Insights and Open Questions from Another Multiband Superconductor: Sr_2RuO_4

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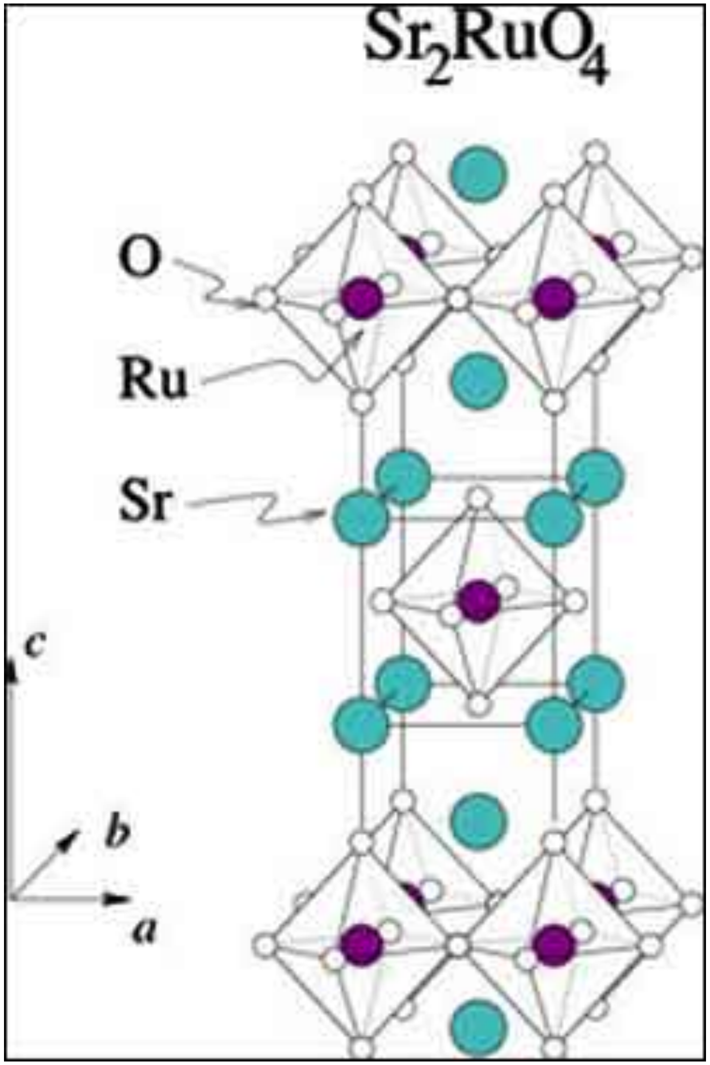
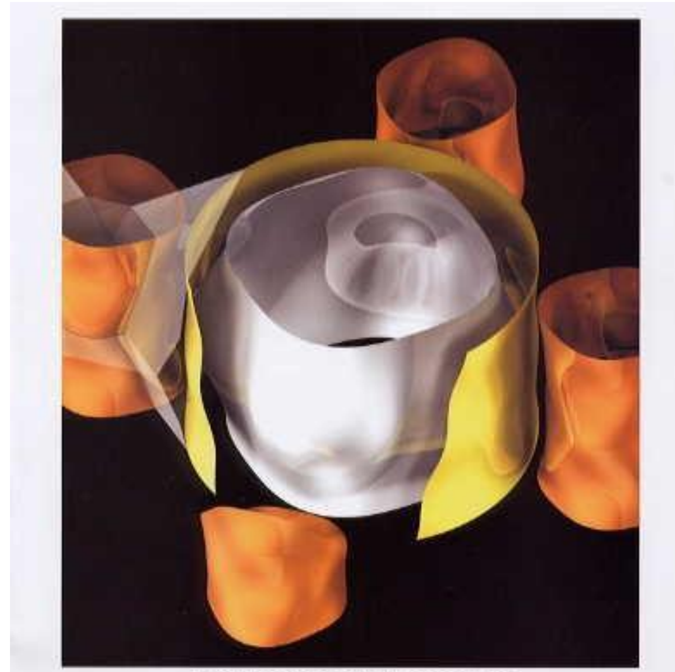
KITP-IRONIC Sept 11, 2014

Strontium Ruthenate





Fermi surface of Sr2RuO4
Bergmann, Mackenzie (1996)

- Same structure as La_2CuO_4 cuprate
- Quasi-two-dimensional
- SC discovered in 1994 by Maeno
- $T_c \leq 1.5K$ (disorder dependent)

Rice & Sigrist (1995) proposed chiral p-wave triplet pairing in analogy with He-3.

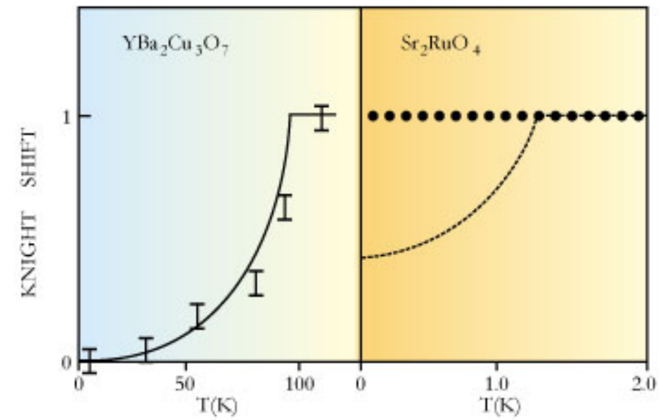
Many experiments consistent with chiral p-wave (NMR, tunneling, muSR, Kerr, magnetometry & HQV)

$$\psi = \Delta_0 \frac{p_x \pm i p_y}{p_F} \chi_{s_c=0}$$

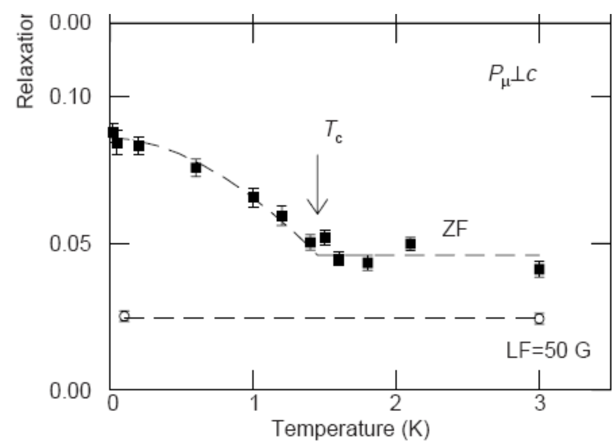
Zero spin projection along c-axis (with SOC)
→ Equal spin pairing in a-b plane

Topological superconductor with Majorana modes at edges, domain walls, vortices. Single Majorana mode for a half-quantized vortex.

Spontaneous charge currents at edges, domain walls, defects.

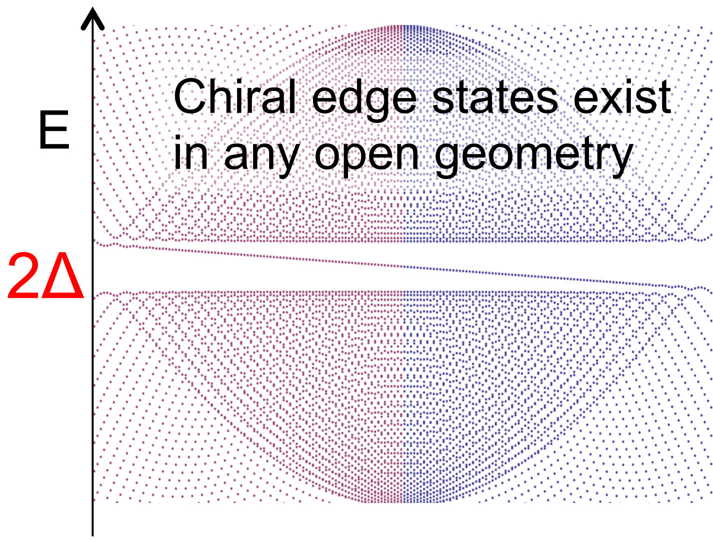


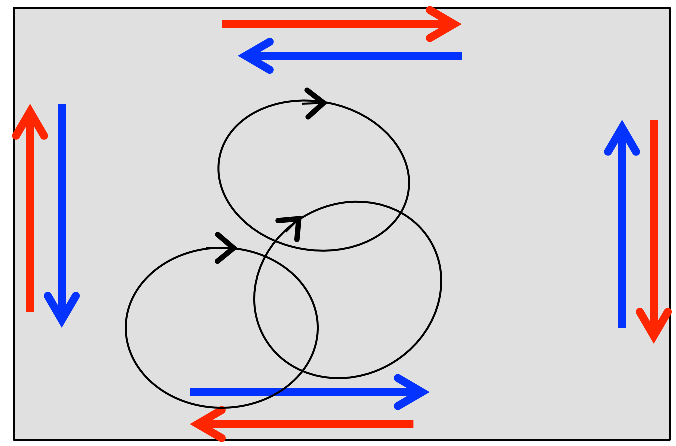
NMR: spin susceptibility → **triplet**
K. Ishida et al. *Nature* **396**, 658 (1998)



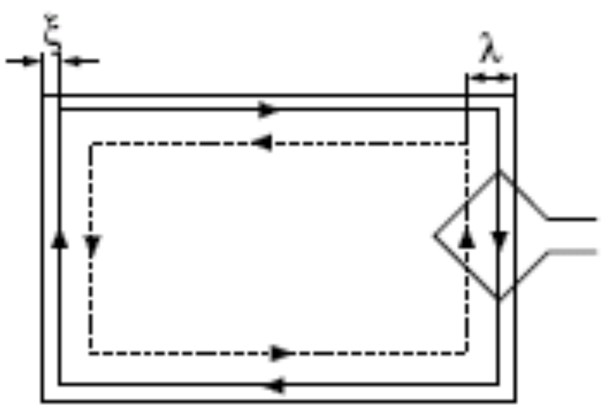
MuSR: internal B fields turn on with T_c → **BTRS**
Luke et al. Nature **394**, 558 (1998)

Spontaneous supercurrents for chiral p-wave





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

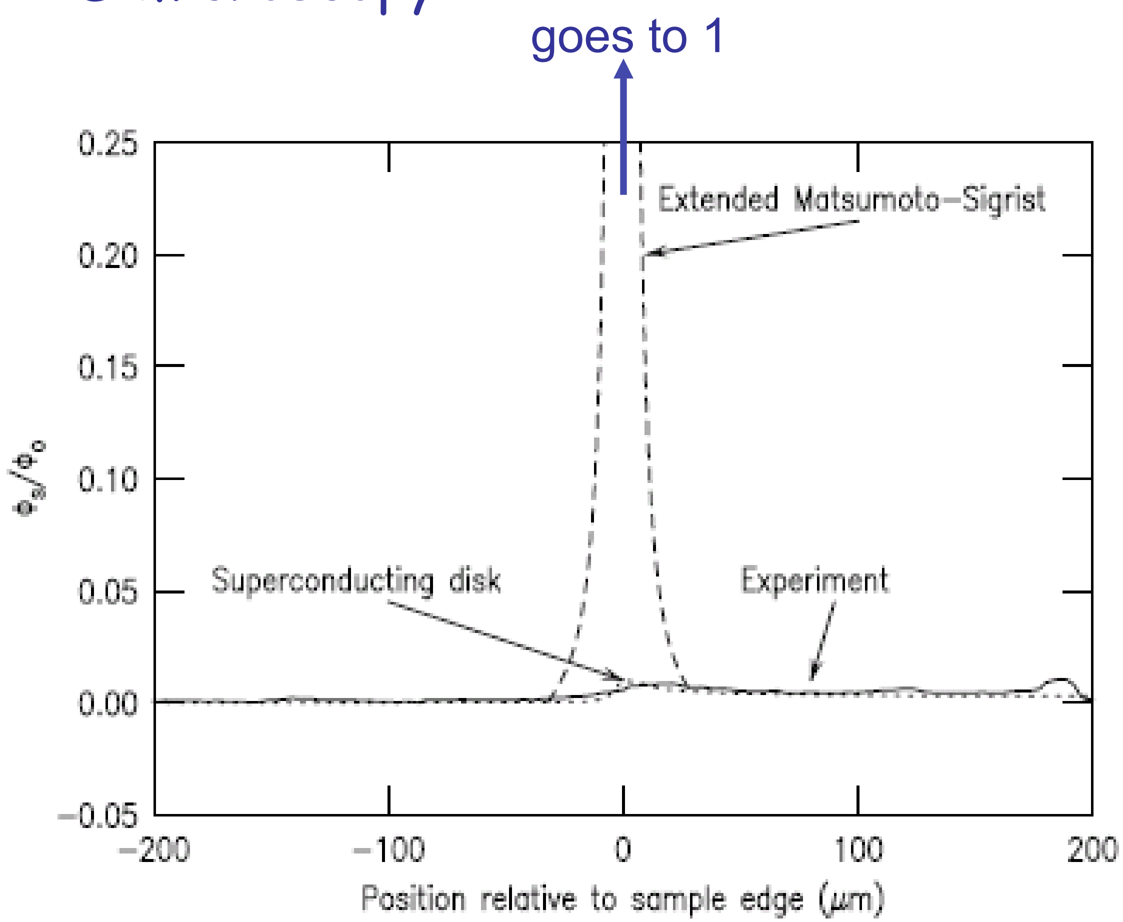


Screening current within λ+ξ of surface

Equilibrium supercurrent within ξ of surface

→ Magnetic field B~10G within λ of surface and B~20G at domain walls.

Scanning SQUID microscopy

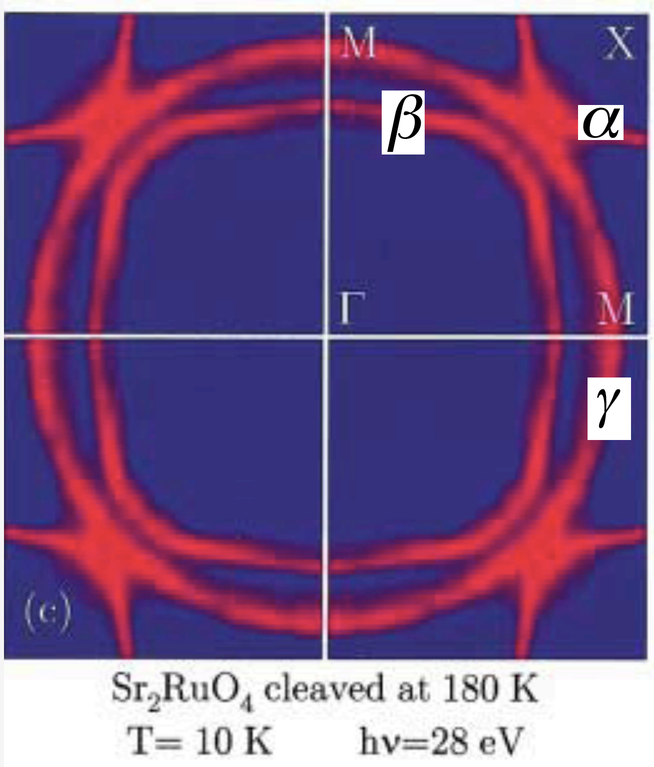


He3 scanning SQUID signal across ab face of Sr_2RuO_4 single crystal at T=0.27K compared to theoretical prediction from modified BdG.

J.R. Kirtley, C.K., C. Hicks, E.A. Kim, Y. Liu, K.A. Moler, Y. Maeno, PRB 76, 014526 (2007).

Similarities to the Iron-based superconductors

- Strongly correlated Fermi Liquid (mass enhancement ~ 4. Mackenzie & Maeno RMP 2003)
- Quasi-two-dimensional
- Superconductivity likely mediated by spin fluctuations (both FM & AFM fluctuations present)
- $Sr_3Ru_2O_7$: Nematic, ferromagnetism; Ca_2RuO_4: Mott insulator.
- Multiple Fermi sheets arising from Ru 4d orbitals, d_{xy}, d_{xz}, d_{yz}
- Substantial spin-orbit coupling (30-100+meV; EJ Rozbicki *et al. J Phys Cond Matt* **23** 094201 (2011); MW Haverkort et al. Phys. Rev. Lett. 101 026406 (2008))

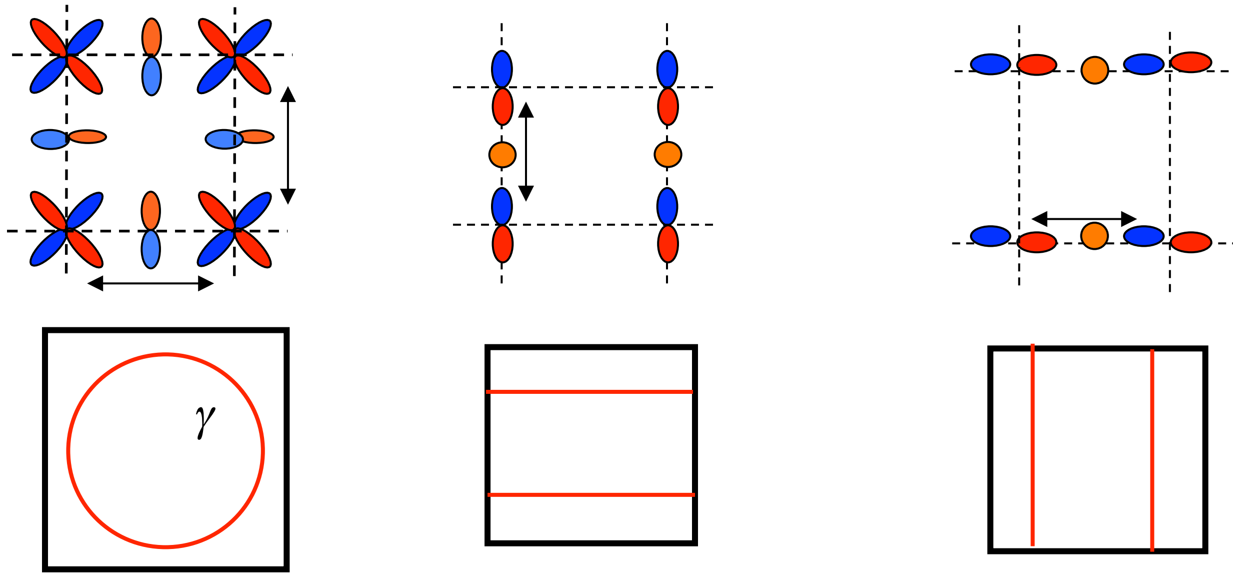


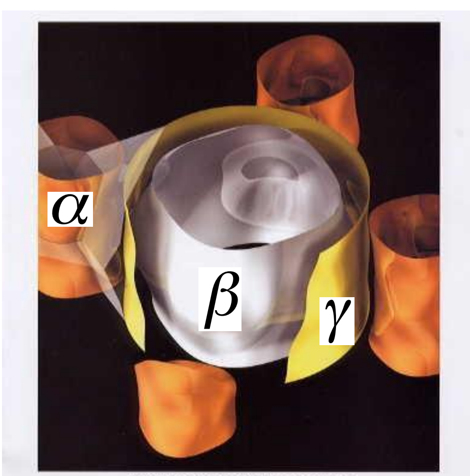
ARPES from A. Damascelli

Sr_2RuO_4 band structure

Ru^{4+} d-orbitals — d_{xy} — d_{yz} — d_{xz}

hybridize with
O 2p-orbitals

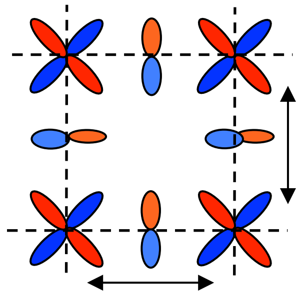


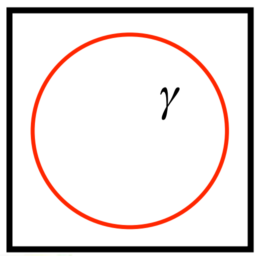


Sr_2RuO_4 band structure

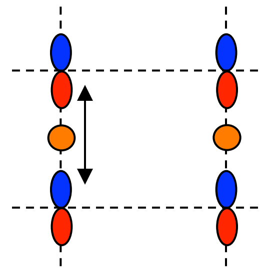
Ru d-orbitals

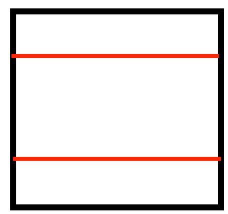
d_{xy}



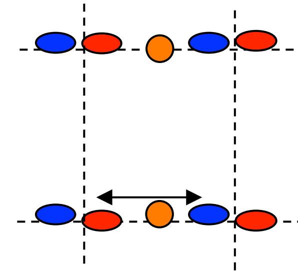


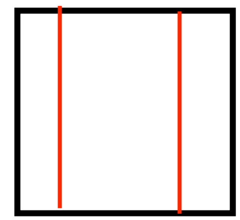
d_{yz}

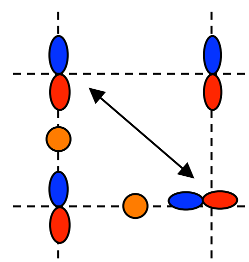




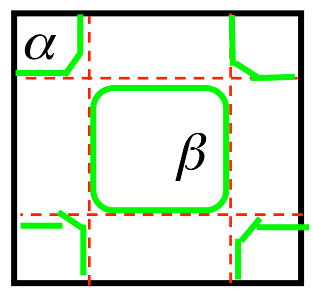
d_{xz}



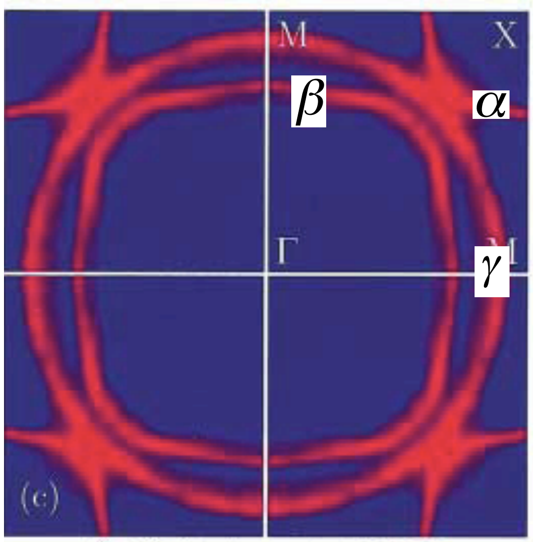




t" ~ 0.1t



(or λ ~ 0.1t)



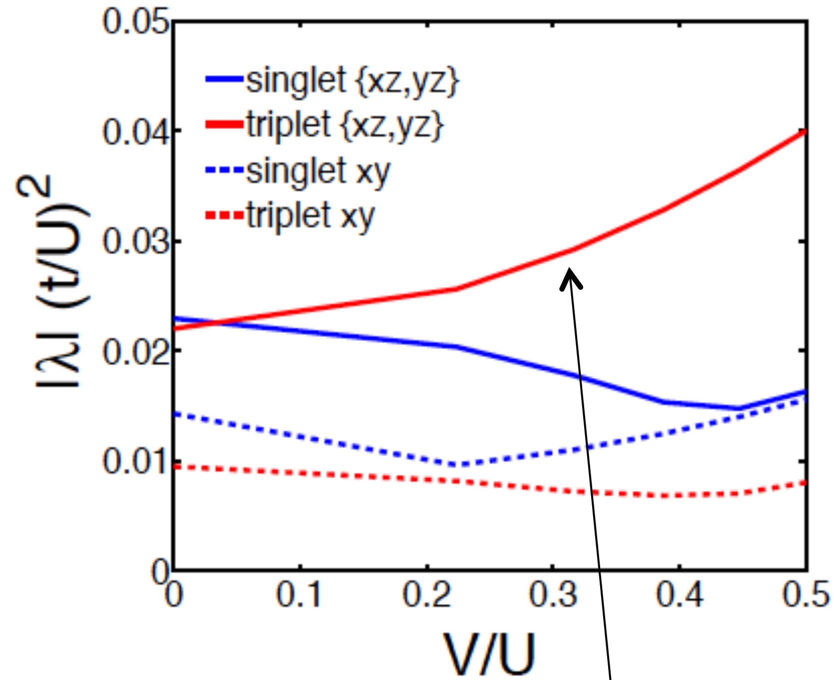
Superconductivity on quasi-1d bands

S. Raghu, A. Kapitulnik and S.A. Kivelson PRL 105, 136401 (2010).

In a weak-coupling RG analysis, find intraorbital p-wave pairing for d_{xz} and d_{yx}.

$$H = H_0 + U\sum_{i\alpha} n_{i\alpha\uparrow} n_{i\alpha\downarrow} + \frac{V}{2}\sum_{i,\alpha\neq\beta} n_{i\alpha} n_{i\beta} + \delta H$$

SOC and interorbital hopping, t”

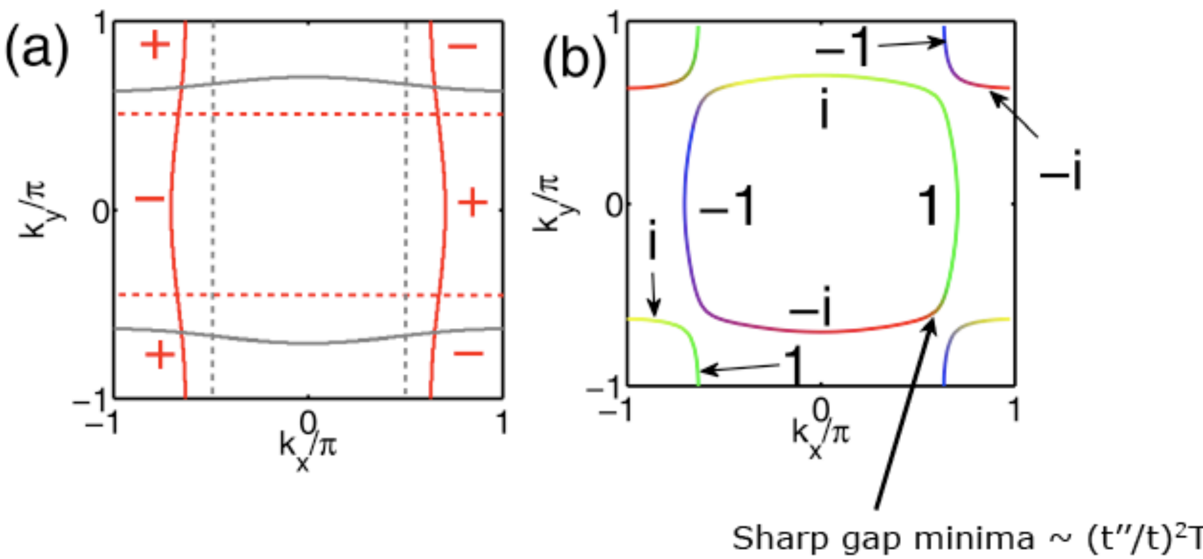


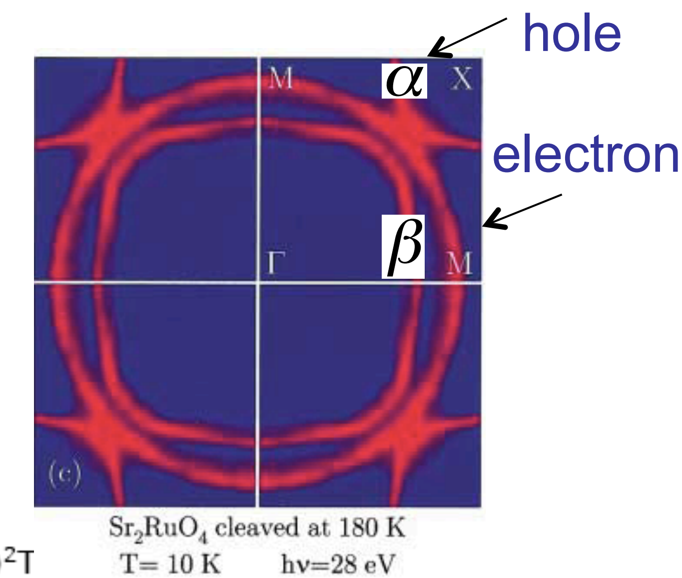
Strongest pairing occurs in quasi-1d bands and is triplet p-wave for V/U not too small.

Raghu, Kapitulnik and Kivelson PRL 105, 136401 (2010).

(a) Bands and pairing phases with no t" (or λ). $\Delta_x \sim \Delta_0 \sin k_x \cos k_y$

Relative phase of intraorbital pairing is π/2.
(b) Bands and pairing phases with d_{xz}-d_{yx} hopping, t", and/or SOC.





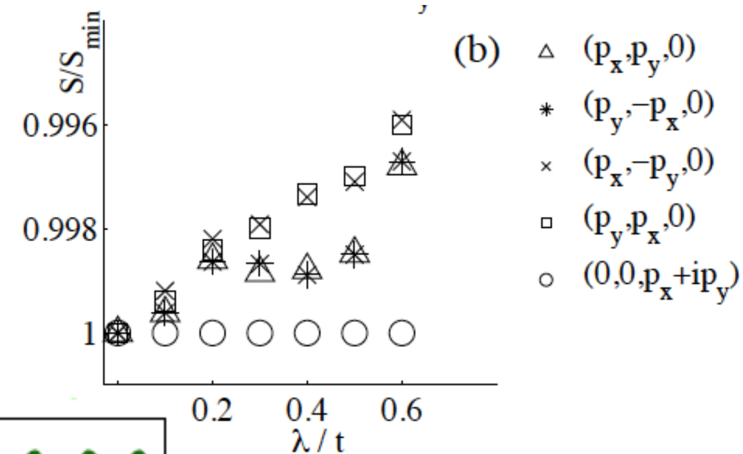
Not topological; may resolve some puzzles like the missing edge currents?

Functional RG on similar 3 band model (with exchange interactions)

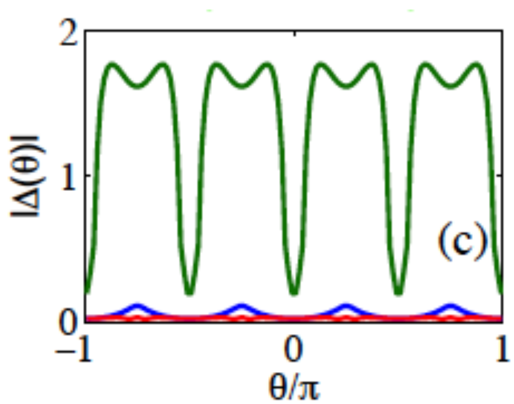
Q.-H. Wang, C. Platt, Y. Yang, C. Honerkamp, F. C. Zhang, W. Hanke, T. M. Rice, R. Thomale, EPL 104, 17013 (2013)

$$H = H_0 + U\sum_{ia} n_{ia\uparrow} n_{ia\downarrow} + \frac{V}{2}\sum_{i,a\neq b} n_{ia} n_{ib} + \frac{J}{2}\sum_{i,a\neq b,ss'} c^{+}_{ias} c^{+}_{ibs'} c_{ias'} c_{ibs} + \frac{J'}{2}\sum_{i,a\neq b,s\neq s'} c^{+}_{ias} c^{+}_{ias'} c_{ibs'} c_{ibs}$$

$J = J'$ and SOC treated perturbatively



→ Find chiral p-wave but with γ band dominant. Gap has significant next nearest bond pairing and deep minima along k_x,k_y.



Pairing symmetry and dominant band with SOC

T Scaffidi, JC Romers and SH Simon, PRB 89, 220510 (2014)

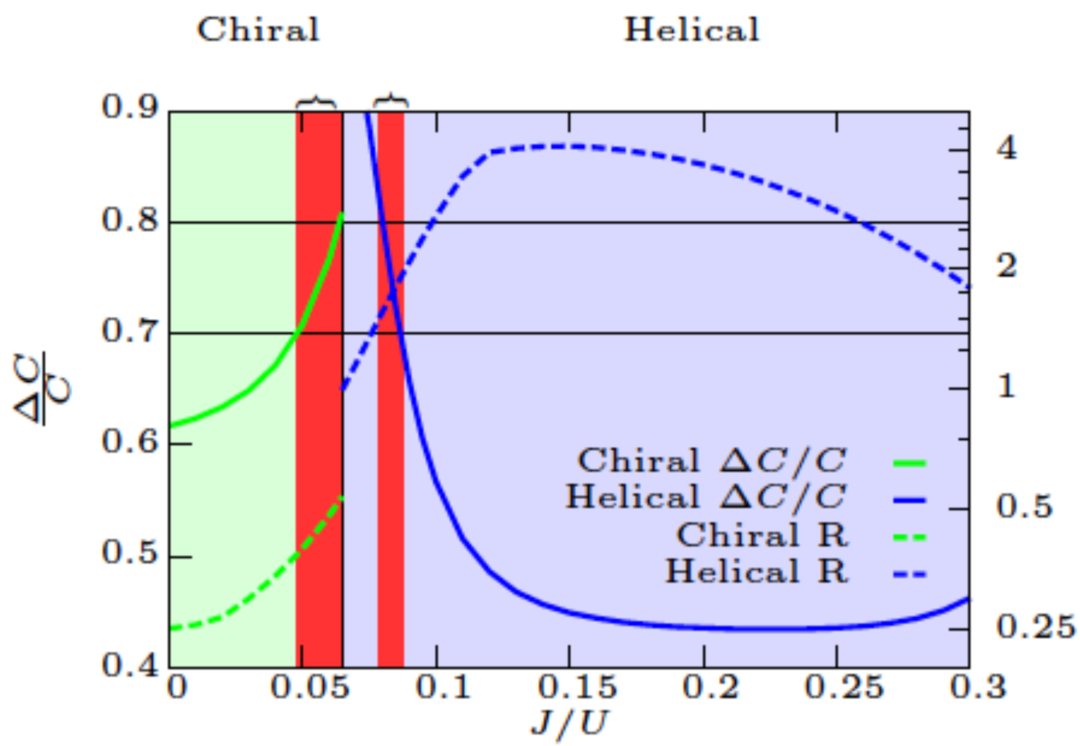
Weak coupling RG analysis (like Raghu et al.) of 3 band model with spin-orbit coupling.

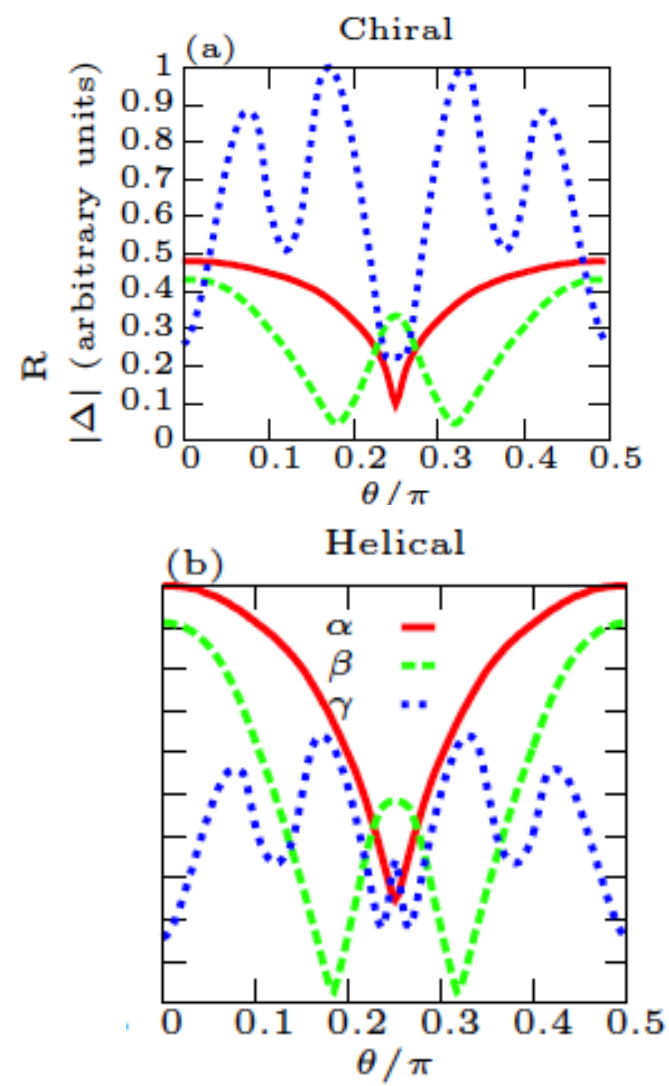
$$H = H_0 + U\sum_{ia} n_{ia\uparrow} n_{ia\downarrow} + \frac{V}{2}\sum_{i,a\neq b} na_{ia} n_{ib} + \frac{J}{2}\sum_{i,a\neq b,ss'} c^+_{ias} c^+_{ibs'} c_{ias'} c_{ibs} + \frac{J'}{2}\sum_{i,a\neq b,s\neq s'} c^+_{ias} c^+_{ias'} c_{ibs'} c_{ibs}$$

H_0 describes α,β,γ bands with SOC. Take J'=J and V=U-2J. Then J/U parametrizes the interaction.

Find H can stabilize either chiral p-wave SC (γ band dominates) or helical phase (like He-3 B phase; α,β bands dominate) depending on value of J/U.

Pairing symmetry and dominant band with SOC

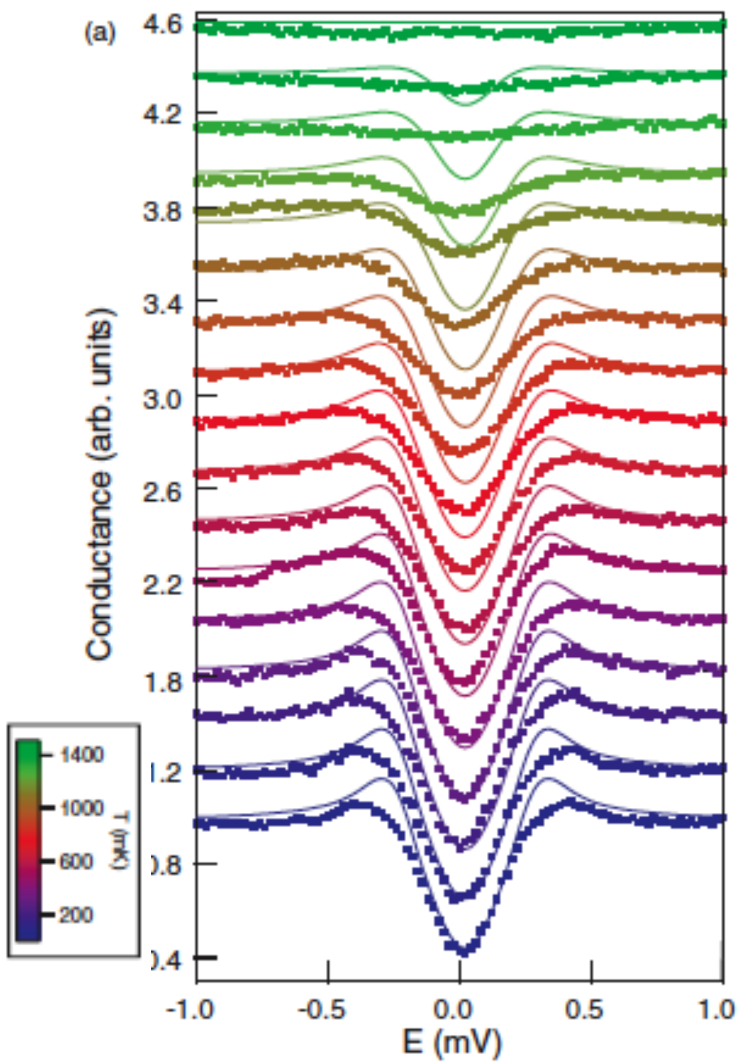




Note: helical state $p_x\hat{x} + p_y\hat{y}$
does not break TRS and has spin (not charge) currents at edge

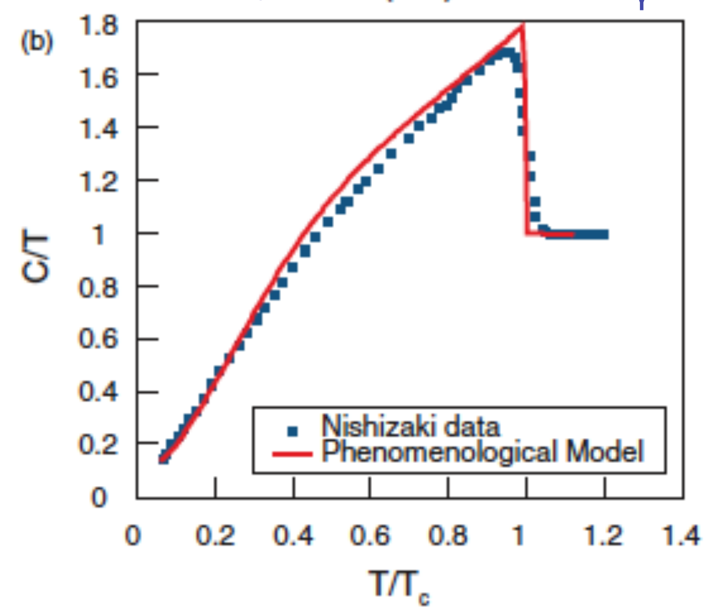
T Scaffidi, JC Romers and SH Simon, PRB 89, 220510 (2014)

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



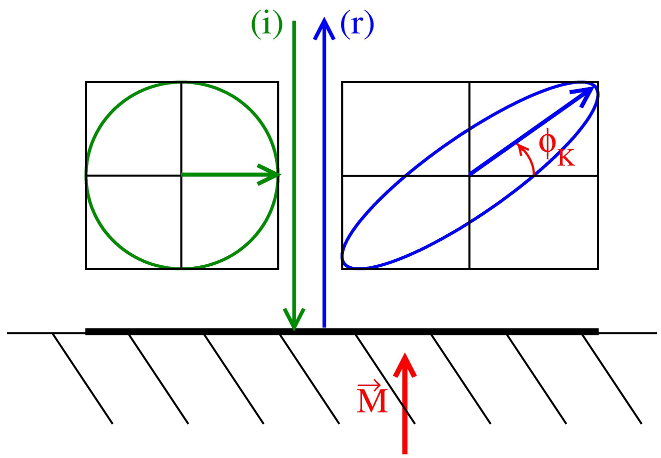
V-shaped gap on background seen below T_c with $2\Delta \sim 5T_c$.
Consistent with near-nodes on quasi-1d bands.

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)

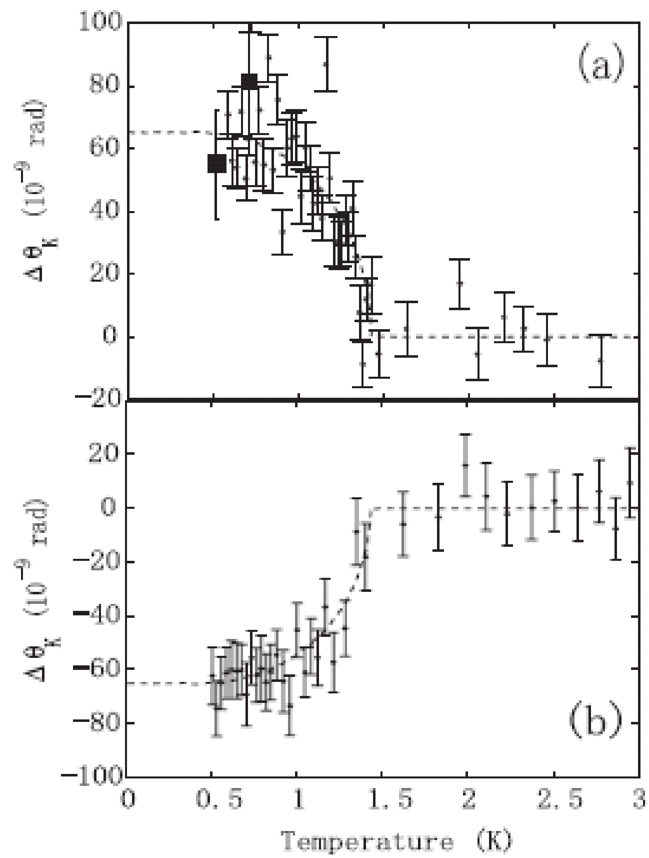
Polar Kerr effect



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

Measure magnetization perpendicular to surface in FM

Effect as observed requires broken time-reversal symmetry



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).

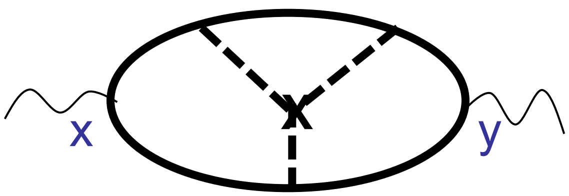
Polar Kerr effect

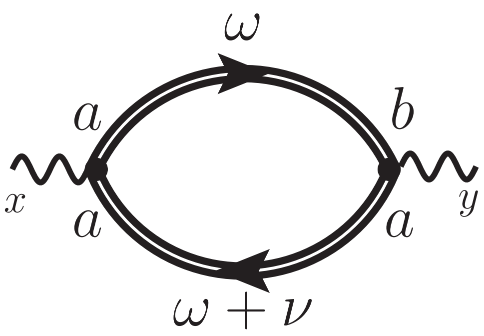
$$\theta_K = \frac{4\pi\sigma''_H(\omega)}{n(n^2-1)\omega} \propto \sigma''_H(\omega)$$ (for $\omega > \omega_p$) $2\sigma_H = \sigma_{xy} - \sigma_{yx}$

Absorptive part of σ_H → system absorbs either right or left circularly polarized light preferentially

In translationally invariant system, uniform field couples only to COM momentum and σ_H=0.

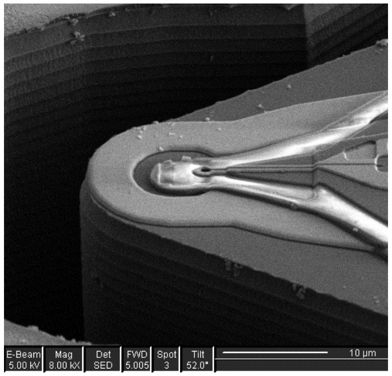
Largest contribution due to disorder identified (skew-scattering) Goryo PRB (2008).





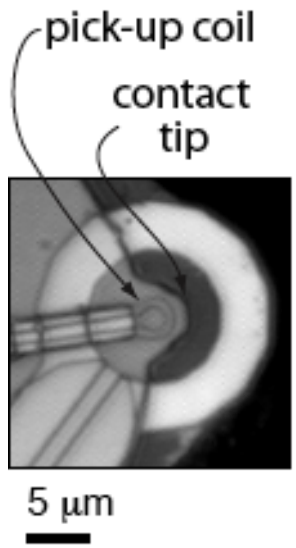
Intrinsic contribution generic to multi-band chiral SC provided there is interband pairing. Observed magnitude → substantial SC on α,β bands. E Taylor & CK, PRL 108, 157001 (2012); J. Phys. 449, 012036 (2013).

Recent experimental searches for surface fields in Sr_2RuO_4

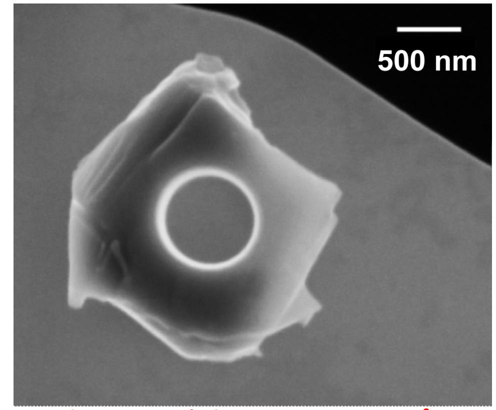


Nano-SQUID. 0.75 micron effective pick-up loop.

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

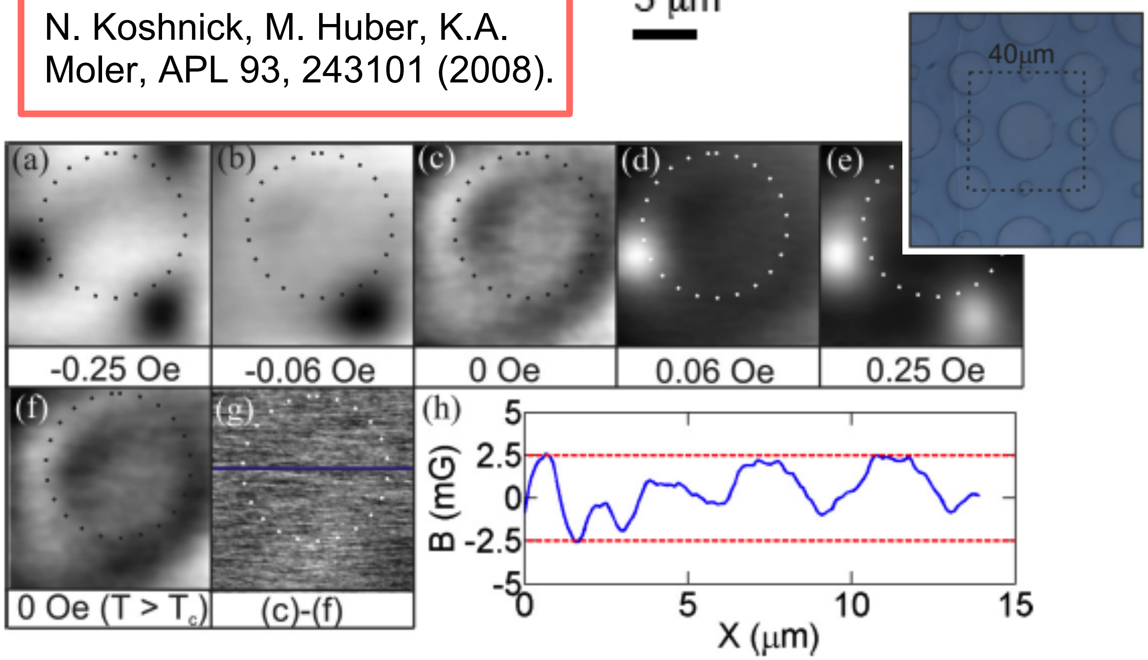


C.W. Hicks, J.R. Kirtley, T.M. Lippman, N.C. Koshnick, M.E. Huber, Y. Maeno, M.B. Maple, K.A. Moler, PRB 81 214501 (2010)



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 and AP Mackenzie PRB 89 144504 (2014)

Experiments put upper bounds on edge currents which are less than 1% of the simple chiral p-wave prediction.

Suppression of supercurrents

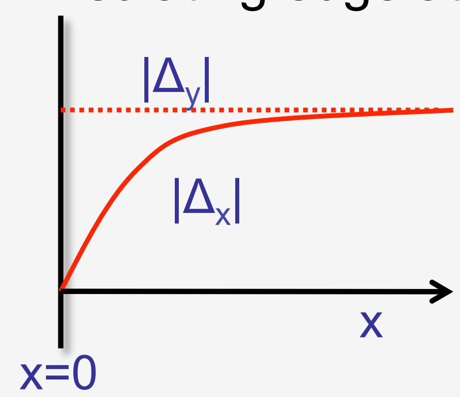
(but need orders of magnitude!)

Current not topologically protected but robust in ideal case (integrated unscreened current, $I = \pm\mu/4\pi$, is independent of Δ, hard/soft surface, harmonic trap) but is sensitive to anything anything that mixes x and y (disorder, rough surface, band structure)

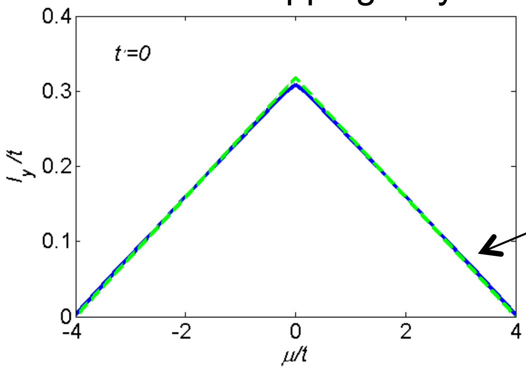
- Disorder, rough or pairbreaking surfaces (order 1 effect; PEC Ashby, CK, PRB 2009.)
- Metallic edge in 3 band model (S Lederer, W Huang, E Taylor, S Raghu and CK, arXiv:1404.4637) find several order 1 effects Current on 1d bands suppressed (vanishes for t”,λ=0); current from xy band reduced; metallic edge reduces current more than insulating edge at low but finite temperature.

c-axis domains?

$$j_y \propto k_3 \mathrm{Im}\left[\Delta_x^* D_x \Delta_y + \Delta_y^* D_x \Delta_x\right]$$



NN hopping only



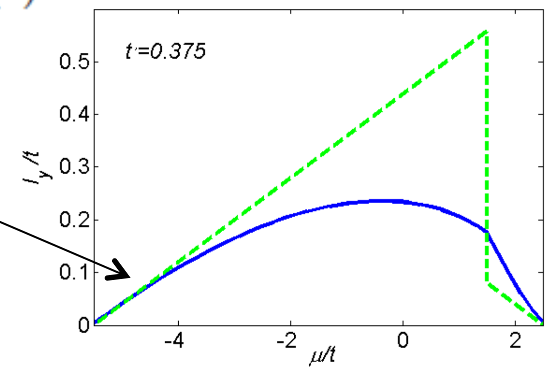
$$j_{CS}(\mathbf{r}) = -\frac{C}{4\pi}(\hat{\mathbf{z}} \times \nabla)A_0(\mathbf{r})$$

Volovik (1992)

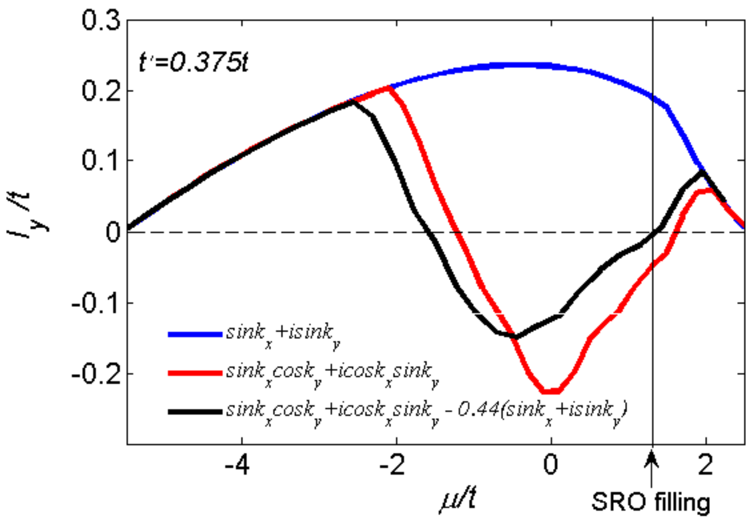
I=±μ/4π=n/4m

Stone & Roy (2004)

NNN hopping included



Band structure matters & can reduce the current

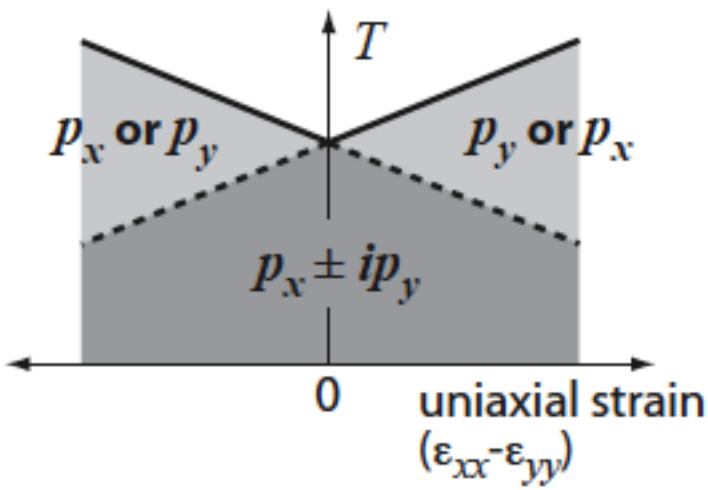


Pairing details matter & can reduce the current

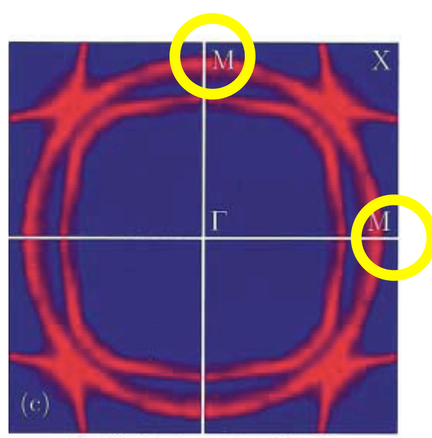
Problems:
If all 3 bands contribute, need substantial reductions for all 3

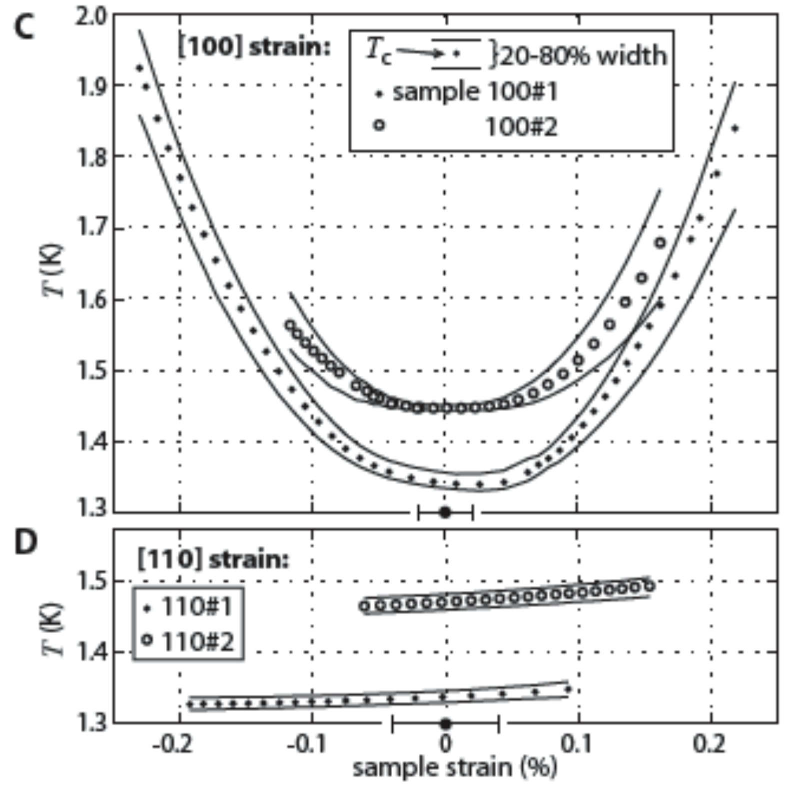
Would also reduce muSR fields below their sensitivity unless the domain wall configuration changes with band structure and/or pairing details.

Strong Increase of Tc of Sr2RuO4 under both Tensile & Compressive Strain



Huge anisotropy suggest van Hove points and γ band may be important for Tc ??





C Hicks, MacKenzie et al. Science 344, 6181, 283-285 (2014)

Open Questions

- Compelling evidence that Sr_2RuO_4 is a triplet SC and several experiments see evidence of broken TR symmetry but OP symmetry still in question.
- Null surface fields and muSR/Kerr effects not reconciled.
- No concensus on which bands dominate SC and by how much.
- No concensus on where the low-lying excitations reside in momentum space