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Miniworkshop on Strong Correlations in Materials and Atom Traps

4 - 15 August 2008

Investigations of time reversal symmetry breaking in unconventional superconductors.

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Search for Broken Time-reversal Symmetry in Unconventional Superconductors

Sr_2RuO_4 , YBCO… and more.

Aharon Kapitulnik http://www.stanford.edu/~aharonk/

STANFORD UNIVERSITY

Students: **Jing Xia**
Elizabeth Schemm

Variety of samples:

- Yoshi Maeno (Kyoto University) - Sr_2RuO_4 single crystals
- D. Bonn and R. Liang (UBC) - YBCO single crystals
- Gertjan Koster & Wolter Siemons (Stanford) - YBCO & $SrRuO_3$ films
- G. Deutscher's group (TAU) - YBCO films
- K. Behnia (ESPCI) - URu_2Si_2 single crystals
- Y. Aoki (Tokyo Metropolitan University) - $PrOs_4Sb_{12}$ crystals
- Fangcheng Chou (MIT) - $Na_{0.33}CoO_2 1.4H_2O$ hydrated crystals
- Alik Palevski (TAU) - sperconductor/ferromagnet proximity structures

Also: Marty Fejer (Stanford) - Sagnac design

Outline:

1. Time reversal breaking effects in unconventional superconductors
2. Sr_2RuO_4
3. The measurement apparatus
4. Searching for Time-reversal symmetry breaking signals in Sr_2RuO_4
5. $YBa_2Cu_3O_{6+x}$
6. Inverse proximity effect in S/F structures
7. URu_2Si_2, $PrOs_4Sb_{12}$, etc.
8. Conclusions

Symmetry of pairs of identical electrons

In general we write for pairs of identical electrons:

$$\Psi(\vec{k}) = \langle \psi | c_{\vec{k}s} c_{-\vec{k}s'} | \psi \rangle = \underbrace{\Phi(\vec{k})}_{\text{orbital}} \cdot \underbrace{\chi(s,s')}_{\text{spin}}$$

For the wave function to be totally antisymmetric under particle exchange:

$$\vec{k} \leftrightarrow -\vec{k} \qquad s \leftrightarrow s'$$

Even parity:	$L = 0, 2, 4, \ldots$ even	$S = 0$ odd	Spin singlet
Odd parity:	$L = 1, 3, 5, \ldots$ odd	$S = 1$ even	Spin triplet

Unconventional superconductivity

In general $\Psi(\vec{k})$ Depends on $\vec{k}$

$$\left\langle \Psi(\vec{k}) \right\rangle_{\substack{Fermi\\ surface}} = \Psi_0$$

Conventional superconductors

$L = 0$ (isotropic)

Momentum average is harmless
For non magnetic impurities:
Anderson Theorem

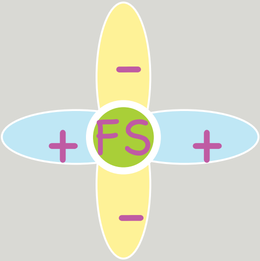
$$\Psi_0 \neq 0$$

Unconventional superconductors

$L > 0$ (anisotropic)

$\Psi(\vec{k})$ depends on $\vec{k}$. Momentum average results in destructive interference.

$$\Psi_0 = 0$$



Suppression of superconductivity

A Hallmark of unconventional superconductors is their sensitivity to scattering, i.e. interference.

Symmetry breaking

In the normal state the symmetry of the wave function include:

$$S = \underbrace{R_O}_{\text{Orbital rotation}} \times \underbrace{R_S}_{\text{Spin rotation}} \times \underbrace{T}_{\text{Time reversal}} \times \underbrace{U(1)}_{\text{Gauge}}$$

Possible broken symmetries:

Orbital rotation	Crystal structure
U(1)	Superconductivity
Spin Rotation	Magnetism
Time reversal	Magnetism
Time reversal	other?

Search for Broken Time Reversal Symmetry in Unconventional Superconductors

➔ For High Tc Superconductors (YBCO, BSCCO, etc.):

anyon superconductivity [Historically was first search]

$d_{x^2-y^2}+id_{xy}$, $d_{x^2-y^2}+is$, etc.*

Staggered-flux state, D-density wave (Laughlin, Chakravarty, Lee, etc.)

Loop-Current Order (does not break translation symmetry: C.Varma)

➔ p-wave Superconductors:

Sr_2RuO_4

UPt_3, $PrOs_4Sb_{12}$, and other heavy fermions

$(TMTSF)_2ClO_4$ and other organic superconductors

➔ Ferromagnetic superconductors

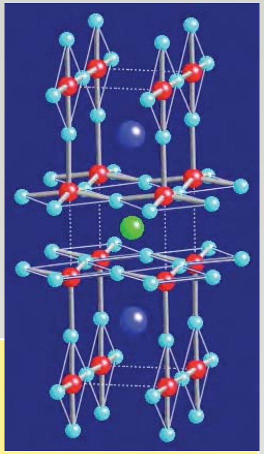
$ErRh_4B_4$, UGe_2, ...

* A significant feature of the mixed symmetry states is that they may produce spontaneous currents and magnetic moments which can be measured using appropriate experimental techniques.

anyon superconductivity

Search for anyon superconductivity in High-Tc Superconductors

$YBa_2Cu_3O_{7-\delta}$



In 2-dimensions, possibilities for quantum statistics are not limited to fermions or bosons.

The N-particles wave function: $\Psi(\vec{r}_1,\vec{r}_2,\vec{r}_3,\vec{r}_4,\ldots\vec{r}_N)$

Exchange any two particles: $\vec{r}_i \rightleftarrows \vec{r}_j$

The wave function acquires a phase:

$$\Psi(\vec{r}_1,\vec{r}_2,..\vec{r}_i,..\vec{r}_j,\ldots\vec{r}_N) \to e^{i\theta_{ij}}\Psi(\vec{r}_1,\vec{r}_2,..\vec{r}_j,..\vec{r}_i,\ldots\vec{r}_N) \quad \text{where} \quad \theta_{ij} = \pi\left(1-\frac{1}{\nu}\right)$$

$\nu = 1$ - bosons

$\nu = \infty$ - fermions

$\nu =$ other integer - anyons: Ground State Breaks Time reversal Symmetry

Expected TRSB effects - very large

V. Kalmayer & R.B. Laughlin, Phys. Rev. Lett. 1987; R.B. Laughlin, Phys. Rev. Lett. 1988.

Search for Broken Time Reversal Symmetry in Unconventional Superconductors

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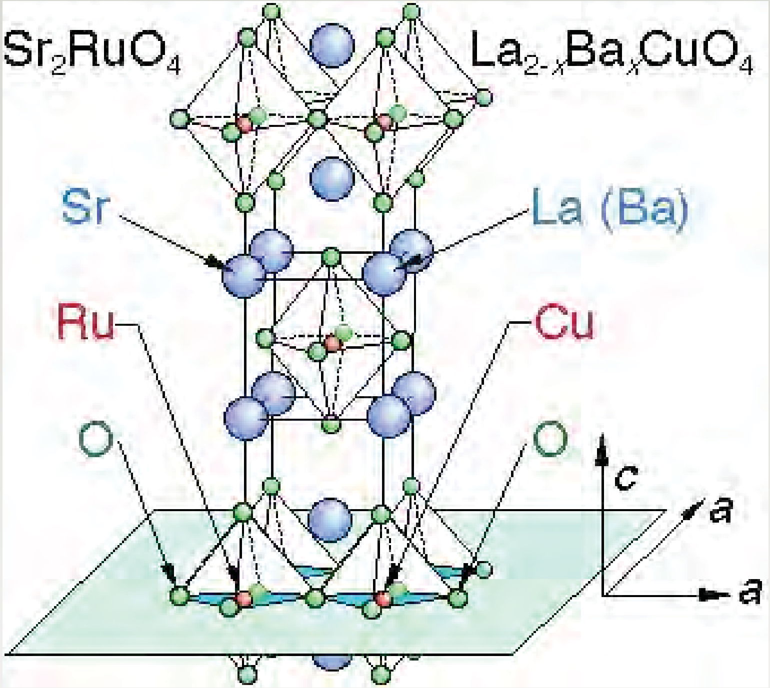
Sr_2RuO_4

Quasi 2-dimensional
Strongly correlated Fermi liquid
$T_C = 1.5$ K



Sr_2RuO_4 is a layered perovskite isostructural with $La_{2-x}Ba_xCuO_4$.

Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita,
J. G. Bednorz & F. Lichtenberg, Nature 372 (1994), 532.

T_C (as discovered) ~ 0.93 K

Sr_2RuO_4 is a strongly correlated Fermi liquid:

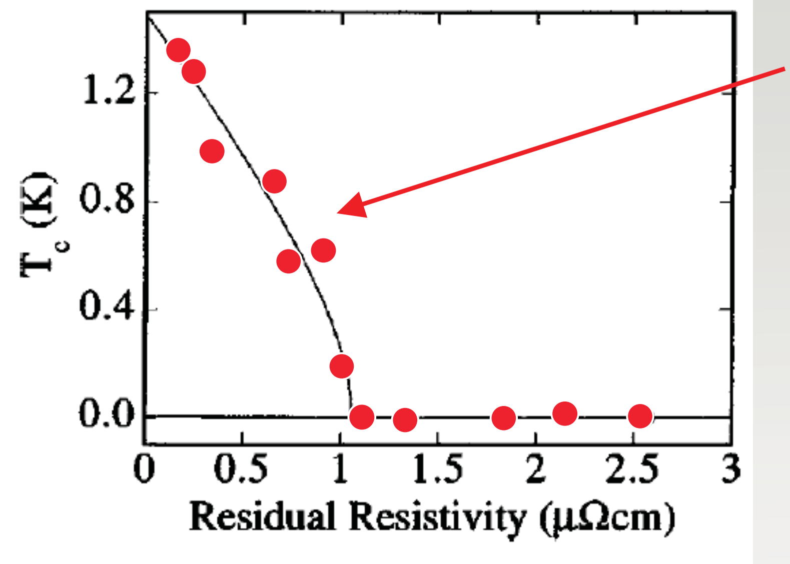
The superconductivity of Sr_2RuO_4 condenses from a metallic state that is a strongly correlated two-dimensional Fermi liquid.
(Low temperature T^2 of resistivity, quantum oscillations)

Early measurements indicated that Sr_2RuO_4 shows evidence of strong triplet(S=1) correlations in the normal state.
(e.g. similarity to ferromagnetic $SrRuO_3$)

Fermi liquid parameters and S=1 bear strong quantitative similarity to those of ^3He*.

* Rice and Sigrist, 1995

Early evidence for unconventional – odd parity pairing



Sensitivity to scattering:

Destruction of superconductivity by nonmagnetic impurities

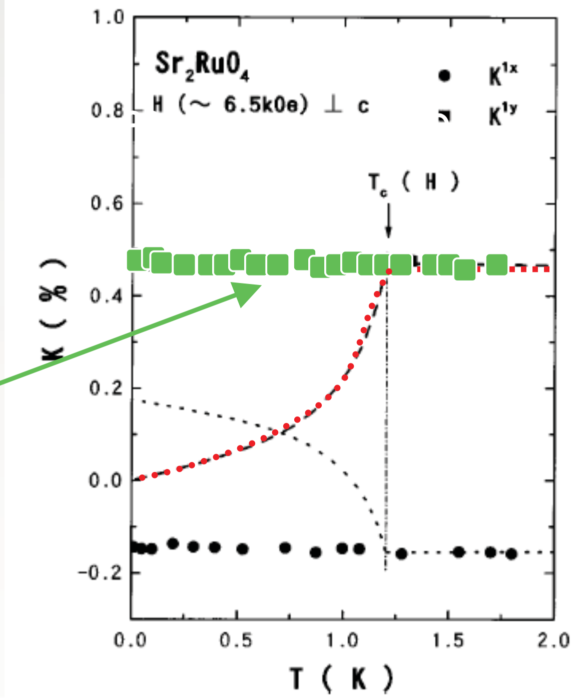
[Makenzie et al., 1998]

Spin triplet pairing

Knight-shift does not Change below T_C.

[Ishida et al., 1998]

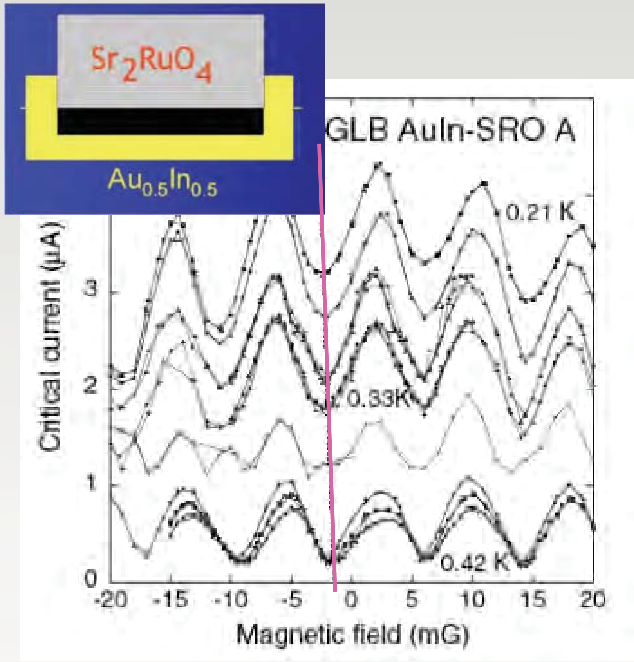
In-plane field



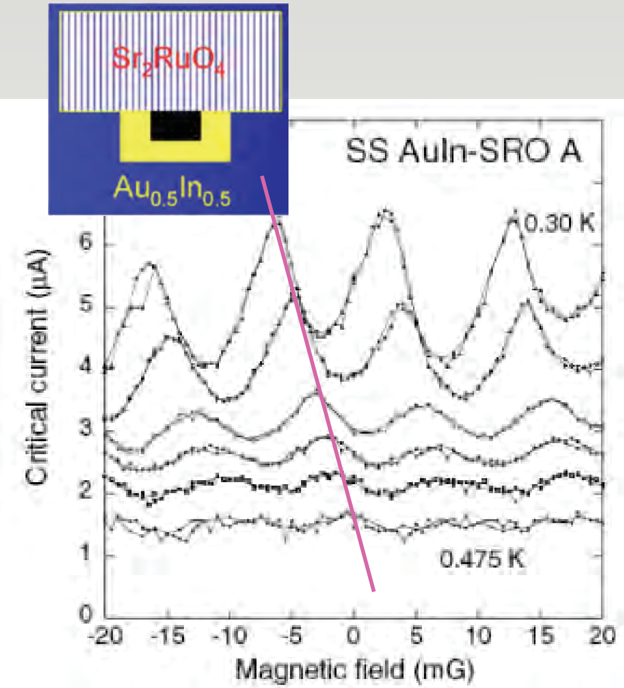
Odd parity

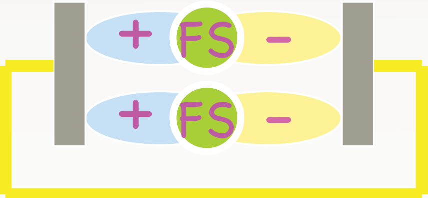
π phase shift between opposite crystal faces in phase sensitive measurements

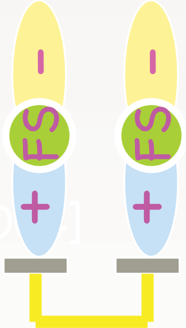
K. D. Nelson, Z. Q. Mao, Y. Maeno,2 Y. Liu, Science, 306 (2004) 1151 – 1154.



Results consistent with odd parity!







What is the actual symmetry of the order parameter of Sr_2RuO_4?

Given:

1. Spin triplet pairing
2. 4-fold symmetry with in-plane (2D) pairing
3. Weak coupling superconductor (low T_c, tunneling)
4. Assume: weak Spin-orbit coupling

(only effect is to pin the spin triplet to the plane)

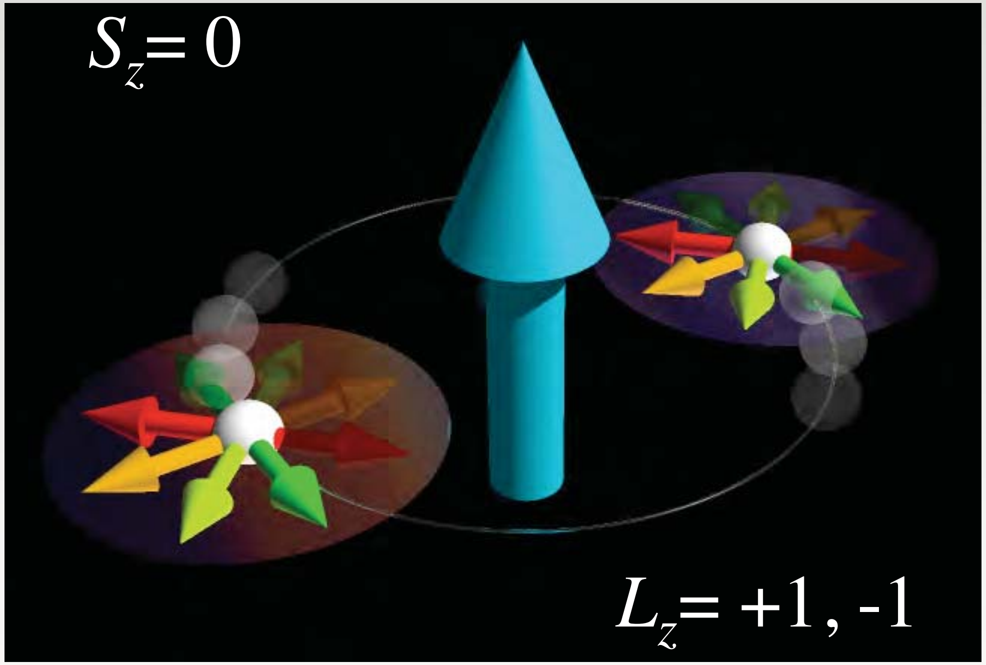
Which state is realized ?

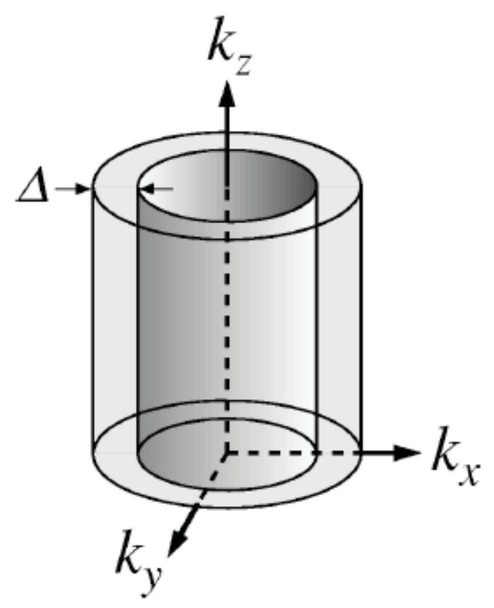
T.M. Rice and M. Sigrist, J. Phys. Cond. Mat. 7, L643 (1995).
G. Baskaran, Physica B 223&224, 490 (1996).

Suggested symmetry for the order parameter of Sr_2RuO_4:

$$\vec{d} = \Delta_0 \hat{z}(p_x \pm i p_y)$$

T.M. Rice and M. Sigrist, J. Phys. Cond. Mat. 7, L643 (1995).
G. Baskaran, Physica B 223&224, 490 (1996).





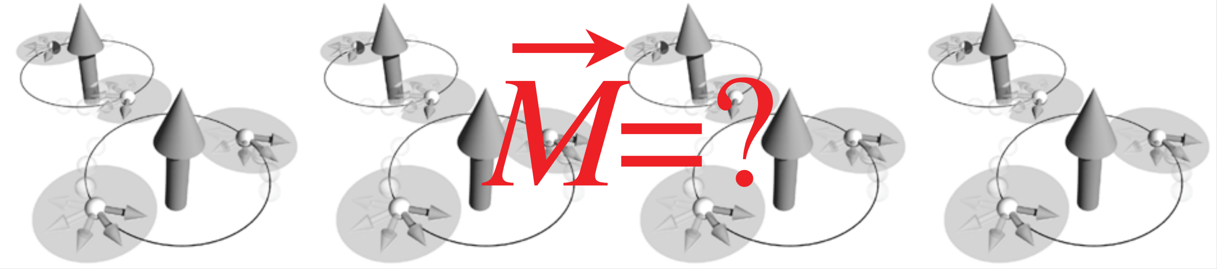
No nodes

This is a chiral state with orbital magnetic moment and degeneracy = 2

Time Reversal Symmetry is Broken!

Is this an example of orbital magnetism?

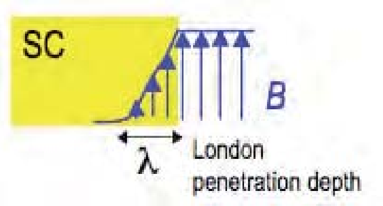
Can we measure a spontaneous magnetization?



$\vec{M}=?$

NO! Because of Meissner Effect! ➔ $M=0$

In general no spontaneous magnetic moment due to compensating Meissner currents.



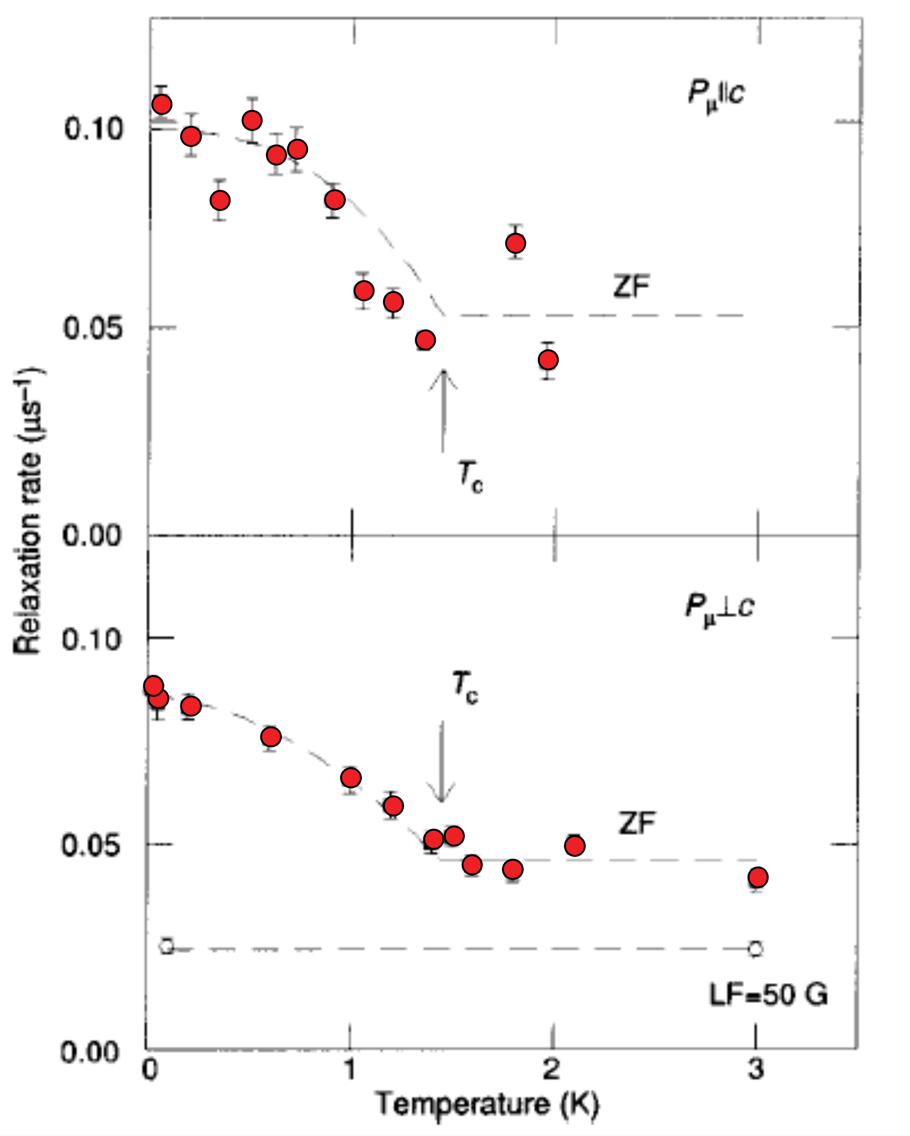
<u>However:</u>
sample will always contain **surfaces and defects** at which the Meissner screening of the TRS-breaking moment is not perfect, and a small magnetic signal may be expected in some cases.

Muon spin rotation as local measurement:

Muons disturb the local order

Observation of a spontaneous extra relaxation of the spin-polarization function below the superconducting transition temperature.

Estimated local field: ~ 0.5 Oe



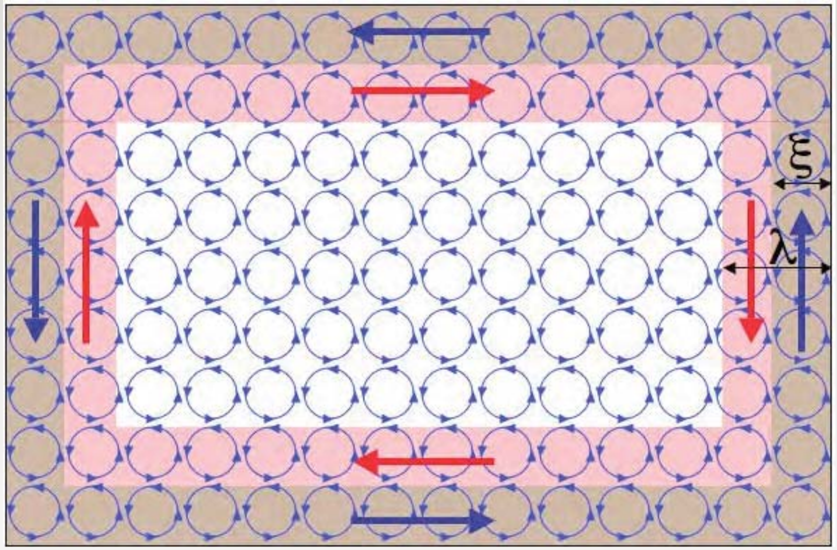
[Luke et al., 2000]

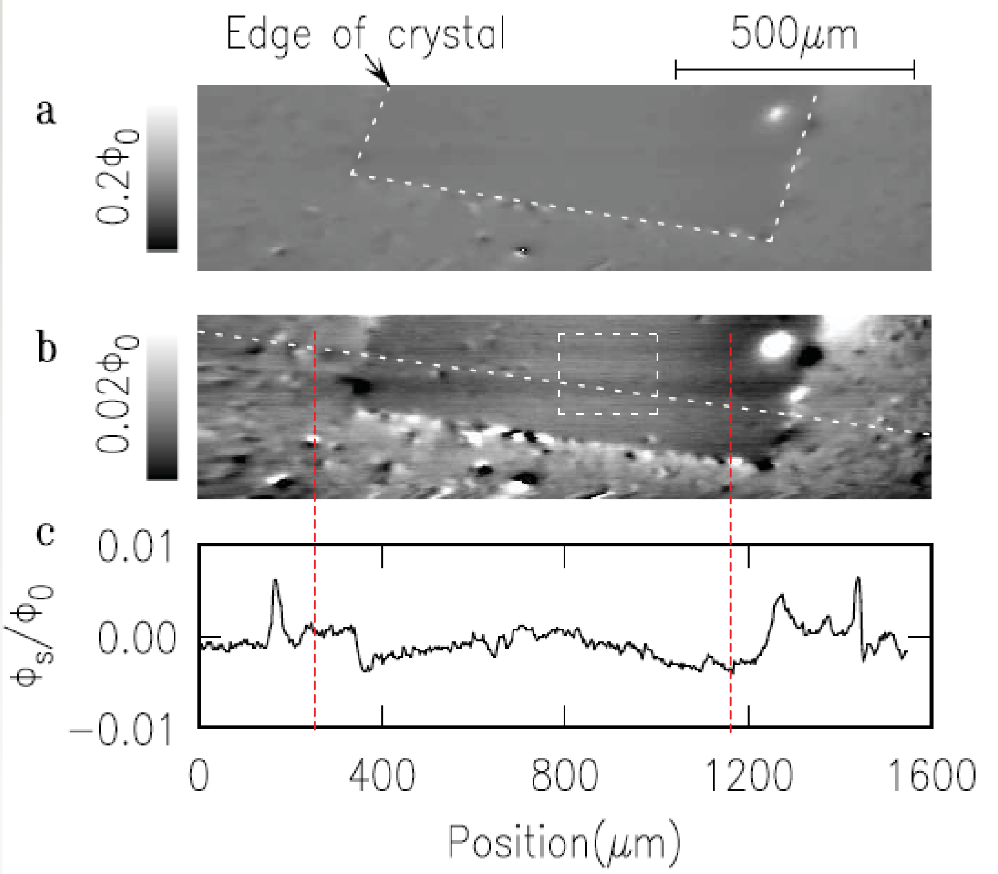
However:

1. The effect was isotropic
2. Signal could come from other sources

Search for edge currents

P.G. Bjornsson, Y. Maeno, M.E. Huber, and K.A. Moler,
Phys. Rev. B 72, 012504 (2005).



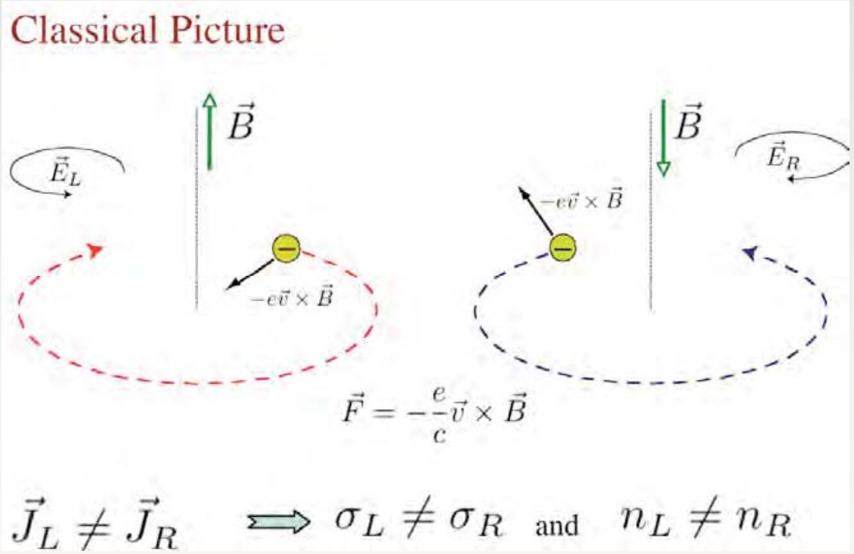


No edge currents were detected using scanning Hall probe and scanning SQUID

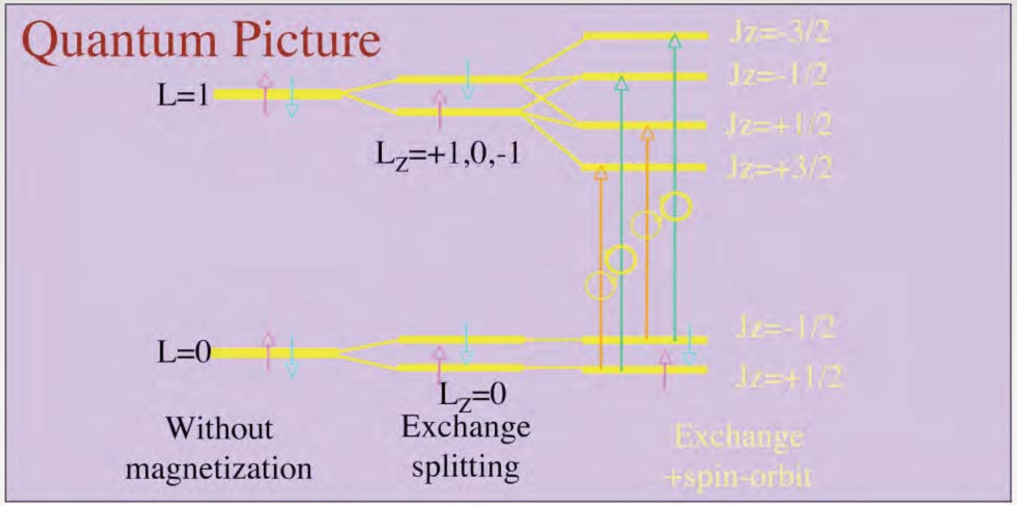
Bulk measurements are needed which do not depend on defects in the superconductor.

Solution:

Magneto-Optical-like Measurements!



$$\vec{J}_L \neq \vec{J}_R \Longrightarrow \sigma_L \neq \sigma_R \text{ and } n_L \neq n_R$$



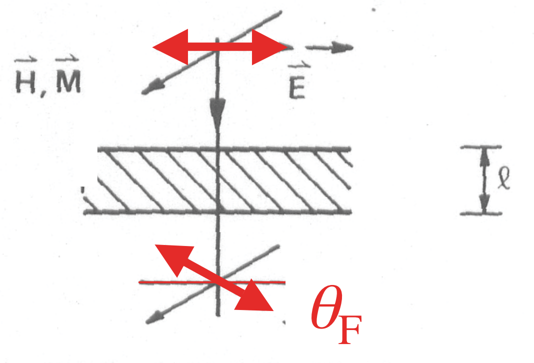
$$n_R \neq n_L$$

Faraday Effect:

At $z=0$ the wave is linearly polarized along x

Then: $\vec{E} = \frac{1}{2} E_0 e^{i(\omega t - kz)}[\hat{x}\cos(\delta/2) + \hat{y}\sin(\delta/2)]$

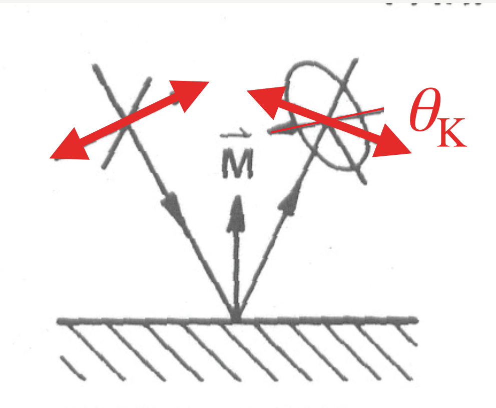
$$\theta_F = \left(\frac{\delta}{2}\right)_{z=\ell} = \frac{\pi\ell}{\lambda_0}(n_R - n_L)$$



(Polar) Kerr Effect:

Rotation of polarization of reflected light

$$\frac{r_R}{r_L} = \left|\frac{r_R}{r_L}\right| e^{i(\phi_R - \phi_L)} = \left|\frac{r_R}{r_L}\right| e^{-i2\theta_K}$$



Start with a material magnetized in the $\hat{z}$ direction.
In the optical regime we cannot define a measurable susceptibility.

[See a more thorough discussion in P.S. Pershan, J. of App. Phys., 38, 1482 (1967)]

We set $\mu=1$ and describe the behavior of the electromagnetic waves in the matter by $\varepsilon(\omega)$ only, or equivalently by $\sigma(\omega) = i\omega\varepsilon(\omega)$.

The general form of the conductivity for a cubic lattice:

$$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ -\sigma_{xy} & \sigma_{xx} & 0 \\ 0 & 0 & \sigma_{zz} \end{pmatrix}$$

Signature for time reversal-symmetry breaking

$$\sigma_{ij} = \sigma'_{ij} + i\sigma''_{ij}$$

Because of the axial symmetry, the index of refraction for right and left circularly polarized light is related to the complex optical conductivity by:

$$\epsilon(\omega) = (n_{R,L} + i\kappa_{R,L})^2 = 1 + i\frac{4\pi\sigma_{R,L}}{\omega}$$

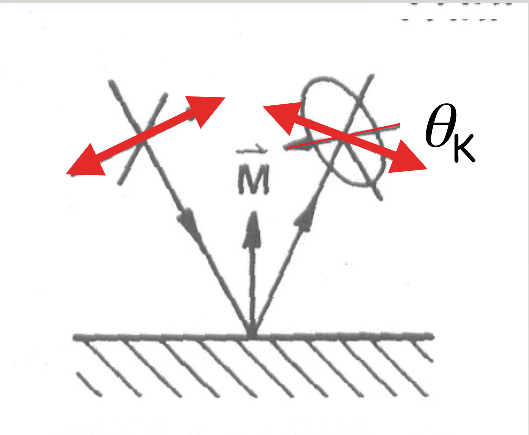
Where: $\sigma_{R,L} = \sigma_{xx} \pm i\sigma_{xy}$

Using the formula for Faraday effect – θ_F:

$$\boxed{\theta_F = -\frac{2\pi\ell}{c}\frac{n\sigma'_{xy} + \sigma''_{xy}}{n^2 + \kappa^2} \approx -\frac{2\pi\ell}{cn}\sigma'_{xy}}$$

$\kappa \ll n$

Consider a Polar Kerr Effect at normal incidence



$$\frac{E_r}{E_0} \equiv r = |r|e^{i\phi} = -\frac{(n+i\kappa)-1}{(n+i\kappa)+1}$$

$$\frac{r_R}{r_L} = \left|\frac{r_R}{r_L}\right| e^{i(\phi_R-\phi_L)}$$

After reflection the complex amplitudes are different.
The polarization is now elliptical with the major axis rotated by:

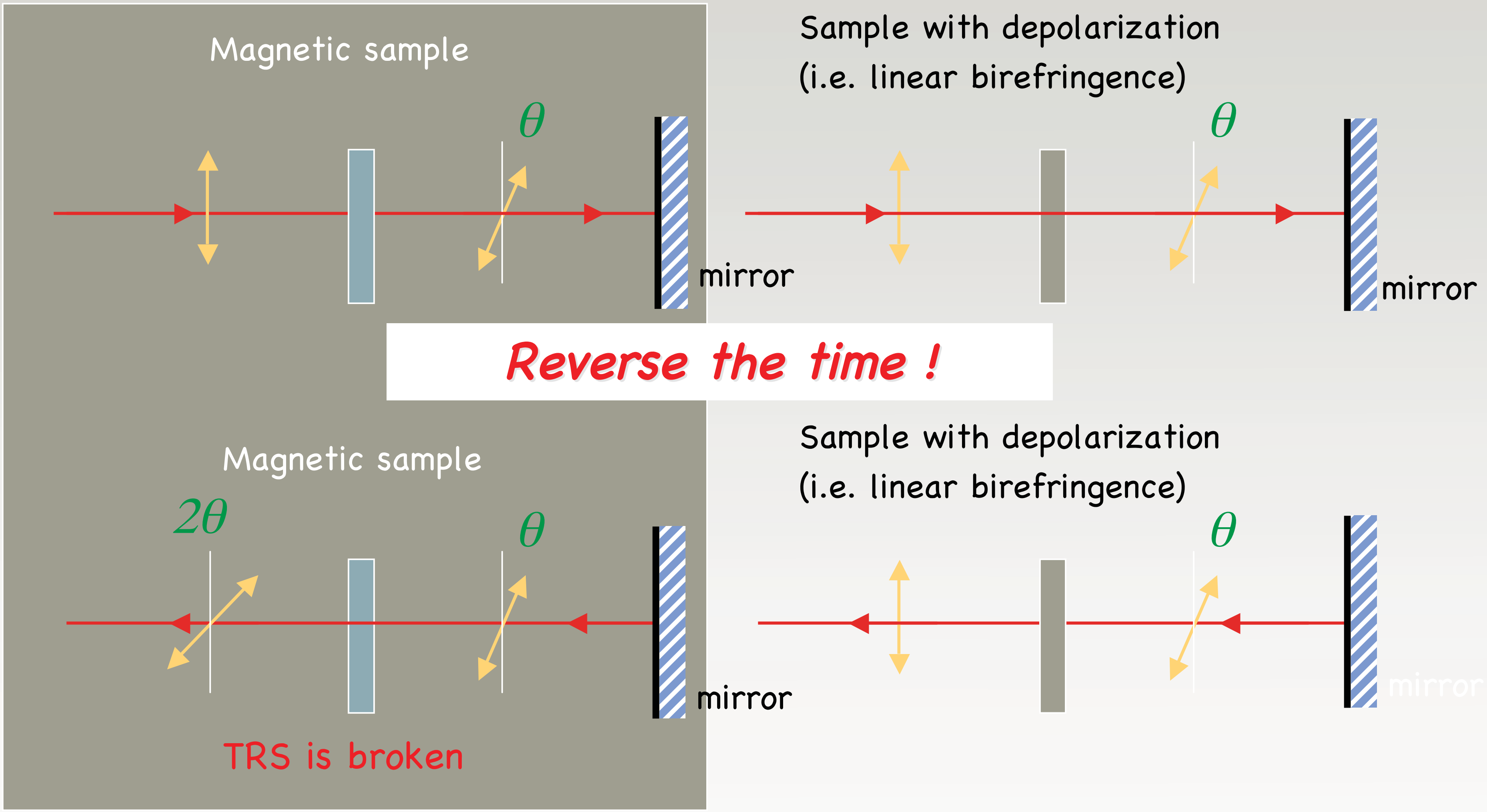
$$\theta_K = -\frac{1}{2}(\phi_R - \phi_L) \approx -\mathrm{Im}\frac{(n_R+i\kappa_R)-(n_L+i\kappa_L)}{(n_R+i\kappa_R)(n_L+i\kappa_L)-1}$$

In the last equality we used a small phase difference and small difference of the *n*-s.

For small κ:

$$\boxed{\theta_K = \frac{2\lambda}{cn(n^2-1)}\sigma''_{xy}}$$

Magneto-optics and Time-Reversal Symmetry

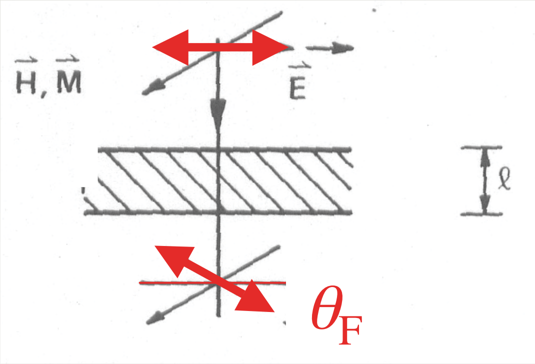


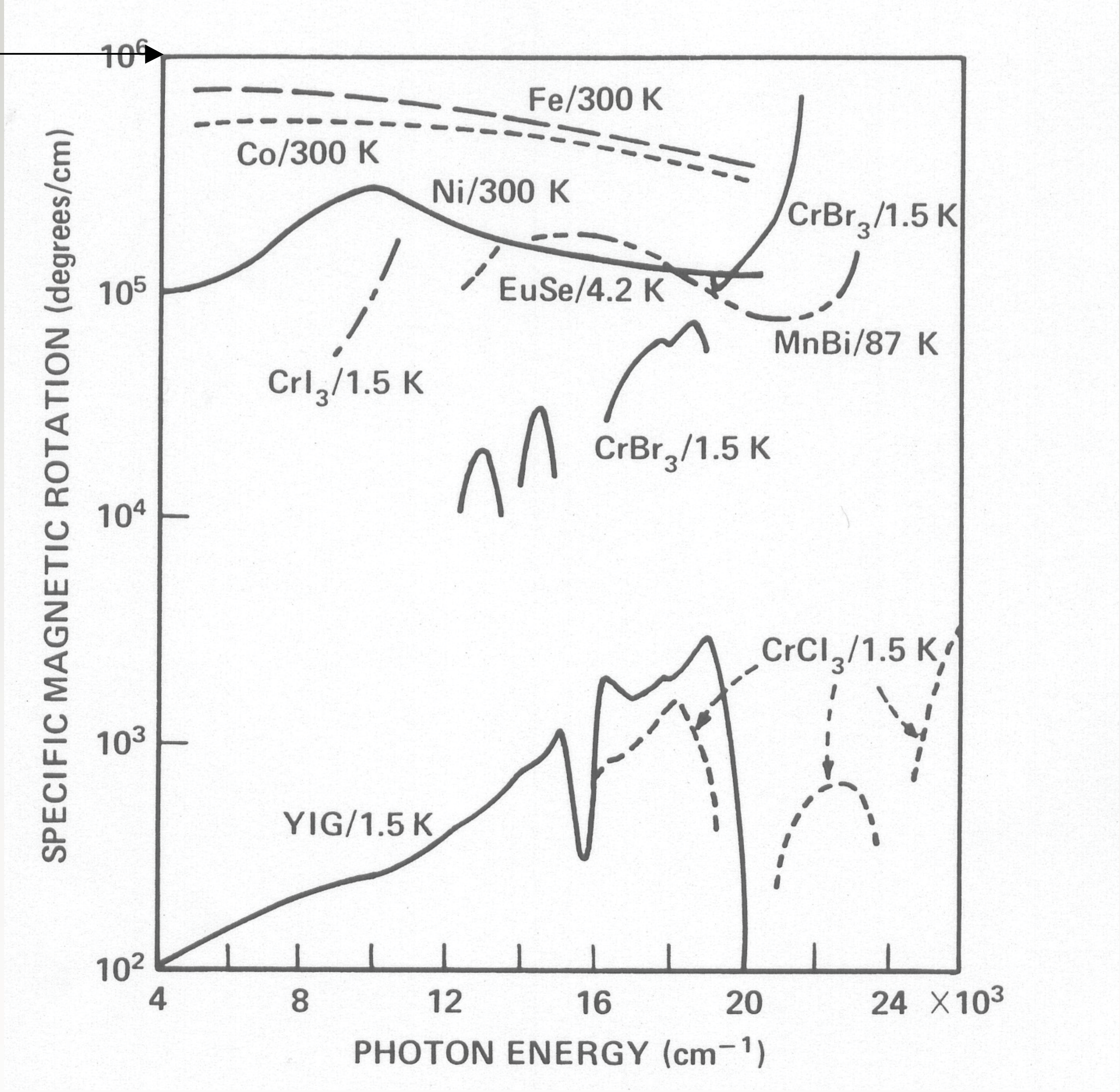
Reverse the time !

We can distinguish between magneto optic signal (Kerr and Faraday) from depolarization effects if we measure the difference between a light beam with its time reversal counter part beam.

Faraday effect in different materials

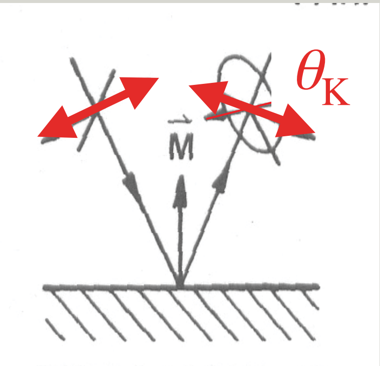
1.75×10^4 rad/cm



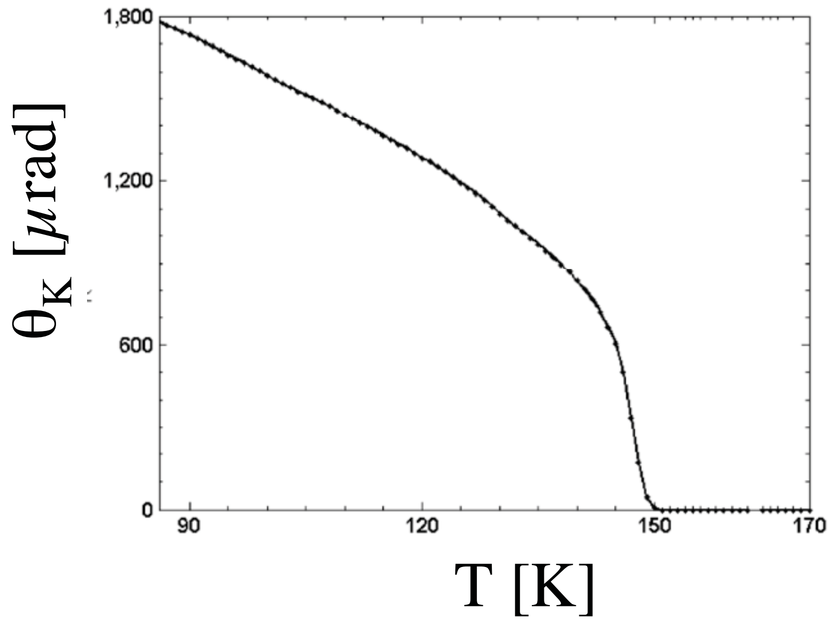


Example:

Kerr effect of thick film Ferromagnetic **$SrRuO_3$**:



Note size of effect:
Saturation value is
~ 10 millirad !!!



For some ferromagnets θ_K can be of order ~rad!

Considerations for the experiment:

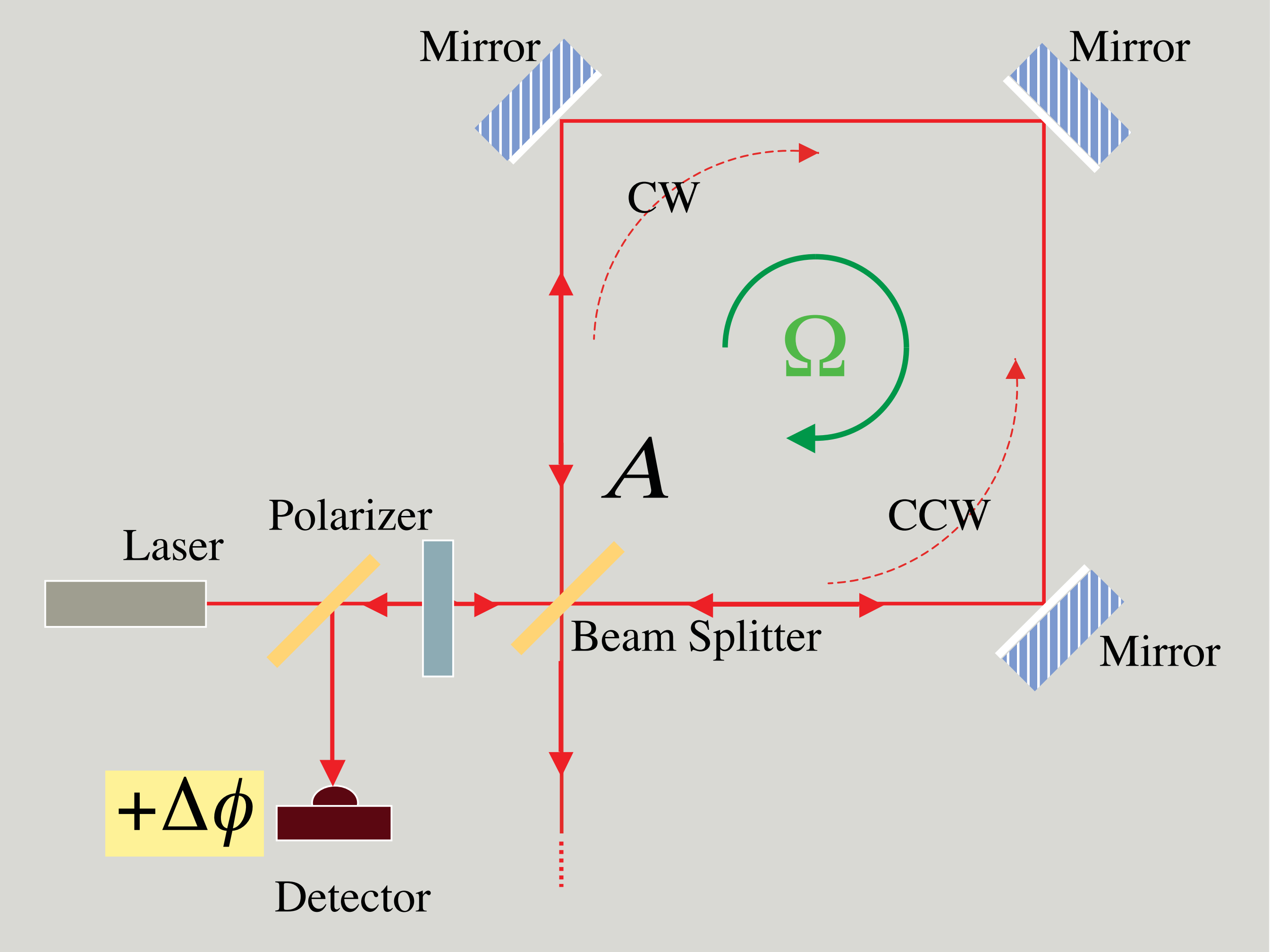
1. We need to detect very small rotations (early estimates for Sr_2RuO_4 gave $\theta_K \sim 10^{-10}$ rad).
2. We need to reject <u>all</u> reciprocal effects such as linear birefringence and optical activity.
3. We need to measure an absolute value of the Kerr effect, rather than a result of a modulated signal*.

A simple cross polarization method will not be enough!

* Note that for searching for TRSB no modulation is possible!

Solution: The Sagnac Effect

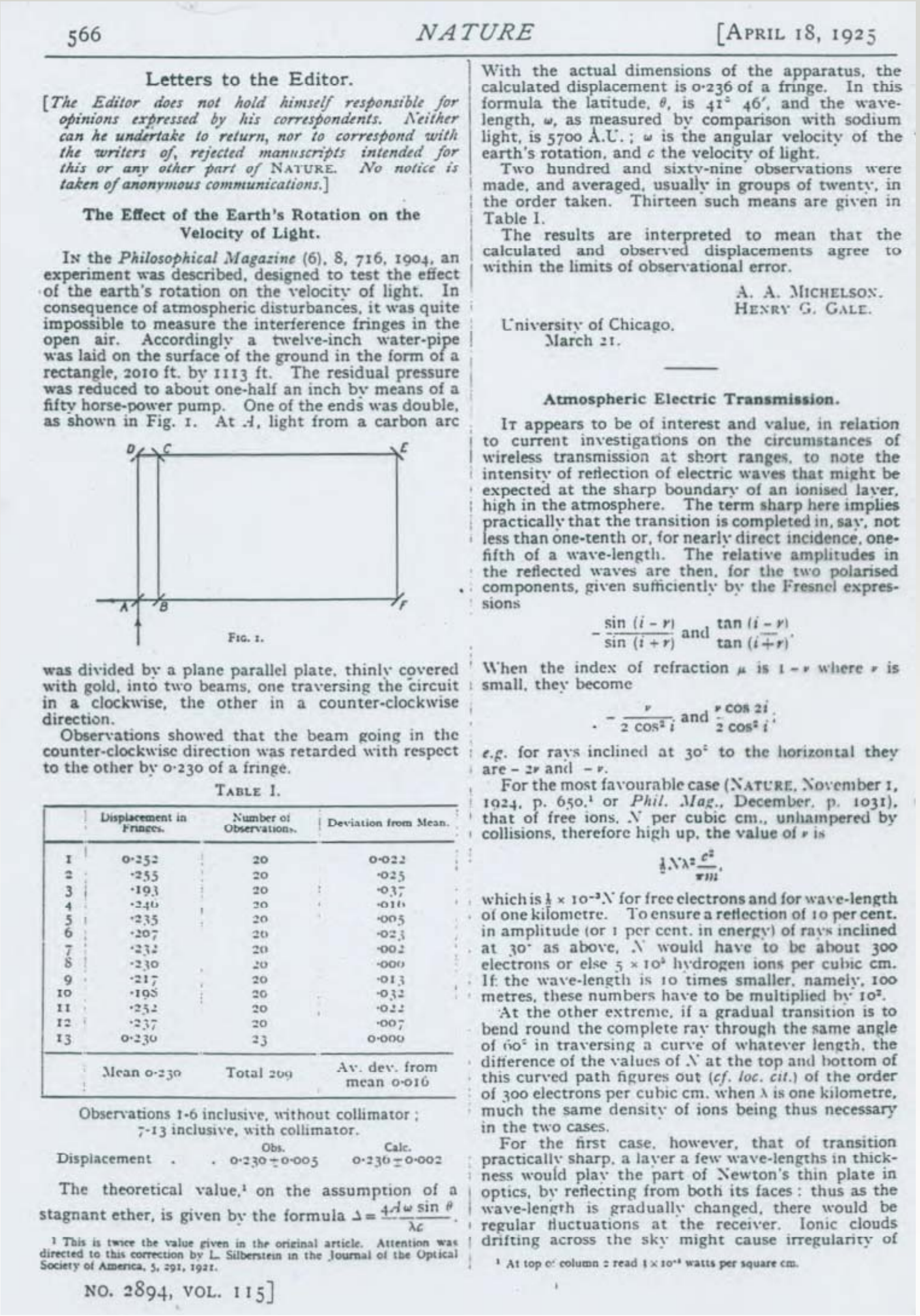
A Sagnac Loop at rest
is reciprocal!



$$\Delta\phi = \frac{2\pi}{\lambda}\frac{4A}{c}\Omega$$

Michelson's Paper

This experiment utilized a large rectangular array of pipes and mirrors, with the legs lying in the direction of the earth's rotation having a length of 2010 feet, and the legs lying along longitudinal lines having a length of 1113 feet. A calibration loop had the same longitudinal length, but only a very short length in the direction of the earth's rotation, so that the effect of the earth's motion in the direction of the light traveling the 2010 foot legs could be compared to the effect in the calibration loop in which light traveled only a negligible distance in this direction. By comparing the fringe displacement of the large loop to that of the calibration loop, the effect of the earth's motion (through the aether) was to be discovered.



566 *NATURE* [April 18, 1925

Letters to the Editor.

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The Effect of the Earth's Rotation on the Velocity of Light.

In the *Philosophical Magazine* (6), 8, 716, 1904, an experiment was described, designed to test the effect of the earth's rotation on the velocity of light. In consequence of atmospheric disturbances, it was quite impossible to measure the interference fringes in the open air. Accordingly a twelve-inch water-pipe was laid on the surface of the ground in the form of a rectangle, 2010 ft. by 1113 ft. The residual pressure was reduced to about one-half an inch by means of a fifty horse-power pump. One of the ends was double, as shown in Fig. 1. At *A*, light from a carbon arc was divided by a plane parallel plate, thinly covered with gold, into two beams, one traversing the circuit in a clockwise, the other in a counter-clockwise direction.

Fig. 1.

Observations showed that the beam going in the counter-clockwise direction was retarded with respect to the other by 0·230 of a fringe.

Table I.

	Displacement in Fringes.	Number of Observations.	Deviation from Mean.
1	0·252	20	0·022
2	·255	20	·025
3	·193	20	·037
4	·246	20	·016
5	·235	20	·005
6	·207	20	·023
7	·232	20	·002
8	·230	20	·000
9	·217	20	·013
10	·195	20	·032
11	·252	20	·022
12	·237	20	·007
13	0·230	23	0·000
	Mean 0·230	Total 269	Av. dev. from mean 0·016

Observations 1-6 inclusive, without collimator;
7-13 inclusive, with collimator.

	Obs.	Calc.
Displacement . .	0·230 ± 0·005	0·236 ± 0·002

The theoretical value,[1] on the assumption of a stagnant ether, is given by the formula $\Delta = \frac{4A\omega \sin\theta}{\lambda c}$. With the actual dimensions of the apparatus, the calculated displacement is 0·236 of a fringe. In this formula the latitude, θ, is 41° 46′, and the wave-length, ω, as measured by comparison with sodium light, is 5700 Å.U.; ω is the angular velocity of the earth's rotation, and c the velocity of light.

Two hundred and sixty-nine observations were made, and averaged, usually in groups of twenty, in the order taken. Thirteen such means are given in Table I.

The results are interpreted to mean that the calculated and observed displacements agree to within the limits of observational error.

A. A. Michelson.
Henry G. Gale.

University of Chicago,
March 21.

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[1] This is twice the value given in the original article. Attention was directed to this correction by L. Silberstein in the Journal of the Optical Society of America, 5, 291, 1921.

* * *

Atmospheric Electric Transmission.

It appears to be of interest and value, in relation to current investigations on the circumstances of wireless transmission at short ranges, to note the intensity of reflection of electric waves that might be expected at the sharp boundary of an ionised layer, high in the atmosphere. The term sharp here implies practically that the transition is completed in, say, not less than one-tenth or, for nearly direct incidence, one-fifth of a wave-length. The relative amplitudes in the reflected waves are then, for the two polarised components, given sufficiently by the Fresnel expressions

$$-\frac{\sin(i-r)}{\sin(i+r)} \text{ and } \frac{\tan(i-r)}{\tan(i+r)}.$$

When the index of refraction μ is $1-\nu$ where ν is small, they become

$$-\frac{\nu}{2\cos^2 i} \text{ and } \frac{\nu\cos 2i}{2\cos^2 i};$$

e.g. for rays inclined at 30° to the horizontal they are -2ν and $-\nu$.

For the most favourable case (NATURE, November 1, 1924, p. 650,[1] or *Phil. Mag.*, December, p. 1031), that of free ions, N per cubic cm., unhampered by collisions, therefore high up, the value of ν is

$$\tfrac{1}{2}N\lambda^2\frac{e^2}{\pi m},$$

which is $\frac{1}{2} \times 10^{-3}N$ for free electrons and for wave-length of one kilometre. To ensure a reflection of 10 per cent. in amplitude (or 1 per cent. in energy) of rays inclined at 30° as above, N would have to be about 300 electrons or else 5×10^5 hydrogen ions per cubic cm. If the wave-length is 10 times smaller, namely, 100 metres, these numbers have to be multiplied by 10^2.

At the other extreme, if a gradual transition is to bend round the complete ray through the same angle of 60° in traversing a curve of whatever length, the difference of the values of N at the top and bottom of this curved path figures out (*cf. loc. cit.*) of the order of 300 electrons per cubic cm. when λ is one kilometre, much the same density of ions being thus necessary in the two cases.

For the first case, however, that of transition practically sharp, a layer a few wave-lengths in thickness would play the part of Newton's thin plate in optics, by reflecting from both its faces: thus as the wave-length is gradually changed, there would be regular fluctuations at the receiver. Ionic clouds drifting across the sky might cause irregularity of

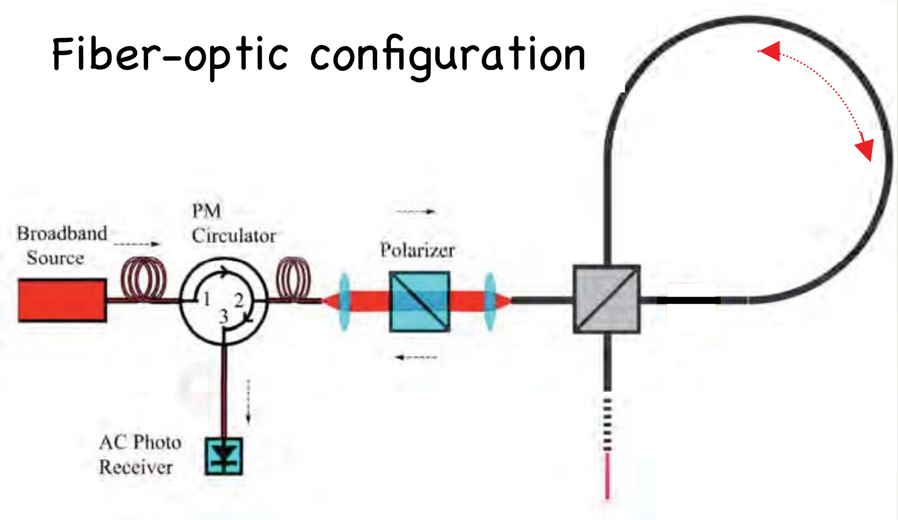
---

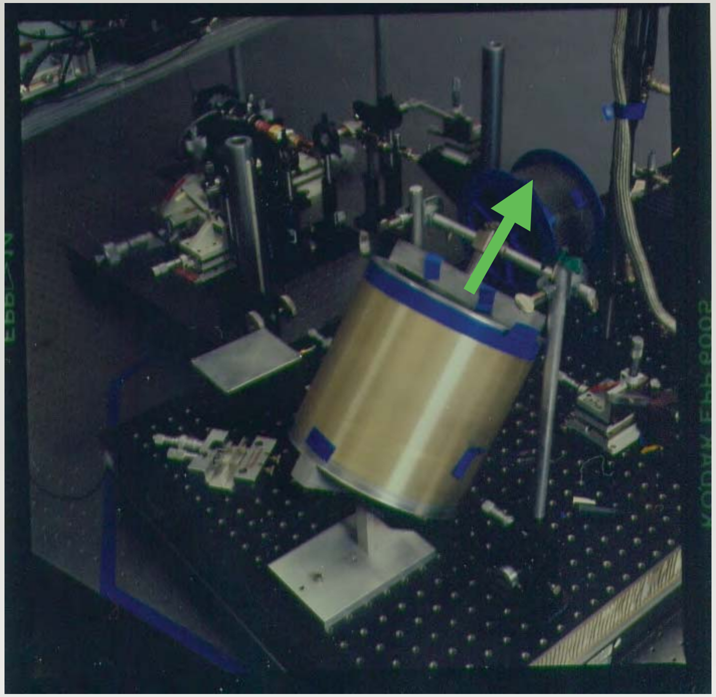
[1] At top of column 2 read $\frac{1}{2} \times 10^{-4}$ watts per square cm.

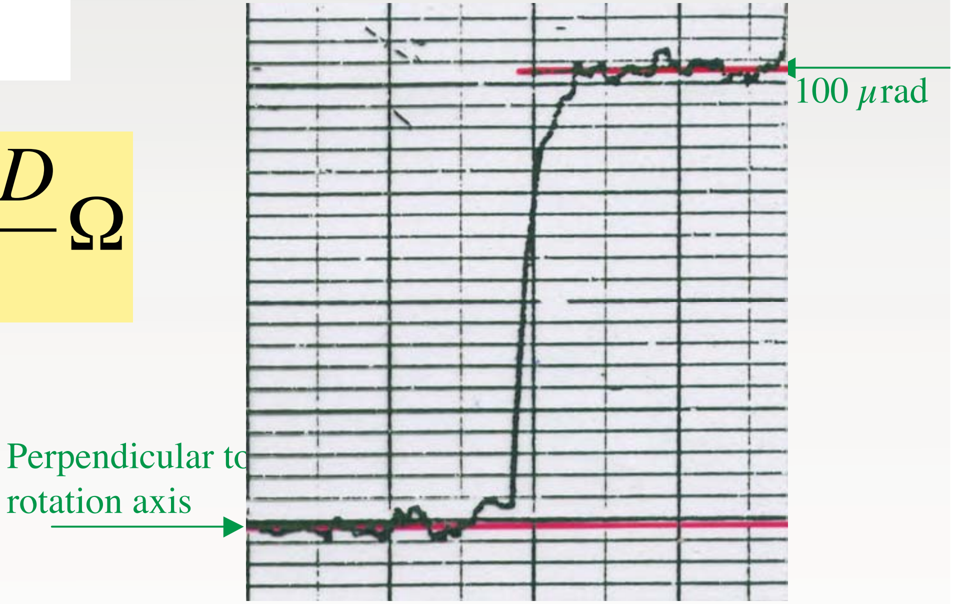
NO. 2894, VOL. 115]

Fiber-optic implementation

Example: Earth Rotation







$$D = 20cm$$
$$\lambda = 1.06\mu m$$
$$\Omega = \frac{2\pi}{24 \cdot 3600}$$
$$L = 1km = 10^5 cm$$

$$\Delta\phi = \frac{2\pi L D}{\lambda c}\Omega$$

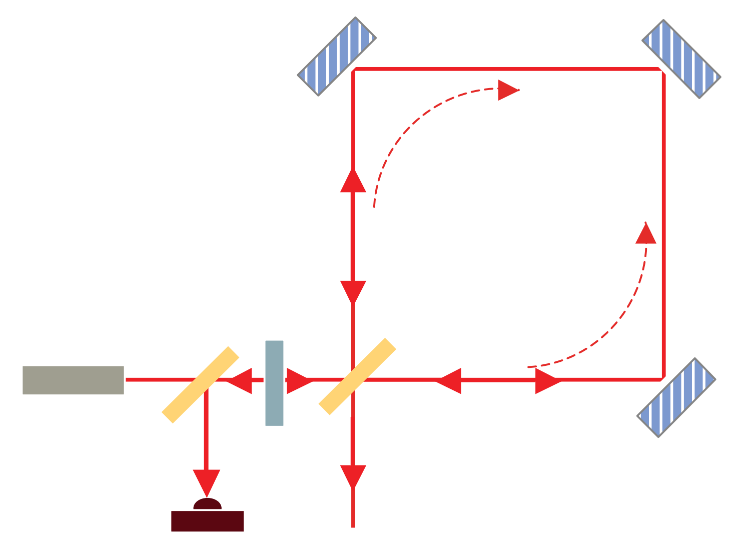
(or, as we did, partially point it to have exactly 100 μrad)

[S. Spielman et al., 1990]

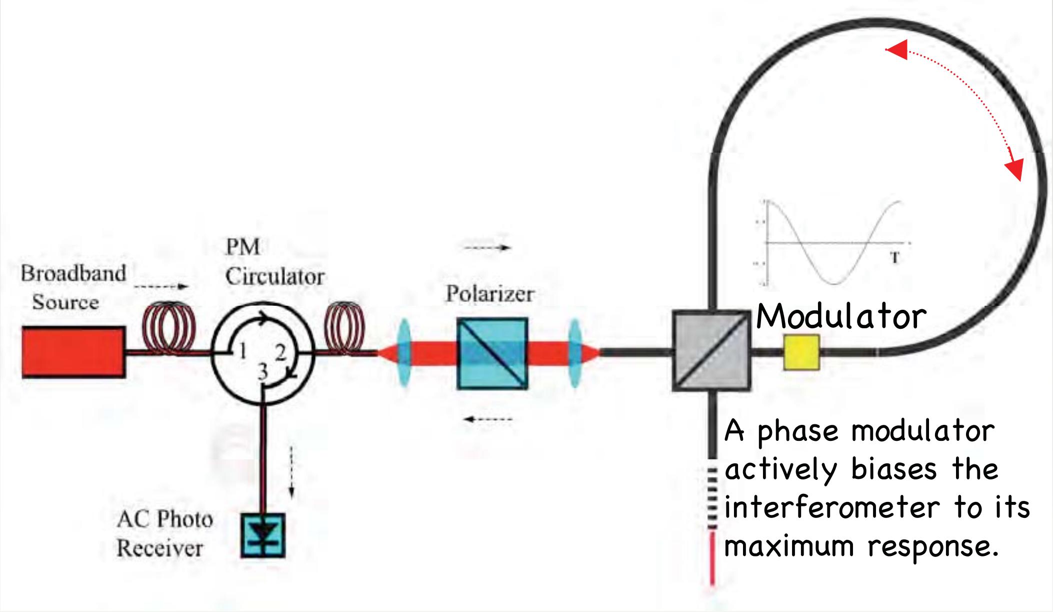
The Sagnac interferometer

A beam of light is split and the two beams are made to follow a trajectory in opposite directions. The phase difference between the two parts is measured by interferometry.

Free-space configuration



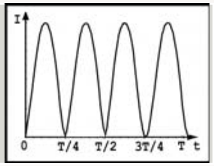
Fiber-optic configuration



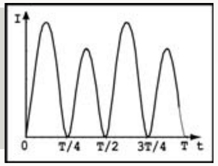
A phase modulator actively biases the interferometer to its maximum response.

Detected intensity

TRS preserved: Bright fringe
No first harmonic



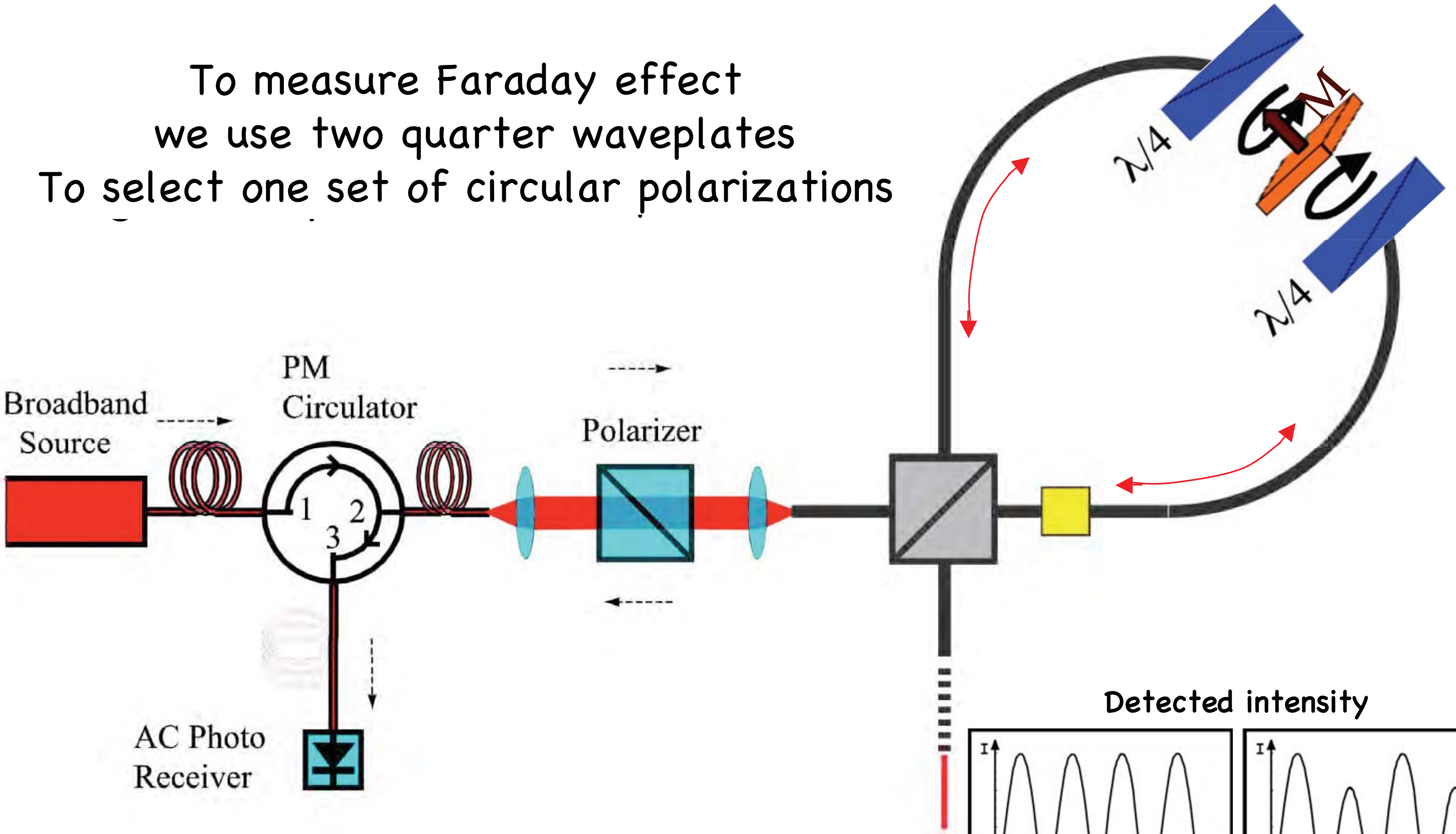
TRS broken: Away from bright fringe
First harmonic detected



$$\phi_{nr} = \tan^{-1}[\frac{J_2(2\phi_m)I_\omega}{J_1(2\phi_m)I_{2\omega}}]$$

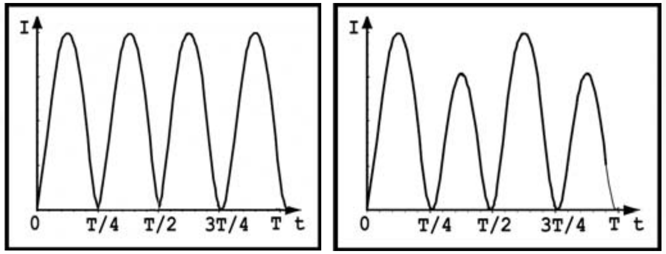
Use Sagnac loop to measure magnetization:

To measure Faraday effect
we use two quarter waveplates
To select one set of circular polarizations

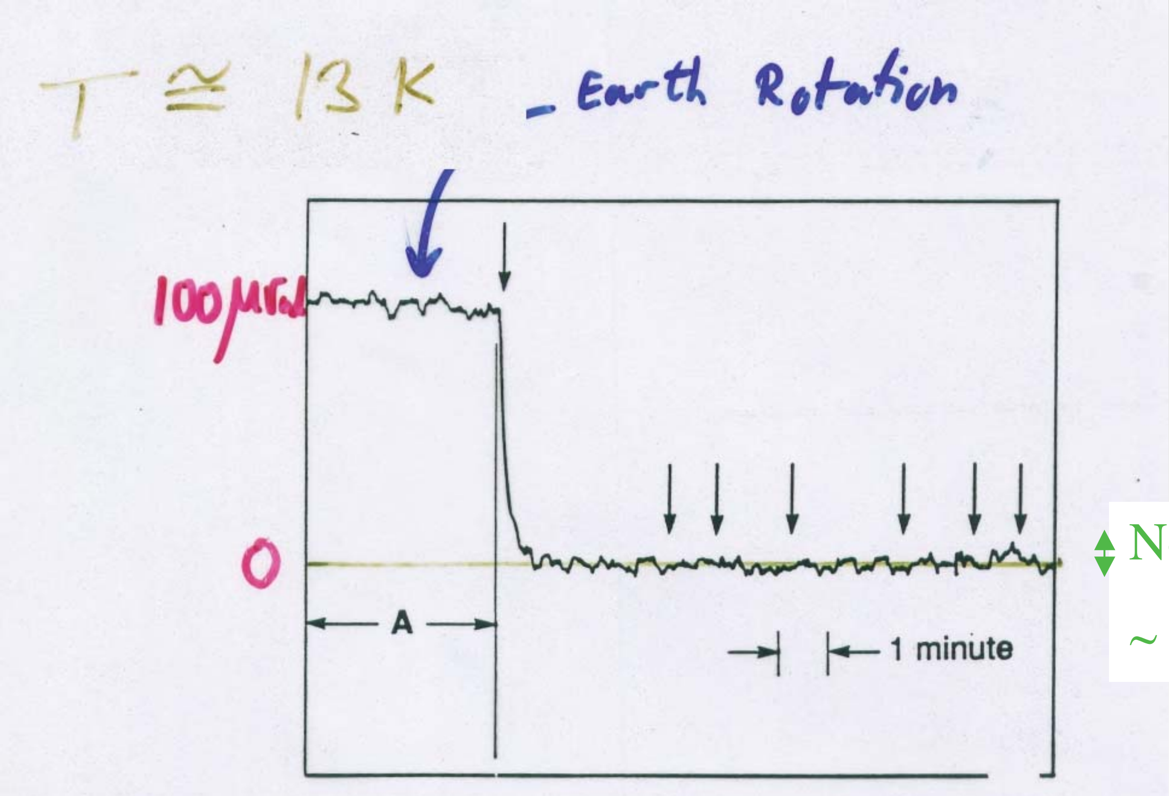


$$\phi_{nr} = \tan^{-1}[\frac{J_2(2\phi_m)I_\omega}{J_1(2\phi_m)I_{2\omega}}]$$

Detected intensity



Optimally doped $YBa_2Cu_3O_{7-\delta}$ Thin Films in Transmission:



Noise

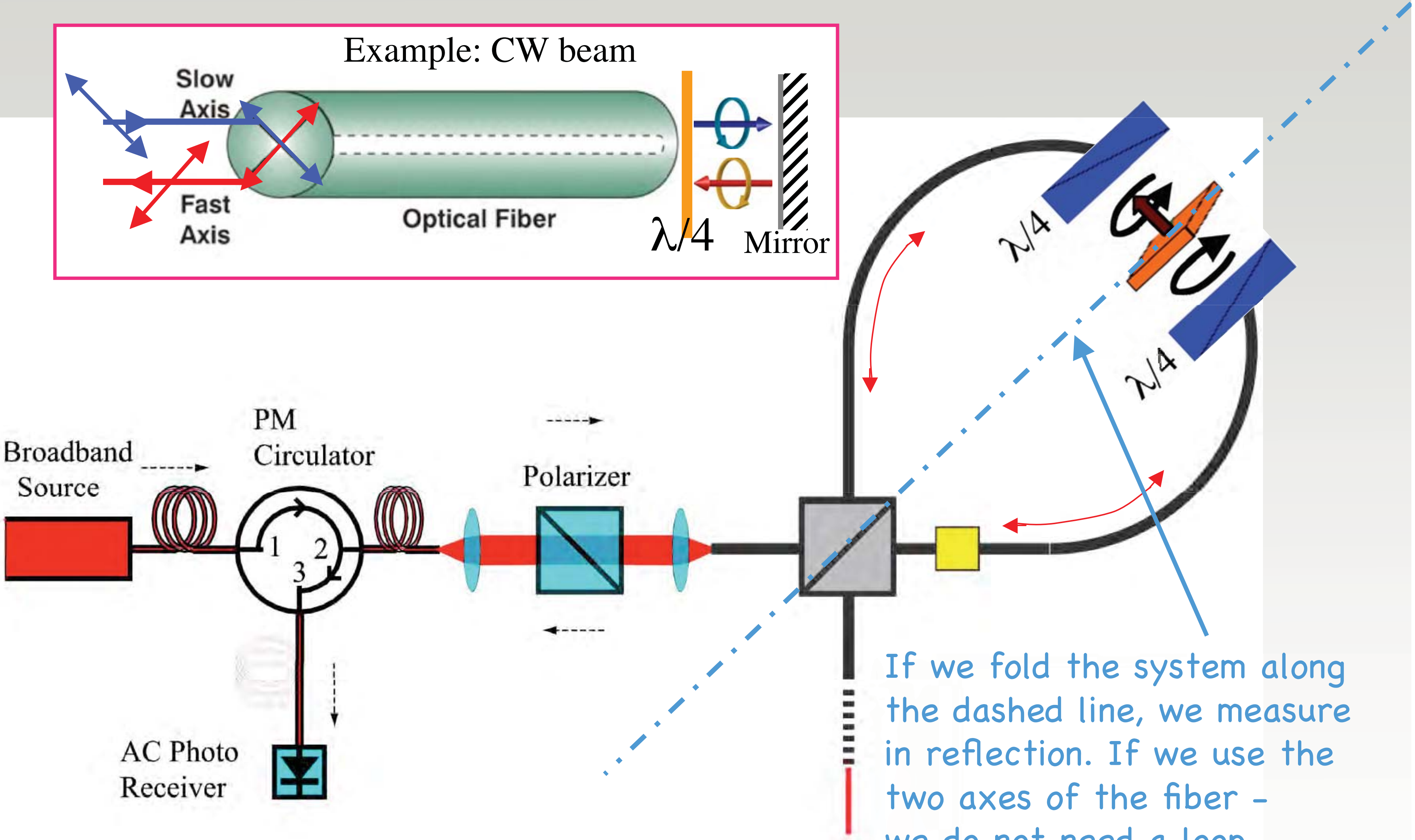
~ 2 μrad/Hz$^{1/2}$

Results: No effect to within 1 μrad

No shot noise limit. Main problems: Drift, need for higher power (~1 mW)

S. Spielman et al.Phys. Rev. Lett. 1990; Phys. Rev. Lett. 1992

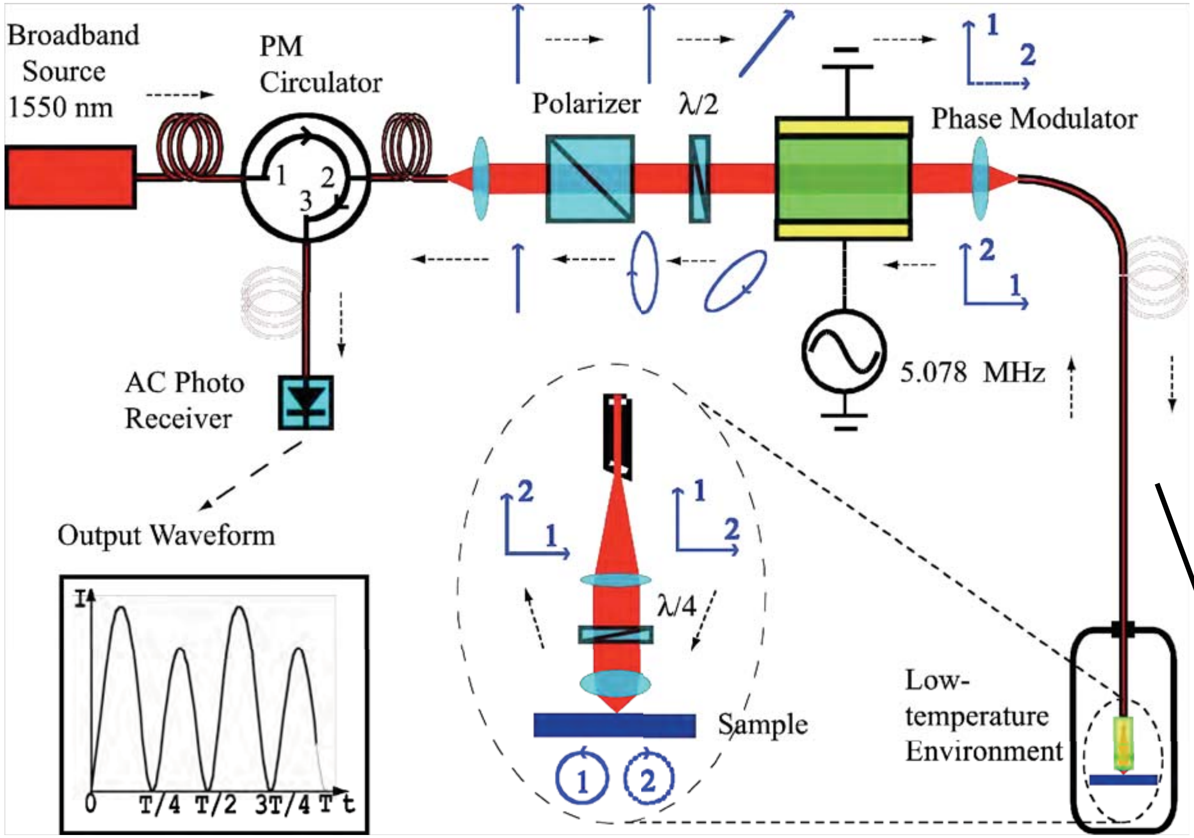
The loopless interferometer


Example: CW beam

If we fold the system along the dashed line, we measure in reflection. If we use the two axes of the fiber – we do not need a loop.

Loopless Sagnac magnetometer

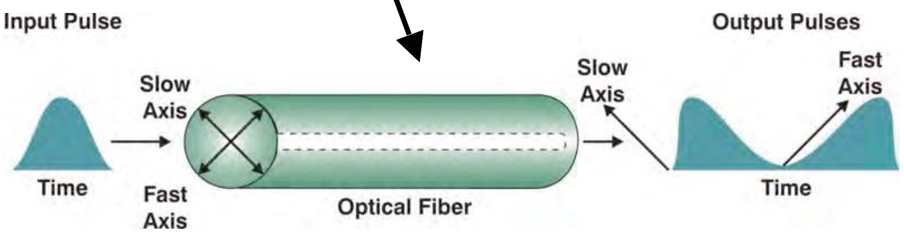
$\lambda = 1.55\ \mu\text{m}$



(1) There is no optical-viewport, allows lower temperatures (0.3 K) operation.

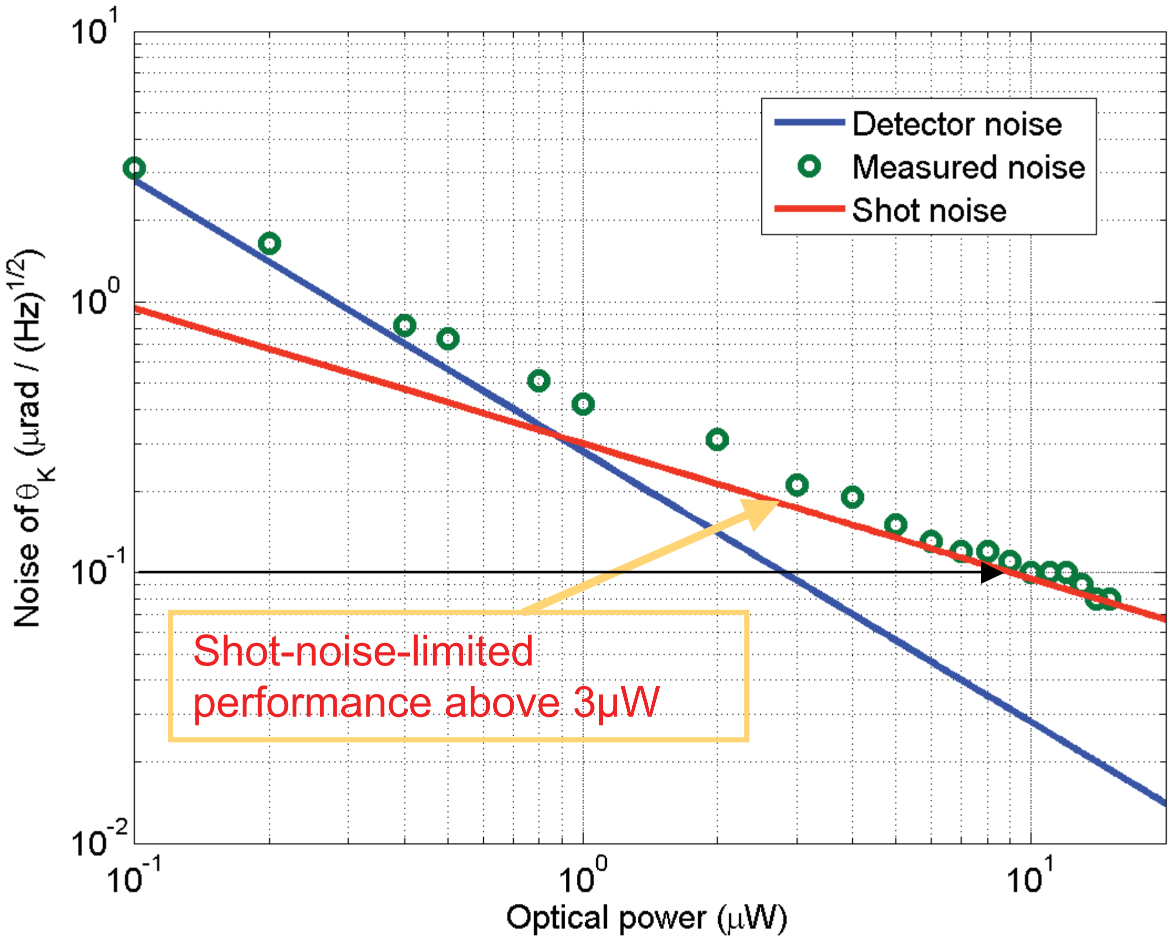
(2) It rejects depolarization effects such as linear birefringence.

(3) Both DC and AC performance are shot-noise limited.



Jing Xia, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik, Appl. Phys. Lett. 89, 062508

Performance: Noise



Shot-noise-limited performance above 3μW

Photon shot noise for 1.55 um wavelength and 80% detector efficiency, P_{ave} in μW:

$$\sigma_{shot\_noise} \cong 0.6\sqrt{\frac{2\hbar\omega\Delta f}{P_{ave}}}$$
$$\cong 0.3/\sqrt{P_{ave}}(\mu rad/\sqrt{Hz})$$

Detector noise: Detector noise found to be 0.5 pW/sqrt(Hz), this gives:

$$\sigma_{\det ector} \cong 0.56\frac{\text{detector}NEP}{P_{ave}}$$
$$\cong 0.28/P_{ave}(\mu rad/\sqrt{Hz})$$

To achieve 10 nano-radian resolution, minimum averaging time will be:

100 seconds, with 10 μW optical power

50 seconds, with 20 μW optical power

Performance: Drift over Time

Power @ detector :

0.7 μW

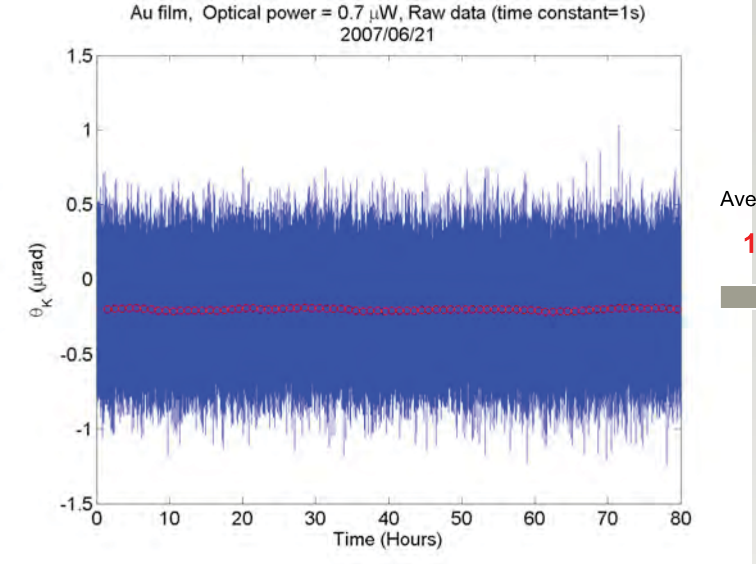
Lockin time constant:

1 second

Temperature:

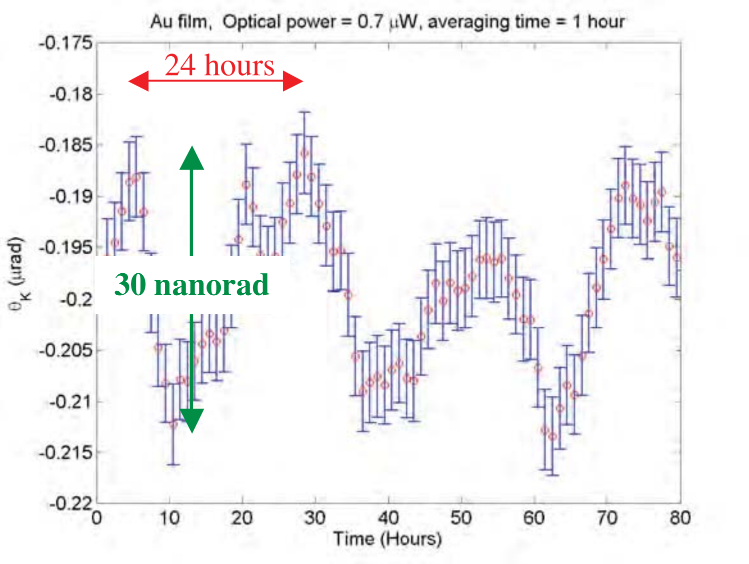
100K to 150K

(warming)



Average over

1 hour



Power @ detector :

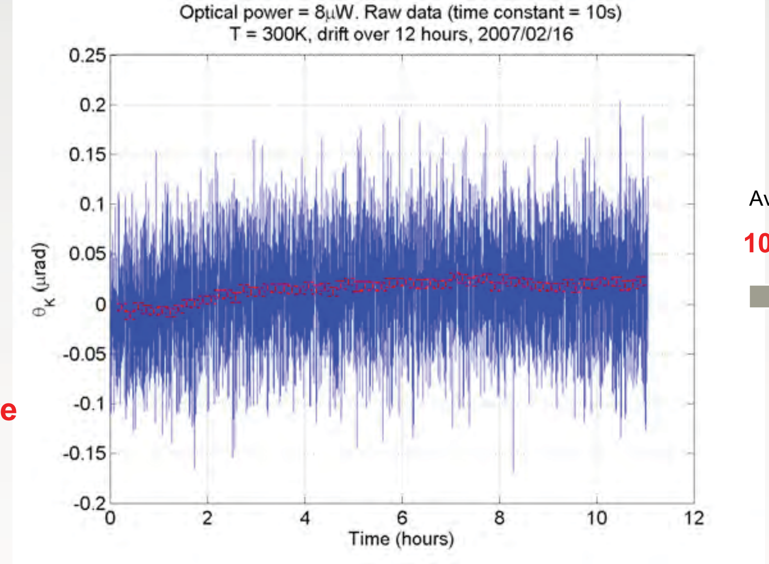
8 μW

Lockin time constant:

10 second

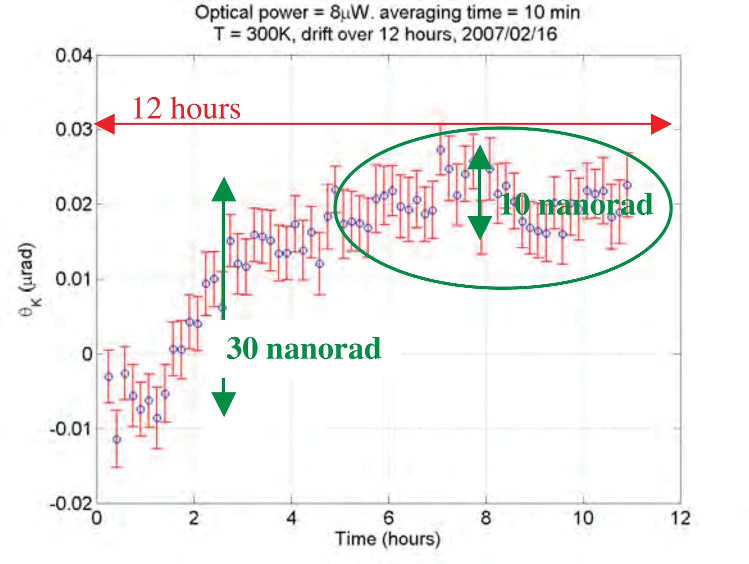
Temperature:

room temperature



Average over

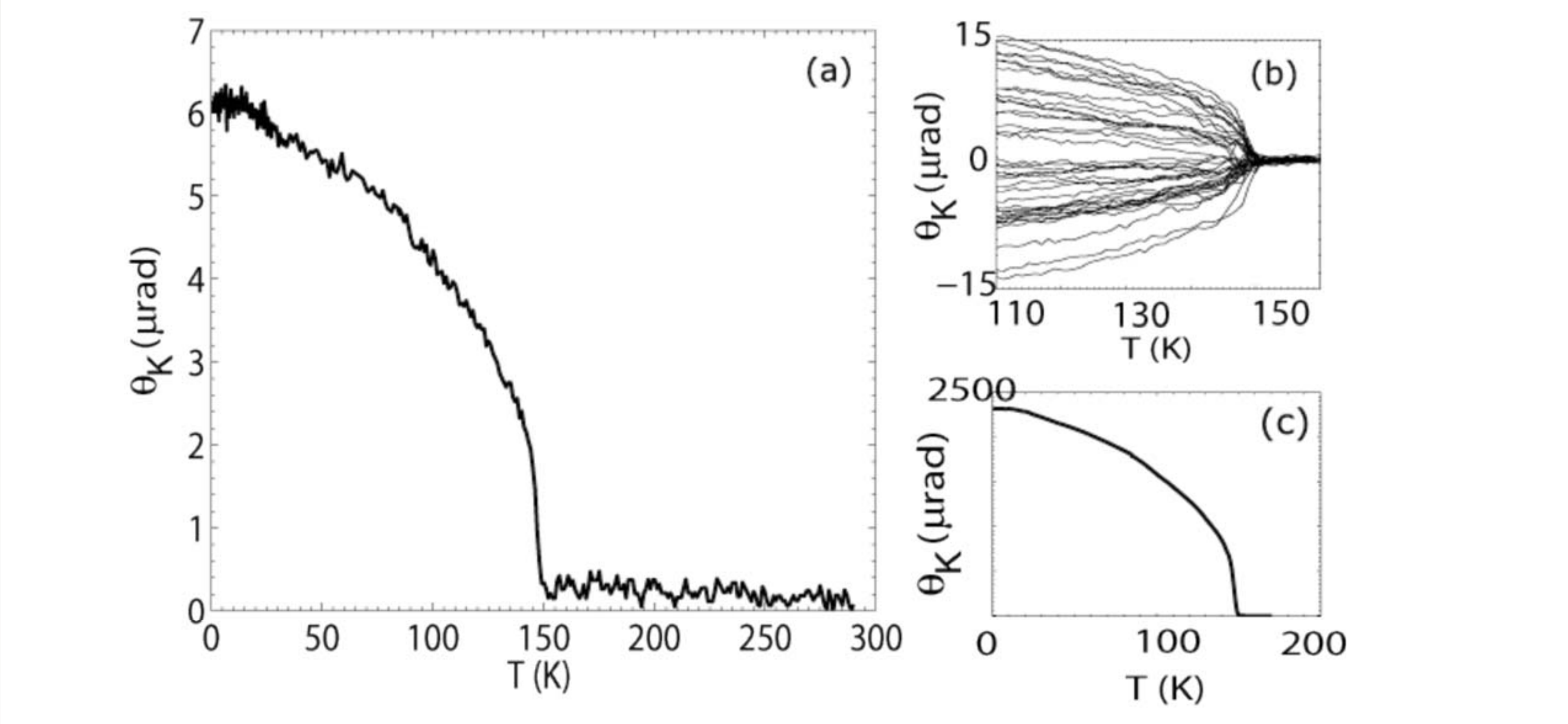
10 minutes



Typical Drift: **10-20 nrad** over a day after careful alignment

Best resolution achieved at a **fixed temperature**: **<10 nrad**

Kerr effect measurements of ferromagnetic Transition in $SrRuO_3$



Polar Kerr effect from a 30 nm $SrRuO_3$ thin film. (a) Kerr rotation in zero magnetic field with temperature down to 0.5 K. (b) Kerr rotations of the same sample measured in different cool-downs in zero fields. (c) Kerr rotation in a saturation field of 200 Oe.

Jing Xia, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik. Appl. Phys. Lett. 89, 062508

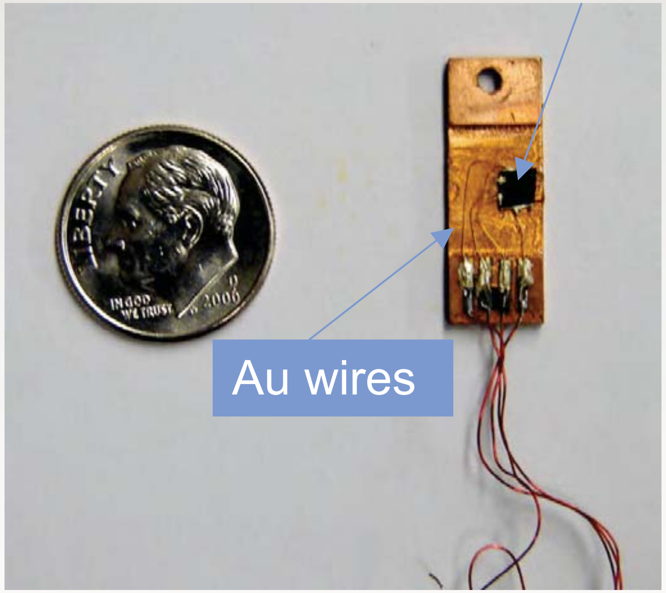
Kerr effect measurements of Sr_2RuO_4

Jing Xia

Marty Fejer
Peter Beyersdorf

Samples:

Yoshi Maeno, Kyoto University

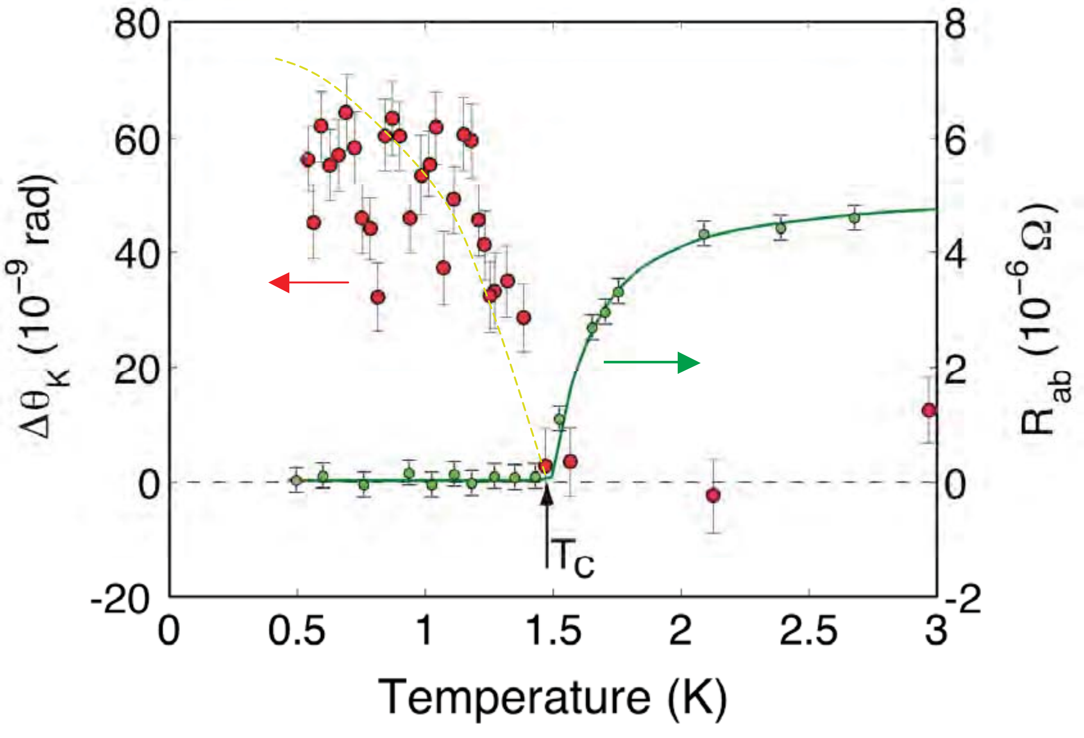


3X3X0.3 mm crystal

Au wires

Jing Xia, Yoshiteru Maeno, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik, Phys. Rev. Lett. 97, 167002 (2006)

Zero field cool



Beam size = 20 μm
Incident power =0.7÷ 2 μW

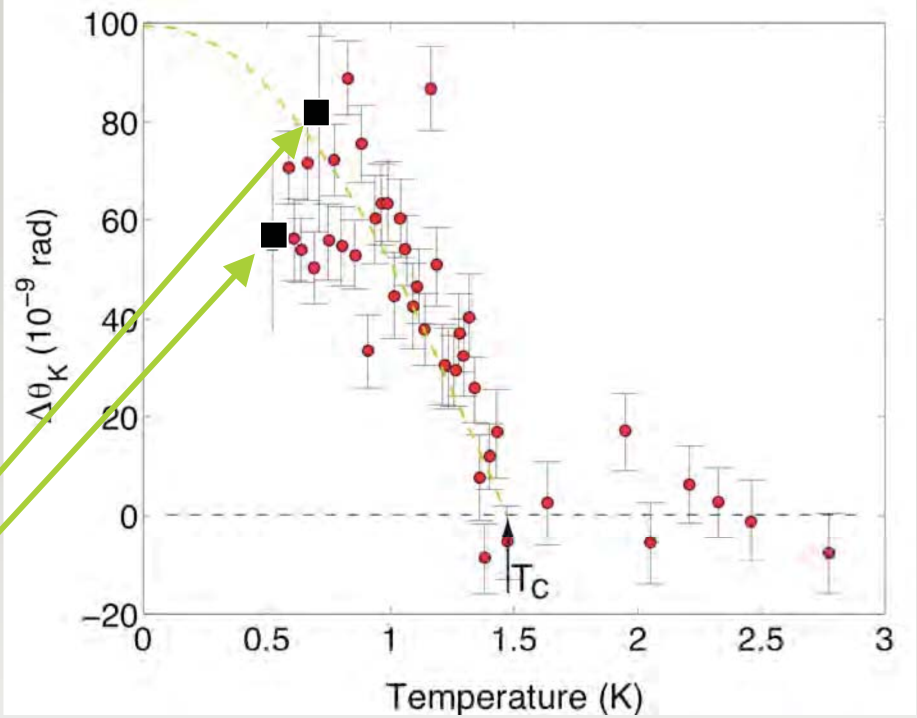
Sign of zero-field-cool data is random

Maximum Kerr rotation of zero-field-cool ~ 65 nanorad

Train the chirality with magnetic field:

cool in H=+97 Oe

Warm up in H=0

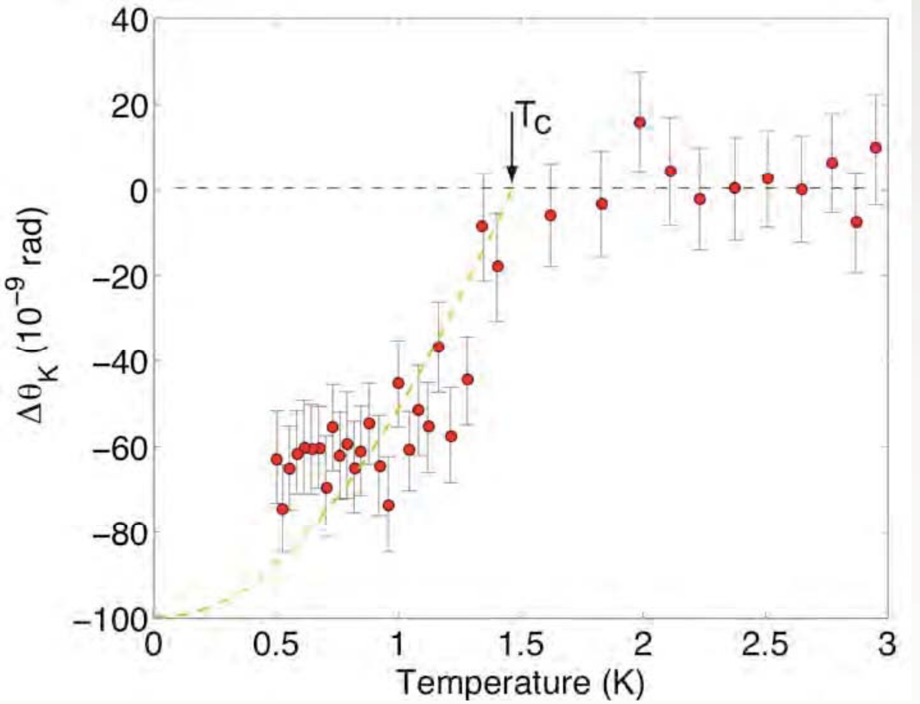


Last two points before field switched to zero.

Dashed lines are guide to the eye

cool in H=-47 Oe

Warm up in H=0



Some theory:

Victor Yakovenko, Phys. Rev. Lett. 98, 087003 (2007)

Start with the lagrangian: $$L = \begin{pmatrix} i\partial_t + \boldsymbol{\nabla}^2/2m + \mu & i(\boldsymbol{\nabla}\cdot\boldsymbol{\Psi} + \boldsymbol{\Psi}\cdot\boldsymbol{\nabla})/2 \\ i(\boldsymbol{\nabla}\cdot\boldsymbol{\Psi}^* + \boldsymbol{\Psi}^*\cdot\boldsymbol{\nabla})/2 & i\partial_t - \boldsymbol{\nabla}^2/2m - \mu \end{pmatrix}$$

where: $$\boldsymbol{\Psi} = \Delta_x\hat{x} + i\Delta_y\hat{y}$$

Calculate the off-diagonal part of the conductivity:

$$\theta_K = \frac{2\pi}{\tilde{n}(\tilde{n}^2-1)}\,\frac{e^2}{d}\,\frac{\Delta^2}{(\hbar\omega)^3}$$

Estimate: $$\theta_K \approx 5\times 10^{-8}\frac{\Delta^2}{(k_B T_c)^2} \approx 200 \ \ \text{nanorad}$$

More theory:

Vladimir Mineev, Phys. Rev. B 76, 212501 (2007).

Using phenomenological two-fluid model we derive the Kerr rotation of the polarization direction of reflected light from the surface of a superconductor in a state breaking time-reversal symmetry. We argue that this effect found recently in superconducting state of Sr_2RuO_4 by Xia et al (Phys.Rev.Lett. 97, 167002 (2006)) originates from the spontaneous magnetization in this superconductor.

$$\theta_K \approx \overbrace{\frac{e^2 k_F}{\pi \enclose{circle}{\hbar\omega}} \frac{\Delta^2}{(\hbar\omega_p)^2}}^{\text{Chiral state}} - \cancelto{\text{negligible}}{\overbrace{\frac{n_n}{n\omega\tau}\frac{eH_s}{mc\omega}}^{\text{Vortex contribution}}}$$

Estimate: $\theta_K \approx 2 \times 10^{-8} \frac{\Delta^2}{(k_B T_c)^2} \approx 80 \;\; \text{nanorad}$

HOWEVER:

In the equation for the transverse current:

$$\vec{j} = \sigma_{xy}\left[\vec{E} - \underbrace{\frac{1}{2e}\frac{\partial}{\partial t}\left(\vec{\nabla}\varphi - \frac{2e}{c}\vec{A}\right)}\right] \times \hat{z}$$

both Yakovenko and Mineev neglect the second term as being ineffective at high frequencies.

The correct derivation requires to find the equation of motion to the superconducting phase φ and substitute it in the above equation for the current. When this is done correctly, and in the absence of scattering, the second term IS the Meissner term and cancels the electric field. The result is that $\vec{j} = 0$

Comment #1:

The beam of light IS NOT a plane wave. It is of finite size with a gaussian profile and thus includes electric field gradients. This leads to a finite effect, of the same order as before that now depends on the size of the beam*:

$$\theta_K \approx \theta_K^0 \times C \times \left(\frac{\lambda}{d_{beam}}\right)^2$$

➔ Signal too small to measure!

---

* Lutchyn & Yakovenko, PRB 77, 144516 (2008); R. Roy and C. Kallin, PRB 77, 174513 (2008)

Comment #2:

It has been shown that impurity scattering induces a finite Kerr effect in a Chiral $p_x \pm ip_y$ superconductor.

Jun Goryo, arXiv:0806.0548v4 [cond-mat.supr-con]

$$\sigma_{xy}^{(v)}(\omega) = \gamma_{BCS}^2 \left(1 - \frac{T}{T_c}\right) \frac{l_i}{\xi_0} \left(\frac{\epsilon_F}{\pi\tau_0}\right)^{3/2} \frac{\sigma_{xy}^{(0)}}{(\omega + i/\tau_0)^3}$$

$$\sigma_{xy}^{(0)} = e^2/2\pi d$$

$$\gamma_{BCS} = |\Delta(0)|/T_c$$

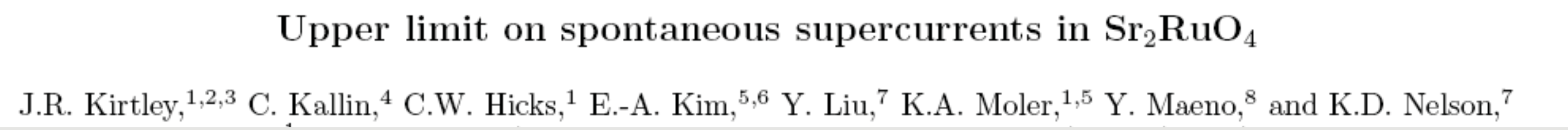
$$q_z^{\pm} = \sqrt{\omega^2 + i\omega\sigma_{xx}^{(v)}(\omega) \pm \omega\sigma_{xy}^{(v)}(\omega)}$$

$$\theta_K = -\mathrm{Im}\left(\frac{\omega(q_z^+ - q_z^-)}{\omega^2 - q_z^+ q_z^-}\right)$$

Goryo obtains $\theta_K \sim 60$ nanorad using measured materials parameters!

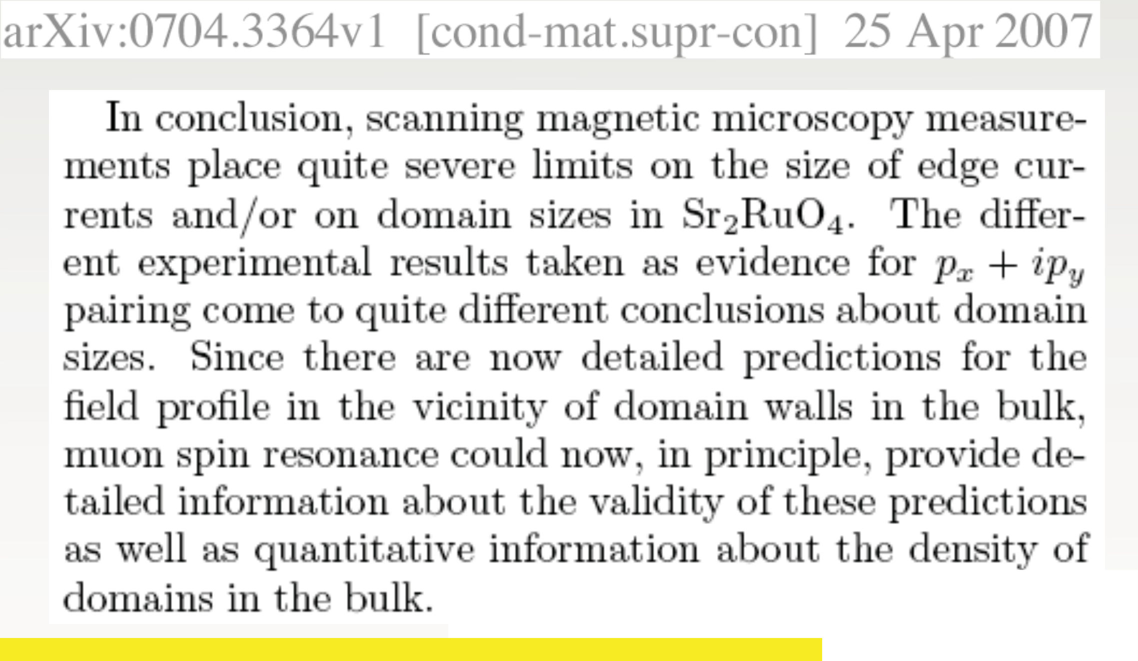
However:

Among other consequences of $p \pm ip$ is the existence of edge currents and currents between domain walls.



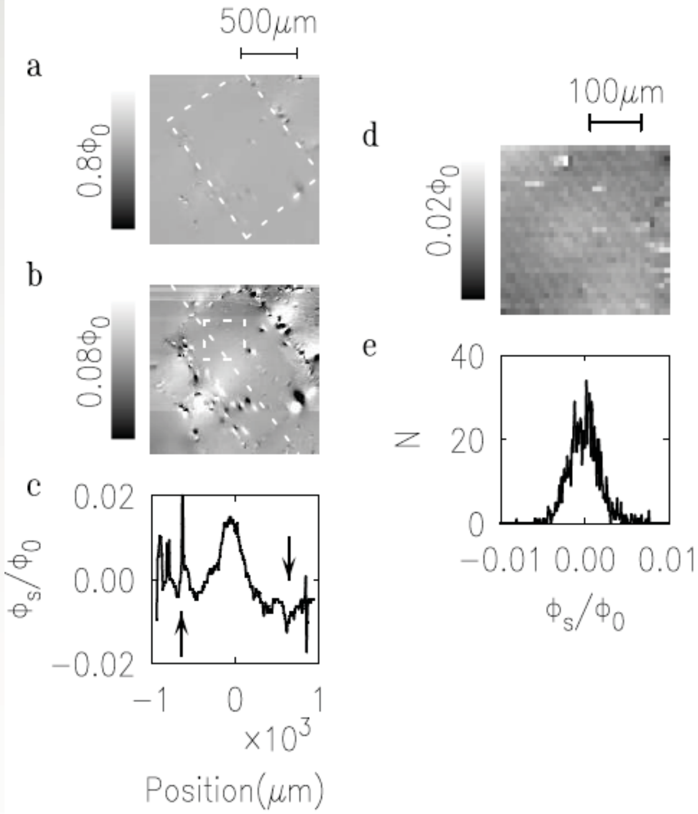
Upper limit on spontaneous supercurrents in Sr_2RuO_4

J.R. Kirtley,[1,2,3] C. Kallin,[4] C.W. Hicks,[1] E.-A. Kim,[5,6] Y. Liu,[7] K.A. Moler,[1,5] Y. Maeno,[8] and K.D. Nelson,[7]



arXiv:0704.3364v1 [cond-mat.supr-con] 25 Apr 2007

In conclusion, scanning magnetic microscopy measurements place quite severe limits on the size of edge currents and/or on domain sizes in Sr_2RuO_4. The different experimental results taken as evidence for $p_x + ip_y$ pairing come to quite different conclusions about domain sizes. Since there are now detailed predictions for the field profile in the vicinity of domain walls in the bulk, muon spin resonance could now, in principle, provide detailed information about the validity of these predictions as well as quantitative information about the density of domains in the bulk.



No detected edge currents!

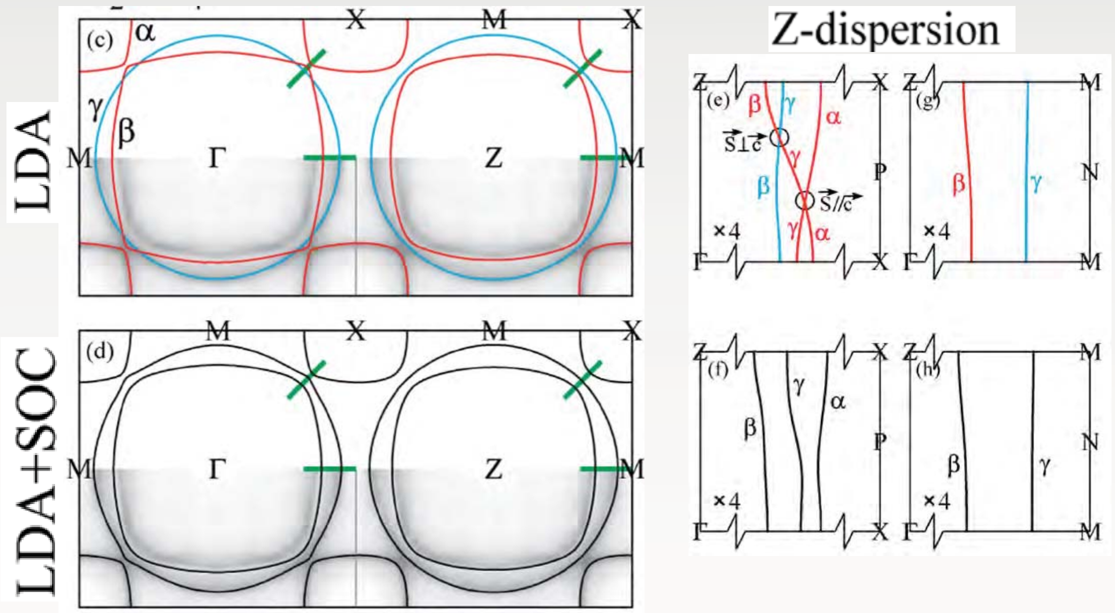
Comment #3:

It has been shown very recently that spin-orbit interaction in Sr_2RuO_4 is very strong in parts of the Fermi surface.

M.W. Haverkort, I. S. Elfimov, L. H. Tjeng, G. A. Sawatzky, and A. Damascelli, Phys. Rev. Lett. 101, 026406 (2008); Guo-Qiang Liu, V. N. Antonov, O. Jepsen, and O.K. Andersen, Phys. Rev. Lett. 101, 026408 (2008).

Spin-orbit coupling induces a strong momentum dependence, normal to the RuO_2 planes, for both orbital and spin character of the low-energy electronic states.

The superconducting state will be characterized by some mixture of triplet and singlet superconductivity.



While TRSB may still exist with spin-orbit scattering, edge currents may be destroyed.

Phase sensitive measurements:
evidence for $p_x \pm ip_y$

Dynamical Superconducting Order Parameter Domains in Sr_2RuO_4

Francoise Kidwingira,[1] J. D. Strand,[1] D. J. Van Harlingen,[1]* Yoshiteru Maeno[2]

- Interference patterns consistent with $p_x \pm ip_y$
- Switching effects consistent with surface domains of order ~0.5 μm

But,
These are surface domains!

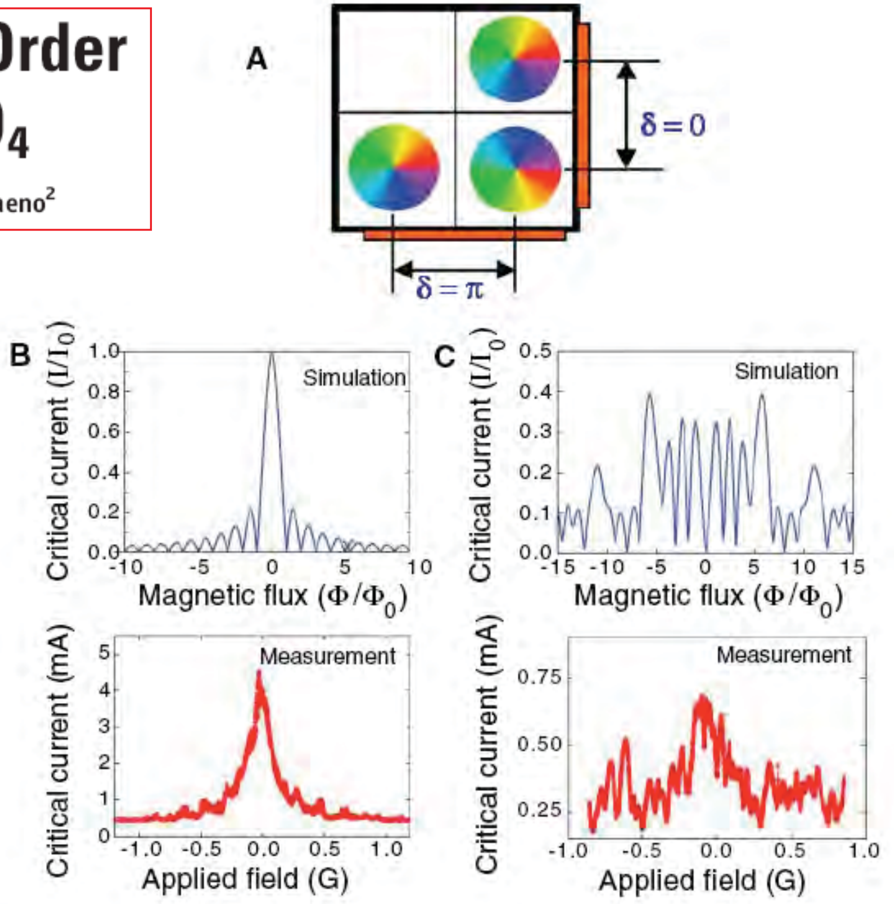


Fig. 4. (**A**) Graphical representation of an SRO crystal with parallel chiral domains showing the order parameter phase winding in opposite directions. The phase difference between domains, δ, is zero in one tunneling direction and π on the orthogonal face. (**B** and **C**) Computer simulations of the diffraction patterns for junctions on orthogonal crystal faces with 10 parallel domains of random size, compared with measurements on those junctions.

Summary of observations:

- Maximum signal is ~65 ÷ 100 nanorad
- Signal onsets at T_C
- Temperature dependence of signal can be fitted with a quadratic dependence on the gap. [$\theta_K \propto \Delta^2 \propto (T_c - T)$]
- Chirality can be trained with a magnetic field.

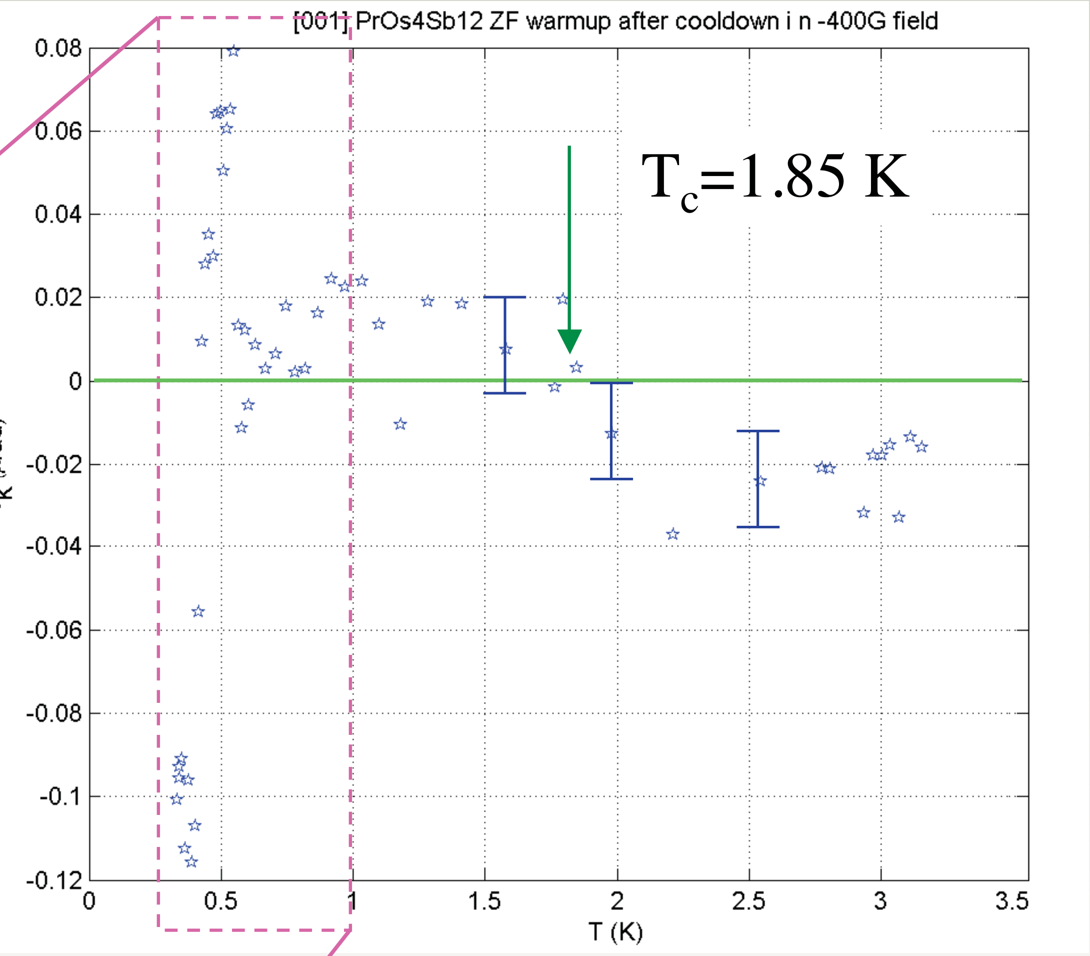
  A minimum field is needed.
- Domain size is large, of order beam size >20 μm (or larger)

  Zero-field cool statistics show some fluctuations
- Signal cannot be explained by trapped flux

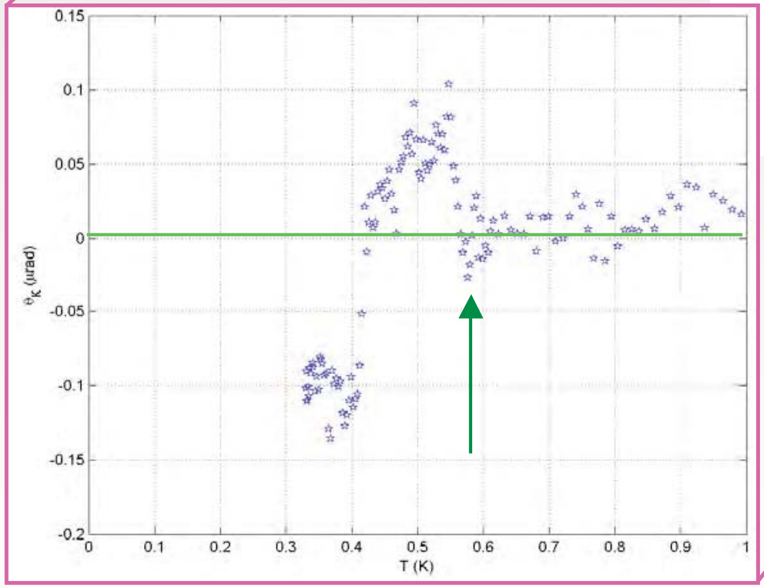
  max. zero-field cool signal equals field cool
- There is no Light-power dependence on the size of the signal (no heating effect).

$PrOs_4Sb_{12}$

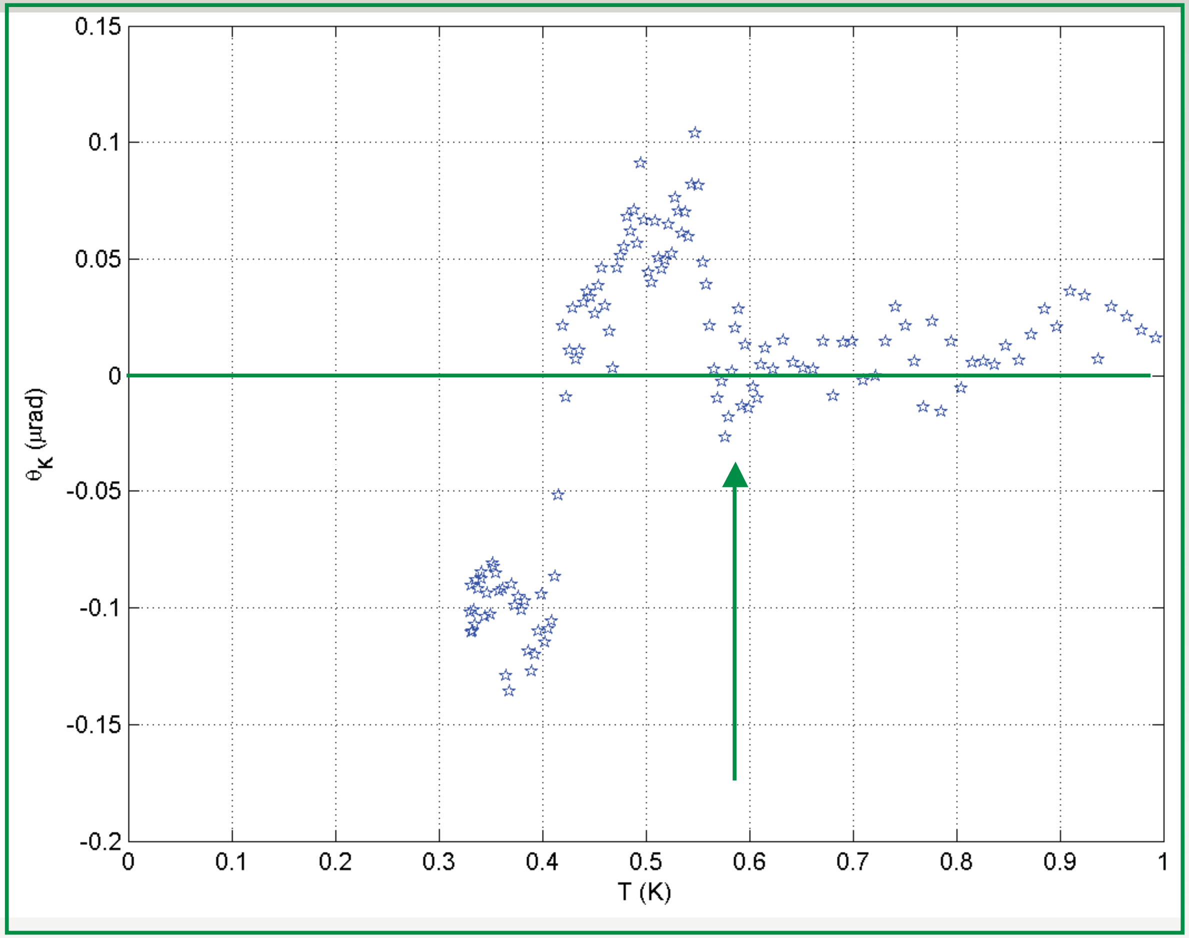
Cool down in -400 Oe
Then
Turn field
to zero

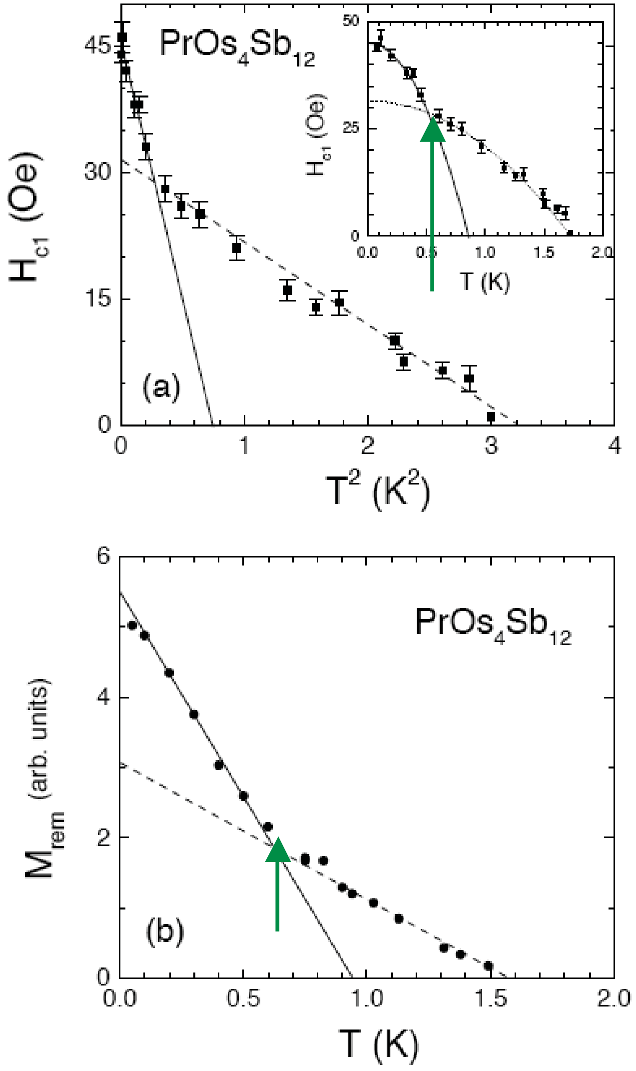


Measure on
Warming up
From 0.3 K



$PrOs_4Sb_{12}$



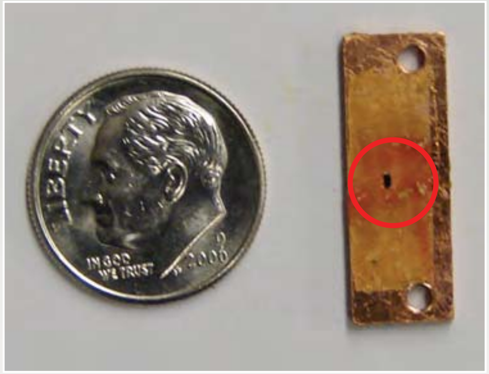


T. Cichorek, A. C. Mota, F. Steglich, N. A. Frederick, W. M. Yuhasz, M. B. Maple, PRL 94, 107002 (2005)

Kerr effect measurements of underdoped $YBa_2Cu_3O_{6+x}$

Jing Xia
Elizabeth Schemm

Marty Fejer
Steven Kivelson



Samples:

D. Bonn and R. Liang (UBC) - YBCO single crystals
Gertjan Koster & Wolter Siemons (Stanford) - YBCO films
G. Deutscher's group (TAU) - YBCO films

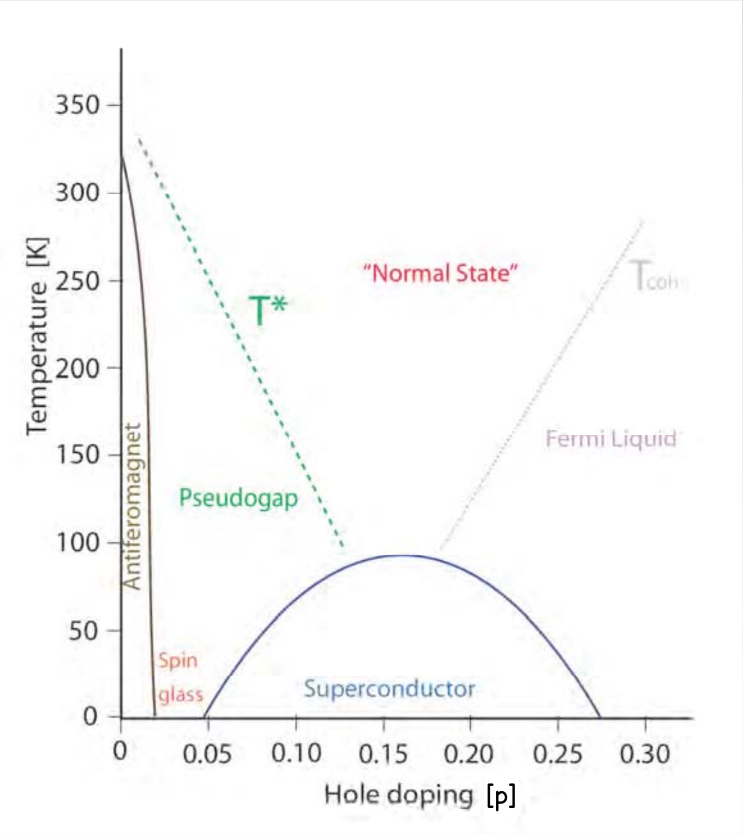
Two major classes of theories have been introduced in an attempt to describe the pseudogap state:

1. T* represents a crossover into a state with preformed pairs with a *d*-wave gap symmetry.

   (P. A. Lee, Physica C 317-318}, 194 (1999);
   V. J. Emery and S. A. Kivelson, Nature 374, 434 (1995))

2. T* marks a true transition into a phase with broken symmetry which ends at a quantum critical point, typically inside the superconducting dome.

   (S. Chakravary *et al.*, *PRB* **63**, 094503 (2001);
   C. M. Varma, Phys. Rev. B 55}, 14554 (1997))

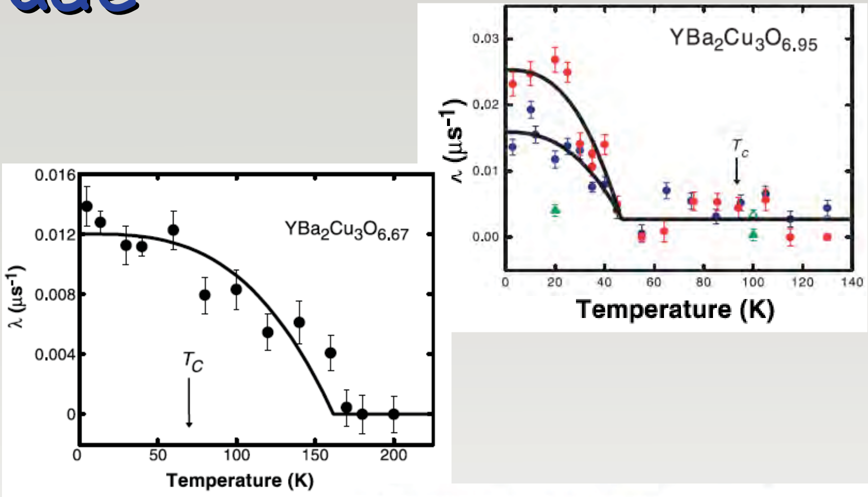


(Schematic) Phase diagram of YBCO

Recent experiments to search for current loop order include

Muon spin relaxation

J.E. Sonier, J.H. Brewer, R.F. Kiefl, R.I. Miller, G.D. Morris, C.E. Stronach, J.S. Gardner, S.R. Dunsiger, D.A. Bonn, W.N. Hardy, R. Liang, R.H. Heffner, Science 292, 1692 (2001).

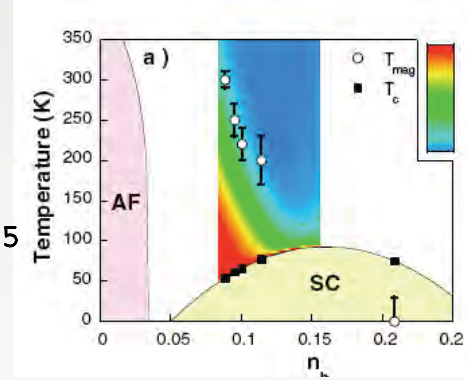


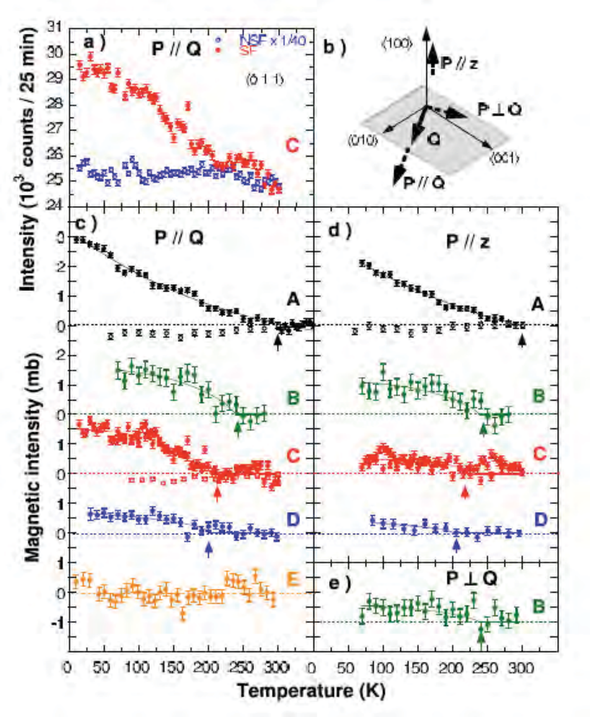
Neutron scattering

C. Stock, W.J.L. Buyers, Z. Tun, R. Liang, D. Peets, D. Bonn, W.N. Hardy, L. Taillefer, *Phys. Rev. B* **66**, 024505 (2002)

B. Fauqué, Y. Sidi, V. Hinkov, S. Pailhes, C.T. Lin, X. Chaud, P. Bourges, *Phys. Rev. Lett.* **96**, 197001 (2006).

H.A. Mook, Y. Sidis, B. Fauqué, V. Balédent, P. Bourges, arXiv:0802.3620 (2008).





More data is needed that is relevant to magnetic properties of YBCO

Use of magneto-optical effects to probe these properties has the advantages of

- Bulk measurement capability
- Ability to use highest quality (often tiny) samples
- Ability to probe both normal and superconducting states

In addition, polar Kerr effect measurements using the loopless Sagnac interferometer provide

- High resolution of magnetic (or other TRSB) signals

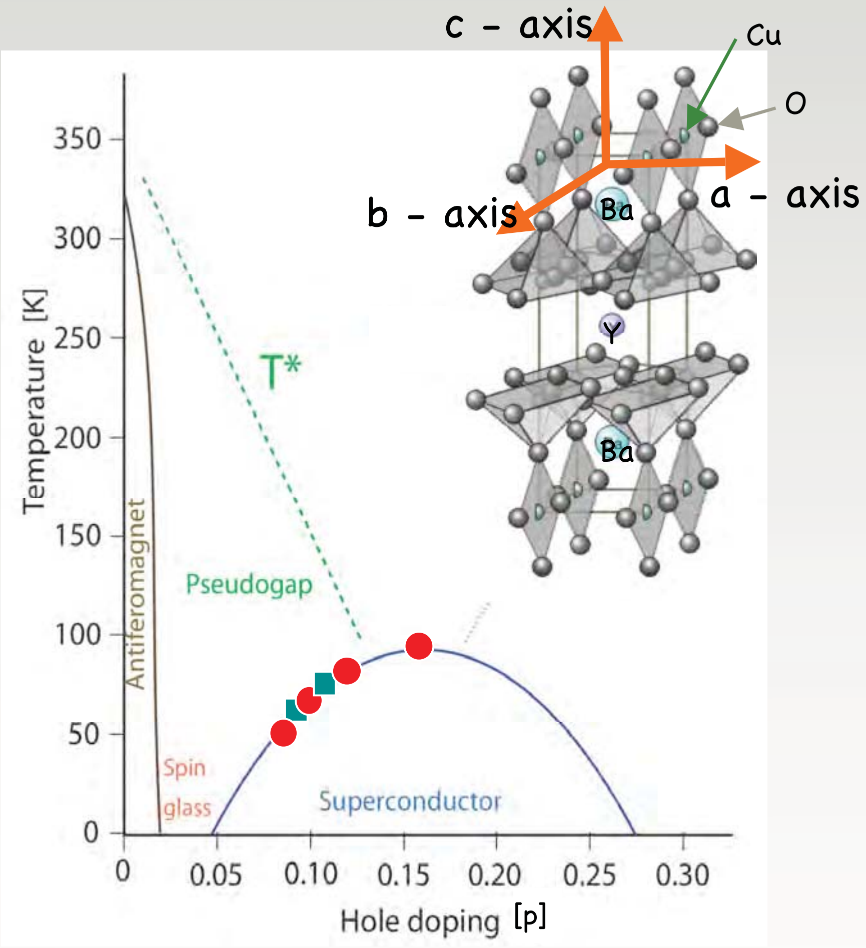
Sagnac measurements: samples

Single crystals (UBC)
- Ortho-I,II,III,VIII
- Mechanically detwinned
- Aligned for measurement along the *c*-axis

(D. Bonn, R. Liang, W. Hardy)

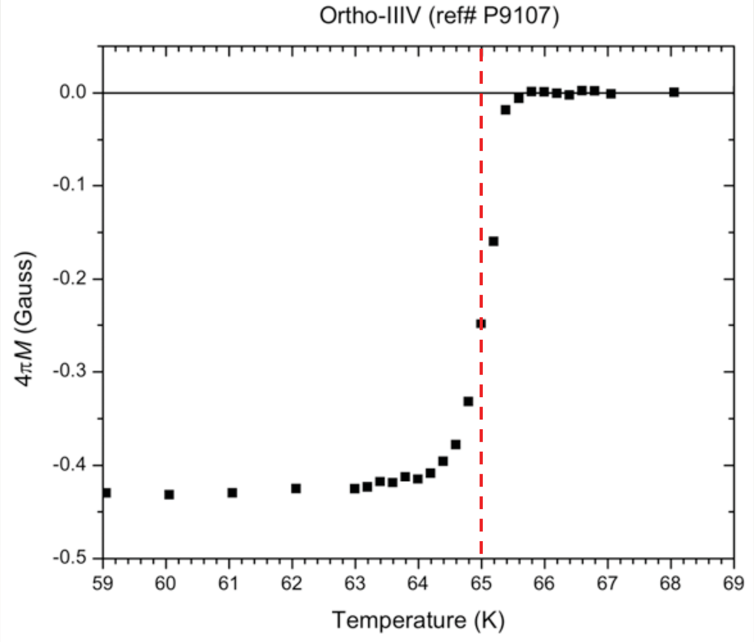
c-axis thin films (Conductus/Stanford)
- Underdoped through annealing in reduced atmosphere

(G. Koster, W. Siemons)

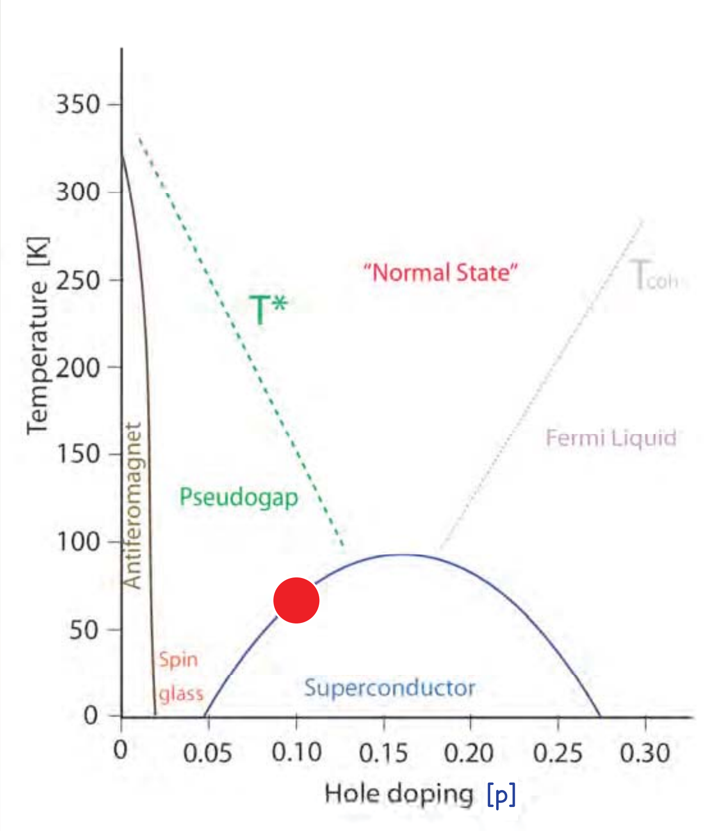


Anatomy of a data set
Ex: $YBa_2Cu_3O_{6.67}$ (ortho-VIII), underdoped single crystal

T_c = 65 K



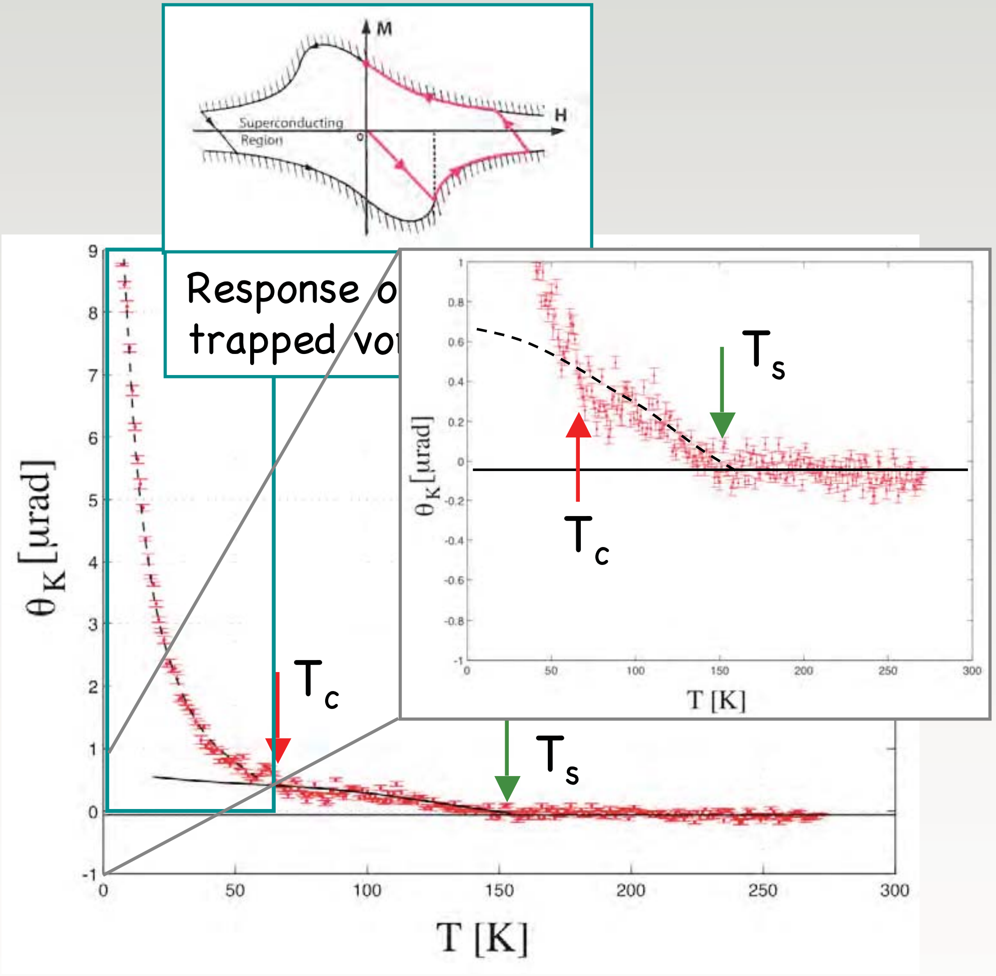
Magnetization data courtesy of D. Bonn



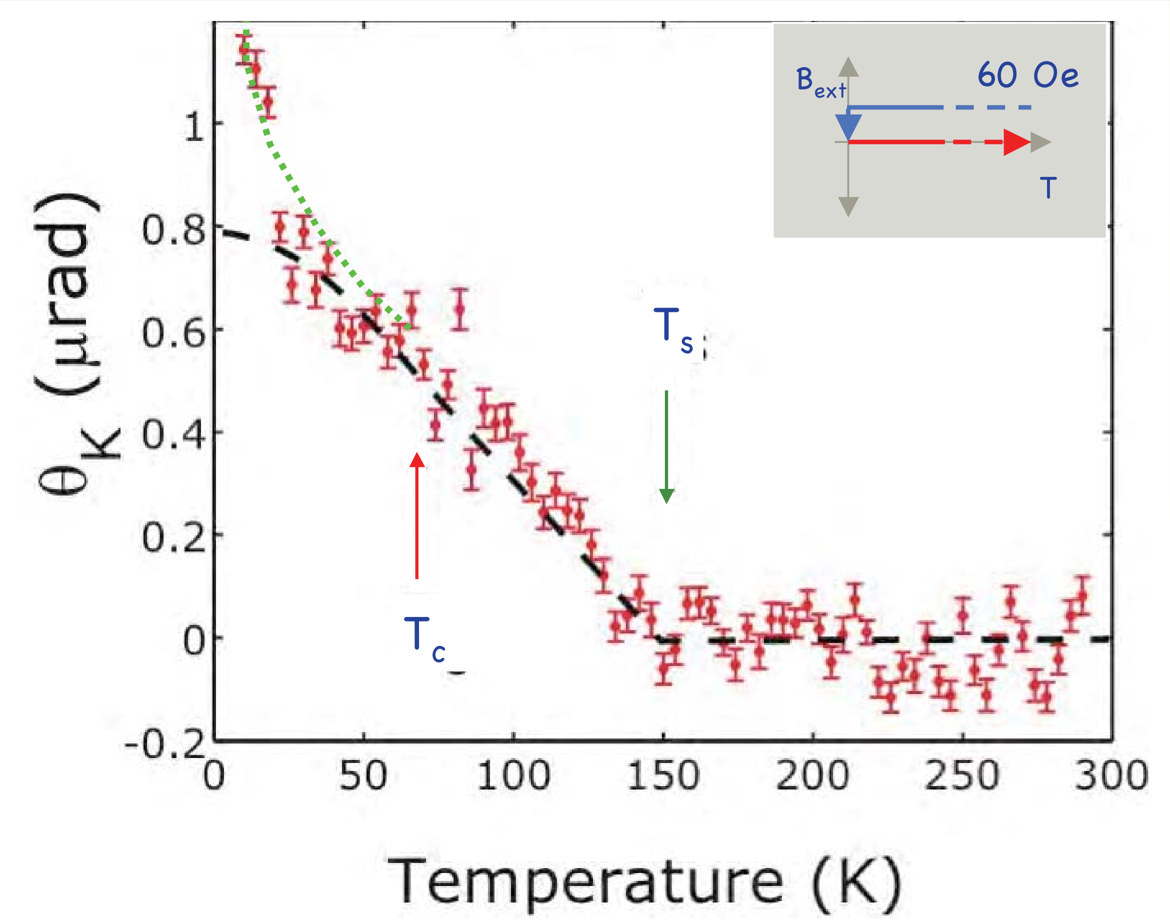
Anatomy of a data set
Ex: $YBa_2Cu_3O_{6.67}$ (ortho-VIII), cooled in high field

We note three distinct régimes:

1. At high temperatures, flat (zero) Kerr rotation
2. Below T_c, a signal dominated by trapped vortices
3. In some intermediate temperature range $T_c < T < T_s$, a small but nonzero Kerr signal



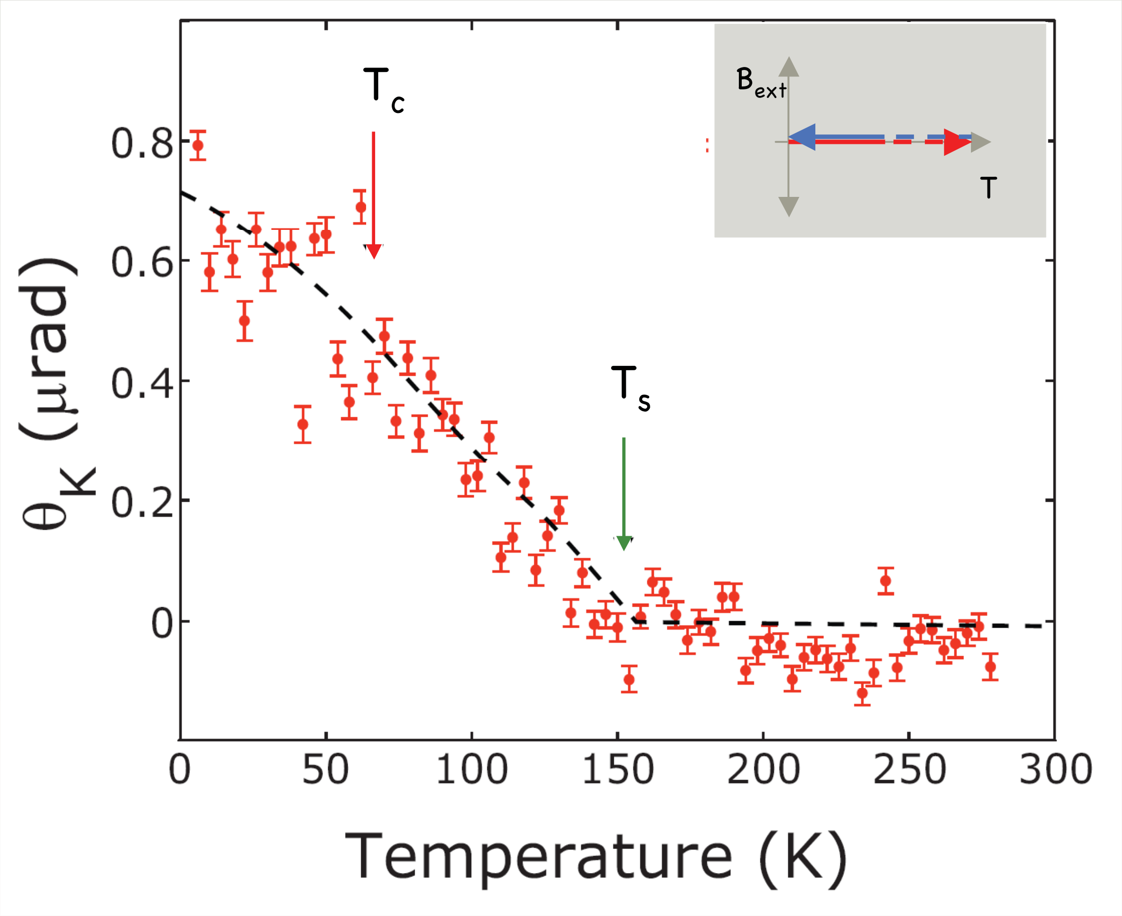
$YBa_2Cu_3O_{6.67}$: Reduce the effect of trapped vortices by cooling in a lower field



Now cool the sample in a smaller (60 Oe) positive field and warm up at zero field

The vortex signal below T_c is weaker, but the signal below T_s remains

$YBa_2Cu_3O_{6.67}$: Cooling in zero field eliminates the vortex effect



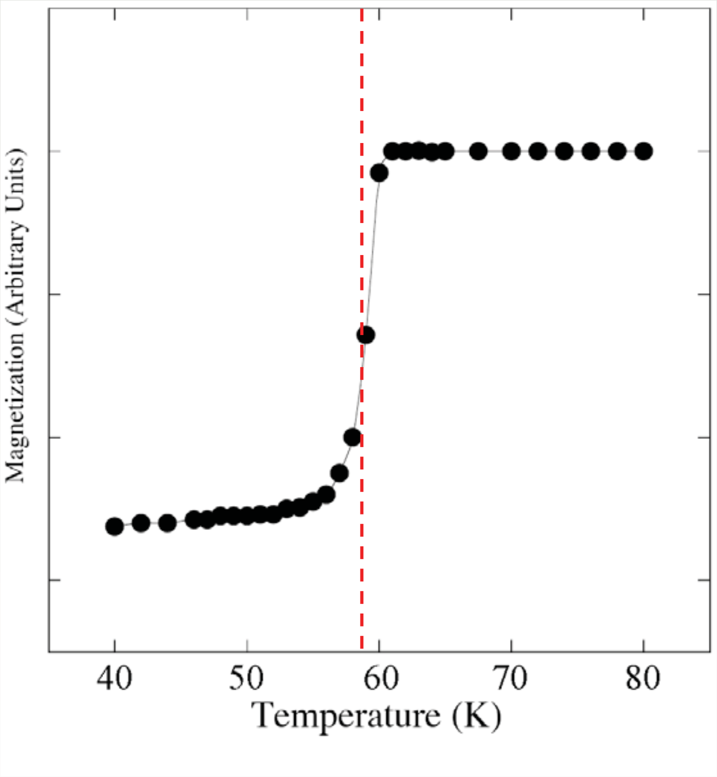
Zero field:
< 3 mOe

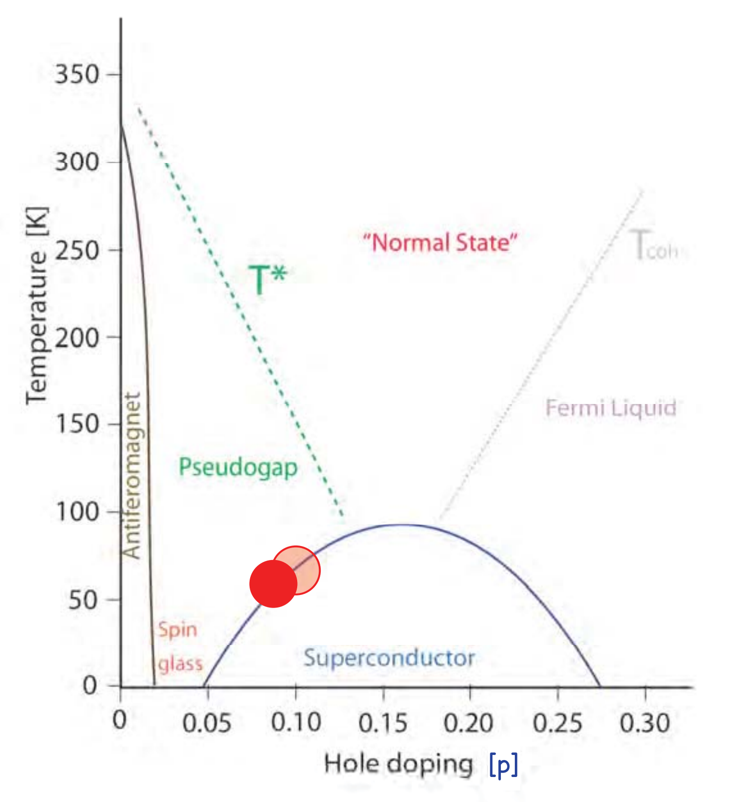
No contribution from trapped vortices

What remains is now <u>pure signal</u>

Repeat this exercise with other samples: $YBa_2Cu_3O_{6.5}$ (ortho-II)

T_c = 59 K

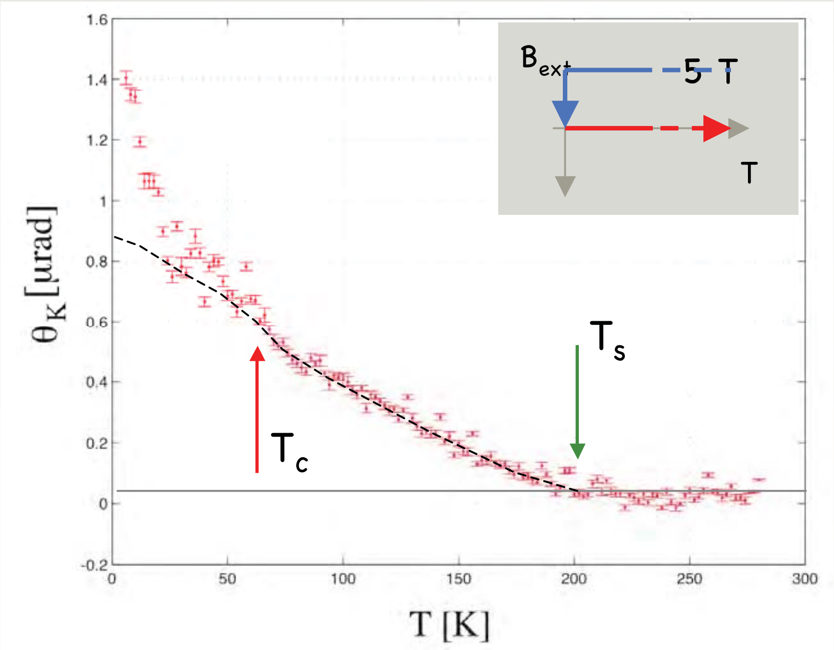


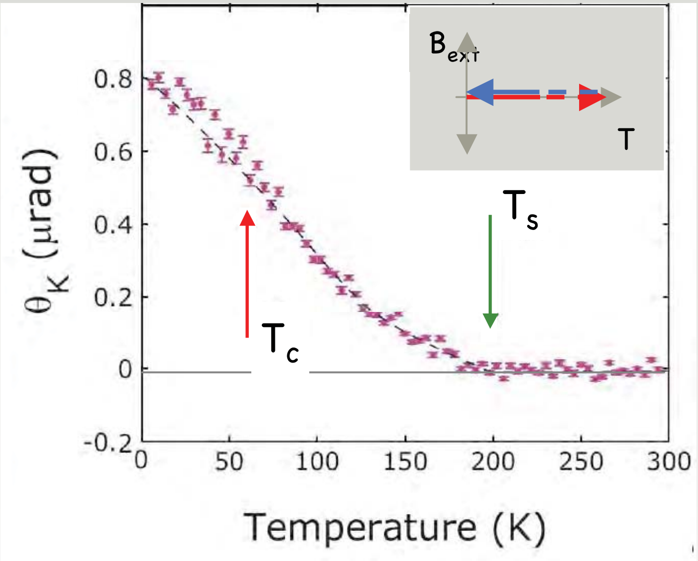


$YBa_2Cu_3O_{6.5}$: The same general Kerr behavior appears

Cool in high field (5 T), warm up in ZF:

- trapped vortex signal seen below T_c
- Kerr signal does not fall to zero until some higher T_s

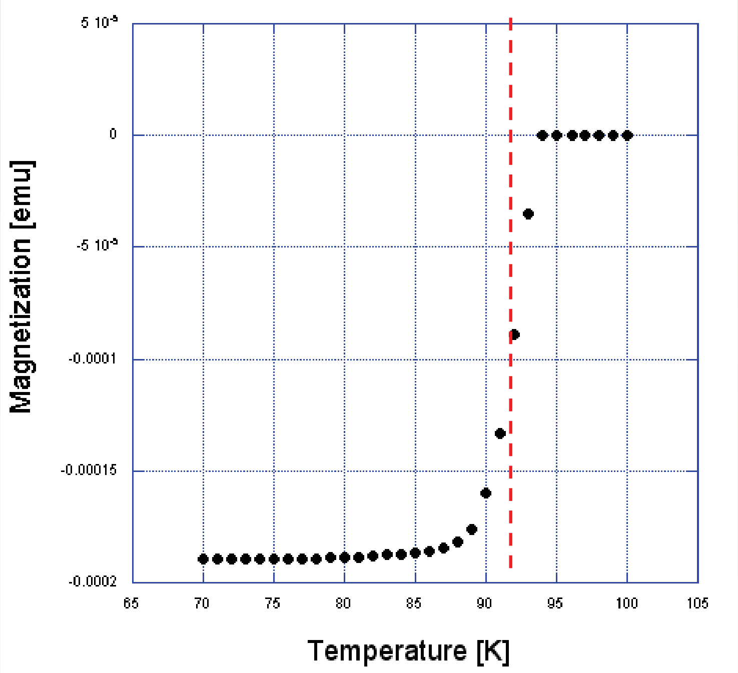


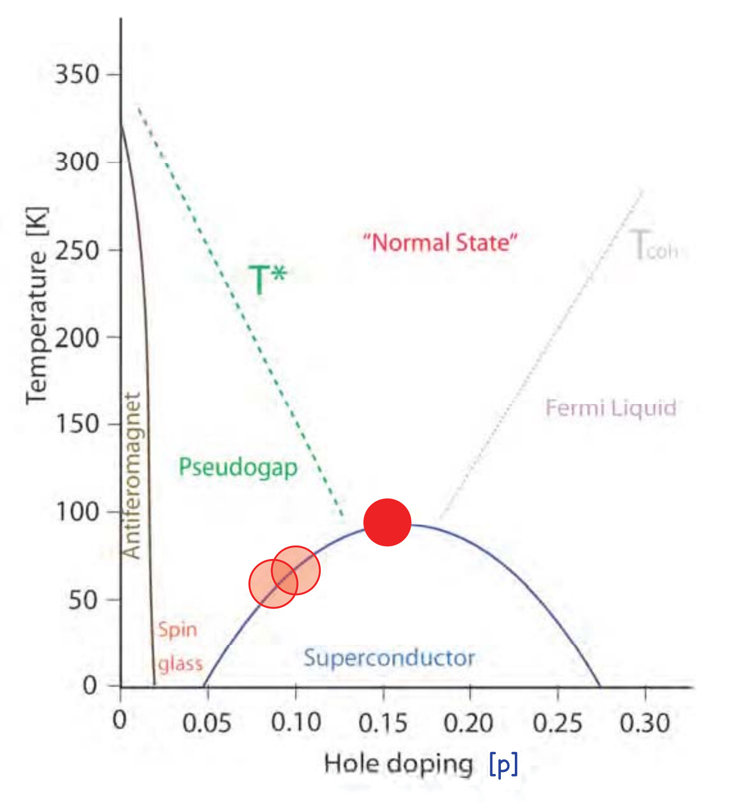


Cooling in zero field allows us to isolate the (non-vortex) signal below T_s

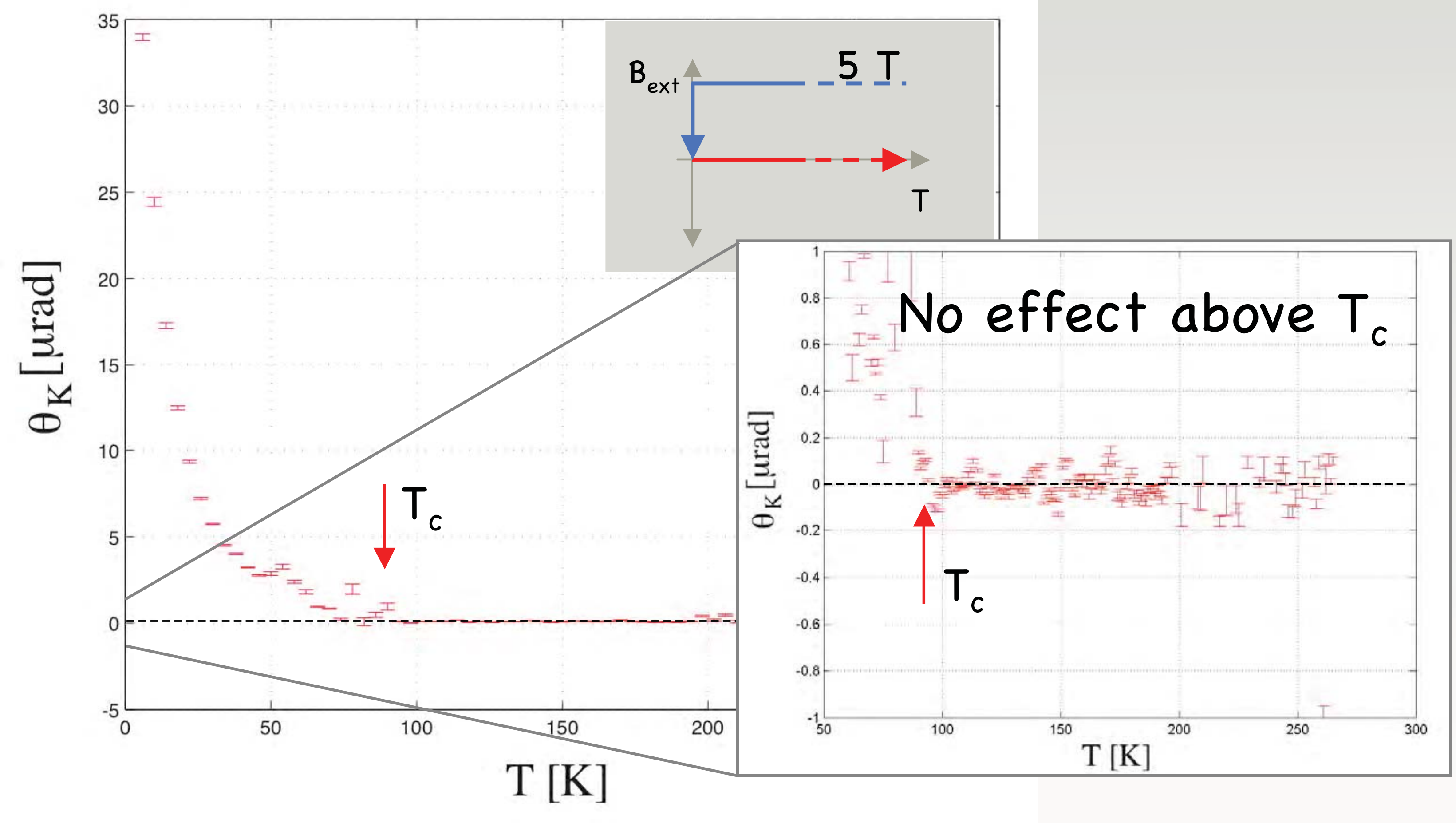
What happens near optimal doping?
$YBa_2Cu_3O_{6.92}$ (ortho-I)

T_c = 91.7 K





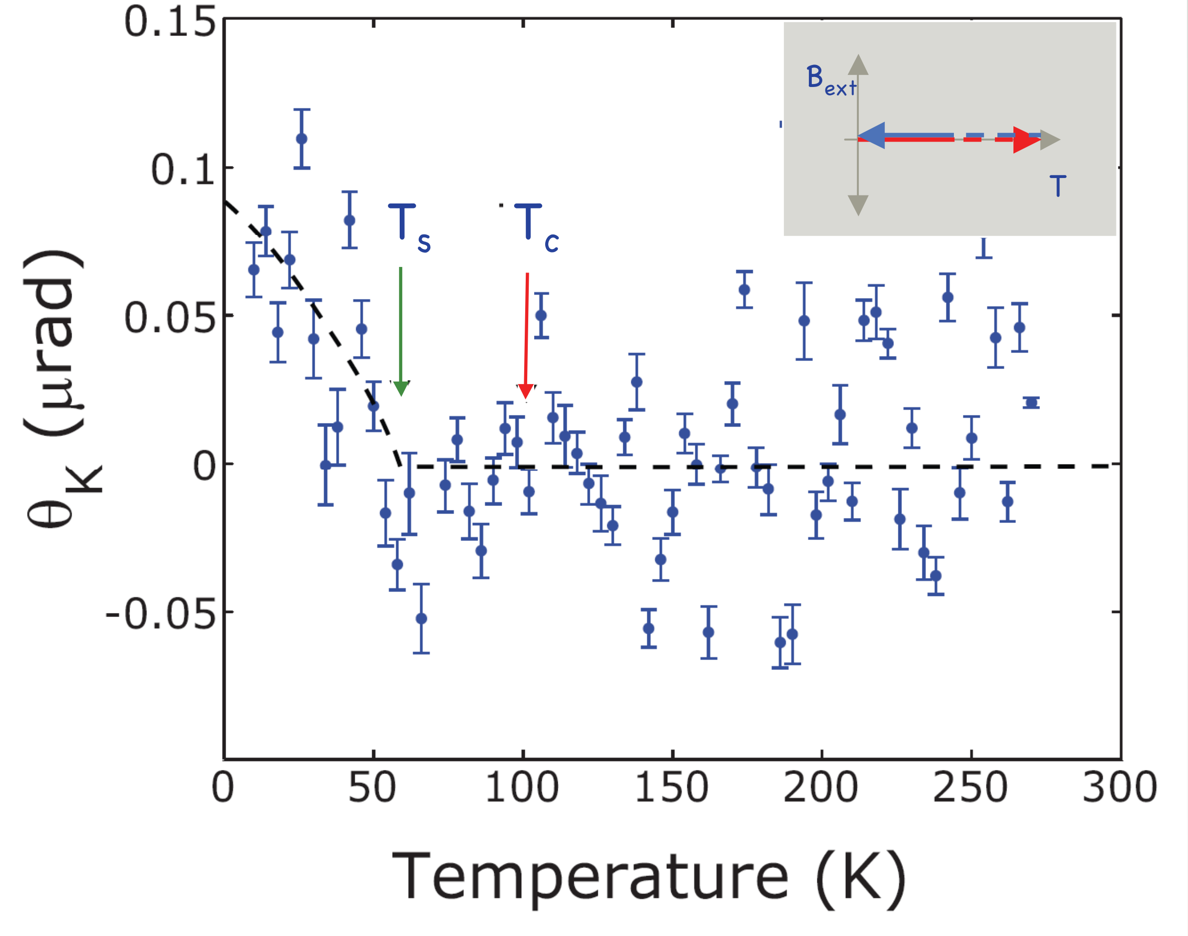
$YBa_2Cu_3O_{6.92}$: After cooling in high field, no signal is seen above T_c



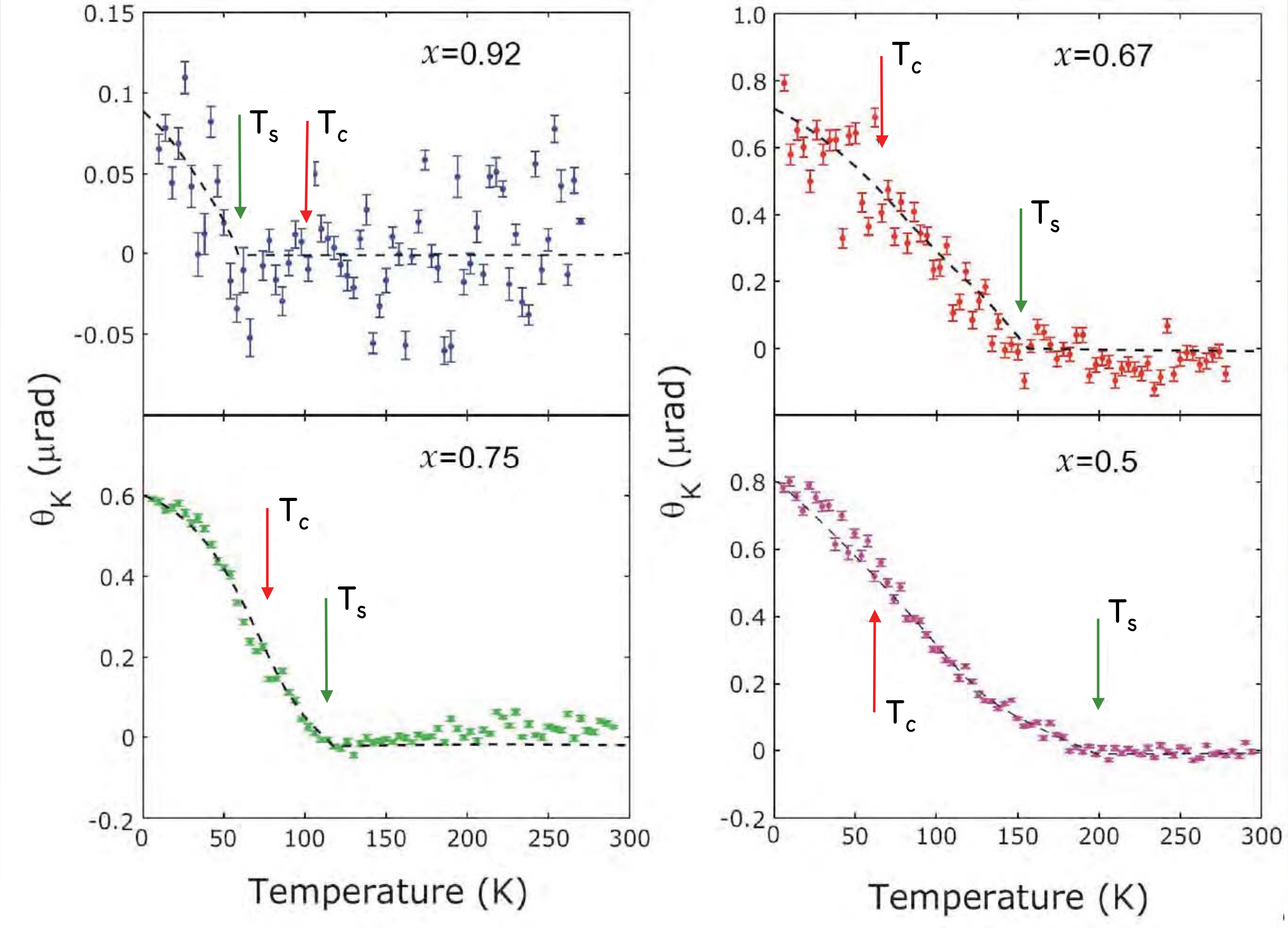
$YBa_2Cu_3O_{6.92}$: After cooling in ZF, the (pure) signal departs from zero *below* T_c

Zero field:
< 3 mOe

Eliminating the vortex contribution is now necessary to see the additional TRSB signal

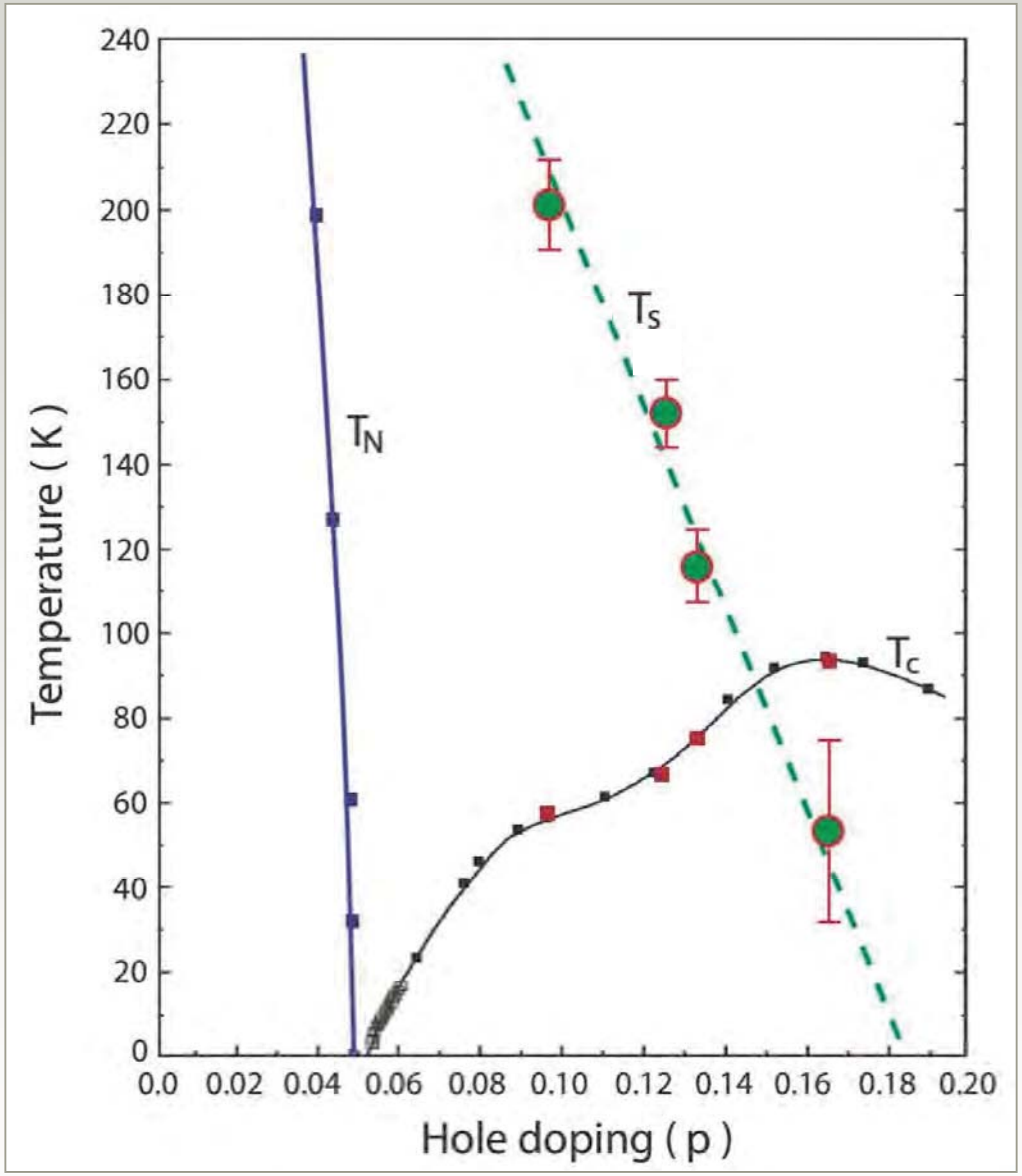


Data from all crystals (zero-field cool, zero-field warmup)



Summary of crystal data

$T_c(p)$ and $T_N(p)$ are experimentally determined[1] for the UBC crystals



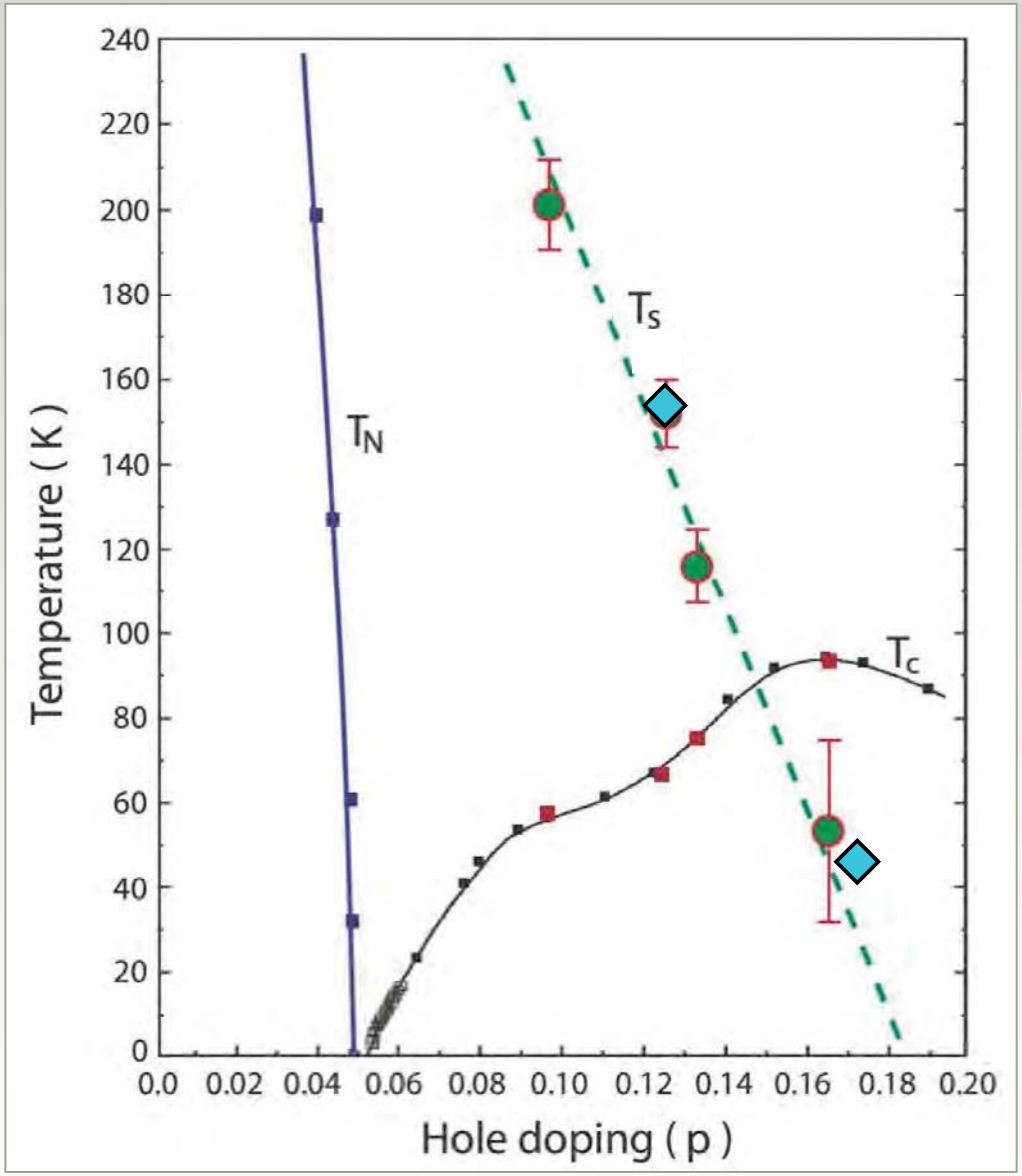
[1] Ruixing Liang, D. A. Bonn and W. N. Hardy, *Physica C* **336**, 57 (2000)

Comparison with μSR data (Sonier *et al.*)

Kerr effect (●)

μSR (◆)

n.b.: μSR measurements also performed on UBC crystals



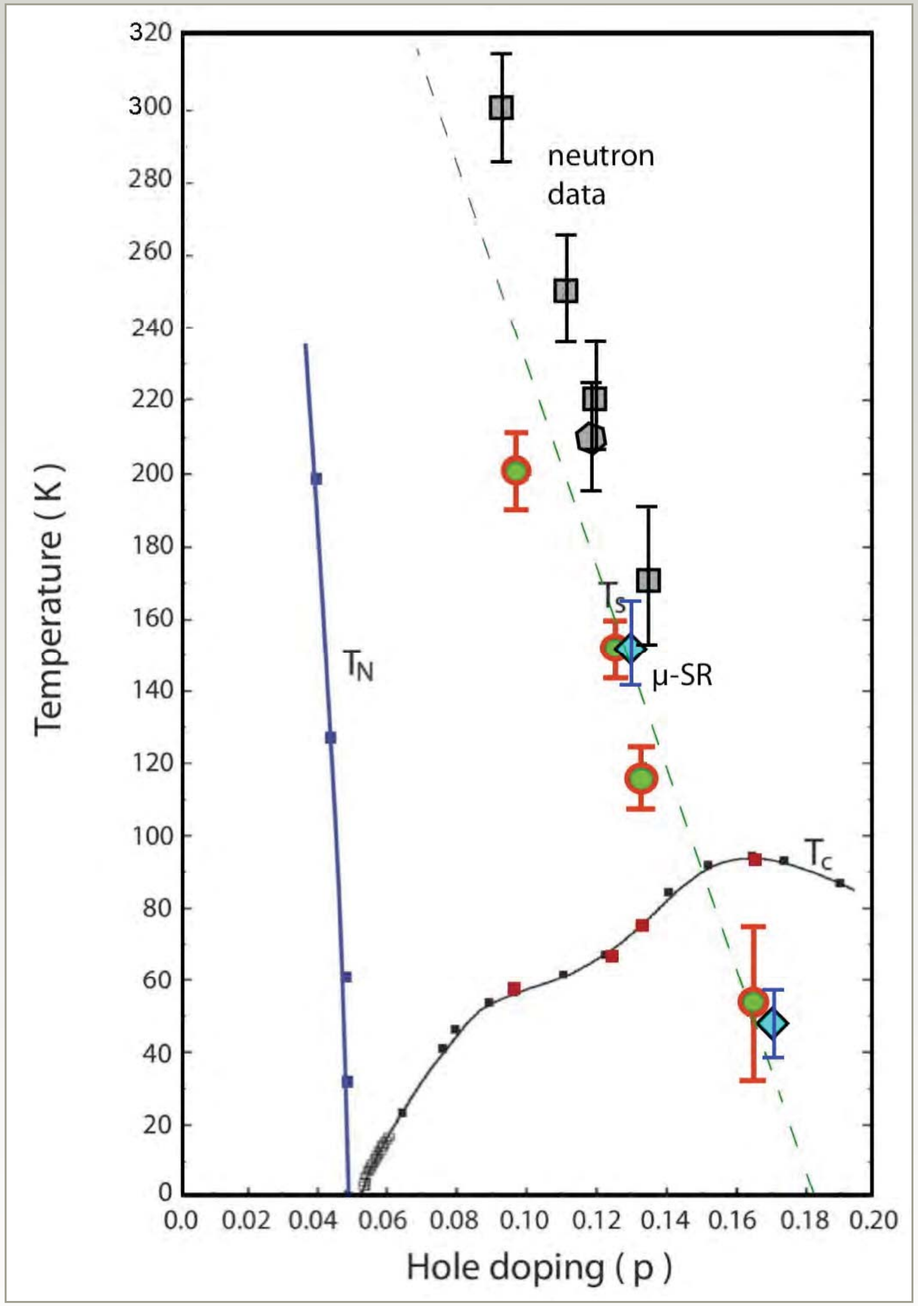
J. E. Sonier *et al.*, *Science* **292**, 1692 (2001)

Comparison with neutron data[1,2]

Kerr effect (●)

μSR (◆)

Elastic neutron scattering (■[1], ⬢[2])



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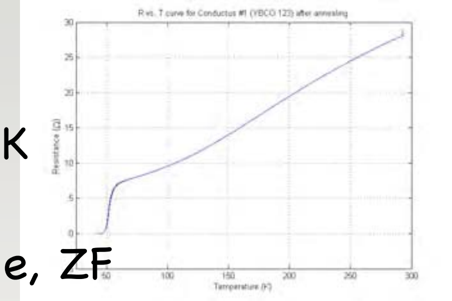
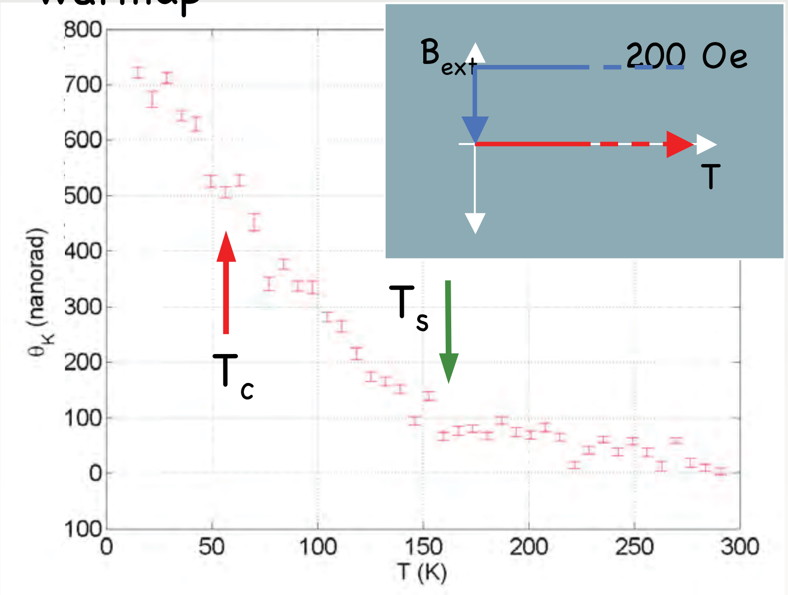
[1] B. Fauqué *et al.*, *PRL* **96**, 197001 (2006); [2] H. A. Mook *et al.*, arXiv:0802.3620 (2008)

Kerr data on underdoped c-axis thin films: A check on origins of the effect

~ $YBa_2Cu_3O_{6.65}$

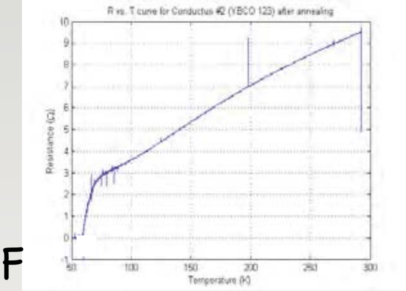
- T_c (onset) = 60 K
- T_s ≈ 160 K
- cooled in 200 Oe, ZF warmup

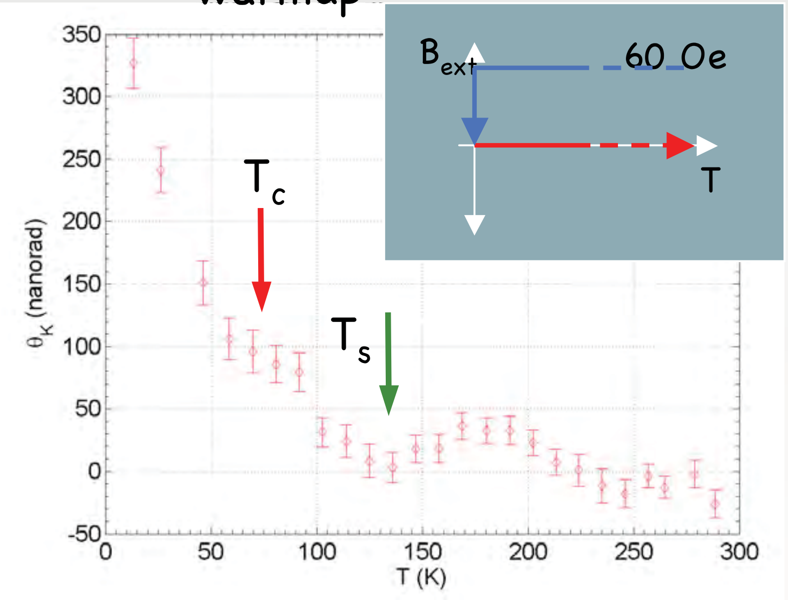




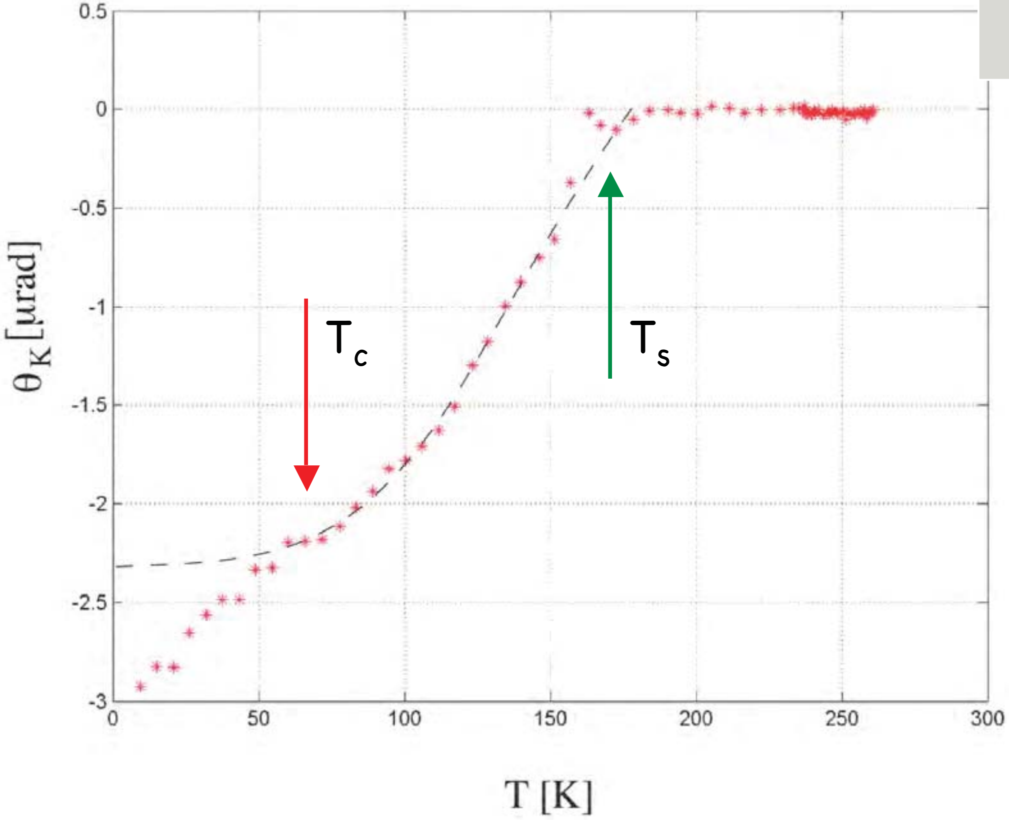
~ $YBa_2Cu_3O_{6.75}$

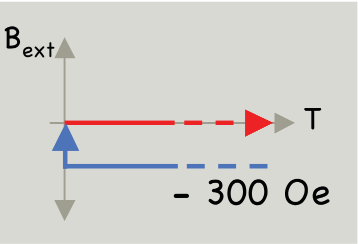
- T_c (onset) = 72 K
- T_s ≈ 140 K
- cooled in 60 Oe, ZF warmup





New Result (although only one film): Measurement along (110) ~$YBa_2Cu_3O_{6.65}$

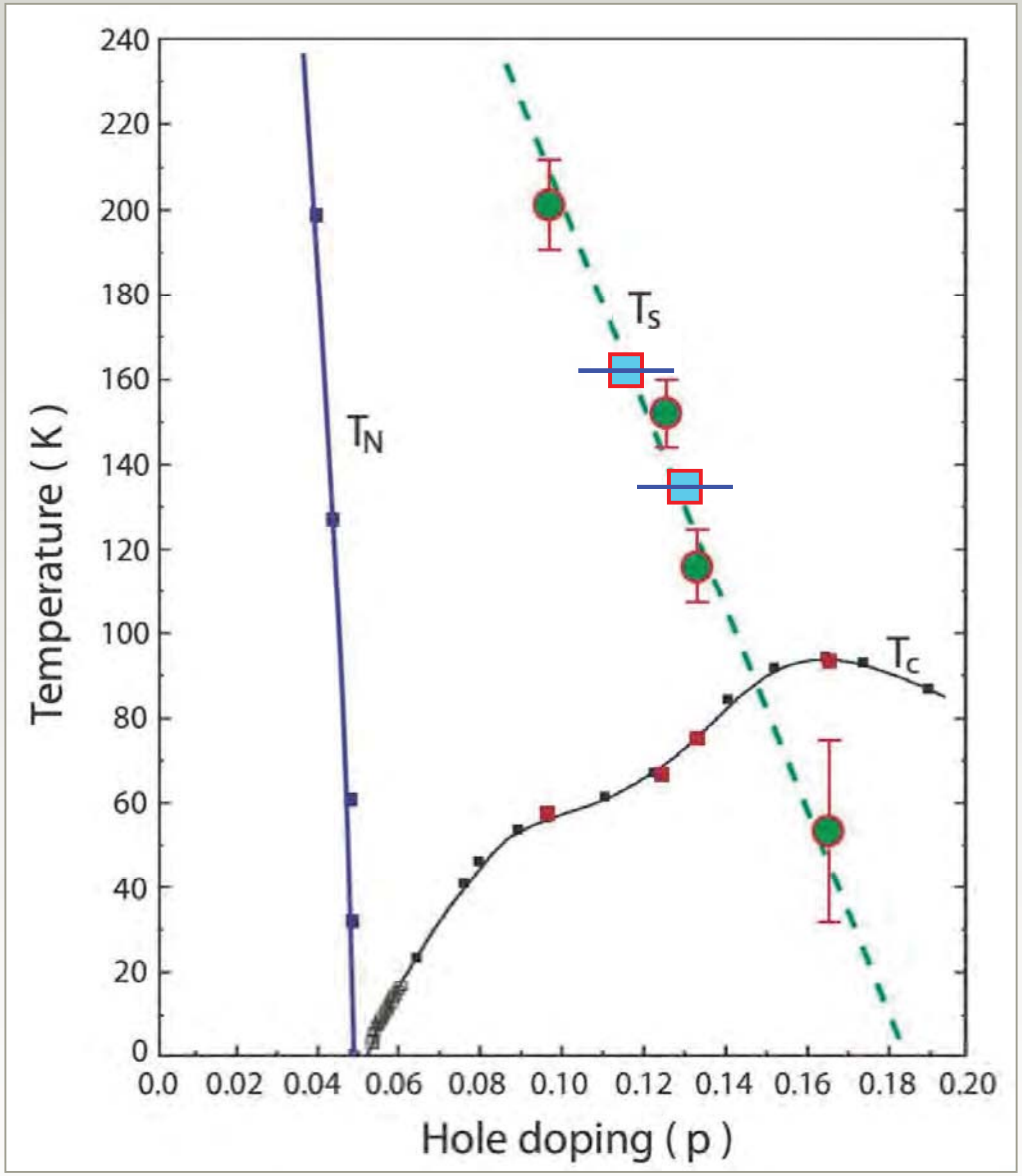




Kerr effect data revisited: thin films included

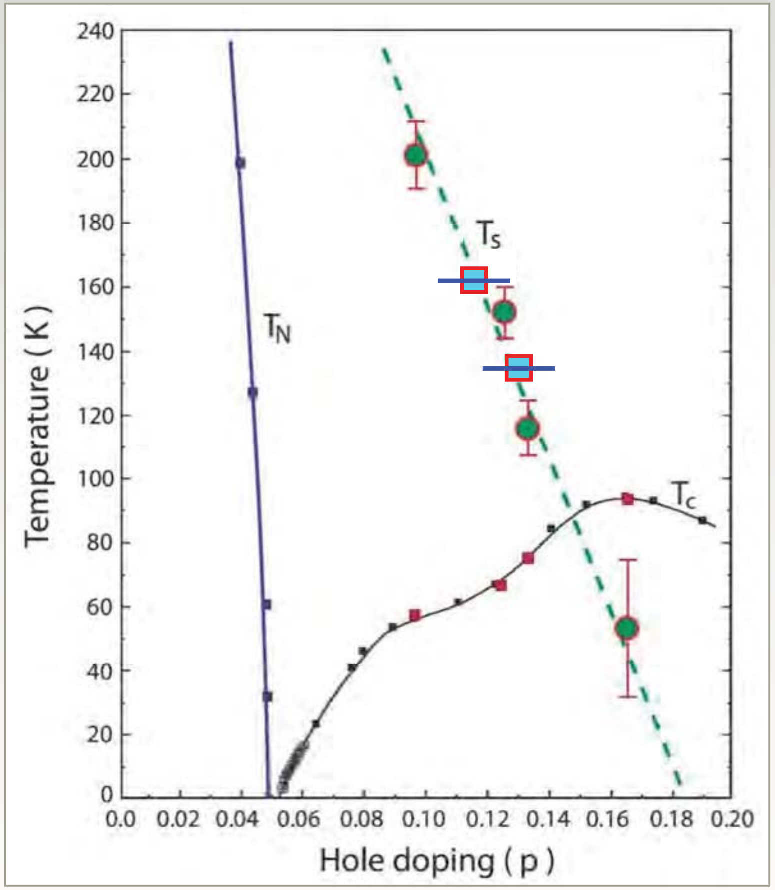
Single crystal (●)

Thin film (-■-)



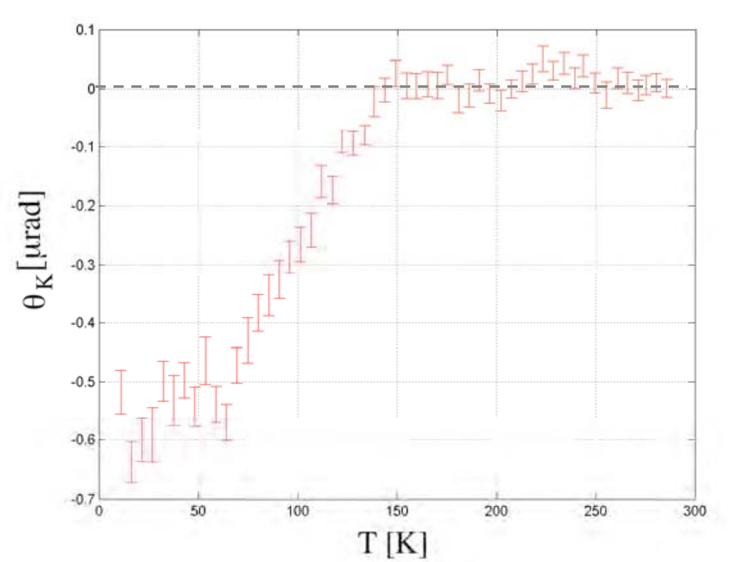
Summary: current observations for YBCO

1. A (very small) time reversal symmetry-breaking signal appears below a temperature T_s >> T_c for all underdoped YBCO samples measured.
2. A (very small) time reversal symmetry breaking signal appears below a temperature $T_s < T_c$ for near optimally doped samples.
3. There is an unusual hysteretic memory effect in the magnetic response (training effects)

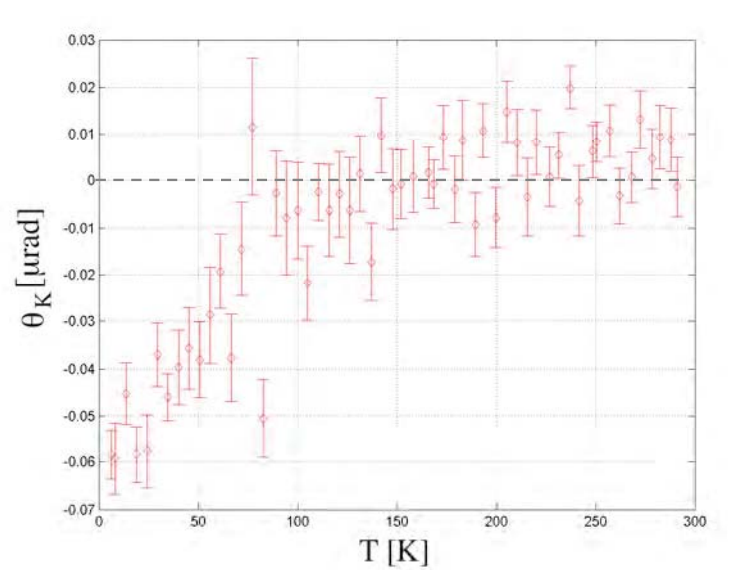


Example of anomalous magnetic behavior: $YBa_2Cu_3O_{6.67}$ underdoped single crystal (ortho-VIII)

- First cool in a - 60 Oe field and warm up in zero field:



- Now cool the same sample in a + 60 Oe field and warm up in zero field:

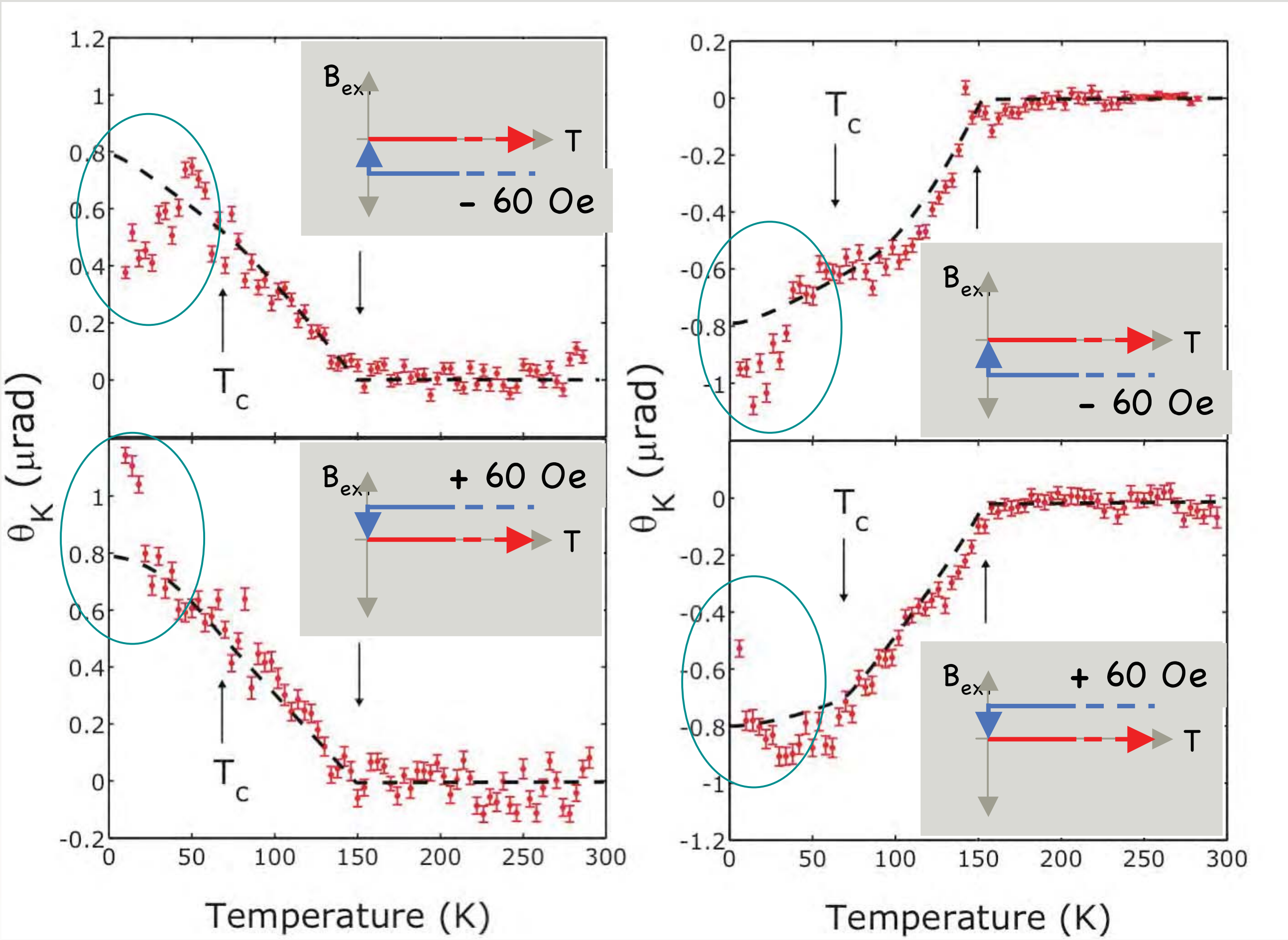


The signal does not change sign, but is 10x smaller in magnitude

$YBa_2Cu_3O_{6.67}$: Applying a large field at room temperature suffices to train the effect

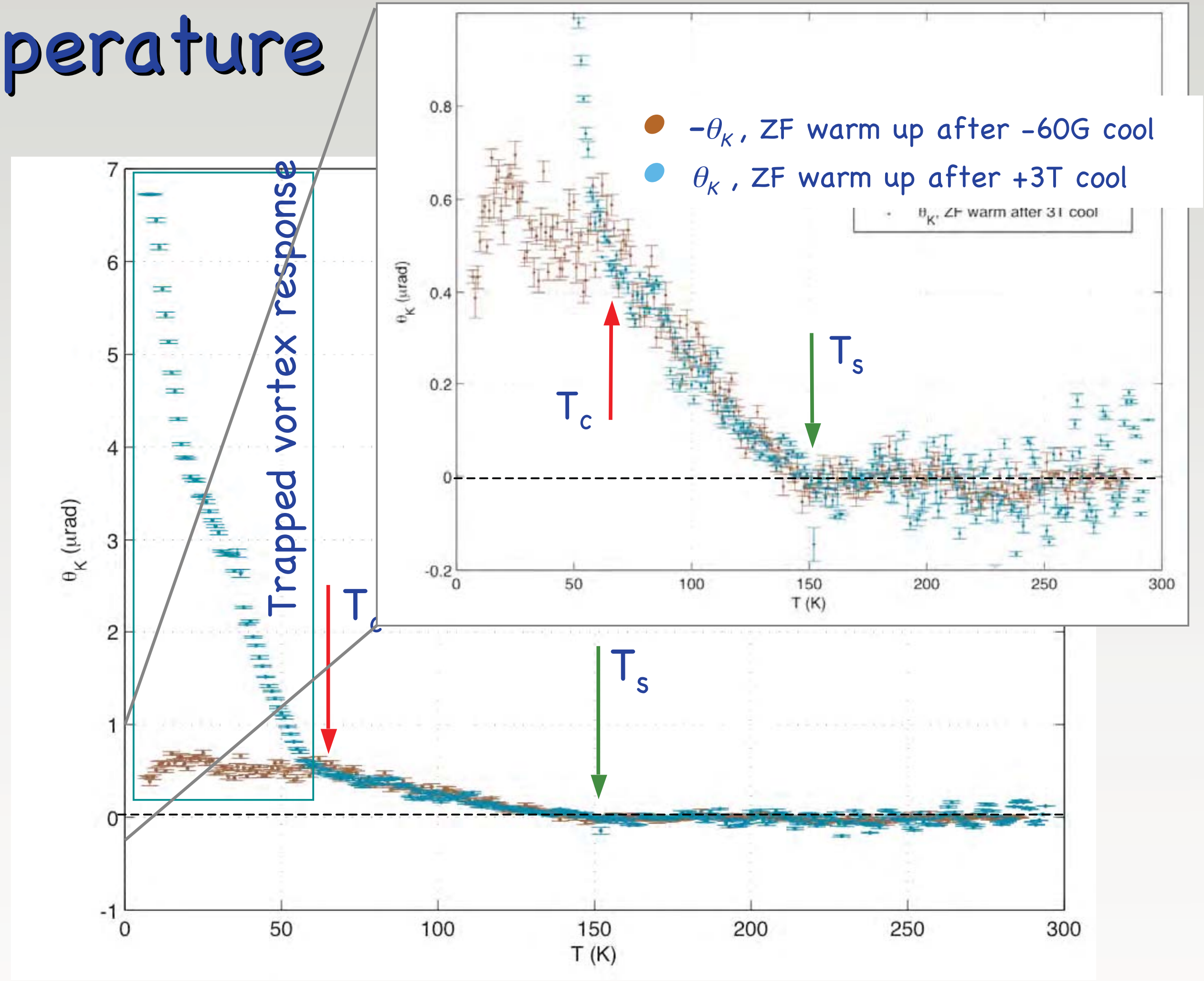
After applying +4T at RT

After applying -4T at RT



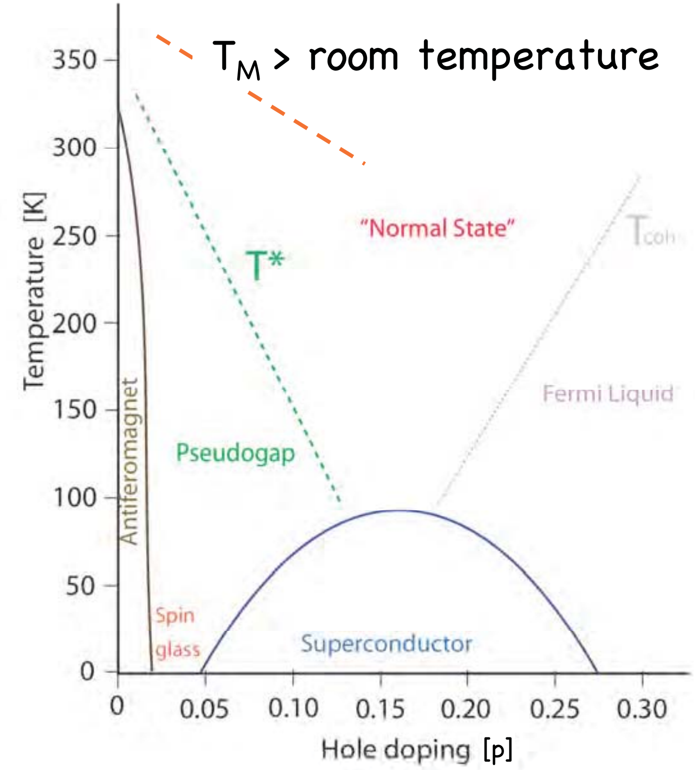
$YBa_2Cu_3O_{6.67}$: Finding the coercive field at room temperature

- First cool the sample in a -60 Oe field and warm up in zero field
- Then cool in a +3 T field and warm up in zero field
- Full reversal of signal is now achieved



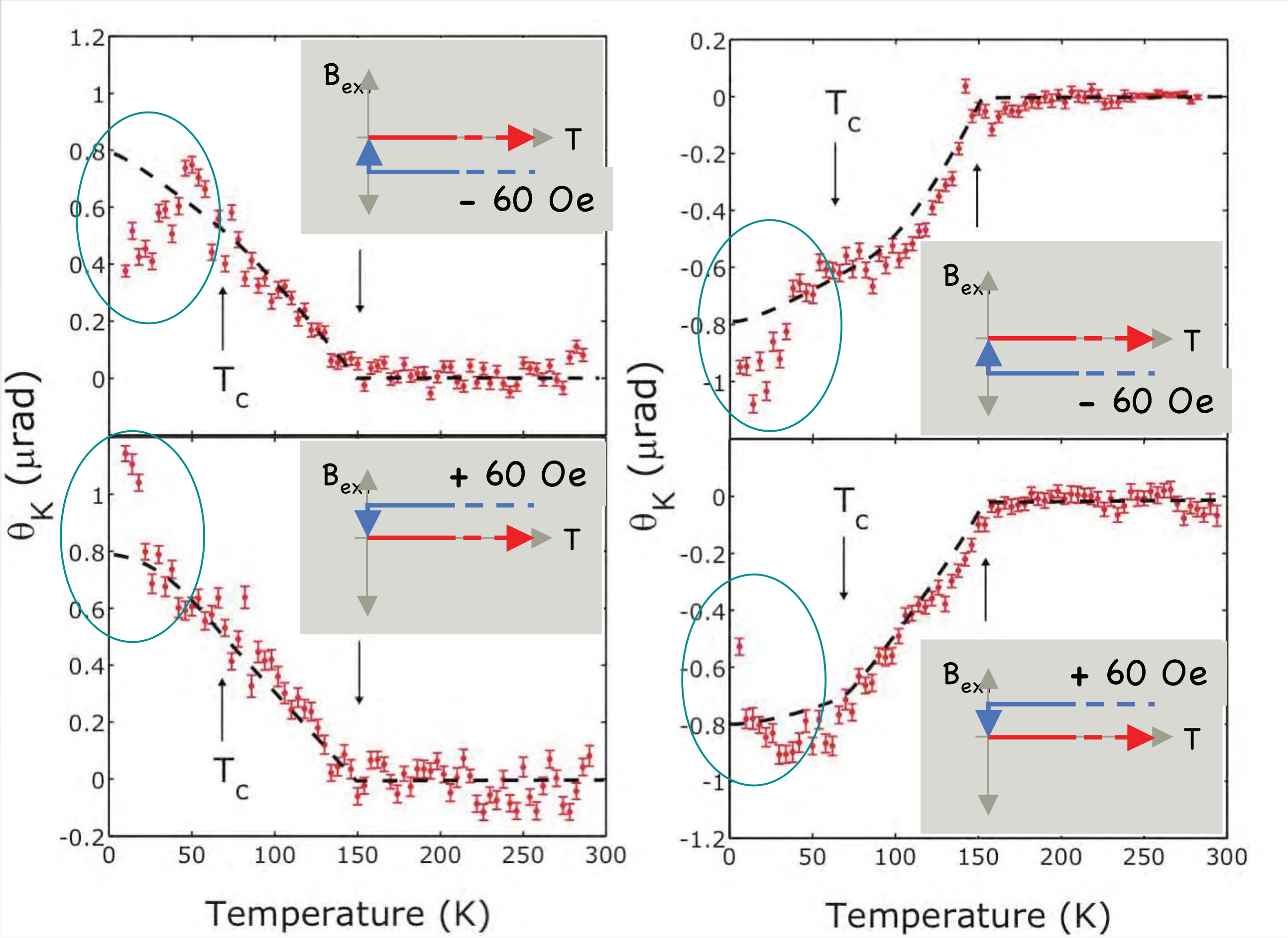
A possible explanation of the magnetic response:

- Similar results have been obtained for the other underdoped crystals (x = 0.5, 0.67, 0.75)
- Magnetic ordering sets in at some T_M above room temperature.
- At T_s the magnetic order acquires some measurable component.



Why are we observing vortices?

Cooling at ± 60 Oe



We do not see vortices in other systems after cooling in such low field

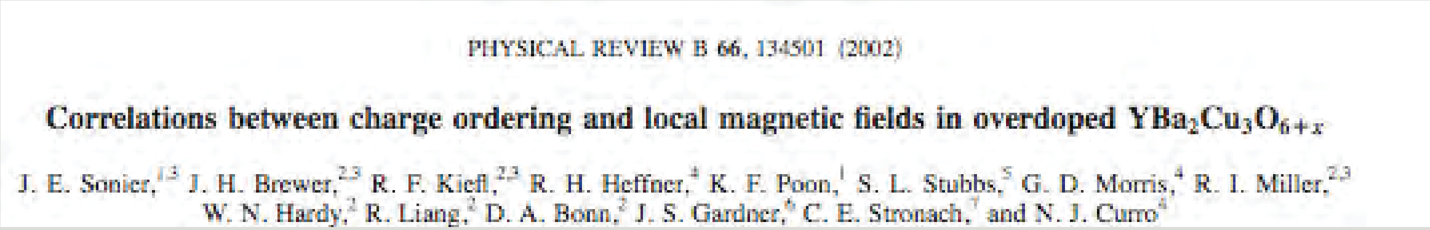
Possible explanation:

There is a magnetic phase in the YBCO crystals at all temperatures we measure.

At T_s, there is another electronic transition that alters the magnetic phase and thus produce a small ferromagnetic moment for us.

The field of the vortices below T_c act on that magnetic phase to produce the vortex response.

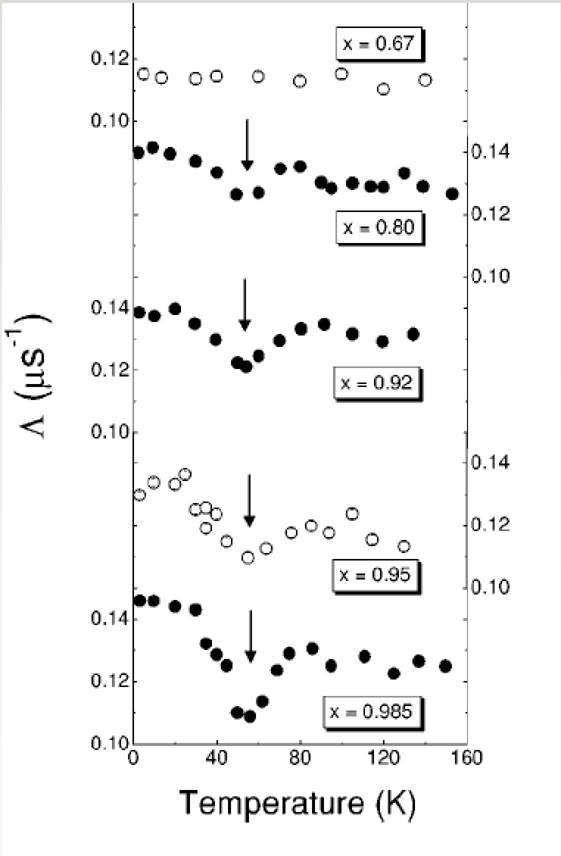
This is in agreement with measurements on optimally doped and overdoped YBCO Crystals which see a very weak structural phase transition near T_s.



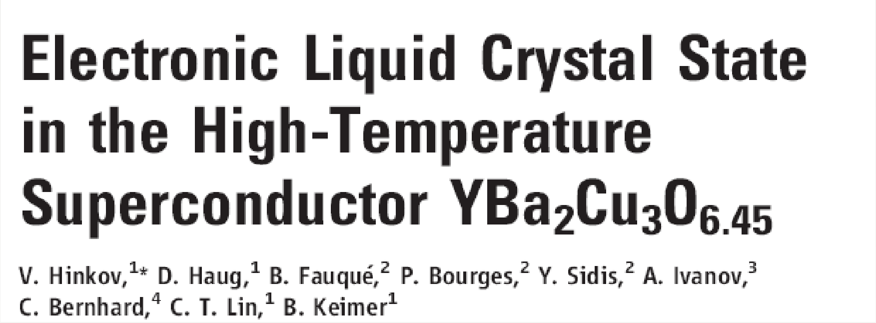
PHYSICAL REVIEW B **66**, 134501 (2002)

Correlations between charge ordering and local magnetic fields in overdoped $YBa_2Cu_3O_{6+x}$

J. E. Sonier,[1,3] J. H. Brewer,[2,3] R. F. Kiefl,[2,3] R. H. Heffner,[4] K. F. Poon,[1] S. L. Stubbs,[5] G. D. Morris,[4] R. I. Miller,[2,3]
W. N. Hardy,[2] R. Liang,[2] D. A. Bonn,[2] J. S. Gardner,[6] C. E. Stronach,[7] and N. J. Curro[4]



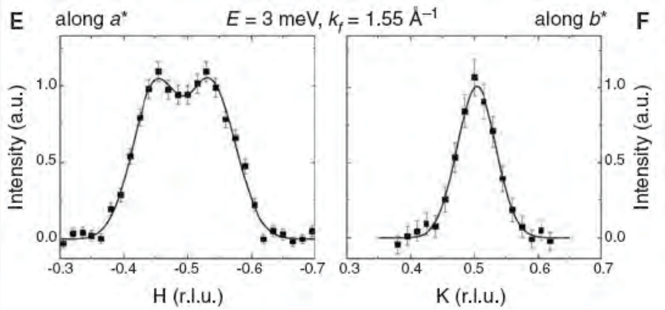
. Temperature dependence of the relaxation rate Λ.



Electronic Liquid Crystal State in the High-Temperature Superconductor $YBa_2Cu_3O_{6.45}$

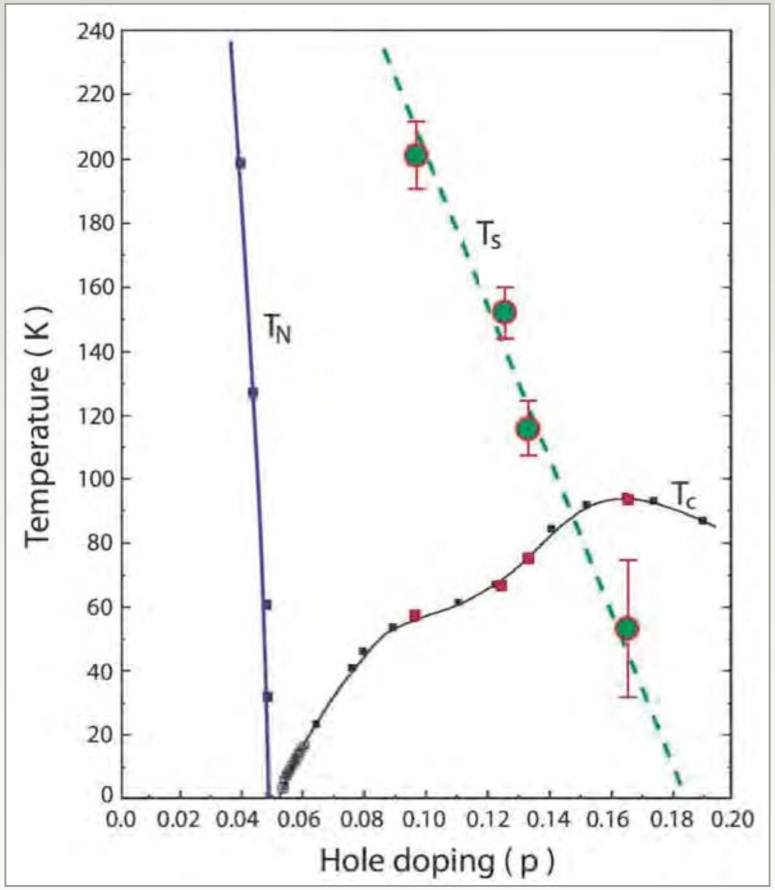
V. Hinkov,[1*] D. Haug,[1] B. Fauqué,[2] P. Bourges,[2] Y. Sidis,[2] A. Ivanov,[3]
C. Bernhard,[4] C. T. Lin,[1] B. Keimer[1]

Science 319, 597 (2008)



Summary

- We see evidence of time reversal symmetry breaking in underdoped YBCO, which
  - onsets at high temperatures in the far-underdoped regime
  - onsets below T_c near optimal doping
- The signal is very small, suggesting that we are observing a secondary effect.
- The sharp onset of Kerr signal at T_s suggests that a phase transition occurs; however, the ordered state is unclear.
- The Kerr signal also displays an unusual hysteretic memory effect, whose origins are still an open question.



Preliminary Results on some interesting Systems:

The power of the Sagnac Magnetometer!!!

First direct observation of Inverse Proximity Effect in Superconductor/Ferromagnet structures

Aharon Kapitulnik
STANFORD UNIVERSITY

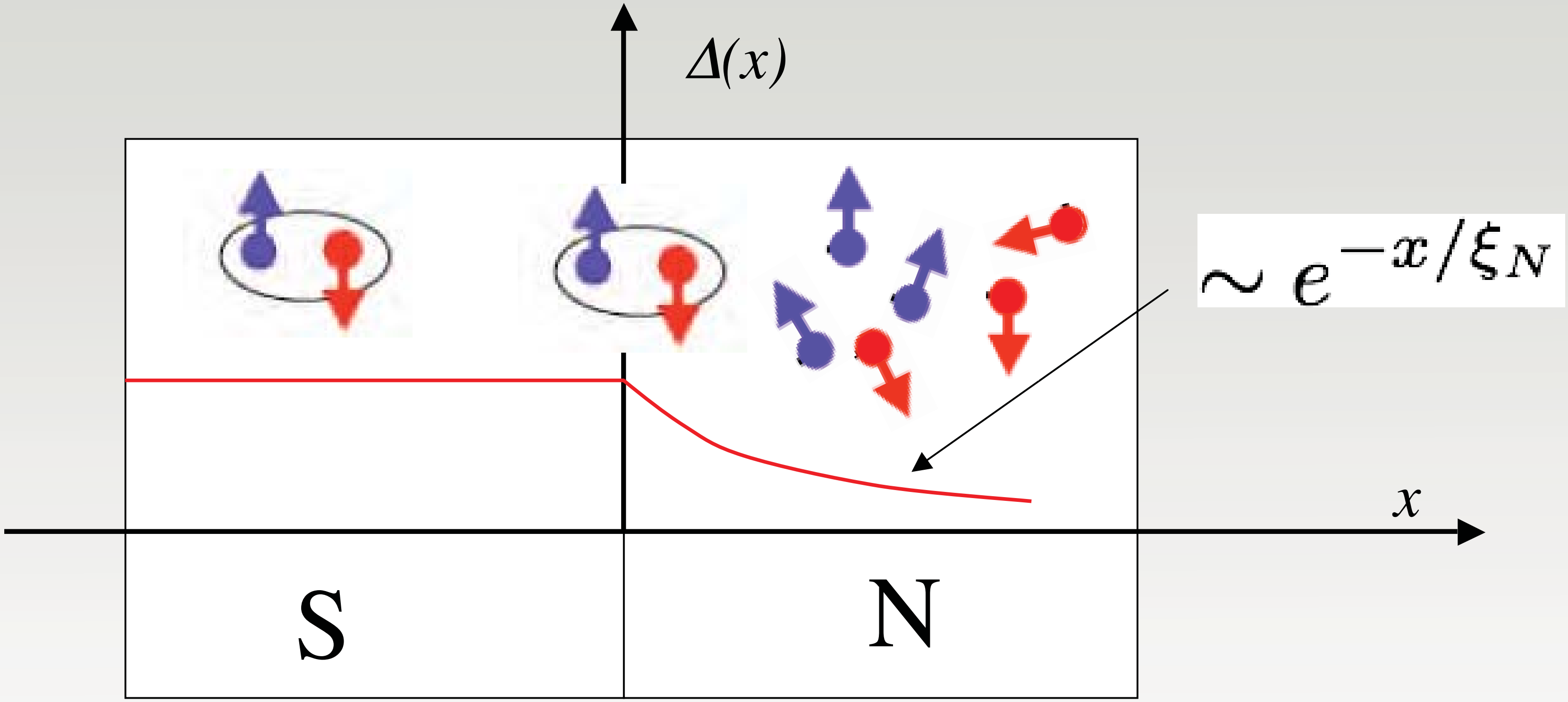
Jing Xia

Samples:

Alexander Palevski
M. Karpovski
V. Shelukhin

(Tel-Aviv University)

Proximity Effect at Superconductor/Normal-metal Interface



Order parameter - Δ	Order parameter - none
Characteristic energy - Δ	Characteristic energy - ε_F, k_BT

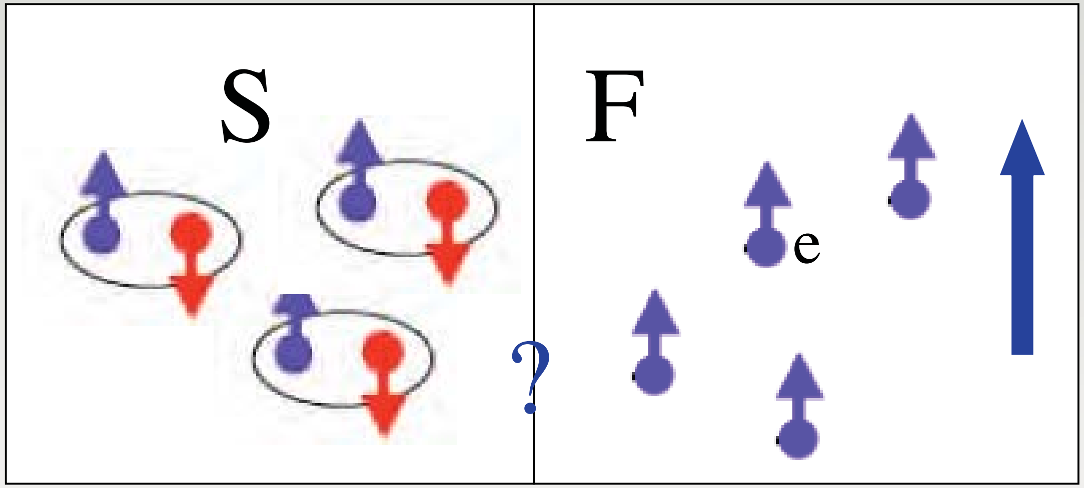
Size of Cooper pairs:

$$\xi_S \sim \sqrt{\hbar D_S / 2\pi k_B T_c}$$

Proximity length:

$$\xi_N \sim \sqrt{\hbar D_N / 2\pi k_B T}$$

Proximity Effect at Superconductor/Ferromagnet Interface

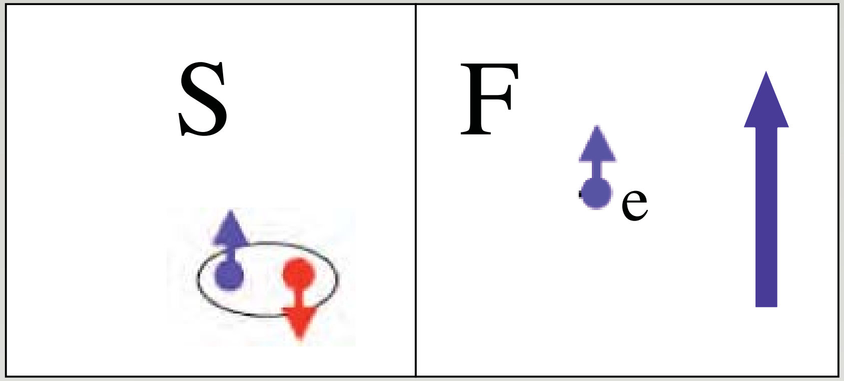


Order parameter - Δ

Characteristic energy - Δ

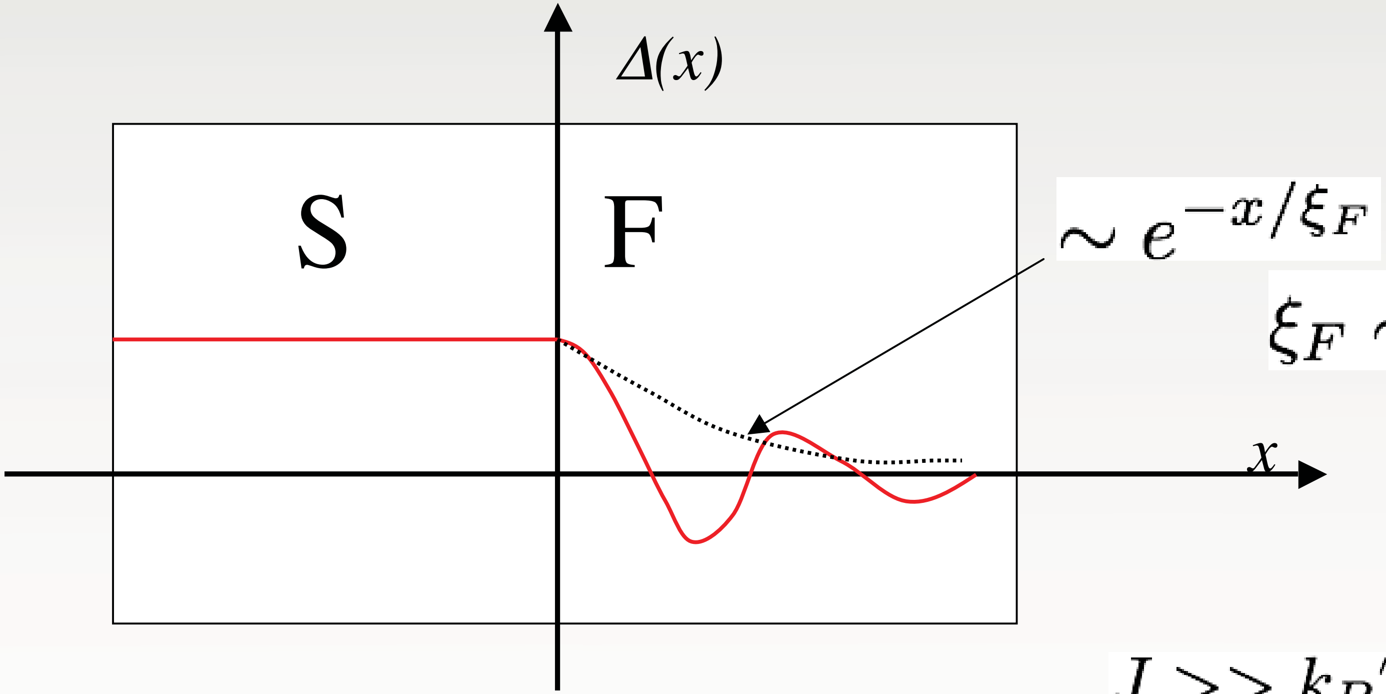
Order parameter - M

Characteristic energy - J



In the ferromagnet, J will tend to break the pairs and align the spins

The result is an oscillating and exponentially decaying superconducting order parameter that penetrates into F layer.



$\sim e^{-x/\xi_F}$

$\xi_F \sim \sqrt{\hbar D_F / J}$

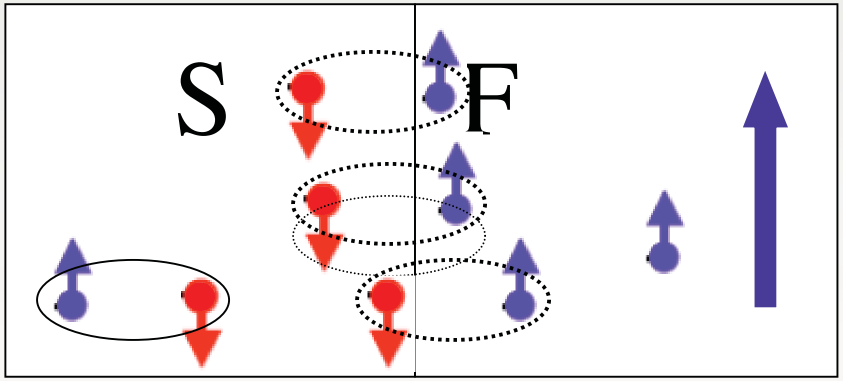
$J >> k_B T \rightarrow \xi_N \gg \xi_F$

Inverse Proximity Effect:

How does the ferromagnet order parameter penetrates into the superconductor?

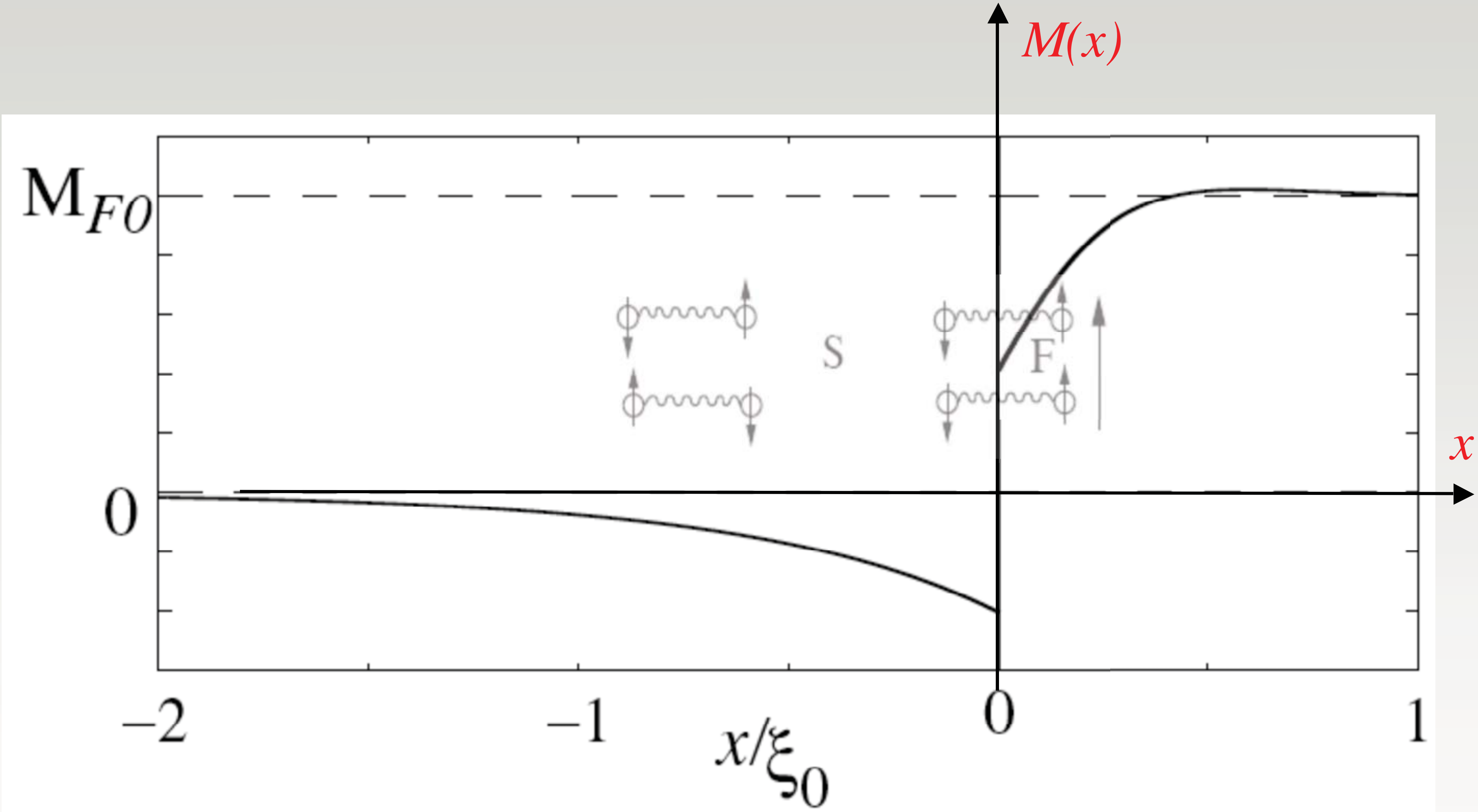
What is the magnetization in the superconductor?

Prediction by Bergeret, Volkov, and Efetov (Phys. Rev. B 69, 174504 (2004):



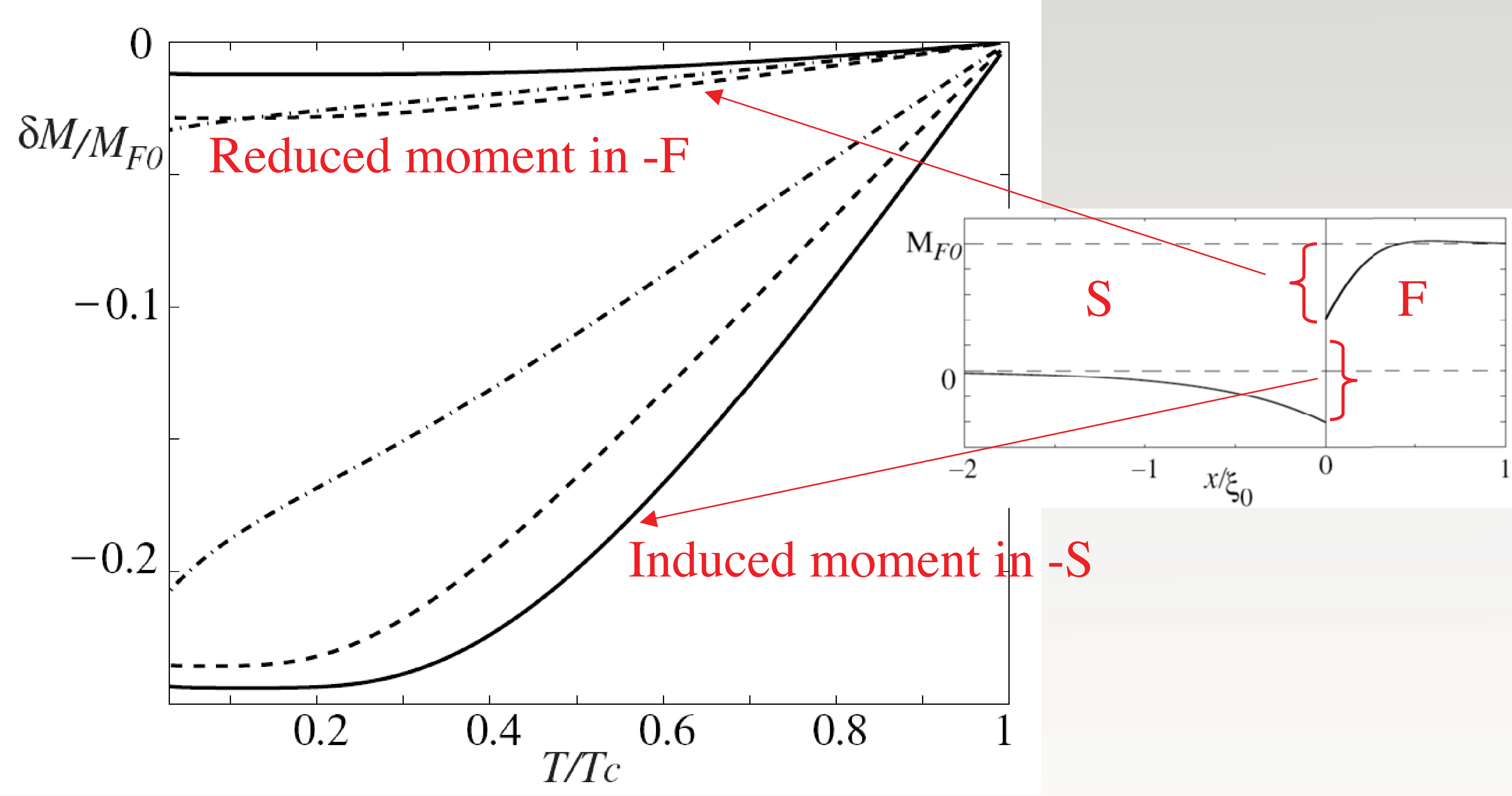
The result is net magnetization in the superconductor but with opposite sign to that in the ferromagnet

Predicted behavior of the magnetization:



Bergeret, Volkov, and Efetov, Phys. Rev. B 69, 174504 (2004)

Temperature dependence of the magnetization:

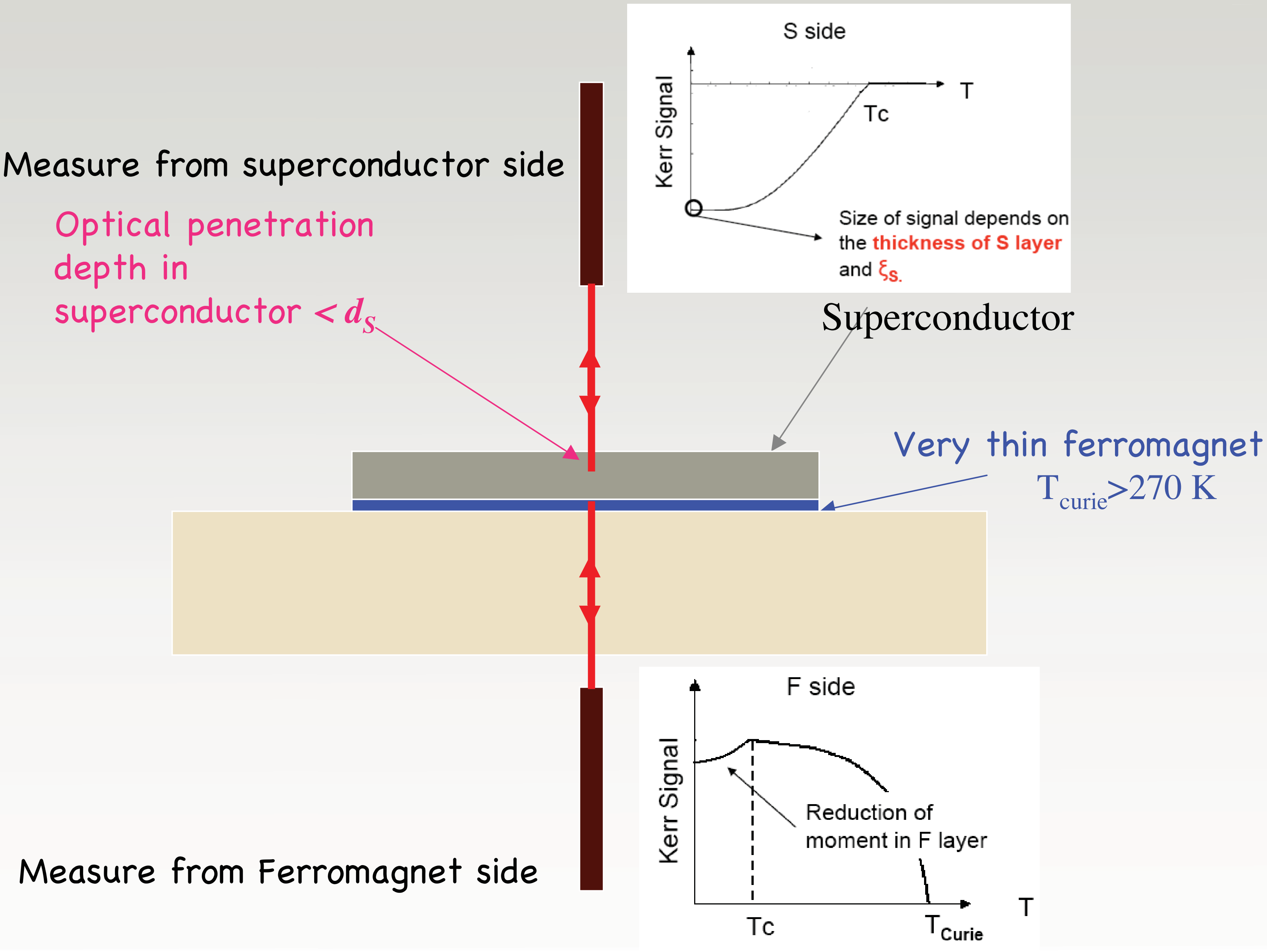


Reduced moment in -F

Induced moment in -S

How can we measure the magnetization in the superconductor?

Ferromagnet/Superconductor Proximity Effect



Measure from superconductor side

Optical penetration depth in superconductor $< d_S$

Size of signal depends on the **thickness of S layer** and ξ_S.

Superconductor

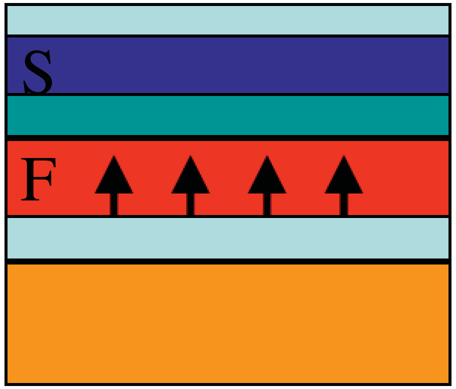
Very thin ferromagnet
T_{curie}>270 K

Reduction of moment in F layer

Measure from Ferromagnet side

Pb/Ni Proximity bilayer

ξ_s~ 83 nm, Large spin orbit interaction



Ge 50 A

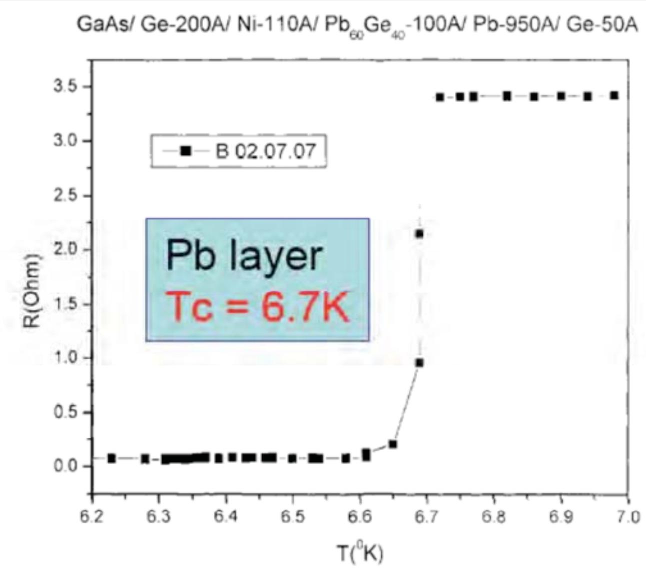
Pb 950 A

$Pb_{60}Ge_{40}$ 100 A

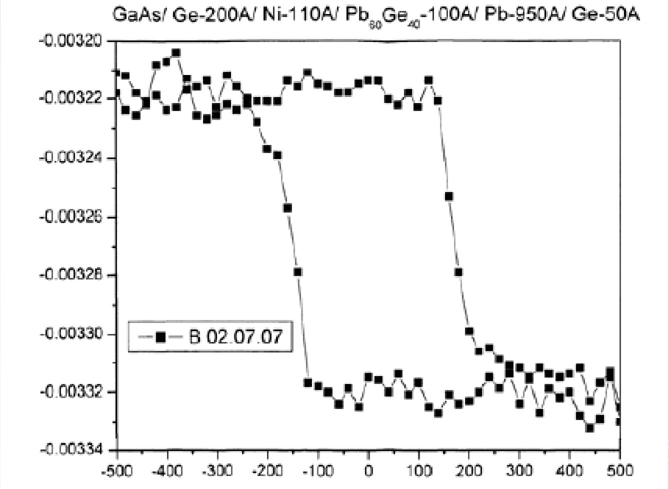
Ni 110A

Ge 200 A

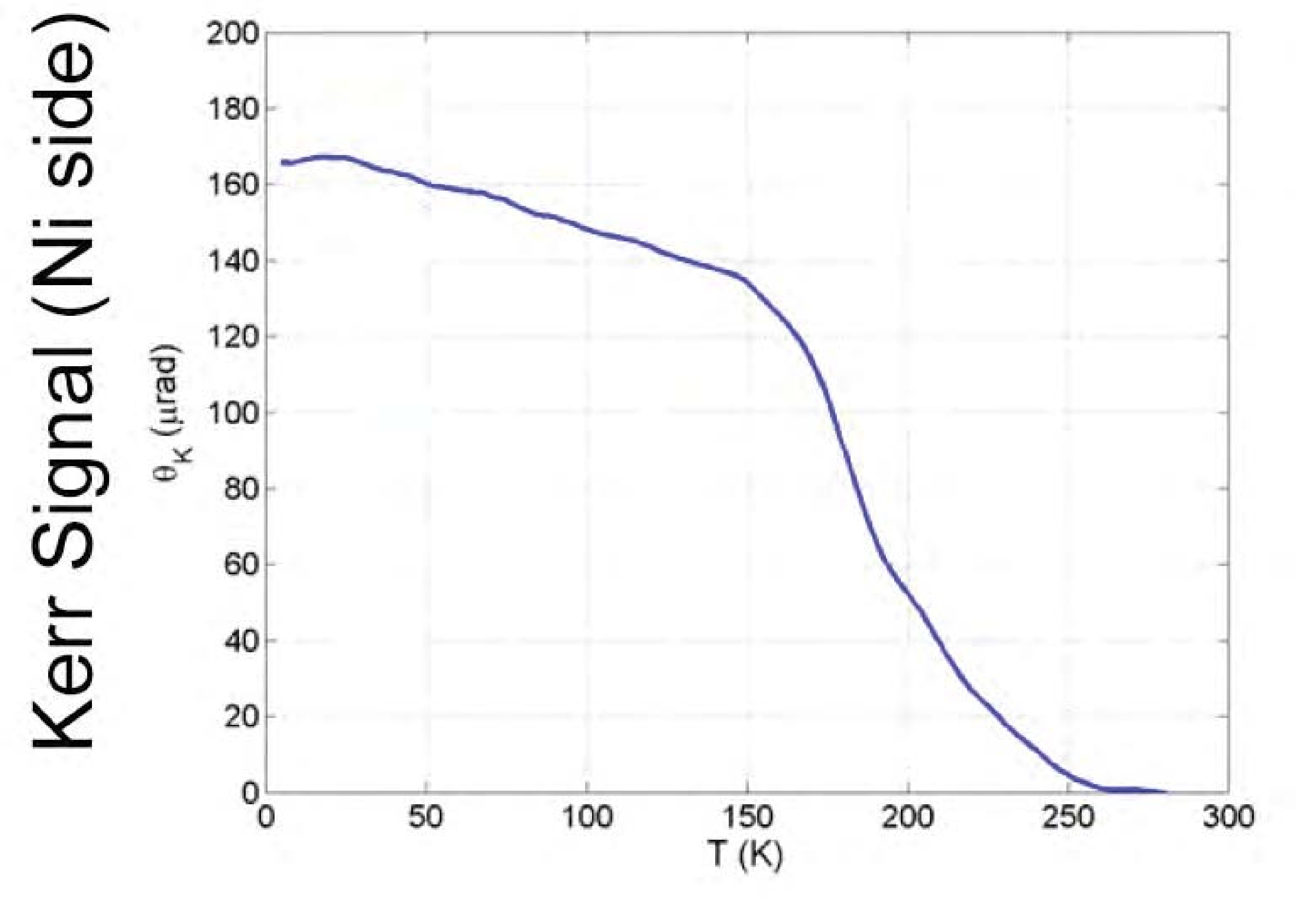
GaAs Substrate



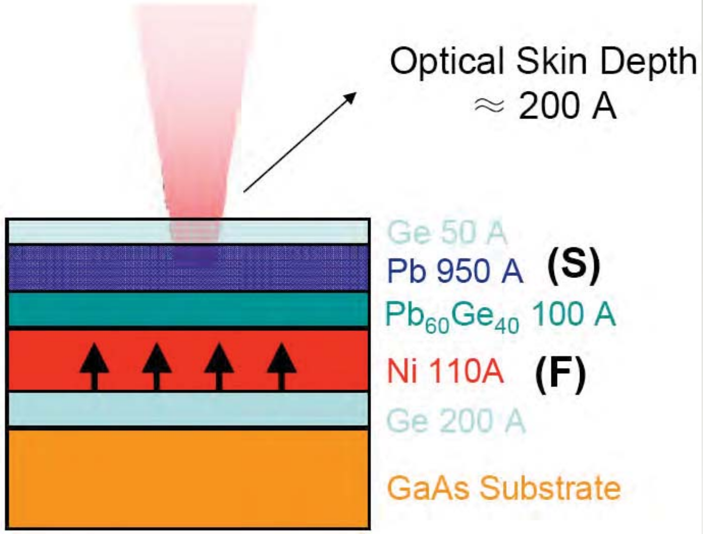
Ni layer hysteresis loop at 8 K



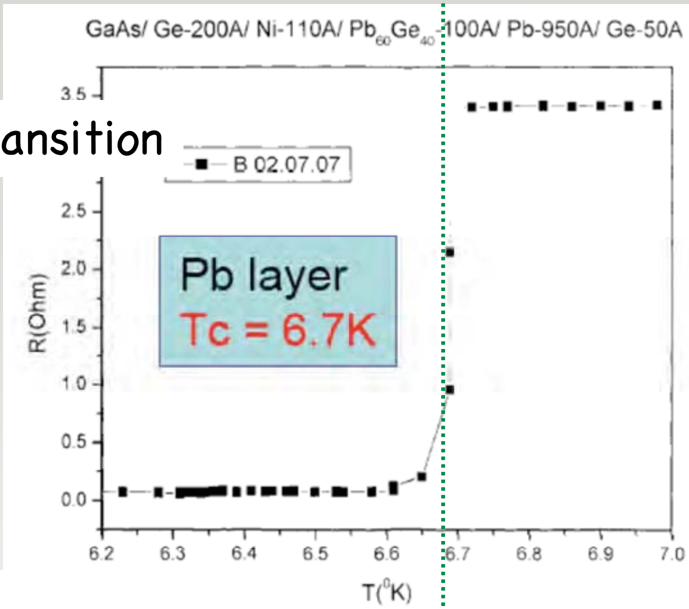
Measurement from Ni side (similar sample)



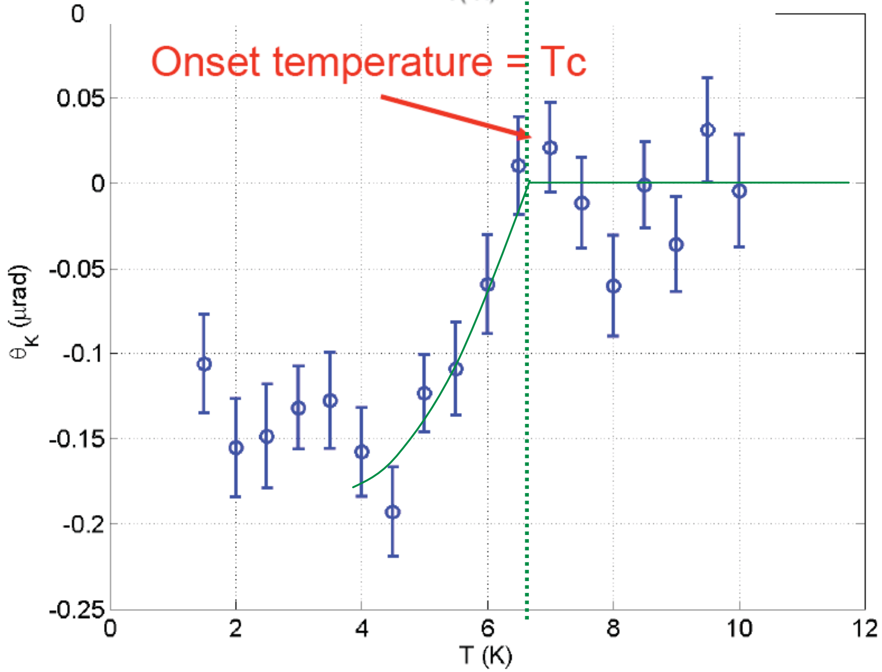
Measurement from Pb side



Resistive Transition



Pb layer
Tc = 6.7K

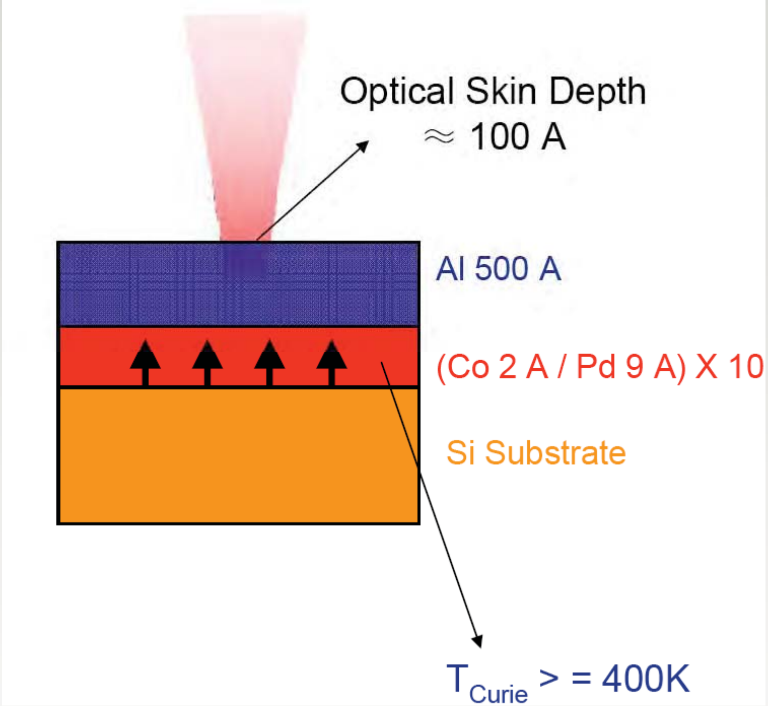


Onset temperature = Tc

Cool in **+1T** down to 10 K, continue in zero field to 1.5 K, then measure at zero-field warmup.

Al/(Co/Pd superlattice) Proximity bilayer

$\xi_s > 150$ nm, Weak spin orbit interaction



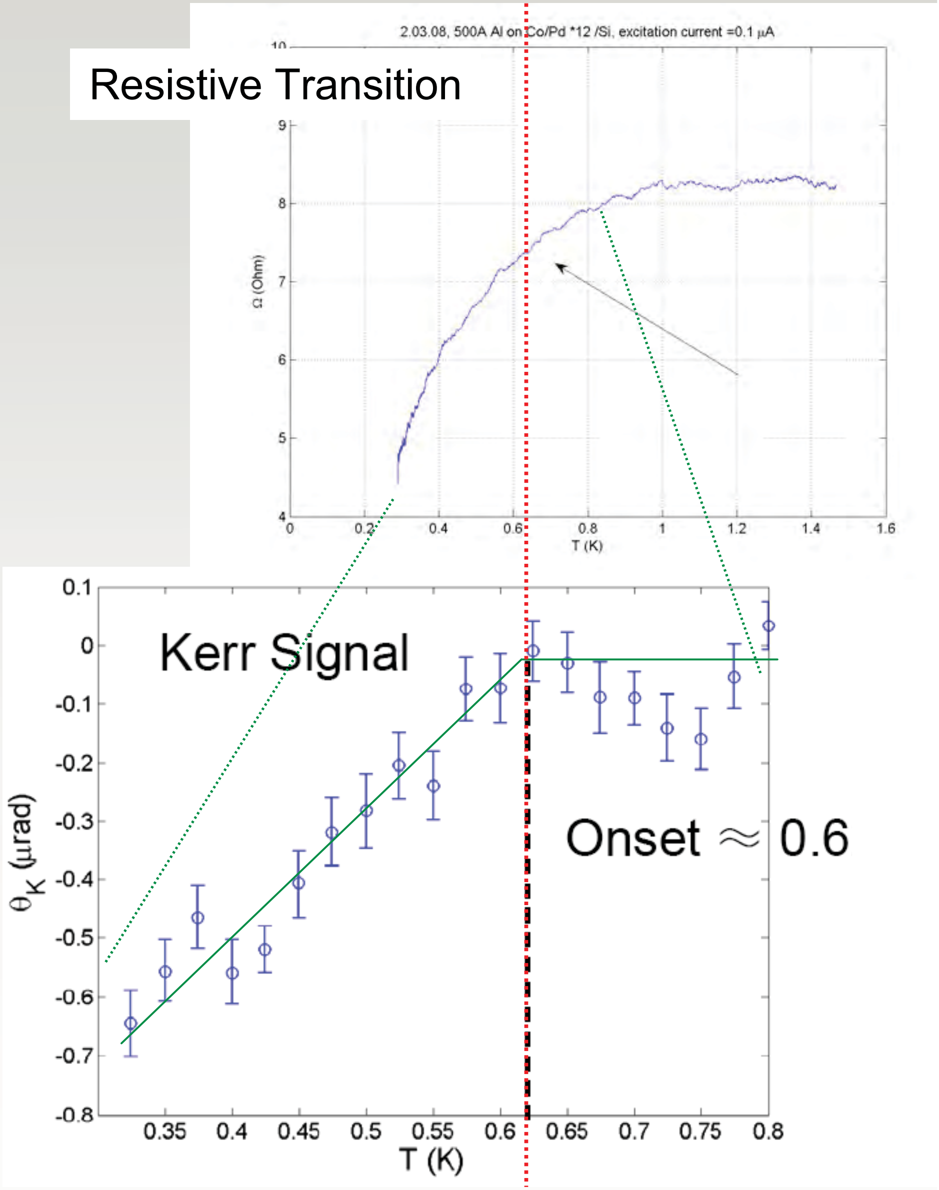
Optical Skin Depth
≈ 100 A

Al 500 A

(Co 2 A / Pd 9 A) X 10

Si Substrate

$T_{Curie} >= 400K$



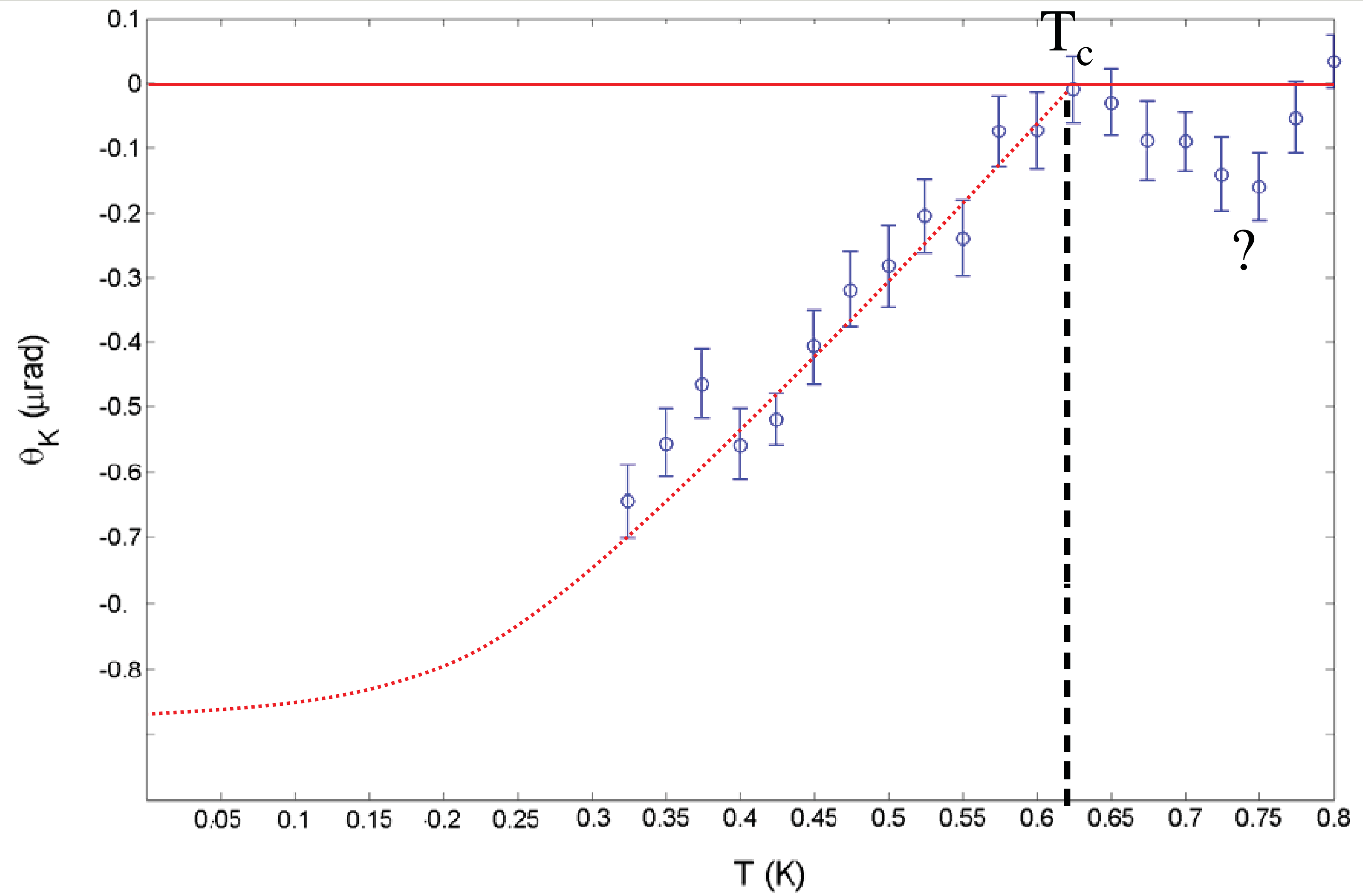
Resistive Transition

Kerr Signal

Onset ≈ 0.6

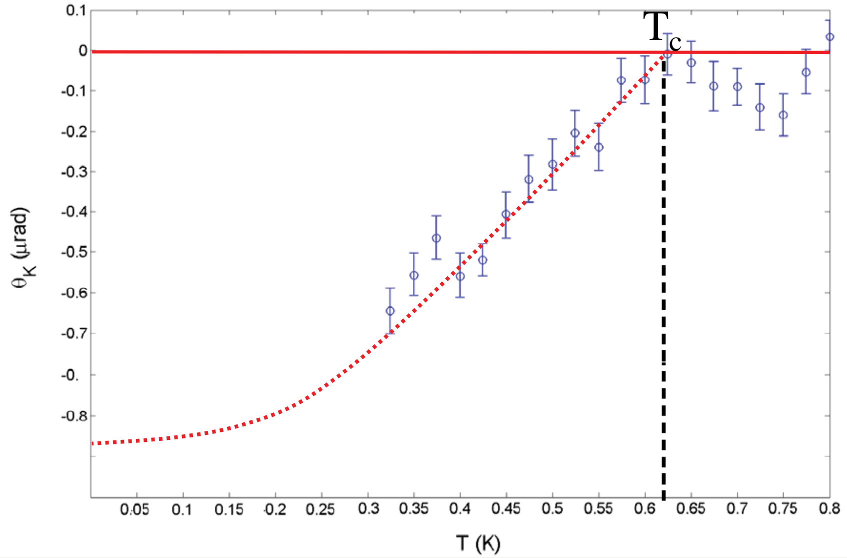
Cool in +1T down to 10 K, continue in zero field to 0.29 K, then measure at zero-field warmup.

Temperature dependence



Some analysis:

$$\delta\theta_K(0)_S \propto \delta M_S(0)$$



We find: $$\frac{\delta\theta_K(0)_S}{\theta_K(0)_F} \approx 0.001$$

δ

Important factors:

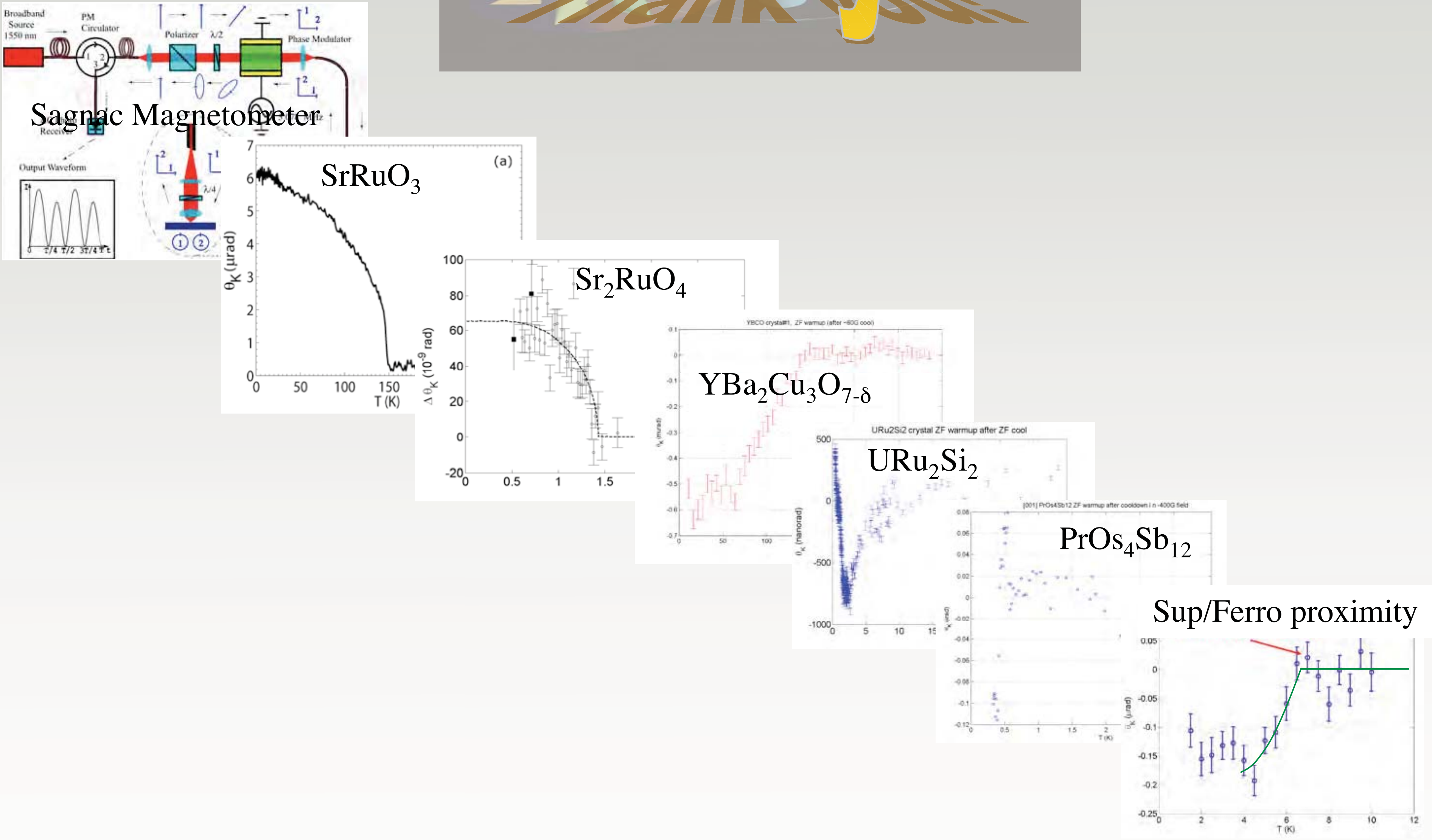
1. We measure ~100 Å into the 500 Å layer
2. The coherence length is ~ 3 times the thickness
3. $J/T_c \sim 350/0.6 \sim 600$

Points 2 + 3 + calculation by Bergeret et al.* gives indeed: $$\frac{\delta\theta_K(0)_S}{\theta_K(0)_F} \approx 0.001$$

*Bergeret, Volkov, and Efetov, Phys. Rev. B 69, 174504 (2004)

More to come on Superconductor/Ferromagnet Proximity

Thank you!



Sagnac Magnetometer

$SrRuO_3$

Sr_2RuO_4

$YBa_2Cu_3O_{7-\delta}$

URu_2Si_2

$PrOs_4Sb_{12}$

Sup/Ferro proximity