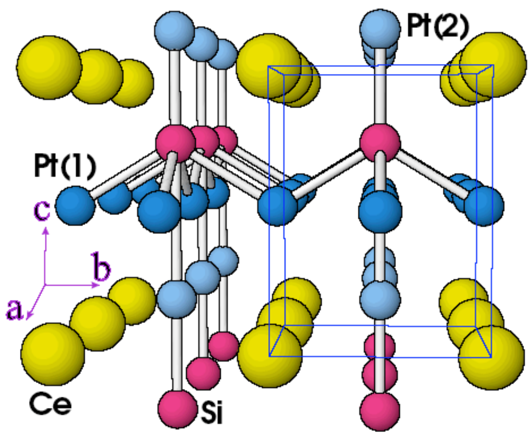
Spin-orbit coupling and superconductivity in materials without inversion symmetry

Sendai, June 29, 2006

Manfred Sigrist, ETH Zürich



$CePt_3Si$

- Parity as a key symmetry for superconductivity
  role of antisymmetric spin-orbit coupling
- Physical properties
  discussion of experimental results

Collaborators:

Theory

ETH Zurich: P.A. Frigeri, N. Hayashi, K. Wakabayashi, I. Milat, Y. Yanase

Uni Wisconsin: D.F. Agterberg, R.P. Kaur

Osaka Uni: A. Koga

Experiment

TU Wien: E. Bauer and his team

Uni Illinois: H-Q. Yuan, …

Kyoto Uni: T. Shibauchi, Y. Matsuda, …

IBM Watson Lab: L. Kruzin-Elbaum

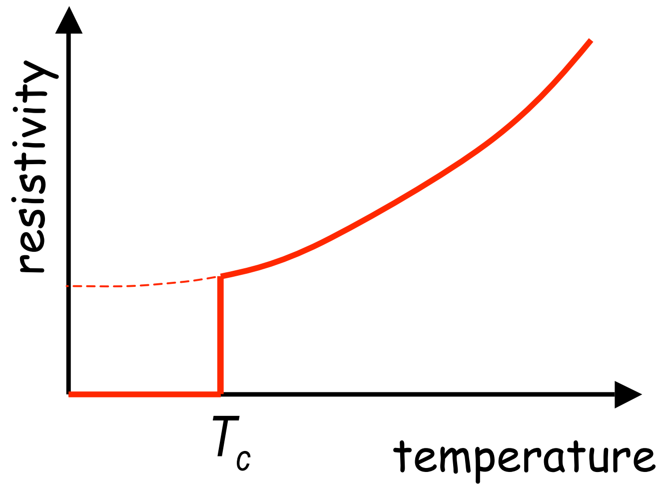
Funding:

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

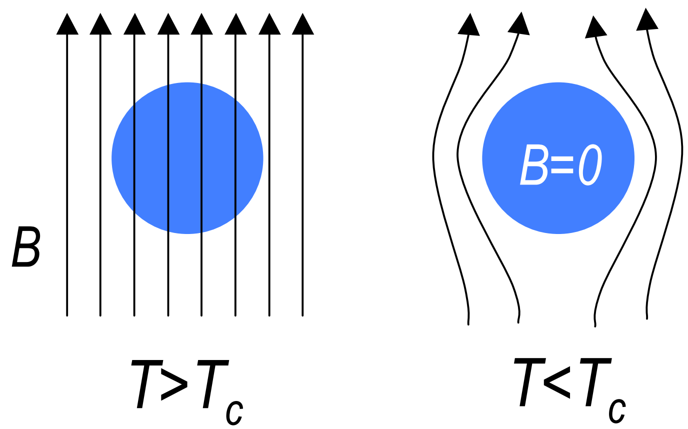
MaNEP
SWITZERLAND

Superconductivity

Electrical resistance (1911)



Field expulsion (1933)
Meissner-Ochsenfeld effect



Superconductivity as a thermodynamic phase

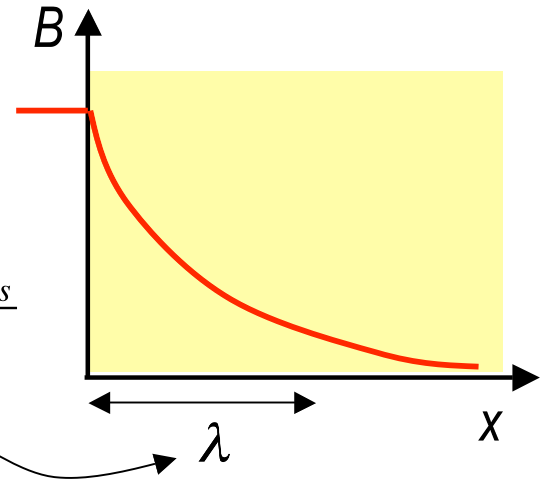
London theory (1935)

$$\left.\begin{aligned} \nabla \times \lambda^2 \vec{j} &= -\vec{B} \\ \nabla \times \vec{B} &= \frac{4\pi}{c}\vec{j} \end{aligned}\right\} \Rightarrow \quad \boxed{\nabla^2 \vec{B} = \lambda^{-2}\vec{B}}$$

density of superconducting electrons

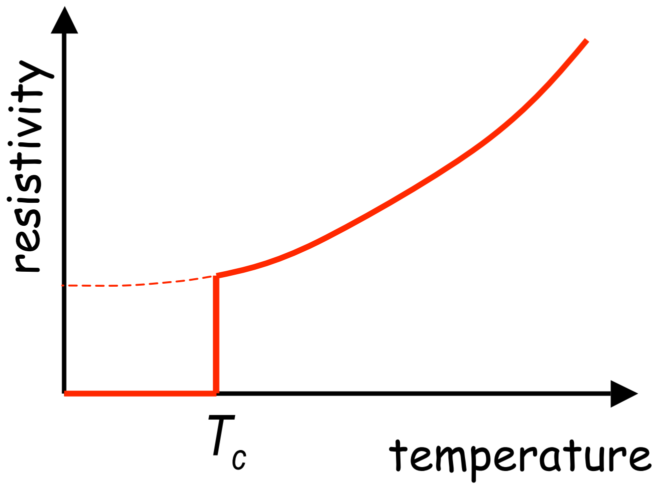
$$\lambda^{-2} = \frac{4\pi e^2 n_s}{mc^2}$$

London penetration depth



Superconductivity

Electrical resistance (1911)



Field expulsion (1933)
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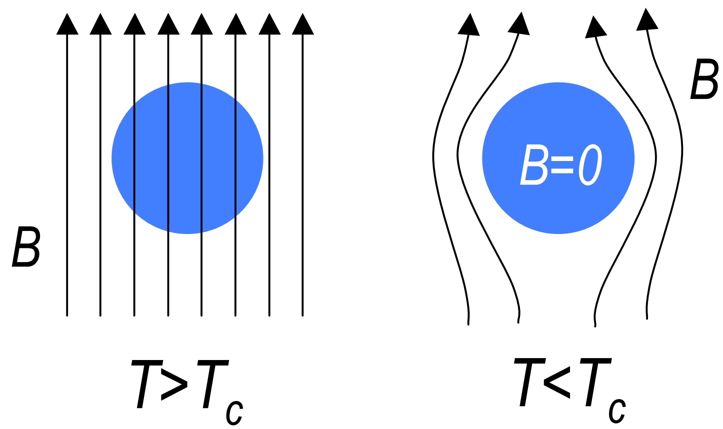


Superconductivity as a thermodynamic phase

Order parameter: $\Psi(\vec{r}) = |\Psi(\vec{r})| e^{i\varphi(\vec{r})}$ condensate with a broken *U(1)*-gauge symmetry

$$F[\Psi, \vec{A}] = \int d^3 r \left[a(T)|\Psi|^2 + b|\Psi|^4 + K|\vec{D}\Psi|^2 + \frac{1}{8\pi}(\vec{\nabla} \times \vec{A})^2 \right]$$

Ginzburg-Landau theory (1950)

minimal coupling $\vec{D} = \vec{\nabla} + i\frac{2e}{\hbar c}\vec{A}$

Mikroscopic viewpoint of superconductivity

Order parameter $\Psi(\vec{r}) = |\Psi(\vec{r})| e^{i\varphi(\vec{r})}$ *complex condensate wave function*

Coherent state of electron pairs (Cooper pairs)

$$|\psi\rangle = \prod_{\vec{k}} \left\{ u_{\vec{k}} + v_{\vec{k}} c^{\dagger}_{\vec{k}\uparrow} c^{\dagger}_{-\vec{k}\downarrow} \right\} |0\rangle$$

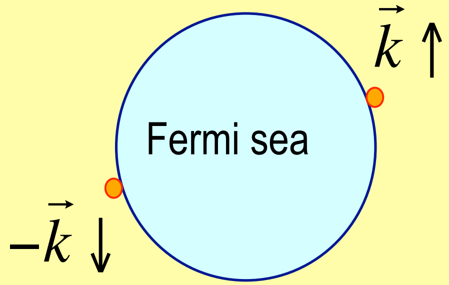
not a state of fixed particle number

$$c_{-\vec{k}\downarrow} c_{\vec{k}\uparrow} |\psi\rangle = u_{\vec{k}} v_{\vec{k}} |\psi\rangle$$

condensate wavefunction

$$\Psi_{\vec{k}} = \langle \psi | c_{-\vec{k}\downarrow} c_{\vec{k}\uparrow} | \psi \rangle = u_{\vec{k}} v_{\vec{k}}$$

Bardeen-Cooper-Schrieffer (1957)



$P_{tot} = 0$

→ fixed phase

violation of *U(1)*-gauge symmetry

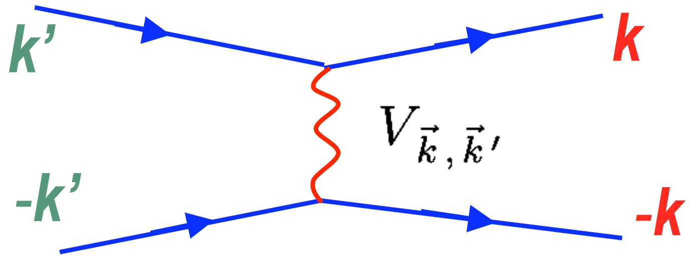
$$c_{\vec{k}} \rightarrow e^{i\alpha} c_{\vec{k}}$$
$$\Rightarrow \Psi_{\vec{k}} \rightarrow e^{2i\alpha} \Psi_{\vec{k}}$$

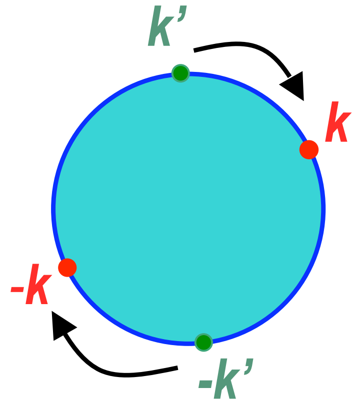
"U(1) - Higgs field"

Pairing interaction

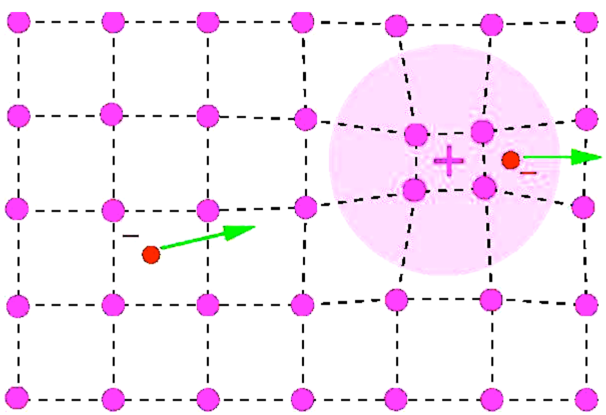
Cooper pair formation (bound state of 2 electrons) needs attractive interaction

$$\mathcal{H}_{pair} = \frac{1}{2\Omega} \sum_{\vec{k},\vec{k}'} \sum_{s,s'} V_{\vec{k},\vec{k}'} c^\dagger_{\vec{k},s} c^\dagger_{-\vec{k},s'} c_{-\vec{k}',s'} c_{\vec{k}',s}$$





electron phonon interaction:



attractive interaction

⬇

scattering between electron states with degenerate energy

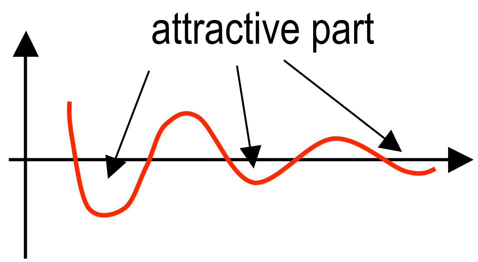
$$\varepsilon_{\vec{k}} = \varepsilon_{-\vec{k}}$$

Alternative mechanism for Cooper pairing

Pairing from purely repulsive interactions: Kohn & Luttinger (1965)

screened Coulomb potential in metal has long-ranged oscillatory tail (sharp Fermi edge)

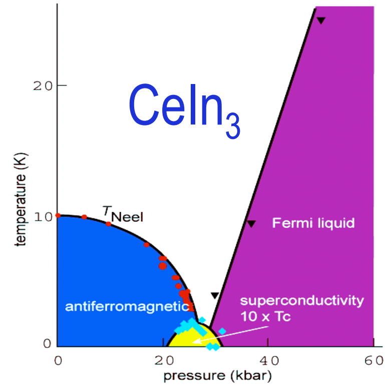
Friedel oscillations: $V(r) \propto r^{-3} \cos(2k_F r)$



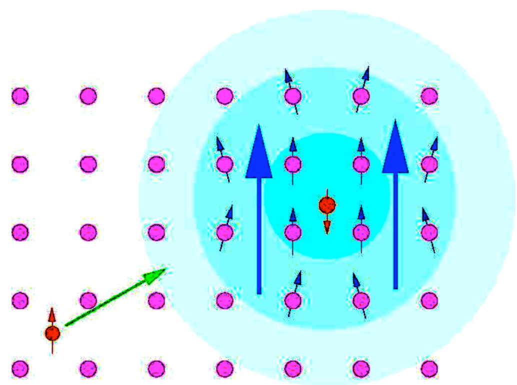
pairing in high-angular momentum channel $l > 0$

$$T_c/T_F \sim \exp\{-(2l)^4\}$$

very low !



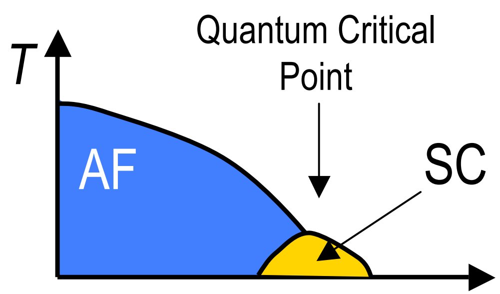
Pairing by magnetic fluctuations: Berk & Schrieffer (1966)



easily spin polarizable medium

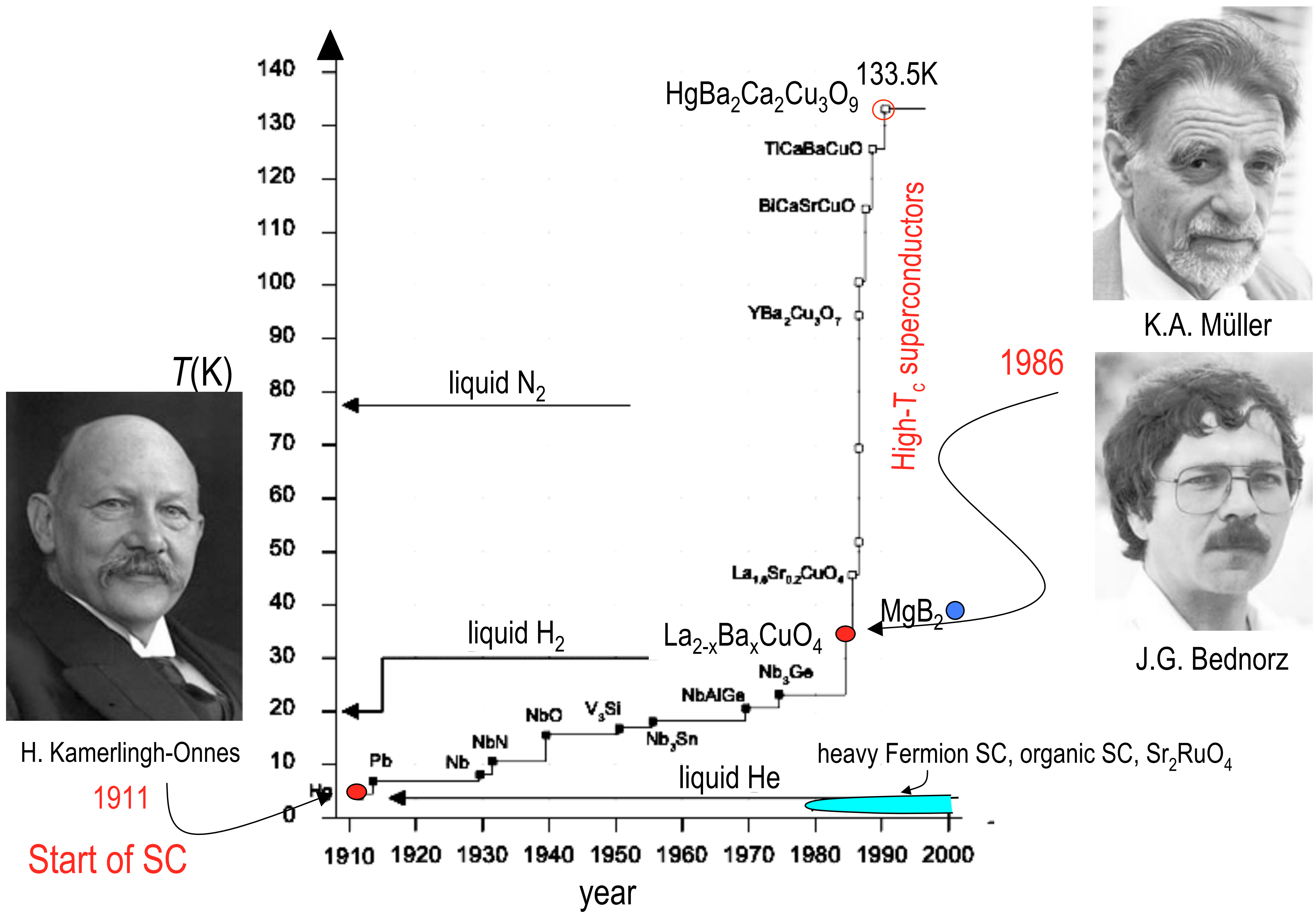
longer ranged interaction

T_c reasonable for higher angular momentum pairing



Novel Superconductors

Unexpected breakthroughs

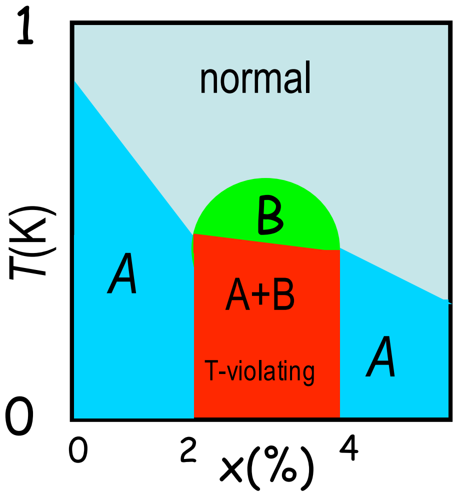


The novel superconductors

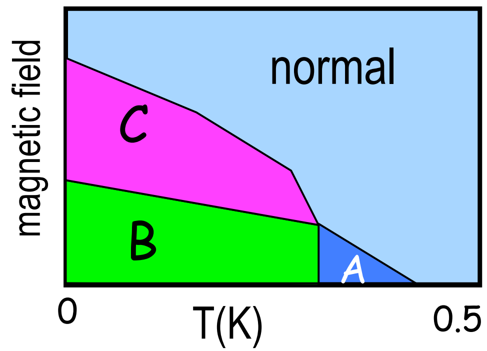
Heavy Fermion superconductors:

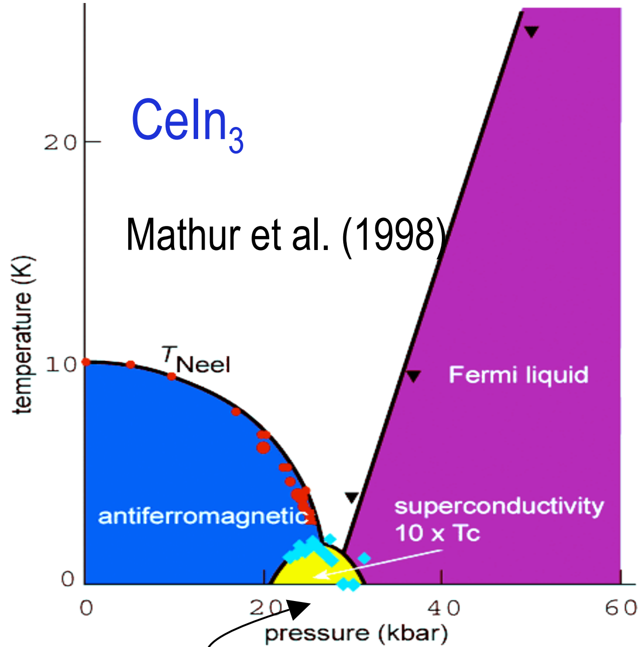
$CeCu_2Si_2$ Steglich et al. (1979)

$U_{1-x}Th_xBe_{13}$ Ott et al. (1983)



UPt_3 Stewart et al. (1984)

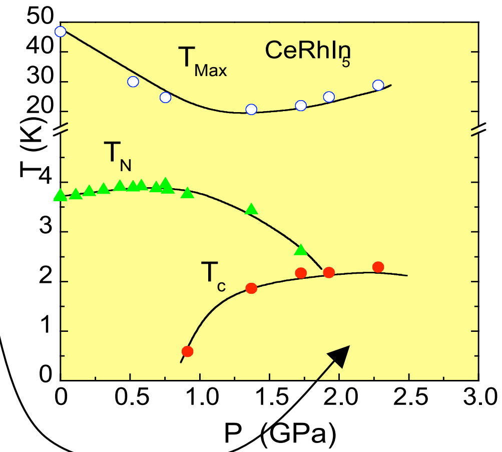




Quantum
Critical point

AF ⟷ PM

$CeRhIn_5$ Thompson et al. (2001)



The novel superconductors

High-temperature superconductors

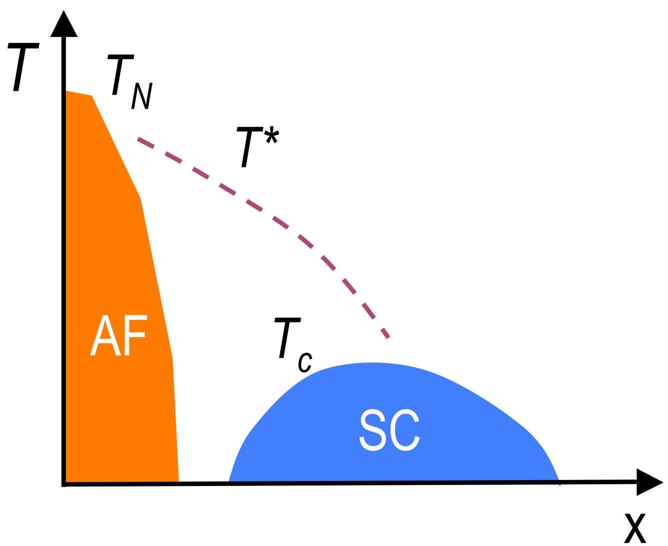
Layered perovskite cooper-oxides

Müller & Bednorz (1986)

$La_{2-x}Sr_xCuO_4$ T_c=45K

$YBa_2Cu_3O_{6+\delta}$ T_c=92K

$HgBa_2Ca_2Cu_3O_9$ T_c=133.5K

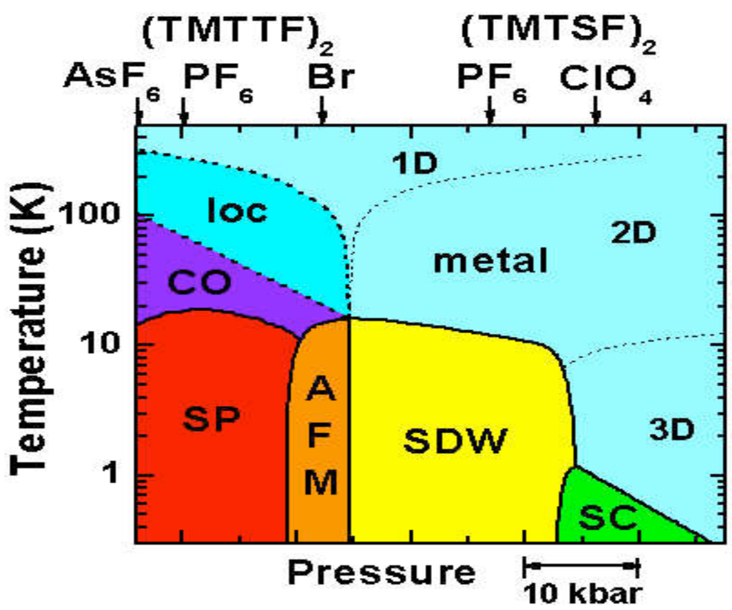


Organic superconductors

Jerome, Bechtgard et al (1980)

$(TMTSF)_2M$ ($M=PF_6$, SbF_6, ReO_4,…) T_c ~ 1K

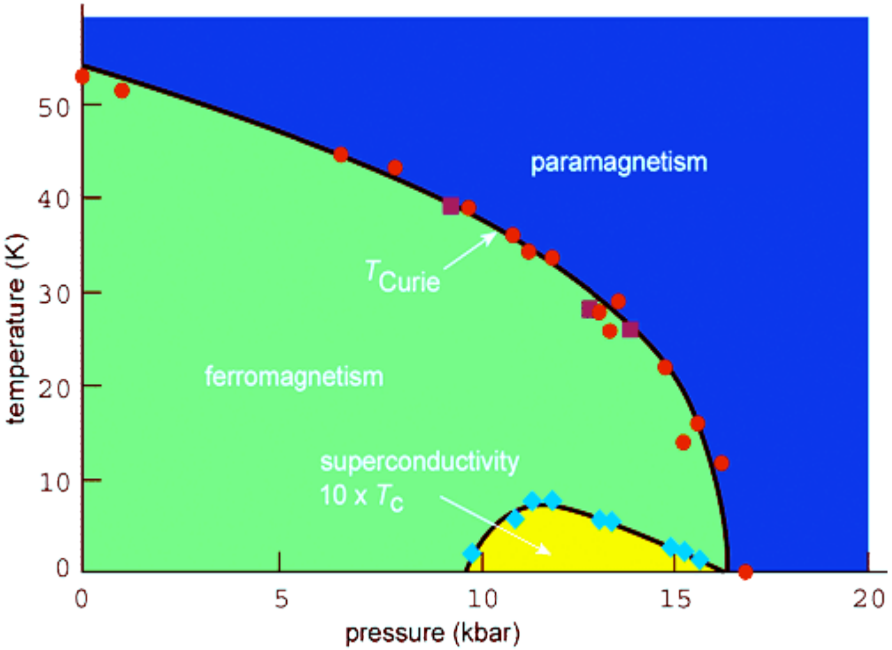
$(BEDT\text{-}TTF)_2M$ ….. T_c ~ 10K



The novel superconductors

Ferromagnetic superconductors:

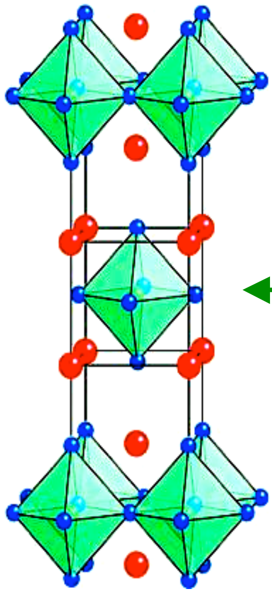
UGe_2 Saxena et a. (2000)



$ZrZn_2$ Pfleiderer et al. (2001)

Superconductivity within
the ferromagnetic phase

Sr_2RuO_4



← RuO_2 plane

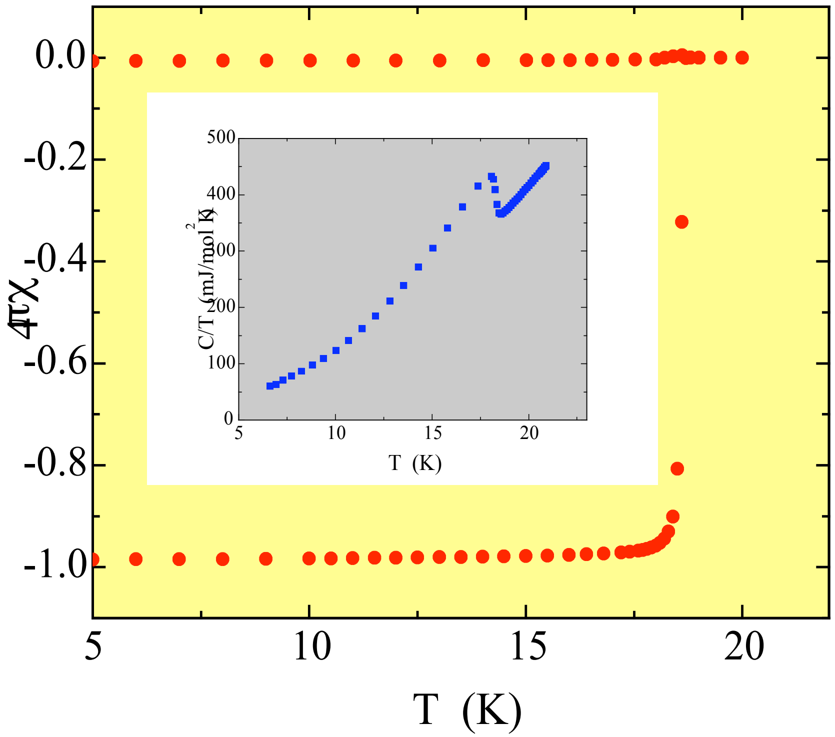
some similarities with
high-T_c superconductors,

but T_c = 1.5 K

spin-triplet superconductor

The novel superconductors

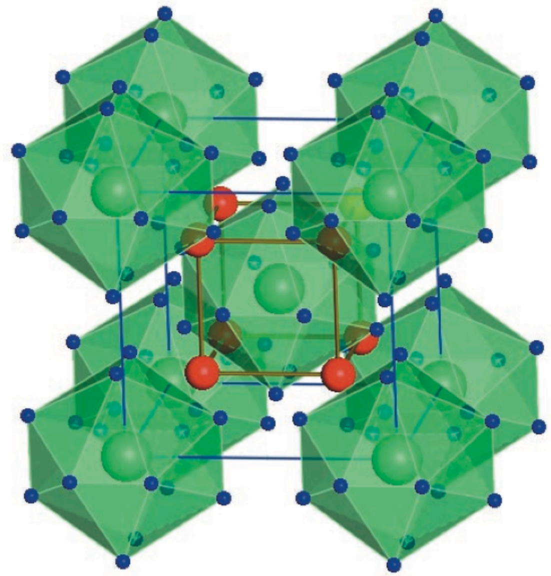
Plutonium compounds



$PuCoGa_5$ T_c = 18 K

Thompson et al. (Los Alamos)

Skutterudite



$PrOs_4Sb_{12}$ T_c = 1.8 K

Bauer et al. PRB 65, R100506 (2002)

Multiple phases

Cooper pairing

and

Symmetry

Alternative ways to Cooper pairing

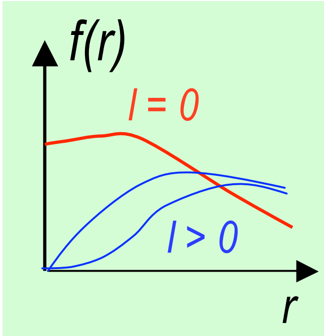
Coulomb and electron-phonon interaction very short-ranged (λ_{TF}) *"contact interaction"*

Bound Cooper pair wavefunction:

$$\psi(\vec{r}, s; \vec{r}', s') = f(|\vec{r} - \vec{r}'|)\chi(s, s')$$

with $f(r \to 0) \neq 0$

relative angular momentum ***l* =0**
important for "contact interaction"



How to avoid Coulomb repulsion?

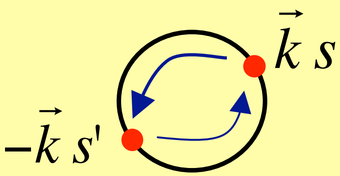
higher-angular momentum pairing

***l* > 0** → $f(r \to 0) \propto r^l$

"contact interaction" not effective

Symmetry of pairs of identical electrons: $\Psi_{ss'}(\vec{k}) = \langle \hat{c}_{\vec{k}s} \hat{c}_{-\vec{k}s'} \rangle = \underbrace{\Phi(\vec{k})}_{\text{orbital}} \underbrace{\chi(s, s')}_{\text{spin}}$

wave function totally antisymmetric under particle exchange



$\vec{k} \to -\vec{k}$ $\quad s \leftrightarrow s'$

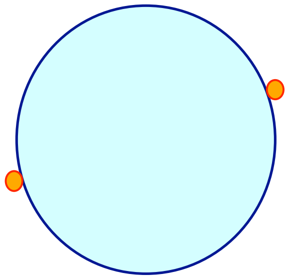
even parity: $l = 0, 2, 4, \ldots$ (even), $S = 0$ singlet (odd)

odd parity: $l = 1, 3, 5, \ldots$ (odd), $S = 1$ triplet (even)

Requirements for the formation of Cooper pairs

Anderson's Theorems (1959,1984)

Cooper pair formation with P=0 relies on symmetries which guarantee degenerate partner electrons

$|-\vec{k}, s'\rangle$  $|\vec{k}, s\rangle$

- Spin singlet pairing: time reversal symmetry

$$|\vec{k}\uparrow\rangle \qquad T|\vec{k}\uparrow\rangle = |-\vec{k}\downarrow\rangle$$

time reversal

harmful:
magnetic impurities
ferromagnetism
paramagnetic limiting

- Spin triplet pairing: time reversal & inversion symmetry

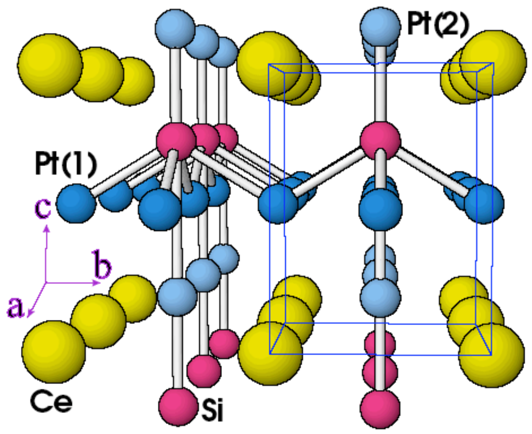
$$|\vec{k}\uparrow\rangle \qquad I|\vec{k}\uparrow\rangle = |-\vec{k}\uparrow\rangle \qquad T|\vec{k}\uparrow\rangle = |-\vec{k}\downarrow\rangle \qquad IT|\vec{k}\uparrow\rangle = |\vec{k}\downarrow\rangle$$

inversion

harmful: crystal structure without inversion center

The essential symmetries

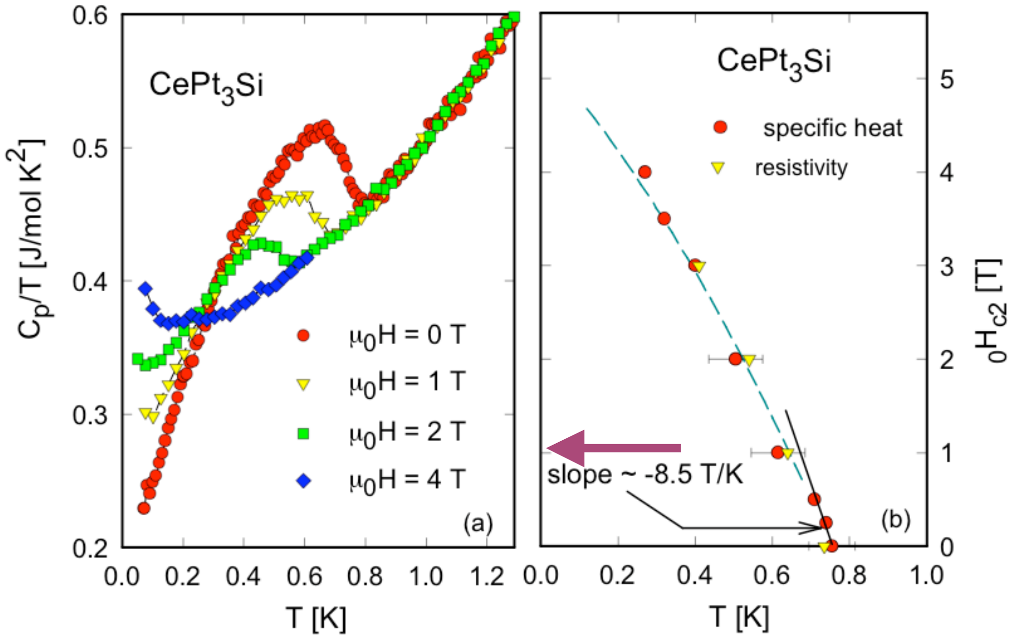
Non-centrosymmetric superconductors



$CePt_3Si$

$CePt_3Si$ Heavy Fermion superconductor: T_c = 0.75 K

E. Bauer et al. PRL **92**,027003 (2004)

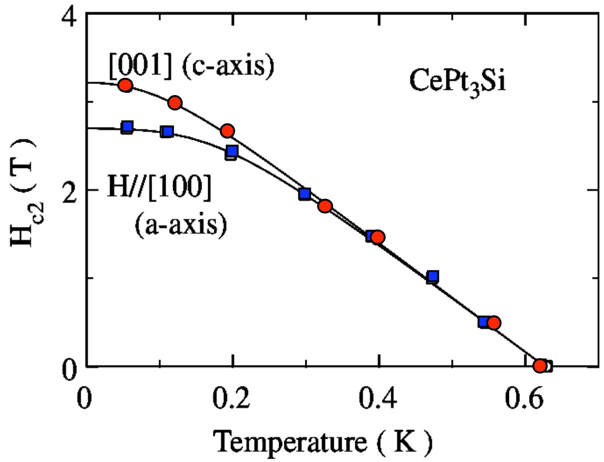


$$\gamma \approx 350 \frac{mJ}{mol K^2}$$

$$H_{c2}(T=0) \rightarrow 5T$$

paramagnetic limiting

$$H_p \approx \frac{\Delta_0}{\sqrt{2}\mu_B} \approx \frac{k_B T_C}{\mu_B} \approx 1T$$



$H_{C2}(0)$ ~ 3T

T. Yasuda et al., JPSJ 73, 1657 (2004)

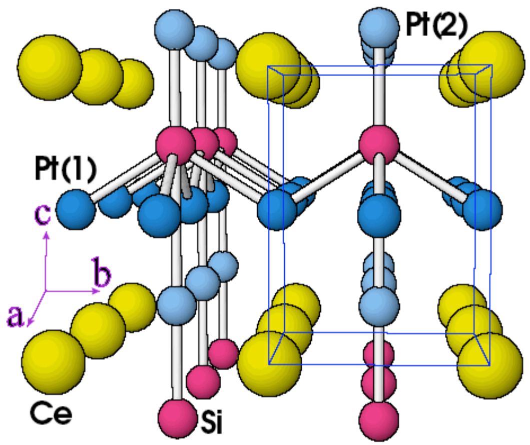
No paramagnetic limiting

↓

spin triplet pairing ?

Symmetry of superconducting phase

$CePt_3Si$



Crystal space group

P4mm tetragonal

generating point group C_{4v}

(mirror plane z → -z missing)

No inversion center: spin triplet pairing?

Anderson's second theorem

Basic Model
of a system without
inversion center

Lack of inversion symmetry

$$\mathcal{H} = \underbrace{\sum_{\vec{k},s} (\epsilon_{\vec{k}} - \mu) c^{\dagger}_{\vec{k}s} c_{\vec{k}s}}_{\text{Electron band}} + \underbrace{\alpha \sum_{\vec{k},s,s'} \vec{\lambda}_{\vec{k}} \cdot \{ c^{\dagger}_{\vec{k}s} \vec{\sigma}_{ss'} c_{\vec{k}s'} \}}_{\text{Spin-orbit coupling}}$$

Electron band — Spin-orbit coupling

Symmetry conditions

- *time reversal symmetry:* $\epsilon_{\vec{k}} = \epsilon_{-\vec{k}}$ and $\vec{\lambda}_{\vec{k}} = -\vec{\lambda}_{-\vec{k}}$

  $\vec{k} \rightarrow -\vec{k}, \ \vec{S} \rightarrow -\vec{S}$

- *inversion symmetry:* $\epsilon_{\vec{k}} = \epsilon_{-\vec{k}}$ and $\vec{\lambda}_{\vec{k}} = \vec{\lambda}_{-\vec{k}}$

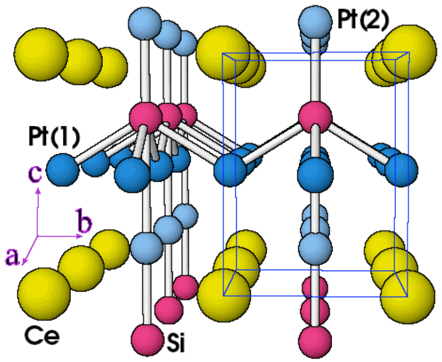
  $\vec{k} \rightarrow -\vec{k}, \ \vec{S} \rightarrow \vec{S}$

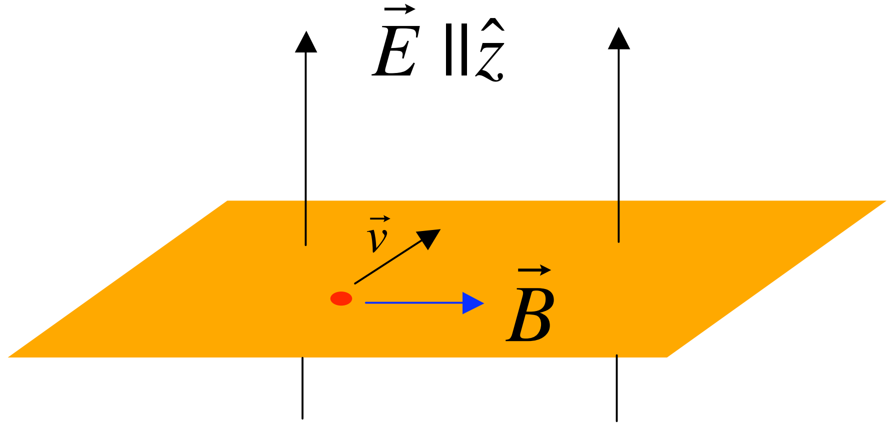
$\vec{\lambda}_{\vec{k}} \neq 0$ ⇒ time reversal and/or inversion symmetry absent

Lack of inversion symmetry

Dresselhaus 1955; Rashba 1960

$CePt_3Si$





x-y-plane not a mirror plane

Special relativity: $\vec{B} \approx -\frac{\vec{v}}{c} \times \vec{E}$

Zeeman coupling: $\vec{B} \cdot \vec{S} \propto (\vec{v} \times \hat{z}) \cdot \vec{S} \propto \vec{\lambda} \cdot \vec{S}$ ➡ $\vec{\lambda}_{\vec{k}} \propto \begin{pmatrix} k_y \\ -k_x \\ 0 \end{pmatrix}$

$$\vec{\lambda}_{\vec{k}} = -\vec{\lambda}_{-\vec{k}}$$

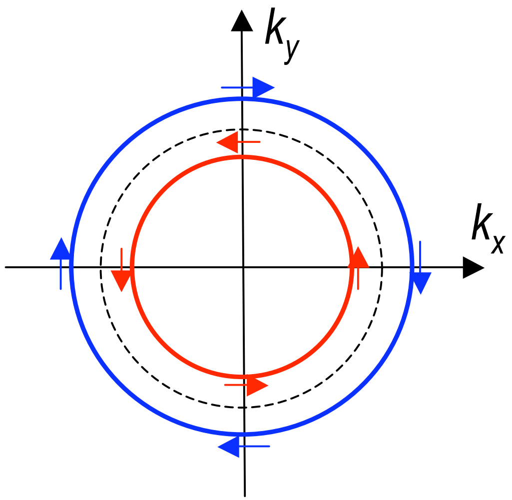
time reversal symmetry conserved

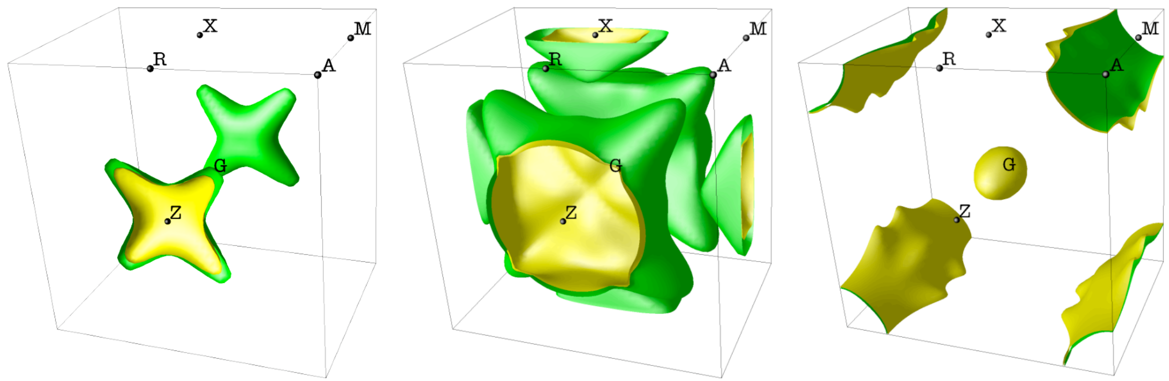
Band splitting

$$\mathcal{H} = \sum_{\vec{k},s} (\epsilon_{\vec{k}} - \mu) c^{\dagger}_{\vec{k}s} c_{\vec{k}s} + \alpha \sum_{\vec{k},s,s'} \vec{\lambda}_{\vec{k}} \cdot \{ c^{\dagger}_{\vec{k}s} \vec{\sigma}_{ss'} c_{\vec{k}s'} \}$$

k-dependent spin splitting (Zeeman)

Energy spectrum: $$E_{\vec{k}\pm} = \epsilon_{\vec{k}} - \mu \pm \alpha |\lambda_{\vec{k}}|$$





Splitted Fermi surface of

$CePt_3Si$

A.Kozhevnikov, V. Anisimov

similar K. Samokhin et al

Superconductivity

Hamiltonian: $\hat{H} = \sum_{\vec{k},s,s'} \left[\xi_{\vec{k}} \sigma^0 + \alpha \vec{\lambda}_k \cdot \vec{\sigma} \right]_{s,s'} \hat{c}^+_{\vec{k},s} \hat{c}_{\vec{k},s'} + \frac{1}{2} \sum_{\vec{k},\vec{k}',s,s'} V_{\vec{k},\vec{k}'} \hat{c}^+_{\vec{k},s} \hat{c}^+_{-\vec{k},s'} \hat{c}_{-\vec{k}',s'} \hat{c}_{\vec{k}',s}$

Mean field: $\Psi_{\vec{k},ss'} = \langle c_{-\vec{k}s'} c_{\vec{k}s} \rangle$

spin singlet, even parity

$$\Psi_{\vec{k},ss'} = \begin{pmatrix} 0 & \psi(\vec{k}) \\ -\psi(\vec{k}) & 0 \end{pmatrix}$$

1 configuration $\frac{\psi(\vec{k})}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

$$\psi(-\vec{k}) = \psi(\vec{k})$$

spin triplet, odd parity

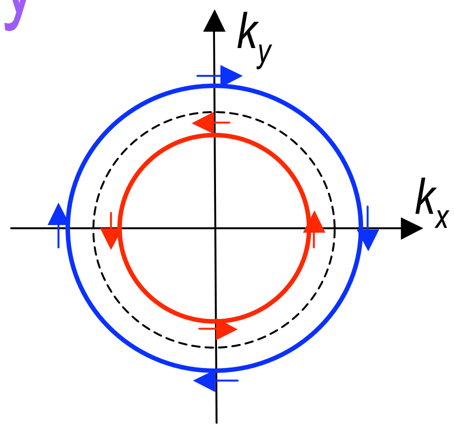
$$\Psi_{\vec{k},ss'} = \begin{pmatrix} -d_x + id_y & d_z \\ d_z & d_x + id_y \end{pmatrix}$$

3 configurations $\begin{cases} (-d_x(\vec{k}) + id_y(\vec{k}))|\uparrow\uparrow\rangle \\ \frac{d_z(\vec{k})}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \\ (d_x(\vec{k}) + id_y(\vec{k}))|\downarrow\downarrow\rangle \end{cases}$

$$\vec{d}(-\vec{k}) = -\vec{d}(\vec{k})$$

Spin-orbit coupling and superconductivity

spin-orbit coupling as a perturbation



spin singlet pairing: minor effect

spin triplet pairing: allmost all pairing states severely suppressed

weakly affected pairing states: $\vec{\lambda}_{\vec{k}} \parallel \vec{d}(\vec{k})$

$CePt_3Si$: $\vec{d}(\vec{k}) \propto \begin{pmatrix} k_y \\ -k_x \\ o \end{pmatrix}$

The Superconducting Phase

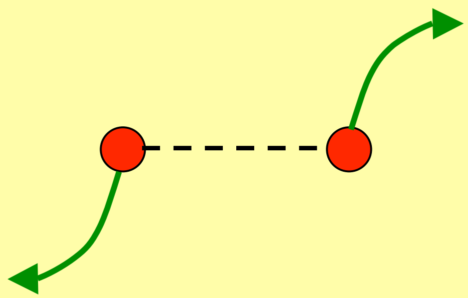
and

the Magnetic Field

Upper critical field

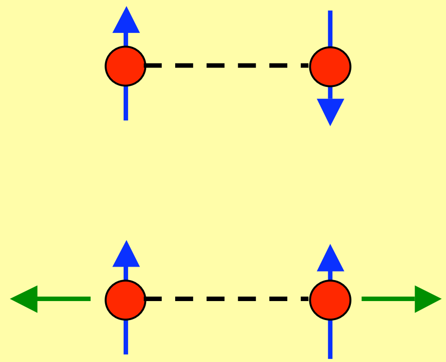
How to destroy Cooper pairs by a magnetic field?

Orbital depairing:



Lorentz force
on moving
charged particles

Spin depairing:

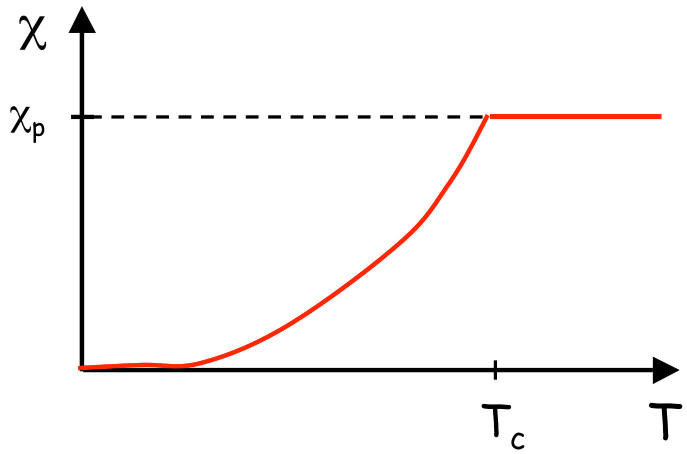


Zeeman coupling
spin polarization

Spin anisotropy

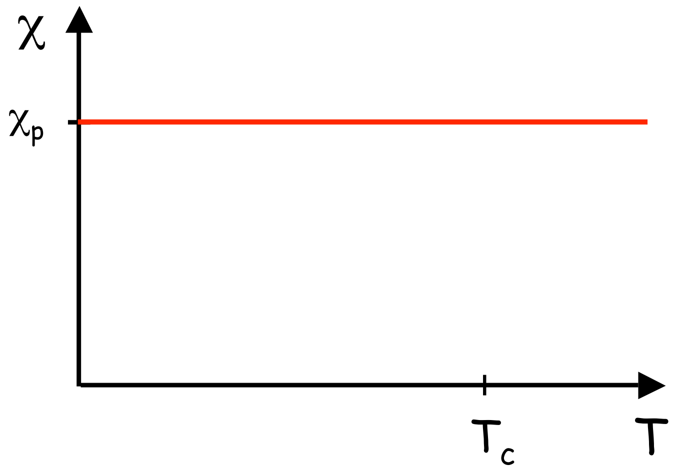
- spin singlet pairing → Yosida behavior of spin susceptibility

pair breaking
by spin polarization



- spin triplet pairing

no pair breaking
for equal spin pairing

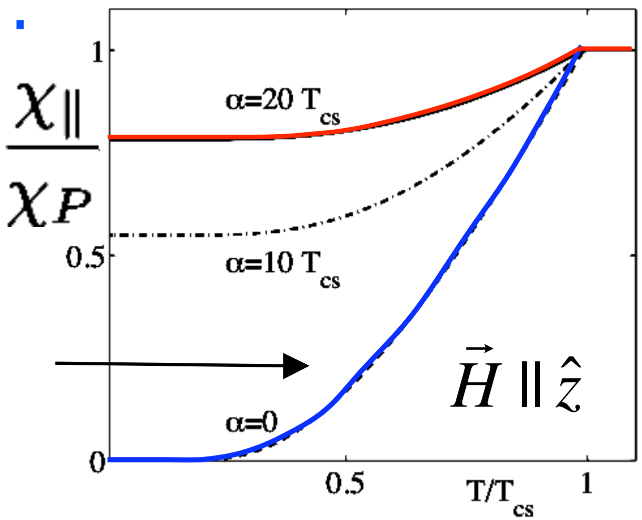


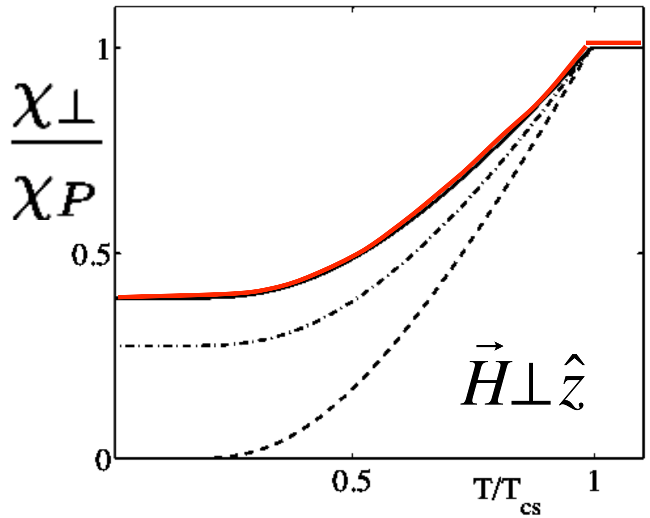
χ = const. for $\vec{d}(\vec{k}) \cdot \vec{H} = 0$

Modified spin susceptibility

"Spin singlet":

Yosida behavior

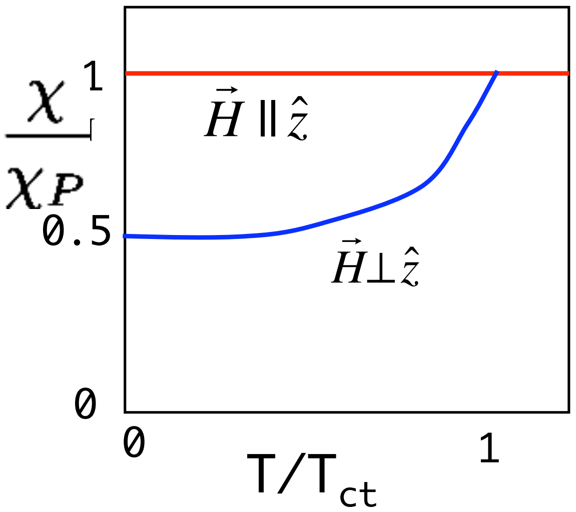




"Spin triplet":

$$\vec{\lambda}_{\vec{k}} \parallel \vec{d}(\vec{k})$$

independent of α



singlet and triplet become similar

Paramagnetic limiting

destruction of superconductivity due to Zeeman splitting of electron spins

Comparison of

superconducting condensation energy

$$E_{cond} = \frac{1}{2}N(0)|\Delta(0)|^2 = \frac{H_c(0)^2}{8\pi}$$

quasiparticle gap

↔

paramagnetic energy

$$E_{para} = \frac{1}{2}\{\chi_P - \chi(0)\}H^2$$

Pauli susceptibility

$$H_p = \frac{|\Delta(0)|/\mu_B\sqrt{2}}{\sqrt{1-\chi(0)/\chi_P}}$$

paramagnetic limiting field

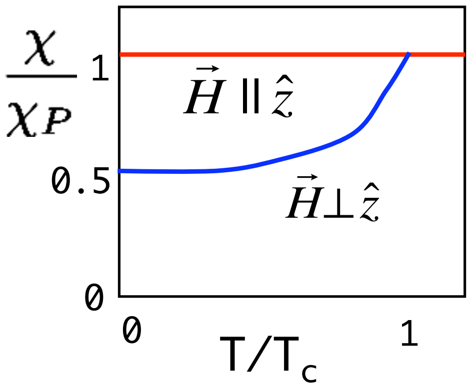
Paramagnetic limiting

destruction of superconductivity due to Zeeman splitting of spin

$$H_p = \frac{|\Delta(0)|/\mu_B\sqrt{2}}{\sqrt{1-\chi(0)/\chi_P}}$$

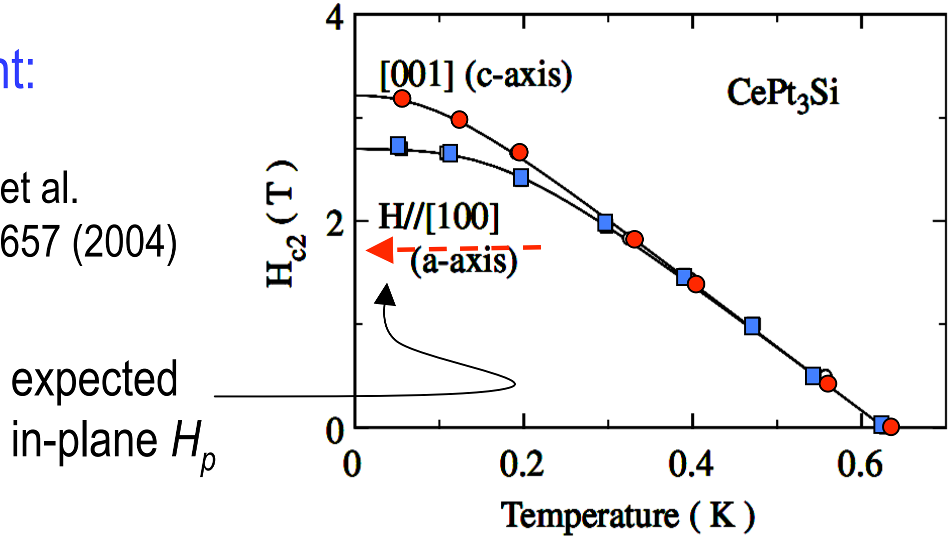
Susceptibility: H || c-axis weak limiting

H || ab-axis intermediate limiting



Experiment:

T. Yasuda et al.
JPSJ 73, 1657 (2004)

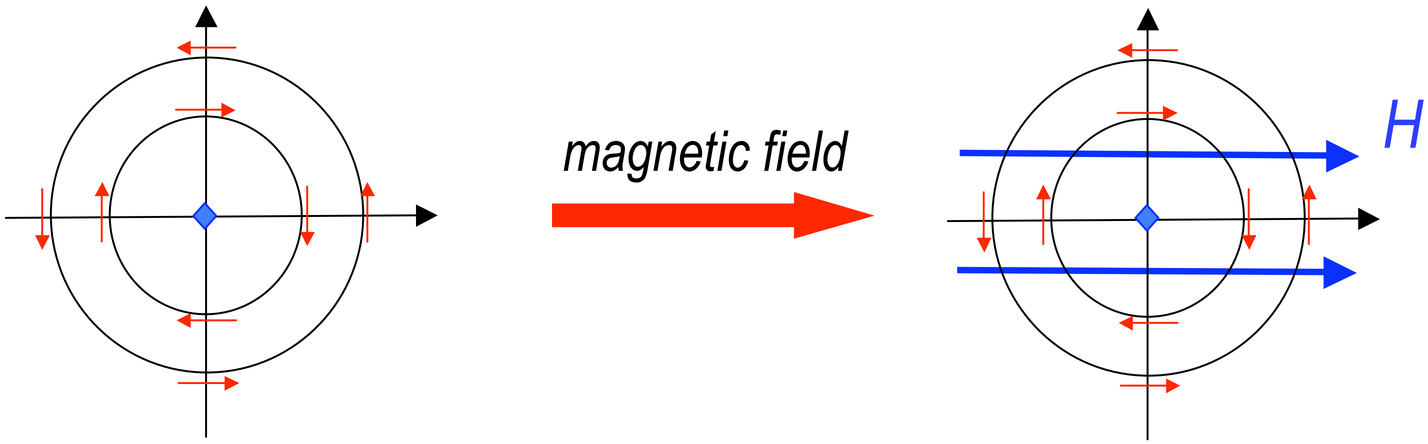


upper critical fields almost identical for both field directions

Helical Phase

Helical phase in a magnetic field

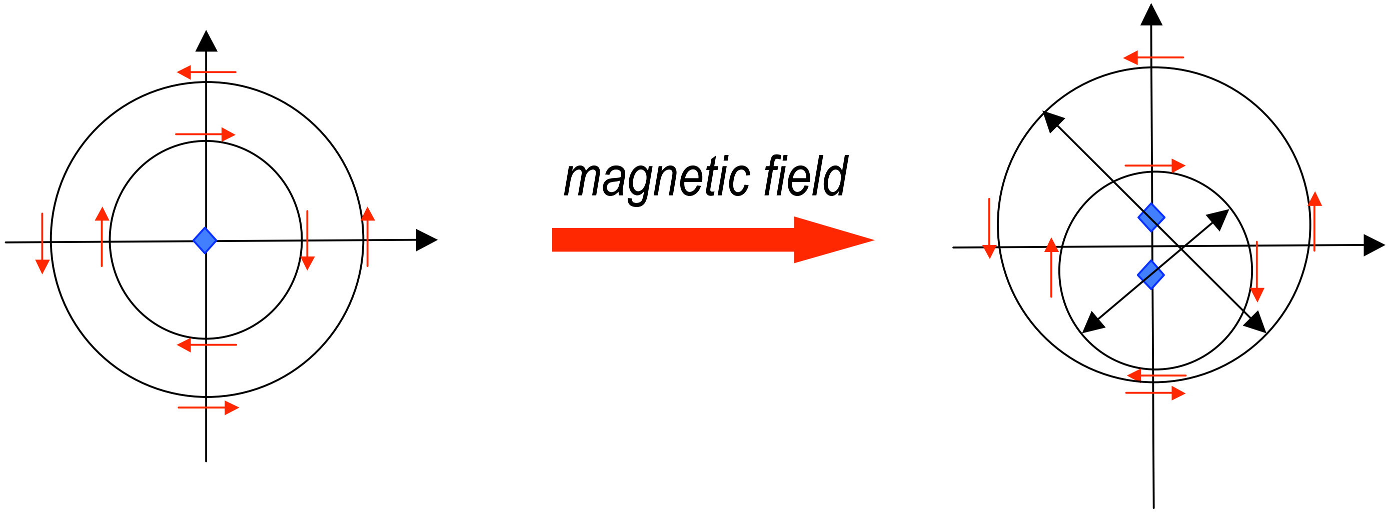
effect of magnetic field on the Fermi surfaces



$$\mathcal{H} = \mathcal{H}_{band} + \sum_{\vec{k},s,s'} (\vec{\lambda}_{\vec{k}} - \mu_B \vec{H}) \cdot \{ c^{\dagger}_{\vec{k}s} \vec{\sigma}_{ss'} c_{\vec{k}s'} \}$$

Helical phase in a magnetic field

effect of magnetic field

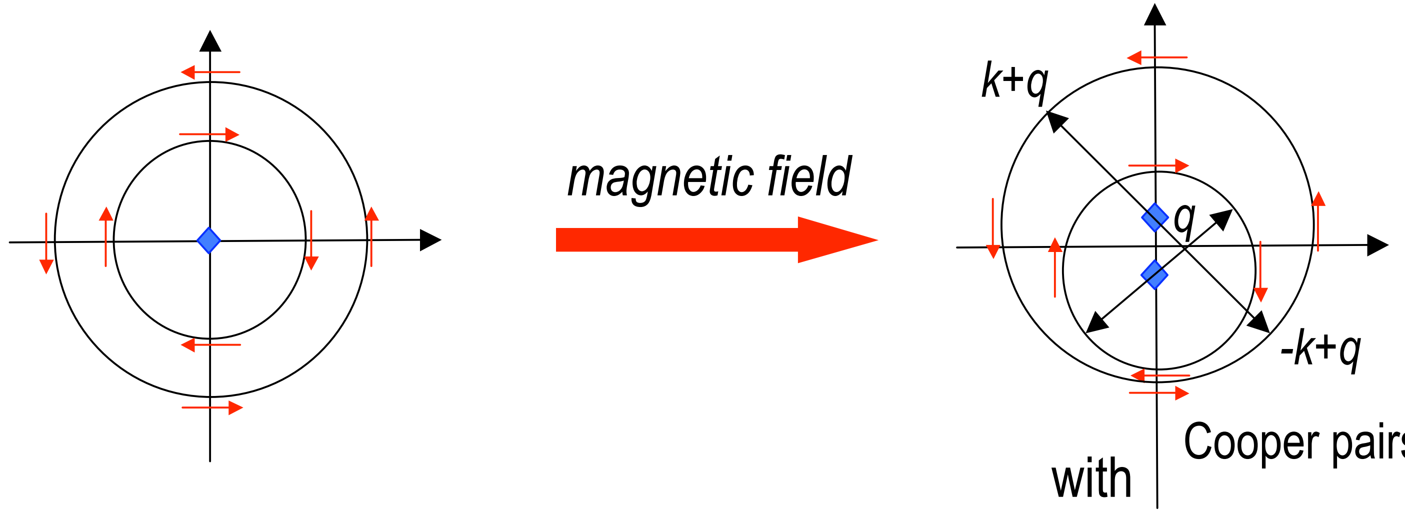


$$\mathcal{H} = \mathcal{H}_{band} + \sum_{\vec{k},s,s'} (\vec{\lambda}_{\vec{k}} - \mu_B \vec{H}) \cdot \{c^\dagger_{\vec{k}s} \vec{\sigma}_{ss'} c_{\vec{k}s'}\}$$

Fermi surface shifts by $\pm q \propto B$

Helical phase in a magnetic field

effect of magnetic field



Cooper pairs with momentum *q*

Ginzburg-Landau expansion for single-component order parameter:

$$F = a|\psi|^2 + b|\psi|^4 + K|\vec{D}\psi|^2 + \epsilon \vec{H} \cdot \hat{z} \times \left\{ \psi(\vec{D}\psi)^* + \psi^*(\vec{D}\psi) \right\} + \frac{\vec{H}^2}{8\pi}$$

$$\vec{D} = \frac{\hbar}{i}\vec{\nabla} + \frac{e}{c}\vec{A}$$

new term possible   Mineev & Samokhin (1994)

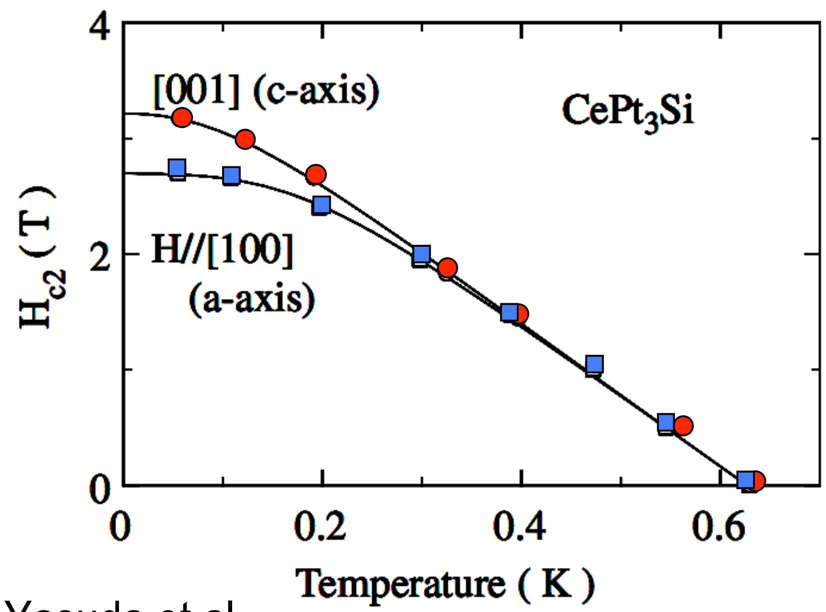
$$\epsilon \vec{H} \cdot \hat{z} \times \vec{J}_s$$

Helical state:

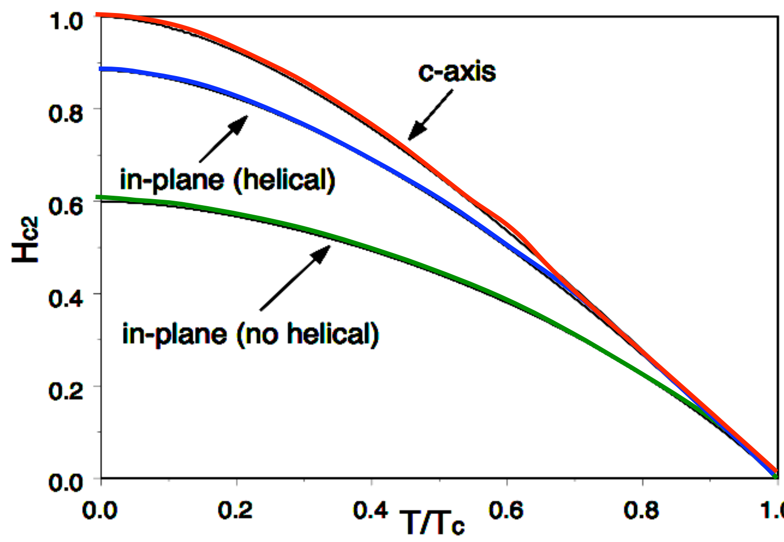
$$\psi(\vec{r}) = f(\vec{r}) e^{i\vec{q}\cdot\vec{r}} \qquad \vec{q} = \frac{\epsilon}{K} \hat{z} \times \vec{H}$$

Helical phase and upper critical field

Additional structure in the order parameter possible in non-centrosym. systems



Yasuda et al.



Kaur, Agterberg & MS

Enhanced H_{c2}:

$$T_c(H) = T_c(0) - \frac{\pi H}{\Phi_0 K a'} - \gamma\delta\widehat{\chi}\vec{H}^2 + \frac{\epsilon^2(\hat{z}\times\vec{H})^2}{4Ka'}$$

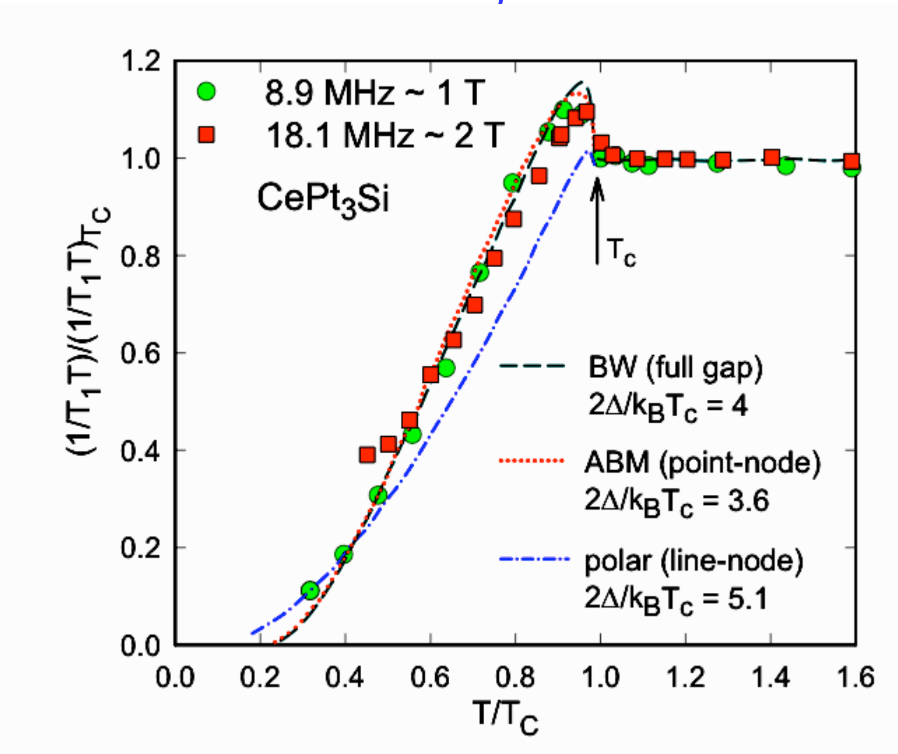
orbital paramagnetic *helical*

depairing

Indications of the pairing symmetry

Quasiparticle gap structure

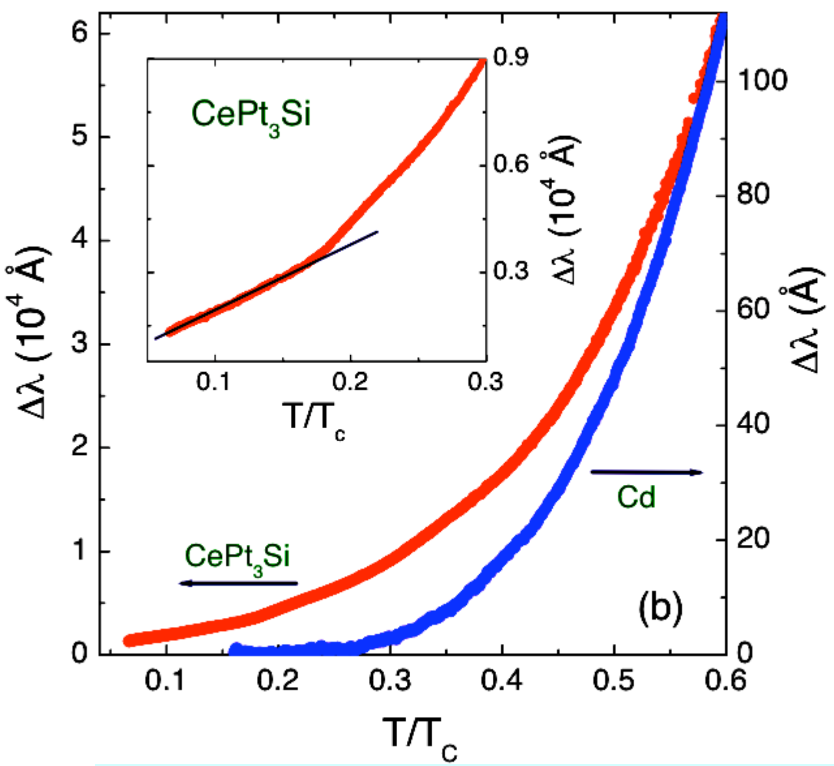
NMR-1/T_1



Hebel-Slichter peak
powerlaw T^3 for $T \to 0$

Bauer et al.

London penetration depth



powerlaw $\Delta\lambda \propto T$ for $T \to 0$

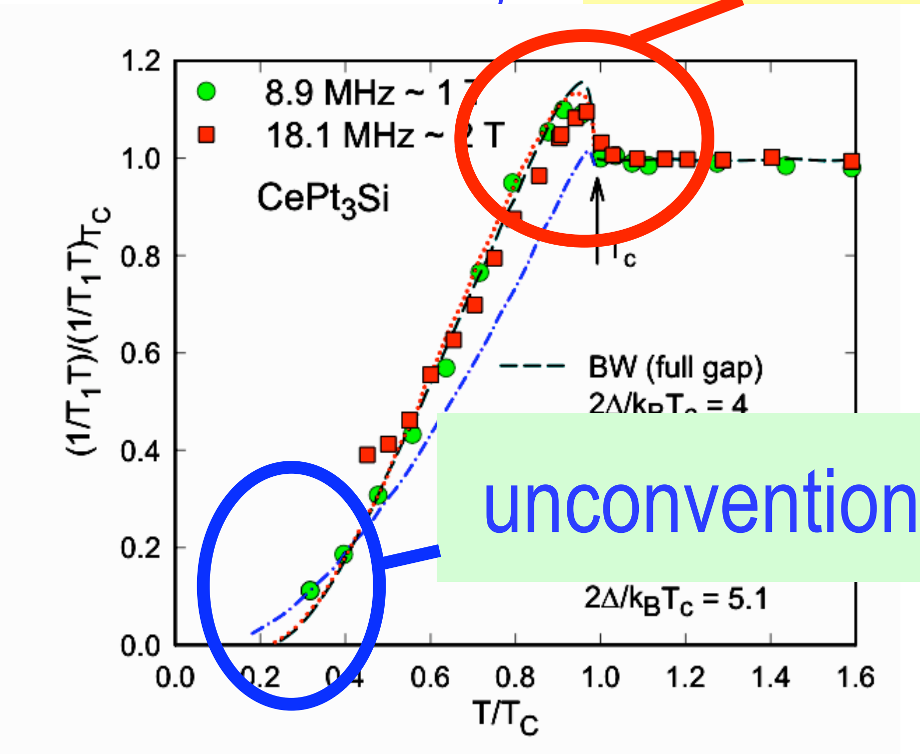
Bonalde et al.

Quasiparticle gap structure

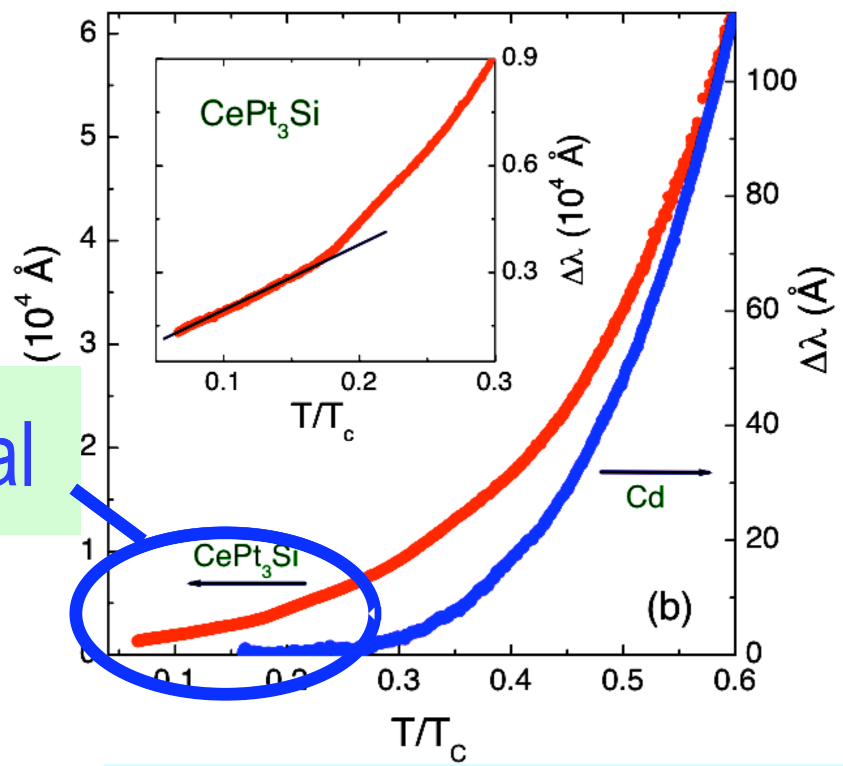
NMR-1/T_1

conventional

n penetration depth



unconventional



Hebel-Slichter peak
powerlaw T^3 for $T \rightarrow 0$

powerlaw $\Delta\lambda \propto T$ for $T \rightarrow 0$

Bauer et al.

Bonalde et al.

Quasiparticle gap structure

Parity mixing *"even + odd-parity"*

inversion symmetry

even-parity state

$$\Delta_{\vec{k},ss'} =$$

$$\psi(\vec{k}) i\sigma^y_{ss'}$$

no inversion symmetry

$$\Delta_{\vec{k},ss'} =$$

$$\psi(\vec{k}) \left\{ (\sigma^0 + \gamma \vec{\lambda}_{\vec{k}} \cdot \vec{\sigma}) i\sigma^y \right\}_{ss'}$$

gaps on two split Fermi surfaces

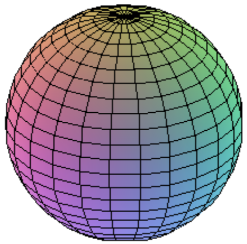
$$|\Delta_{\vec{k}\pm}| = |\psi(\vec{k})| \left| 1 \pm \gamma |\vec{\lambda}_{\vec{k}}| \right|$$

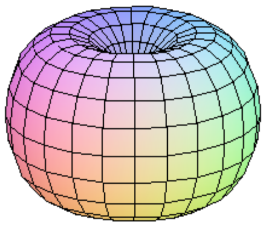
Quasiparticle gap structure

Parity mixing *s*- + *p*-wave

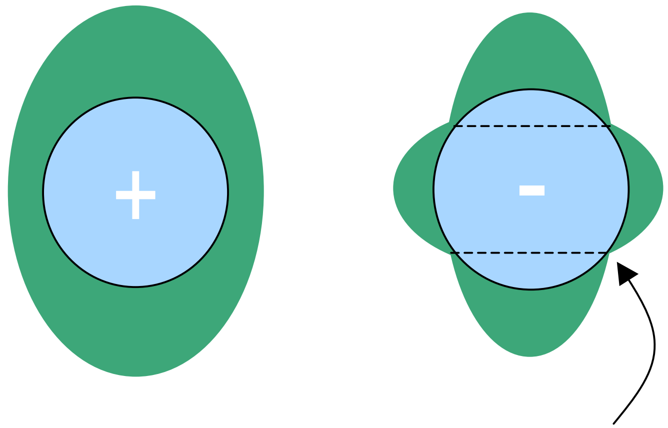
$$|\Delta_{\vec{k}\pm}| = |\psi(\vec{k})| \left|1 \pm \gamma|\vec{\lambda}_{\vec{k}}|\right|$$

$$\psi = \Delta_s \qquad \vec{\lambda}_{\vec{k}} = \hat{x}k_y - \hat{y}k_x$$





2 Fermi surfaces: + and -

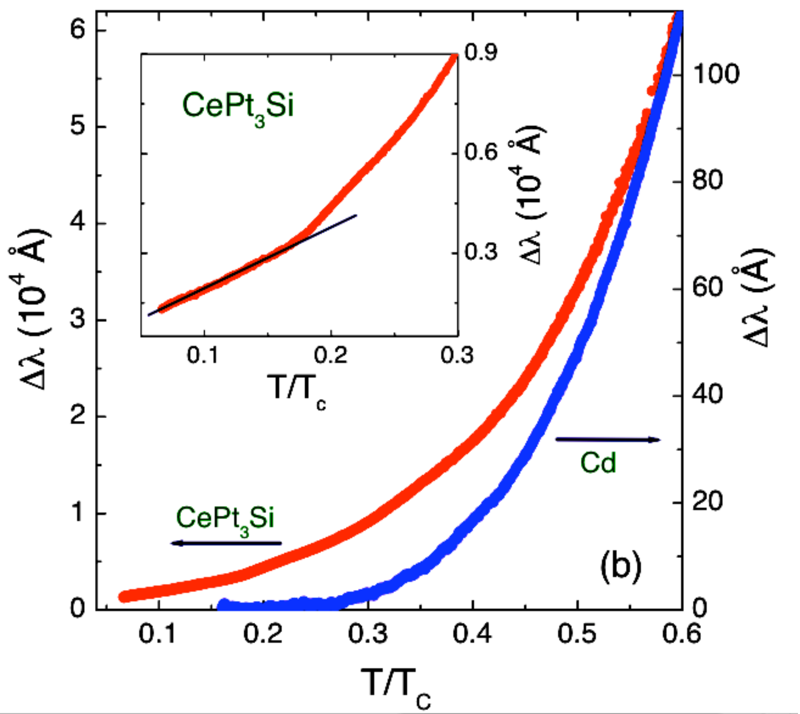


Anisotropic gaps:

- different on the two Fermi surfaces
- no spin degeneracy ("spinless Fermions")
- accidential line nodes possible!

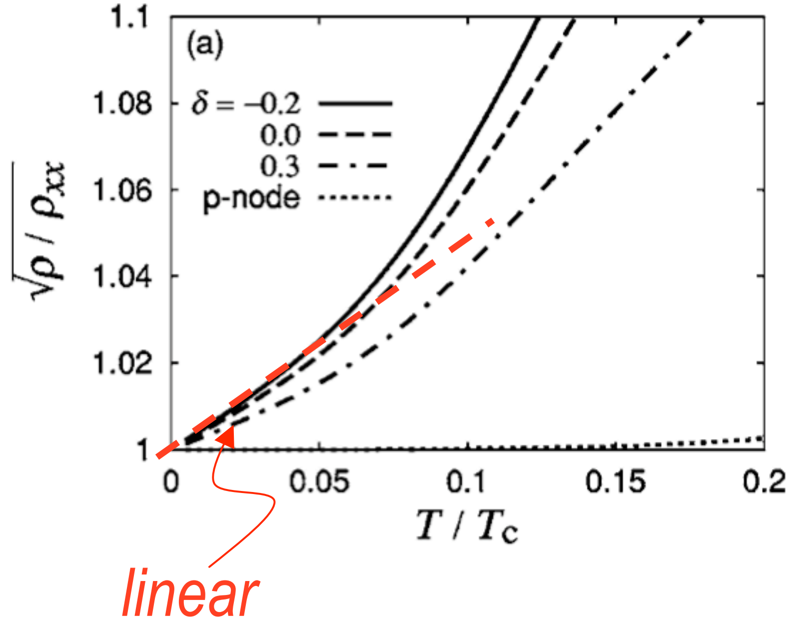
London penetration depth and superfluid density

T-linear behavior for *T* → *0*



Bonalde et al 2004

mixed parity state with nodes



Hayashi et al 2004

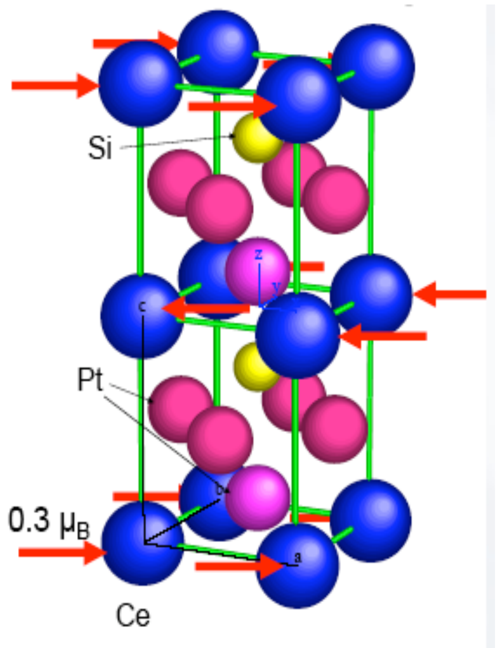
effect of accidental nodes !?

Complication for $CePt_3Si$

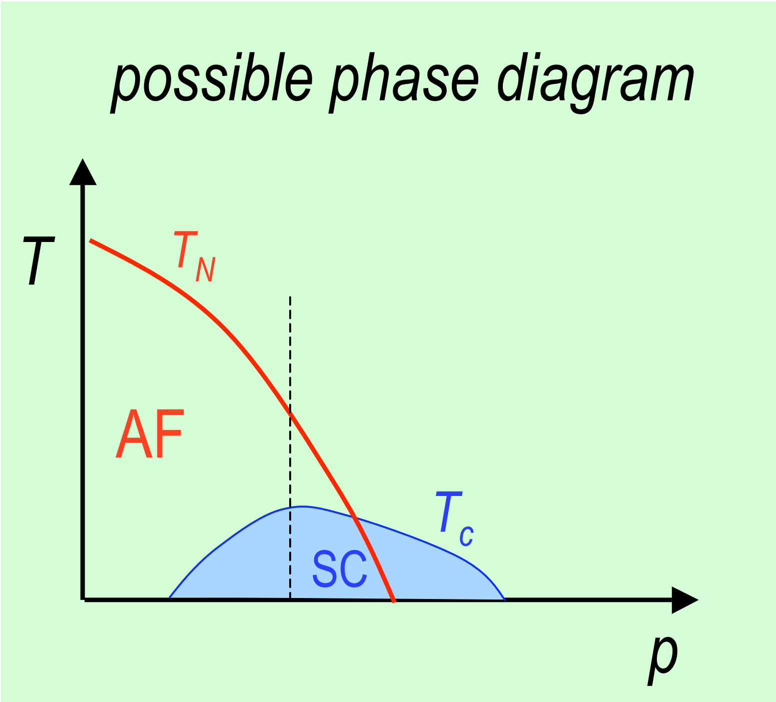
heavy Fermion compound: localized 4f-moments of Ce

- *superconductivity:* $T_c = 0.75\ K$

- *antiferromagnetism:* $T_N = 2.2K$



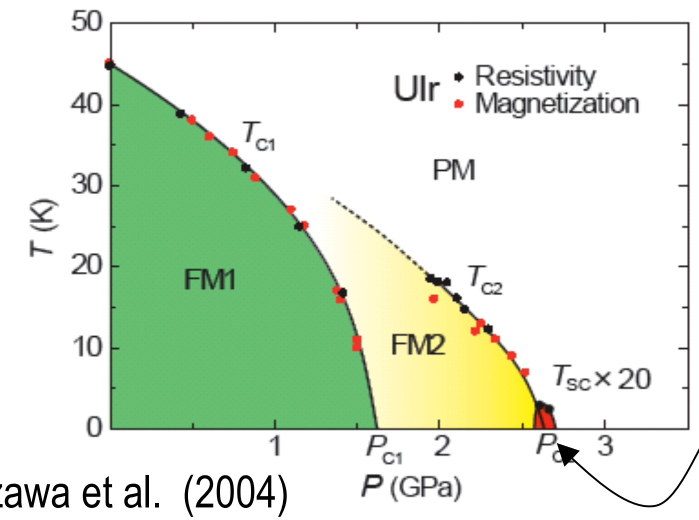
N. Metoki et al. (2004)



Other recently discovered non-centrosymmetric superconductors

UIr

Ferromagnetic quantum phase transition



Akazawa et al. (2004)

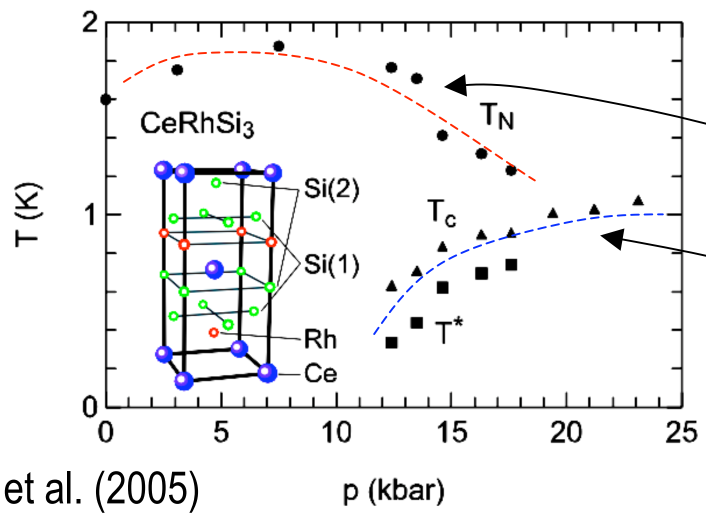
Space group: P2$_1$ *monoclinic*

Coexistence of
Superconductivity and Ferromagnetism ! ?

superconductivity T_c=0.15 K

CeRhSi$_3$

Antiferromagnetic quantum phase transition



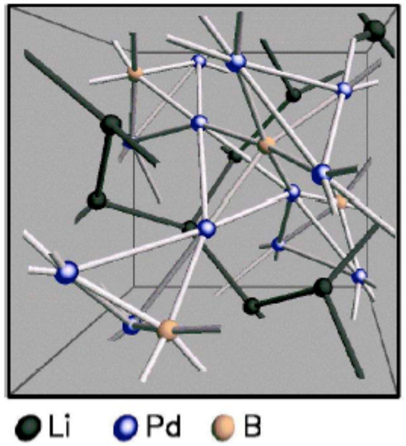
Kimura et al. (2005)

Space group: I4mm *tetragonal*

T_N~ 2 K

T_c~ 1 K

Li_2Pd_3B, Li_2Pt_3B



Togano et al. (2004)

Space group:

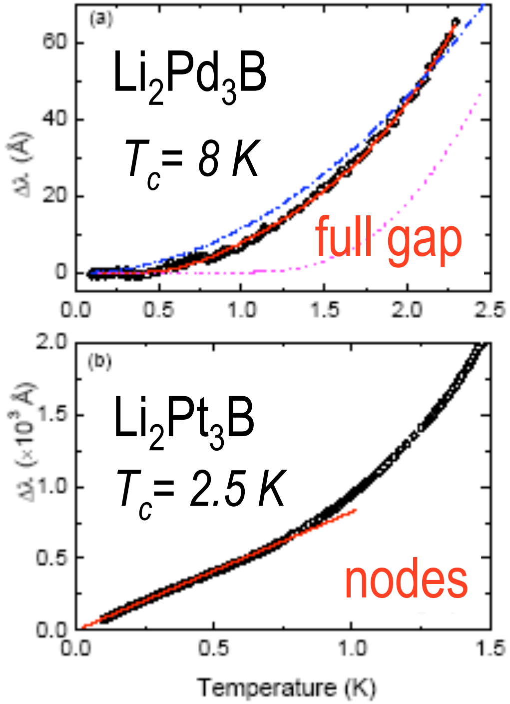
$P4_332$ cubic

alloy interpolation:

$Li_2(Pd_xPt_{1-x})_3B$

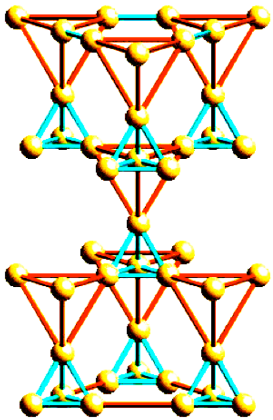
varying spin-orbit coupling

London penetration depth



Yuan et al. (2005)

KOs_2O_6



Yonezawa et al. (2004)

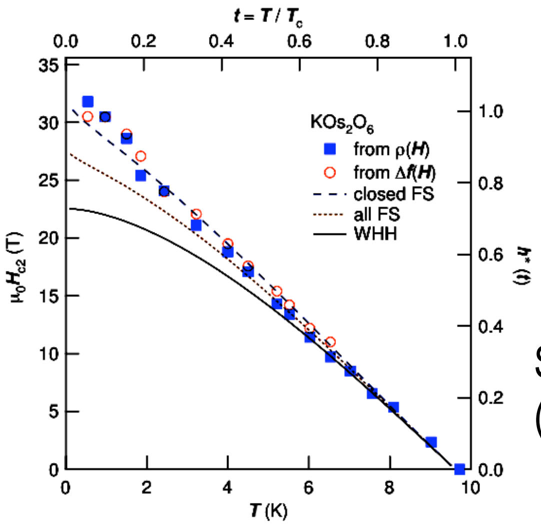
destorted pyrochlor lattice

Space group: $F\bar{4}3m$

tetrahedral

Schuck et al. (2006)

H_{c2}



T_c=9.6 K

Shibauchi et al. (2006)

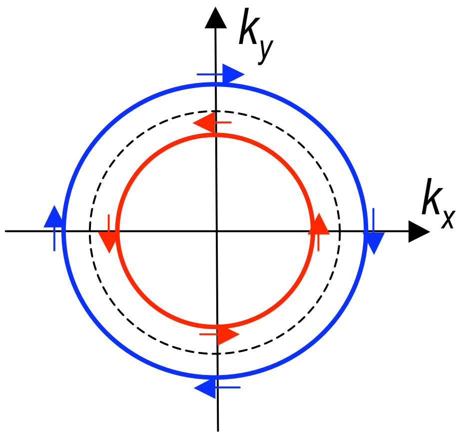
Conclusions

Symmetry of Cooper pairs:

inversion symmetry		*no inversion symmetry*	
even-parity	spin-singlet	mixed-parity	mixed-spin
odd-parity	spin-triplet		

no inversion symmetry ➡ antisymmetric spin-orbit coupling

strong Fermi surface effect:



- paramagnetic effect
- gap structure
- helical phase in high magnetic fields
- ....