Title: Muon Spin Rotation/Relaxation Studies of Unconventional Superconductivity

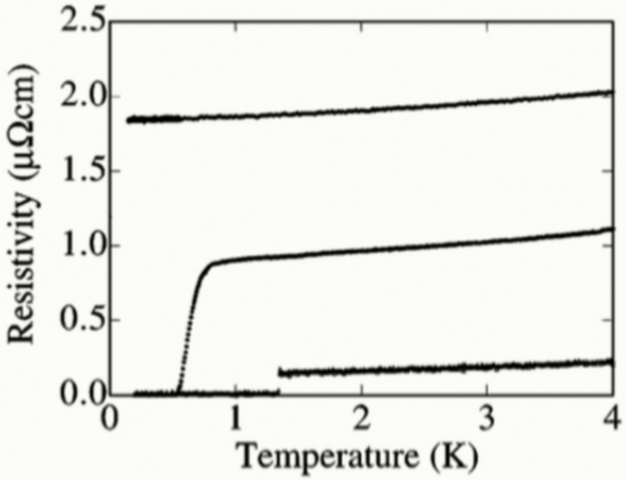
Date: Apr 30, 2015 11:00 AM

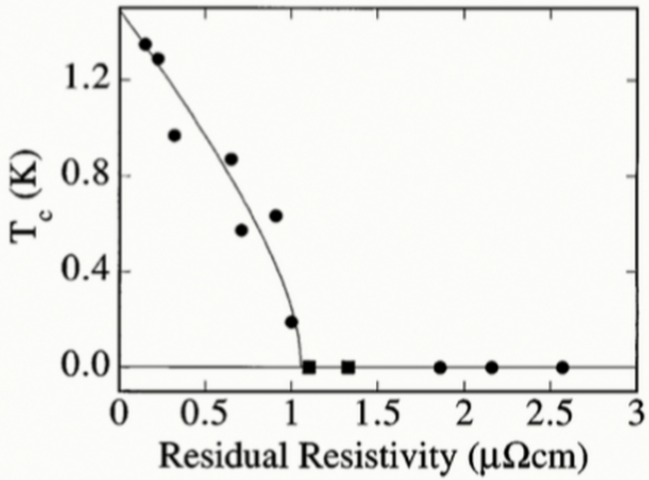
URL: http://pirsa.org/15040158

Abstract: Muon spin rotation/relaxation is a powerful technique for studying unconventional superconductors, whose order parameter doesn't have the same symmetry as its host material's crystal structure. I will describe our work on Sr2RuO4, UPt3, CuxBi2Se3 and other topical systems, some of which exhibit broken time reversal symmetry in their superconducting states.

Superconducting State

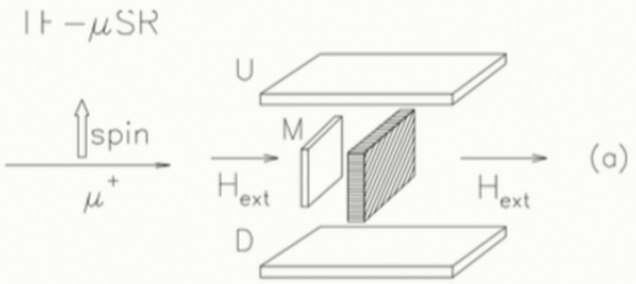
- Dependence of T_c on ρ_0
- Extreme sensitivity to (non)-magnetic impurities

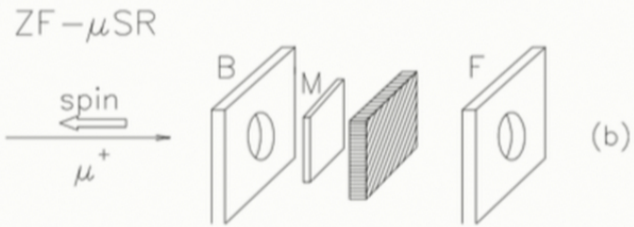


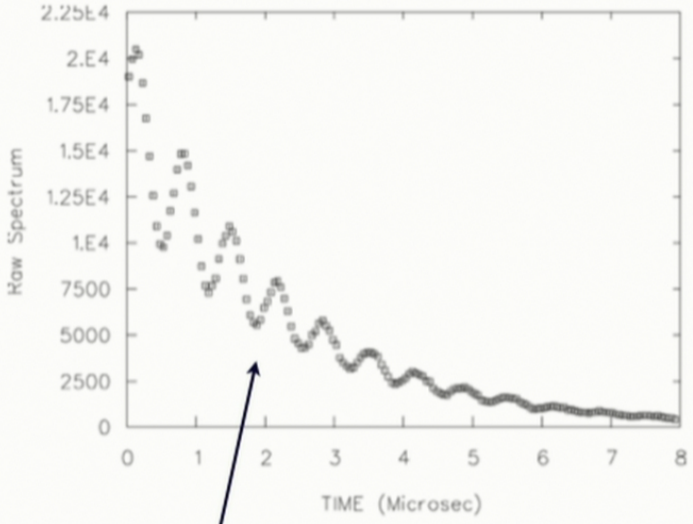


Mackenzie *et al*., Phys. Rev. Lett. **80**, 161 (1998).

Experimental Geometry





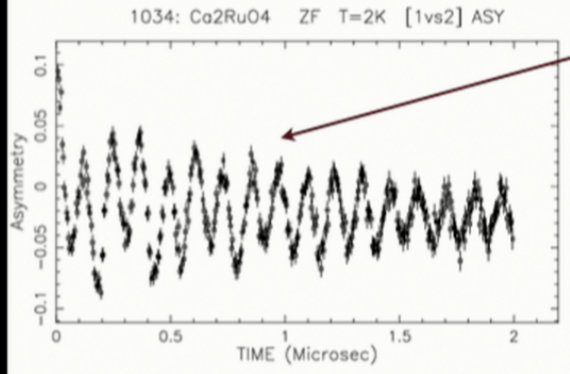


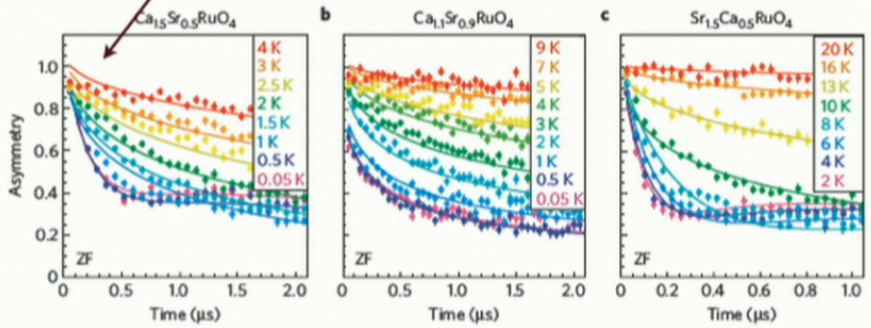
$\tau_\mu = 2.2\mu s$

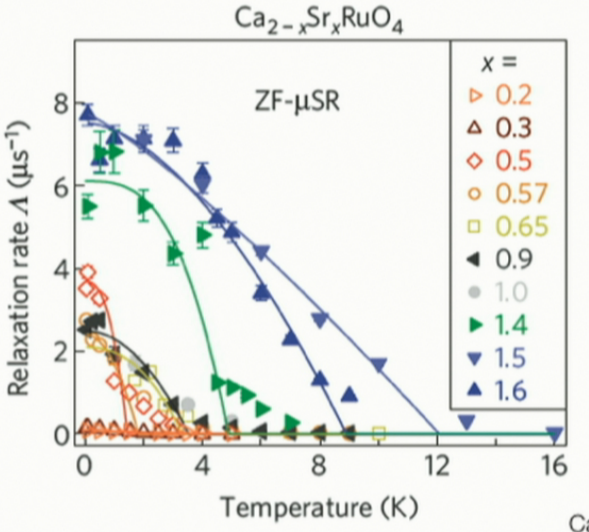
Zero Field ZF-μSR

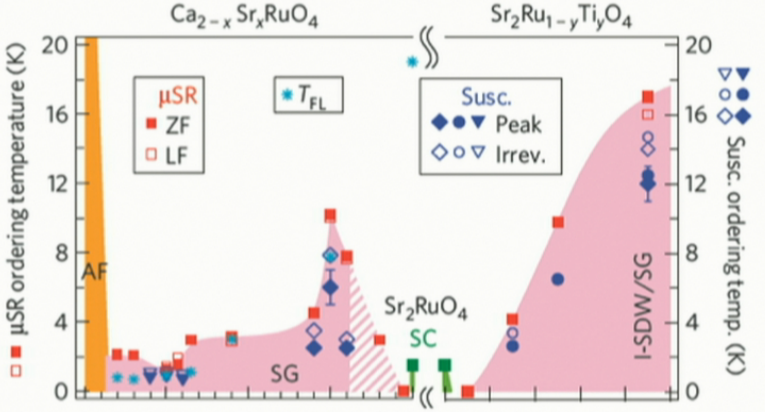
Ordered state, v∝ Moment $\propto\sqrt{I_B}$

Random frozen spins give characteristic relaxation.





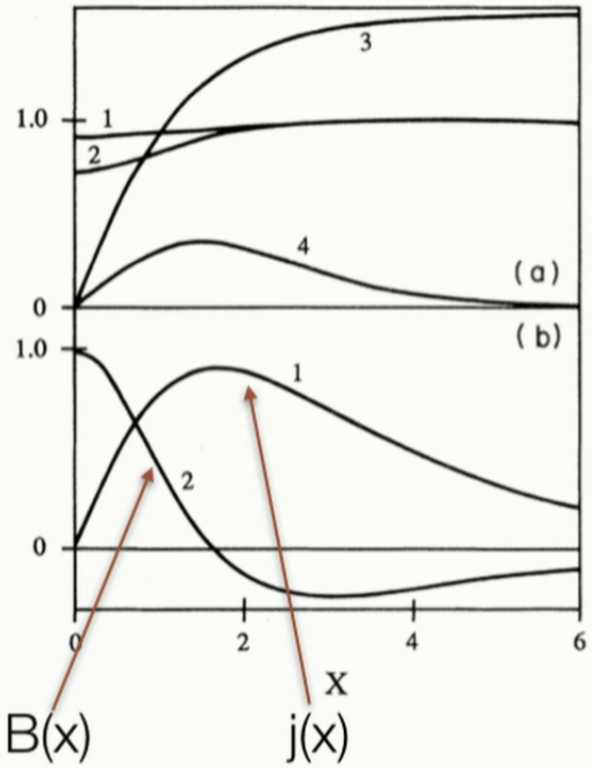




Carlo *et al.*, Nat. Mat. **11**, 323 (2012).

Broken Time Reversal Symmetry

- Surfaces, domain walls, defects generate physical supercurrents and magnetic fields.
  - eg. k_x+ik_y/k_x-ik_y



Sigrist & Ueda, R.M.P. **63**, 239 (1991).

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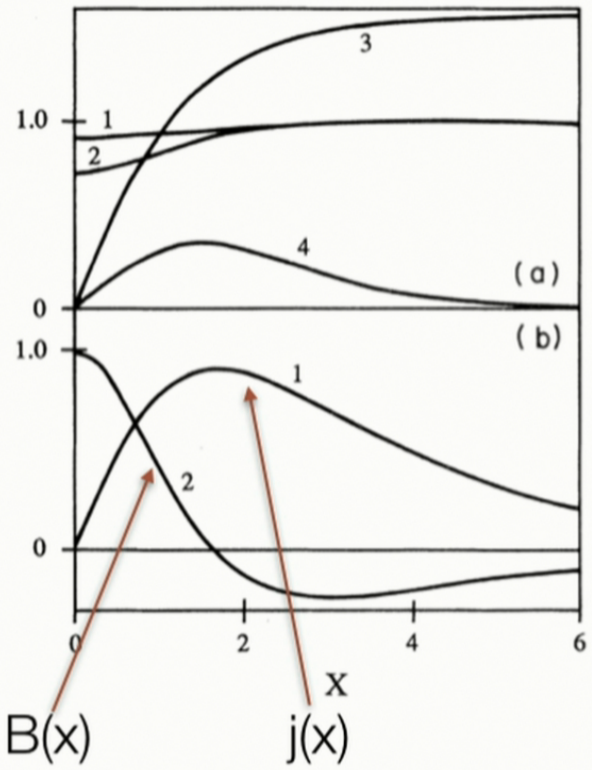
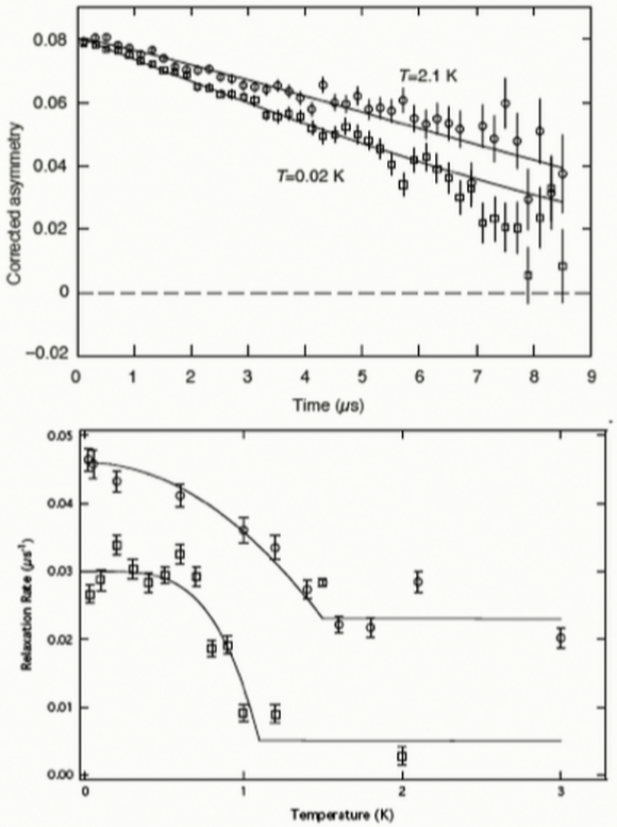
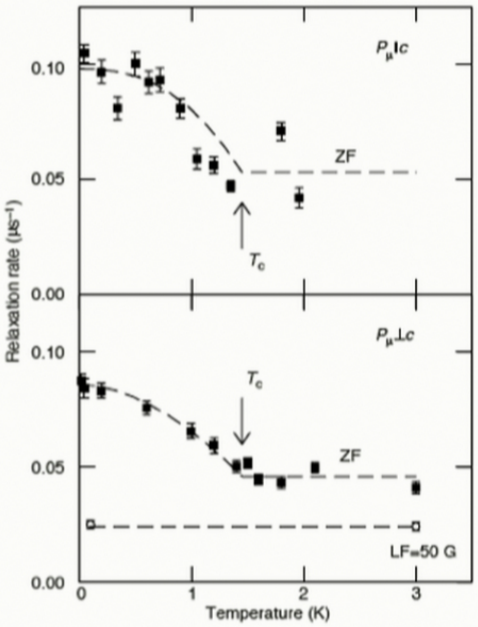


Sigrist & Ueda, R.M.P. **63**, 239 (1991).

Sr_2RuO_4: ZF-μSR



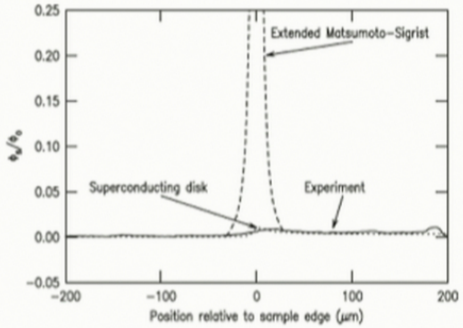
Luke and Sonier, Physics in Canada **67**, 93 (2011).



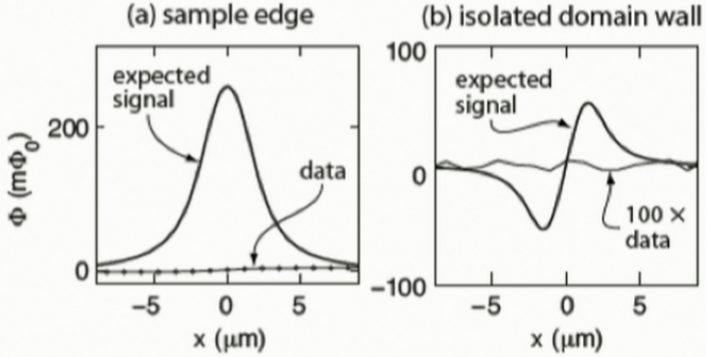
Luke *et al.*, Nature **394**, 156 (1998).

Surface Probes

- No supercurrents detected at surfaces of Sr_2RuO_4.

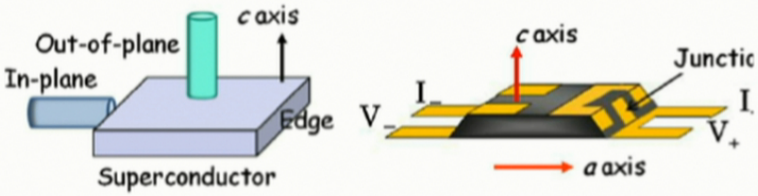


Kirtley *et al.*, Phys. Rev. B **76**, 014526 (2007).

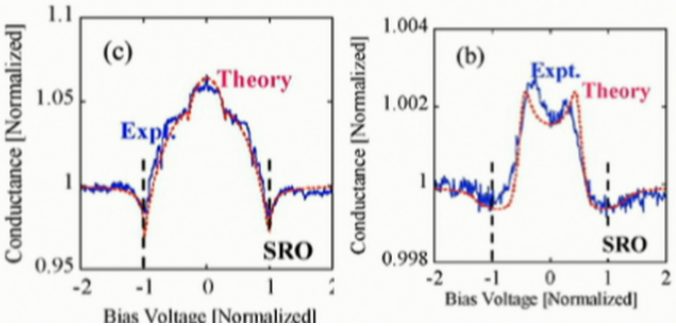


Hicks *et al.*, Phys. Rev. B **81**, 214501 (2010).

- Tunneling detects edge states

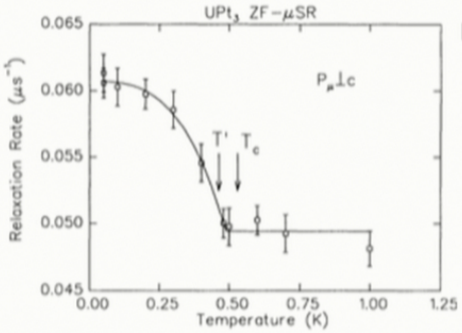


Kashiwaya *et al.*, Phys. Rev. Lett. **107**, 077003 (2011).

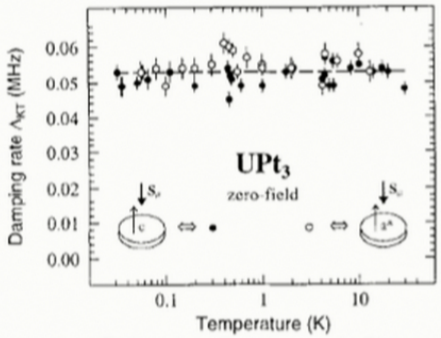


UPt_3

- ZF-μSR
  - spontaneous local field below T_c-.
  - Not seen in Europe.

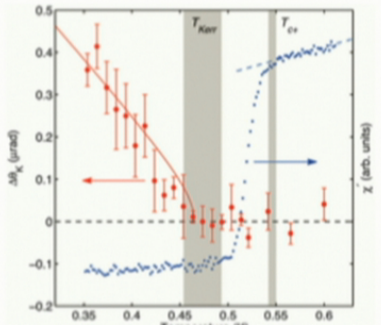


Luke *et al.*, Phys. Rev. Lett. **71**, 1466 (1993).



Dalmas de Reotier *et al.*, Phys. Lett. A **205**, 239 (1995).

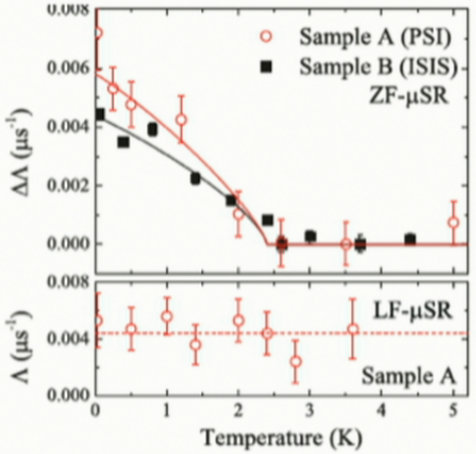
- Kerr rotation
  - below T_c-.

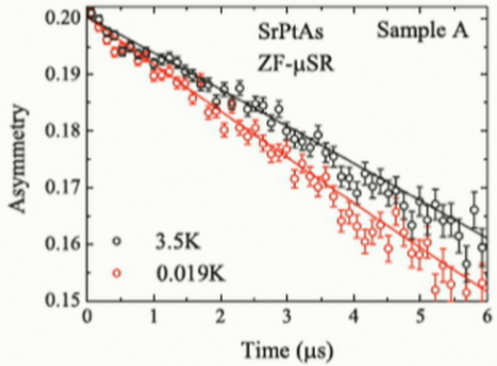


Schemm *et al.*, Science **345**, 190 (2014).

Non-Centrosymmetric Superconductors

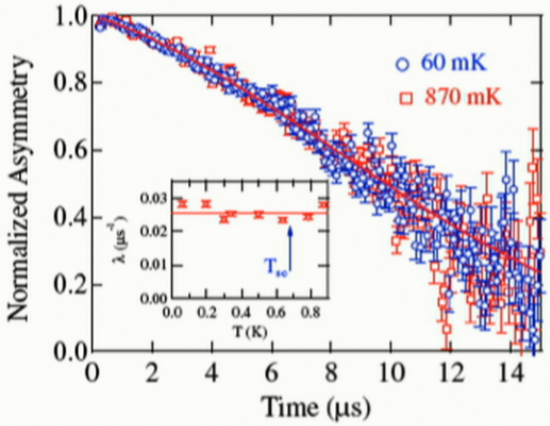
- SrPtAs





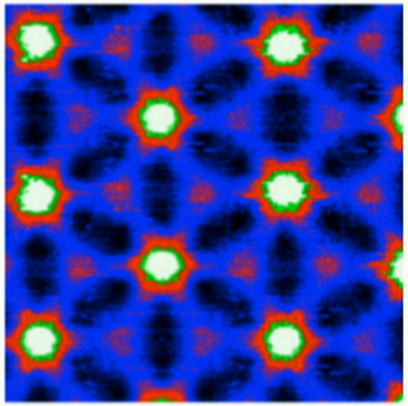
Biswas *et al.*, Phys. Rev. B **87**, 180503R (2013).

- $LaPt_3Si$

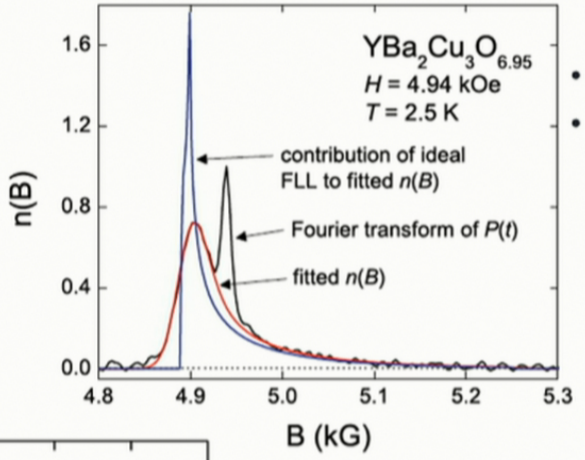


Kawasaki *et al.*, JPSJ **82**, 084713 (2013).

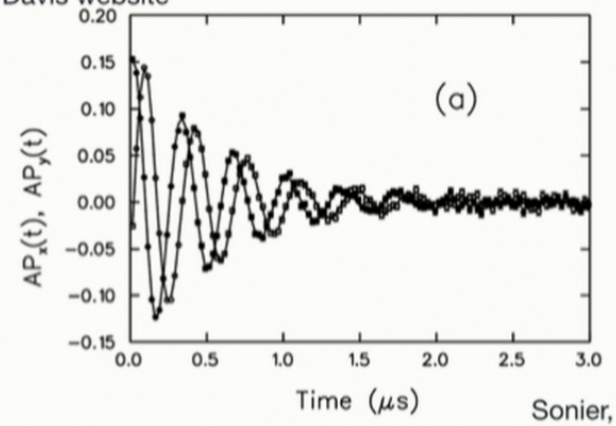
Vortex State



J.C. Davis website



- 2 lengthscales: λ, ξ
- Disorder: broadening of line shape features (convolute with Gaussian).



Ceramics - Gaussian

$$\sigma \propto \sqrt{<\Delta H^2>} \propto \frac{1}{\lambda^2}$$

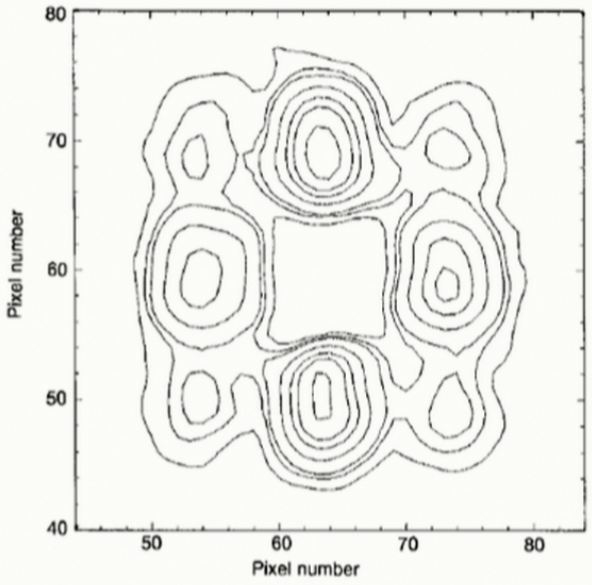
$$\frac{1}{\lambda^2} = \frac{4\pi n_s e^2}{m^* c^2} \times \frac{1}{(1+\xi/l)}$$

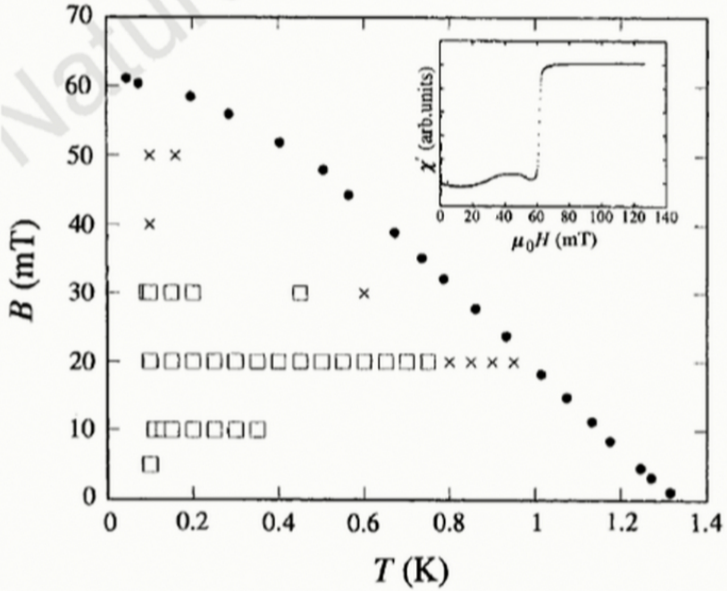
in the "clean limit" $\xi \ll l$

$$\sigma \propto \frac{1}{\lambda^2} \propto \frac{n_s}{m^*}$$

Sonier, Rep. Prog. Phys. **70**, 1717 (2007).

Sr_2RuO_4: Square Vortex Lattice - SANS

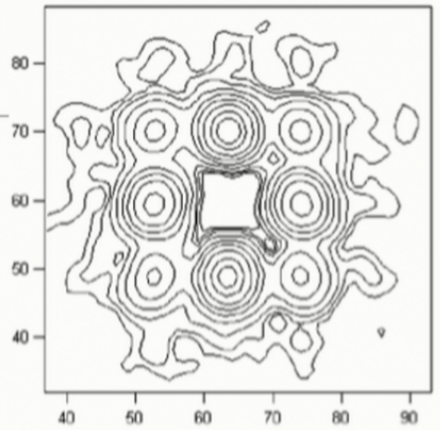


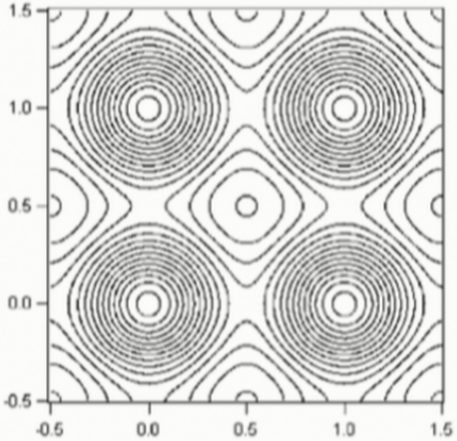


Riseman et al., Nature **396**, 242 (1998).

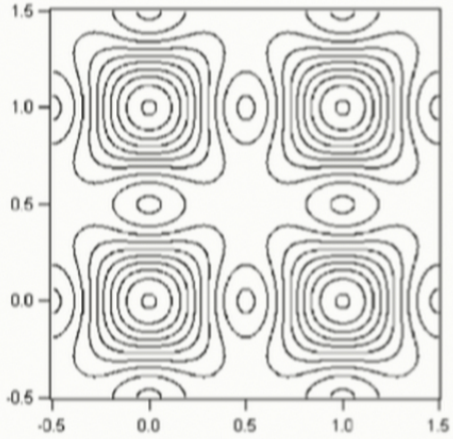
Vortex Lattice - Agterberg

- G.L. Theory for a 2-component order parameter with B//c.
- Detailed comparison with small angle neutron scattering favours Agterberg model.

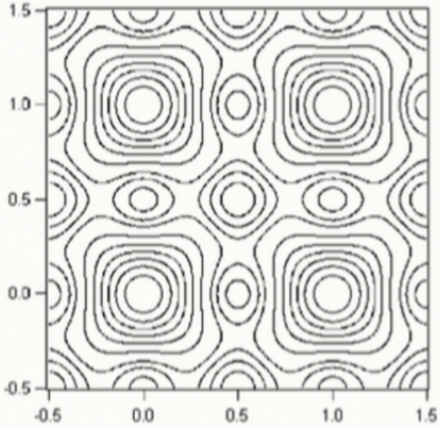




1Comp. G.L.



Agterberg v=.2

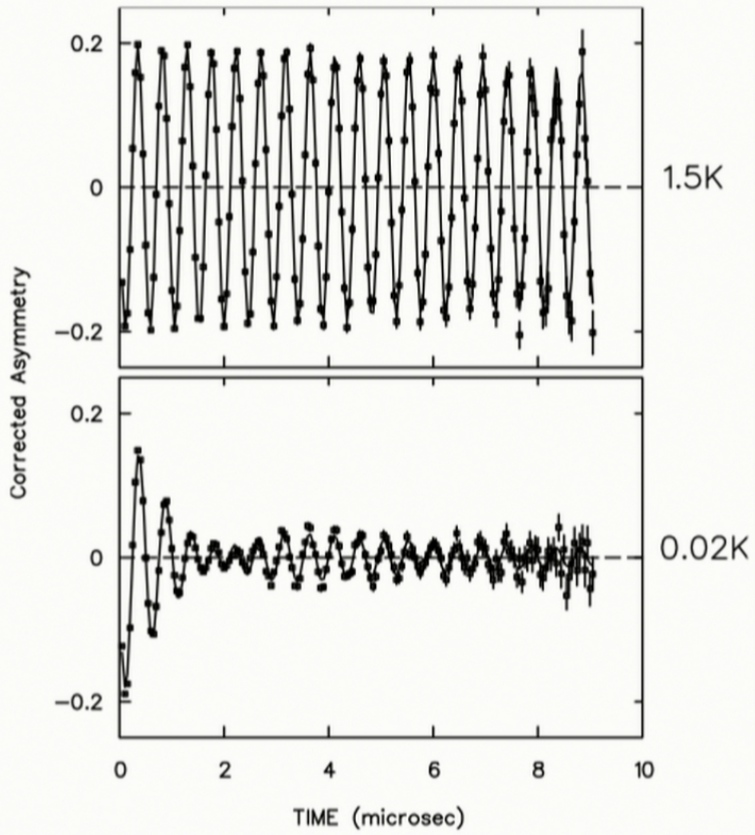


Observed

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

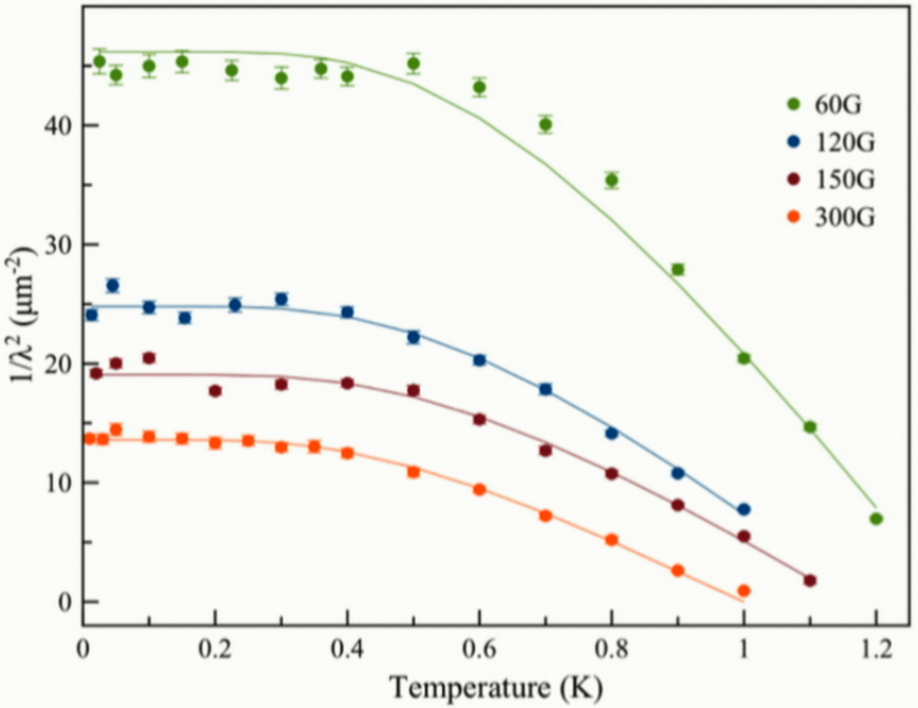
Sr_2RuO_4 TF-μSR Analysis

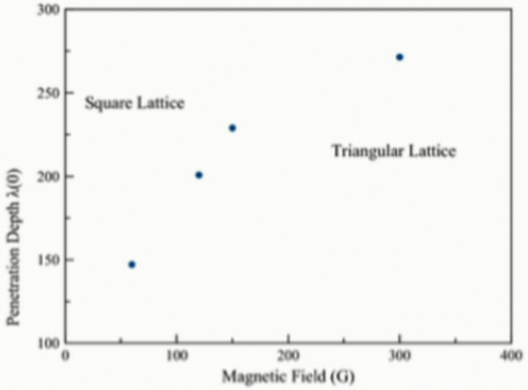
- Square lattice data fit to microscopic Agterberg theory.
- Triangular lattice fit to Ginzburg-Landau model.
- Obtain κ for each field from global fit, then extract λ(T,H).



Superfluid Density

- Fit to weak coupled BCS.

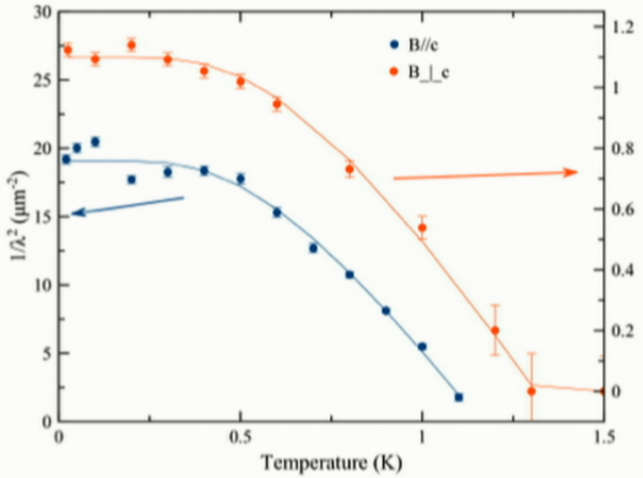


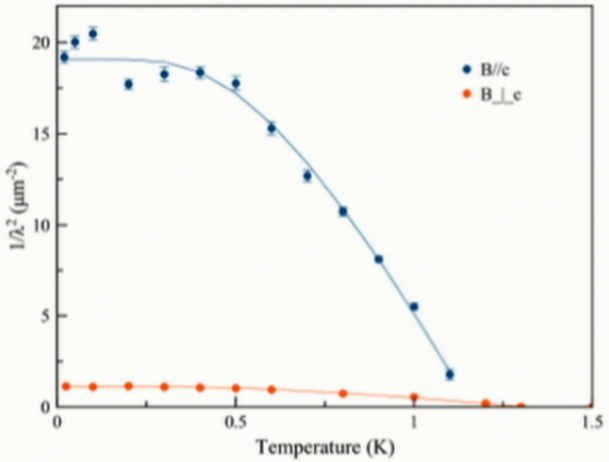


- Neutrons give 194nm at 20mT
- all bands give 100nm
- γ alone gives 171nm.

c-axis

- $\lambda_c(0)$=4000nm.
- No evidence for nodes.





$1/\lambda^2=1/\lambda_c\lambda_{ab}$

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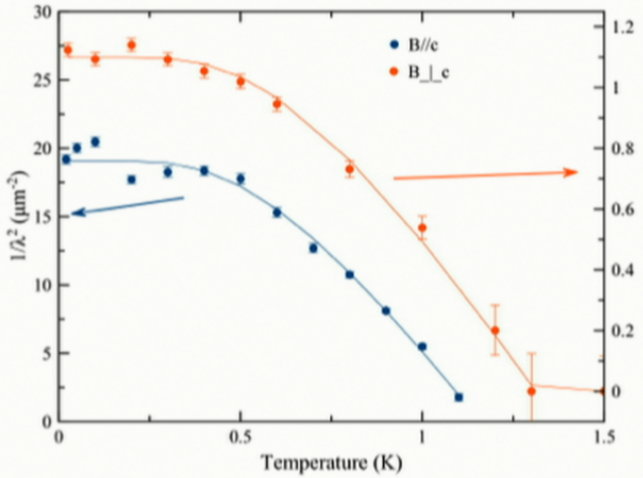

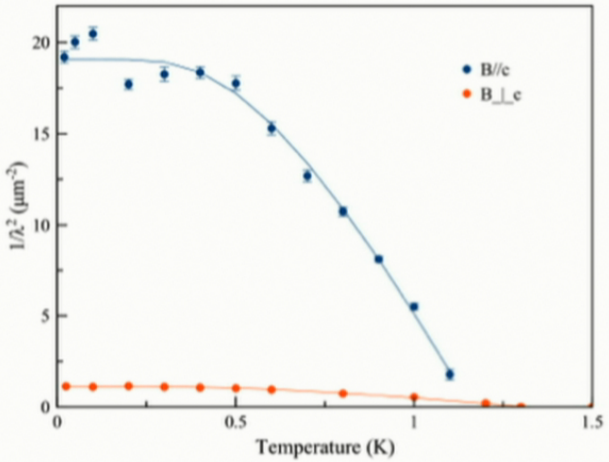

$1/\lambda^2=1/\lambda_c\lambda_{ab}$

Conclusions

- Broken time reversal in Sr_2RuO_4 below T_c in Meissner state.
- Penetration depth temperature dependence: gapless.
- Broken time reversal observed in a small but increasing number of superconductors.