最近の実験研究の話題：
非従来型超伝導における様々な対称性

京大院理　固体電子物性研究室
芝内 孝禎

1. Introduction
   非従来型超伝導における対称性の破れ

2. 重い電子系超伝導体URu_2Si_2におけるカイラルd波超伝導

3. 鉄ヒ素系新高温超伝導体における拡張s波超伝導

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原子力機構

芳賀 芳範
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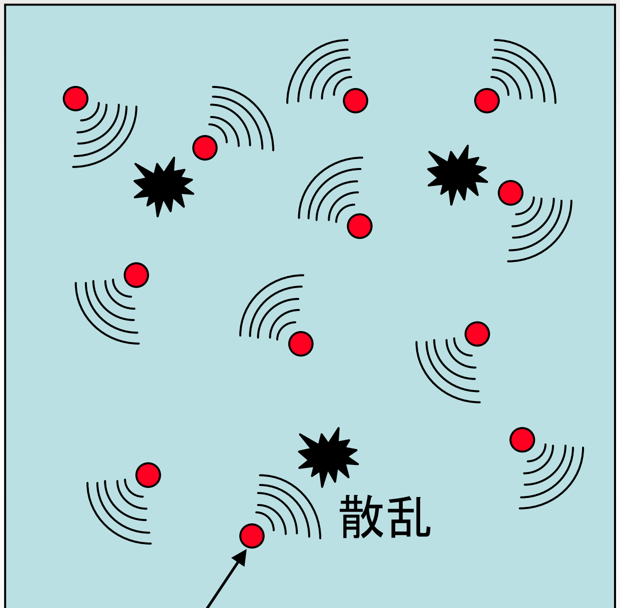
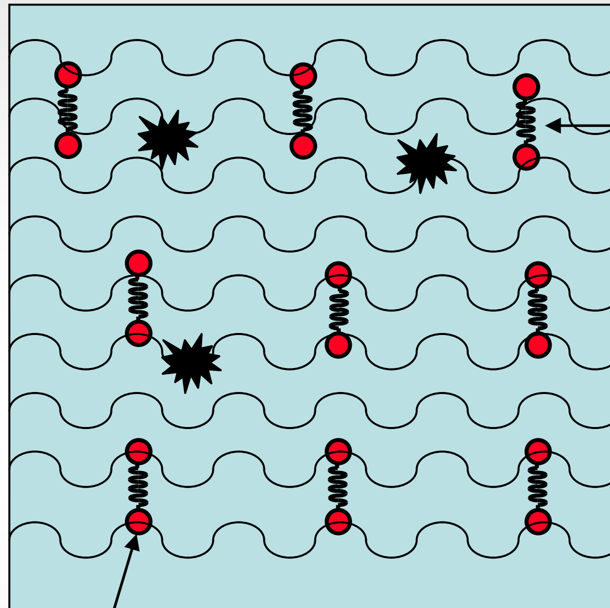
超伝導: 巨視的量子現象

金属



超伝導



2つの電子がペアを組むには「のり」が必要

従来超伝導体の「のり」＝結晶格子の振動

電子の波はバラバラ
➔電気抵抗が発生する

電子はペアを組んで揃った波となる
（コヒーレントな波）
➔電気抵抗ゼロ

位相が確定

超伝導:　相転移「自発的ゲージ対称性」の破れ

ゲージ変換(波動関数の位相を一様に変化させる)

電子の消滅演算子　$a_k \rightarrow \quad a_k' = a_k e^{i\theta}$

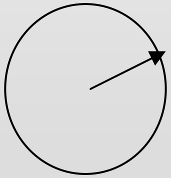
高温(常伝導状態) 秩序変数 $\Psi = \langle a_{k\uparrow}\, a_{-k\downarrow} \rangle = 0 \quad \rightarrow \Psi' = 0$

T＝T$_c$ で相転移

低温(超伝導状態)　電子対(Cooper対)を組む

秩序変数 $\Psi = \langle a_{k\uparrow}\, a_{-k\downarrow} \rangle \neq 0 \quad \rightarrow \Psi' = e^{i2\theta}\,\Psi$

ゲージ変換対称性$U(1)$が破られている



回転対称性がない

超伝導に関する対称性の破れ

異方的超伝導　Unconventional superconductivity

Full symmetry group $\mathcal{G}$　$\mathcal{G} = U(1) \otimes G \otimes SU(2) \otimes T$

$U(1)$	gauge symmetry
G	symmetry group of **crystal lattice**
$SU(2)$	symmetry group of **spin** rotation
T	**time** reversal symmetry operation

One or more symmetries in addition to $U(1)$ are broken at T_c

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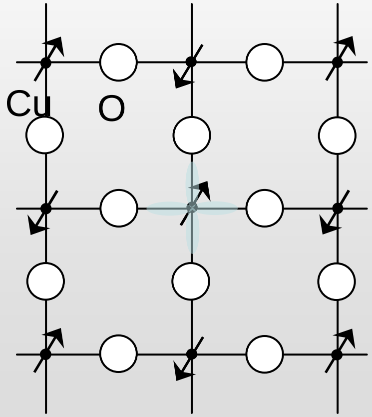
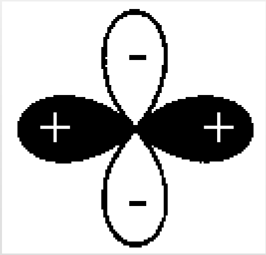
（例1）高温超伝導体

結晶構造　CuO_2面

（4回対称）





対波動関数

$d_{x^2-y^2}$

（2回対称）

超伝導に関する対称性の破れ

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（例2）　粒子の交換に対して反対称（フェルミオン）

	軌道部分	スピン部分
スピン1重項超伝導	対称 (s,d,…)	反対称 （↑↓－↓↑）
スピン3重項超伝導	反対称(p,f,…)	対称 （↑↑, ↓↓, ↑↓+↓↑)

^{3}He, Su_2RuO_4, etc…

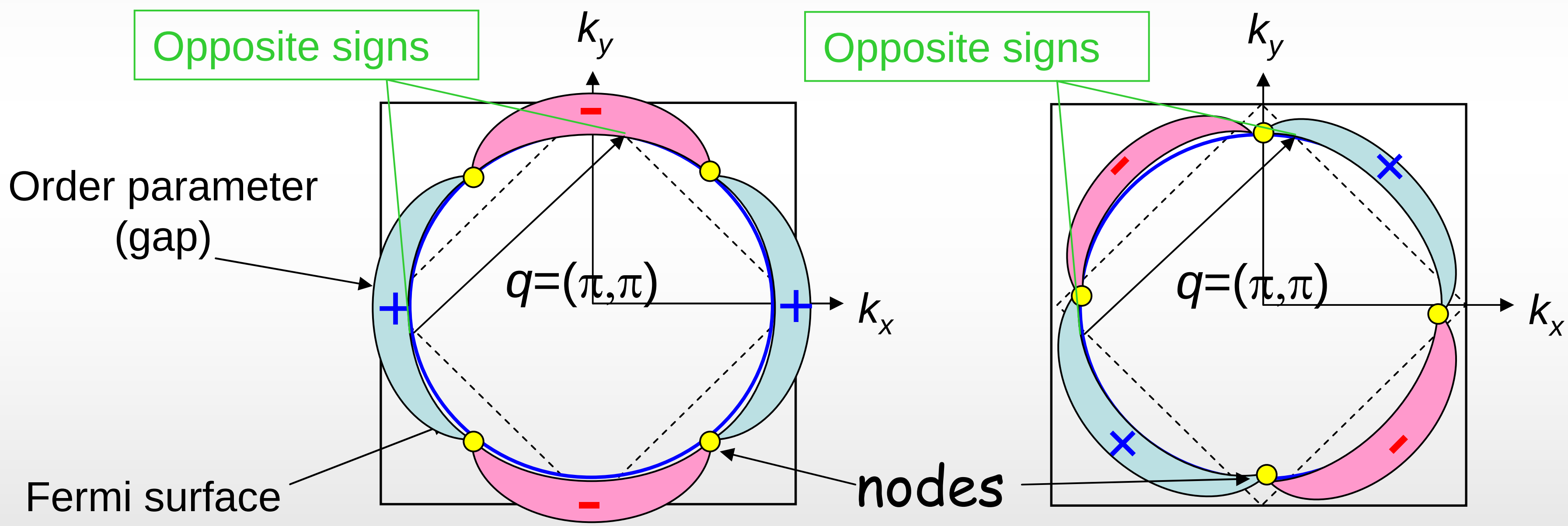
Pairing mechanism ←→ nodes in the gap

$H_{int} = V_{k,k'} c^{+}_{-k'\downarrow} c^{+}_{k'\uparrow} c_{k'\uparrow} c_{-k'\downarrow}$ $V_{k,k'}$ may be anisotropic in unconventional SCs

ex) Superconductivity mediated by **antiferromagnetic fluctuaions** with $q=(\pi,\pi)$

$$V(\mathbf{q}) = - I^2(\mathbf{q})\chi_0(\mathbf{q}) / [1- I^2(\mathbf{q})\chi_0^{\,2}(\mathbf{q})]$$

Favors opposite order parameters on the two points connecting by q vector



$d_{x^2-y^2}$ $(k_x^2-k_y^2)$

zeros at $k_x=+k_y$, $-k_y$

d_{xy} (k_xk_y)

zeros at $k_x=0$, $k_y=0$

Breaking time reversal symmetry

$\mathcal{G} = U(1) \otimes G \otimes SU(2) \otimes T$

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = H\psi(x,t)$$

$$H = -\frac{\hbar^2\nabla^2}{2m} + V(x)$$

$t \longrightarrow -t$

$$i\hbar\frac{\partial}{\partial(-t)}\psi'(x,-t) = H\psi'(x,-t)$$

$$-i\hbar\frac{\partial}{\partial t}\psi^*(x,t) = H\psi^*(x,t)$$

$$\psi'(x,-t) = \psi^*(x,t)$$

If the order parameter has imaginary part $\quad \Psi(x,k) = \psi_1(k) + i\psi_2(k)$

then its time reversal state becomes different $\quad \Psi^*(x,k) = \psi_1(k) - i\psi_2(k)$

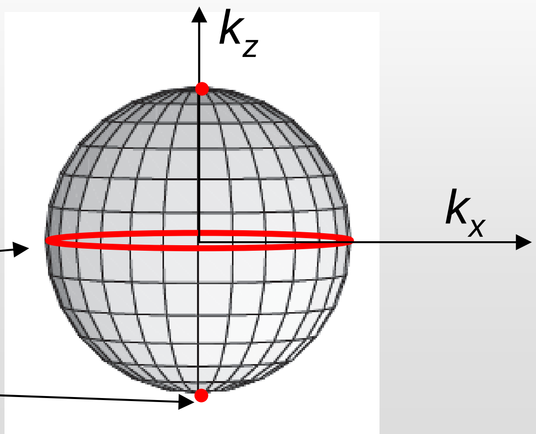
Time reversal symmetry is broken

example **Chiral *d*-wave**

$$\Delta \propto \hat{k}_z(\hat{k}_x \pm i\hat{k}_y)$$

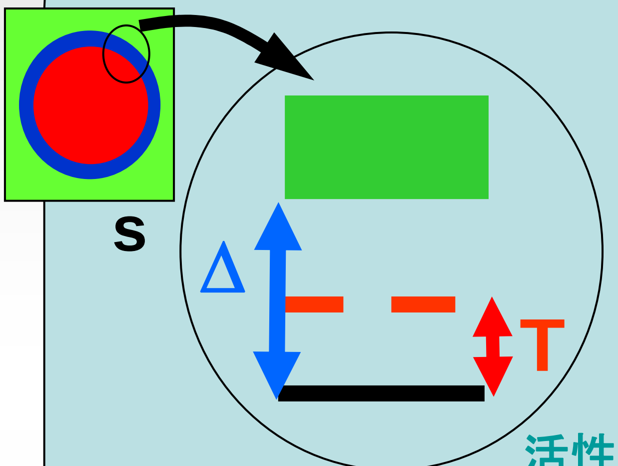
horizontal line node $\quad k_z = 0$

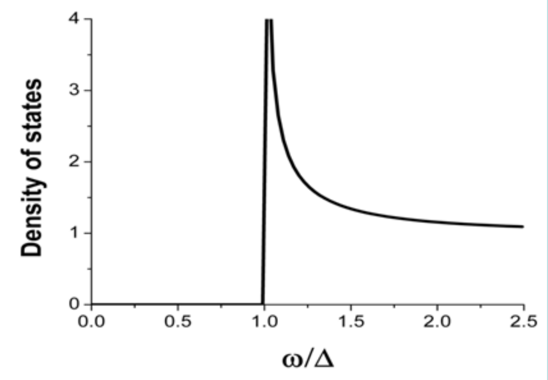
point node $\quad k_x = k_y = 0$



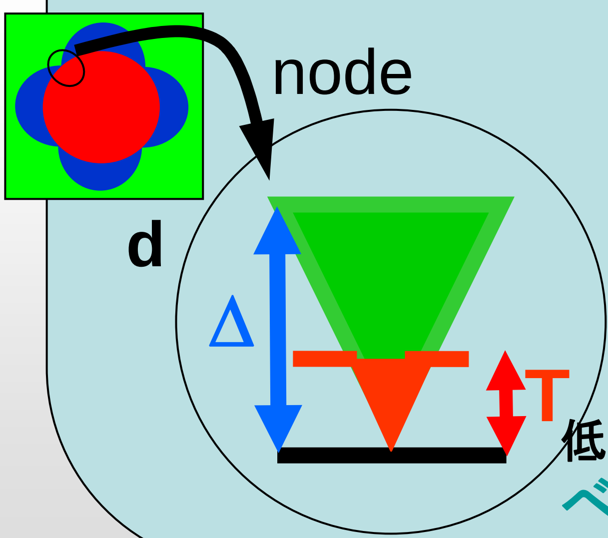
How to determine symmetry of unconventional superconductors

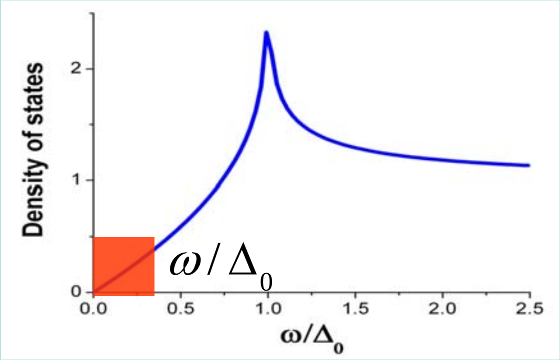
励起準粒子の性質を調べる（バルク測定）
比熱、磁場侵入長、熱伝導度、NMR緩和率 etc





低温で熱励起なし
活性化型の温度依存性　exp(-Δ/T)





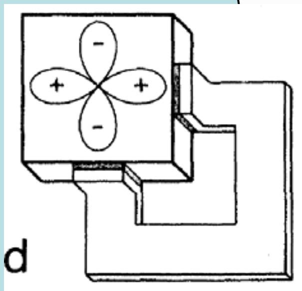
低温で熱励起あり
べき乗の温度依存性　T^n

角度分解型光電子分光
(ARPES)
超伝導ギャップの
波数空間依存性
を測定可能

表面敏感 →
バルクと異なる
表面特異な状態？

接合を用いた測定

位相の情報
が得られる

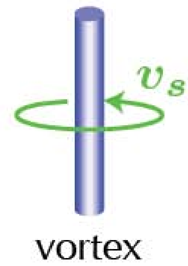


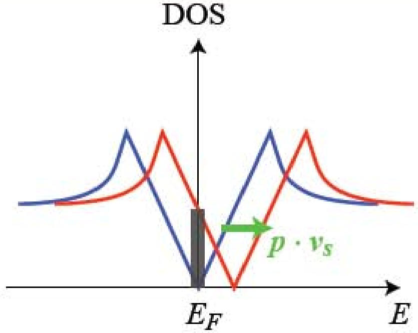
高度に制御された
接合の作製が必要
（銅酸化物高温
超伝導体のみで成功）

熱伝導率の角度依存性

ドップラーシフト　$E(p) \to E(p) + v_s \cdot p$

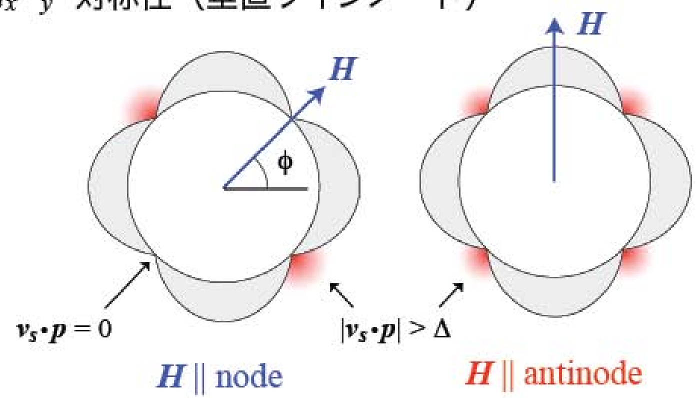
G.E. Volovik, JETP Lett. **58**, 469 (1993)

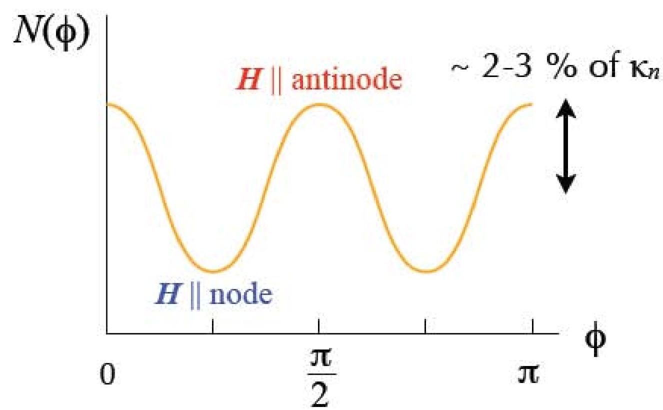




状態密度の角度依存性

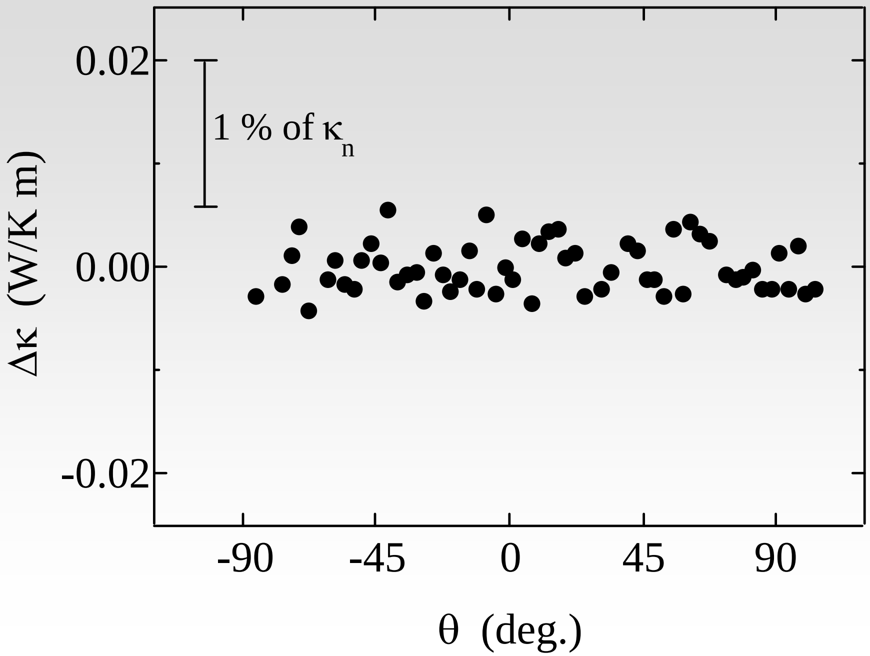
$d_{x^2-y^2}$ 対称性（垂直ラインノード）



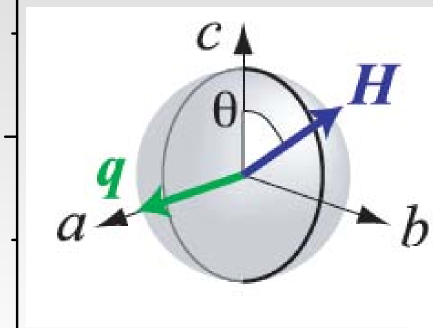


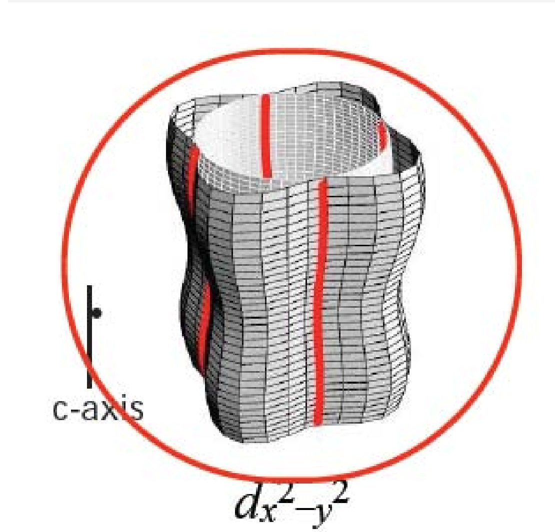
$d_{x^2-y^2}$ symmetry　４回対称性の振動

$CeIrIn_5$

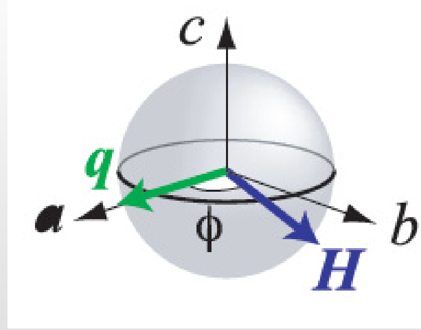


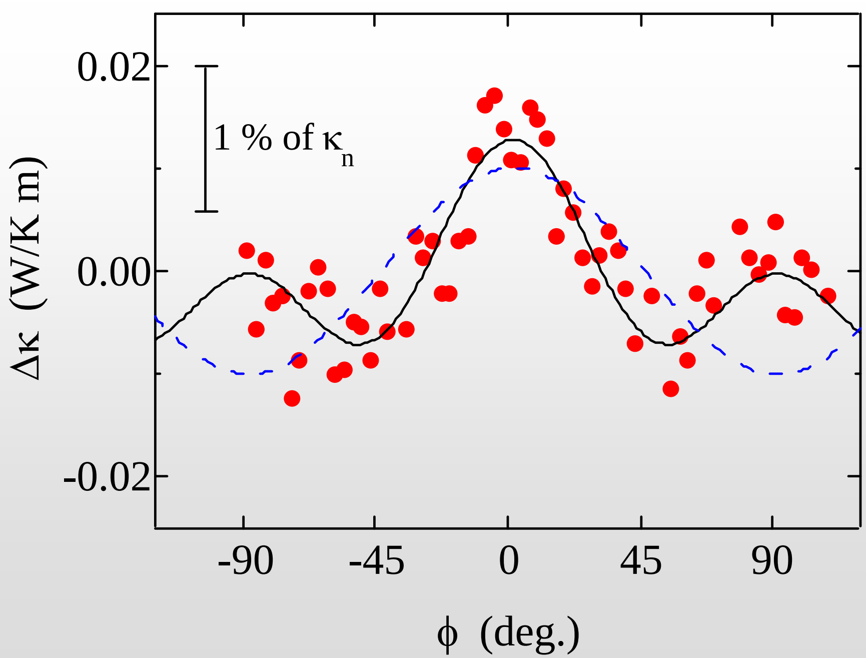
H || *bc*-plane





H || *ab*-plane



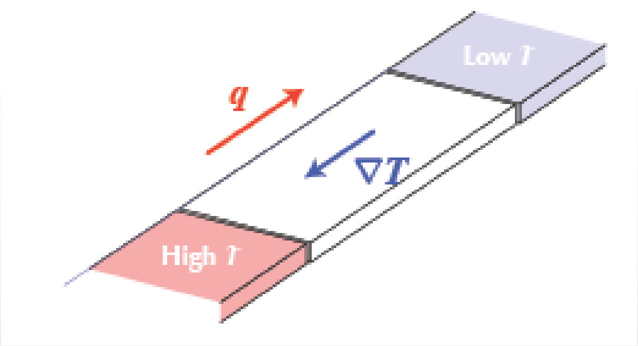


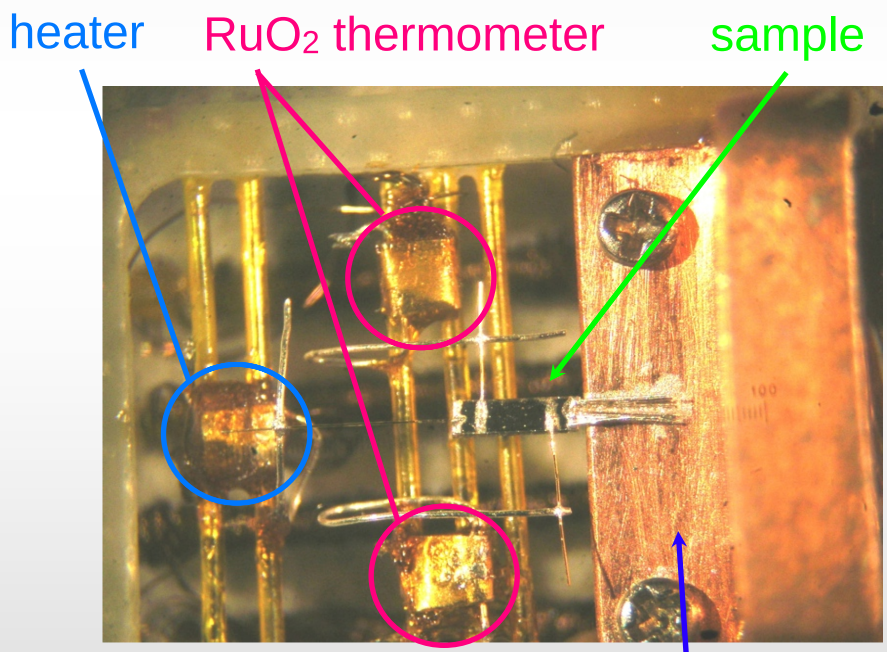
$d_{x^2-y^2}$ symmetry

Y. Kasahara *et al.*
Phys. Rev. Lett. **100**, 207003 (2008).

Superconducting state of URu_2Si_2 studied by the thermal transport measurements

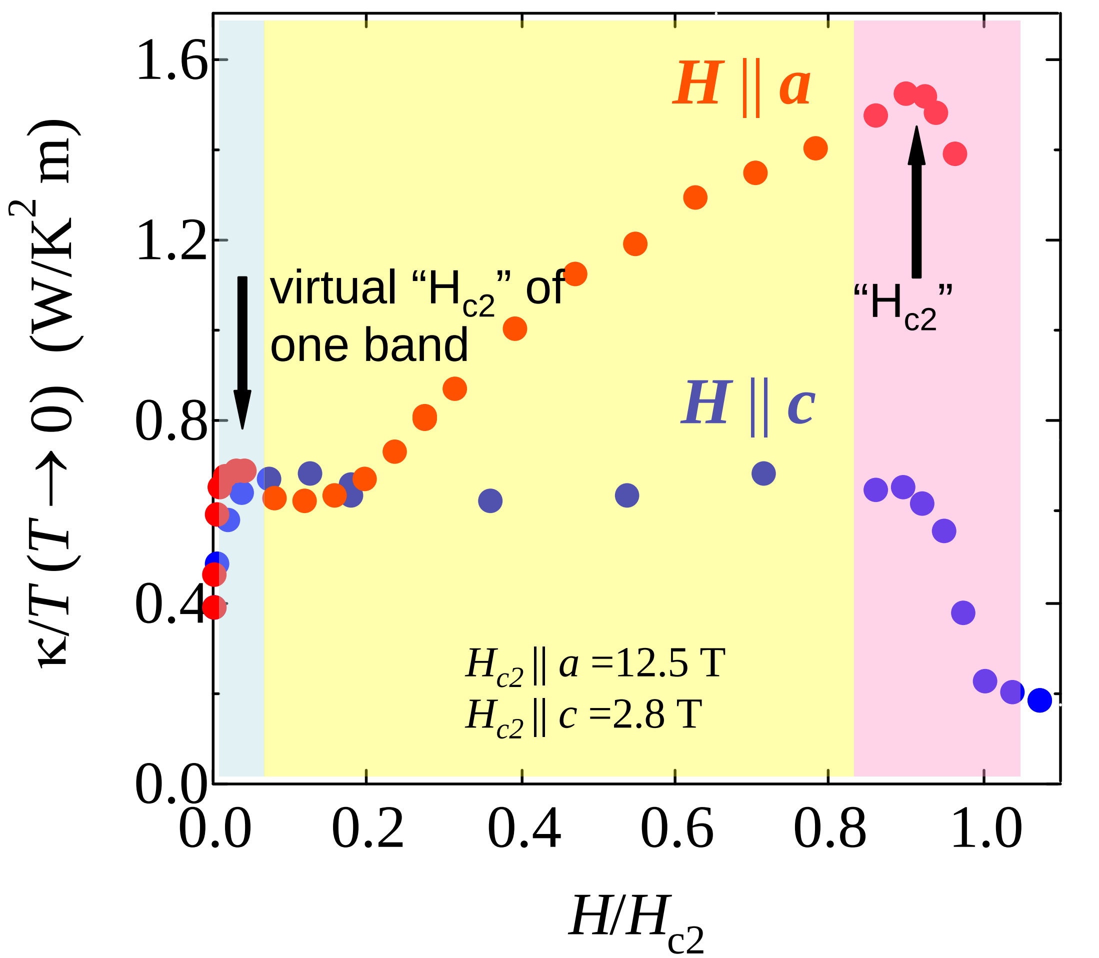
$$q = -\kappa \nabla T$$



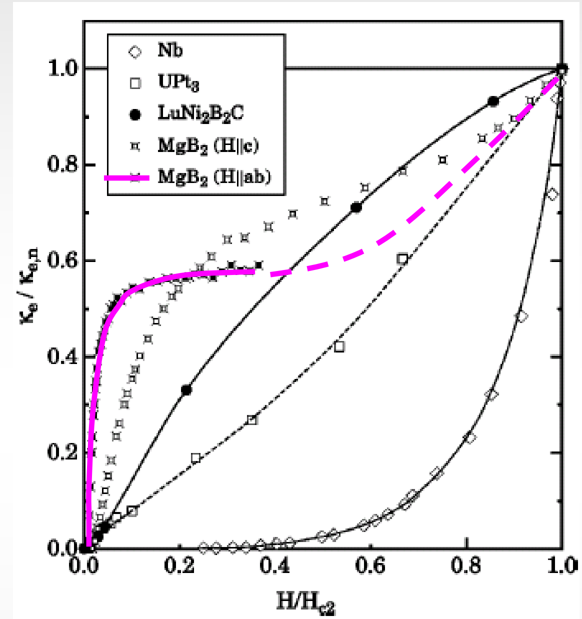


Y. Kasahara *et al*. Phys. Rev. Lett. **99**, 116402 (2007).

URu_2Si_2



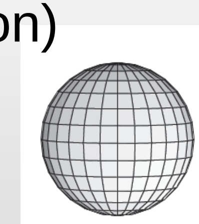
1. Steep increase at low H
2. Plateau-like behavior
3. Jump at H_{c2}



A.V.Sologubemko *et al*. PRB (2002)

Multiband superconductivity (consistent with the compensation)

$$\xi \propto v_F \propto 1/m^*$$



Low-H behavior of κ Light hole band with small "H_{c2}"

High-H behavior of κ Heavy electron band with large "H_{c2}"

Low field behavior of the thermal conductivity, which is governed by the **light sperical hole band**

URu_2Si_2

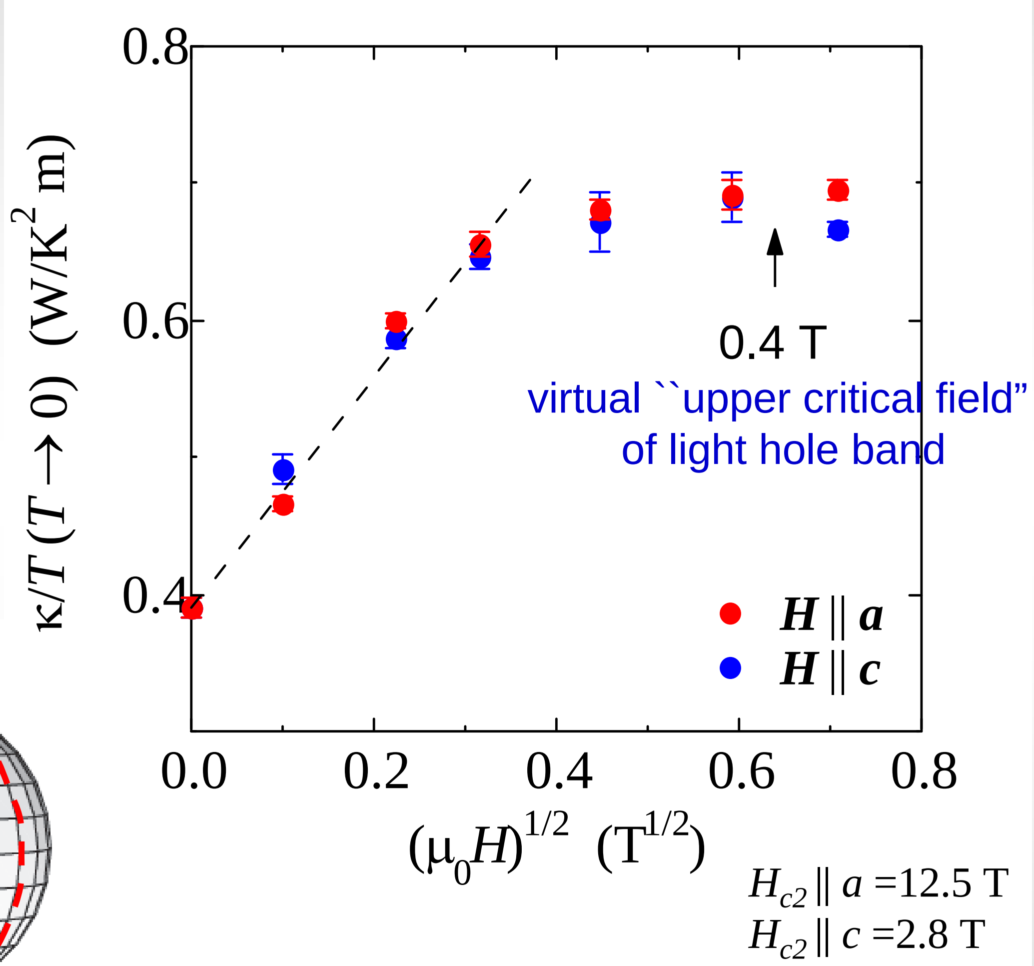
***H* < 0.4 T :**

In spite of large anisotropy of H_{c2}, κ is nearly isotropic.

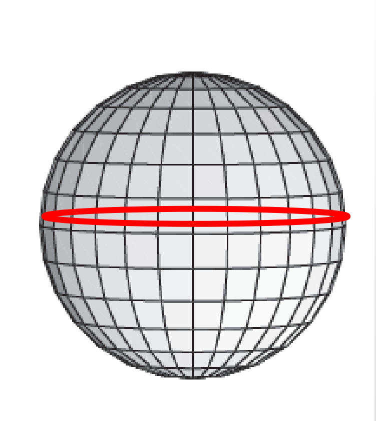
⇒ Spherical band

Steep increase with *H*

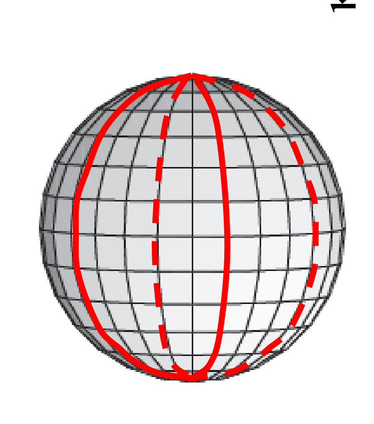
$$\kappa/T(T\to 0) \sim \sqrt{H}$$



line node in the light hole band



or



Horizontal

Vertical

Low field behavior of the thermal conductivity, which is governed by the **light sperical hole band**

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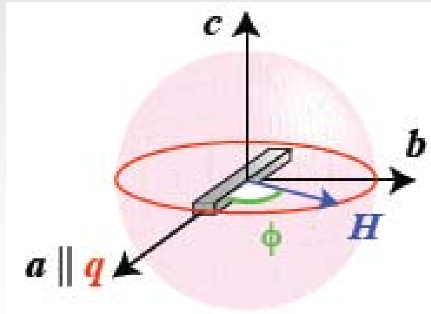
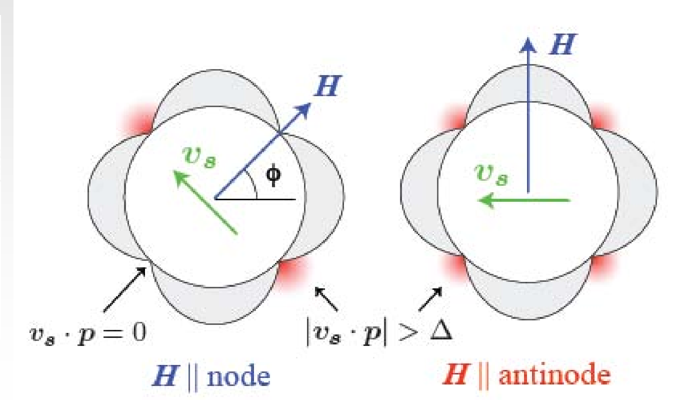
Spherical band





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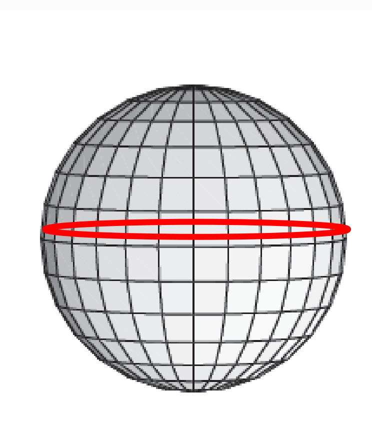

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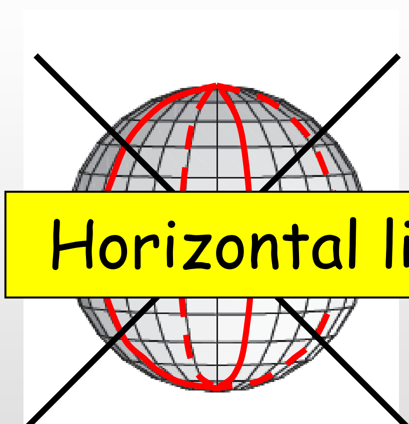
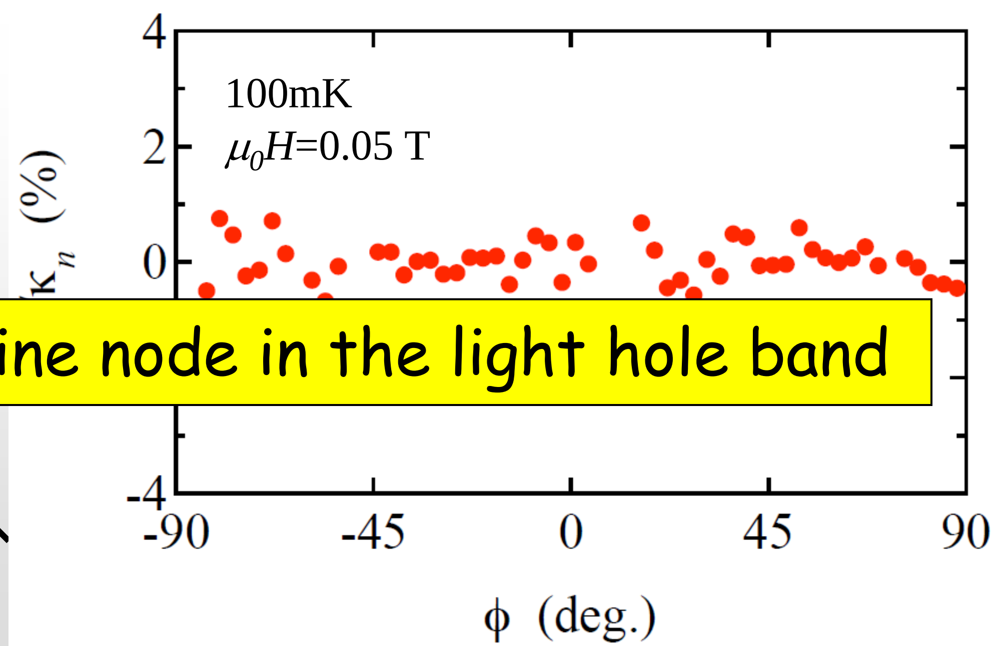


Horizontal

Vertical



Horizontal line node in the light hole band

High field behavior of the thermal conductivity, which is governed by the **elliptical heavy electron band**

URu_2Si_2

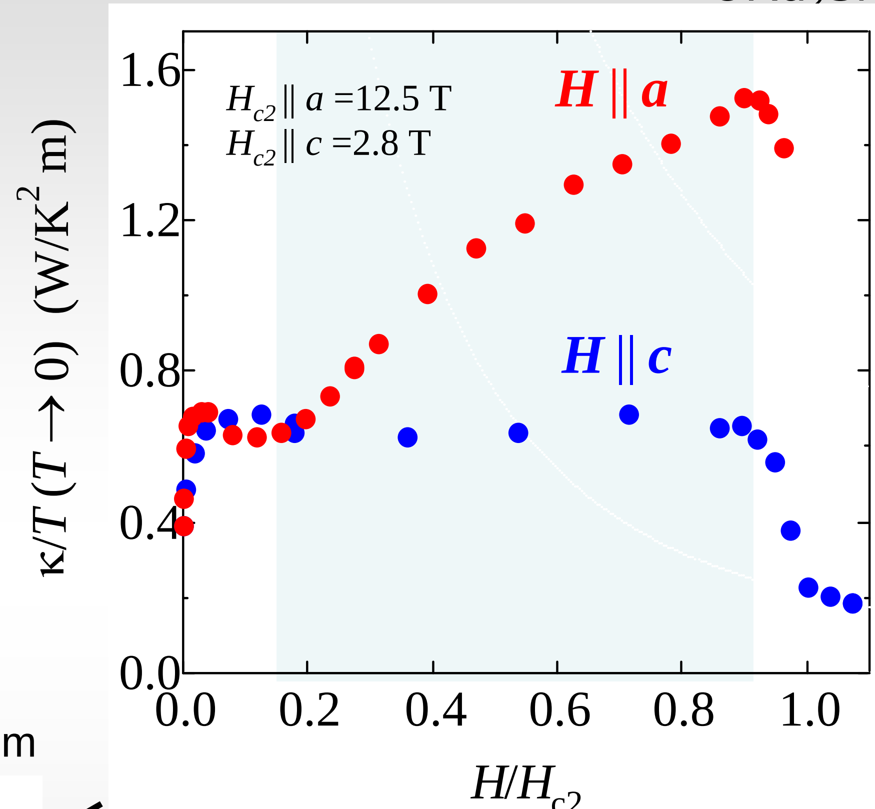
Anisotropic *H*-dependence

H* || *a : **convex *H*-dependence**

*Doppler shift occurs for **H** || a*

H* || *c : ***H*-independent**

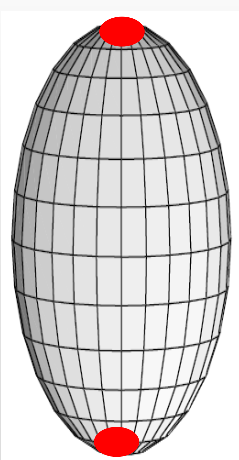
*Doppler shift does NOT occur for **H** || c*

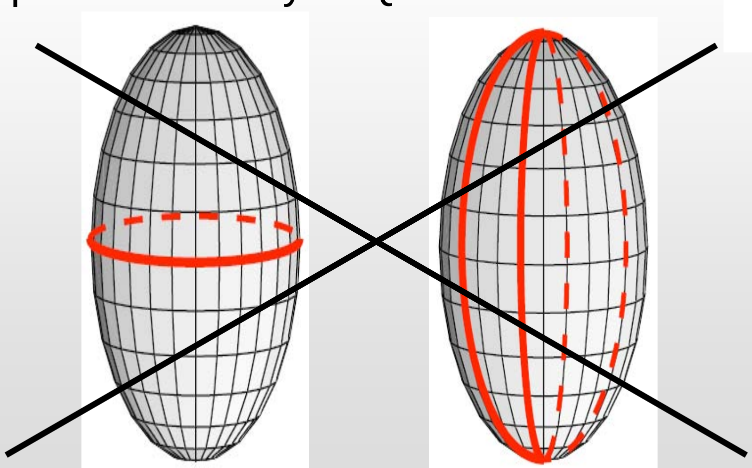


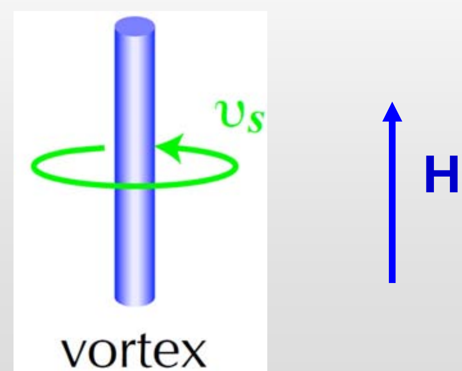
Doppler shift of the QP energy spectrum

$$E'(\boldsymbol{p}) \rightarrow E(\boldsymbol{p}) + \boldsymbol{v_s} \cdot \boldsymbol{p}$$

superfluid velocity QP momentum







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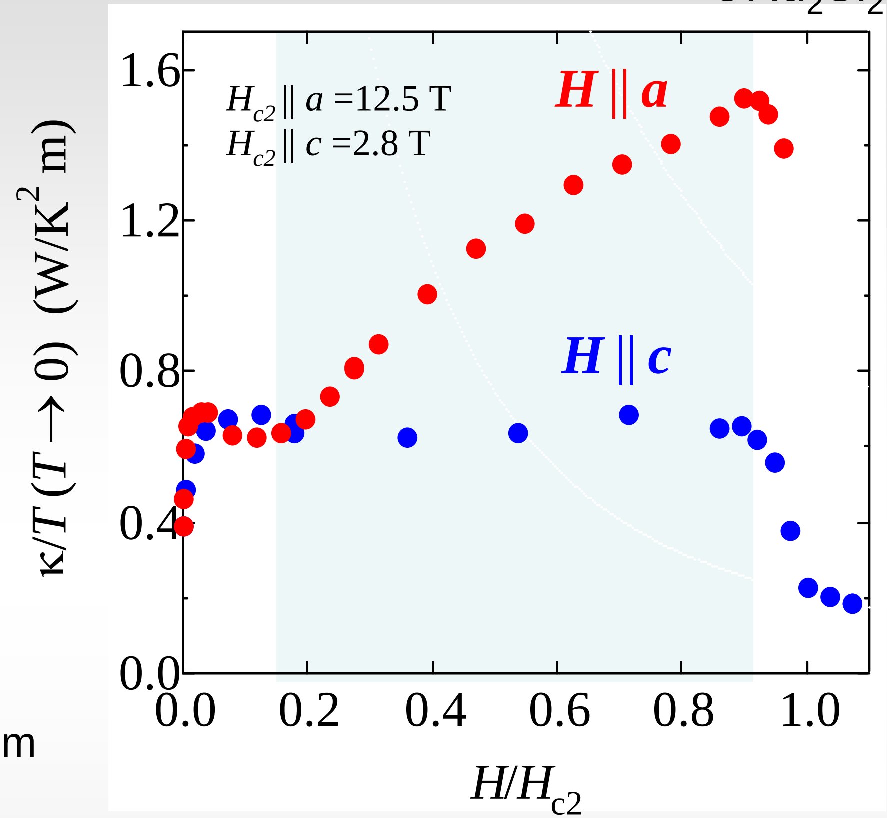
URu_2Si_2



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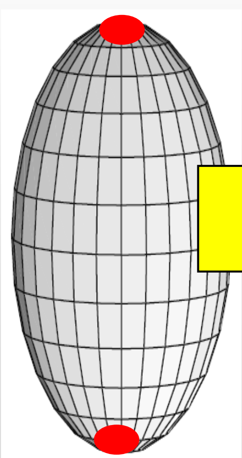
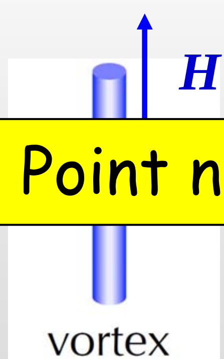
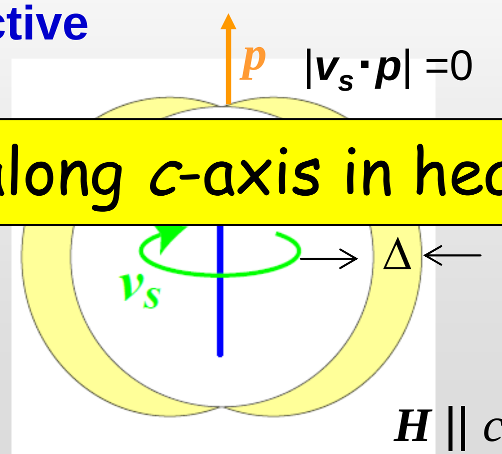
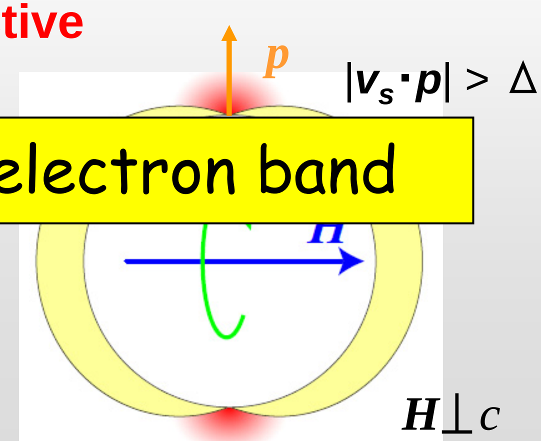




inactive



active



Point node along *c*-axis in heavy electron band

Superconducting gap function of URu_2Si_2

(1) Spin-singlet

(2) Horizontal line node (light hole band)

(3) Point node along the *c*-axis (heavy electron band)

A simple classification by group theory

Even-parity (spin-singlet) pair states in a tetragonal crystal with point group D_{4h}

symmetry	basis function	nodal structure
A_{1g}	$1, k_x^2+k_y^2, k_z^2$	Full gap
A_{2g}	$k_x k_y(k_x^2-k_y^2)$	Vertical line node
B_{1g} $(d_{x^2-y^2})$	$k_x^2-k_y^2$	Vertical line node
B_{2g} (d_{xy})	$k_x k_y$	Vertical line node
E_g (1,0)	$k_x k_z$	Vertical line node + Horizontal line node
E_g (1,1)	$k_z(k_x+k_y)$	Vertical line node + Horizontal line node
E_g $(1,i)$	$k_z(k_x+ik_y)$	**Horizontal line node + Point node**

Superconducting gap function of URu_2Si_2

(1) Spin-singlet

(2) Horizontal line node (light hole band)

(3) Point node along the *c*-axis (heavy electron band)

Superconducting gap symmetry

Chiral *d*-wave (E_g)

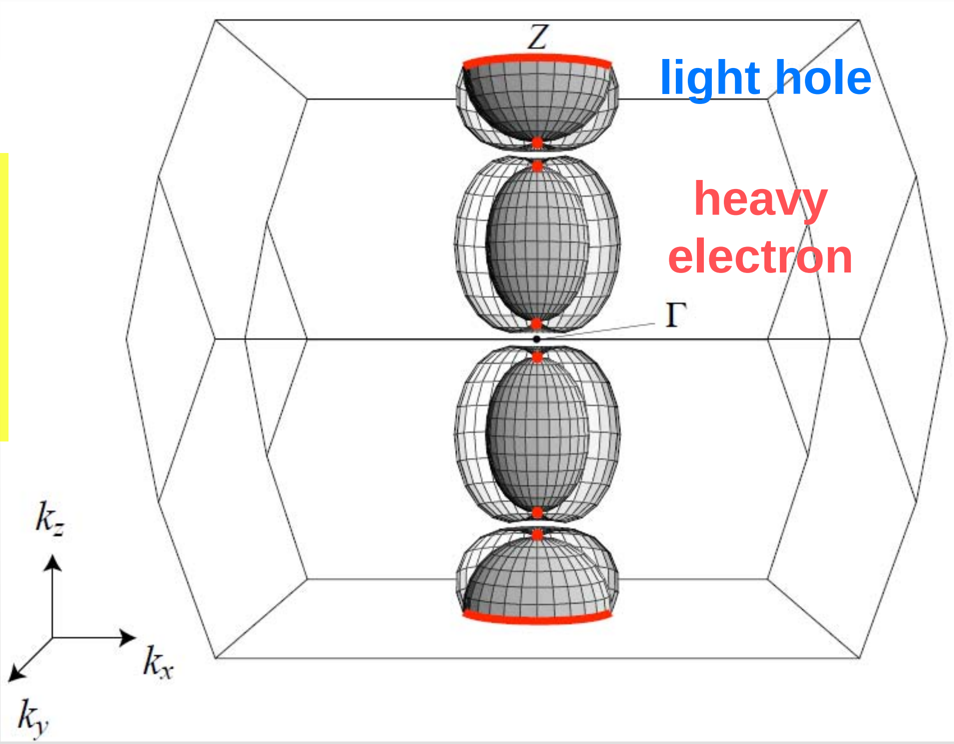
$$\hat{k}_z(\hat{k}_x \pm i\hat{k}_y)$$

$$\Delta = \Delta_0 \sin\frac{k_z}{2}c\left(\sin\frac{k_x+k_y}{2}a \pm i\sin\frac{k_x-k_y}{2}a\right)$$

(Body center tetragonal)

horizontal line node $k_z = 0, \pm\frac{2\pi}{c}$

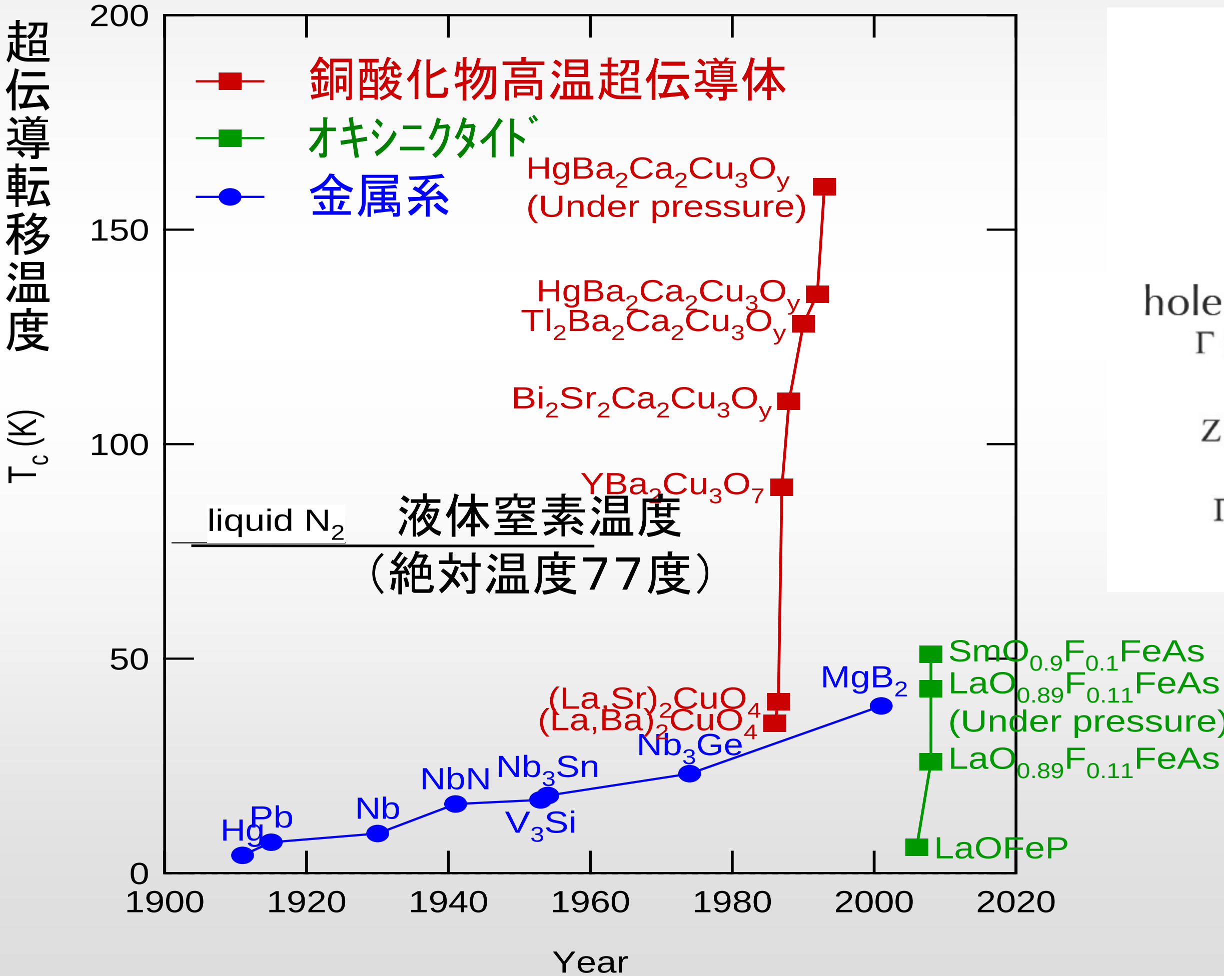
point node $k_x = k_y = 0$

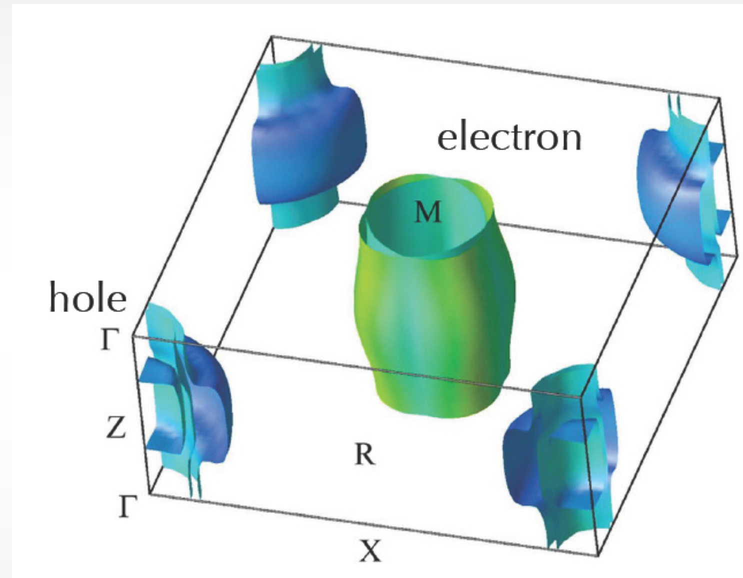


Y. Kasahara *et al*. Phys. Rev. Lett.99, 116402 (2007).

Microwave penetration depth measurements in the new Fe-based high-T_c superconductors

K. Hashimoto *et al.*, Phys. Rev. Lett. **102**, 017002 (2009).





Multiband electronic structure

Probing low-energy quasiparticle excitations

$\lambda(T)$, $\sigma_1(T)$

Surface impedance measurements

• Penetration depth $\lambda(T)$

a direct probe for superfluid density

$$Z_s = R_s + iX_s = \left(\frac{i\mu_0\omega}{\sigma_1 - i\sigma_2}\right)^{-1/2}$$

$$n_s = \frac{\lambda^2(0)}{\lambda^2(T)}$$

$$X_s = \mu_0\omega\lambda(T)$$

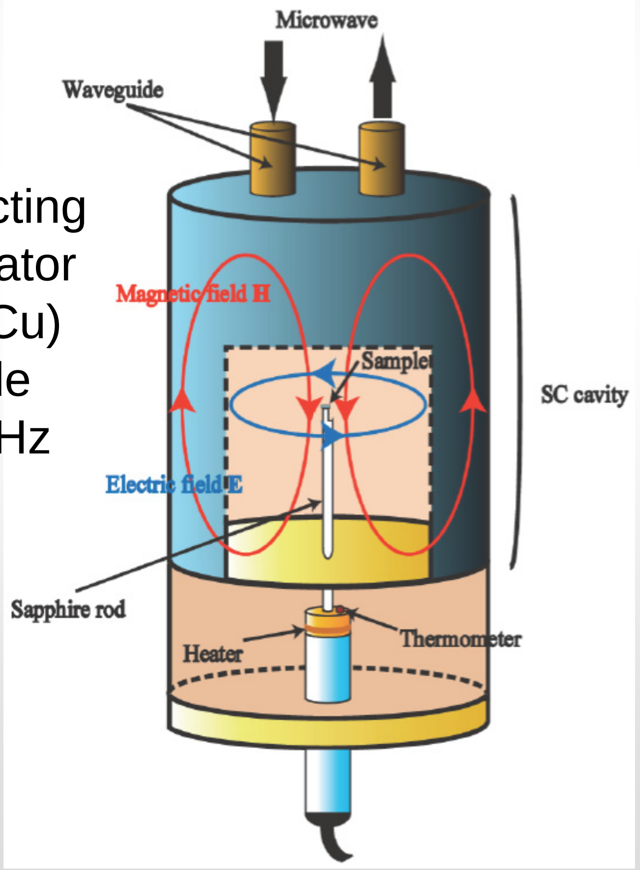
• full gap superconductors

$$\frac{\delta\lambda_{ab}(T)}{\lambda_{ab}(T)} \approx \sqrt{\frac{\pi\Delta}{2k_B T}} \exp\left(-\frac{\Delta}{k_B T}\right)$$

• superconductors with line nodes

$$\frac{\delta\lambda_{ab}(T)}{\lambda_{ab}(T)} \approx \frac{\ln 2}{\Delta} k_B T$$

Superconducting cavity resonator (Pb plated Cu)
TE_{011} mode
f_0=27.75 GHz
Q_0~10^6



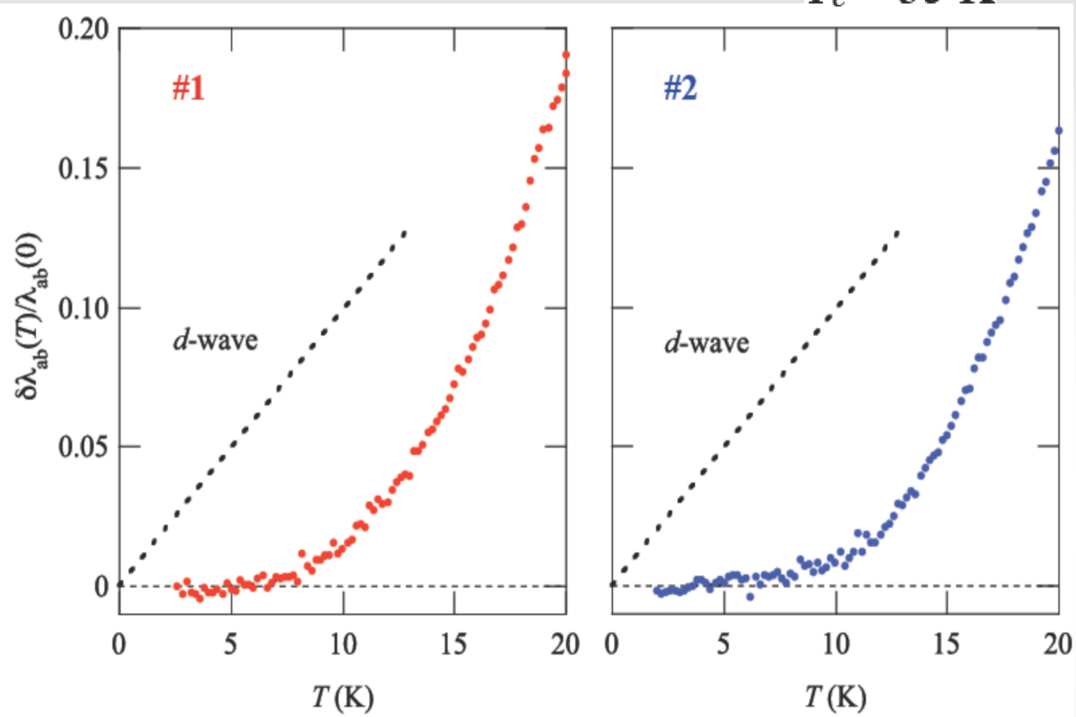
λ >10^3 A: reasonably representative of the bulk

Results: penetration depth

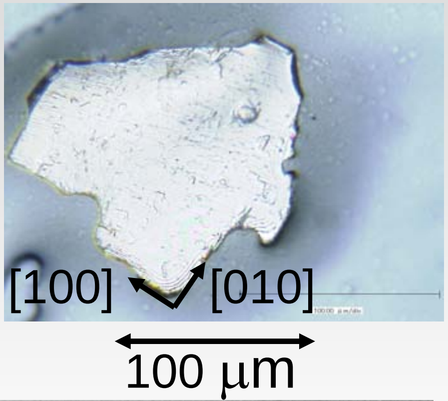
K. Hashimoto *et al.*, Phys. Rev. Lett. 102, 017002 (2009).

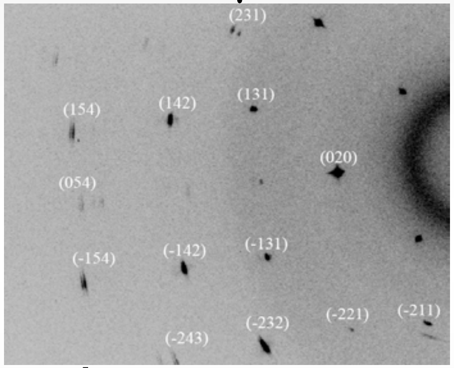
PrFeAsO$_{1-y}$

$T_c \sim 35$ K



M. Ishikado *et al.*





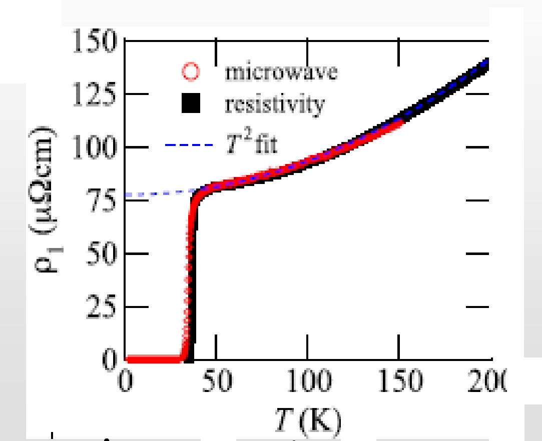
Laue pattern

- line node

$$\frac{\delta\lambda_{ab}(T)}{\lambda_{ab}(T)} \approx \frac{\ln 2}{\Delta} k_B T$$

$$(2\Delta/k_B T_c = 4)$$

Inconsistent with the data



Sharp SC transition

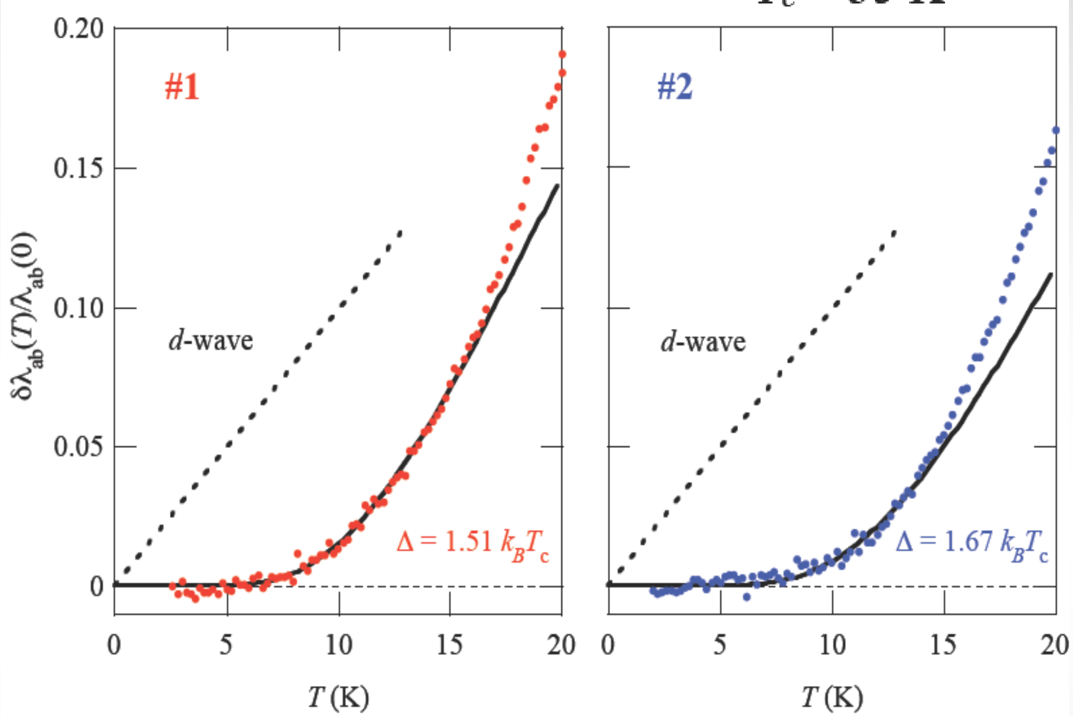
Results: penetration depth

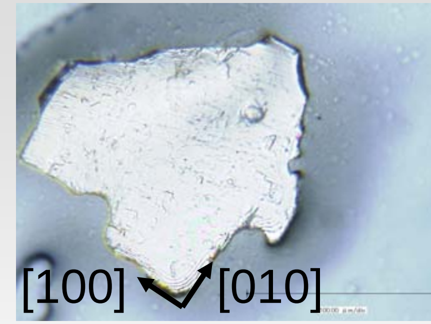
K. Hashimoto *et al.*, Phys. Rev. Lett. 102, 017002 (2009).

M. Ishikado *et al.*

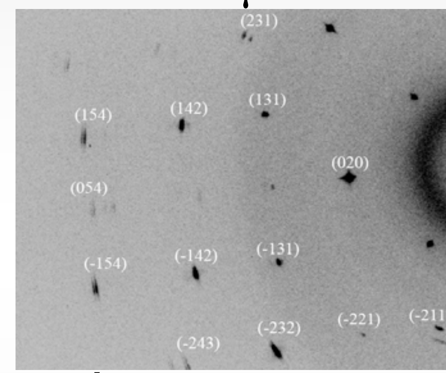
$PrFeAsO_{1-y}$

$T_c \sim 35$ K





100 μm



Laue pattern

- line node

$$\frac{\delta\lambda_{ab}(T)}{\lambda_{ab}(T)} \approx \frac{\ln 2}{\Delta} k_B T$$

$$(2\Delta/k_B T_c = 4)$$

Inconsistent with the data

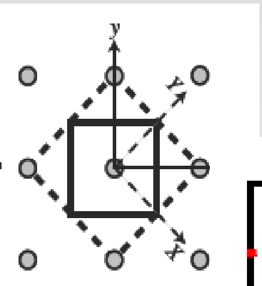
- full gap

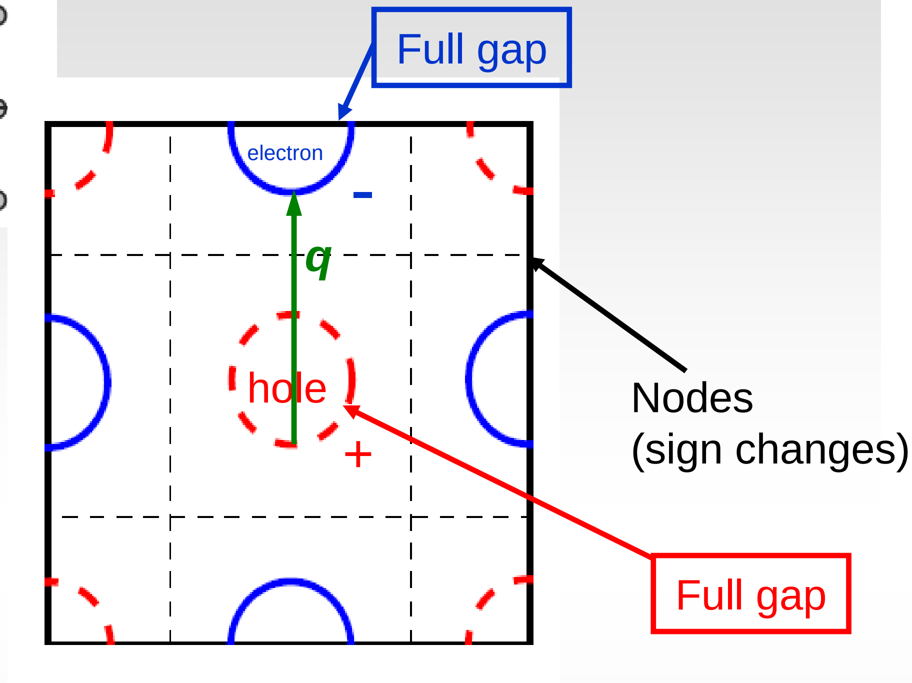
$$\frac{\delta\lambda_{ab}(T)}{\lambda_{ab}(0)} \approx \sqrt{\frac{\pi\Delta}{2k_B T}} \exp\left(-\frac{\Delta}{k_B T}\right)$$

$\Delta_{min}/k_B T_c \sim 1.5 \quad \pm 0.2$

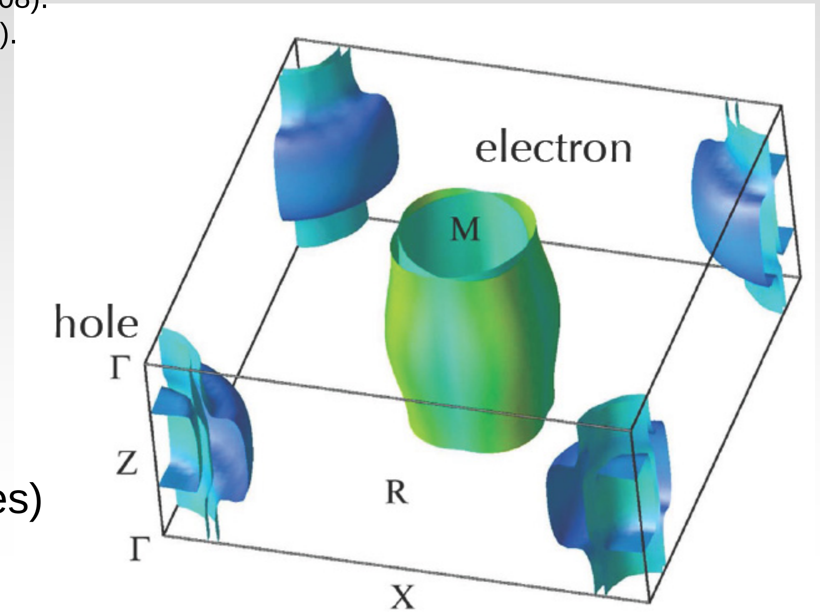
Discussion

I. I. Mazin *et al*., Phys. Rev. Lett. **101**, 057003 (2008).
K. Kuroki *et al*., Phys. Rev. Lett. **101**, 087004 (2008).
K. Seo *et al*., Phys. Rev. Lett. **101**, 206404 (2008).

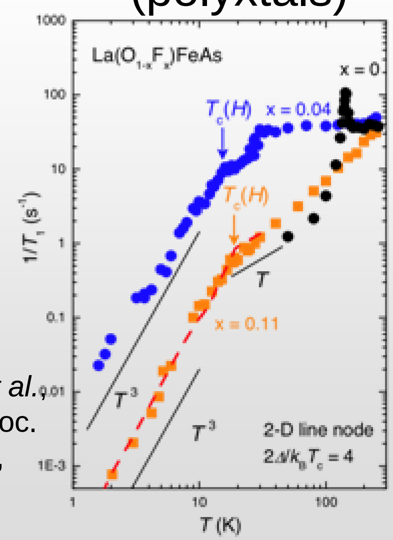




Unfolded BZ

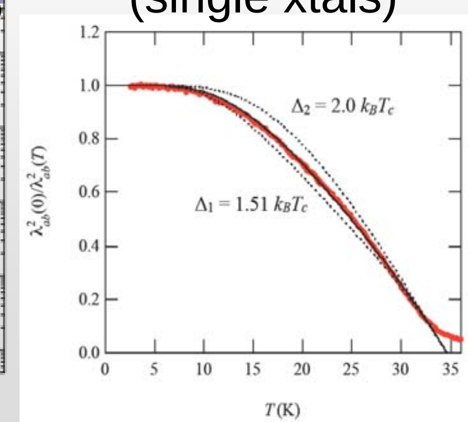


NMR
(polyxtals)



Y. Nakai *et al*., J. Phys. Soc. Jpn. **77**, 073701 (2008).

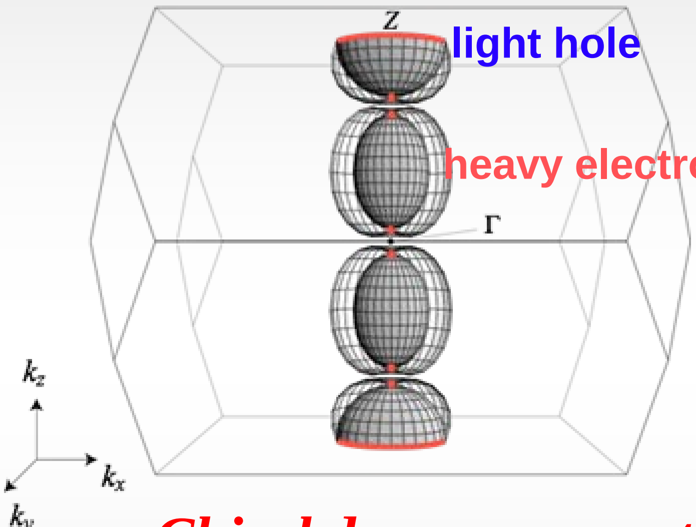
penetration depth
(single xtals)



AF spin fluctuations with q~(π,0) favors $s_{+/-}$ pairing state

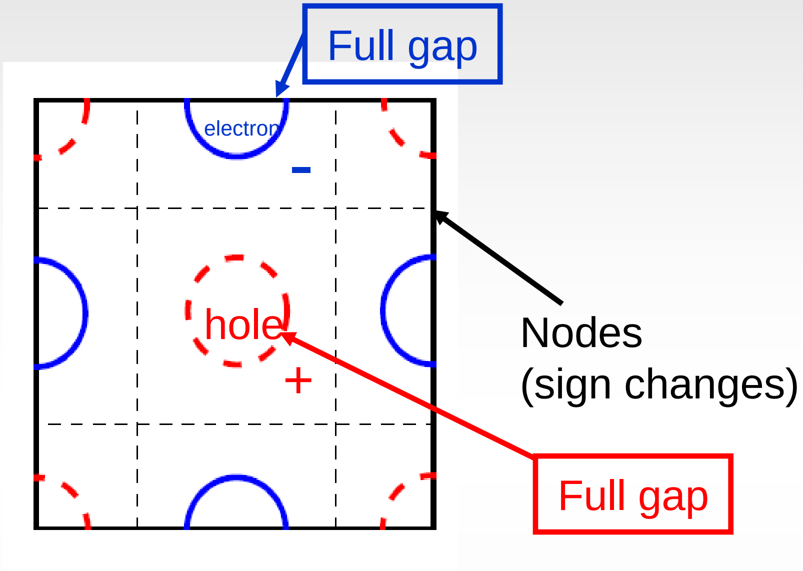
Summary various symmetries in unconventional superconductors

URu_2Si_2



Chiral d-wave symmetry

Fe-based high-T_c superconductors



Extended s-wave symmetry

異方的な対形成機構から発現する
様々な新しい対称性を持つ
非従来型超伝導が発現