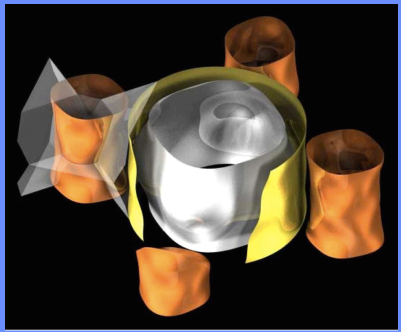
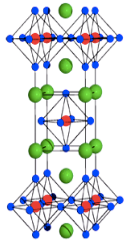
Example 1:

The spin-triplet superconductor Sr_2RuO_4



Sr_2RuO_4 - quasi-2D-superconductor



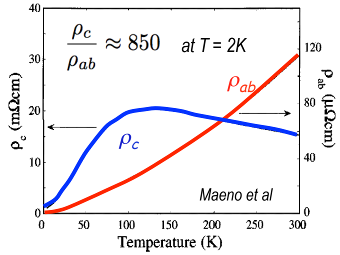
$T_c \approx 1.5K$

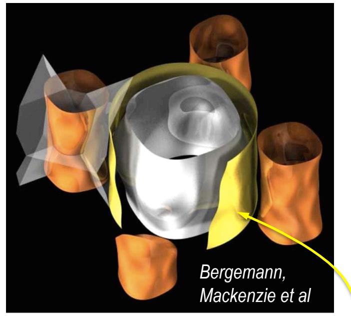
Maeno et al 1994

layered crystal structure

⬇

quasi-2D metal





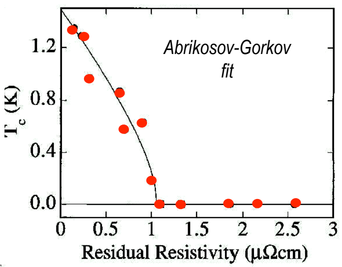
3 quasi-2D bands

derived from 4d-t_{2g} orbitals of Ru

most likely γ-band strongly dominant

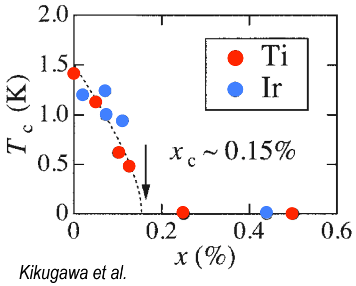
Unconventional pairing - disorder effect

sensitivity to non-magnetic impurities



Mackenzie et al.

$Sr_2Ru_{1-x}M_xO_4$ (M= Ti,Ir)



Kikugawa et al.

textbook like suppression of T_c

mean free path $\ell \leq \xi \approx 660Å$

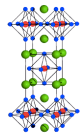
$T_c = 0$

superconducting phases - analogy to ^{3}He

basic symmetries:

$$\mathcal{G} = G \times S \times \mathcal{K} \times U(1)$$

p-wave pairing states:



point group: D_{4h} tetragonal

spin-orbit coupling strong

inplane pairing $(\vec{k} = (k_x, k_y, 0))$

^{3}He phases

B-phase

$$\vec{d}(\vec{k}) = \hat{x}k_x + \hat{y}k_y + \hat{z}k_z$$

A-phase

$$\vec{d}(\vec{k}) = \hat{z}(k_x \pm ik_y)$$

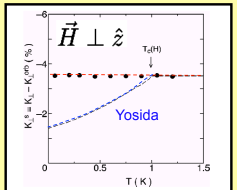
⟷

Γ	$\vec{d}(\vec{k})$	
A_{1u}	$\vec{d} = \hat{x}k_x + \hat{y}k_y$	B-phase
A_{2u}	$\vec{d} = \hat{x}k_y - \hat{y}k_x$	B-phase
B_{1u}	$\vec{d} = \hat{x}k_x - \hat{y}k_y$	B-phase
B_{2u}	$\vec{d} = \hat{x}k_y + \hat{y}k_x$	B-phase
E_u	$\vec{d} = \hat{z}(k_x \pm ik_y)$	A-phase

$$\hat{\Psi}_{\vec{k}} = (\vec{d}(\vec{k}) \cdot \hat{\vec{\sigma}}) i\hat{\sigma}^y$$

Experimental evidence for pairing symmetry

spin-polarizability



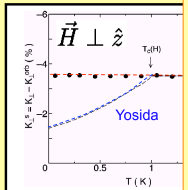
NMR-Knight shift

Ishida et al (1998)

inplane equal-spin pairing $\vec{d} \parallel \hat{z}$

Experimental evidence for pairing symmetry

spin-polarizabil

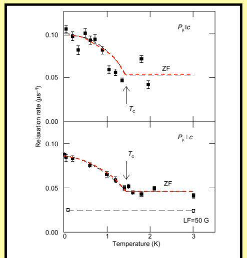


NMR-Knight shi

Ishida et al (1998)

inplane equal-spin pairing $\vec{d}$

magnetic moment



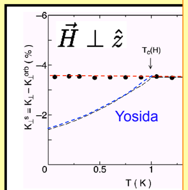
µSR zero-field relaxation

Luke et al (1998)

intrinsic magnetism

Experimental evidence for pairing symmetry

spin-polarizabi

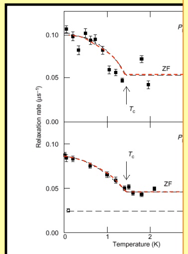


NMR-Knight shi

Ishida et al (1998)

inplane equal-spin pairing $\vec{d}$

magnetic mome

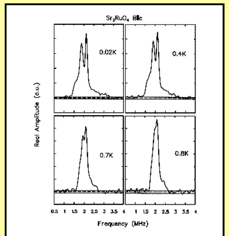


µSR zero-field relax

Luke et al (1998)

intrinsic magne

field distribution



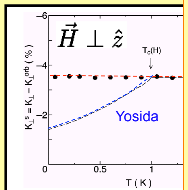
µSR field distribution in vortex phase

Luke et al (2000)

2-component order parameter

Experimental evidence for pairing symmetry

spin-polarizabi

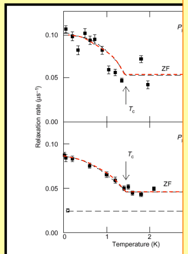


NMR-Knight shi

Ishida et al (1998)

inplane equal-spin pairing $\vec{d}$

magnetic mome

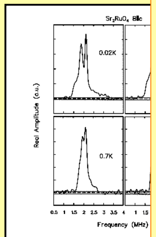


µSR zero-field relax

Luke et al (1998)

intrinsic magne

field distribu

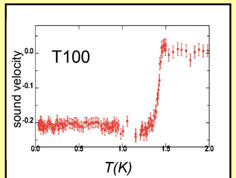


µSR field dis in vortex p

Luke et al (200

2-component order parame

Ultrasound absorption



Sound velocity renormalization for transversal mode

Lupien, Taillefer et al.

2-component order parameter

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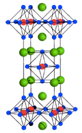

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$$\hat{\Psi}_{\vec{k}} = (\vec{d}(\vec{k}) \cdot \hat{\vec{\sigma}}) i \hat{\sigma}^y$$

Sr_2RuO_4 - chiral p-wave superconductor

$$\vec{d}(\vec{k}) = \hat{z}(k_x \pm i k_y) \Rightarrow \hat{\Psi}_{\vec{k}} = \begin{pmatrix} 0 & k_x \pm i k_y \\ k_x \pm i k_y & 0 \end{pmatrix}$$

degeneracy: 2

topological phase

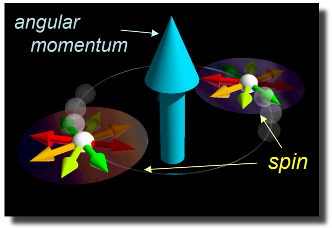
$$k_x + i k_y \overset{\hat{K}}{\longleftrightarrow} k_x - i k_y$$

broken time reversal symmetry $\mathcal{K}$

$$D_{4h} \times SU(2) \times \mathcal{K} \times U(1)_\phi$$

$\downarrow$ analog to ^{3}He A-phase

$$U(1)_{S_z} \times U(1)_{L_z+\phi}$$



Deguchi & Maeno

Sr_2RuO_4 - chiral p-wave superconductor

$$\vec{d}(\vec{k}) = \hat{z}(k_x \pm i k_y) \Rightarrow \hat{\Psi}_{\vec{k}} = \begin{pmatrix} 0 & k_x \pm i k_y \\ k_x \pm i k_y & 0 \end{pmatrix}$$

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broken time reversal symmetry $\mathcal{K}$

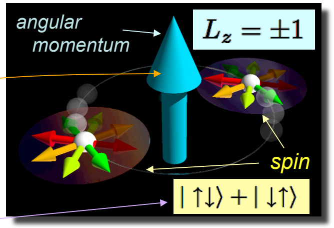
$$D_{4h} \times SU(2) \times \mathcal{K} \times U(1)_\phi$$

$\downarrow$

orbital rotation

$$U(1)_{S_z} \times U(1)_{L_z+\phi}$$

spin rotation



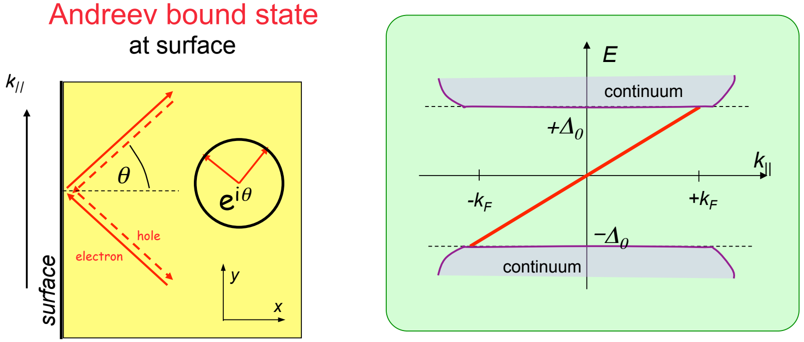
Deguchi & Maeno

Edge states & Spontaneous currents

Spontaneous currents

at inhomogeneities, surface and domain wall

Andreev bound state
at surface



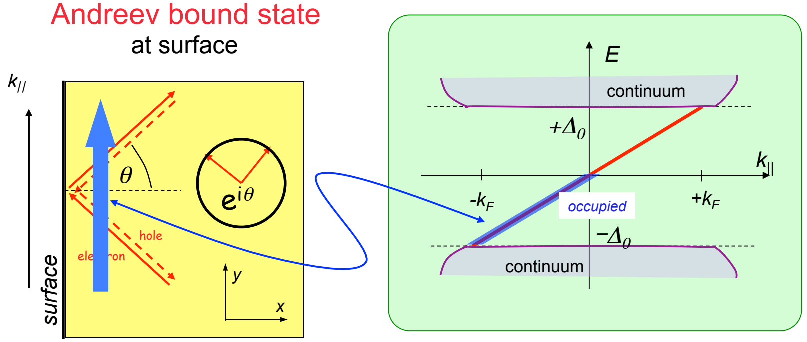
subgap spectrum $E_{k_{\|}} = \Delta_0 \sin\theta_{\hat{k}} = \Delta_0 \dfrac{k_{\|}}{k_F}$

penetration depth $\xi = \hbar v_F / \Delta_0$

Spontaneous currents

at inhomogeneities, surface and domain wall

Andreev bound state
at surface



surface
current

subgap spectrum $E_{k_{\|}} = \Delta_0 \sin\theta_{\hat{k}} = \Delta_0 \dfrac{k_{\|}}{k_F}$

penetration depth $\xi = \hbar v_F / \Delta_0$

Spontaneous currents

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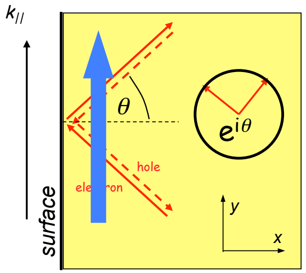
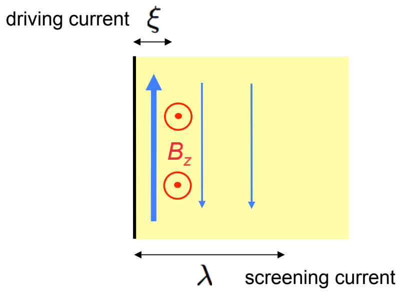




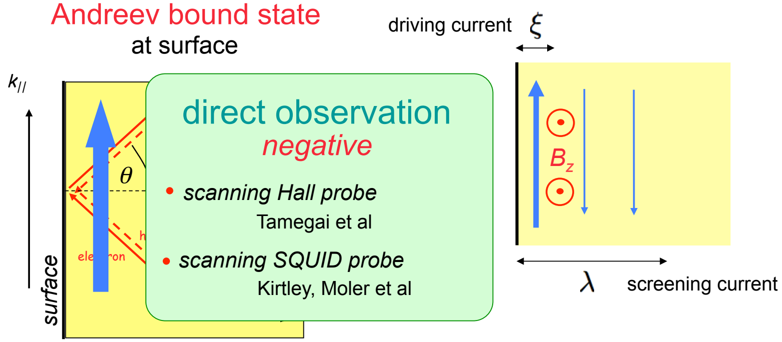
surface
current

analogous at domain walls
and around impurities

Spontaneous currents

at inhomogeneities, surface and domain wall

Andreev bound state
at surface



direct observation
negative

- *scanning Hall probe*
  Tamegai et al
- *scanning SQUID probe*
  Kirtley, Moler et al

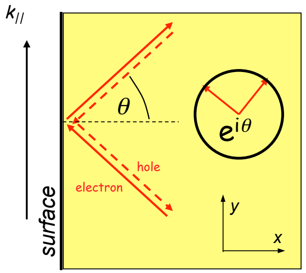
surface
current

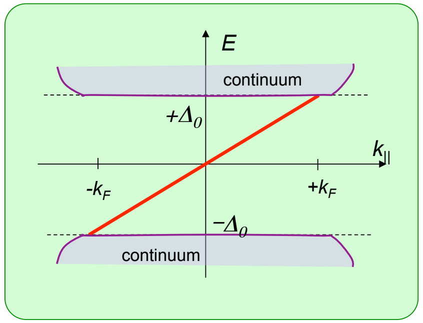
analogous at domain walls
and around impurities

Quasiparticle states

at inhomogeneities, surface and domain wall

Andreev bound state
at surface





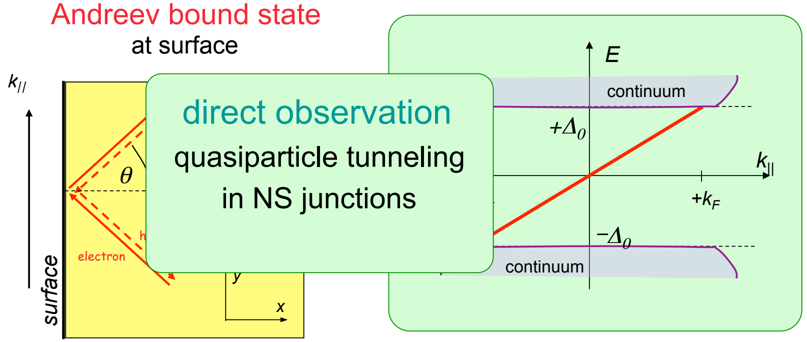
subgap spectrum $E_{k_{||}} = \Delta_0 \sin\theta_{\hat{k}} = \Delta_0 \dfrac{k_{||}}{k_F}$

penetration depth $\xi = \hbar v_F / \Delta_0$

Quasiparticle states

at inhomogeneities, surface and domain wall

Andreev bound state
at surface



direct observation

quasiparticle tunneling
in NS junctions

subgap spectrum $E_{k_{||}} = \Delta_0 \sin\theta_{\hat{k}} = \Delta_0 \dfrac{k_{||}}{k_F}$

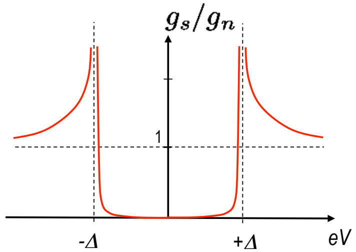
penetration depth $\xi = \hbar v_F / \Delta_0$

Quasiparticle tunneling in NS junctions

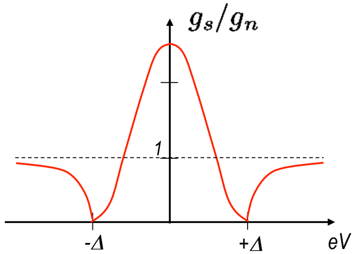
Tunneling conductance

$$g(eV) = \frac{dI}{dV}(eV)$$

conventional superconductor



chiral p-wave superconductor



Honerkamp, Matsumoto & MS
Yamashiro, Tanaka et al.

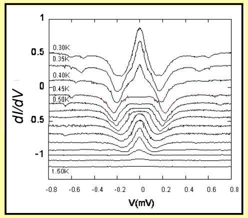
Quasiparticle tunneling in NS junctions

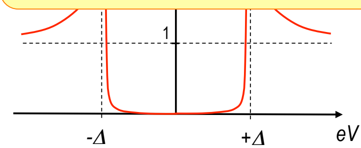
Tunneling conductance

(eV)

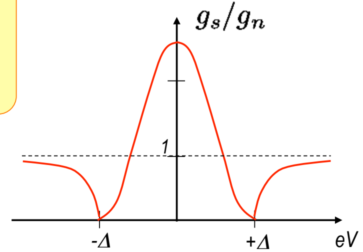
NS-tunneling

Mao, Liu et al.





chiral p-wave superconductor



Honerkamp, Matsumoto & MS
Yamashiro, Tanaka et al.

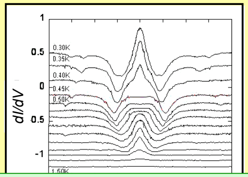
Quasiparticle tunneling in NS junctions

Tunneling conductance

(eV)

NS-tunneling

normal metal | Sr_2RuO_4

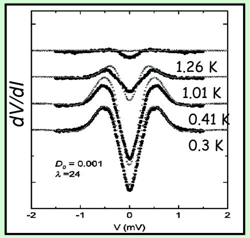


Mao, Liu et al.

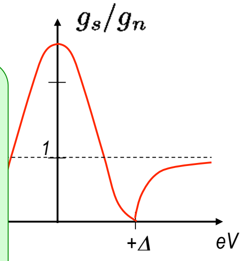
Point contact spectroscopy

Sr_2RuO_4

Laube, Goll,
von Lohneysen et al.



chiral p-wave superconductor



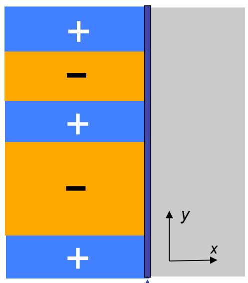
onerkamp, Matsumoto & MS
amashiro, Tanaka et al.

Further evidence for chiral p-wave pairing

Phase sensitive experiments

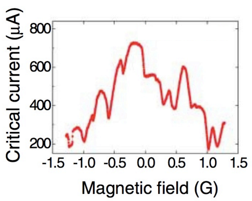
Josephson effect and domain walls

two domains $\vec{d}_{\pm}(\vec{k}) = \eta_0 \hat{z}(k_x \pm i k_y)$



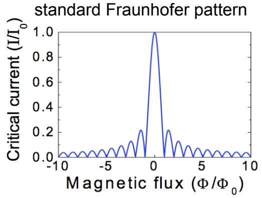
Josephson contact

interference effect in magnetic field



Kidwingira, van Harlingen et al (2006)

standard Fraunhofer pattern



Bouhon & MS

$$I = \max_{\alpha} \int dy I_c(y) \sin[kx + \phi(y) + \alpha]$$

critical current

intrinsic phase shift associated with domain

$k = \frac{2\pi}{\Phi_0} \tilde{d} H_{ex}$ $\Phi_0 = \frac{hc}{2e}$

Phase sensitive experiments

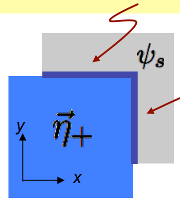
SQUID type of measurements

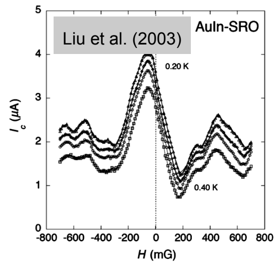
corner „SQUID“ geometry

$J_y \propto i\{\psi^* \eta_x - \psi_s \eta_x^*\} \propto \sin(\alpha)$

phase difference
$\pm\pi/2$

$J_x \propto i\{\psi^* \eta_y - \psi_s \eta_y^*\} \propto \sin(\alpha + \pi/2)$



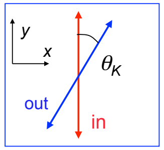


Interference pattern off-centered

broken time reversal
chirel p-wave

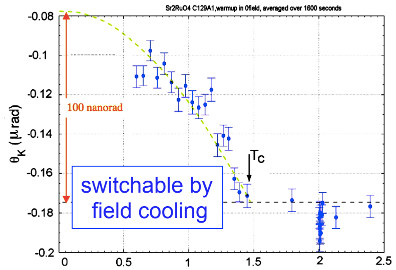
Kerr effect

rotation of polarzation axis for reflected light



$$\theta_K \approx -Im \frac{(n_+ + i\kappa_+) - (n_- + i\kappa_-)}{(n_+ + i\kappa_+)(n_- + i\kappa_-) - 1}$$

$$\theta_K \approx \frac{4\pi\sigma''_{xy}}{n(n^2-1)\omega} = \frac{2\pi e^2}{n(n^2-1)d}\frac{\Delta^2}{(\hbar\omega)^3} \quad ?$$



Kapitulnik et al. (2006)

strongly reduced for $\hbar\omega \gg \Delta$

debate:

effects of gauge-invariance

Yakovenko, Kallin, Mineev, …
Buhmann & MS

in 90s: Joynt; Yip & Sauls, ...

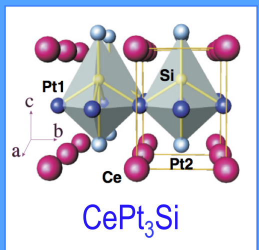
Status of evidence for chiral p-wave

NMR Knight shift $\vec{H} \perp z$ / $\vec{H} \parallel z$	consistent / unexplained
µSR ZF relaxation rate	consistent
flux distribution/ultrasound (2-comp OP)	consistent
phase sensitive test / Josephson effect	consistent
edge states in quasiparticle tunneling	consistent
direct observation of spontaneous currents	negative
phenomenology of 3K-phase	consistent
limiting behavior for inplane field	unexplained
Kerr effect	consistent
disorder effects non-magnetic impurities	consistent

Case 2:

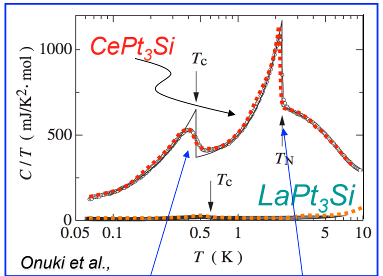
Superconductors without inversion center

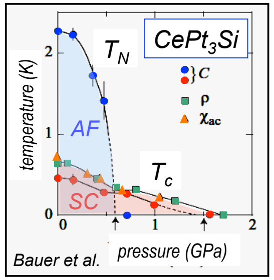
Key symmetries for Cooper pairing



Heavy Fermion superconductor $CePt_3Si$

Superconductivity and magnetism



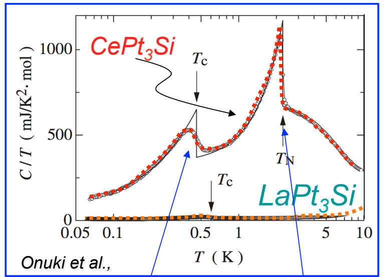


T_c = 0.45 K T_N = 2.2 K

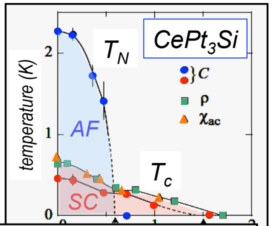
discovered by Ernst Bauer et al (2003)

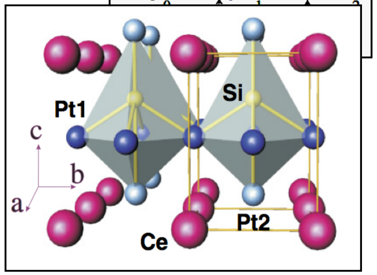
Heavy Fermion superconductor $CePt_3Si$

Superconductivity and magnetism



T_c = 0.45 K T_N = 2.2 K





non-centrosymmetric crystal

P4mm ➡ C_{4v}

tetragonal

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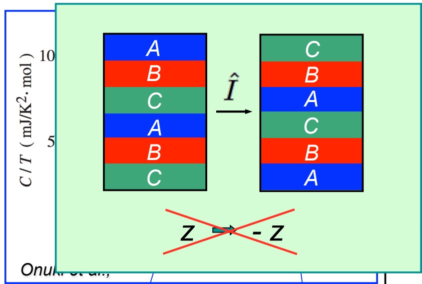

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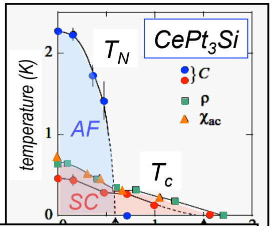
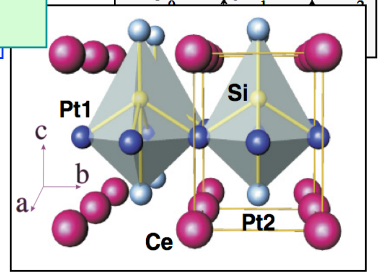




non-centrosymmetric crystal

P4mm ➡ C_{4v}

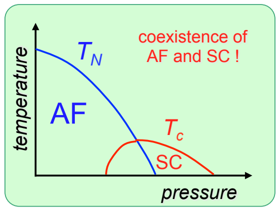
tetragonal

Other Ce-based compounds

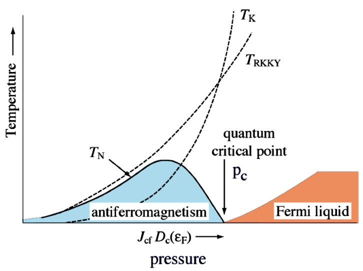
$CeRhSi_3$ $CeIrSi_3$ $CeCoGe_3$

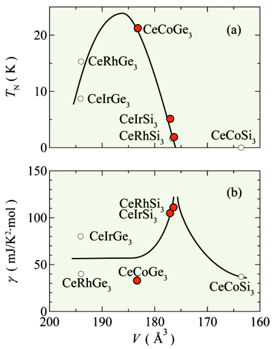
antiferromagnets with superconductivity under pressure at QCP

non-centrosymmetric   point group C_{4v}



Doniach's phase diagram

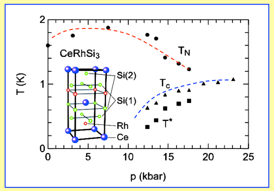




Onuki et al

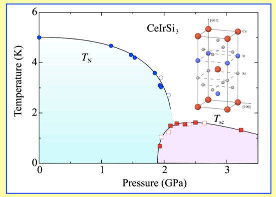
Other Ce-based compounds

$CeRhSi_3$



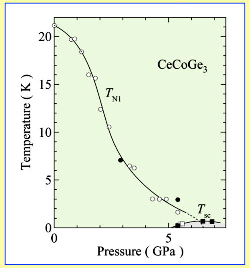
Kimura et al. (2005)

$CeIrSi_3$

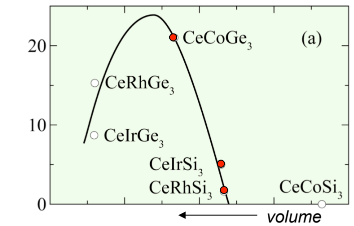


Onuki et al. (2005)

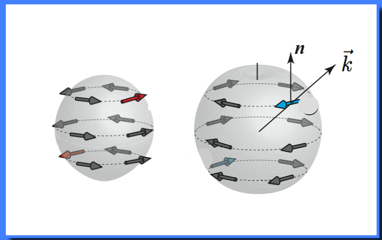
$CeCoGe_3$



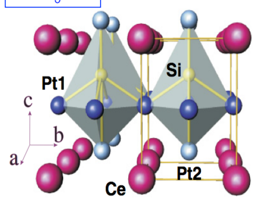
Onuki et al. (2007)



Electronic states of non-centrosymmetric metal



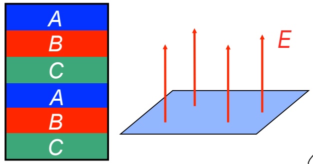
Non-centrosymmetric superconductors



no inversion center

$$\mathcal{H} = \sum_{\vec{k},s} \epsilon_{\vec{k}} c^\dagger_{\vec{k}s} c_{\vec{k}s} + \sum_{\vec{k},s,s'} \vec{g}_{\vec{k}} \cdot \vec{\sigma}_{ss'} c^\dagger_{\vec{k}s} c_{\vec{k}s'}$$

spin-orbit coupling



tetragonal

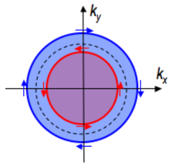
D_{4h} → C_{4v}

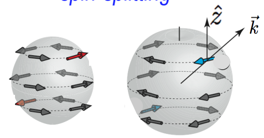
Rashba spin-orbit coupling

$$\vec{g}_{\vec{k}} = \alpha(\hat{z} \times \vec{k})$$

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

spin-splitting





Non-centrosymmetric superconductors — pairing symmetry

gap function

$$\hat{\Delta}_{\vec{k}} = \begin{pmatrix} \Delta_{\vec{k},\uparrow\uparrow} & \Delta_{\vec{k},\uparrow\downarrow} \\ \Delta_{\vec{k},\downarrow\uparrow} & \Delta_{\vec{k},\downarrow\downarrow} \end{pmatrix}$$

$$\hat{\Delta}_{\vec{k}} = i \sum_{\mu=0}^{3} d_\mu(\vec{k}) \hat{\sigma}^\mu \hat{\sigma}^y$$

parity

$$[d_0(\vec{k}), \vec{d}(\vec{k})] = [\underbrace{d_0(-\vec{k})}_{\substack{\text{even} \\ \text{spin-singlet}}}, \underbrace{-\vec{d}(-\vec{k})}_{\substack{\text{odd} \\ \text{spin-triplet}}}]$$

symmetry operation

$$g[d_0(\vec{k}), \vec{d}(\vec{k})] = [d_0(R_g \vec{k}), R^s_g \vec{d}(R_g \vec{k})]$$

$$\mathcal{H} = \sum_{\vec{k},s} \epsilon_{\vec{k}} c^\dagger_{\vec{k}s} c_{\vec{k}s} + \sum_{\vec{k},s,s'} \vec{g}_{\vec{k}} \cdot \vec{\sigma}_{ss'} c^\dagger_{\vec{k}s} c_{\vec{k}s'}$$

symmetry classification

inversion is not a symmetry

→ mixed-parity pairing

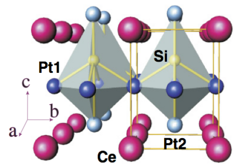
full-symmetry pairing state

$$d_0(\vec{k}) = \Delta_e \qquad \vec{d}(\vec{k}) = \Delta_o \vec{g}_{\vec{k}}$$

$$\hat{\Delta}_{\vec{k}} = (\Delta_e + \Delta_o \vec{g}_{\vec{k}} \cdot \hat{\vec{\sigma}}) i \hat{\sigma}^y$$

non-unitary $\quad \hat{\Delta}^\dagger \hat{\Delta} \not\propto \hat{\sigma}^0$

Non-centrosymmetric superconductors — pairing symmetry



D_{4h}

~~Inversion $z \to -z$~~

C_{4v}

full-symmetry pairing state

	$d_0(\vec{k}) = \Delta_e$	$\vec{d}(\vec{k}) = \Delta_o \vec{g}_{\vec{k}}$
D_{4h}	Γ_1^+	Γ_2^-
C_{4v}	Γ_1	Γ_1

D_{4h}

even-parity component

Γ^+ → Γ

odd-parity component

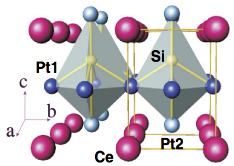
$\Gamma^+ \otimes \Gamma_2^-$ → Γ

C_{4v}

Γ

Γ	$d_0(\vec{k})$	$\vec{d}(\vec{k})$
Γ_1	1	$\vec{g}_{\vec{k}}$
Γ_2	$k_x k_y (k_x^2 - k_y^2)$	$k_x k_y (k_x^2 - k_y^2) \vec{g}_{\vec{k}}$
Γ_3	$k_x^2 - k_y^2$	$(k_x^2 - k_y^2) \vec{g}_{\vec{k}}$
Γ_4	$k_x k_y$	$k_x k_y \vec{g}_{\vec{k}}$
Γ_5	$\{k_x k_z, k_y k_z\}$	$\{k_x k_z \vec{g}_{\vec{k}}, k_y k_z \vec{g}_{\vec{k}}\}$

Non-centrosymmetric superconductors pairing symmetry



D_{4h}

Inversion $z \to -z$

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	$d_0(\vec{k}) = \Delta_e$	$\vec{d}(\vec{k}) = \Delta_o \vec{g}_{\vec{k}}$
D_{4h}	Γ_1^+	Γ_2^-
C_{4v}	Γ_1	Γ_1

D_{4h}

even-parity component Γ^+

odd-parity component $\Gamma^+ \otimes \Gamma_2^-$

C_{4v}: Γ

Γ	$d_0(\vec{k})$	$\vec{d}(\vec{k})$
Γ_1	1	$\vec{g}_{\vec{k}}$
Γ_2	$k_x k_y (k_x^2 - k_y^2)$	$k_x k_y (k_x^2 - k_y^2) \vec{g}_{\vec{k}}$
Γ_3	$k_x^2 - k_y^2$	$(k_x^2 - k_y^2) \vec{g}_{\vec{k}}$
Γ_4	$k_x k_y$	$k_x k_y \vec{g}_{\vec{k}}$
Γ_5	$\{k_x k_z, k_y k_z\}$	$\{k_x k_z \vec{g}_{\vec{k}}, k_y k_z \vec{g}_{\vec{k}}\}$

$$\boxed{\hat{\Delta}_{\vec{k}} = (\Delta_e + \Delta_o \vec{g}_{\vec{k}} \cdot \hat{\vec{\sigma}}) i \hat{\sigma}^y}$$

mixed-parity pairing

Mixed parity states are *non-unitary*

unitary superconducting states: $\hat{\Delta}\hat{\Delta}^\dagger = |\Delta|^2 \hat{\sigma}_0 \propto$ *2x2 unit matrix*

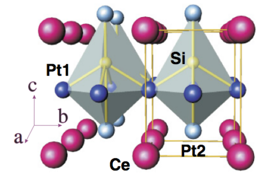
$$\hat{\Delta} = \left\{ \psi(\vec{k})\hat{\sigma}_0 + \vec{d}(\vec{k}) \cdot \hat{\vec{\sigma}} \right\} i\hat{\sigma}_y$$

$$\hat{\Delta}\hat{\Delta}^\dagger = (|\psi|^2 + |\vec{d}|^2)\hat{\sigma}_0 + \underbrace{\{\psi^* \vec{d} + \psi \vec{d}^*\}}_{\propto \vec{\lambda}_{\vec{k}}} \cdot \hat{\vec{\sigma}} + \underbrace{i\{\vec{d} \times \vec{d}^*\}}_{\propto \vec{H}} \cdot \hat{\vec{\sigma}}$$

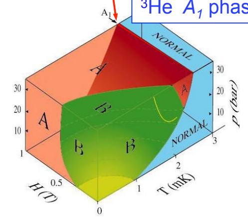
inversion symmetry violated

time reversal symmetry violated

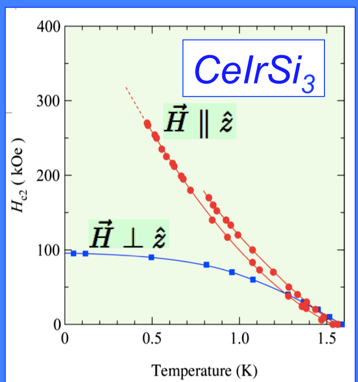
$CePt_3Si$



^3He A_1 phase



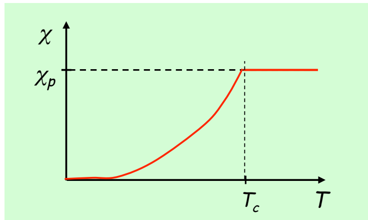
Upper critial field



Spin susceptibility

- *spin singlet pairing* $\longrightarrow$ *Yosida behavior of spin susceptibility*

pair breaking by spin polarization

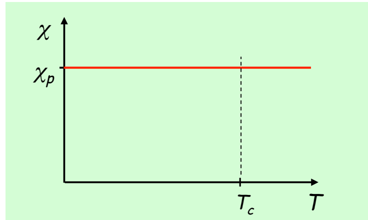


- *spin triplet pairing*

no pair breaking for equal-spin pairing

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

note: $\vec{S} \parallel \vec{H}$ with $\vec{d} \perp \vec{S}$



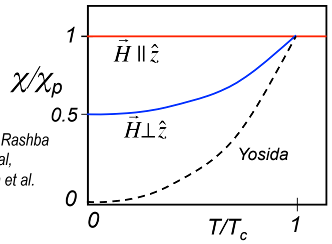
Spin susceptibility & Rashba spin-orbit coupling

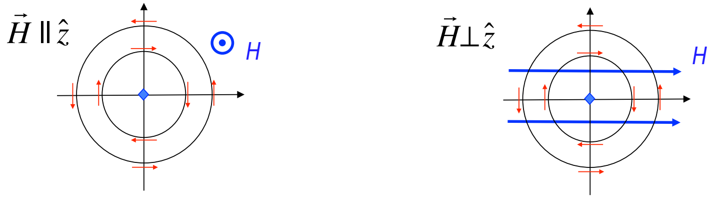
spin susceptibility of non-centrosymmetric SC

$$\vec{g}_{\vec{k}} = \hat{z} \times \vec{k} = \begin{pmatrix} k_y \\ -k_x \\ 0 \end{pmatrix}$$

as in $CePt_3Si$, $CeRhSi_3$, $CeIrSi_3$

Gorkov & Rashba
Frigeri et al,
Samokhin et al.





"transverse field"
interband spin polarization

partially "transverse field"
interband spin polarization limited

Spin susceptibility & Rashba spin-orbit coupling

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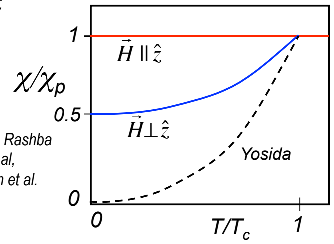

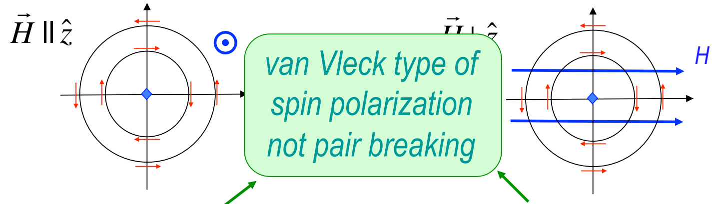

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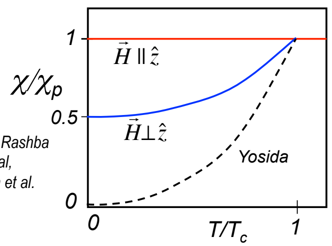

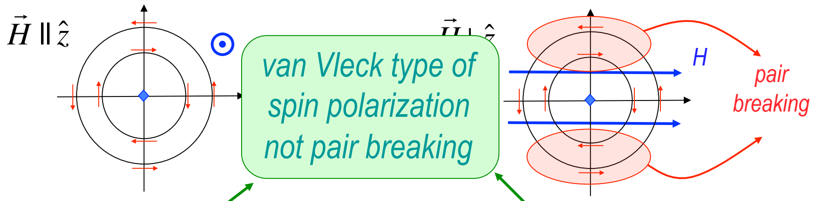

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interband spin polarization

partially "transverse field"
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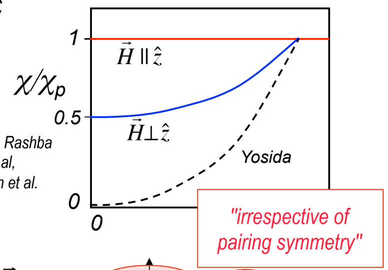
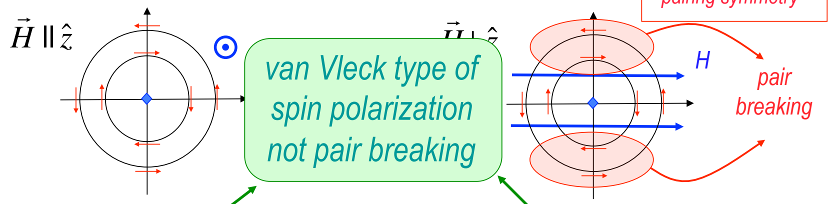
Spin susceptibility & Rashba spin-orbit coupling

spin susceptibility of non-centrosymmetric SC

$$\chi_{\mu\nu}(T=0) \approx \chi_p \left\{ \delta_{\mu\nu} - \left\langle \frac{g^{\mu}_{\vec{k}} g^{\nu}_{\vec{k}}}{|\vec{g}_{\vec{k}}|^2} \right\rangle_{\vec{k}} \right\}$$

Gorkov & Rashba
Frigeri et al,
Samokhin et al.





"transverse field"
interband spin polarization

partially "transverse field"
interband spin polarization limited

Paramagnetic limiting

spin susceptibility of non-centrosymmetric SC

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Gorkov & Rashba
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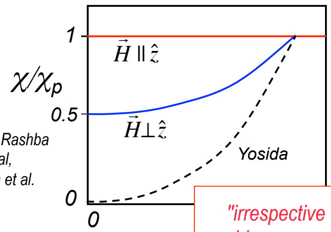

"irrespective of pairing symmetry"

paramagnetic limiting field

$$H_p = \frac{H_c(0)}{\sqrt{4\pi(\chi_P - \chi(0))}}$$

$\vec{H} \perp \hat{z}$ paramagnetic limiting

$\vec{H} \parallel \hat{z}$ no paramagn. limiting

Paramagnetic limiting

spin susceptibility of non-centrosymmetric SC

$$\chi_{\mu\nu}(T=0) \approx \chi_P \left\{ \delta_{\mu\nu} - \left\langle \frac{g^\mu_{\vec{k}} g^\nu_{\vec{k}}}{|\vec{g}_{\vec{k}}|^2} \right\rangle_{\vec{k}} \right\}$$

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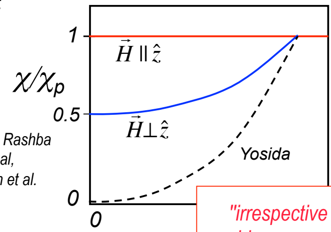
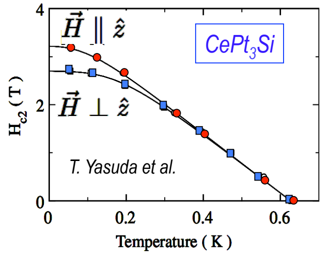


"irrespective of pairing symmetry"



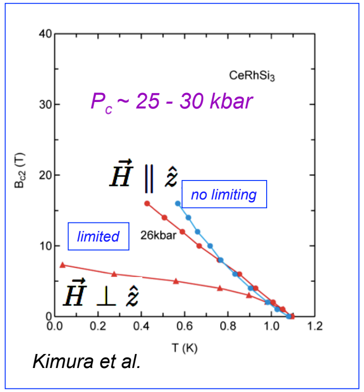
does not follow the expectations !

$\vec{H} \perp \hat{z}$ paramagnetic limiting

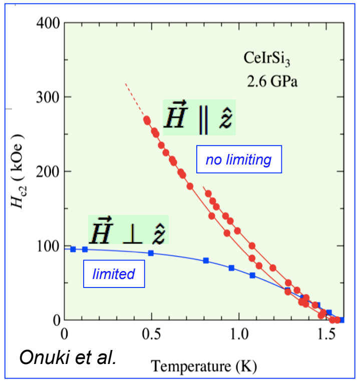
$\vec{H} \parallel \hat{z}$ no paramagn. limiting

Upper critical field and paramagnetic limiting

$CeRhSi_3$



$CeIrSi_3$

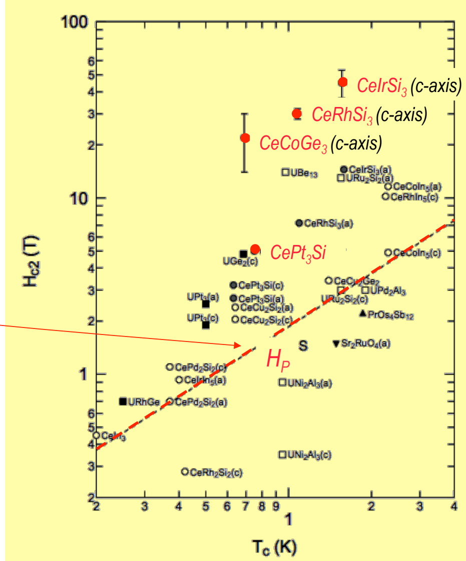


fits very well to theoretical expectations of paramagnetic limiting

Comparison of different heavy Fermion superconductors

paramagnetic limit (BCS weak coupling)

$$H_P = 1.85 k_B T_c / g\mu_B$$

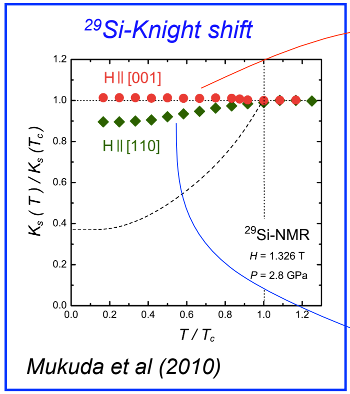


Non-centrosymmetric superconductors

$CeIrSi_3$
$CeRhSi_3$
$CeCoGe_3$

highest H_{c2} among heavy Fermion materials

Upper critical field and paramagnetic limiting



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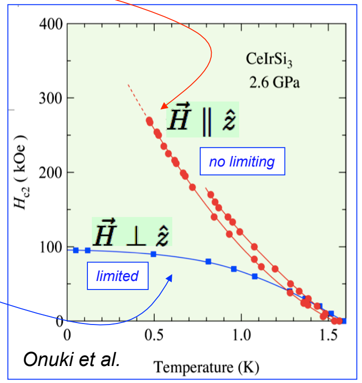

fits very well to theoretical
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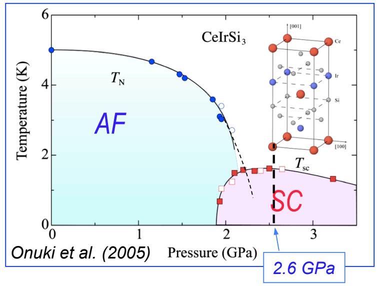
Upper critical field and paramagnetic limiting

Phase diagram - QPT



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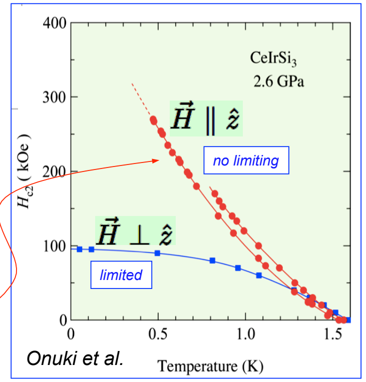


quantum critical fluctuations

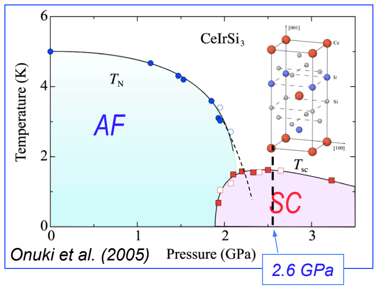
➡ unusual T-dependence of H_{c2}

for $\vec{H} \parallel \hat{z}$

Tada, Fujimoto and Kawakami (2009)

Upper critical field and paramagnetic limiting

Phase diagram - QPT



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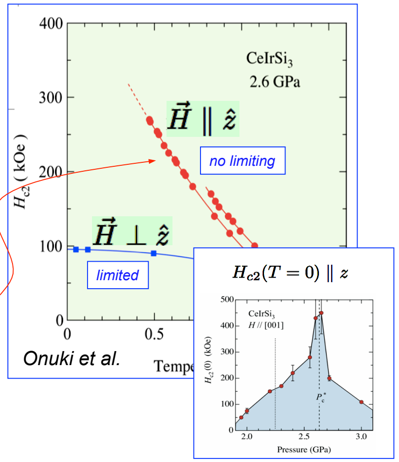

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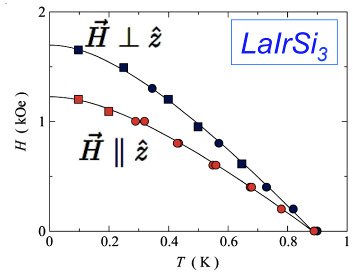
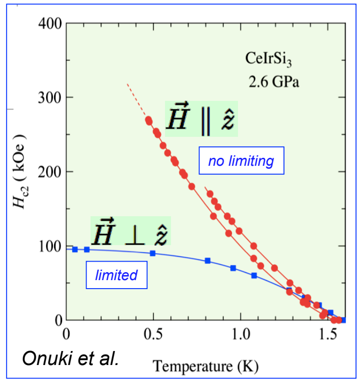
Upper critical field and paramagnetic limiting

Comparison with the
non-heavy Fermion variant



$CeIrSi_3$



- 100 x smaller H_{c2}
- orbital depairing relevant
  light electrons ➡ large ξ

Conclusion & Remarks

inversion key symmetry for Cooper pairing

without inversion symmetry ➡ mixed-parity pairing

dominant unconventional component

rich phenomena and complex phenomenology

Intriguing novel features:

magnetoelectric phenomena connection to spintronics and multiferroics   Edelstein, Mineev, Samokhin, Eschrig, Aoyama, …

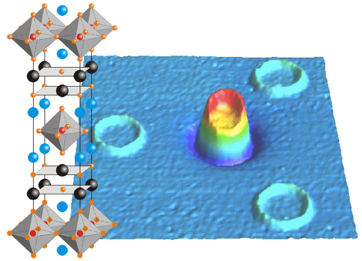
Josephson effect phase sensitive probes
Hayashi, Linder, Subdo, Borkje, Klam, …

Coexistence of magnetism and superconductivity at quantum critical points   Yanase, Fujimoto, …

Order parameter symmetry of unconventional superconductors

Identified order parameters

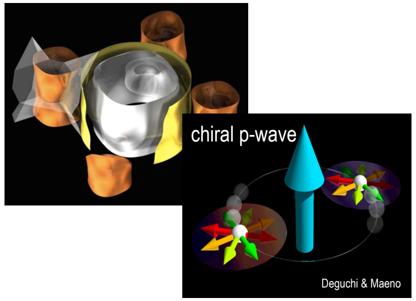
- *High-T_c superconductors*
  $La_{2-x}Sr_xCuO_4$, $YBa_2Cu_3O_7$, …



spin singlet, *d*-wave pairing

$$\psi(\vec{k}) = k_x^2 - k_y^2$$ 1D rep.

- *Ruthenate* Sr_2RuO_4



2D metallic analog to ^3He
spin triplet chiral *p*-wave

$$\vec{d}(\vec{k}) = \hat{z}(k_x \pm ik_y)$$ 2D rep.

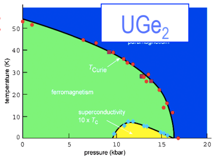
Order parameter symmetry of unconventional superconductors

open order parameters

- *Heavy Fermion superconductors*

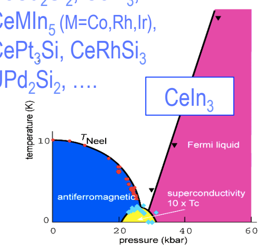
likely spin triplet

UBe_{13}, UPt_3,
UGe_2 , $ZnZr_2$
$PrOs_4Sb_{12}$



likely spin singlet   mixed parity

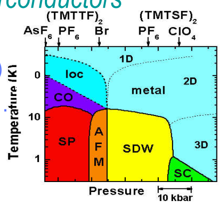
$CeCu_2Si_2$, $CeIn_3$,
$CeMIn_5$ (M=Co,Rh,Ir),
$CePt_3Si$, $CeRhSi_3$
UPd_2Si_2, ….



- *Organic superconductors*

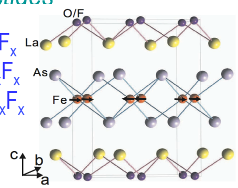
$(TMTSF)_2M$
(M=PF_6, SbF_6, …)
$(BEDT\text{-}TTF)_2M$ …

singlet or triplet



- *Fe-oxypnictides*

$LaFeAsO_{1-x}F_x$
$NdFeAsO_{1-x}F_x$
$SmFeAsO_{1-x}F_x$
$CaFe_2As_2$
$BaFe_2As_2$



unconv. multi-band spin singlet ?

Conclusions and final remarks

- Superconductivity in strongly correlated electron systems likely unconventional
  - strong Coulomb repulsion favors angular momentum *l > 0*
  - exotic pairing mechanisms in particular close to quantum critical points
- Unconventional order parameters give rise to new phenomena
  - quasi-particle properties, tunneling and Josephson effect
  - mixed phase, vortex matter, flux dynamics
  - superconducting multi-phase diagrams
  - magnetism and connection to competing phases
  - disorder effects

➡ higher dimensional order parameters (Sr_2RuO_4, $(U,Th)Be_{13}$, UPt_3, …) are more interesting than one-dimensional ones (high-T_c superconductors, …)

Many chapters on unconventional superconductivity are still unwritten and new materials are discovered at an accelerating pace (sample purity is mandatory ! ?)