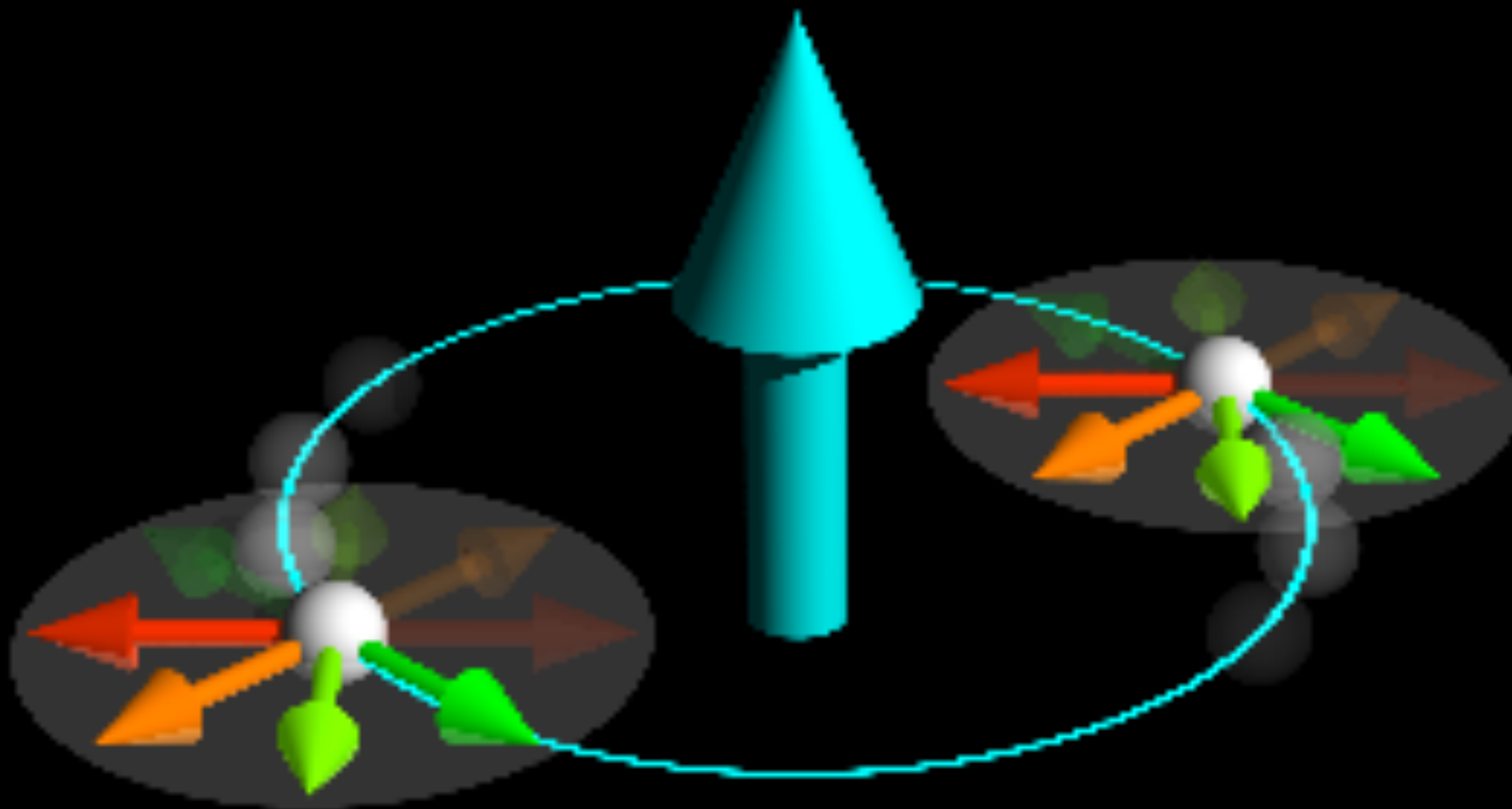
Chiral Superconductivity

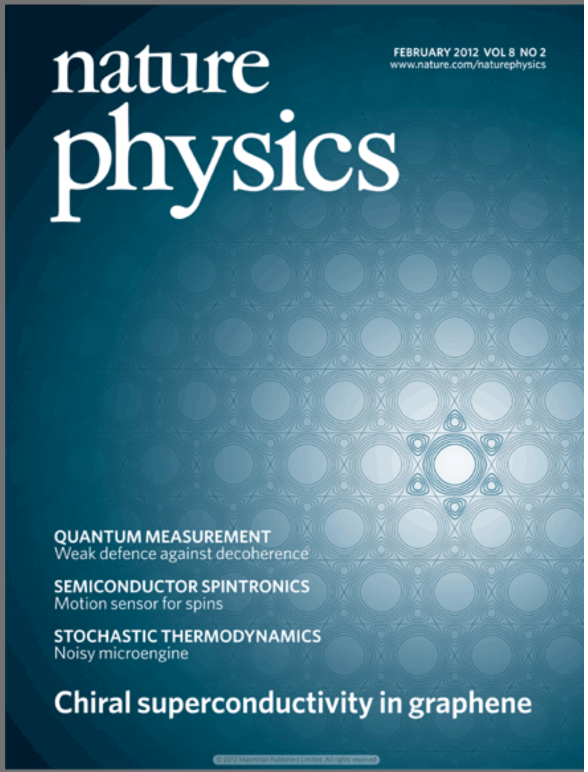


Catherine Kallin, McMaster

KITP Conference, Sept 26, 2014

Chiral Superconductivity

- Breaks time reversal symmetry (TRSB) and parity: Cooper pairs with angular momentum. p±ip, d±id, f±if, …
- May be topological; may support Majorana modes
- Key goal is realizing chiral SC in physical systems, which requires understanding and detecting key signatures.



Chiral Superconductivity

Chiral p-wave phase exists in He-3 A (also B phase: helical)

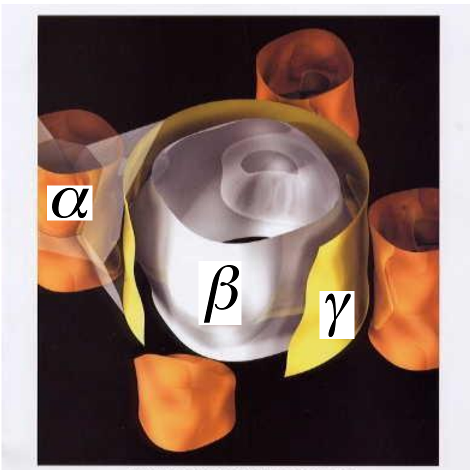
Proposals include

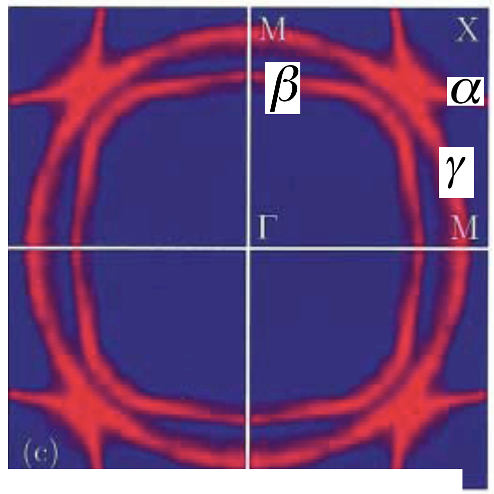
- chiral p-wave in Sr_2RuO_4 → $k_x \pm ik_y$
- chiral f-wave in UPt_3 → $k_z(k_x^2 - k_y^2 \pm ik_xk_y)$
- Possibly in other heavy fermions: $PrOs_4Sb_{12}$
- chiral d-wave in SrPtAs, doped graphene, sodium doped cobaltates
- Also non-chiral but TRSB s+id proposed in pnictides
- various proximity induced "chiral p-wave like" systems, cold atoms

Chiral Superconductivity

- Challenges in detecting the TRSB
- differences between p-wave and higher angular momenta
- Microscopics of real systems: multibands & pairing potential
- Detecting possible Majorana modes

Microscopics for Sr_2RuO_4:
Multiband and possible large gap anisotropy





Quasi-2d/tetragonal

γ – mainly d_{xy}

α,β - mainly d_{xz}, d_{yz}

strong SOC

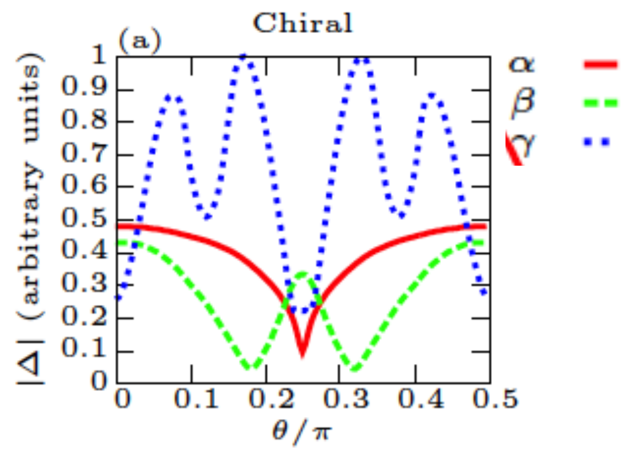
T_c=1.5K

Triplet; all 3 bands contribute

RG studies: Raghu, Kapitulnik & Kivelson PRL 105, 136401 (2010)
Wang, Platt,Yang, Honerkamp, Zhang,Hanke, Rice,Thomale, EPL 104, 17013 (2013)
Scaffidi, Romers & Simon, PRB 89, 220510 (2014)

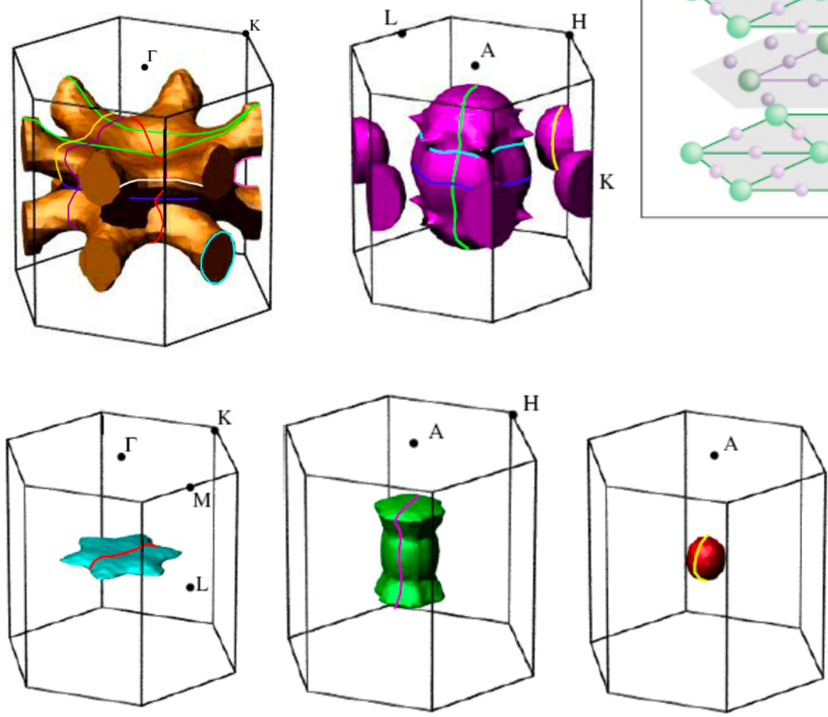
On-site repulsive interactions & exchange & SOC → chiral p-wave can be stable (may be close in energy to helical) with dominant NNN bond pairing (large gap anisotropy)

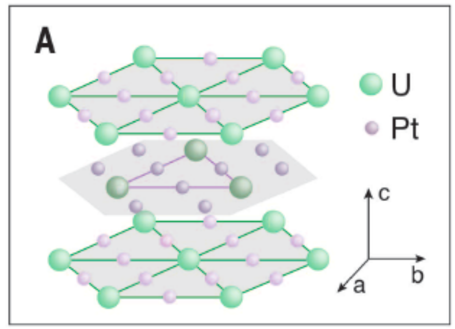
$$\vec{\Delta}(\vec{k}) = \left[\{\sin(k_x) + a\sin(k_x)\cos(k_y)\} + i\{\sin(k_y) + a\sin(k_y)\cos(k_x)\}\right]\hat{c}$$

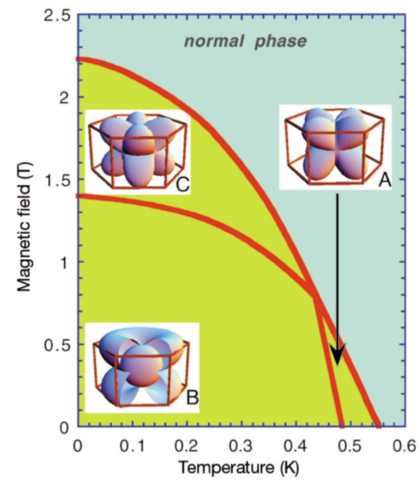


UPt_3

5 sheets of the Fermi surface







Two superconducting transitions:
T_{cA}=1.55K T_{cB}=1.49K

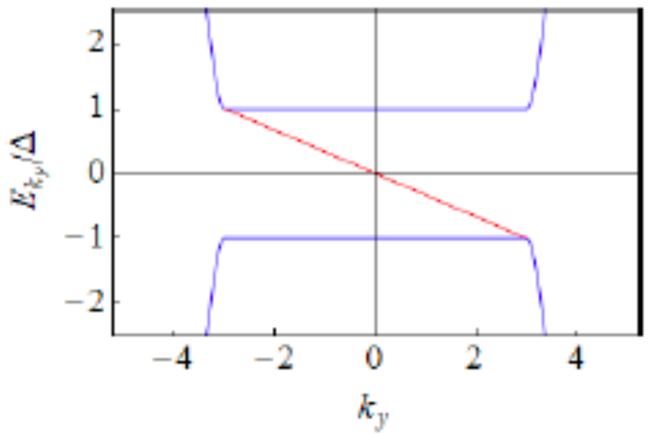
$$\vec{\Delta}(\vec{k},T) = \Delta(T)k_z\left[k_x^2 - k_y^2 + ia(T)k_x k_y\right]\hat{c}$$

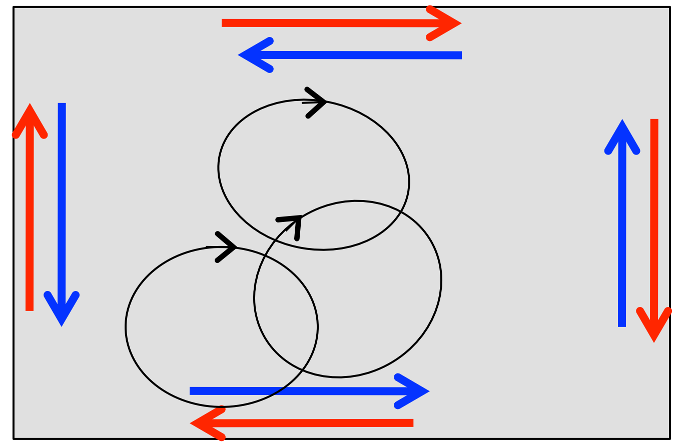
$$or \quad \vec{\Delta}(\vec{k},T) = \Delta(T)k_z^2\left[k_x + ia(T)k_y\right]\hat{c}$$

McMullan, Rourke, Norman, Huxley, Doiron-Leyraud, Flouquet, Lonzarich, McCollam, Julian, New J Phys. 10 (2008)

Spontaneous supercurrents for chiral p-wave

Chiral edge states exist in any open geometry





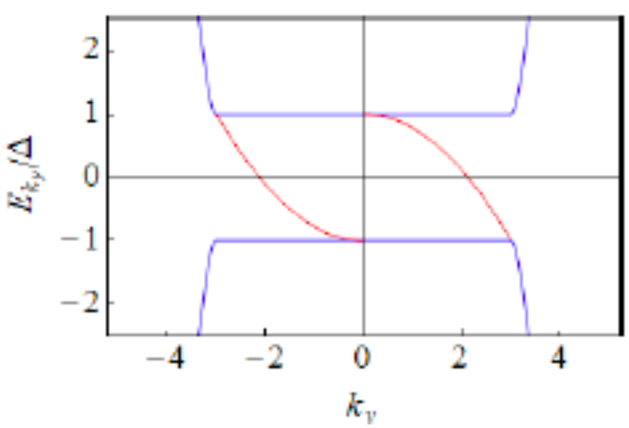
(for single domain) Stone and Roy (2004); Matsumato and Sigrist (1999)

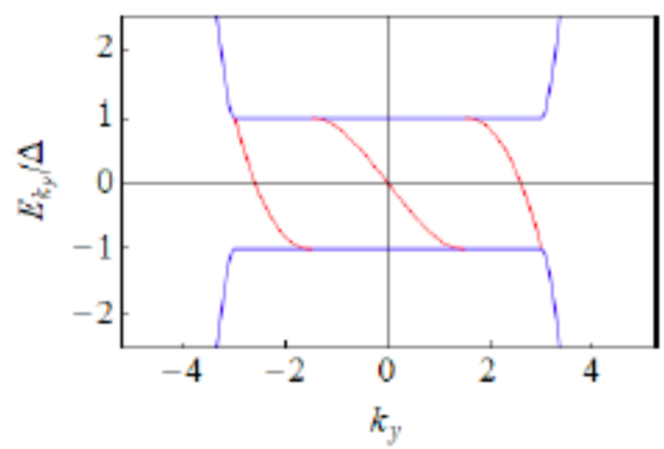
Equilibrium supercurrent within ξ of surface. Screening current within λ+ξ of surface.

→ Magnetic field within λ+ξ of surface & domain walls (also at impurities)

Continuum limit approx for 1 band chiral p-wave → B~10G. Realistic models → B<10G, but generically currents/fields are robust and zero only with fine-tuning. Special to chiral p-wave.

Higher Angular Momenta: Chiral d, f,..

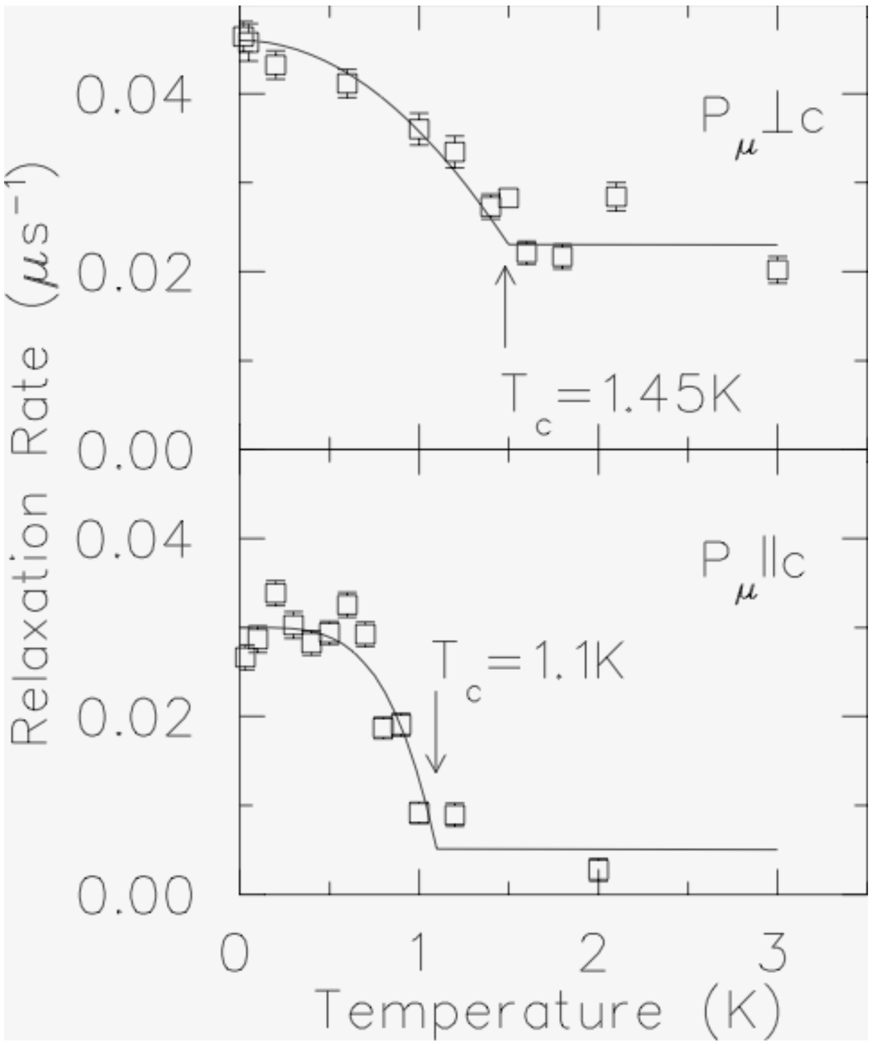




Current vanishes in the continuum limit for non-p-wave chiral SC.
On lattice may or may not vanish (depends on symmetry) but smaller than chiral p-wave (for same material parameters)
Chiral d on triangular lattice typically has current <10% chiral p.
W Huang, E Taylor, CK (unpublished)

TRSB probes: muSR, Kerr effect, scanning SQUID/Hall bar, tunneling

Sr2RuO4: Muon spin resonance sees internal fields below T_c

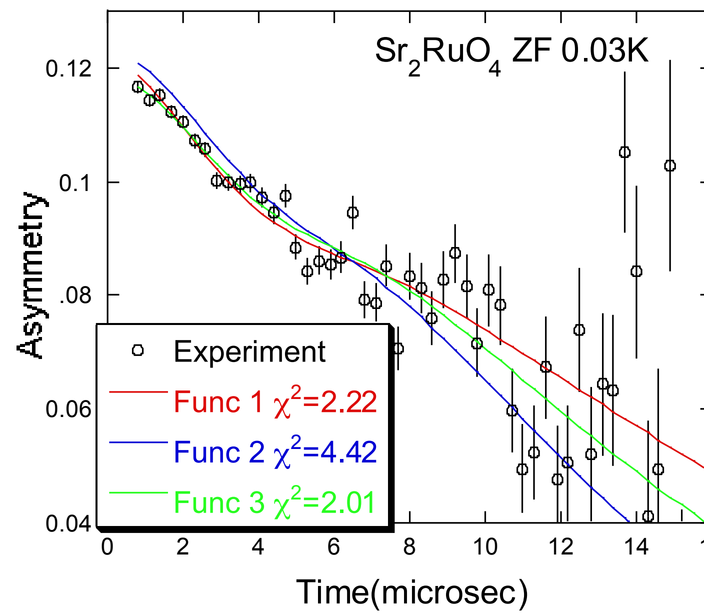


G.M. Luke et al., Physica B 289, 373 (2000).

Interpreted as due to fields at domain walls → domains ~15 microns in size.

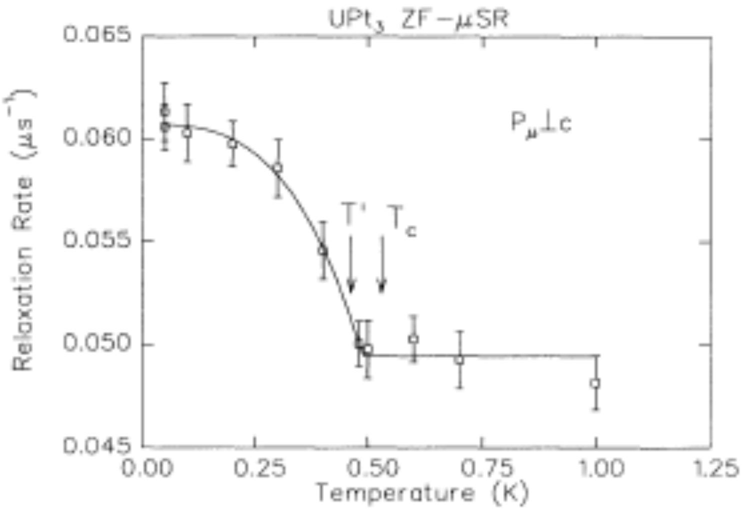
Other possibilities within chiral p-wave:

- impurities
- fields induced by muon (green curve below includes this effect)



W. Higemoto et al., unpublished

muSR for UPt_3



G.M. Luke et al. PRL 71, 1466 (1993).

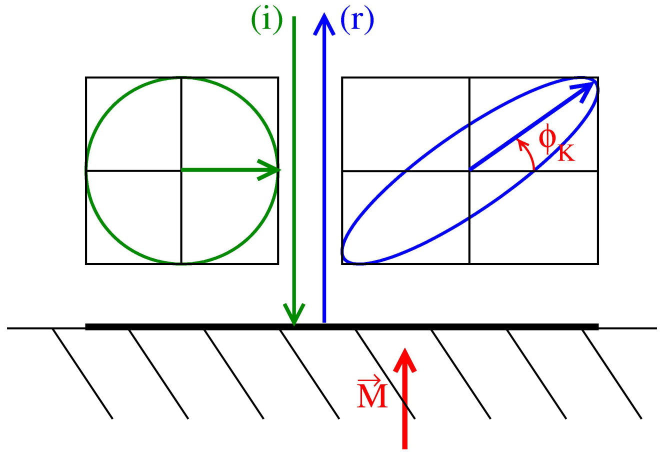
Internal magnetic fields smaller than those observed in Sr_2RuO_4 by roughly factor of 10

Tc_A=0.55K, Tc_B=0.48K

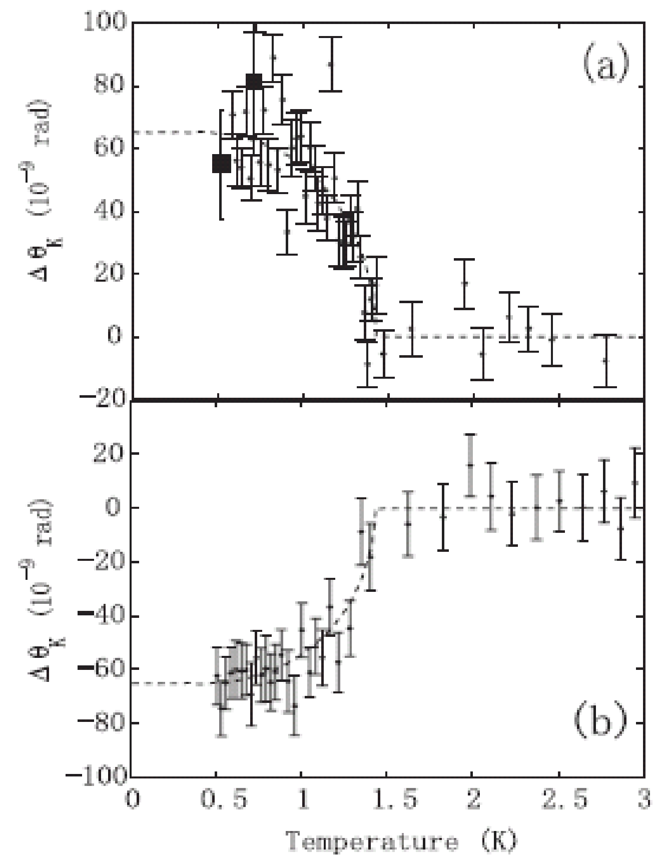
Expect no observable signal in clean, single-domain chiral SC (except from muon itself)

null muSR: PD de Rotier et al. Phys Lett A 205, 239 (1995). Cleaner samples

Polar Kerr effect



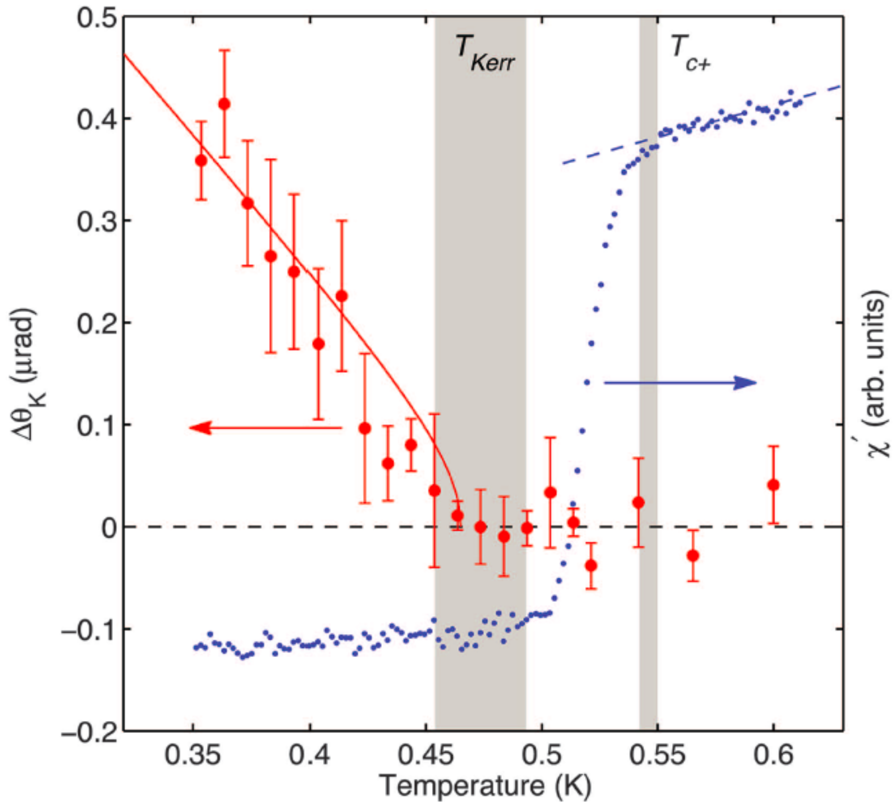
Linearly polarized light is reflected as elliptically polarized light, with rotation of polarization axis by Kerr angle



Cooled in (a) 93 G (b) -43 G
[ω=0.8ev; Θ=60 nanorads]

J. Xia, Y. Maeno, P.T. Beyersdorf, M.M. Fejer, A. Kapitulnik, PRL 97, 167002 (2006).

Kerr effect in UPt3: BTRS in B-phase



Kerr angle > 10X larger than in Sr2RuO4

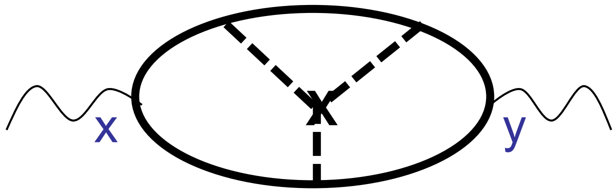
ER Schemm, WJ Gannon, CM Wishne, WP Halperin, A Kapitulnik, Science 345 p. 190 (2014).

Kerr angle determined by $\sigma_H=(\sigma_{xy}(\omega)-\sigma_{yx}(\omega))/2$

In system with Galilean invariance: $\mathbf{j}_s = \frac{ie^2\rho_s/m}{\omega+i\delta}\mathbf{E} \Rightarrow \sigma_{xy}=0$

→ No Kerr effect without breaking translation symmetry but broken translation symmetry and BTRS insufficient

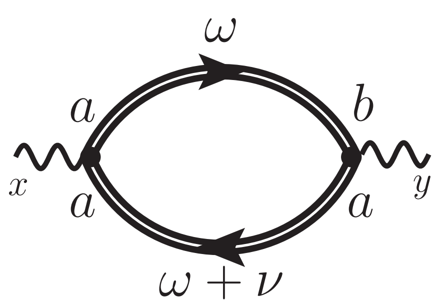
Skew scattering (order $n_i U^3$) contributes



J. Goryo, PRB 78, 060501 (2008).

Estimate: θ_K~40nrads for l_{imp}~1000Å.

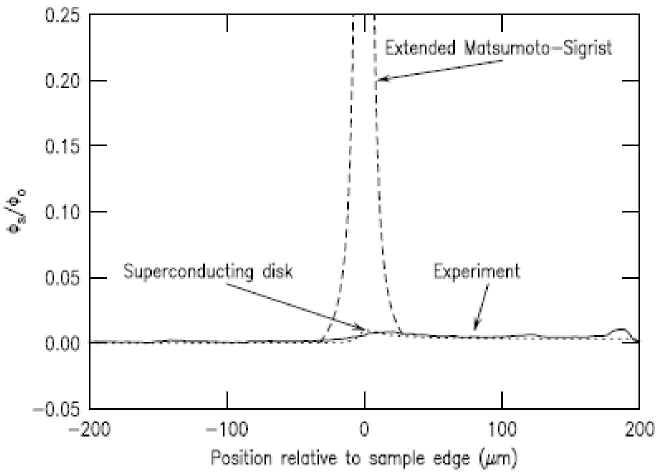
This contribution vanishes for chiral d, f,… pairing in continuum limit.
Higher order term with p-h asymmetry: $(n_i U^2)^2$



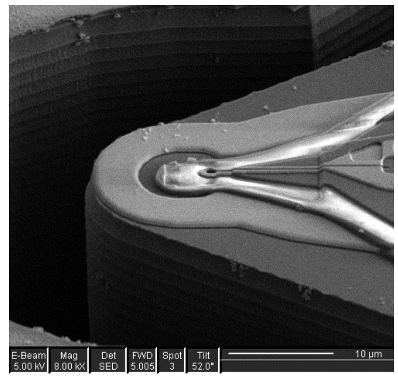
Intrinsic contribution for multi-band chiral SC provided there is interband pairing. Observed magnitude → substantial SC on α,β bands. E Taylor & CK, PRL (2012); J. Phys. (2013); Wysokinski et al. PRL (2012);Granhand et al. PRB (2013)

For isotropic chiral: Yip & Sauls J. Low Temp. Phys. 86 (1992).

Recent experimental searches for surface fields in Sr_2RuO_4



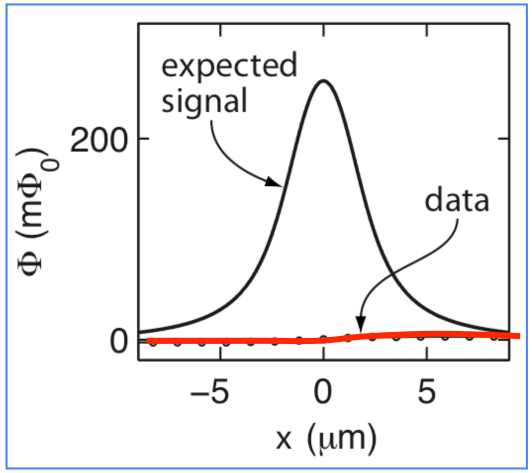
JR Kirtley, CK, C Hicks, EA Kim, Y Liu, KA Moler, Y Maeno, PRB 76, 014526 (2007).

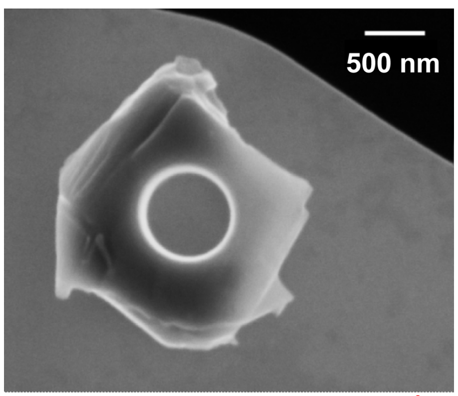


Nano-SQUID. 0.75 micron effective pick-up loop.

N. Koshnick, M. Huber, K.A. Moler, APL 93, 243101 (2008).

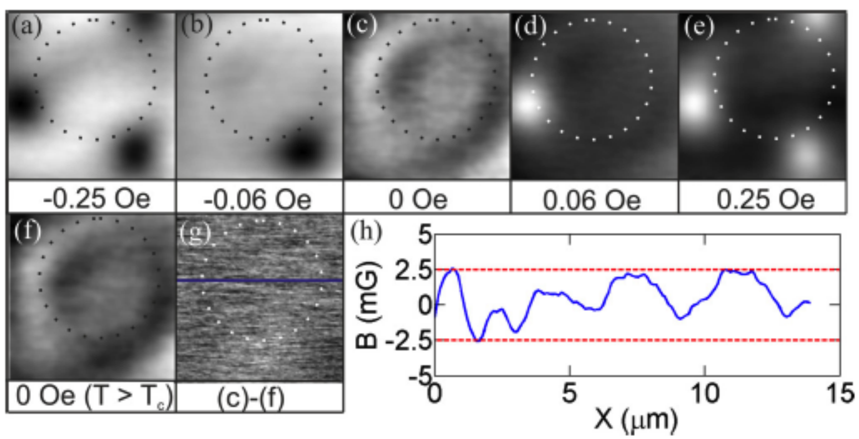
C.W. Hicks, J.R. Kirtley, T.M. Lippman, N.C. Koshnick, M.E. Huber, Y. Maeno, M.B. Maple, K.A. Moler, PRB 81 214501 (2010)





Sr_2RuO_4 Nanocrystal

J. Jang, D.G. Ferguson, V. Vakaryuk, R. Budakian, S.B. Chung, P.M. Goldbart, Y. Maeno Science, 331, p. 186 (2011)



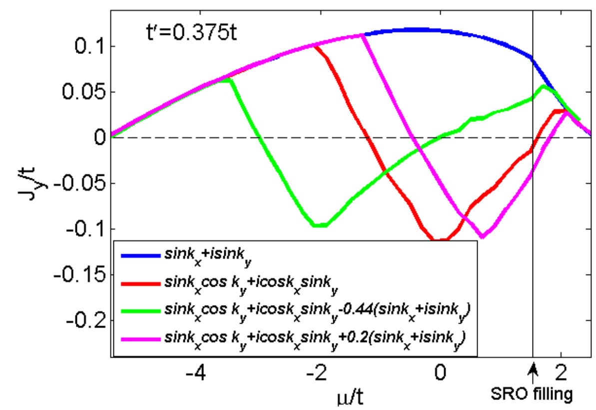
PJ Curran, SJ Bending, WM Desoky, AS Gibbs, SL Lee, AP Mackenzie PRB 89 144504 (2014)

Experiments put upper bounds on surface fields of ±2.5 mG
Almost 3 orders less than prediction

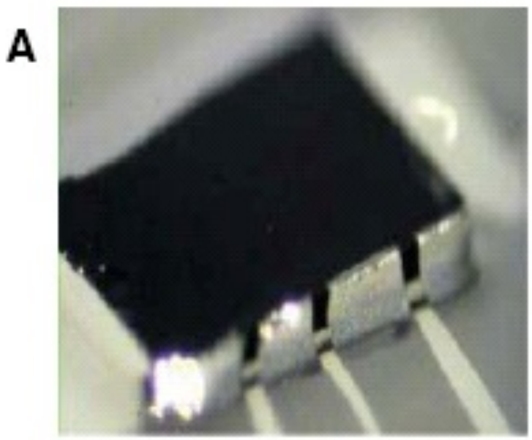
Suppression of supercurrents

(but need orders of magnitude!)

- Leggett has proposed $\langle L_z \rangle \sim (\Delta/E_F)^2 N\hbar/2$ for an alternative wf. *Quantum Liquids* by A.J. Leggett (2006).
- Disorder, rough or pairbreaking surfaces (order 1 effect) PEC Ashby and CK, PRB (2009).
- Retroflective surface can drive current to zero (order 1 for typical surface) JA Sauls, PRB 84, 214509 (2011).
- 3 band model (large order 1) Y Imai, K Wakabayashi, M Sigrist, PRB 88, 144503 (2013).
- Metallic edge in 3 band model (several order 1 effects) S Lederer, W Huang, E Taylor, S Raghu and CK, PRB to appear (2014).
- Current can reverse on [11] surface (order 1) A Bouhon and M Sigrist, arXiv: 1409.6900.
- Substantial NNN pairing (large order 1) W Huang, S Lederer, E Taylor, S Raghu and CK (unpublished)
- Also depends on domain sizes/configurations
- Null surface currents plus sizeable muSR is difficult.



Phase-sensitive measurements

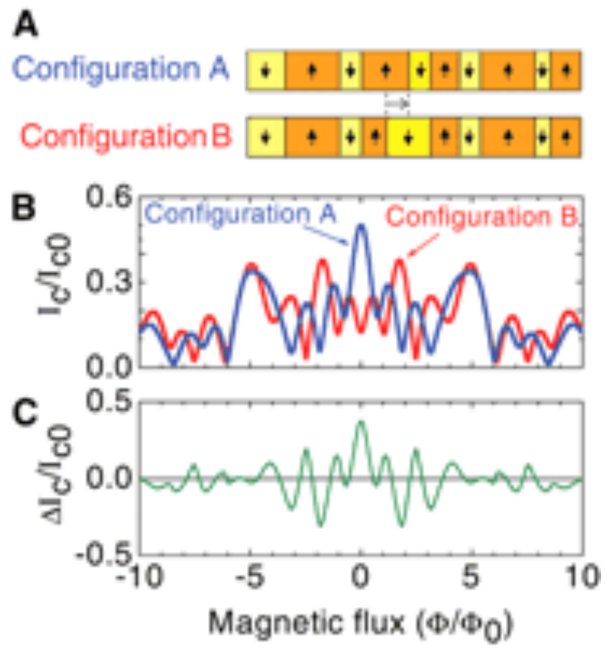


SRO single crystal (black) with 4 Josephson junctions. Gray ribbons are Pb thin film counterelectrodes. A field B is applied along c-axis.

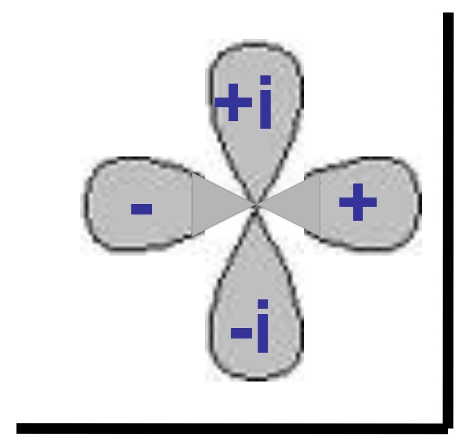
Ideal junction of area A gives Fraunhofer pattern:

$$I_c(\Phi) = J_c A \frac{\sin(\pi\Phi/\Phi_0)}{\pi\Phi/\Phi_0}$$

Observe "Fraunhofer-type patterns" which could be due to small, dynamic domain walls intersecting surface at angle (not π/2) and anisotropic band structure. (Sigrist, 2010).

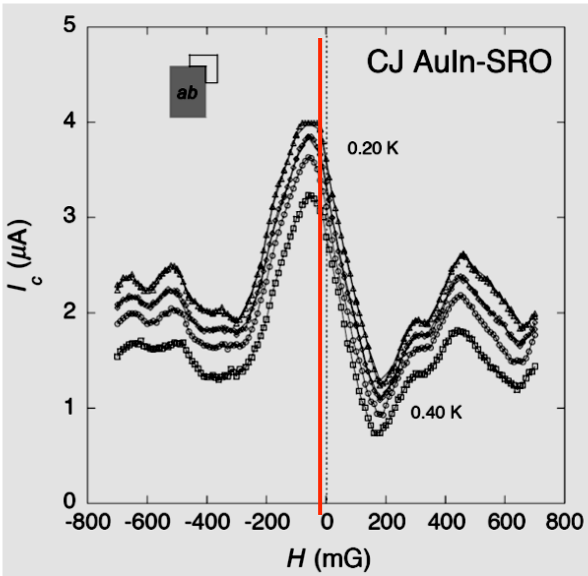


NOTE: Expected pattern seen in one corner junction. (Liu et al.)



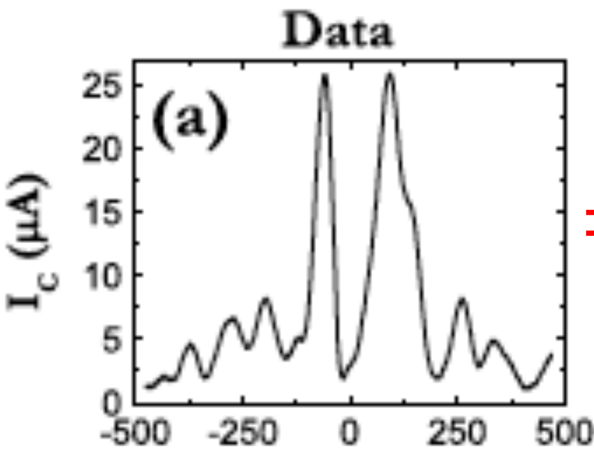
F. Kidwingira, J.D. Strand, D.J. Van Harlingen, and Y. Maeno, Science 314, 1271 (2006).

Corner junction



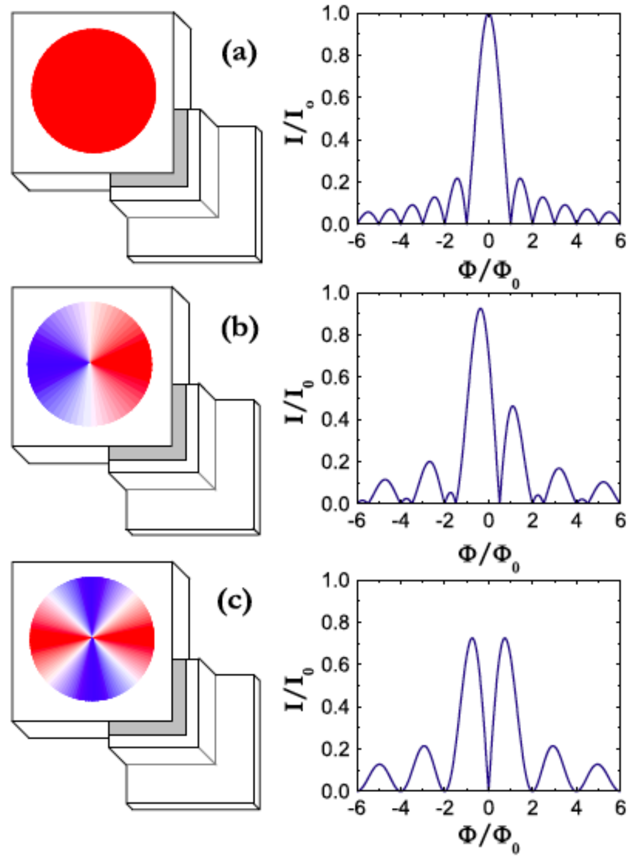
$\pm\frac{\pi}{2}$

SRO: Nelson et al. Science (2004)



±π

UPt3: Strand et al PRL (2009)

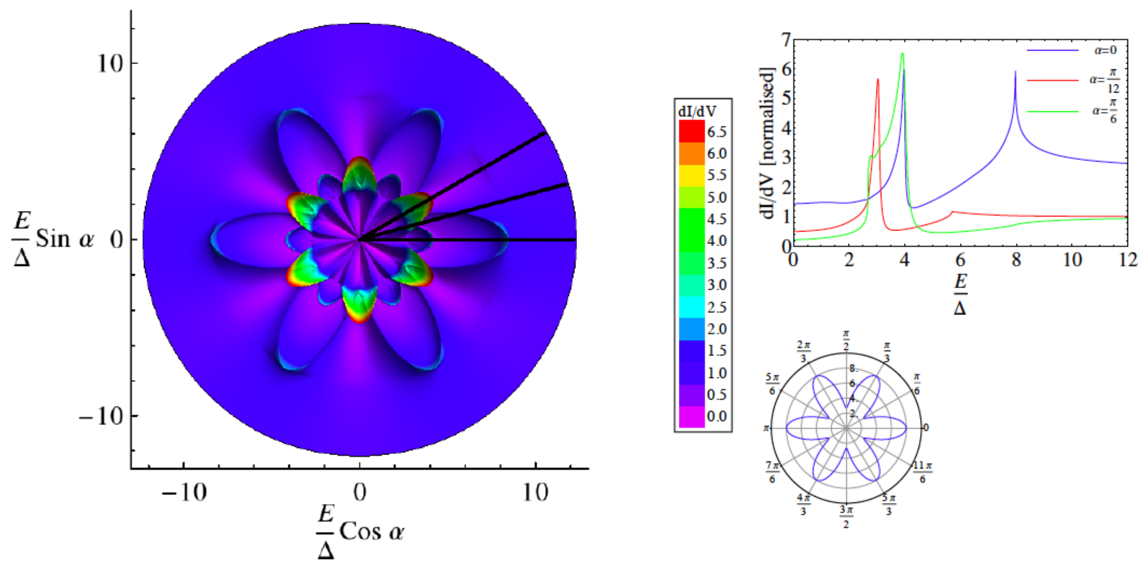


S-wave

Chiral p-wave

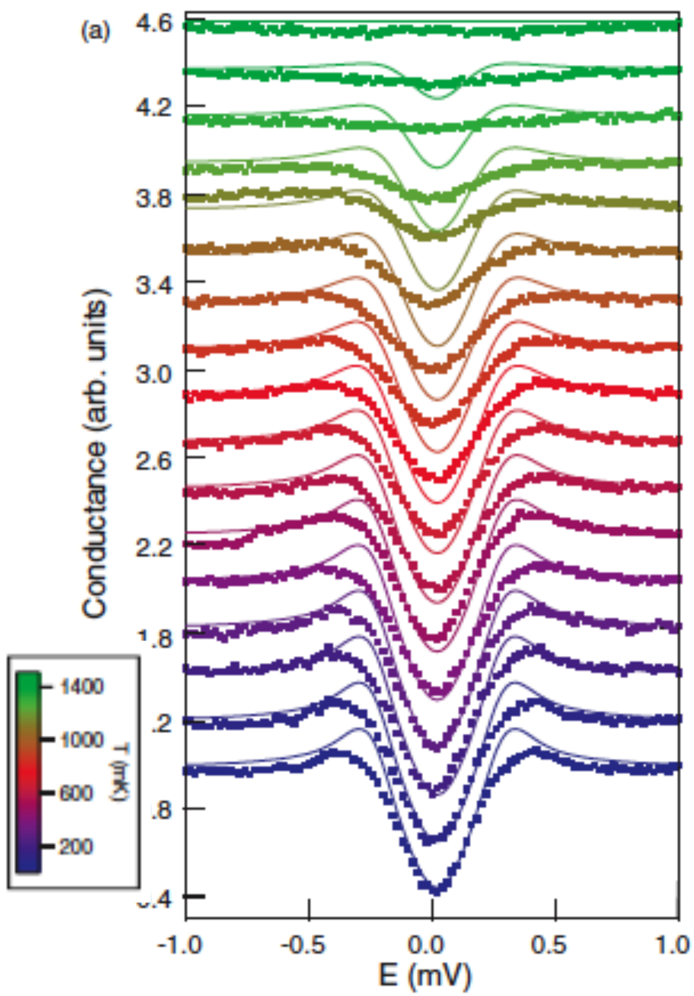
D-wave

"Accessing topological superconductivity via a combined STM and renormalization group analysis" L Elster, C Platt, R Thomale, W Hanke, and EM Hankiewicz, arXiv:1408.3551



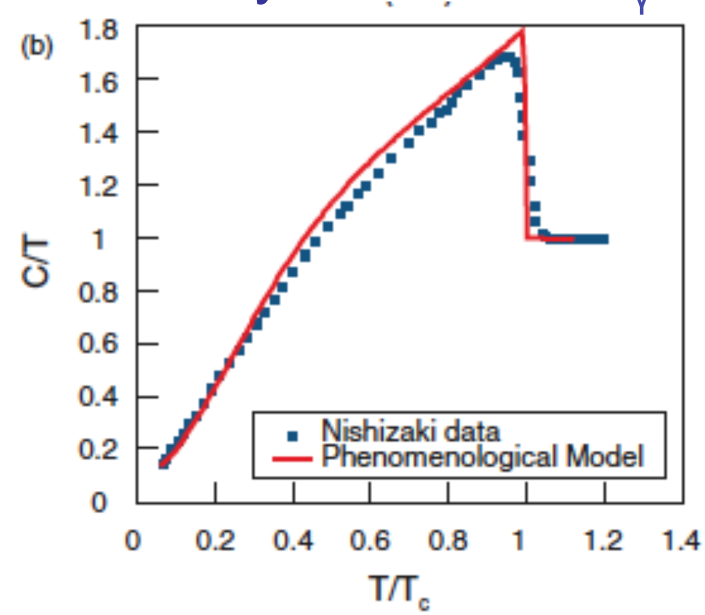
Predicted STM differential conductance, dI/dV, for d+id in graphene

c-axis STM data gives evidence for SC on α,β bands with near nodes



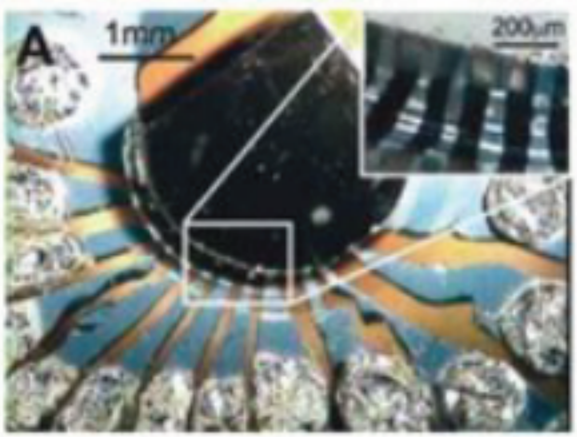
V-shaped gap on background seen below T_c with $2\Delta \sim 5T_c$.
Consistent with near-nodes on quasi-1d bands.

SC on all 3 bands comparable.
Specific heat fit by model with $\Delta_\gamma = 0.7\Delta_\alpha$



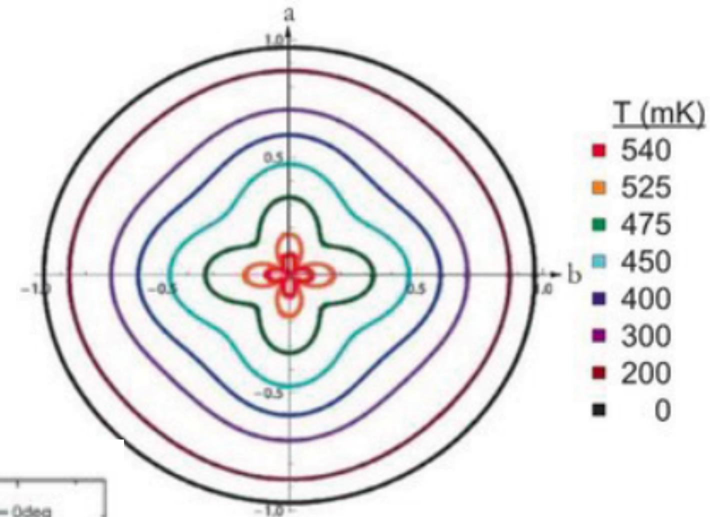
I. A. Firmo, S. Lederer, C. Lupien, A. P. Mackenzie, J. C. Davis and S. A. Kivelson, PRB **88,** 134521 (2013)

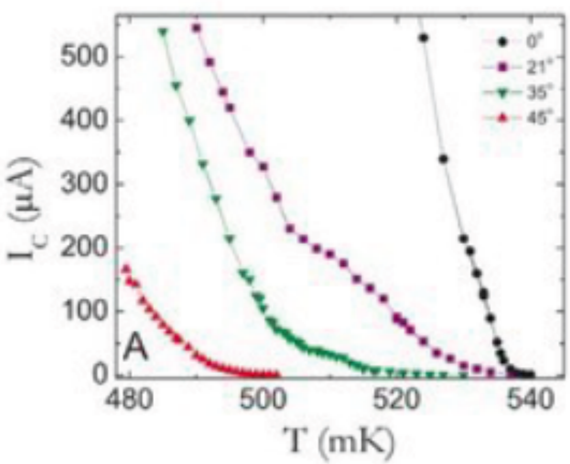
Gap anisotropy of UPt_3 from $I_c(T,\theta)$

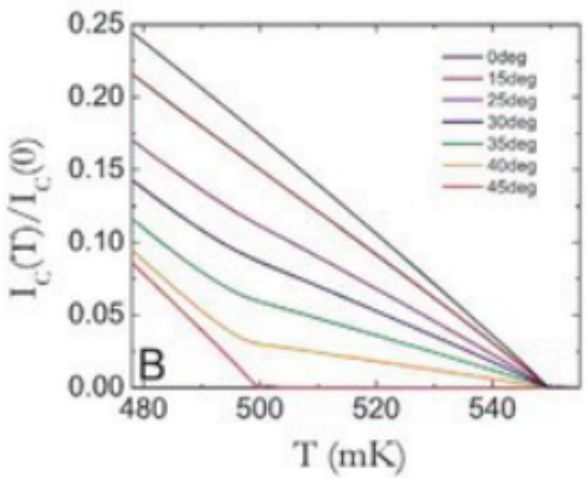


Josephson junctions on UPt_3

$$\Delta = k_z\left[\left(k_x^2 - k_y^2\right)\Delta_R(T) + i2k_xk_y\Delta_I(T)\right]$$



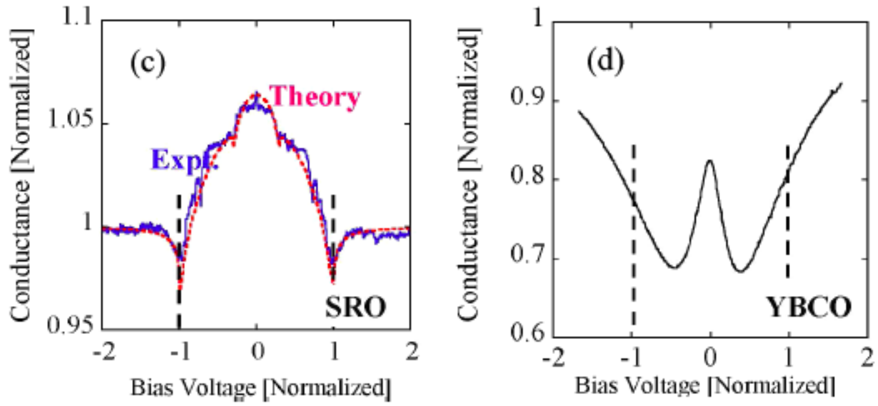




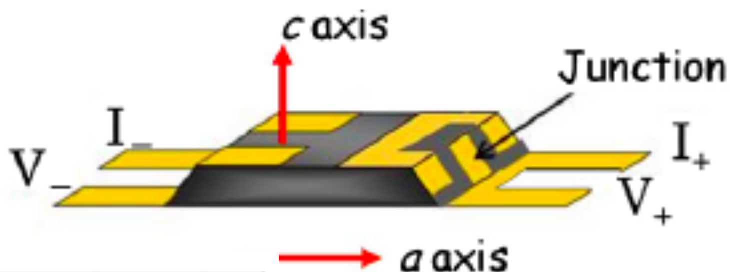
JD Strand, DJ Bahr, DJ van Harlingen,JP Davis, WJ Gannon, WP Halperin, Science (2010)

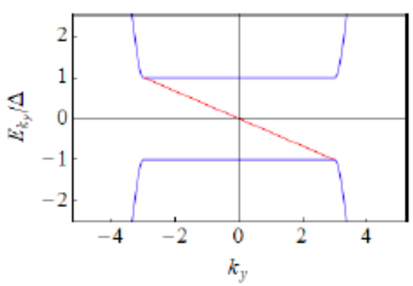
Experimental Search for Majorana modes

Sr_2RuO_4 In-plane Tunneling Spectroscopy

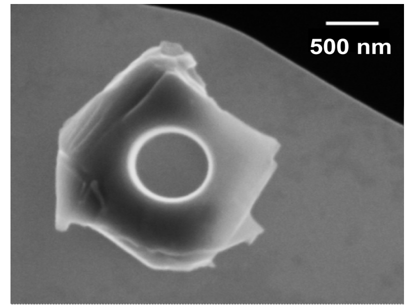


Kashiwaya, Kashiwaya, Kambara ,Furuta, Yaguchi,Tanaka, Maeno, PRL 107 (2011)



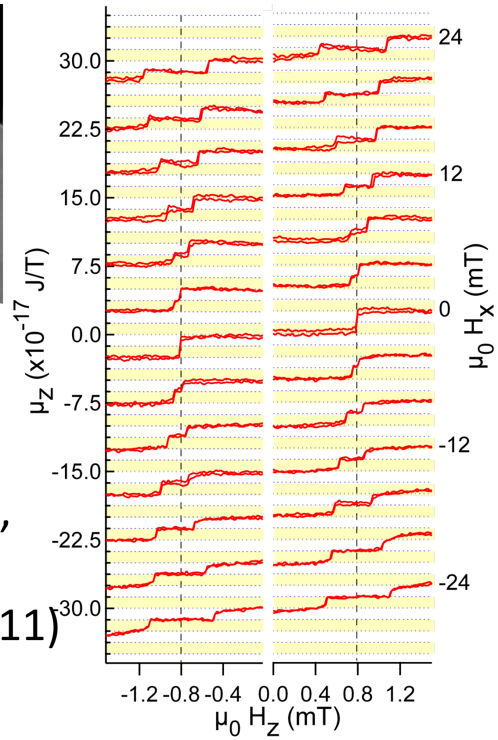


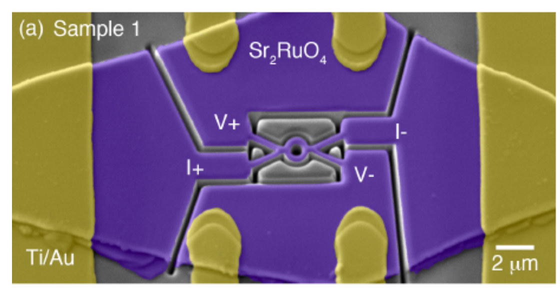
Ultrasensitive Cantilever Magnetometry



Sr_2RuO_4 Nanocrystal

Jang, Ferguson, Vakaryuk, Budakian, Chung, Goldbart, Maeno, Science (2011)





Little-Parks expt. Y Liu (APS 2014)

If one or both of these materials are chiral SCs, unambiguously determining this is important step

Chiral Superconductivity Q's

- How to understand/reconcile various TRSB experiments (possibly chiral SC with correct microscopics) – tunneling may give key info
- How to experimentally detect Majorana modes
- How to discover (other) chiral SCs?