Search for Broken Time-reversal Symmetry in Unconventional Superconductors

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With: **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 (110)-axis films films
K. Behnia (ESPCI) - URu_2Si_2 single crystals
Y. Aoki, H. Sato (TMU, Japan) - $PrOs_4Sb_{12}$ single crystals
Alex Palevski (TAU) - Superconductor/Ferromagnet Proximity

Also: Steve Kivelson (Stanford) - Theoretical ideas
Marty Fejer (Stanford) - Initial Sagnac design

Outline:

1. Time-reversal symmetry breaking and Magneto-optics
2. Experimental considerations and the Sagnac interferometer
3. A test case: studies of $SrRuO_3$
4. Search for TRSB in Sr_2RuO_4
5. The pseudogap in $YBa_2Cu_3O_{6+x}$
6. Inverse proximity effect in S/F bilayers
7. Results on other unconventional superconductors
8. Conclusions

A comment on time-reversal symmetry

$$i\hbar\frac{\partial\Psi(\vec{x},t)}{\partial t} = \hat{\mathcal{H}}\Psi(\vec{x},t)$$

T-symmetry is the symmetry of physical laws under a time reversal transformation:

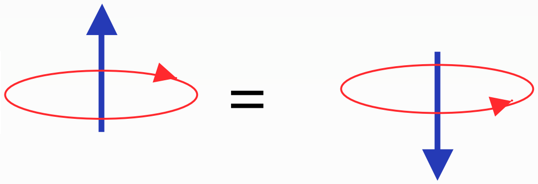
$$\mathcal{T}: \quad t \rightarrow -t$$

With no spin-consideration: $\mathcal{T}\Psi(\vec{x},t) = \Psi^{*}(\vec{x},t)$

With spin-consideration, also includes spin-rotation.

For example: $\mathcal{T}\,[\uparrow,\uparrow,\uparrow,\ldots\uparrow] = [\downarrow,\downarrow,\downarrow\ldots\downarrow]$

This is because: $\mathcal{T}$



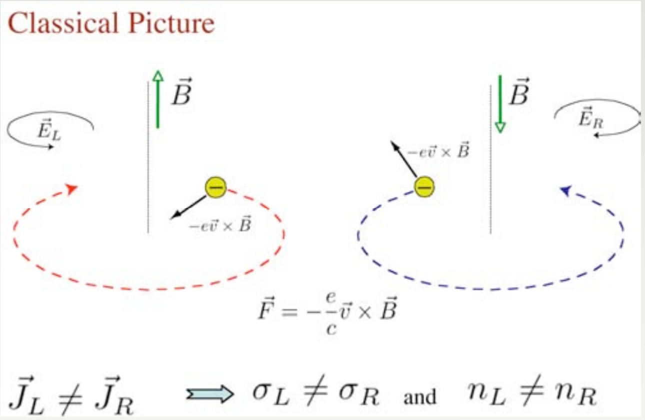
Search for Broken Time Reversal Symmetry in Unconventional Superconductors

- ➔ For High-Tc Superconductors:
  - anyon superconductivity [Historically was first search]
  - $d_{x^2+y^2}+id_{xy}$, $d_{x^2+y^2}+is$, etc.*
  - D-density wave (staggered-flux state, breaks translation symmetry)
  - Loop-Current Order (does not break translation symmetry)
- ➔ 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.

Magneto-optics as a probe for time-reversal symmetry breaking

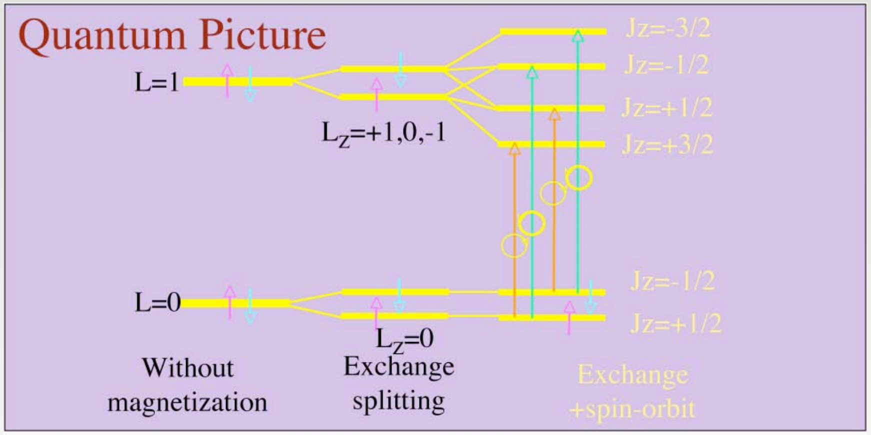
Bulk, macroscopic, measurements are needed which do not depend on imperfections in the superconductor.


Classical Picture

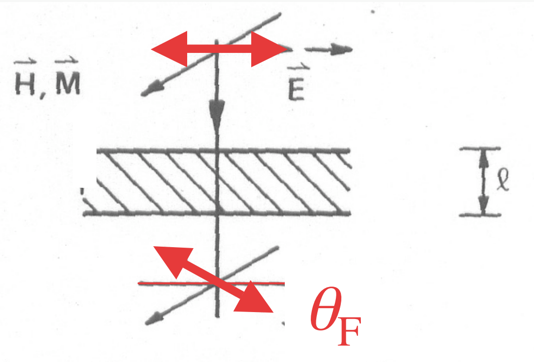
$\vec{F} = -\frac{e}{c}\vec{v}\times\vec{B}$

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

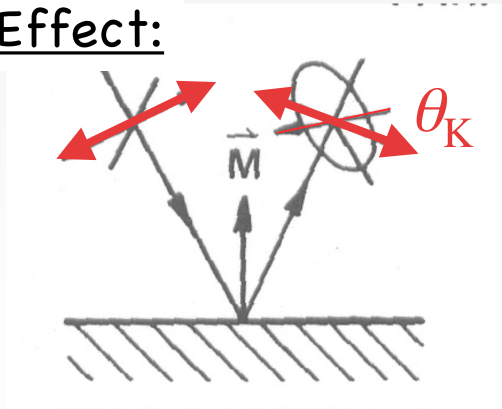
$$n_R \neq n_L$$


Quantum Picture

Faraday Effect:



(Polar) Kerr Effect:

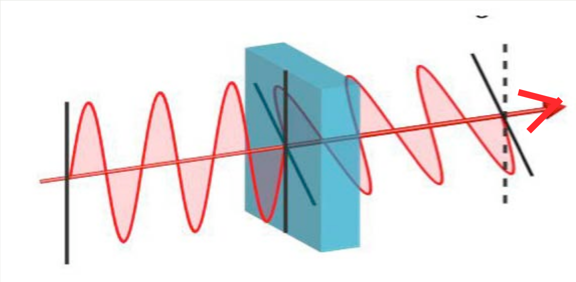


Plane-waves and Time-Reversal Symmetry

$$\mathcal{T}: \quad t \to -t$$

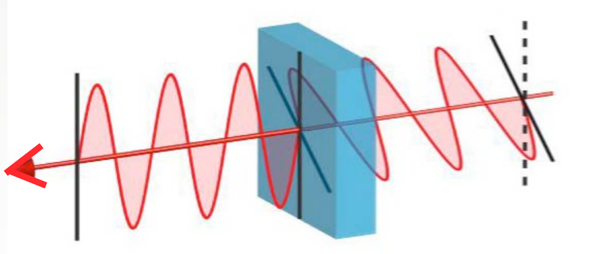
For a plane-wave beam of light moving in the z direction, the electric field:

$$E \propto e^{-ikz}$$



and the time-reversal operation gives:

$$E(t \to -t) = \mathcal{T}E(t) \propto e^{+ikz}$$



Magneto-optics and Time-Reversal Symmetry

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

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:

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

Where: $J_{R,L} = J_x \pm iJ_y$ and $\sigma_{R,L} = \sigma_{xx} \pm i\sigma_{xy}$

$$\boxed{\theta_F = \frac{1}{2}\frac{\omega\ell}{c}\mathcal{R}e\left[\tilde{n}_L - \tilde{n}_R\right]} \qquad \boxed{\theta_K = -\mathcal{I}m\left[\frac{\tilde{n}_L - \tilde{n}_R}{\tilde{n}_L\tilde{n}_R - 1}\right]}$$

or:

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

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

The complete calculation of the Kerr effect depends on the material’s conductivity and band structure.

For example*, the imaginary part of the off-diagonal conductivity is:

$$\sigma''_{xy}(\omega) = \frac{\pi e}{4\hbar\omega m V}\sum_{n}\sum_{m}\left(\left|\langle n|J_R|m\rangle\right|^2 - \left|\langle n|J_L|m\rangle\right|^2\right)\times\left[\delta(\omega_{mn}-\omega)+\delta(\omega_{mn}+\omega)\right]\langle n|\hat{\rho}|n\rangle$$

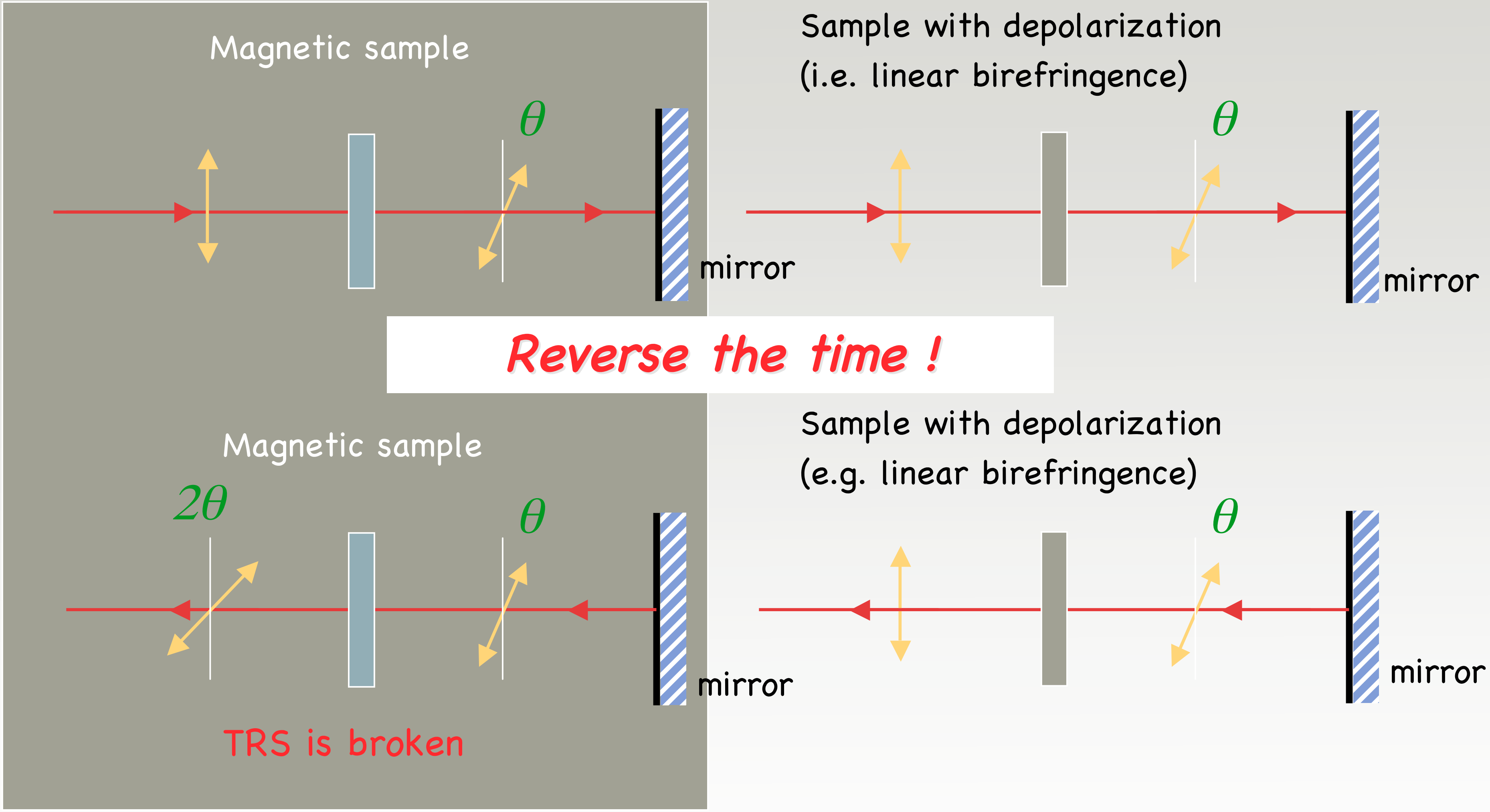
asymmetry due to magnetization

Allowed transitions

Ground state population

* H.S. Bennett & E.A. Stern, Phys. Rev. 137, A448 (1965)

Magneto-optics and Time-Reversal Symmetry



Magnetic sample

Sample with depolarization
(i.e. linear birefringence)

Reverse the time !

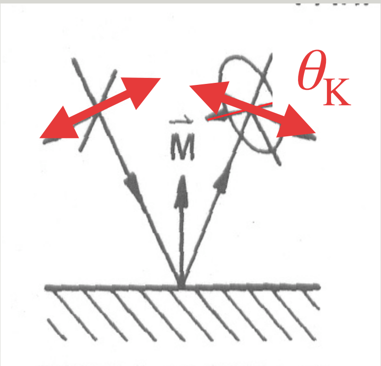
Magnetic sample

Sample with depolarization
(e.g. linear birefringence)

TRS is broken

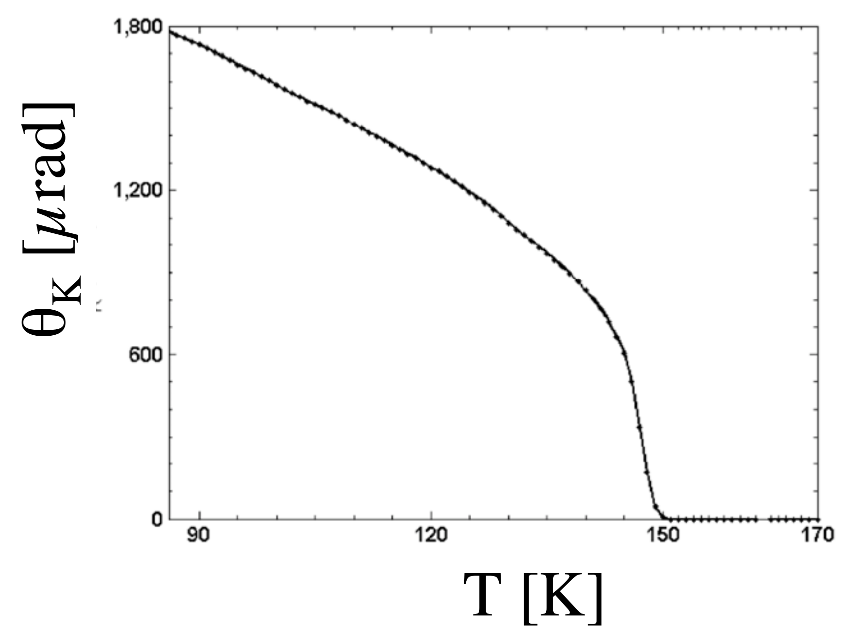
We can distinguish between magneto optic signal (Kerr and Faraday) from depolarization effects if we measure the difference between a light beam with its time reversal counter part beam.

Scale of MO effects in oxide-ferromagnets:



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!

TRSB effects in unconventional superconductors are expected to be much smaller effects!

Example: Considerations for the Sr_2RuO_4 experiment:

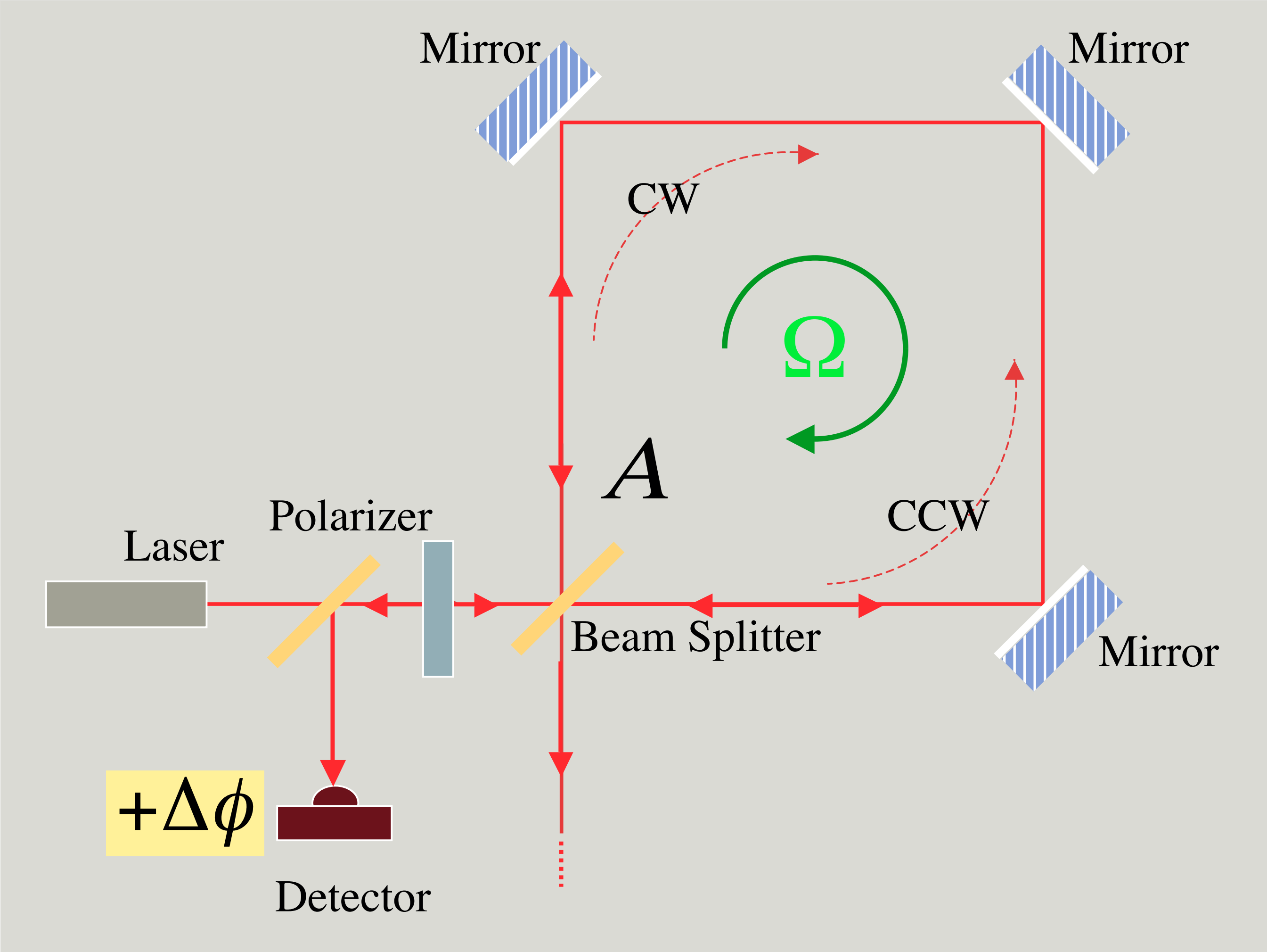
1. A tiny effect - depending on theory, estimates of Kerr rotation for Sr_2RuO_4 gave $\theta_K \sim 10^{-10} \div 10^{-8}$ rad.
2. Reject <u>all</u> reciprocal effects such as linear birefringence and optical activity.
3. Measure an absolute value of the Kerr effect, rather than a result of a modulated signal*.

A simple cross polarization method will not be enough!

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

Solution: use the Sagnac Effect

A Sagnac Loop at rest
is reciprocal!



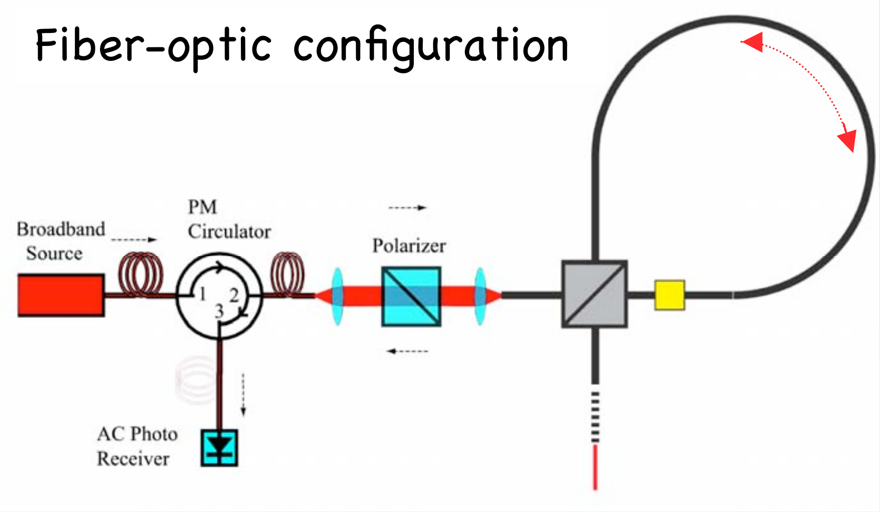
$+\Delta\phi$

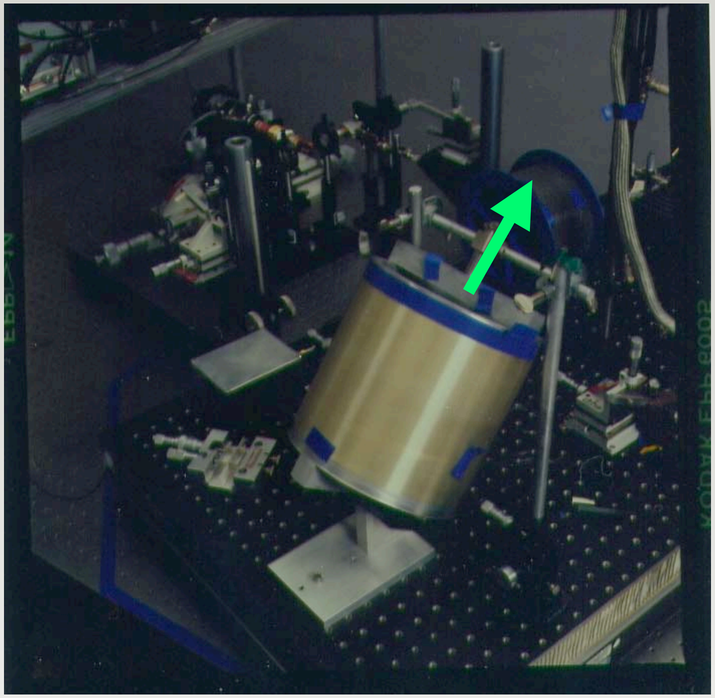
$$\Delta\phi = \frac{2\pi}{\lambda}\frac{4A}{c}\Omega$$

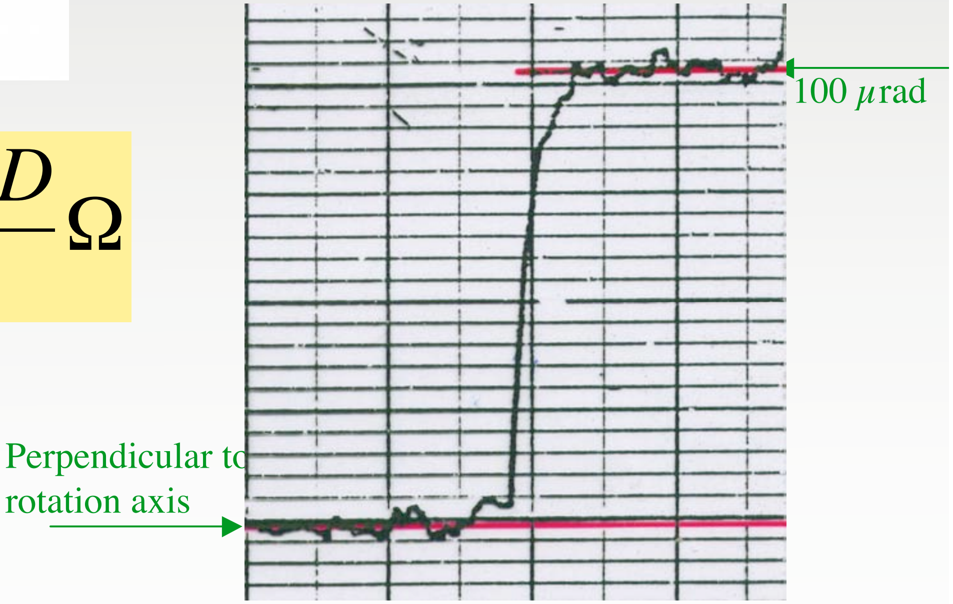
Fiber-optic implementation

Example: Earth Rotation

Fiber-optic configuration







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

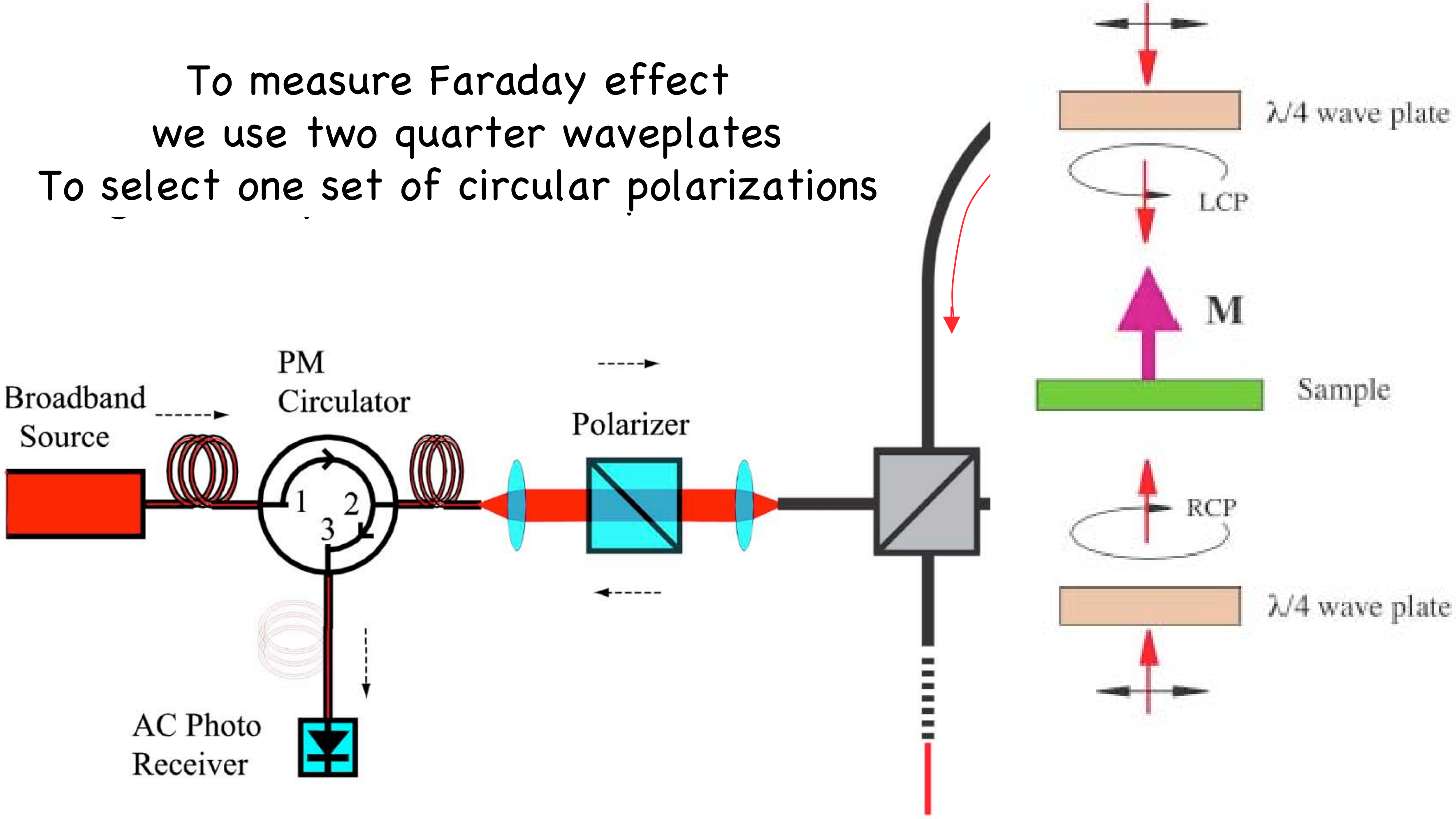
$$\Delta\phi = \frac{2\pi LD}{\lambda c}\Omega$$

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

[S. Spielman et al., 1990]

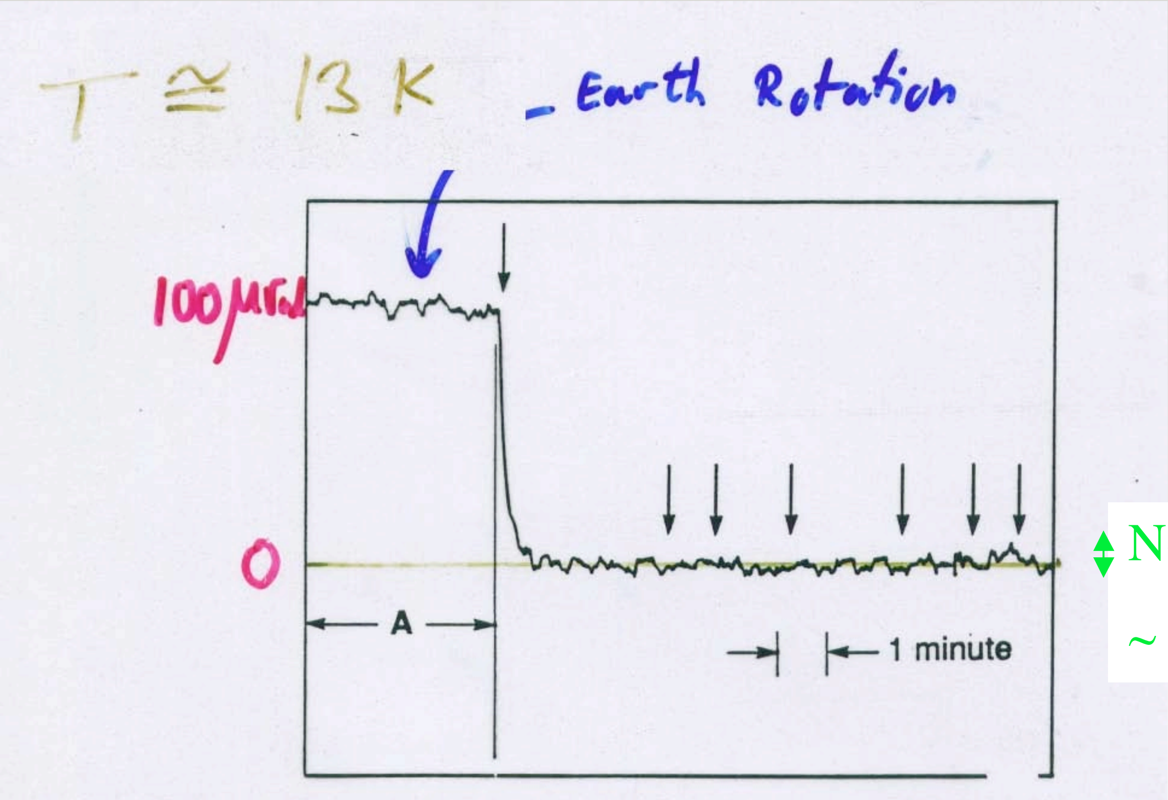
Use Sagnac loop to measure magnetization:

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



Idea first used to test for anyon-superconductivity in high-Tc*

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



↕ Noise

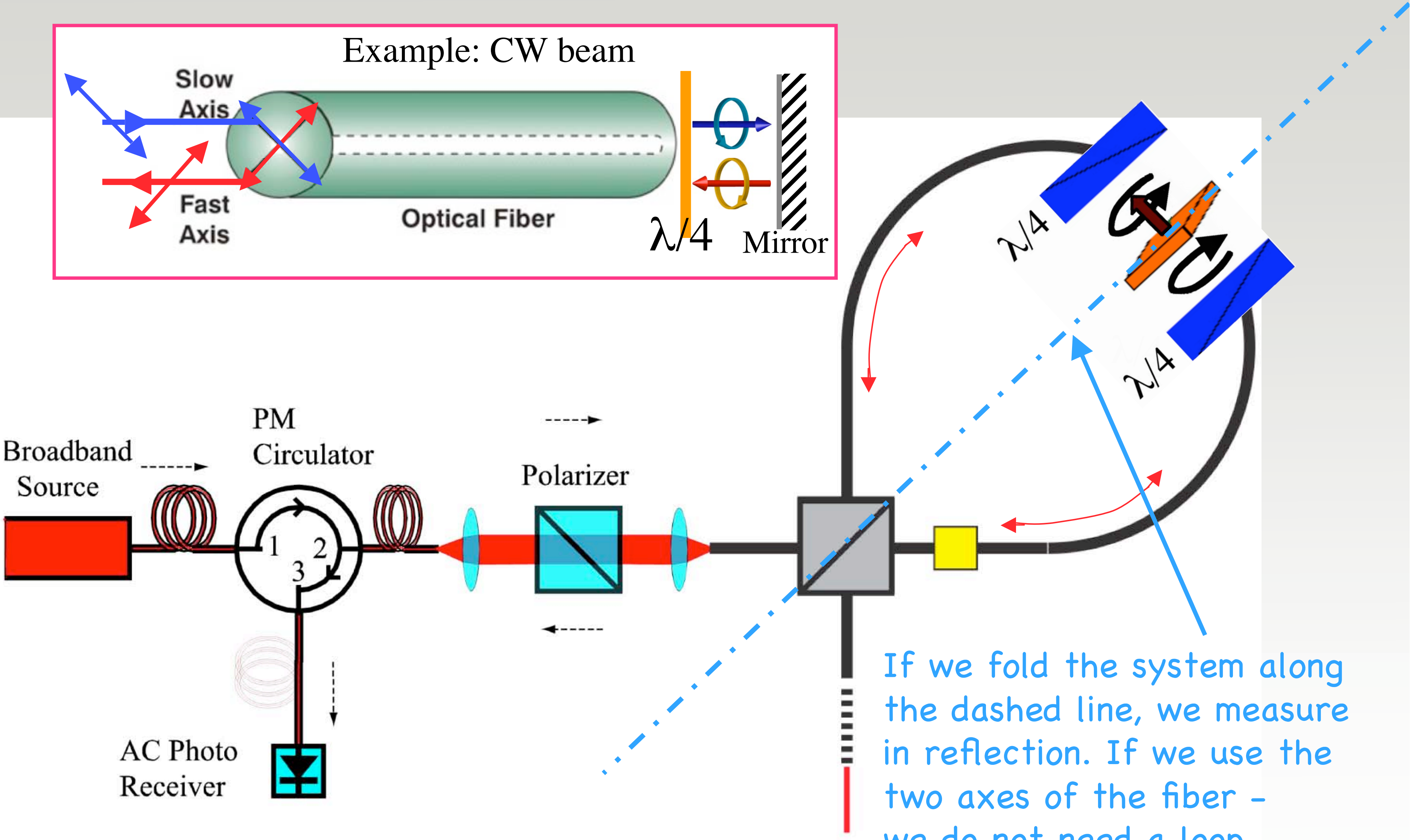
~ 2 µrad/$Hz^{1/2}$

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

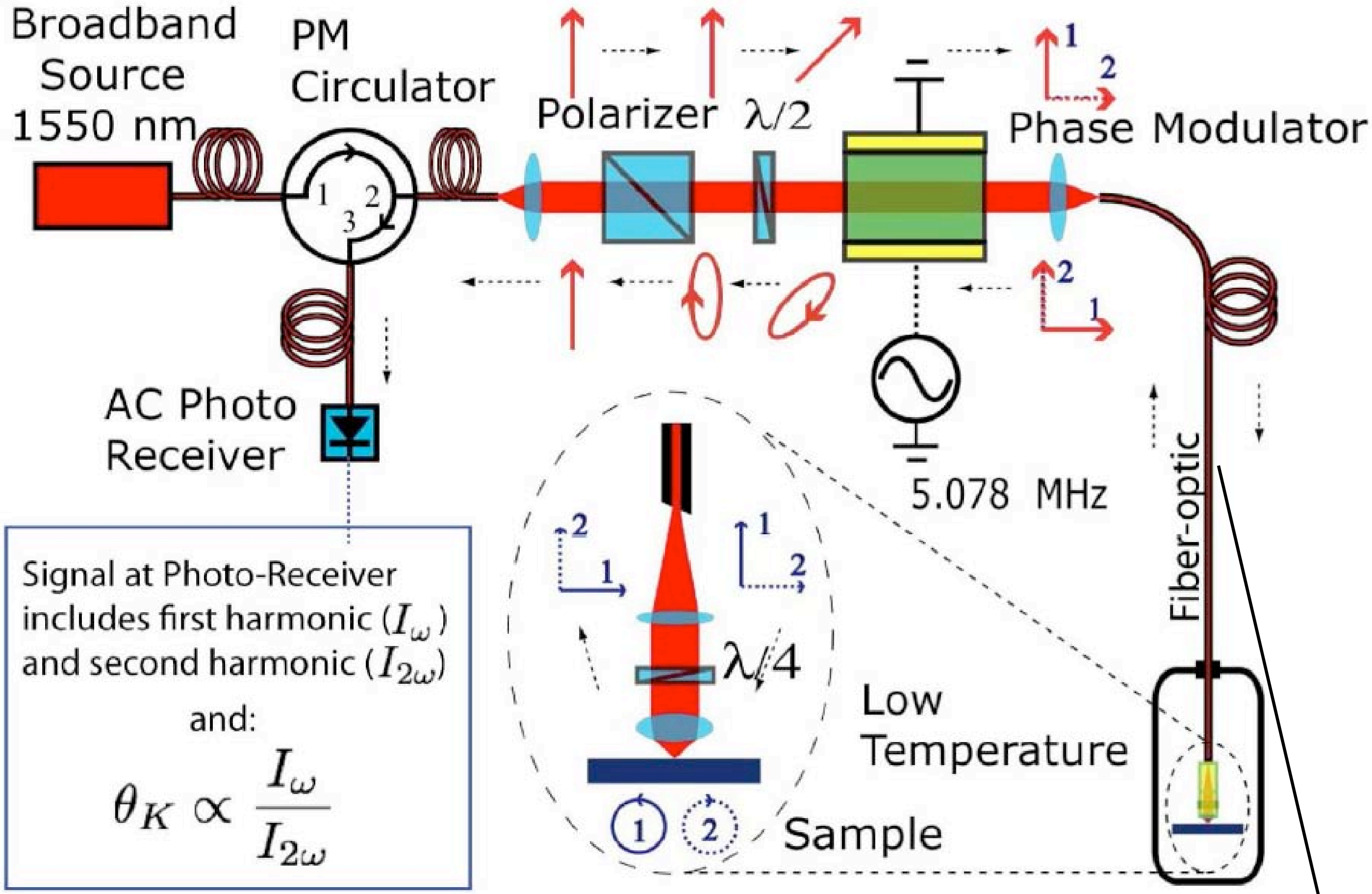
The zero-area-loop interferometer



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.

Zero-area-loop Sagnac magnetometer

λ=1.55 μm



Signal at Photo-Receiver includes first harmonic (I_ω) and second harmonic ($I_{2\omega}$)

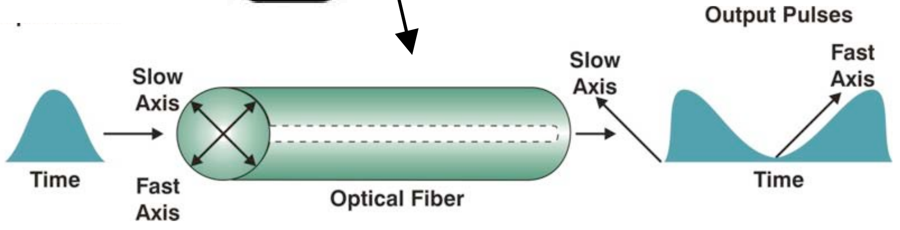
and:

$$\theta_K \propto \frac{I_\omega}{I_{2\omega}}$$

here is no optical-iewport, allows lower emperatures (0.3 K) peration.

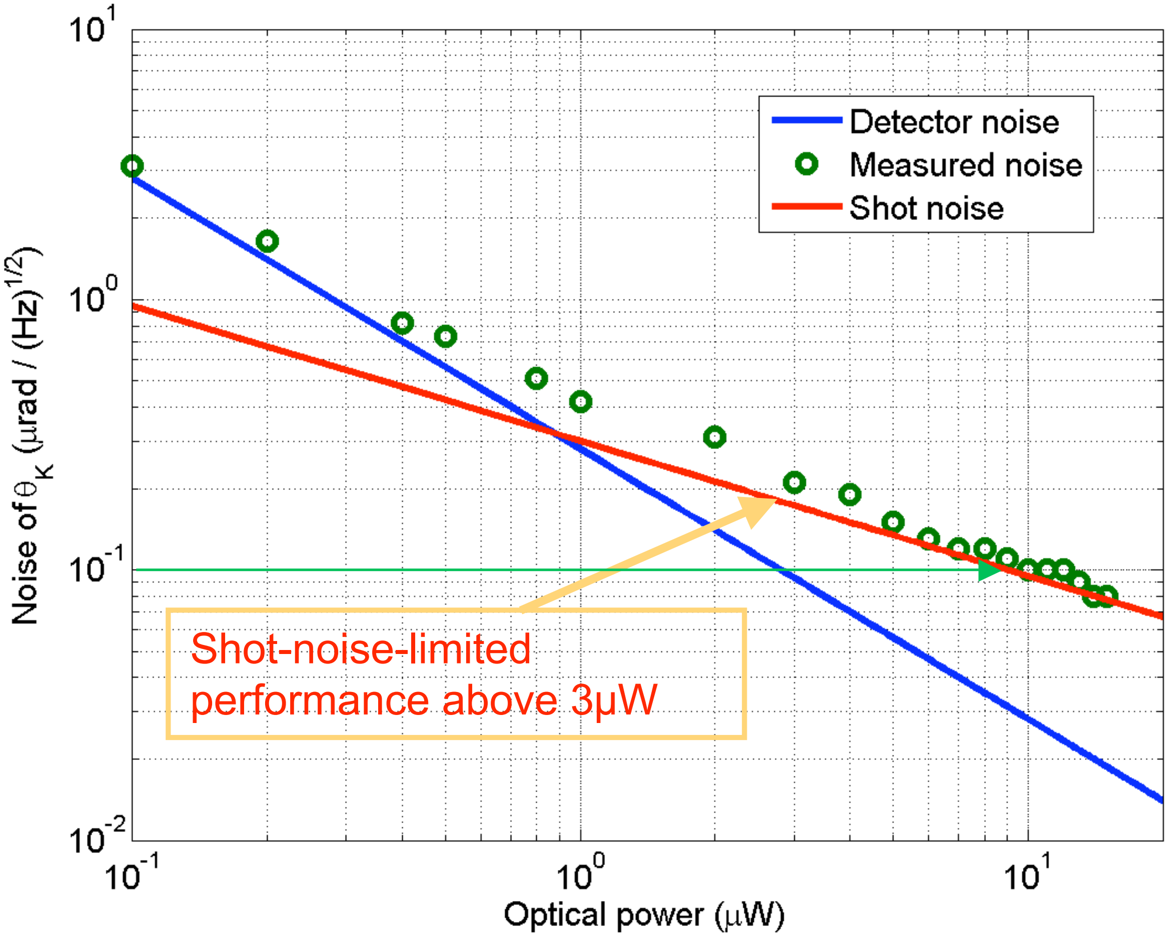
rejects epolarization effects uch as linear irefringence.

oth DC and AC erformance are shot-oise 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 uW:

$$\sigma_{shot\_noise} \cong 0.6\sqrt{\frac{2\hbar\omega\Delta f}{P_{ave}}}$$

$$\cong 0.3/\sqrt{P_{ave}}\,(\mu rad/\sqrt{Hz})$$

Detector noise:

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

$$\sigma_{detector} \cong 0.56\frac{\mathrm{detector}NEP}{P_{ave}}$$

$$\cong 0.28/P_{ave}(\mu rad/\sqrt{Hz})$$

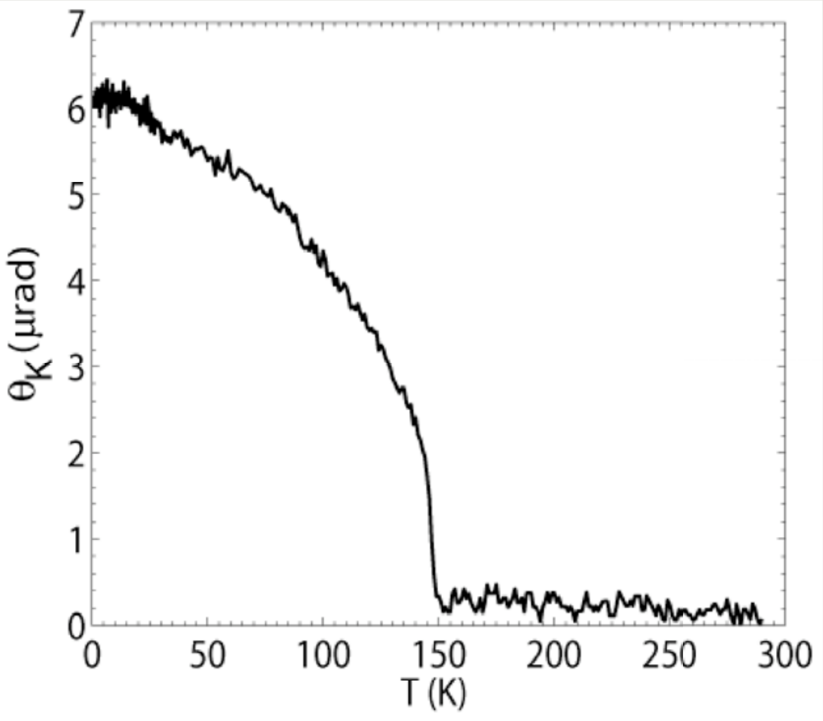
To achieve 20 nano-radian resolution, minimum averaging time will be:

25 seconds, with 10 uW optical power

500 seconds, with 1 uW optical power

It works! Studies on $SrRuO_3$ Ultra-thin Films

Kerr effect measurements of ferromagnetic Transition in multi-domain, $SrRuO_3$ film (0.5K ÷ 290K):



Polar Kerr effect from a 30 nm $SrRuO_3$ thin film.

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

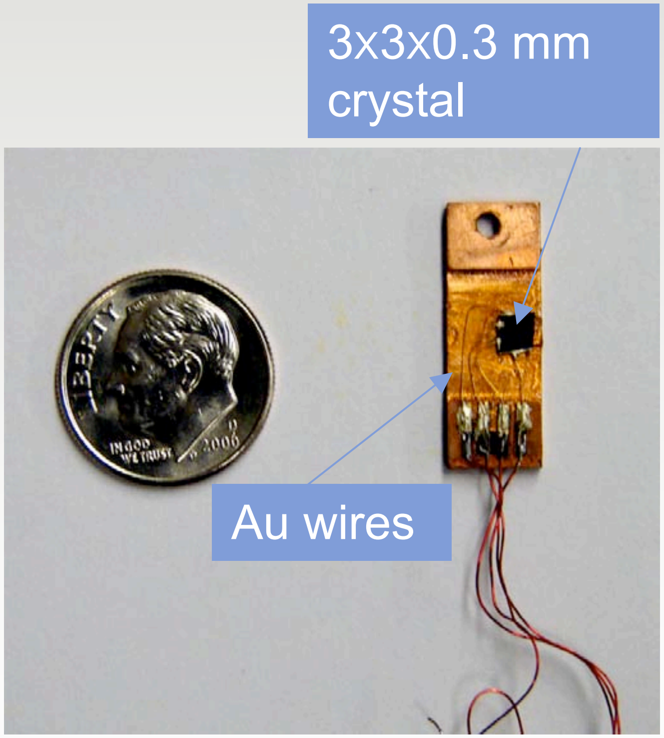
Kerr effect measurements on Sr_2RuO_4

Jing Xia

Marty Fejer
Peter Beyersdorf

Samples:

Yoshi Maeno, Kyoto University

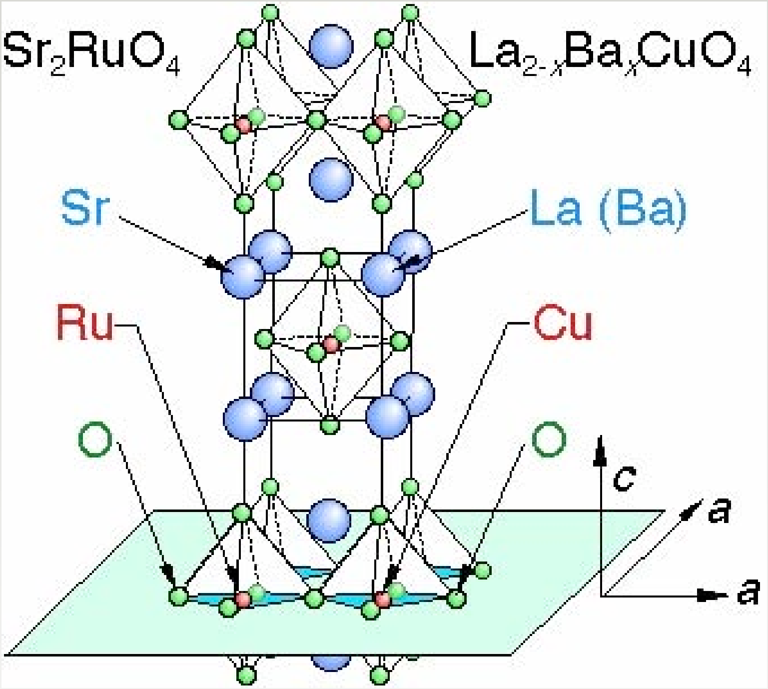

3x3x0.3 mm crystal

Au wires

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

Sr_2RuO_4

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



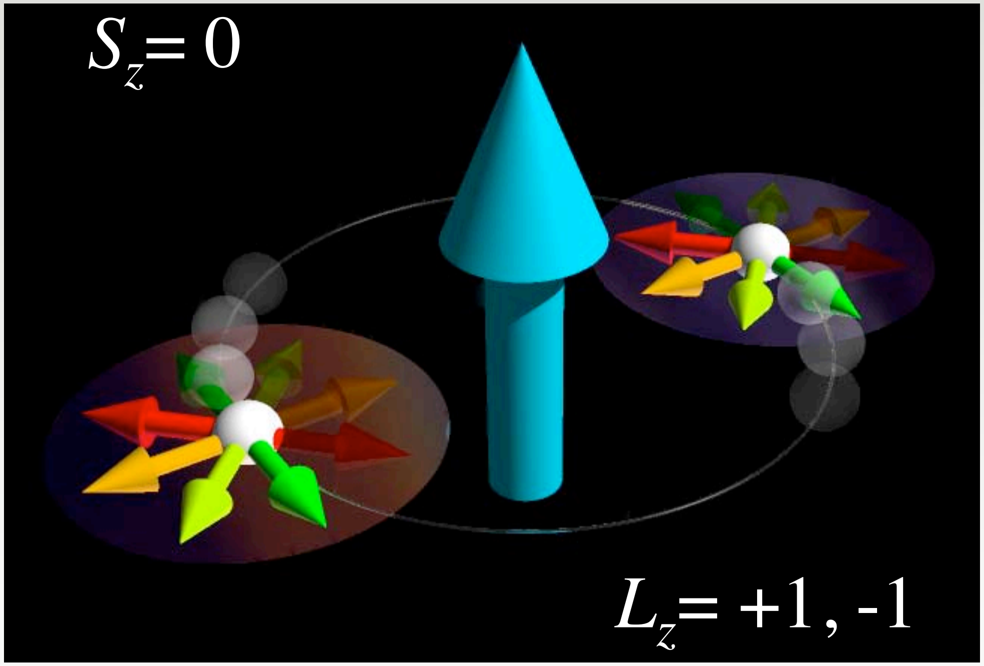
Sr_2RuO_4 is a layered perovskite isostructural with $La_{2-x}Ba_xCuO_4$.

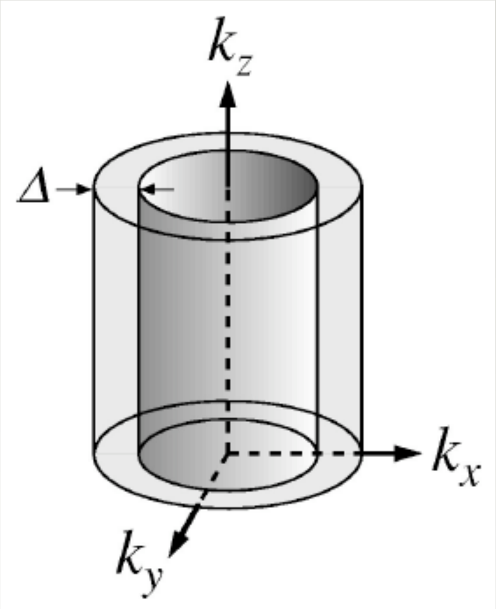
Y. Maeno, H. Hashimoto, K. Yoshida, S. Nishizaki, T. Fujita, J. G. Bednorz & F. Lichtenberg, Nature 372 (1994), 532.

T_C (as discovered) ~ 0.93 K

Suggested symmetry for the order parameter of Sr_2RuO_4: $\vec{d} = \Delta_0 \hat{z}(p_x \pm ip_y)$

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





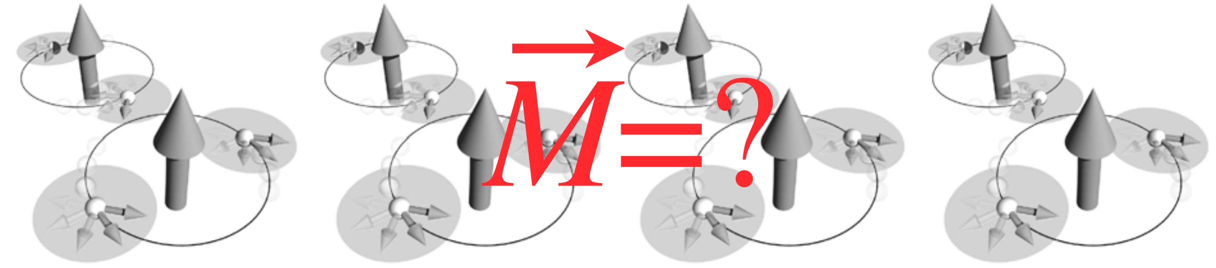
No nodes

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

Time Reversal Symmetry is Broken!

Is this an example of orbital magnetism?

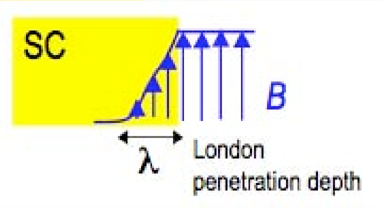
Can we measure a spontaneous magnetization?



$\vec{M}=?$

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

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



<u>However:</u>

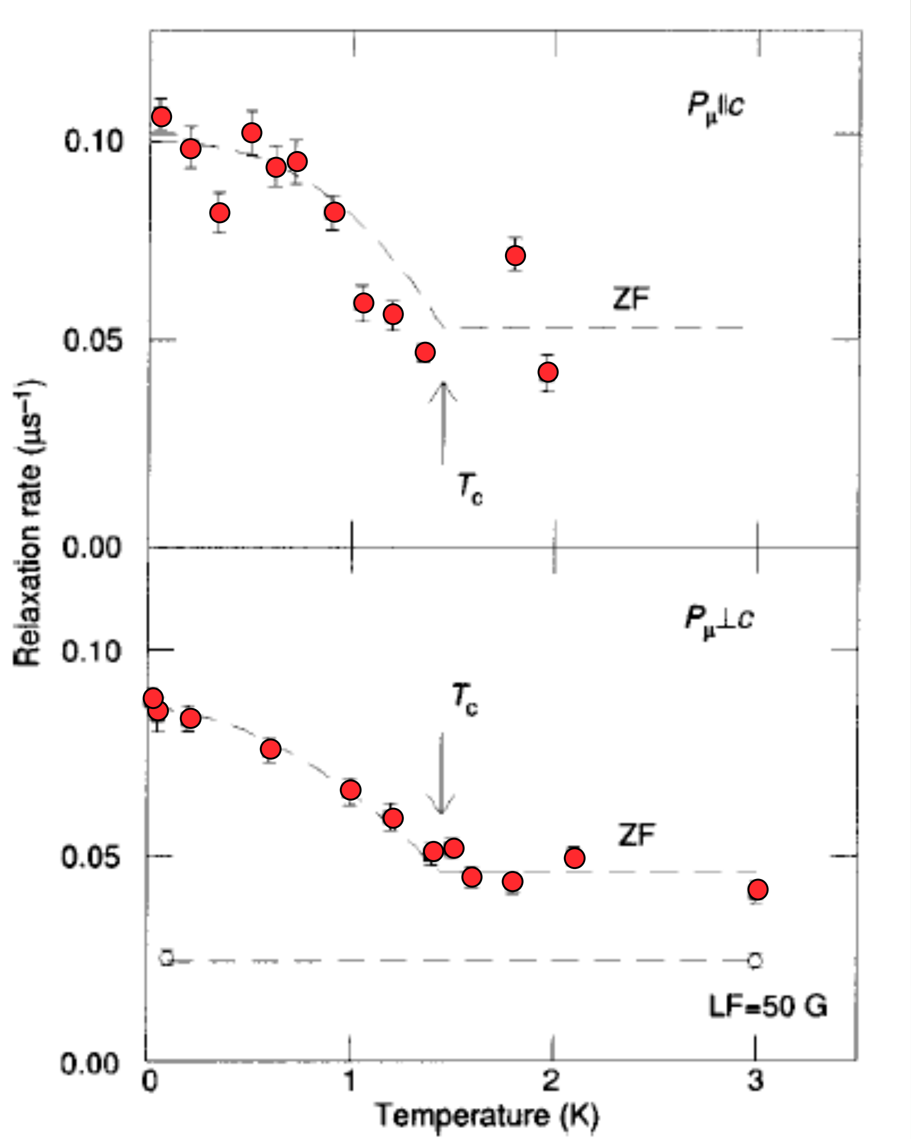
sample will always contain **surfaces and defects** at which the Meissner screening of the TRS-breaking moment is not perfect, and a small magnetic signal is expected.

Muon spin rotation as local measurement:

Muons disturb the local order

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

Estimated local field: ~ 0.5 Oe



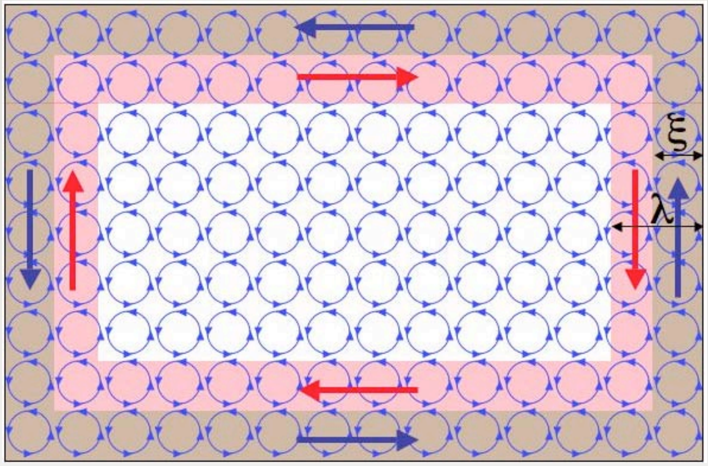
<u>However:</u>

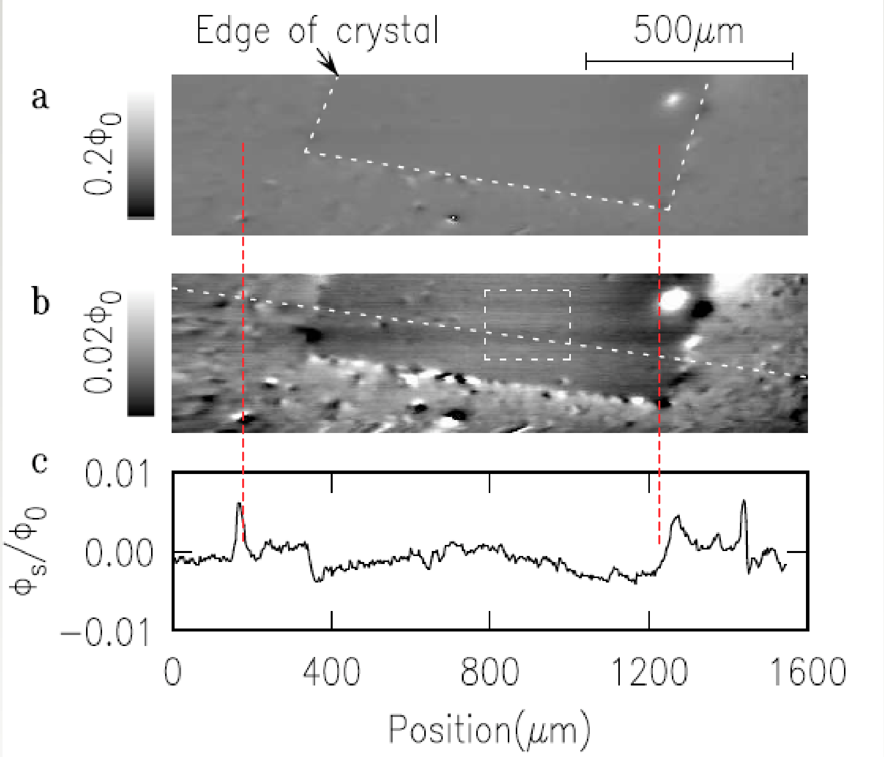
1. The effect was isotropic
2. Signal could come from other sources

[Luke et al., 2000]

Search for edge currents

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

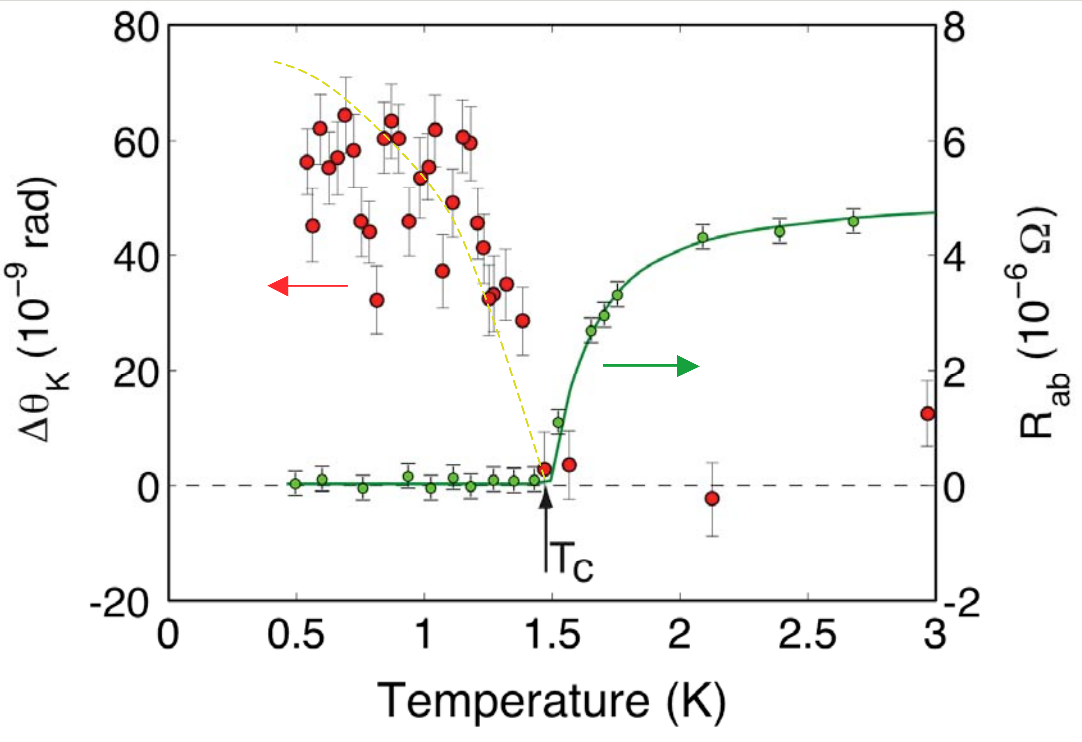




No edge currents were detected using scanning Hall probe and scanning SQUID.

*Note: This may challenge the pure p±ip state, but NOT the possibility for time-reversal symmetry breaking.

Zero field cool



Beam size = 20 μm

Incident power =0.7÷ 2 μW

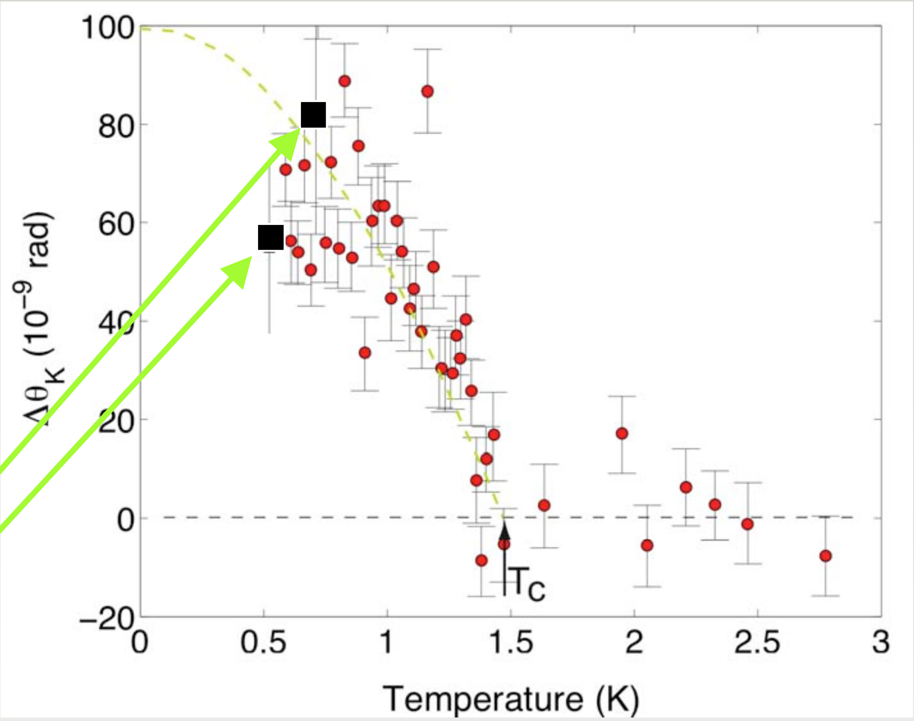
Sign of zero-field-cool data is random

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

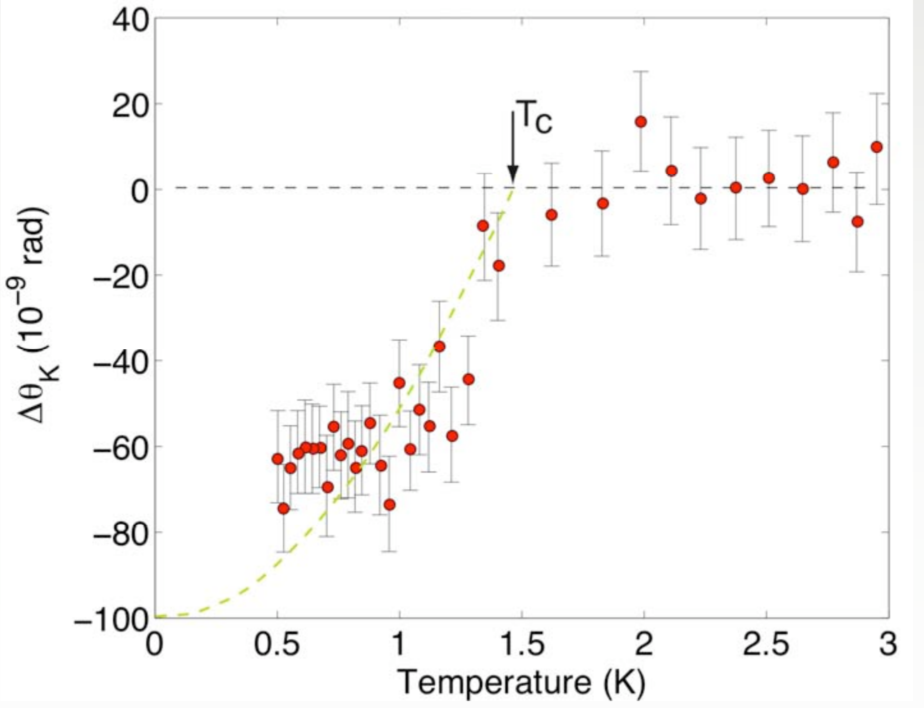


Last two points before field switched to zero.

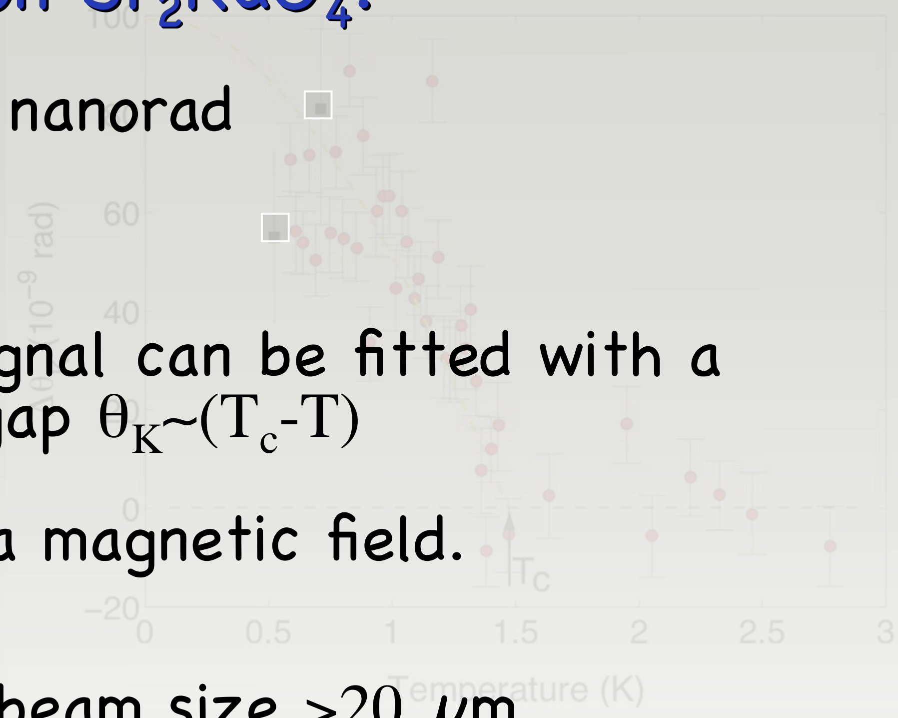
Dashed lines are guide to the eye

cool in H=-47 Oe

Warm up in H=0



Summary of observations on Sr_2RuO_4:



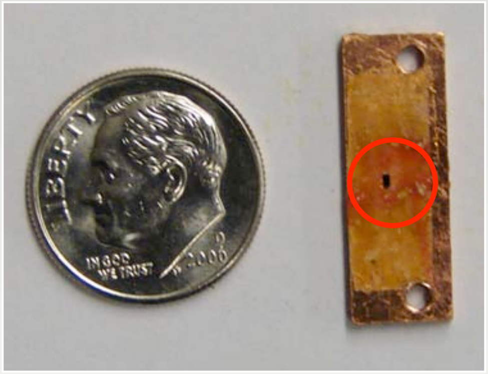
- Maximum signal is ~65 ÷ 100* nanorad
- Signal onsets at T_c
- Temperature dependence of signal can be fitted with a quadratic dependence on the gap $\theta_K \sim (T_c - T)$
- Chirality can be trained with a magnetic field.
  A minimum field is needed.
- Domain size is large, of order beam size $>20\ \mu m$
  Zero-field cool 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).

* Effect and its size can be explained theoreticaly taking into account impurity scattering. [Jun Goryo, Phys. Rev. B 78, 060501(R) (2008).]

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

One of the most challenging puzzles that has emerged within the phenomenology of the high-temperature superconductors is to understand the occurrence and role of the normal-state ``pseudogap" phase in underdoped cuprates.

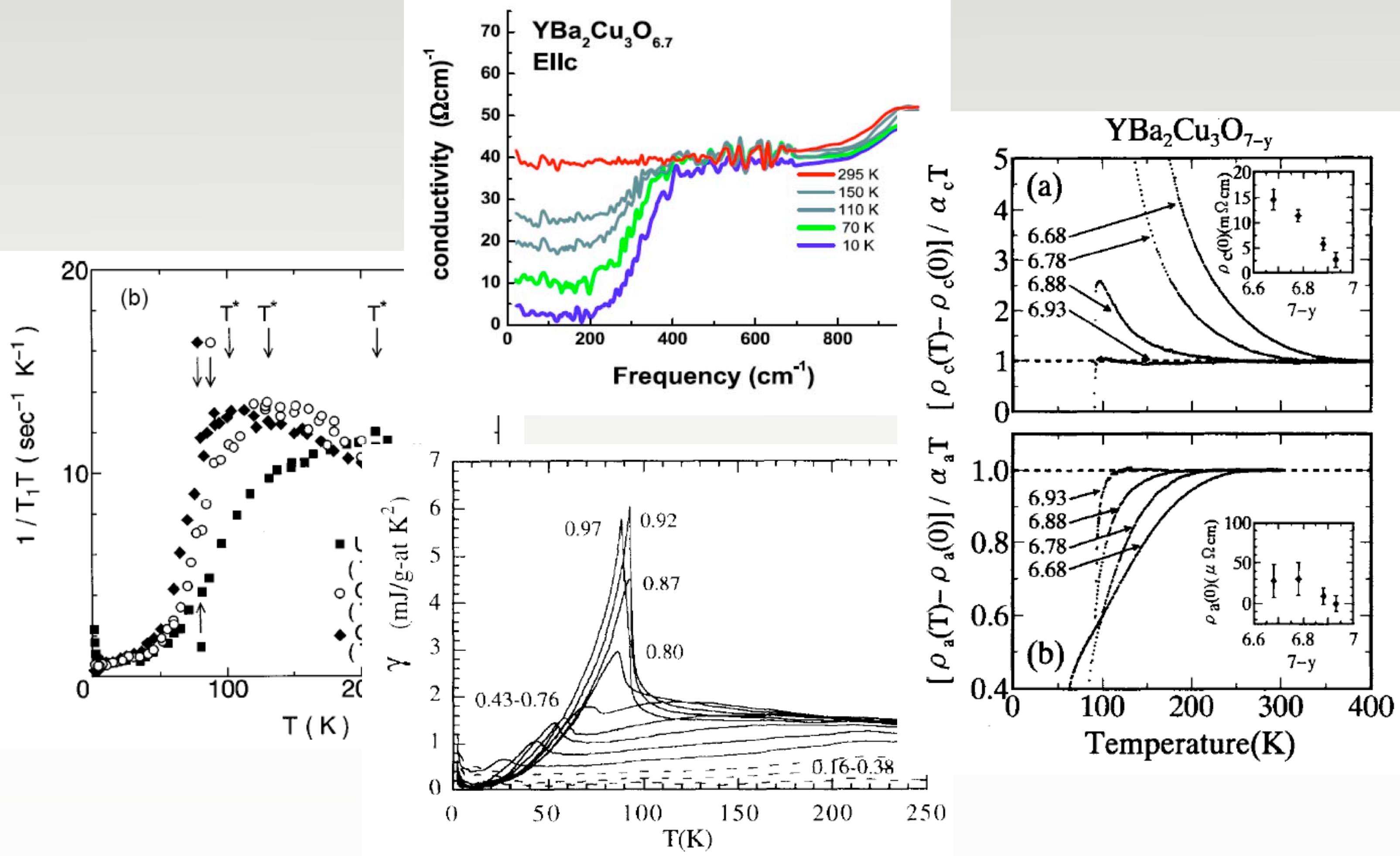


FIG 1 γ for $YBa_2Cu_3O_{6+x}$ relative to $YBa_2Cu_3O_6$ [4]

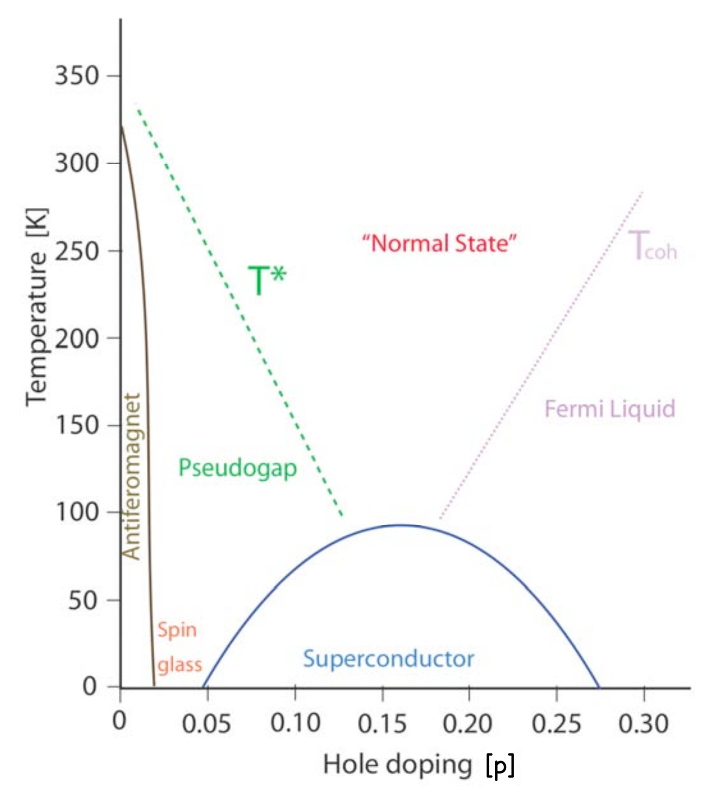
Two major classes of theories have been introduced in an attempt to describe the pseudogap state:

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))

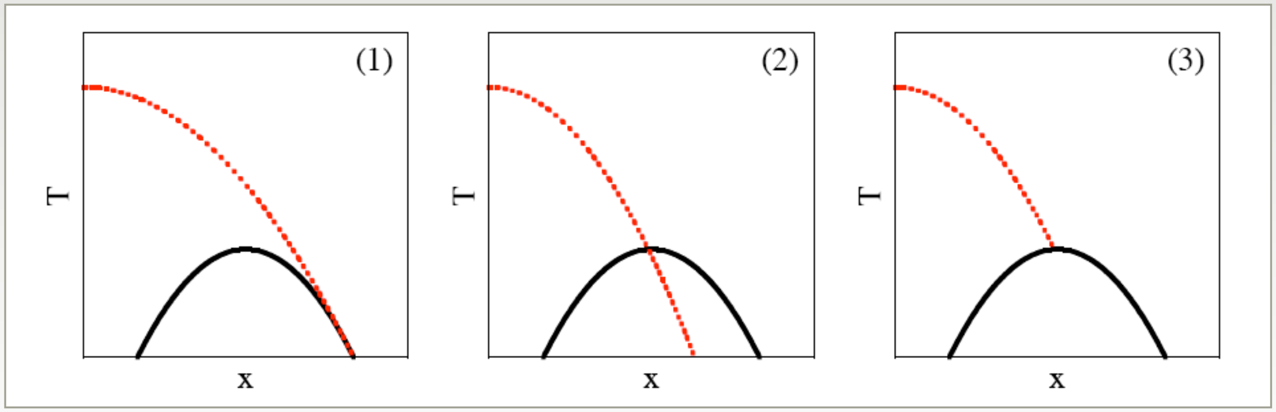


(Schematic) Phase diagram of YBCO

Possible relations between T* and superconductivity

The T* "phase" line may:

1. become degenerate with T_c or
2. cut through the T_c dome, or
3. end at the T_c dome.



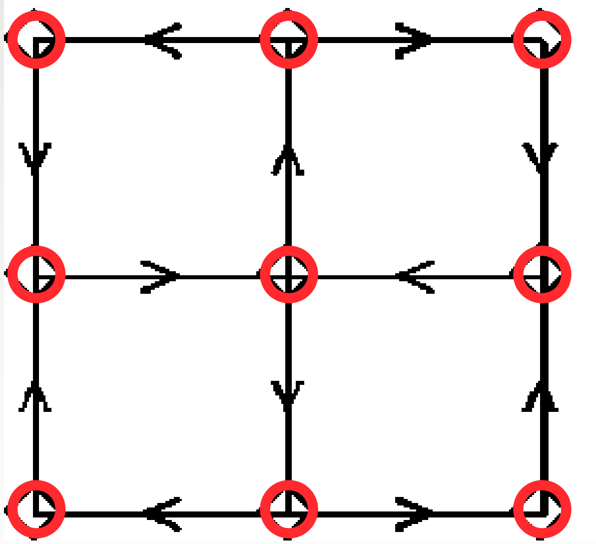
The pseudogap state may:

1. compete with superconductivity, or
2. enhance it.

M. R. Norman *et al.*, *Adv. Phys.* **54**, 715-733 (2005)

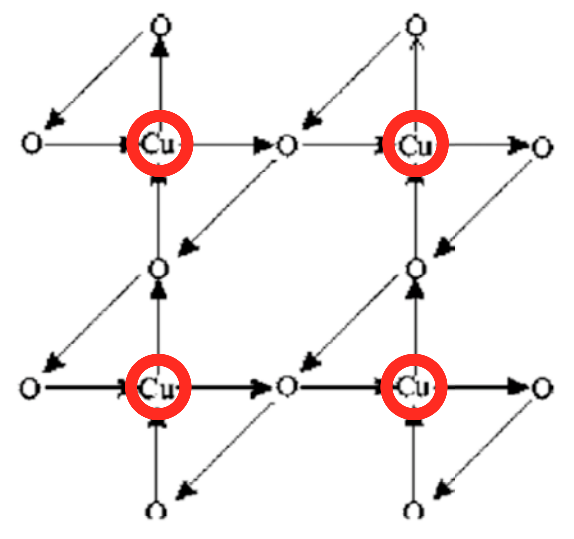
Recent theoretical work has lead to renewed interest in magnetic signatures of the pseudogap

In particular, several recent theories propose current loops of different ordering, e.g.:



Breaks translational symmetry

S. Chakravary *et al.*, *PRB* **63**, 094503 (2001)

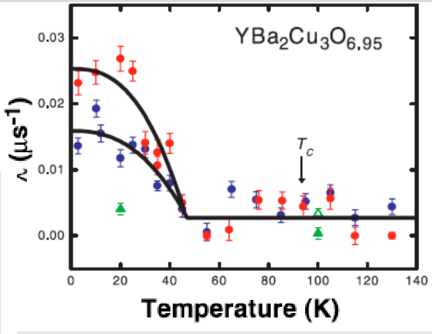


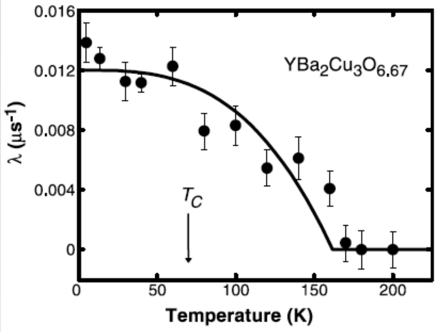
Does not break translational symmetry

C. M. Varma, Phys. Rev. B 55}, 14554 (1997)

Recent experiments to search for current loop order include

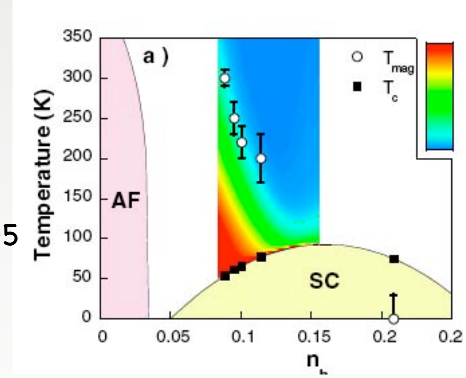
Muon spin relaxation

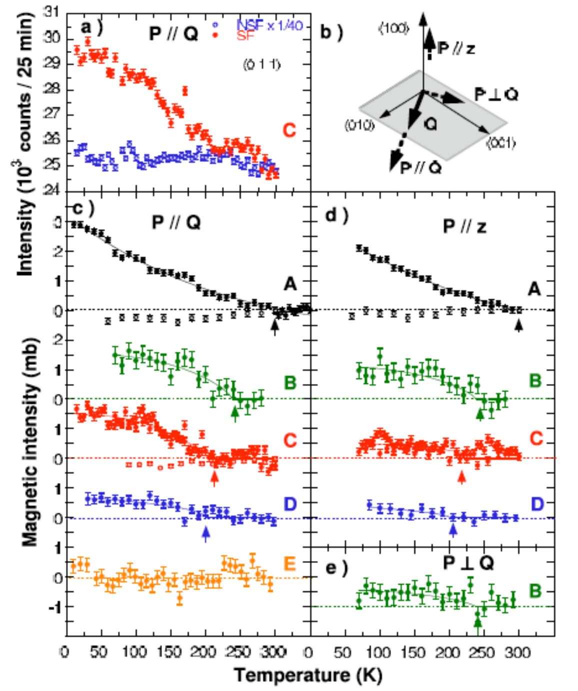




J.E. Sonier, J.H. Brewer, R.F. Kiefl, R.I. Miller, G.D. Morris, C.E. Stronach, J.S. Gardner, S.R. Dunsiger, D.A. Bonn, W.N. Hardy, R. Liang, R.H. Heffner, Science 292, 1692 (2001).

Neutron scattering



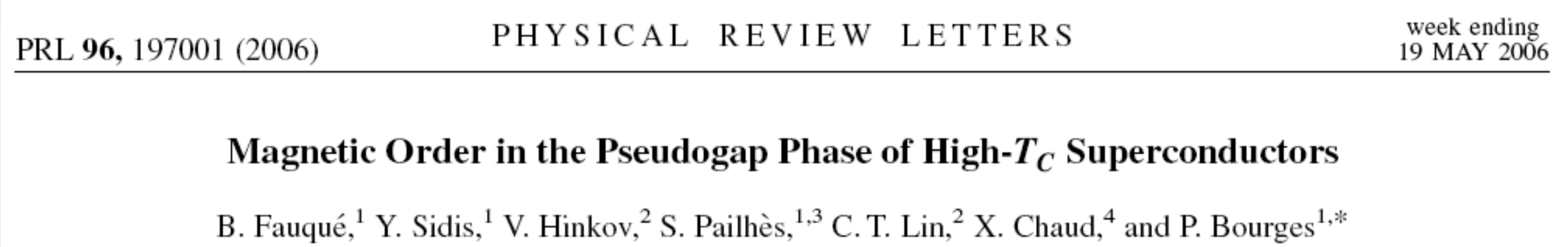


C. Stock, W.J.L. Buyers, Z. Tun, R. Liang, D. Peets, D. Bonn, W.N. Hardy, L. Taillefer, *Phys. Rev. B* **66**, 024505 (2002)

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).

Elastic neutron scattering

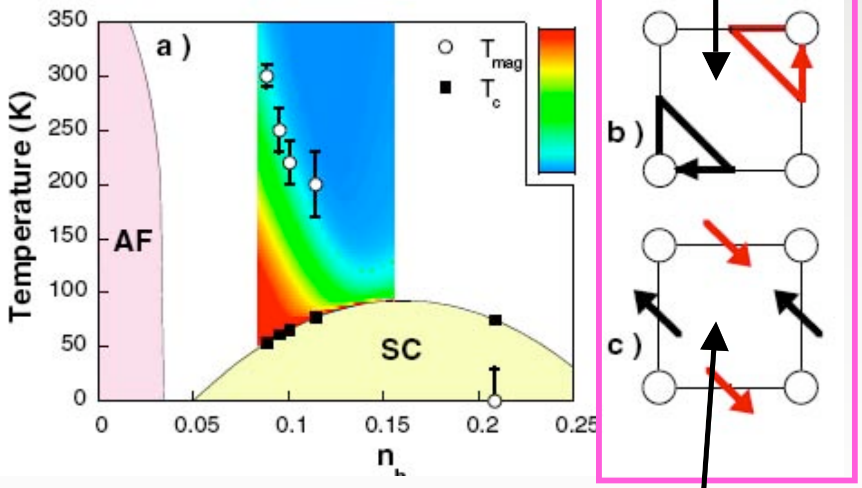


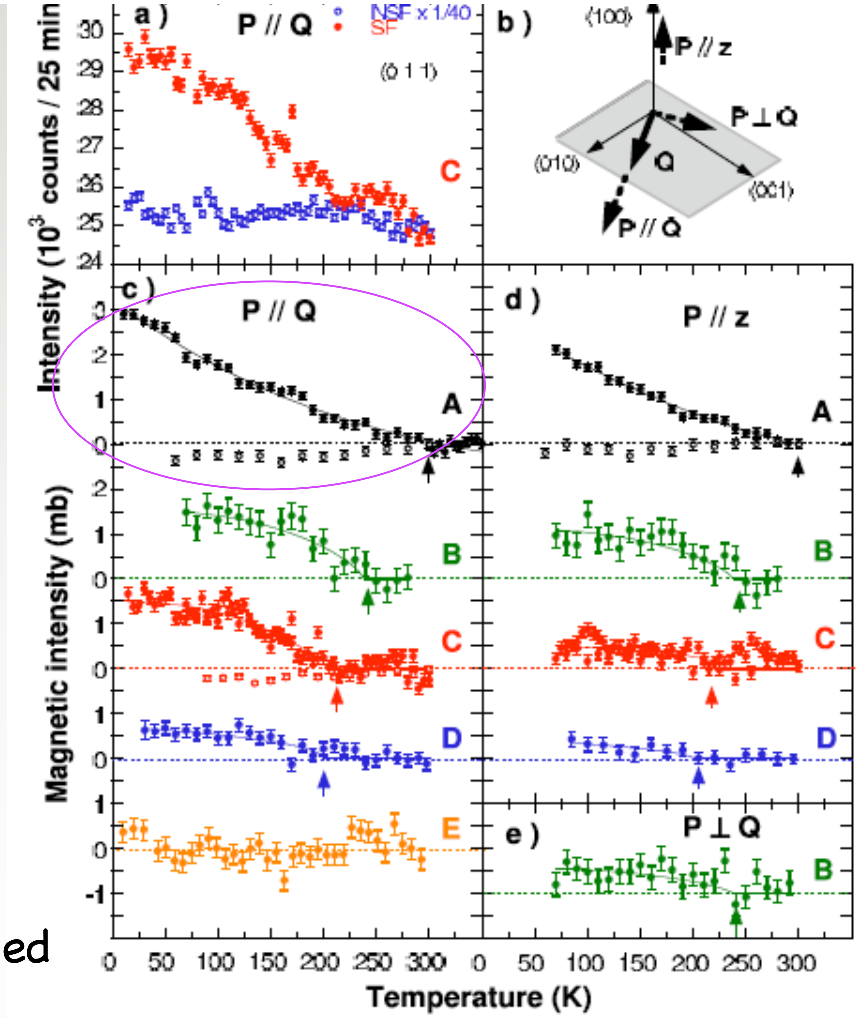
PRL **96,** 197001 (2006) PHYSICAL REVIEW LETTERS week ending 19 MAY 2006

Magnetic Order in the Pseudogap Phase of High-T_C Superconductors

B. Fauqué,[1] Y. Sidis,[1] V. Hinkov,[2] S. Pailhès,[1,3] C. T. Lin,[2] X. Chaud,[4] and P. Bourges[1,*]

Theoretical motivation: Flux phases,
in particular C. Varma's current loop:

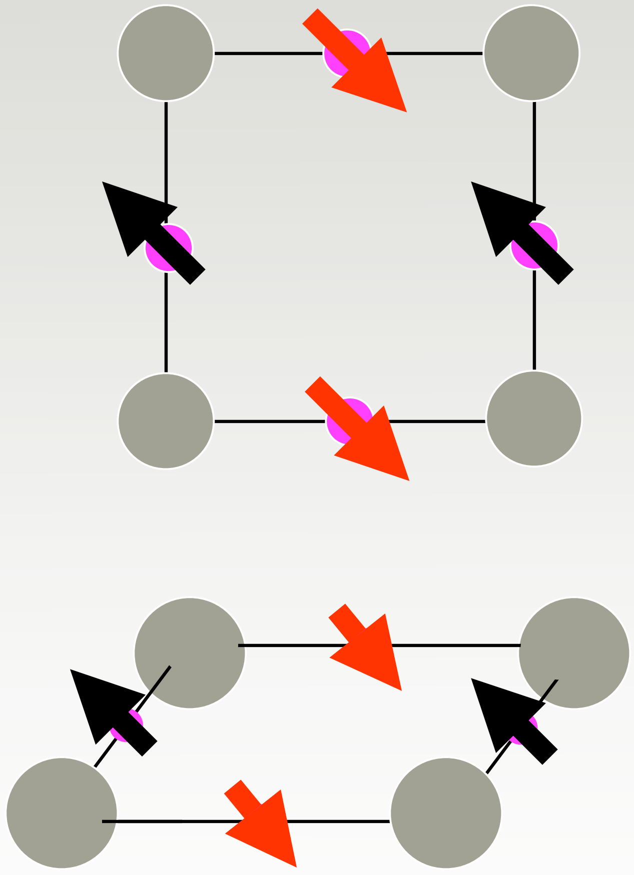




Explanation of effect if moments are involved

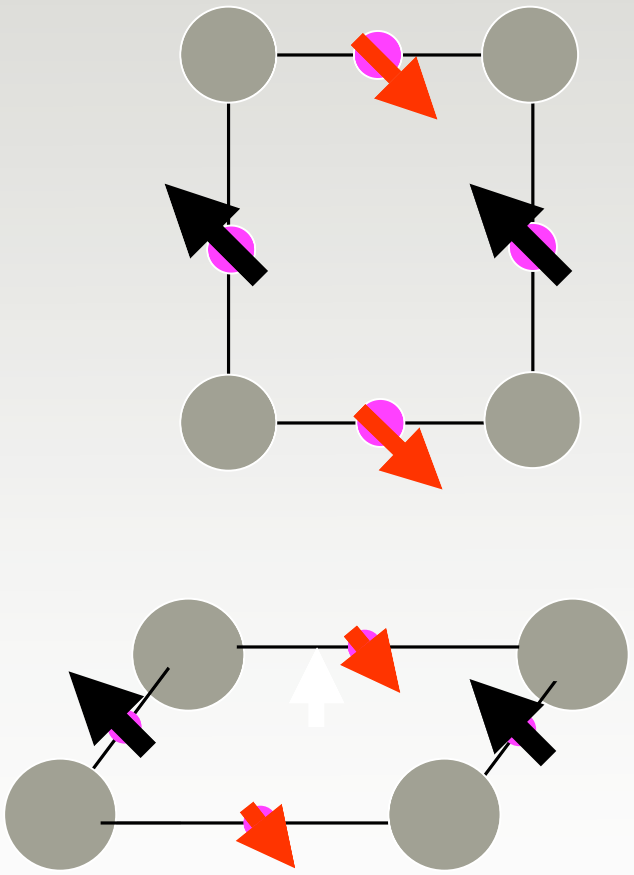
Reconciliation of neutron and Sagnac data:

Model
(Tetragonal)



$M=0$

Real YBCO
(Orthorhombic)



$M\neq 0$

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

samples

Single crystals (UBC)

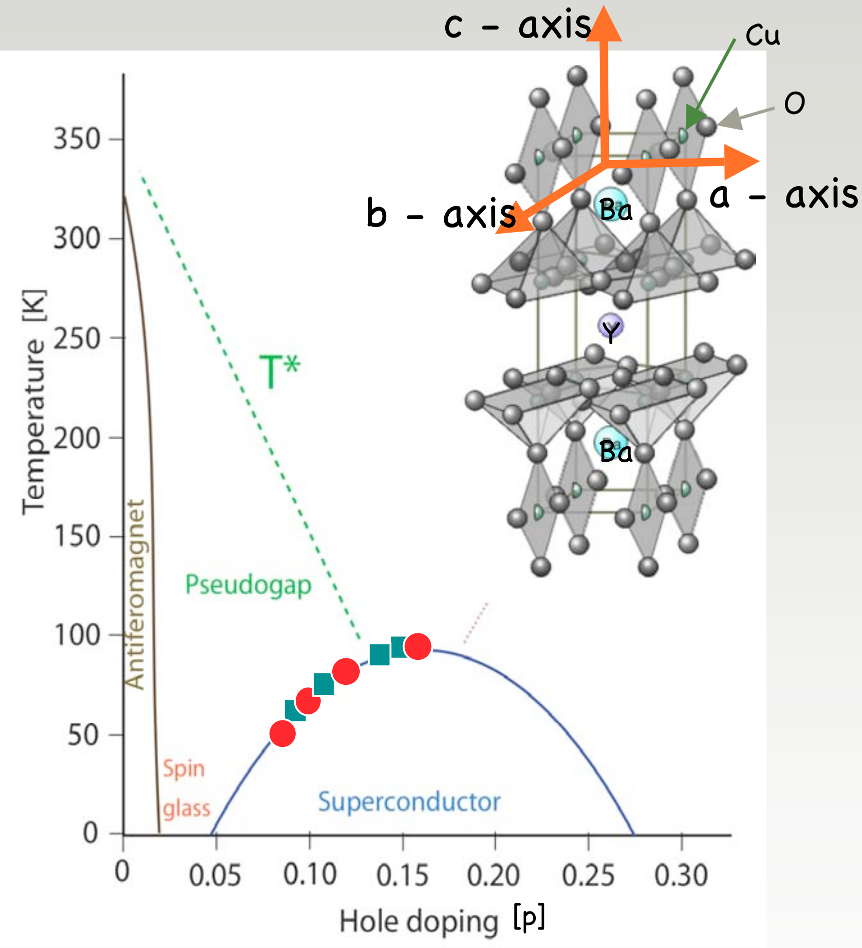
- Ortho-I,II,III,VIII
- Mechanically detwinned
- Aligned for measurement along the *c*-axis

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

c-axis thin films (Conductus/Stanford)

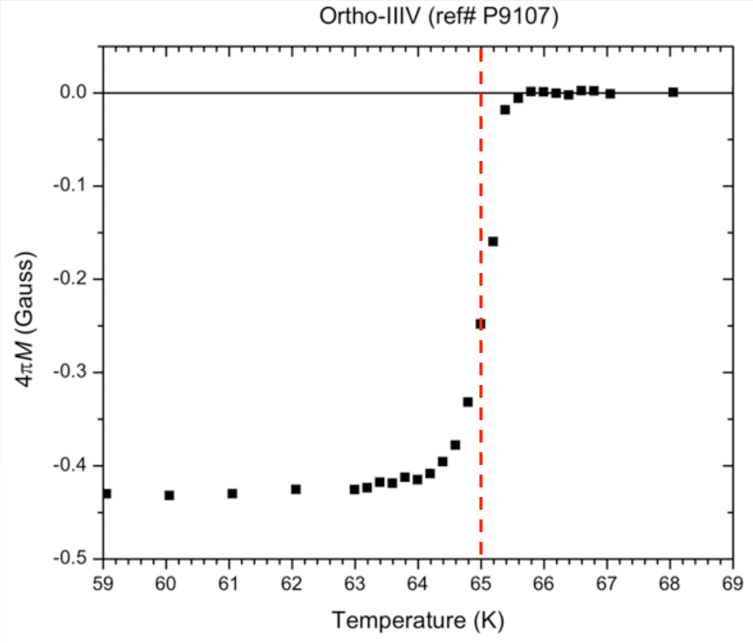
- Underdoped through annealing in reduced atmosphere

(G. Koster, W. Siemons, Stanford
G. Deutscher's group, TAU)

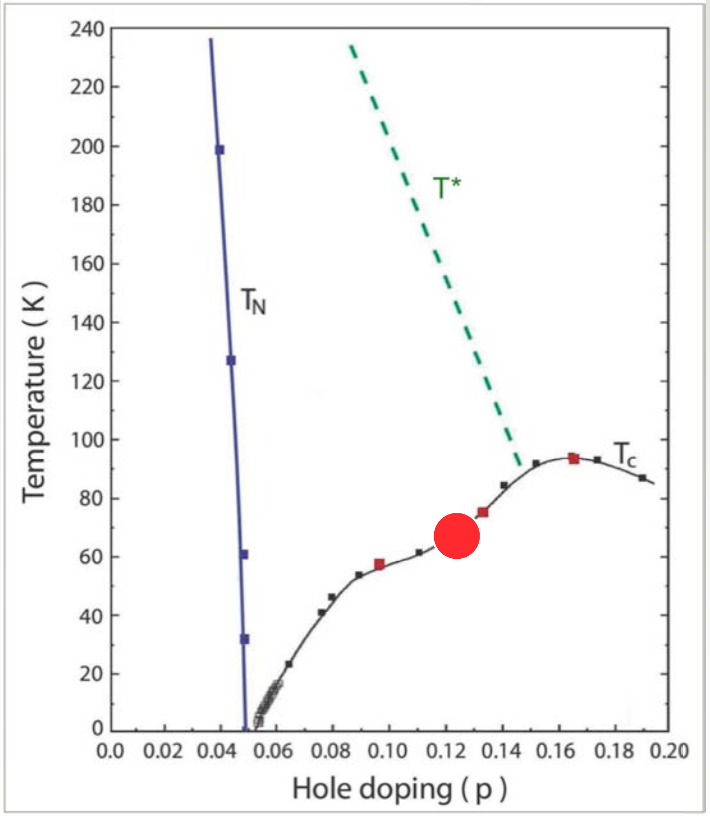


Anatomy of a data set $YBa_2Cu_3O_{6.67}$ (ortho-VIII), underdoped single crystal

T_c = 65 K



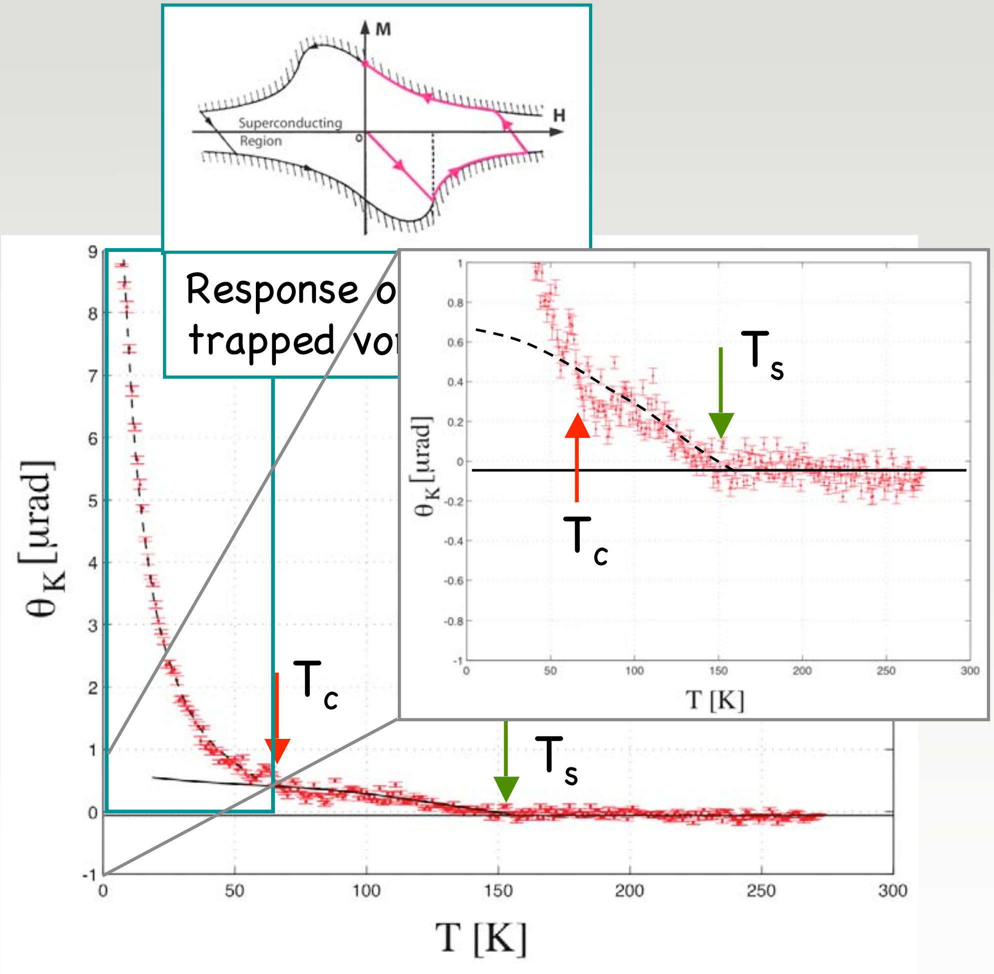
Magnetization data courtesy of D. Bonn



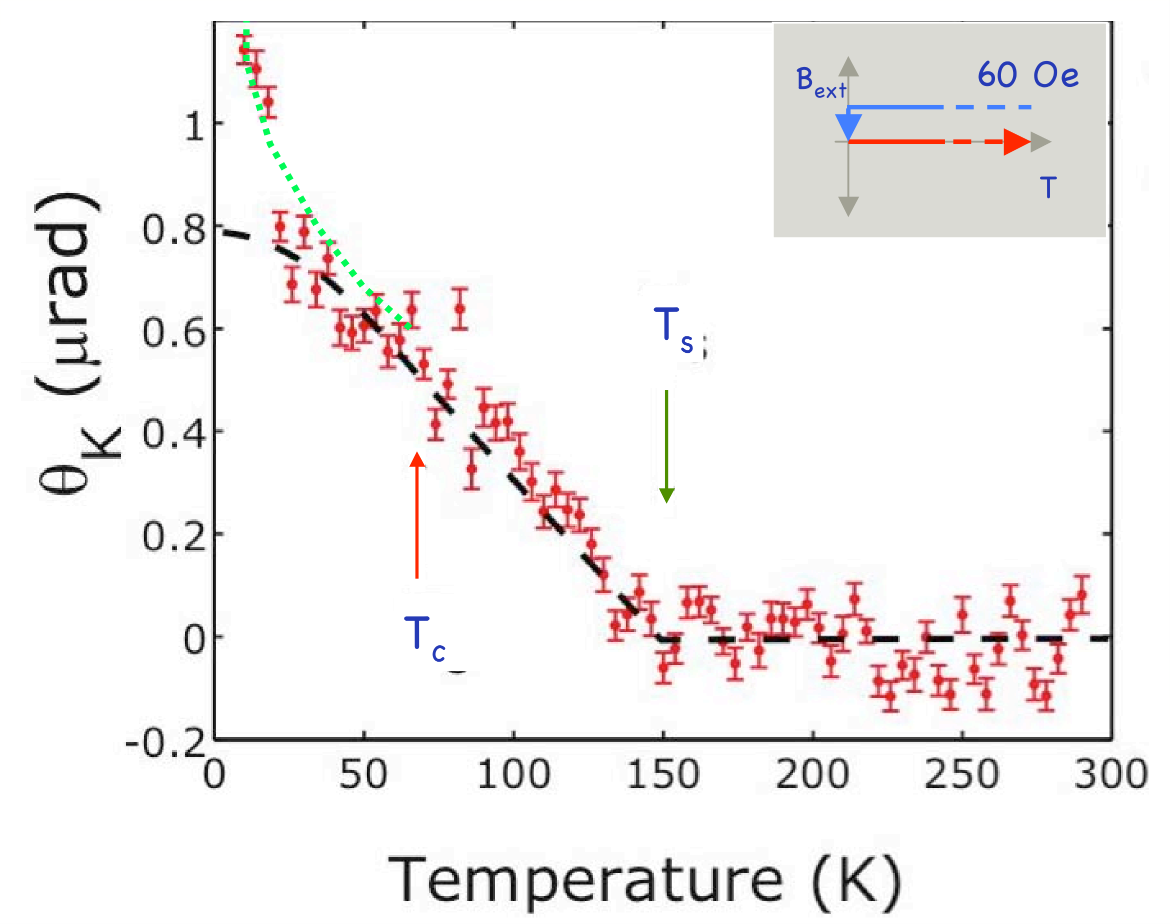
Anatomy of a data set
Ex: $YBa_2Cu_3O_{6.67}$ (ortho-VIII), cooled in high field

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



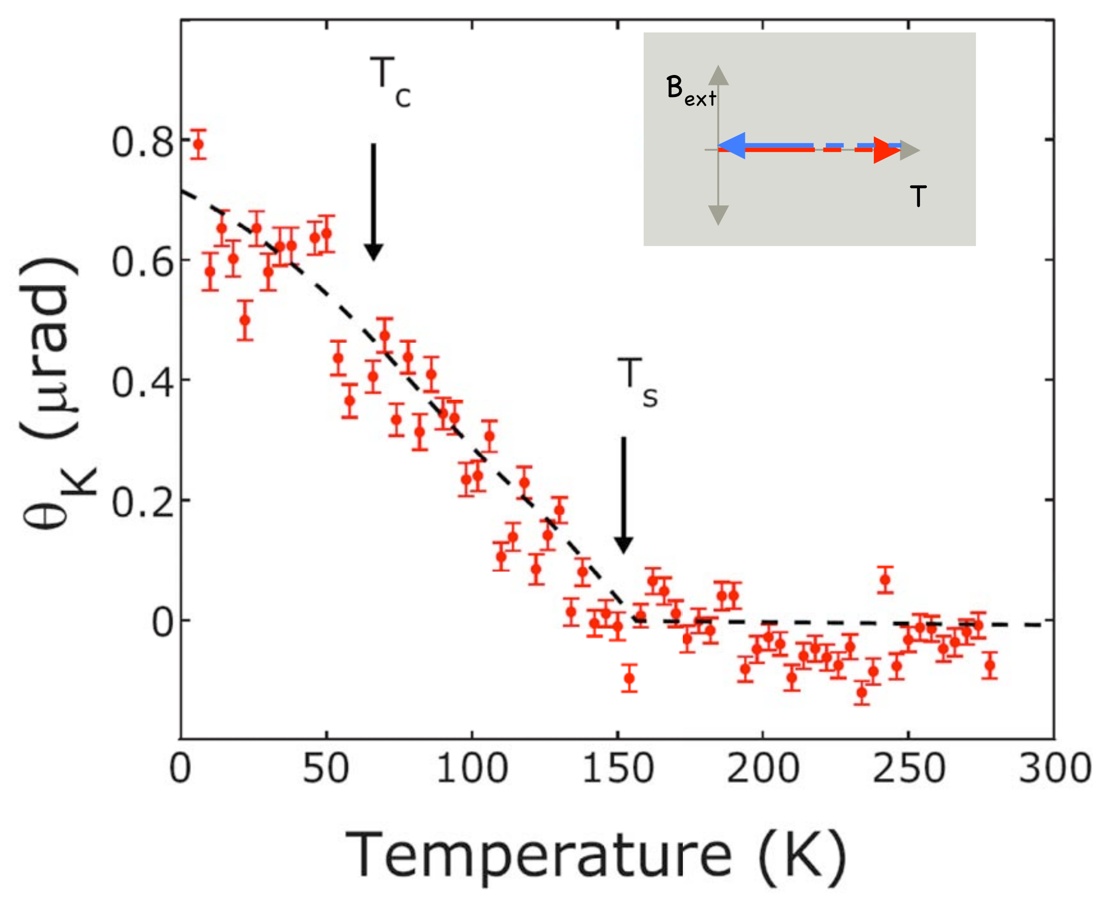
$YBa_2Cu_3O_{6.67}$: Reduce the effect of trapped vortices by cooling in a lower field



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



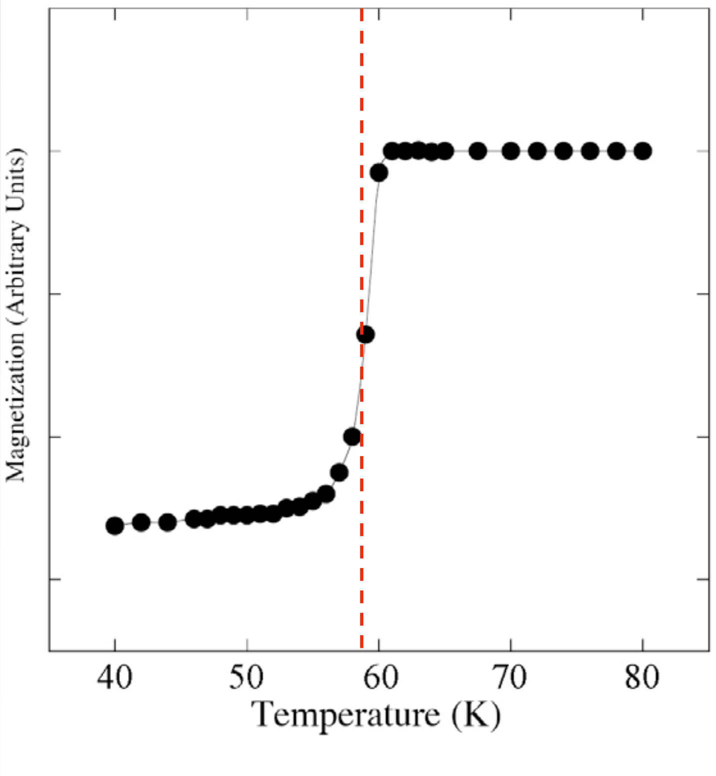
Zero field:
< 3 mOe

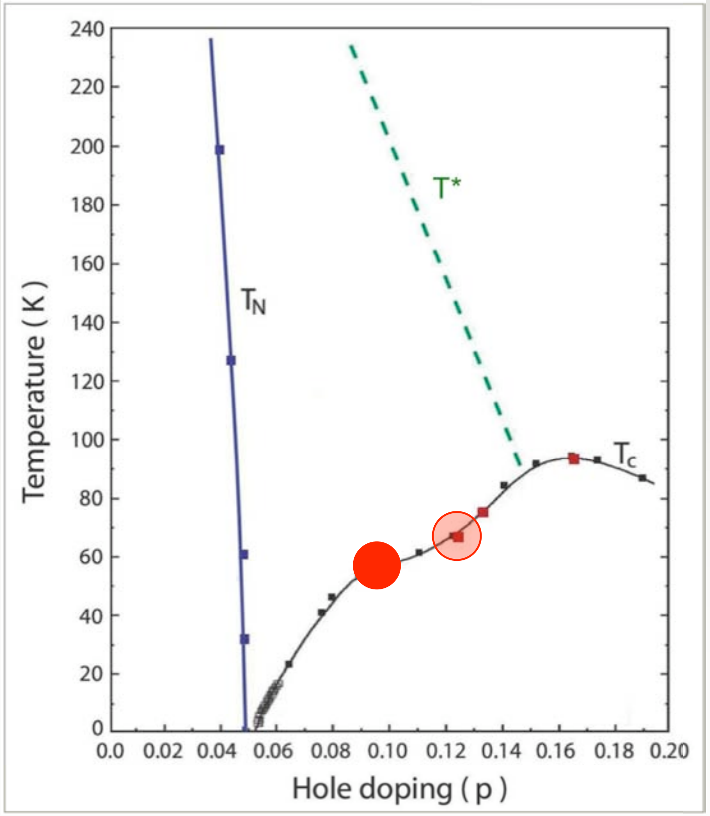
No contribution from trapped vortices

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

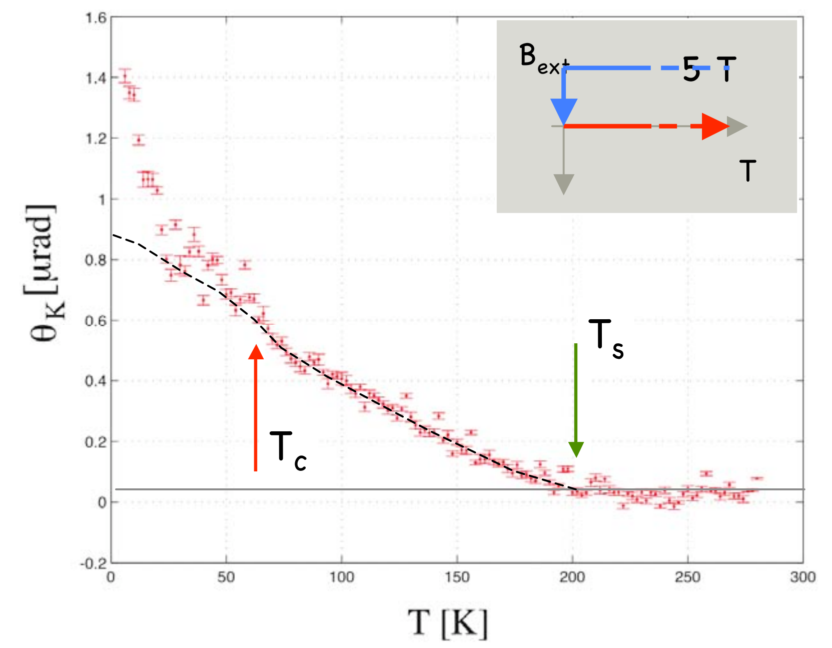


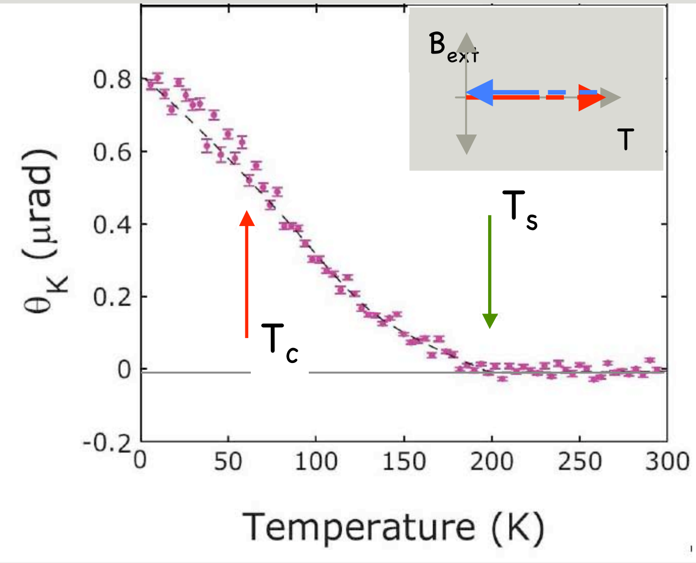


$YBa_2Cu_3O_{6.5}$: The same general Kerr behavior appears

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

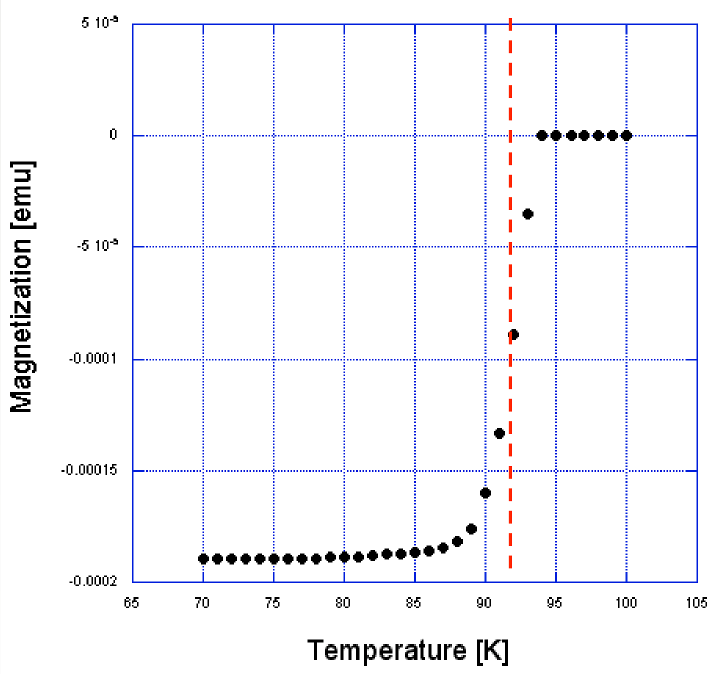


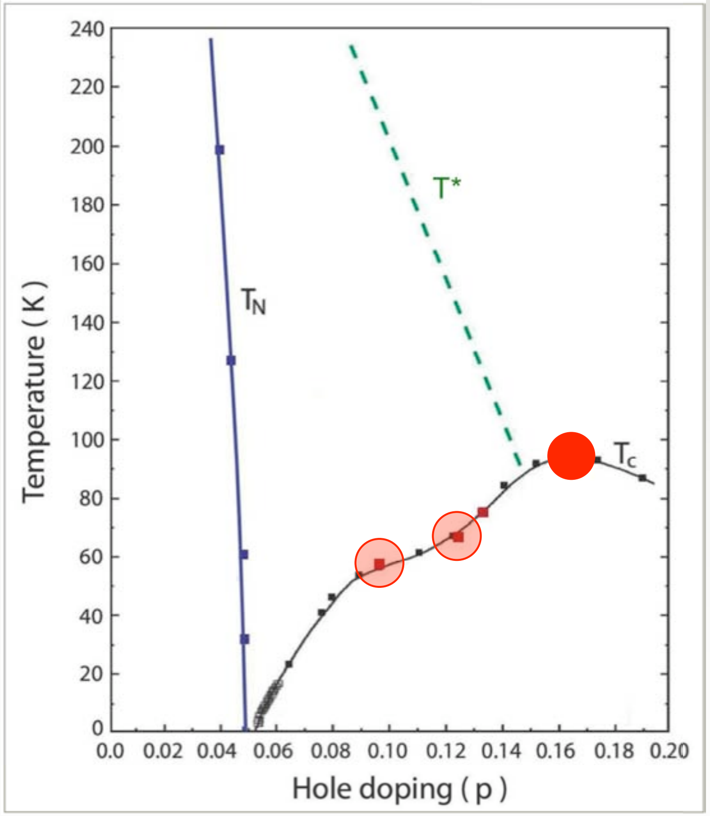


Cooling in zero field allows us to isolate the (non-vortex) signal below T_s

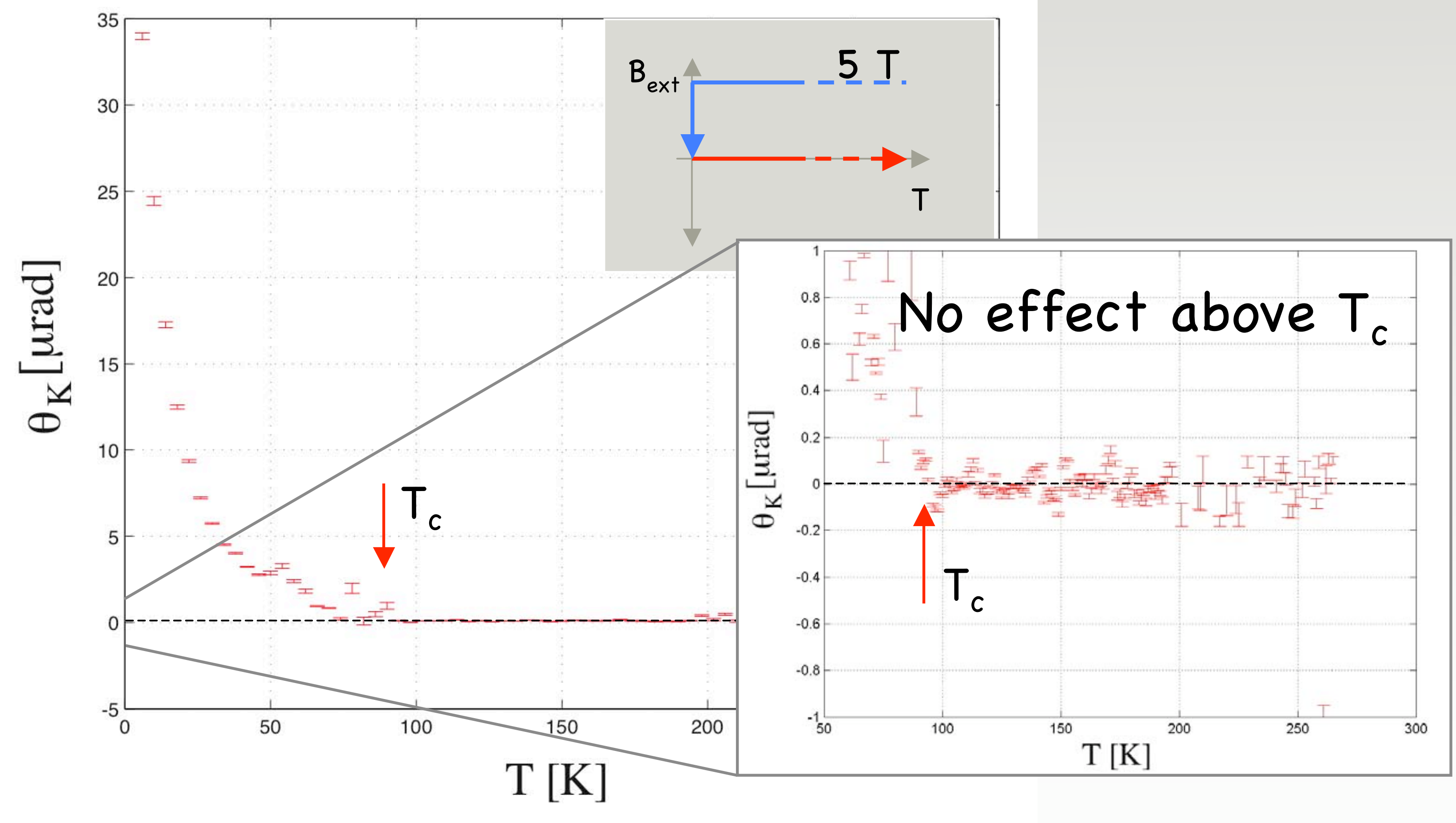
What happens near optimal doping?
$YBa_2Cu_3O_{6.92}$ (ortho-I)

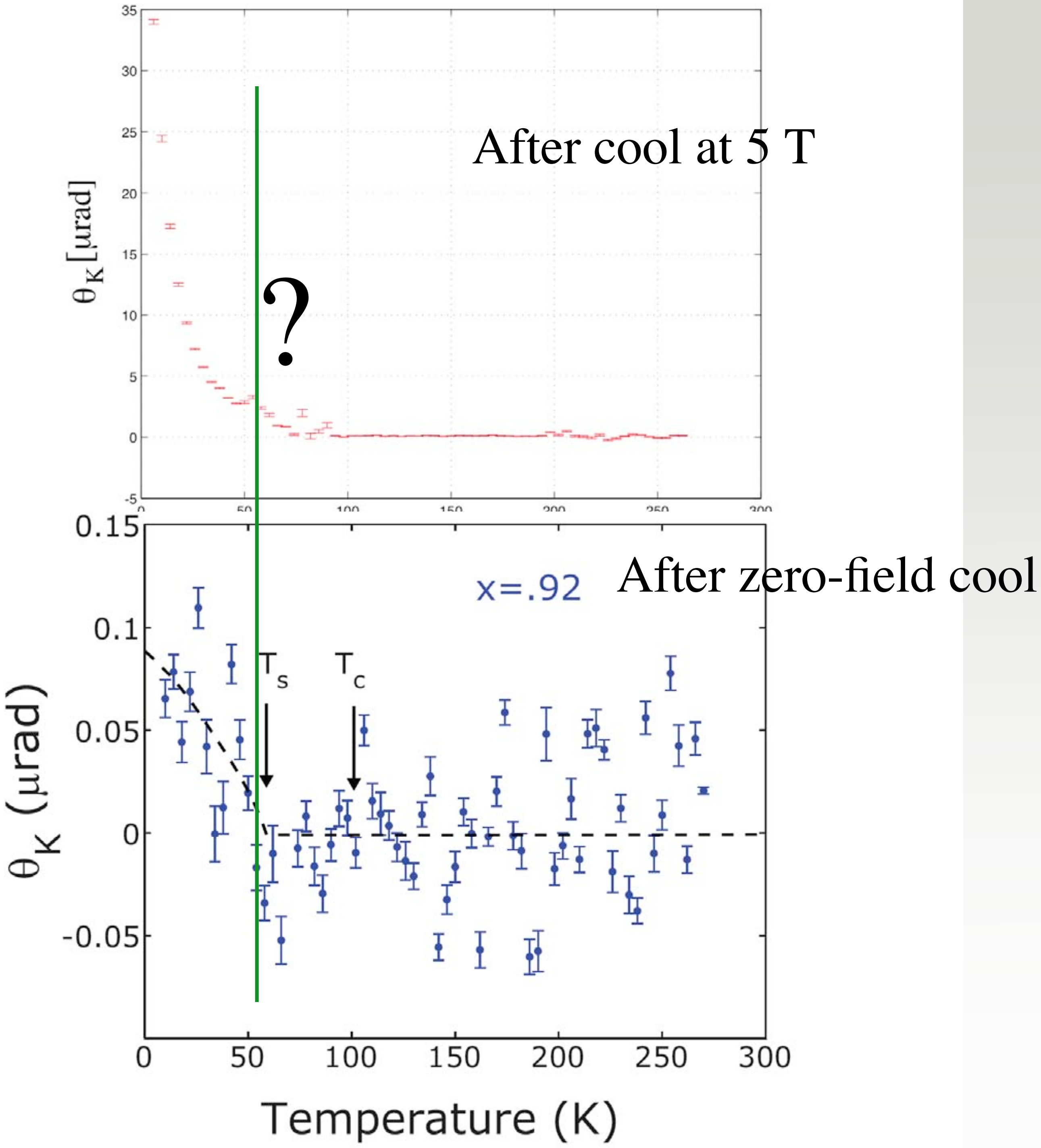
T_c = 91.7 K





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


No effect above T_c



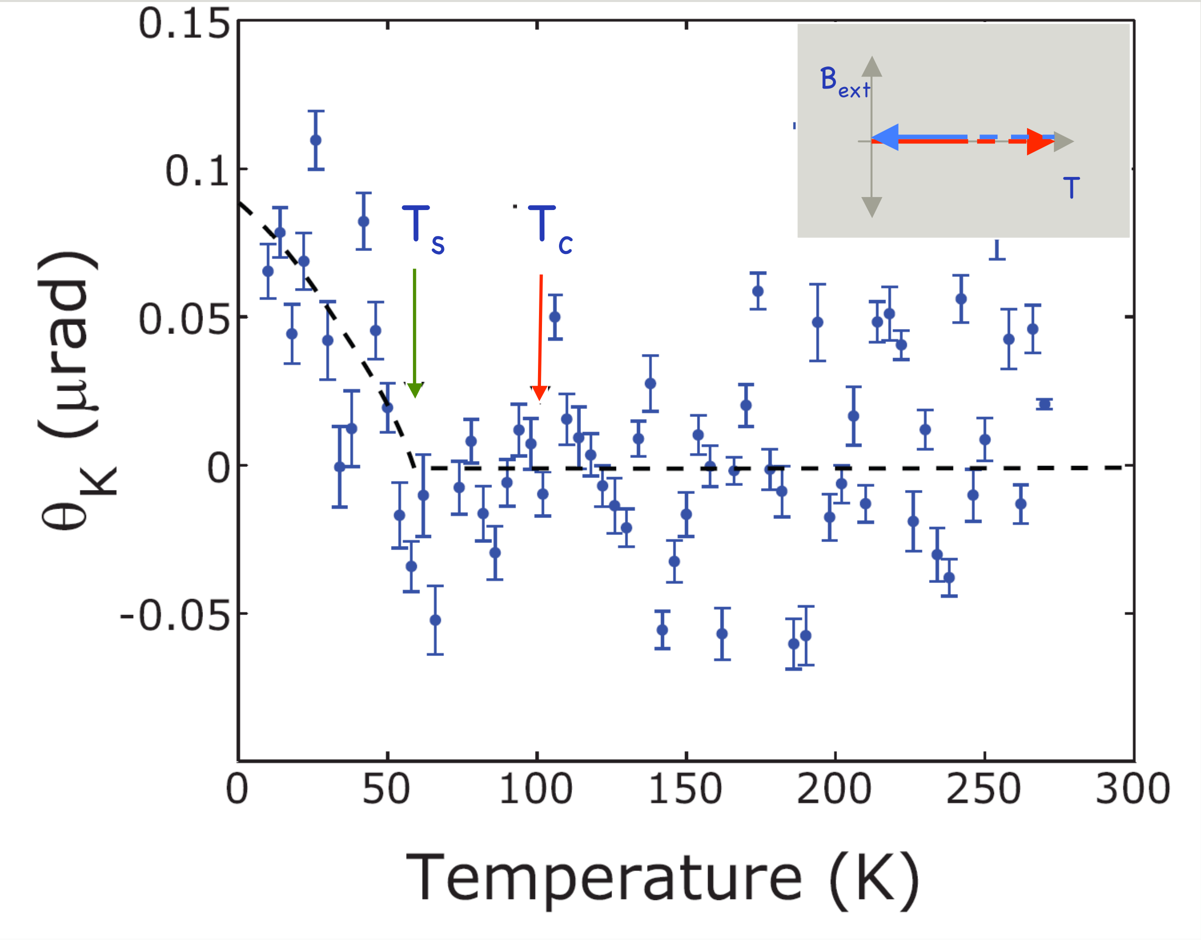
After cool at 5 T

After zero-field cool

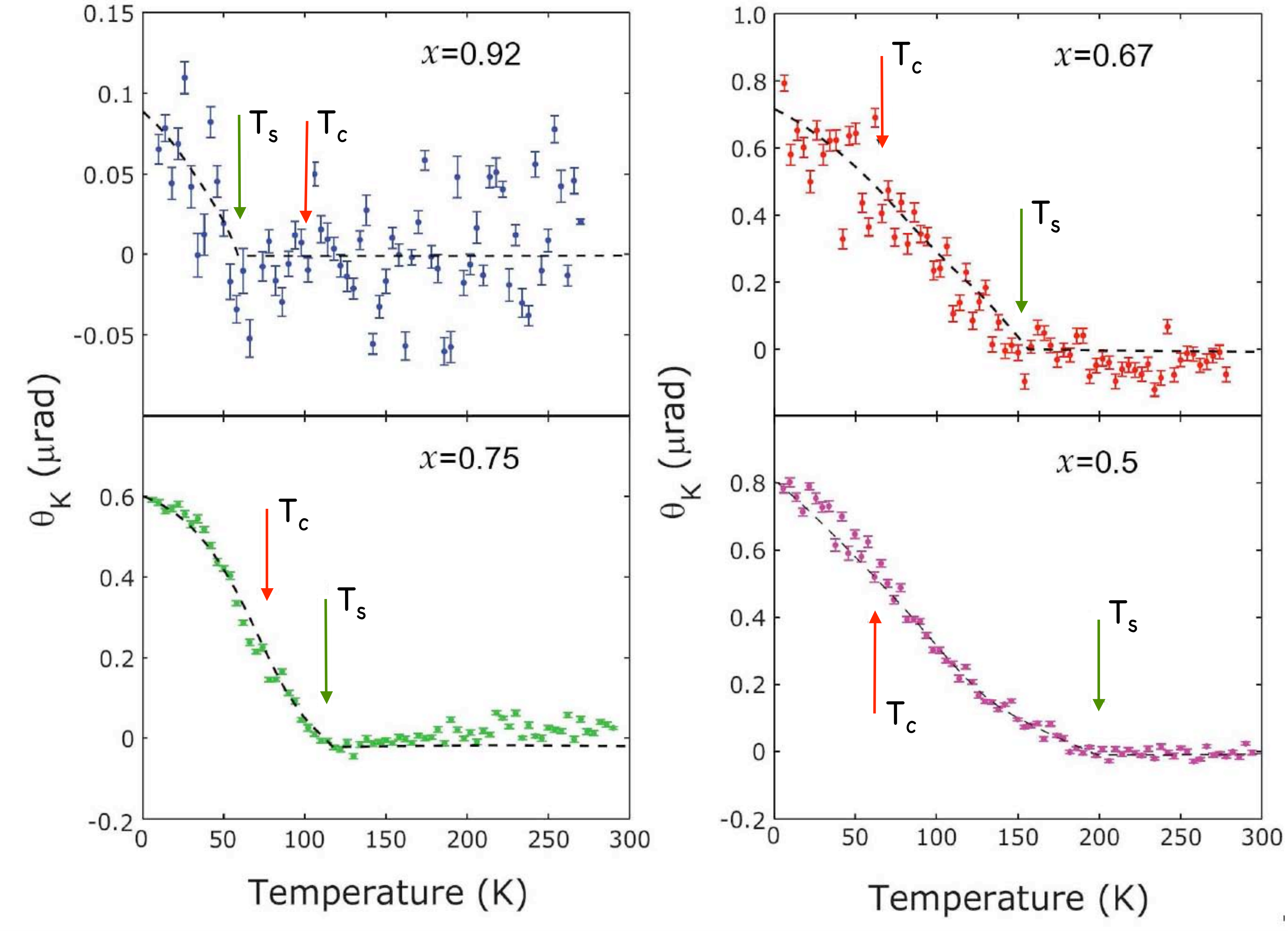
$YBa_2Cu_3O_{6.92}$: After cooling in ZF, the (pure) signal departs from zero *below* T_c

Zero field:
< 3 mOe

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

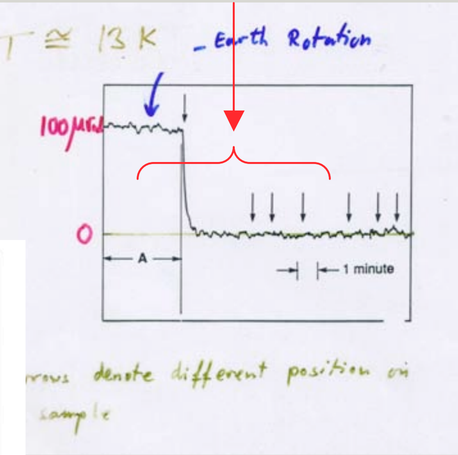


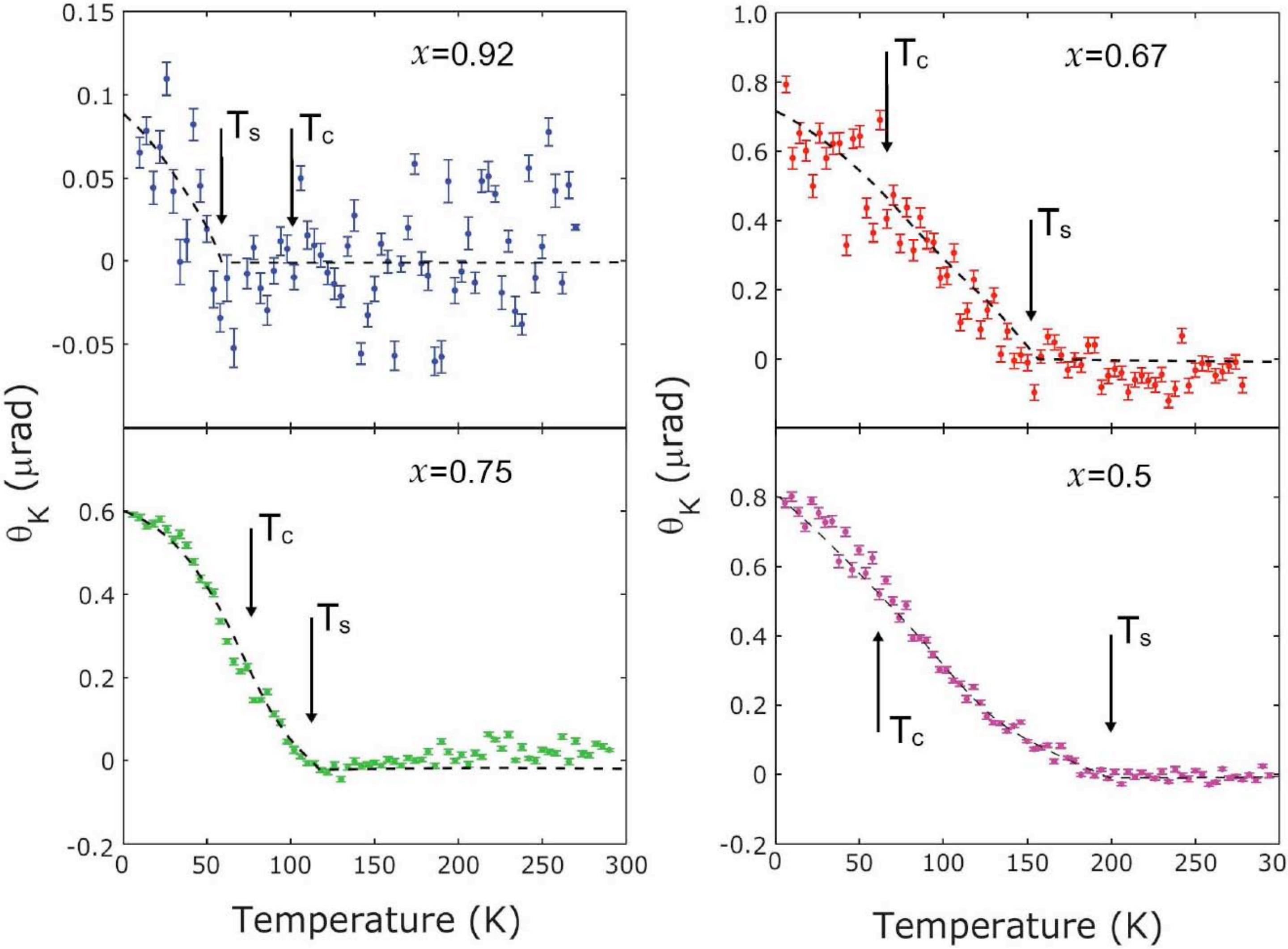
Data from all crystals (zero-field cool, zero-field warmup)



A new transition discovered at temperature very close to the pseudo-gap temperature for $YBa_2Cu_3O_{6+x}$

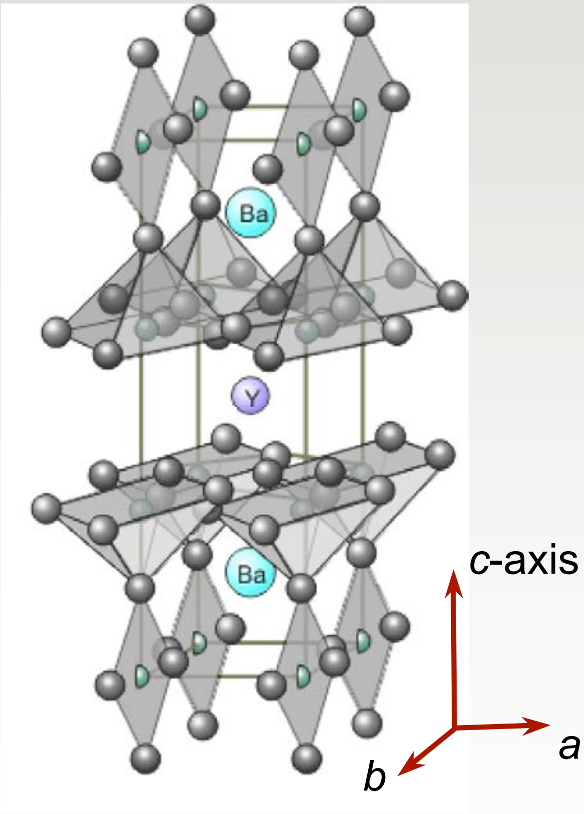
Reminder: 1990 ➔ no signal with a sensitivity of 1 μrad



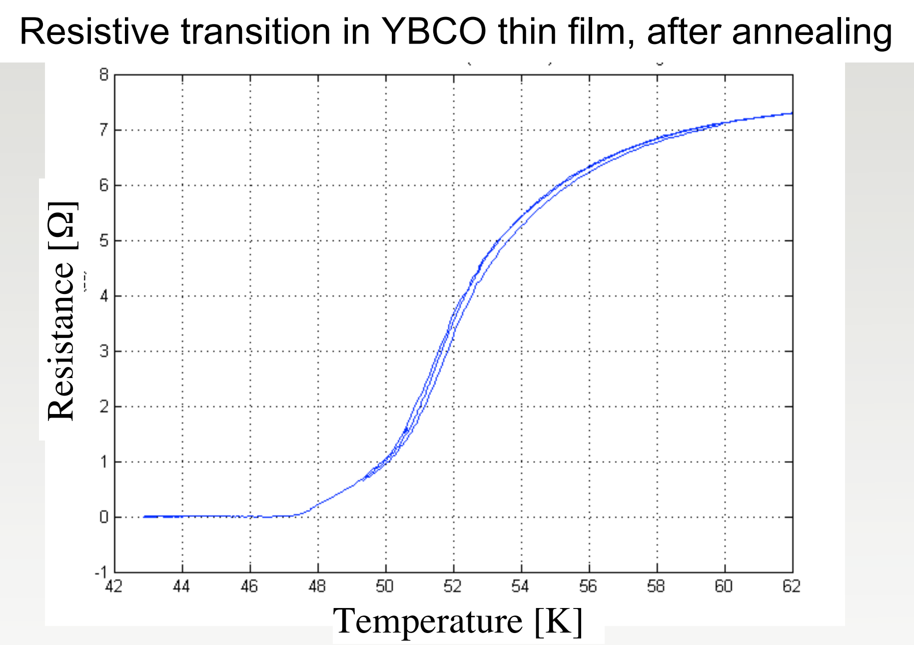


Measurement on thin films

- θ_K measured as a function of temperature in zero applied field
- Samples studied:
  - commercially prepared *c*-axis 1000-1500 Å thin films of YBCO on STO
  - above, annealed in reduced O_2 atmosphere
  - doping level estimated from resistive transition



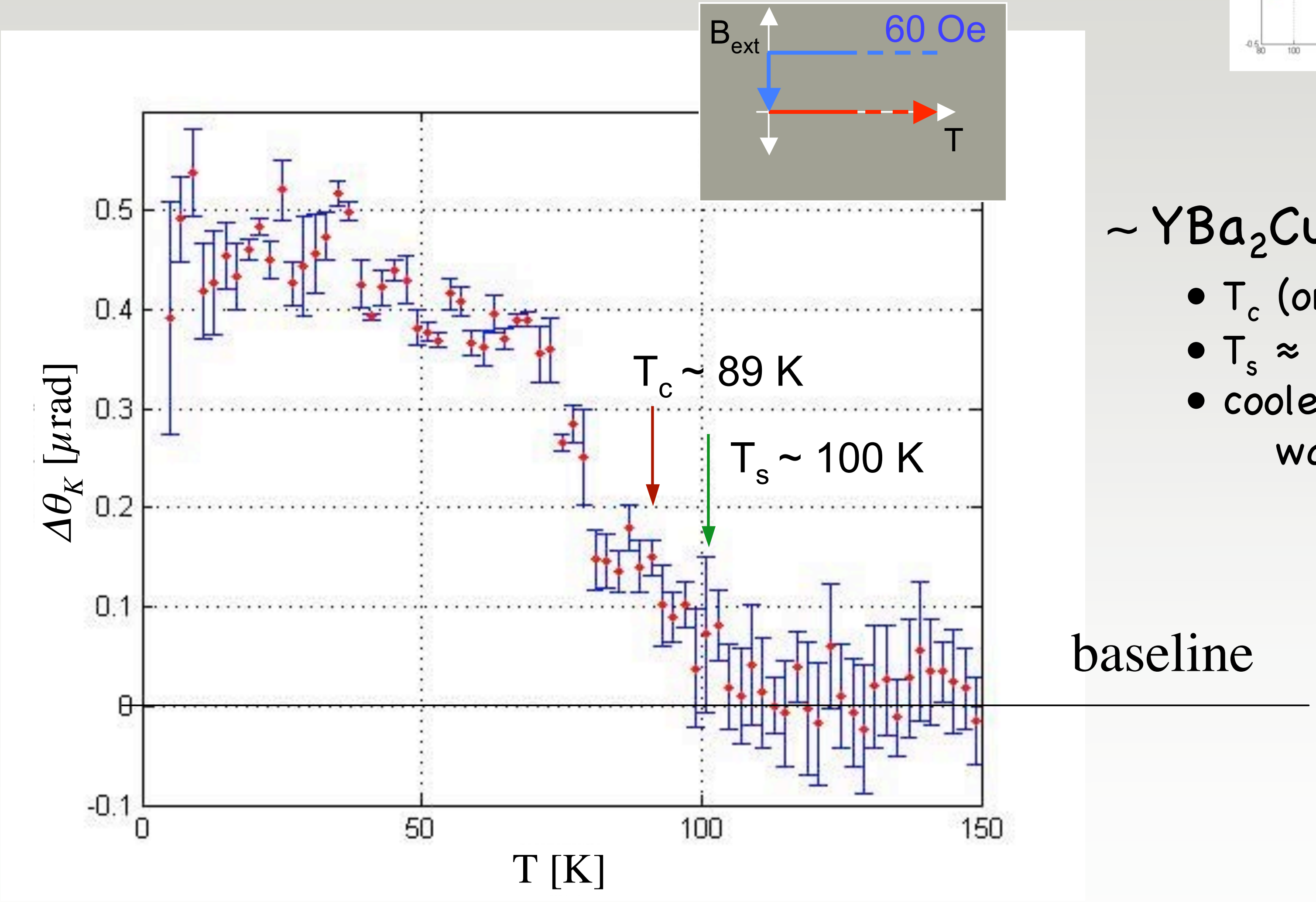
Thin films, relative to the single crystals used in earlier studies, tend to be messy…

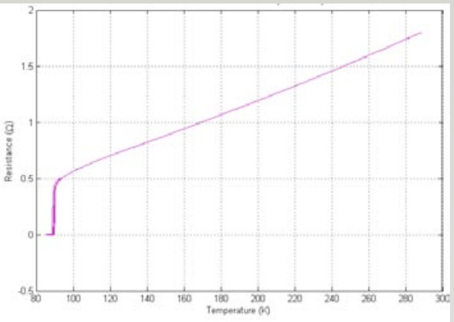


- polycrystalline
- twinned
- inhomogeneous
- …

…and therefore allow us to probe the sensitivity of our previous observations to disorder in the sample.

Results: films before annealing
T_c(onset) ~ 89 K

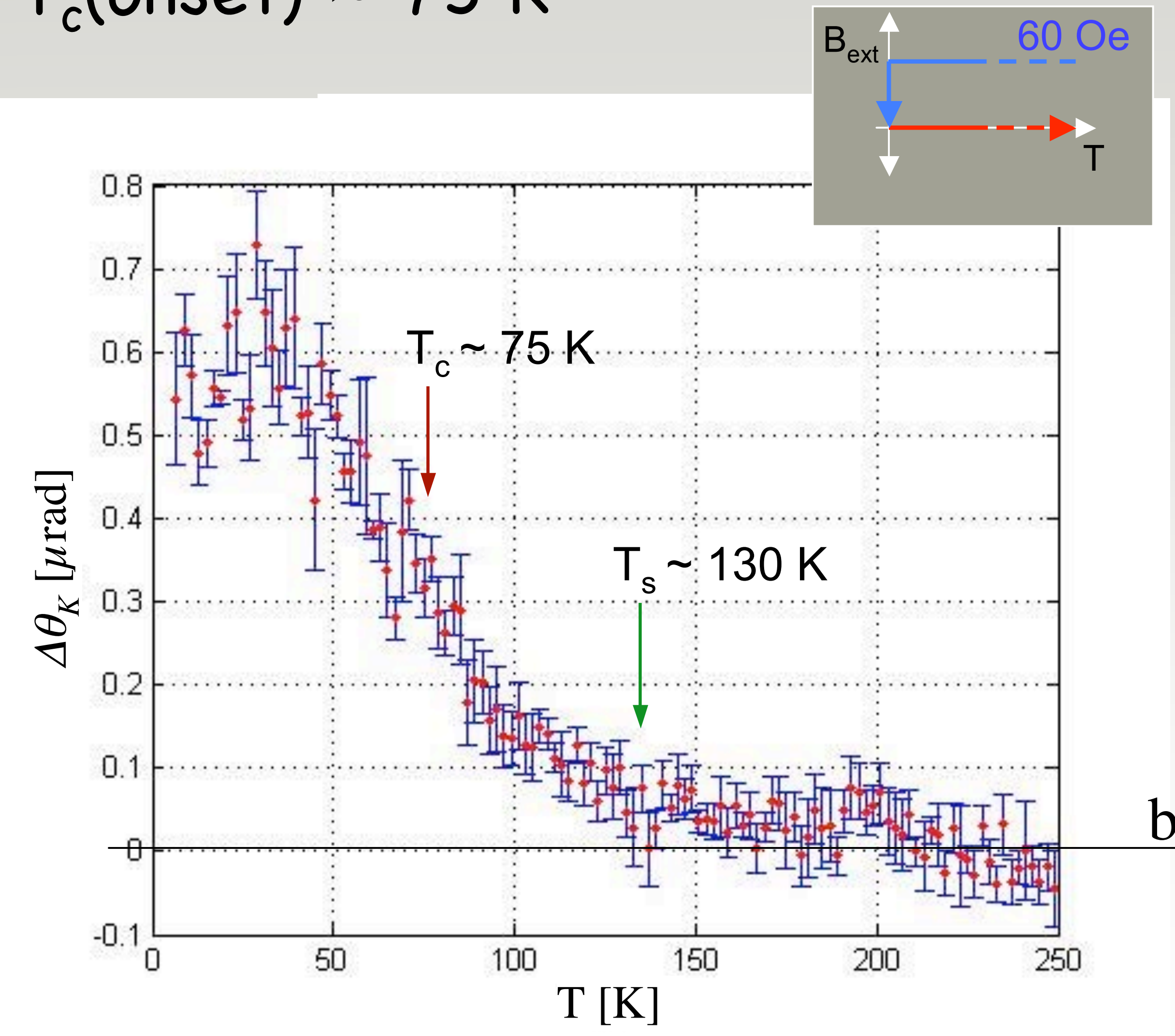


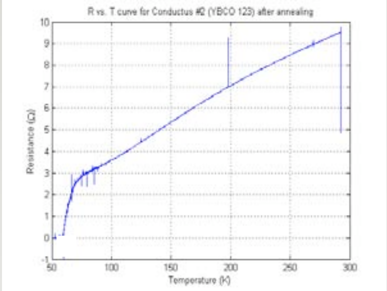


~ $YBa_2Cu_3O_{6.88}$

- T_c (onset) = 89 K
- T_s ≈ 100 K
- cooled in 60 Oe, ZF warmup

Results: films after annealing in reduced O_2
T_c(onset) ~ 75 K

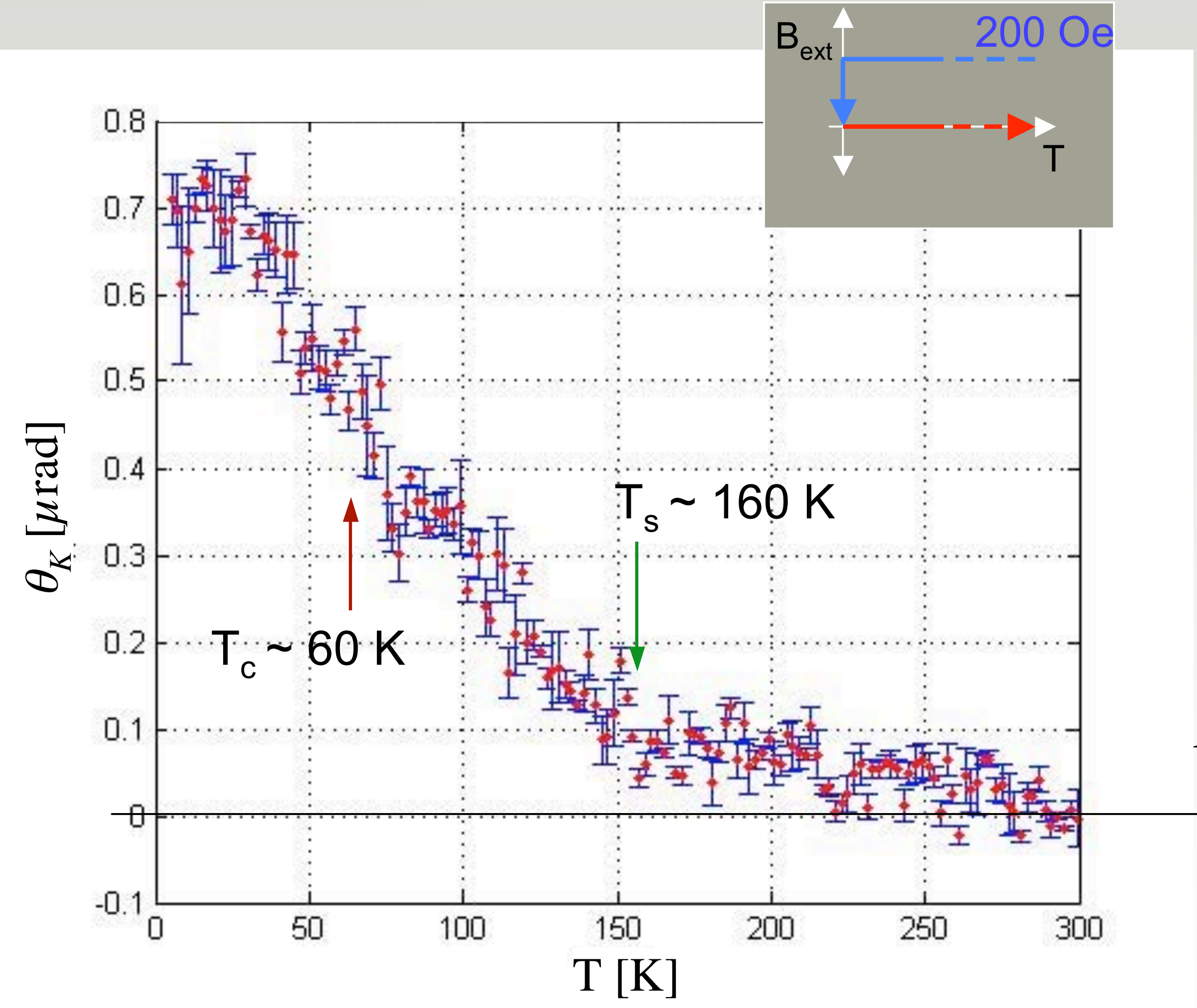




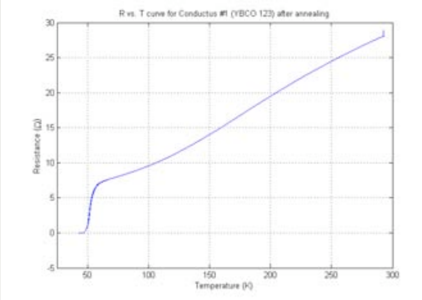
~ $YBa_2Cu_3O_{6.75}$

- T_c (onset) = 75 K
- T_s ≈ 140 K
- cooled in 60 Oe, ZF warmup

Results: films after annealing in reduced O_2
T_c(onset) ~ 60 K



baseline

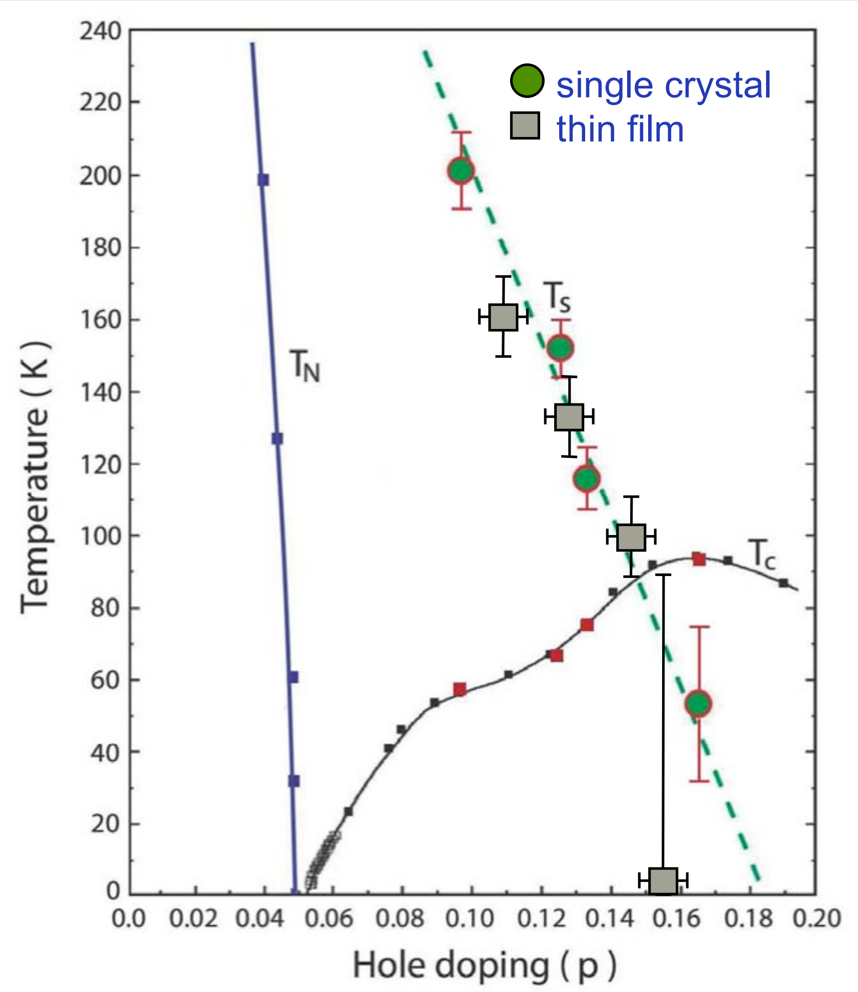


~ $YBa_2Cu_3O_{6.65}$

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

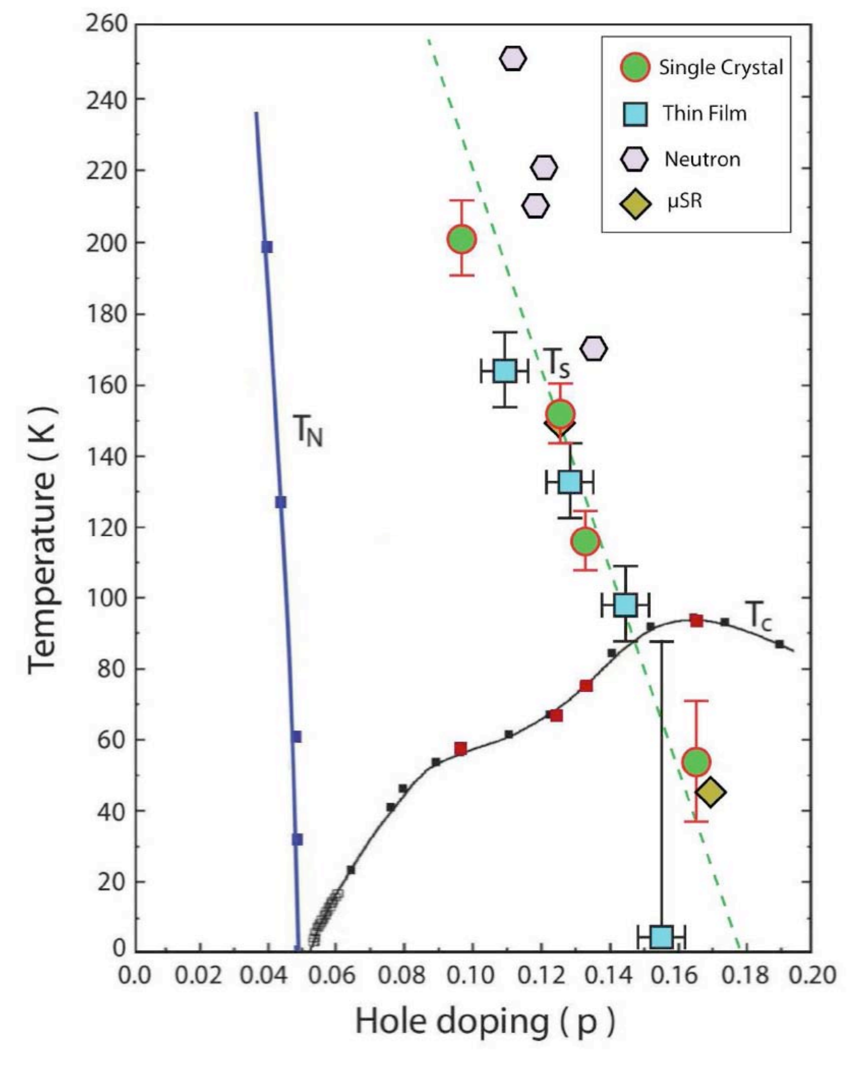
Summary

- Thin film samples of $YBa_2Cu_3O_{6+x}$ provide a natural point of comparison to highly ordered single crystals.
- Kerr rotation measurements on films show TRSB signals comparable in magnitude and onset temperature to single crystals with similar doping.
- Results suggest that the observed behavior is robust to disorder.



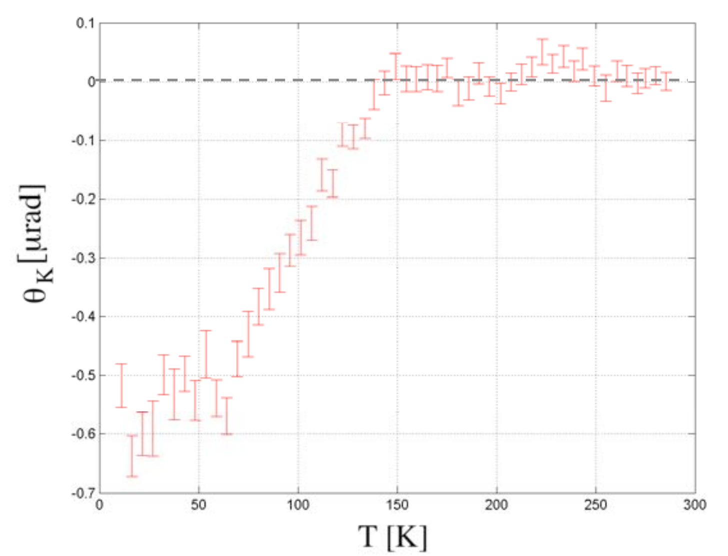
Summary: current observations for YBCO

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.



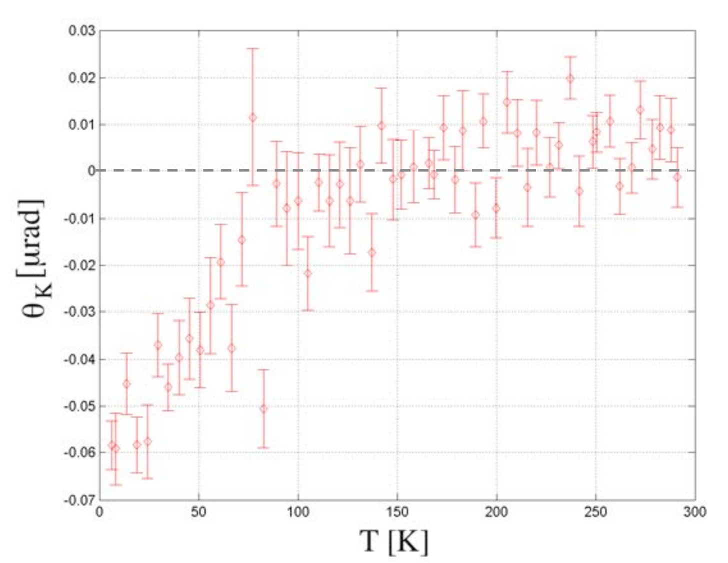
Example of anomalous magnetic behavior: $YBa_2Cu_3O_{6.67}$ underdoped single crystal (ortho-VIII)

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

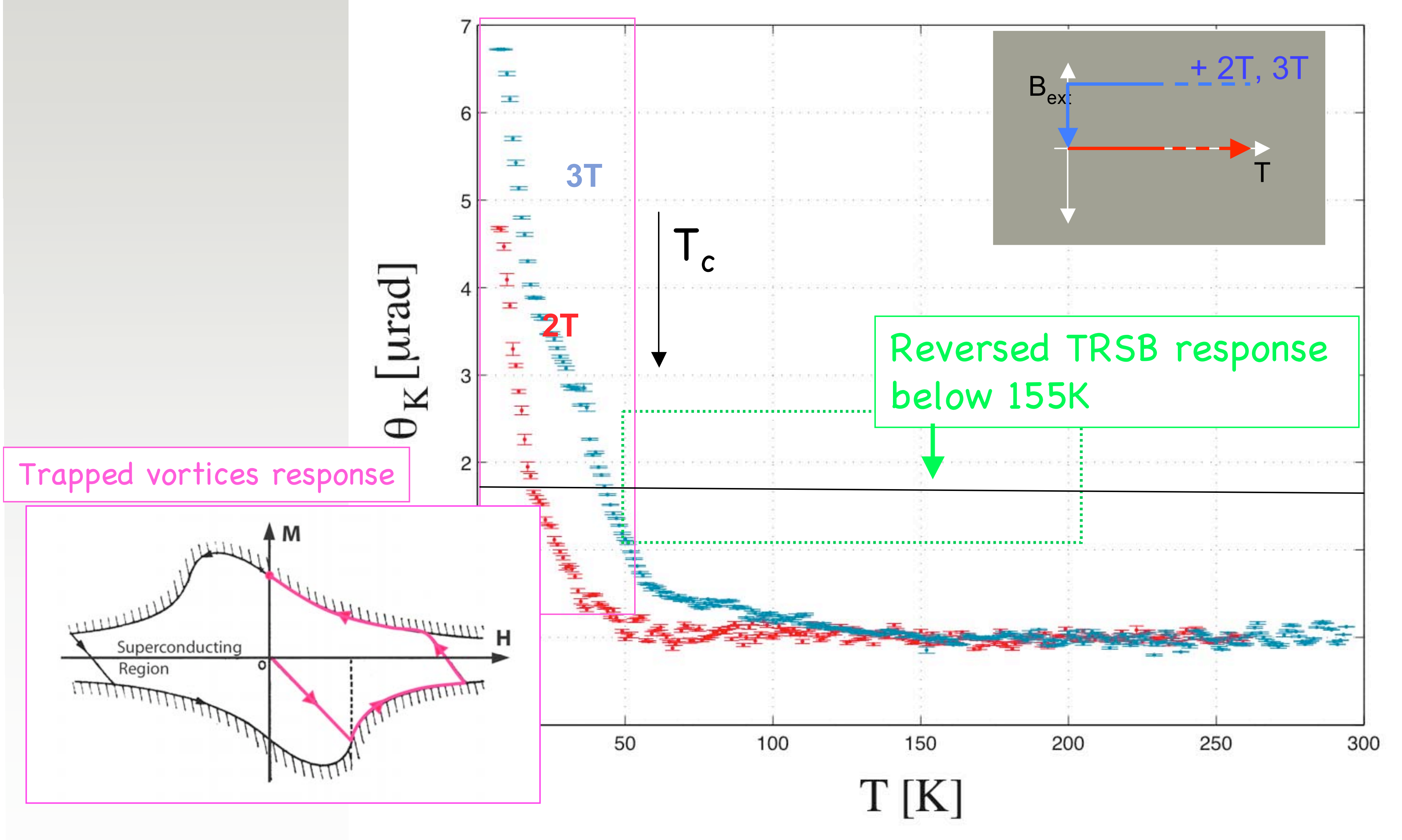


- Now cool the same sample in a +60 Oe field and warm up in zero field:

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



$YBa_2Cu_3O_{6.67}$: Finding the coercive field

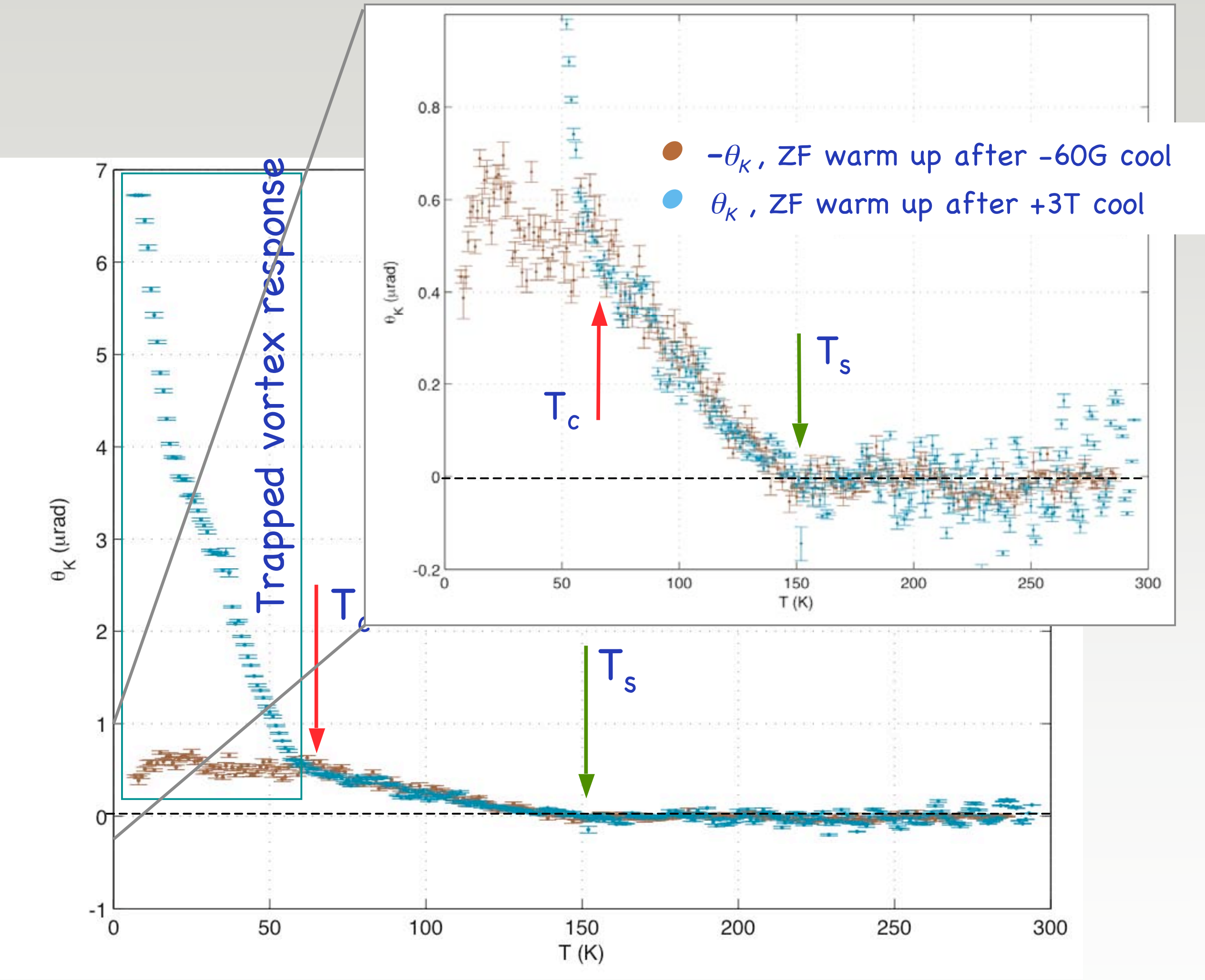


Trapped vortices response

Reversed TRSB response below 155K

$YBa_2Cu_3O_{6.67}$: Finding the coercive field

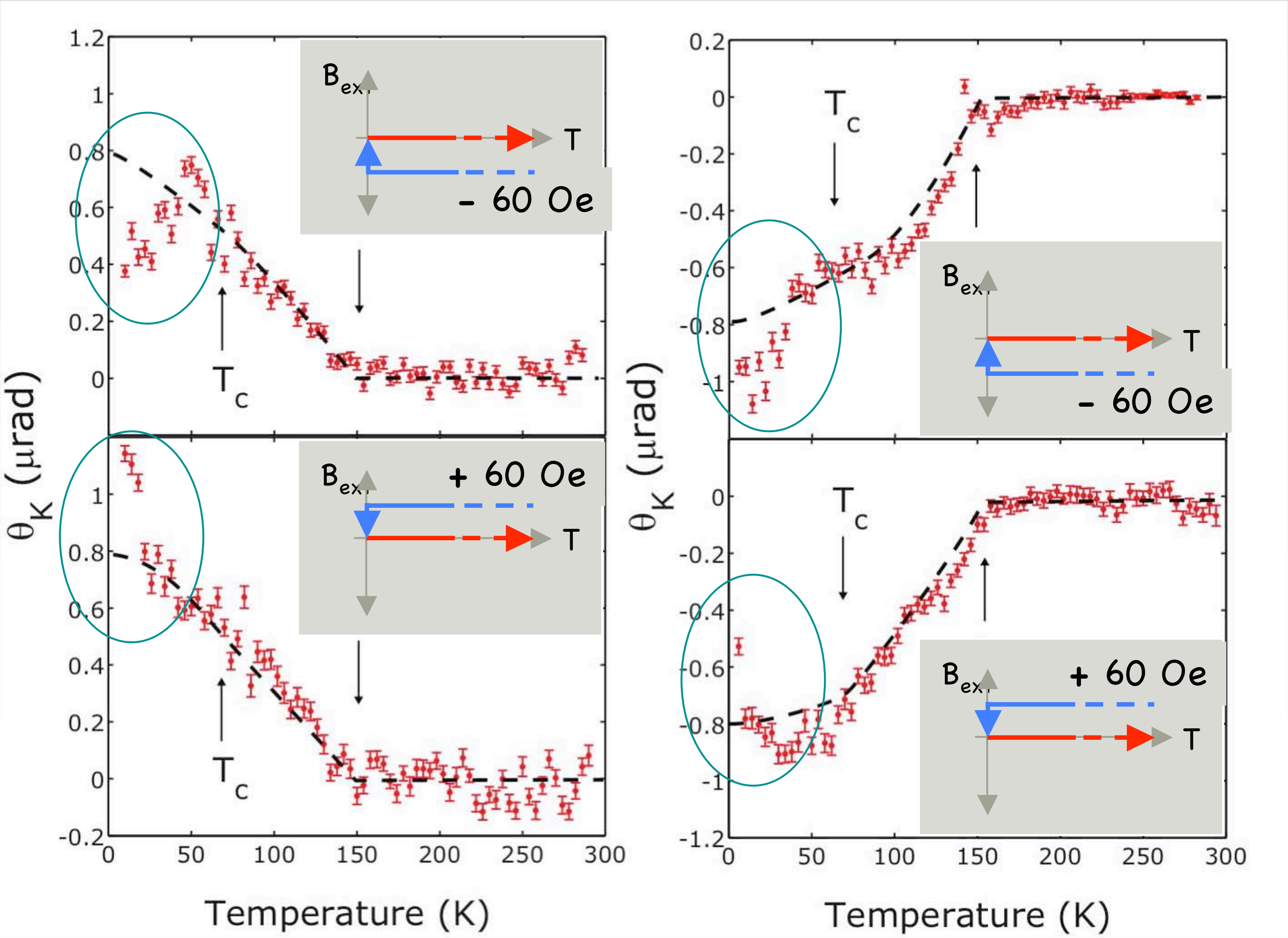
- First cool the sample in a -60 Oe field and warm up in zero field
- Then cool in a +3 T field and warm up in zero field
- Full reversal of signal is now achieved



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

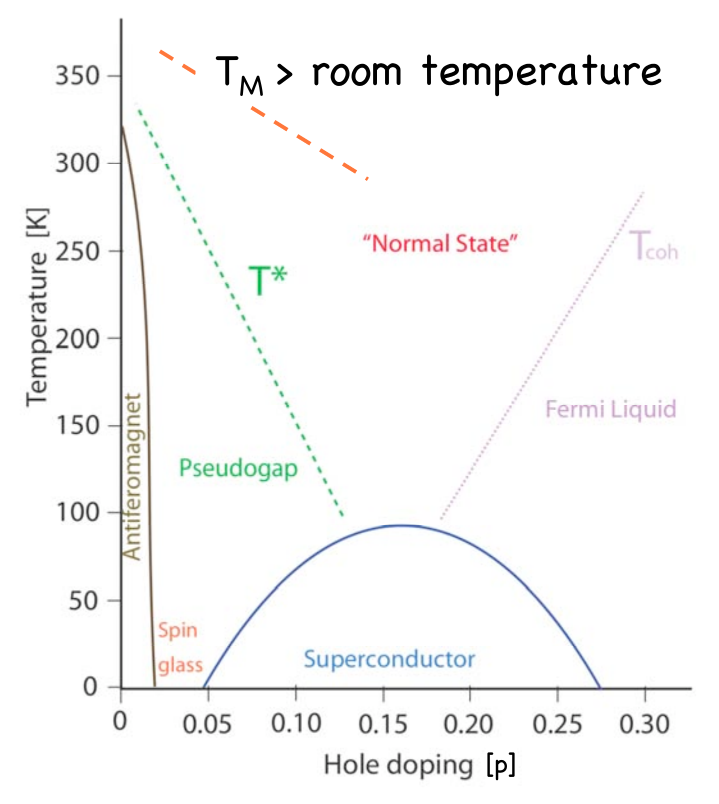
After applying +4T at RT

After applying -4T at RT



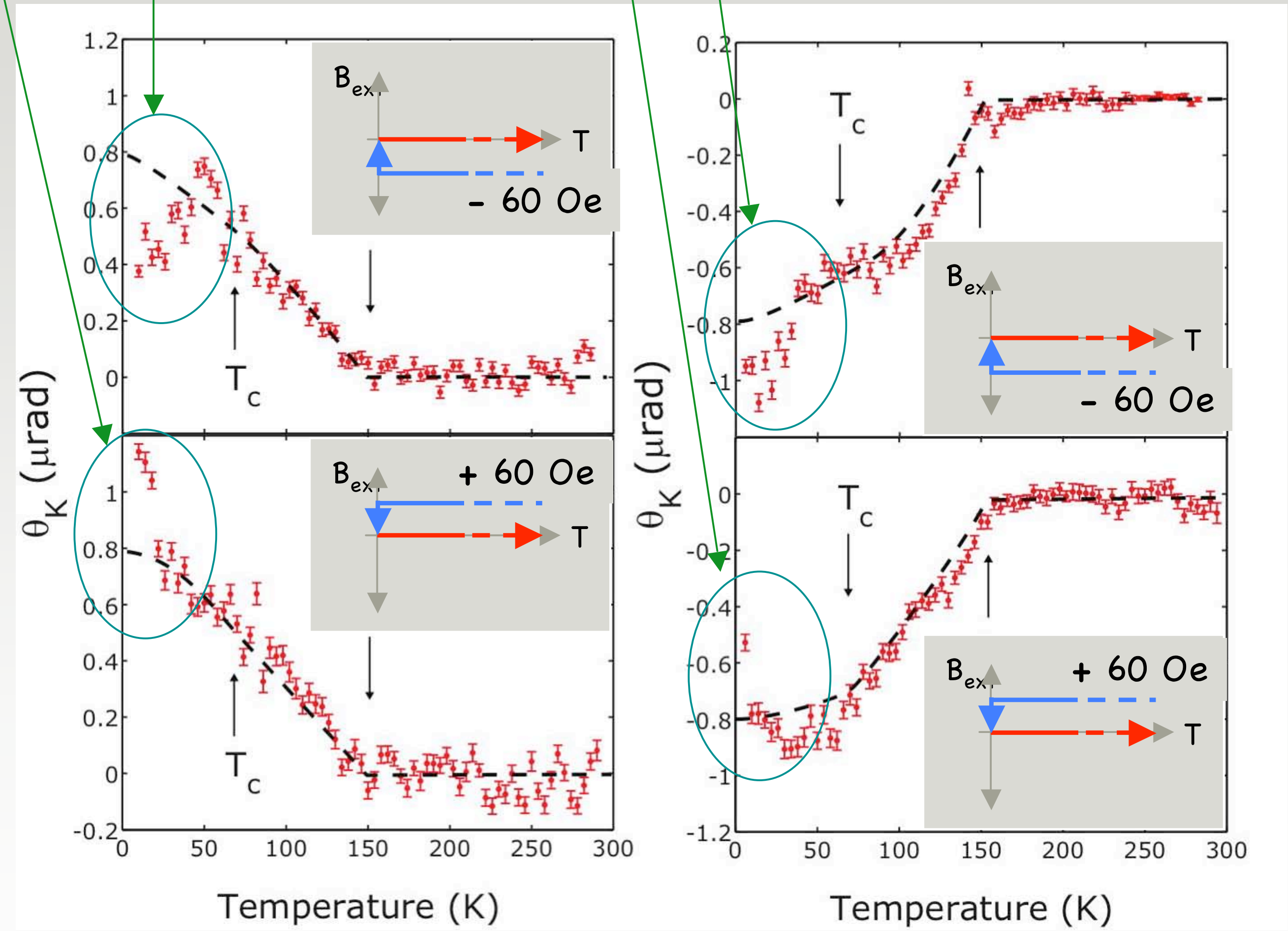
A possible explanation of the magnetic response:

- 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” (maybe spin-glass-like) in the YBCO crystals at all temperatures we measure.

At T_s, there is another electronic transition that “squashes” the magnetic phase and thus produce a small ferromagnetic moment for us to see.

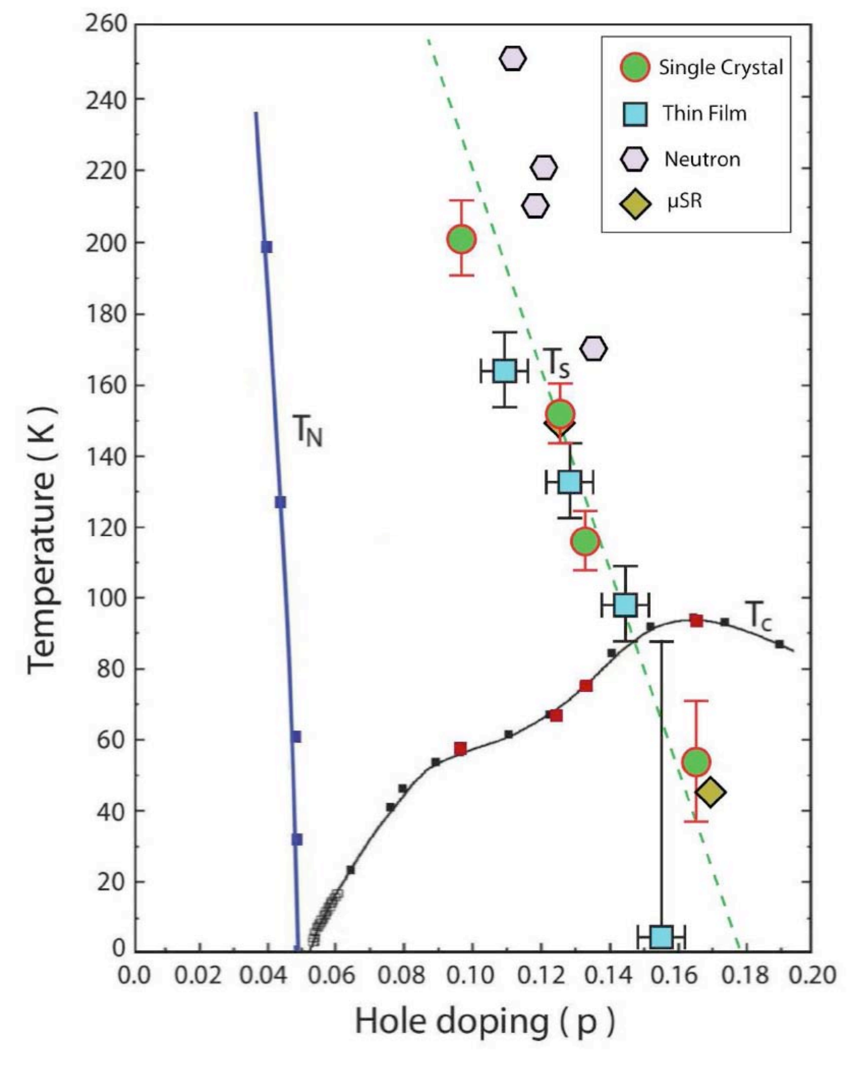
The field of the vortices below T_c act on that magnetic phase to produce the vortex response.

This is in agreement with measurements on optimally doped and overdoped YBCO Crystals which see a very weak structural phase transition near T_s. And with neutron data on more underdoped crystals that see “stripes”.

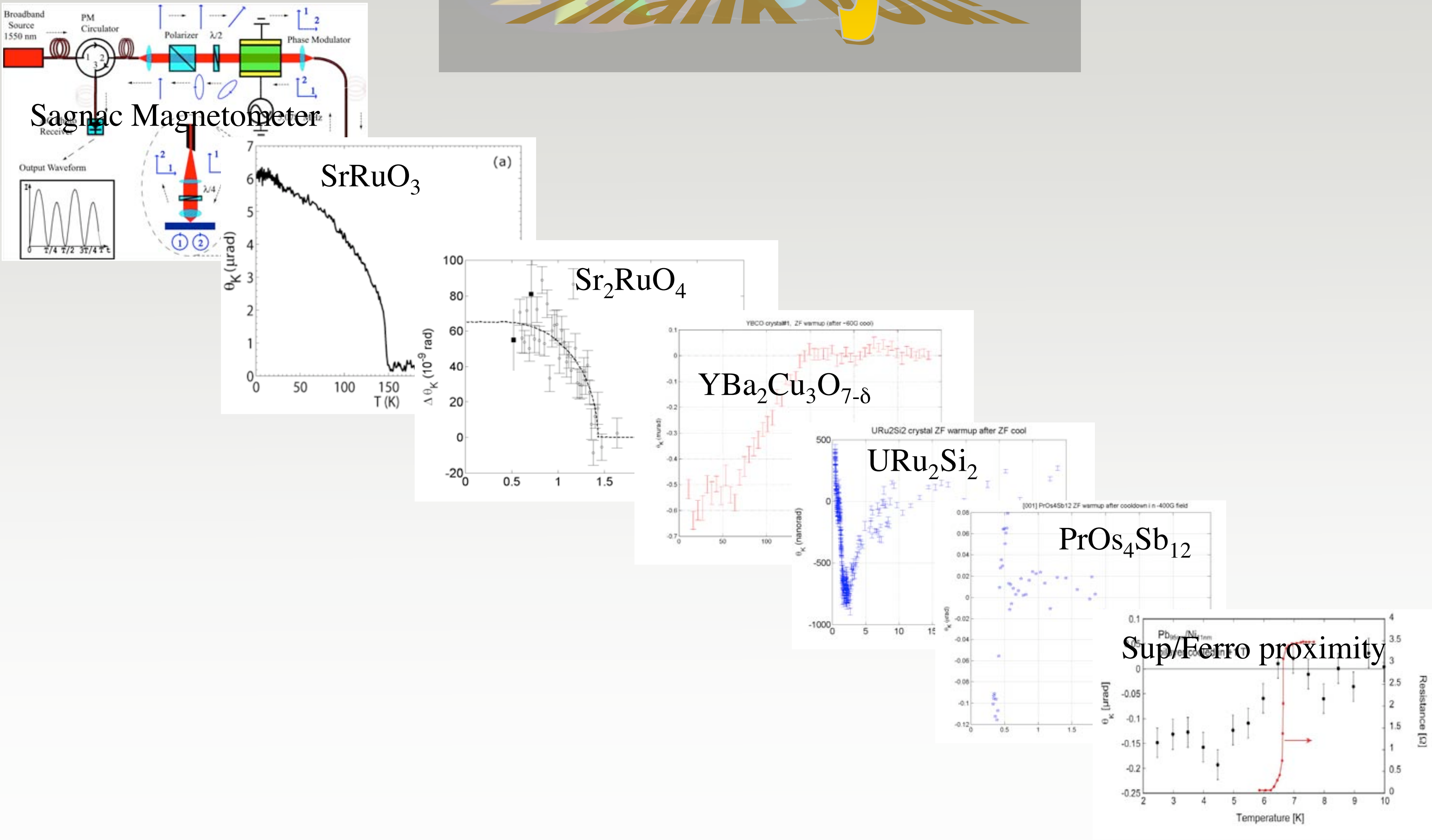
Summary: current observations for YBCO

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, which may point to some magnetic effect above room temperature.

➔ The above points may suggest that the new order found at Ts is not magnetic in origin, but rather another transition couple to the magnetic state to bring out a small Kerr effect.



Thank you!



Sagnac Magnetometer

$SrRuO_3$

Sr_2RuO_4

$YBa_2Cu_3O_{7-\delta}$

URu_2Si_2

$PrOs_4Sb_{12}$

Sup/Ferro proximity