University of St Andrews
School of Physics and Astronomy

SUPA

Superconductivity and Electron Correlations in Ruthenates

Andy Mackenzie

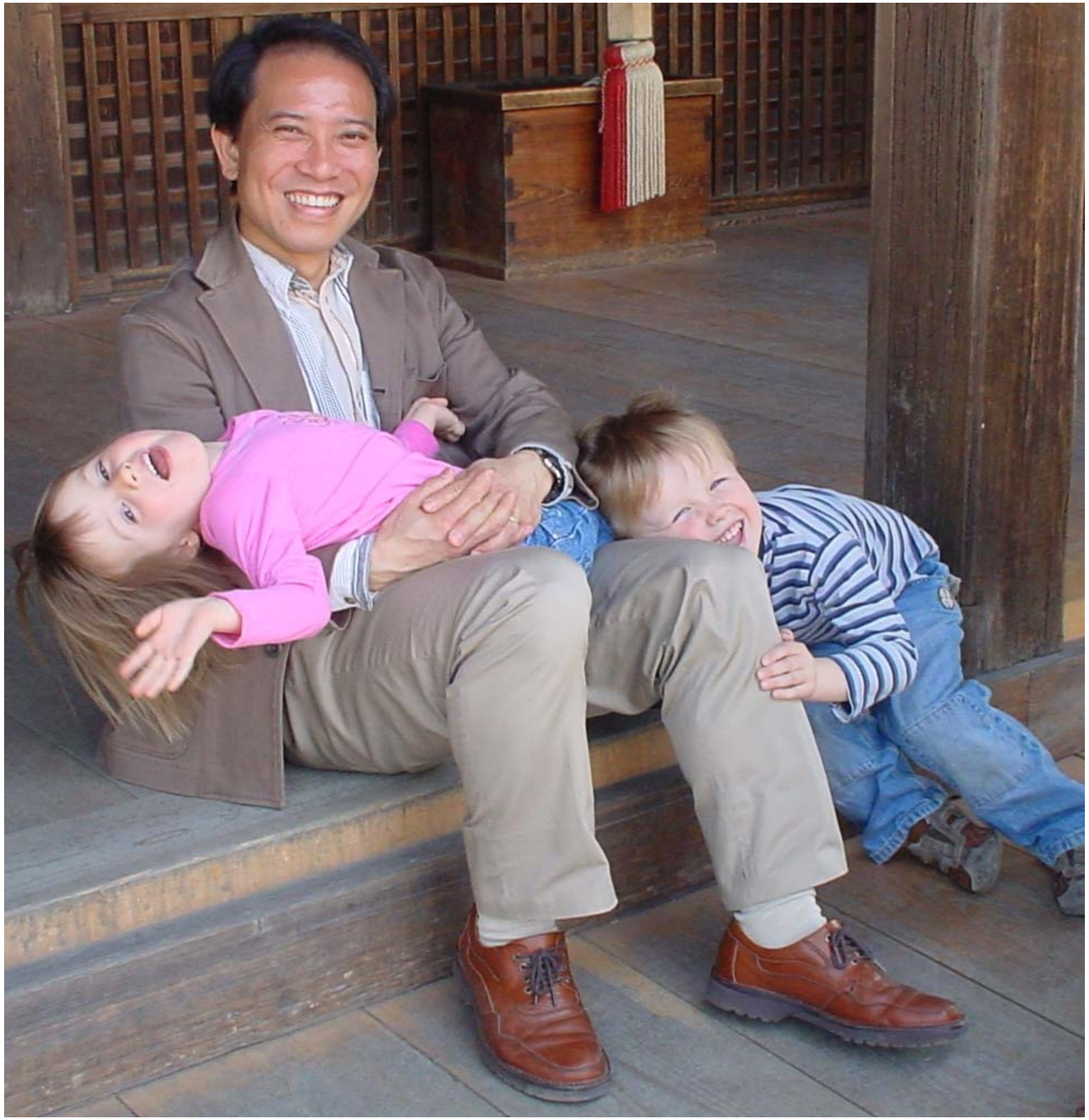
University of St Andrews, UK

EPSRC

The Leverhulme Trust

THE ROYAL SOCIETY

Key collaborator: Yoshi Maeno, Kyoto University



Contents

1. Electronic structure 'roadmap'

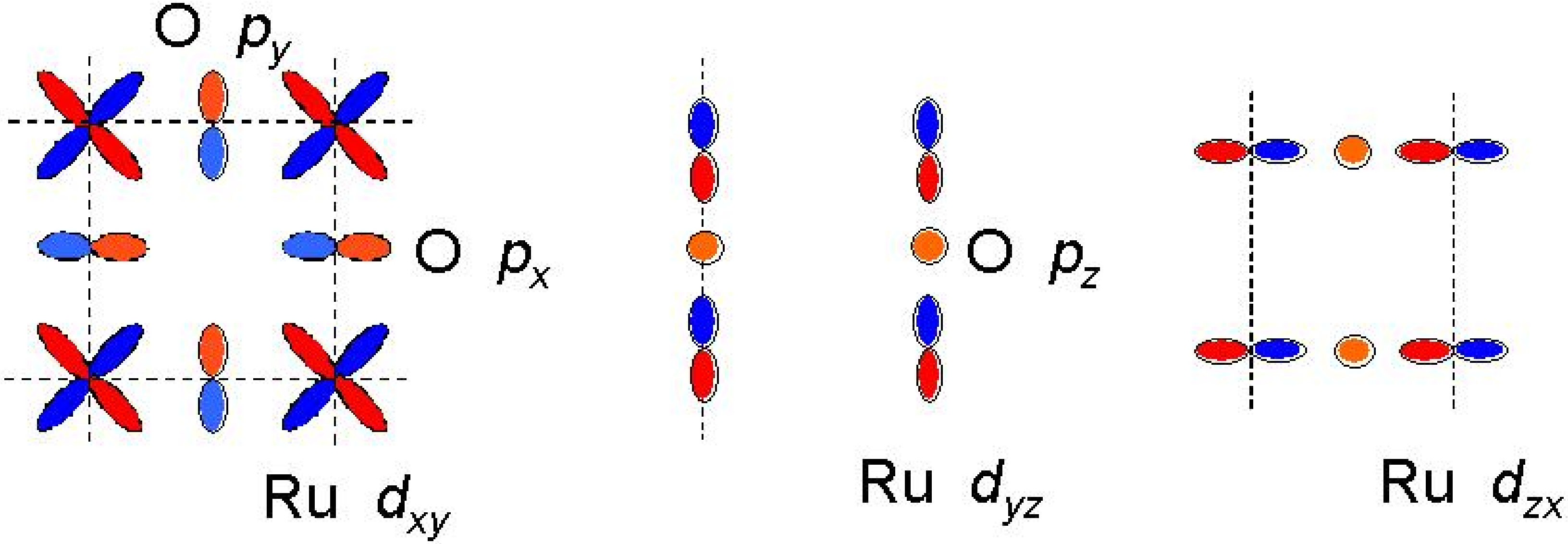
2. Discovery of superconductivity in Sr_2RuO_4

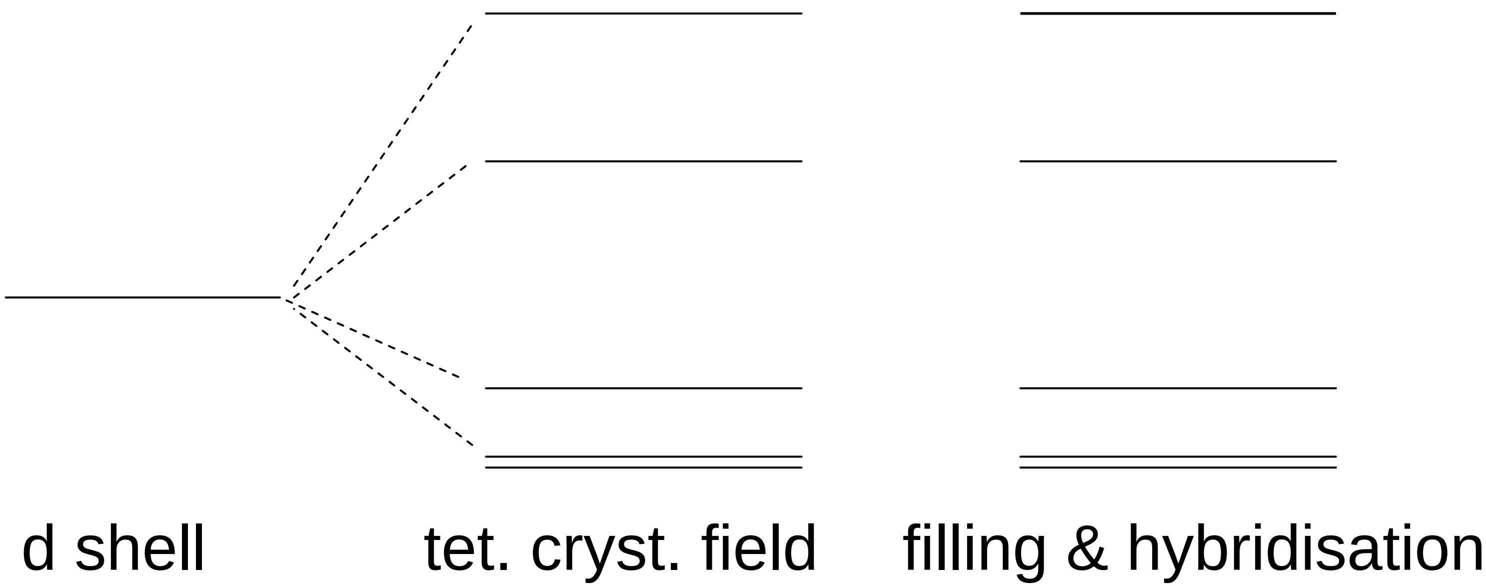
3. Crystal growth enabling clean-limit physics

4. Review of evidence for an odd parity, spin triplet condensate

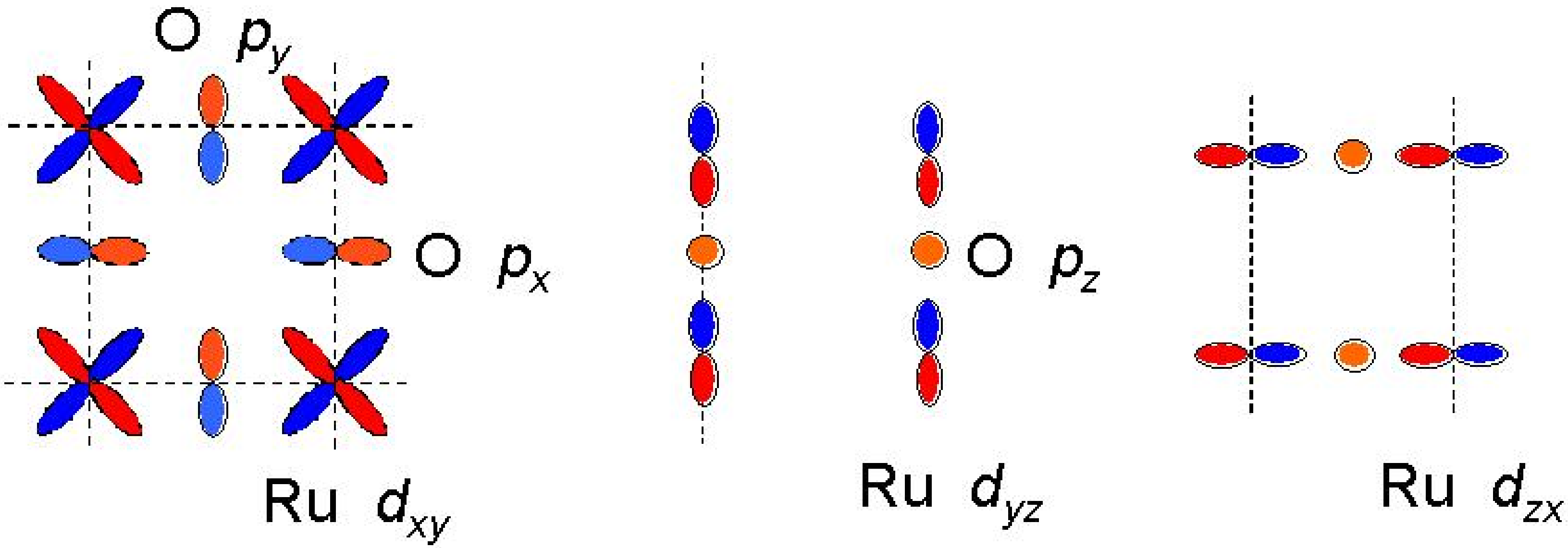
5. Towards understanding electronic correlations and the mechanism of the superconductivity

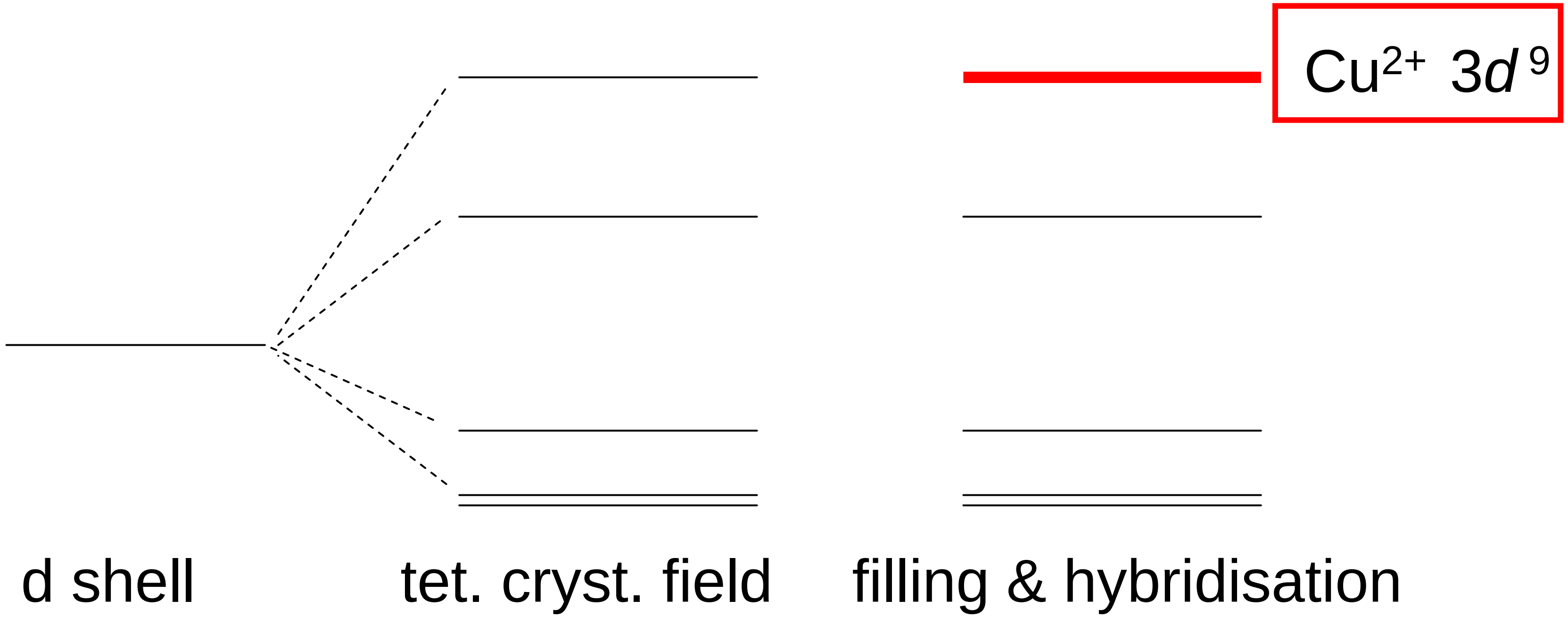
Electronic structure considerations



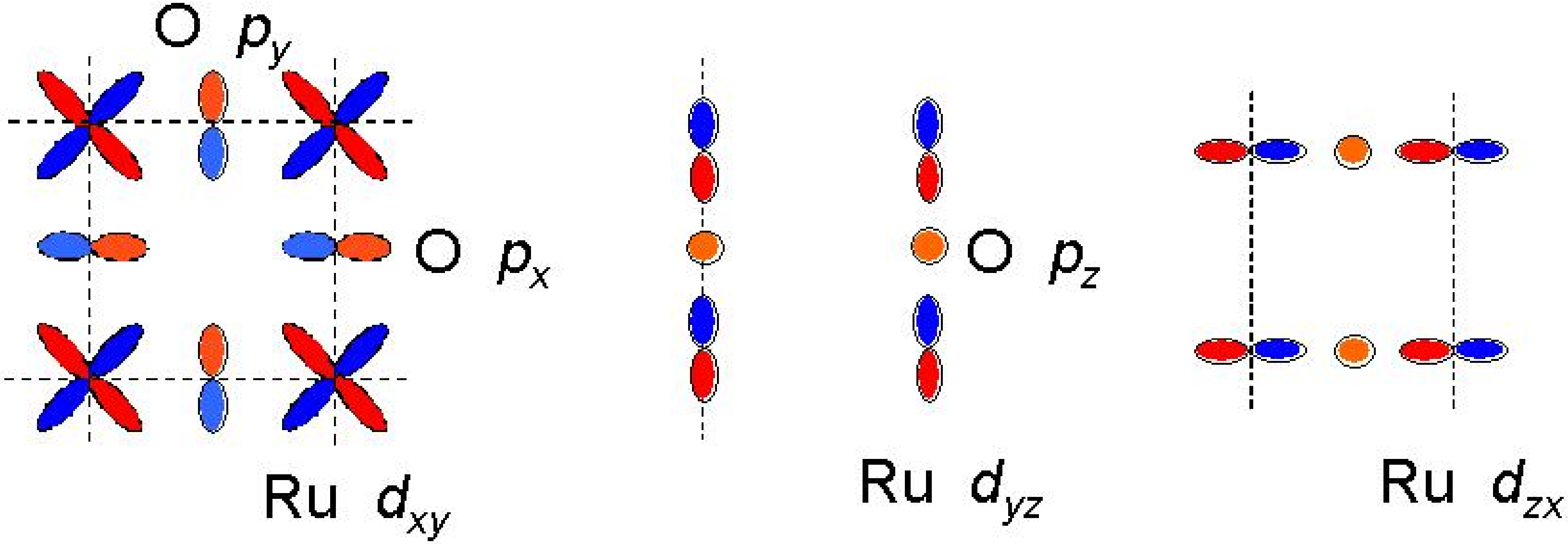


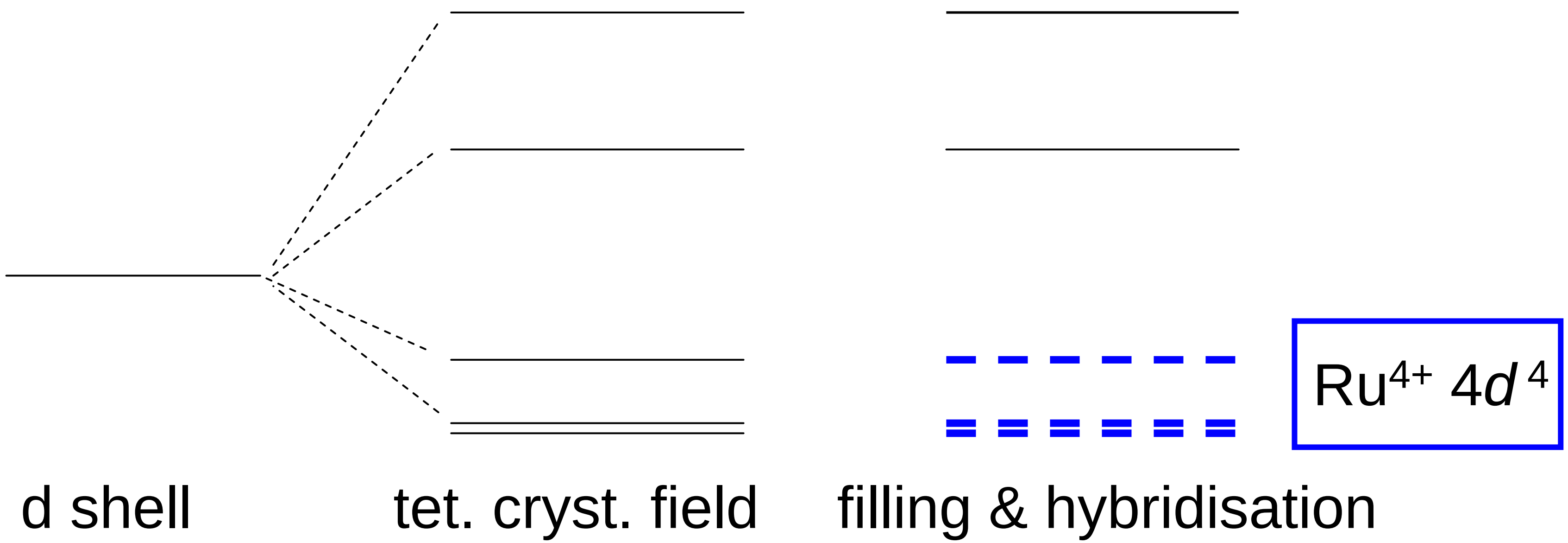
Electronic structure considerations





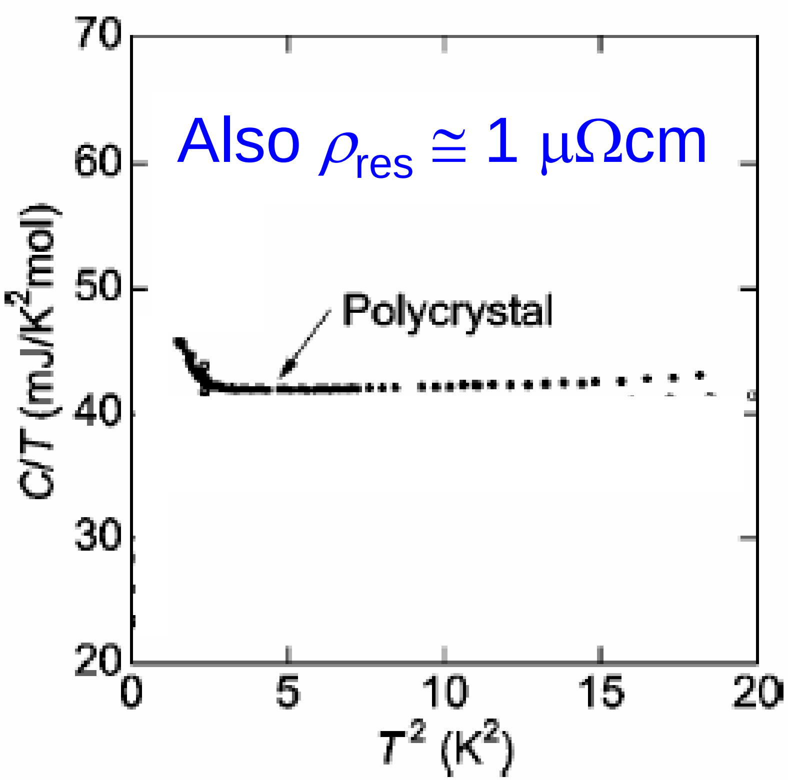
Electronic structure considerations

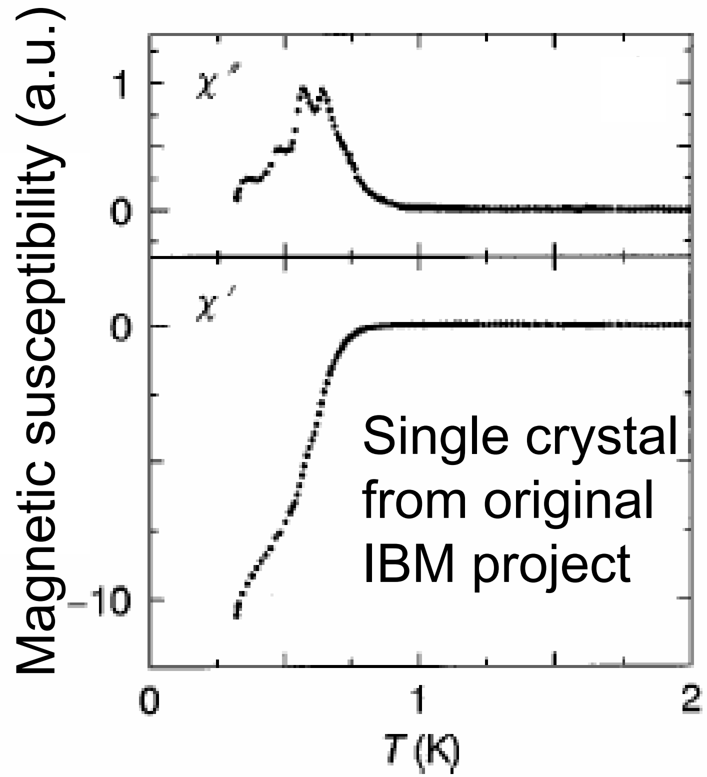




Discovery of superconductivity in Sr_2RuO_4

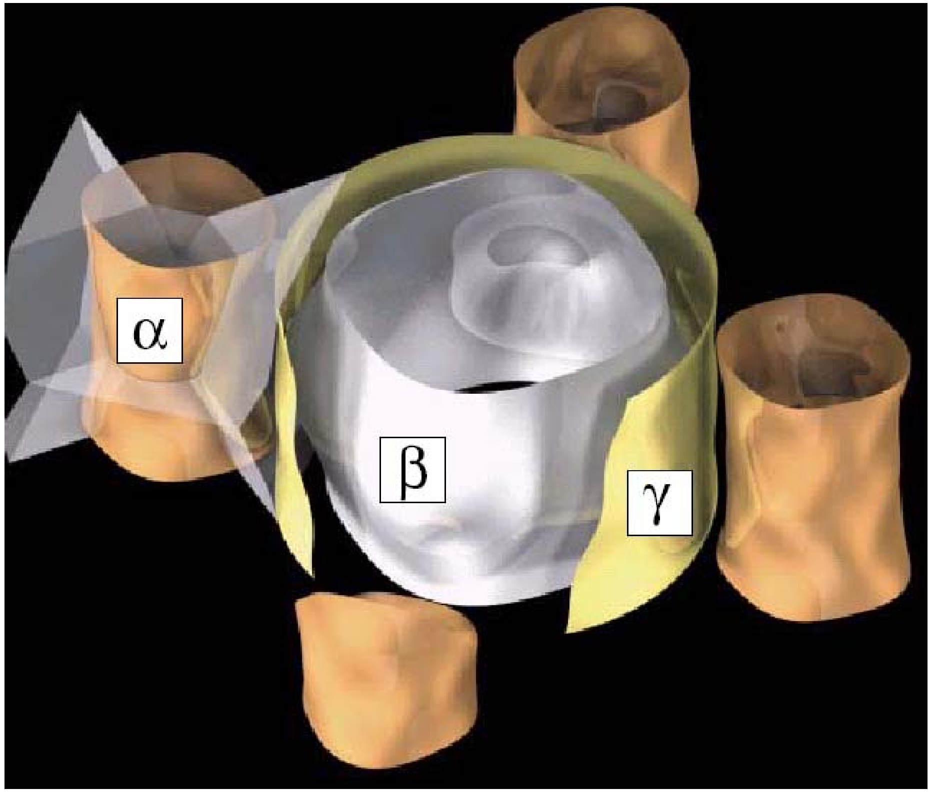
1988 G. Bednorz $\rightarrow$ Y. Maeno: ‘Check out ruthenates’

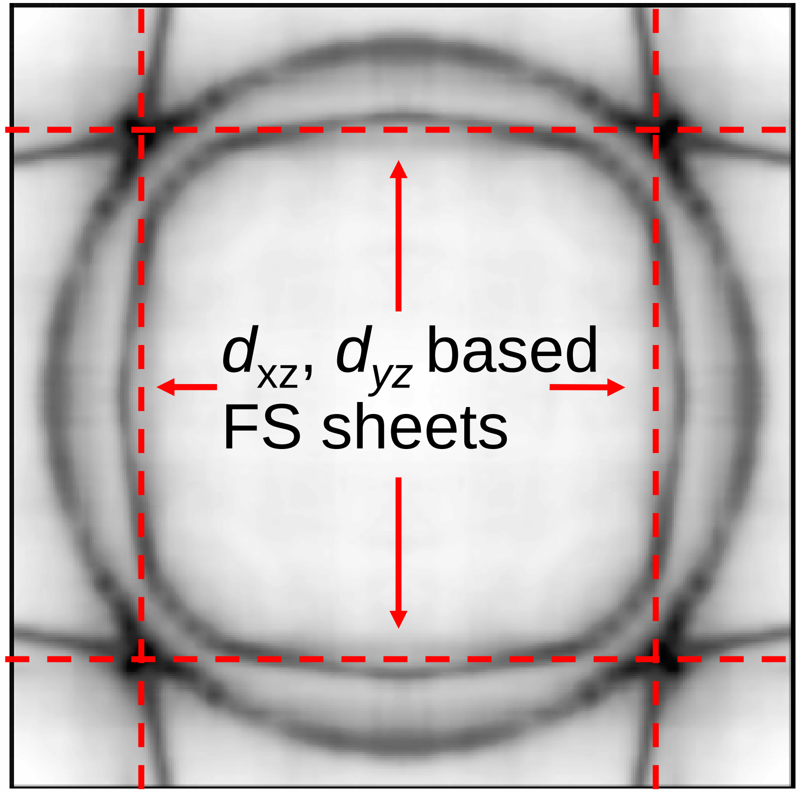




Y. Maeno *et al.*, Nature **372**, 532 (1994)

Exquisite knowledge of Fermi surface from de Haas – van Alphen effect and angle resolved photoemission, proving that **metallic Sr_2RuO_4 is a quasi-2D Fermi liquid**



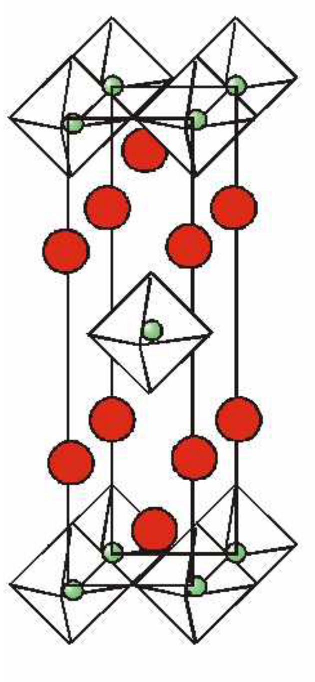


Mackenzie *et al.*, Phys. Rev. Lett. **76**, 3786 (1996).

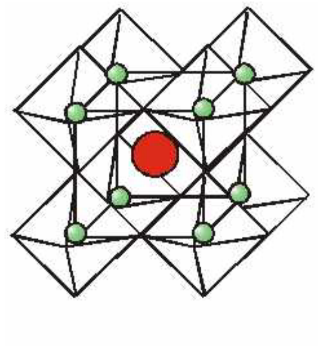
C. Bergemann *et al.,* Adv. Phys. **52** (2003).

A. Damascelli *et al.,* Phys. Rev. Lett. **85**, 5194 (2000).

Tendency to ferromagnetism in ruthenates.



Sr_2RuO_4:
superconductor



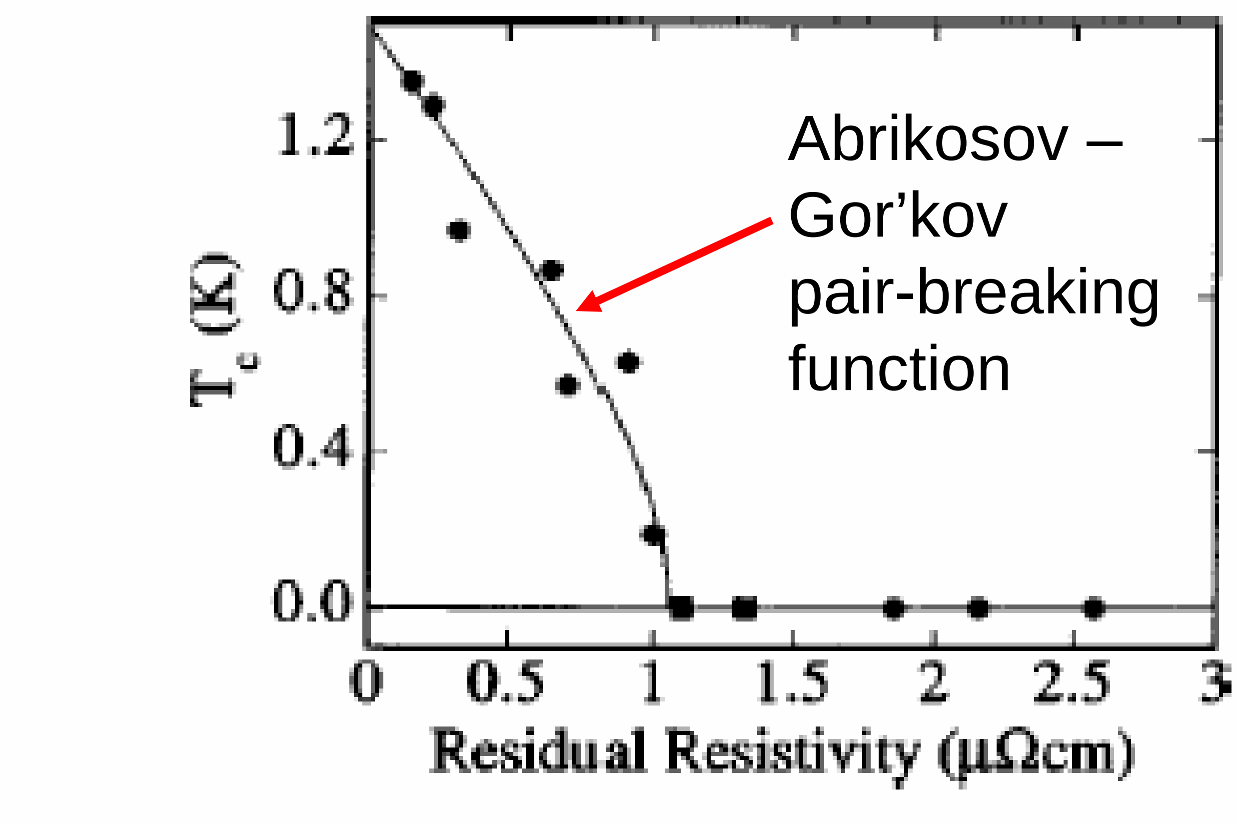
$SrRuO_3$:
ferromagnet

Might the superconductivity be spin triplet?

T.M. Rice & M. Sigrist, J. Phys. Cond. Mat. **7**, L43 (1995)

G. Baskaran, Physica B **224**, 490 (1996)

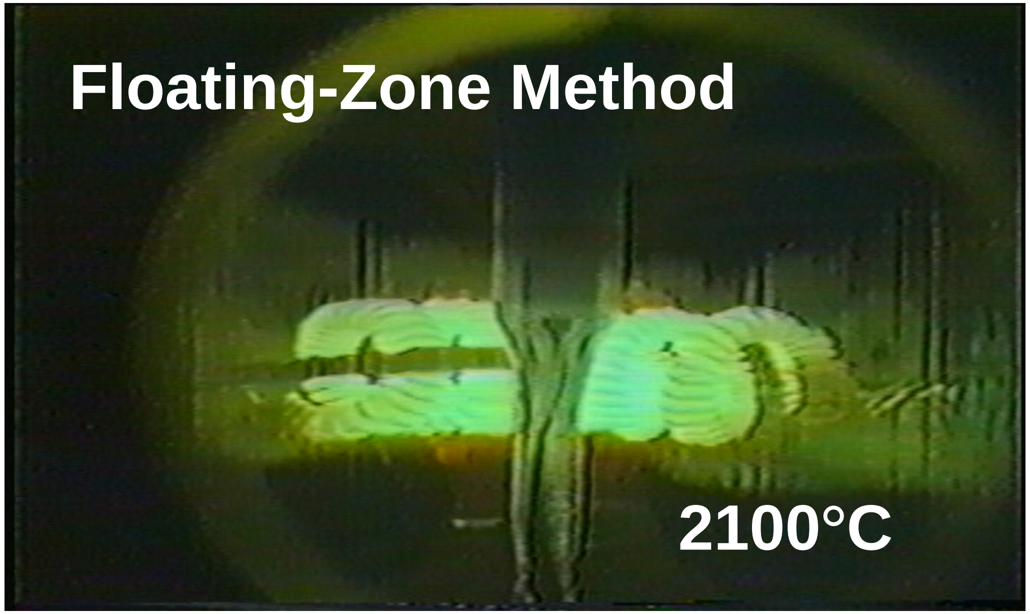
Unconventional superconductivity is sensitive to impurities and Sr_2RuO_4 has a long coherence length

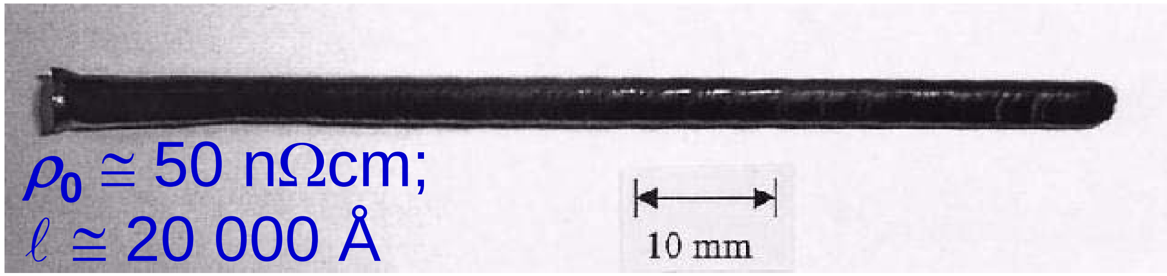


Extreme sensitivity non-magnetic disorder:
ℓ < 1000 Å no observable superconductivity!

A.P. Mackenzie *et al.*, Phys. Rev. Lett. **80**, 161 (1998).

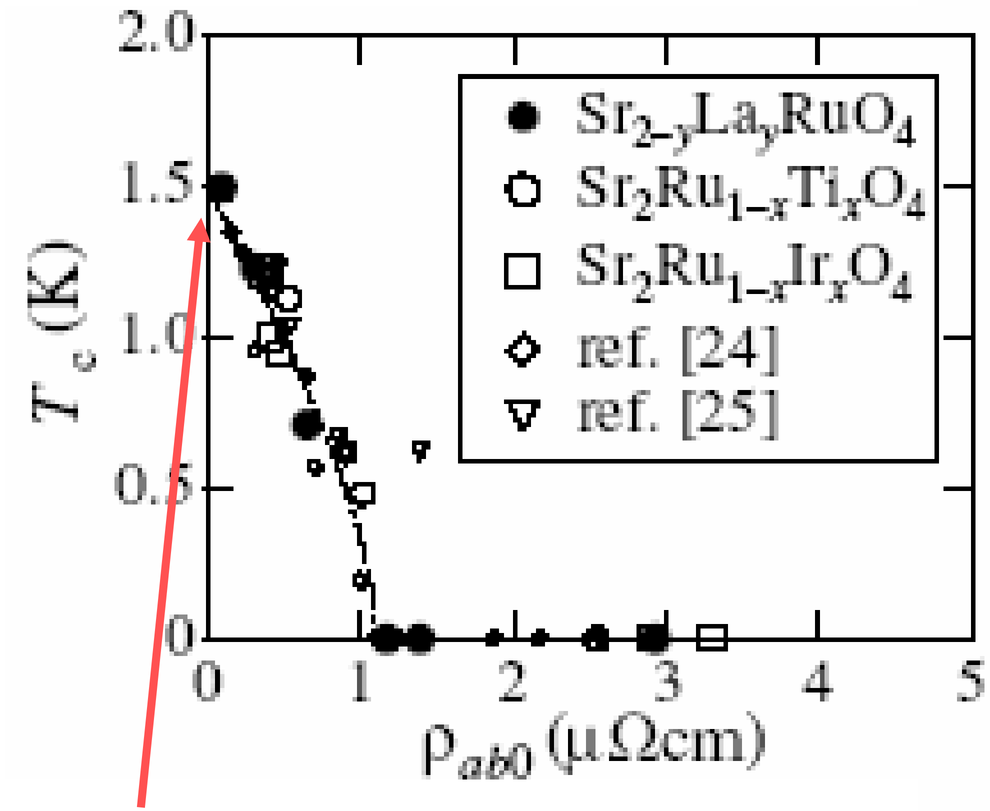
A triumph of modern crystal growth

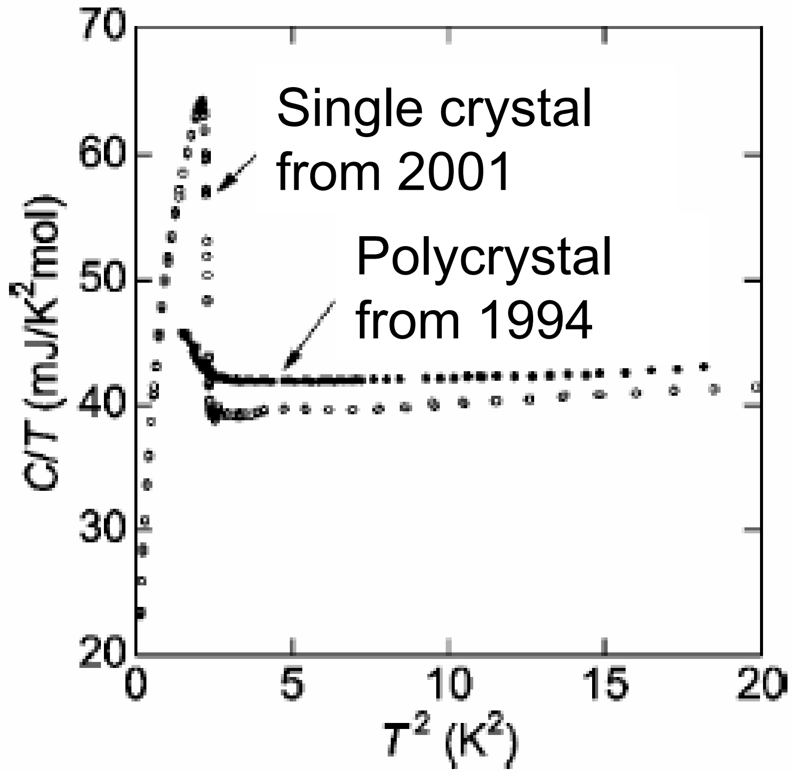




Z.Q. Mao, Y. Maeno and H. Fukazawa,
Mat. Res. Bull. **35**, 1813 (2000).

… and the result in terms of physics: Proper clean-limit unconventional superconductivity in a material with $\xi \sim 10^3$ Å

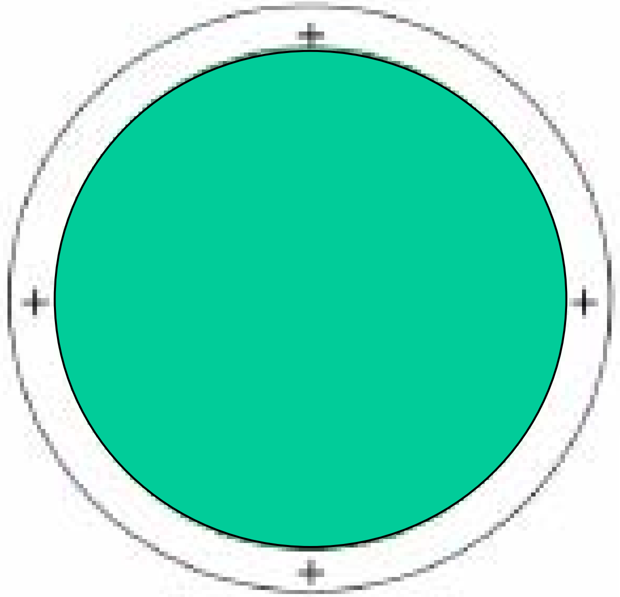


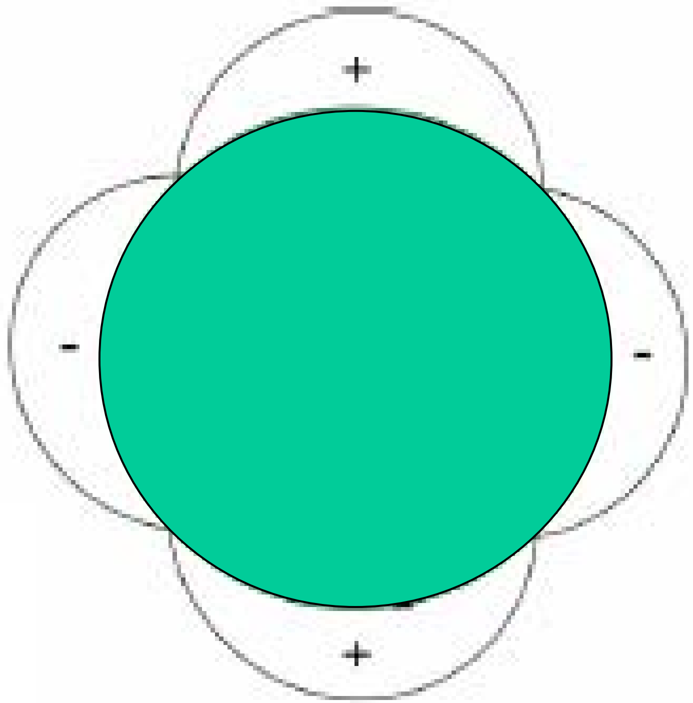


Maximum T_c 'predicted' from 1998 work

Brief comments on vector order parameters

For s-wave, d-wave etc. superconductors the Cooper pairs bind in a single-component spin singlet.





Describing the **k** dependence of the order parameter requires only a complex number $\Delta(\mathbf{k})$.

Brief comments on vector order parameters

Triplet pairing has a three component spin state, and an elegant full description can be given using a complex vector **d**(**k**).

d = **x**f_x(**k**) + **y**f_y(**k**) + **z**f_z(**k**) where **x,y,z** are unit vectors in spin space.

Useful properties of **d**: For a given Cooper pair at (**k,-k**), the spins lie in the plane perpendicular to **d.**

The energy gap at **k** is proportional to |**d**|.

R. Balian and N.R. Werthamer, Phys. Rev. **131**, 1553 (1963).

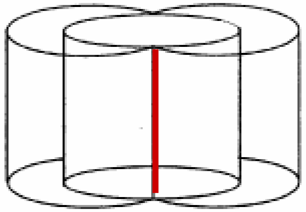
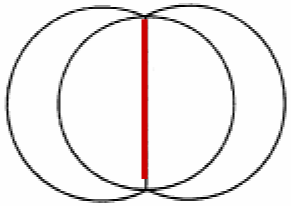
A.J. Leggett, Rev. Mod. Phys. **47**, 331 (1975).

Example vector order parameters allowed in a tetragonal crystal like Sr_2RuO_4

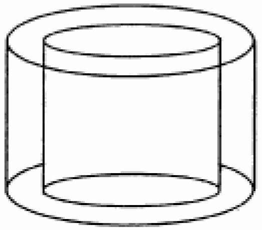
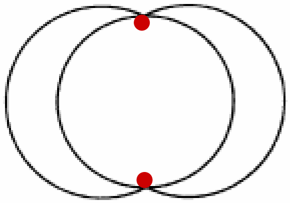
Gap structure

d-vector | 2D | 3D

$\mathbf{z}k_x$ $\begin{bmatrix} 0 \\ 0 \\ k_x \end{bmatrix}$

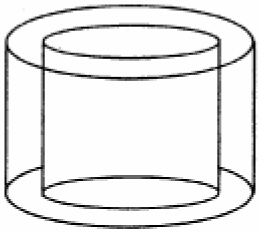
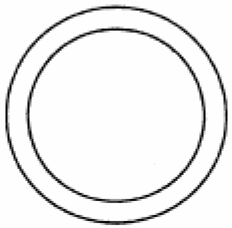



$\mathbf{z}(k_x + ik_y)$ $\begin{bmatrix} 0 \\ 0 \\ k_x + ik_y \end{bmatrix}$

A phase of ^{3}He

$\mathbf{x}k_x + \mathbf{y}k_y$ $\begin{bmatrix} k_x \\ k_y \\ 0 \end{bmatrix}$ or $\begin{bmatrix} k_x \\ k_y \\ k_z \end{bmatrix}$

B phase of ^{3}He

Discriminating between singlet and triplet pairing

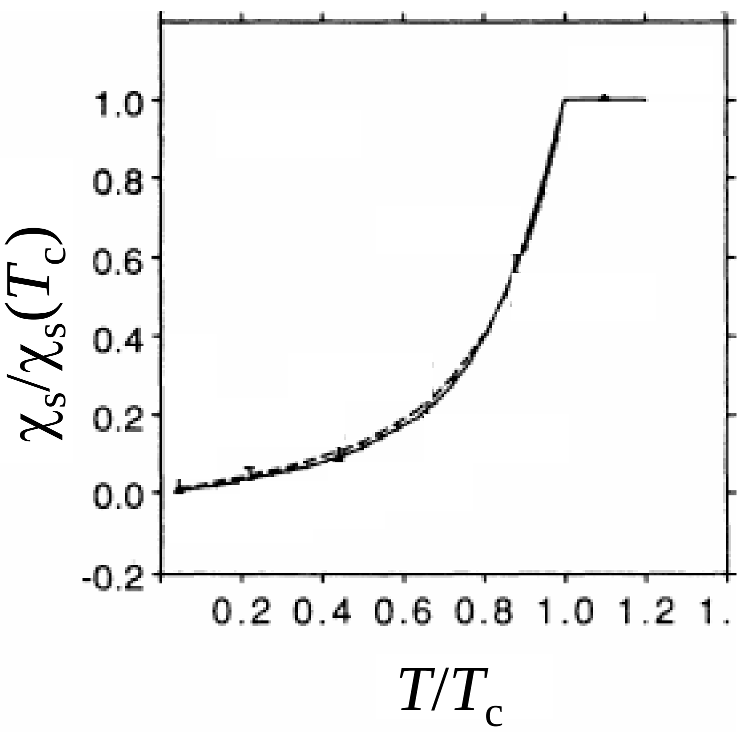
Order parameter has spin part and orbital part and in principle either can be probed. Probes of the effect of odd parity discussed by Dale van Harlingen.

Spin part: There is an intrinsic energetic competition between a condensation of non-magnetic singlet pairs and the energy gain of Zeeman splitting in an applied magnetic field.

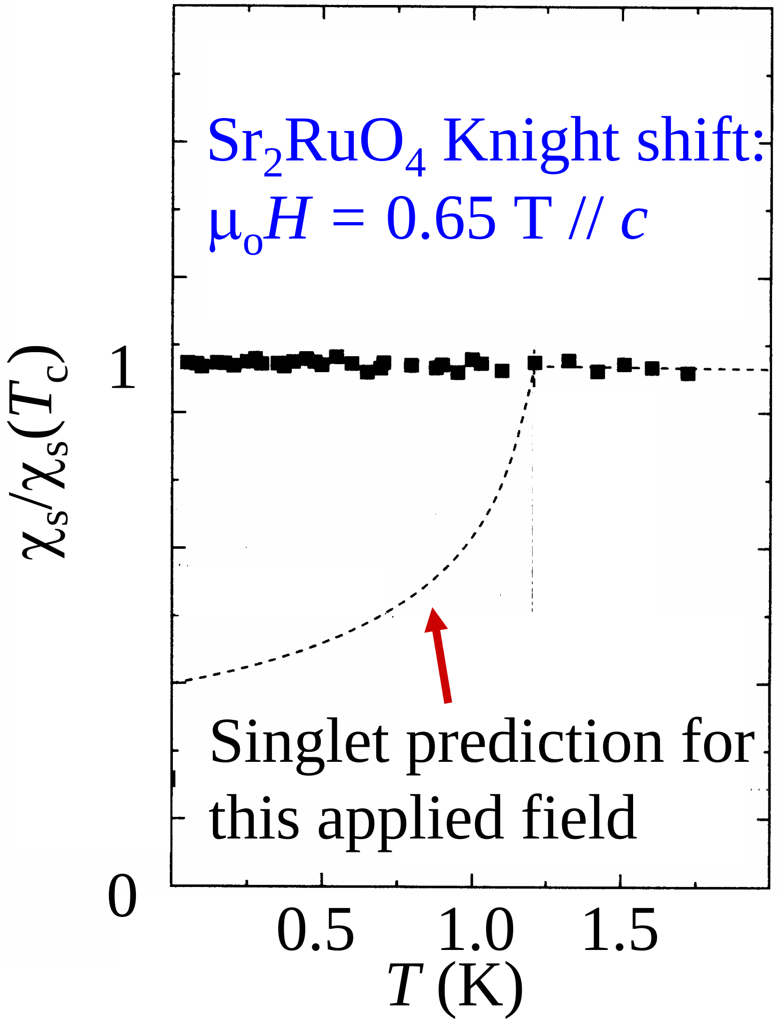
Low field: superconductivity wins and the spin susceptibility χ_s drops to zero as $T \to 0$.

K. Yosida, Phys. Rev. **110**, 769 (1958)

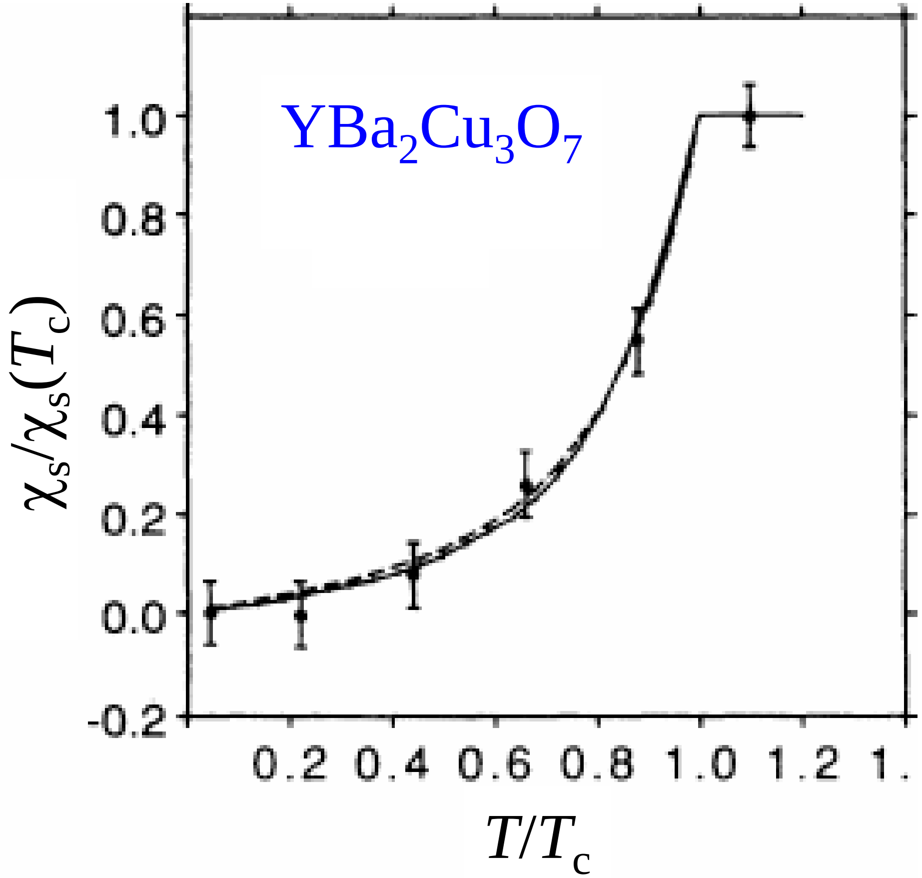
For triplet superconductors this does not have to be the case.



Spin susceptibility by NMR Knight shift



K. Ishida *et al.*, Nature **396** 658 (1998).



S.E. Barrett *et al*., Phys. Rev. B **41**, 6283 (1990).

See also Sr_2RuO_4 'neutron Knight shift', J.A. Duffy *et al.*, Phys. Rev. Lett. **85**, 5412 (2000).

Spin susceptibility and parity measurements are consistent with a p-wave state: if so, which one?

Idea: discriminate by examining time reversal symmetry

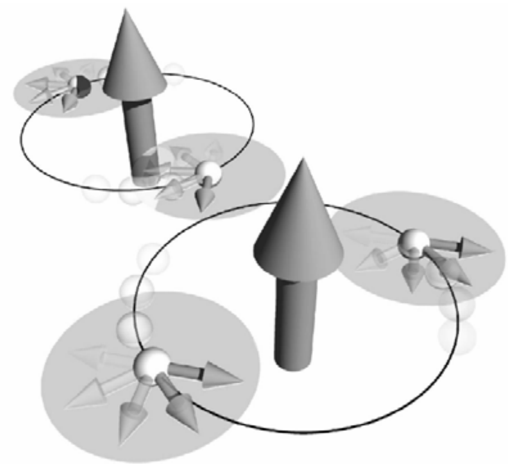
Only one of the pure p states for a lattice-free superconductor breaks time reversal symmetry at T_c.

d-vector

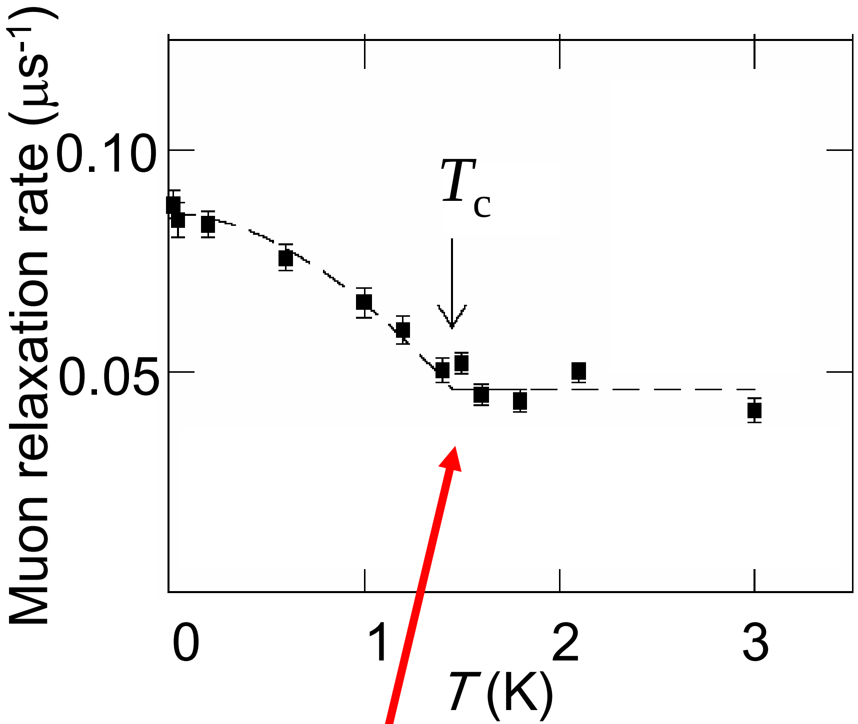
$\mathbf{z}(k_x + ik_y)$

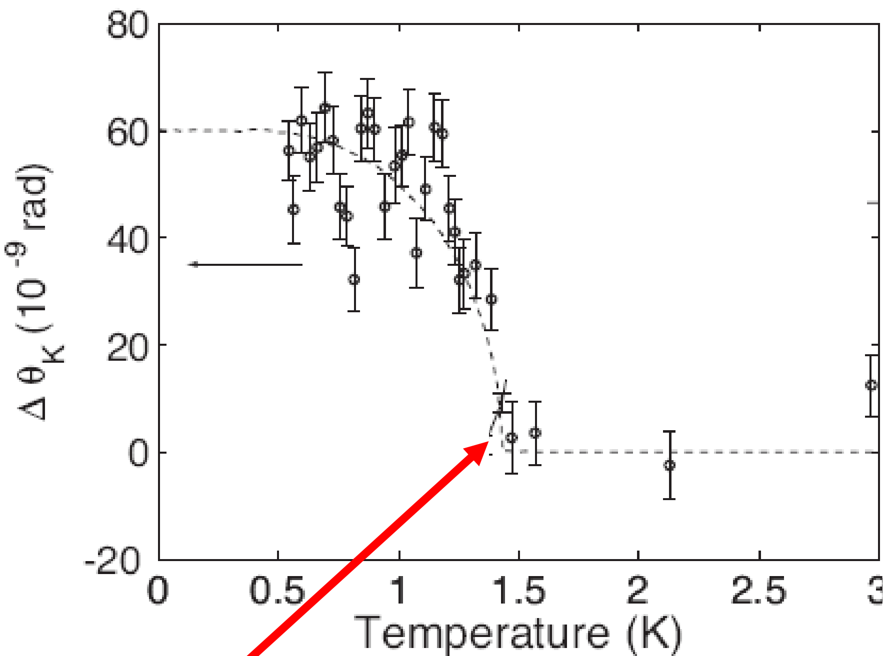
$$\begin{bmatrix} 0 \\ 0 \\ k_x + ik_y \end{bmatrix}$$

TRS-breaking



Experiments: spontaneous muon relaxation and spontaneous Kerr rotation onset at T_c





Weak magnetism associated with superconductivity; tracks T_c.

G.M. Luke *et al.*, Nature **394**, 558 (1998); J. Xia *et al.*, Phys. Rev. Lett. **97**, 167002 (2006).

Also consistent with magnetic field distribution in flux lattice:

P.G. Kealey *et al.*, Phys. Rev. Lett. **84**, 6094 (2000).

Evidence supports triplet pairing, odd parity and time reversal symmetry breaking at T_c

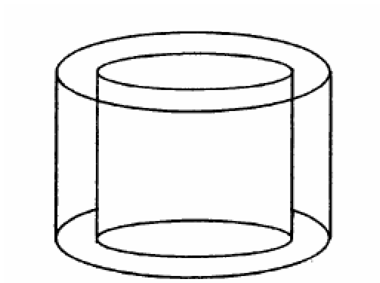
Is Sr_2RuO_4 a simple superconducting analogue of A phase ^{3}He in two dimensions?

d-vector

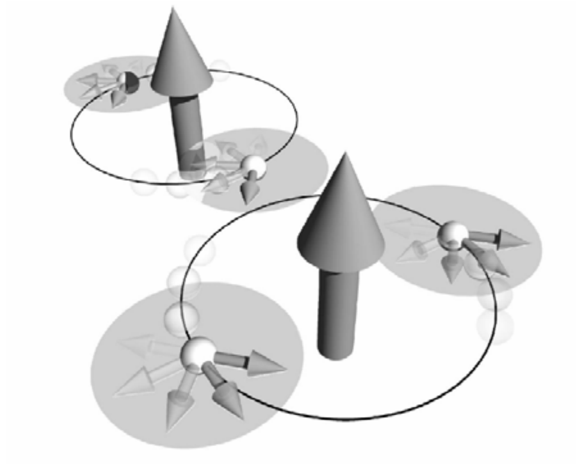
$\mathbf{z}(k_x + \mathrm{i}k_y)$

$$\begin{bmatrix} 0 \\ 0 \\ k_x + ik_y \end{bmatrix}$$

Gap structure

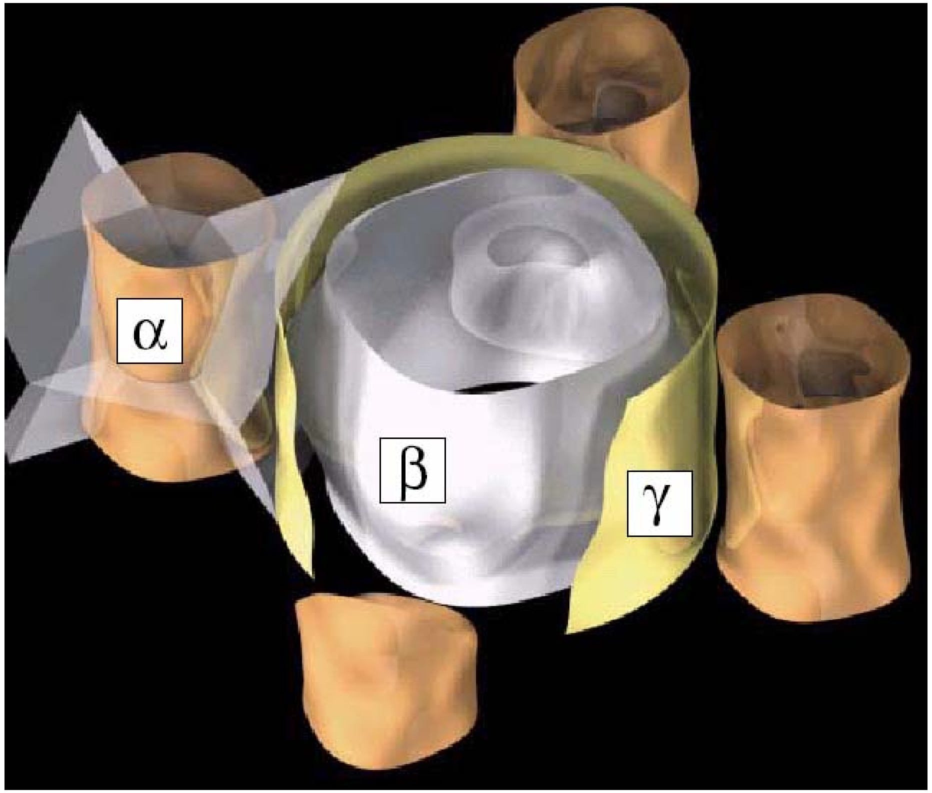


Spin and orbital pair ang. mom.



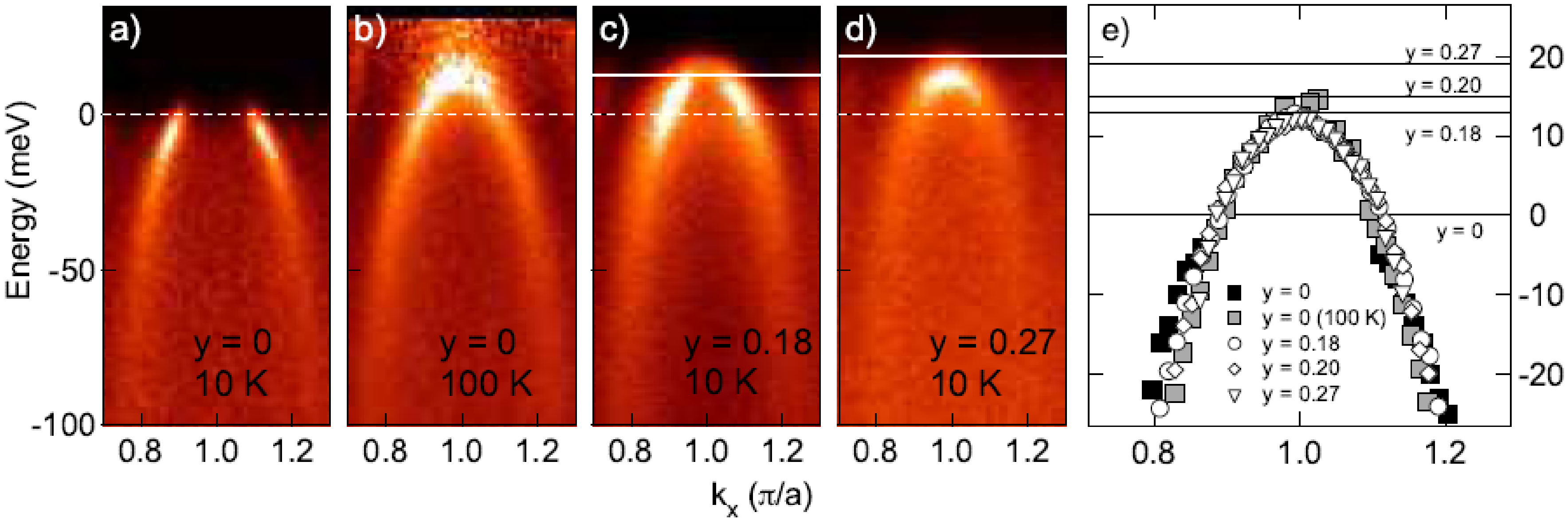
Problem with such a naïve interpretation: actual gap contains line nodes or extremely deep gap minima. See discussion in Mackenzie & Maeno, Rev. Mod. Phys. **75**, 657 (2003).

Future challenge # 1: Are the existing inconsistencies with $\mathbf{d}=\mathbf{z}(k_x + ik_y)$ fundamental or are they mainly due to the presence of a strong periodic potential and multiple bands?



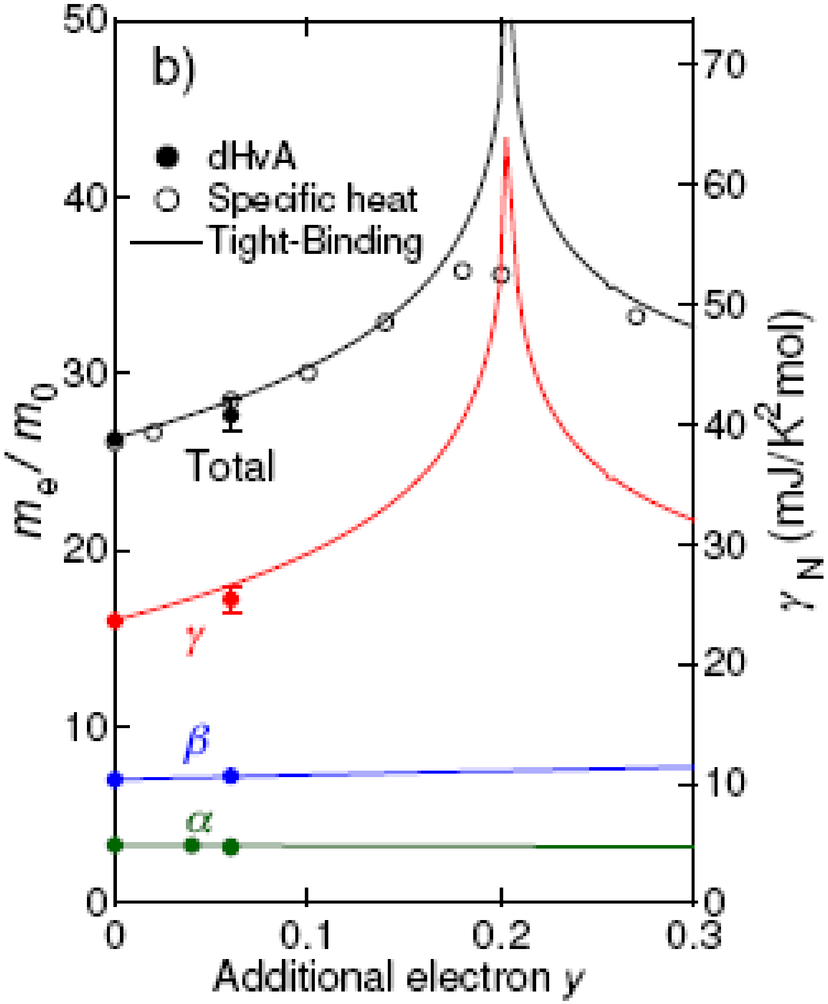
Plug: KITP Miniprogram 'Sr_2RuO_4 and Chiral Superconductivity' December '07.

Future challenge # 2: Understanding the mechanism behind the condensation.



Shifting the Fermi level of $Sr_{2-y}La_yRuO_4$ by electron doping and combining dHvA and ARPES to establish whole bandwidth renormalisation of a factor of 6: LDA + U in a real material!

K.M. Shen, N. Kikugawa, C. Bergemann, L. Balicas, F. Baumberger, W. Meevasana, N.J.C. Ingle, Y. Maeno, Z.X. Shen & A.P. Mackenzie, to appear in Phys. Rev. Lett. (2007).

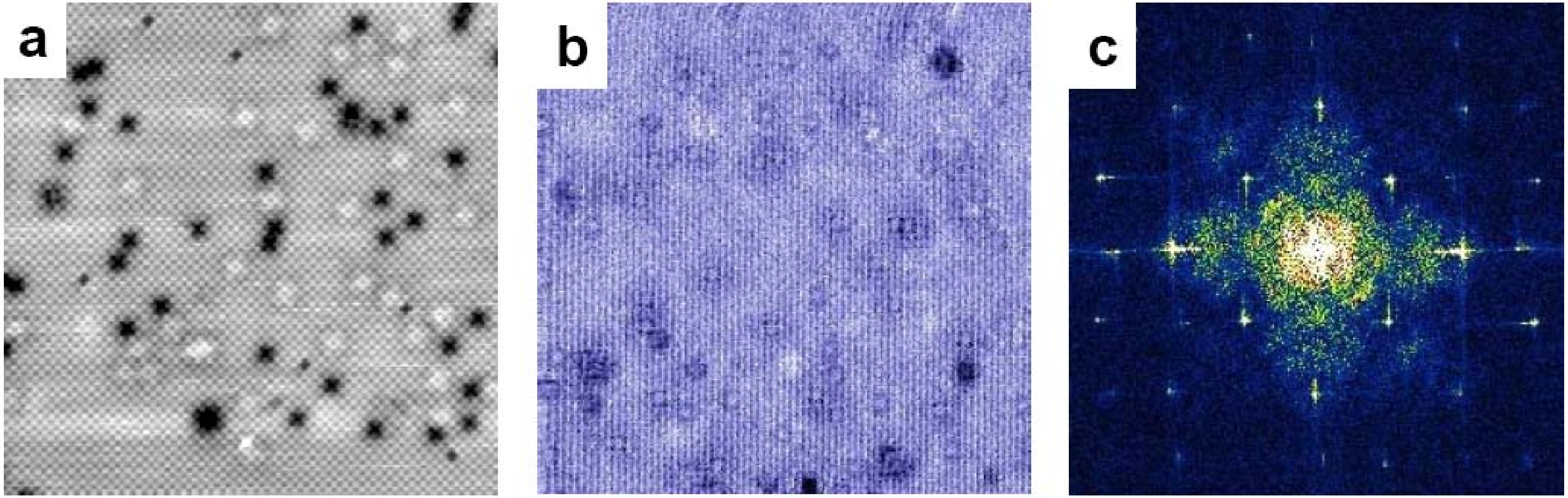


Postulate a tight-binding parameterisation of the renormalised quasiparticle bands and check against thermodynamic measurements.

Aim: aid construction of realistic spin fluctuation theories.

Further goal: Develop quantitative probes of spin-orbit coupling and its variation through the Brillouin zone of Sr_2RuO_4.

Future challenge # 3: Understand how the superconductivity of Sr_2RuO_4 fits into the rich range of ground states being uncovered in clean ruthenates.



dHvA and STM QPI and ARPES: Fermi velocities in $Sr_3Ru_2O_7$ of 10 km/s and below: direct observation of d-shell heavy fermions.

Phase diagram tuning promotes formation of an 'electronic nematic' from this heavy liquid – why, and how does it relate to Sr_2RuO_4 physics?

St Andrews – Cornell – Stanford collaboration on $Sr_3Ru_2O_7$

Conclusions

- Sr_2RuO_4 definitely possesses an unconventional order parameter i.e. (non-s-wave) pairing.

- To observe the superconductivity at all one needs samples of a quality that was previously not thought possible in a three-component oxide.

- There is now good evidence for an odd parity, triplet paired state.

- Significant work remains to fully determine the gap symmetry and resolve some apparent paradoxes in the overall picture painted by the existing experiments.

- Ruthenates will continue to be a playground for correlated electron physics for many years to come.