Update on Exotic Superconductivity in Sr_2RuO_4

Steve Simon
Jesper Romers
and especially Thomas Scaffidi

Scaffidi, Romers, Simon PRB 89 220510R (2014)
Scaffidi, Simon arXiv 1410.6073

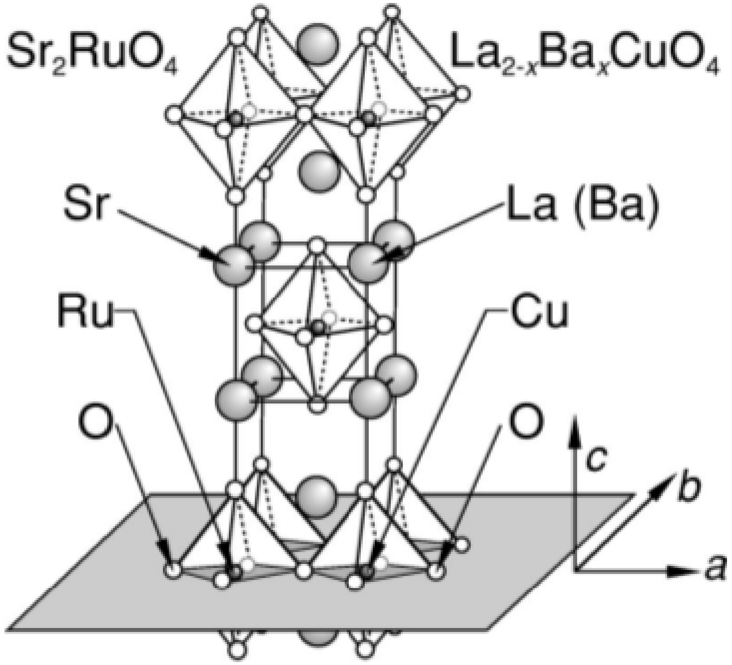
Many thanks: Andy Mackenzie, Clifford Hicks
Jim Sauls, Steve Kivelson, Sri Raghu, Catherine Kallin

General Outline

1. Background, and Triplet Pairing
2. T-breaking or not? (The conflict that framed the field)
3. 2D or 1D. Another conflict?
4. Resolution of 2D vs 1D
5. Resolution of T-breaking or not

Some Basic Facts

From RMP 75, 657 (2003) Maeno+Mackenzie



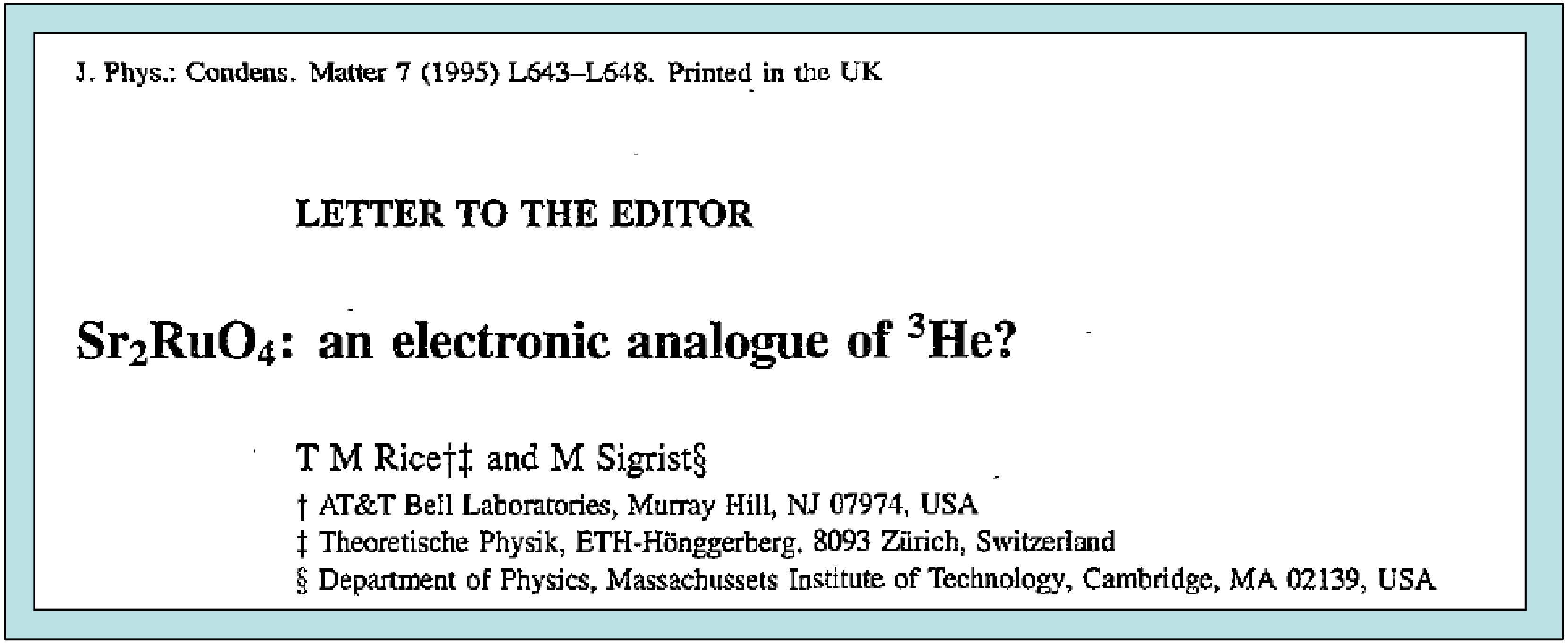
Hopping in Ru-O planes

Very two dimensional
$\rho_c / \rho_{ab} \sim 1000$

High T_c Analog
(Perovskite)

Superconductivity discovered: 1994 $T_c \sim 1.5K$

- Very 2D (like high T_c). Has Fermi surface with no doping.
- Fairly strong Hubbard/Hund interactions on site
  Measured Effective Mass ~ 3-4 x LDA Mass



J. Phys.: Condens. Matter 7 (1995) L643–L648. Printed in the UK

LETTER TO THE EDITOR

Sr_2RuO_4: an electronic analogue of ^3He?

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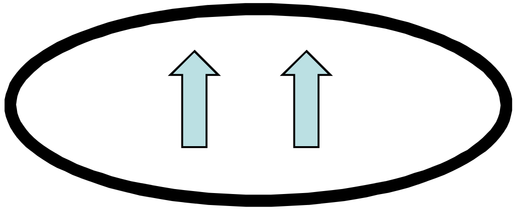
^3He Superfluid = Triplet BCS Paired Superconductor

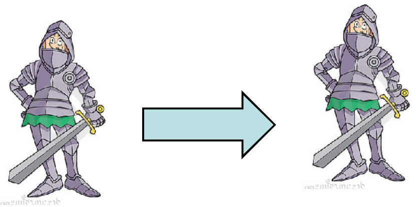


spins = symmetric

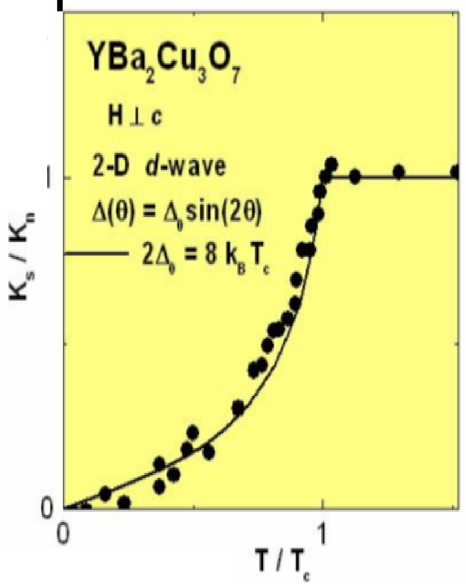
$g(\mathbf{r}_1 - \mathbf{r}_2)$ = antisymmetric

Evidence for Triplet

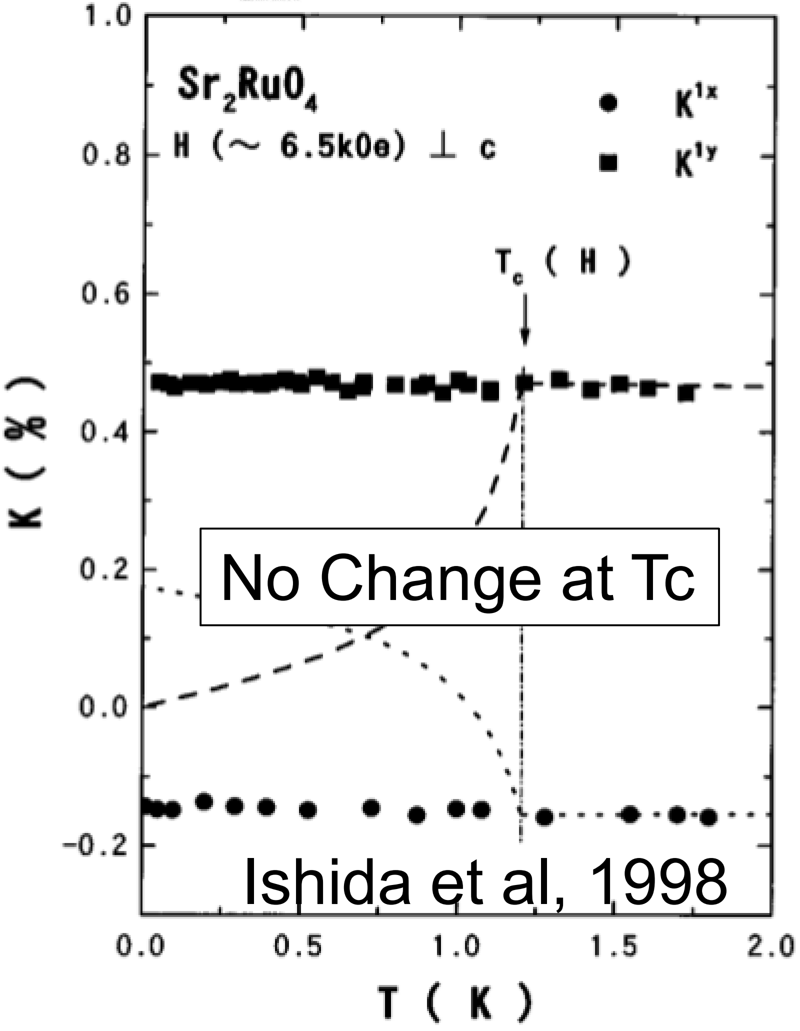
NMR Knight Shift
Measures spin susceptibility



Compare:



YBCO = “Conventional” Singlet



No Change at Tc

Ishida et al, 1998

How unusual is this?

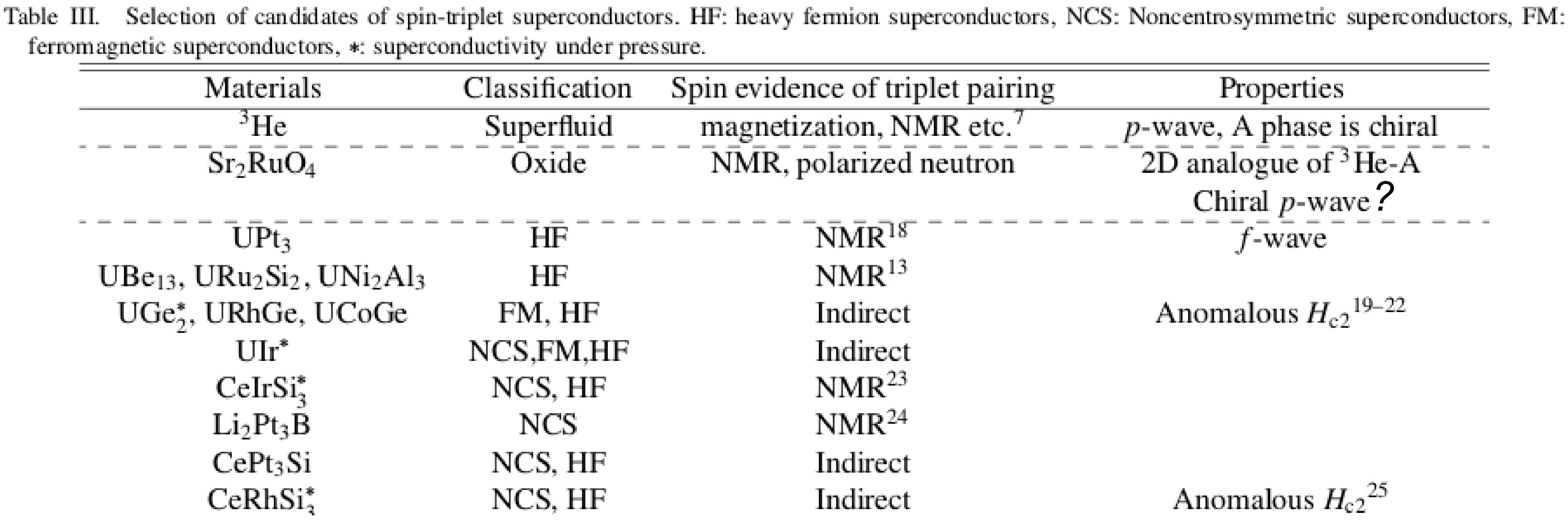


Table III. Selection of candidates of spin-triplet superconductors. HF: heavy fermion superconductors, NCS: Noncentrosymmetric superconductors, FM: ferromagnetic superconductors, $*$: superconductivity under pressure.

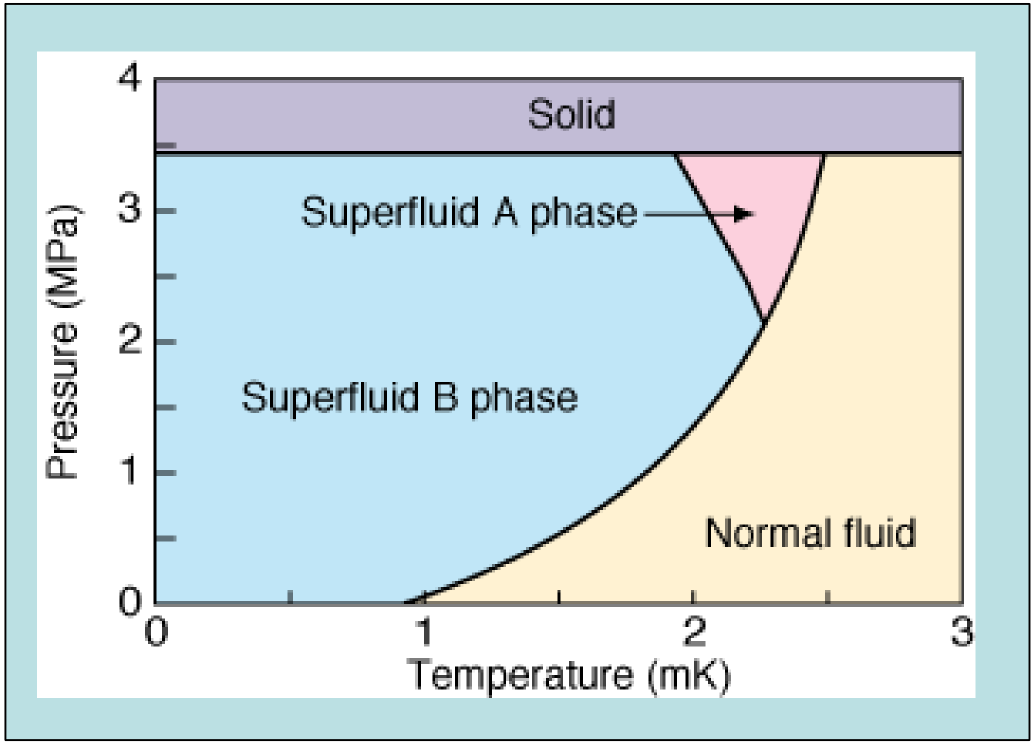
Materials	Classification	Spin evidence of triplet pairing	Properties
^{3}He	Superfluid	magnetization, NMR etc.[7]	p-wave, A phase is chiral
Sr_2RuO_4	Oxide	NMR, polarized neutron	2D analogue of ^{3}He-A Chiral p-wave?
UPt_3	HF	NMR[18]	f-wave
UBe_{13}, URu_2Si_2, UNi_2Al_3	HF	NMR[13]	
UGe_2^*, URhGe, UCoGe	FM, HF	Indirect	Anomalous H_{c2}[19–22]
UIr*	NCS,FM,HF	Indirect	
$CeIrSi_3^*$	NCS, HF	NMR[23]	
Li_2Pt_3B	NCS	NMR[24]	
$CePt_3Si$	NCS, HF	Indirect	
$CeRhSi_3^*$	NCS, HF	Indirect	Anomalous H_{c2}[25]

From Maeno 2012 Review

Pretty unusal...

^{3}He Superfluidity

Lee, Richardson,
Osheroff, Nobel '96
Leggett, Nobel '03



A = Chiral = T-breaking =
Anderson-Brinkman-Morel = p_x+ip_y for both $|\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\rangle$

B = Helical = T-invariant =
Balian-Wertheimer = p_x+ip_y for $|\uparrow\uparrow\rangle$ and p_x-ip_y for $|\downarrow\downarrow\rangle$

Both of these phases are “topological” in 2D

Chiral = D Class
Helical = DIII Class

Both classes have Majorana quasiparticles, and can be used for topological quantum computation (at least in principle).

… is it really one of these?

A = Chiral = T-breaking =
Anderson-Brinkman-Morel = p_x+ip_y for both $|\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\rangle$

B = Helical = T-invariant =
Balian-Wertheimer = p_x+ip_y for $|\uparrow\uparrow\rangle$ and p_x-ip_y for $|\downarrow\downarrow\rangle$

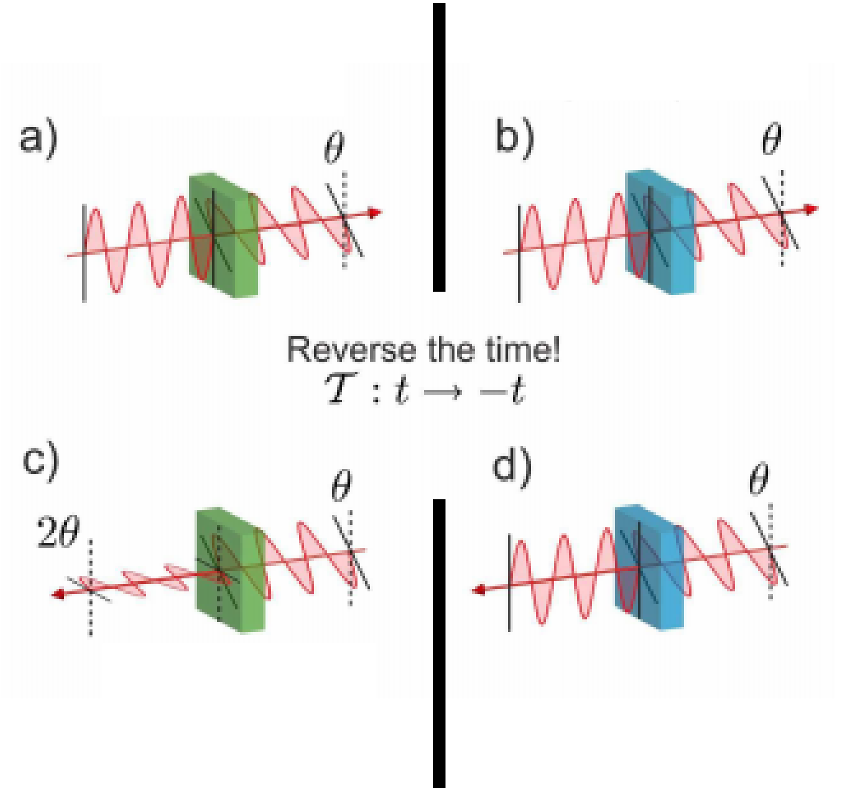
General Outline

1. Background, and Triplet Pairing
2. T-breaking or not? (The conflict that framed the field) ⬅
3. 2D or 1D. Another conflict?

Evidence for T-breaking

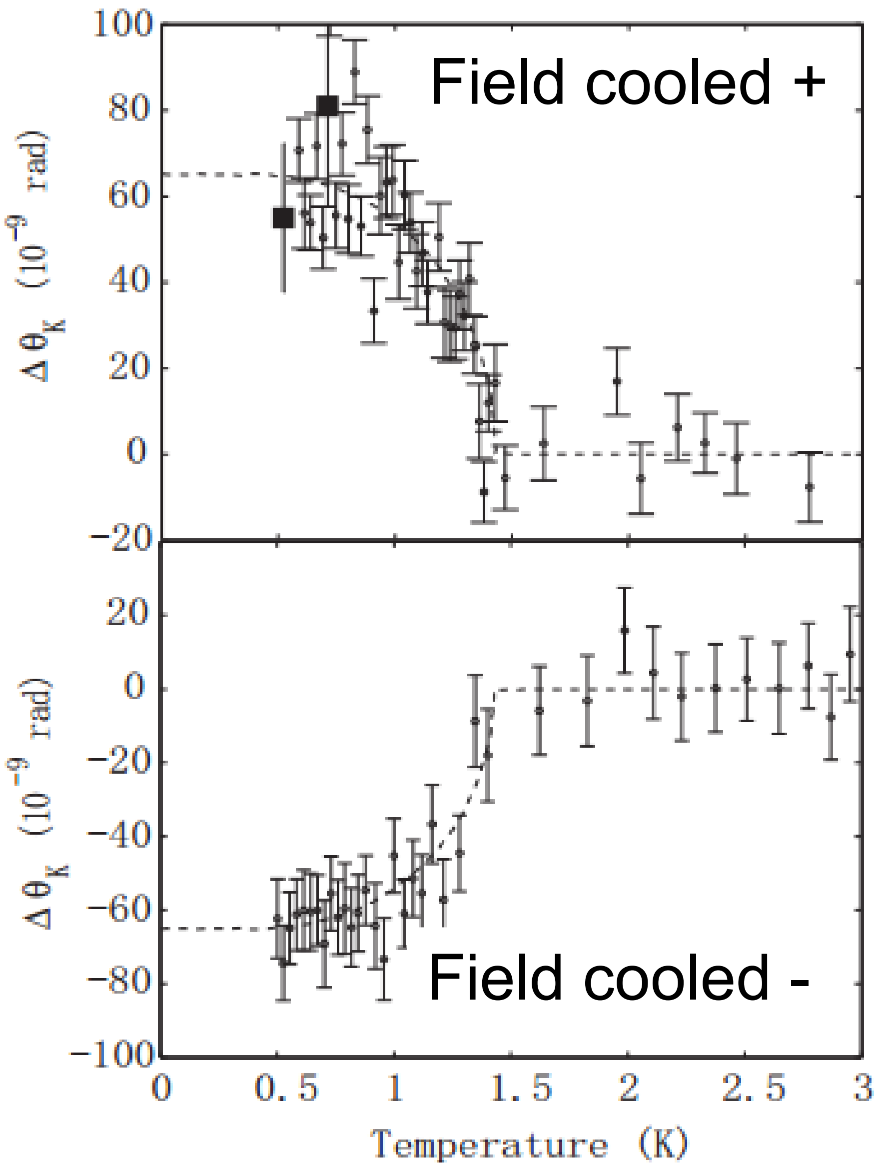
Kapitulnik et al (2006)

Optical (Polar) Kerr Rotation



Broken T

Unbroken T



Expect Edge Currents for Chiral (T-breaking)

Matsumoto-Sigrist (1999), Roy-Stone (2004), …

- Angular momentum $\hbar$ per pair
- Currents screened in bulk, but within λ of surface
  expect roughly ~ 10 G spontaneous field

But wait… angular momentum isn't even a good quantum number in a crystal.

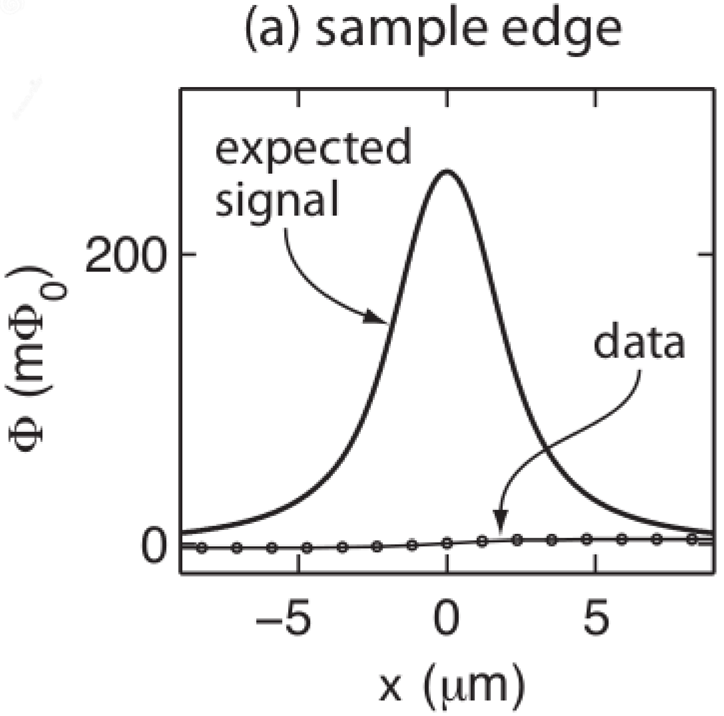
Repeat calculation using tight binding band structure and lattice order parameter $\sin(k_x) + i \sin(k_y)$ = neighbor pairing on a square lattice.

Still expect ~10G

Non-Measurement of Edge Currents

Scanning SQUID (Hicks, Kirtley, Moler, 2009)

+ Earlier experiments with scanning Hall bar.



Edge currents if present are at least 500 x too small !

General Outline

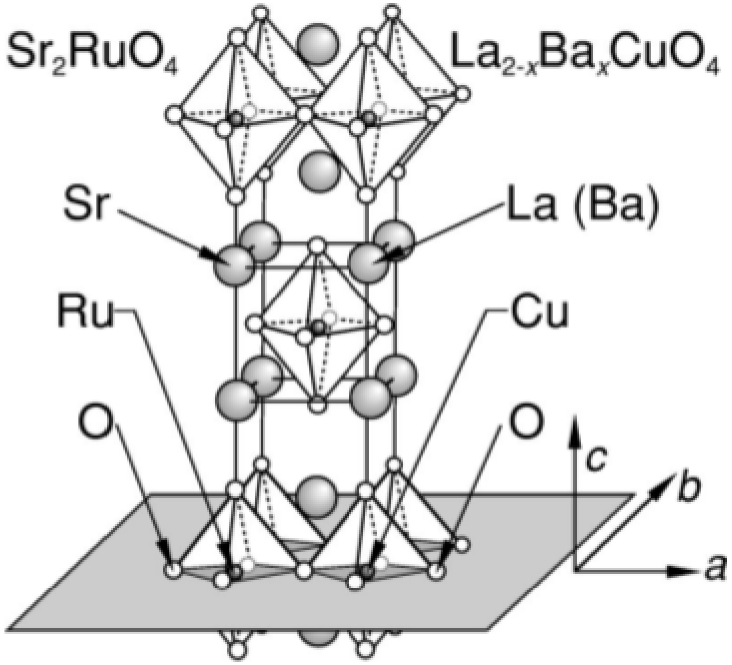
1. Background, and Triplet Pairing
2. T-breaking but no edge currents (The conflict)
3. 2D or 1D. Another conflict?

A possible solution to the T-breaking conflict was proposed (Raghu, Kapitulnik, Kivelson 2010).

This solution doesn’t work, but it correctly highlights a very important issue!

Some Basic Facts

From RMP 75, 657 (2003) Maeno+Mackenzie

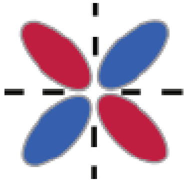


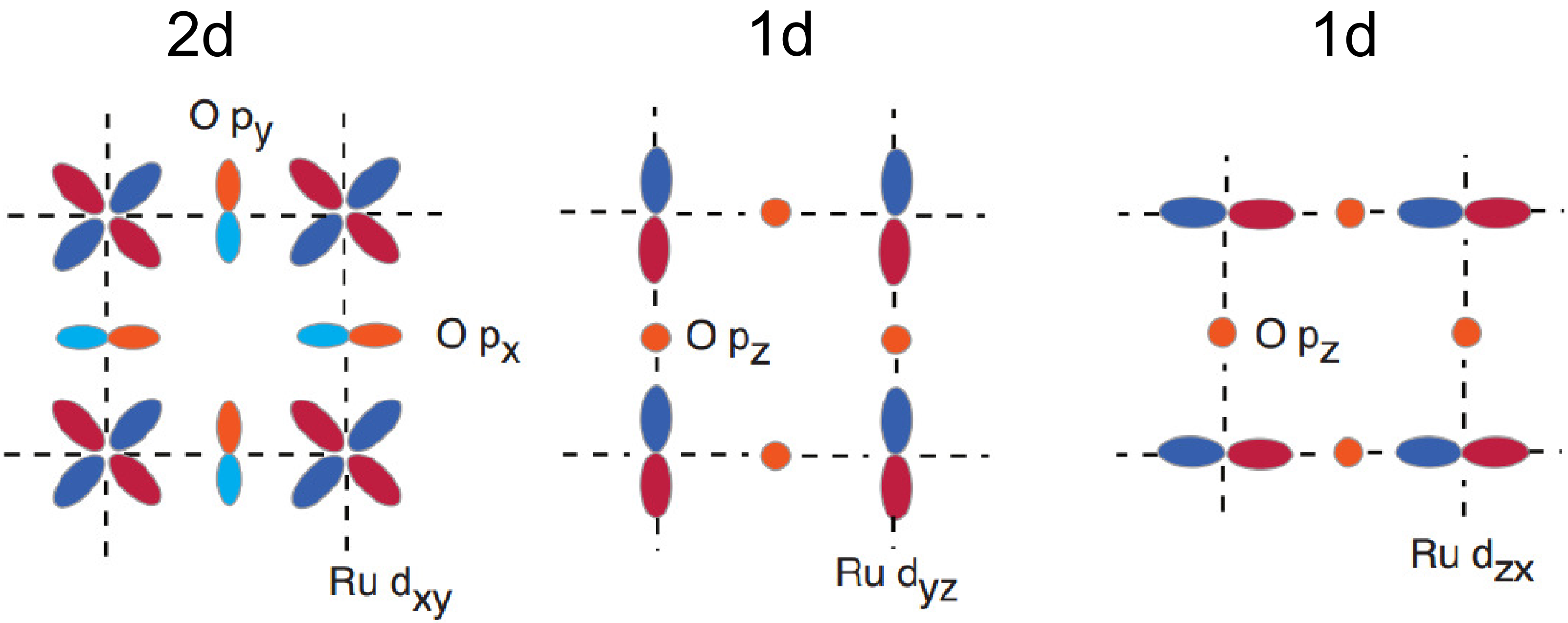
High T_c Analog
(Perovskite)

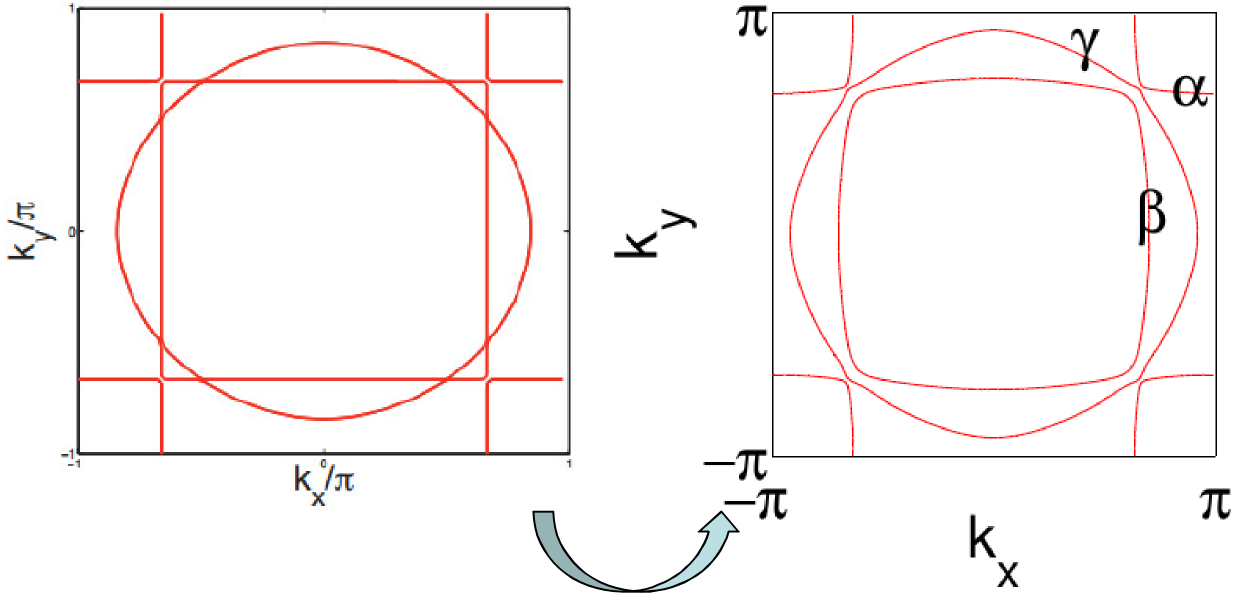
Ru-O planes

After crystal field splitting
3 Ru d-orbitals are near
Fermi surface

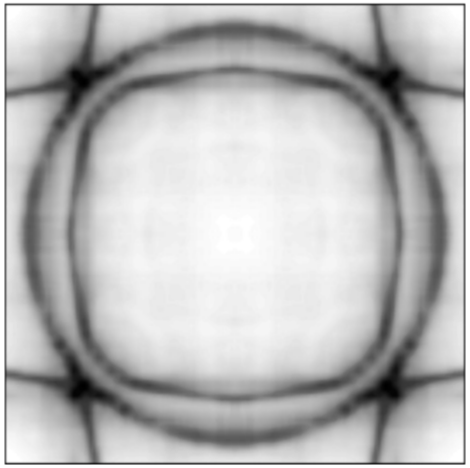
d_{xy}, d_{xz}, d_{yz}







Band mixing and spin orbit



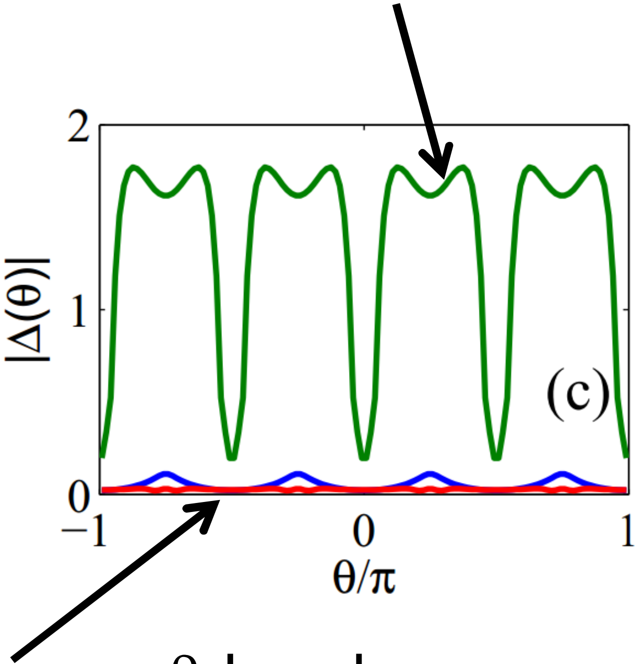
ARPES bandstructure
Damiscelli 2000

Conventional Wisdom: *The 2D γ band is the important one*

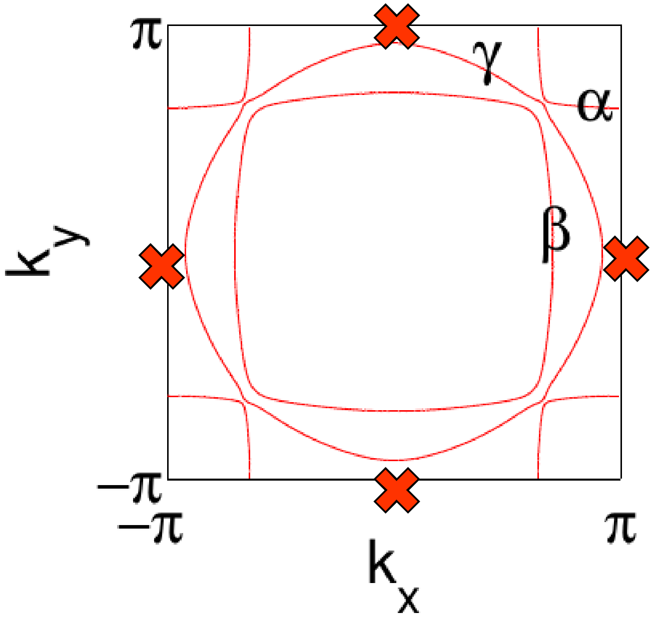
Approaching a Van Hove singularity (at midpoint of edge of zone) it is very close to unstable to Ferromagnetism (Stoner criterion).

Supported by functional RG calculation (Wang, … Rice, 2013)

Gap on γ band



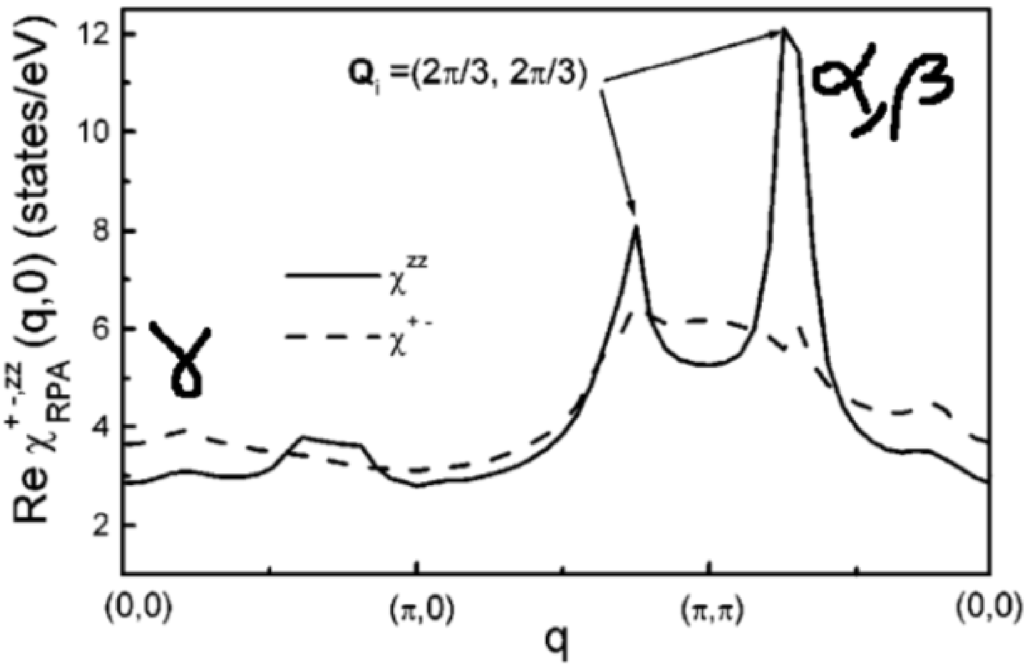
Gap on α,β band



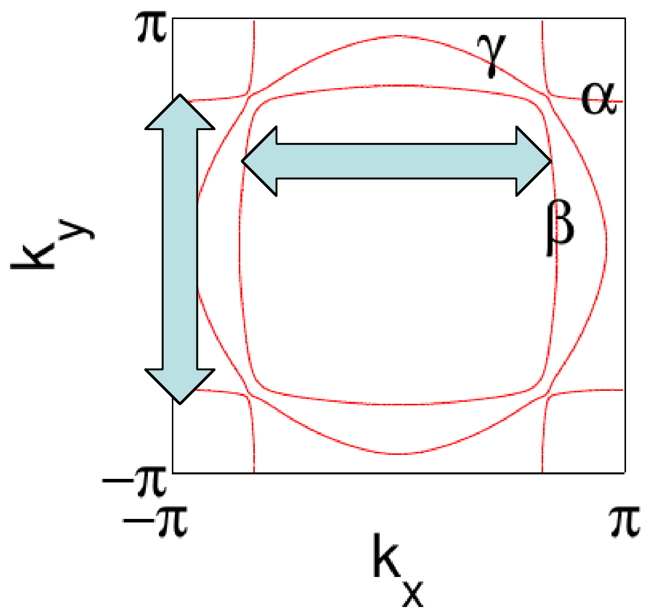
New(ish) Idea: (Raghu, Kapitulnik, Kivelson 2010)

1D physics of α,β *bands is the important thing!*

γ Van Hove is not very important in the spin susceptability



Eremin (2002)

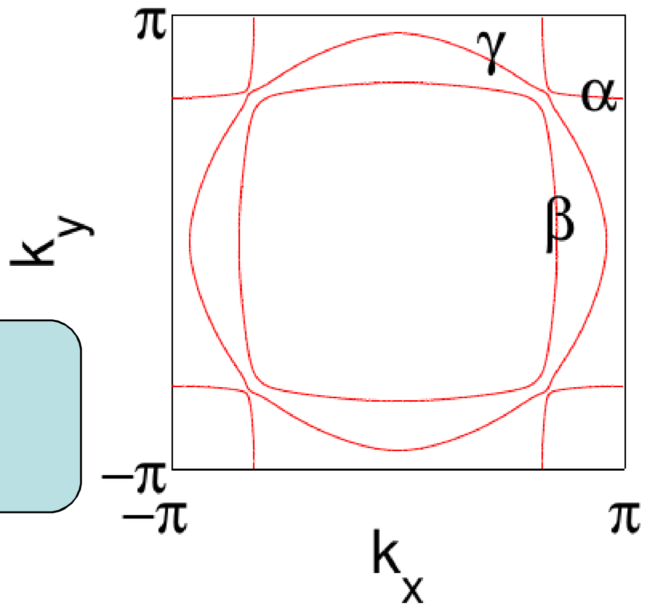


New(ish) Idea: (Raghu, Kapitulnik, Kivelson 2010)

1D physics of α,β bands is the important thing!

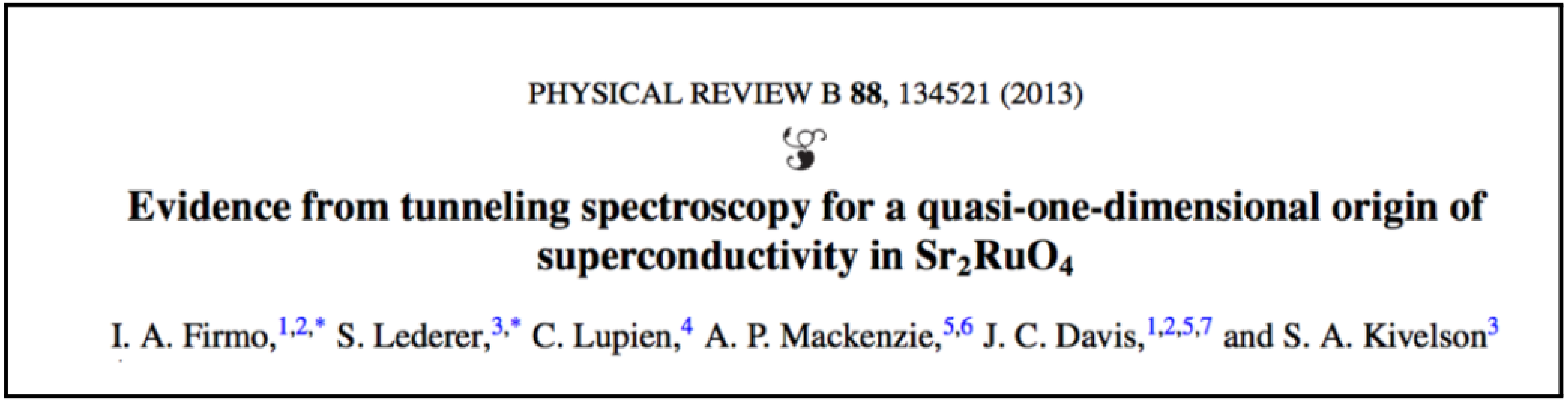
γ Van Hove is not very important in the spin susceptability

Also supported by a microscopic RG calculation!



Claim: T-breaking supercond on α and β
Could have cancelling edge currents

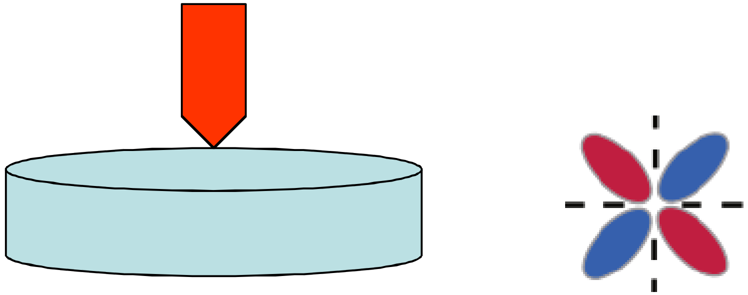
New(ish) Idea supported by experiment



PHYSICAL REVIEW B **88**, 134521 (2013)

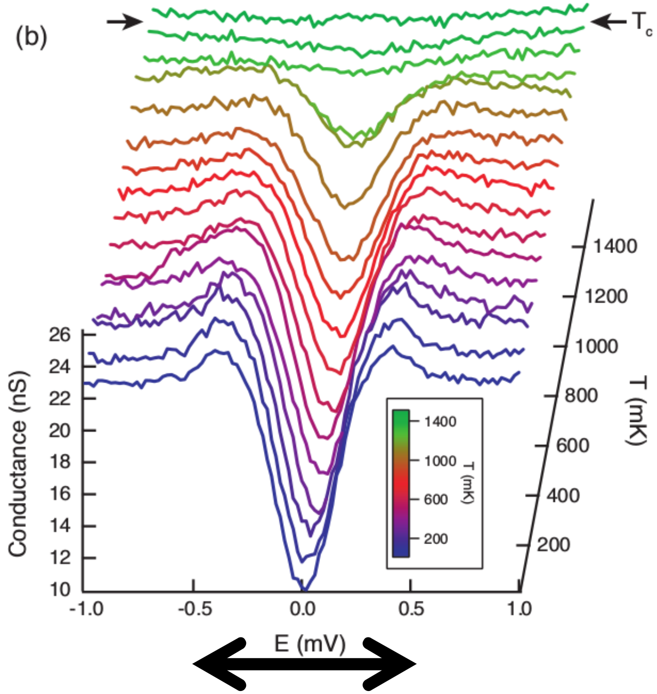
Evidence from tunneling spectroscopy for a quasi-one-dimensional origin of superconductivity in Sr_2RuO_4

I. A. Firmo,[1,2,*] S. Lederer,[3,*] C. Lupien,[4] A. P. Mackenzie,[5,6] J. C. Davis,[1,2,5,7] and S. A. Kivelson[3]



STM measures mostly
xz ,yz orbitals
therefore α, β bands

Fairly strong gap seen in STM



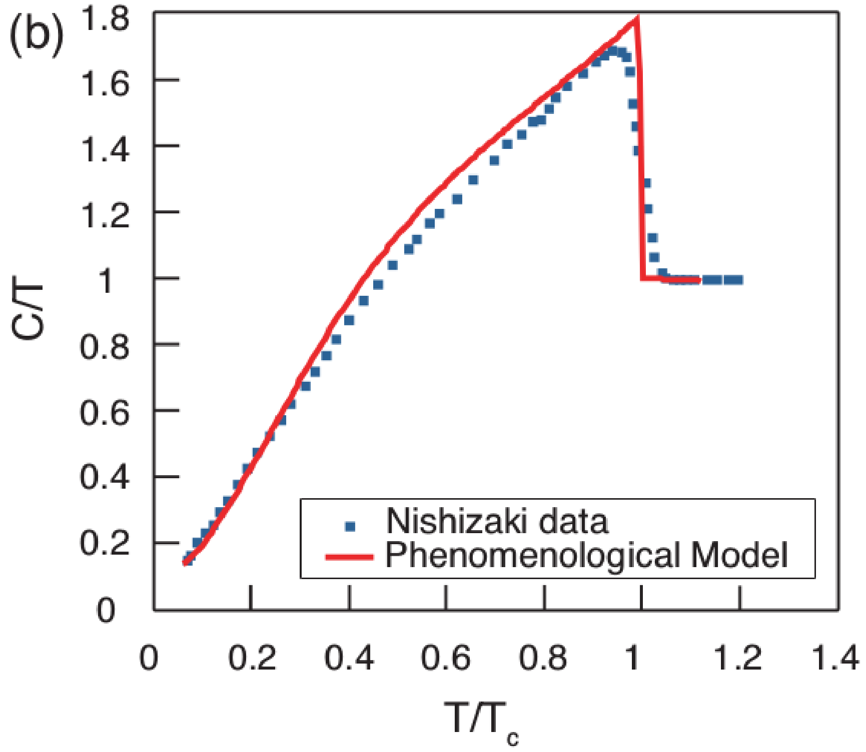
gap ~ T_c

γ (2D) Or α,β (1D)

Same paper : neither completely agrees w/ experiment !

Specific heat data requires sizable gap on all three bands

C/T vanishes at low T



No ungapped density of states

Possibly point nodes?

ETH
RG gives supercond
on 2D γ band

Stanford
RG gives supercond
on 1D α,β band

How could they get such different results?

… and why do neither get gaps on all bands?

What goes in the RG calculation:

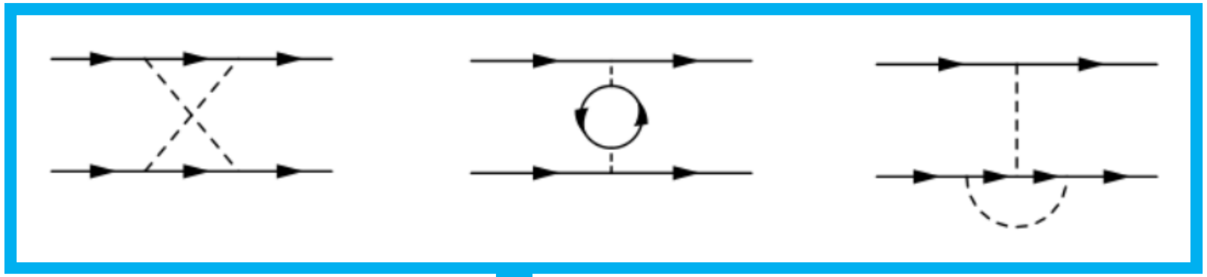
Simplified band structure

No band mixing or spin orbit!

Hubbard U

Hund J

J/U not agreed upon up To factor ~5



Order parameter

Which step could be be disputed....

What goes in the RG calculation:

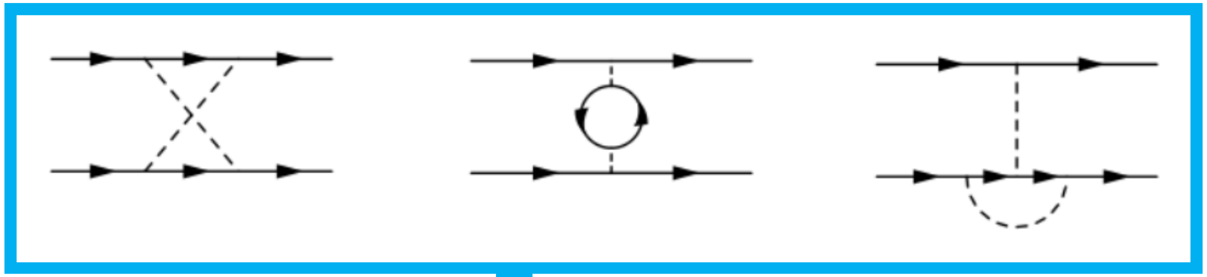
Simplified band structure

No band mixing or spin orbit!

Hubbard U

Hund J

J/U not agreed upon up To factor ~5



Order parameter

Scaffidi, Romers, Simon PRB 89 220510R (2014)

Re-do the RG with spin-orbit / band mixing properly included for a range of J/U values

General Outline

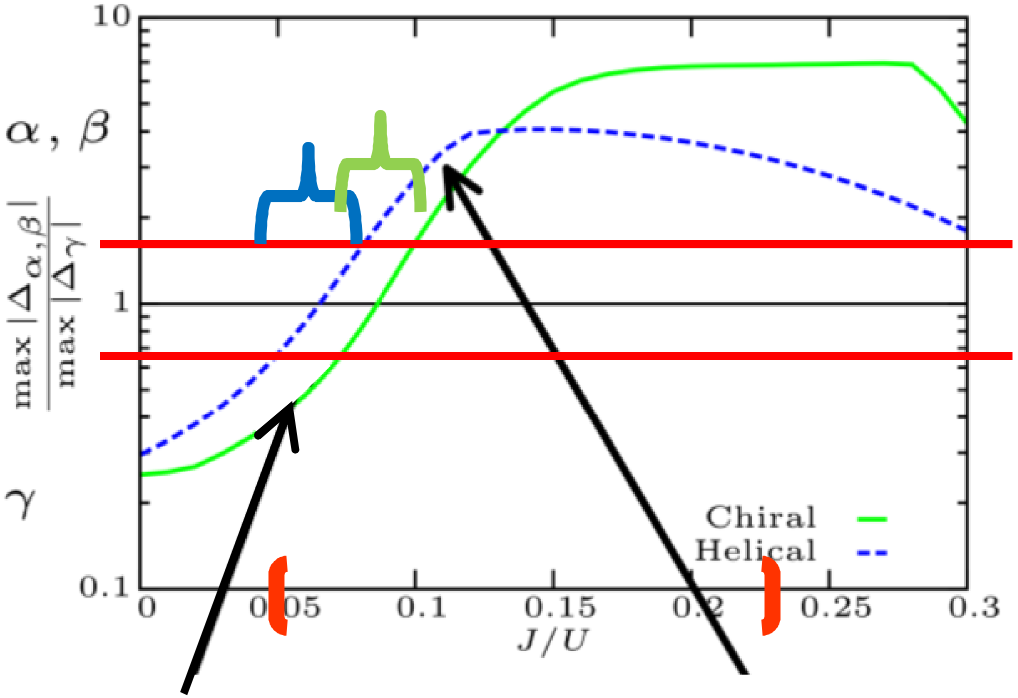
1. Background, and Triplet Pairing
2. T-breaking but no edge currents (The conflict)
3. 2D or 1D. Another conflict?
4. Our “resolution” of the 2D/1D debate

- Triplet always wins over singlet
- Ratio of gap on γ to α,β can be close to 1 for a range of J/U!!
- For J/U > 0.065 helical wins over chiral… but only by a tiny bit

- Results:

1) band mixing and spin orbit puts gap on all bands.

2) J/U matters

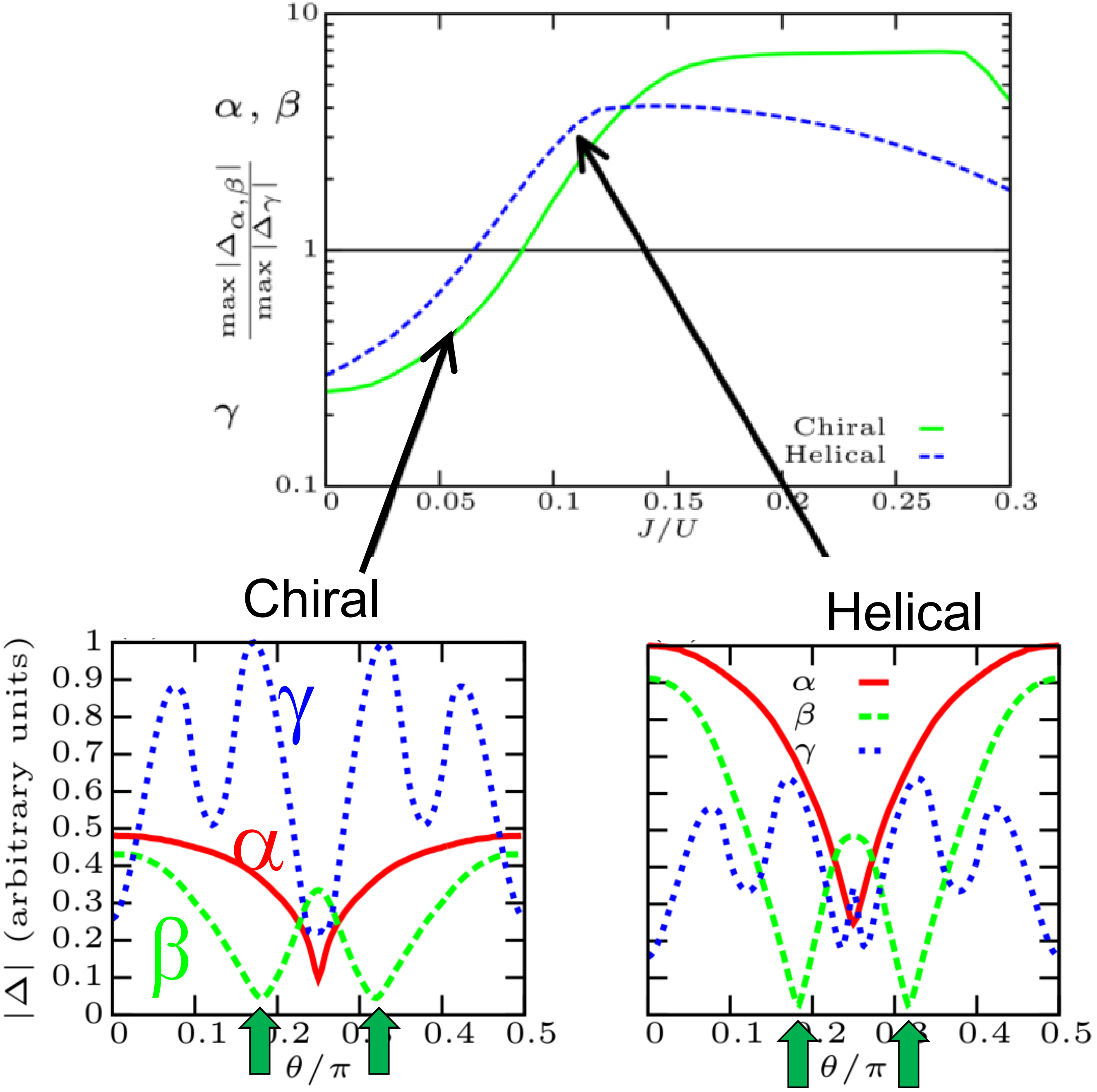


Chiral

Helical

0.05 < J/U <0.23

Nearly Nodes!

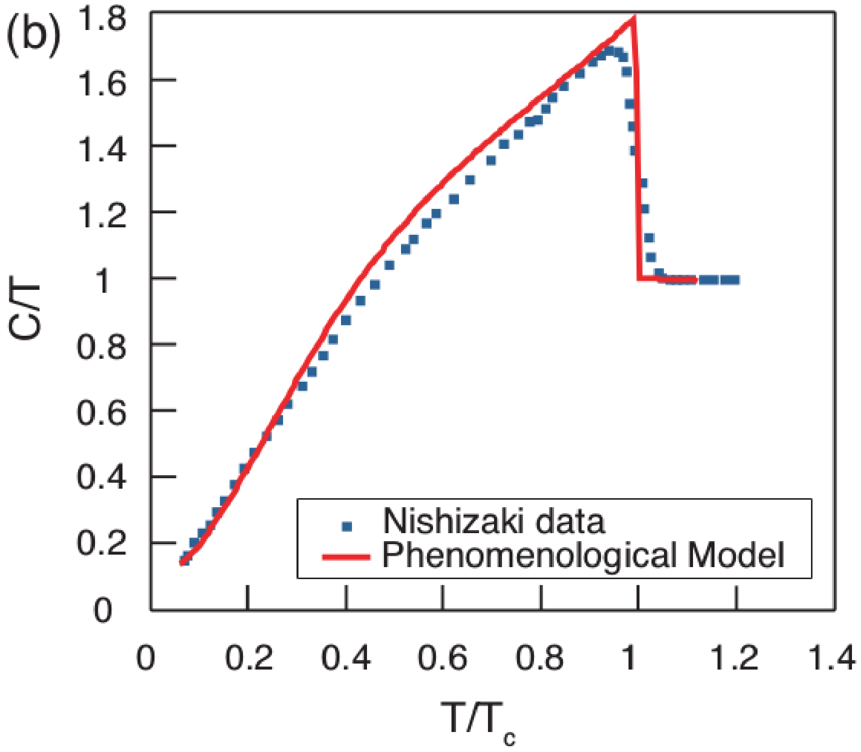


Chiral

Helical

0.05 < J/U <0.23

C/T vanishes at low T



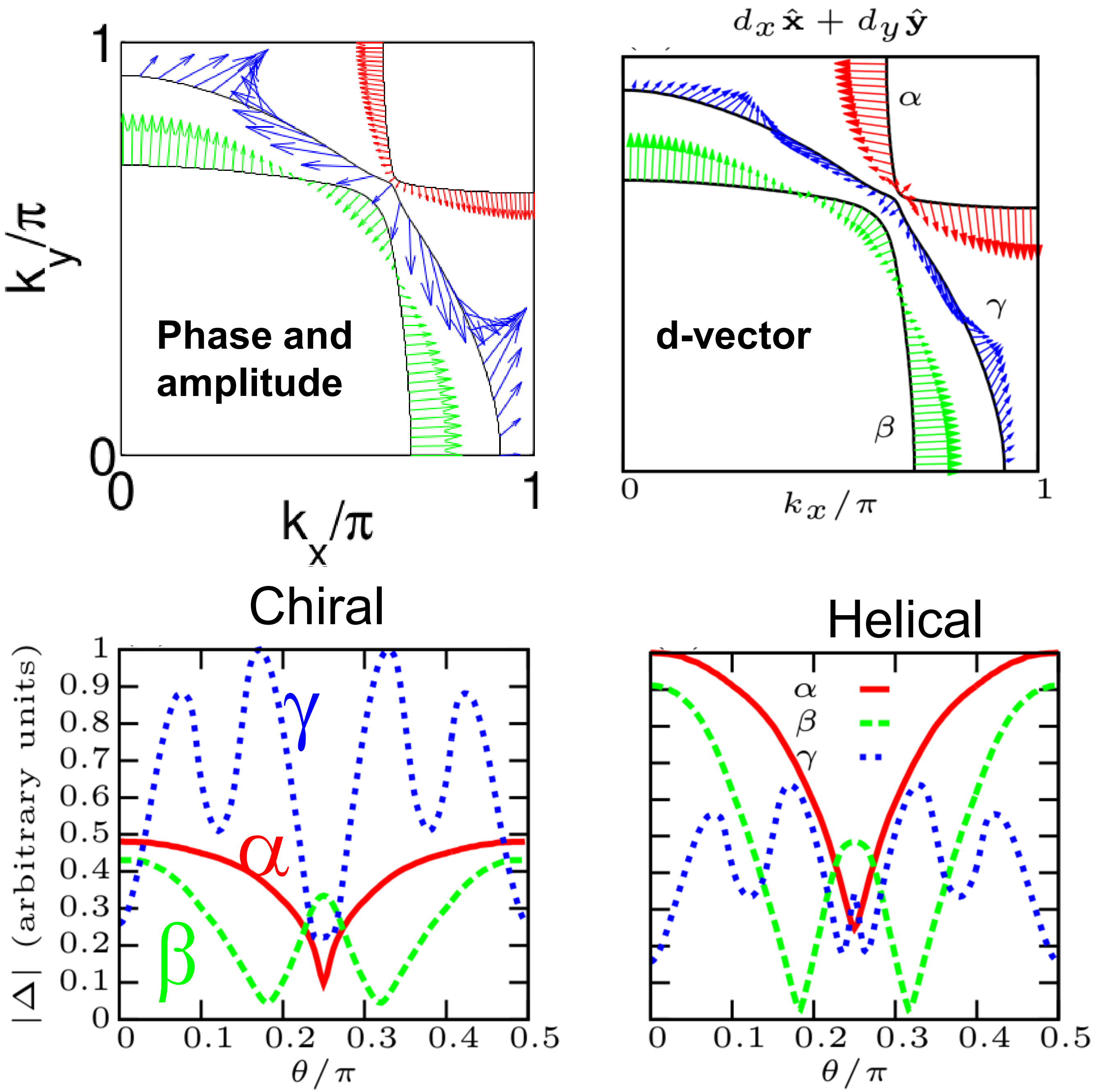
No ungapped density of states

Possibly point nodes?

Explained by Near Nodes?

Phases

- multiple twists!



Phases

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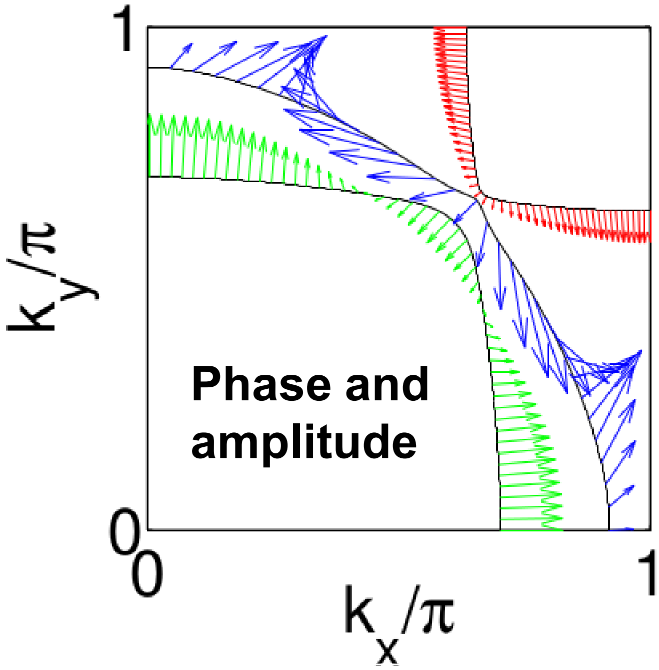


Phase and amplitude

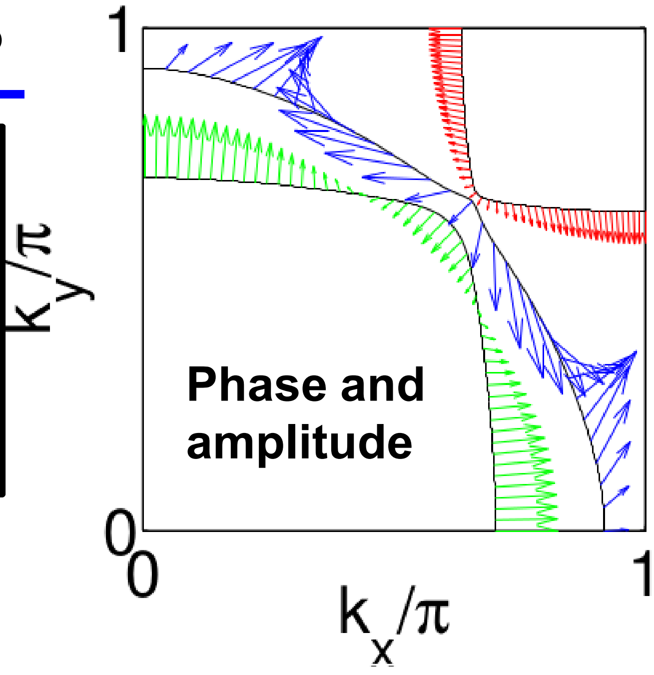
Chiral

- Weren't we looking for chiral p-wave?
- Shouldn't that force phase ~ $e^{i\theta}$?

What do we mean by chiral p-wave?

“Chiral p-wave” usually means $L_{pair}=1$

In a x-tal L is not good quantum number!



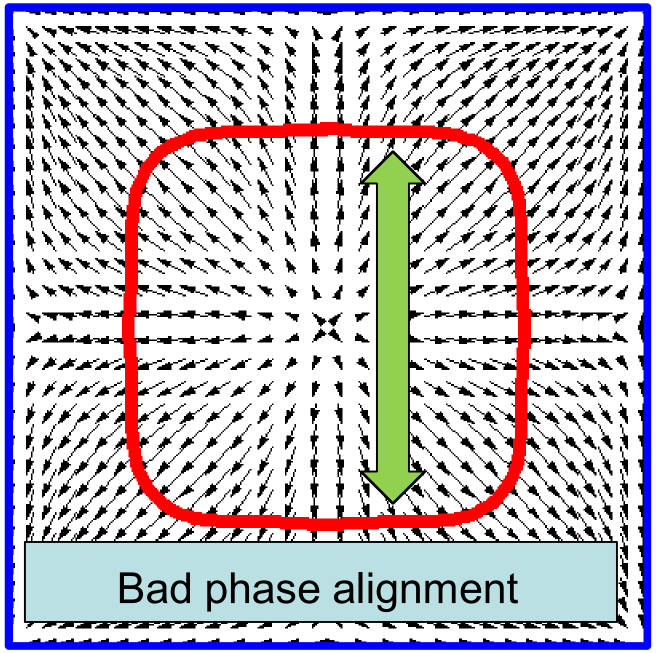
Chiral

Chiral-p means: Transforms like

$\sin(k_x) + i\sin(k_y)$ under lattice symmetries.

Chern number C = # of twists of the phase =1 mod 4.

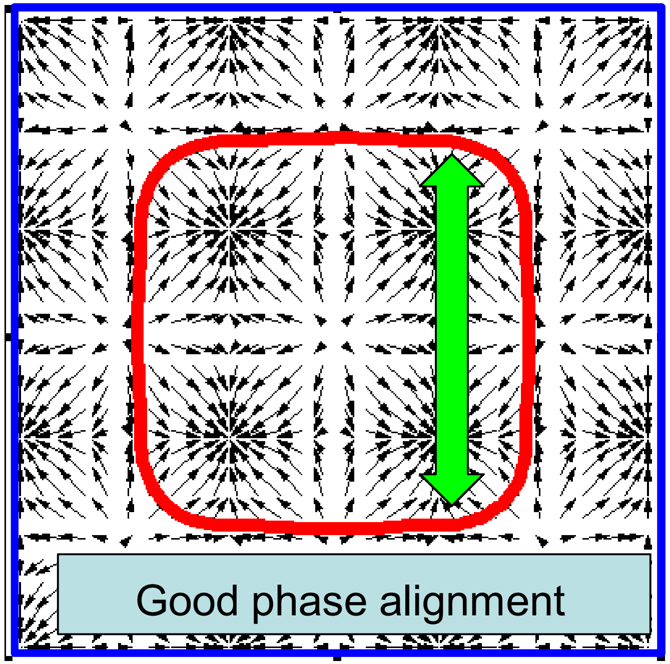
Why So Twisty?



Bad phase alignment

$\sin(k_x) + i\sin(k_y)$ Neighbor pairing

Very weak



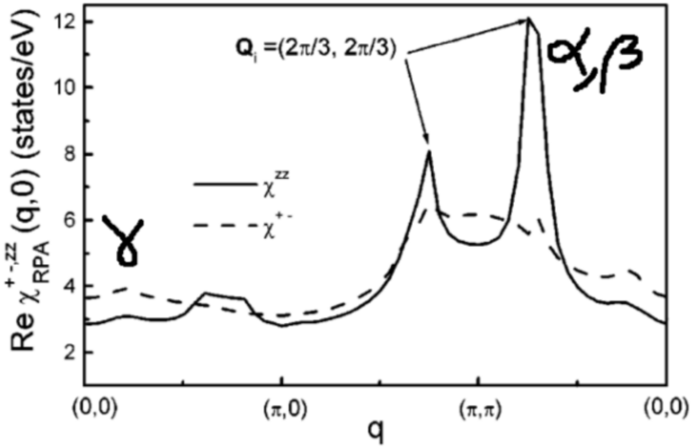
Good phase alignment

$\sin(3k_x) + i\sin(3k_y)$ Next Neighbor

Very strong

Also some of

$\sin(k_x)\cos(k_y) + i\sin(k_y)\cos(k_x)$



Direction of arrows should line up across nesting wavevector.

What do we mean by chiral p-wave?

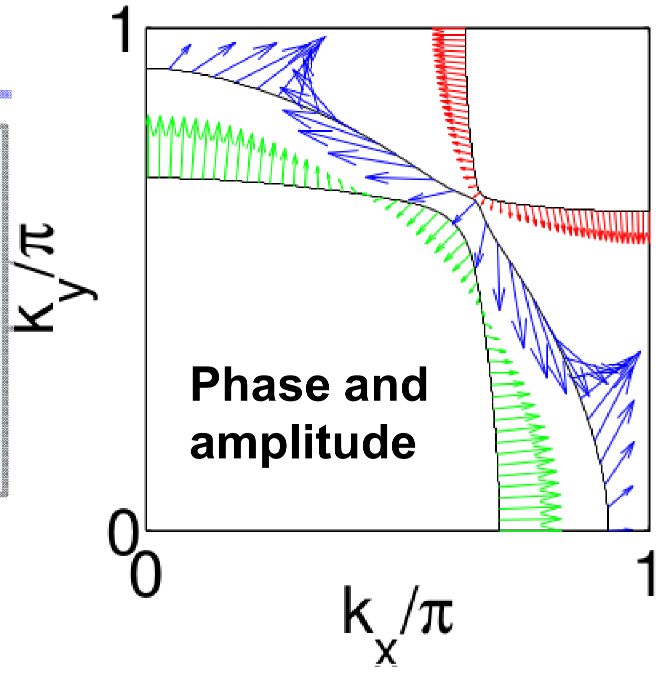
"Chiral p-wave" usually means $L_{pair}=1$

In a x-tal L is not good quantum number!

Chiral-p can only mean: Transforms like

$$\sin(k_x) + i\sin(k_y)$$

under lattice symmetries.



Chiral

Chern number C = # of twists of the phase =1 mod 4.

α band C = 1

β band C= -3

γ band C= -3

Total C = -7

Predicts

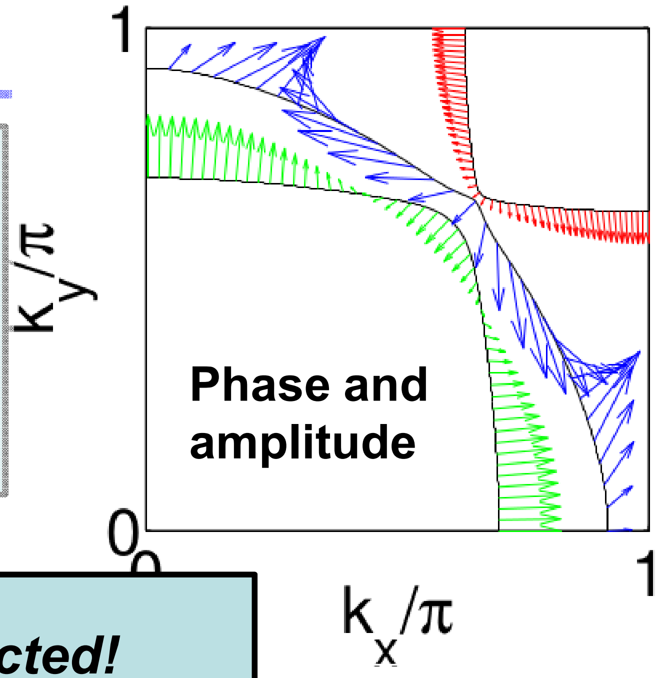
$$\kappa_{xy} = \frac{C}{2}\frac{\pi^2 k_B^2 T}{6\pi\hbar}$$

Thermal Hall Effect
(Righi-Leduc) per layer
Topologically Protected!

What do we mean by chiral p-wave?

“Chiral p-wave” usually means $L_{pair}=1$

In a x-tal L is not good quantum number!



Chiral

Edge charge current NOT topologically protected!

Tada, Nie, Oshikawa, arXiv:1409.7459, PRL 2015.

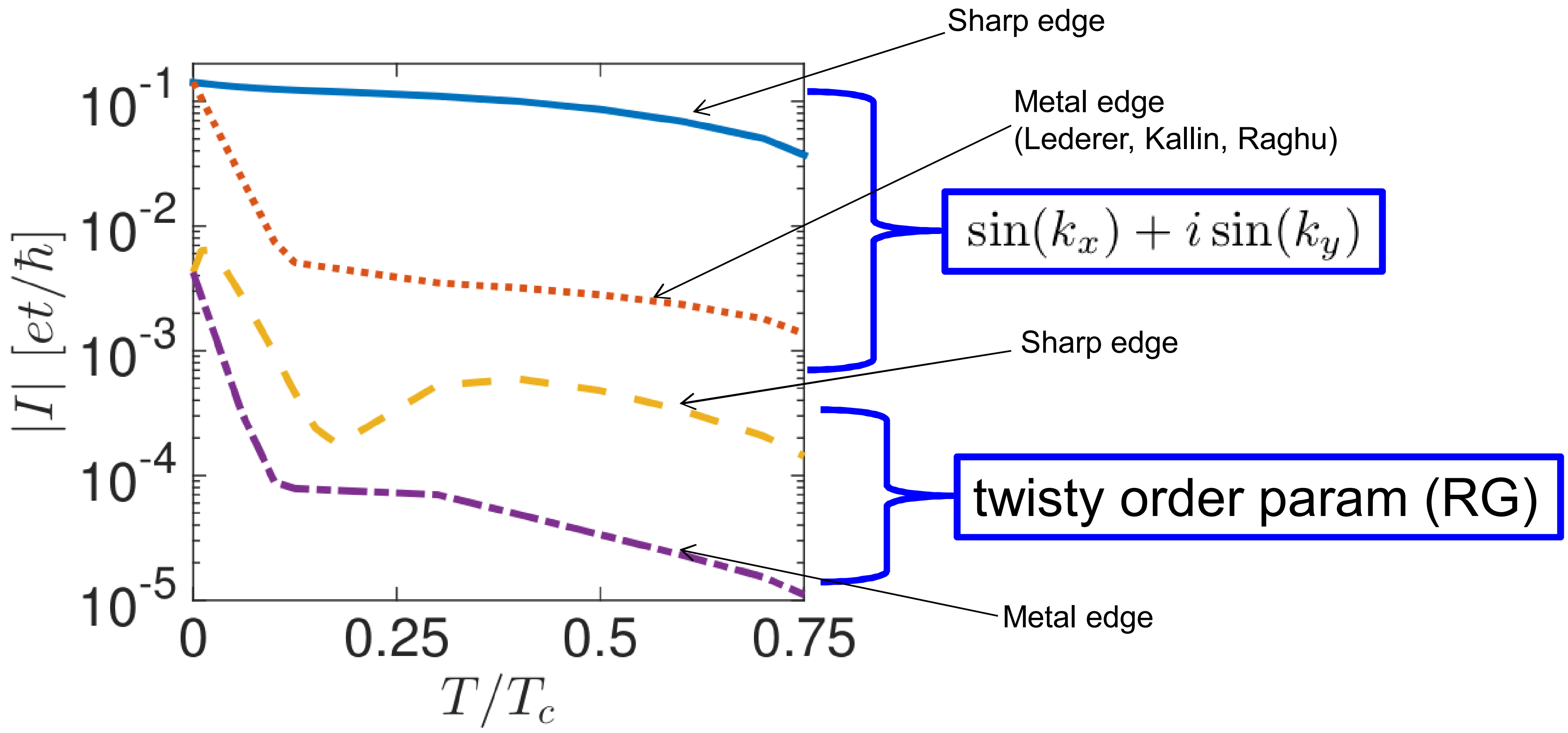
In continuum, if C=1, edge charge current is there.
If C≠1 edge charge current is zero!

Also Volovik 2014; Huang Taylor Kallin 2014; Bouhon Sigrist 2014

$$\overbrace{J_{edge} \sim \int d\theta\, \mathrm{Re}[\Delta(\theta)]\mathrm{Im}[\Delta(\theta)]v_x(\theta)v_y(\theta)}$$

Predictions for Edge Charge Currents

For chiral "p-wave" order



Sharp edge

Metal edge
(Lederer, Kallin, Raghu)

$\sin(k_x) + i\sin(k_y)$

Sharp edge

twisty order param (RG)

Metal edge

(Full BCS real-space 3-band model)

So is it chiral p-wave?

- T-breaking experiments hard to explain otherwise

- Given the complex structure of the expected gap function very large reduction in edge charge current is expected.

Still unresolved...

- Although there are deep "near nodes," below some (perhaps low) T, we should see full gap behavior.

- This has not been seen yet.

(C$_v$, acoustic attenuation, …)

Update on Exotic Superconductivity in Sr_2RuO_4

Steve Simon
Jesper Romers
and especially Thomas Scaffidi

UNIVERSITY OF
OXFORD

Thank you for Listening