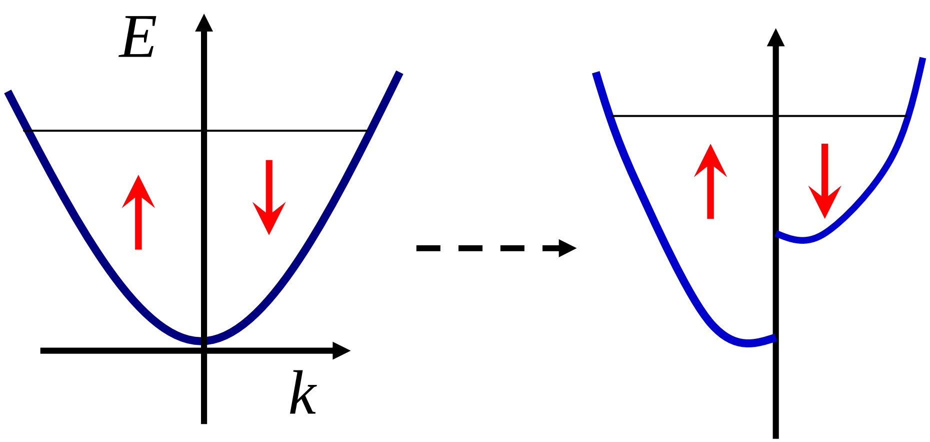
- Driving force: **exchange interaction among electrons**.



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

- Stoner criterion:

$$UN_0 > 1$$

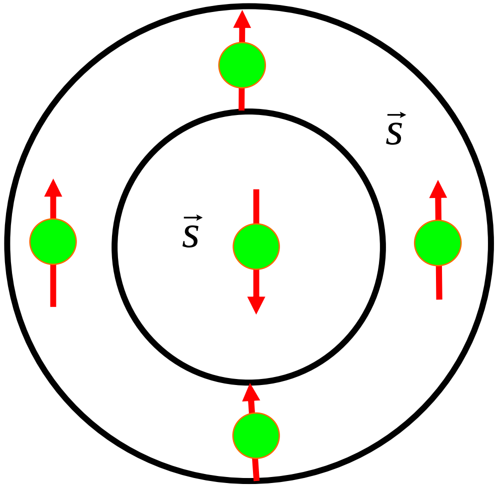


U – average interaction strength; N_0 – density of states at the Fermi level

Fe	Co	Ni

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

- Spin rotational symmetry is broken.

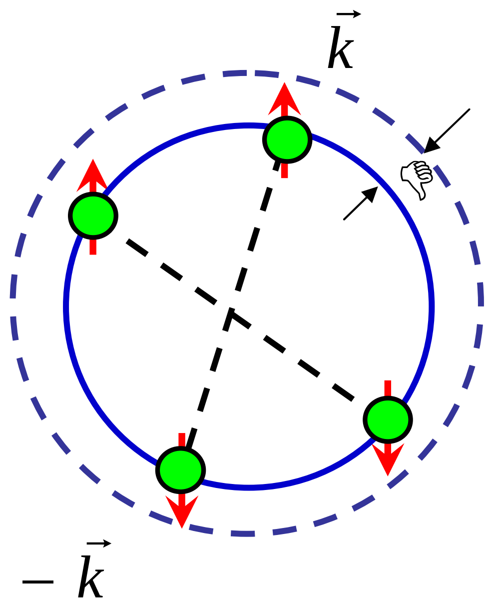


- Orbital rotational symmetry is **NOT** broken: spin polarizes along **a fixed direction** on the Fermi surface.

- *cf.* conventional superconductivity.

Cooper pairing between electrons with opposite momenta.

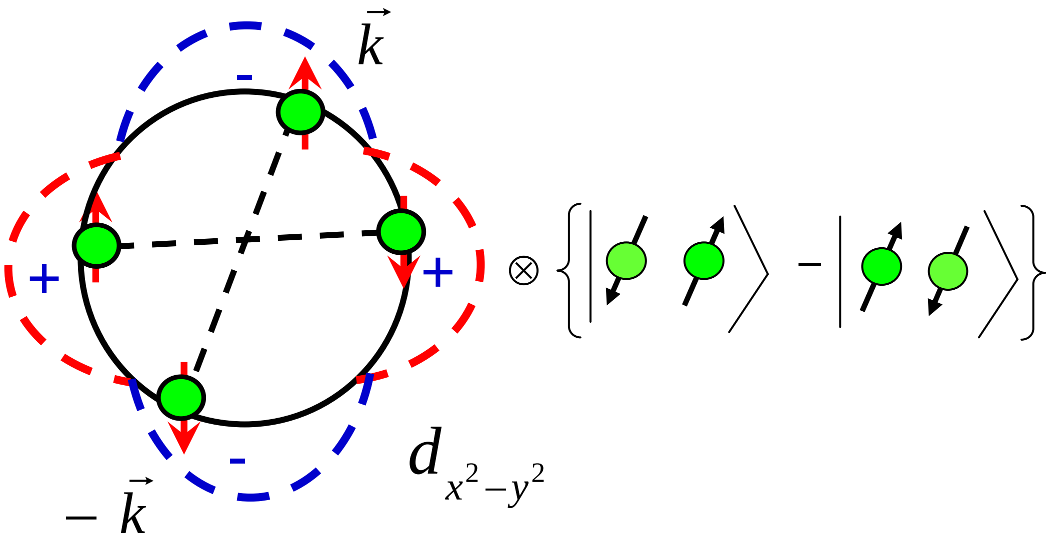
s-wave: pairing amplitude does not change over the Fermi surface.

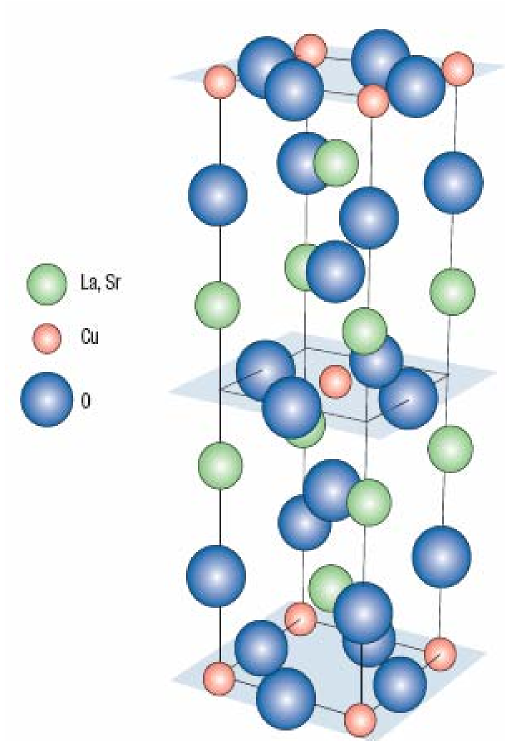


cf. Unconventional superconductivity

• 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.





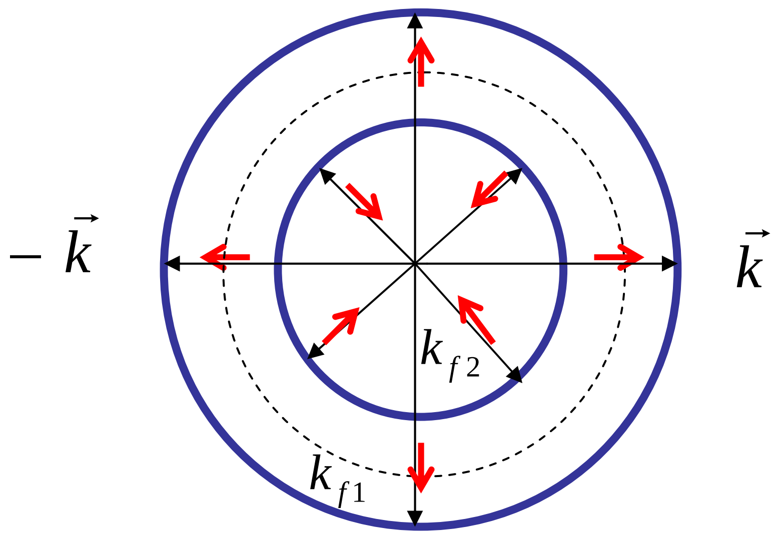
• *p*-wave: Sr_2RuO_4, ^{3}He-A and B.

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

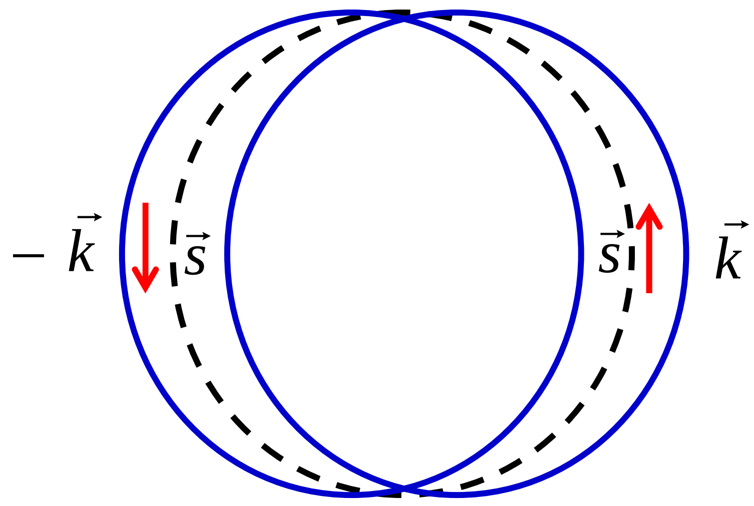
New states of matter: **unconventional magnetism**!

• High partial wave channel generalizations of ferromagnetism (e.g. *p*, *d-wave*...) .

• Spin polarization varies over the Fermi surface.



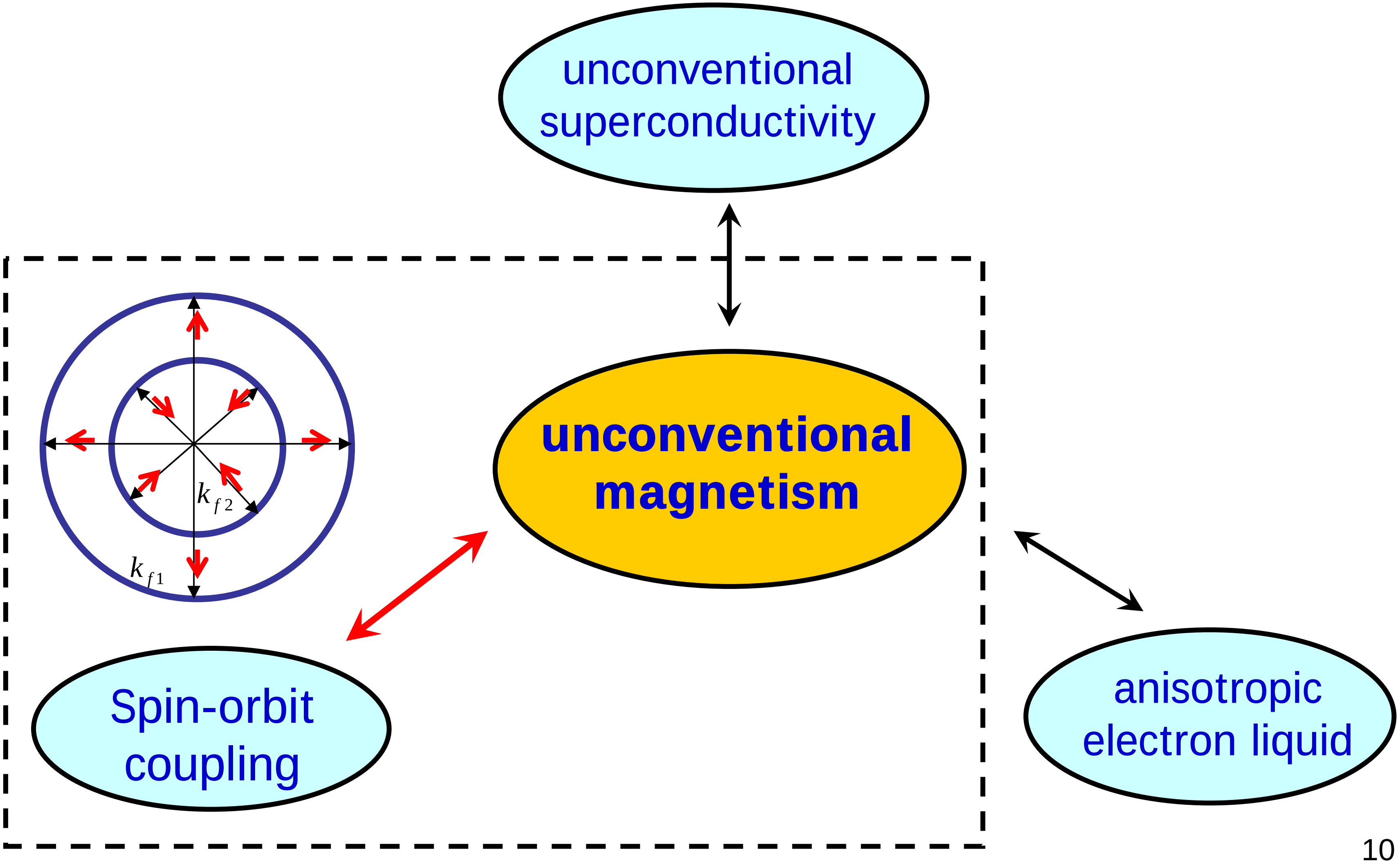
isotropic *p*-wave magnetic state



anisotropic *p*-wave magnetic state

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

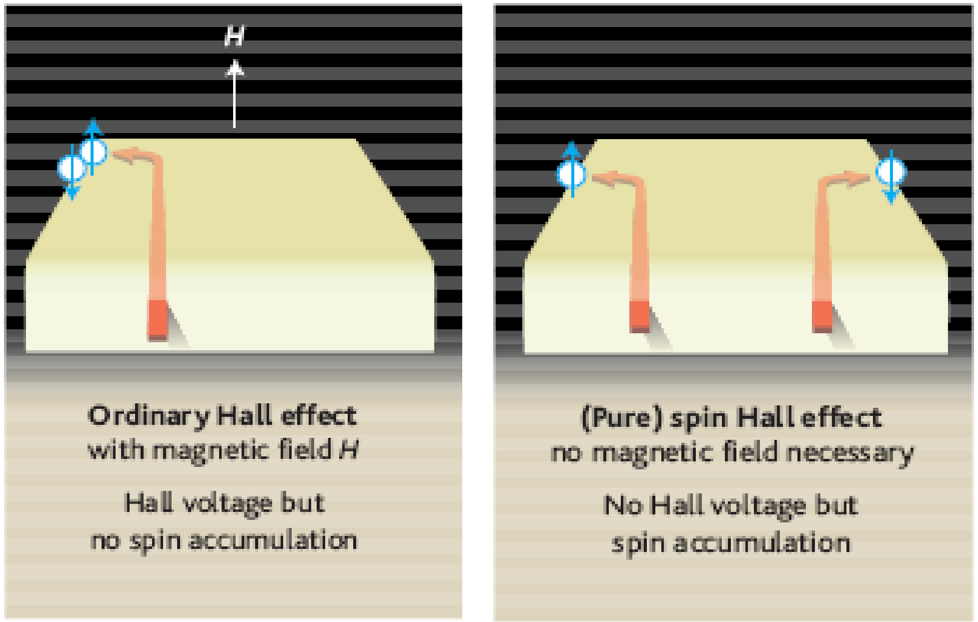
Introduction: dynamic generation of spin-orbit coupling



Spintronics: controlling spin degree of freedom

- Electric fields manipulation, rather than magnetic fields.

- **Spin Hall effect**: electric fields induced transverse spin accumulations due to **spin-orbit coupling**.



Science 309, 2004 (2005).

Theory:
S. Murakami et al., *Science* **301**, 1348 (2003); J. Sinova *et al*., *PRL* **92**, 126603 (2004); J. Hirsch, *PRL* **83**, 1834 (1999).......

Experiment:
Y. K. Kato, et al., *Science* **306**, (2004); J. Wunderlich, et al., *PRL*. **94**, 047204 (2005); N. P. Stern et al., PRL 97, 126603 (2006) ....

Microscopic origin of spin-orbit coupling

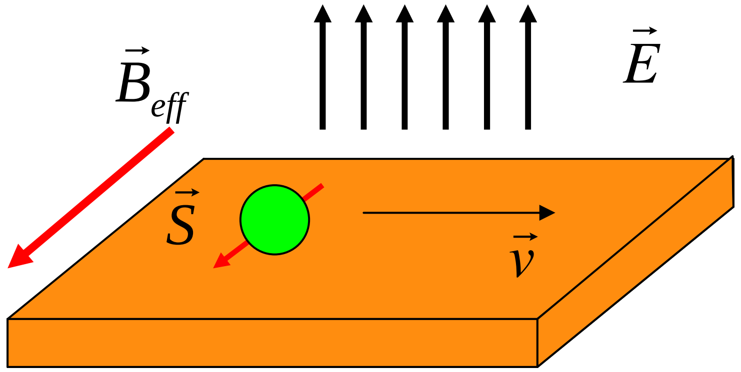
- Spin-orbit coupling originates from relativity.

- An electron moving in an $\vec{E}$ field. In the co-moving frame, the $\vec{E}$ field is moving.

- Due to relativity, an internal effective $\vec{B}$ field is induced and couples to electron spin.

$$\vec{B}_{eff} = \frac{\vec{v}}{c} \times \vec{E}$$

$$H_{so} \propto -\vec{S} \cdot \vec{B}_{eff}$$



Unconventional magnetism: dynamic generation of spin-orbit (SO) coupling without relativity!

- Conventional mechanism**:**

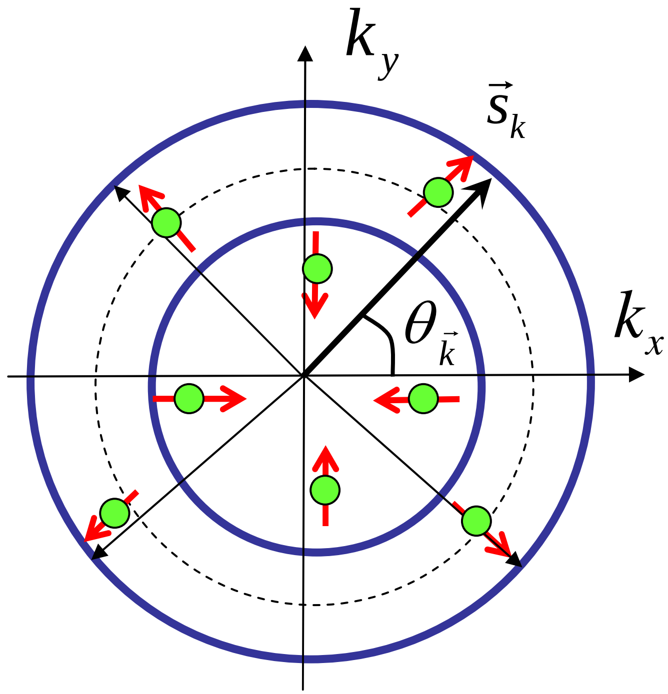
  A **single-body** effect; not directly related to many-body interactions.

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

Dynamically generate SO coupling through **unconventional magnetic phase transitions.**

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

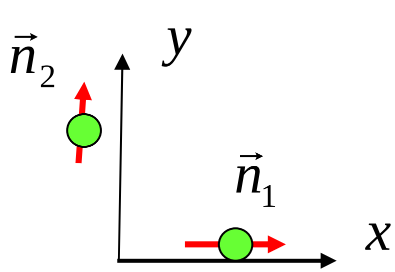
The isotropic *p*-wave magnetic phase



- Spin is not conserved; helicity $\vec{\sigma}\cdot\vec{k}$ is a good quantum number; no net spin-moment.

- Order parameter: spin dipole moment in momentum space (not in the coordinate space).

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

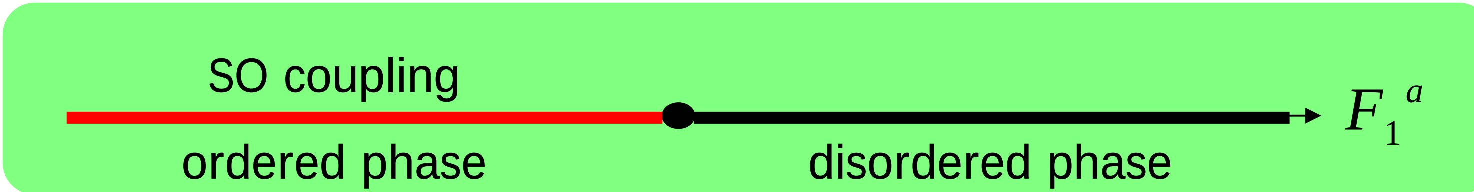


- **Isotropic phase with spin-orbit coupling.**

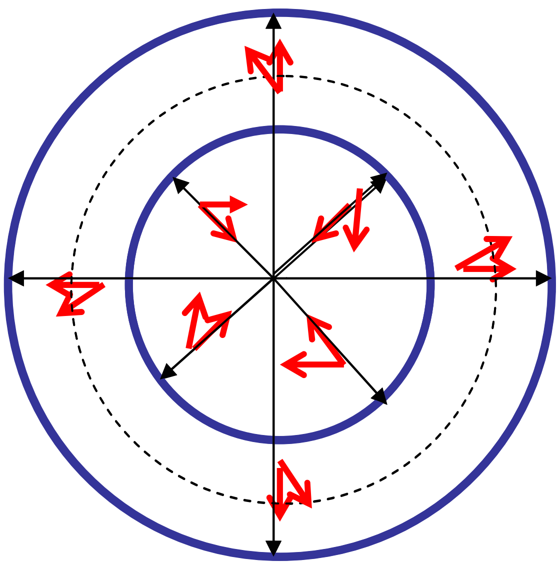
$$H_{MF} = H_0 + \bar{n}\sum_k \psi_\alpha^+ \vec{\sigma}_{\alpha\beta}\cdot\vec{k}\,\psi_\beta$$
$$\bar{n} = |\vec{n}_1| = |\vec{n}_2|$$

C. Wu et al., PRL 93, 36403 (2004);
C. Wu et al., cond-mat/0610326.

The subtle symmetry breaking pattern

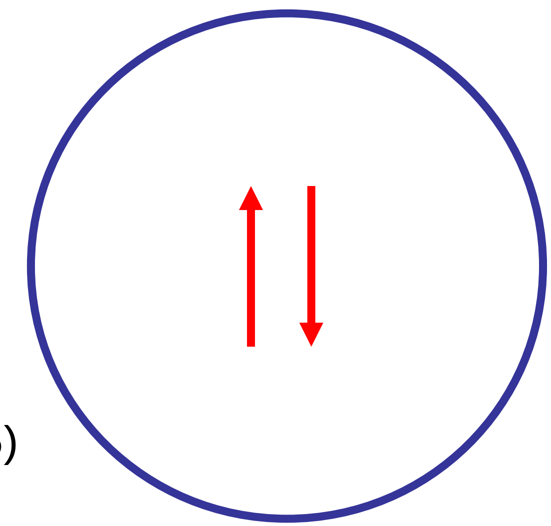


- $\vec{J}$ is conserved , but $\vec{L}, \vec{S}$ are not separately conserved.
- **Independent** orbital and spin rotational symmetries.



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

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

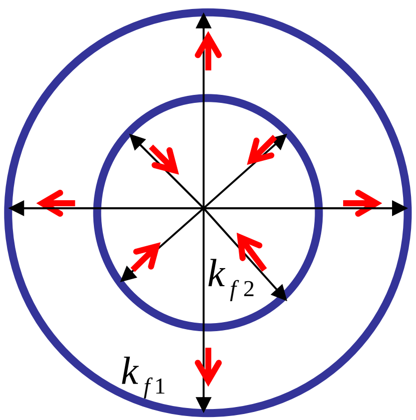


- **Relative spin-orbit** symmetry breaking.

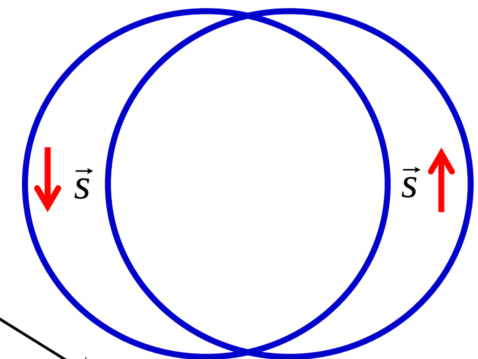
Introduction: electron liquid crystal phase with spin

unconventional superconductivity

unconventional magnetism



Spin-orbit coupling



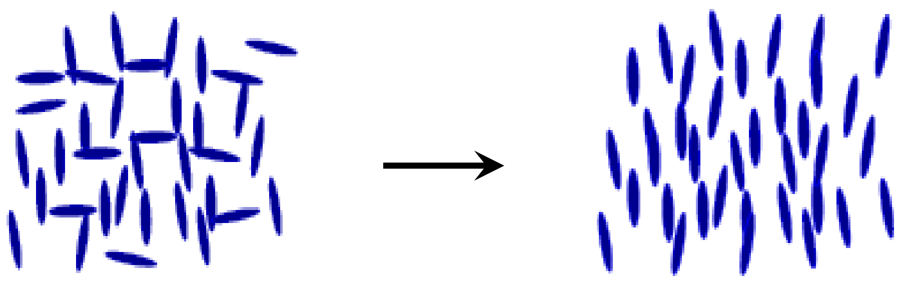
anisotropic electron liquid

Anisotropy: liquid crystalline order

- Classic liquid crystal: LCD.

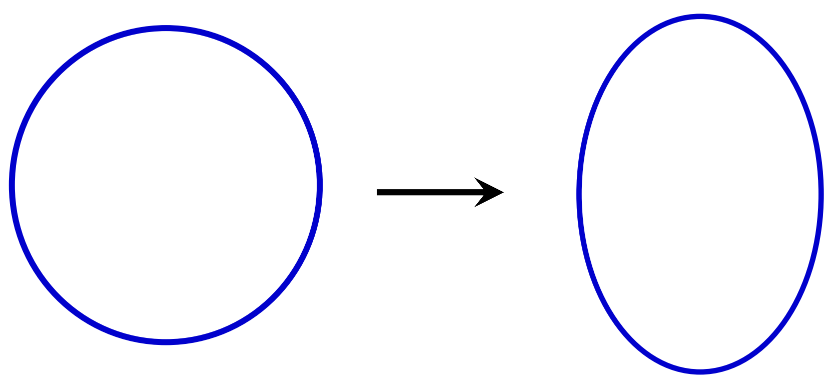
Nematic phase: rotational anisotropic but translational invariant.

isotropic phase



nematic phase

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

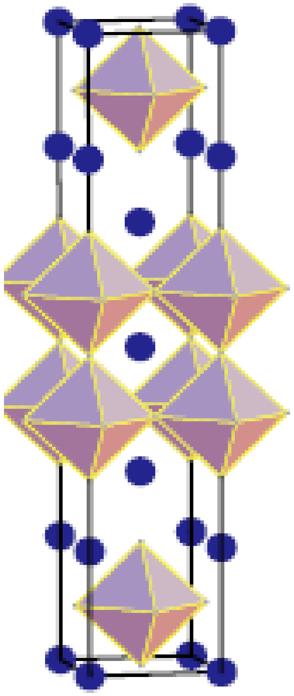


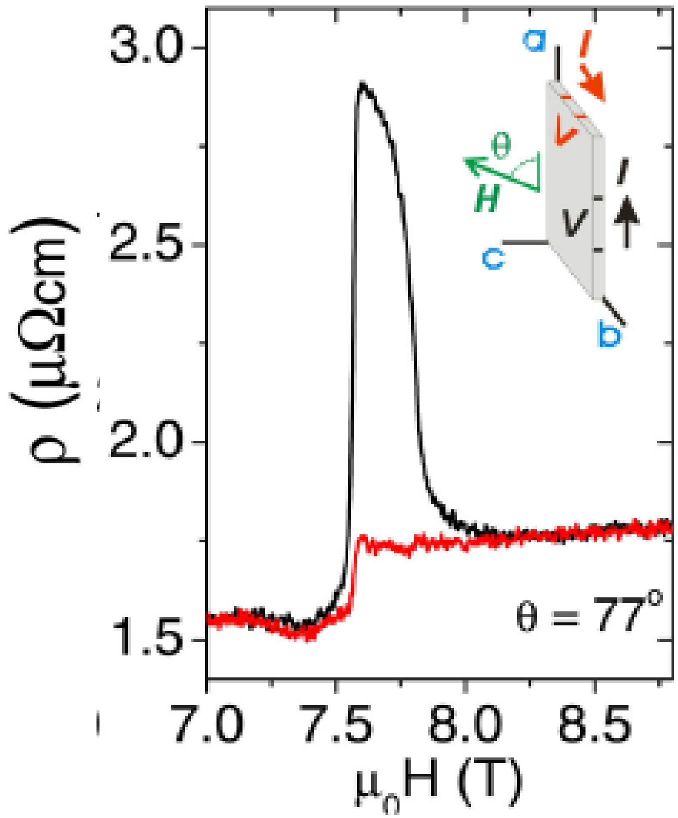
Fermi surface anisotropic distortions

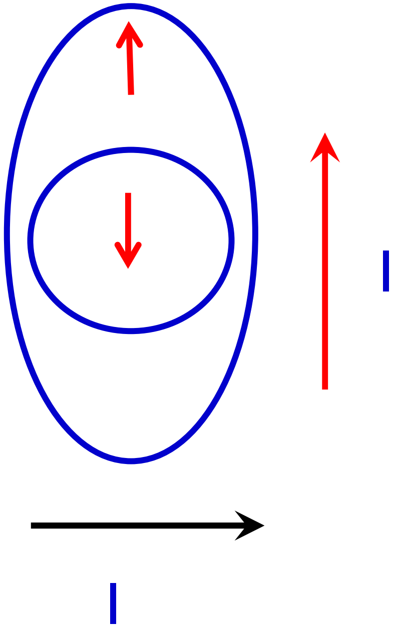
S. Kivelson, et al, Nature 393, 550 (1998); V. Oganesyan, et al., PRB 64,195109 (2001).

Nematic electron liquid in $Sr_3Ru_2O_7$ at high B fields

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

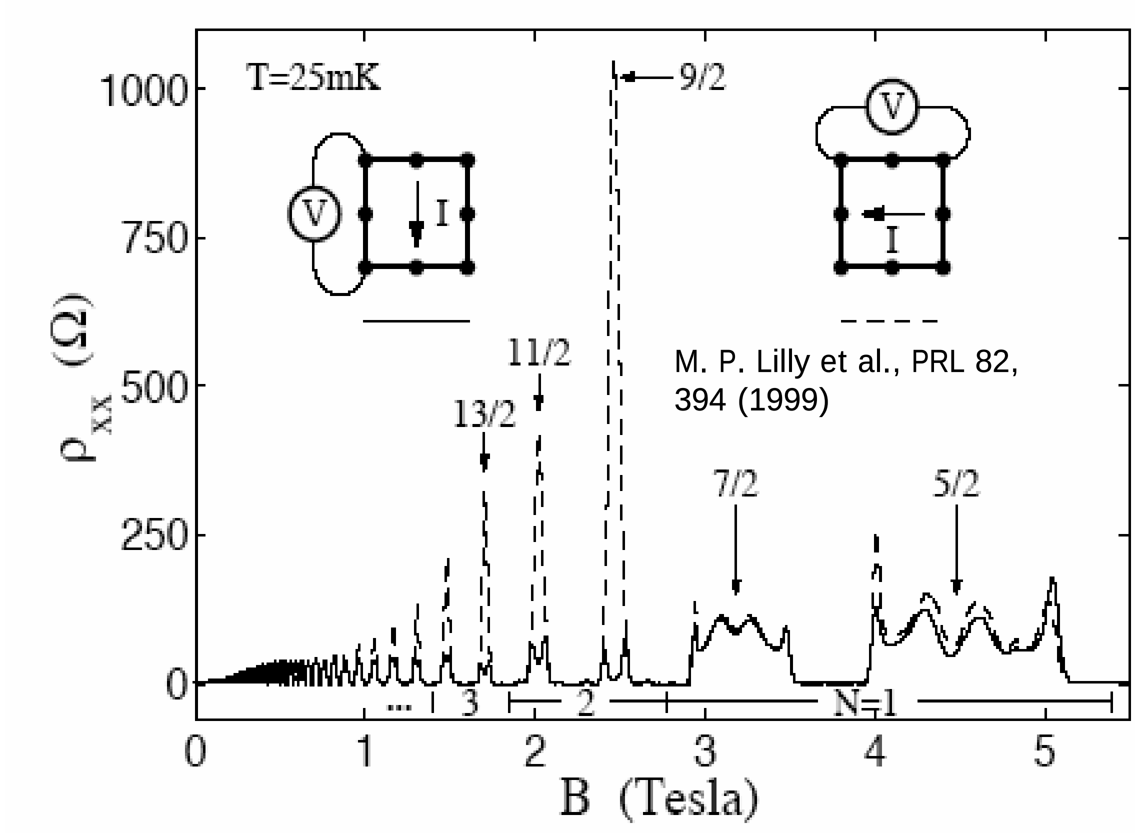






S. A. Grigera et al., Science 306 1154, (2004). R. A. Borzi et al.. Science express (2006).

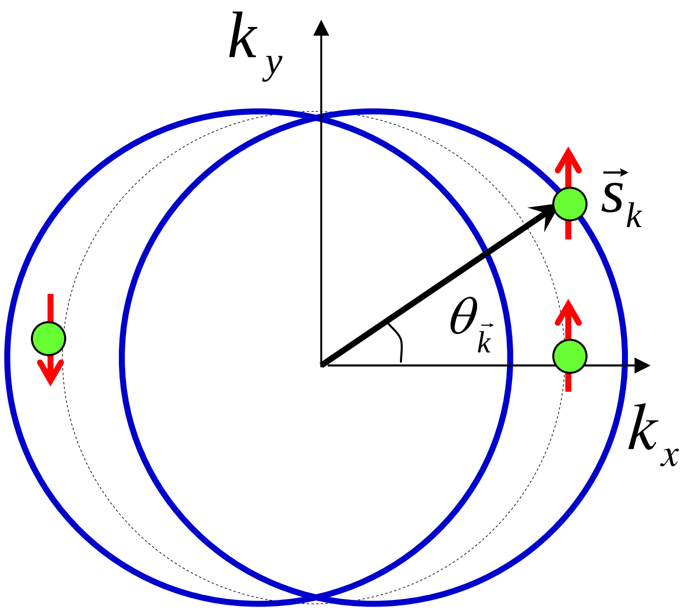
Nematic electron liquid in 2D GaAs/AlGaAs at high B fields



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); L. Radzihovsky et al., PRL 88, 216802 (2002).

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).

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

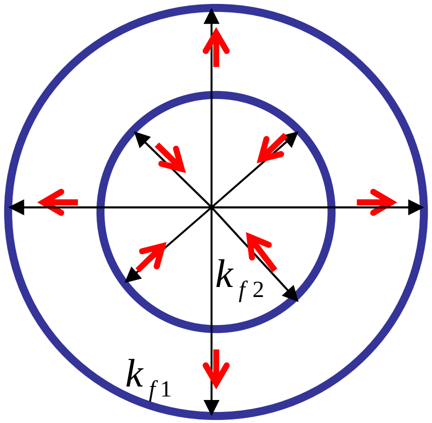
- Both orbital and spin rotational symmetries are broken.

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

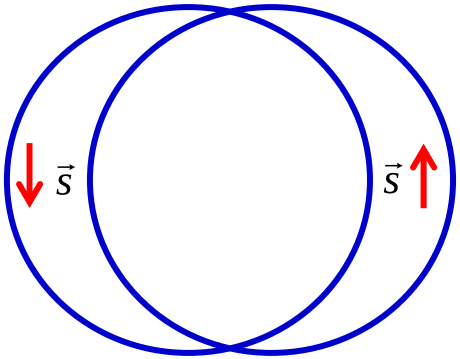
V. Oganesyan, et al., PRB 64,195109 (2001). C. Wu et al., PRL 93, 36403 (2004); Varma et al., Phys. Rev. Lett. 96, 036405 (2006)

Summary of the introduction part

unconventional superconductivity



unconventional magnetism



spin-orbit coupling

electron liquid crystal with spin

Outline

- Introduction.

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

  - Fermi surface instability of the Pomeranchuk type.

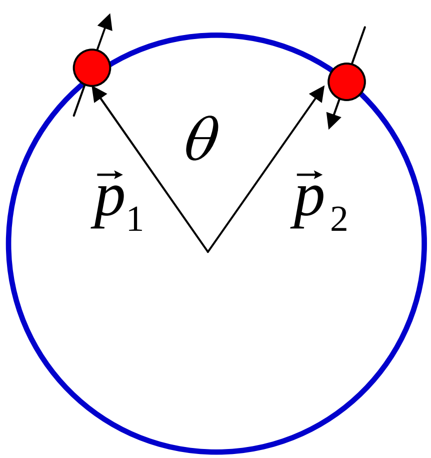
  - Mean field phase structures.

- Low energy collective modes.

- 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.

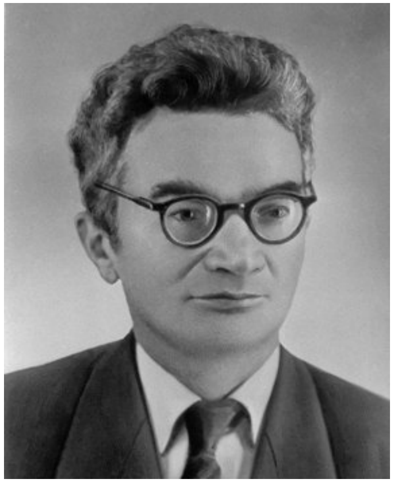
- Interaction functions (no SO coupling):

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

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

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

Pomeranchuk instability criterion



I. Pomeranchuk

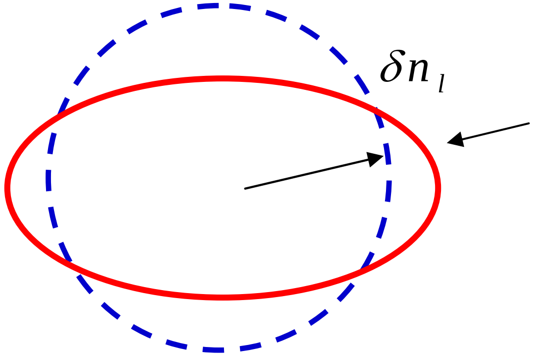
- Fermi surface: elastic membrane.
- Stability:

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

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

- Surface tension vanishes at:

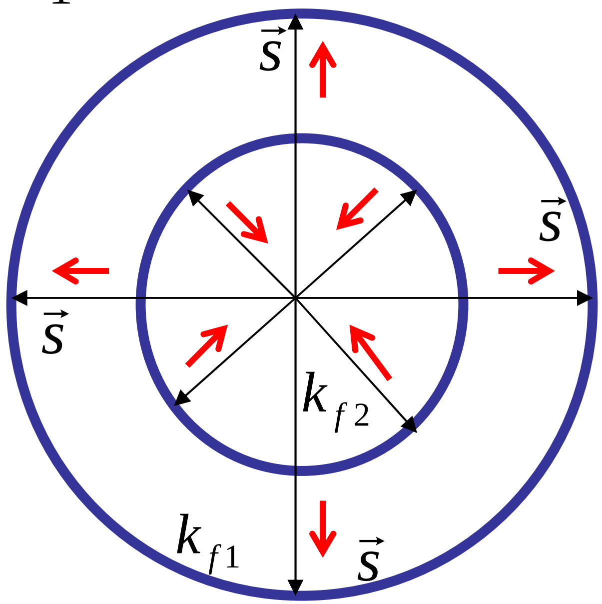
$$F_l^{s,a} < -(2l+1)$$



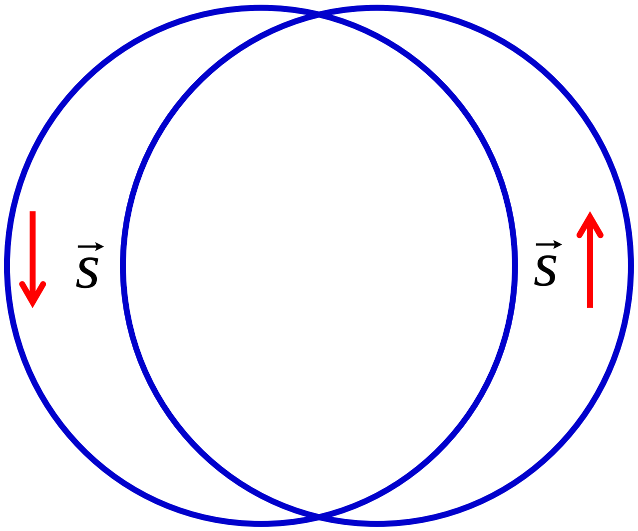
- Ferromagnetism: the F_0^a channel.
- Nematic electron liquid: the F_2^s channel.

Unconventional magnetism: Pomeranchuk instability in the spin channel

F_1^a



$\beta - \text{phase}$

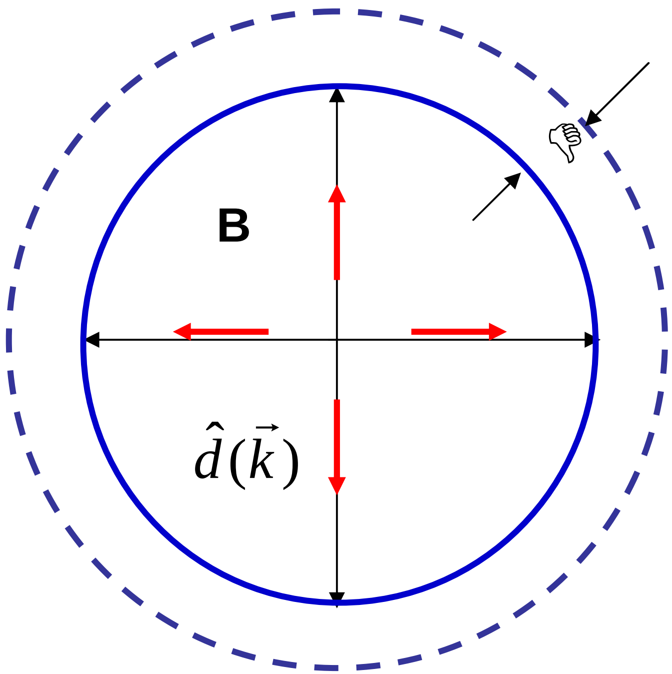


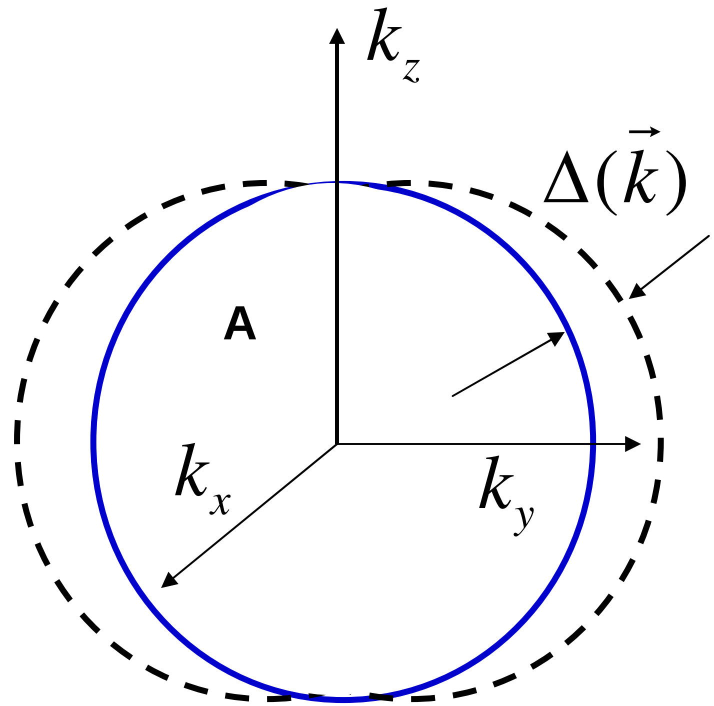
$\alpha - \text{phase}$

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

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

- *p*-wave triplet Cooper pairing.





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

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

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

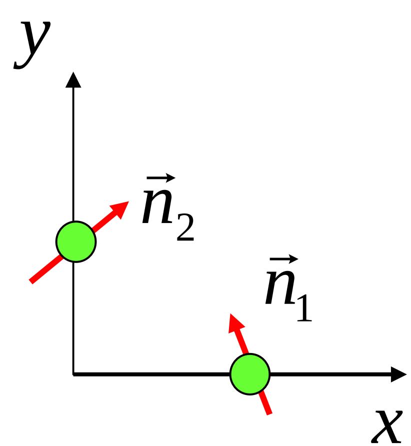
A. J. Leggett, Rev. Mod. Phys 47, 331 (1975)

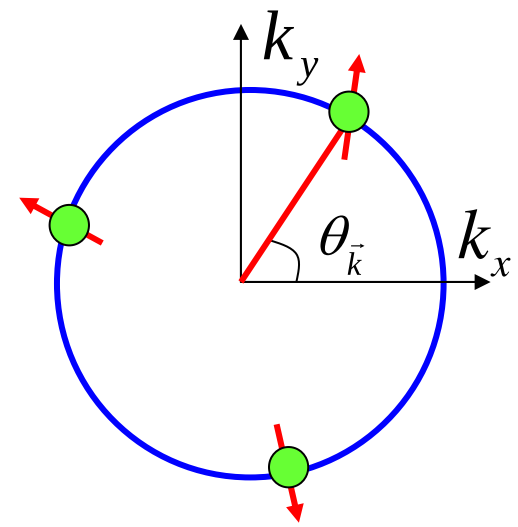
The order parameters: the 2D *p*-wave channel

- 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.

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

Mean field theory and Ginzburg-Landau free energy

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

$$F_1^a \qquad H_{\text{int}} = \sum_q f_1^a(\vec{q})\{\vec{n}_1(\vec{q})\cdot\vec{n}_1(\vec{q}) + \vec{n}_2(\vec{q})\cdot\vec{n}_2(\vec{q})\}$$

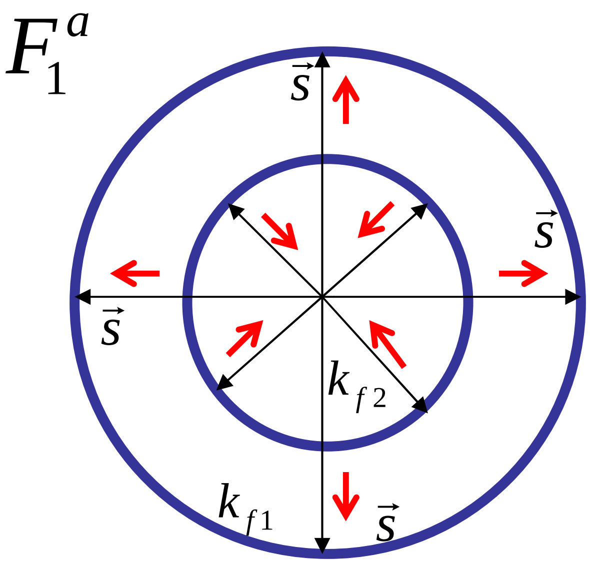
$$H_{MF} = \sum_k \psi^+(k)[\varepsilon(k) - \mu - (\vec{n}_1\cos\theta_k + \vec{n}_2\sin\theta_k)\cdot\vec{\sigma}]\psi(k)$$

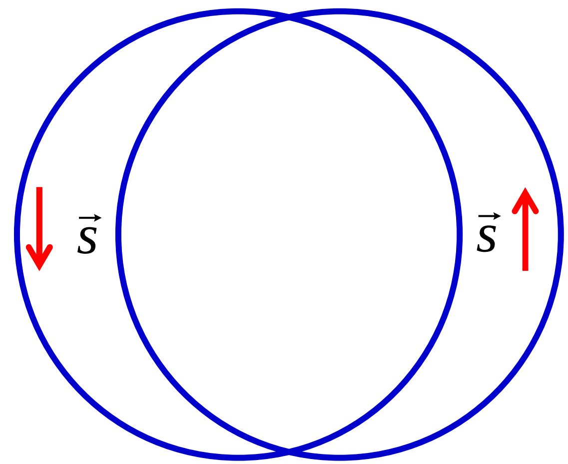
- Symmetry constraints: rotation (spin, orbital), parity, time-reversal.

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

$$r = \frac{N_0}{2}\frac{1 + F_1^a/2}{|F_1^a|} \qquad F_1^a < -2 \;\Longrightarrow\; \text{instability!}$$

β and α-phases (*p*-wave)



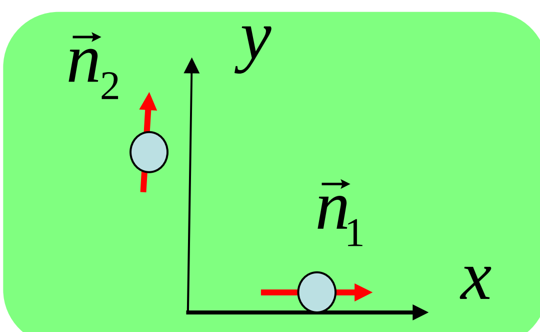


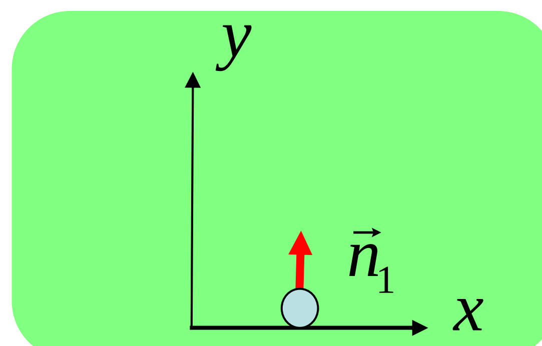
$$v_2 < 0 : \beta - \text{phase}$$

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

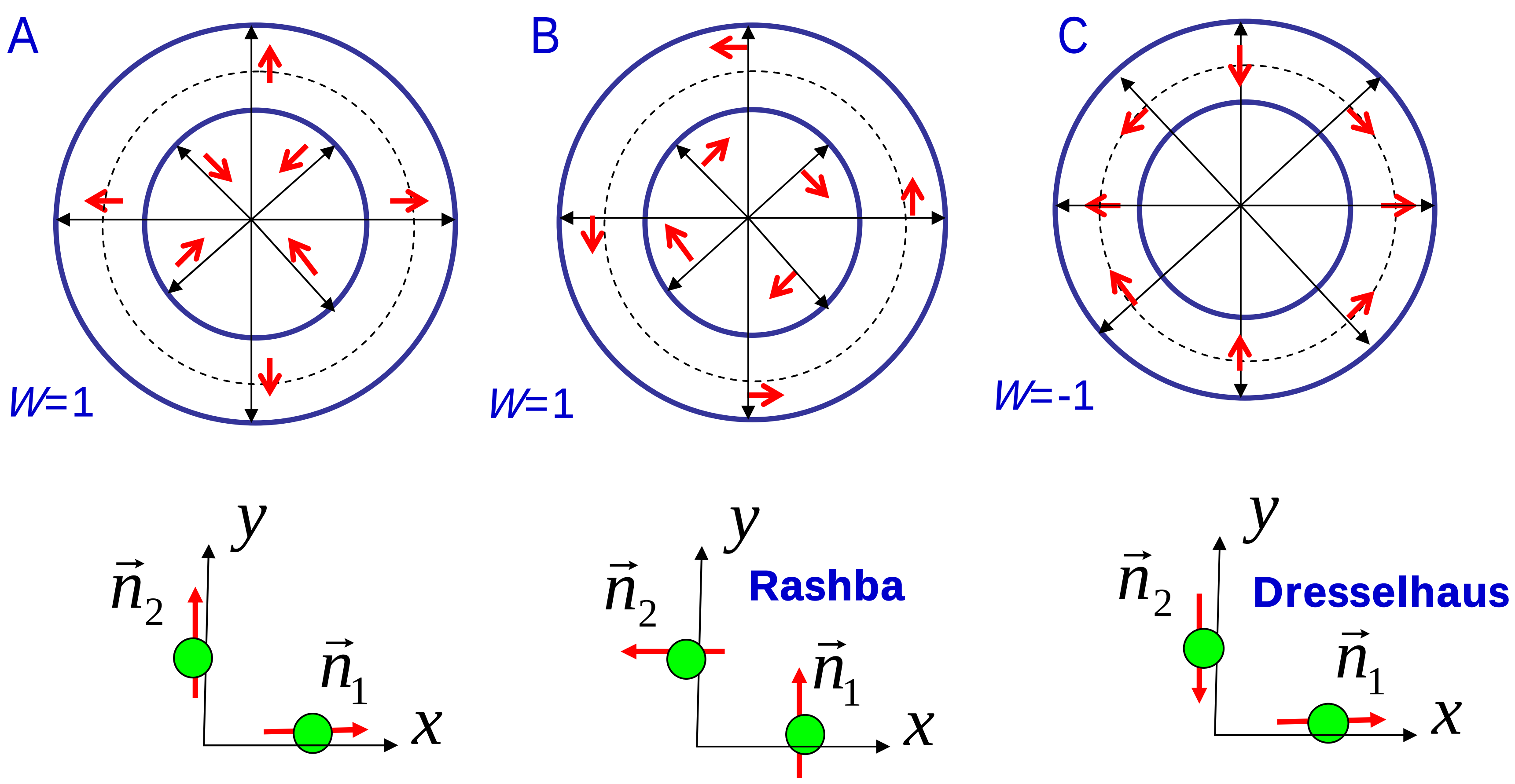
$$v_2 > 0 : \alpha - \text{phase}$$

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



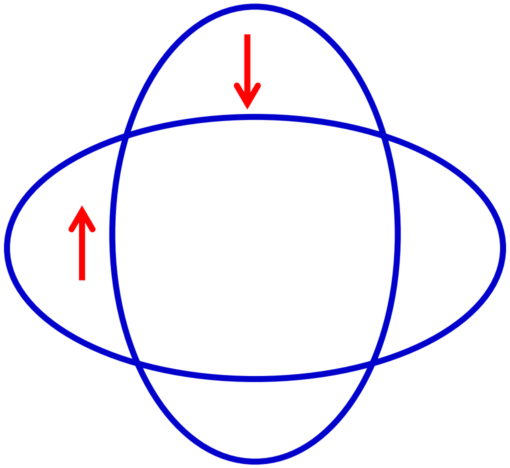


The Ω-phases: vortices in momentum space

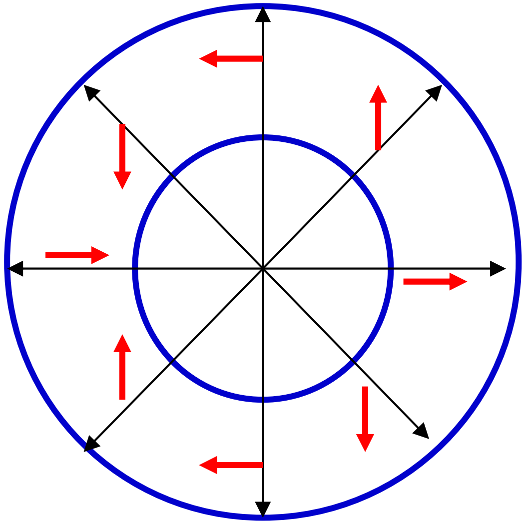


- Perform global spin rotations, A→ B→ C.

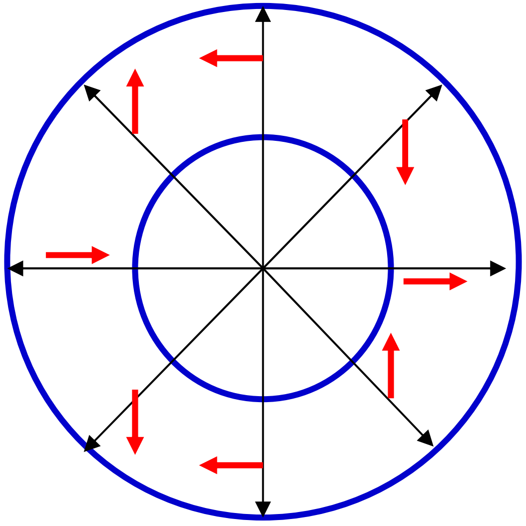
2D *d*-wave α and β-phases



α-phase



β-phase: w=2



β-phase: w=-2

Outline

- Introduction.

- Mechanism for unconventional magnetic states.

- **Collective excitations.**

  - Symmetry spontaneously breaking: low energy Goldstone modes; Neutron scattering spectra.

  - Ground state chiral instability.

- Possible experimental realization and detection methods.

The α-phases: orbital & spin channel Goldstone (GS) modes

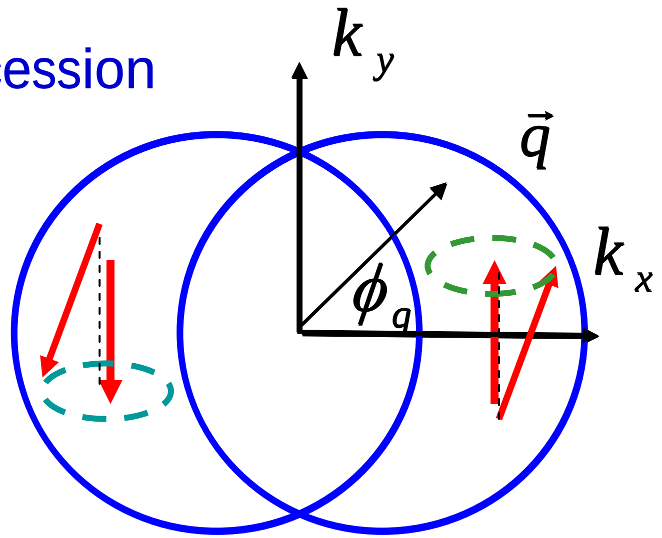
- Orbital channel GS mode: FS oscillations (intra-band transition).

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

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).

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

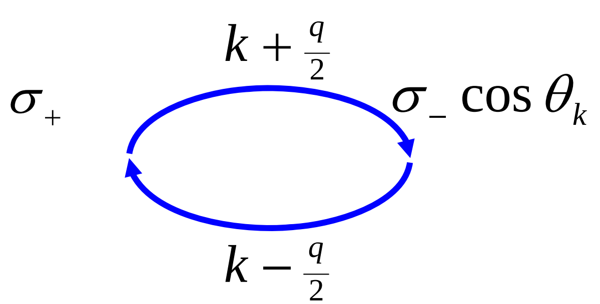


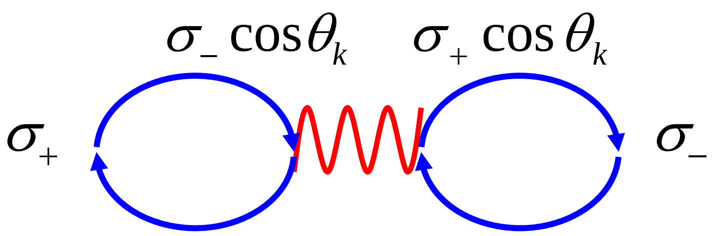
Nearly isotropic, underdamped and linear dispersions at small q.

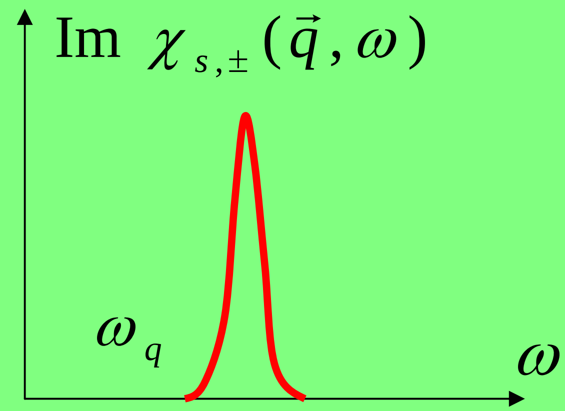
The α-phases: neutron spectra

- *Elastic* neutron spectra: no Bragg peaks. Order parameters do not couple to neutron moments directly.

- *In-elastic* neutron spectra: **resonance peaks** develop **at $T<T_c$** due to the coupling between GS modes and spin-waves (spin-flip channel).

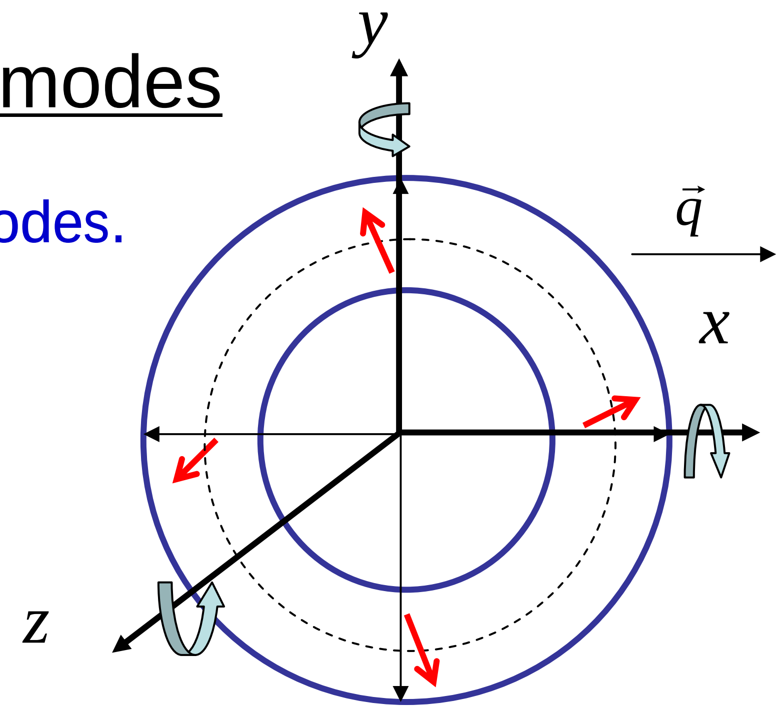






$$\mathrm{Im}\,\chi_{s,\pm}(\vec{q},\omega) \approx N_0 \omega_q^2 \delta(\omega^2 - \omega_q^2)$$

The β-phases: GS modes



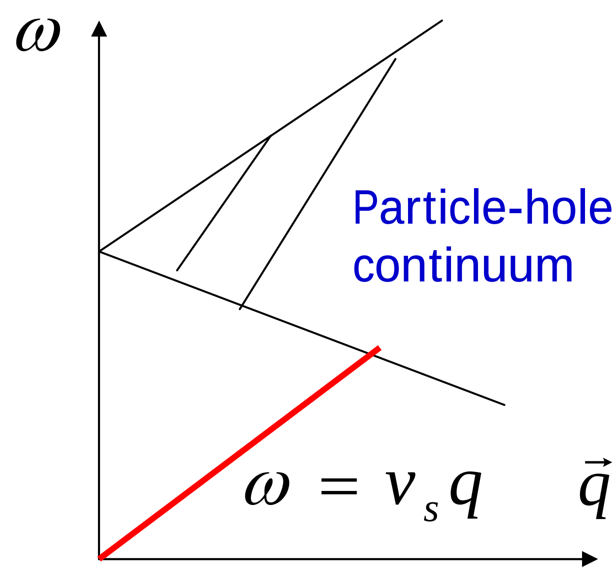
- 3 branches of relative spin-orbit modes.

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

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

- 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.



Spontaneous chiral instability: the *p*-wave β-phase

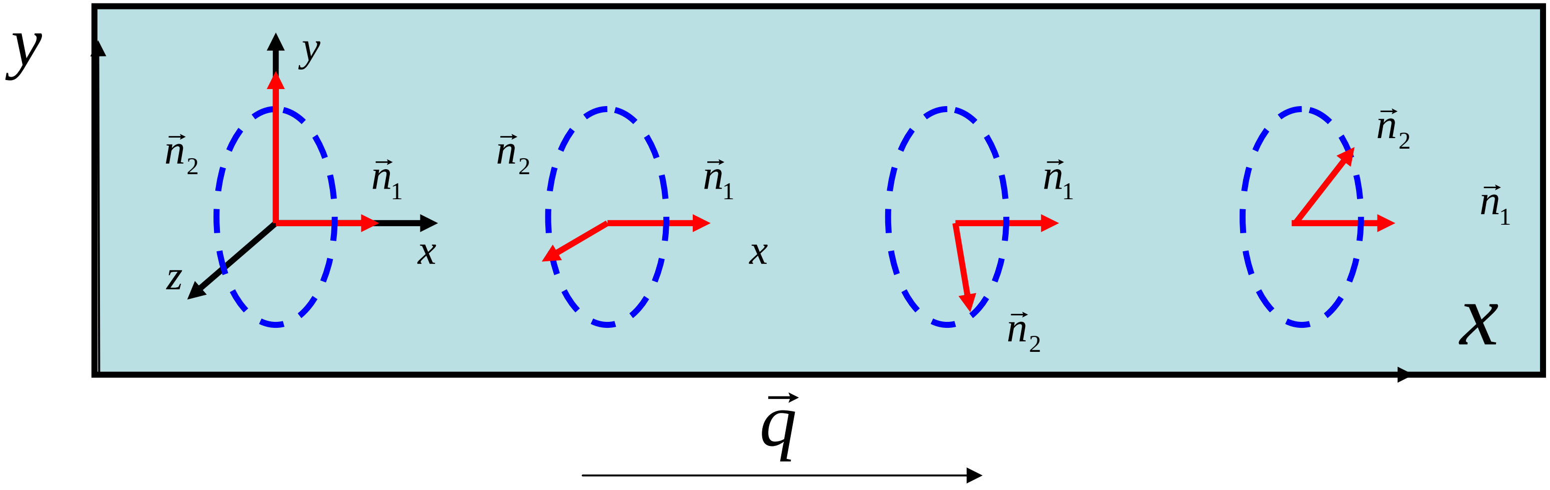
- The uniform state can not be the true ground state.

- Linear spatial derivative term satisfying all the symmetry constraints.

$$F_{grad}(\partial_b \vec{n}_a) = \gamma_1 \partial_a \vec{n}_b . \partial_a \vec{n}_b + \gamma_2 (\partial_x \vec{n}_2 - \partial_y \vec{n}_1) \cdot (\vec{n}_1 \times \vec{n}_2)$$

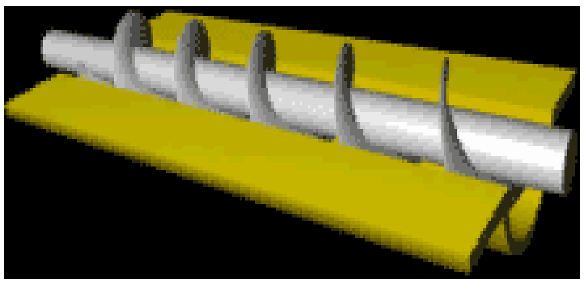
- Spiral of spin-dipole moments.

$$F_{grad}(q) = \gamma_1 \bar{n}^2 q^2 - \gamma_2 \bar{n}^3 q \quad q_c = \gamma_2 \bar{n} / (2\gamma_1)$$

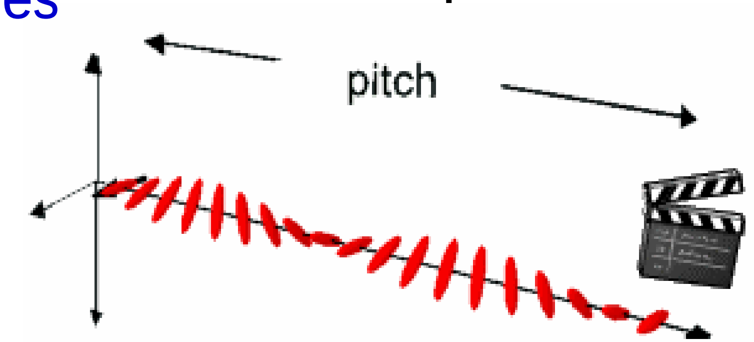


cf. Chirality: explicit parity breaking

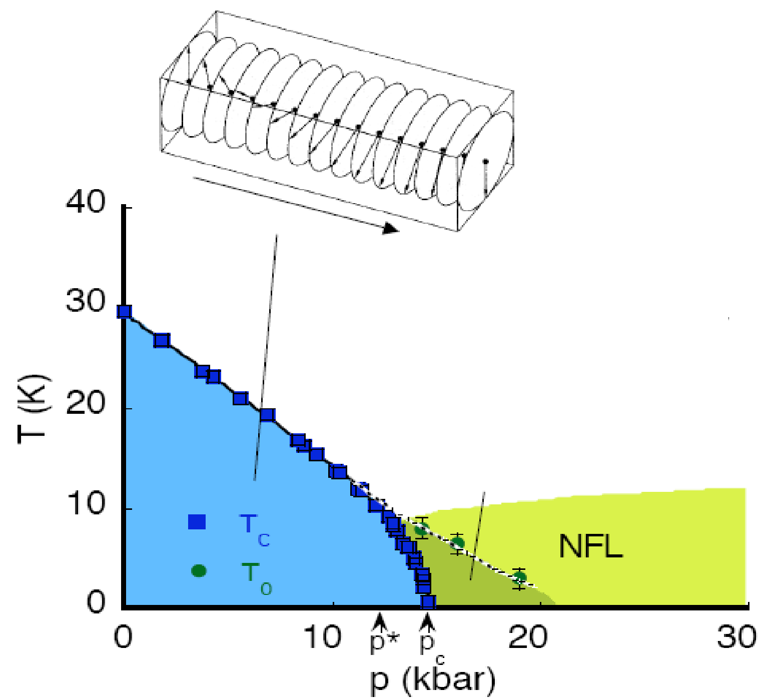
- Cholesteric liquid crystals. Molecules are chiral.



helical phase



- Helical magnet: MnSi. Lattices lack of the inversion center.



Dzyaloshinskii-Moriya interaction:

$$H_{DM} = \gamma \vec{S}\cdot(\vec{\nabla}\times\vec{S})$$

C. Pfleiderer et al., Nature 427, 227 (2004).

The *p*-wave β-phase: spontaneous chiral instability

• **Chiral instability** in the **originally non-chiral** system.

• Dynamic generation of Dzyaloshinskii-Moriya-like spin-orbit coupling.

$$\gamma_2(\partial_x \vec{n}_2 - \partial_y \vec{n}_1) \cdot (\vec{n}_1 \times \vec{n}_2)$$

No spin-moments; spirals of spin-dipole moment.

• This chiral instability does not occur in the ferromagnetic transition and in any other channel Pomeranchuk instability.

Outline

- Introduction.

- Mechanism for unconventional magnetic phase transitions.

- Low energy collective modes.

- **Possible experimental realization and detection methods.**

A natural generalization of ferromagnetism

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

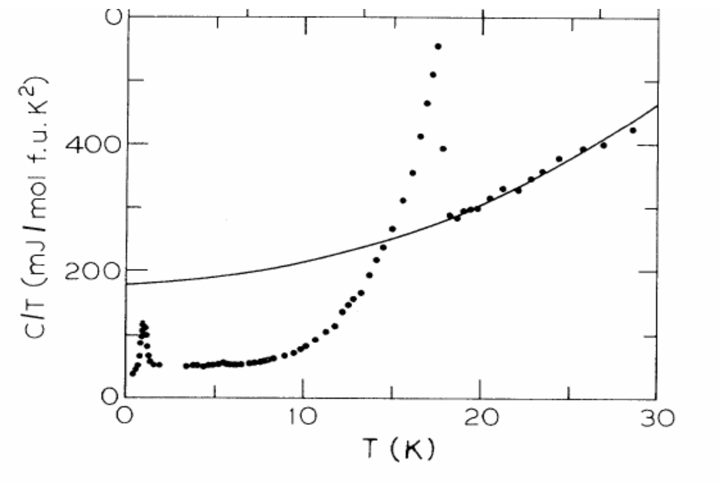
	s-wave	*p*-wave	*d*-wave
SC/SF	Hg, 1911	^{3}He, 1972	high T_c, 1986
magnetism	Fe, ancient time	?	?

• Optimistically, unconventional magnets are probably not rare.

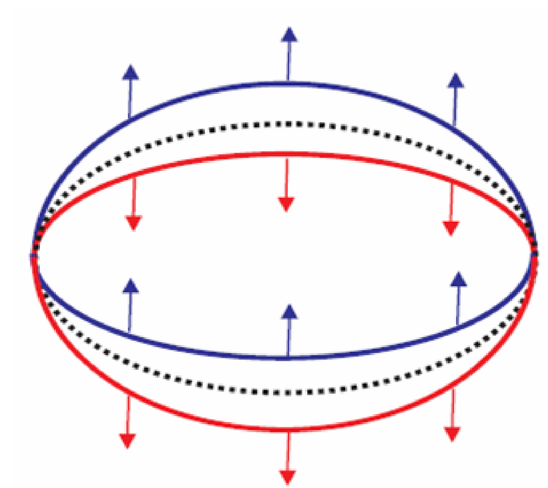
cf. Antiferromagnetic materials are actually very common in transition metal oxides. But they were not well-studied until neutron-scattering spectroscopy was available.

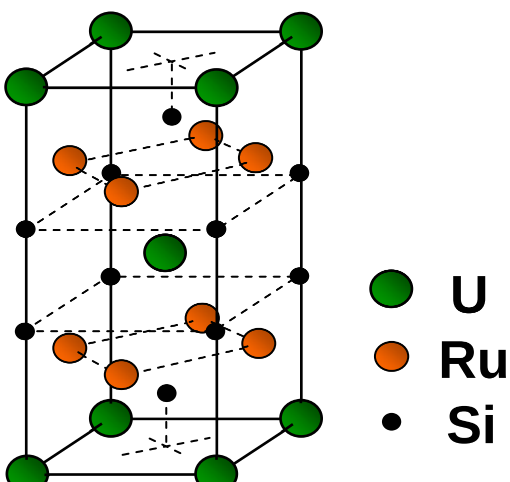
Search for unconventional magnetism (I)

- URu_2Si_2: hidden order behavior below 17.5 K.



T. T. M. Palstra et al., PRL 55, 2727 (1985); A. P. Ramirez et al., PRL 68, 2680 (1992)





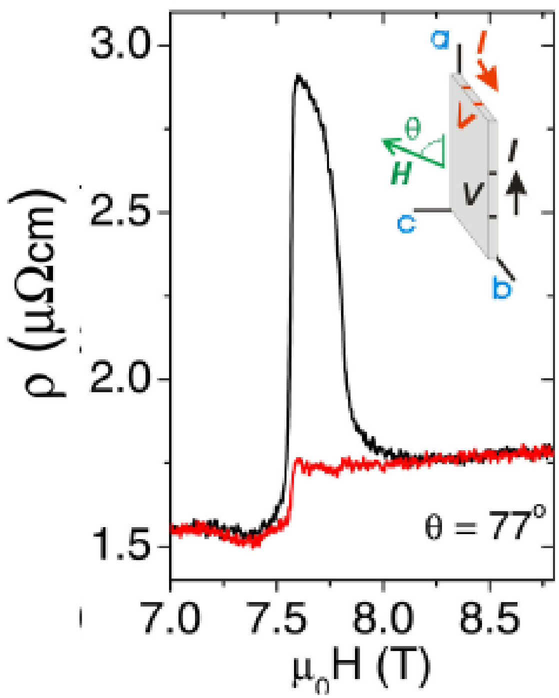
helicity order (the *p*-wave α-phase);

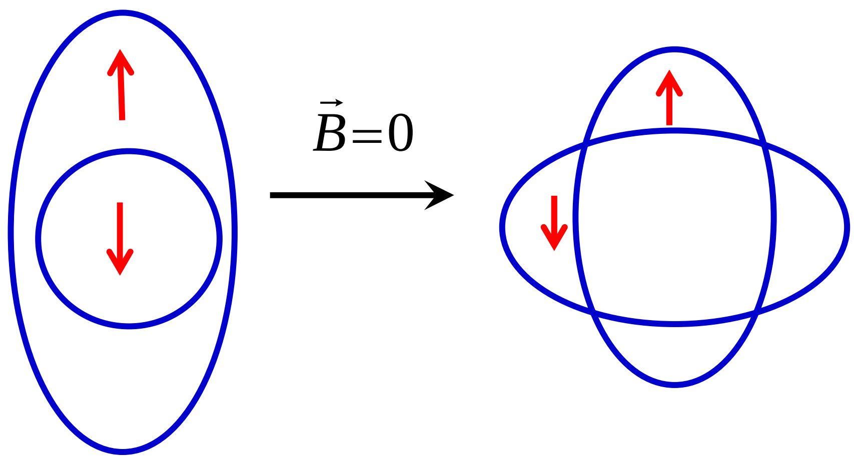
Varma et al., Phys. Rev Lett. 96, 036405 (2006)

Search for unconventional magnetism (II)

- $Sr_3Ru_2O_7$ (large external B field): a mixture of the instabilities in the density and spin channels.

- We need an instability purely in the spin channel with zero field.





Search for unconventional magnetism (III)

• 2D electron gas. Quantum Monte-Carlo simulation of Landau parameters.

Y. Kwon, D. M. Ceperley, and R. M. Martin, PRB 50, 1684 (1994).

• F^a_1 is negative and decreases as the density is lowered.

	$r_s = 1.0$	$r_s = 2.0$	$r_s = 3.0$	$r_s = 5.0$
F_0^s	-0.60(1)	-0.99(1)	-1.63(1)	-3.70(3)
F_0^a	-0.34(3)	-0.41(8)	-0.49(7)	-0.5(1)
F_1^s	-0.14(2)	-0.10(1)	-0.03(1)	0.12(2)
F_1^a	-0.19(2)	-0.24(1)	-0.26(1)	-0.27(2)
F_2^s	-0.07(2)	-0.16(3)	-0.27(3)	-0.50(5)
F_2^a	0.01(2)	0.07(3)	0.14(3)	0.32(5)
m^*/m	0.93(1)	0.95(1)	0.99(1)	1.06(1)
g^*/g	1.52(6)	1.7(2)	2.0(3)	1.9(4)

$$n \propto r_s^{-2}$$

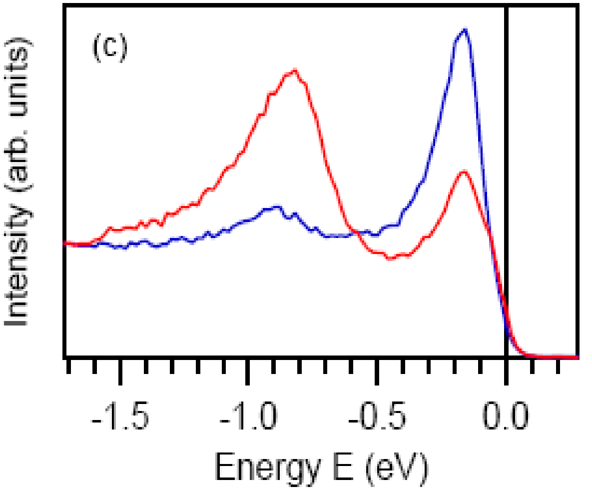
• It would be great if the simulation can be further extended into even lower density regime.

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):

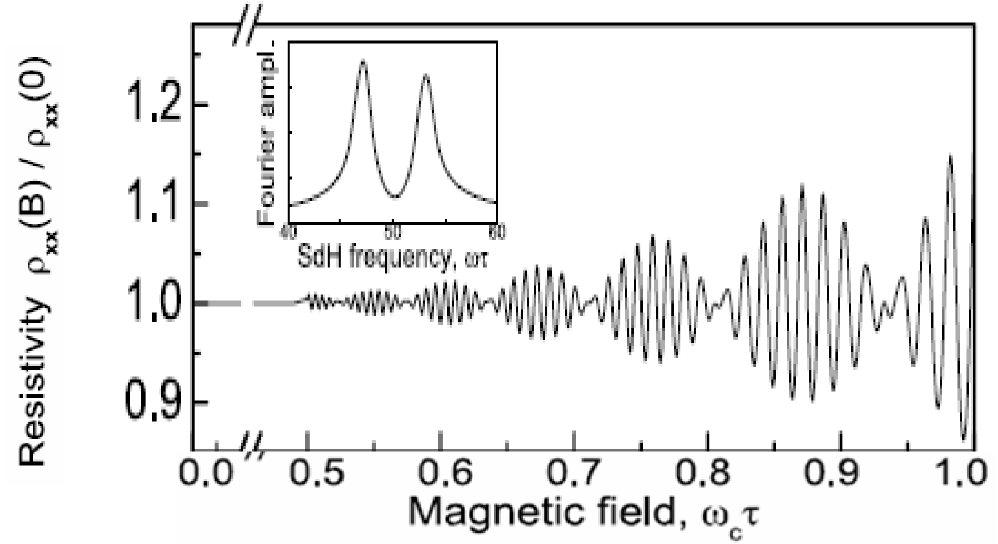
The band-splitting is proportional to order parameter, thus is temperature and pressure dependent.

Detection (II): neutron scattering and transport

- Elastic neutron scattering: no Bragg peaks;
Inelastic neutron scattering: resonance peaks below T_c.

- Transport properties.

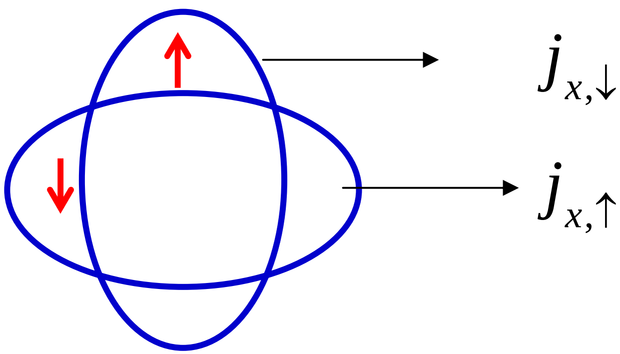
β-phases: Temperate dependent beat pattern in the Shubnikov - de Hass magneto-oscillations of $\rho(B)$.



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

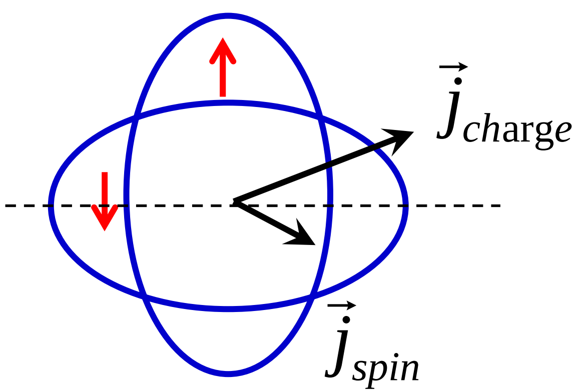
Detection (III): transport properties

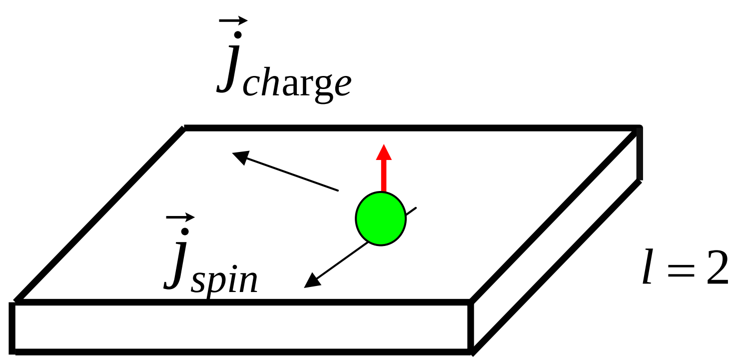
- Spin current induced from charge current (d-wave). The directions of change and spin currents are symmetric about the x-axis.



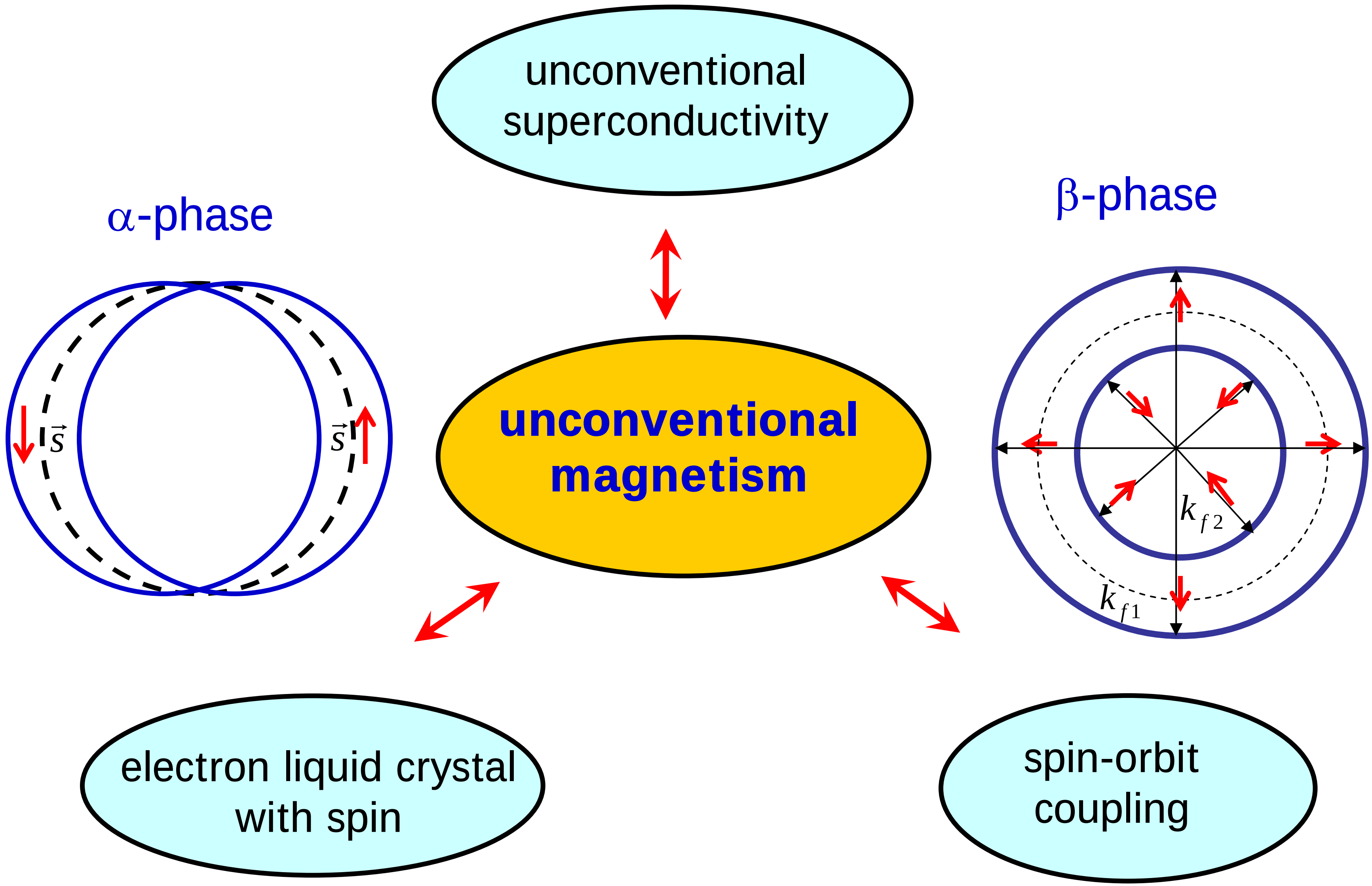
$$j_{x,charge} = j_{x,\uparrow} + j_{x,\downarrow}$$

$$j_{x,spin} = j_{x,\uparrow} - j_{x,\downarrow}$$





Summary


unconventional superconductivity
α-phase
β-phase
unconventional magnetism
$\vec{S}$
$\vec{S}$
k_{f2}
k_{f1}
electron liquid crystal with spin
spin-orbit coupling

Two dimensional metal-insulator transition?

Conjecture: