# μSR Evidence for Spontaeous Magnetic Fields in Superconducting $Sr_2RuO_4$

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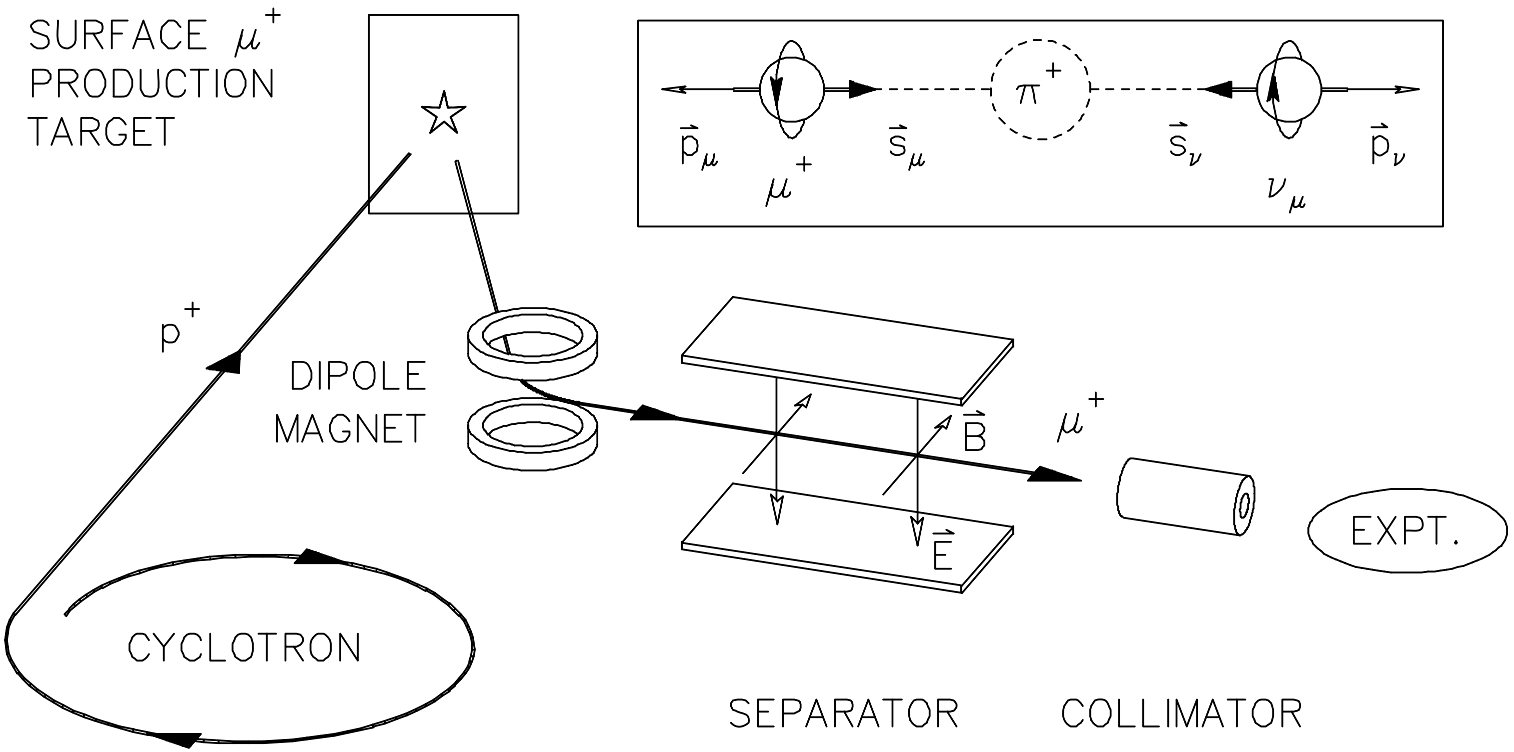
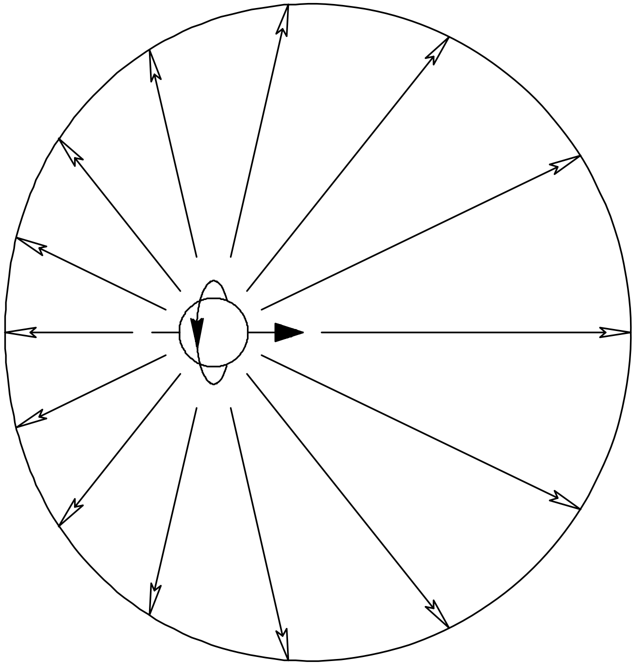
# Muon Production



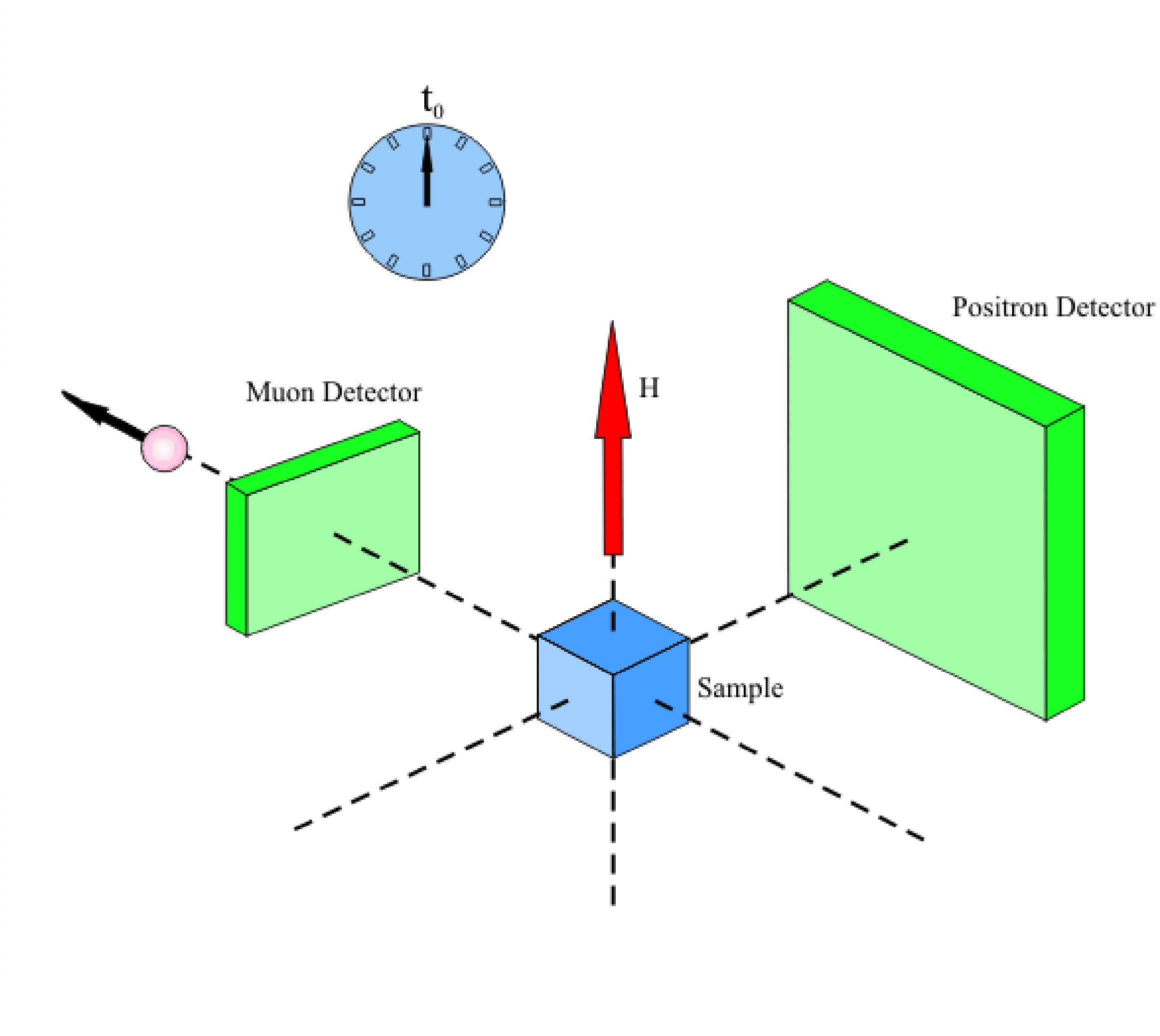
# Muon Polarization

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (26ns)
  - 100% polarization

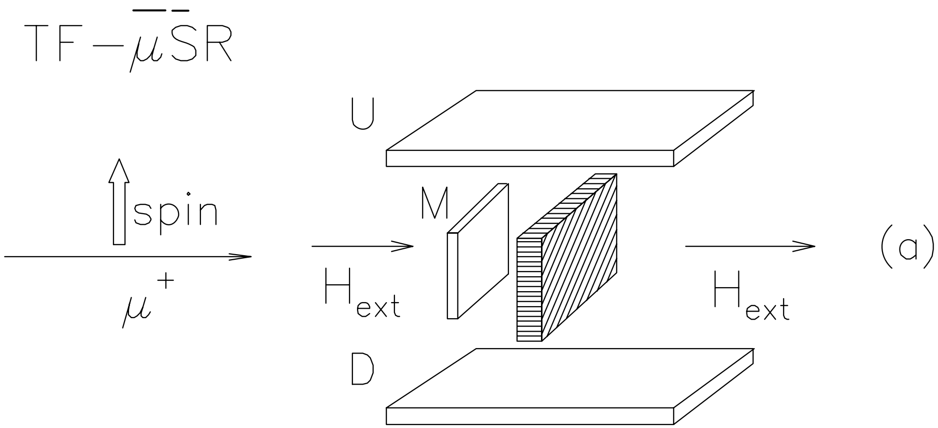
- $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$ (2.2μs)
  - <a> = 1/3

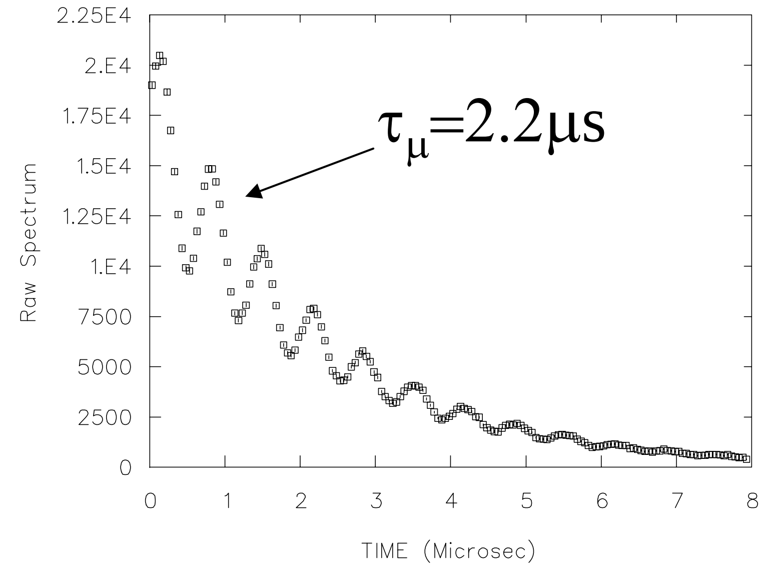


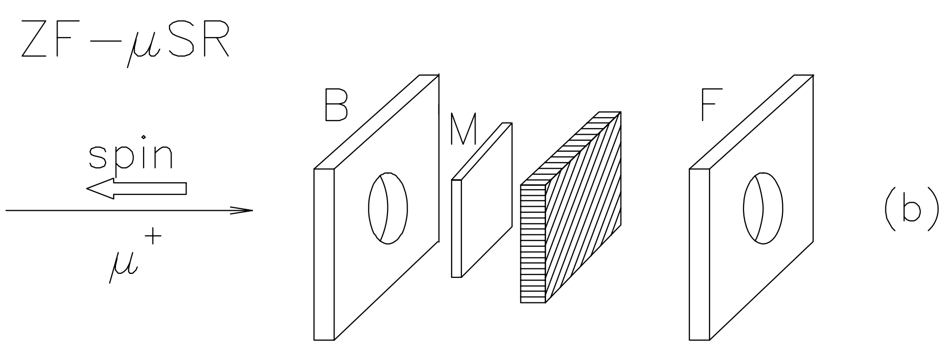
# μSR Experiment

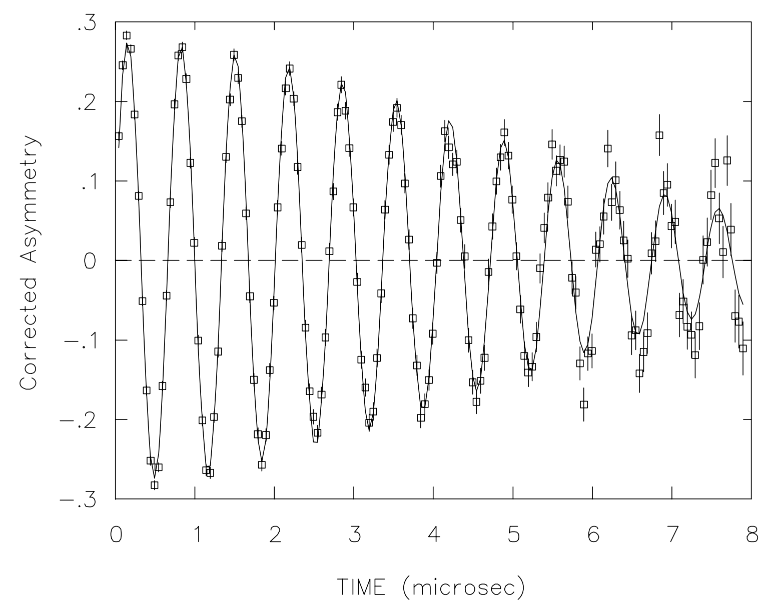


# Experimental Geometry



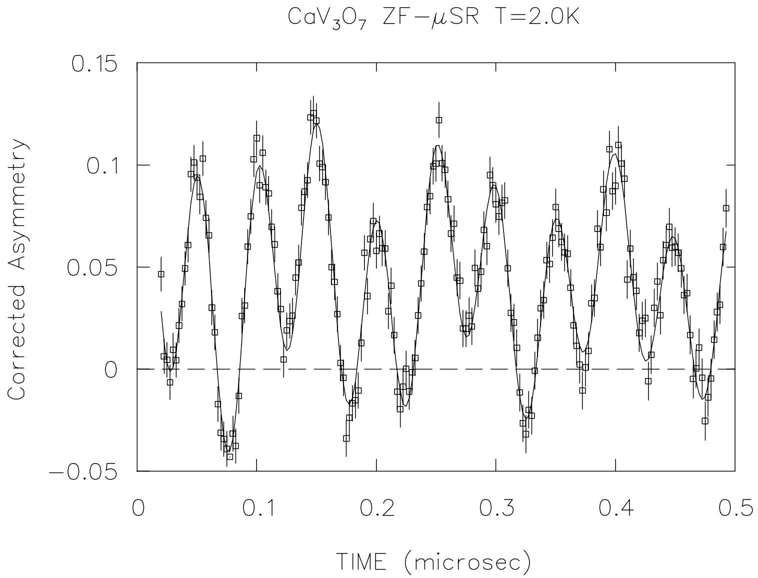



# ZF-μSR

**Ordered Systems**

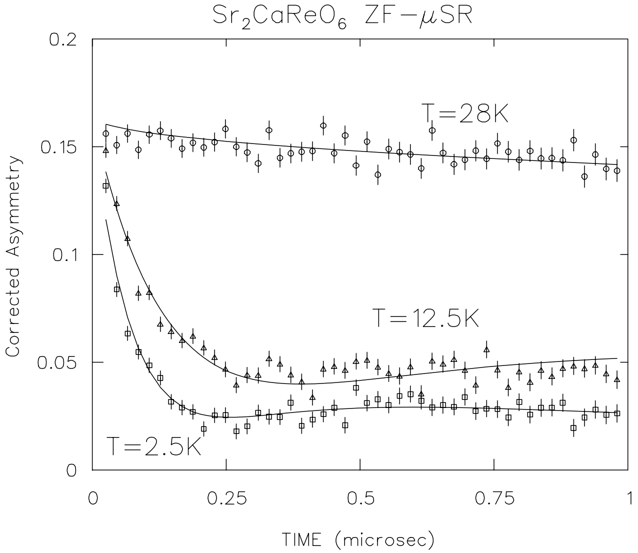
- Order Parameter

$$\omega_\mu = \gamma_\mu B_{loc}$$

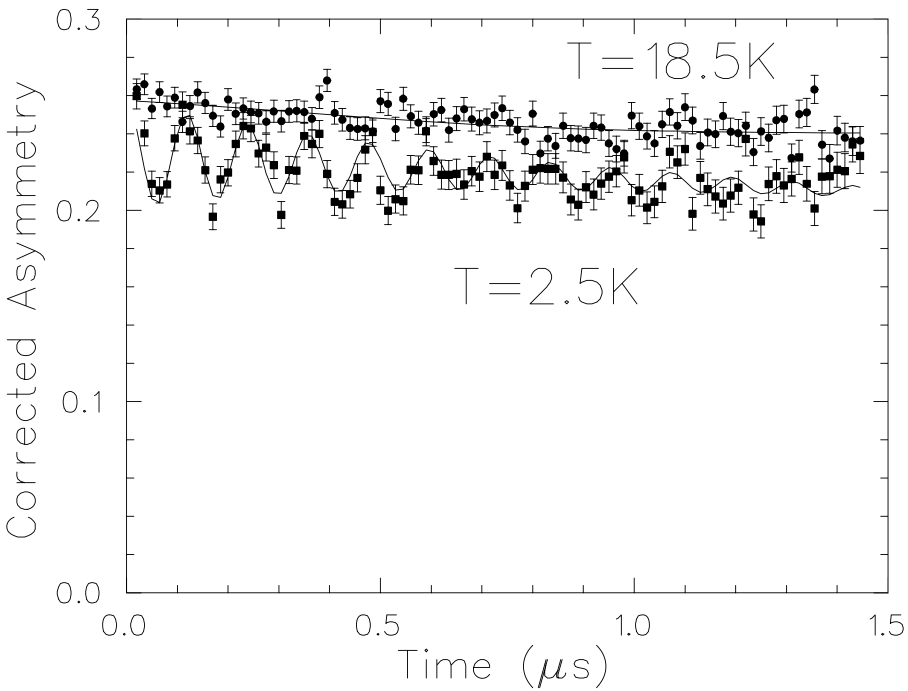


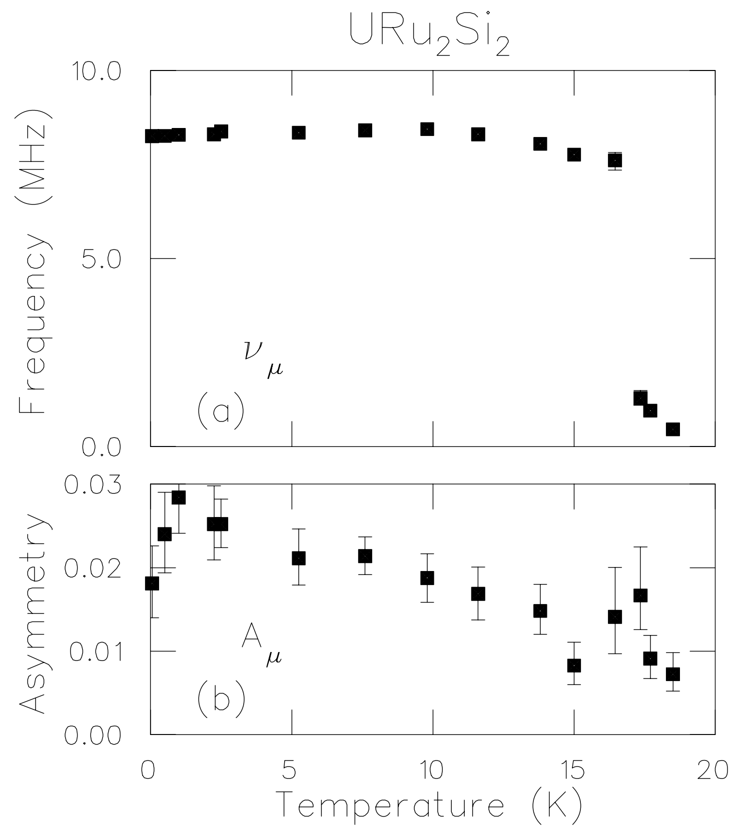

**Random spin systems**

- *eg.* spin glasses
- Real space probe
  - sensitive to local internal field.



# μSR - Volume Sensitive Probe



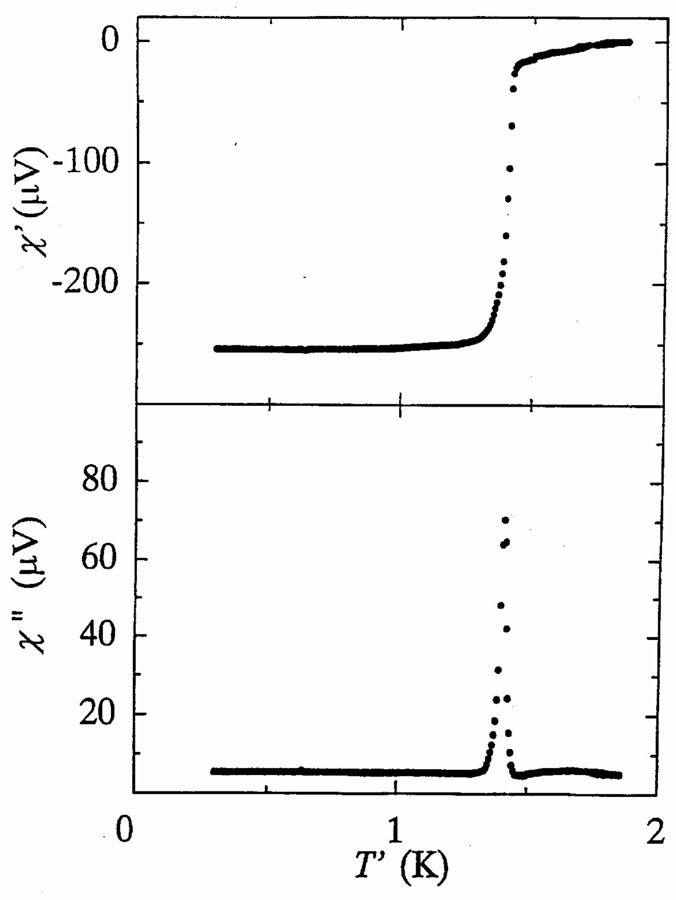




- **Not** a surface sensitive (usually) probe.

- Distinguish between sparse large moments and dense small moments.

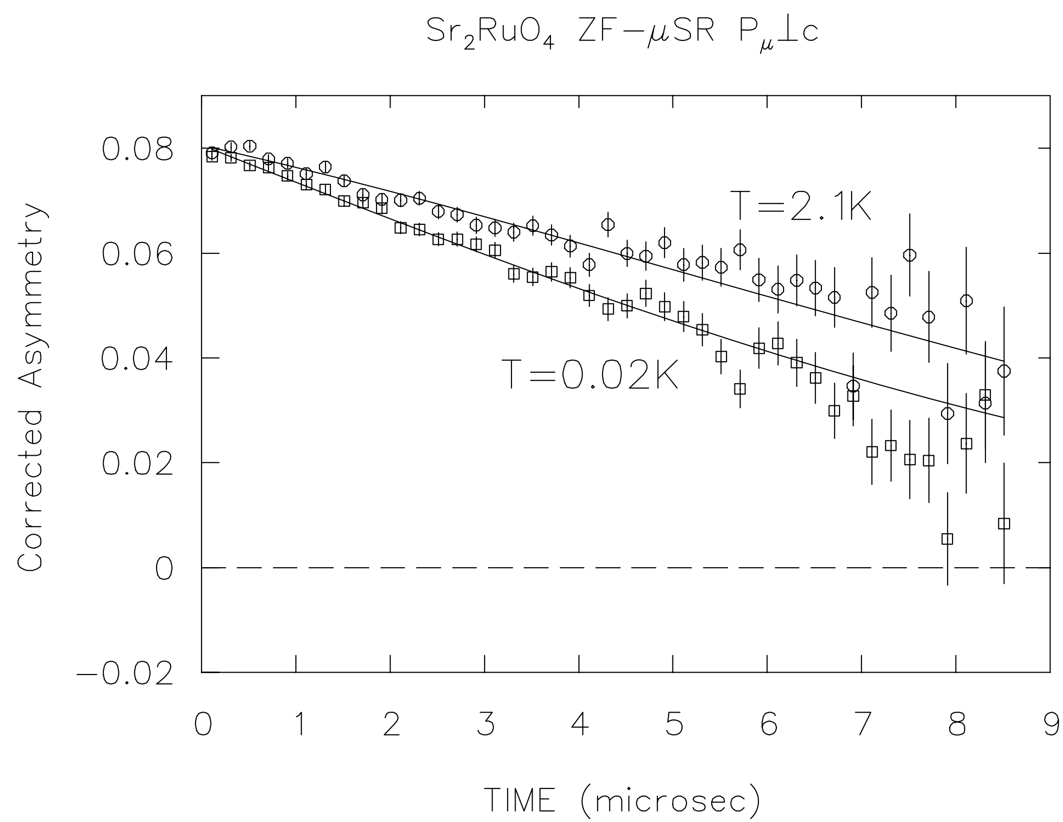
# μSR Measurement

- Samples grown by TSFZ (Maeno).
- $T_c$=1.45K
  - $P_\mu$//c, //a
- $T_c$=1.1K
  - $P_\mu$//c

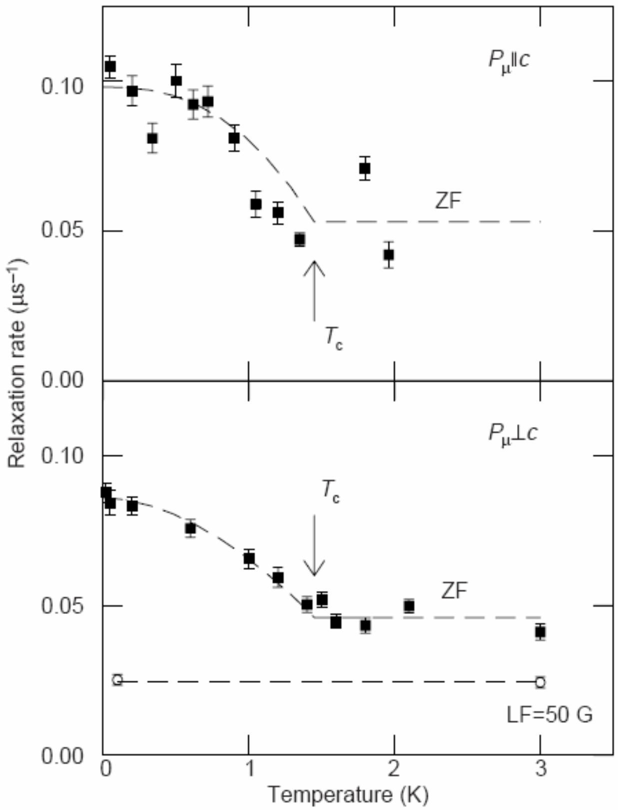


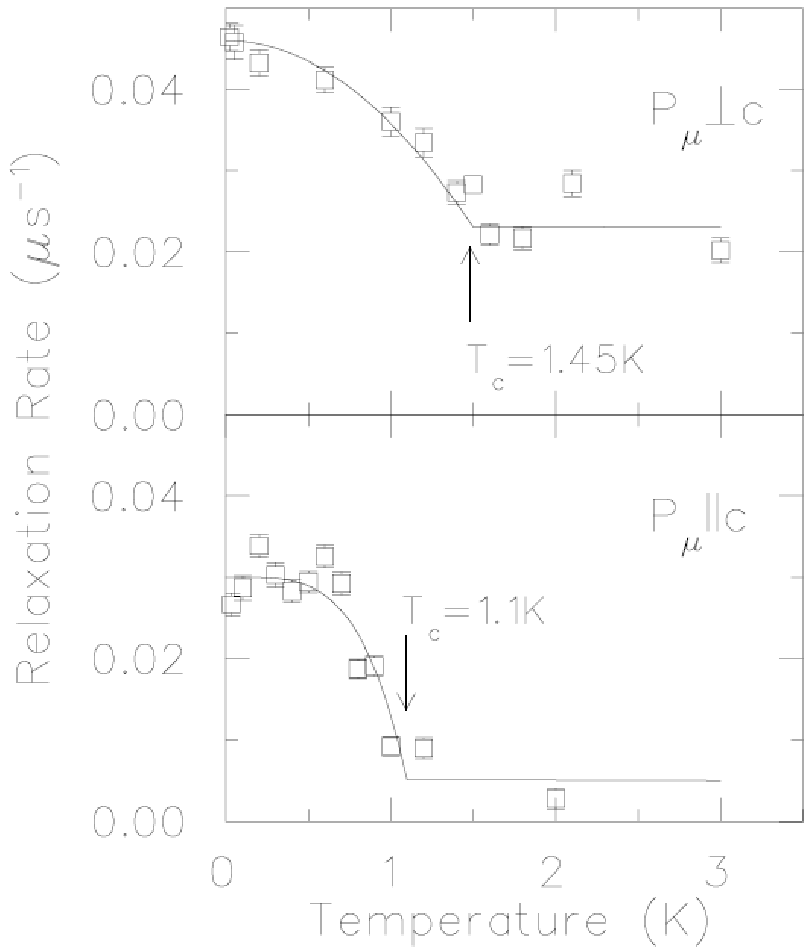
# ZF-$\mu$SR

- Broken TRS$\rightarrow$ spontaneous field: cf. Anyons
  - Spin moment: hyperfine field
  - Spin/orbital moment: supercurrents around inhomogeneity in $\Delta$: impurities, surfaces, domain walls, muon?



# Broken Time Reversal Symmetry




- Spontaneous field seen below $T_c$, for $P_m$//c, //a.
- $B_{loc}$~1G.

Luke et al., Nature **394**, 558 (1998).

# Symmetry of S.C. State

$Sr_2RuO_4$: tetragonal $D_{4h}$

Pair wavefunction: $\psi(\mathbf{k})$ even parity, $\mathbf{d}(\mathbf{k})$ odd parity

| $\Gamma$ | $\psi(\mathbf{k})$ | $\Gamma$ | $\mathbf{d}(\mathbf{k})$ |
|---|---|---|---|
| $A_{1g}$ | 1 | $A_{1u}$ | $\mathbf{x}k_x+\mathbf{y}k_y$ |
| $A_{2g}$ | $k_xk_y(k_x^2-k_y^2)$ | $A_{2u}$ | $\mathbf{x}k_y-\mathbf{y}k_x$ |
| $B_{1g}$ | $k_x^2-k_y^2$ | $B_{1u}$ | $\mathbf{x}k_x-\mathbf{y}k_y$ |
| $B_{2g}$ | $k_xk_y$ | $B_{2u}$ | $\mathbf{x}k_y+\mathbf{y}k_x$ |
| $E_g$ | ------- | $E_u$ | $\{\mathbf{z}k_x,\mathbf{z}k_y\}$ |

Sigrist & Ueda, RMP.

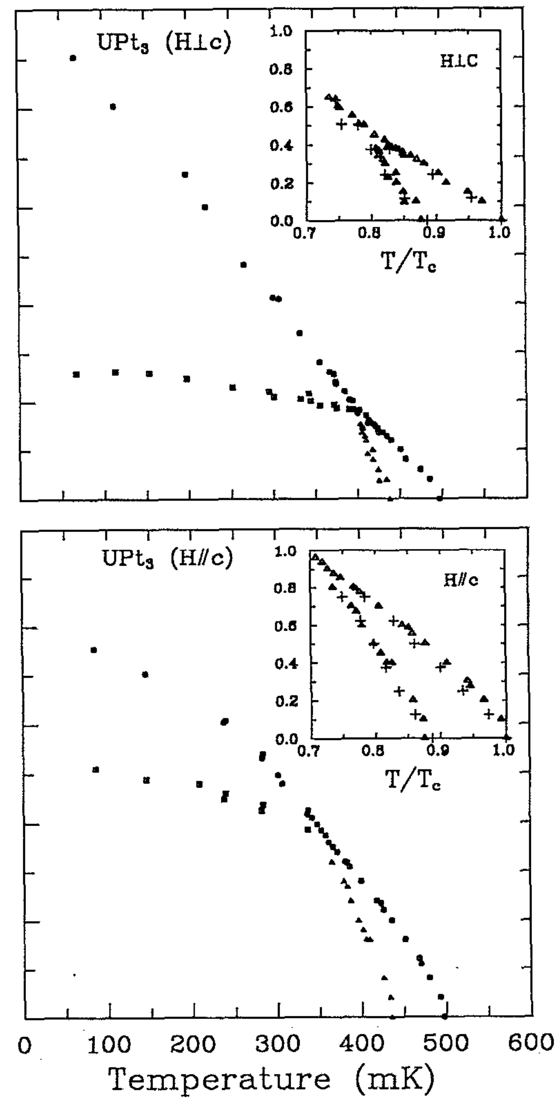
$E_u$ $\mathbf{d}(\mathbf{k}) = \mathbf{z}(k_x \pm k_y)$ nodes

$\mathbf{d}(\mathbf{k}) = \mathbf{z}k_x;\ \mathbf{z}k_y$ nodes

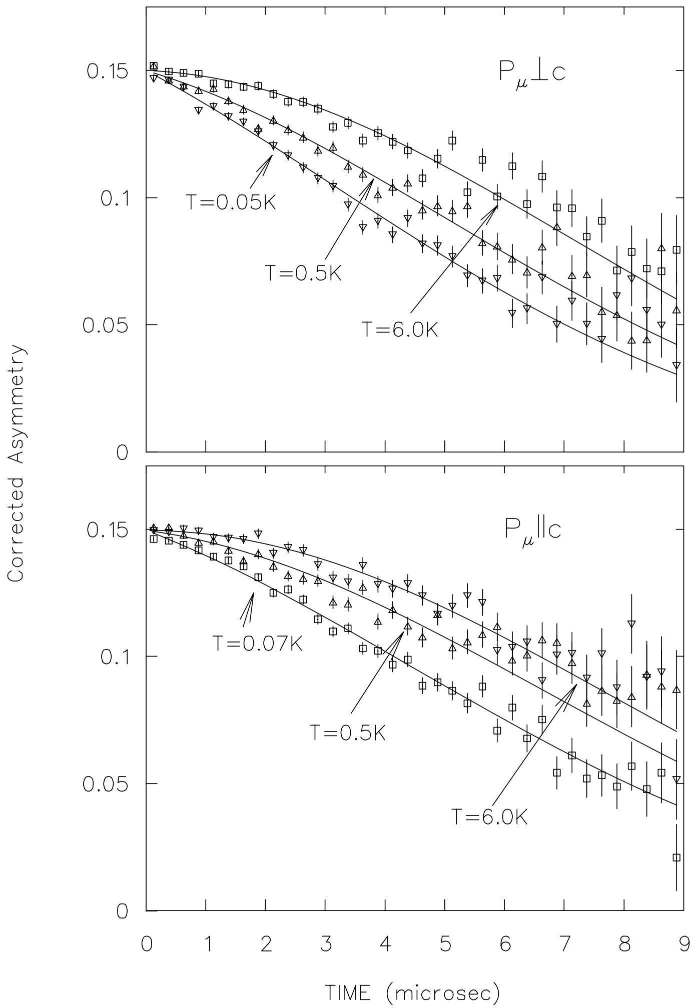
$\mathbf{d}(\mathbf{k}) = \mathbf{z}(k_x \pm ik_y)$ nodeless; Only broken T state, otherwise, need complex combination of states from different reps: expect multiple transitions

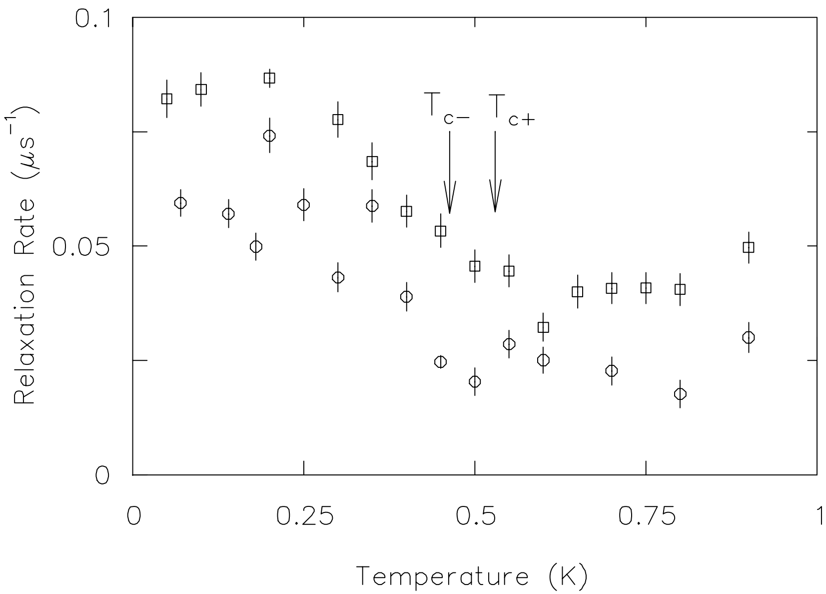
# Unconventional Superconductors

- Multiple superconducting phases. cf. $UPt_3$
    - requires extra degrees of freedom in order parameter.
- Non-s-wave pairing. cf. cuprates (d-wave).



# $UPt_3$ ZF-$\mu$SR



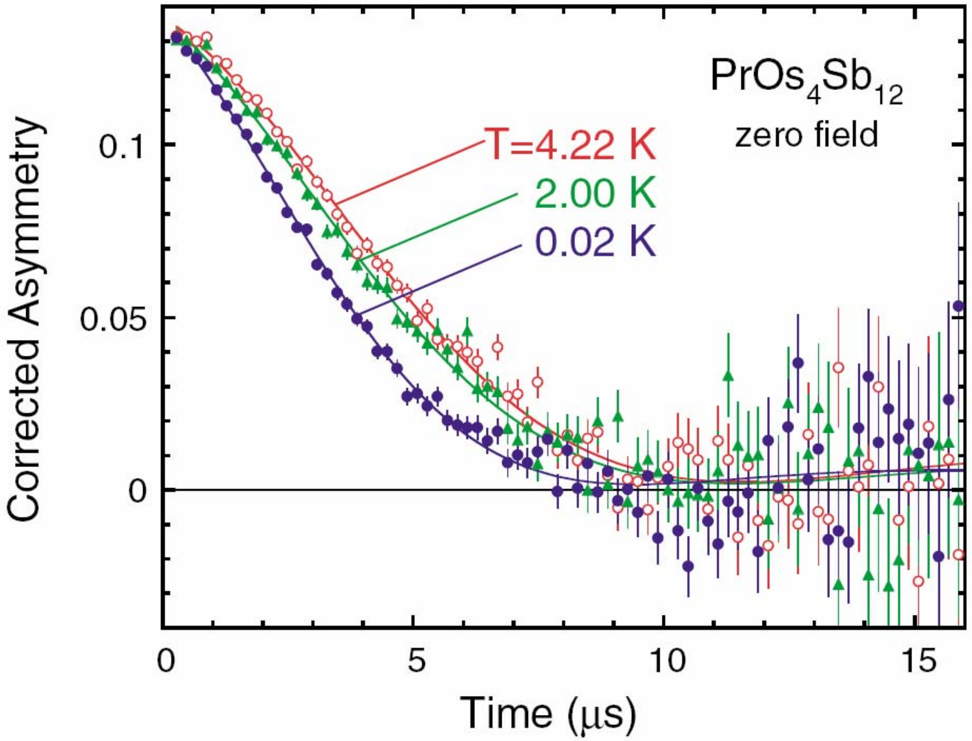

Luke et al., PRL **71**, 1466 (1993).

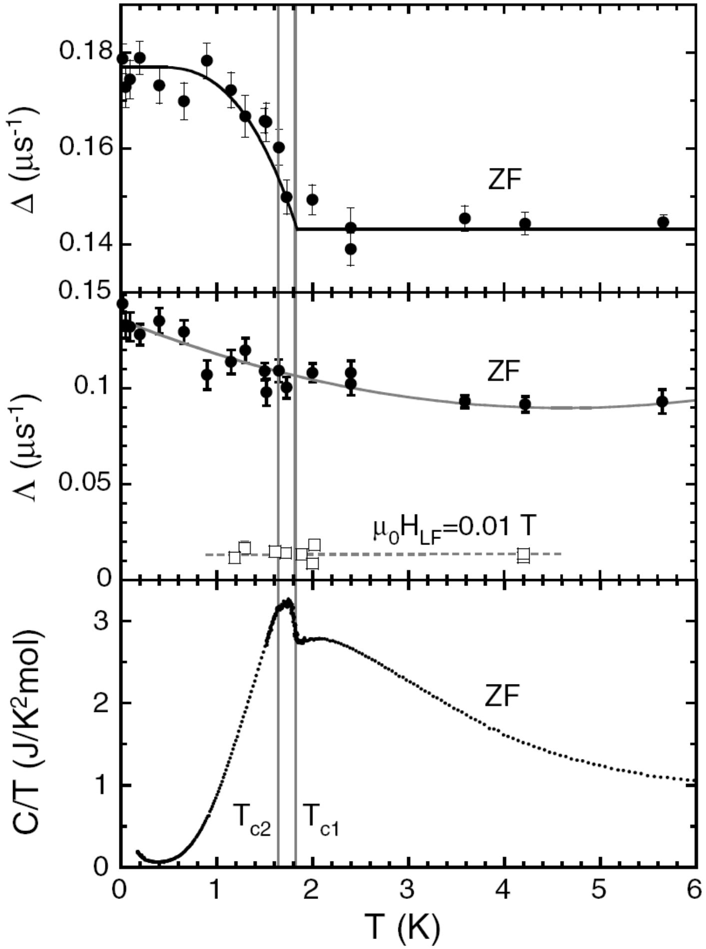
- Spontaneous internal magnetic field below lower $T_c$.
- Broken time reversal symmetry.

# Collaborators

- Y.J. Uemura (Columbia)
- Y. Maeno (Kyoto)
- M. Sigrist (ETH)

# $PrOs_4Sb_{12}$




Aoki *et al.*, Phys. Rev. Lett. **91**, 67003 (2003).