Unconventional Superconductivity

from a Symmetry and Topology Perspective

Manfred Sigrist

ETH zürich

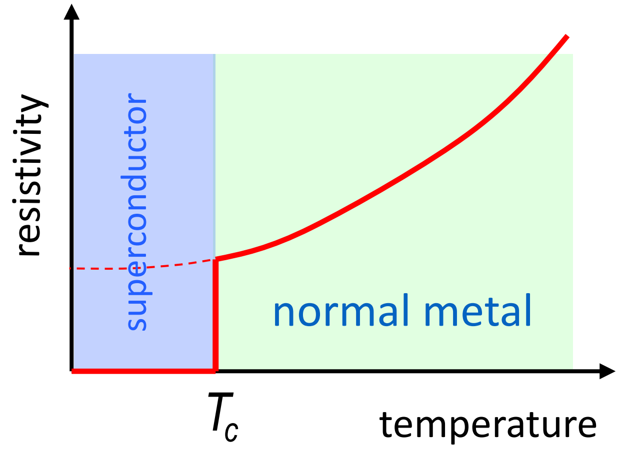
outline:

- material classes of novel superconductors
- unconventional superconductivity – Cooper pairing symmetry
- chiral superconductors – topological phase
- key symmetries: time reversal and inversion
- non-centrosymmetric superconductors – artificially structured systems

Superconductivity

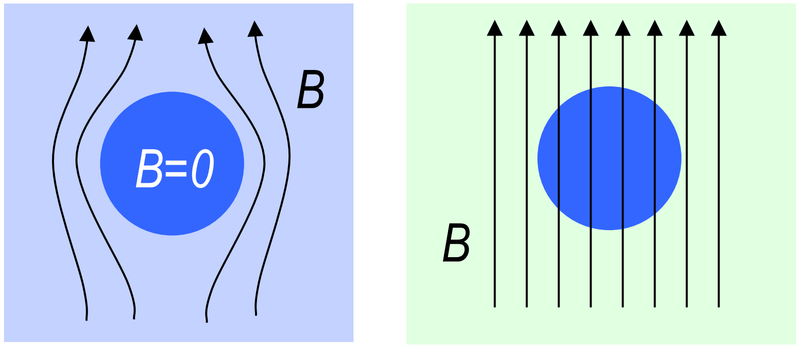
vanishing electrical resistance

1911



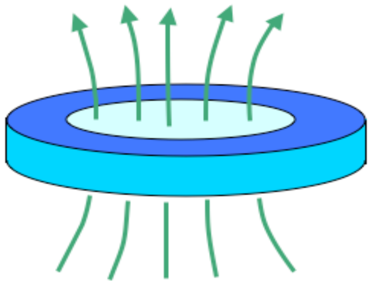
Meissner-Ochsenfeld effect

1933



superconductor   normal metal

flux quantization



$$\Phi = n\Phi_0 = n\frac{hc}{2e}$$

London equation

$$\vec{\nabla}^2\vec{B} - \lambda^{-2}\vec{B} = 0$$

screening of magnetic field

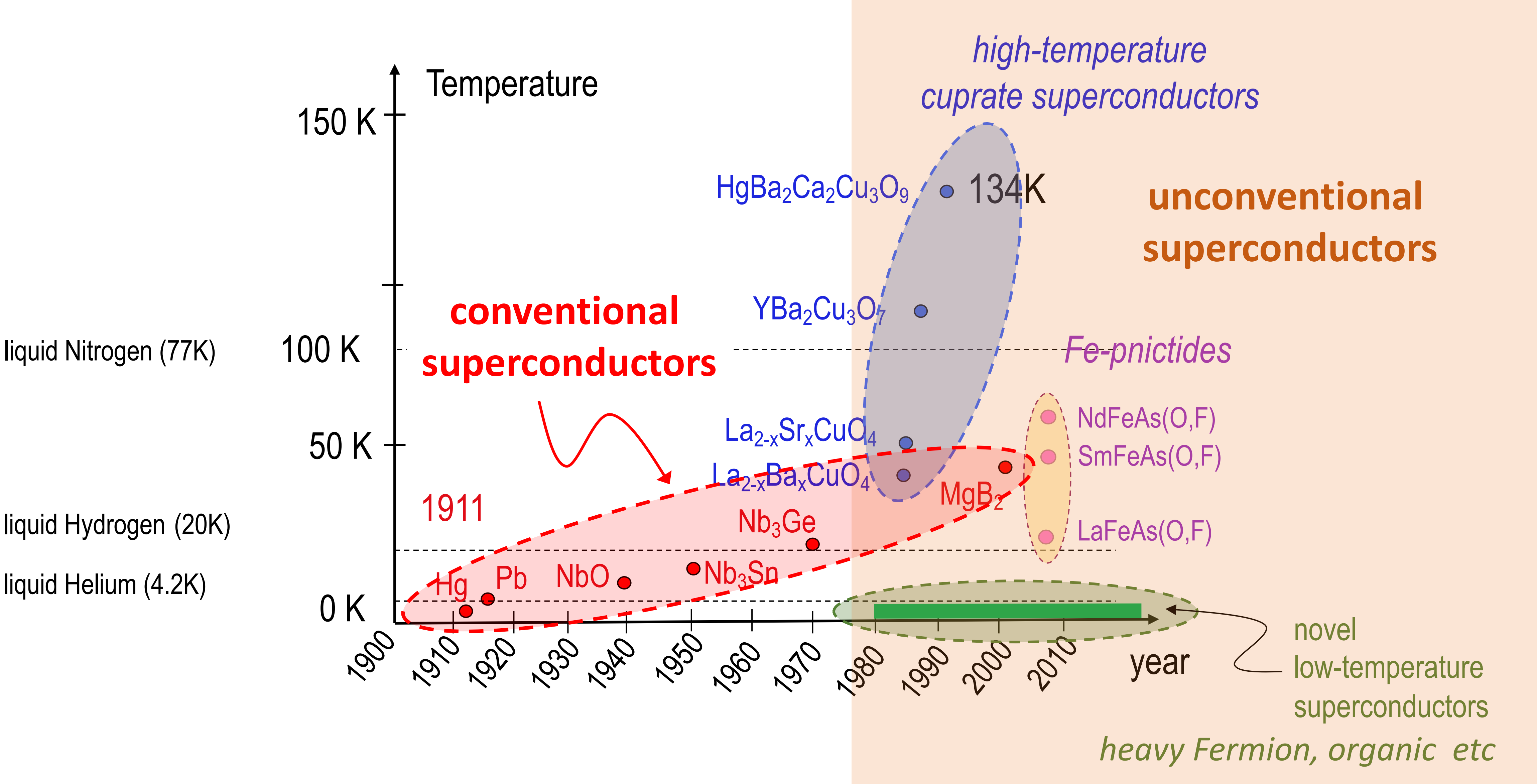
Ginzburg-Landau theory

$$\Psi(\vec{r}) = |\Psi(\vec{r})|e^{i\phi(\vec{r})}$$

complex macroscopic condensate wavefunction

spontaneously broken *U(1)* - gauge symmetry

Evolution of critical temperature in superconductors



Novel superconductors

How to find new superconductors with high T_c ?

Matthias' rules: *trivialized*

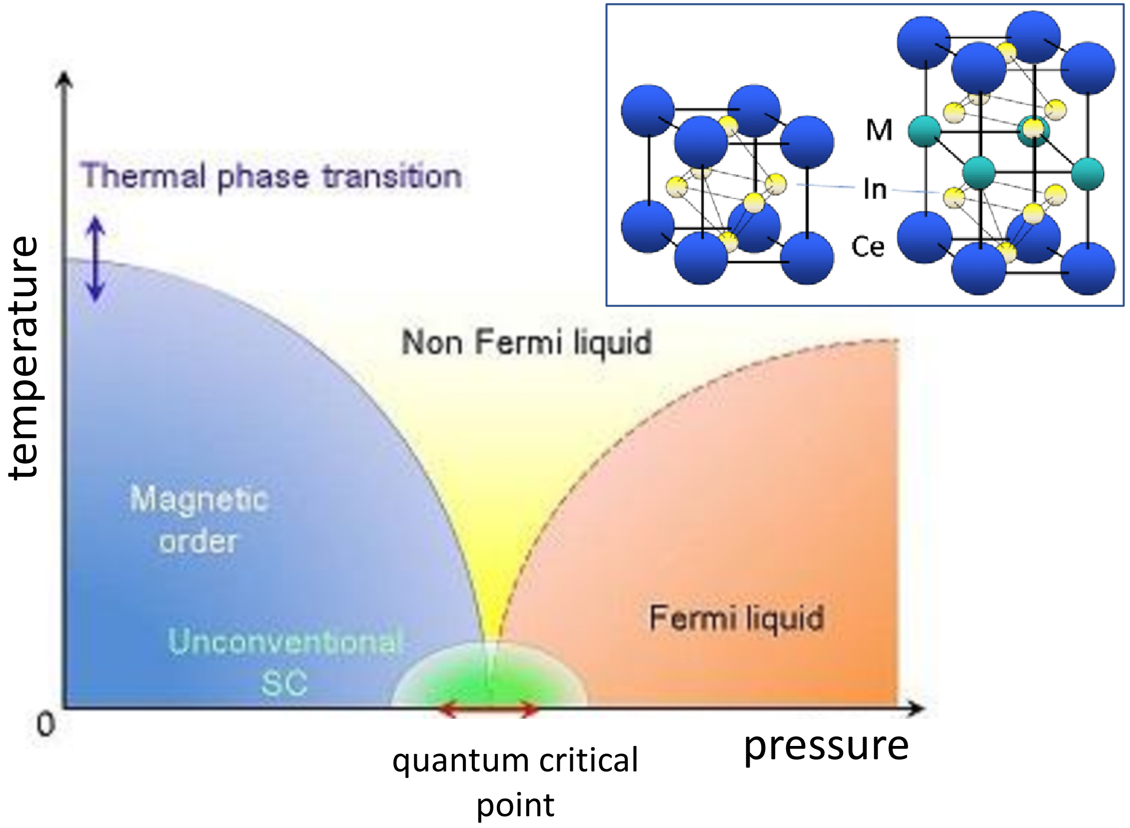
1. high crystal symmetry
2. high density of states
3. stay away from oxygen
4. stay away from magnetism
5. stay away from insulators
6. stay away from theorists

Bernd T. Matthias (1918-1980)

Novel superconductors

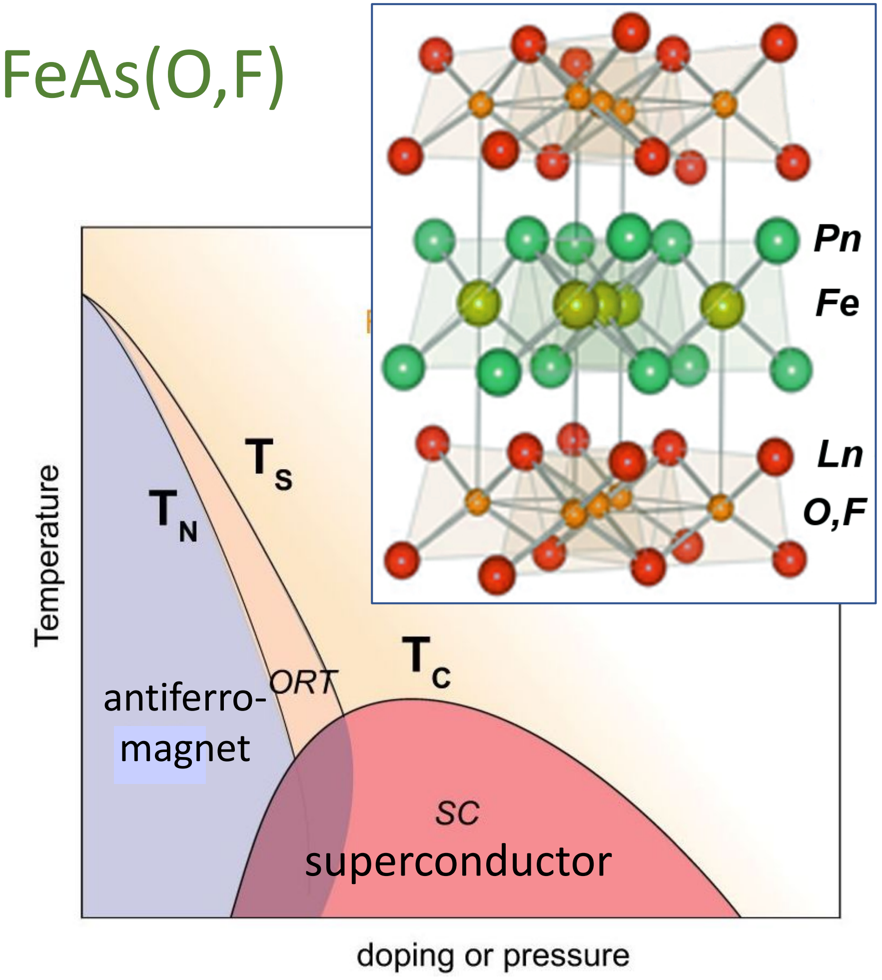
Heavy Fermion superconductors

$CeIn_3$ $CeRhIn_5$ $CeRhSi_3$



Iron-based superconductors

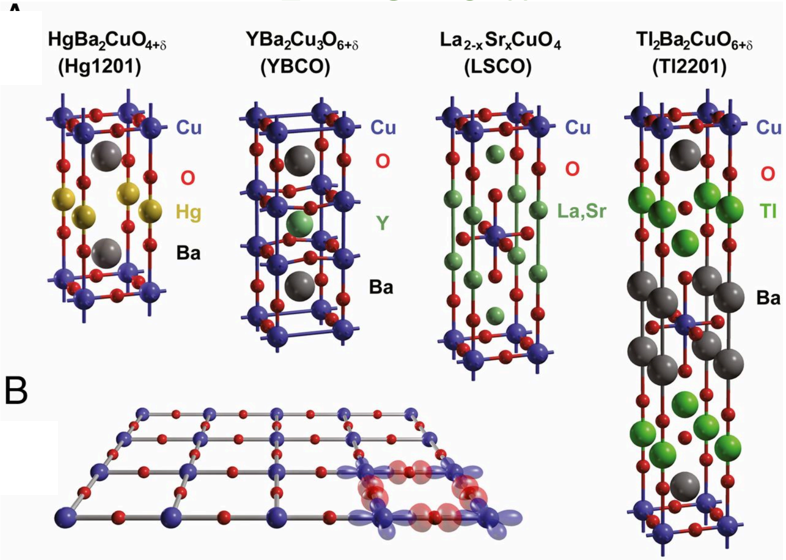
*Ln*FeAs(O,F)

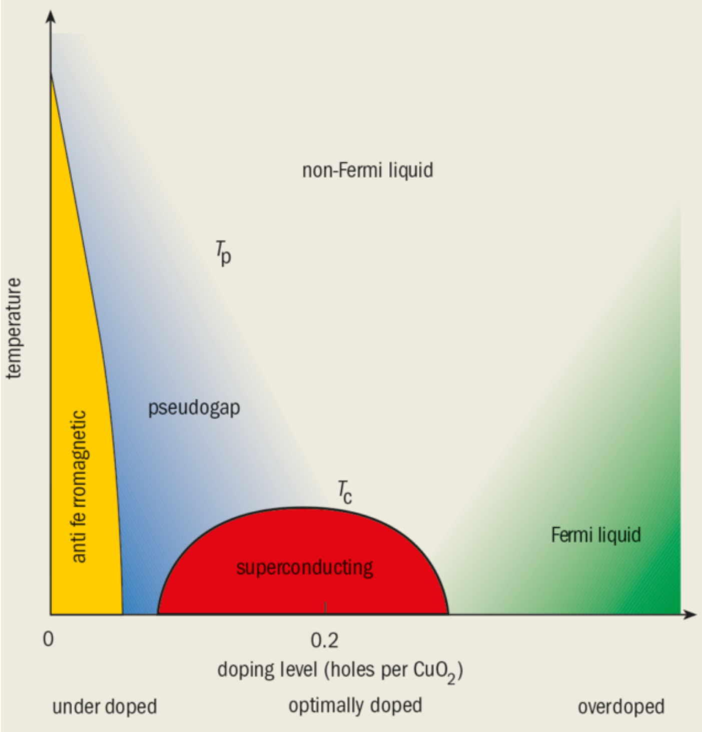


Novel superconductors

Cuprate high-temperature superconductors

$YBa_2Cu_3O_{6+x}$





layered structure of CuO_2 planes

$$T_c \sim 30 - 134 \text{ K}$$

superconductivity through doping of an antiferromagnetic insultator

Novel superconductors

Cuprate high-temperature superconductors

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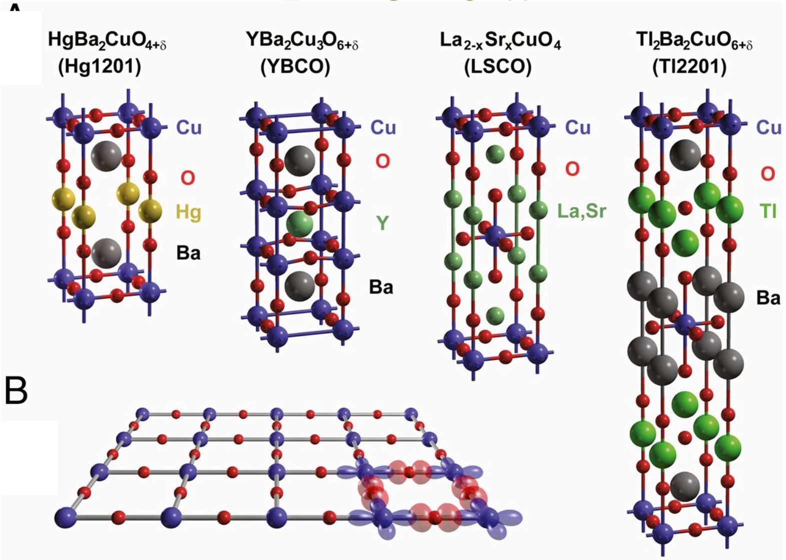

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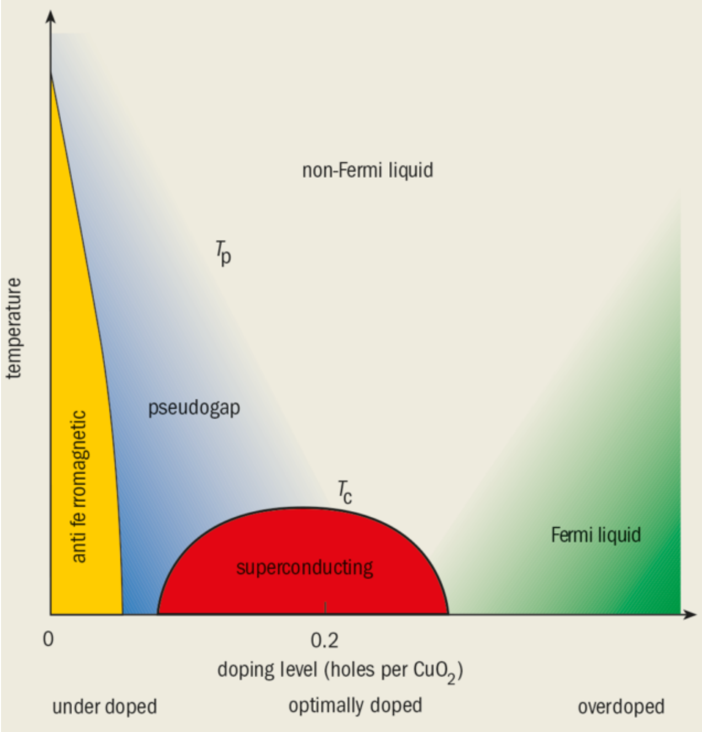

superconductivity through doping of an antiferromagnetic insultator

Matthias‘ rules:

1. ~~high crystal symmetry~~
2. high density of states
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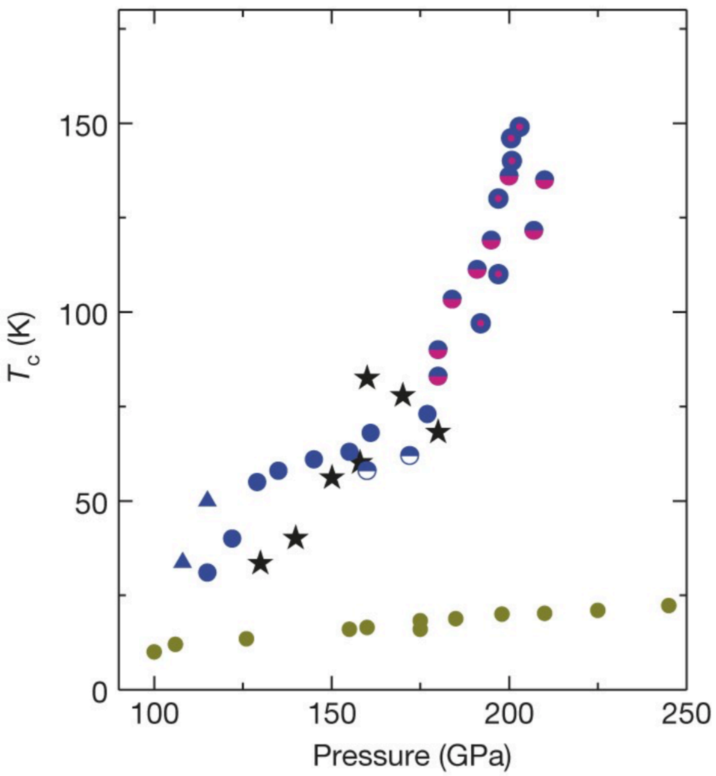
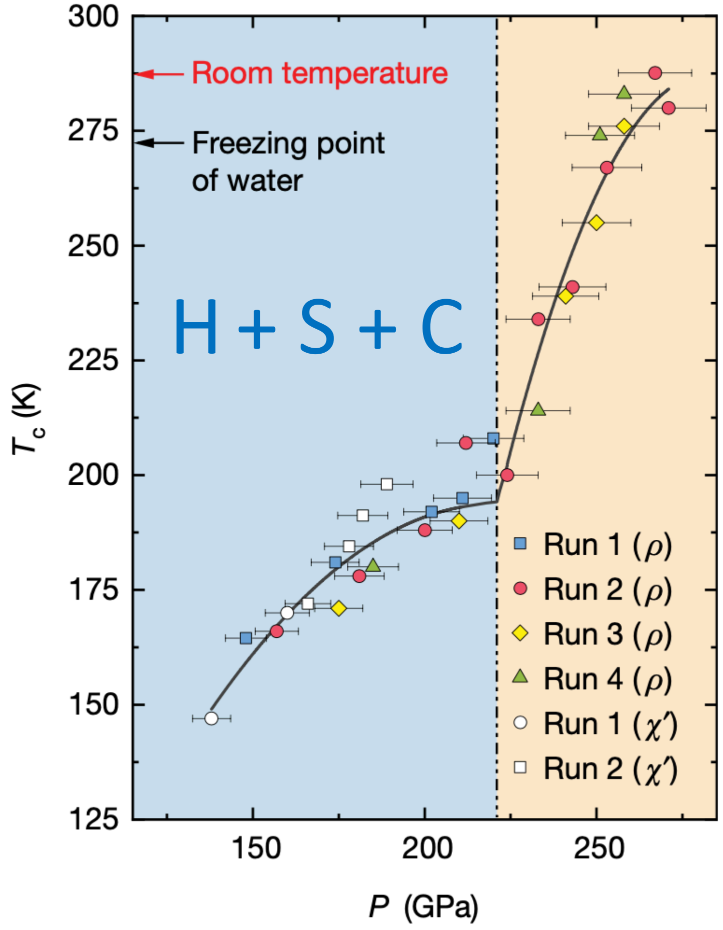
6. stay away from theorists

Novel superconductors

High pressure phases: "metallic H"



Drozdov et al, Nature (2015)



Snider et al, Nature (Oct '20)

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1. ~~high crystal symmetry~~
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predicted by

Neil Ashcroft (1968)

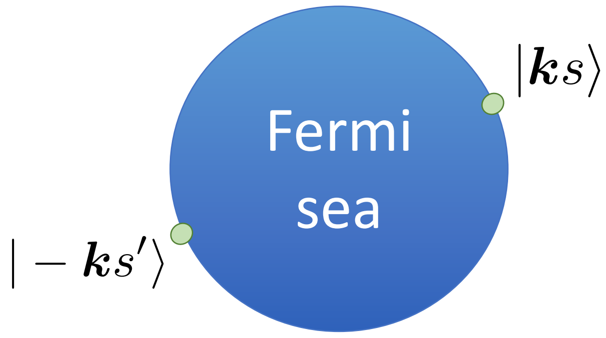
Conventional vs Unconventional Superconductivity

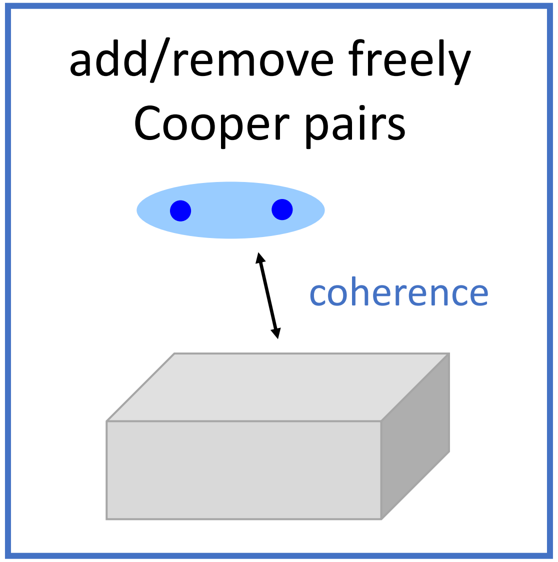
BCS concept and Cooper pairing

Superconductivity - BCS concept

Bardeen Cooper Schrieffer

superconductivity - a Fermi surface instability

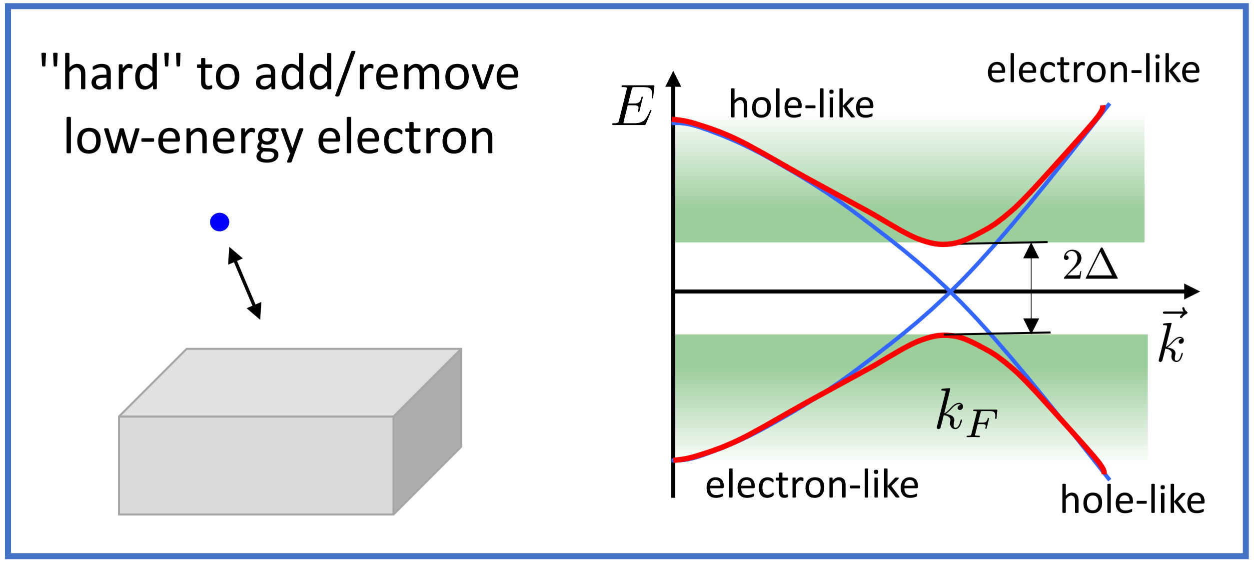




attractive electron-electron interaction

electrons of opposite momenta correlate to form a coherent state of Cooper pairs

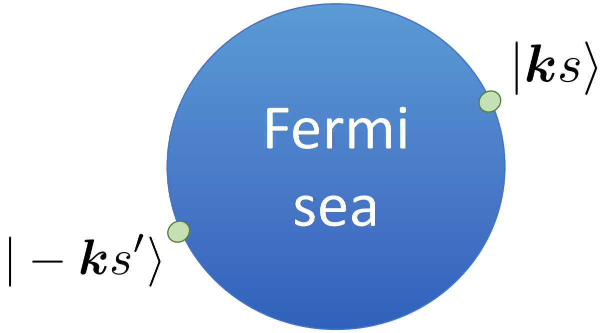
$$|\Psi_{\mathrm{BCS}}\rangle = \prod_{\boldsymbol{k},s,s'} \left[u_{\boldsymbol{k},ss'} + v_{\boldsymbol{k},ss'}|\boldsymbol{k},s;-\boldsymbol{k},s'\rangle\right]$$



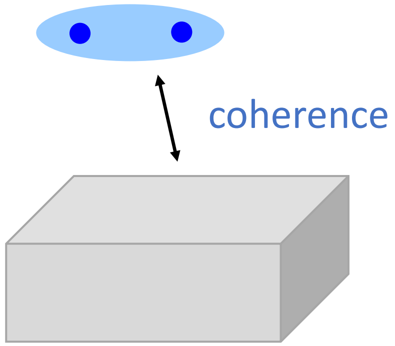
Superconductivity - BCS concept

Bardeen Cooper Schrieffer

superconductivity - a Fermi surface instability



add/remove freely Cooper pairs

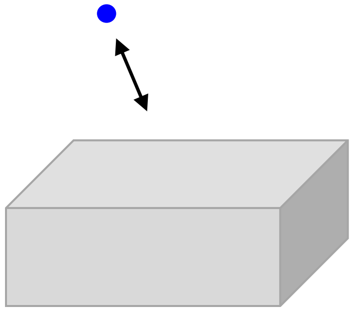


attractive electron-electron interaction

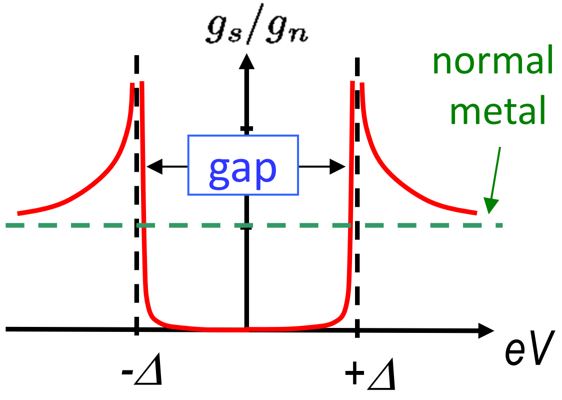
electrons of opposite momenta correlate to form a coherent state of Cooper pairs

$$|\Psi_{\rm BCS}\rangle = \prod_{\boldsymbol{k},s,s'} \left[u_{\boldsymbol{k},ss'} + v_{\boldsymbol{k},ss'}\,|\boldsymbol{k},s;-\boldsymbol{k},s'\rangle\right]$$

"hard" to add/remove low-energy electron



electron tunneling spectrum



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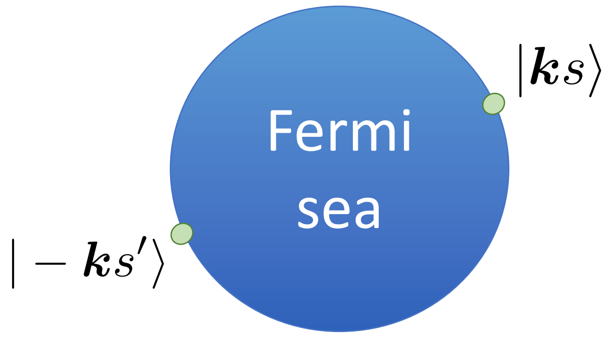


pair wave function

$$|\vec{k},s;-\vec{k},s'\rangle = c^\dagger_{\vec{k}s} c^\dagger_{-\vec{k}s'}|0\rangle$$

$$\Psi_{ss'}(\boldsymbol{k}) = \langle\Psi_{\mathrm{BCS}}|\hat{c}_{-\boldsymbol{k}s'}\hat{c}_{\boldsymbol{k}s}|\Psi_{\mathrm{BCS}}\rangle$$

$$= \sum_{\tilde{s}} u_{-\boldsymbol{k},s'\tilde{s}}\, v_{\boldsymbol{k},s\tilde{s}}$$ off-diagonal

attractive electron-electron interaction

electrons of opposite momenta correlate to form a coherent state of Cooper pairs

$$|\Psi_{\mathrm{BCS}}\rangle = \prod_{\boldsymbol{k},s,s'}\left[u_{\boldsymbol{k},ss'} + v_{\boldsymbol{k},ss'}|\boldsymbol{k},s;-\boldsymbol{k},s'\rangle\right]$$

spontaneous symmetry breaking

$$U(1): c_{\vec{k}s} \longrightarrow e^{i\phi}c_{\vec{k}s}$$

$$\Rightarrow \hat{\Psi}(\vec{k}) \longrightarrow e^{i2\phi}\hat{\Psi}(\vec{k})$$

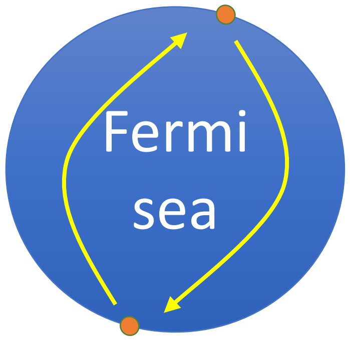
broken *U(1)*-gauge symmetry

Meissner-screening / London

Superconductivity - symmetry properties

Pauli exclusion principle - Fermion exchange

$|\boldsymbol{k}s\rangle$



$|-\boldsymbol{k}s'\rangle$

$\boldsymbol{k} \leftrightarrow -\boldsymbol{k} \quad s \leftrightarrow s'$

$$\Psi_{ss'}(\boldsymbol{k}) \to \Psi_{s's}(-\boldsymbol{k}) = -\Psi_{ss'}(\boldsymbol{k})$$

$$\Psi_{ss'}(\boldsymbol{k}) = \phi(\boldsymbol{k})\,\chi_{ss'}$$

orbital

angular momentum ℓ

parity $(-1)^{\ell}$

spin

$\left|\frac{1}{2}\right\rangle \otimes \left|\frac{1}{2}\right\rangle$

singlet / triplet

even parity	spin singlet
$\ell = 0, 2, \ldots$	$\frac{\lvert\uparrow\downarrow\rangle - \lvert\downarrow\uparrow\rangle}{\sqrt{2}}$
s-wave, *d*-wave	

odd parity	spin triplet
$\ell = 1, 3, \ldots$	$\lvert\uparrow\uparrow\rangle, \ \lvert\downarrow\downarrow\rangle$
p-wave, *f*-wave	$\frac{\lvert\uparrow\downarrow\rangle + \lvert\downarrow\uparrow\rangle}{\sqrt{2}}$

Superconductivity - symmetry properties

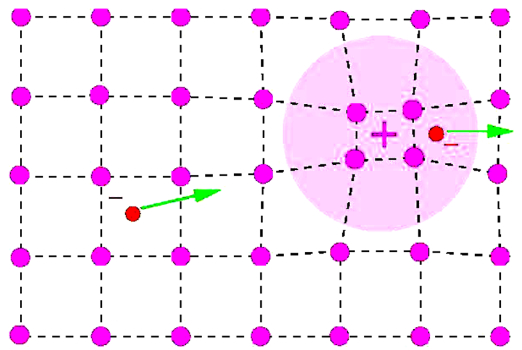
conventional superconductors

$$\ell = 0,\ S = 0$$

s-wave pairing

attractive pairing interaction

electron-phonon coupling

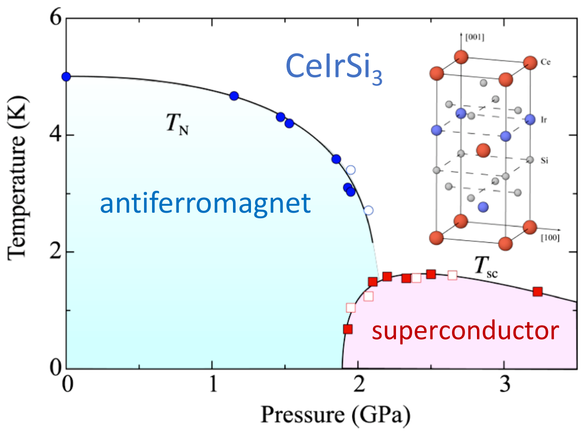


contact interaction

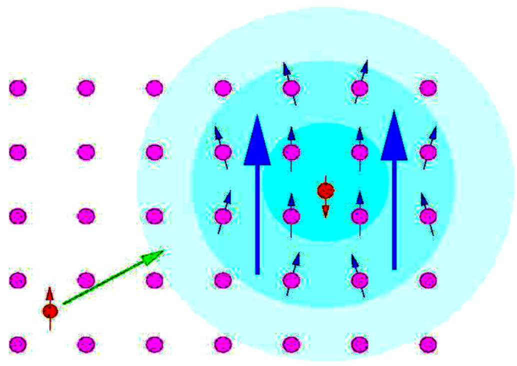
unconventional superconductors

$$\ell \neq 0,\ S = 0, 1$$

p,d,f-wave pairing



spin fluctuation exchange



longer-ranged interaction

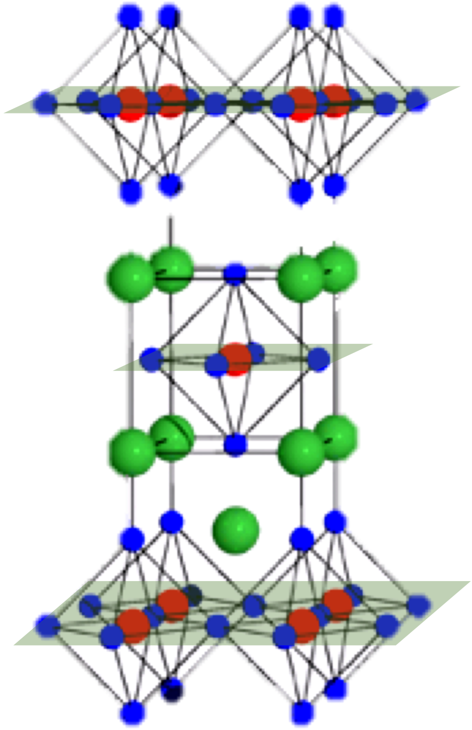
Chiral superconductor

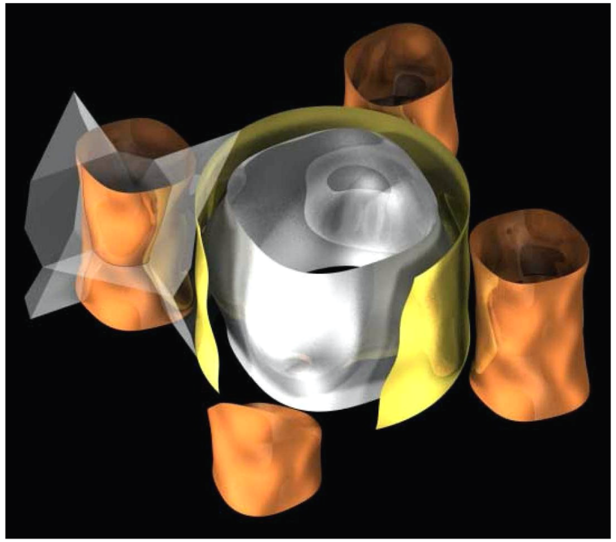
example of a
topological superconductor

Chiral superconductors

Unconventional superconductors with quasi-2D electronic properties

Sr_2RuO_4



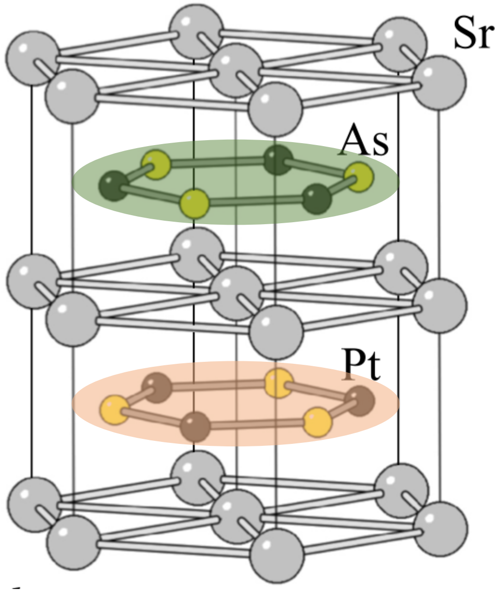


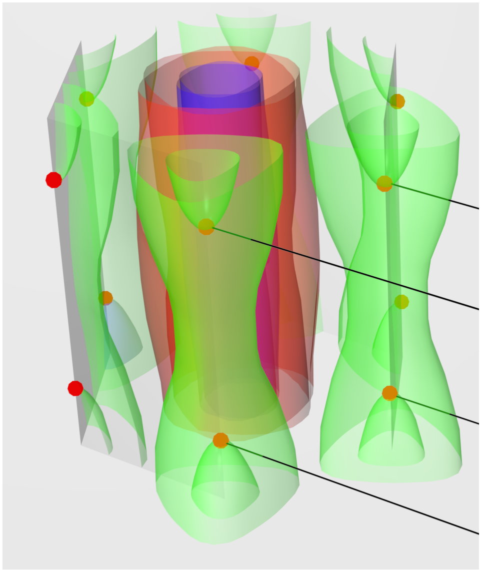
tetragonal

Maeno et al (1994)

$T_c \approx 1.5K$

SrPtAs





Nishikubo, Kudo & Nohara (2011)

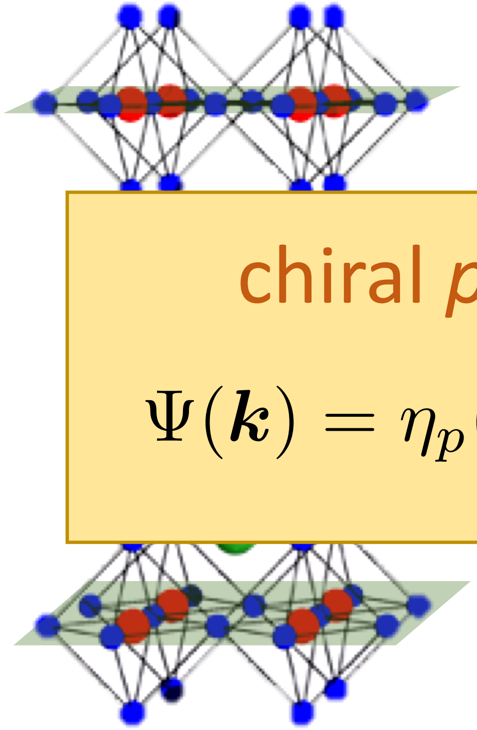
hexagonal

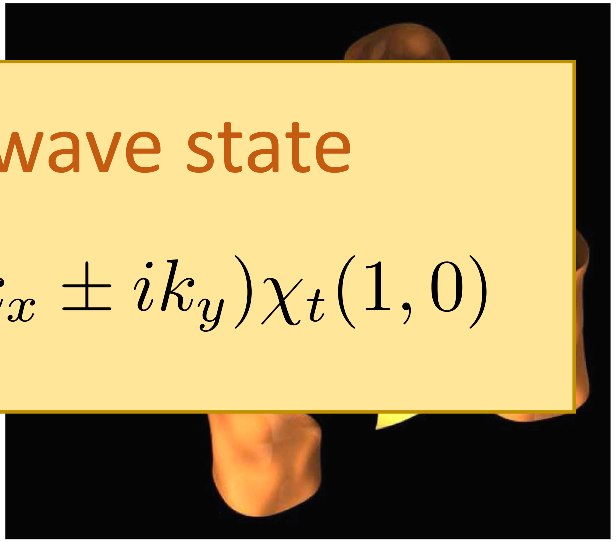
$T_c \approx 2.4K$

Chiral superconductors

Unconventional superconductors with quasi-2D electronic properties

Sr_2RuO_4





chiral *p*-wave state

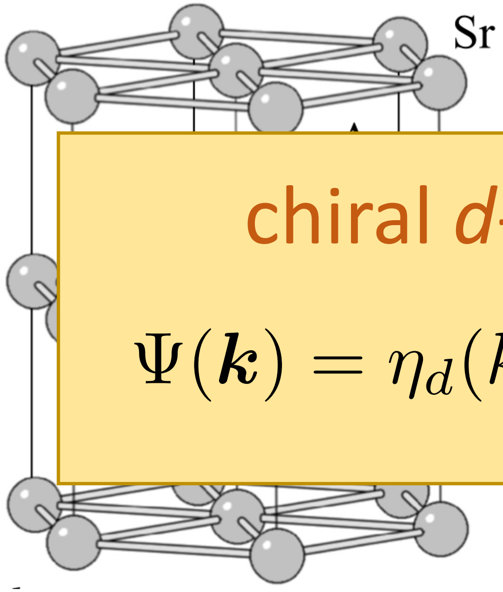
$$\Psi(\boldsymbol{k}) = \eta_p (k_x \pm i k_y) \chi_t(1,0)$$

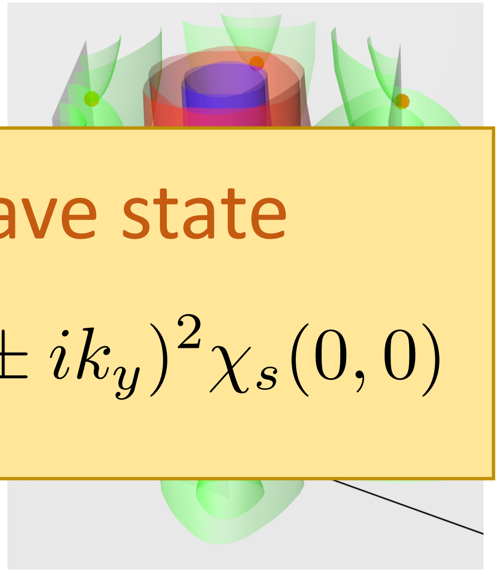
tetragonal

Maeno et al (1994)

$T_c \approx 1.5K$

SrPtAs





chiral *d*-wave state

$$\Psi(\boldsymbol{k}) = \eta_d (k_x \pm i k_y)^2 \chi_s(0,0)$$

Nishikubo, Kudo & Nohara (2011)

hexagonal

$T_c \approx 2.4K$

Chiral p-wave phase

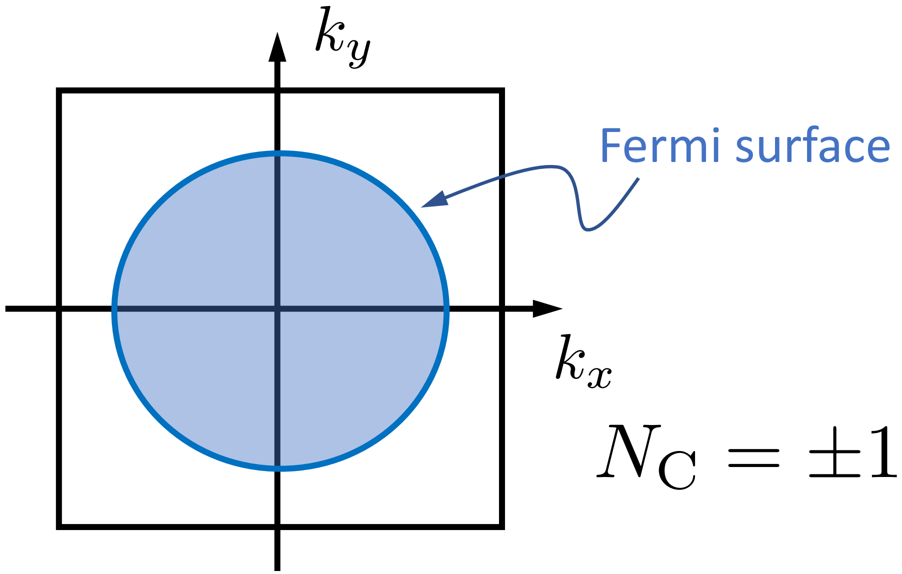
Cooper pair wave function

odd parity spin triplet

$$\Psi(\boldsymbol{k}) = \eta_p(k_x \pm i k_y)\chi_t(1,0)$$

- angular momentum $L_z = \pm\hbar$
- inplane equal spin pairing $\chi_t(1,0) = \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}$
- time reversal symmetry breaking
  ➡ intrinsic magnetism
- 2-fold degenerate
  ➡ chiral domains

topological superconductor



$N_{\mathrm{C}} = \pm 1$

topological invariant Chern number

$$N_{\mathrm{C}} = \frac{1}{2\pi}\oint_{\mathrm{FS}} d\boldsymbol{k}\cdot\boldsymbol{\nabla}_{\boldsymbol{k}}\arg[\Psi(\boldsymbol{k})]$$

$$\Psi(\boldsymbol{k})|_{\mathrm{FS}} = \eta_0 k_F e^{\pm i\theta_{\boldsymbol{k}}}\chi_t(1,0)$$

Chiral *p*-wave phase – symmetry and magnetism

$$\Psi(\boldsymbol{k}) = \eta_p(k_x + ik_y)\chi_t(1,0) = \eta_0 k e^{i\theta_{\boldsymbol{k}}}\chi_t(1,0)$$

rotation around *z*-axis

angular momentum

$$\hat{g}_\phi \Psi(\boldsymbol{k}) = \Psi(\hat{R}_\phi \boldsymbol{k}) = \Psi(\boldsymbol{k})e^{i\phi} \quad \Longleftrightarrow \quad \hat{L}_z$$

U(1) gauge transformation

charge

$$\hat{\Phi}_\phi \Psi(\boldsymbol{k}) = \Psi(\boldsymbol{k})e^{i\phi} \quad \Longleftrightarrow \quad \hat{N}/2$$

$$\hat{g}_\phi \hat{\Phi}_{-\phi} = 1 \quad \Rightarrow$$

conserved "charge" $\hat{L}_z - \frac{\hat{N}}{2}$

Chiral *p*-wave phase – symmetry and magnetism

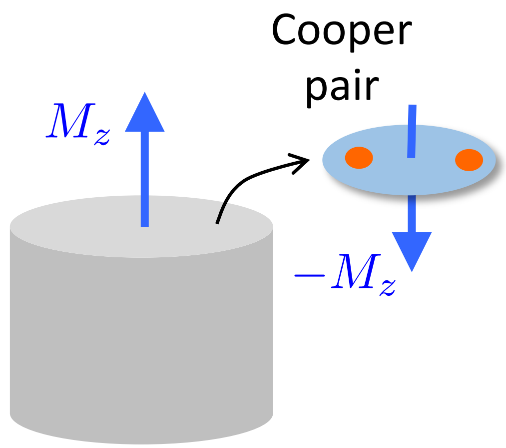
magnetization

$$M_z = \mu_B L_z \quad \xrightarrow{?} \quad M_z = \mu_B \frac{n_s}{2}$$

$1\mu_B$ / Cooper pair

conserved "charge"

$$\hat{L}_z - \frac{\hat{N}}{2} = 0$$



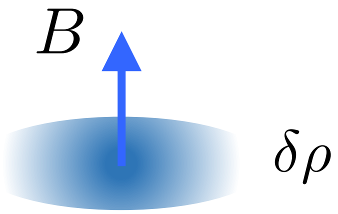
anomalous electromagnetism

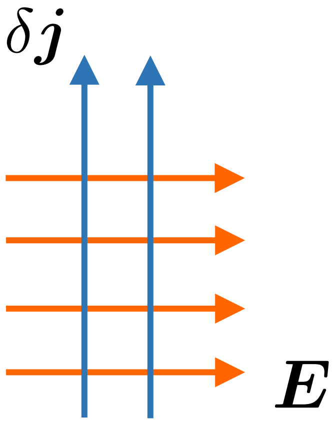
charge density

$$\rho = \frac{e^2}{\hbar c}\hat{\boldsymbol{z}} \cdot \boldsymbol{B}$$

electrical current density

$$\boldsymbol{j} = \frac{e^2}{\hbar}\boldsymbol{E} \times \hat{\boldsymbol{z}}$$





spontaneous magnetic fields and current distributions

at edges and around impurities

Chiral *p*-wave phase – symmetry and magnetism

magnetization

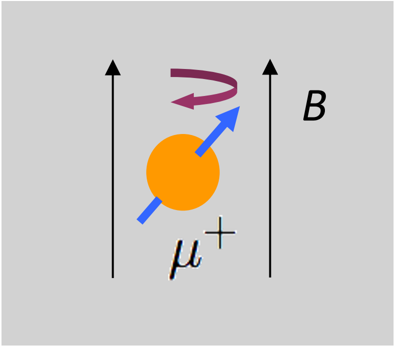
?

$$M_z = \mu_B L_z \quad \rightarrow \quad M_z = \mu_B \frac{n_s}{2}$$

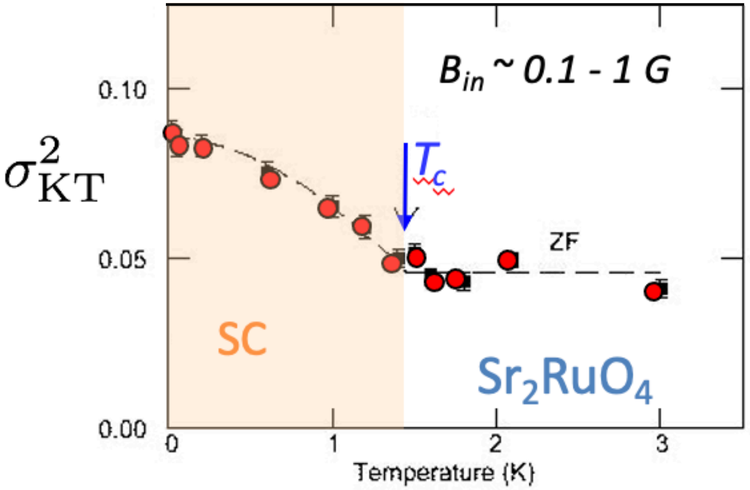
$1\mu_B$ / Cooper pair

local probe for magnetism

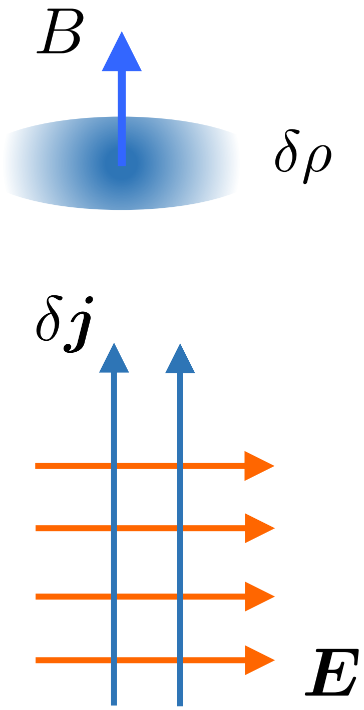
zero-field depolarization rate of muons



μSR - *zero-field relaxtion*



Luke et al (1998)



spontaneous magnetic fields and current distributions

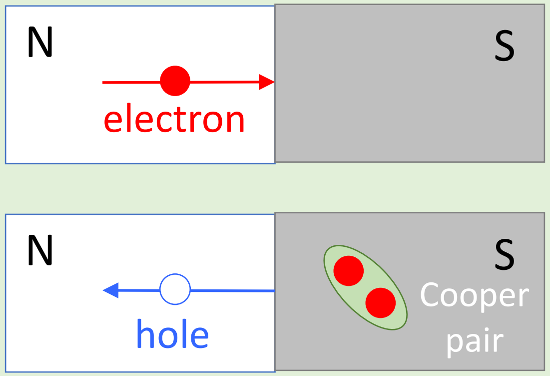
at edges and around impurities

Chiral p-wave phase – chiral edge states

bulk edge correspondence

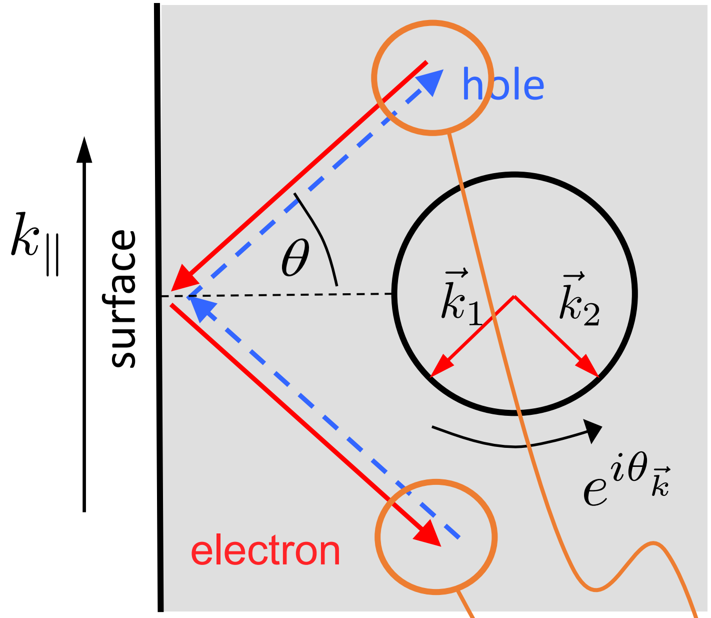
scattering at surface ➡ subgab bound states

Andreev reflection



electron combines to a Cooper pair
leaving hole of opposite momentum

coherent state in normal metal
electron-hole superposition



closed path of electron and hole

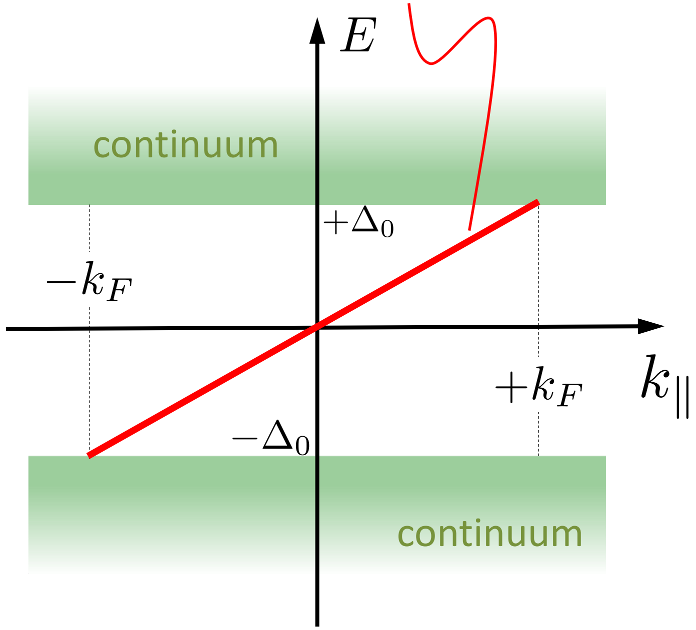
Bohr-Sommerfeld discussion

$$\oint \boldsymbol{p}\cdot d\boldsymbol{s} = h(2\pi n + \phi_+ + \phi_-)$$

phase shifts

chiral edge state

subgap quasiparticle state
electron-hole superposition



$$N_C = +1$$

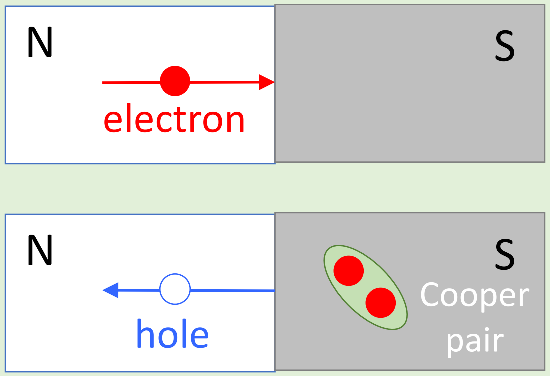
phase winding structure

Chiral *p*-wave phase – chiral edge states

bulk edge correspondence

scattering at surface ➡ subgab bound states

Andreev reflection



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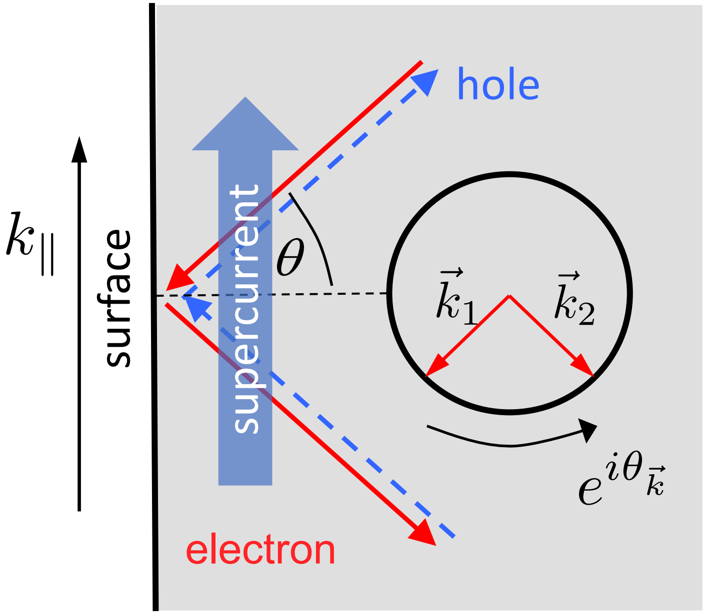

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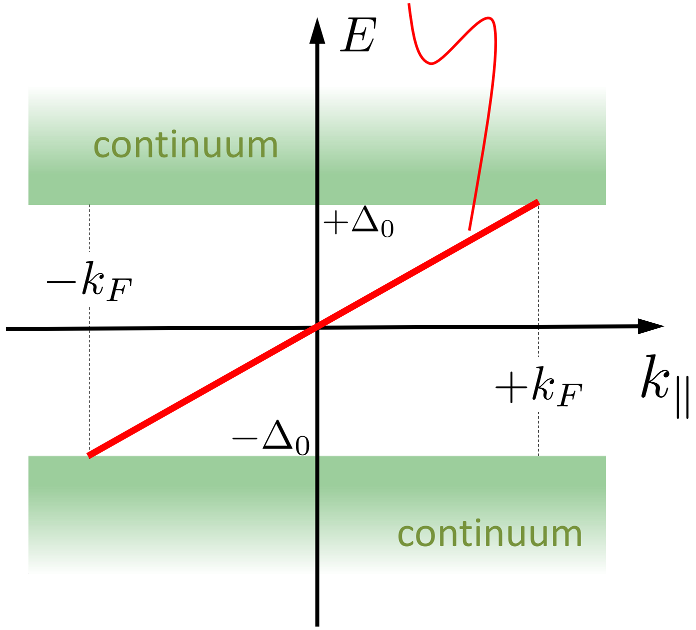
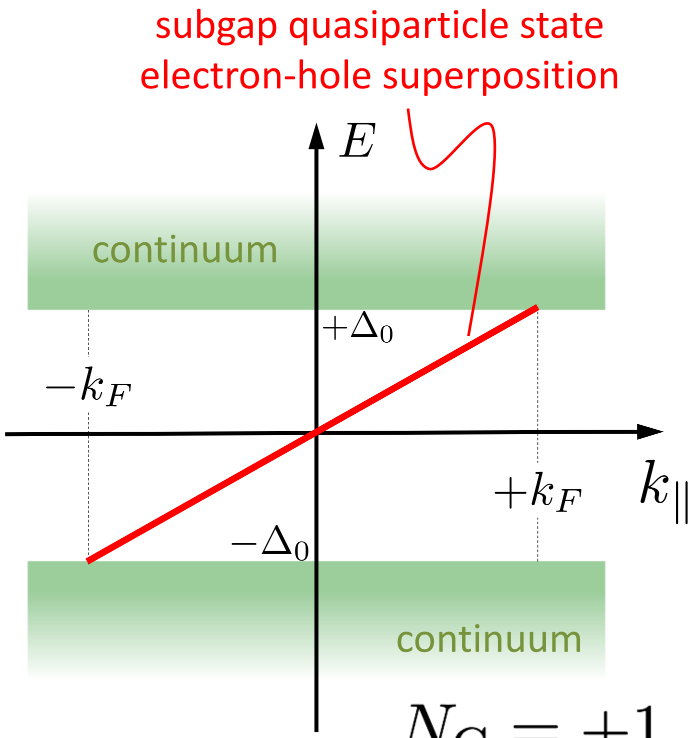


$$N_{\rm C} = +1$$

phase winding structure

Chiral *p*-wave phase – chiral edge states

chiral edge state



$$N_C = +1$$

analog to $\nu = 1$
Quantum Hall State ?

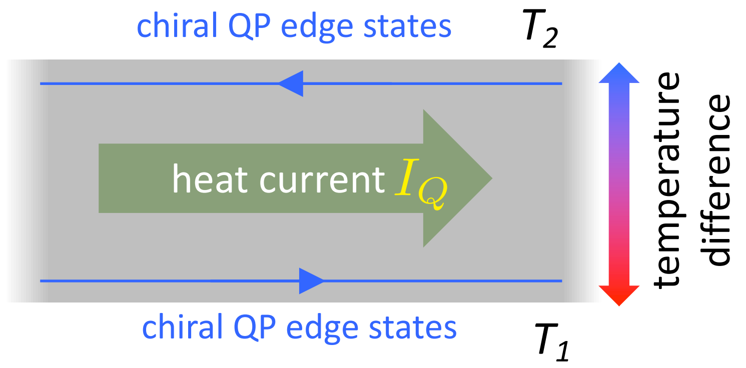
edge state quasi-particle current

charge not conserved ➡ surface supercurrent not universal

energy conserved ➡ surface heat current universal

Quantized Thermal Hall effect

spontaneous Righi-Leduc effect



$$I_Q = \kappa_{xy} \Delta T$$

$$\kappa_{xy} = \frac{\pi k_B^2 T}{12\hbar} N_C$$

$$T \ll T_c$$

Chiral *d*-wave phase

Cooper pair wave function

even parity spin singlet

$$\Psi(\boldsymbol{k}) = \eta_d (k_x \pm i k_y)^2 \chi_s(0,0)$$

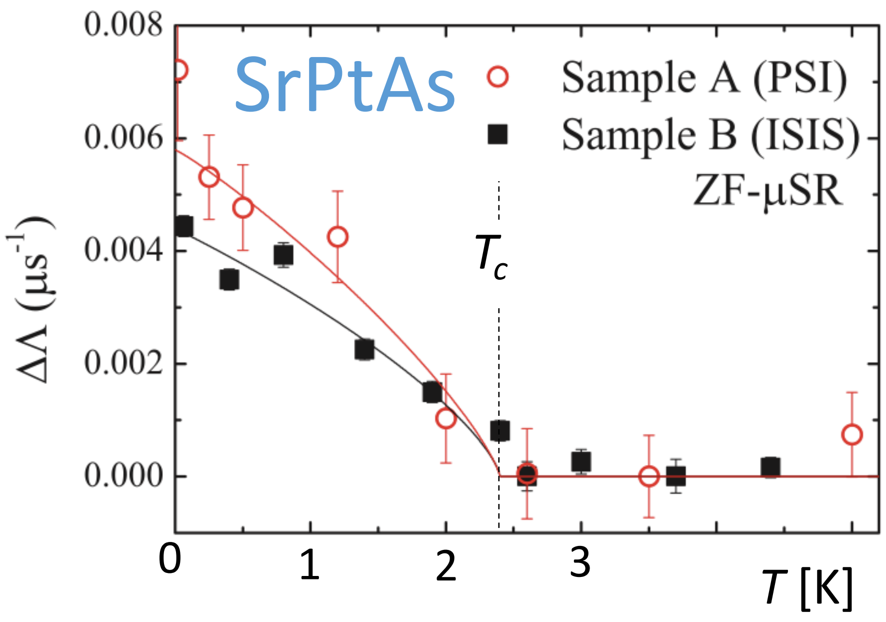
- angular momentum $L_z = \pm 2\hbar$
- spin singlet pairing $\chi_s(0,0) = \dfrac{|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle}{\sqrt{2}}$
- time reversal symmetry breaking
  ➡ intrinsic magnetism
- 2-fold degenerate
  ➡ chiral domains

topological superconductor

Chern number $N_C = \pm 2$

spontaneous magnetism

μSR-zero-field relaxation rate

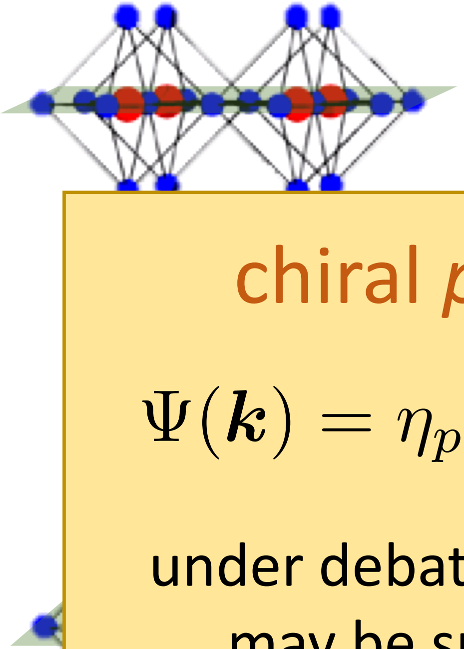


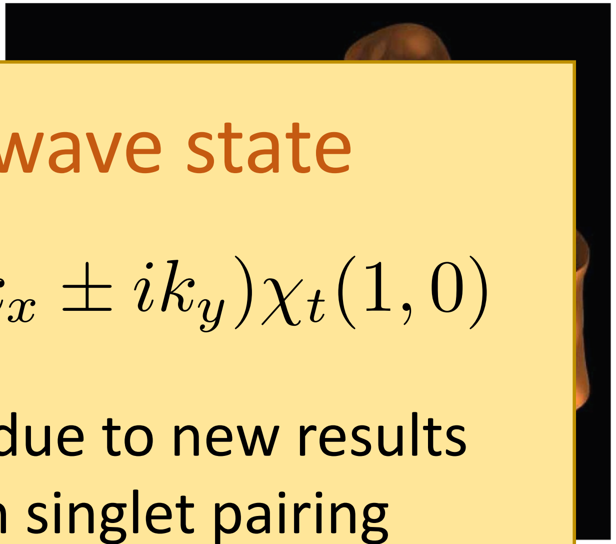
PSI – μSR group, Biswas et al (2014)

Chiral superconductors

Unconventional superconductors with quasi-2D electronic properties

Sr_2RuO_4





chiral *p*-wave state

$$\Psi(\boldsymbol{k}) = \eta_p (k_x \pm i k_y) \chi_t(1,0)$$

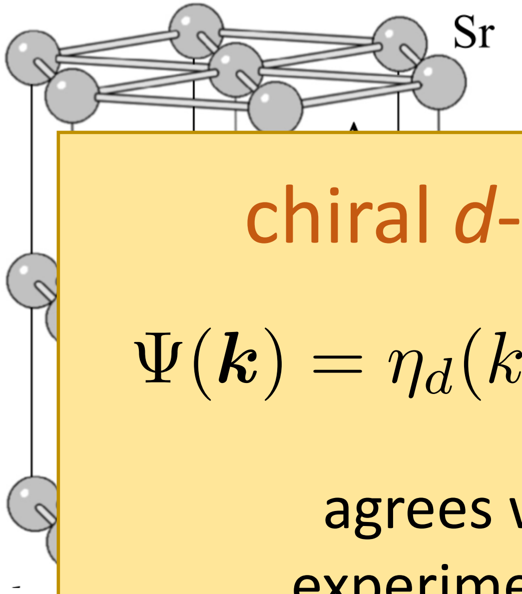
under debate due to new results
may be spin singlet pairing

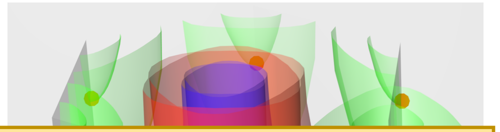
tetragonal

Maeno et al (1994)

$T_c \approx 1.5K$

SrPtAs





chiral *d*-wave state

$$\Psi(\boldsymbol{k}) = \eta_d (k_x \pm i k_y)^2 \chi_s(0,0)$$

agrees with present
experimental evidence

Nis

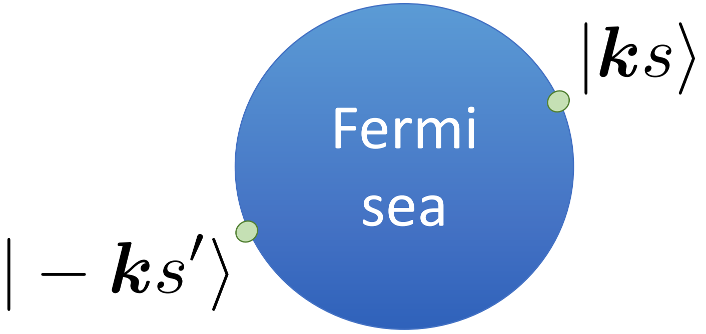
$T_c \approx 2.4K$

Key symmetries
non-centrosymmetric superconductores

Superconductivity - key symmetries

time reversal and inversion symmetry

$$\mathcal{H}_0 = \sum_{\boldsymbol{k},s} \xi_{\boldsymbol{k}s} \hat{c}^\dagger_{\boldsymbol{k}s} \hat{c}_{\boldsymbol{k}s}$$ electron kinetic energy



degenerate partners form zero-momentum Cooper pairs

time reversal:

$$|\boldsymbol{k}s\rangle \longrightarrow \hat{K}|\boldsymbol{k}s\rangle = |-\boldsymbol{k}\bar{s}\rangle \quad \Rightarrow \quad \xi_{\boldsymbol{k}s} = \xi_{-\boldsymbol{k}\bar{s}}$$

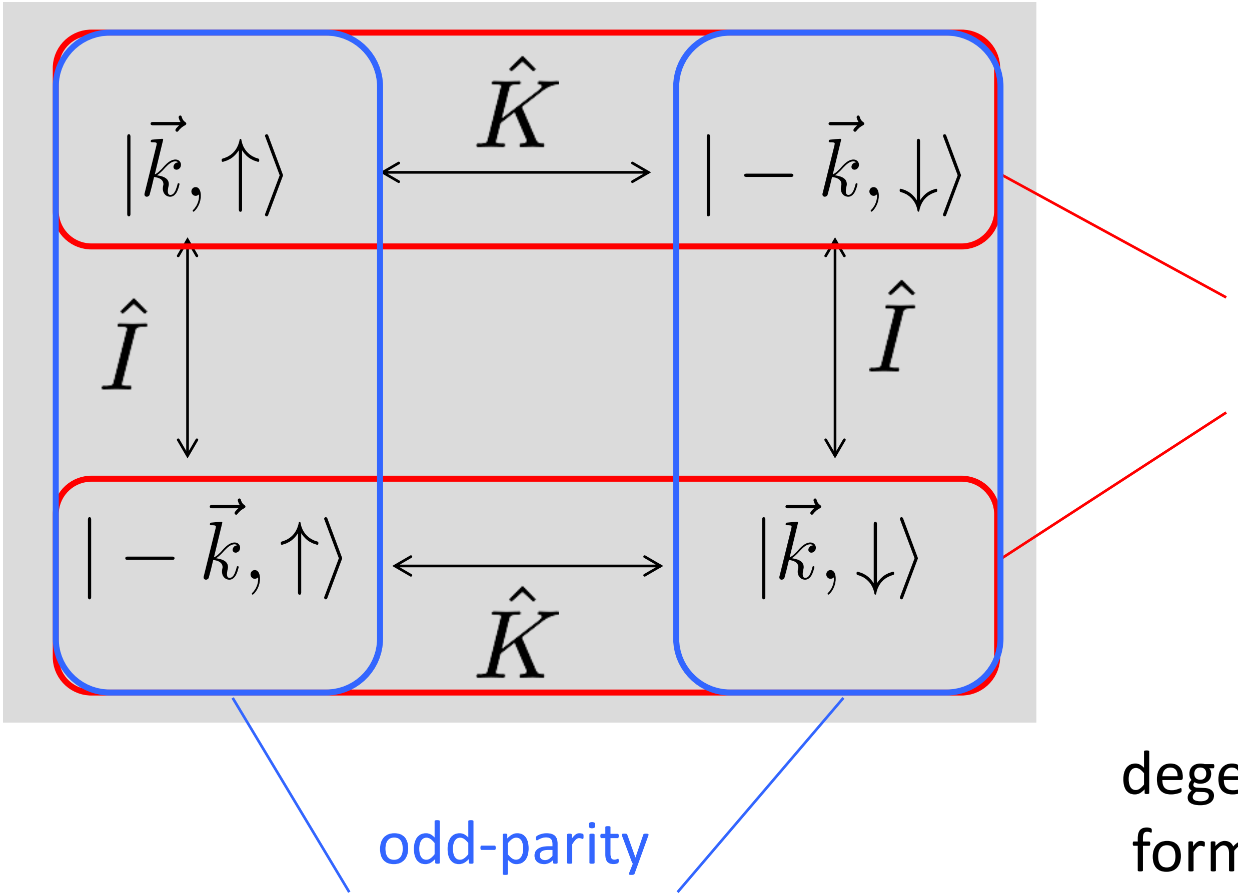
opposite spin partners

inversion:

$$|\boldsymbol{k}s\rangle \longrightarrow \hat{I}|\boldsymbol{k}s\rangle = |-\boldsymbol{k}s\rangle \quad \Rightarrow \quad \xi_{\boldsymbol{k}s} = \xi_{-\boldsymbol{k}s}$$

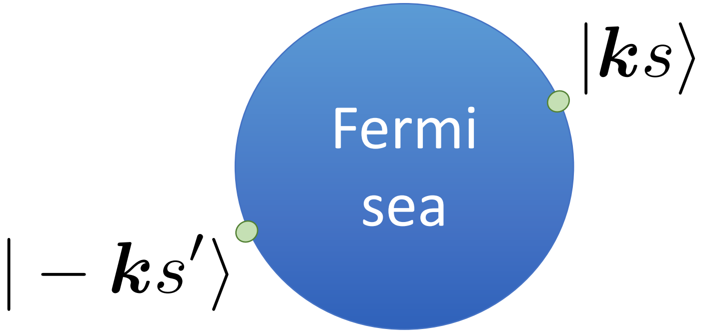
same spin partners

Anderson's Theorem



even-parity
spin-singlet
pairing

odd-parity
spin-triplet
pairing



guarantee for
degenerate partners to
form zero-momentum
Cooper pair states

Superconductivity - key symmetries

time reversal and inversion symmetry

$$\mathcal{H}_0 = \sum_{\boldsymbol{k},s} \xi_{\boldsymbol{k}} \hat{c}^\dagger_{\boldsymbol{k}s} \hat{c}_{\boldsymbol{k}s} \longrightarrow \mathcal{H}_0 = \sum_{\boldsymbol{k},s,s'} \Xi_{\boldsymbol{k},ss'} \hat{c}^\dagger_{\boldsymbol{k}s} \hat{c}_{\boldsymbol{k}s'}$$

$$\xi_{\boldsymbol{k}} = \xi_{-\boldsymbol{k}}$$

$$\hat{\Xi}_{\boldsymbol{k}} = \xi_{\boldsymbol{k}}\, \hat{\sigma}^0 + \boldsymbol{\lambda}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma}$$

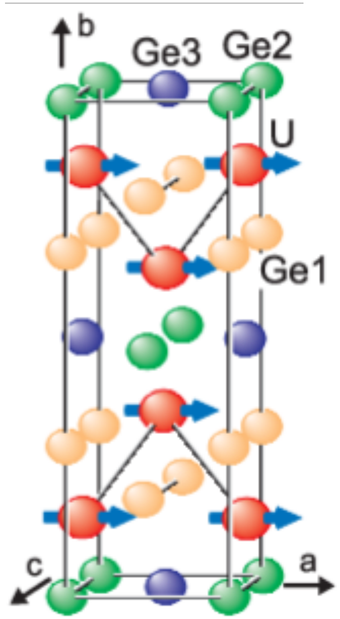
$$\hat{K} : \hat{\Xi}_{\boldsymbol{k}} = \hat{\sigma}^y \hat{\Xi}_{-\boldsymbol{k}} \hat{\sigma}^y = \xi_{-\boldsymbol{k}}\, \hat{\sigma}^0 - \boldsymbol{\lambda}_{-\boldsymbol{k}} \cdot \boldsymbol{\sigma}$$

$$\hat{I} : \hat{\Xi}_{\boldsymbol{k}} = \hat{\Xi}_{-\boldsymbol{k}} = \xi_{-\boldsymbol{k}}\, \hat{\sigma}^0 + \boldsymbol{\lambda}_{-\boldsymbol{k}} \cdot \boldsymbol{\sigma}$$

lacking:

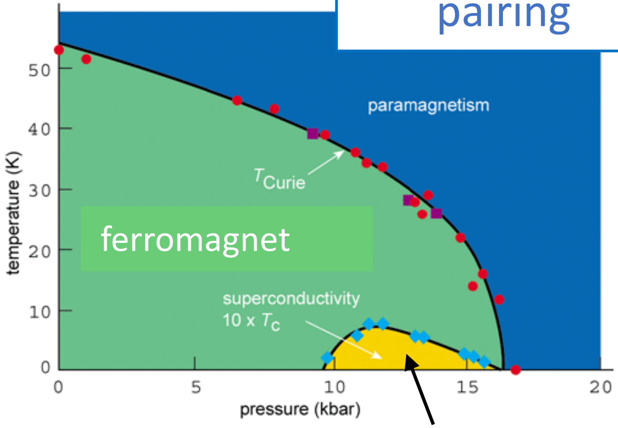
time reversal symmetry $\quad \boldsymbol{\lambda}_{\boldsymbol{k}} = \boldsymbol{\lambda}_{-\boldsymbol{k}}$ $\quad \boldsymbol{\lambda}_{\boldsymbol{k}} = \boldsymbol{H}$

Zeeman field



UGe_2

no spin singlet pairing



superconductor

Superconductivity - key symmetries

time reversal and inversion symmetry

$$\mathcal{H}_0 = \sum_{\boldsymbol{k},s} \xi_{\boldsymbol{k}} \hat{c}^\dagger_{\boldsymbol{k}s} \hat{c}_{\boldsymbol{k}s} \longrightarrow$$

$$\mathcal{H}_0 = \sum_{\boldsymbol{k},s,s'} \Xi_{\boldsymbol{k},ss'} \hat{c}^\dagger_{\boldsymbol{k}s} \hat{c}_{\boldsymbol{k}s'}$$

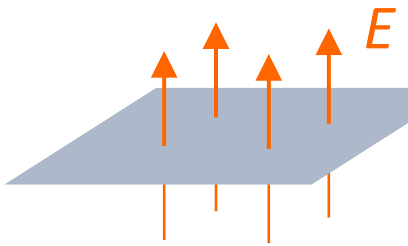
$$\hat{\Xi}_{\boldsymbol{k}} = \xi_{\boldsymbol{k}}\ \hat{\sigma}^0 + \boldsymbol{\lambda}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma}$$

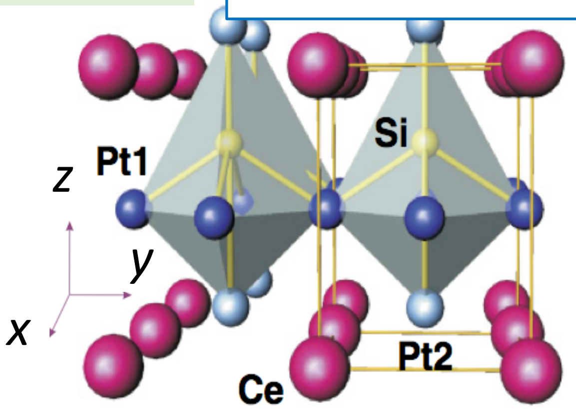
$$\xi_{\boldsymbol{k}} = \xi_{-\boldsymbol{k}}$$

spin triplet pairing restricted

$$\hat{K} : \hat{\Xi}_{\boldsymbol{k}} = \hat{\sigma}^y \hat{\Xi}_{-\boldsymbol{k}} \hat{\sigma}^y = \xi_{-\boldsymbol{k}}\ \hat{\sigma}^0 - \boldsymbol{\lambda}_{-\boldsymbol{k}} \cdot \boldsymbol{\sigma}$$

$$\hat{I} : \hat{\Xi}_{\boldsymbol{k}} = \hat{\Xi}_{-\boldsymbol{k}} = \xi_{-\boldsymbol{k}}\ \hat{\sigma}^0 + \boldsymbol{\lambda}_{-\boldsymbol{k}} \cdot \boldsymbol{\sigma}$$





$CePt_3Si$

lacking:

time reversal symmetry $\quad \boldsymbol{\lambda}_{\boldsymbol{k}} = \boldsymbol{\lambda}_{-\boldsymbol{k}}$

$$\left(\frac{\boldsymbol{v}}{c} \times \boldsymbol{E}\right) \cdot \boldsymbol{S} = \boldsymbol{B} \cdot \boldsymbol{S}$$

inversion symmetry $\quad \boldsymbol{\lambda}_{\boldsymbol{k}} = -\boldsymbol{\lambda}_{-\boldsymbol{k}}$

$\boldsymbol{\lambda}_{\boldsymbol{k}} = \alpha \boldsymbol{k} \times \hat{\boldsymbol{z}}$ Rashba spin-orbit coupling

Superconductivity - key symmetries

time reversal and inversion symmetry

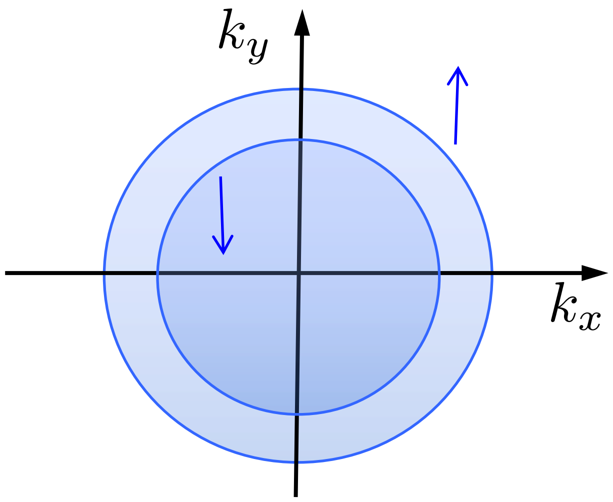
$$\mathcal{H}_0 = \sum_{\boldsymbol{k},s} \xi_{\boldsymbol{k}} \hat{c}^\dagger_{\boldsymbol{k}s} \hat{c}_{\boldsymbol{k}s} \longrightarrow \mathcal{H}_0 = \sum_{\boldsymbol{k},s,s'} \Xi_{\boldsymbol{k},ss'} \hat{c}^\dagger_{\boldsymbol{k}s} \hat{c}_{\boldsymbol{k}s'}$$

$$\xi_{\boldsymbol{k}} = \xi_{-\boldsymbol{k}}$$

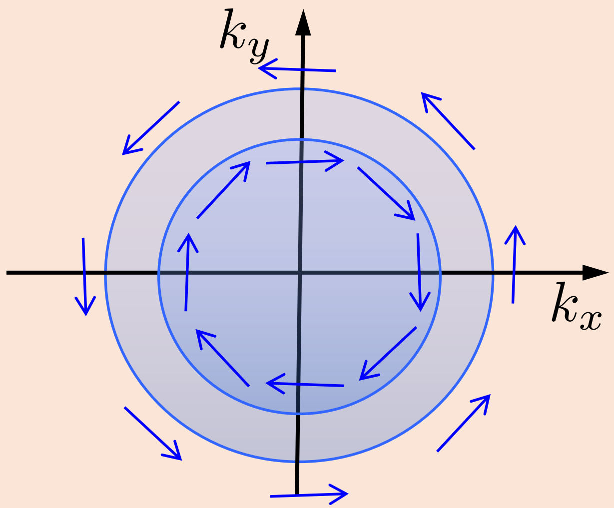
$$\hat{\Xi}_{\boldsymbol{k}} = \xi_{\boldsymbol{k}}\, \hat{\sigma}^0 + \boldsymbol{\lambda}_{\boldsymbol{k}} \cdot \boldsymbol{\sigma}$$

Fermi surface spin splitting

magnetic field $\boldsymbol{\lambda}_{\boldsymbol{k}} = \boldsymbol{H}$

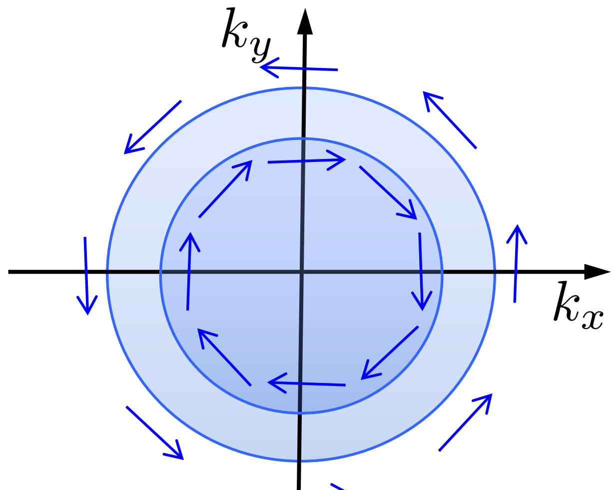


Rashba SOC $\boldsymbol{\lambda}_{\boldsymbol{k}} = \alpha \boldsymbol{k} \times \hat{\boldsymbol{z}}$



Superconductivity - non-centrosymmetric superconductors

$$\mathcal{H}_0 = \sum_{\boldsymbol{k},s,s'} \{\xi_{\boldsymbol{k}}\hat{\sigma}^0 + \underbrace{\alpha(k_x\hat{\sigma}^y - k_y\hat{\sigma}^x)}_{\text{Rashba spin-orbit coupling}}\}\hat{c}^\dagger_{\boldsymbol{k}s}\hat{c}_{\boldsymbol{k}s'}$$



electronic spin structure *determines* Cooper pairing symmetry

mixed-parity pairing

odd parity

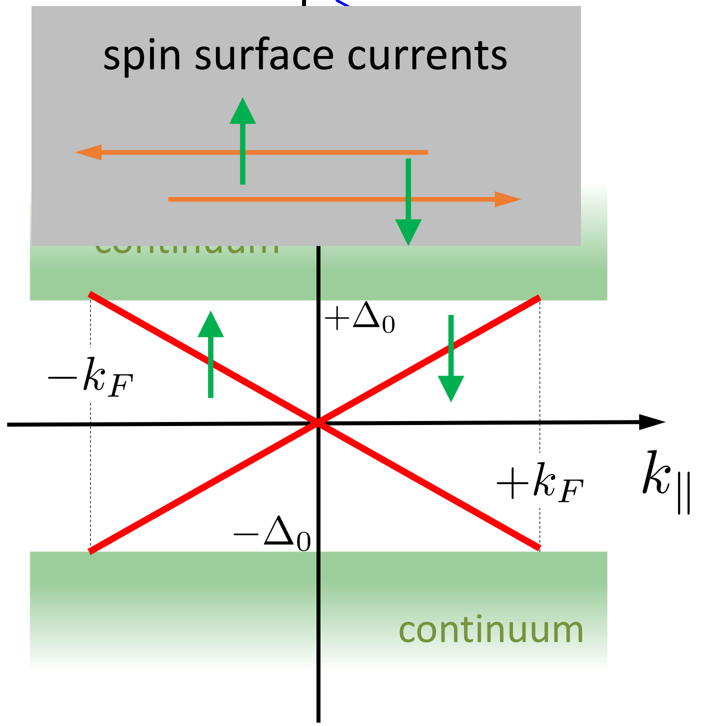
even parity

$$\hat{\Psi}(\boldsymbol{k}) = \begin{pmatrix} i\eta_o(k_x - ik_y) & \eta_e \\ -\eta_e & i\eta_o(k_x + ik_y) \end{pmatrix}$$

$|\eta_o| > |\eta_e|$

helical edge states

topological



Superconductivity - non-centrosymmetric superconductors

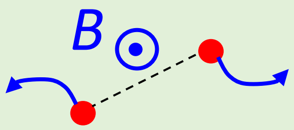
robustness against magnetic fields

depairing mechanisms

- orbital depairing

$$H_c^{\mathrm{orb}} = \frac{\Phi_0}{2\pi\xi_0^2}$$

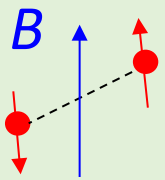
coherence length
Cooper pair radius



"Lorentz force"

- paramagnetic depairing

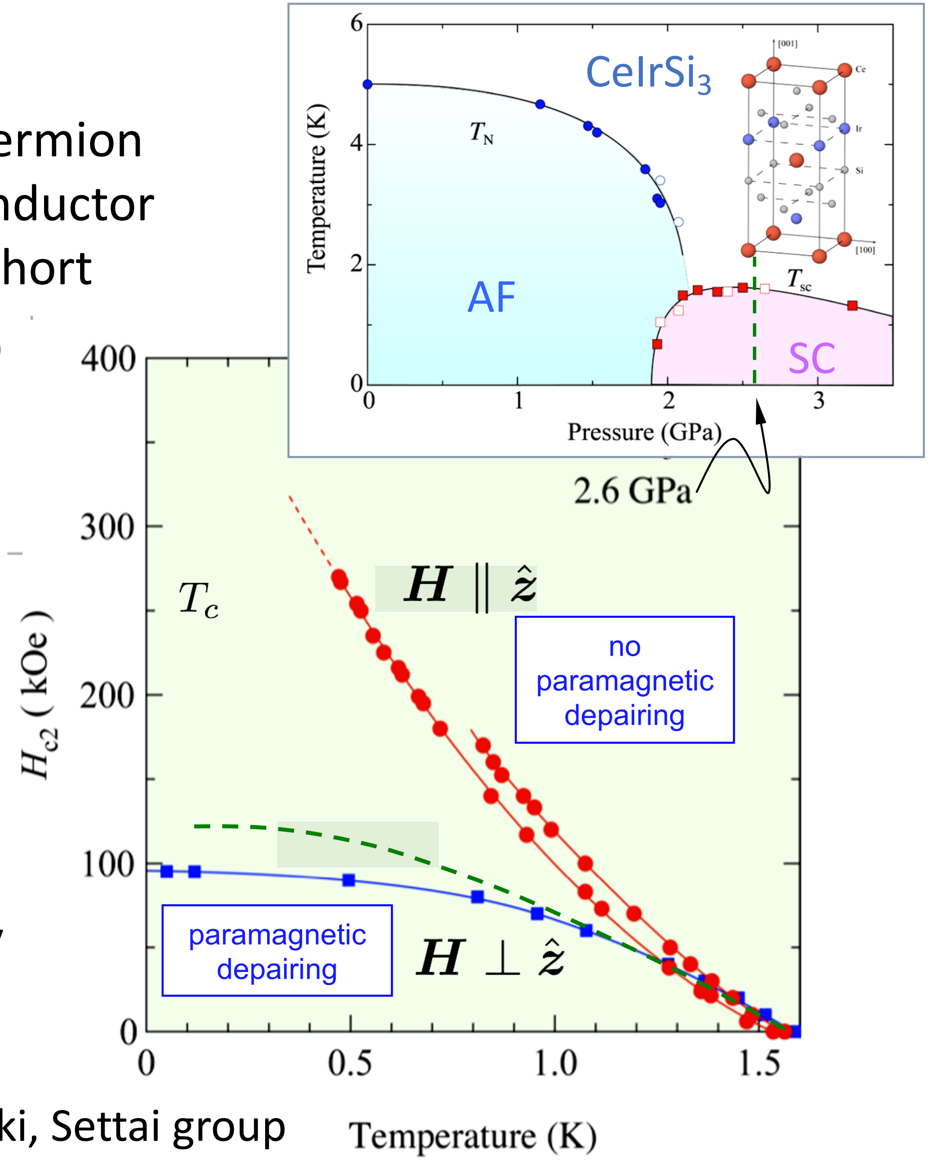
$$H_c^{\mathrm{para}} = \frac{k_B T_c}{\mu_B}$$



spin polarization
spin singlet

heavy Fermion superconductor
very short
ξ_0

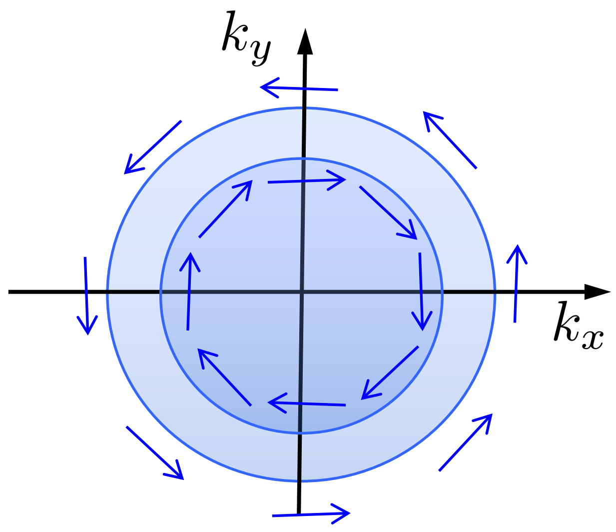
affected by
inversion symmetry



Onuki, Settai group

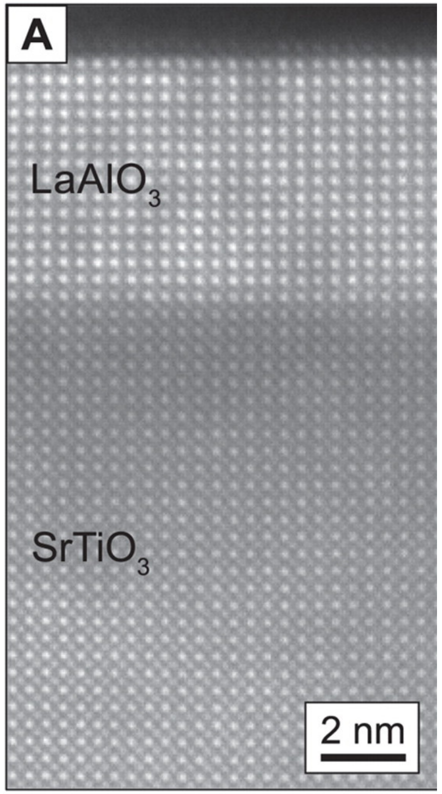
Superconductivity - helical phase

magneto-electric effect



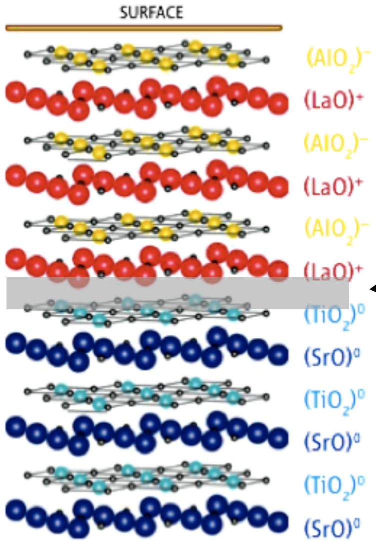
Superconductivity - artificial non-centrosymmetricity

superconductivity at interface $LaAlO_3$ / $SrTiO_3$



$LaAlO_3$

$SrTiO_3$

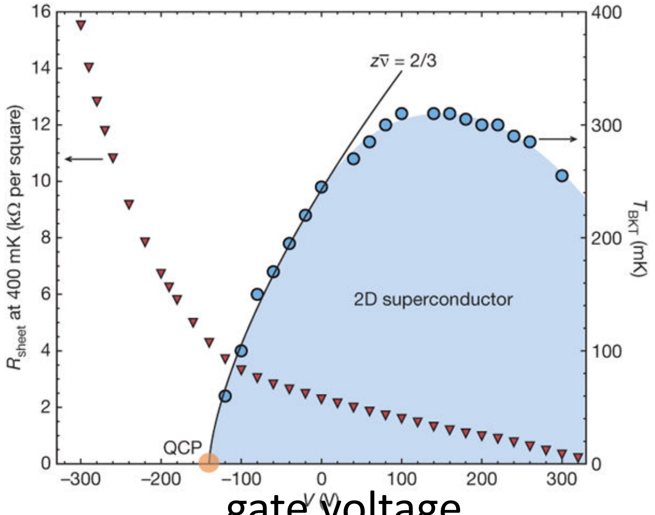


polar band insulator

2D metallic state

non-polar band insulator

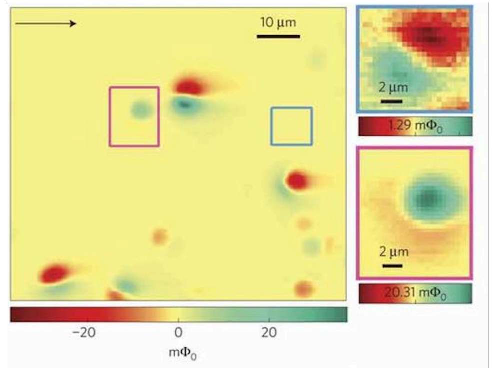
superconductivity



gate voltage

role of non-centrosymmetricity ?

signatures of magnetism-SC coexistence



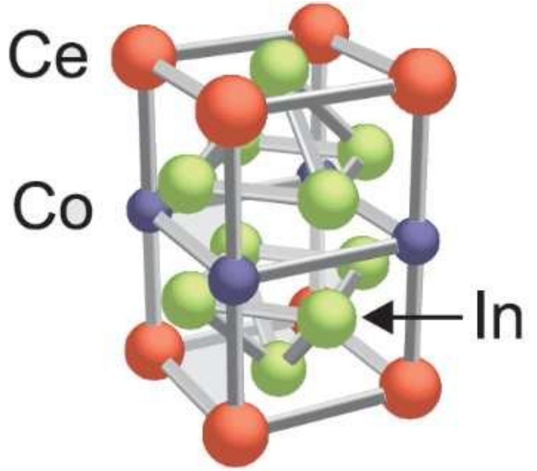
groups of H.W. Huang
J. Mannhardt
JM. Triscone
K.A. Moler, …

Superconductivity - artificial non-centrosymmetricity

superconductivity in superlattices $CeCoIn_5/YbCoIn_5$

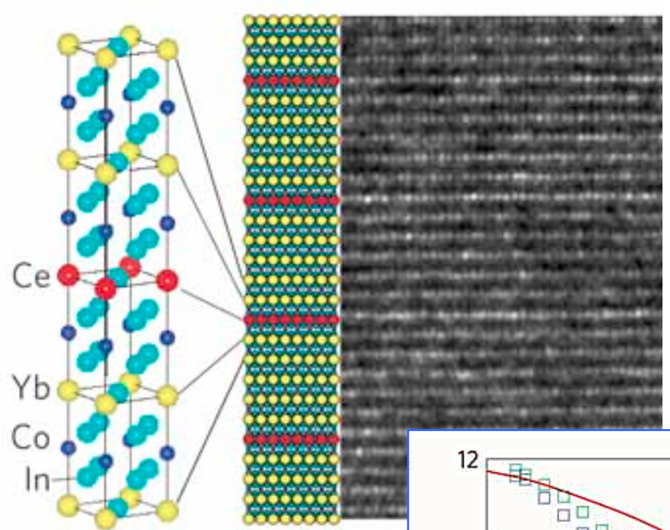
$CeCoIn_5$

heavy Fermion superconductor



centrosymmetric crystal

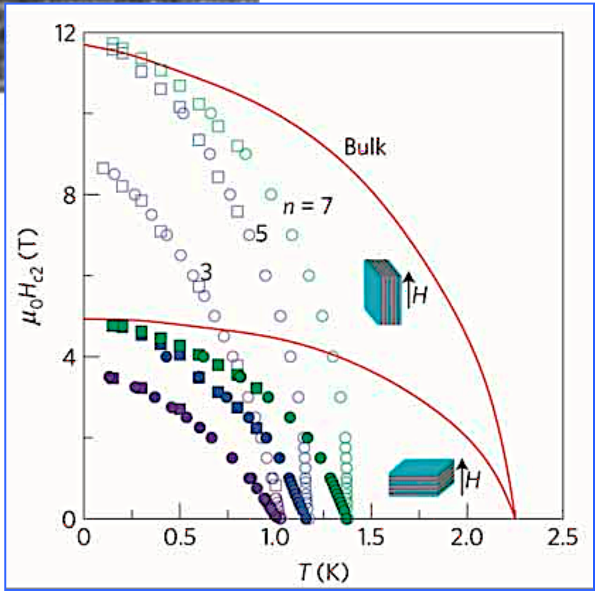
T_c = 2.4 K



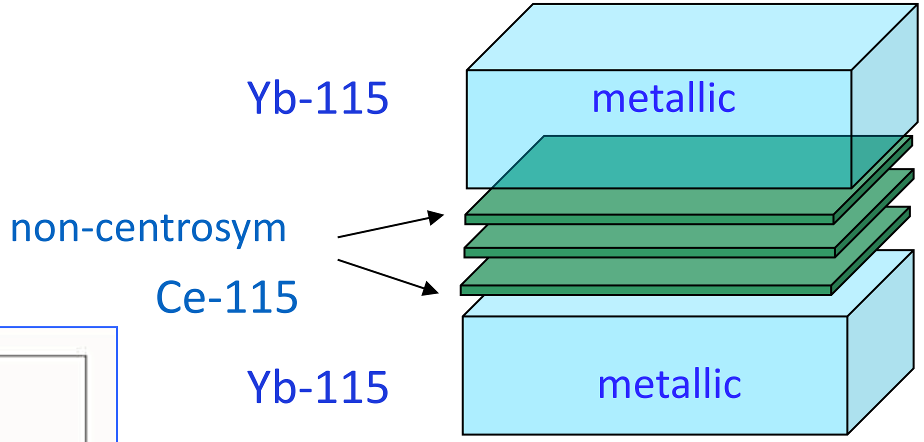
(Ce,Yb) = (*n*,*5*)

Matsuda group

very robust against paramagnetic limiting



model system (Ce,Yb)= (3,5)



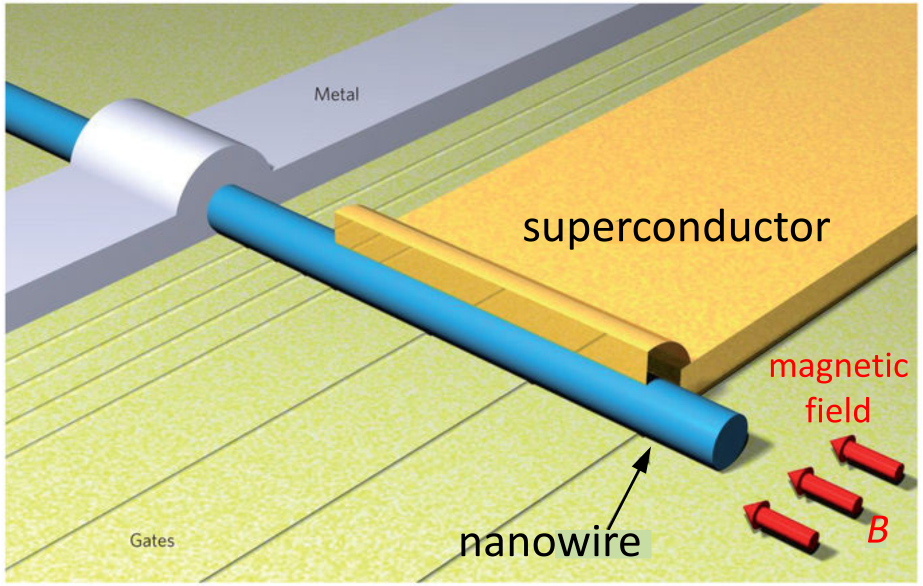
Yanase group

with external magnetic fields

- pair density wave phase
- complex stripe phase
- topological crystalline SC

Superconductivity - design of topological pairing

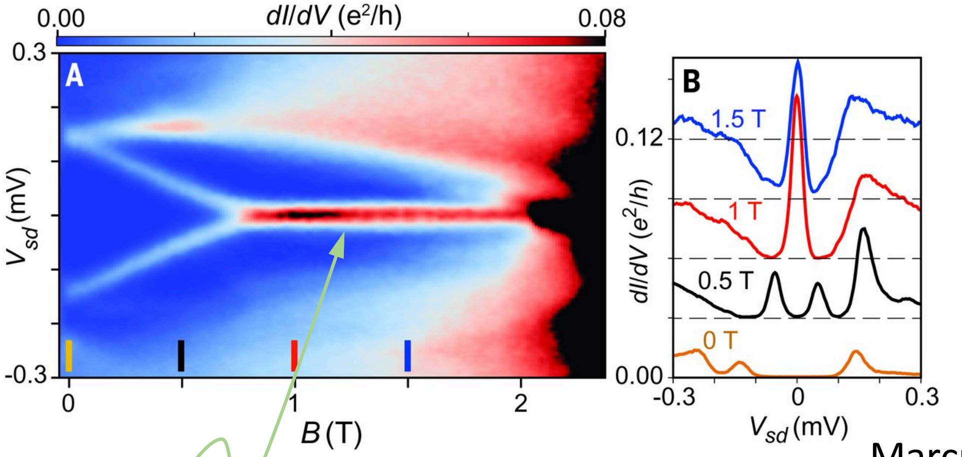
generating Majorana Fermions in nanowires



M. Franz: Nature NanoTech 8, 149 (2013)

edge state at ends of nanowire

tunneling spectroscopy



Marcus group

Majorana mode

topological superconductor

exp groups of Kouvenhoven, Marcus, Yasdani, ...

proximity induced odd-parity superconductivity in nanowire

spin-orbit coupling: *s*-wave induces mixed-parity *s+p*-wave

magnetic field: only "spin-polarized" *p*-wave remains

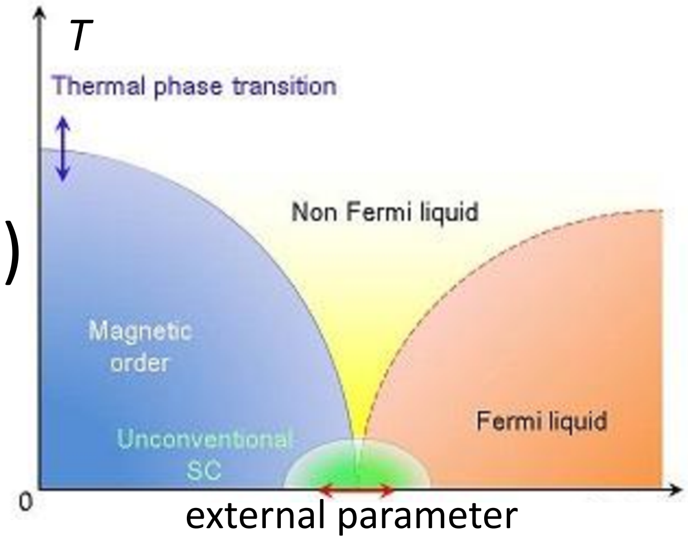
theoretical proposal: Oreg, Refael & von Oppen

hopes for topological quantum computation

Conclusion

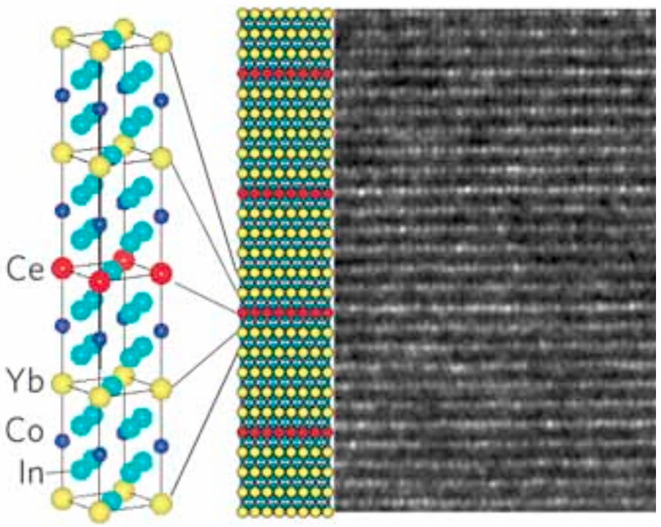
unconventional superconductors

- larger set of superconducting phases and additional spontaneously broken symmetries (e.g. time reversal)
- topological superconducting phases
- novel superconducting phenomena



key symmetries: time reversal and inversion

- influence on structure of pairing states
- design of superconducting phases through artificial structuring



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US/South America: *R. Budakian, Y. Liu, A. Kapitulnik, J. Kirtley, Q. Mao, G. Luke, K. Moler, I. Bonalde, Y. Uemura …..*