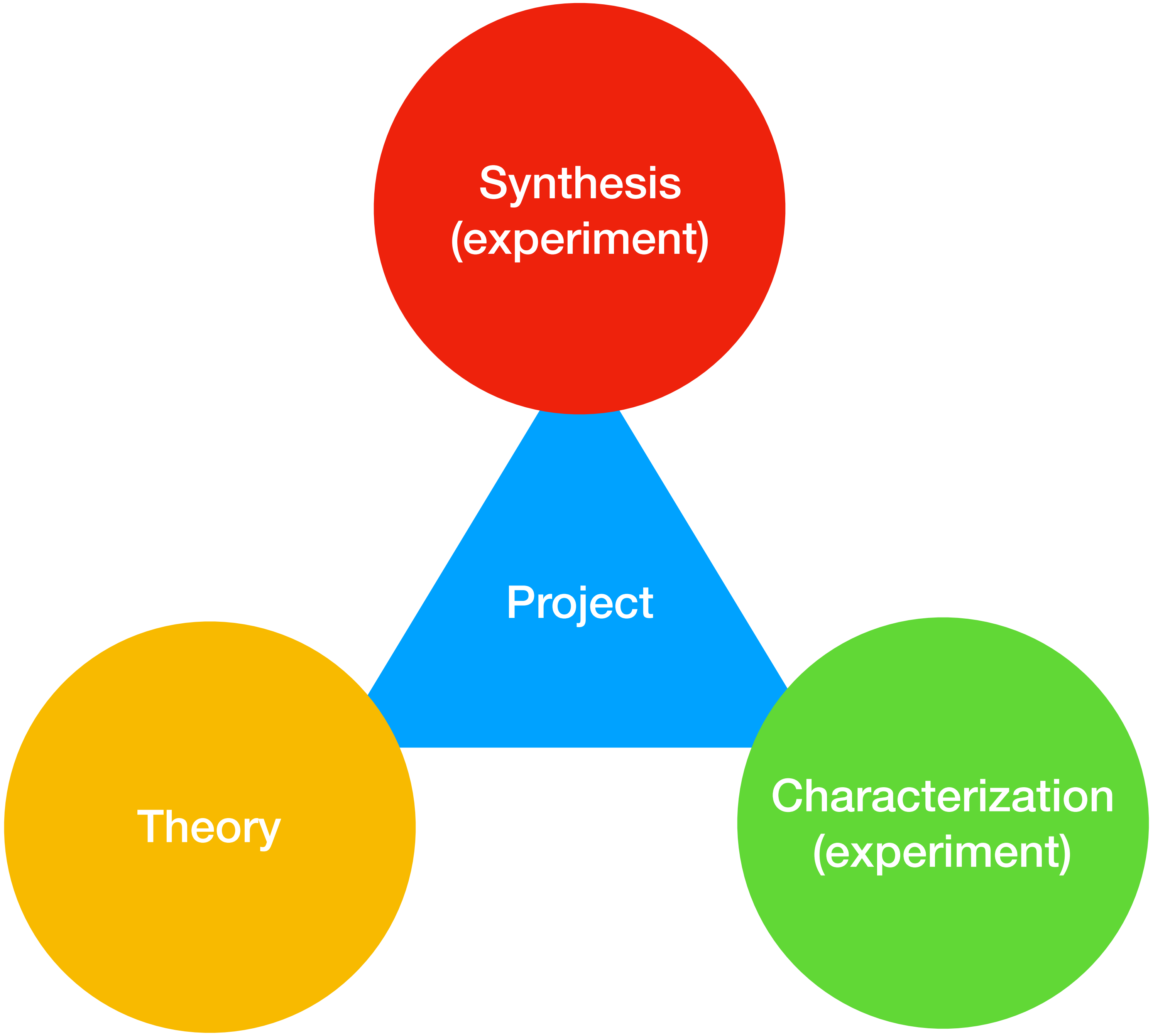
Quantum materials research

characterizations

Hyunsoo Kim
Department of Physics & Astronomy
Texas Tech University

Fundamentals of Quantum Materials Research



Basic concepts of materials characterization

Solid State Physics:
study interactions between particles in a solid, and consequences (properties and various phases)

Physical properties of a solid state

- x-ray and microanalysis
- magnetic: susceptibility
- thermodynamic: specific heat
- transport: electrical resistivity
- optical properties

Advanced characterization

- New technique or higher precision
- Allows to measure different quantities
- Allows to access different phases or states.
- Collaborations
- Often, need to visit national facilities

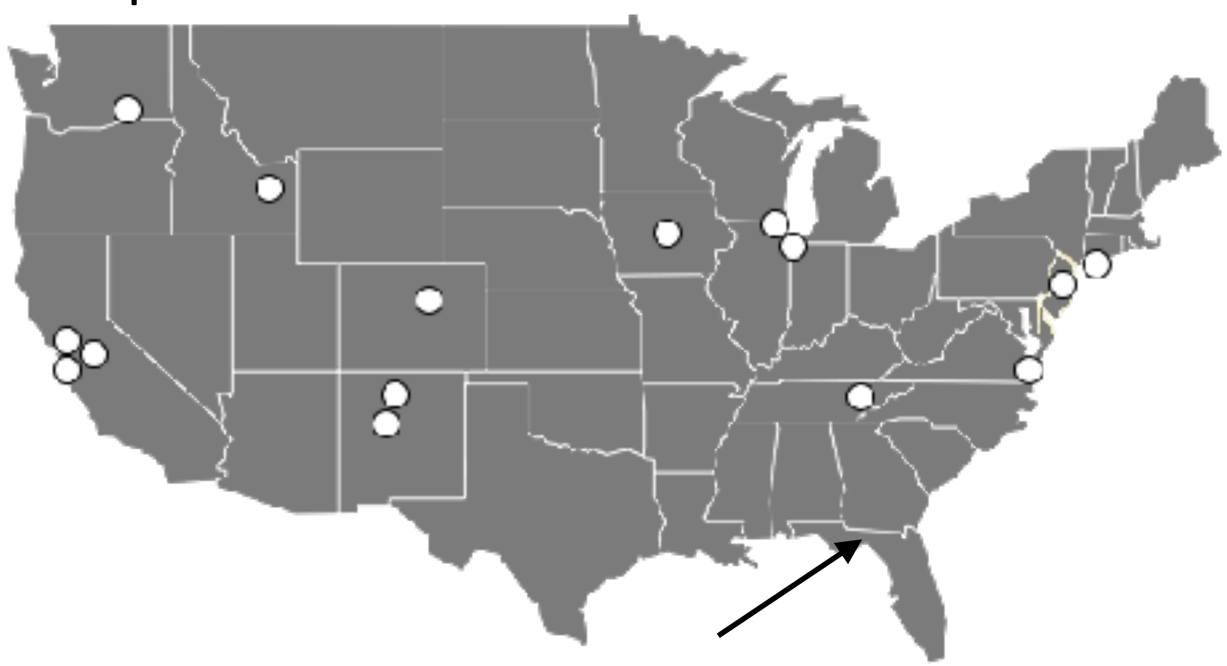
Linear response: Y = **Z** X

- **X**: Apply perturbation (tuning parameters)
- **Y**: Investigate the response
- Find out **Z** (represent physical properties)

Tuning parameters

- Temperature
- Field
- Pressure
- Chemical substitution
- Pulse laser

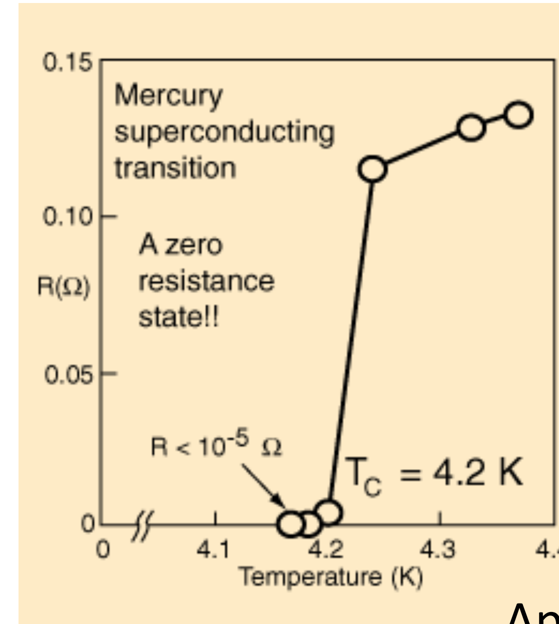
open circles: DOE lab



NSF, National High Magnetic Field Lab

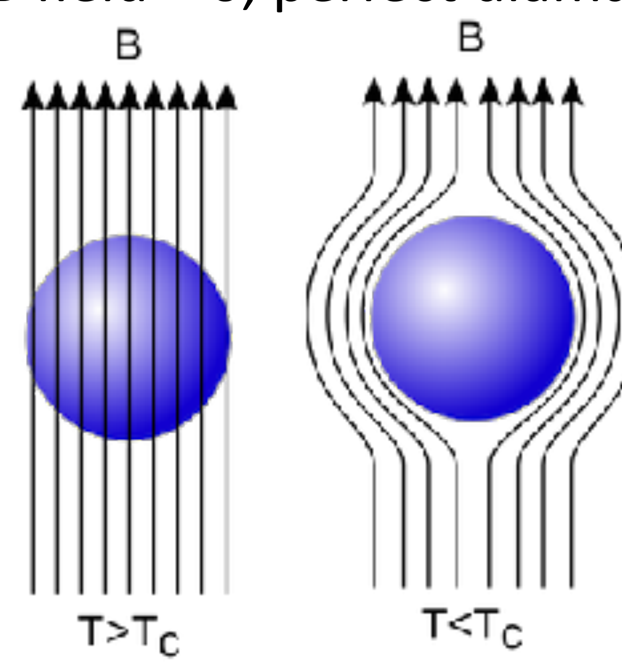
Superconductivity

Resistance=0, perfect conductor



April 8th (1911)

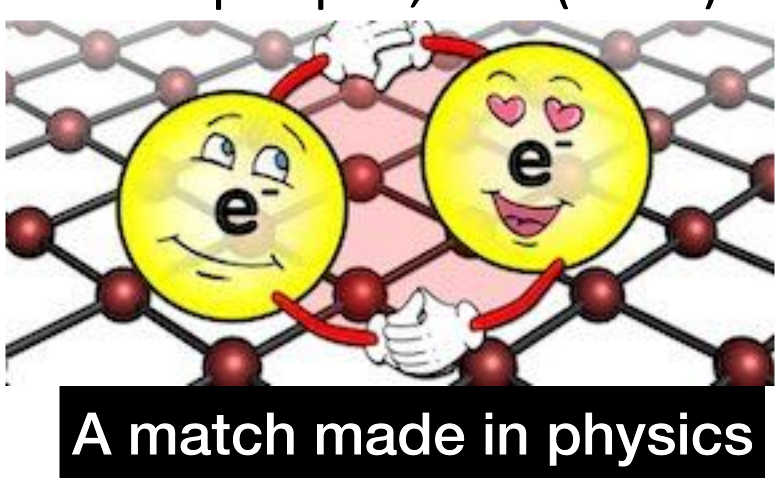
B field = 0, perfect diamagnet



Meissner effect (1933)

First macroscopic quantum phenomenon
H. London

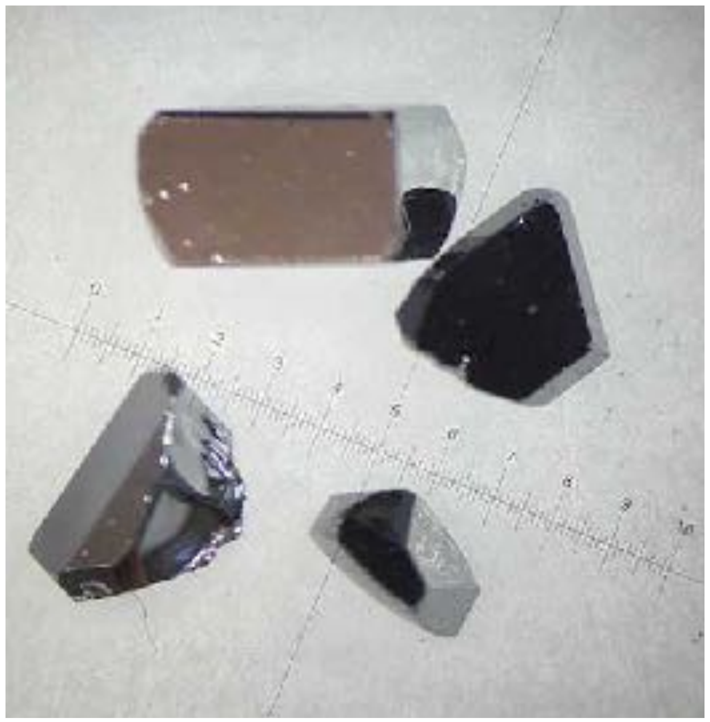
Microscopic theory
Cooper pair, BCS (1957)



MagLab

Superconductivity: Examples

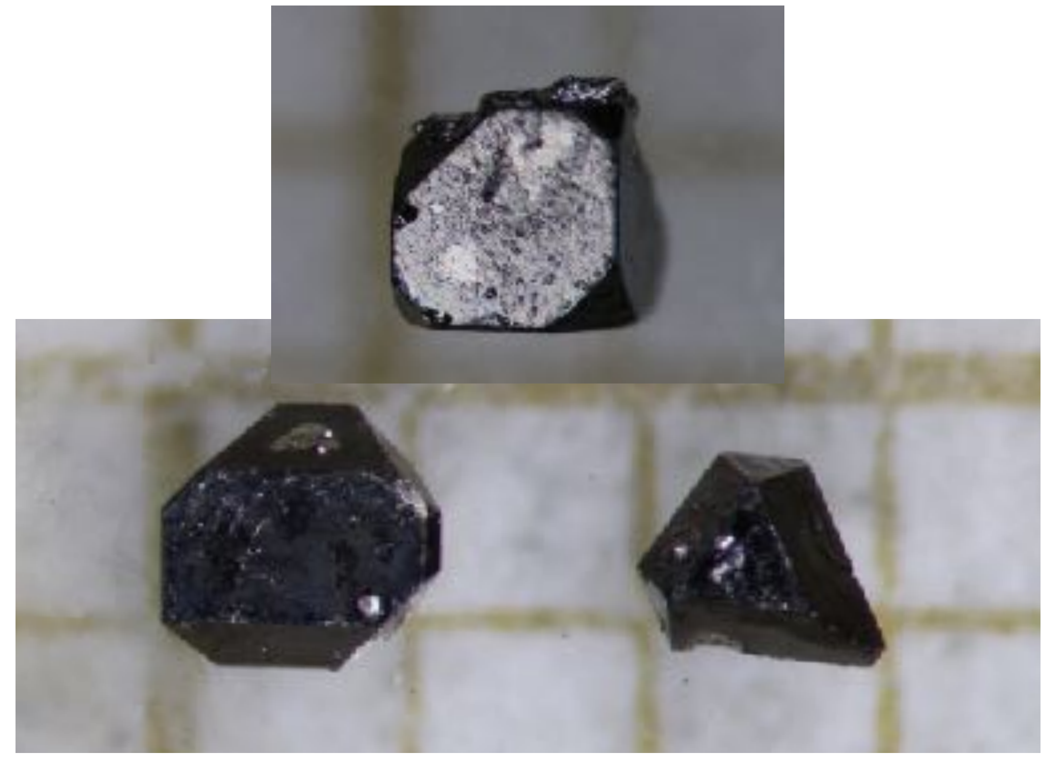
UTe_2



Basic characterizations
- resistivity
- magnetic susceptibility
- specific heat

S. Ran et al., Science 365, 684 (2019)
S. Ran et al., Nature Physics 15, 1250 (2019)

YPtBi



Advanced characterization
- London penetration depth
- Superconducting energy gap

H. Kim et al., Science Advances 4, eaao4513 (2018)

Electrical transport: resistivity

What can we learn?
Conductivity: how easy electrons can flow

$$\mathbf{j} = \sigma \mathbf{E} \qquad V = IR \qquad \text{(Ohm's law)}$$

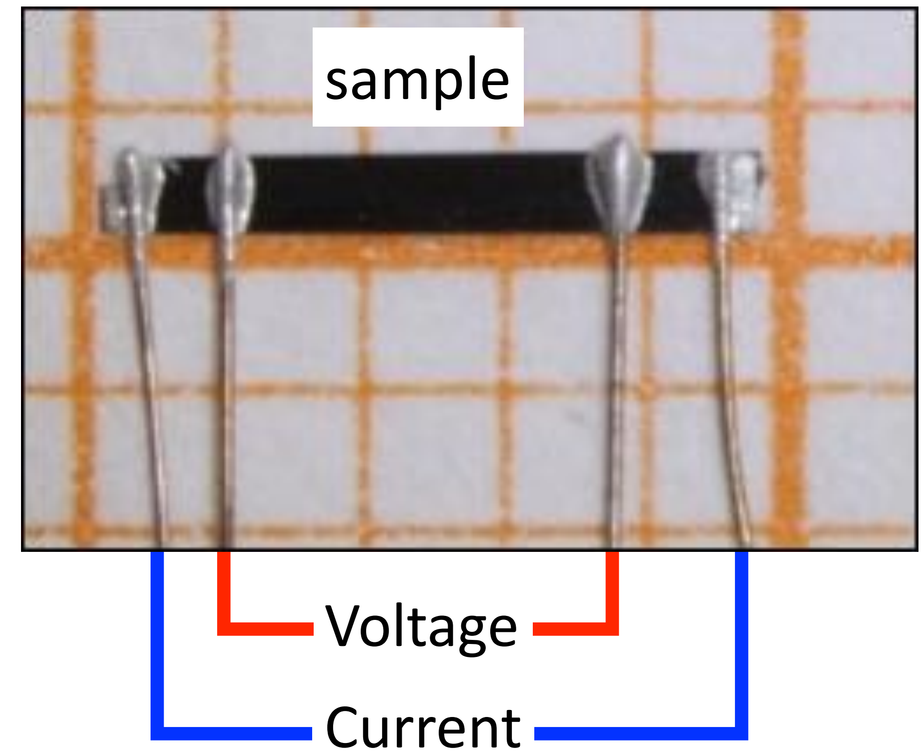
j : current density
E: electric field

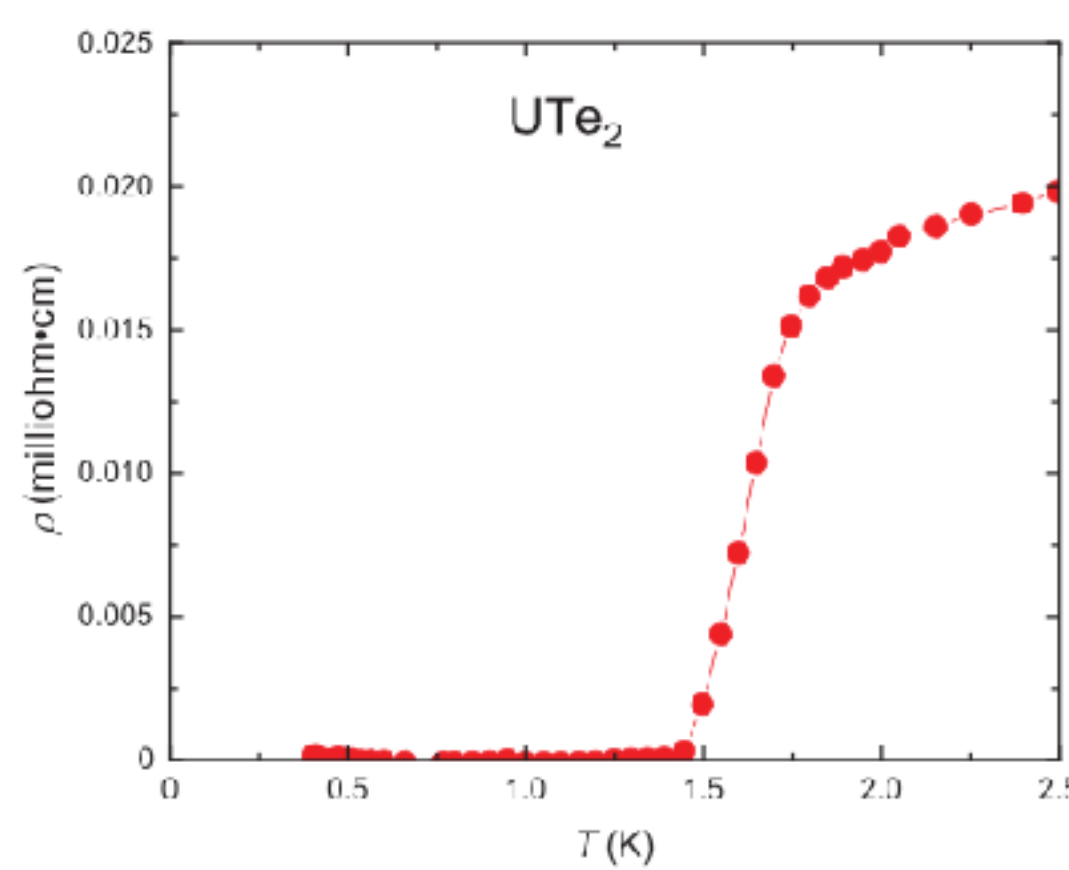
$$\sigma = \frac{1}{\rho} = \frac{ne^2\tau}{m} \qquad \text{(Drude model)}$$

m: mass of electron
n : carrier concentration ~ 10^{22} cm^{-3}
$\boldsymbol{\tau}$: scattering or collision time ~ 10^{-9} s

- Electron scattered by lattice vibration (phonon)
- Temperature dependence from change in electron-phonon scattering

4-probe resistance measurement





S. Ran et al., Science 365, 684 (2019)

Magnetic susceptibility

What is magnetic susceptibility?
How easy we can induce magnetization M.

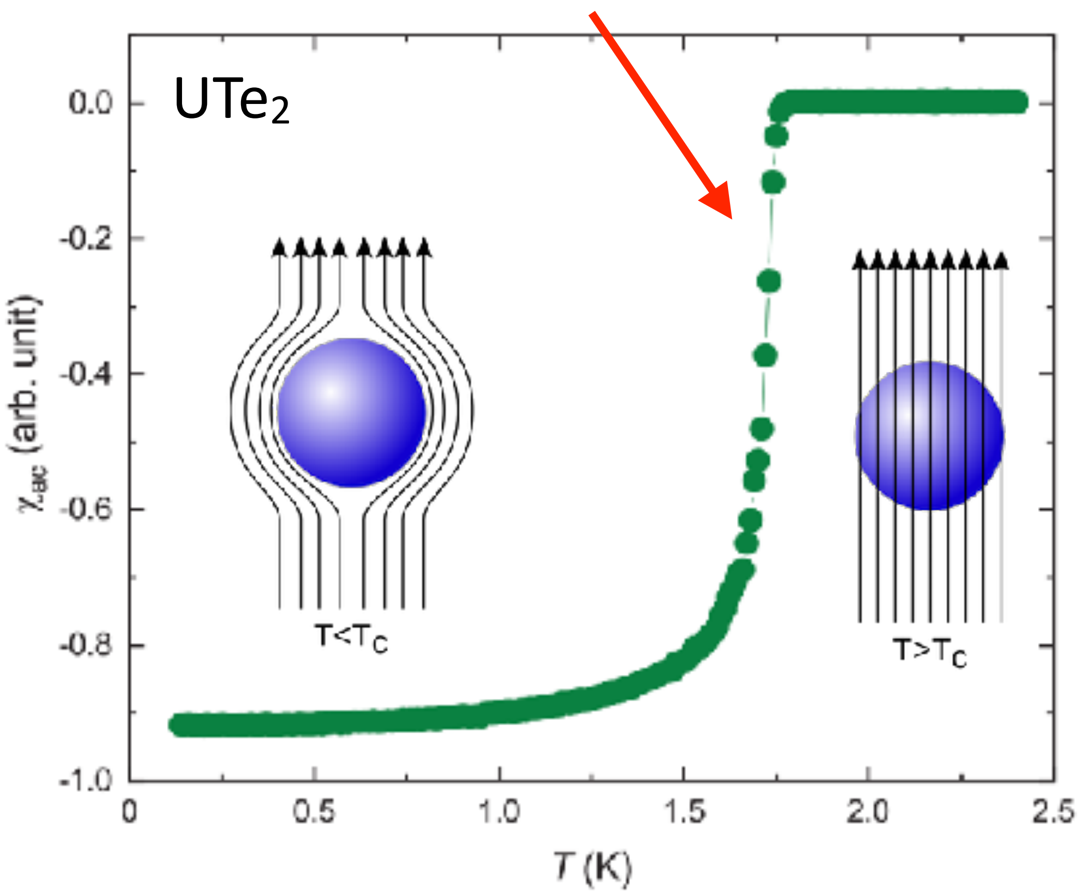
$$M = \chi H$$

H: magnetic field we apply
χ : magnetic susceptibility

$$B = \mu_0(H + M) = \mu_0(H + \chi H) = \mu_0(1 + \chi)H$$

$$B = \mu H \qquad \mu = \mu_0(1 + \chi)$$

Superconducting phase transition



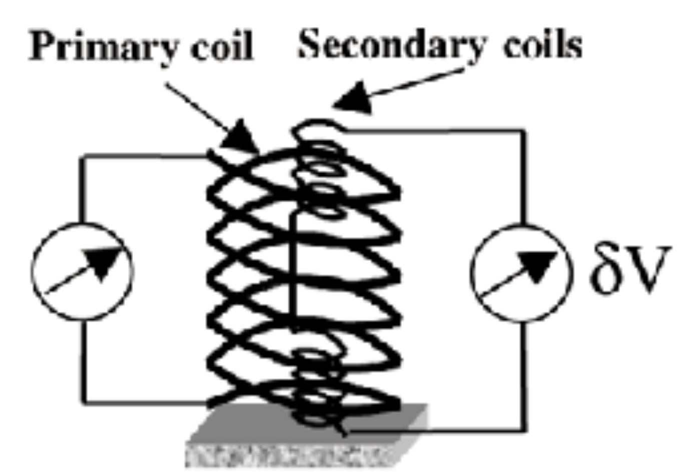
S. Ran et al., Science 365, 684 (2019)

What can we learn?
Magnetic ground state

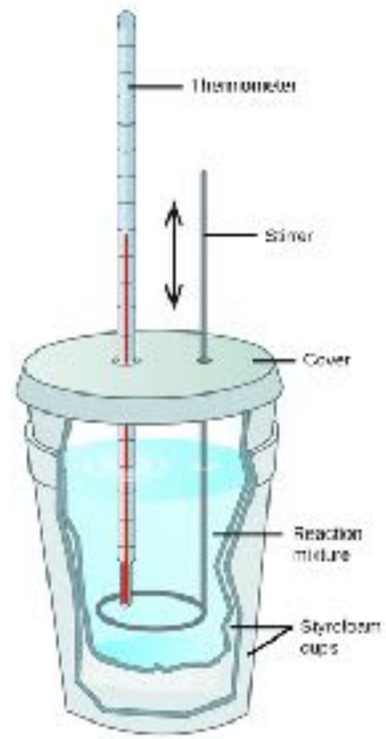
$\chi > 0$	paramagnetic: metals
$-1 \leq \chi < 0$	diamagnetic: insulators
$\chi = 0$	non-magnetic

superconductor $\qquad \chi = -1$
perfect diamagnetic

B = 0 (inside a superconductor)
Meissner effect



Specific heat, C



What is this? How easily you can change its temperature.
What can we learn? Thermodynamic properties (entropy)

$$\Delta T = \frac{1}{C}\Delta Q$$

Calorimetry

In a non-superconducting solid,

$$C_{total} = C_{electron} + C_{lattice}$$

$$C_{electron} = \gamma T$$

$C_{lattice} \approx \text{constant}$ Near 300 K

Temperature below T~200K

$$C_{lattice} \propto T^3$$

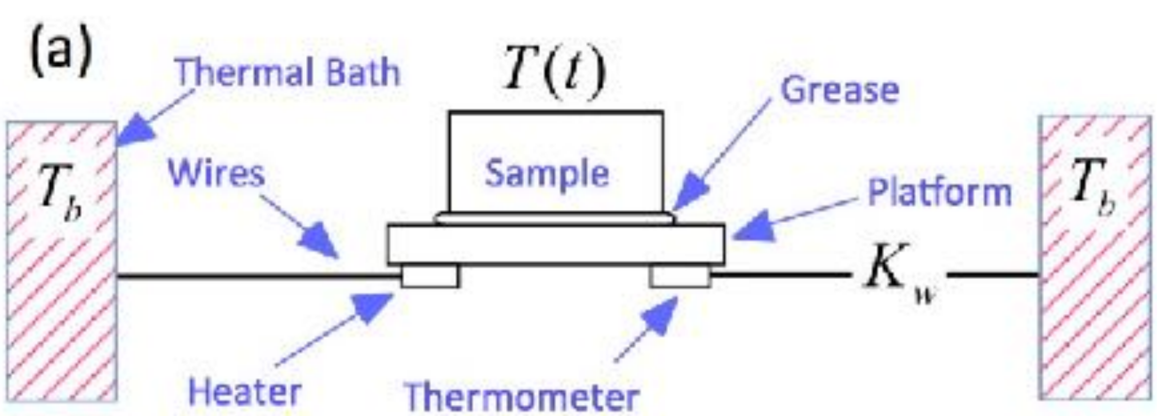
In a superconductor,

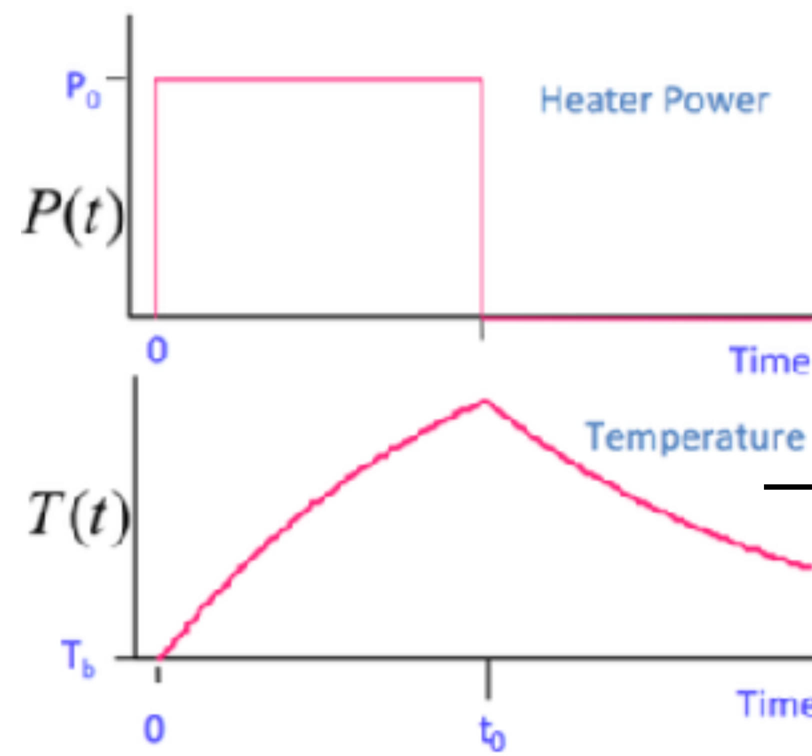
$$C_{total} = C_{electron} + C_{lattice}$$

$$\downarrow \qquad (T = T_c)$$

$$C_{\text{total}} = C_{\text{pair}} + C_{\text{lattice}}$$

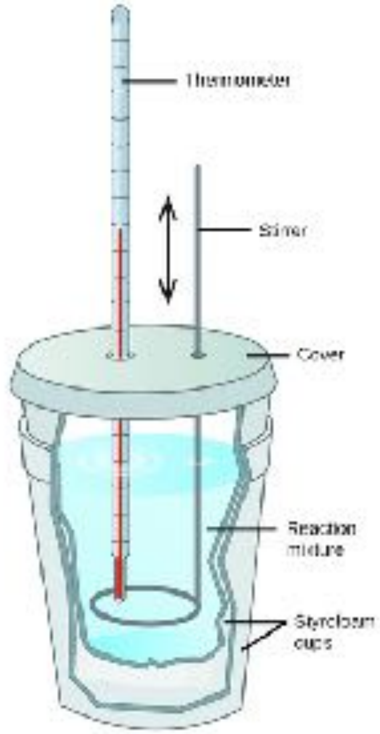
C_{total} changes at T_c!





Relaxation time proportional to Specific heat

Specific heat, C



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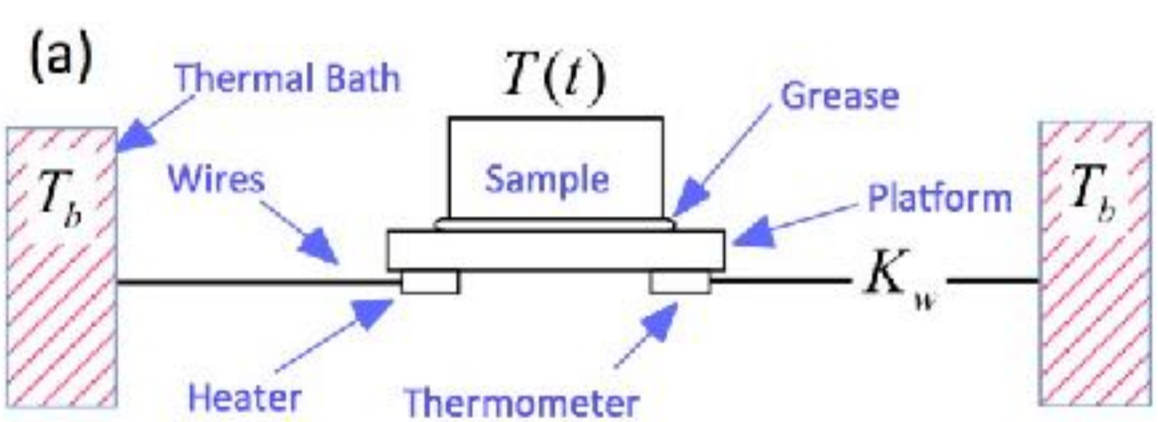
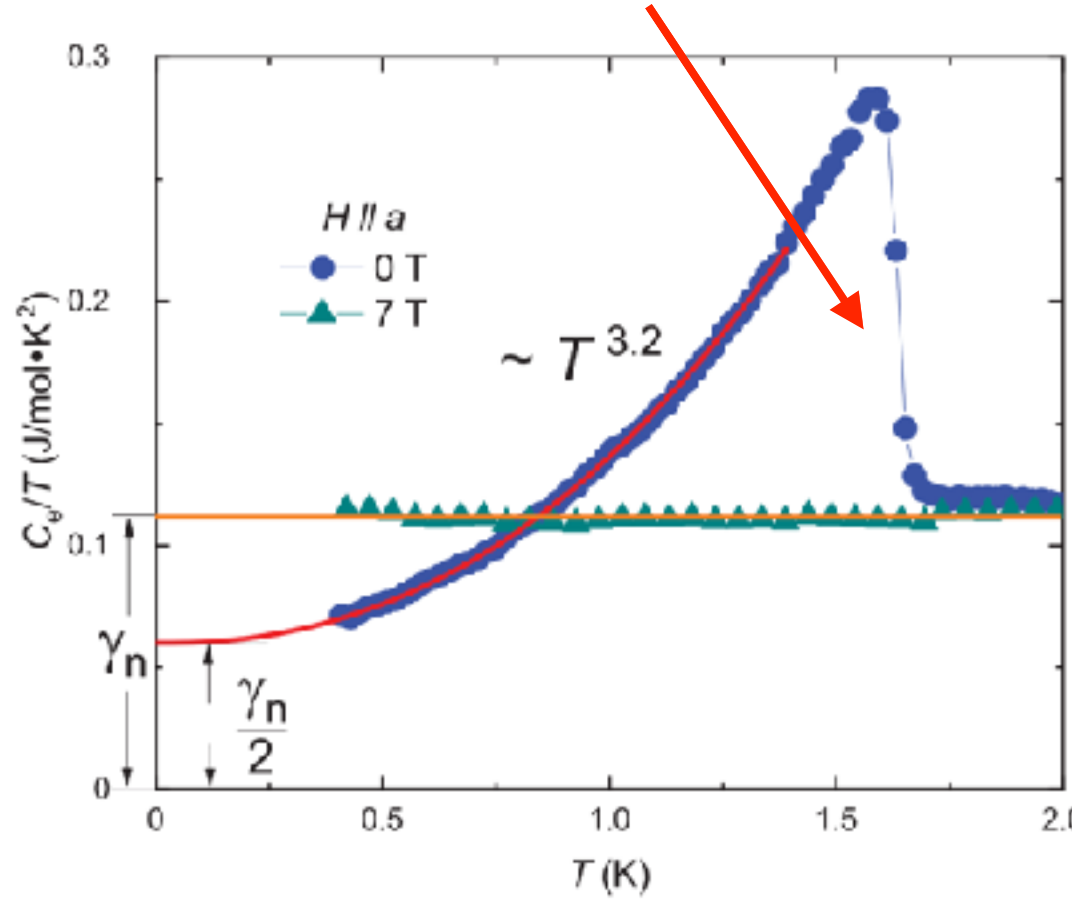
$$C_{total} = C_{electron} + C_{lattice}$$

$$\downarrow \qquad (T = T_c)$$

$$C_{\mathrm{total}} = C_{\mathrm{pair}} + C_{\mathrm{lattice}}$$

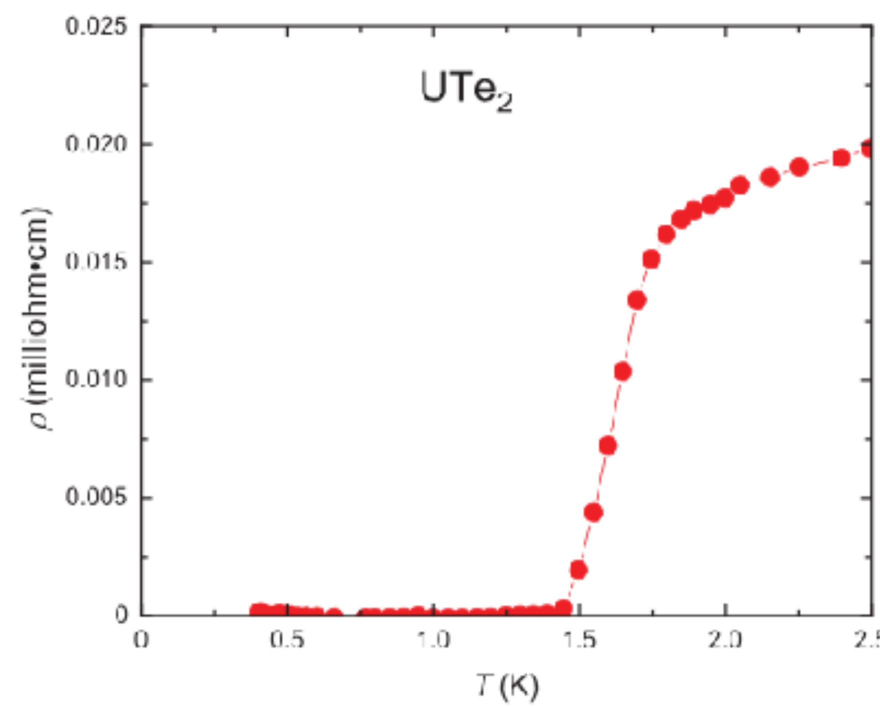
C_{total} discontinuous at T_c! (BCS, Cooper pair)



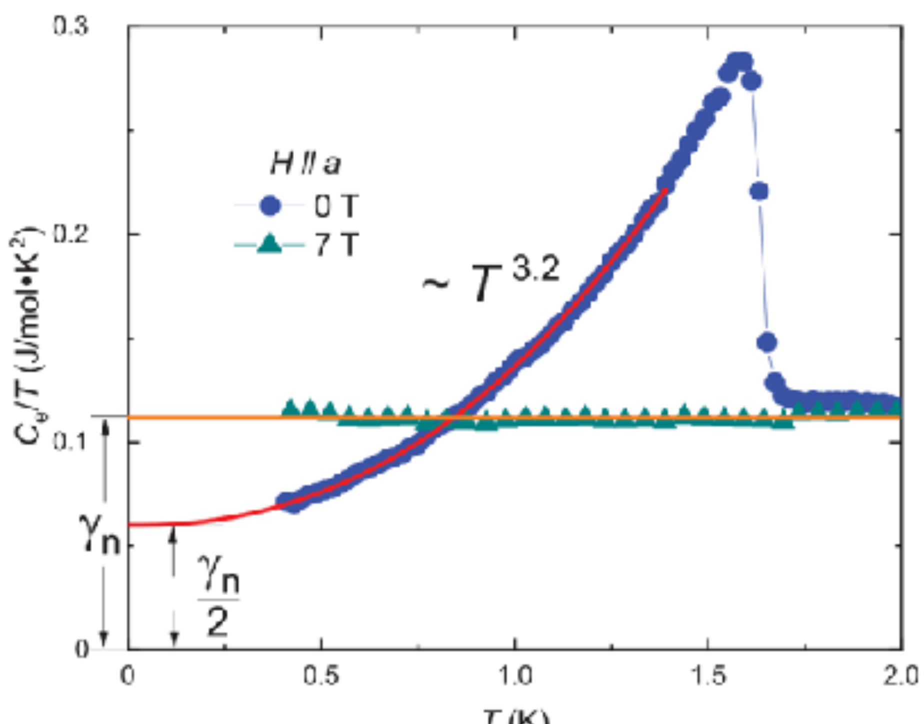


Superconductivity

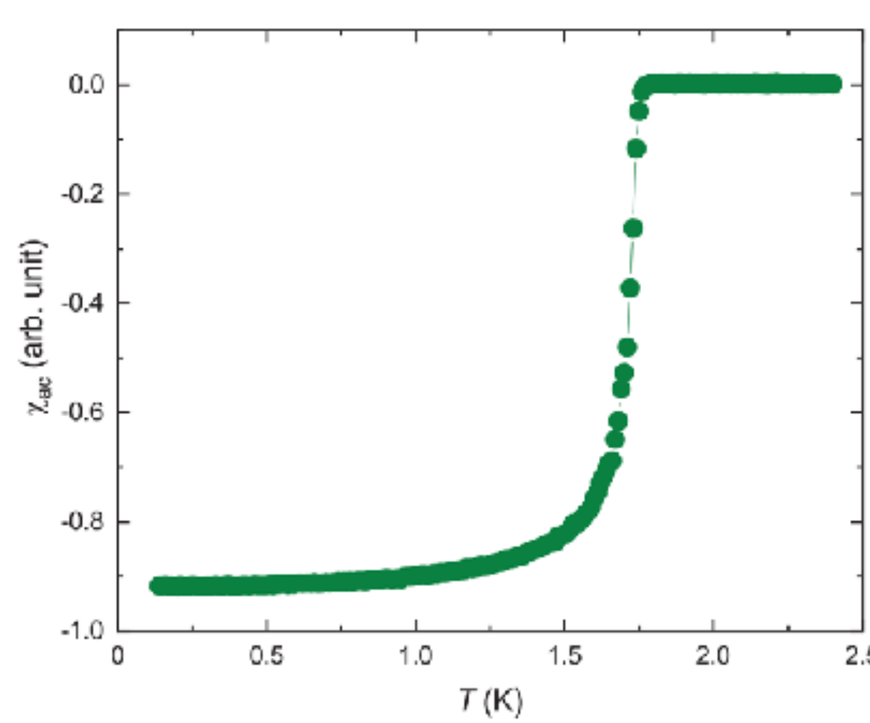
R=0, perfect conductor



B=0, perfect diamagnet



Cooper pair

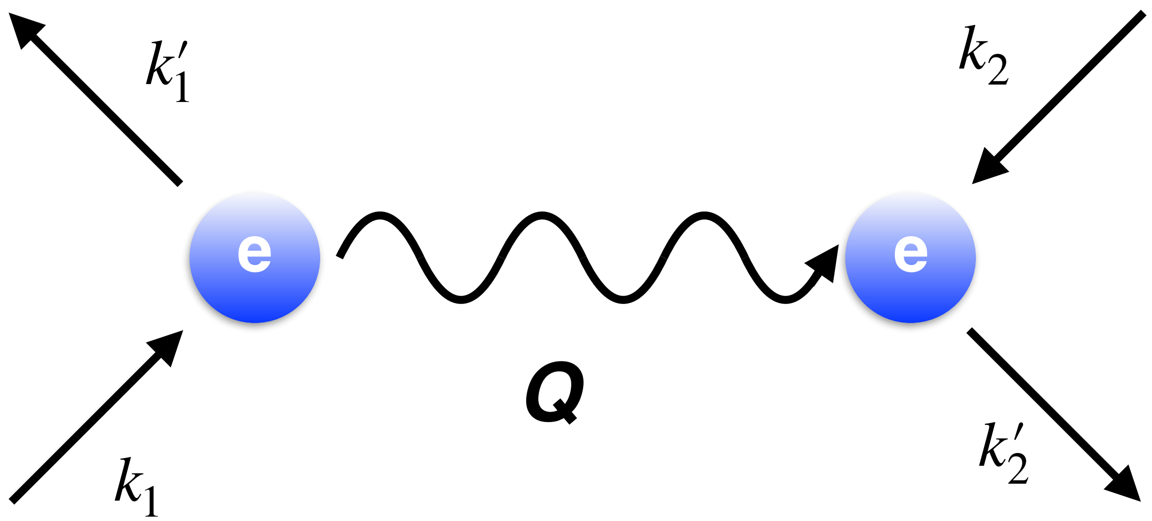


S. Ran et al., Science 365, 684 (2019)

Superconductivity: Microscopic theory

condensate of Cooper pairs of conduction electrons

Cooper pair

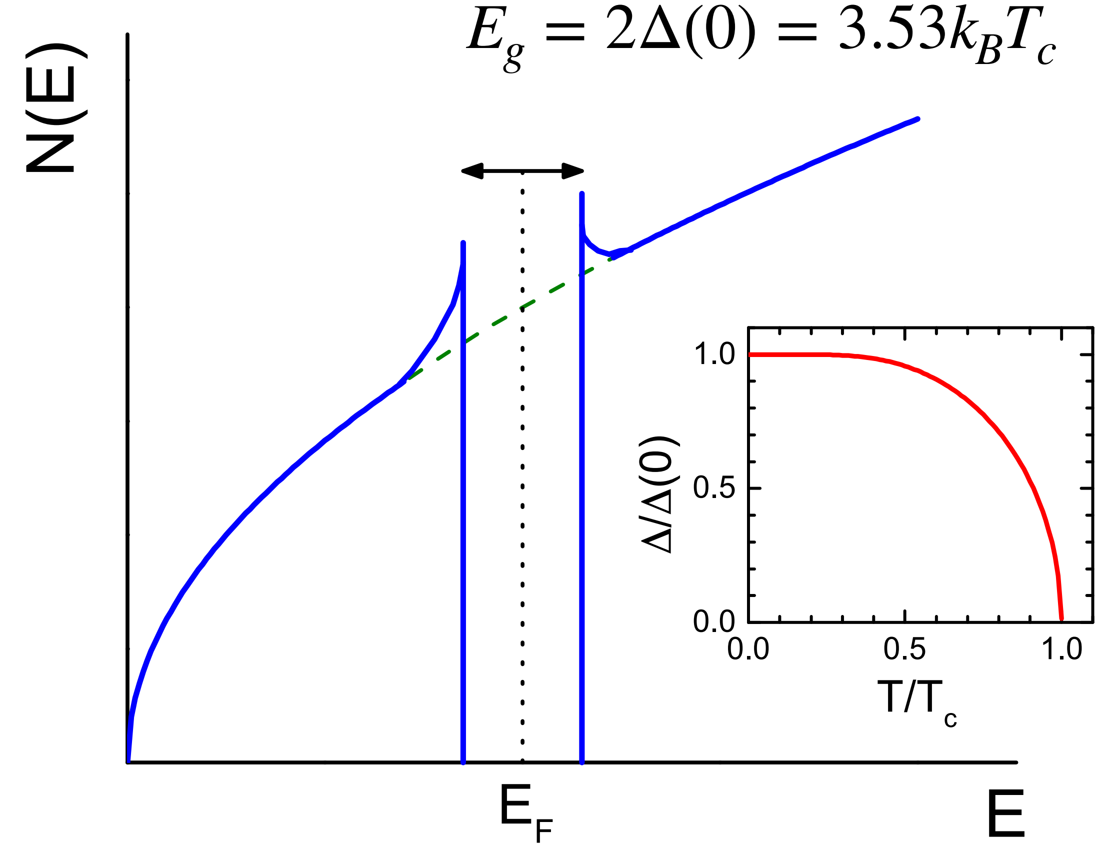


glue ***Q***

- lattice vibration
- spin fluctuation
- orbital fluctuation

(BCS)

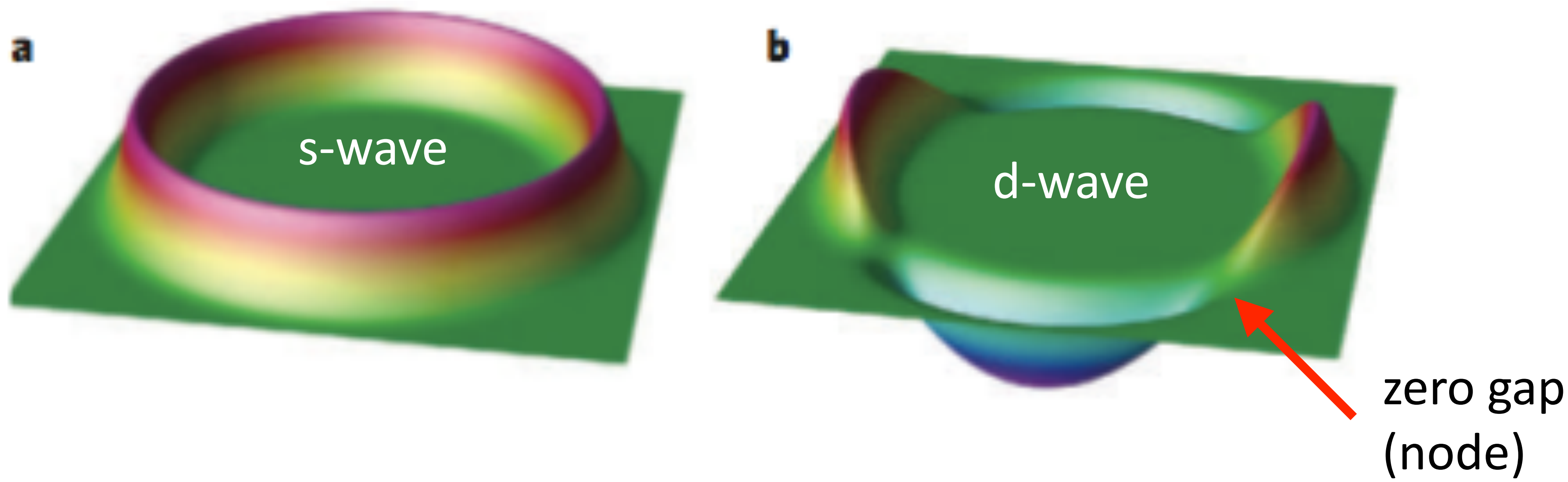
$$E_g = 2\Delta(0) = 3.53 k_B T_c$$



superconducting gap function

$$\Delta(k) = |\Delta| e^{i\phi}$$

Superconducting energy gap, $\Delta(k_x, k_y) = |\Delta| e^{i\phi}$



I. I. Mazin, Nature 464, 183 (2010)

conventional superconductor vs. unconventional superconductor

*symmetry of gap < symmetry of crystal lattice

Symmetry of spin-1/2 Cooper pairing state

total wave function Ψ = (spin part) x (orbital part)

antisymmetric for particle exchange, i.e., $\Psi(r_1, r_2) = -\Psi(r_2, r_1)$

<u>spin part</u>

singlet (S = 0, odd)

$$|0,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\uparrow\downarrow\rangle)$$

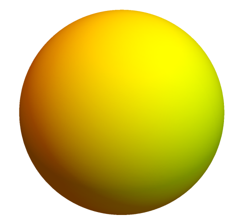
triplet (S = 1, even)

$$|1,1\rangle = |\uparrow\uparrow\rangle$$

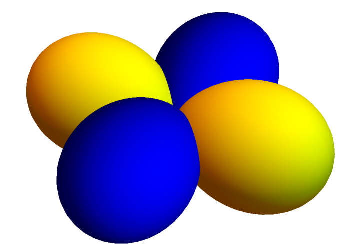
$$|1,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle)$$

$$|1,-1\rangle = |\downarrow\downarrow\rangle$$

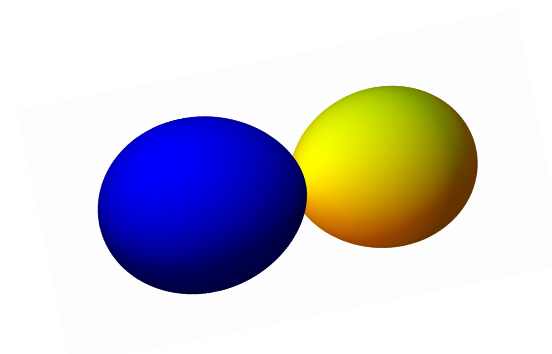
<u>orbital part</u>



s-wave (even)



d-wave (even)



p-wave (odd)

noncentrosymmetric superconductor: parity is not a good quantum number

$\Longrightarrow$mixing of both parity states

High spin Cooper pairing beyond S = 1 triplet?

High spin pairing in solid state? Yes !

Hamiltonian of multi-electron atom

$$H = H_0 + H_{\text{electronic}} + H_{\text{SOC}}$$

$$H_{\text{electronic}} \propto \frac{e^2}{|\mathbf{r}_i - \mathbf{r}_j|} - U_i(\mathbf{r}_i)$$ electronic interaction

$$H_{\text{SOC}} \propto \mathbf{L}_i \cdot \mathbf{S}_i$$ spin-orbit interaction dominant when Z is large.

In compounds with strong spin-orbit coupling (heavy elements), total angular momentum j and m_j are good quantum numbers.

total angular momentum of a pair: J = L + S

e.g. s = 1/2, l = 1 (p-orbital) $\Longrightarrow$ j = 3/2 (p-character)

Cooper pair from j=3/2 quasiparticles can have up to J=3 septet.

j=3/2 Cooper pairing states

j = 1/2 fermions (4 states)

- **J = 0 → 1 spin singlet**
- **J = 1 → 3 spin triplet**

j = 3/2 fermions (16 states)

- **J = 0 → 1 spin singlet**
- **J = 1 → 3 spin triplet**
- **J = 2 → 5 spin quintet**
- **J = 3 → 7 spin septet**

singlet (S = 0, odd)

$$|0,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\uparrow\downarrow\rangle)$$

P. M. R. Brydon et al., PRL 116, 177001 (2016)
H. Kim et al., Sci. Adv. 4, eaao4513 (2018)

triplet (S = 1, even)

$$|1,1\rangle = |\uparrow\uparrow\rangle$$

$$|1,0\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle)$$

$$|1,-1\rangle = |\downarrow\downarrow\rangle$$

How to study Cooper pairing states?

j=3/2 Cooper pairing states

$J=0$ singlet state

$$|J=0,m_J=0\rangle = \tfrac{1}{2}\Big(|\tfrac{3}{2},-\tfrac{3}{2}\rangle - |-\tfrac{3}{2},\tfrac{3}{2}\rangle - |\tfrac{1}{2},-\tfrac{1}{2}\rangle + |-\tfrac{1}{2},\tfrac{1}{2}\rangle\Big);$$

$J=1$ triplet states

$$\begin{aligned}
|J=1,m_J=1\rangle &= \tfrac{1}{\sqrt{10}}\Big(\sqrt{3}|\tfrac{3}{2},-\tfrac{1}{2}\rangle - 2|\tfrac{1}{2},\tfrac{1}{2}\rangle + \sqrt{3}|-\tfrac{1}{2},\tfrac{3}{2}\rangle\Big)\\
|J=1,m_J=0\rangle &= \tfrac{1}{\sqrt{20}}\Big(3|\tfrac{3}{2},-\tfrac{3}{2}\rangle - |\tfrac{1}{2},-\tfrac{1}{2}\rangle - |-\tfrac{1}{2},\tfrac{1}{2}\rangle + 3|-\tfrac{3}{2},\tfrac{3}{2}\rangle\Big)\\
|J=1,m_J=-1\rangle &= \tfrac{1}{\sqrt{10}}\Big(\sqrt{3}|-\tfrac{3}{2},\tfrac{1}{2}\rangle - 2|-\tfrac{1}{2},-\tfrac{1}{2}\rangle + \sqrt{3}|\tfrac{1}{2},-\tfrac{3}{2}\rangle\Big);
\end{aligned}$$

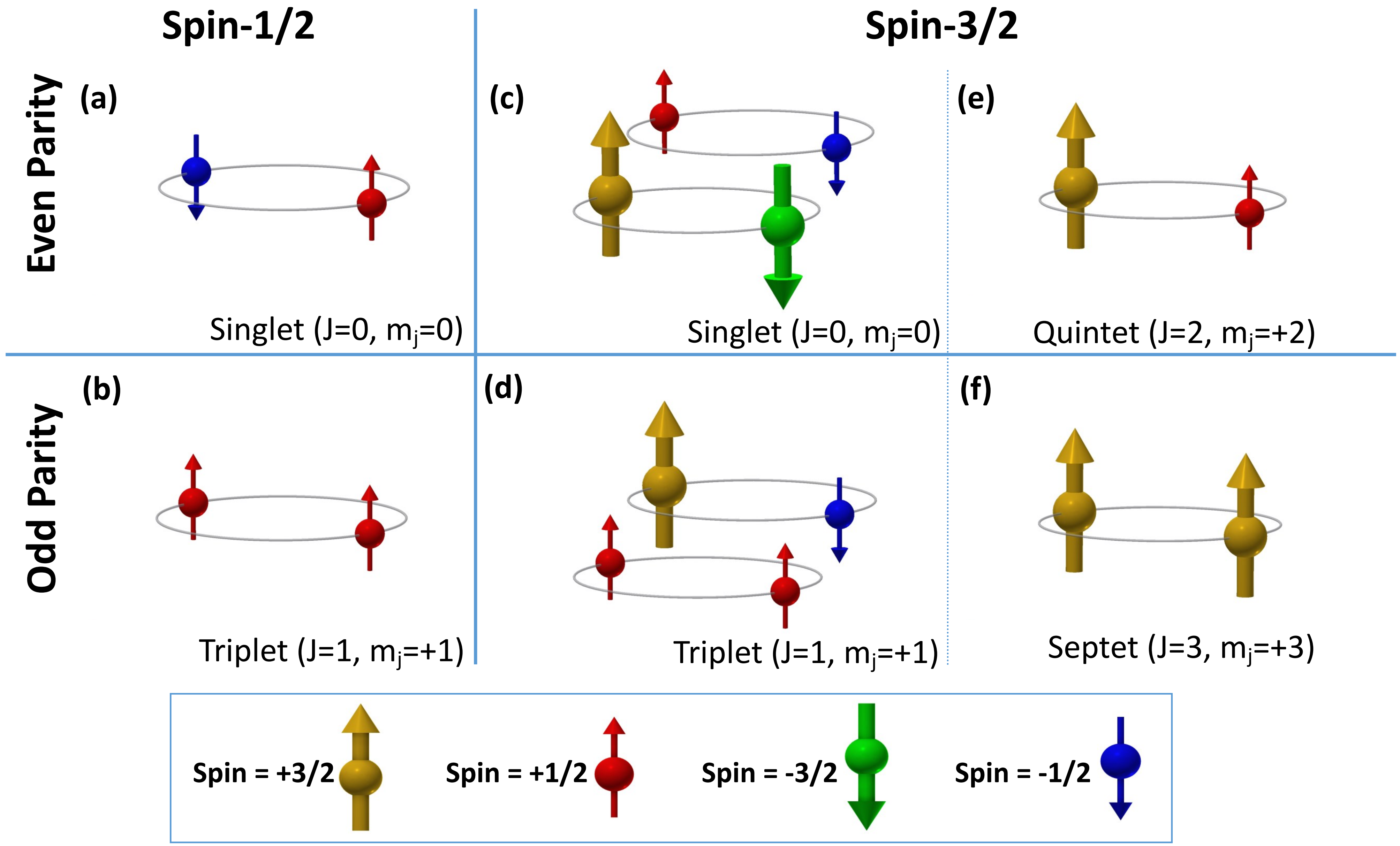
$J=2$ quintet states

$$\begin{aligned}
|J=2,m_J=2\rangle &= \tfrac{1}{\sqrt{2}}\Big(|\tfrac{3}{2},\tfrac{1}{2}\rangle - |\tfrac{1}{2},\tfrac{3}{2}\rangle\Big)\\
|J=2,m_J=1\rangle &= \tfrac{1}{\sqrt{2}}\Big(|\tfrac{3}{2},-\tfrac{1}{2}\rangle - |-\tfrac{1}{2},\tfrac{3}{2}\rangle\Big)\\
|J=2,m_J=0\rangle &= \tfrac{1}{2}\Big(|\tfrac{3}{2},-\tfrac{3}{2}\rangle + |\tfrac{1}{2},-\tfrac{1}{2}\rangle - |\tfrac{1}{2},-\tfrac{1}{2}\rangle - |-\tfrac{3}{2},\tfrac{3}{2}\rangle\Big)\\
|J=2,m_J=-1\rangle &= \tfrac{1}{\sqrt{2}}\Big(|-\tfrac{3}{2},\tfrac{1}{2}\rangle - |\tfrac{1}{2},-\tfrac{3}{2}\rangle\Big)\\
|J=2,m_J=-2\rangle &= \tfrac{1}{\sqrt{2}}\Big(|-\tfrac{3}{2},-\tfrac{1}{2}\rangle - |-\tfrac{1}{2},-\tfrac{3}{2}\rangle\Big);
\end{aligned}$$

and $J=3$ septet states

$$\begin{aligned}
|J=3,m_J=3\rangle &= |\tfrac{3}{2},\tfrac{3}{2}\rangle\\
|J=3,m_J=2\rangle &= \tfrac{1}{\sqrt{2}}\Big(|\tfrac{3}{2},\tfrac{1}{2}\rangle + |\tfrac{1}{2},\tfrac{3}{2}\rangle\Big)\\
|J=3,m_J=1\rangle &= \tfrac{1}{\sqrt{5}}\Big(|\tfrac{3}{2},-\tfrac{1}{2}\rangle + \sqrt{3}|\tfrac{1}{2},\tfrac{1}{2}\rangle + |-\tfrac{1}{2},\tfrac{3}{2}\rangle\Big)\\
|J=3,m_J=0\rangle &= \tfrac{1}{\sqrt{20}}\Big(|\tfrac{3}{2},-\tfrac{3}{2}\rangle + 3|\tfrac{1}{2},-\tfrac{1}{2}\rangle + 3|-\tfrac{1}{2},\tfrac{1}{2}\rangle + |-\tfrac{3}{2},\tfrac{3}{2}\rangle\Big)\\
|J=3,m_J=-1\rangle &= \tfrac{1}{\sqrt{5}}\Big(|\tfrac{3}{2},-\tfrac{1}{2}\rangle + \sqrt{3}|-\tfrac{1}{2},-\tfrac{1}{2}\rangle + |\tfrac{1}{2},-\tfrac{3}{2}\rangle\Big)\\
|J=3,m_J=-2\rangle &= \tfrac{1}{\sqrt{2}}\Big(|-\tfrac{3}{2},-\tfrac{1}{2}\rangle + |-\tfrac{1}{2},-\tfrac{3}{2}\rangle\Big)\\
|J=3,m_J=-3\rangle &= |-\tfrac{3}{2},-\tfrac{3}{2}\rangle.
\end{aligned}$$

j=3/2 high spin Cooper pairing



H. Kim et al., Sci. Adv. 4, eaao4513 (2018)

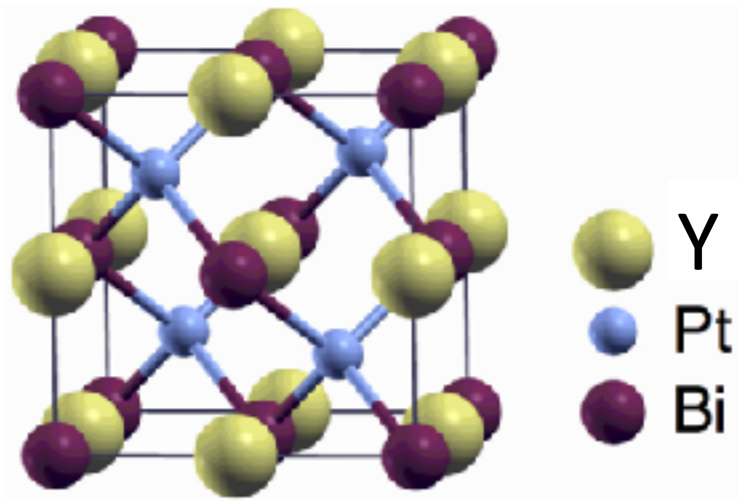
Half-Heusler RTBi (R=rare earth, T=Pt,Pd)

Topology
- Strong spin orbit interaction
- Band inversion
- Topological band structure
- Topological surface state
- Relativistic quasiparticles (Dirac and Weyl)

Superconductivity
- High-spin Cooper pairing
- Topological superconductivity
- Majorana fermion
- Low carrier superconductor
- non-centrosymmetric superconductor

Quantum information science and technology
- Topological qubits
- Superconducting qubits

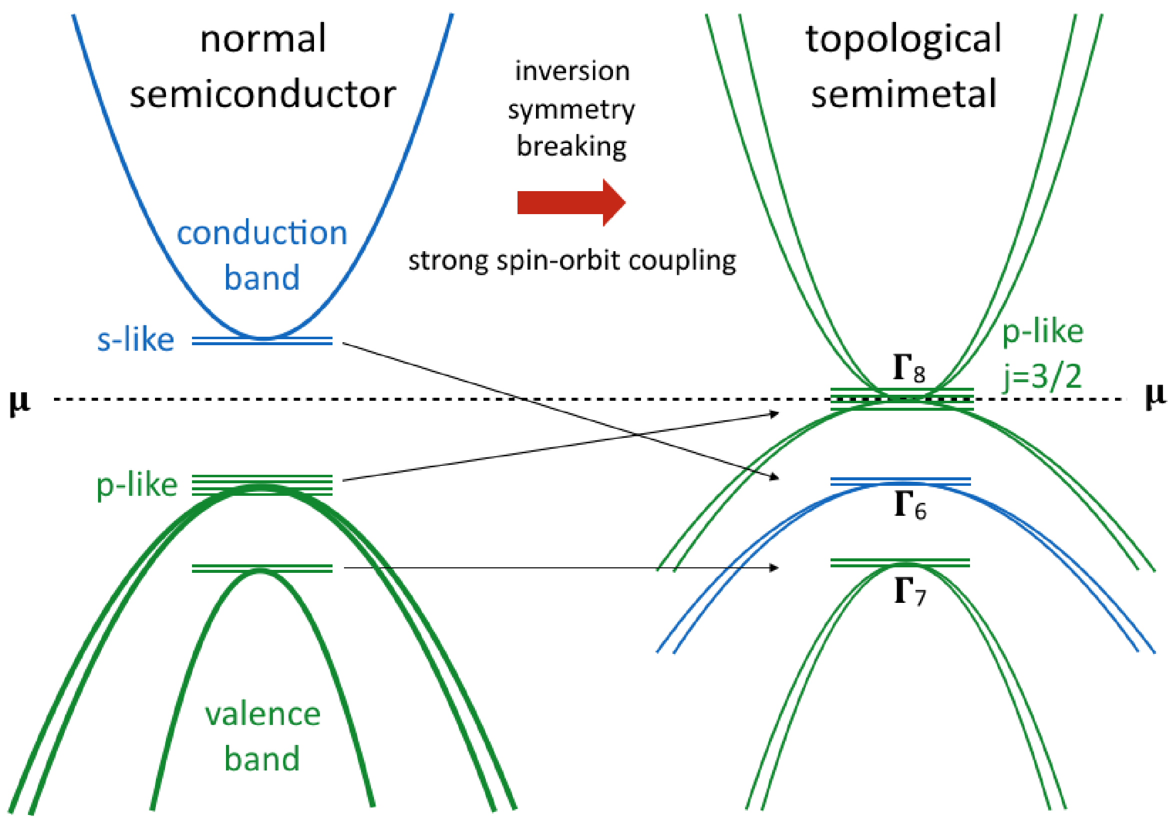
half-Heusler RTBi compounds: Topological semimetal



D. Xiao et al., PRL 105, 096404 (2010)

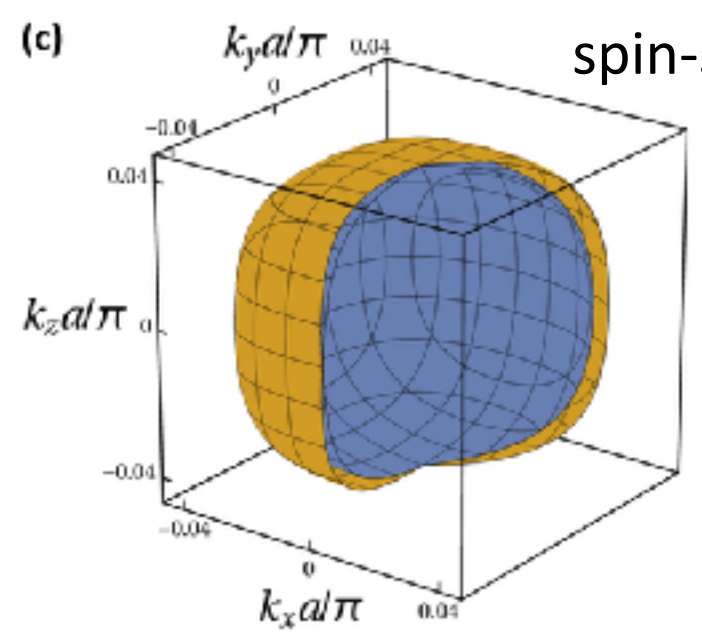
- half-Heusler YPtBi (fcc)

  = YBi (rocksalt) + PtBi (zincblende)
- strong spin-orbit coupling
- no inversion symmetry: spin-split band
- mixed parity Cooper pairing state



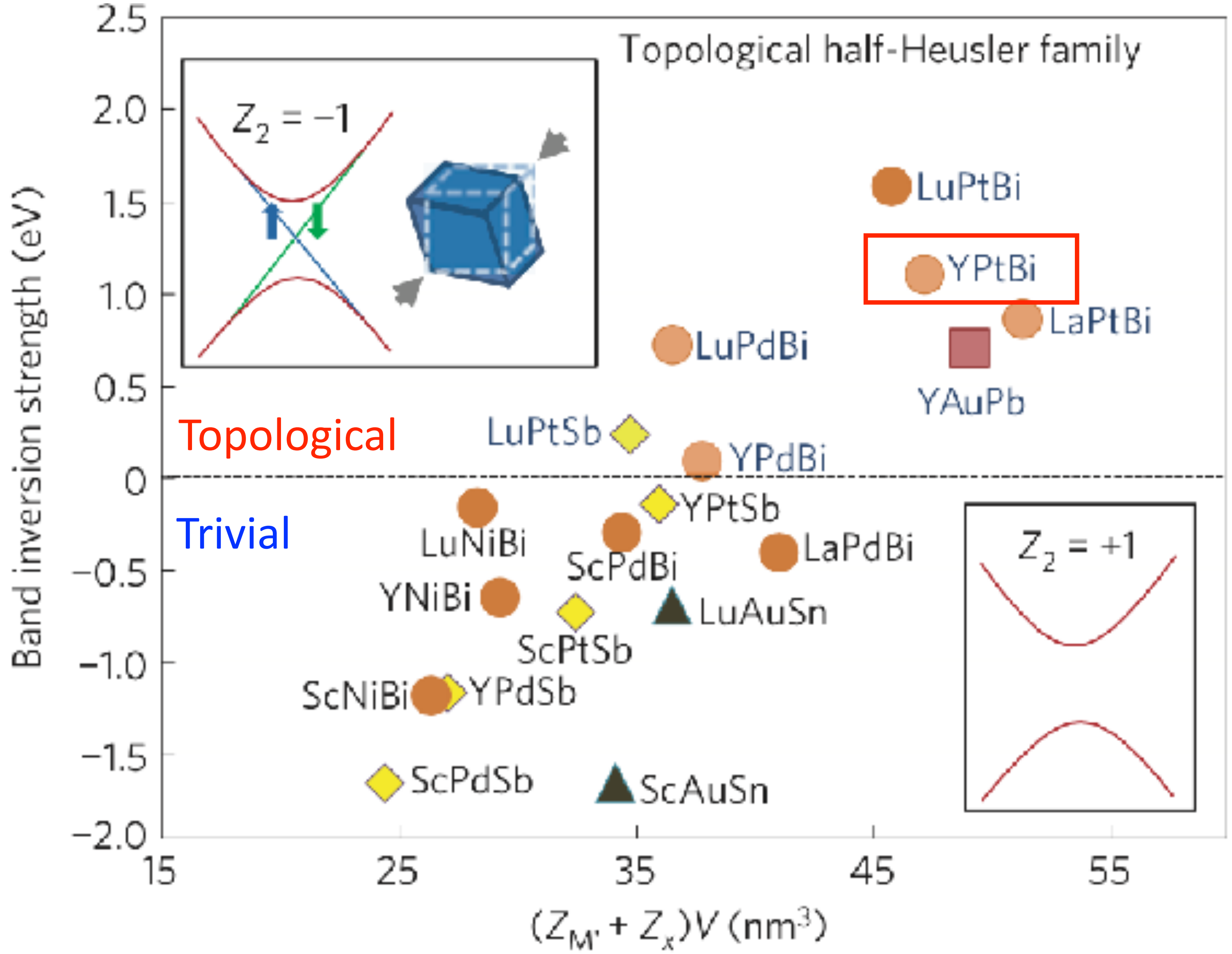
H. Kim et al., Sci. Adv. 4, eaao4513 (2018)

- band inversion
- spin-split band (Fermi surface)
- zero-gap semiconductor or semimetal
- j=3/2 conduction electrons
- Luttinger-Kohn Hamiltonian



spin-split Fermi surface of YPtBi

Strong Band Inversion in RTBi



MM'X

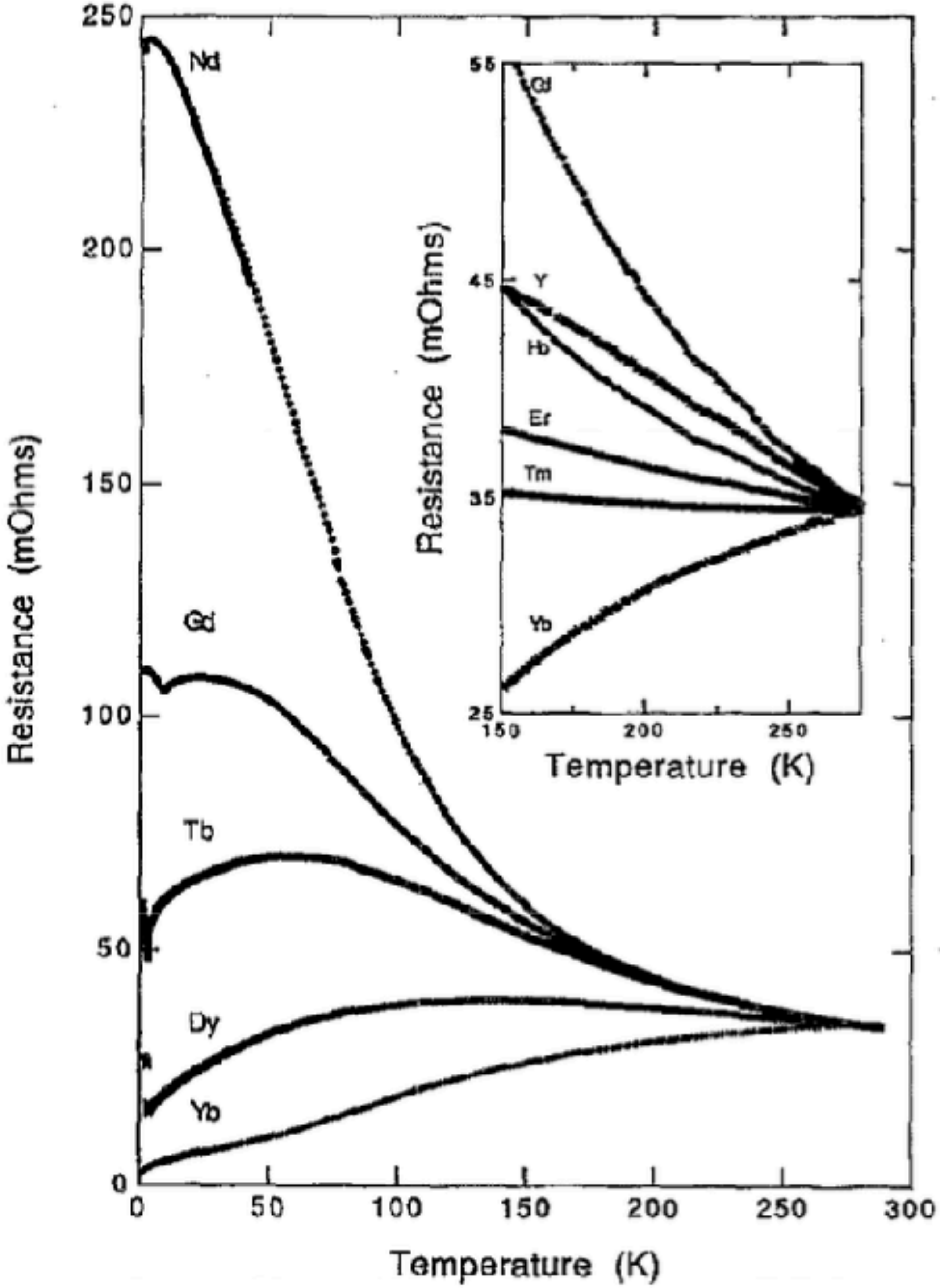
Z: nuclear charge of M' and X

V: unit cell volume

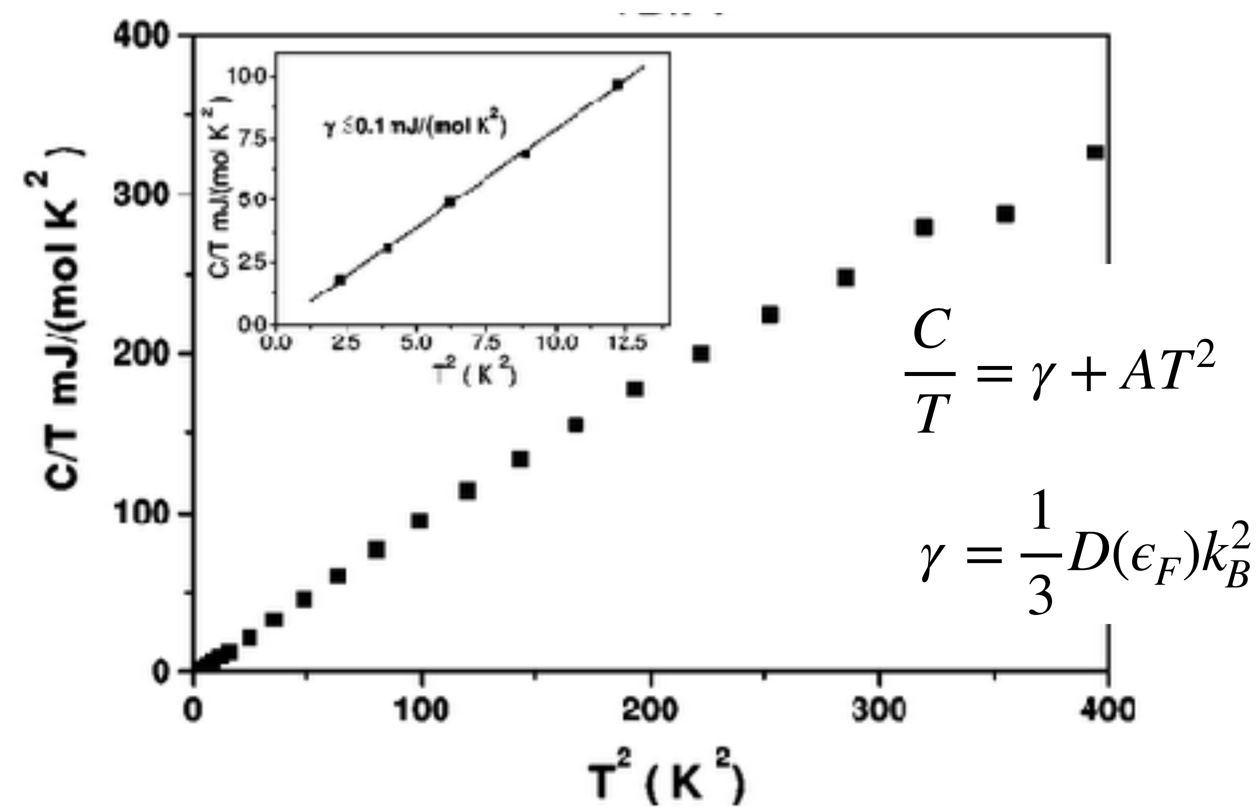
RPtBi compounds show strong band inversion!

H. Lin et al., Nature Materials 9, 546 (2010)

Normal State Properties RPtBi (R = rare earth)

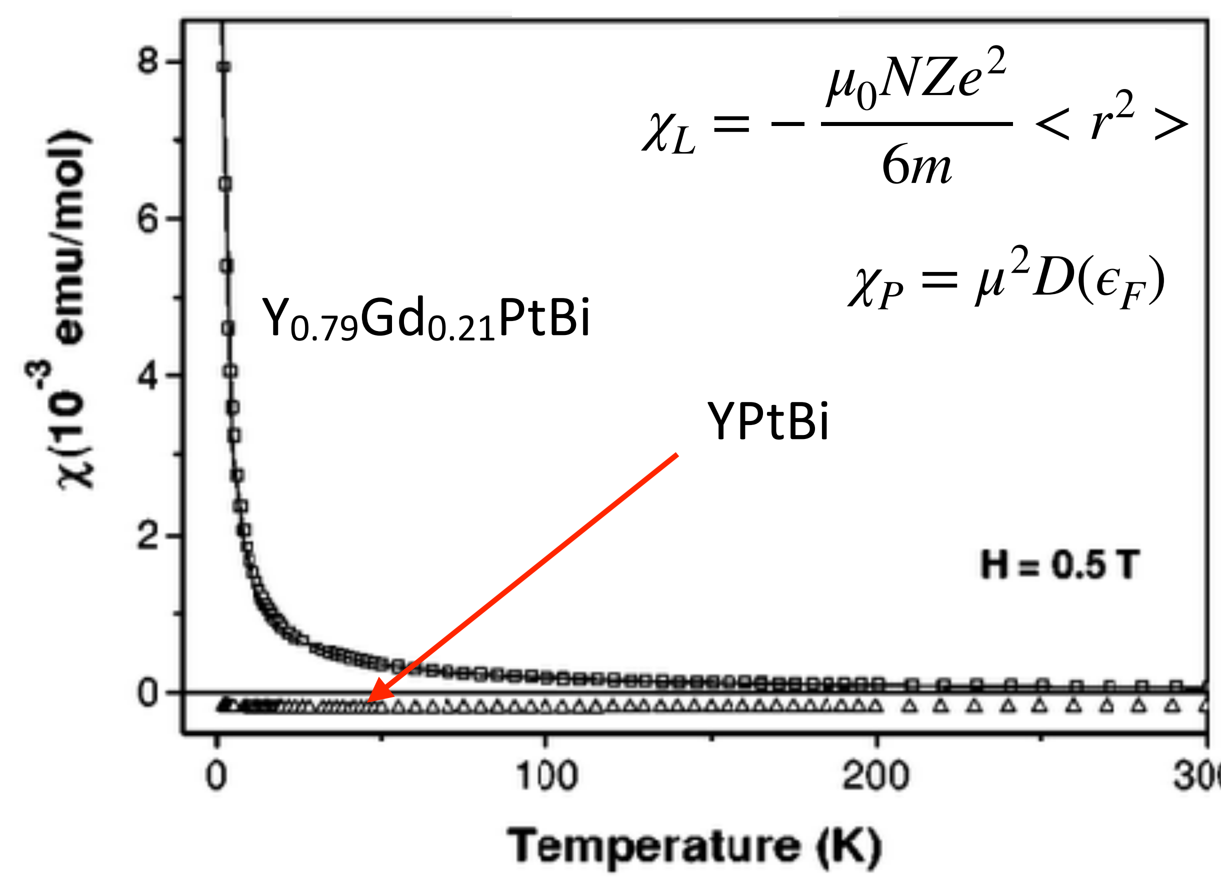


P. C. Canfield et al., J. Appl. Phys. 70, 5800 (1991)



$$\frac{C}{T} = \gamma + AT^2$$

$$\gamma = \frac{1}{3}D(\epsilon_F)k_B^2$$

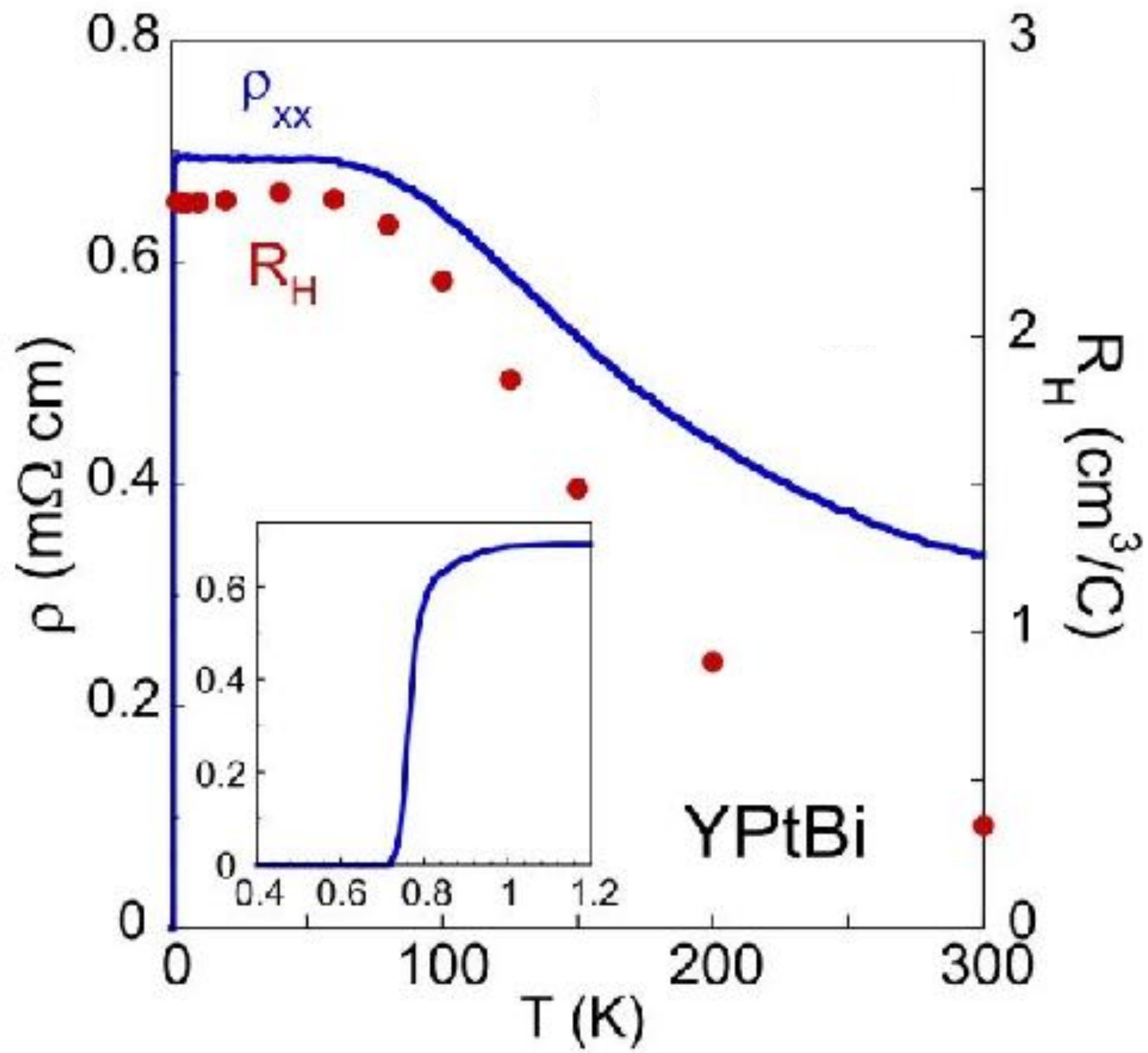


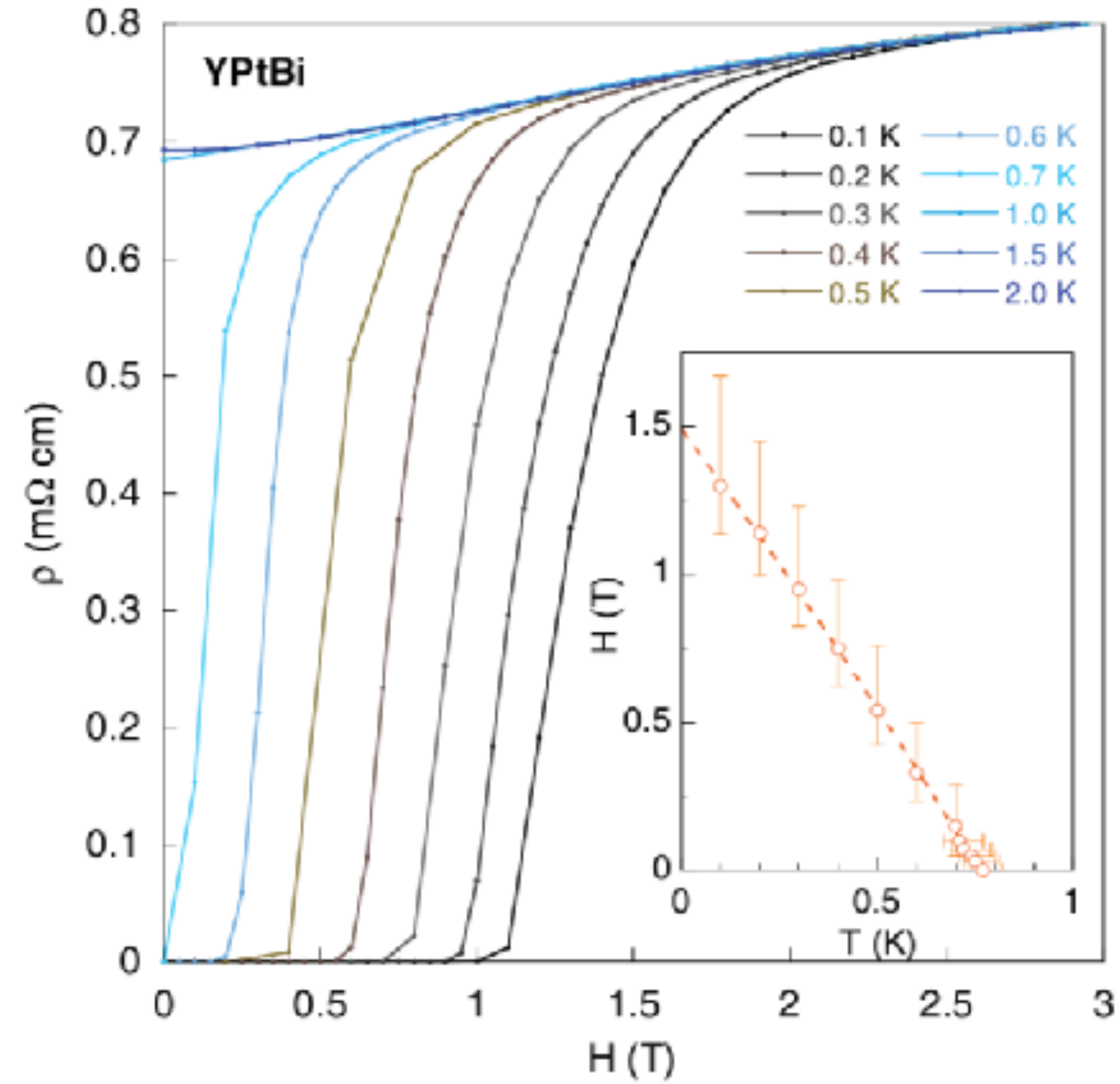
$$\chi_L = -\frac{\mu_0 NZe^2}{6m} < r^2 >$$

$$\chi_P = \mu^2 D(\epsilon_F)$$

P. G. Pagliuso et al., PRB 60, 4176 (1999)

Superconductivity in YPtBi





$$T_c = 0.78 \text{ K}$$

$$n = 2 \times 10^{18} \text{ cm}^{-3}$$

$$R_H = \frac{1}{ne}$$

$$H_{c2}(0) = 1.5 \text{ T}$$

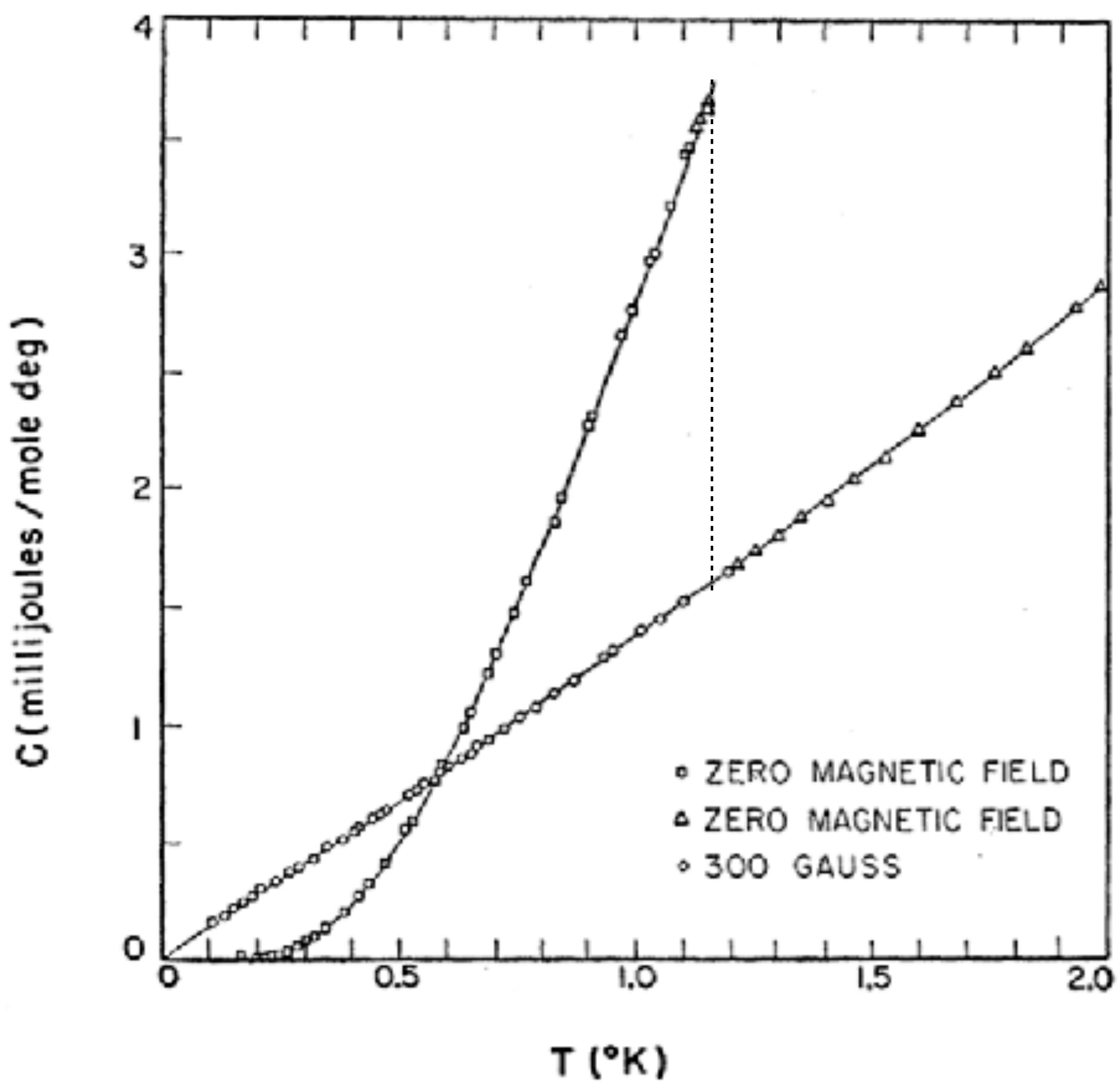
$$\xi(0) = \left(\frac{\Phi_0}{2\pi H_{c2}(0)} \right)^{1/2} = 15 \text{ nm}$$

N. P. Butch et al., PRB 84, 220504 (2011)

Probing superconducting energy gap

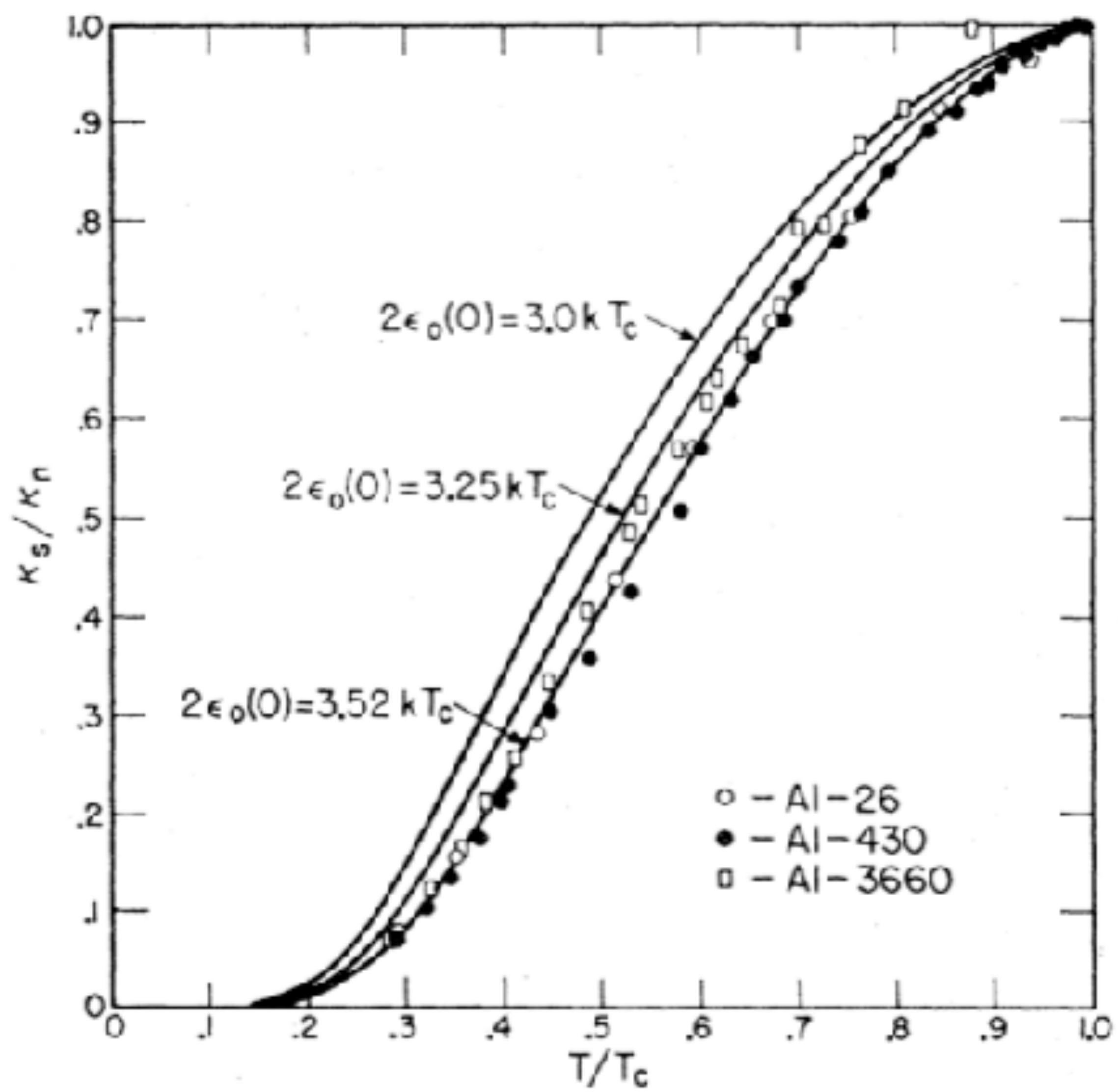
e.g. Aluminum: s-wave full gap, thermally activated quasiparticles

Electronic specific heat



N. E. Phillips, Phys. Rev. 114, 676 (1959)

Electronic thermal conductivity



C. B. Satterthwaite, Phys. Rev. 125, 873 (1962)

- exponentially decreasing heat capacity and thermal conductivity
- no quasiparticles, i.e., fully gapped superconducting gap
- nodal superconducting gap would exhibit a power-law

Activation behavior of s-wave superconducting gap

Electronic specific heat

$$\frac{C_{es}}{\gamma T_c} \propto \exp\left(-\frac{bT_c}{T}\right) \qquad C_{en} = \gamma T$$

$$\gamma = \frac{1}{3} D(\epsilon_F) k_B^2$$

sensitivity proportional to normal state density of states or carrier density

YPtBi: n ~ 10^{18} cm^{-3}

Electronic thermal conductivity

$$\frac{\kappa_{es}}{\kappa_{en}} \propto \left(\frac{\Delta}{k_B T}\right)^2 \exp\left(-\frac{\Delta}{k_B T}\right) \qquad \kappa = \frac{1}{3} C v l$$

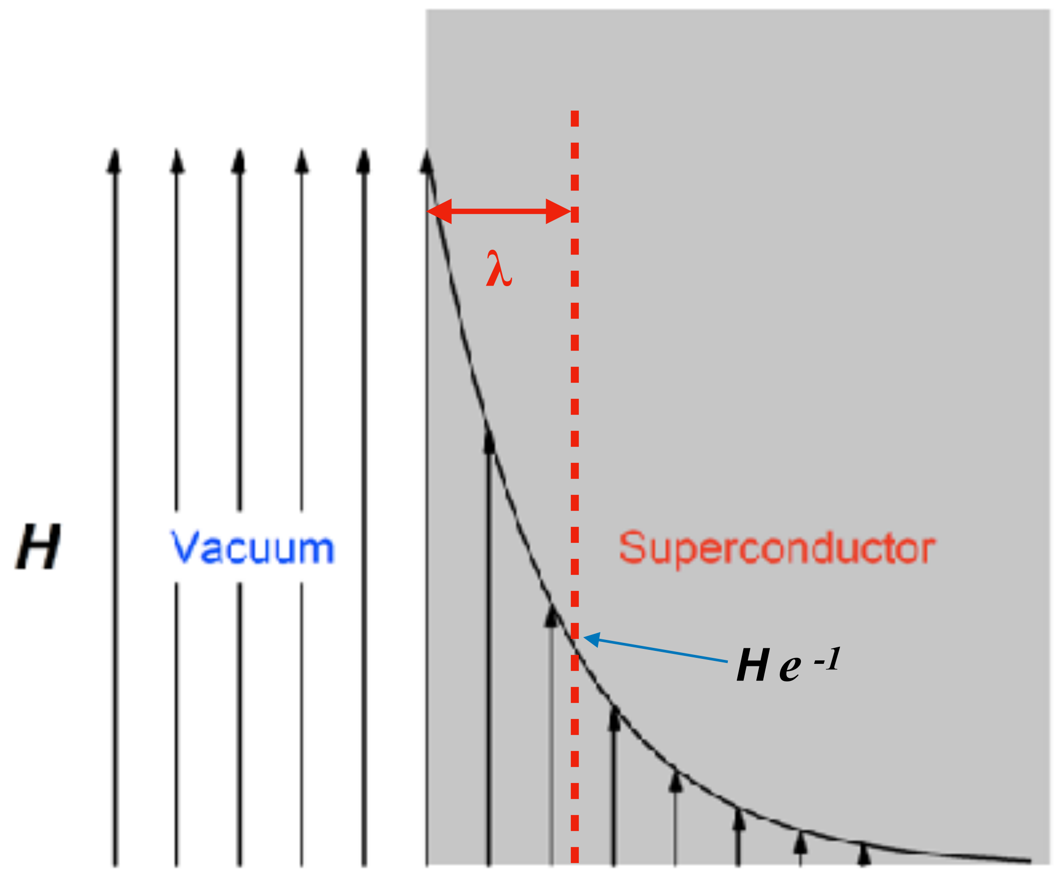
$$\kappa_{en} = \frac{\pi^2}{3}\frac{n k_B T}{m v_F^2} \cdot v_F \cdot l = \frac{\pi^2 n k_B^2 \tau}{3m} T$$

London penetration depth

$$\Delta\lambda_L = \lambda_L(0)\sqrt{\frac{\pi\Delta(0)}{2k_B T}} \exp\left(-\frac{\Delta(0)}{k_B T}\right) \qquad \lambda_L(0) = \sqrt{\frac{mc^2}{4\pi n e^2}}$$

London penetration depth and Meissner effect

London penetration depth λ



London equation

$$\mathbf{j}(\mathbf{r}) = \frac{c}{4\pi}\frac{\mathbf{A}(\mathbf{r})}{\lambda_L^2}$$

$$\nabla^2 H = \frac{1}{\lambda_L^2} H$$

inside superconductor

$$H = H_0 \exp\left(-\frac{x}{\lambda_L}\right)$$

works only for isotropic case.

Semiclassical London theory and superfluid density

$$\mathbf{j}(\mathbf{r}) = \frac{c}{4\pi}\frac{\mathbf{A}(\mathbf{r})}{\lambda_{ii}^2}$$

anisotropic components of London penetration depth

$$\lambda_{ii}^2 = \frac{c}{4\pi R_{ii}}$$

London penetration depth

$$R_{ii} \approx \frac{e^2}{2\pi^3 \hbar c}\oint dS_F \frac{\mathbf{v_F v_F}}{v_F}\int_{\Delta(k)}^{\infty} dE_k \left(-\frac{\partial f}{\partial E_k}\right)\frac{E(k)}{E^2(k)-\Delta^2(k)}$$

$$n_{ii}(T) = \frac{c m_{ii}}{e^2} R_{ii}(T)$$

superfluid density component

normalized superfluid density component

$$\rho_{ii}(T) = \frac{n_{ii}(T)}{n} = \frac{R_{ii}(0)}{R_{ii}(T)} = \frac{\lambda_{ii}^2(0)}{\lambda_{ii}^2(T)}$$

B. S. Chandrasekhar and D. Einzel, Ann. Physik. 2, 535 (1993)

Semiclassical London theory and superfluid density

3D spherical Fermi surface in-plane a-component

$$\rho_a(T) = 1 - \frac{3}{4\pi T}\int_0^1 (1-z^2)\int_0^{2\pi} \cos^2\phi \int_0^\infty \cosh^{-2}\left(\frac{\sqrt{\epsilon^2 + \Delta^2(T,\theta,\phi)}}{2T}\right) d\epsilon\, d\phi\, dz$$

isotropic s-wave pairing in both 2D and 3D

$$\rho(T) = 1 - \frac{1}{2T}\int_0^\infty \cosh^{-2}\left(\frac{\sqrt{\epsilon^2 + \Delta^2(T)}}{2T}\right) d\epsilon$$

$$\frac{\Delta\lambda(T)}{\lambda(0)} \approx \frac{1-\rho(T)}{2}$$

isotropic s-wave: T-exponential

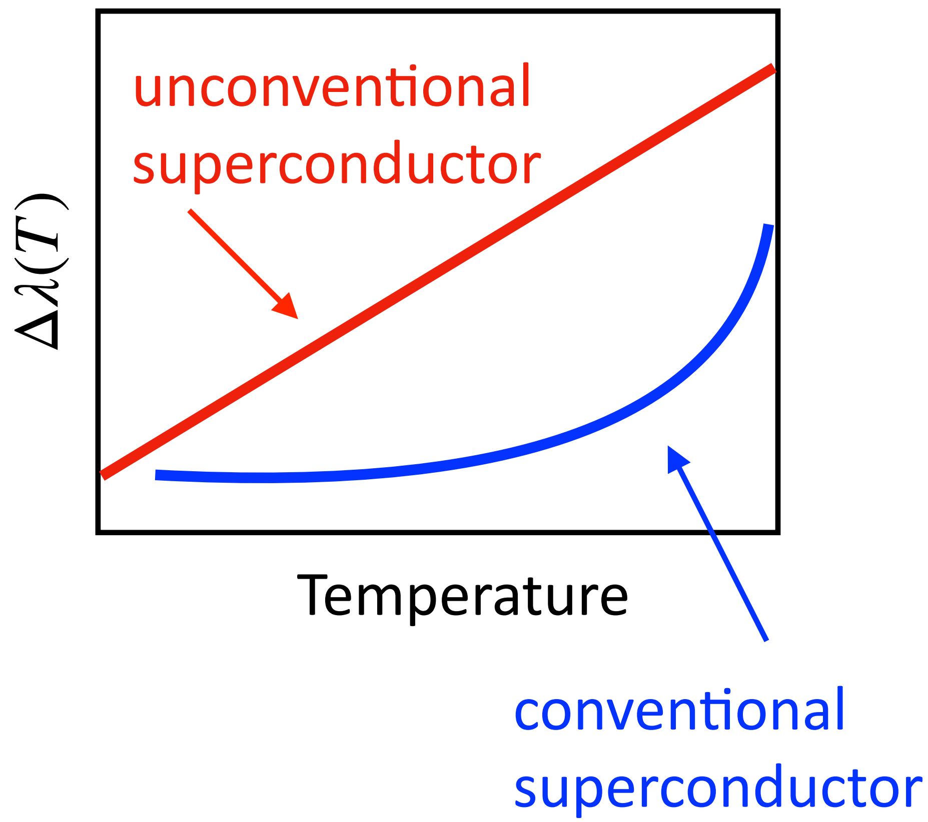
$$\Delta\lambda_L = \lambda_L(0)\sqrt{\frac{\pi\Delta(0)}{2k_B T}}\exp\left(-\frac{\Delta(0)}{k_B T}\right)$$

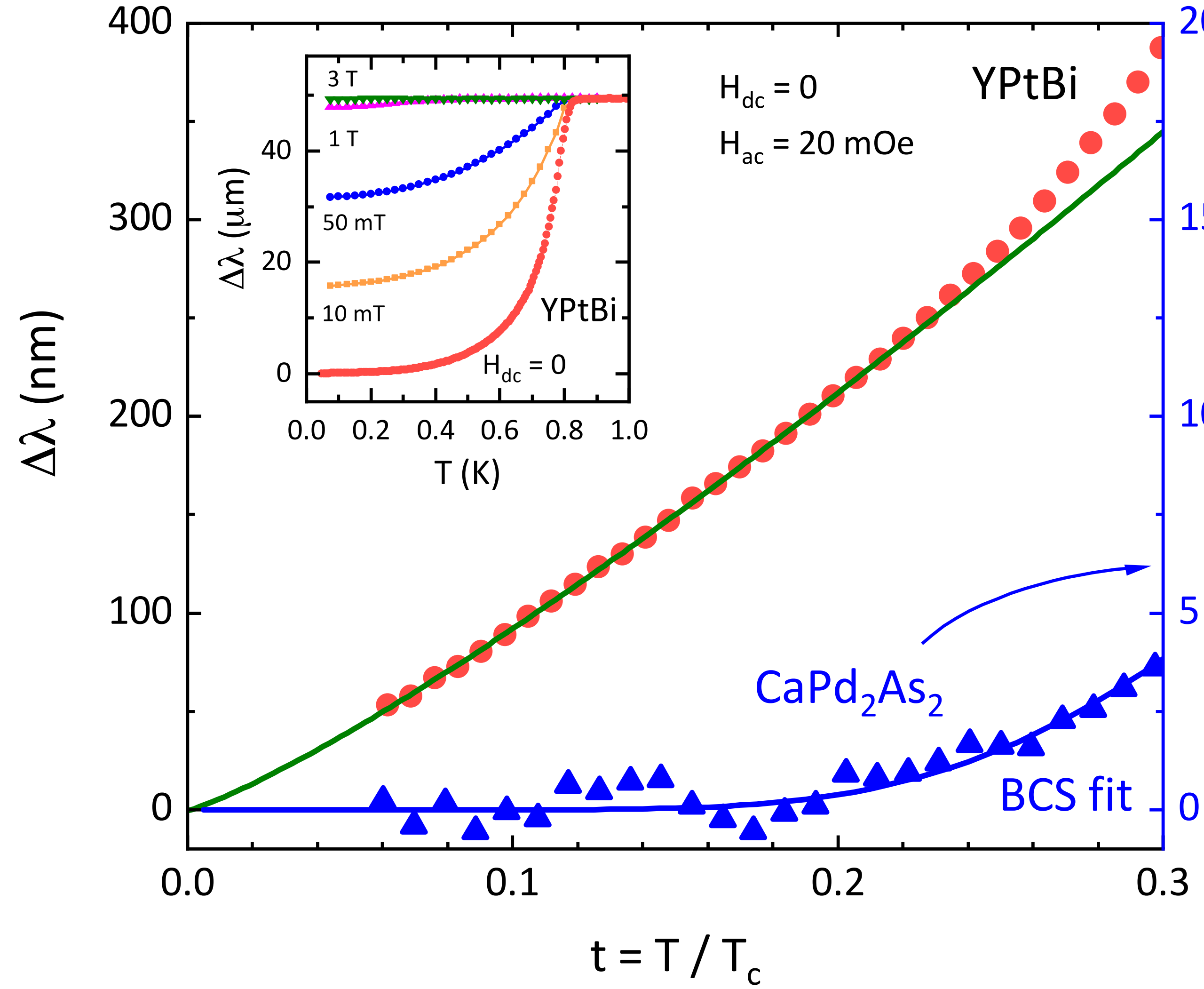
line nodal : T-linear

$$\Delta\lambda_L(T) = \lambda_L(0)\frac{2\ln 2}{\alpha\Delta(0)}T$$

London penetration depth in YPtBi

radio frequency
-oscillator
~ 1Å precision



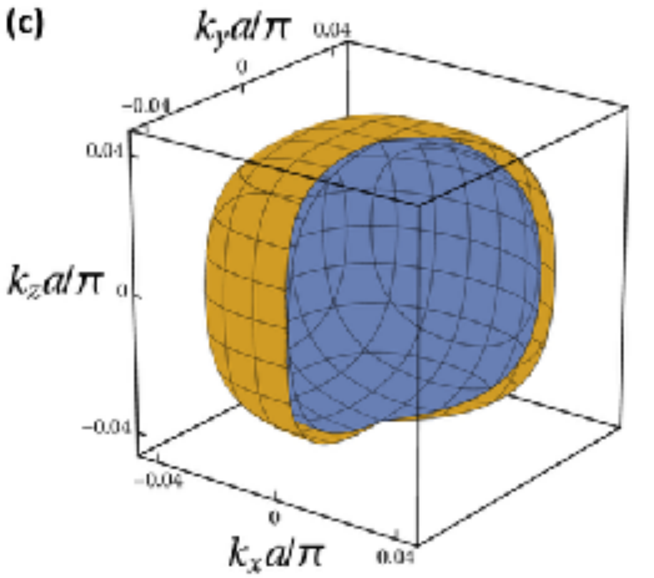


H. Kim et al., Science Advances 4, eaao4513 (2018)

conventional superconductor $$\Delta\lambda_L = \lambda_L(0)\sqrt{\frac{\pi\Delta_0}{2k_BT}}\exp\left(-\frac{\Delta_0}{k_BT}\right)$$

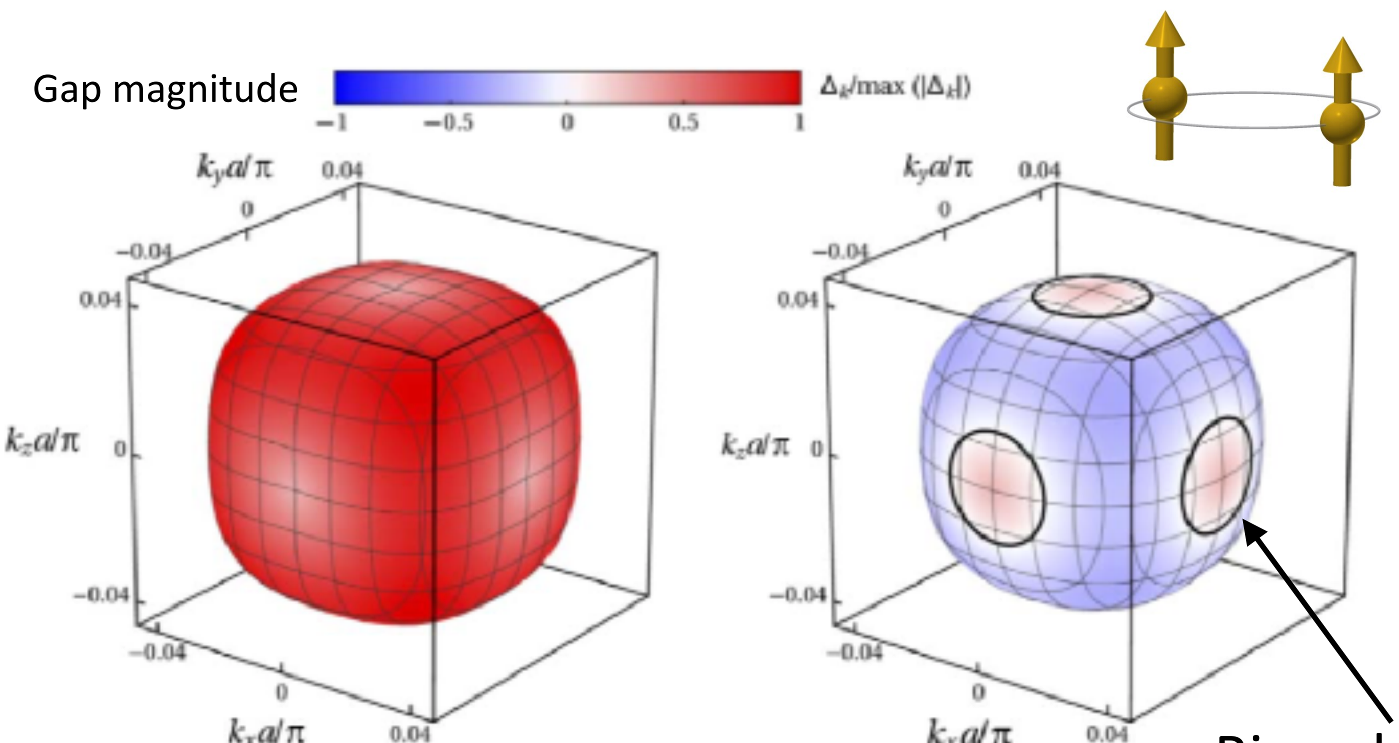
unconventional superconductor $\Delta\lambda_L \propto T^n$ $\quad n \approx 1$ Lines of zero gap (nodes)

J=3 Septet Cooper pair in YPtBi



j=3/2 Fermi surface
:Energy-momentum relation
of active electrons

J = 3 septet

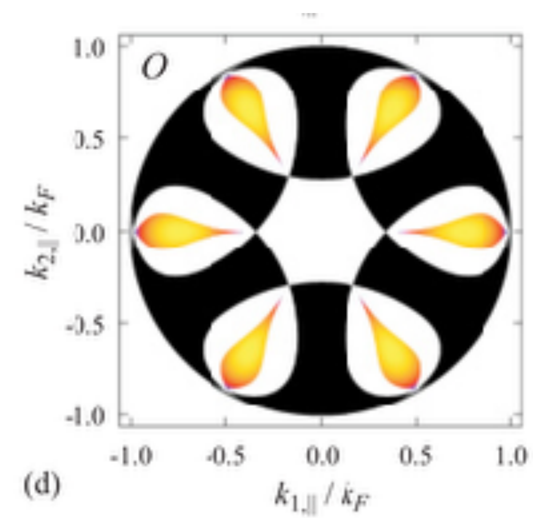


Ring-shape line nodes

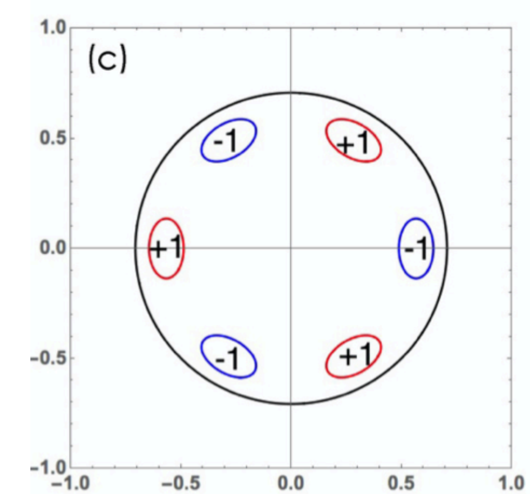
- mixed s-wave singlet and p-wave septet pairing
- First high spin (beyond J=1 triplet) superconductor?
- Topological superconductor

H. Kim et al., Sci. Adv. 4, eaao4513 (2018)

Majorana surface fluid



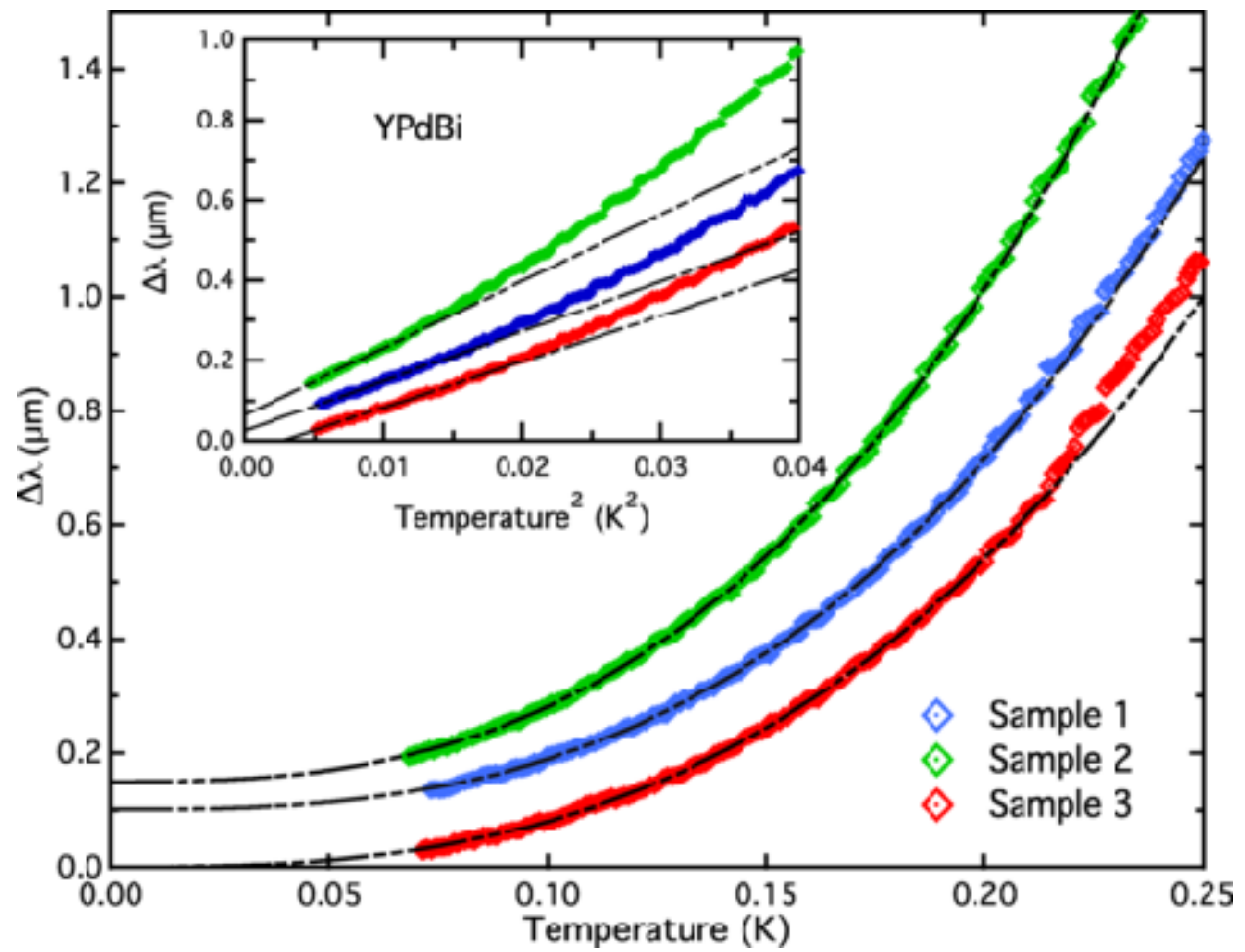
C. Timm et al.,
PRB 96, 094526 (2017)



W. Yang et al.,
PRB 96, 144514 (2017)

YPtBi: ‘silicon’ of
Quantum computation?

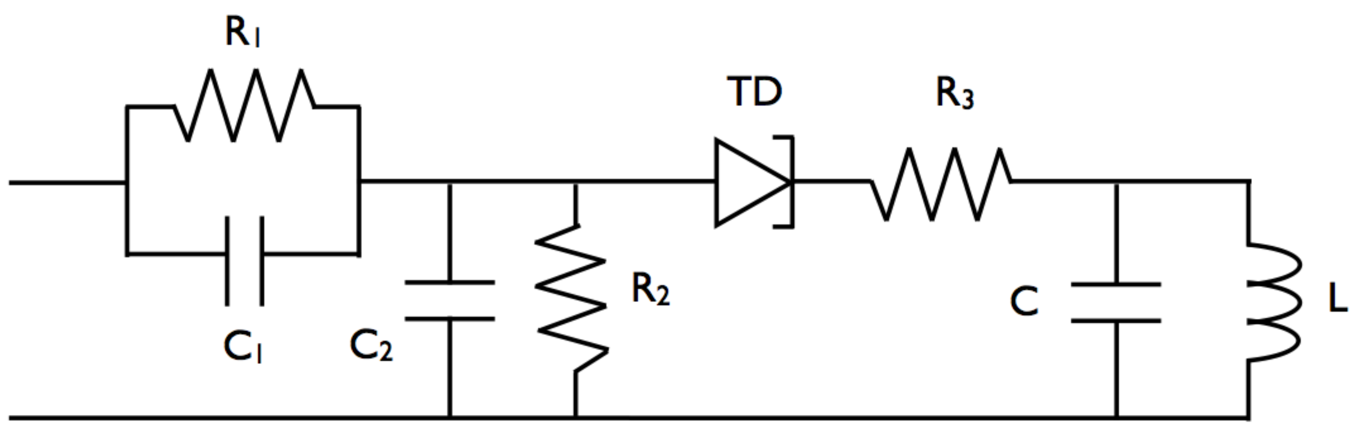
London penetration depth in YPdBi



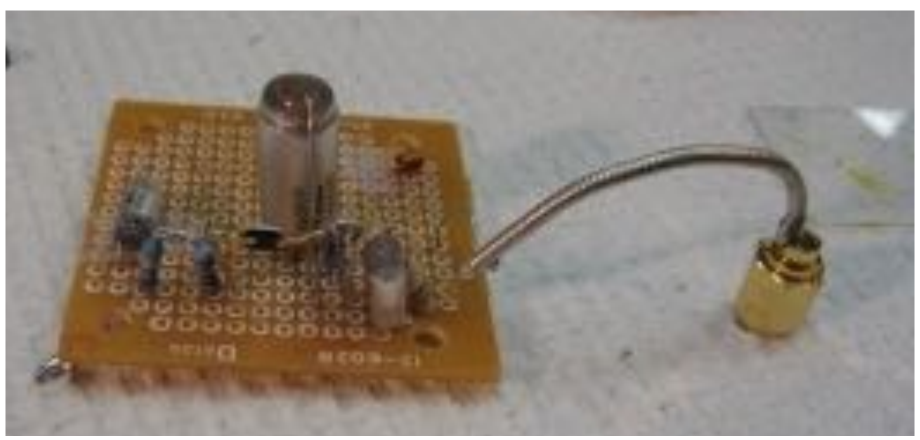
S. M. A. Radmanesh et al., Phys. Rev. B 98, 241111 (2018)

$$\Delta\lambda(T) \propto T^2$$

Radio frequency oscillator: Tunnel diode oscillator (TDO)



Sample inside inductor coil



$$\frac{\Delta f}{f_0} \approx \frac{1}{2}\frac{V_s}{V_c}4\pi\chi$$

V_s : sample volume
V_c : coil volume

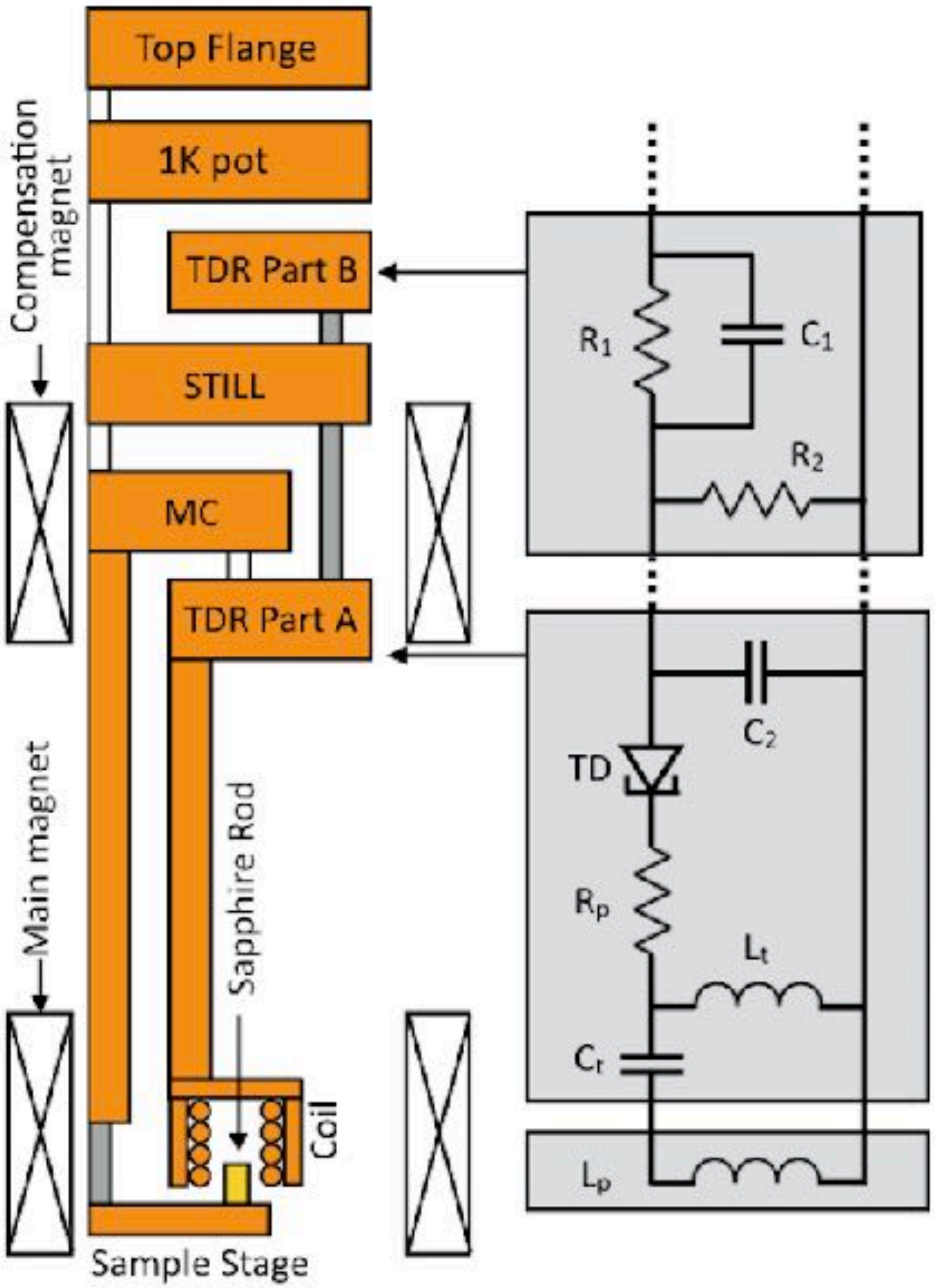
$$\frac{\Delta f}{f_0} \approx \frac{V_s}{2V_c}\left(1 - \frac{\lambda_L}{R}\tanh\frac{R}{\lambda_L}\right)$$

R : effective sample dimension shape-dependent

$$R \gg \lambda_L \qquad \Delta f(T) \propto \Delta\lambda_L(T)$$

Frequency resolution 10 mHz/10 MHz, 0.001 ppm
Penetration depth length resolution of TDO technique ~10^{-10} m (size of atom)

Tunnel diode oscillator (TDO) technique



$$\frac{\Delta f}{f_0} \approx \frac{1}{2}\frac{V_s}{V_c}4\pi\chi$$

infinite slab of thickness 2d

$$\frac{\Delta f}{f_0} \approx \frac{1}{2}\frac{V_s}{V_c}\left[1 - \mathrm{Re}\frac{\tanh(\alpha d)}{\alpha d}\right]$$

normal metal

$$\alpha = (1-i)/\delta$$

$$\delta = (c/2\pi)\sqrt{\rho/f_0}$$

superconductor

$$\alpha = 1/\lambda$$

finite slab with effective dimension R

$$\frac{\Delta f}{f_0} \approx \frac{V_s}{2V_c(1-N)}\left(1 - \frac{\lambda}{R}\tanh\frac{R}{\lambda}\right)$$

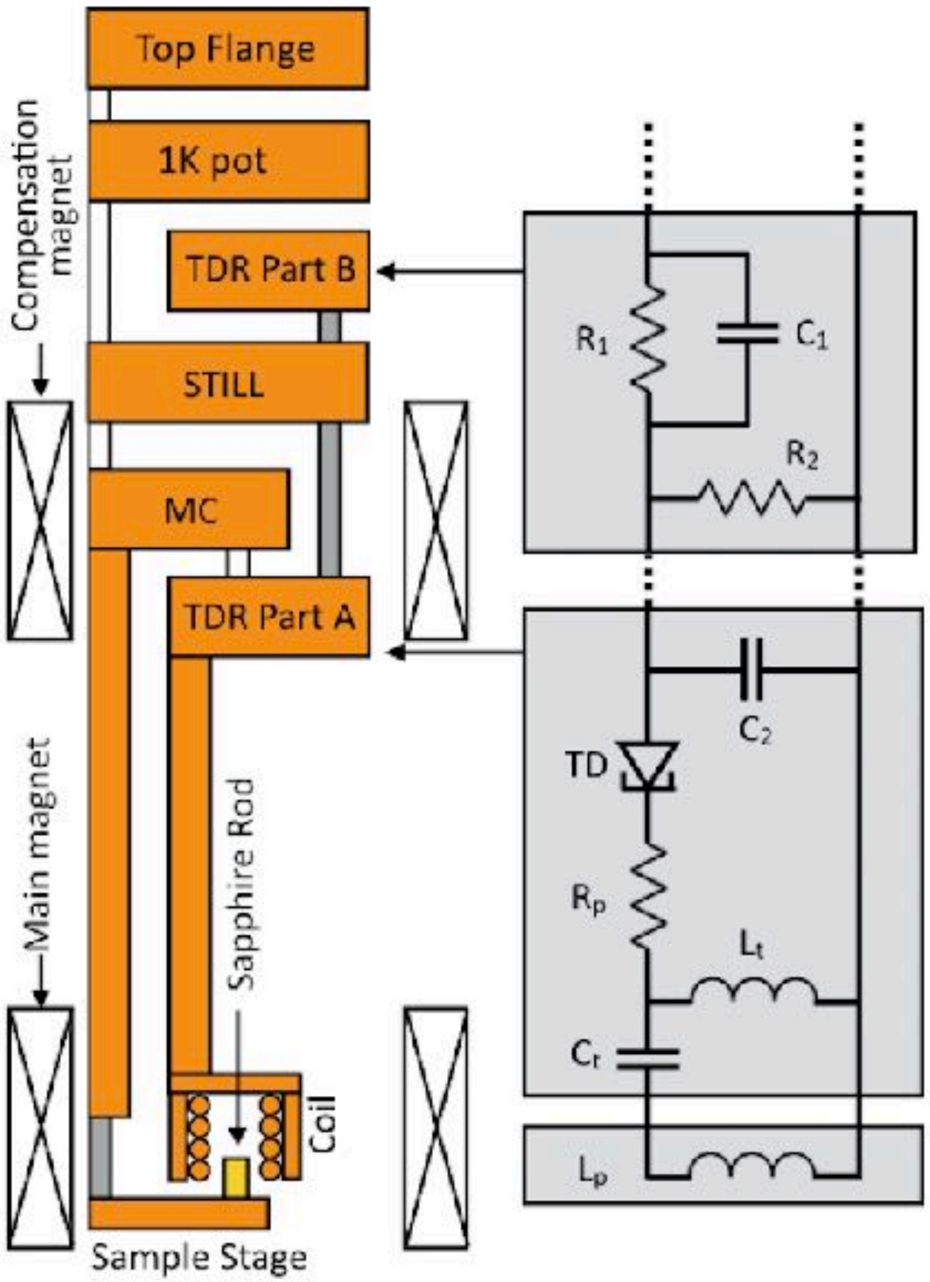
$$R \gg \lambda$$

$$\Delta f(T) \propto \Delta\lambda(T)$$

H. Kim et al., Rev. Sci. Instrum. 89, 094704 (2018)

mK-High field TDO

DOE Ames lab



H. Kim et al., Rev. Sci. Instrum. 89, 094704 (2018)

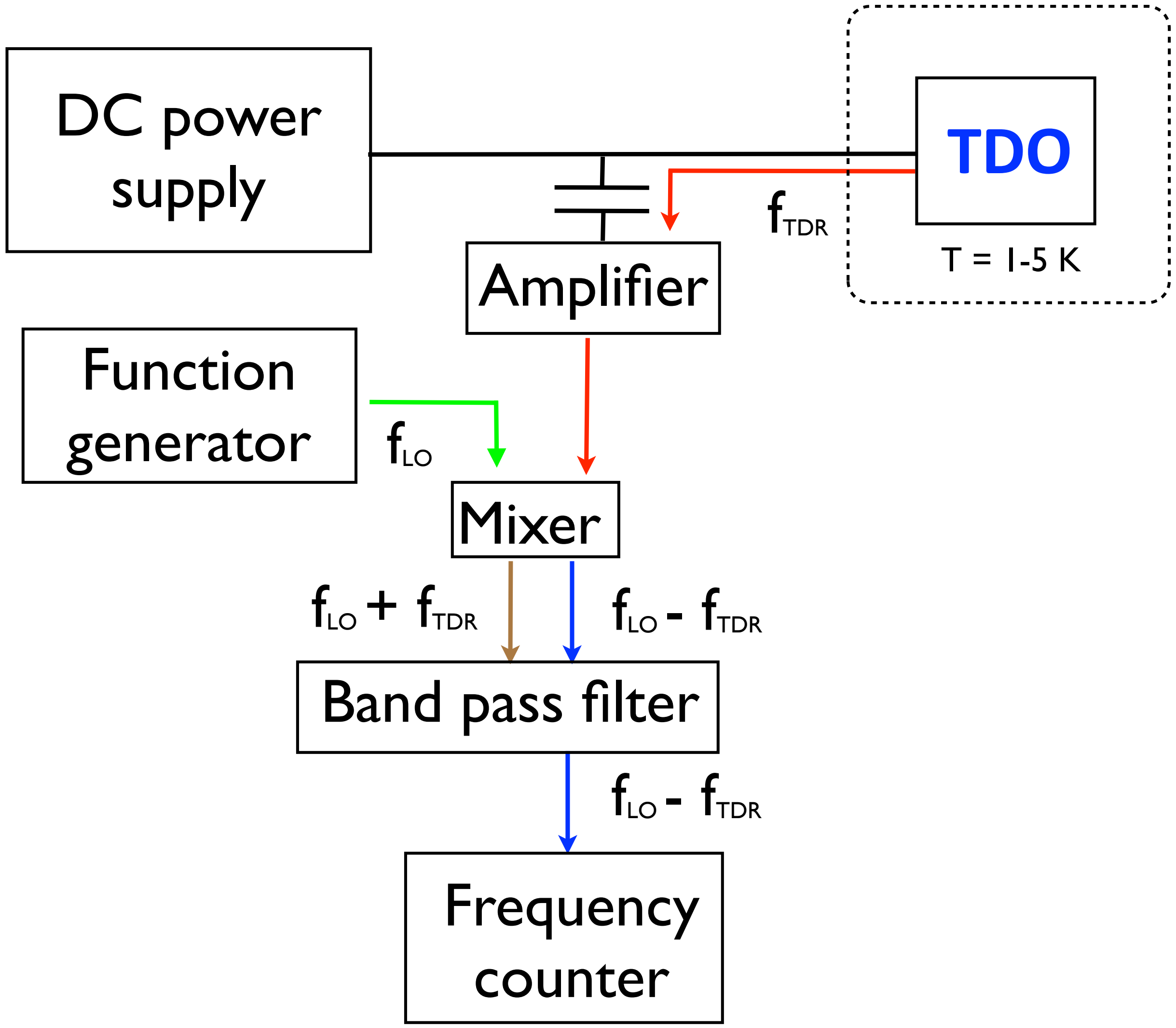
M/C (T = 20 mK)

TDO
1.5 K

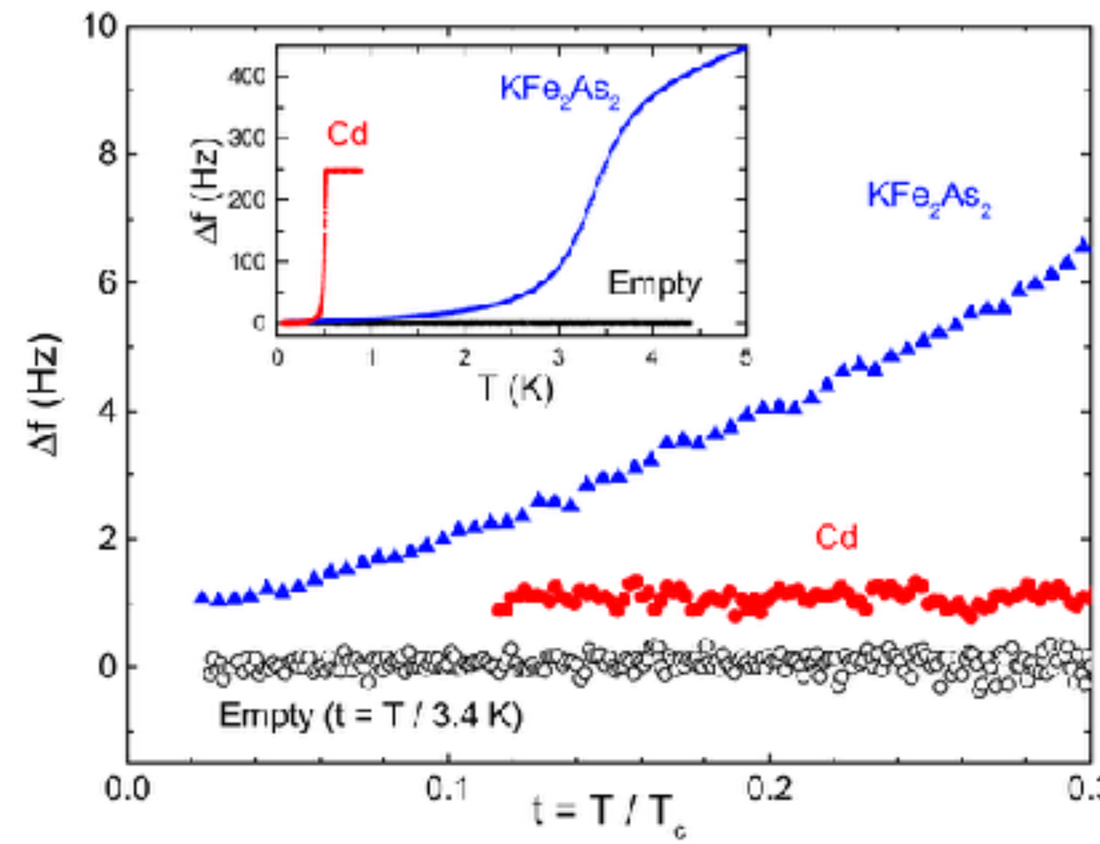
Coil
1.5 K

Sample
30 mK

TDO measurement setup



$$\Delta f(T) \propto \Delta\lambda(T)$$



KFe_2As_2 : line nodal gap

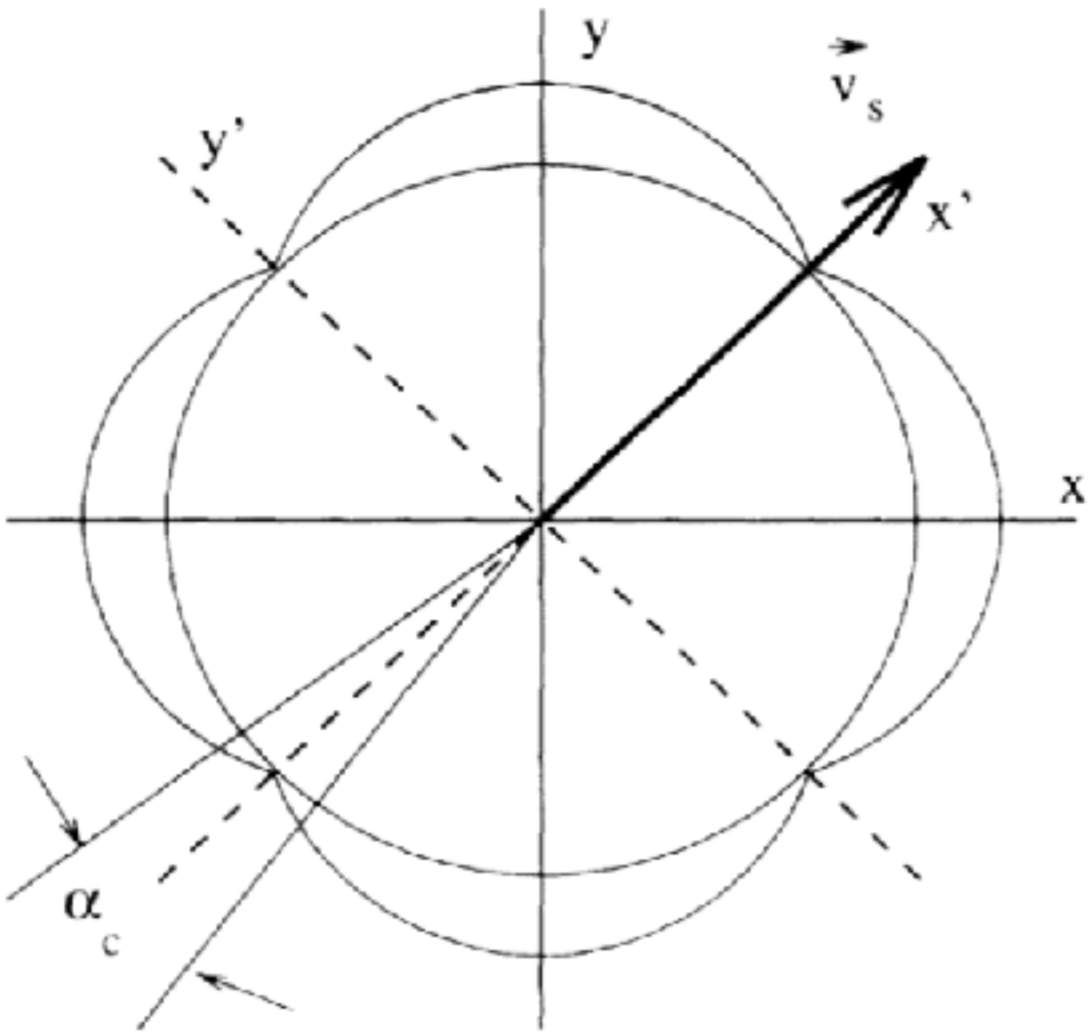
$$\Delta\lambda_L(T) \propto T^n$$

Cd : isotropic gap

$$\Delta\lambda_L = \lambda_L(0)\sqrt{\frac{\pi\Delta(0)}{2k_BT}}\exp\left(-\frac{\Delta(0)}{k_BT}\right)$$

H. Kim et al., Rev. Sci. Instrum. 89, 094704 (2018)

Superconducting energy gap spectroscopy



Nonlinear Meissner effect
(e.g., d_{x2-y2} -symmetry)

H // node
$$\frac{1}{\lambda_{\text{eff}}} = \frac{1}{\lambda}\left(1 - \frac{2}{3}\frac{H}{H_c}\right)$$

H // antinode
$$\frac{1}{\lambda_{\text{eff}}} = \frac{1}{\lambda}\left(1 - \frac{1}{\sqrt{2}}\frac{2}{3}\frac{H}{H_c}\right)$$

S. K. Yip and J. A. Saul PRL 69, 2264 (1992)

Summary

- Quantum materials research can lead to a breakthrough in technology.
- Topological quantum materials can be “silicon” of quantum computation technology.
- There is need for finding topological materials.
- High spin j=3/2 materials host topological superconductivity
- YPtBi is a candidate for the first high spin superconductor

Thank you for your attention!