Strontium Ruthenate
Why this material has remained interesting for 20 years and what is new now

Steve Simon
Jesper Romers
Thomas Scaffidi

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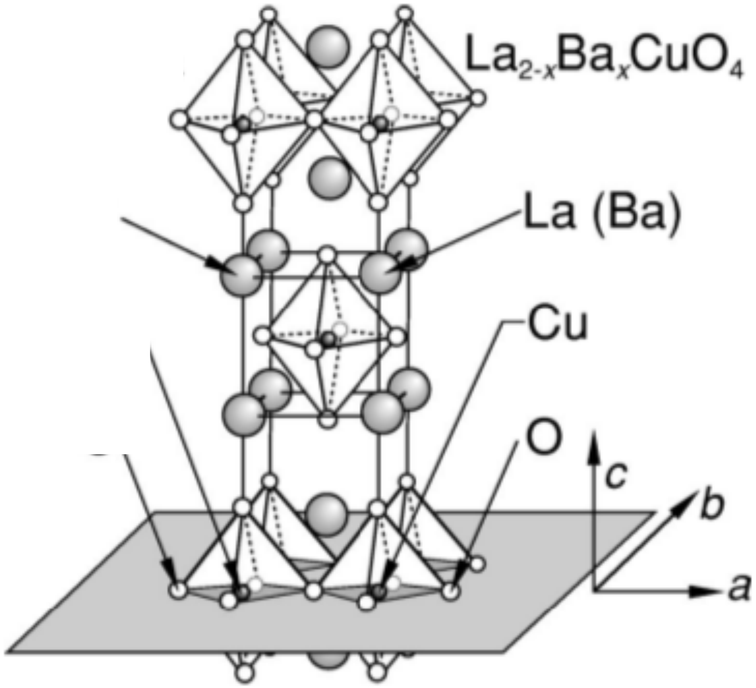
EPSRC

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

High Temperature Superconductivity



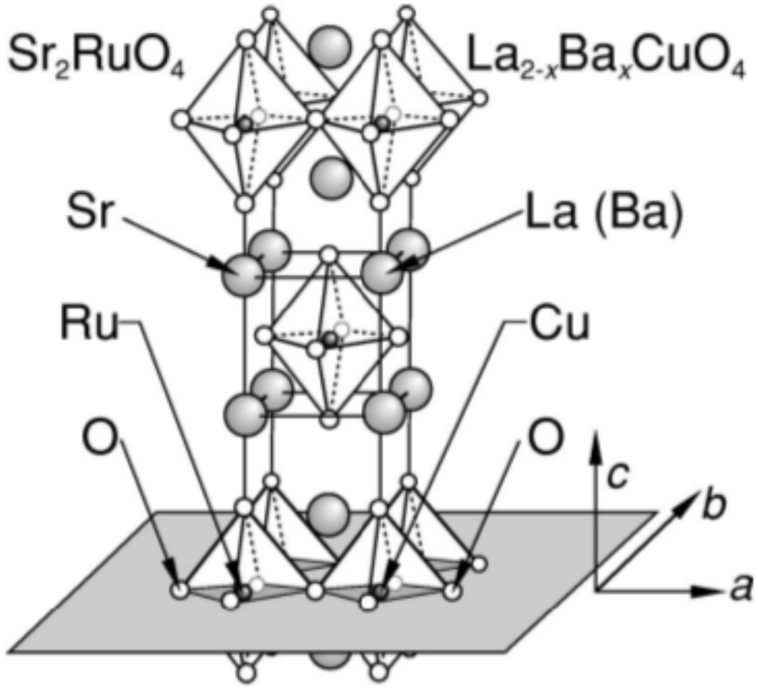
Bednorz and Müller, 1986
(Nobel Prize, 1987)

1. Very two dimensional
2. Conduction in Cu-O planes
3. An insulator without Ba

"Layered Perovskite" Structure

30 years of study and still ***very*** controversial (>> 10^5 publications)

Strontium Ruthenate (Sr_2RuO_4)
first non-cuprate analog: $T_c \approx 1.5$ K



Maeno [Hashimoto], 1994

1. Very two dimensional
2. Conduction in Ru-O planes
3. A Fermi liquid above T_c

“Layered Perovskite” Structure

20 years of study and still ***very*** controversial (~10^4 publications)
[Needless to say: I will discuss only a handful of these!]

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

LETTER TO THE EDITOR

Sr_2RuO_4: an electronic analogue of ^3He?

T M Rice†‡ and M Sigrist§
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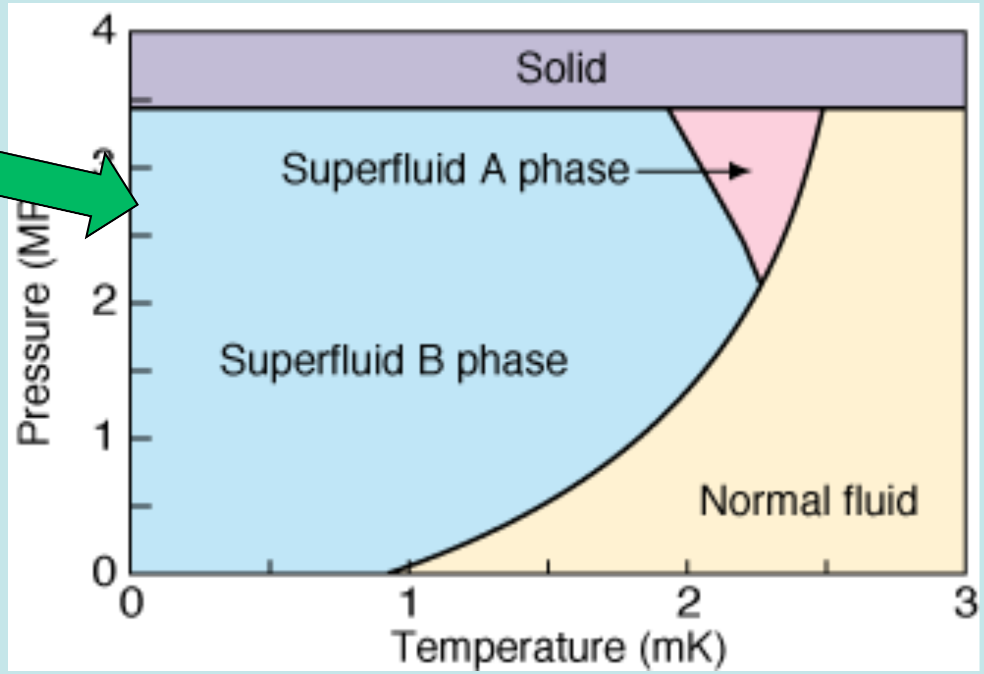
§ Department of Physics, Massachussets Institute of Technology, Cambridge, MA 02139, USA

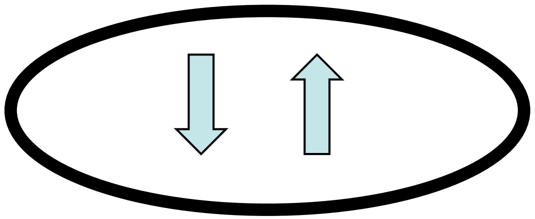
^3He Superfluidity:

Lee, Osheroff, Richardson
(~1972, Nobel 1996)

Theory: Leggett
(Nobel 2003)



Conventional Superconductor



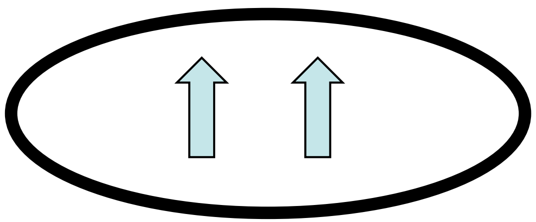
Singlet (conventional) pairing

spins = ↑↓ - ↑↓ = antisymmetric (S=0)

orbital g($\mathbf{r}_1 - \mathbf{r}_2$) = symmetric (L=0, …)

$U(1)_{phase}$ order parameter

Superfluid ^3He = A Triplet "Superconductor"



Triplet pairing (^3He, Sr_2RuO_4, UPt_3)

spins = ↑↑ = symmetric (S=1)

orbital g($\mathbf{r}_1 - \mathbf{r}_2$) = antisymmetric (L=1, …)

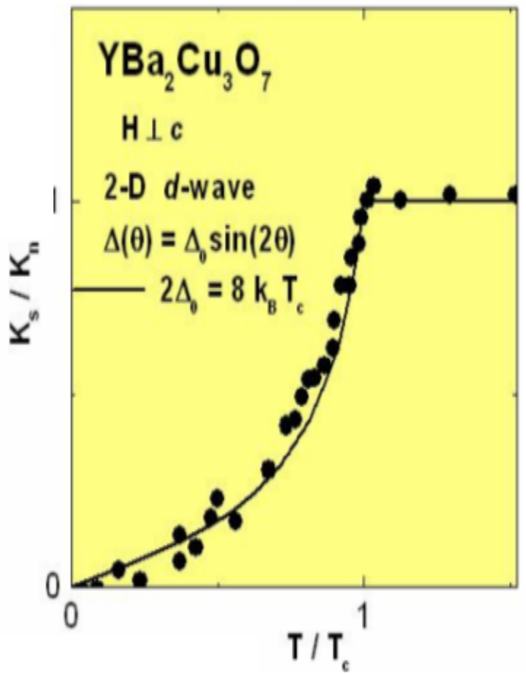
$SO(3)_{spin} \times SO(3)_{orbit} \times U(1)_{phase}$ order param

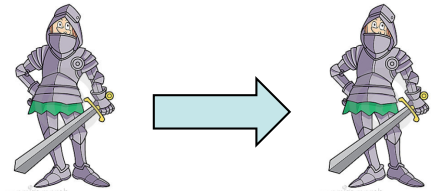
Driven by strong short ranged repulsion

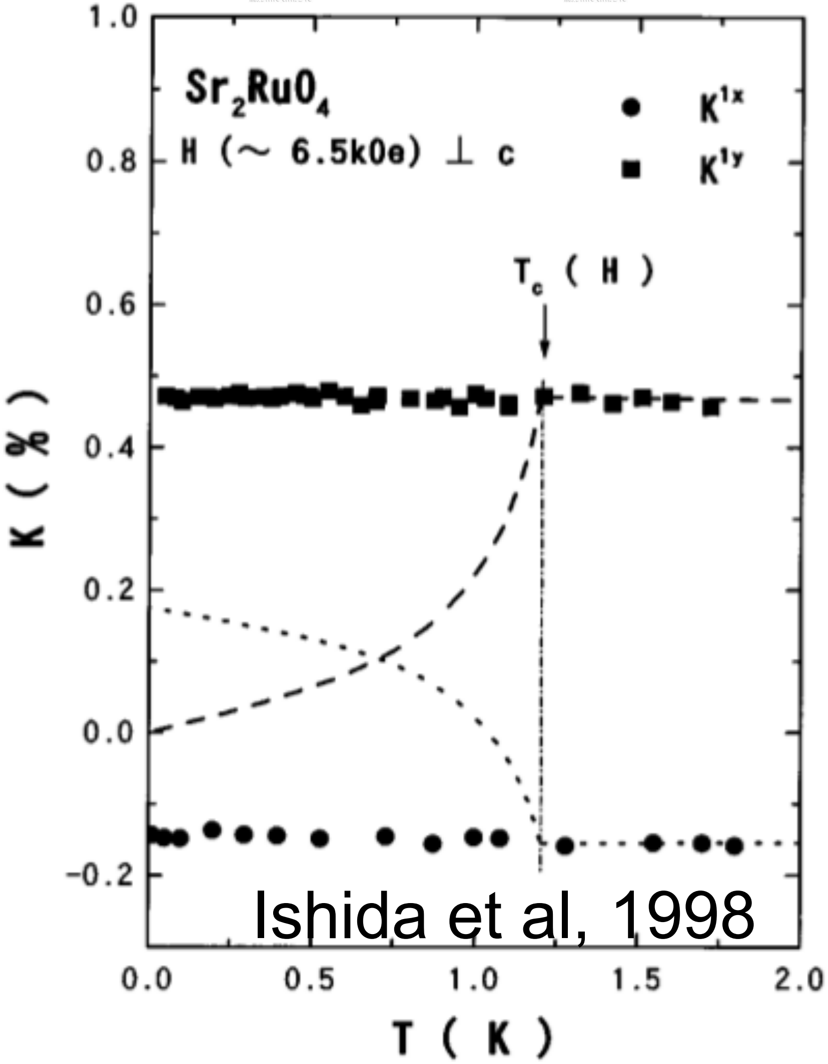
Evidence for Triplet?

NMR Knight Shift
Measures spin susceptibility

YBCO

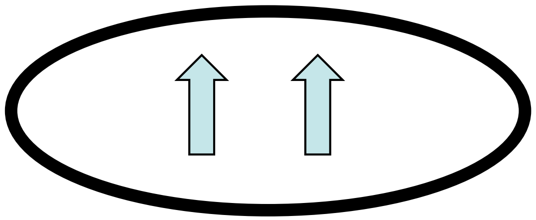






Ishida et al, 1998

Shows NO CHANGE at T_c



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$SO(3)_{spin} \times SO(3)_{orbit} \times U(1)_{phase}$ order param

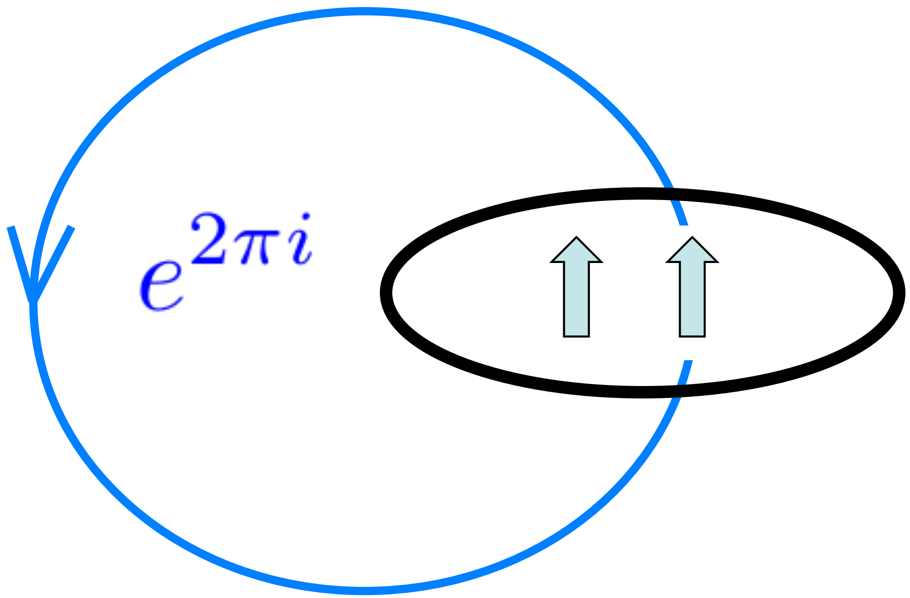
Driven by strong short ranged repulsion

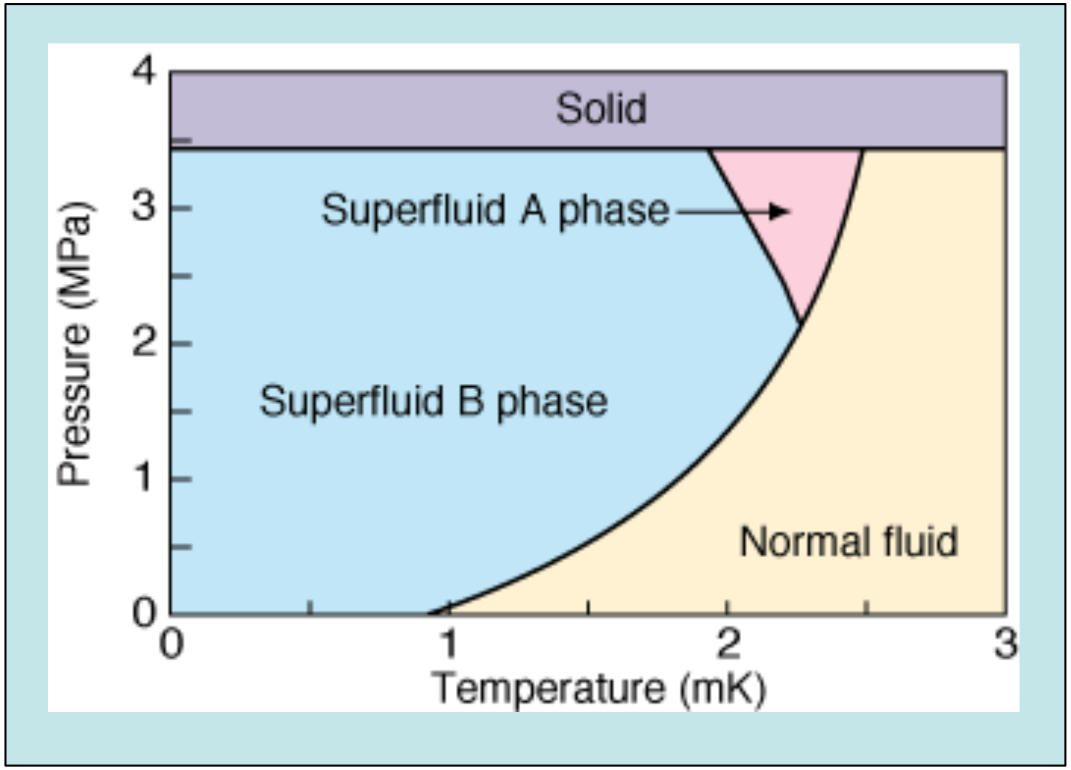
^3He	Sr_2RuO_4
Neutral	Charged
Isotropic 3D	2D layers
Weak Spin-orbit	Strong Spin-orbit
Spherical Fermi Surface	Complicated Band Structure
$\epsilon(\mathbf{p}) = \mathbf{p}^2/2m$	$\epsilon(\mathbf{p})$ complicated

Pair wavefunction with orbital angular momentum L=1 in 2D

$$\psi(\mathbf{r}_1, \mathbf{r}_2) \sim e^{\mp i \arg(\mathbf{r}_1 - \mathbf{r}_2)}$$

$$\psi_{\mathbf{p}} \sim e^{\pm i \arg \mathbf{p}} \sim p_x \pm i p_y$$





2D versions

A=chiral (p_x+ip_y)
B=helical

Both are "Topological Superconductors"

Protected Edge Modes
(Analogy= Quantum Hall)

Chiral (T-breaking) : = p_x+ip_y for both $|\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\rangle$

Helical (T-invariant) = p_x+ip_y for $|\uparrow\uparrow\rangle$ and p_x-ip_y for $|\downarrow\downarrow\rangle$

VOLUME 86, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JANUARY 2001

chiral

Non-Abelian Statistics of Half-Quantum Vortices in *p*-Wave Superconductors

D. A. Ivanov

(Based on earlier work by Read-Green, Volovik, Kopnin-Salomaa)

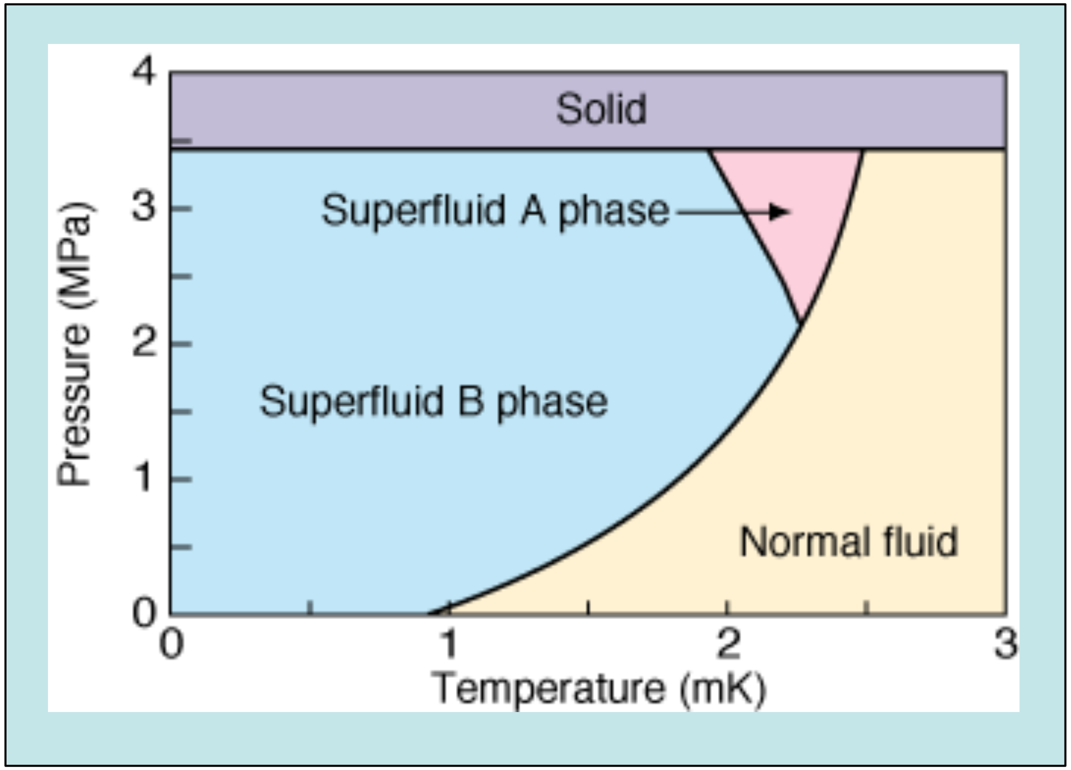
In the chiral phase,
vortex core contains a *isolated majorana operator.*

$$\left.\begin{aligned} \gamma_i^\dagger &= \gamma_i \\ \{\gamma_i, \gamma_j\} &= \delta_{ij} \end{aligned}\right\} \text{Two Majoranas =Dirac fermion} \left\{\begin{aligned} c^\dagger &= \gamma_1 + i\gamma_2 \\ c &= \gamma_1 - i\gamma_2 \end{aligned}\right.$$

An isolated majorana grouped with another (far away) is a protected qubit. *Cannot be flipped by any local parity conserving operator!*

Useful in quantum computation...

How to know if it is T-breaking?



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How to know if it is T-breaking? (expect magnetization μ_B per pair)
... But magnetic fields are screened by supercurrents!

1. Measure fields (currents) *near* edge (prediction ~ mT)

Chiral (T-breaking) : = p_x+ip_y for both $|\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\rangle$

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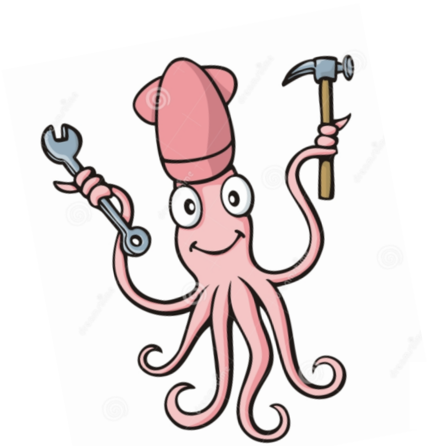
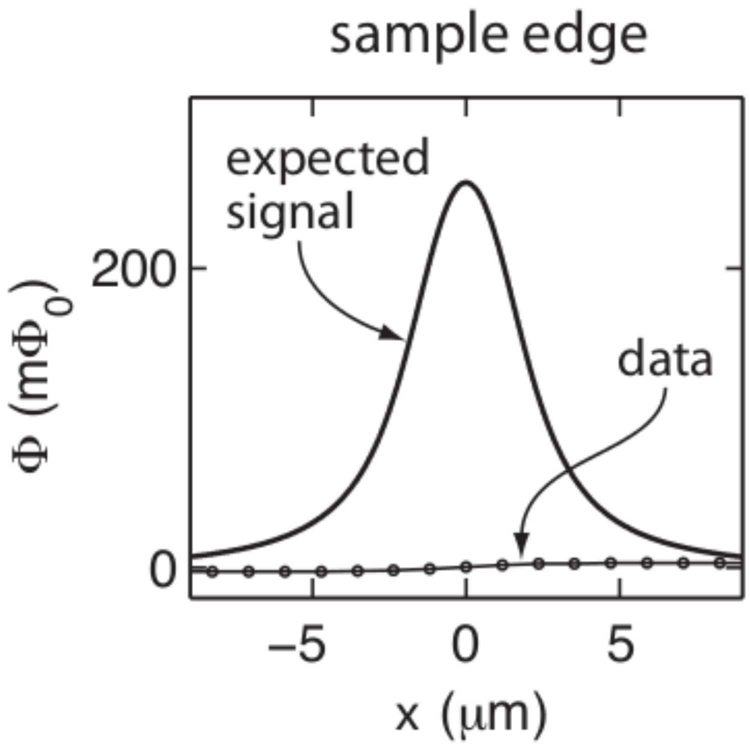
PHYSICAL REVIEW B **81**, 214501 (2010)

Limits on superconductivity-related magnetization in Sr_2RuO_4 from scanning SQUID microscopy

Clifford W. Hicks,[1,2] John R. Kirtley,[3] Thomas M. Lippman,[1,3] Nicholas C. Koshnick,[3] Martin E. Huber,[4] Yoshiteru Maeno,[5] William M. Yuhasz,[6] M. Brian Maple,[7] and Kathryn A. Moler[1,3]



Scanning SQUID



Non-Measurement of Edge Currents

Edge currents, if present, are 500x too small !

How to know if it is T-breaking? (expect magnetization μ_B per pair)
... But magnetic fields are screened by supercurrents!

1. Measure fields (currents) *near* edge (prediction ~ mT)
2. Kerr Rotation

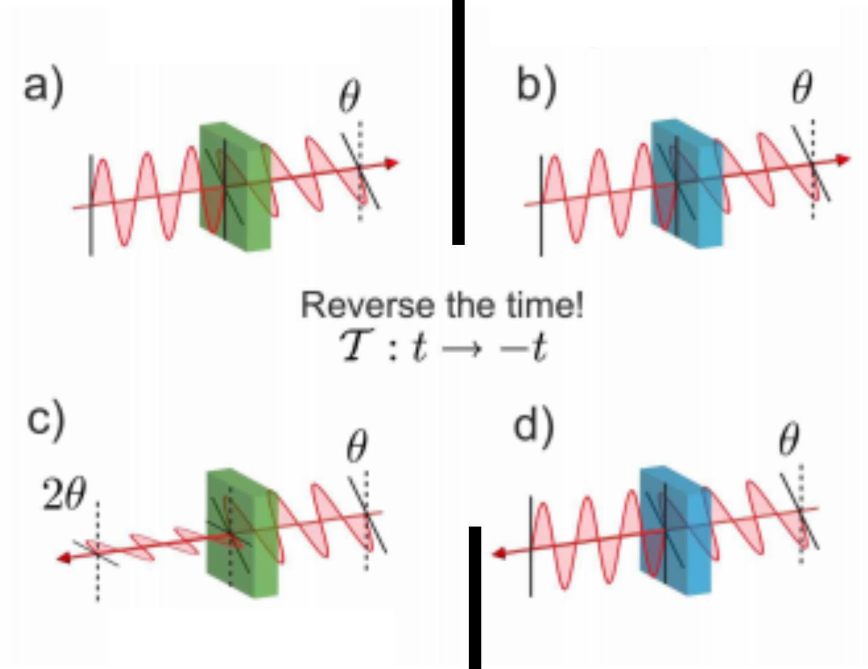
Chiral (T-breaking) : = p_x+ip_y for both $|\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\rangle$

Helical (T-invariant) = p_x+ip_y for $|\uparrow\uparrow\rangle$ and p_x-ip_y for $|\downarrow\downarrow\rangle$

PRL **97,** 167002 (2006) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2006

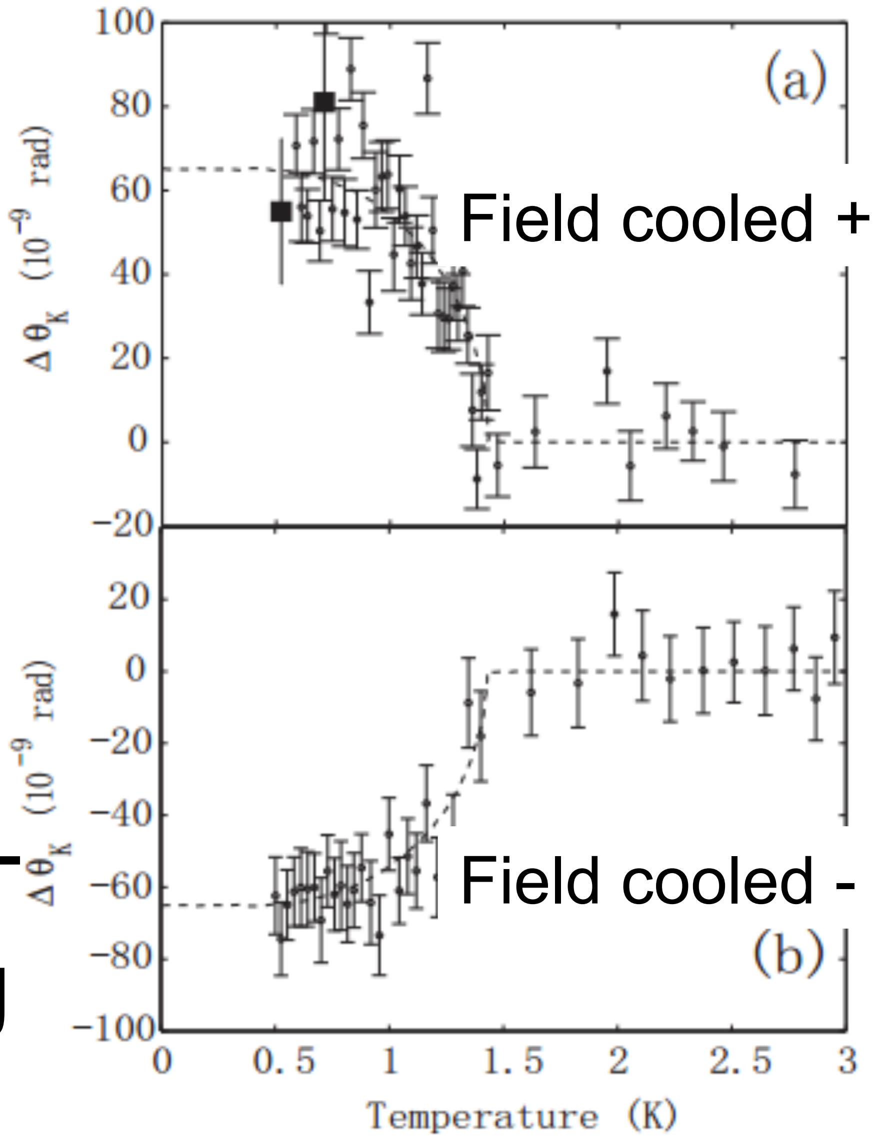
High Resolution Polar Kerr Effect Measurements of Sr_2RuO_4: Evidence for Broken Time-Reversal Symmetry in the Superconducting State

Jing Xia,[1] Yoshiteru Maeno,[2] Peter T. Beyersdorf,[3] M. M. Fejer,[4] and Aharon Kapitulnik[1,4]



Broken T

Unbroken T



Evidence for T-breaking

The conflict that has framed the field for 10 years:

T-breaking...

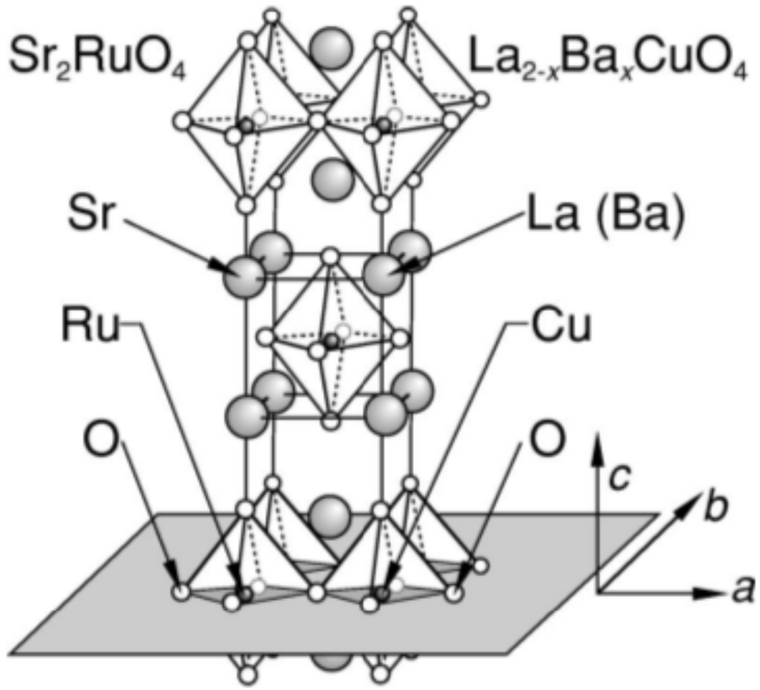
?

... but no edge currents

Some New Ideas Needed to Resolve This...

(Need more detailed understanding of the material !!)

Some Basic Facts



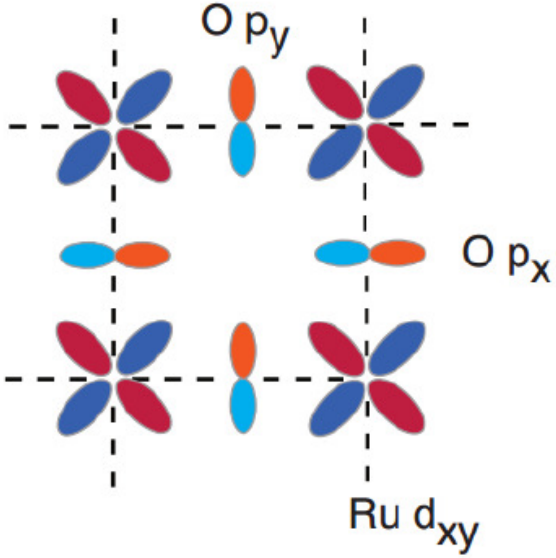
High T_c Analog
(Perovskite)

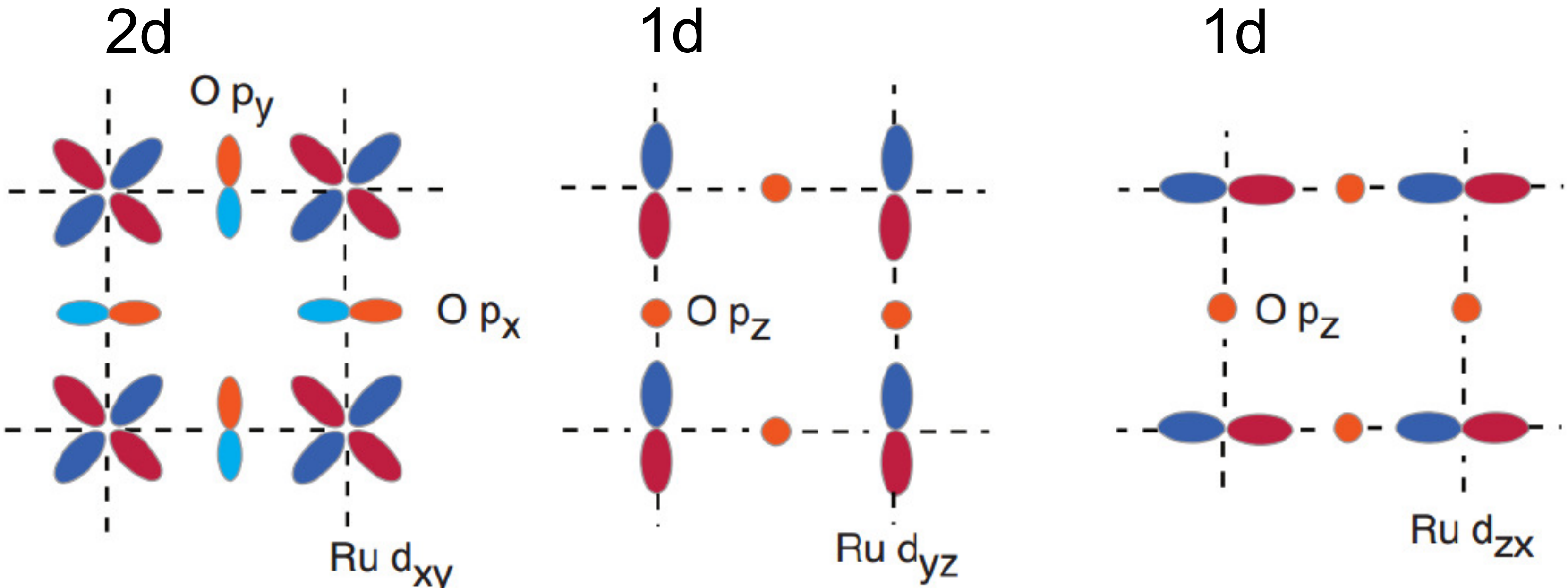
Ru orbitals are “active”

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

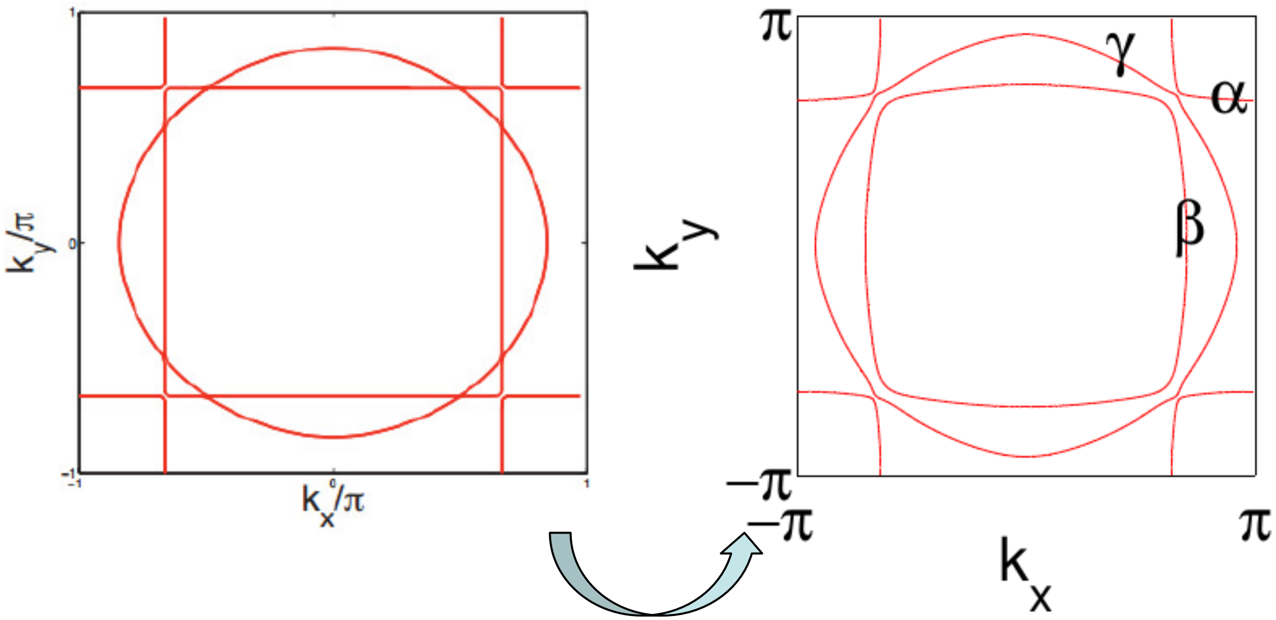
d_{xy}, d_{xz}, d_{yz}

2d

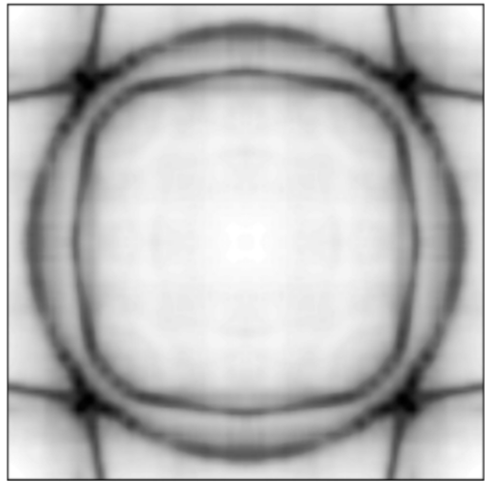




Which band is the important one??



Band mixing and spin orbit (1000K)



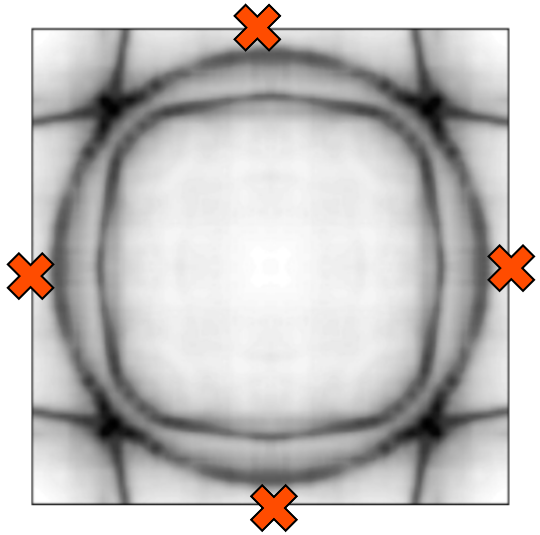
ARPES bandstructure
Damiscelli 2000

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)

- Strong chiral gap on γ band
- Weak (almost no) gap on α,β band



ARPES bandstructure
Damiscelli 2000

New(ish) Idea

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

PRL **105,** 136401 (2010) PHYSICAL REVIEW LETTERS week ending 24 SEPTEMBER 2010

Hidden Quasi-One-Dimensional Superconductivity in Sr_2RuO_4

S. Raghu, A. Kapitulnik, and S. A. Kivelson

Scenario by which supercond is on α,β bands only:
edge currents could cancel even with T breaking.

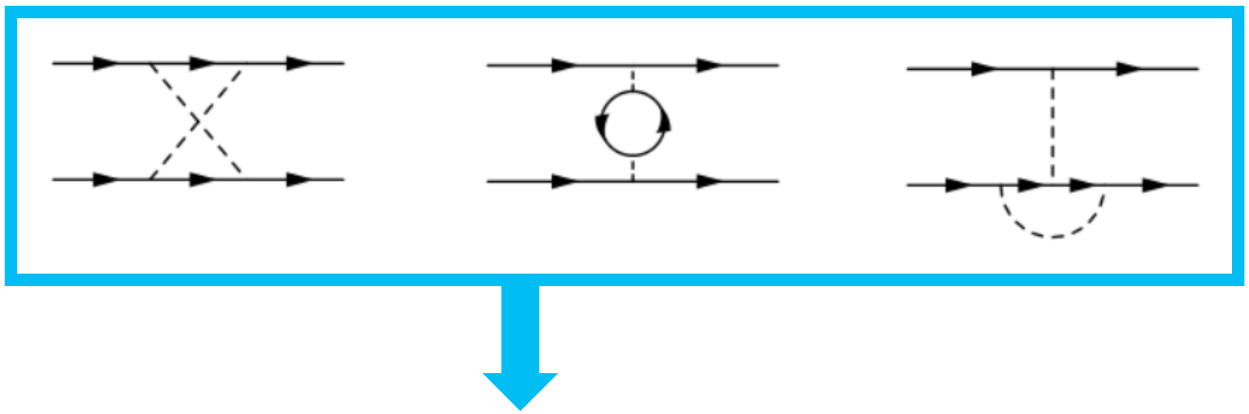
Supported by a microscopic RG calculation
"exact" in limit of weak interaction

(triplet: chiral and helical close to degenerate…)

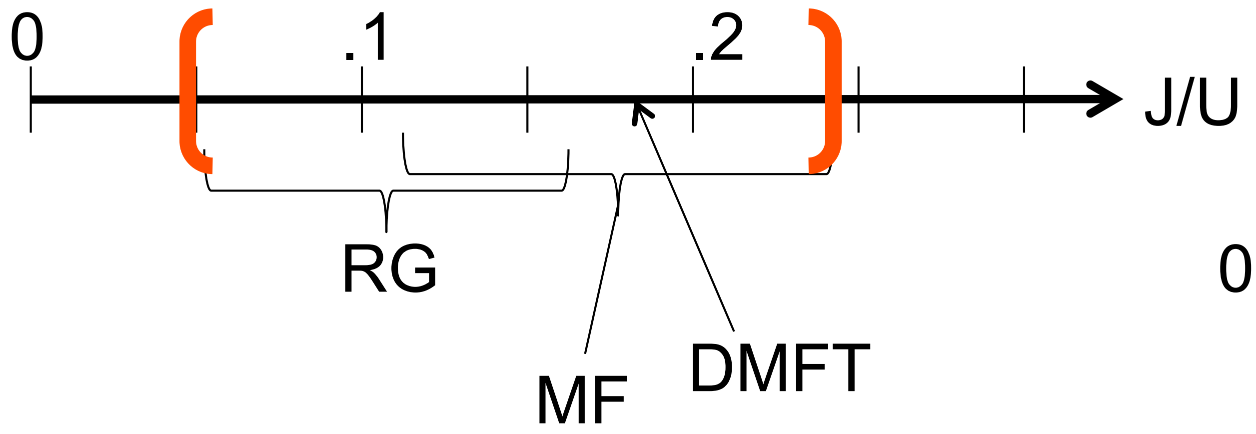
How the RG calculations work:

Simplified band structure
(no band mixing or spin orbit)

Hubbard Interactions J/U

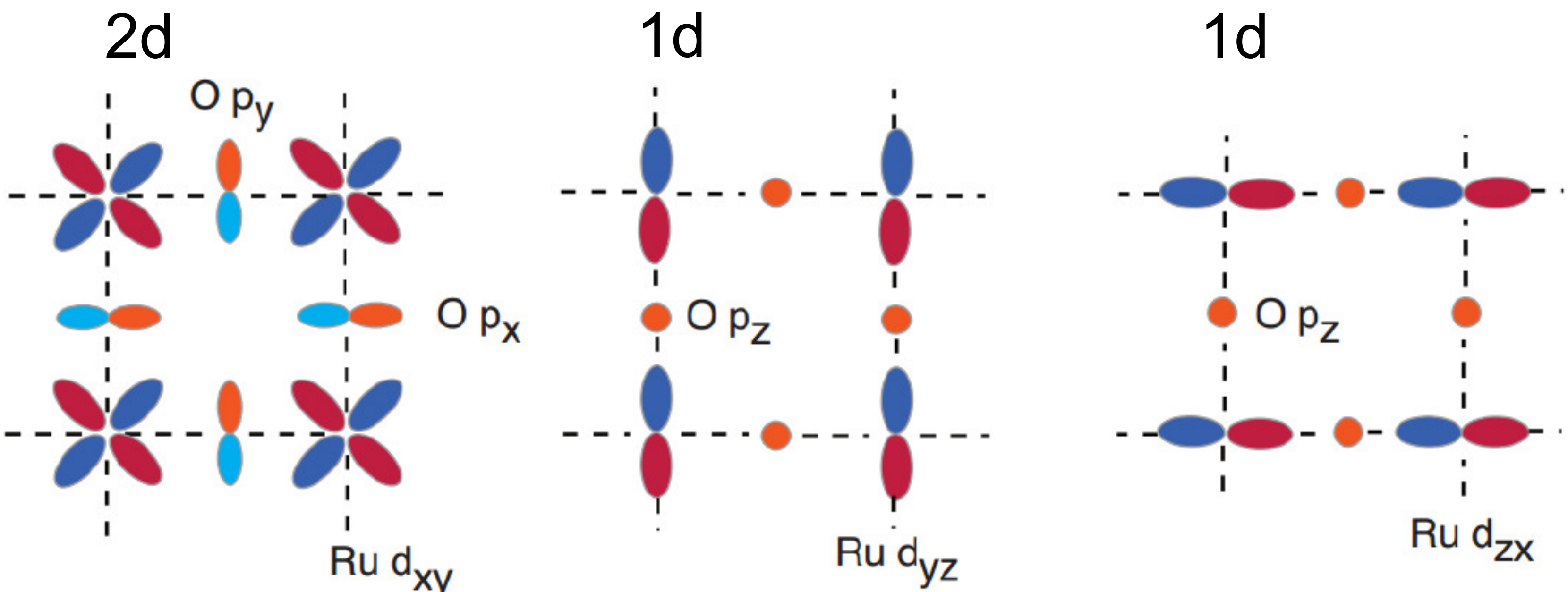


Order parameter

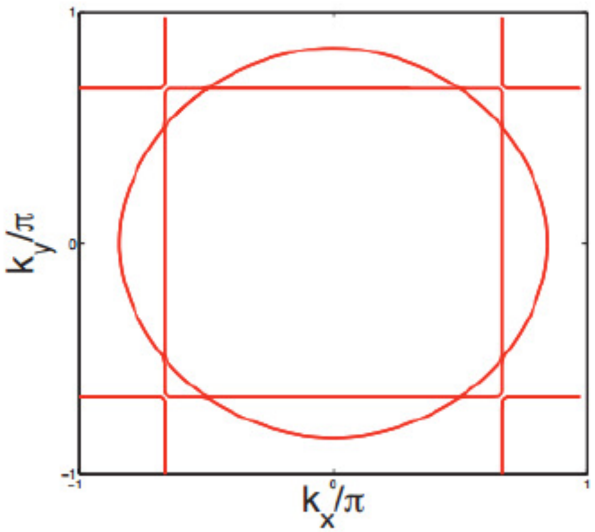


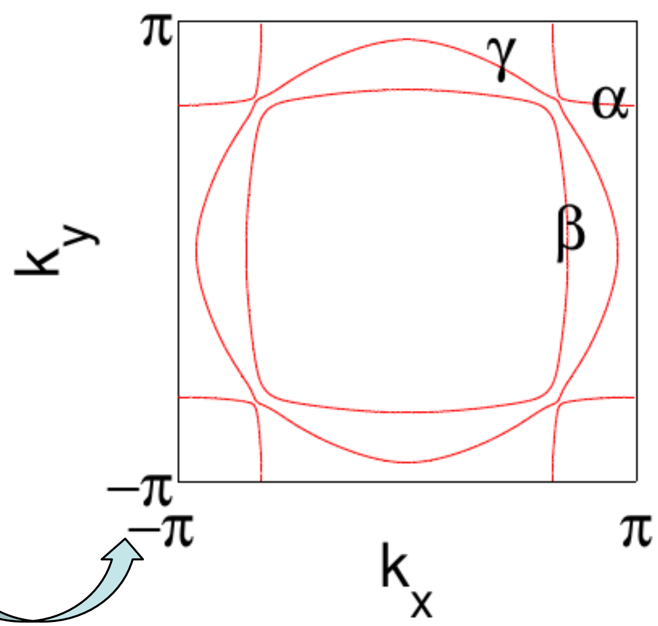
One “unknown” parameter

0.05 < J/U <0.23

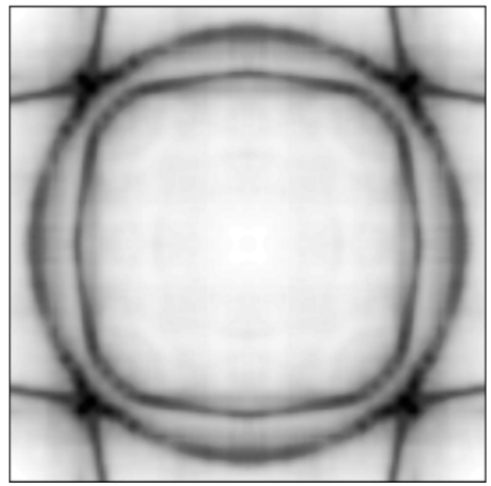


Which band is the important one??





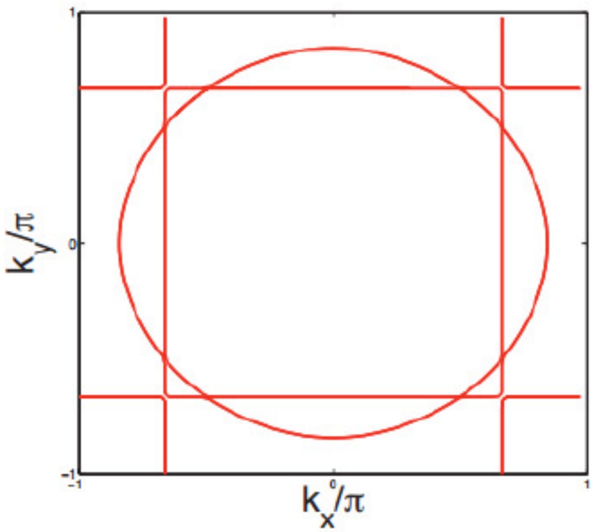
Band mixing and spin orbit (1000K)

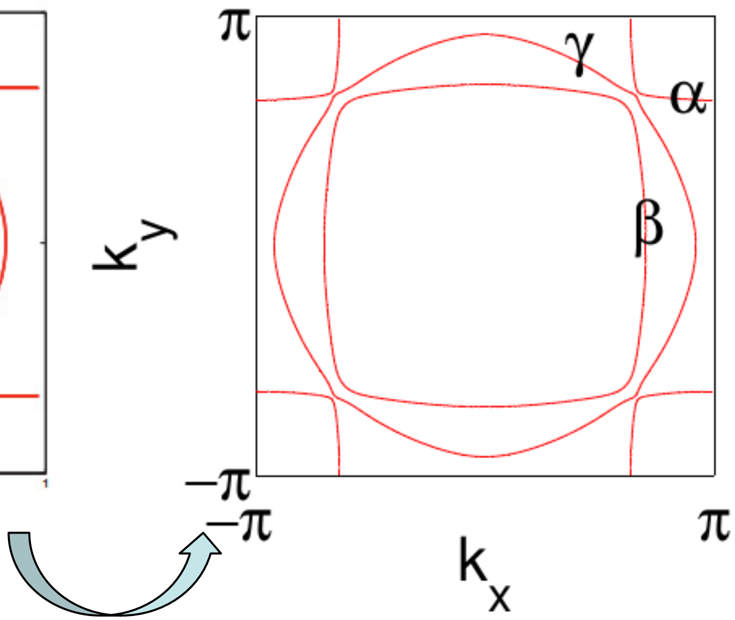


ARPES bandstructure
Damiscelli 2000

Actually, ALL bands are important!

Which band is the important one??





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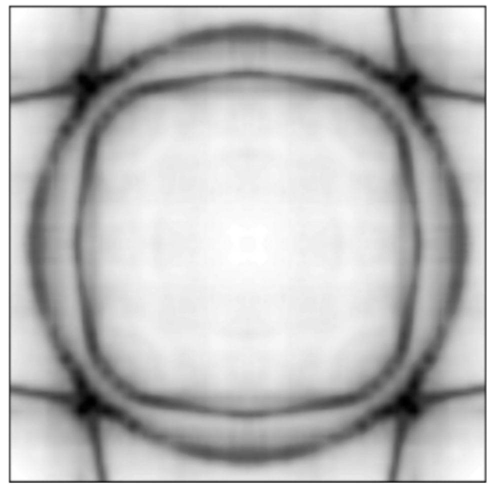
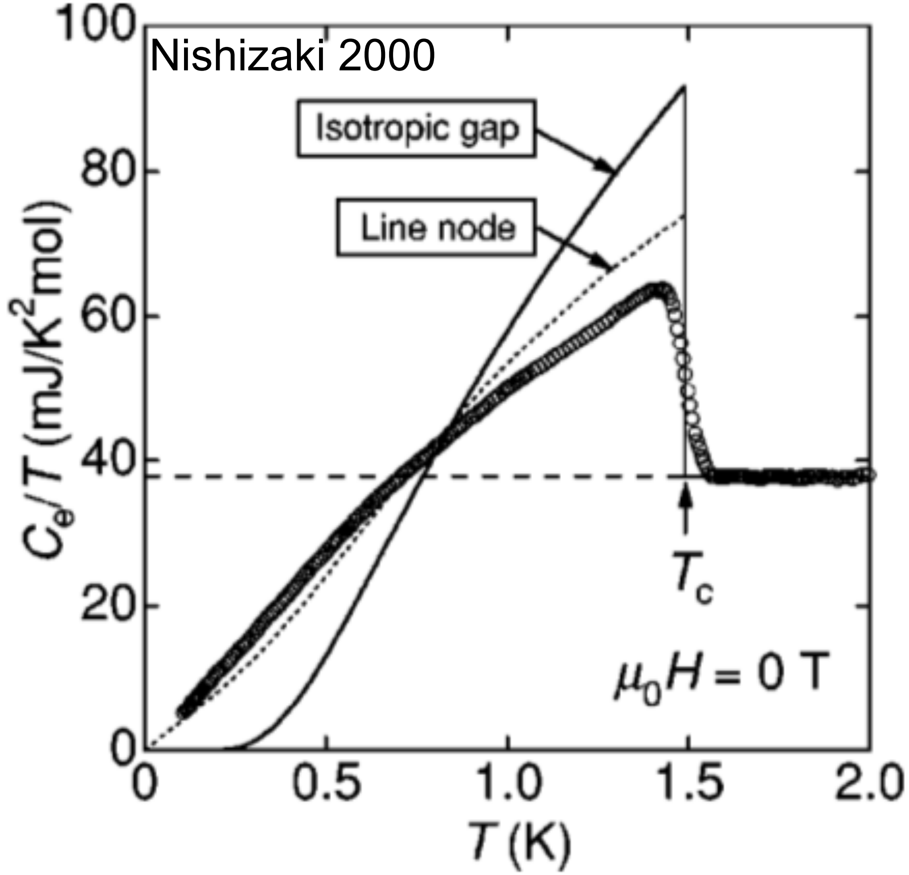


ARPES bandstructure
Damiscelli 2000

Specific heat data requires sizable gap on all three bands

Residual Density of States

C/T vanishes at low T



No ungapped density of states

So what was missing in prior RG calculations?

What is missing in prior RG calc?

- RG starts with band structure as input.
- Spin-orbit and band mixing (1000 Kelvin!) is included only *after* RG is run down to gap scale ~1K.

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

Re-do the RG with spin-orbit included first

- Only one unknown parameter = interaction ratio J/U

$0.05 < J/U < 0.23$

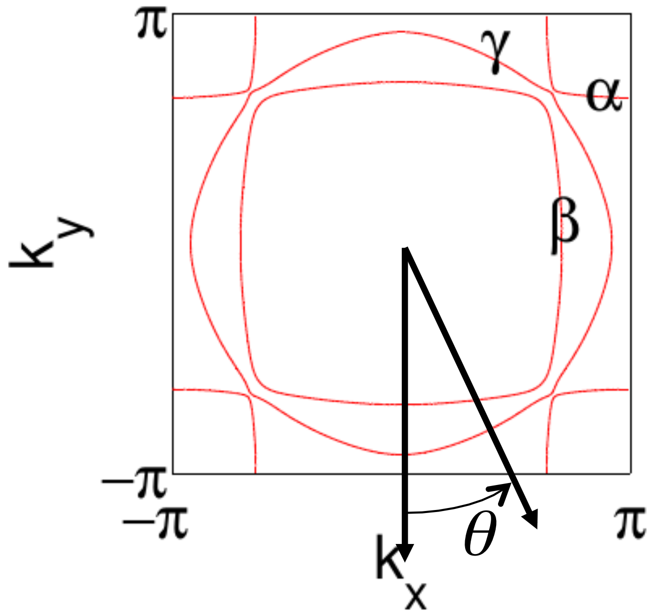
Some results

- Triplet always wins over singlet

- For J/U > 0.065 helical wins over chiral… but only by a tiny bit

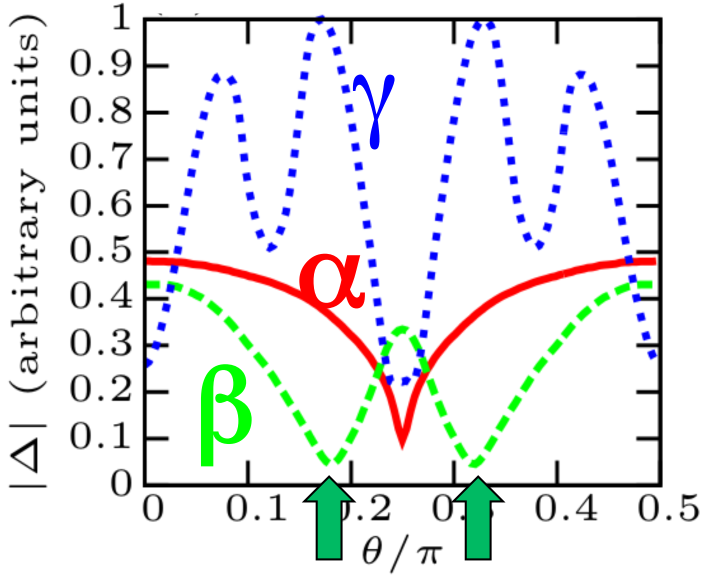
•Ratio of gap on γ to α, β close to 1 for a range of J/U !!
(agrees with specific heat data)

0.05 < J/U <0.23



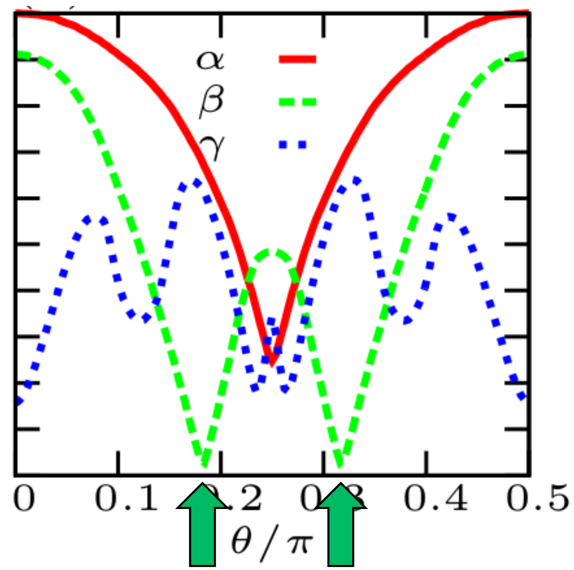
Nearly Nodes!

Chiral



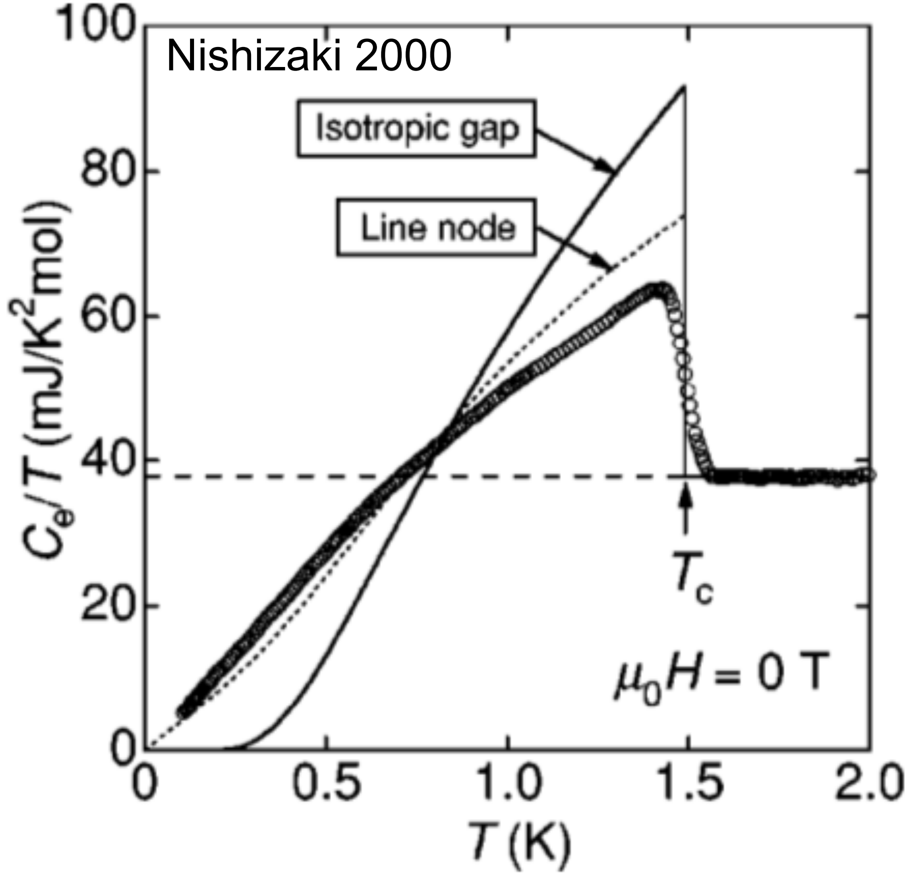
J/U = 0.06

Helical



J/U = 0.08

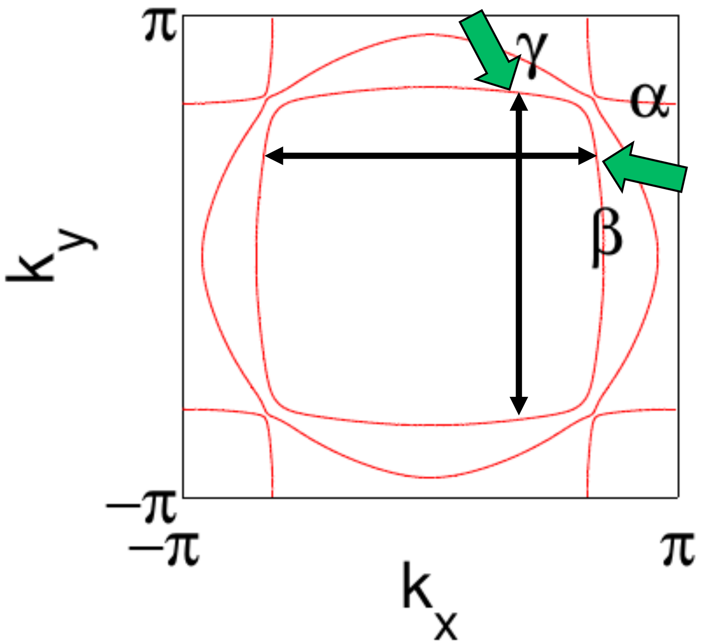
Residual Density of States
C/T vanishes at low T



No ungapped density of states

Nodes or Nearly Nodes = points on Fermi surface where superconducting gap is very small.

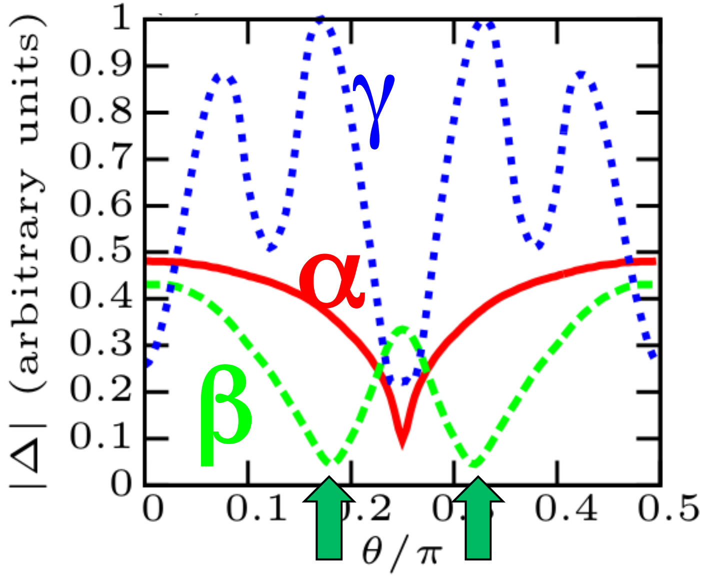
C/T vanishes linearly..



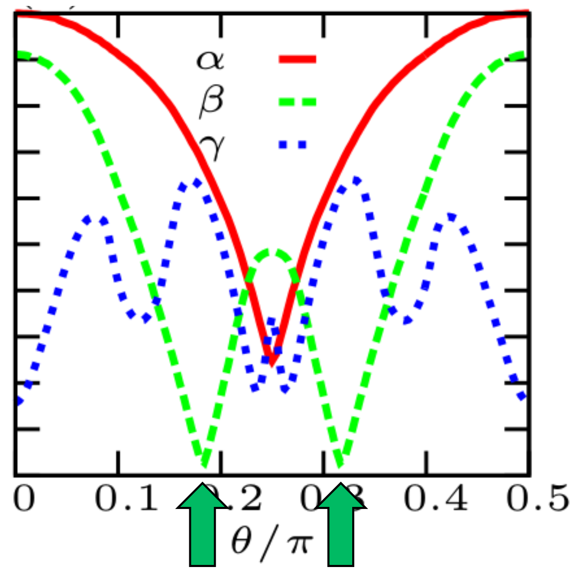
π nesting

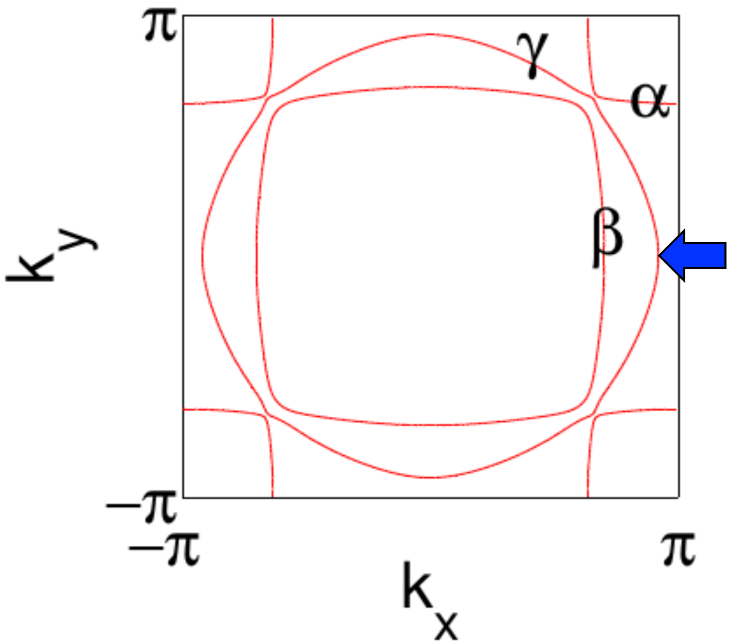
Nearly Nodes!

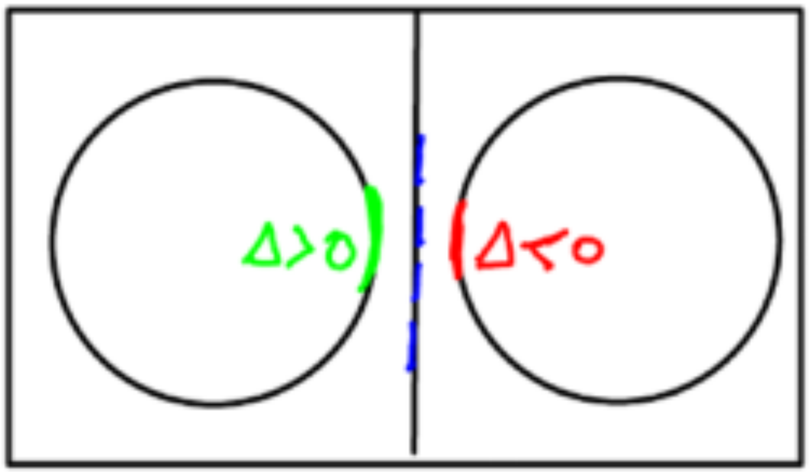
Chiral



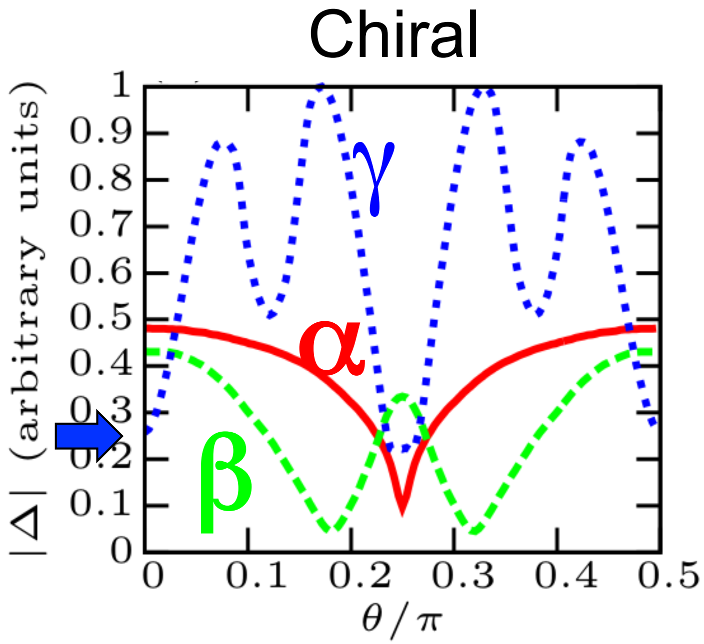
Helical

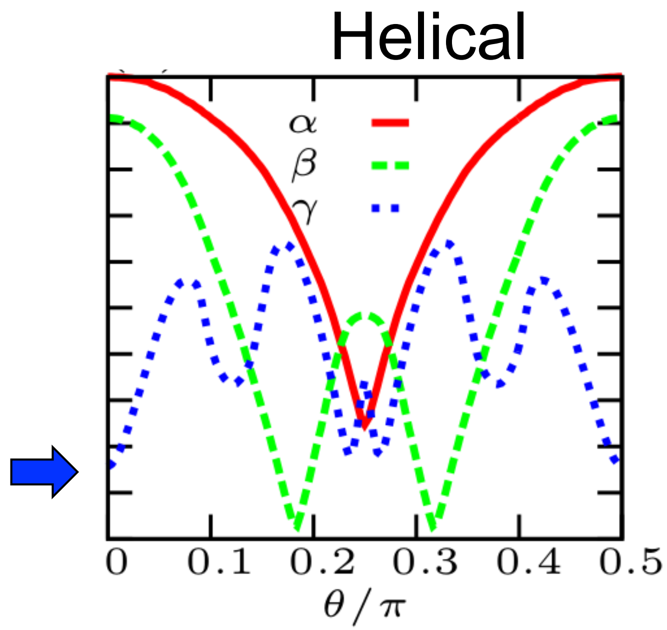


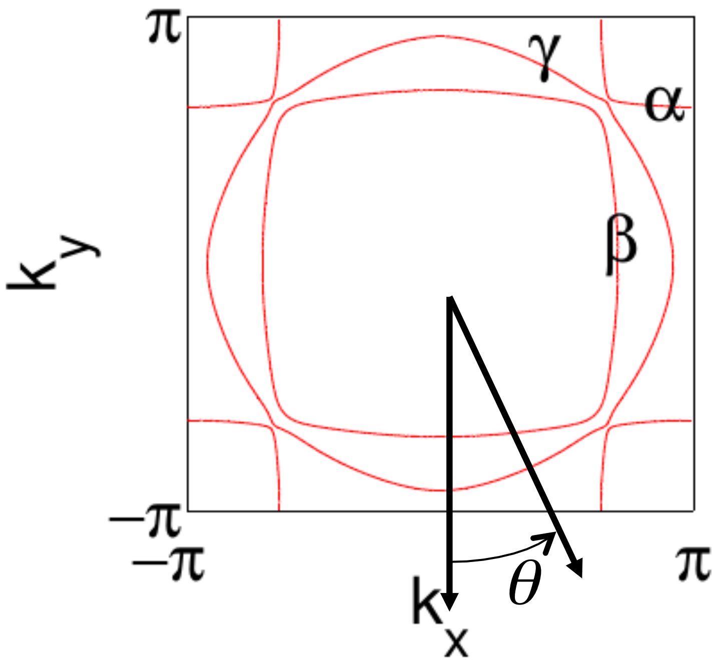




Nearly Nodes!

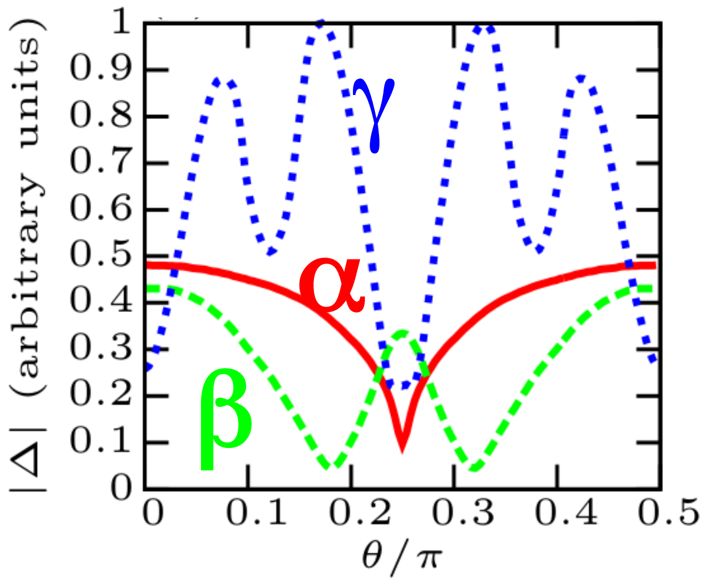


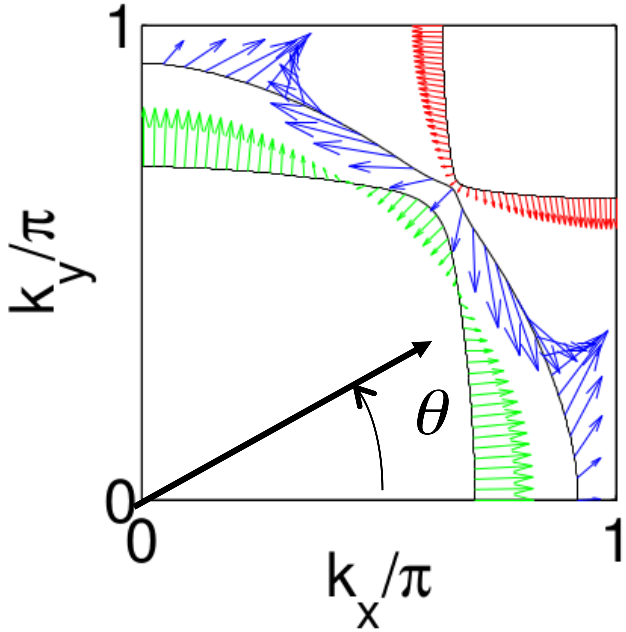


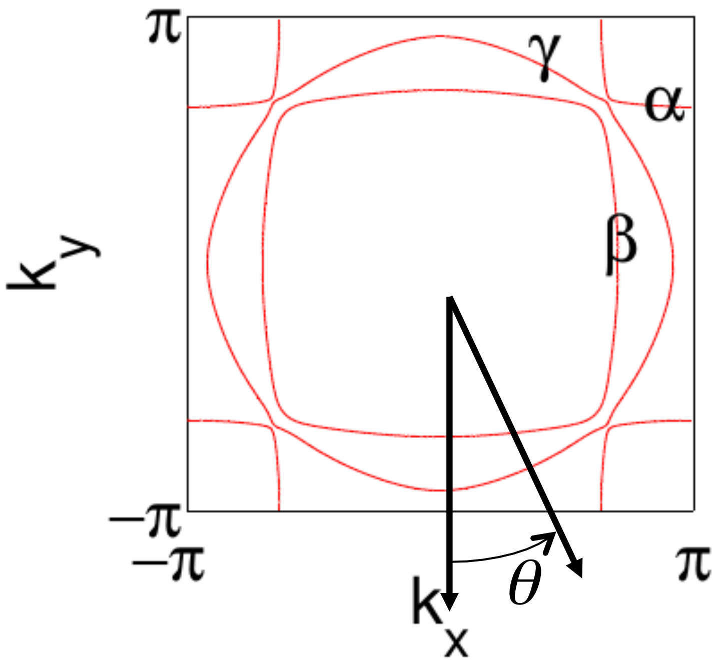


Phases

- β and γ have multiple twists!



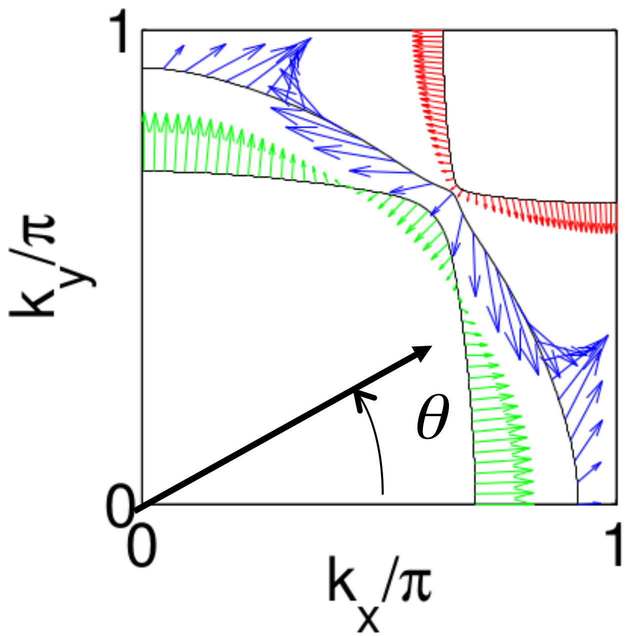




Phases

- β and γ have multiple twists!

Phase and amplitude

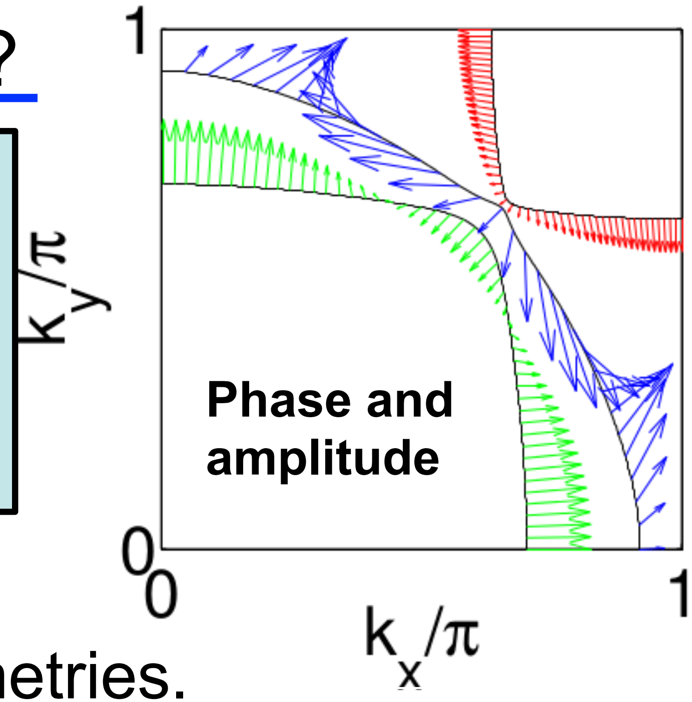


- Weren't we looking for chiral p-wave?
- Shouldn't that force phase ~ $e^{i\theta}$?

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 can only mean: Transforms like $\sin(k_x) + i\sin(k_y)$ under lattice symmetries.

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

α band C = 1
β band C= -3
γ band C= -3

Total C = -7

Predicts

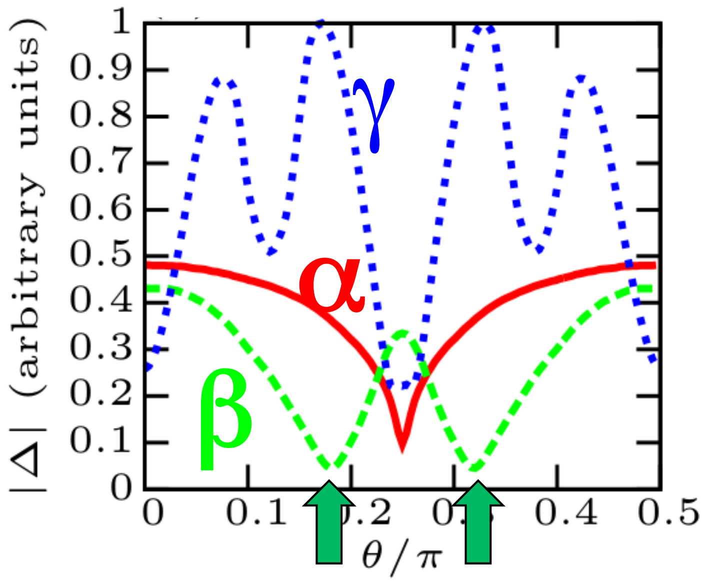
$$\kappa_{xy} = \frac{C}{2}\frac{\pi^2 k_B^2 T}{6\pi\hbar}$$

Thermal Hall Effect (Righi-Leduc) per layer
Topologically Protected!
Analogy = Quantum Hall Conductance

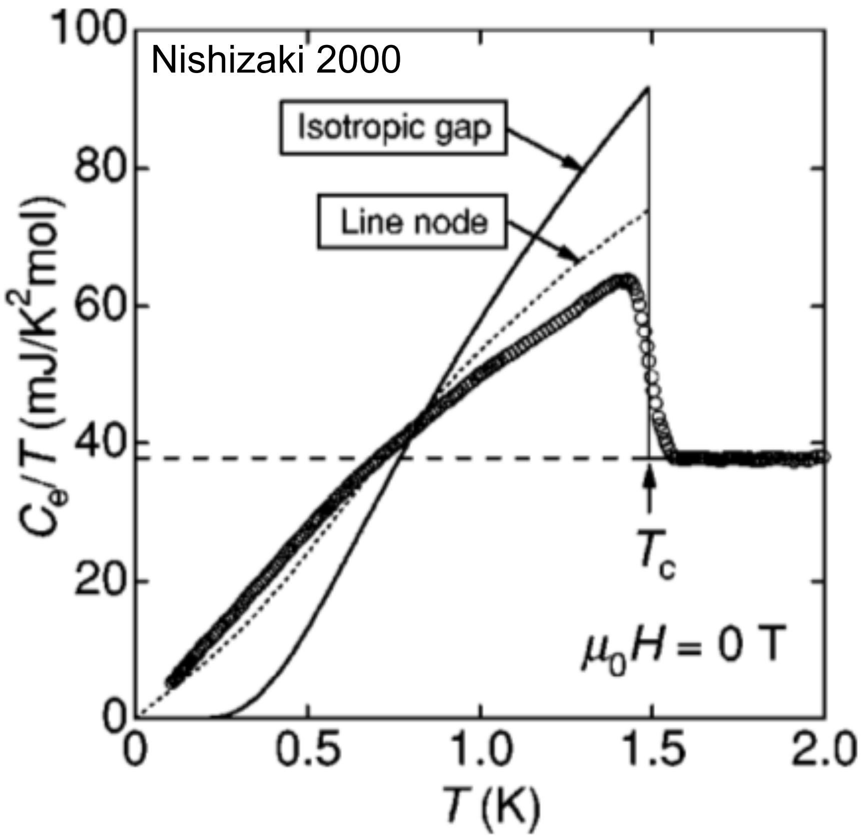
BUT:

To see quantized thermal Hall

Must be at T < Δ_{min}



C/T vanishes at low T



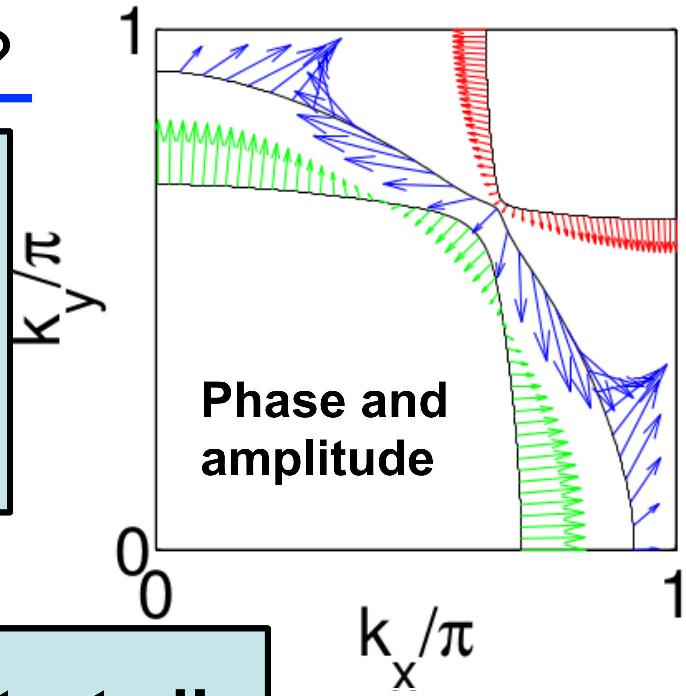
Explained by near nodes?

Can we measure this at much lower T ?

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 current is NOT topologically protected!

Sensitive to many details:

Angle of the Edge Cut
Dirt at the Edge
Details of Gap Function

Calculations suggest that above gap scale, edge current is *tiny*.

Only at $T < \Delta_{min}$ will edge currents appear.

So is it chiral p-wave?

• T-breaking experiments hard to explain otherwise
(with some caveats)

• Given the structure of the expected gap function (and given disordered edges) very large reduction in edge current is expected at all temperatures examined so far.

OR

… We really don't understand something…

Strontium Ruthenate

Why this material has remained interesting for 20 years and what is new now

Steve Simon
Jesper Romers
Thomas Scaffidi

UNIVERSITY OF OXFORD

EPSRC

Thank you for Listening