Odd-frequency superconductivity in Sr_2RuO_4 measured by Kerr effect

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Outline

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- Introduction to odd-frequency (ω) superconductivity
  - SF, SN junctions
- Odd-ω bulk superconductivity in multiband systems
  - Simple two-band superconductors
- Odd-ω superconductivity and Kerr effect in Sr_2RuO_4

Different Phases of Matter

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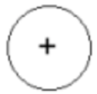
Ordered states → symmetry of order parameter, Δ

Superconductivity: $\Delta \sim F = \langle \psi_\alpha \psi_\beta \rangle$

Fermi-Dirac statistics

- spin-singlet, *s*-wave
  $\uparrow\downarrow - \downarrow\uparrow$



- spin-triplet, *p*-wave
  $\uparrow\downarrow + \downarrow\uparrow$
  $\uparrow\uparrow, \downarrow\downarrow$

Different Phases of Matter

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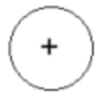
Ordered states → symmetry of order parameter, Δ

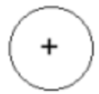
Superconductivity: $\Delta \sim F = \langle \psi_\alpha(t)\psi_\beta(0)\rangle$ ($t \leftrightarrow \omega$, frequency)

Fermi-Dirac statistics

- even-ω, spin-singlet, *s*-wave
  - $\uparrow\downarrow - \downarrow\uparrow$



- **odd-ω**, spin-triplet, *s*-wave
  - $\uparrow\downarrow + \downarrow\uparrow$
  - $\uparrow\uparrow, \downarrow\downarrow$

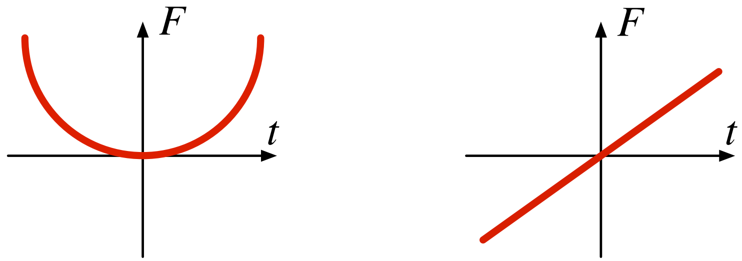


Odd-ω Pairing

BCS order parameter: $F(\mathbf{r},t;\mathbf{r}',t'\to t) = \langle \psi(\mathbf{r},t)\psi(\mathbf{r}',t'\to t)\rangle$

vanishes for odd-ω pairing

Equal-time odd-ω order parameter: $\left.\frac{\mathrm{d}F(\mathbf{r},t;\mathbf{r}',t')}{\mathrm{d}t}\right|_{t\to t'}$



even-ω odd-ω

SF Interface

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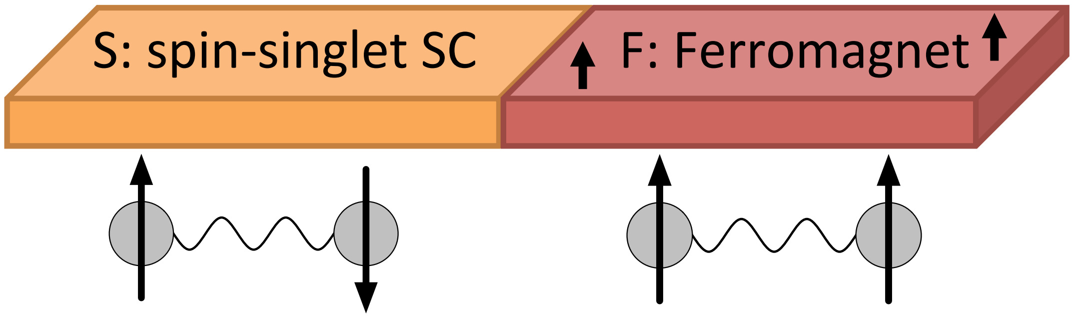
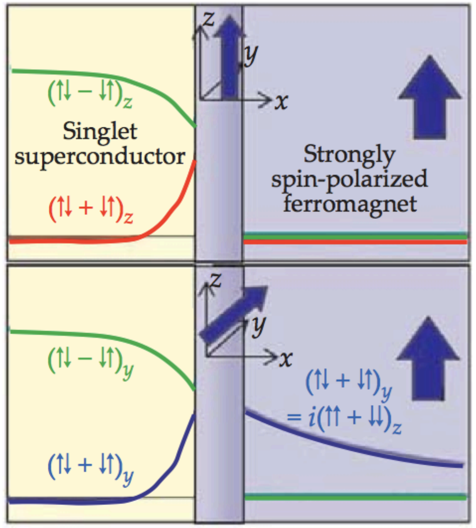


Spin-rotation symmetry breaking



[1]

Spin-singlet *s*-wave SC → **odd-ω** spin-triplet *s*-wave pairing

- Long-range superconducting proximity effect in F
- *s*-wave = disorder robust

[1]: Eschrig, Phys. Today 64, 43 (2011)

SN Interface

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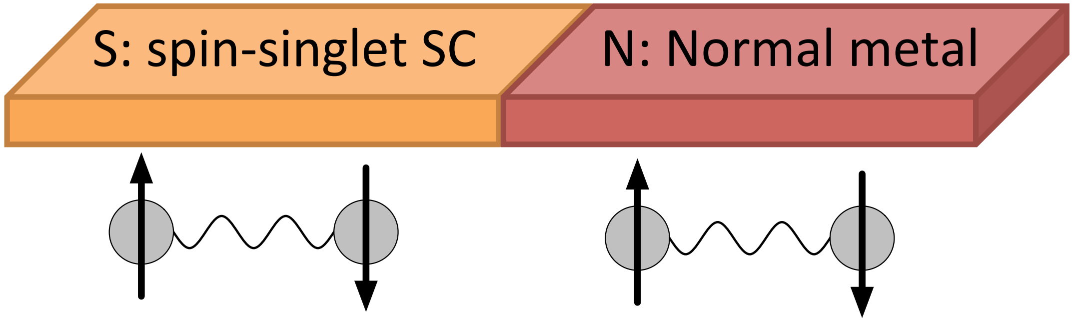
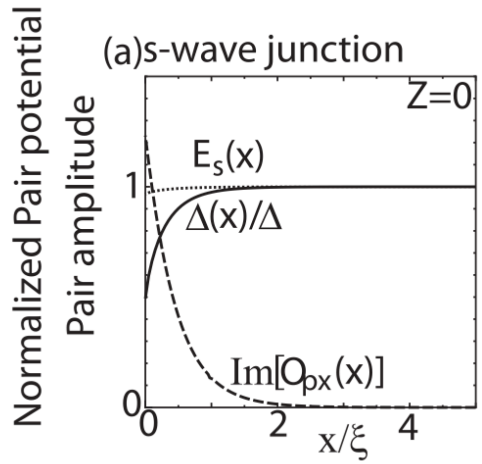


Translation symmetry breaking



[1]

Spin-singlet *s*-wave SC → **odd-ω** spin-singlet *p*-wave pairing

- Only high-transparency junctions
- *p*-wave = only ballistic systems

[1]: Tanaka et al, PRL 99, 037005 (2007)

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Odd-ω Bulk Superconductivity in Multiband Systems

- A clue from Bi_2Se_3
- Simple two-band superconductors

Bi_2Se_3 – SC Hybrid Structure

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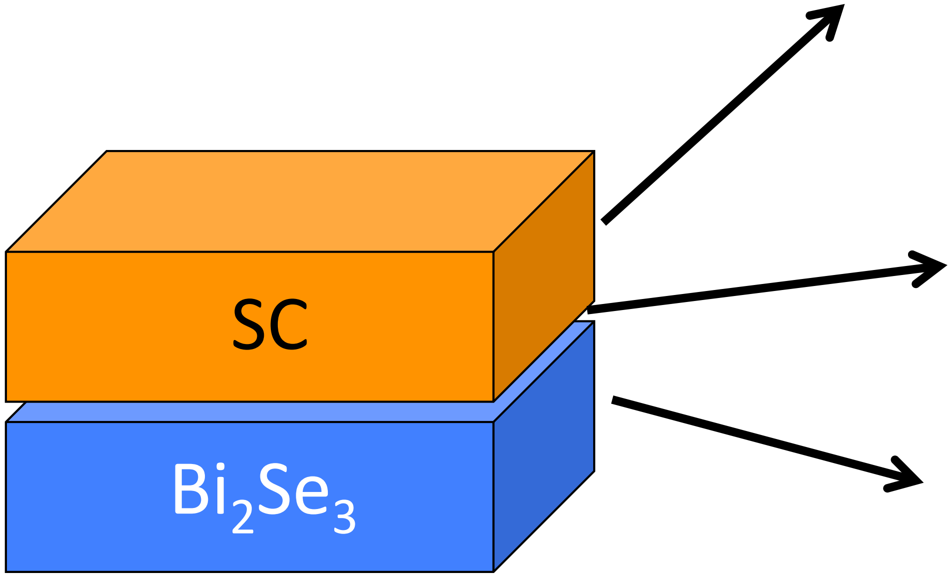

$$H_{\mathrm{SC}} = \sum_{\mathbf{k},\sigma} (-2\cos(k_x a) - 2\cos(k_y a) + \mu_{\mathrm{SC}}) c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}$$
$$+ \frac{1}{2} \sum_{\mathbf{k},\sigma,\sigma'} \Delta_{\sigma\sigma'}(\mathbf{k}) c^{\dagger}_{\mathbf{k}\sigma} c^{\dagger}_{-\mathbf{k}\sigma'} - \Delta^{*}_{\sigma\sigma'}(-\mathbf{k}) c_{-\mathbf{k}\sigma} c_{\mathbf{k}\sigma'}$$

2D superconductor

$$H_T = -\sum_{\mathbf{k},\sigma} T_1 c^{\dagger}_{\mathbf{k}\sigma} b_{1\mathbf{k}\sigma} + T_2 c^{\dagger}_{\mathbf{k}\sigma} b_{2\mathbf{k}\sigma} + \mathrm{H.c.}$$

Local tunneling

$$H_{\mathrm{TI}} = \gamma_0 - 2\sum_{\mathbf{k},i} \gamma_i \cos(k_i a) + \sum_{\mathbf{k},\mu} d_\mu \Gamma_\mu$$

Bi_2Se_3 (τ orbital Pauli matrix) [1]

$$\begin{pmatrix} d_0 = \epsilon - 2\sum_i t_i \cos(k_i a),\ d_i = -2\lambda_i \sin(k_i a) \\ \Gamma_0 = \tau_x \otimes \sigma_0, \Gamma_x = -\tau_z \otimes \sigma_y, \Gamma_y = \tau_z \otimes \sigma_x, \Gamma_z = \tau_y \otimes \sigma_0 \end{pmatrix}$$

ABS and Balatsky, PRB 87, 220506(R) (2013), [1]: Rosenberg and Franz, PRB 85, 195119 (2012)

Superconducting Symmetries in Bi_2Se_3

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Singlet/triplet, spatial (*s*/*p*/*d*), even/odd-ω, even/odd orbital

Superconductor			Even-frequency		Odd-frequency	
Γ	Basis function	J_z	Even-orbital	Odd-orbital	Even-orbital	Odd-orbital
A_{1g}	$\psi = 1$	0	A_{1g} singlet, A_{2u} triplet ($m_s = \pm 1$)	-	-	A_{1g} singlet, A_{2u} triplet ($m_s = \pm 1$)
B_{1g}	$\psi = k_x^2 - k_y^2$	±2	B_{1g} singlet, B_{2u} triplet ($m_s = \pm 1$)	-	-	B_{1g} singlet, B_{2u} triplet ($m_s = \pm 1$)
B_{2g}	$\psi = 2k_xk_y$	±2	B_{2g} singlet, B_{1u} triplet ($m_s = \pm 1$)	-	-	B_{2g} singlet, B_{1u} triplet ($m_s = \pm 1$)
A_{1u}	$\mathbf{d} = (k_x, k_y, 0)$	0	A_{1u} triplet ($m_s = \pm 1$)	A_{1g} triplet ($m_s = 0$)	A_{1g} triplet ($m_s = 0$)	A_{1u} triplet ($m_s = \pm 1$)
A_{2u}	$\mathbf{d} = (k_y, -k_x, 0)$	0	A_{2u} triplet ($m_s = \pm 1$), A_{1g} singlet	-	-	A_{2u} triplet ($m_s = \pm 1$), A_{1g} singlet
B_{1u}	$\mathbf{d} = (k_x, -k_y, 0)$	±2	B_{1u} triplet ($m_s = \pm 1$), B_{2g} singlet	B_{1g} triplet ($m_s = 0$)	B_{1g} triplet ($m_s = 0$)	B_{1u} triplet ($m_s = \pm 1$), B_{2g} singlet
B_{2u}	$\mathbf{d} = (k_y, k_x, 0)$	±2	B_{2u} triplet ($m_s = \pm 1$), B_{1g} singlet	B_{2g} triplet ($m_s = 0$)	B_{2g} triplet ($m_s = 0$)	B_{2u} triplet ($m_s = \pm 1$), B_{1g} singlet
E_{2u}^{+}	$\mathbf{d} = (0, 0, k_x + ik_y)$	1	E_{2u}^{+} triplet ($m_s = 0$)	A_{1g} triplet ($m_s = 1$), $B_{1g}+iB_{2g}$ triplet ($m_s = -1$)	A_{1g} triplet ($m_s = 1$), $B_{1g}+iB_{2g}$ triplet ($m_s = -1$)	E_{2u}^{+} triplet ($m_s = 0$)
E_{2u}^{-}	$\mathbf{d} = (0, 0, k_x - ik_y)$	−1	E_{2u}^{-} triplet ($m_s = 0$)	A_{1g} triplet ($m_s = -1$), $B_{1g}-iB_{2g}$ triplet ($m_s = 1$)	A_{1g} triplet ($m_s = -1$), $B_{1g}-iB_{2g}$ triplet ($m_s = 1$)	E_{2u}^{-} triplet ($m_s = 0$)

ABS and Balatsky, PRB 87, 220506(R) (2013)

Frequency and Orbital

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Complete reciprocity in oddness in frequency and orbital index

Superconductor			Even-frequency		Odd-frequency	
Γ	Basis function	J_z	Even-orbital	Odd-orbital	Even-orbital	Odd-orbital
A_{1g}	$\psi = 1$	0	A_{1g} singlet, A_{2u} triplet ($m_s = \pm 1$)	-	-	A_{1g} singlet, A_{2u} triplet ($m_s = \pm 1$)
B_{1g}	$\psi = k_x^2 - k_y^2$	± 2	B_{1g} singlet, B_{2u} triplet ($m_s = \pm 1$)	-	-	B_{1g} singlet, B_{2u} triplet ($m_s = \pm 1$)
B_{2g}	$\psi = 2k_x k_y$	± 2	B_{2g} singlet, B_{1u} triplet ($m_s = \pm 1$)	-	-	B_{2g} singlet, B_{1u} triplet ($m_s = \pm 1$)
A_{1u}	$\mathbf{d} = (k_x, k_y, 0)$	0	A_{1u} triplet ($m_s = \pm 1$)	A_{1g} triplet ($m_s = 0$)	A_{1g} triplet ($m_s = 0$)	A_{1u} triplet ($m_s = \pm 1$)
A_{2u}	$\mathbf{d} = (k_y, -k_x, 0)$	0	A_{2u} triplet ($m_s = \pm 1$) A_{1g} singlet	-	-	A_{2u} triplet ($m_s = \pm 1$), A_{1g} singlet
B_{1u}	$\mathbf{d} = (k_x, -k_y, 0)$	± 2	B_{1u} triplet ($m_s = \pm 1$) B_{2g} singlet	B_{1g} triplet ($m_s = 0$)	B_{1g} triplet ($m_s = 0$)	B_{1u} triplet ($m_s = \pm 1$), B_{2g} singlet
B_{2u}	$\mathbf{d} = (k_y, k_x, 0)$	± 2	B_{2u} triplet ($m_s = \pm 1$) B_{1g} singlet	B_{2g} triplet ($m_s = 0$)	B_{2g} triplet ($m_s = 0$)	B_{2u} triplet ($m_s = \pm 1$), B_{1g} singlet
E_{2u}^{+}	$\mathbf{d} = (0, 0, k_x + ik_y)$	1	E_{2u}^{+} triplet ($m_s = 0$)	A_{1g} triplet ($m_s = 1$), $B_{1g} + iB_{2g}$ triplet ($m_s = -1$)	A_{1g} triplet ($m_s = 1$), $B_{1g} + iB_{2g}$ triplet ($m_s = -1$)	E_{2u}^{+} triplet ($m_s = 0$)
E_{2u}^{-}	$\mathbf{d} = (0, 0, k_x - ik_y)$	-1	E_{2u}^{-} triplet ($m_s = 0$)	A_{1g} triplet ($m_s = -1$), $B_{1g} - iB_{2g}$ triplet ($m_s = 1$)	A_{1g} triplet ($m_s = -1$), $B_{1g} - iB_{2g}$ triplet ($m_s = 1$)	E_{2u}^{-} triplet ($m_s = 0$)

ABS and Balatsky, PRB 87, 220506(R) (2013)

Multiband Superconductors

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- S: Spin (even: spin-triplet; odd: spin-singlet)
- P: Spatial parity (even: *s*,*d*-wave; odd: *p*,*f*-wave)
- O: Orbital or band parity (even; odd orbital)
- T: Time (even; odd-frequency)

SPOT = -1

$S = 0$	P	T	O	$S = 1$	P	T	O
even-ω	$+$	$+$	$+$	even-ω	$-$	$+$	$+$
even-ω	$-$	$+$	$-$	even-ω	$+$	$+$	$-$
odd-ω	$+$	$-$	$-$	odd-ω	$+$	$-$	$+$
odd-ω	$-$	$-$	$+$	odd-ω	$-$	$-$	$-$

ABS and Balatsky, PRB 88, 104514 (2013)

Simple Two-Band Superconductor

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$$H_{ab} = \sum_{k\sigma} \varepsilon_a(k) a^\dagger_{k\sigma} a_{k\sigma} + \varepsilon_b(k) b^\dagger_{k\sigma} b_{k\sigma}$$

$$+ \sum_k \Delta_a(k) a^\dagger_{k\uparrow} a^\dagger_{-k\downarrow} + \Delta_b(k) b^\dagger_{k\uparrow} b^\dagger_{-k\downarrow} + \text{H.c.}$$

Interband hybridization

↓

$$H_{cd} = \sum_{k\sigma} \varepsilon_c(k) c^\dagger_{k\sigma} c_{k\sigma} + \varepsilon_d(k) d^\dagger_{k\sigma} d_{k\sigma}$$ Diagonal bands

$$+ \sum_k \Delta_c(k) c^\dagger_{k\uparrow} c^\dagger_{-k\downarrow} + \Delta_d(k) d^\dagger_{k\uparrow} d^\dagger_{-k\downarrow} + \text{H.c.}$$ Intraband pairing

$$+ \sum_k \Delta_{cd}(k) \left[c^\dagger_{k\uparrow} d^\dagger_{-k\downarrow} + d^\dagger_{k\uparrow} c^\dagger_{-k\downarrow} \right] + \text{H.c.}$$

Interband pairing

$$\Delta_{cd} = \frac{(\Delta_b - \Delta_a)|\Gamma|}{\sqrt{(\varepsilon_a - \varepsilon_b)^2 + 4|\Gamma|^2}}$$

ABS and Balatsky, PRB 88, 104514 (2013)

Time-Dependent Pairing

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Time-ordered s-wave interband pairing:

$$F^{\pm}(\tau) = \frac{1}{2N_{\mathbf{k}}} \sum_{\mathbf{k}} \mathcal{T}_{\tau} \langle c_{-\mathbf{k}\downarrow}(\tau) d_{\mathbf{k}\uparrow}(0) \pm d_{-\mathbf{k}\downarrow}(\tau) c_{\mathbf{k}\uparrow}(0) \rangle$$

$F^{e} = F^{+}(\tau \to 0^{+})$ Even-ω, even-interband pairing

$F^{o}_{\omega} = \left. \frac{\partial F^{-}}{\partial \tau} \right|_{\tau \to 0^{+}}$ Odd-ω, odd-interband pairing

ABS and Balatsky, PRB 88, 104514 (2013)

Odd-ω, Odd-Interband Pairing

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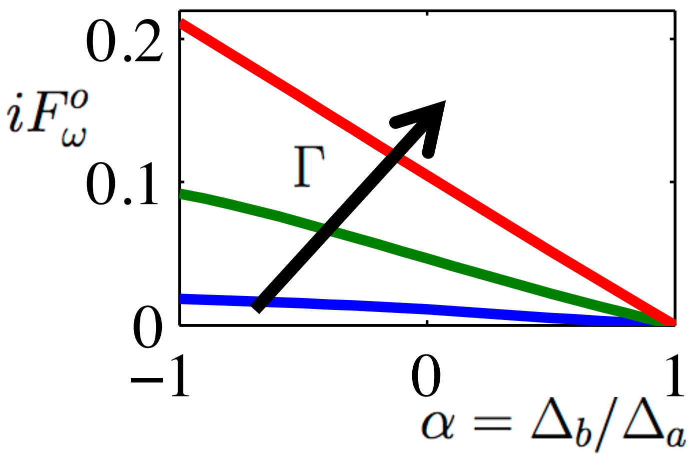
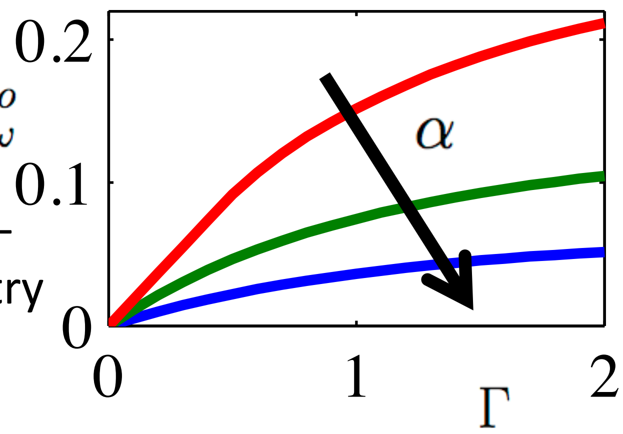
For $\begin{cases} \varepsilon_a = \varepsilon_b \\ \Delta_a = -\Delta_b \end{cases}$ $\Rightarrow$ $\begin{cases} \varepsilon_{c,d} = \varepsilon_a \mp \Gamma \\ \Delta_c = \Delta_d = 0 \\ \Delta_{cd} = \Delta_a \text{ Interband pairing} \end{cases}$ $\xrightarrow{\Gamma < \Delta_a}$ $\begin{cases} F^e = -\frac{1}{2N_{\mathbf{k}}} \sum_{\mathbf{k}} \frac{\Delta_a}{\sqrt{\varepsilon_a^2 + |\Delta_a|^2}} \quad \text{BCS equation} \\ F^o_\omega = i\Gamma F^e \quad \text{Odd-}\omega \end{cases}$



Preserves time-reversal symmetry $\mathcal{KT}$



ABS and Balatsky, PRB 88, 104514 (2013)

Using Perturbation Theory

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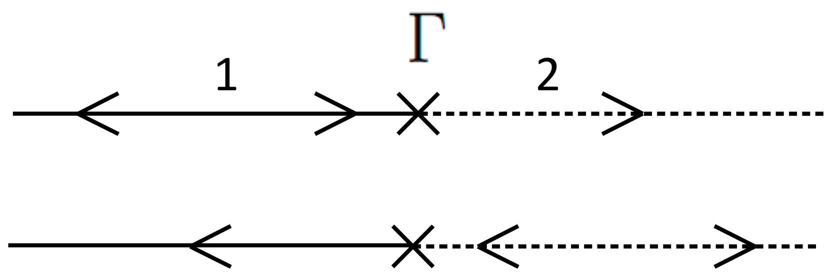
$$H = \sum_{k\sigma} \varepsilon_1(k) a^\dagger_{k\sigma} a_{k\sigma} + \varepsilon_2(k) b^\dagger_{k\sigma} b_{k\sigma} + \sum_{k\sigma} \Gamma(k) a^\dagger_{k\sigma} b_{k\sigma} + \mathrm{H.c.}$$

$$+ \sum_{k} \Delta_1(k) a^\dagger_{k\uparrow} a^\dagger_{-k\downarrow} + \Delta_2(k) b^\dagger_{k\uparrow} b^\dagger_{-k\downarrow} + \mathrm{H.c.}$$

Interband pairing F_{12}:



$F_1 \Gamma G_2$

$-\overleftarrow{G}_1 \Gamma F_2$

Komendova, Balatsky, and ABS, PRB 92, 04517 (2015)

Interband Pairing

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Perturbation theory to infinite order in Γ

Odd-interband: $F_{12}^{\mathrm{odd}}(k,i\omega) = \frac{F_{12} - F_{21}}{2} = i\omega\Gamma(\Delta_1 - \Delta_2)/D$

Even-interband: $F_{12}^{\mathrm{even}}(k,i\omega) = \frac{F_{12} + F_{21}}{2} = \Gamma(\Delta_1\varepsilon_2 - \Delta_2\varepsilon_1)/D$

$$\left(\begin{array}{l} D = (\omega^2 + E_1^2)(\omega^2 + E_2^2) - \Gamma^2[2(\varepsilon_1\varepsilon_2 - \omega^2) - \Delta_2^*\Delta_1 - \Delta_1^*\Delta_2] + \Gamma^4 \\ E_j^2 = \varepsilon_j^2 + |\Delta_j|^2 \end{array} \right)$$

Odd-frequency pairing: $\Gamma \neq 0, \Delta_1 \neq \Delta_2$

Komendova, Balatsky, and ABS, PRB 92, 04517 (2015)

Interband Frequency Dependence

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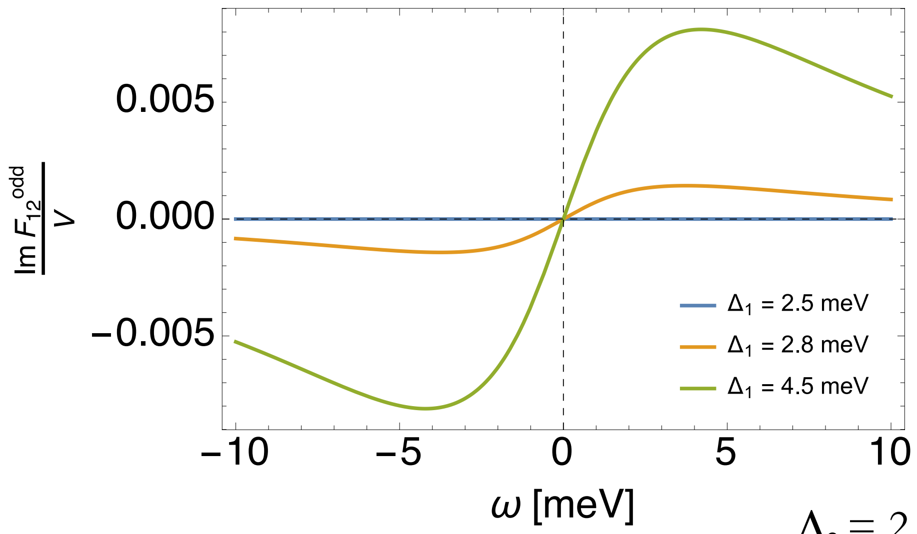
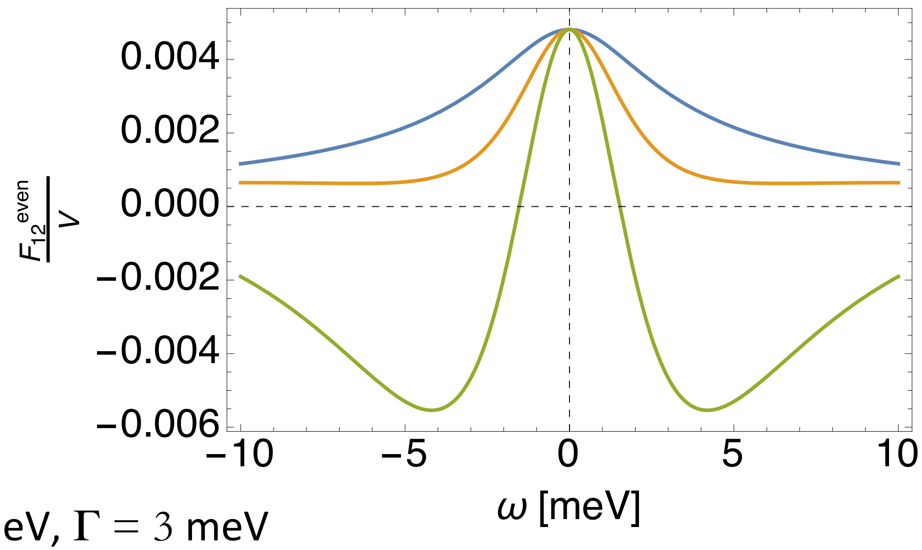
Odd-frequency



Even-frequency



$\Delta_2 = 2.5$ meV, $\Gamma = 3$ meV

Odd-frequency pairing: $\Gamma \neq 0, \Delta_1 \neq \Delta_2$

Komendova, Balatsky, and ABS, PRB 92, 04517 (2015)

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Odd-ω Superconductivity in Sr_2RuO_4

- Superconductivity in Sr_2RuO_4
- Two- and three-orbital models
- Odd-ω pairing measured by Kerr effect

Strontium Ruthenate, Sr_2RuO_4

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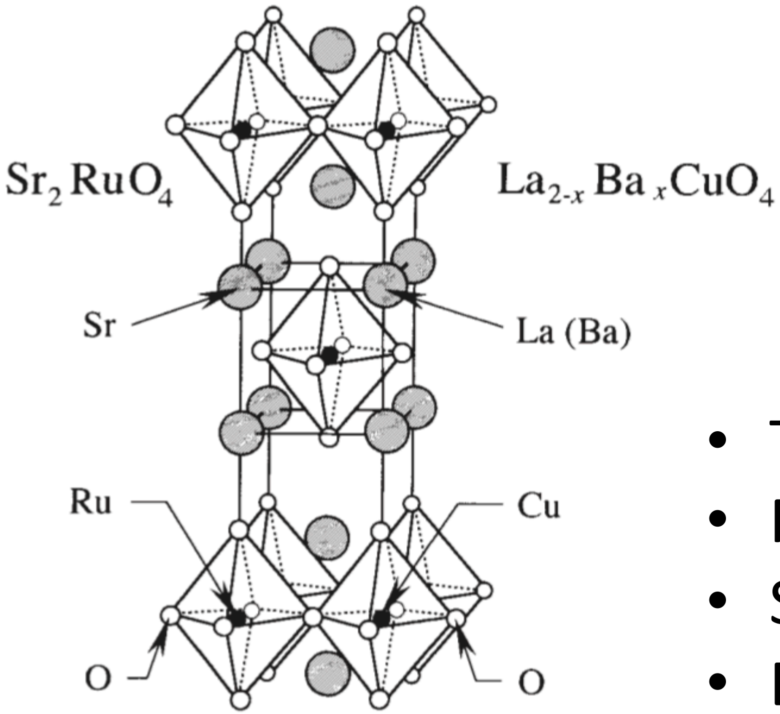

Superconductivity in a layered perovskite without copper

Y. Maeno*, H. Hashimoto*, K. Yoshida*, S. Nishizaki*, T. Fujita*, J. G. Bednorz† & F. Lichtenberg†‡

Nature 372, 532 (1994)

- T_c = 1.5K
- Non-*s*-wave (disorder sensitive)
- Spin-triplet (neutron scattering, Knight shift)
- Breaks time-reversal symmetry (Kerr effect)

→ Spin-triplet chiral p_x+ip_y-wave symmetry

Properties of Sr_2RuO_4

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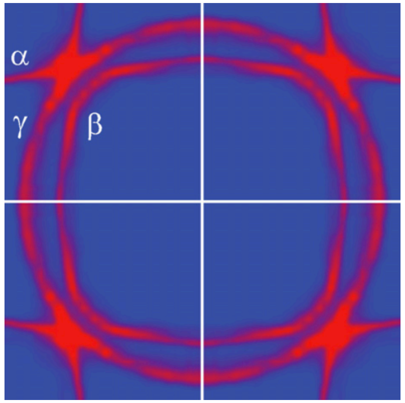
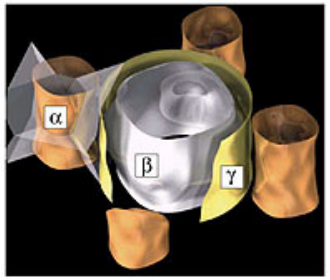
Three Fermi surfaces (FSs)



[1]



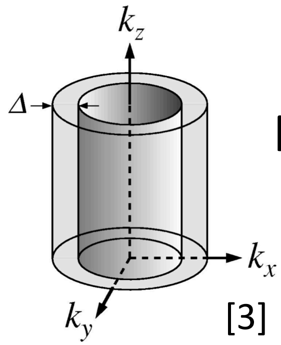
[2]

Superconducting state

$$\begin{pmatrix} \Delta_{\uparrow\uparrow}(\mathbf{k}) & \Delta_{\uparrow\downarrow}(\mathbf{k}) \\ \Delta_{\downarrow\uparrow}(\mathbf{k}) & \Delta_{\downarrow\downarrow}(\mathbf{k}) \end{pmatrix} = \begin{pmatrix} -d_x(\mathbf{k}) + id_y(\mathbf{k}) & \psi(\mathbf{k}) + d_z(\mathbf{k}) \\ -\psi(\mathbf{k}) + d_z(\mathbf{k}) & d_x(\mathbf{k}) + id_y(\mathbf{k}) \end{pmatrix}$$

Triplet **d**-vector for chiral state

$$\mathbf{d}(\mathbf{k}) = (0, 0, k_x \pm ik_y)$$



[3]

Fully gapped on cylindrical FS

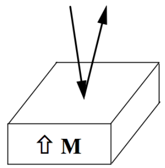
Three Ru 4d orbitals:

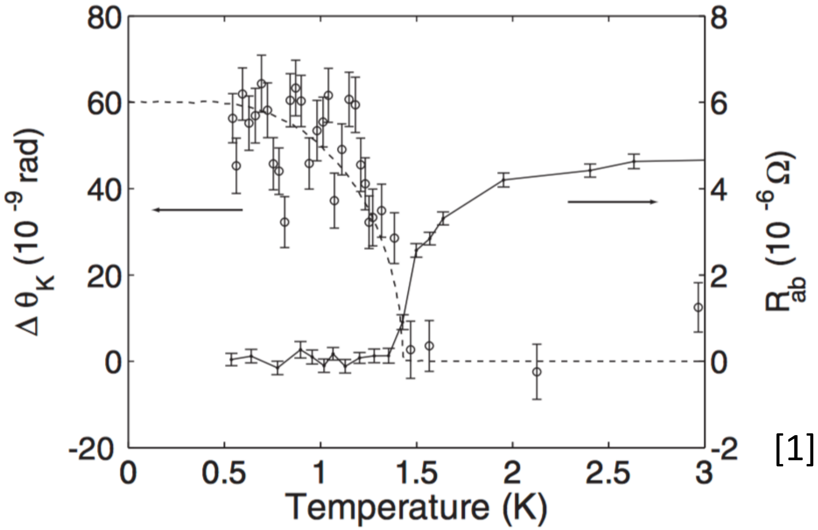
- *xy* → γ (electron-like)
- *xz*, *yz* → β (electron-like) and α (hole-like)

[1]: Damascelli et al, PRL 85, 5194 (2000), [2]: Phys. Today 54 (2001), [3]: Mackenzie and Maeno, RMP 75, 657 (2003)

Kerr Effect in Sr_2RuO_4

Reflected light has a slightly rotated plane of polarization if material breaks time-reversal symmetry (TRS)





[1]

SC state in Sr_2RuO_4 breaks TRS

But …

Clean single-band chiral SC has zero Kerr effect

→ Interband pairing with relative superconducting phases [2]

Electric-field driven interband transitions with relative SC phases
→ finite transverse Hall current response → finite Kerr effect

[1]: Xia et al, PRL 97, 167002 (2006), [2]: Taylor and Kallin, PRL 108, 157001 (2012); Wysokinski et al, PRL 108, 077004 (2012)

Two-Orbital Model for Sr_2RuO_4

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Hamiltonian $\sum_{\mathbf{k}} \Psi^\dagger_{\mathbf{k}} \hat{H}_{\mathbf{k}} \Psi_{\mathbf{k}}$ with $\hat{H}_{\mathbf{k}} = \begin{pmatrix} \hat{H}_0(\mathbf{k}) & \check{\Delta}(\mathbf{k}) \\ \check{\Delta}^\dagger(\mathbf{k}) & -\hat{H}_0(-\mathbf{k}) \end{pmatrix}$

$$\Psi^\dagger_{\mathbf{k}} = (c^\dagger_{\mathbf{k}\uparrow 1}\, c^\dagger_{\mathbf{k}\uparrow 2}\, c_{-\mathbf{k}\downarrow 1}\, c_{-\mathbf{k}\downarrow 2})$$

- *xz* (1),*yz* (2) orbitals
  → α, β bands
- Spin-triplet $\mathbf{d} \parallel \hat{\mathbf{z}}$

$$\hat{H}_0(\mathbf{k}) = \begin{pmatrix} \xi_1 & \epsilon_{12} \\ \epsilon_{12} & \xi_2 \end{pmatrix}, \quad \check{\Delta}(\mathbf{k}) = \begin{pmatrix} \Delta_1 & \Delta_{12} \\ \Delta_{12} & \Delta_2 \end{pmatrix}$$

Intraorbital energy (ξ_1)

Interorbital hybridization (ϵ_{12})

Interorbital pairing (Δ_{12})

Intraorbital pairing (Δ_2)

Odd-ω Pairing and Kerr Effect

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Odd-ω, odd-interorbital pairing:

$$F_{12} - F_{21} = i\omega[(\Delta_2 - \Delta_1)\epsilon_{12} + \Delta_{12}(\xi_1 - \xi_2)]/D \qquad (D \sim \omega^2)$$

Interorbital hybridization + gap asymmetry

Interorbital pairing + dispersion asymmetry

Kerr effect: [1]

$$\sigma_H \propto \epsilon_{12}\mathrm{Im}(\Delta_1^*\Delta_2) + \xi_1\mathrm{Im}(\Delta_2^*\Delta_{12}) - \xi_2\mathrm{Im}(\Delta_1^*\Delta_{12})$$

Interorbital hybridization + gap asymmetry

Interorbital pairing + dispersion asymmetry

→ Intrinsic Kerr effect evidence of odd-ω superconductivity

Komendova and ABS, PRL 119, 087001 (2017), [1]: Taylor and Kallin, PRL 108, 157001 (2012)

Generic Three-Orbital Model

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$$\hat{H}_0(\mathbf{k}) = \begin{pmatrix} \xi_1 & \epsilon_{12} & \epsilon_{13} \\ \epsilon_{12} & \xi_2 & \epsilon_{23} \\ \epsilon_{13} & \epsilon_{23} & \xi_3 \end{pmatrix}, \quad \check{\Delta}(\mathbf{k}) = \begin{pmatrix} \Delta_1 & \Delta_{12} & \Delta_{13} \\ \Delta_{12} & \Delta_2 & \Delta_{23} \\ \Delta_{13} & \Delta_{23} & \Delta_3 \end{pmatrix}$$

xy (1), *xz* (2),*yz* (3) orbitals → γ, α, β bands

General interorbital pairing:

$$F_{AS} = \sum_{i,j,k=1,\dots,N} \epsilon_{ijk} F_{ij}$$
$$F_{AS}(-\omega) = -F_{AS}(\omega)$$

odd-ω, odd-interorbital

$$F_S = \sum_{i\neq j=1,\dots,N} F_{ij}$$
$$F_S(-\omega) = F_S(\omega)$$

even-ω, even-interorbital

Komendova and ABS, PRL 119, 087001 (2017)

Examples Odd-ω Pairing

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- No interorbital pairing and $\epsilon_{ij} = \Gamma$:

$$F_{\rm odd} = 2\Gamma i\omega[\Delta_1(\epsilon_2 - \epsilon_3)(\epsilon_2 + \epsilon_3 + \Gamma) + |\Delta_1|^2(\Delta_3 - \Delta_2) + \text{two cyclic permutations}]/D_3$$

- Only $\epsilon_{23} \neq 0, \Delta_{23} \neq 0$ (*xz*, *yz* → α, β bands with hybridization, xy → γ band)

$$F_{\rm odd} = 2i\omega[\Delta_{23}(\epsilon_3 - \epsilon_2) + \epsilon_{23}(\Delta_3 - \Delta_2)]/D_3'$$

→ Odd-ω pairing requires only limited interorbital processes, exactly same as finite Kerr rotation [1]

Komendova and ABS, PRL 119, 087001 (2017), [1]: Gradhand et al, PRB 88, 094504 (2013)

Pair Amplitudes in Sr_2RuO_4

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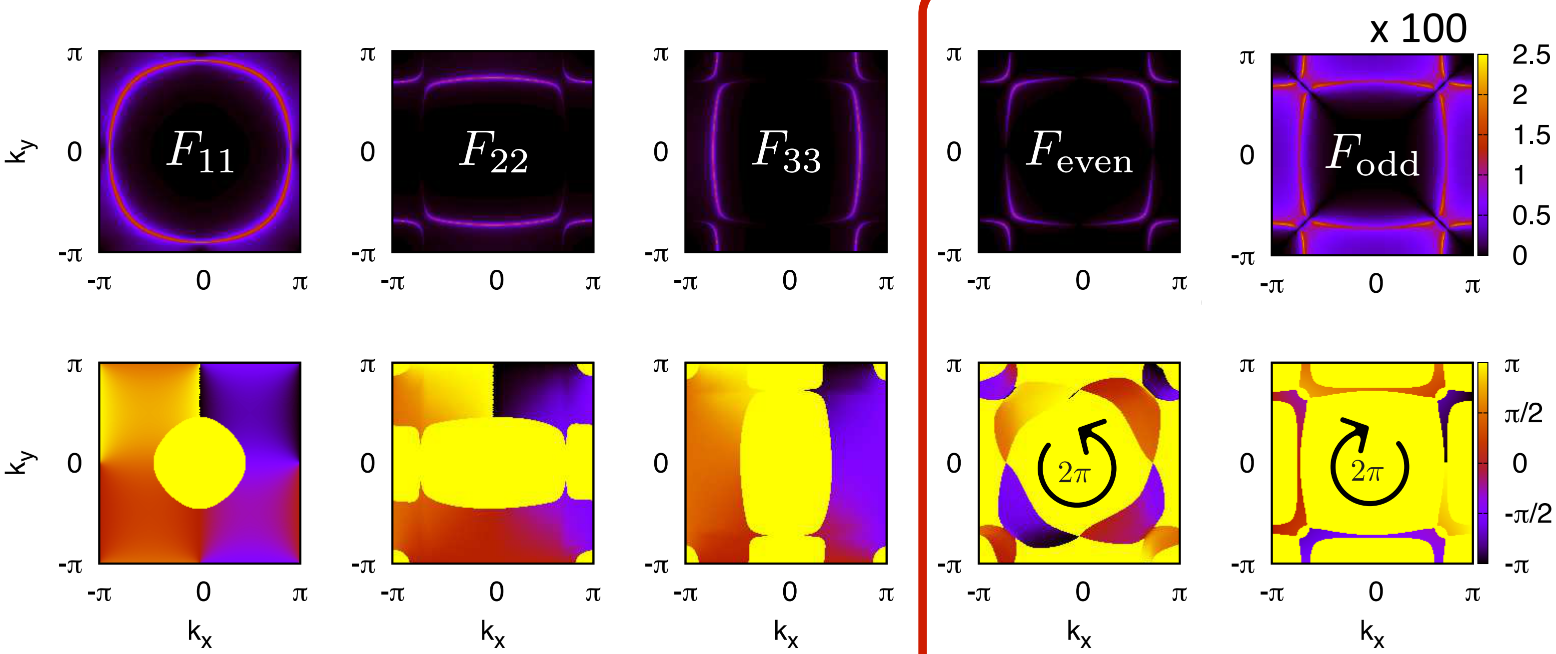
Only $\epsilon_{23} \neq 0, \Delta_{23} \neq 0$



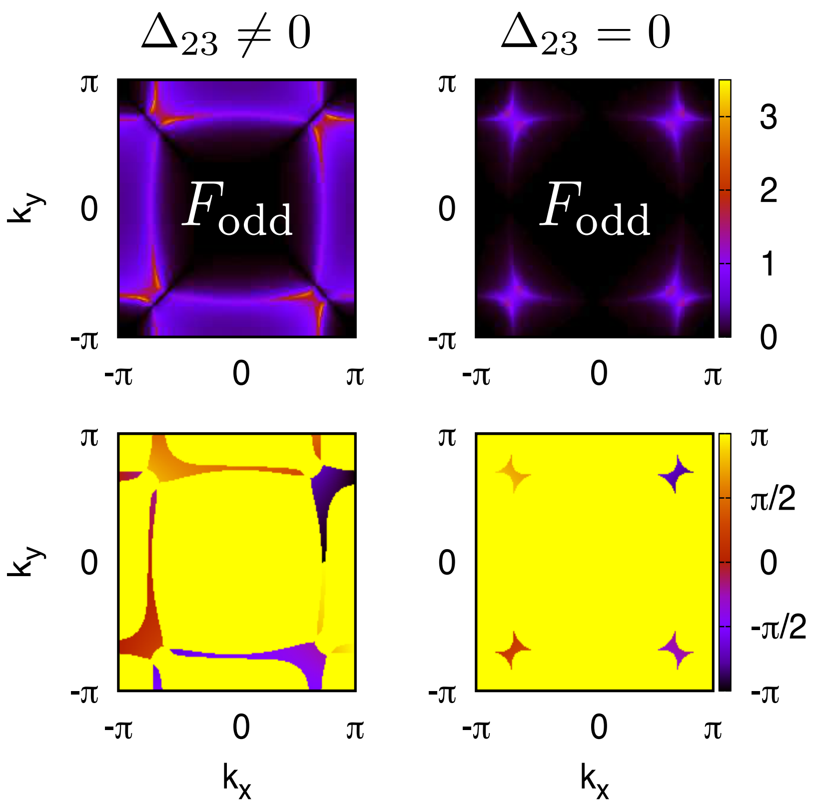
- α, β bands only
- Chiral *p*-wave symmetry

Komendova and ABS, PRL 119, 087001 (2017)

Odd-ω Pairing in k-Space

Amplitude

Phase



- Chiral *p*-wave symmetry
- Peaked at α, β hybridization
- Nodal structure dependent on exact parameters

Komendova and ABS, PRL 119, 087001 (2017)

Summary

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- Bulk odd-ω superconductivity in multiband systems
  - Finite interband/orbital pairing or hybridization
- Odd-ω pairing in Sr_2RuO_4 measured by Kerr effect
- Future directions:
  - Other odd-ω bulk superconductors (UPt_3, …)
  - Consequences of odd-ω pairing?
  - Band/orbital → layer, wires, …

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