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Workshop on Principles and Design of Strongly Correlated Electronic Systems

2 - 13 August 2010

Time Reversal Symmetry Breaking Effects in Unconventional Superconductors (What can Kerr Effect Measurements Teach Us About High-Tc Superconductors (especially the pseudogap)

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Stanford University
U.S.A.

What can Kerr effect measurements teach us about high-Tc superconductors (especially the pseudogap)

Aharon Kapitulnik, Stanford University

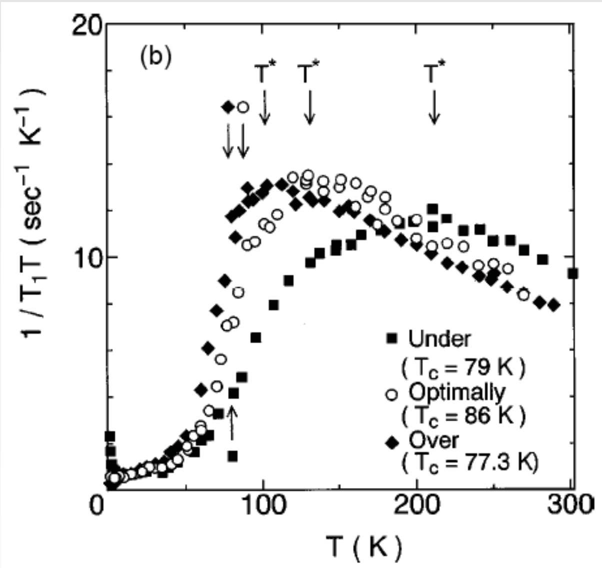
<u>With:</u> Jing Xia
Elizabeth Schemm
Hovnatan karapetyan

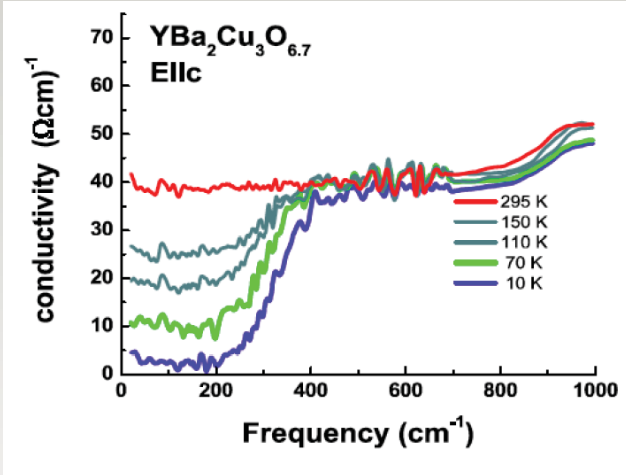
and… Steve Kivelson

<u>Variety of samples:</u>

D. Bonn, R. Liang, W. Hardy (UBC) - YBCO single crystals
Gertjan Koster & Wolter Siemons (Stanford) - YBCO (001)-axis films
G. Deutscher's group (TAU) - YBCO (110) and (001)-axis films
Marcus Hucker, Genda Gu, John Tranquada (BNL) - LBCO crystals
Y. Yoshida and H. Eisaki (Tsukuba, Japan) - Bi:2201 crystals

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.





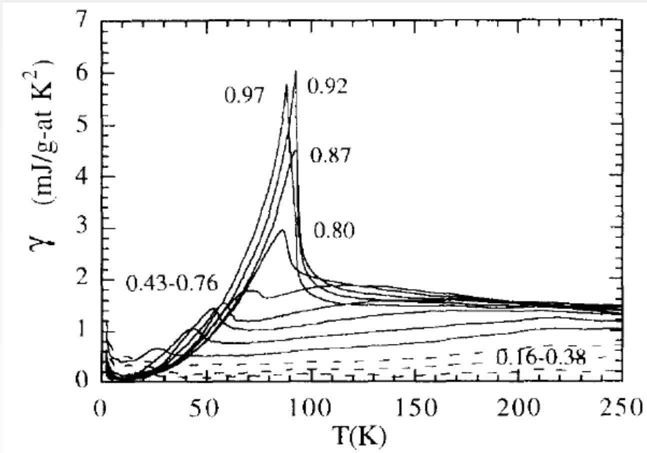
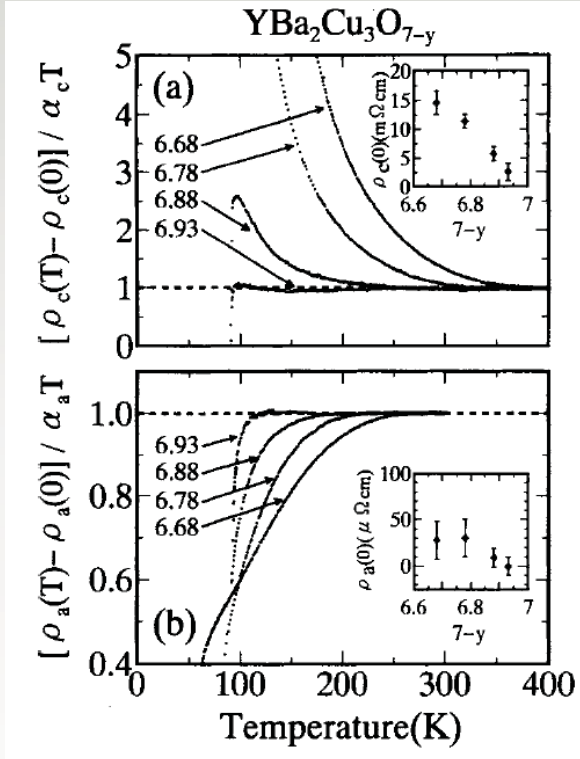


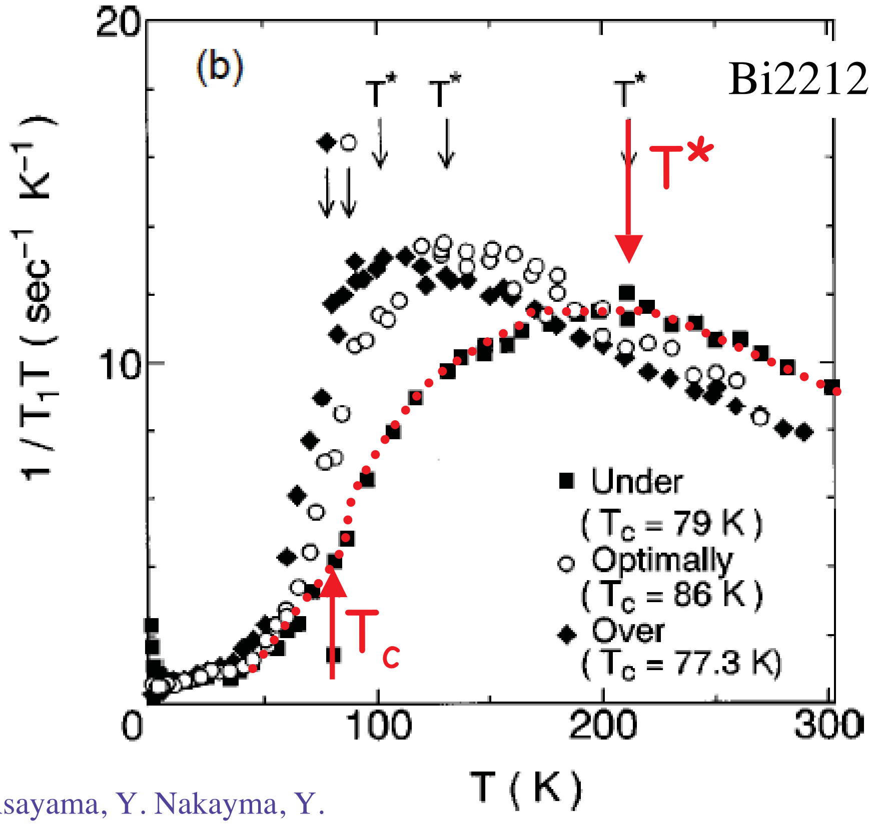
FIG 1 γ for $YBa_2Cu_3O_{6+x}$ relative to $YBa_2Cu_3O_6$[4]



Initial magnetic Measurements

- W. W. Warren, Jr., R. E. Walstedt, G. F. Brennert, R. J. Cava, R. Tycko, R. Bell and G. Dabbagh, Phys. Rev. Lett. 62, 1193 (1989).
- H. Alloul, T. Ohno and P. Mendels, Phys. Rev. Lett. 63, 1700 (1989).
- D. C. Johnston, Phys. Rev. Lett. 62, 957 (1989).

Suggested a **spin gap** appearing at $T^* >> T_c$



K. Ishida, K. Yoshida, T. Mito, Y. Tokunaga, Y. Kitaoka, K. Asayama, Y. Nakayma, Y. Shimoyama and K. Kishio, NMR spin relaxation rate for Bi2212 as a function of doping, Phys. Rev. B 58, R5960 (1998).

Pseudogap in ARPES...

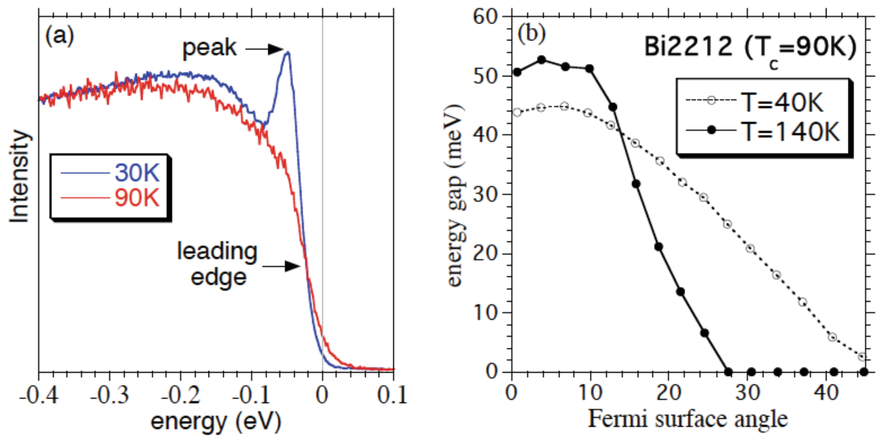
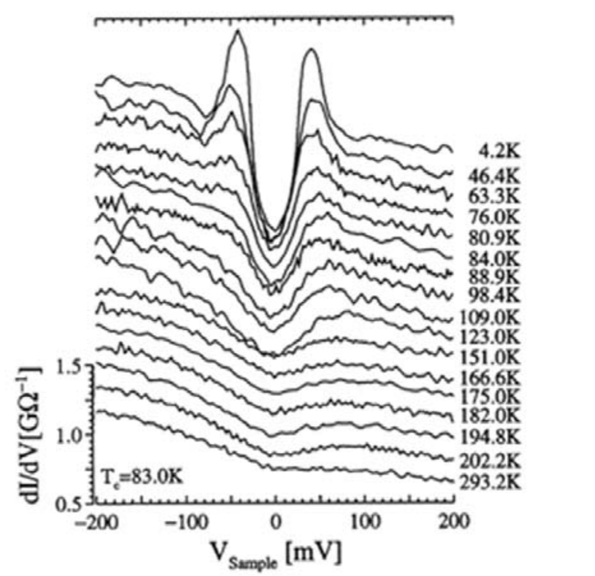


Figure 5 – (a) ARPES spectrum at (π,0) for an underdoped Bi2212 sample in the superconducting state (30K) and the pseudogap phase (90K). The sharp peak in the superconducting state is replaced by a leading edge gap in the pseudogap phase. (b) Angular anisotropy of the superconducting gap (40K) and the pseudogap (140K) for an optimal doped Bi2212 sample. Data courtesy of Adam Kaminski and Juan Carlos Campuzano.

Bi:2212

C. Renner, B. Revaz, K. Kadowaki, I. Maggio-Aprile, and O.Fischer, Phys. Rev. Lett. 80, 149 (1998).

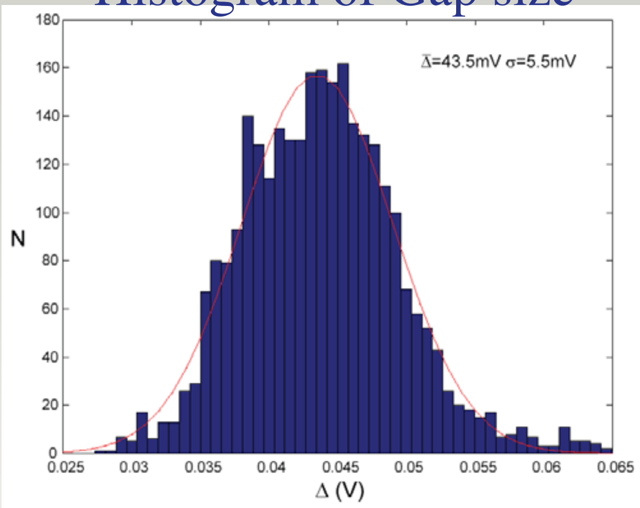
...and Pseudogap in STM

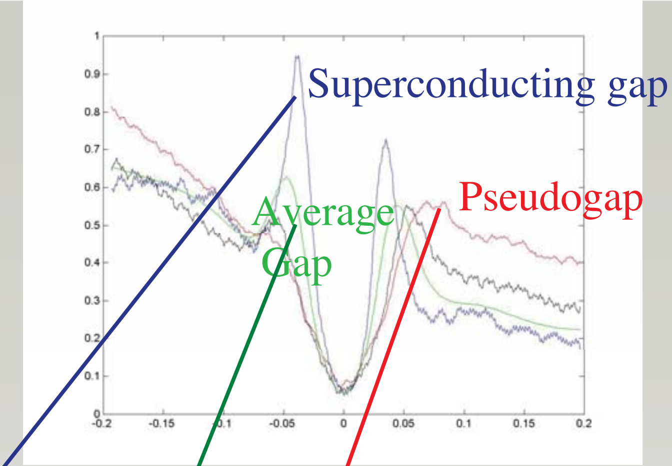


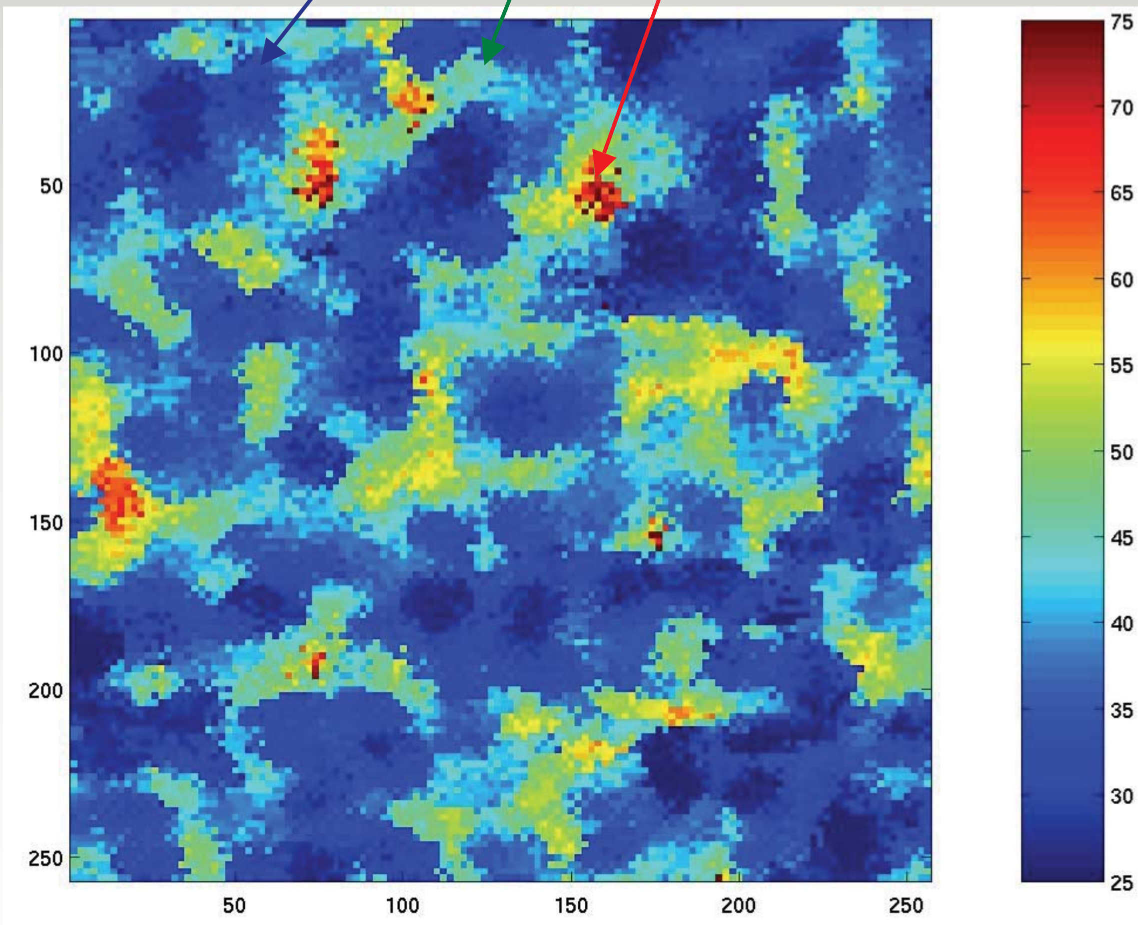
Make the connection to the charge sector

Inhomogeneities in STM

Histogram of Gap size





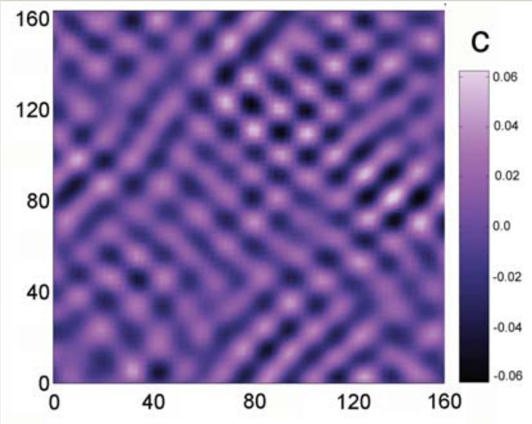


Bi:2212

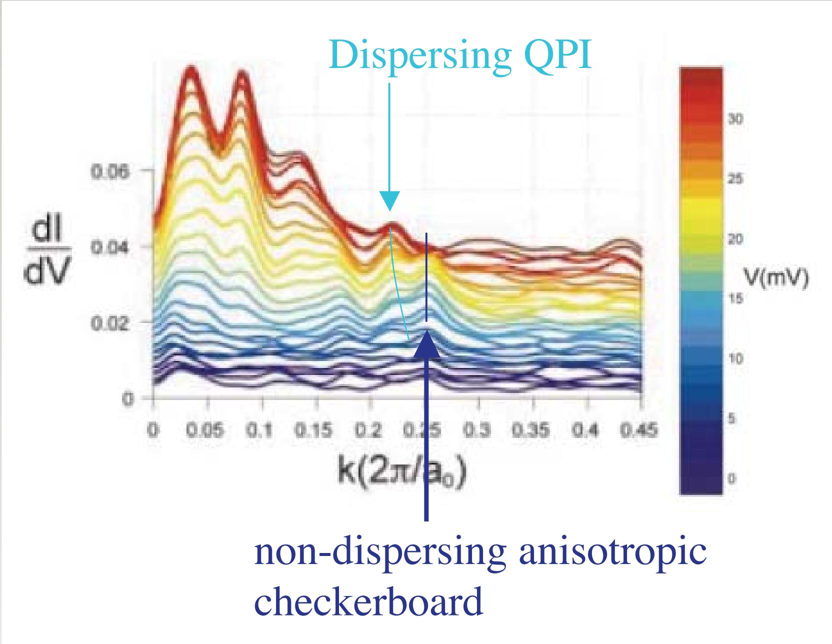
C. Howald, P. Fournier, and A. Kapitulnik, PRB 64, 100504 (2001).

Non-dispersing (and anisotropic) charge modulation…

Bi:2212



C. Howald, H. Eisaki, N. Kaneko, M. Greven, and A. Kapitulnik, Periodic density-of-states modulations in superconducting Bi2Sr2CaCu2O8+d, PRB 67, 014533 (2003).



… is found in the large gap (pseudogap) regions, disappearing at some temperature T* >Tc:

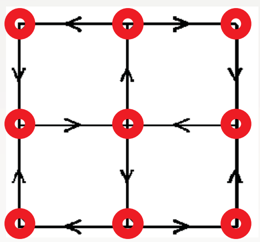
- M. Vershinin, S. Misra, S. Ono, Y. Abe, Y. Ando and A. Yazdani, Local Ordering in the Pseudogap State of the High-Tc Superconductor Bi2Sr2CaCu2O8+d, Science 303, 1995 (2004).
- K. K. Gomes, A.N. Pasupathy A. Pushp, S.Y. Ono, Ando and A. Yazdani A 2007 Visualizing pair formation on the atomic scale in the high-Tc superconductor Bi2Sr2CaCu2O8+y Nature 447 569 (2007).

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

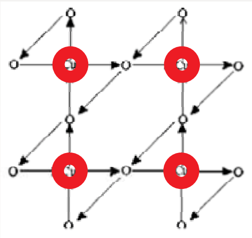
1. T* represents a crossover into a state with preformed pairs and a *d*-wave gap symmetry.

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

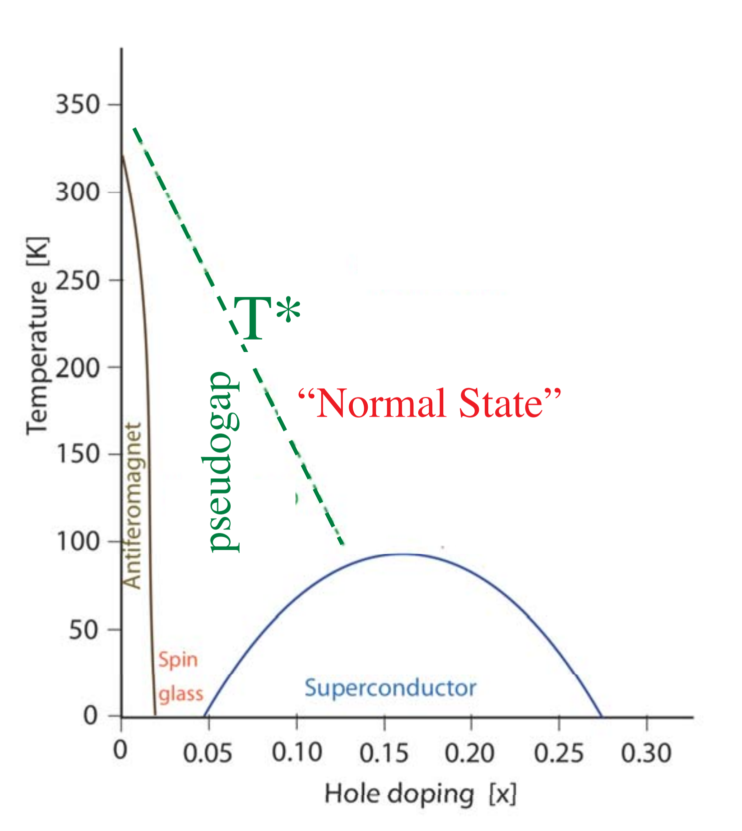
2. T* marks a true transition into a phase with broken symmetry which ends at a quantum critical point, typically inside the superconducting dome.



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



C. M. Varma, PRB **55**, 14554 (1997)]

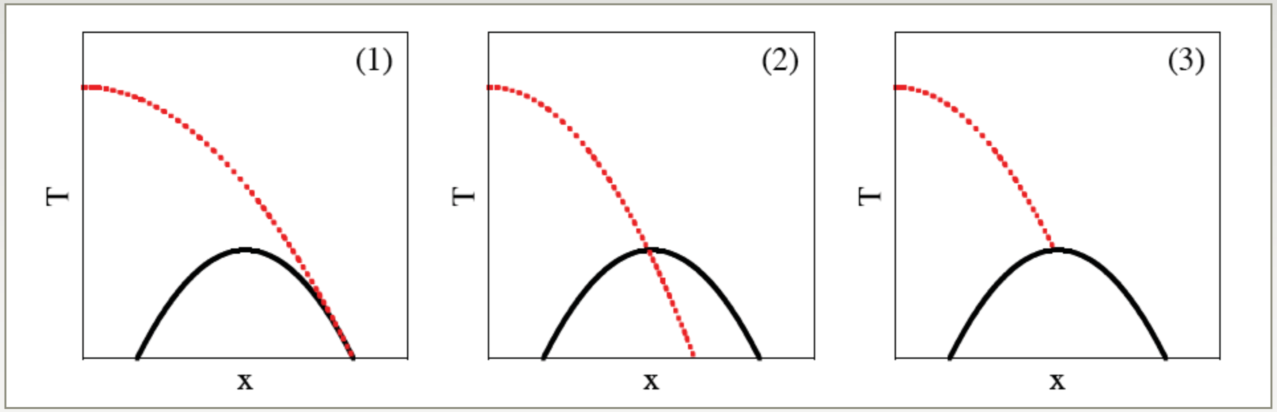


(Schematic) Phase diagram of YBCO

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)

key questions associated with the pseudogap phenomenon and its relevance to high-Tc superconductivity*

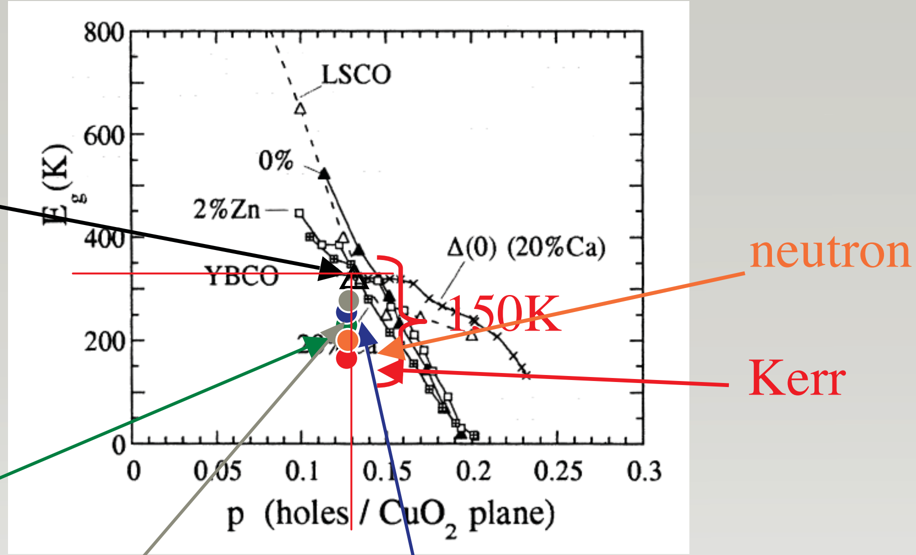
M. R. Norman; D. Pines; C. Kallin (Advances in Physics, Vol. 54, No. 8, December 2005, 715-733)

- Is the pseudogap a friend or a foe of high Tc?
- Is there long range order associated with T*?
- Is the pseudogap phase a non-Fermi liquid phase?
- If T* cuts through the Tc dome as a function of doping, is the superconducting state different on opposite sides of the T* line?
- Is charge ordering central to the pseudogap phenomenon?
- Is the undoped phase really a Mott insulator?
- What is the role of the lattice?

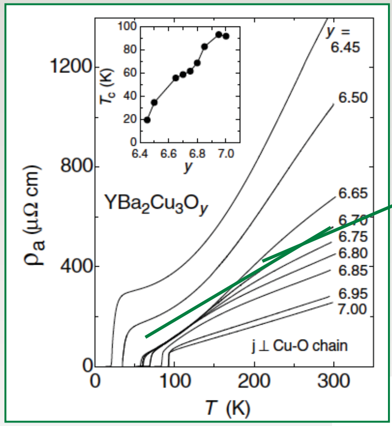
Some observations about determining T*

$YBa_2Cu_3O_{6+x}$ example: x=0.7

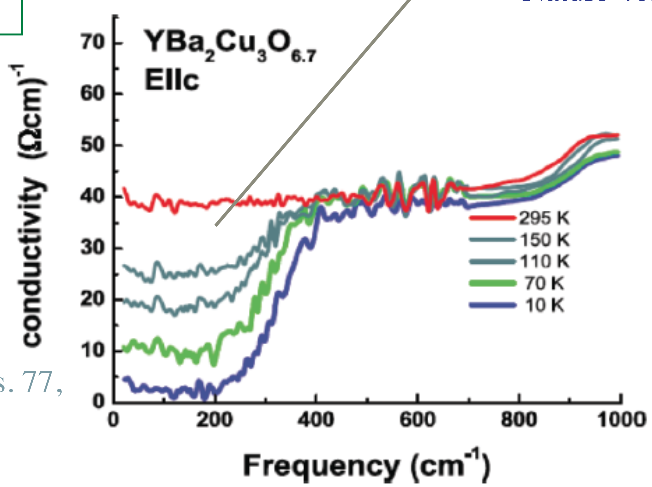
J.W. Loram, K.A. Mirza, J.R. Cooper, and J.L. Tallon, Specific Heat Evidence on the Normal State Pseudogap, J. Phys. Chem Solids 59, 2091(1998).

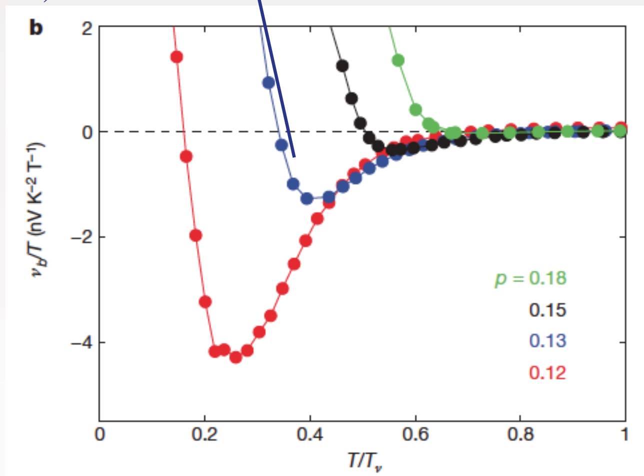


Kouji Segawa and Yoichi Ando, Transport Anomalies and the Role of Pseudogap in the 60-K Phase of YBa2Cu3O7-d, PRL 86, (2001).



R. Daou, J. Chang, David LeBoeuf, Olivier Cyr-Choiniere, Francis Laliberte, Nicolas Doiron-Leyraud, B. J. Ramshaw, Ruixing Liang, D. A. Bonn, W. N. Hardy, Louis Taillefer, Broken rotational symmetry in the pseudogap phase of a high-Tc superconductor, Nature 463, 519 (2010).



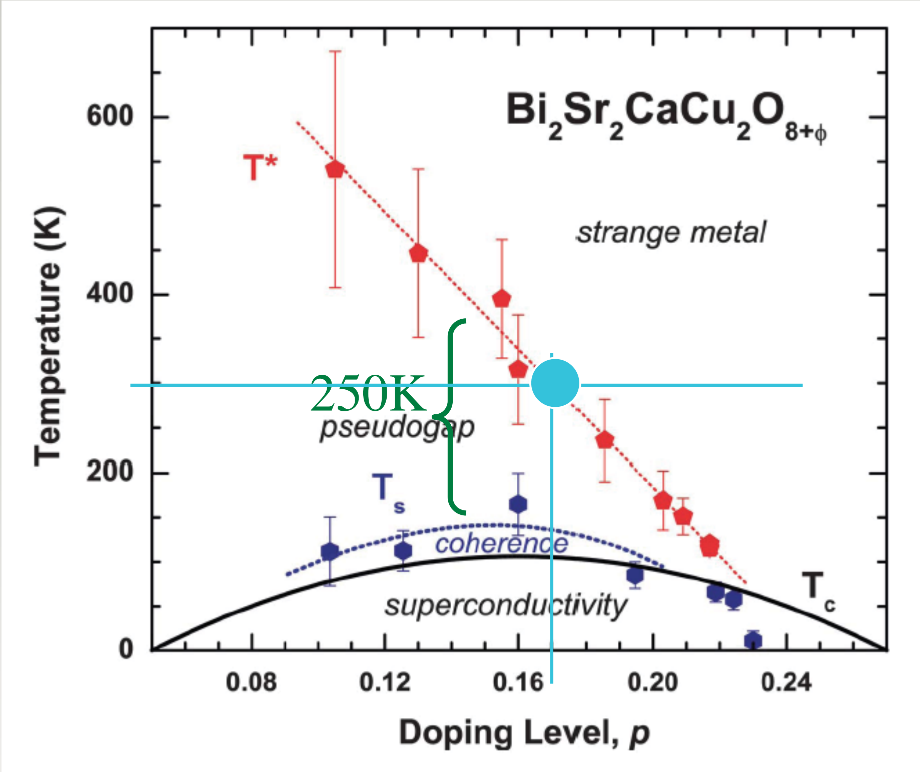


D. N. Basov and T. Timusk, Electrodynamics of high-Tc superconductors, Rev. Mod. Phys. 77, 721 (2005).

$Bi_2Sr_2CaCu_2O_8$

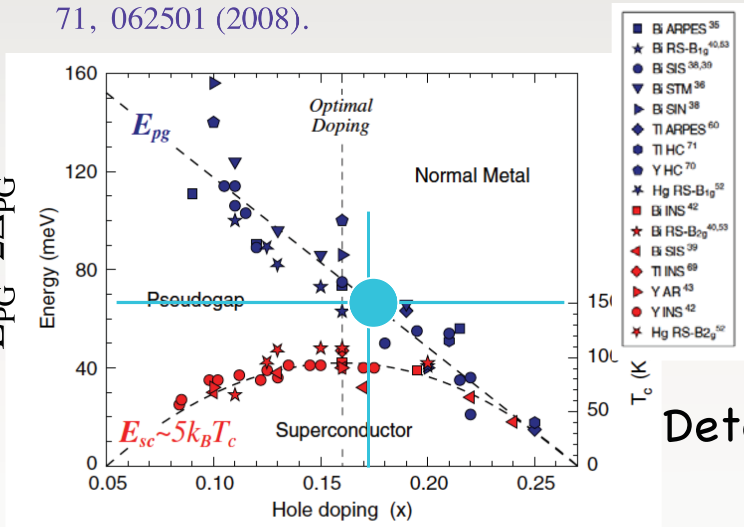
T. Shibauchi, L. Krusin-Elbaum, Ming Li, M. P. Maley, and P. H. Kes , Closing the Pseudogap by Zeeman Splitting in Bi2Sr2CaCu2O8+y at High Magnetic Fields, PRL 86, 5763 (2001).

Determined from closing of pseudogap at high field



S. Hufner, M. A. Hossain, A. Damascelli, and G. A. Sawatzky, Two gaps make a high-temperature superconductor?, Rep. Prog. Phys. 71, 062501 (2008).

$E_{PG}=2\Delta_{PG}$

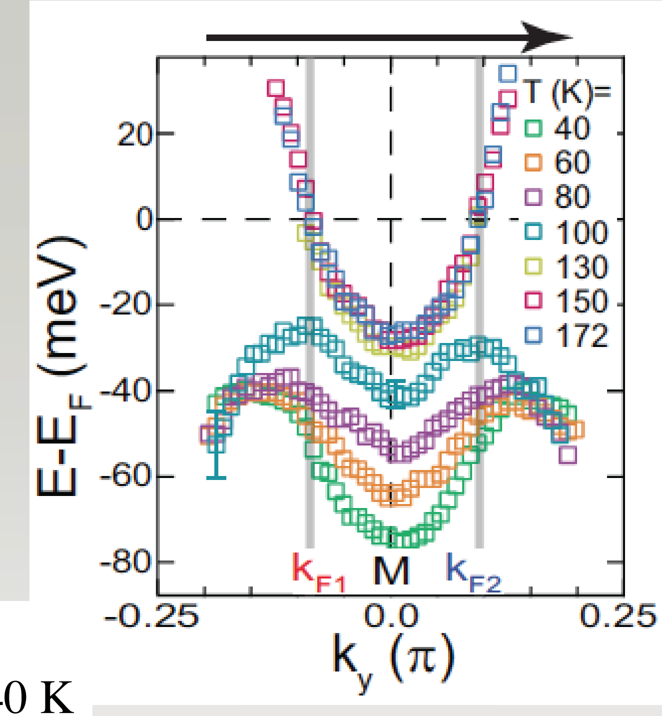


Determined from ARPES, Optical

But, good agreement for: $Bi_2Sr_2CuO_6$

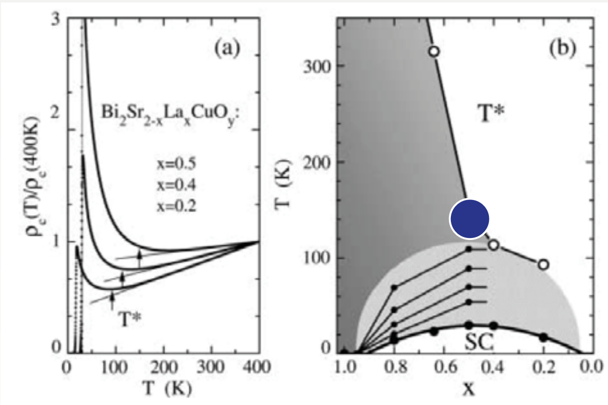
Makoto Hashimoto, Rui-Hua He, Kiyohisa Tanaka, Jean-Pierre Testaud, Worawat Meevasana, Rob G. Moore, Donghui Lu, Hong Yao, Yoshiyuki Yoshida, Hiroshi Eisaki, Thomas P. Devereaux, Zahid Hussain and Zhi-Xun Shen, Particle–hole symmetry breaking in the pseudogap state of Bi2201, Nature Physics 6, 417 (2010).

"Here we report ARPES data from (optimally doped) Bi2201, which reveal both particle–hole symmetry breaking and pronounced spectral broadening—indicative of spatial symmetry breaking without long-range order at the opening of the pseudogap. Our finding supports the STM proposal that the pseudogap state is a broken-symmetry state that is distinct from homogeneous superconductivity."

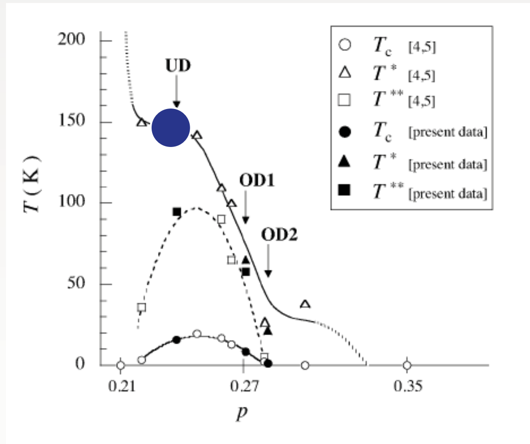


$T_c = 34$ K,
$T^* = 125 - 140$ K

A. N. Lavrov, Y. Ando and S. Ono, Two mechanisms of pseudogap formation in Bi-2201: Evidence from the c-axis magnetoresistance, Europhys. Lett., 57, 267 (2002).

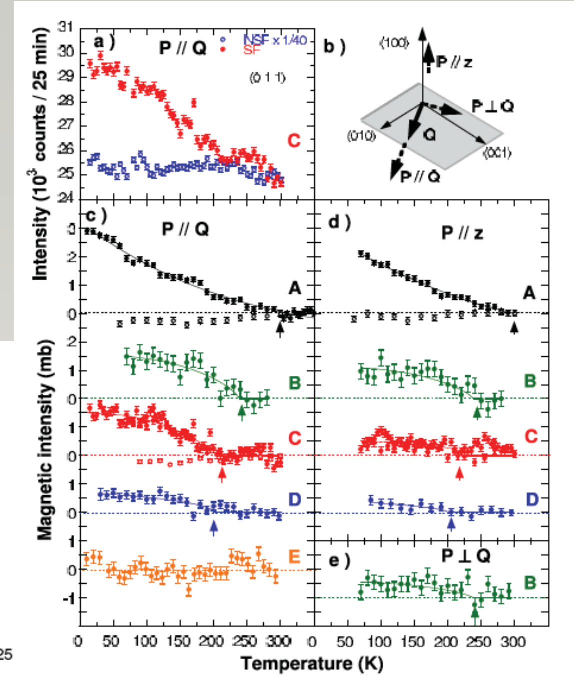


K. Kudo, T. Sasaki, E. Ohmichi, T. Osada, Y. Miyoshi, and N. Kobayashi, Pseudogap in Pb-doped Bi2201 Studied by the Out-of-Plane Resistivity in Magnetic Fields up to 40 T, AIP Conf. Proc., 2006 - Volume 850, pp. 505-506

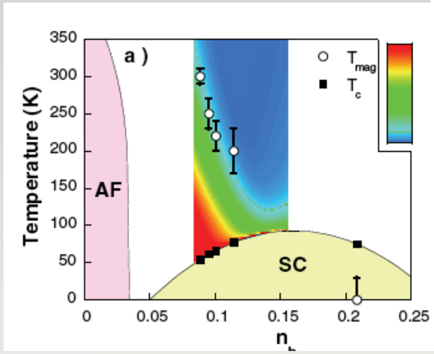


Neutron scattering to search for loop-phases

- 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).

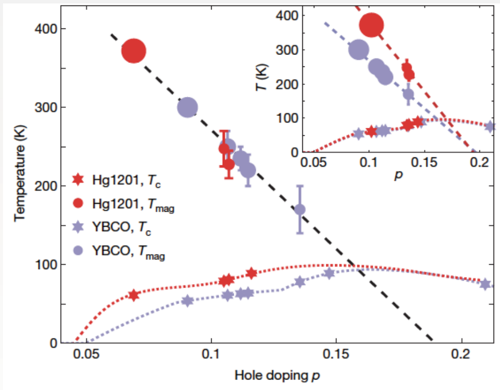


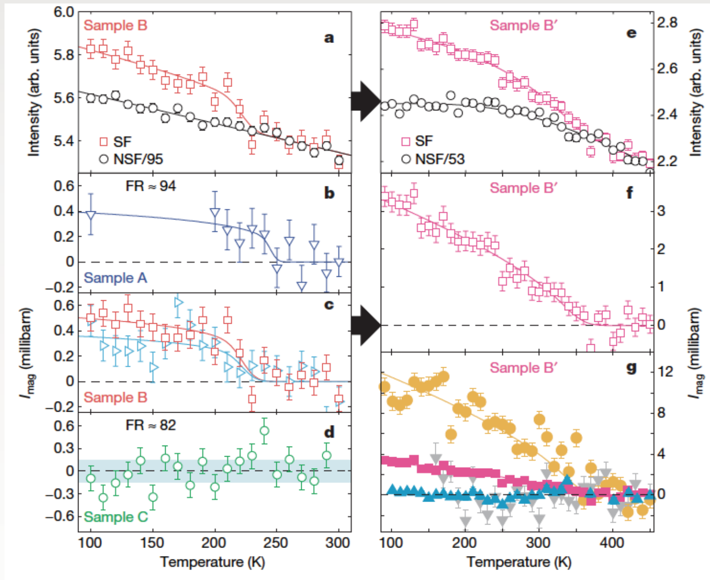
$YBa_2Cu_3O_{6+x}$



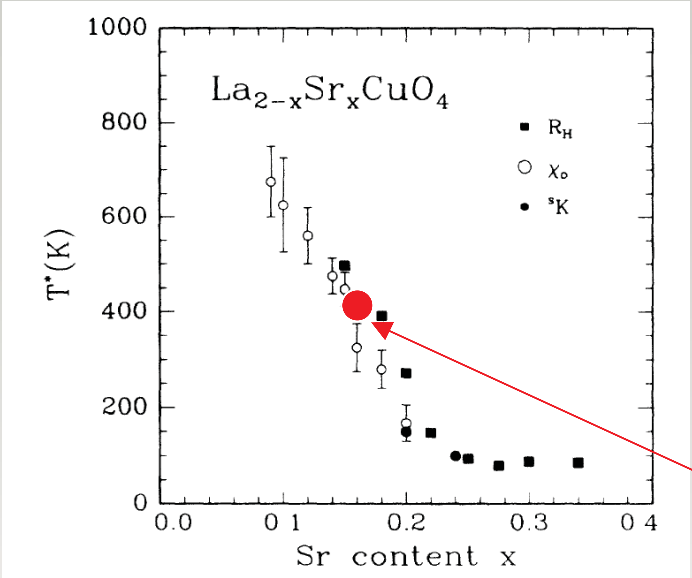
Y. Li, V. Baledent, N. Barisic, Y. Cho, B. Fauque, Y. Sidis, G. Yu, X. Zhao, P. Bourges, & M. Greven, Unusual magnetic order in the pseudogap region of the superconductor HgBa2CuO4+d, Nature 455, 372 (2008).

$HgBa_2CuO_{4+d}$





But, for $La_{2-x}Sr_xCuO_4$



H. Y. Hwang, B. Batlogg, H. Takagi, H. L. Kao, J. Kwo, R. J. Cava, J. J. Krajewski, and W. F. Peck, Jr., Scaling of the temperature dependent Hall effect in La2-xSrxCuO4, PRL 72, 2636 (1994).

$x = 0.13$

T. Startseva and T. Timusk, A. V. Puchkov, D. N. Basov, H. A. Mook, M. Okuya, T. Kimura, and K. Kishio, Temperature evolution of the pseudogap state in the infrared response of underdoped La2-xSrxCuO4, PRB 59, 7184 (1999).

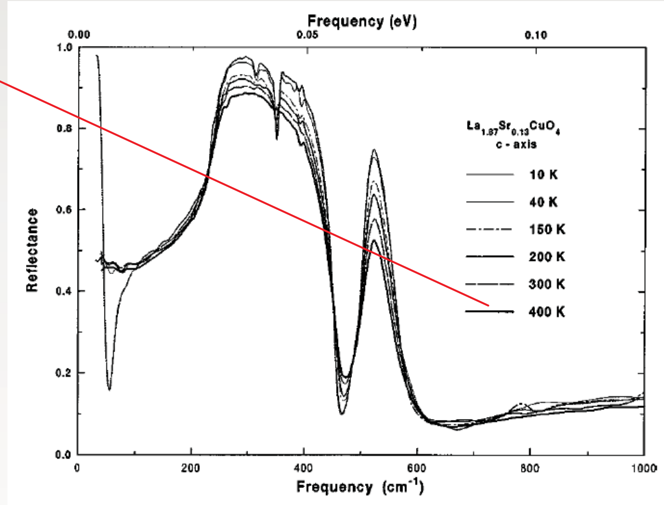


FIG. 4. The reflectance of $La_{1.87}Sr_{0.13}CuO_4$ with $E\|c$ axis is shown. The temperature sequences are 10, 40, 150, 200, 300, and 400 K.

Neutron scattering to search for loop-phases in LSCO:

V. Balédent, B. Fauqué, Y. Sidis, N.B. Christensen, S. Pailhès, K. Conder, E. Pomjakushina, J. Mesot, P. Bourges, 2D orbital-like magnetic order in La2-xSrxCuO4, PRL 105, 027004 (2010)

We here report the observation below 120 K of a similar magnetic ordering in the archetypal cuprate La2−xSrxCuO4 (LSCO) system for x=0.085. In contrast to the previous reports, the magnetic ordering in LSCO is only short range with an in-plane correlation length of 10Å and is bidimensional (2D).

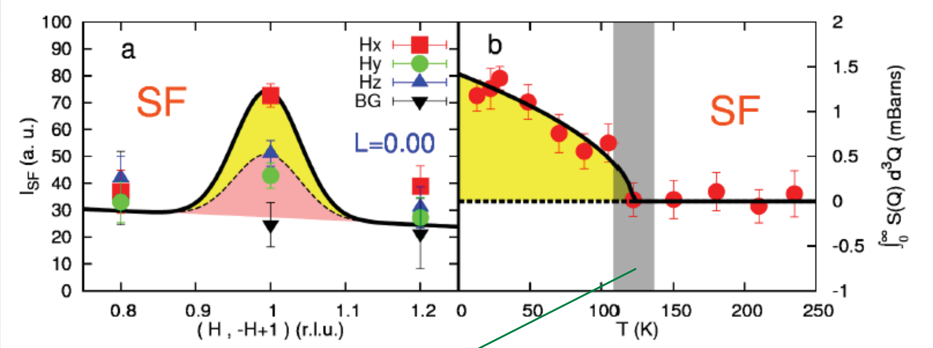
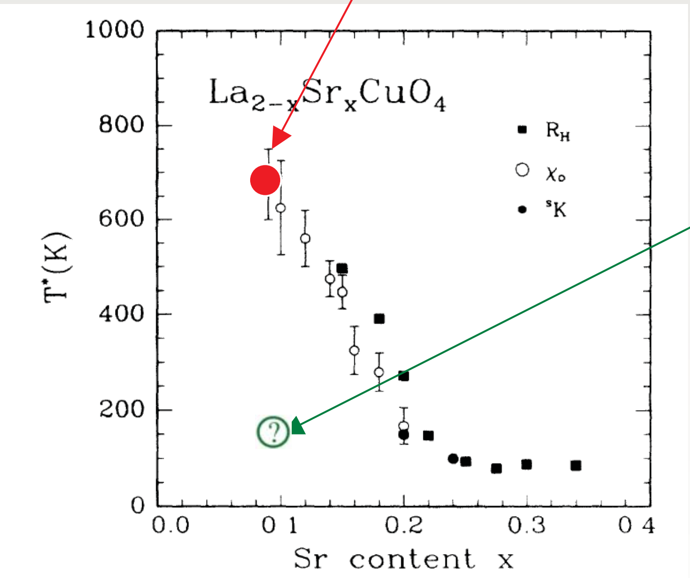


FIG. 3: A) Polarization analysis of the difference of scans measured at 30 K and 120 K in the spin-flip channel around **Q**=(1,0,0) along a diagonal direction (1,-1). The neutron polarization is applied successively along three different directions $\mathbf{H}_\alpha$. The label α correspond to the Cartesian axis $\{x, y, z\}$, so that the x axis is parallel to **Q**, while the z axis stands for the direction perpendicular to the scattering plane. B) Temperature dependence of Q-integrated magnetic intensity, S_{mag}.

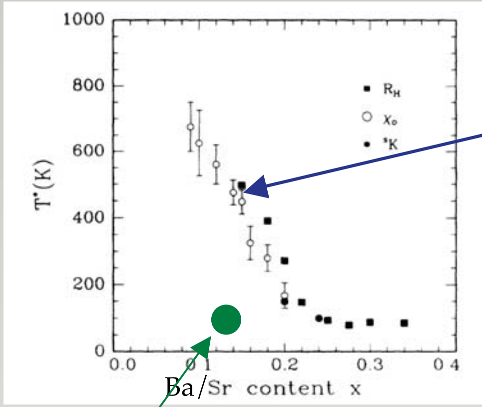
$x = 0.085$

?



...and for $La_{2-x}Ba_xCuO_4$

Basic T* (deviation of resistivity, NMR, etc. is the same as for LSCO):



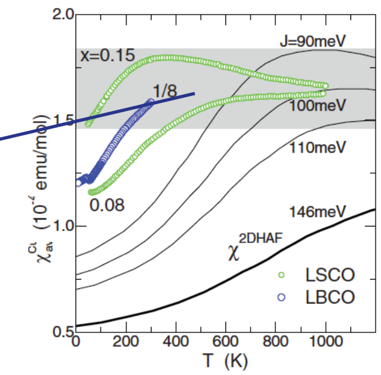
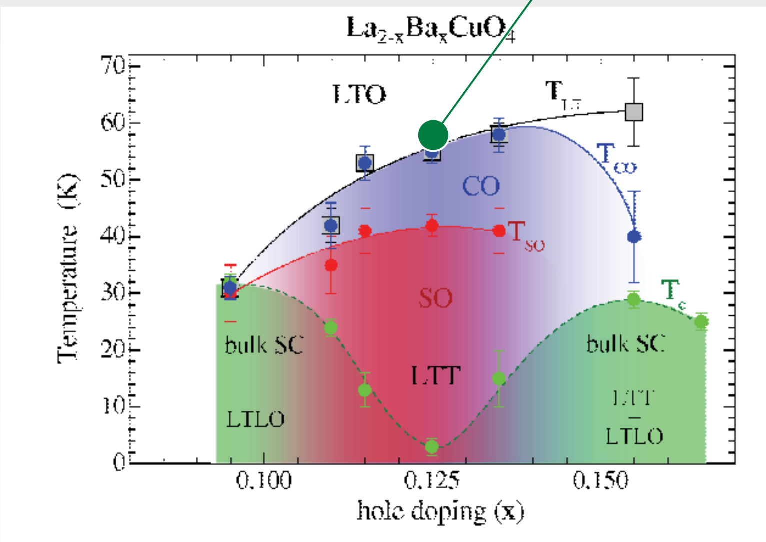
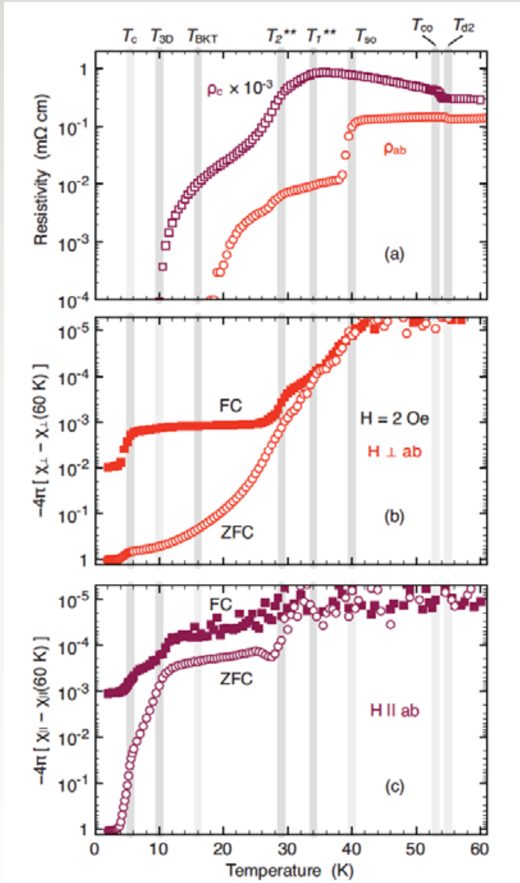


FIG. 8. (Color online) χ_{av}^{Cu} vs T for the $La_{1.875}Ba_{0.125}CuO_4$ single crystal and for polycrystalline $La_{2-x}Sr_xCuO_4$ (Ref. 40). Solid lines correspond to χ^{2DHAF} for different J (Ref. 1).

However:

J. M. Tranquada, G. D. Gu, M. Hucker, Q. Jie, H.-J. Kang, R. Klingeler, Q. Li, N. Tristan, J. S. Wen, G. Y. Xu, Z. J. Xu, J. Zhou, and M. v. Zimmermann, Evidence for unusual superconducting correlations coexisting with stripe order in La1.875Ba0.125CuO4, PRB 78, 174529 2008





Some intermediate observations:

1. For same material system, different probes indicate different T*

2. Most probes extract T* from some change in the system's behavior. In general it looks like a crossover.

4. The only experiments to indicate a true broken symmetry below T* (and above Tc) are the neutron scattering , finding loop/moments order below some T* (also Kerr effect measurements, possibly also Nernst).

However:

In LSCO or LBCO there is no such long range order, and the short range ordering sets many hundreds of degrees below T* from other measurements.

5. In several systems, LBCO in particular, charge ordering seems to be the most prominent phenomenon before Tc.

Insight from Kerr measurements

Insight from Kerr effect Measurements:

We observe a true phase transition,

but…

What is the origin of the transition?

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

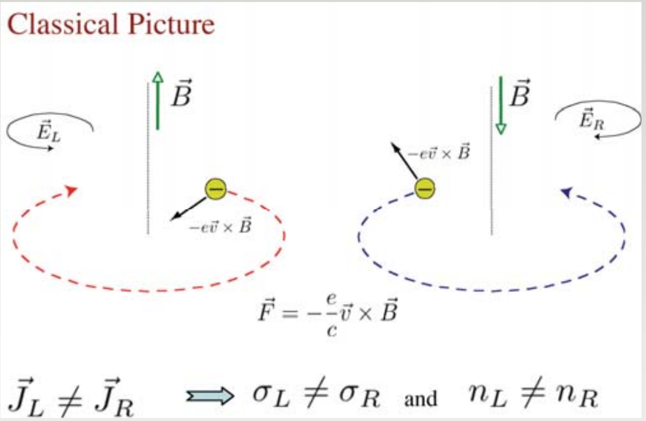
In addition, polar Kerr effect measurements using the loopless Sagnac interferometer provide

- High sensitivity for magnetic (or other TRSB) signals

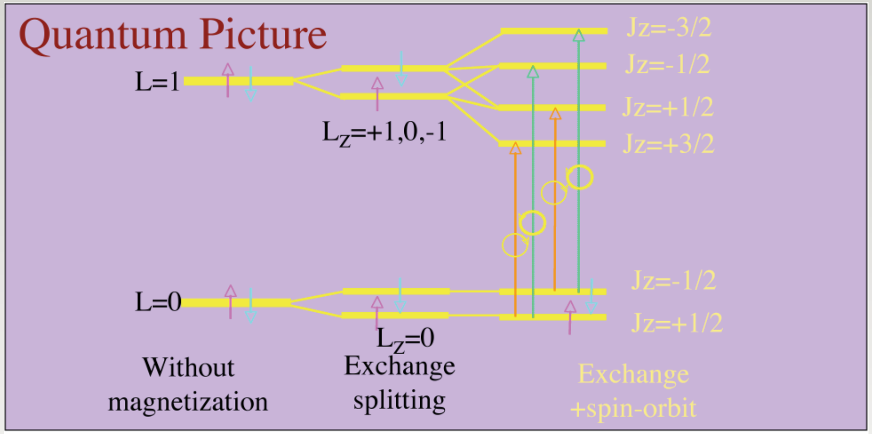
(100 nanorad/(Hz)$^{1/2}$ ➔ nano-radians sensitivity!!!)

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

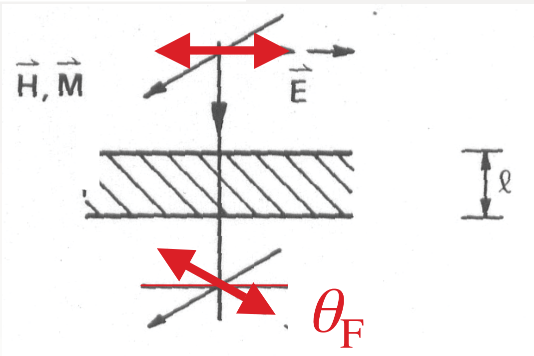
This is a bulk measurement as we probe one optical penetration depth into the material.



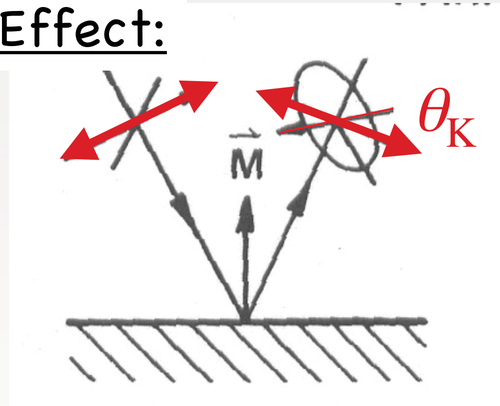
$$n_R \neq n_L$$



Faraday Effect:



(Polar) Kerr Effect:



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 μ=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

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

Relating the dielectric function and index of refraction to the conductivity:

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

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

Faraday Angle:

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

and

Kerr Angle:

$$\theta_K = -\mathcal{I}m\left[\frac{\tilde{n}_L - \tilde{n}_R}{\tilde{n}_L\tilde{n}_R - 1}\right]$$

While, for small κ:

$$\theta_F \approx -\frac{2\pi\ell}{cn}\sigma'_{xy}$$

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

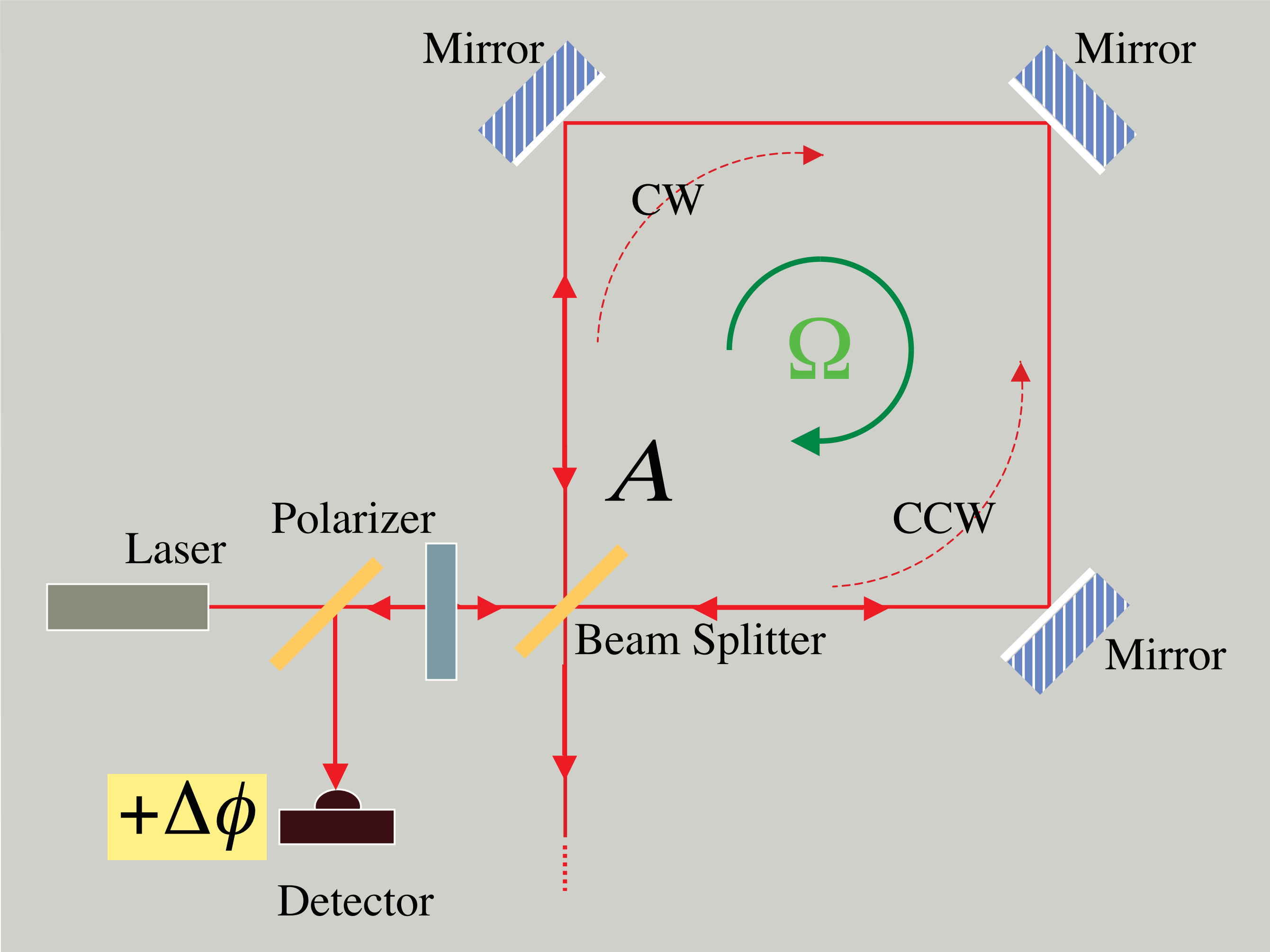
The apparatus

- A. Kapitulnik, J.S. Dodge, and M.M. Fejer, High-Resolution Magneto-optic Measurements with a Sagnac Interferometer, J. Appl. Phys. 75, 6872 (1994).

- Jing Xia, Peter T. Beyersdorf, Martin M. Fejer, and Aharon Kapitulnik, Modified Sagnac interferometer for high-sensitivity magneto-optic measurements atcryogenic temperatures, Appl. Phys. Lett. 89, 062508 (2006).

The Sagnac Effect

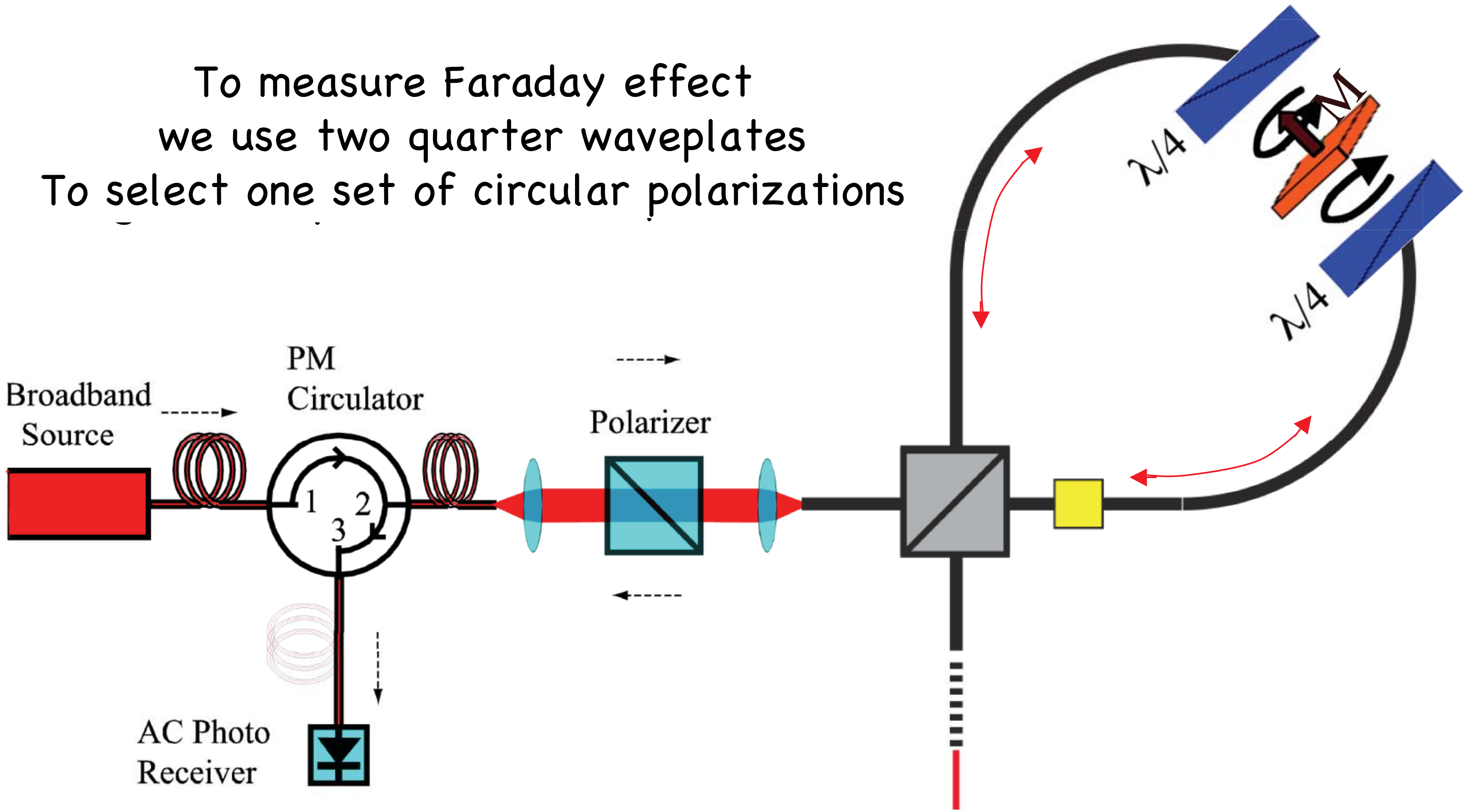
A Sagnac Loop at rest
is reciprocal!



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

Use Sagnac loop to measure magnetization:

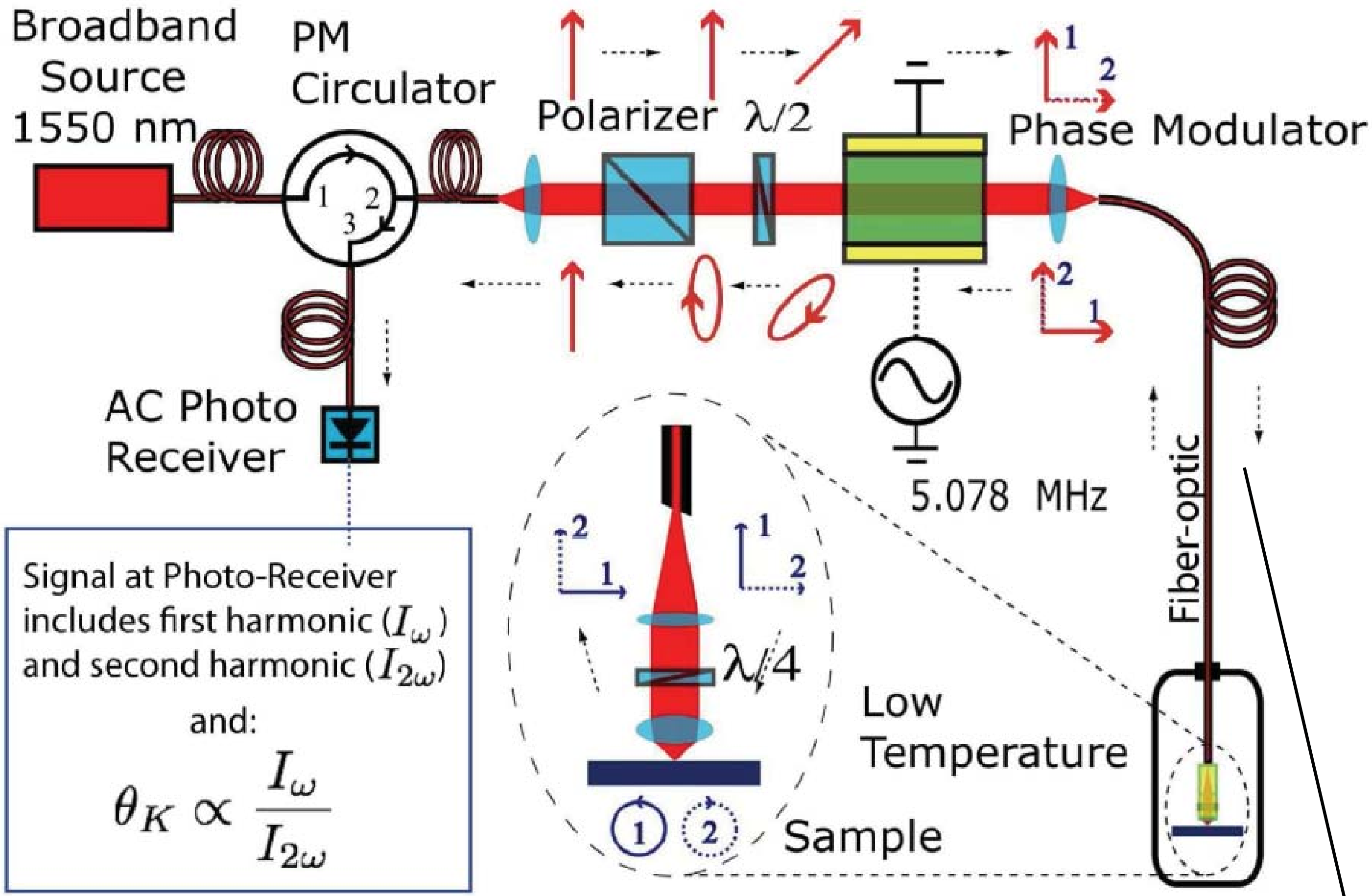
To measure Faraday effect
we use two quarter waveplates
To select one set of circular polarizations



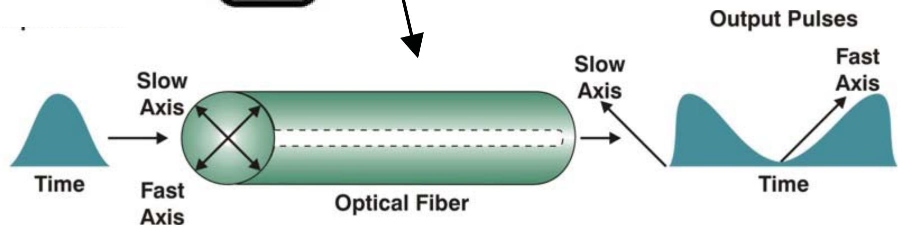
Complete rejection of reciprocal (non-TRSB) effects!
Extremely high sensitvity for non-reciprocal effects (TRSB)!

Zero-area-loop Sagnac magnetometer:

λ=1.55 μm



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.**



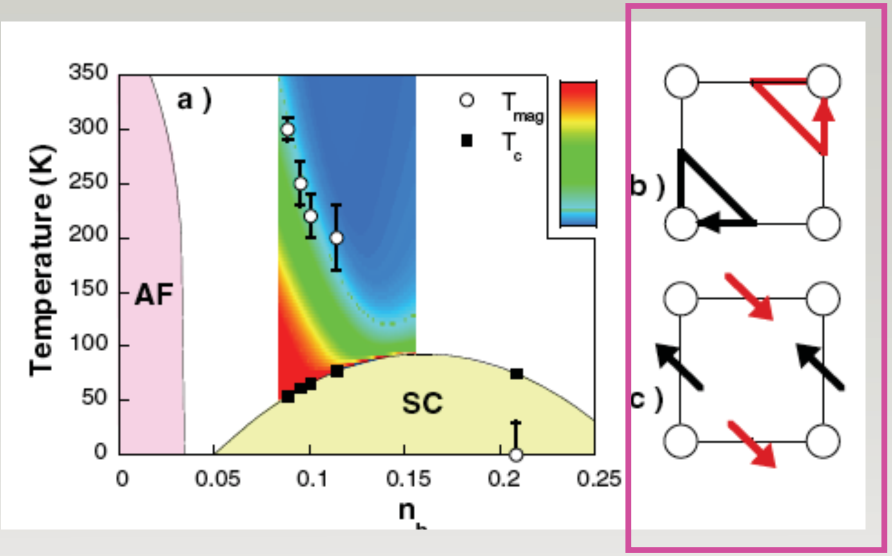
Jing Xia, Peter Beyersdorf, M. M. Fejer, and A. Kapitulnik, Appl. Phys. Lett. 89, 062508

Results on YBCO

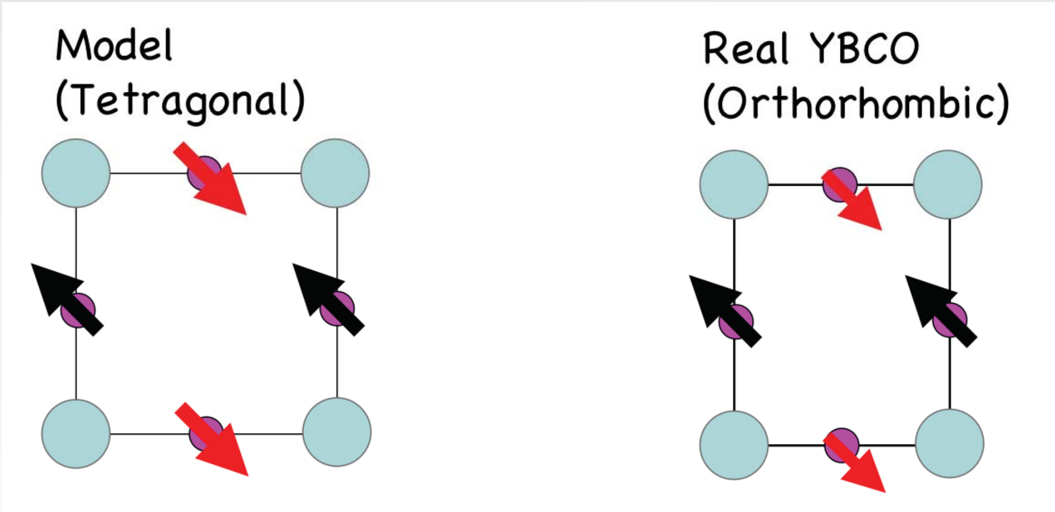
- Polar Kerr Effect Measurements of YBa2Cu3O6+x: Evidence for Broken Symmetry Near the Pseudogap Temperature, Jing Xia, Elizabeth Schemm, G. Deutscher, S.A. Kivelson, D. A. Bonn, W. N. Hardy, R. Liang, W. Siemons, G. Koster, M. M. Fejer, A. Kapitulnik, Phys. Rev. Lett. 100, 127002 (2008).

- Aharon Kapitulnik, Jing Xia, Elizabeth Schemm and Alexander Palevski, Polar Kerr effect as probe for time-reversal symmetry breaking in unconventional superconductors, New J. Phys. 11, 055060 (2009).

Initial motivation



Assume signal comes from moments on the oxygen.



Net ferromagnetic moment = 0

Net ferromagnetic moment ≠ 0 → Finite Kerr effect

Samples of $YBa_2Cu_3O_{6+x}$

Single crystals (UBC)

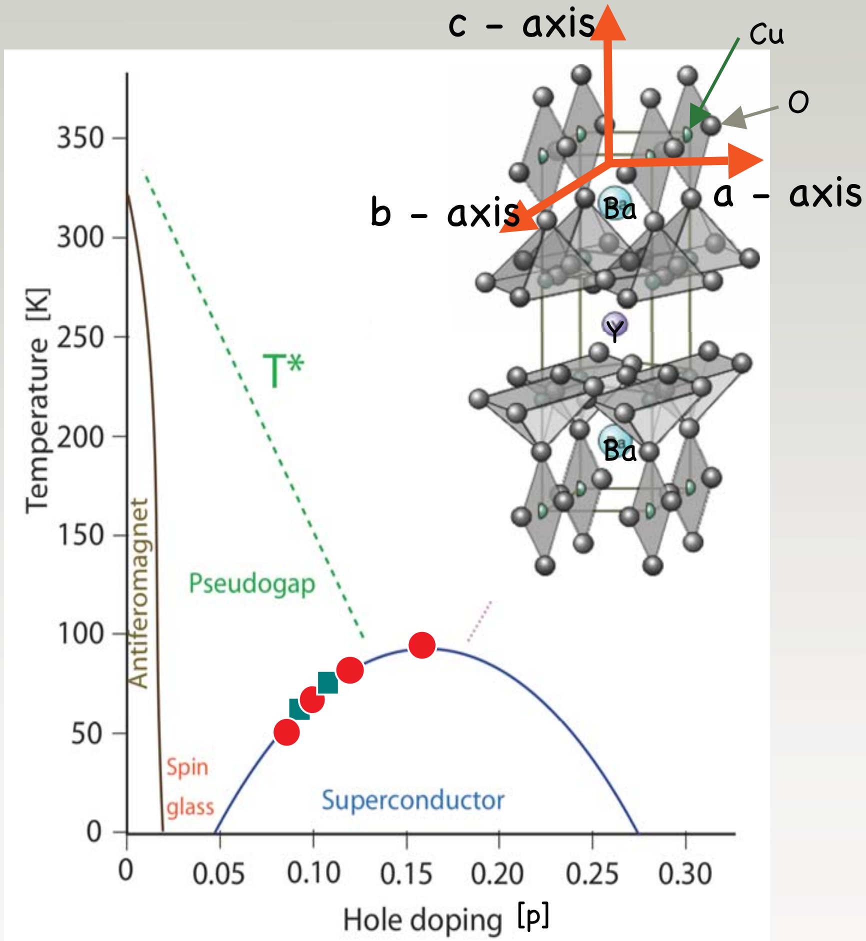
- Ortho-I,II,III,VIII
- Mechanically detwinned
- Aligned for measurement along the *c*-axis

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

c-axis thin films (Conductus/Stanford)

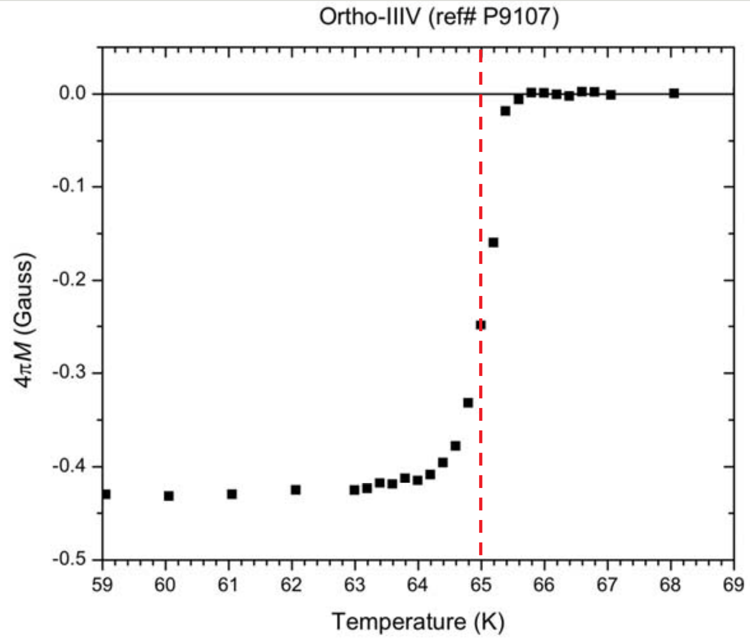
- Underdoped through annealing in reduced atmosphere

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

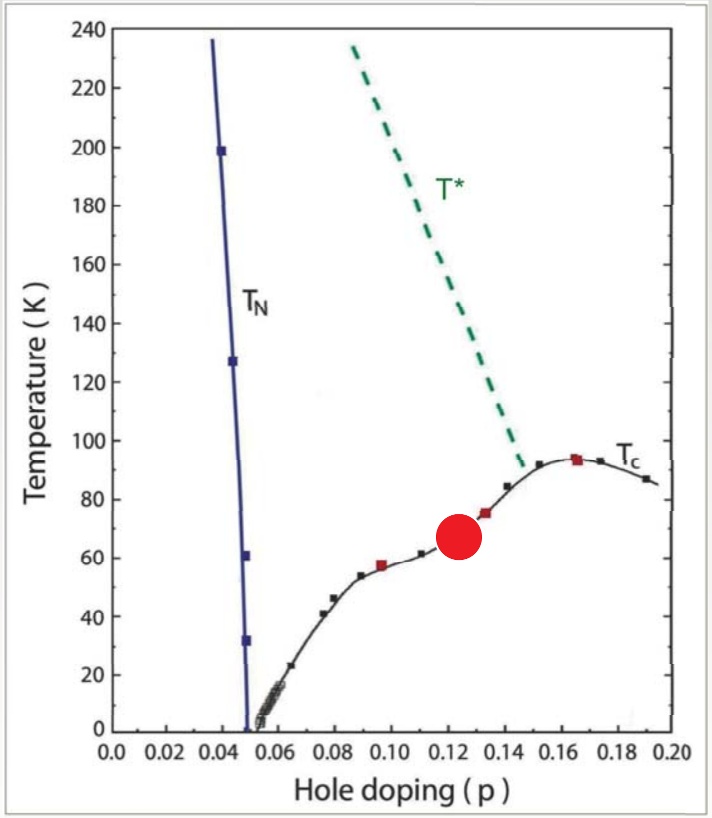


Anatomy of a data set
Ex: $YBa_2Cu_3O_{6.67}$ (ortho-VIII), underdoped single crystal

T_c = 65 K



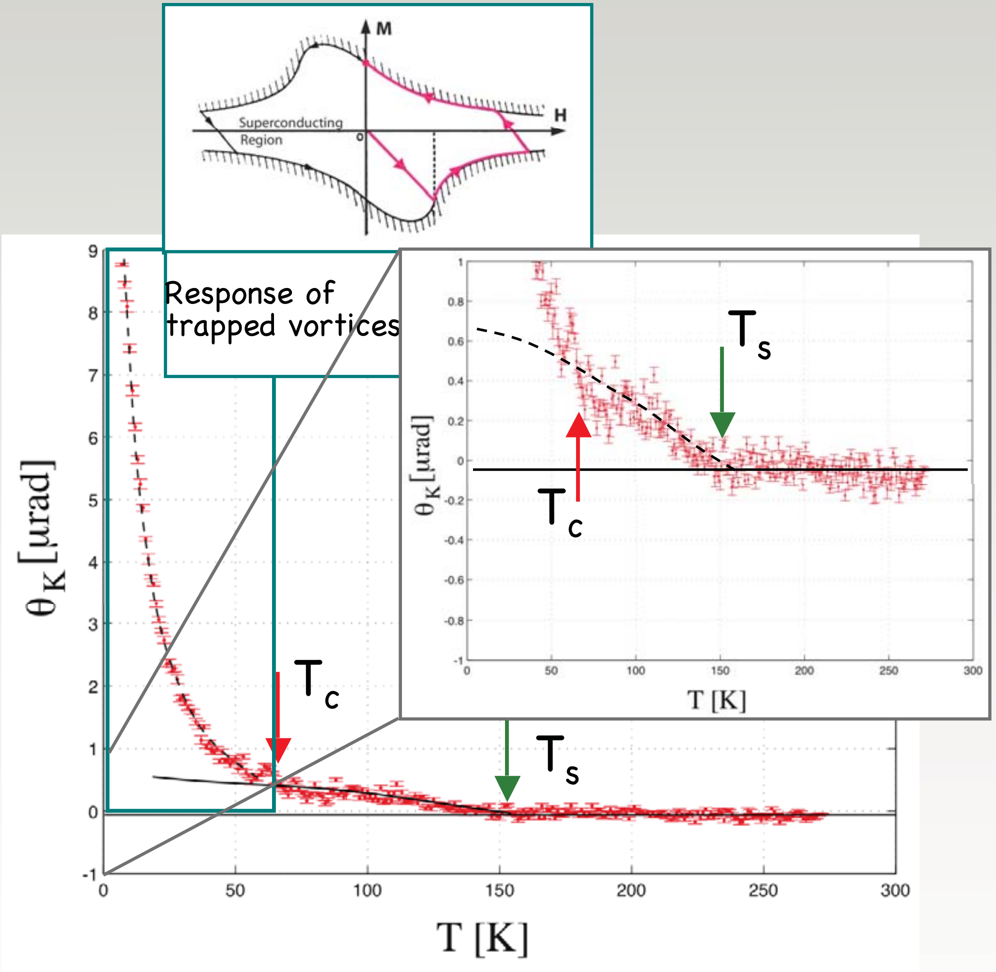
Magnetization data courtesy of D. Bonn



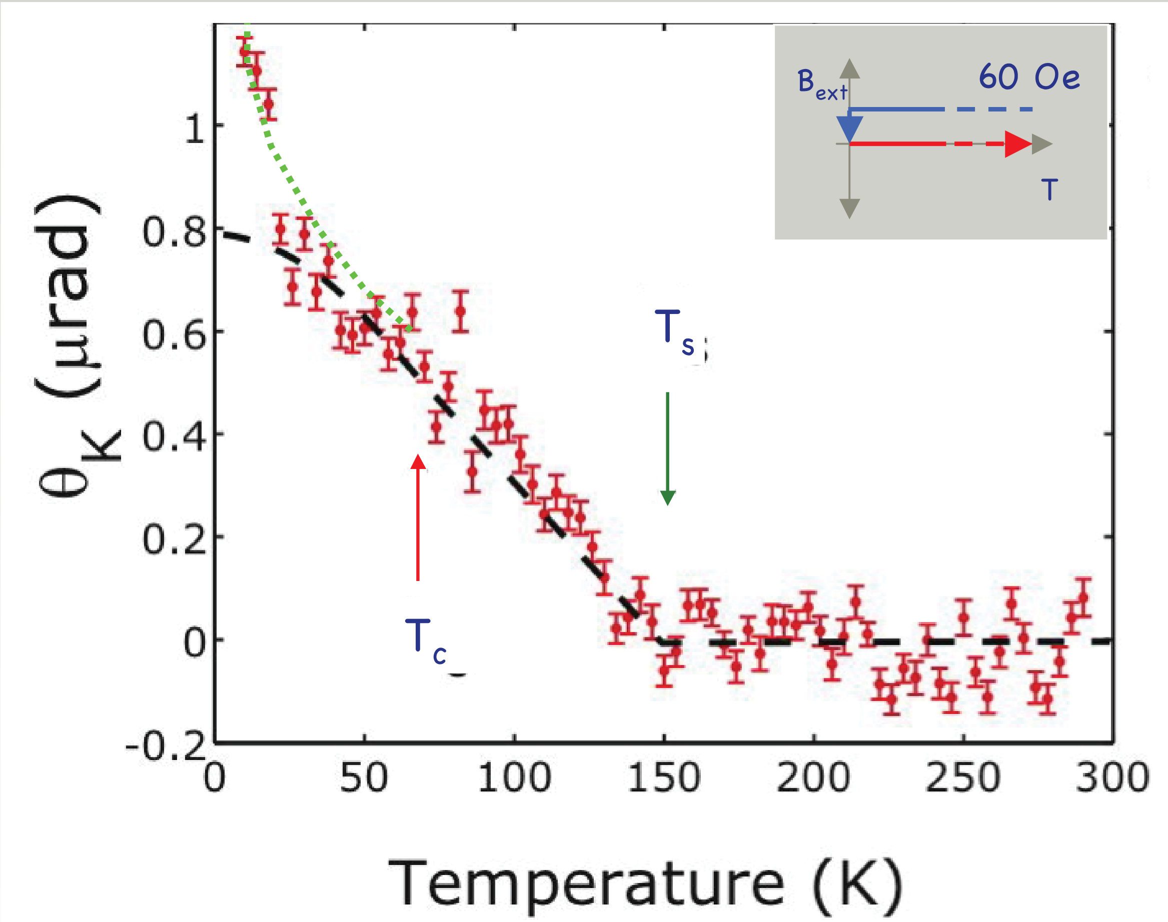
Anatomy of a data set
Ex: $YBa_2Cu_3O_{6.67}$ (ortho-VIII)
cooled in high field -- measured in zero field

We note three distinct regimes:

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



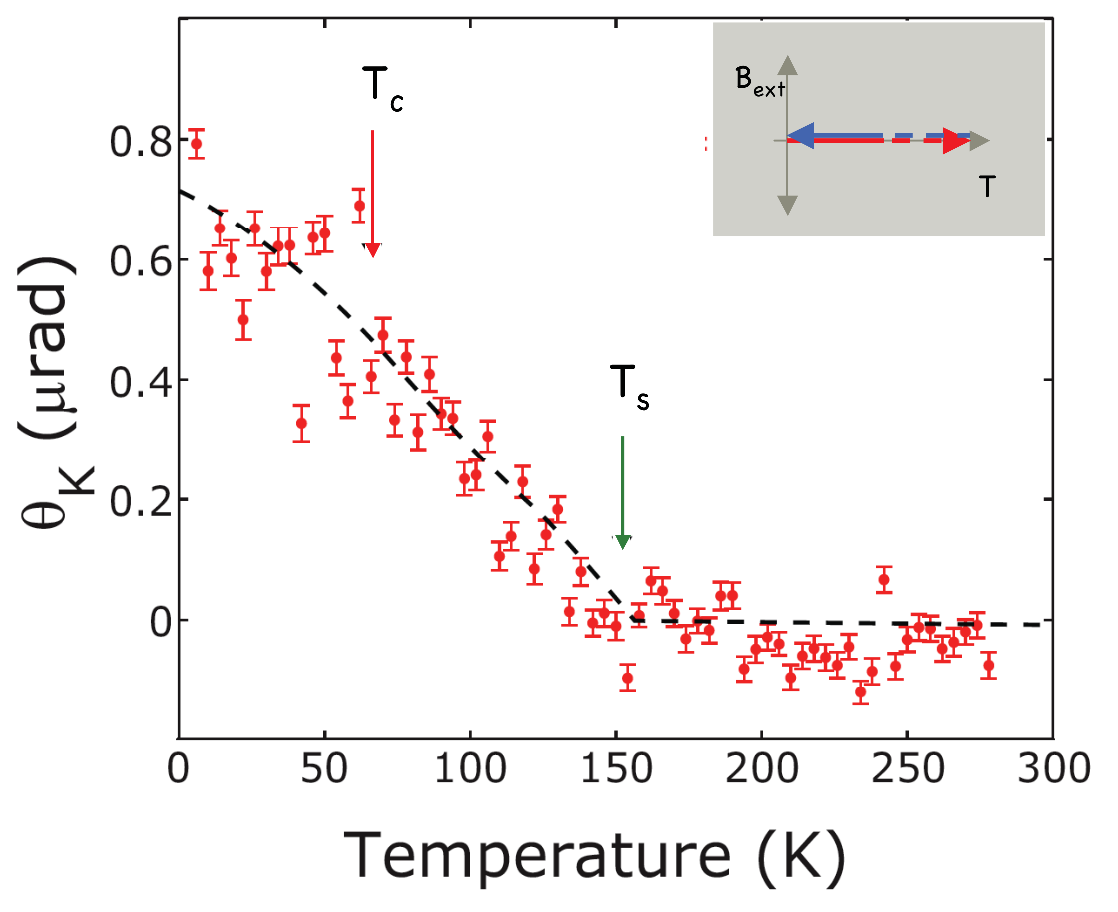
$YBa_2Cu_3O_{6.67}$: Reduce the effect of trapped vortices by cooling in a lower field



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



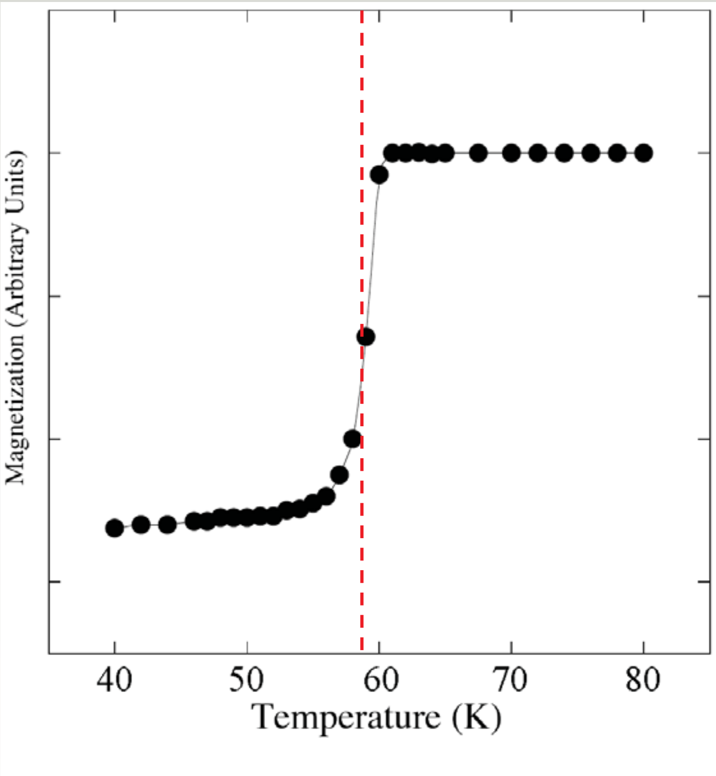
Zero field:
< 3 mOe

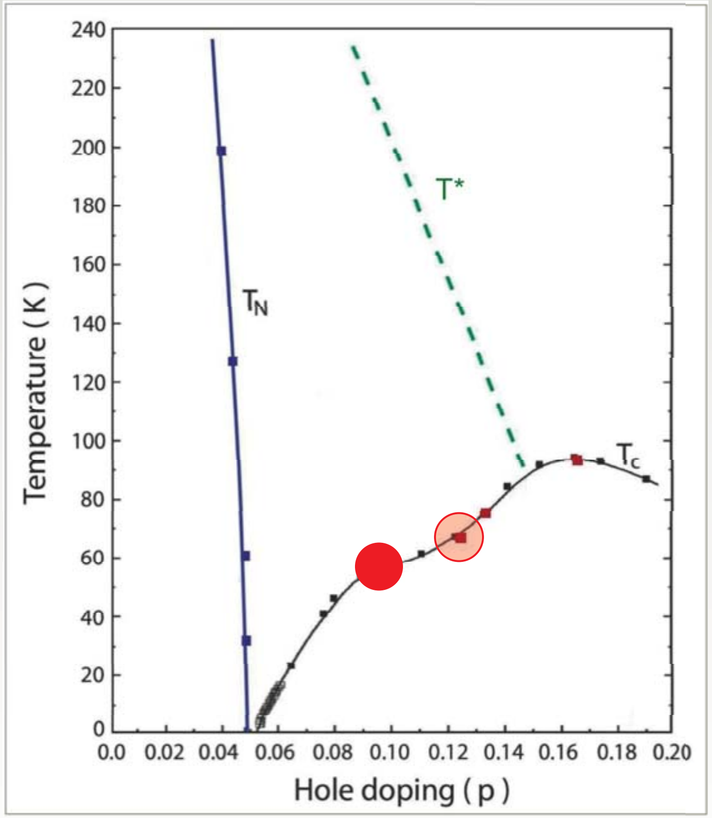
No contribution from trapped vortices

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

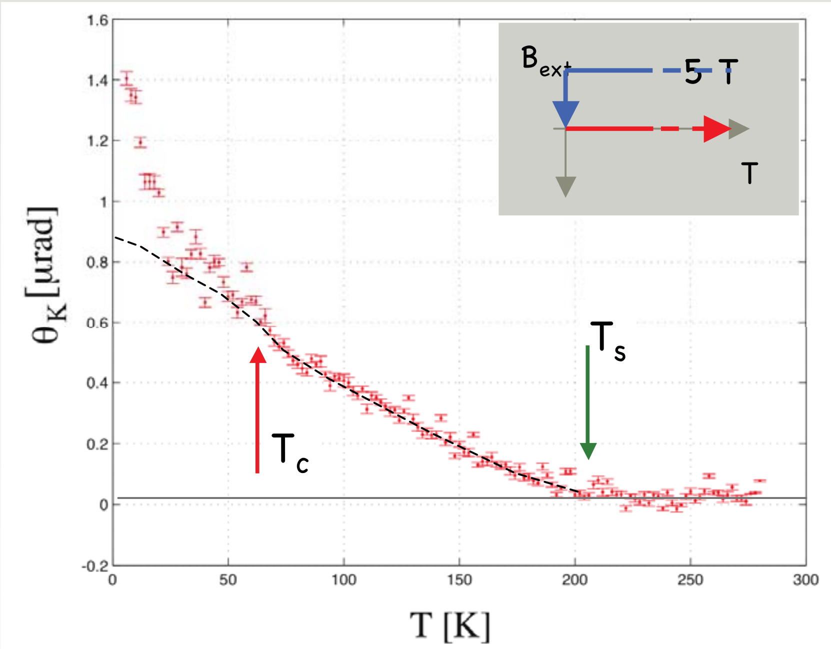


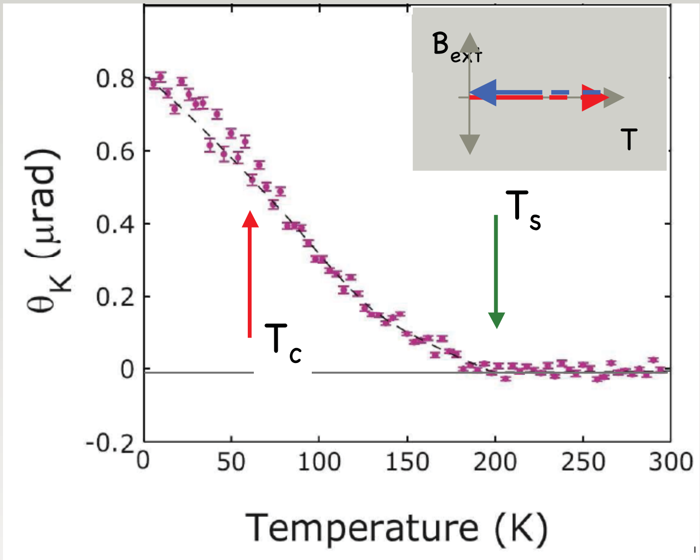


$YBa_2Cu_3O_{6.5}$: The same general Kerr behavior appears

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

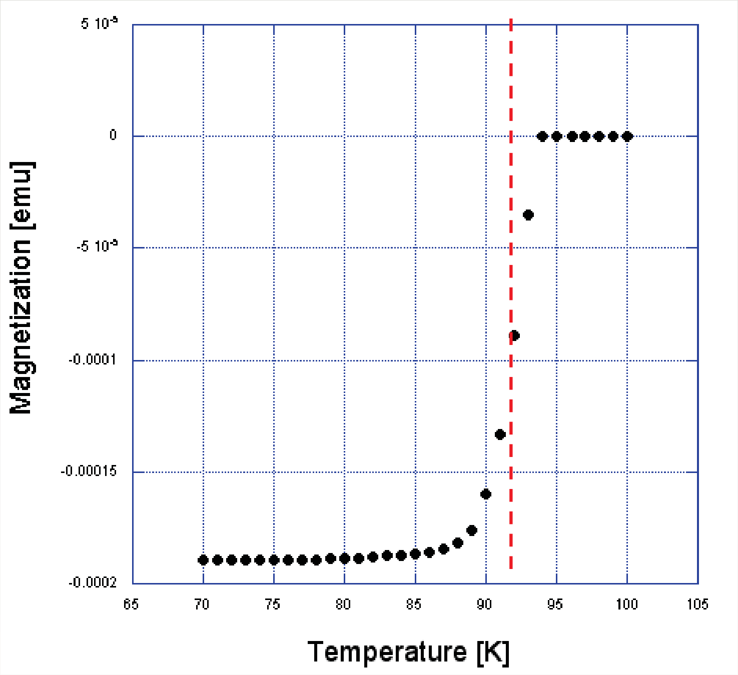


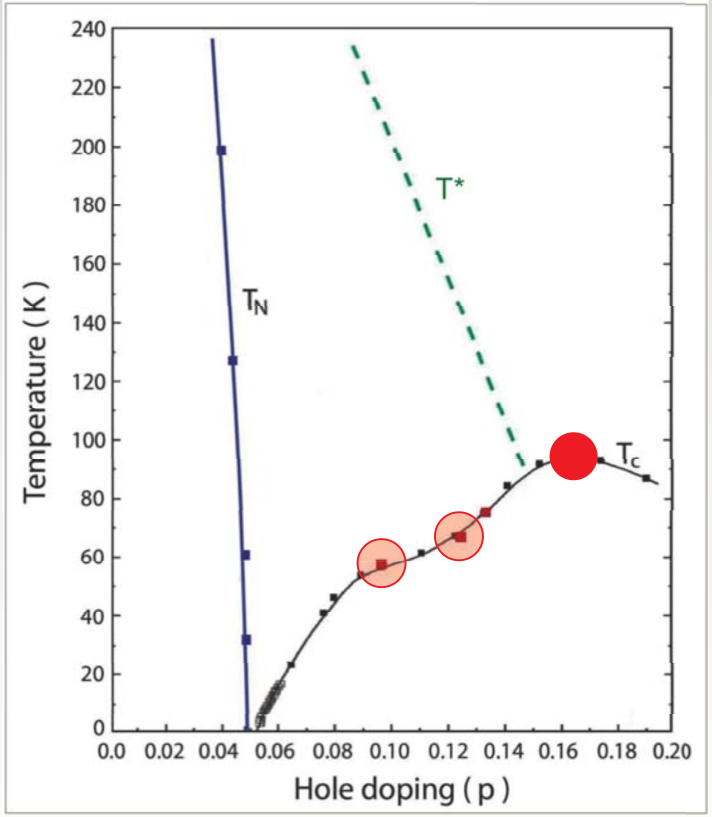


Cooling in zero field allows us to isolate the (non-vortex) signal below T_s

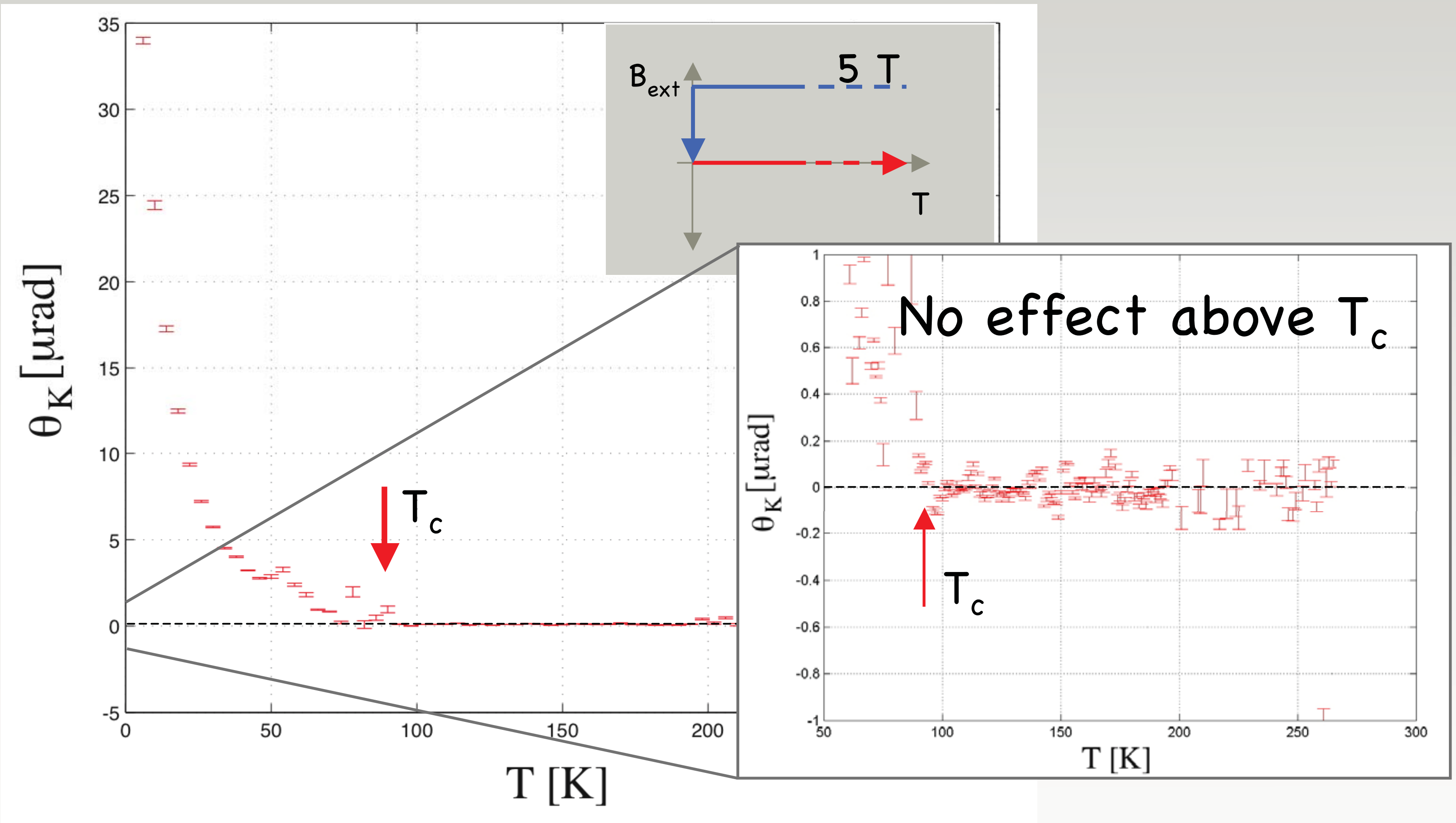
What happens near optimal doping?
$YBa_2Cu_3O_{6.92}$ (ortho-I)

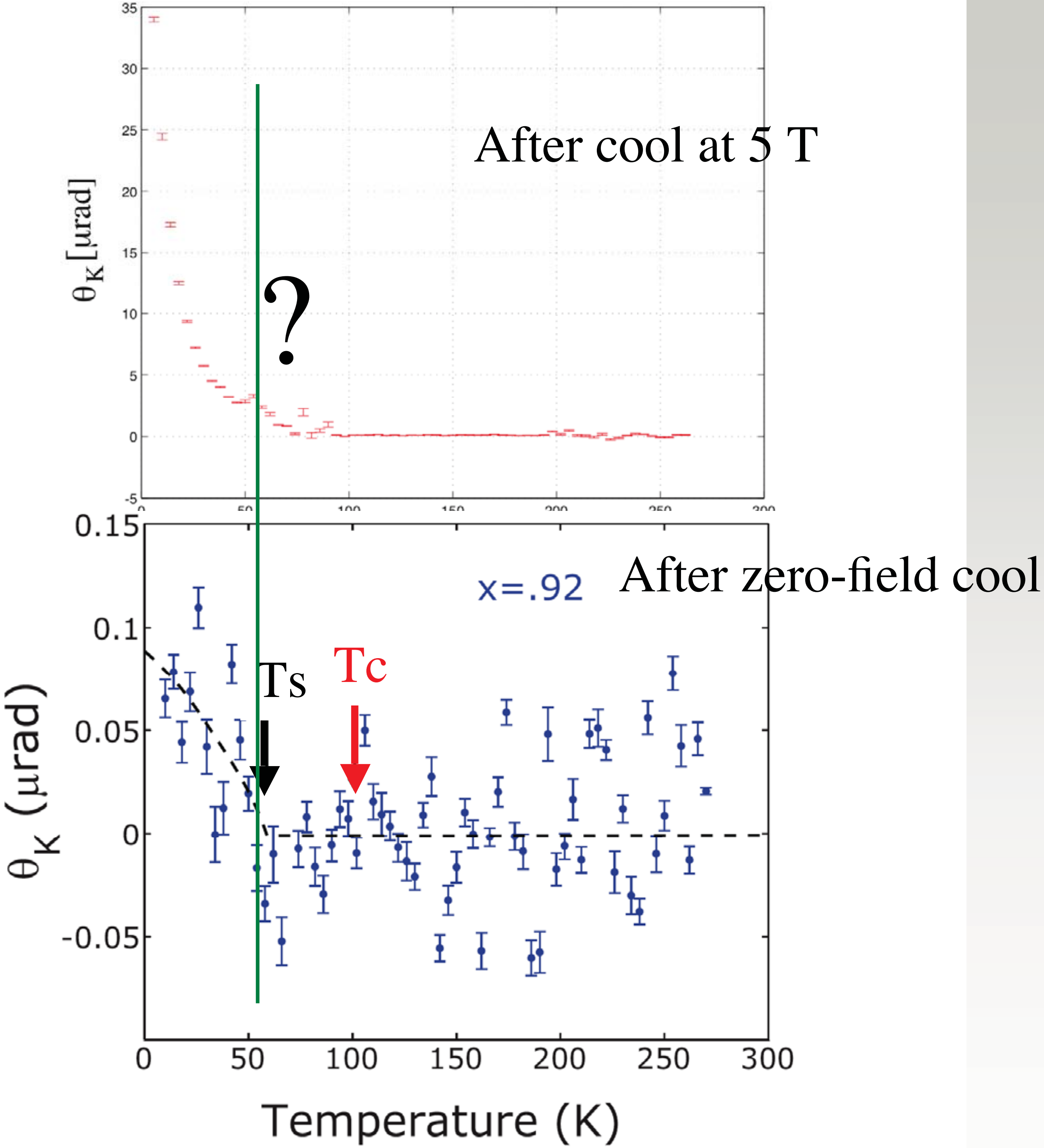
T_c = 91.7 K





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



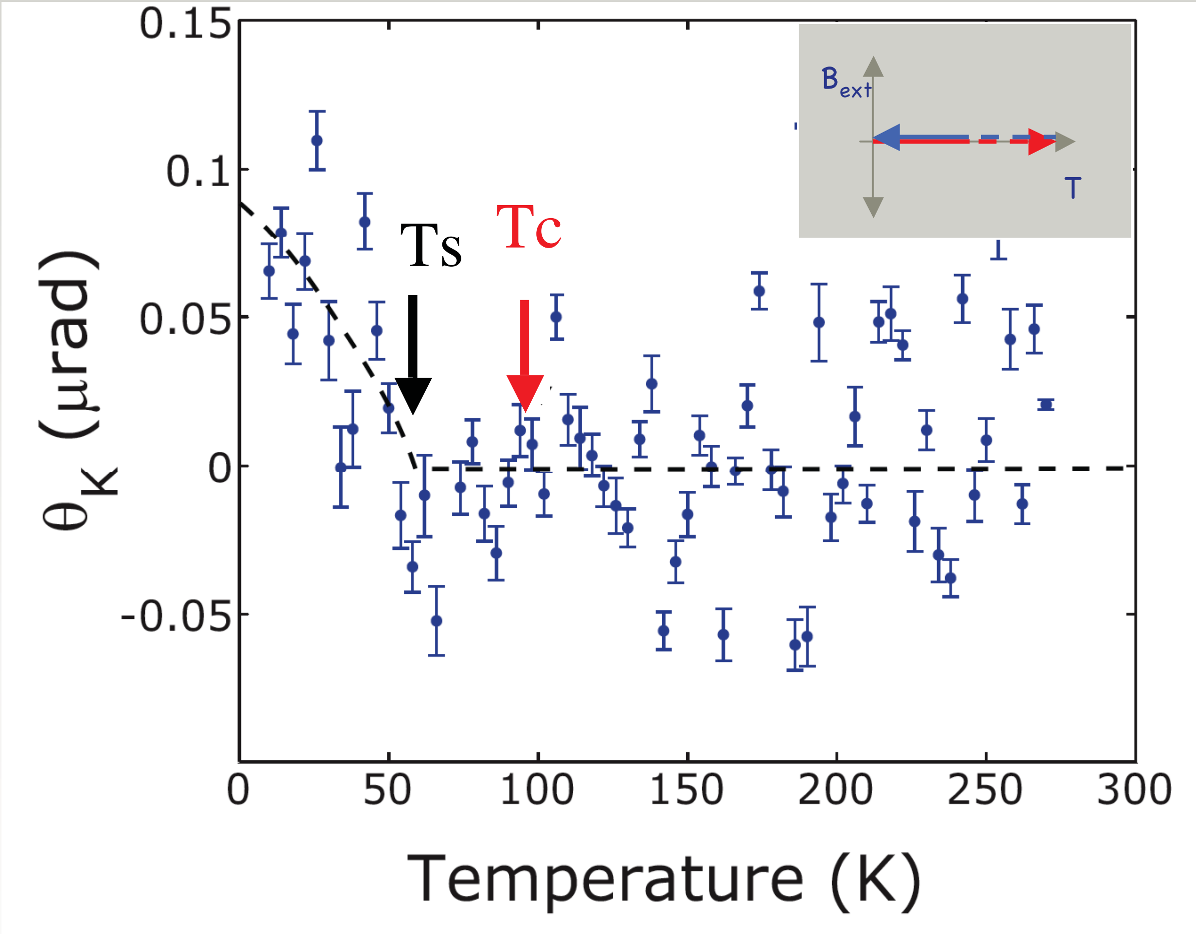


After cool at 5 T
θ_K [μrad]
?
After zero-field cool
x=.92
Ts
Tc
θ_K (μrad)
Temperature (K)

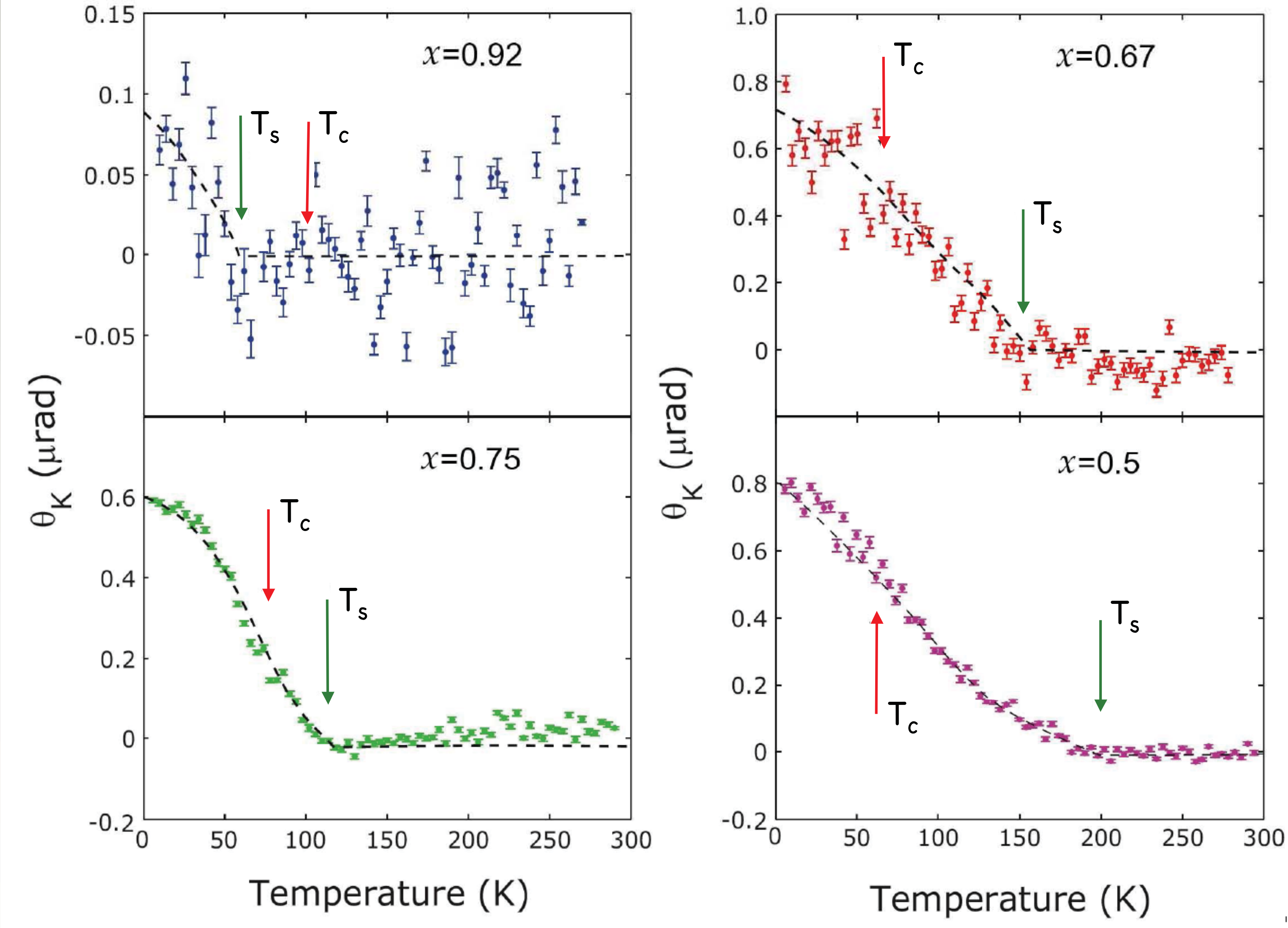
$YBa_2Cu_3O_{6.92}$: After cooling in ZF, the (pure) signal departs from zero *below* T_c

Zero field:
< 3 mOe

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

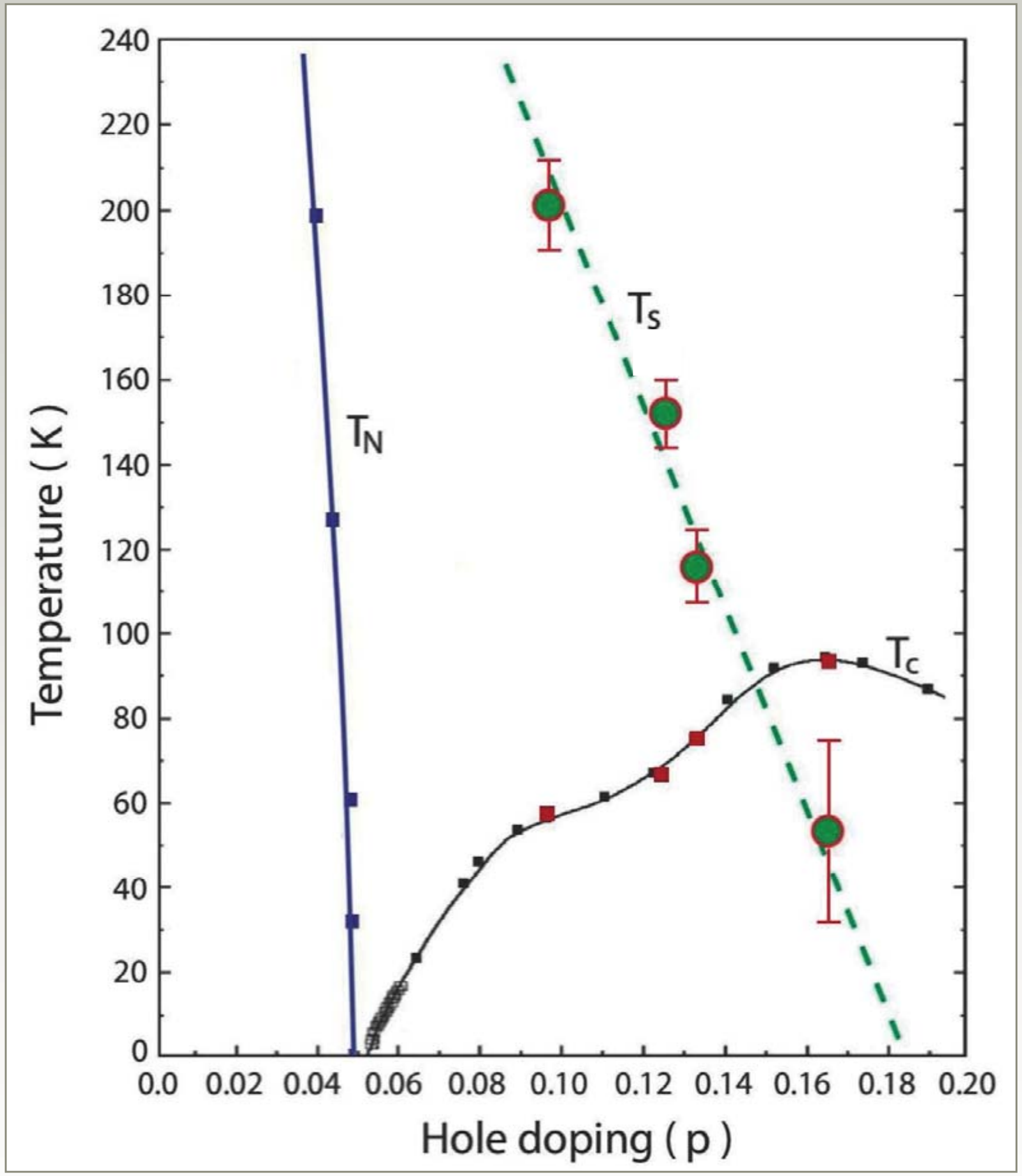


Data from all crystals (zero-field cool, zero-field warmup)



Summary of crystal data

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



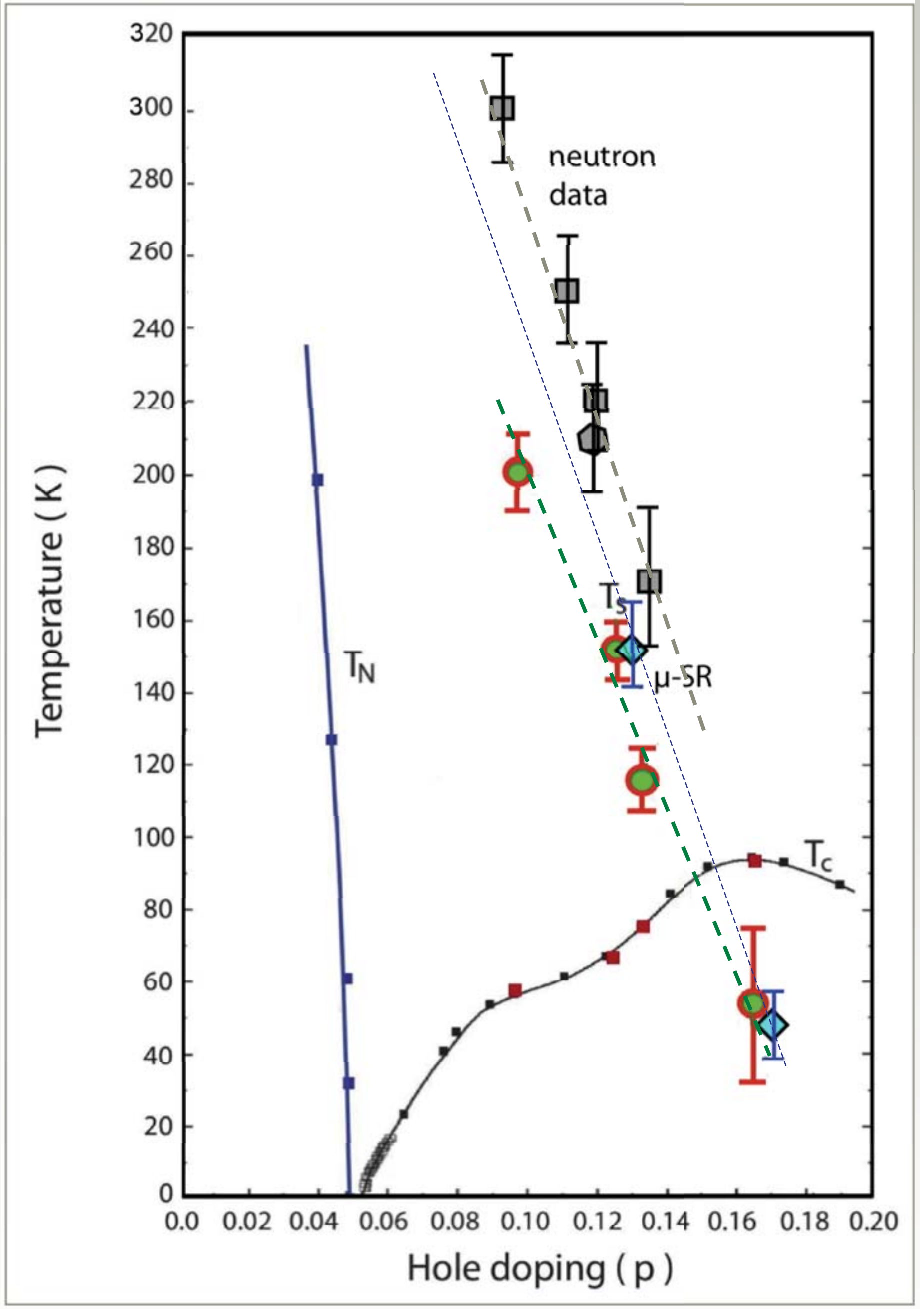
[1] Ruixing Liang, D. A. Bonn and W. N. Hardy, Physica C **336**, 57 (2000)

Comparison with μSr and neutron data

Kerr effect (●)

μSR (◇)

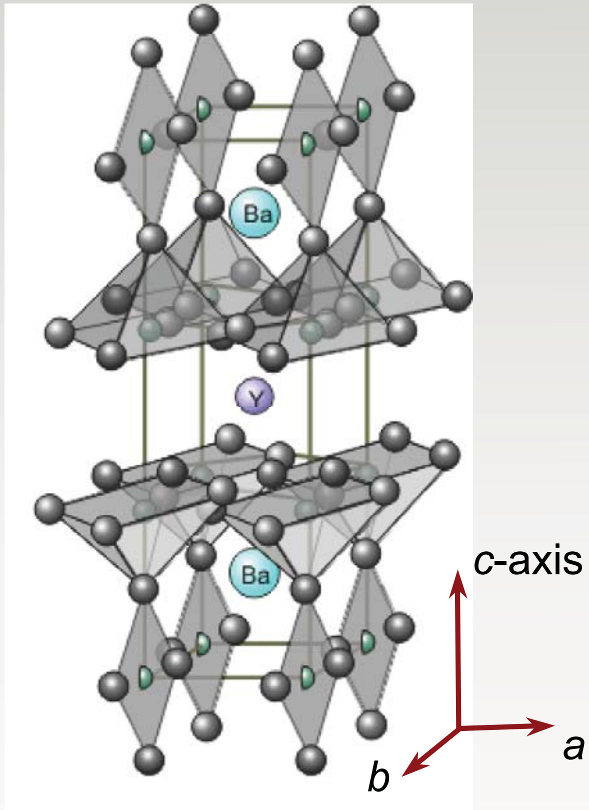
Elastic neutron scattering (□ [1], ⬡ [2])



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

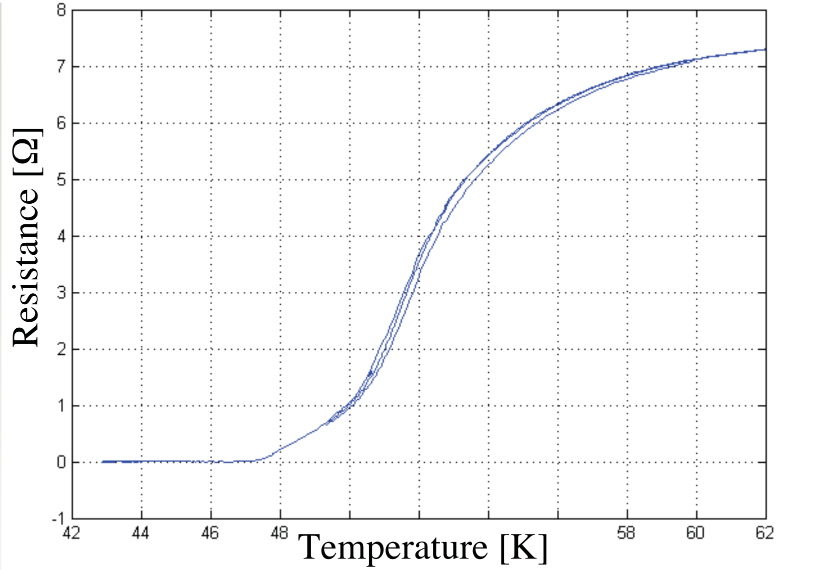
Measurement on thin films

- 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...

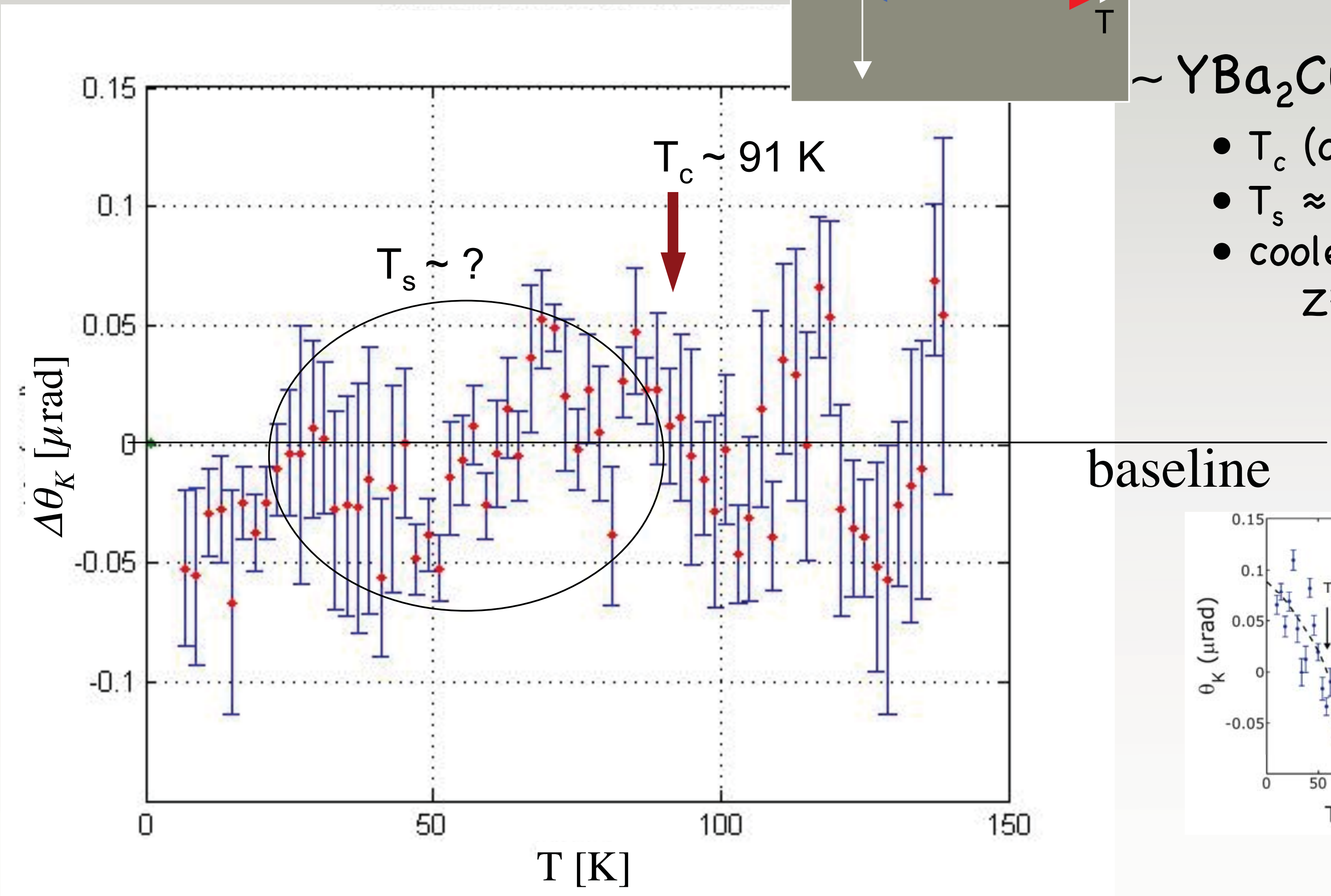
Resistive transition in YBCO thin film, after annealing

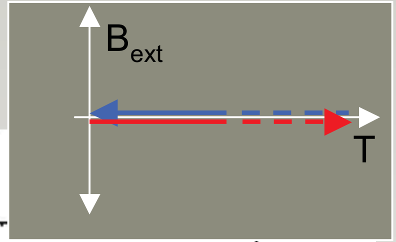


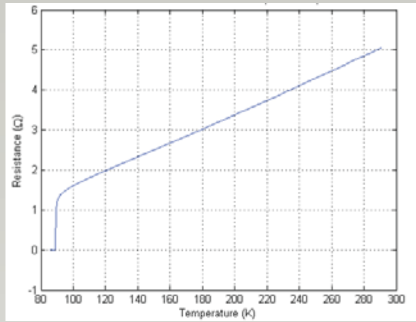
- polycrystalline
- twinned
- inhomogeneous
- ...

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

Results: films before annealing
T_c(onset) ~ 91K

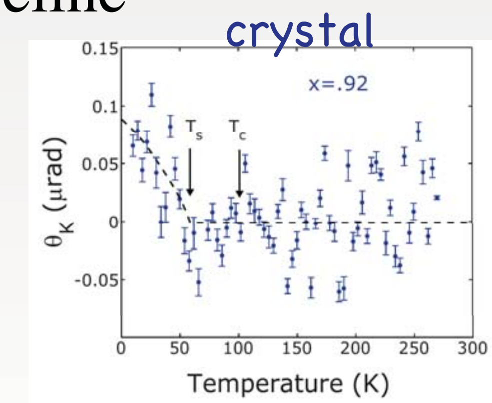




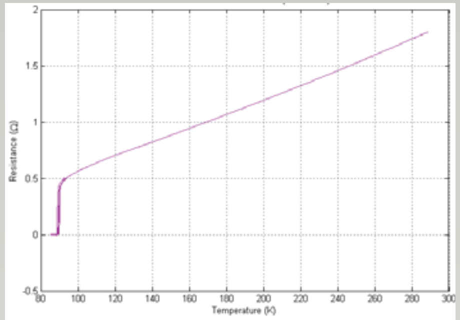


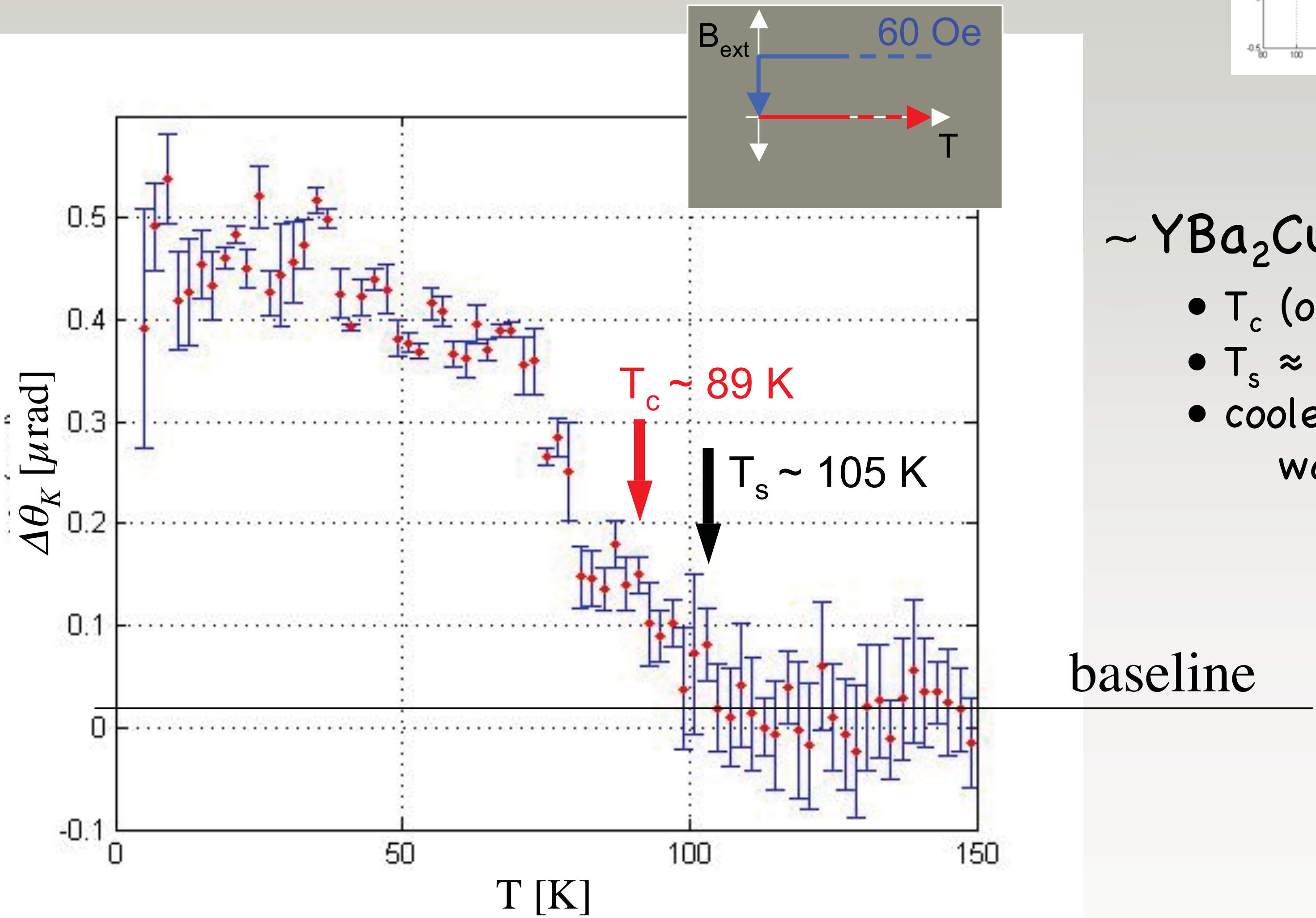
~ $YBa_2Cu_3O_{6.90}$

- T_c (onset) = 91 K
- T_s ≈ ?? K
- cooled in ZF,
  ZF warmup



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

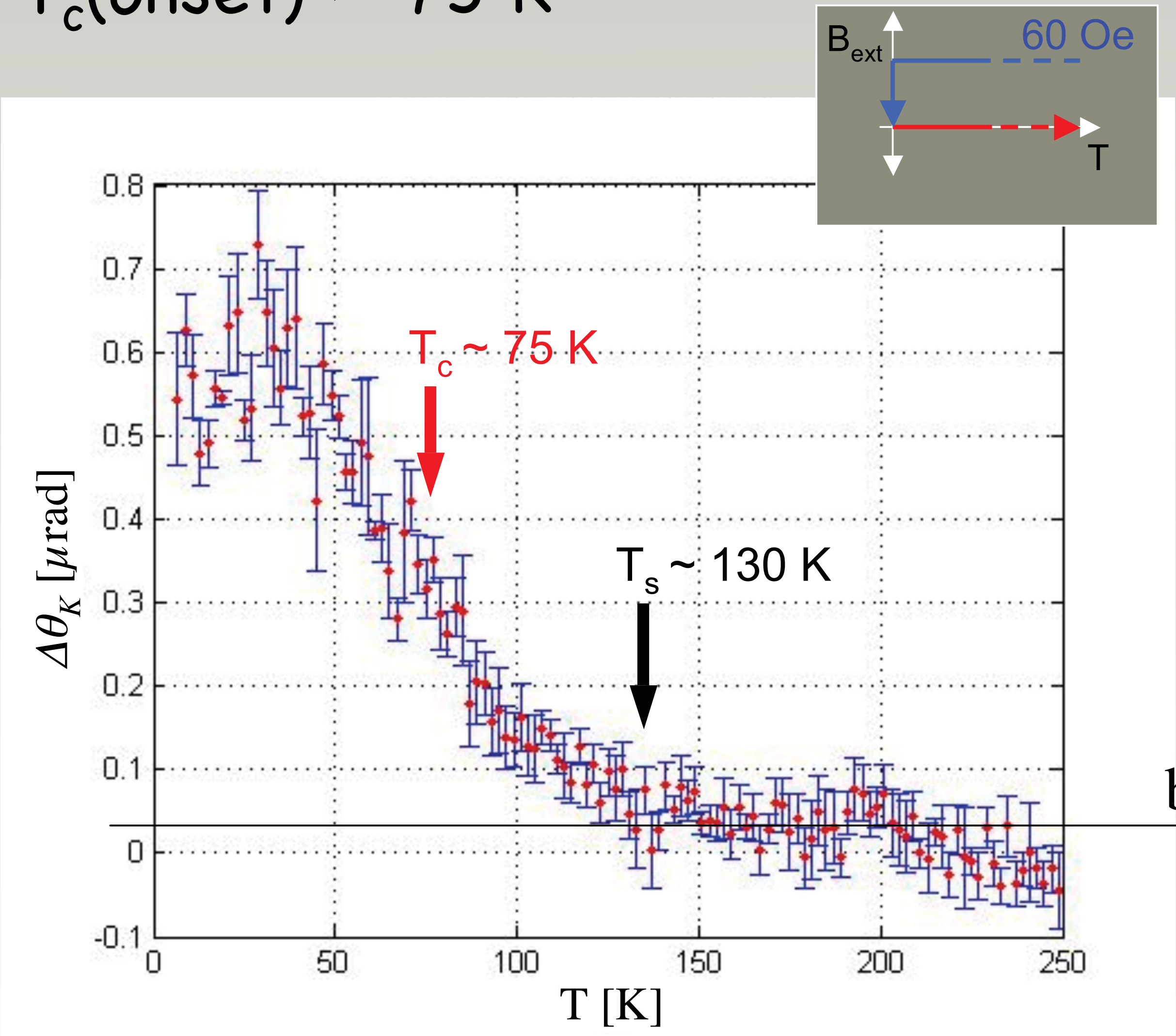


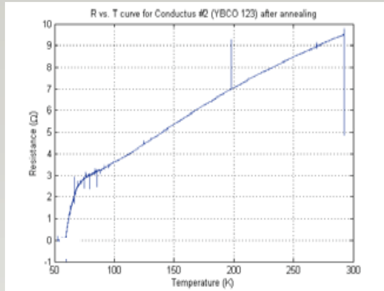


~ $YBa_2Cu_3O_{6.88}$

- T_c (onset) = 89 K
- T_s ≈ 105 K
- cooled in 60 Oe, ZF warmup

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

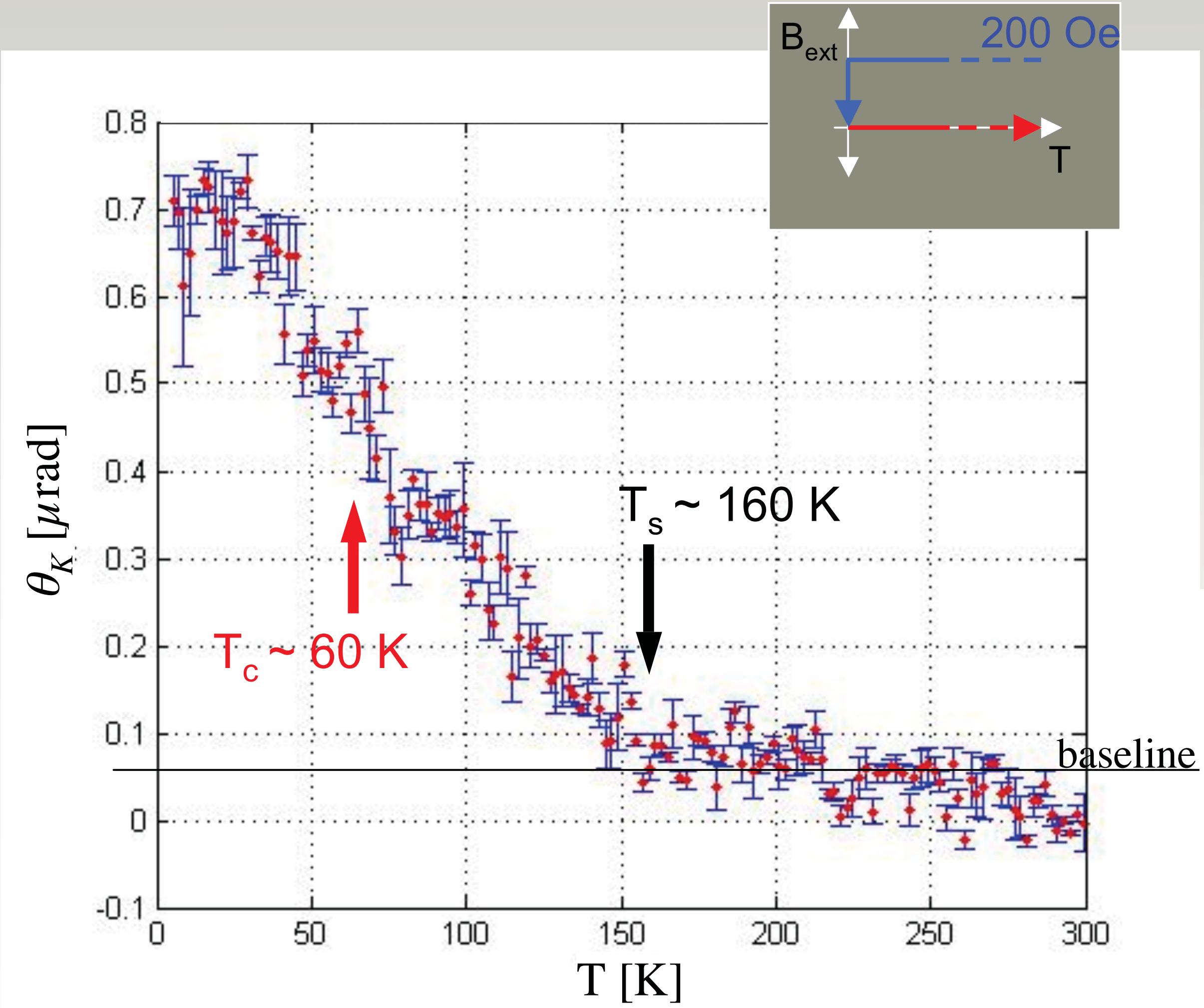


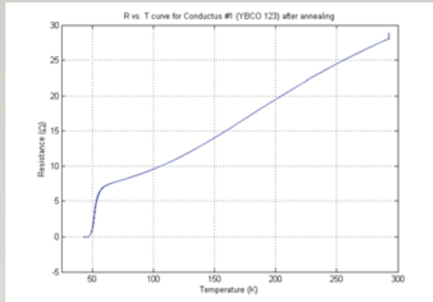


~ $YBa_2Cu_3O_{6.75}$

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

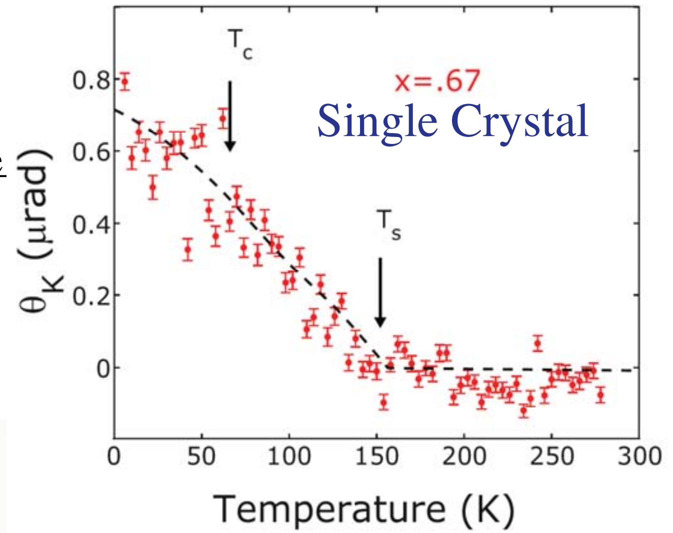
Results: films after annealing in reduced O_2
T_c(onset) ~ 60 K



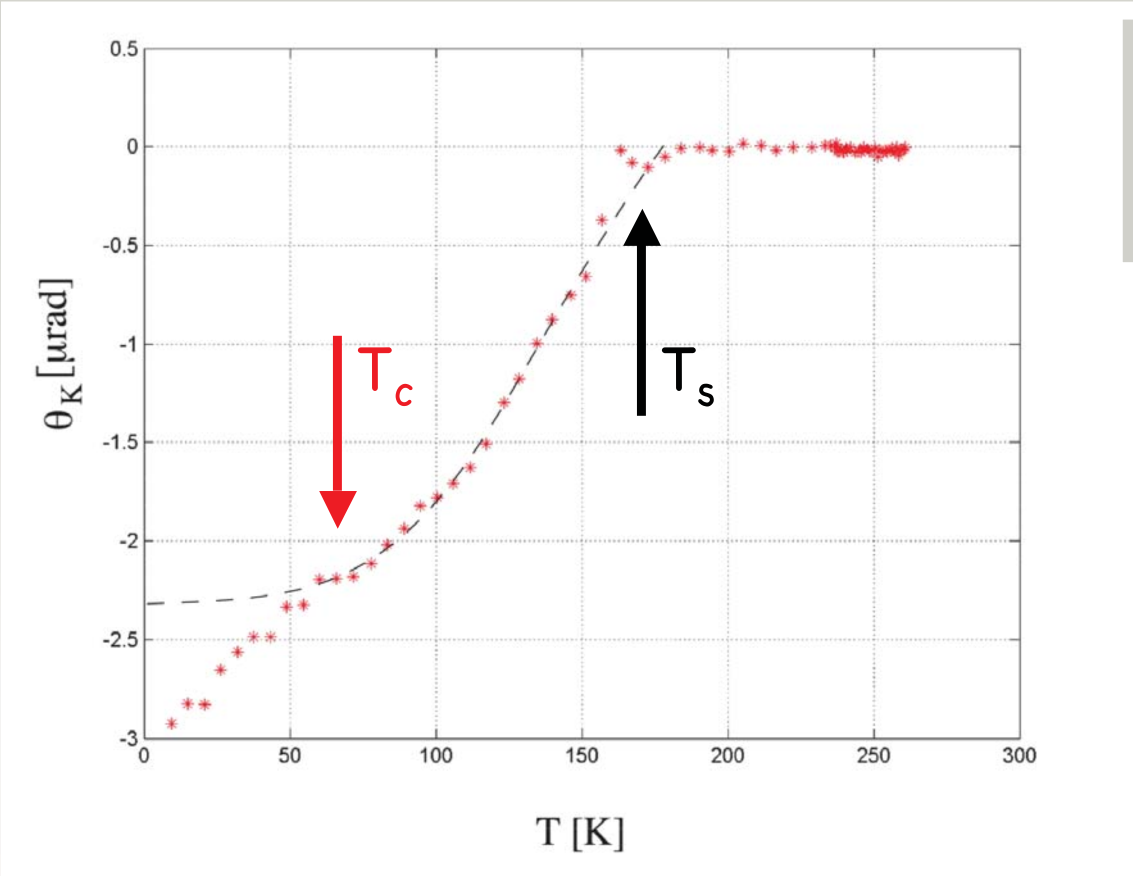


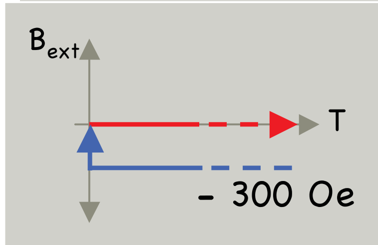
~ $YBa_2Cu_3O_{6.65}$

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



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



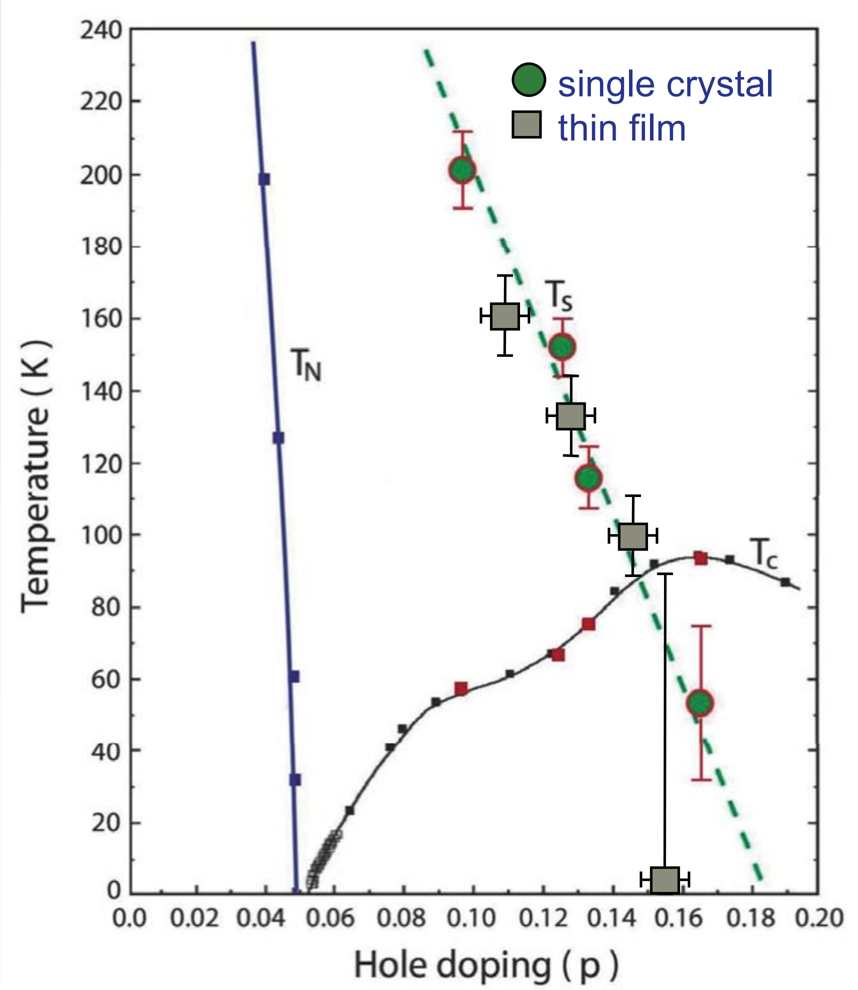


For same doping:

$$\theta_K(001)/\theta_K(110) \sim 0.3$$

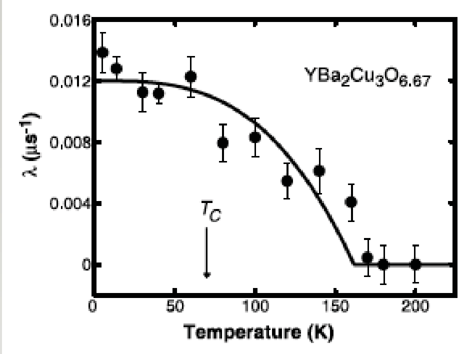
Summary

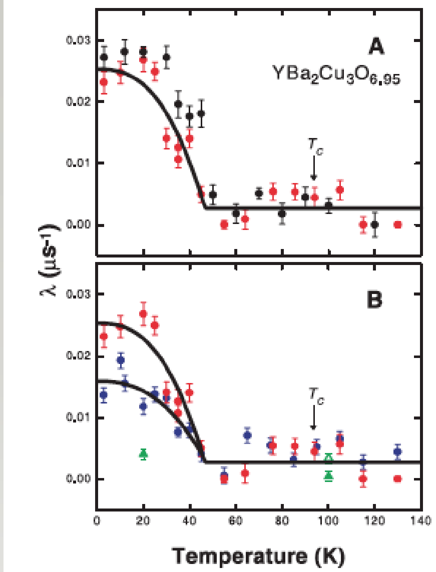
- Thin film samples of $YBa_2Cu_3O_{6+x}$ provide a natural point of comparison to highly ordered single crystals.
- Kerr rotation measurements on films show TRSB signals comparable in magnitude and onset temperature to single crystals with similar doping.
- Results suggest that the observed behavior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



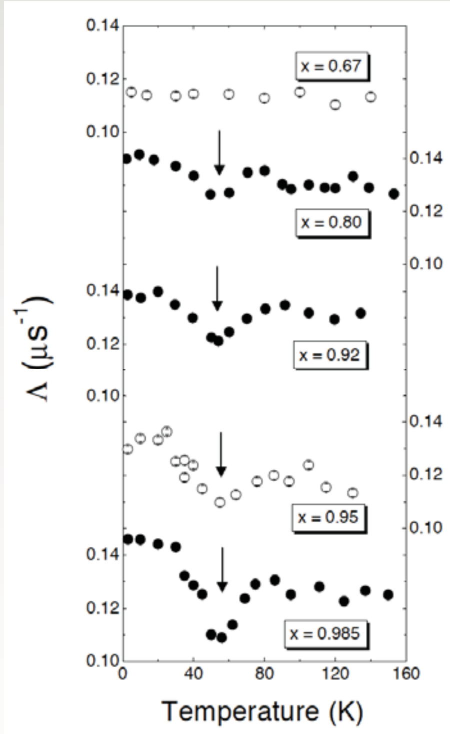
What about μ-SR

While the initial μ-SR indicated a possible TRSB phase transition at T^*:





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, Anomalous Weak Magnetism in Superconducting YBa2Cu3O6+x, Science 292, 1692 (2001)



Subsequent studies claimed that the observed signal is ALL due to charge ordering:

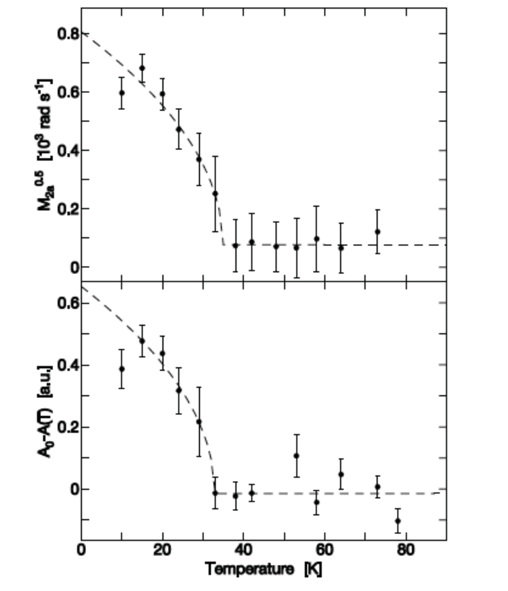
J.E. Sonier, J.H. Brewer, R.F. Kiefl, R.H. Heffner, K. Poon, S.L. Stubbs, G.D. Morris, R.I. Miller, W.N. Hardy, R. Liang, D.A. Bonn, J.S. Gardner, N.J. Curro, Correlations Between Charge Ordering and Local Magnetic Fields in Overdoped YBa2Cu3O6+x, PRB 66, 134501 (2002).

"A comparison to the results of NQR and lattice structure experiments on highly doped samples provides compelling evidence for strong coupling of charge, spin and structural inhomogeneities."

NQR data

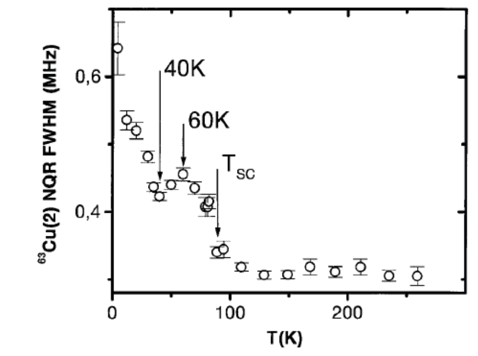
S. Kramer and M. Mehring, Low-Temperature Charge Ordering in the Superconducting State of YBa2Cu3O7-d, PRL 83, 396n(1999).

"In this Letter we present clear evidence for a transition into an ordered charge density wave state below Tc~35 K in highly doped YBCO7-d with a superconducting transition temperature Tsc ~90 K."



B. Grevin, Y. Berthier, and G. Collin, PRL 84, 1636 (2000).

"In this Comment, we show that the evolution of the charge ordering with temperature below Tsc, and even in the normal state, may be more subtle than a simple transition to a CDW below 35 K."

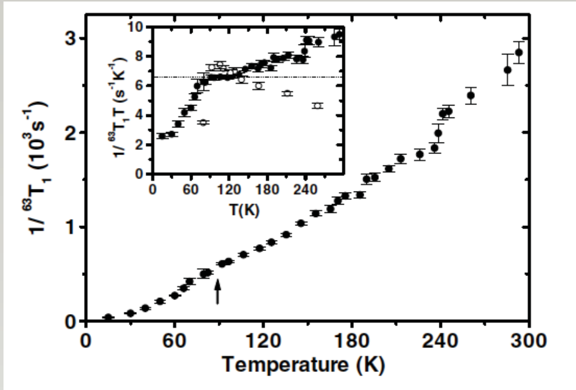


S. Kramer and M. Mehring, PRL 84, 1637 (2000).

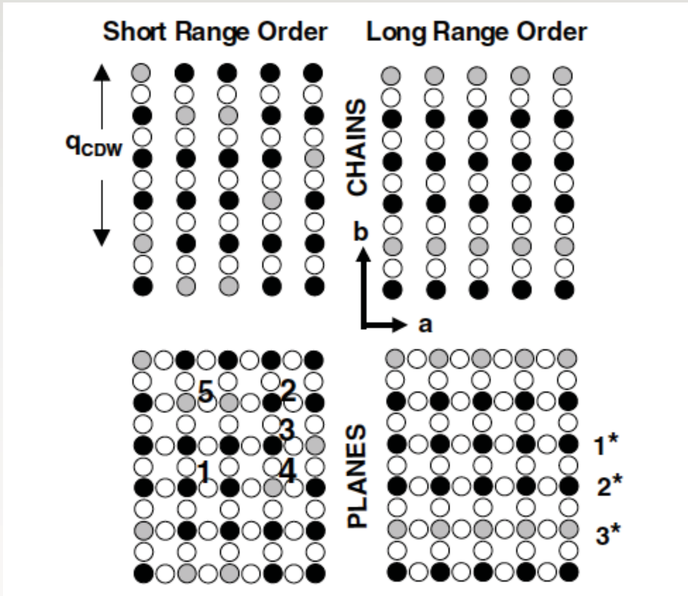
"There is, however, a difference in the samples used by Gre´vin et al. and ours. Their sample was overdoped, ours were slightly underdoped"

B. Gre´vin, Y. Berthier, and G. Collin, In-Plane Charge Modulation below Tc and Charge-Density-Wave Correlations in the Chain Layer in YBa2Cu3O7, PRL 85, 1310 (2000).

“In this Letter, we demonstrate the existence of CDW correlations in the chains of fully doped Y-123. We show ex- perimentally that this chain CDW state is closely related to the in-plane charge ordering below Tc.”



Model: CDW in the chains induce ordering in the planes

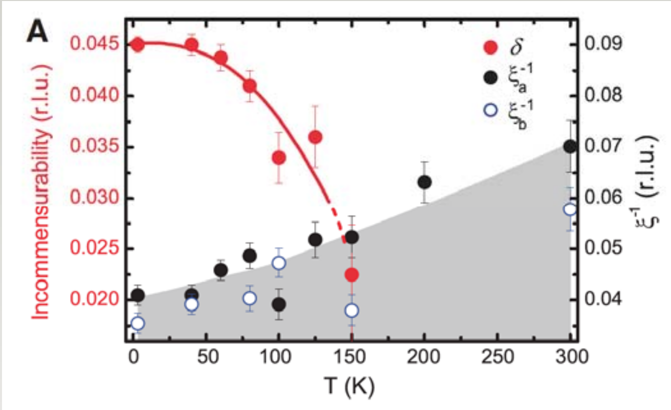


Conclusion:

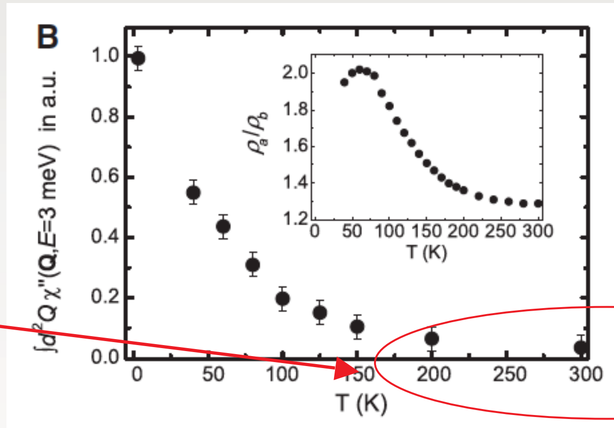
There is Charge ordering at 35 - 60 K for near optimally doped YBCO!

For very underdoped:

V. Hinkov, D. Haug, B. Fauqué, P. Bourges, Y. Sidis, A. Ivanov, C. Bernhard, C. T. Lin, B. Keimer, Electronic Liquid Crystal State in the High-Temperature Superconductor YBa2Cu3O6.45, Science 319, 597 (2008).



(A) Incommensurability δ (red symbols), half-width-at half-maximum of the incommensurate peaks along a* (black symbols) and along b* (open blue symbols) in reciprocal lattice units. The upper border of the shaded area follows The ξ^{-1} axis is scaled to twice the value of the d axis, hence δ-points lying inside the shaded area indicate an incommensurate peak separation below ξ_a^{-1}.



(B) Imaginary part of the Q-integrated spin susceptibility $\chi''(\omega)$ at 3 meV. The inset shows the ratio of the electrical resistivity along a* and b* of a sample with similar doping levels as ours, reproduced from (Ando).

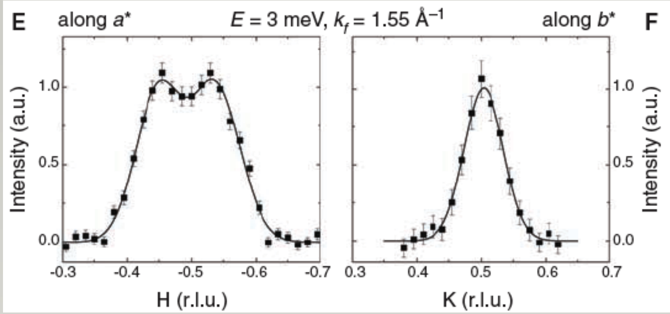
Conclusion:

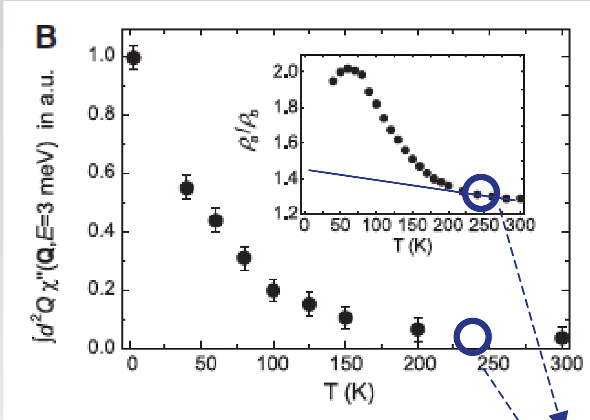
There is Charge ordering at ~*T** for very underdoped YBCO!

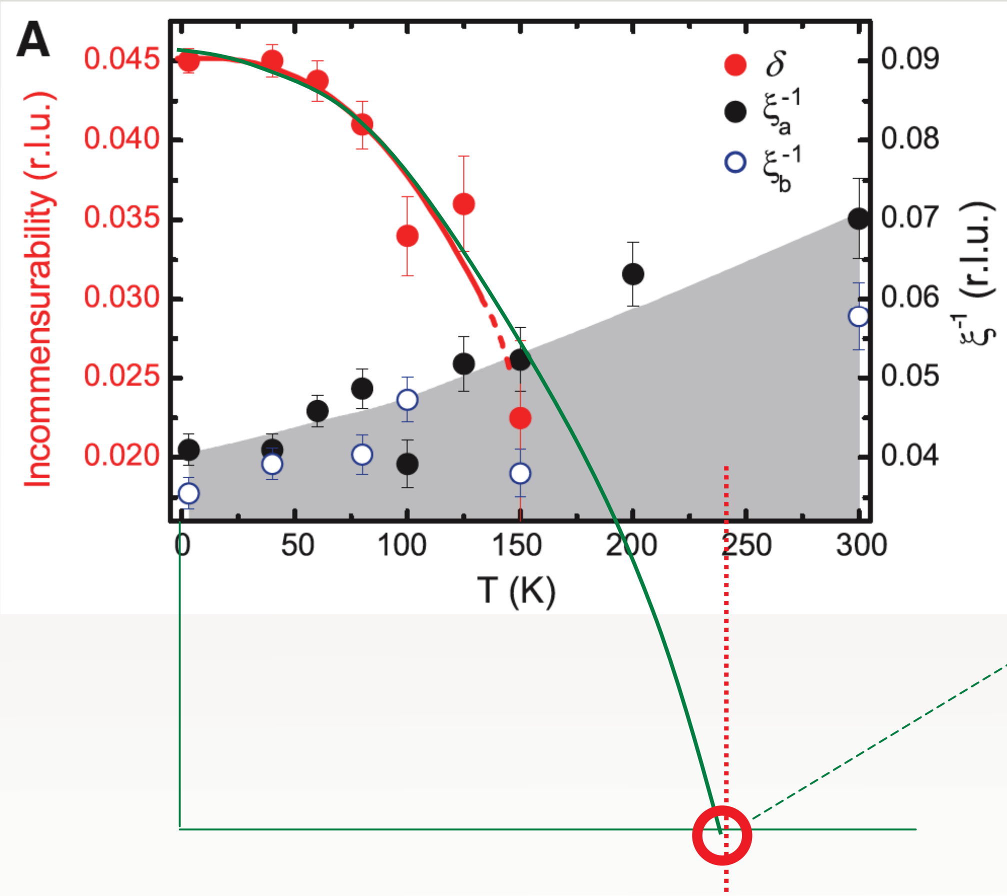
Electronic Liquid Crystal State in the High-Temperature Superconductor $YBa_2Cu_3O_{6.45}$

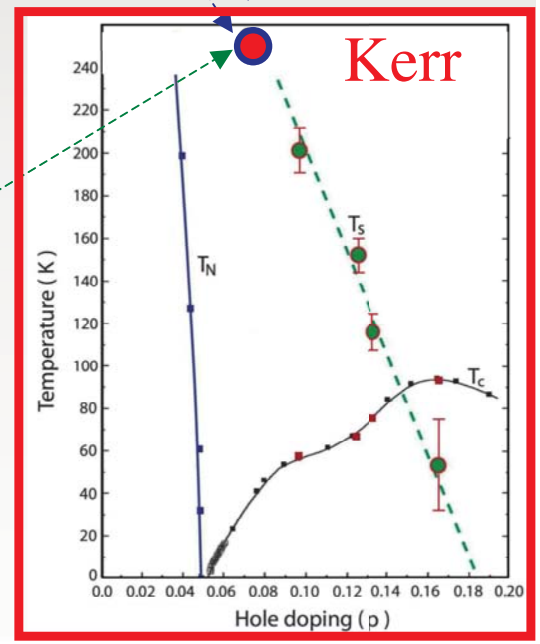
V. Hinkov,[1]* D. Haug,[1] B. Fauqué,[2] P. Bourges,[2] Y. Sidis,[2] A. Ivanov,[3] C. Bernhard,[4] C. T. Lin,[1] B. Keimer[1]

Science 319, 597 (2008)



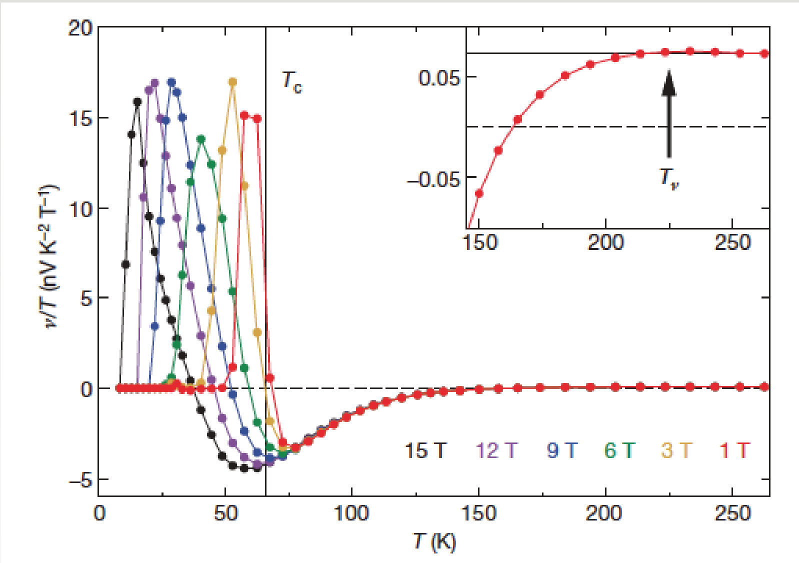


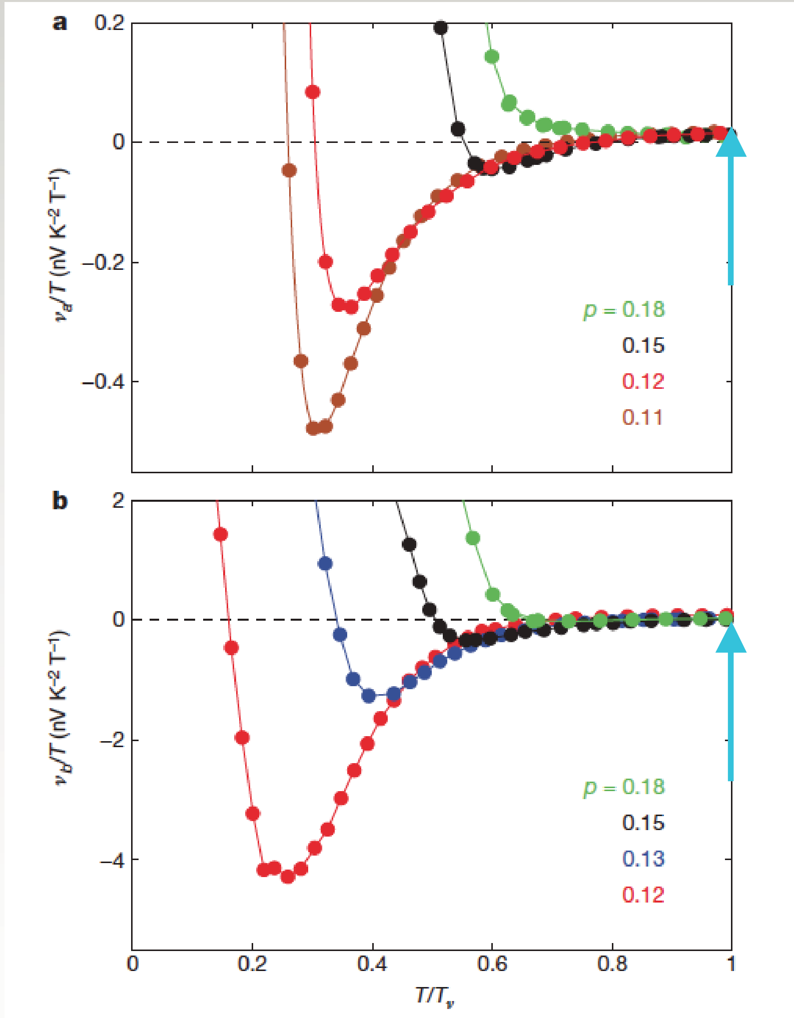


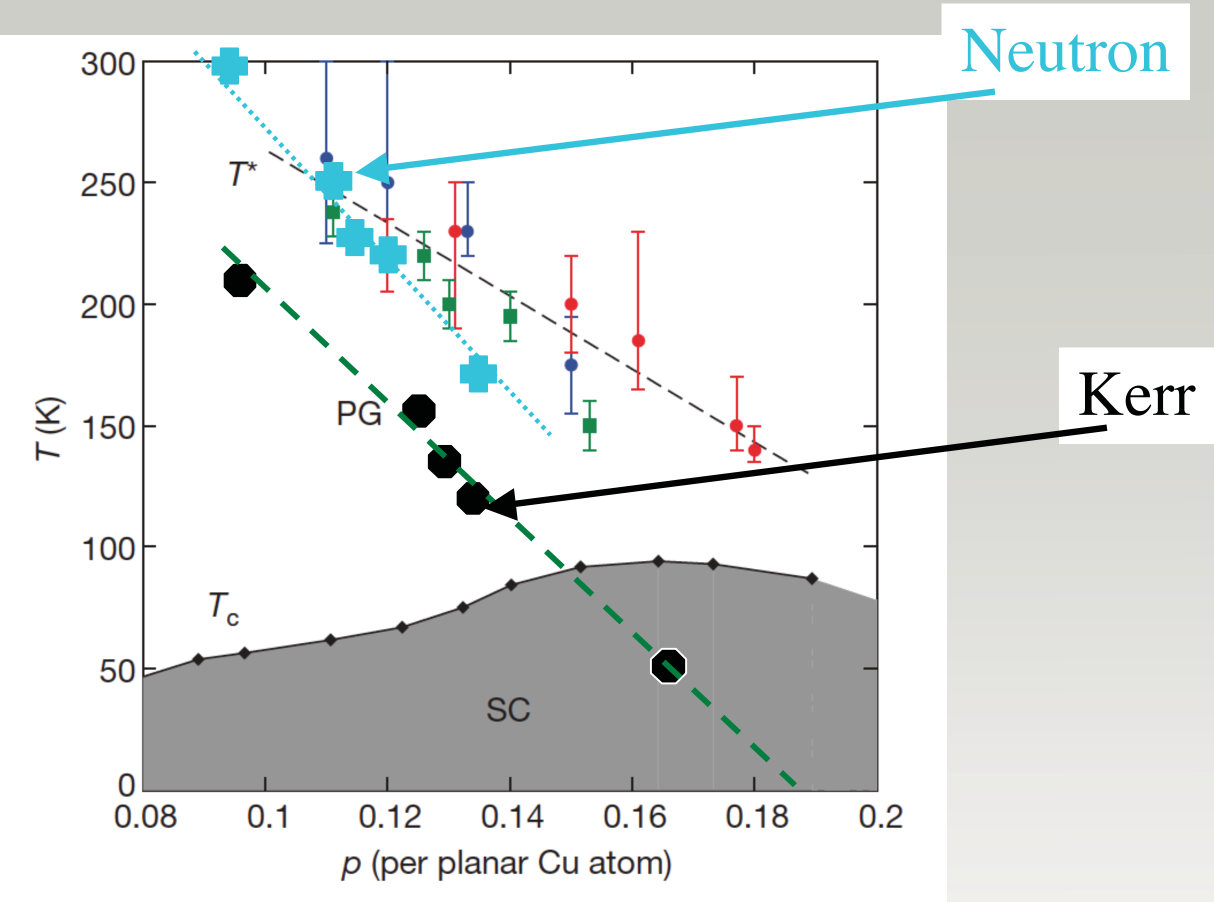


Recent Nernst measurements:

R. Daou, J. Chang1, David LeBoeuf, Olivier Cyr-Choiniere, Francis Laliberte, Nicolas Doiron-Leyraud, B. J. Ramshaw, Ruixing Liang, D. A. Bonn, W. N. Hardy, & Louis Taillefer, Broken rotational symmetry in the pseudogap phase of a high-Tc superconductor, Nature 463, 519 (2010).







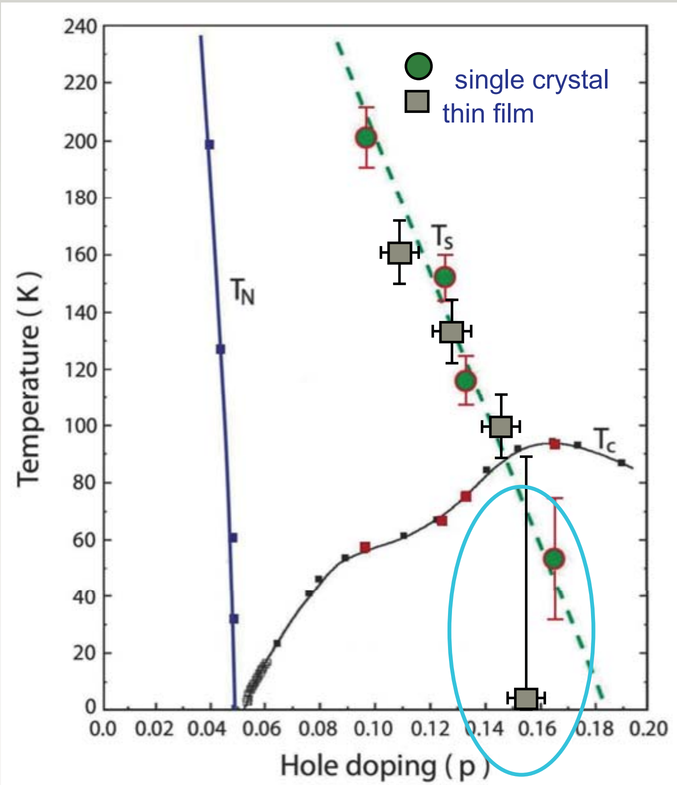
Nernst signal fits the magnetic signal from neutron

➔ Nernst measures time reversal symmetry breaking and NOT C4 to C2 transition!

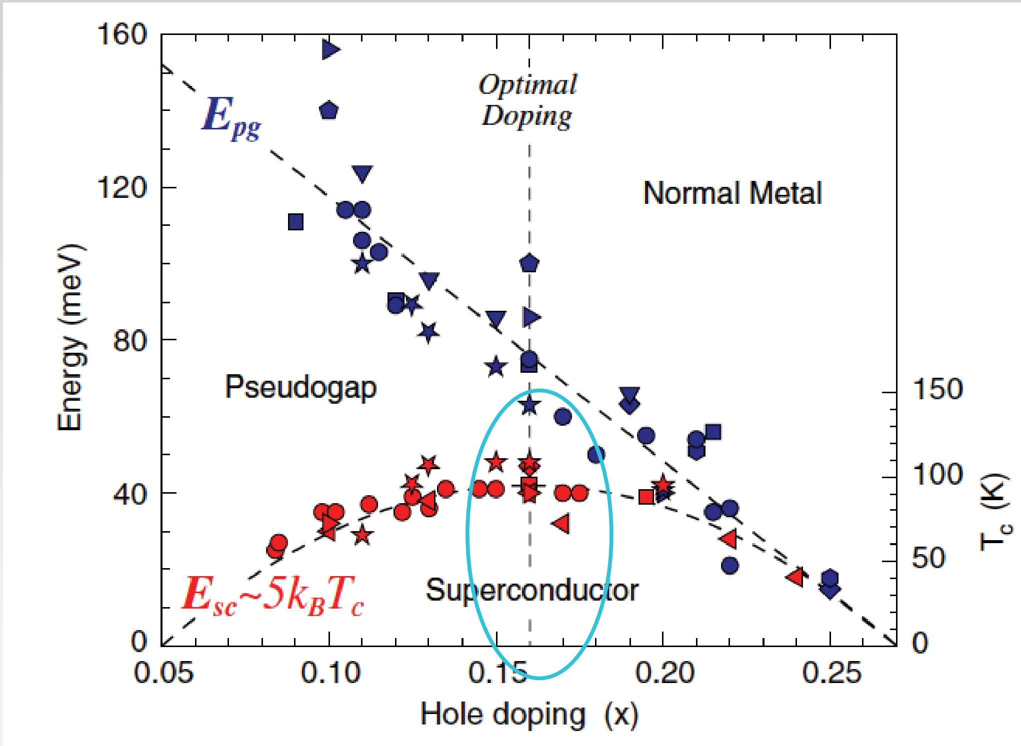
See: C. M. Varma, Victor M. Yakovenko, A. Kapitulnik, Violation of Onsager Reciprocity in Underdoped Cuprates ?, arXiv:1007.1215 (submitted).

Note:

$YBa_2Cu_3O_{6+x}$



$Bi_2Sr_2CaCu_2O_{8+d}$



Optimally doped: T* < Tc

Optimally doped: T* > Tc

Indeed, Charge order (stripes) found in the superconducting state persist to the pseudogap state and disappear at ~ T*

Beyond YBCO

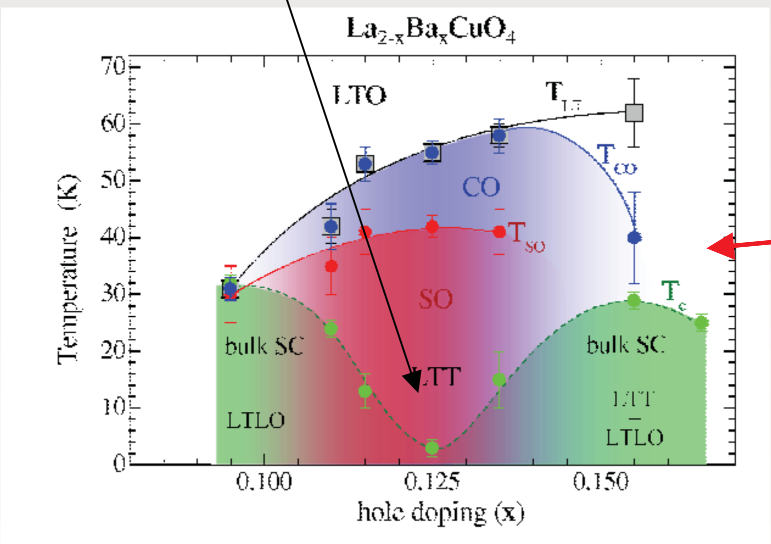
H. Karapetyan, E. Schemm, V. Nathan, J. Xia, S. Kivelson, and A. Kapitulnik (unpublished)

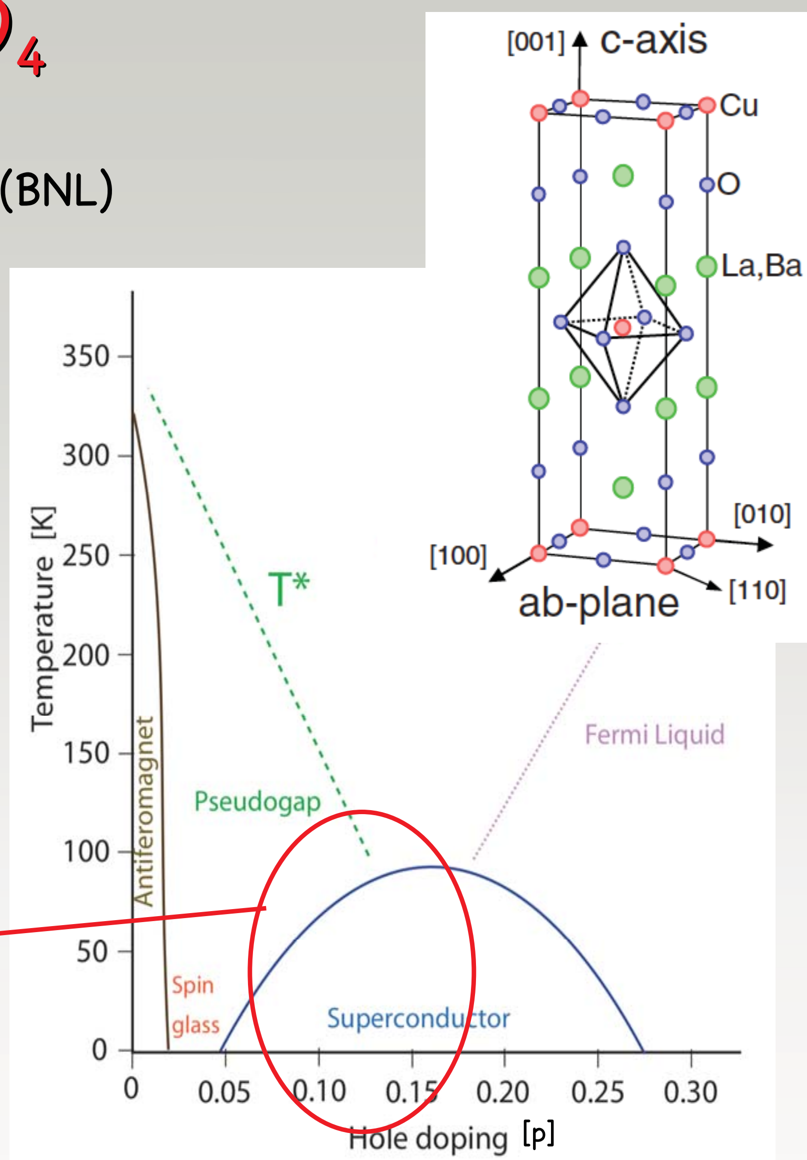
Samples of $La_{2-x}Ba_xCuO_4$

Single crystals:

Marcus Hucker, Genda Gu, John Tranquada (BNL)

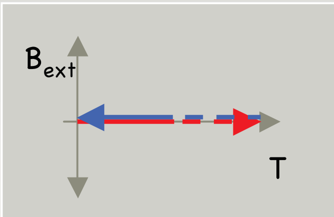
X=0.125

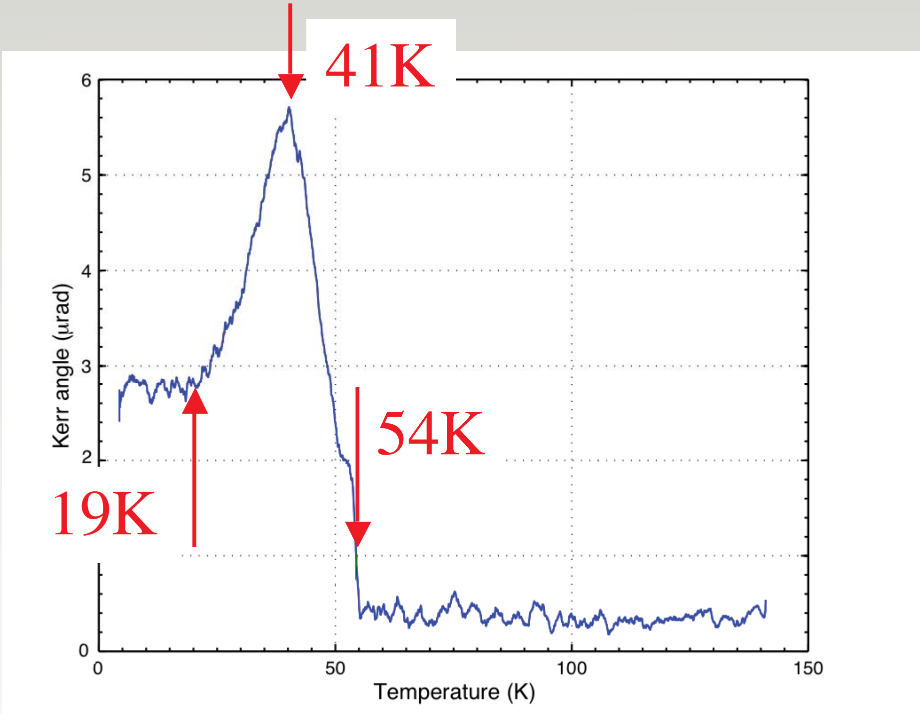


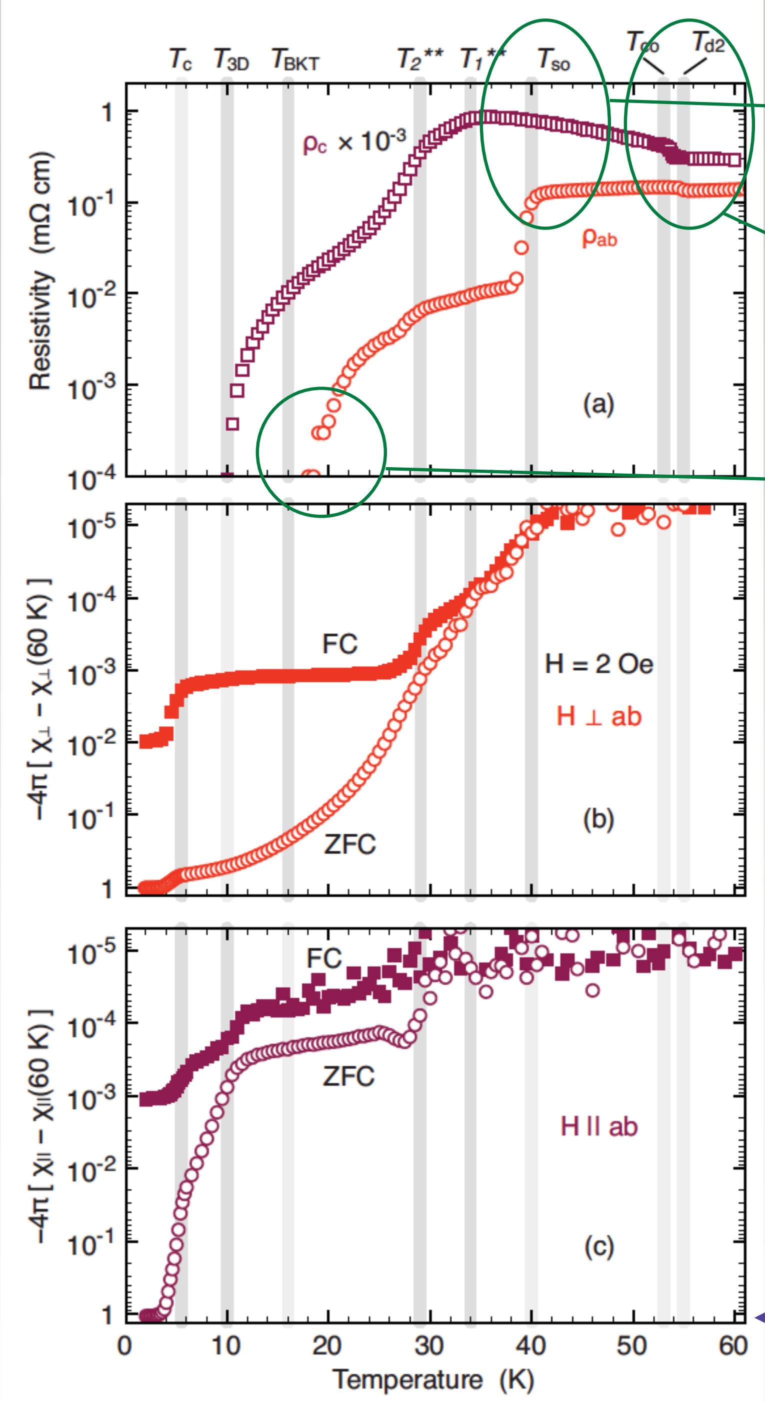


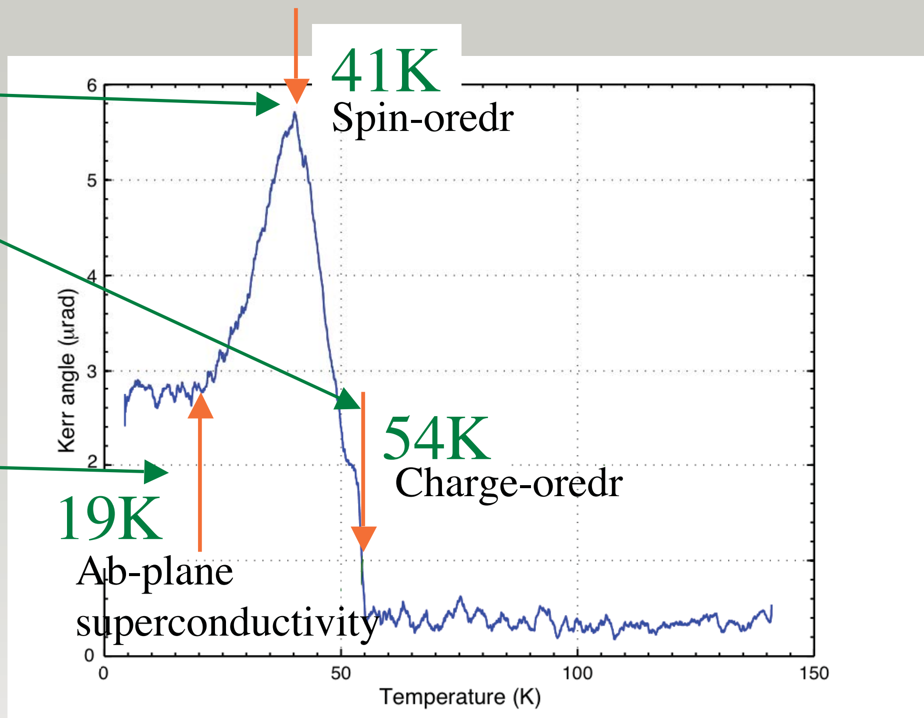
$La_{1.875}Ba_{0.125}CuO_4$

Zero-field cool Kerr measurement







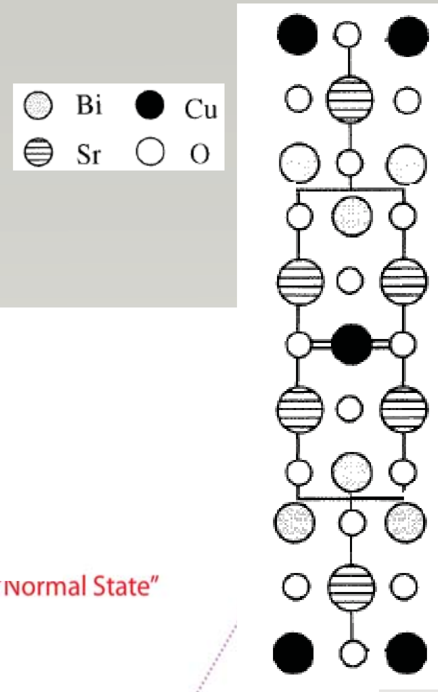


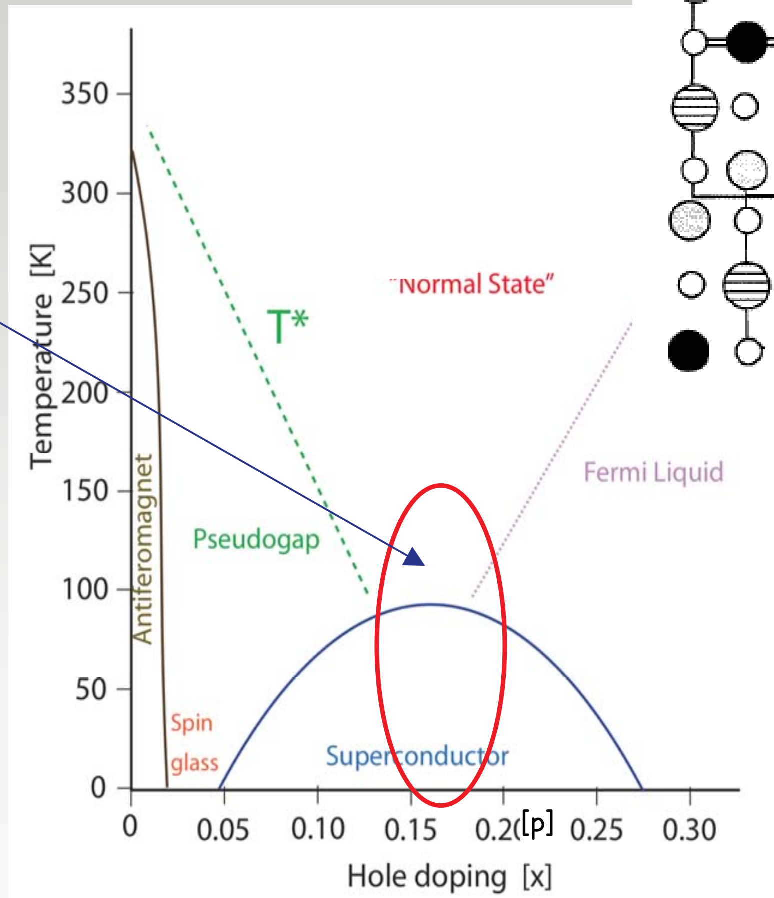
J. M. Tranquada, G. D. Gu, M. Hucker, Q. Jie, H.-J. Kang, R. Klingeler, Q. Li, N. Tristan, J. S. Wen, G. Y. Xu, Z. J. Xu, J. Zhou, and M. v. Zimmermann, Evidence for unusual superconducting correlations coexisting with stripe order in La1.875Ba0.125CuO4, PRB 78, 174529 2008

Pb-Bi2201

Single crystals (Hiroshi Eisaki, Tsukuba, japan)

$Pb_{0.55}Bi_{1.5}Sr_{1.6}La_{0.4}CuO_{6+\delta}$

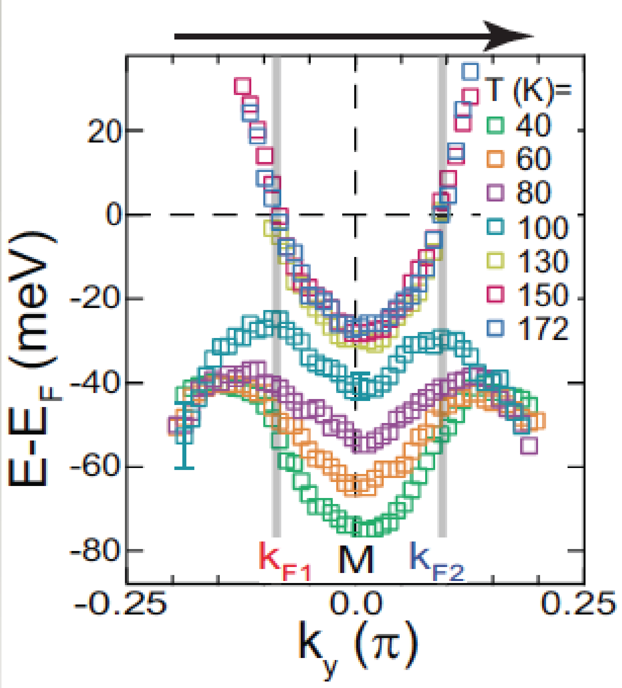




$Pb-Bi_2Sr_2CuO_6$

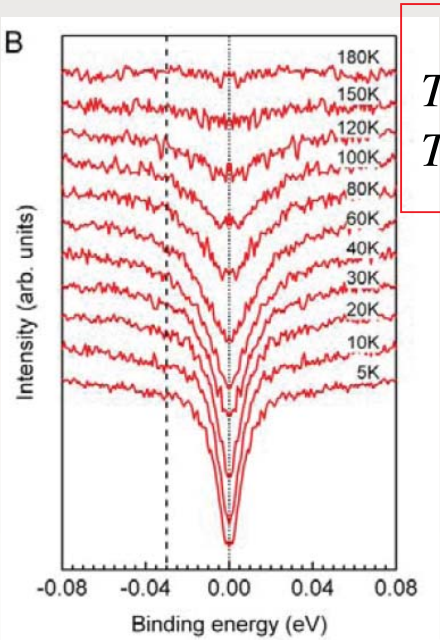
Makoto Hashimoto, Rui-Hua He, Kiyohisa Tanaka, Jean-Pierre Testaud, Worawat Meevasana, Rob G. Moore, Donghui Lu, Hong Yao, Yoshiyuki Yoshida, Hiroshi Eisaki, Thomas P. Devereaux, Zahid Hussain and Zhi-Xun Shen, Particle–hole symmetry breaking in the pseudogap state of Bi2201, Nature Physics 6, 417 (2010).

T_c = 34 K,
T^* = 125 - 140 K



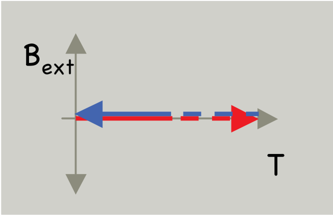
J.-H. Ma,Z.-H. Pan,F. C. Niestemski, M. Neupane, Y.-M. Xu, P. Richard, K. Nakayama, T. Sato, T. Takahashi, H.-Q. Luo, L. Fang, H.-H. Wen, Ziqiang Wang, H. Ding and V. Madhavan, Coexistence of competing orders with two energy gaps in real and momentum space in high-Tc superconductor Bi2Sr2-xLaxCuO6+d, PRL 101, 207002 (2008).

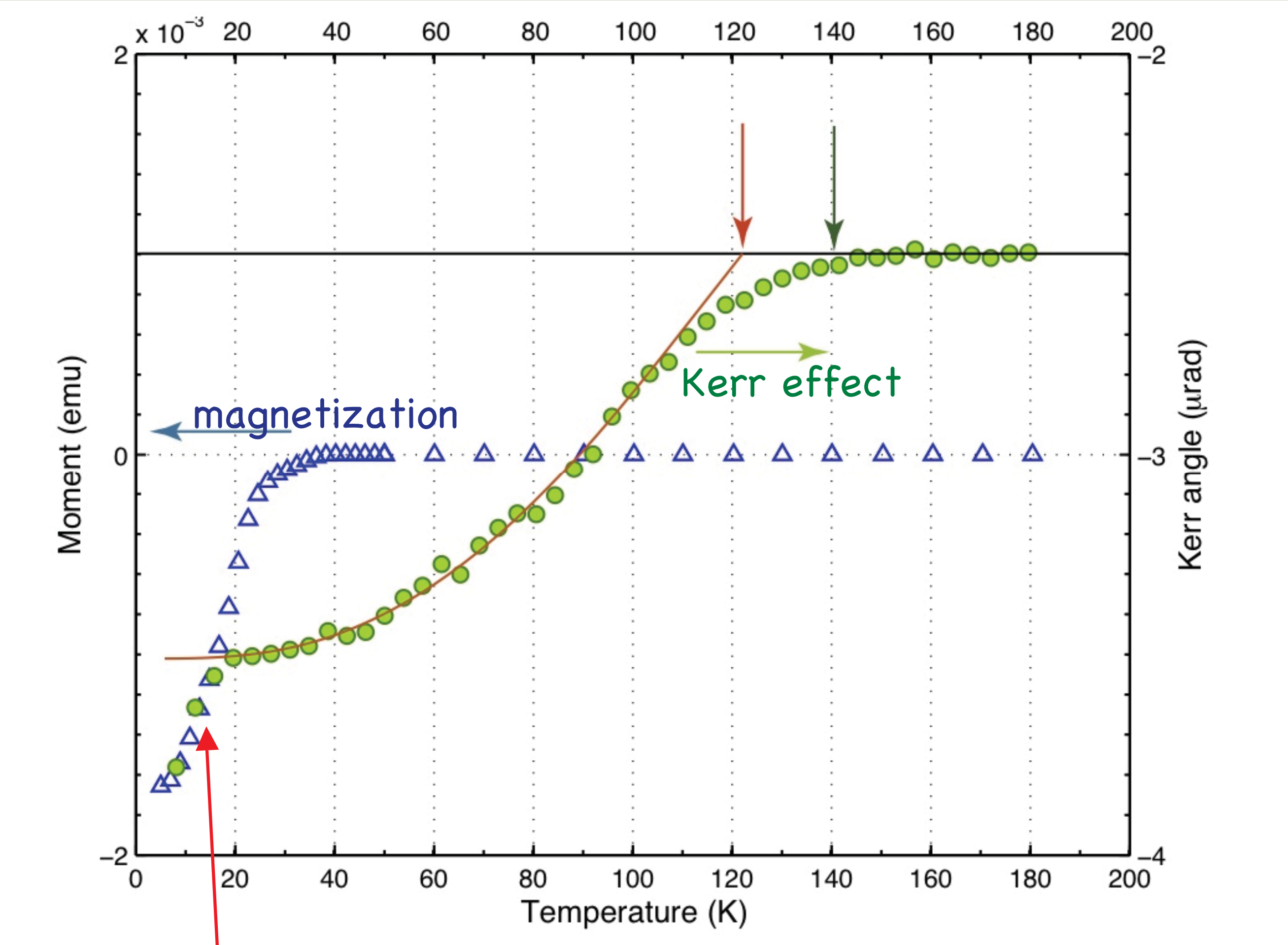
"Through a combined study of scanning tunneling microscopy and angle-resolved photoemission spectroscopy, we report the observation of two distinct gaps (a small-gap and a large-gap) that coexist both in real space and in the anti-nodal region of momentum space in the superconducting phase of Bi2Sr2-xLaxCuO6+δ. We show that the small-gap is associated with superconductivity. The large-gap persists to temperatures above the transition temperature Tc and is found to be linked to short-range charge ordering."



T_c = 32 K,
T^* = 125 - 140 K

Zero-field cool Kerr measurement (Warmed in ~5 Oe)



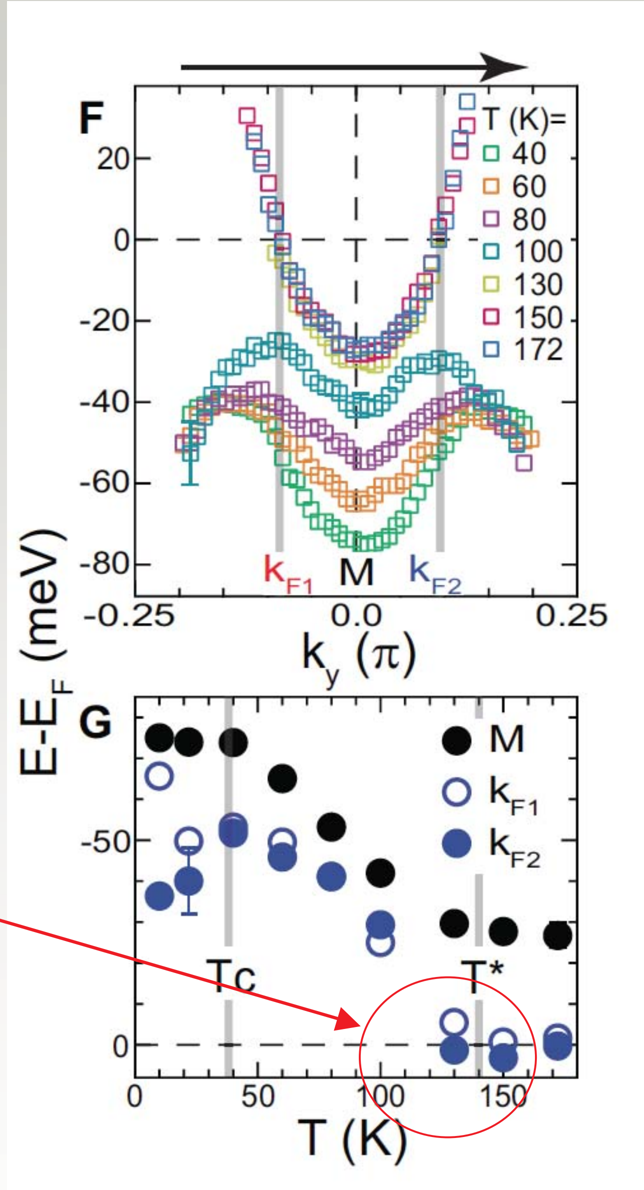


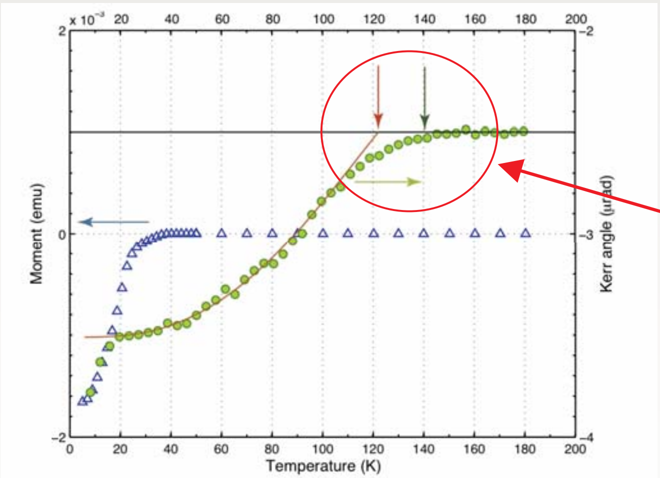
Superconducting response

New (unpublished) photoemission measurements:

R.-H. He,M. Hashimoto, J. P. Testaud, H. Yao, K. Tanaka, H. Eisaki,5 W. Meevasana, R. G. Moore, D. H. Lu, Y. Yoshida, M. Ishikado, T. P. Devereaux, S. A. Kivelson, Z. Hussain, Z.-X. Shen, From a single-band metal to a complex superconductor with multiple eigenstates in Bi2201, to be published.

Temperature evolution of the antinodal states above *Tc* through *T**





Simulations of a model that relies on charge ordering below T*:

R.-H. He,M. Hashimoto, J. P. Testaud, H. Yao, K. Tanaka, H. Eisaki,5 W. Meevasana, R. G. Moore, D. H. Lu, Y. Yoshida, M. Ishikado, T. P. Devereaux, S. A. Kivelson, Z. Hussain, Z.-X. Shen, From a single-band metal to a complex superconductor with multiple eigenstates in Bi2201, to be published.

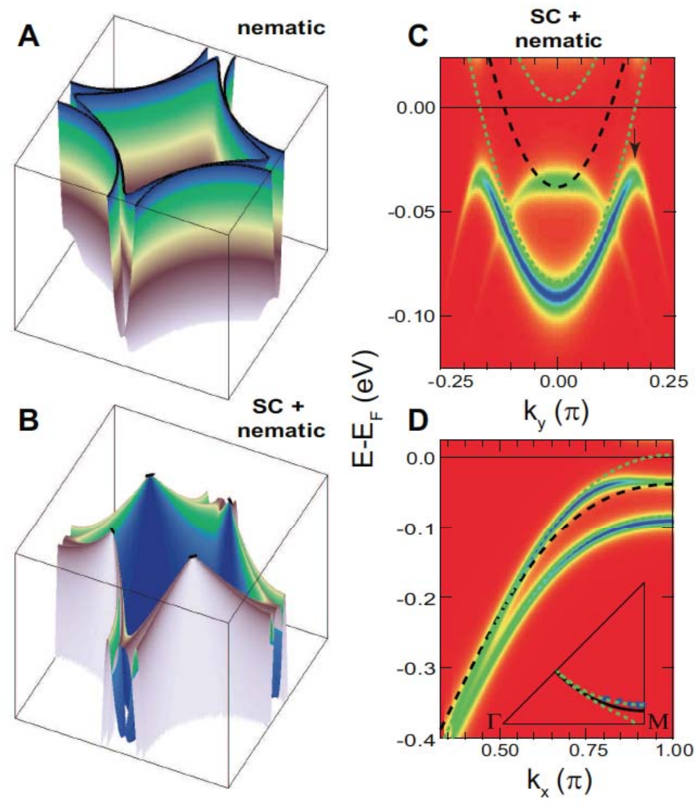
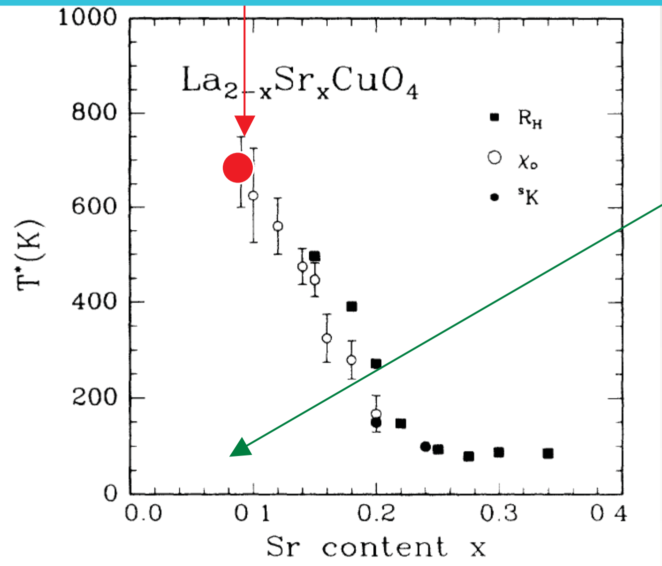


Figure S 6: **Simulations for the superconductivity-nematic-order coexistence. A (B)**, Cartoon for the band structure in the nematic phase without (with) coexisting *d*-wave superconductivity ($\Delta = 35$ meV). Two sets of bands from orthogonal domains are superimposed. **C (D)**, Renormalized band dispersions perpendicular to (along) Γ-M in the coexisting state. Black (green) dashed curves are the bare (distorted) band dispersions. Renormalized band dispersions are moderately broadened for visualization purpose. Back-bending is pointed out by arrow. Insets: k_G from the experiment that falls on the distorted Fermi surface in green. Color scale is proportional to the intrinsic spectral weight in **B**-**C**.

$La_{2-x}Sr_xCuO_4$

V. Balédent, B. Fauqué, Y. Sidis, N.B. Christensen, S. Pailhès, K. Conder, E. Pomjakushina, J. Mesot, P. Bourges, 2D orbital-like magnetic order in La2-xSrxCuO4, PRL 105, 027004 (2010)

We here report the observation below 120 K of a similar magnetic ordering in the archetypal cuprate La2−xSrxCuO4 (LSCO) system for x=0.085. In contrast to the previous reports, the magnetic ordering in LSCO is only short range with an in-plane correlation length of 10Å and is bidimensional (2D). Such a less pronounced order suggests an interaction with other electronic instabilities. In particular, LSCO also exhibits a strong tendency towards stripes ordering at the expense of the superconducting state.



?

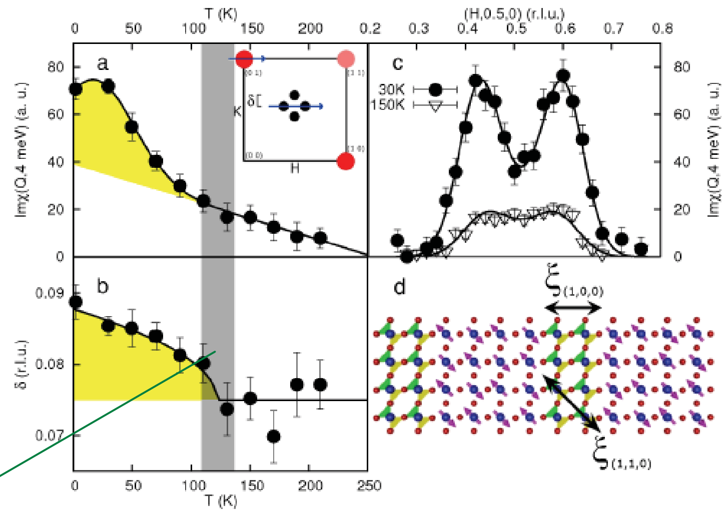


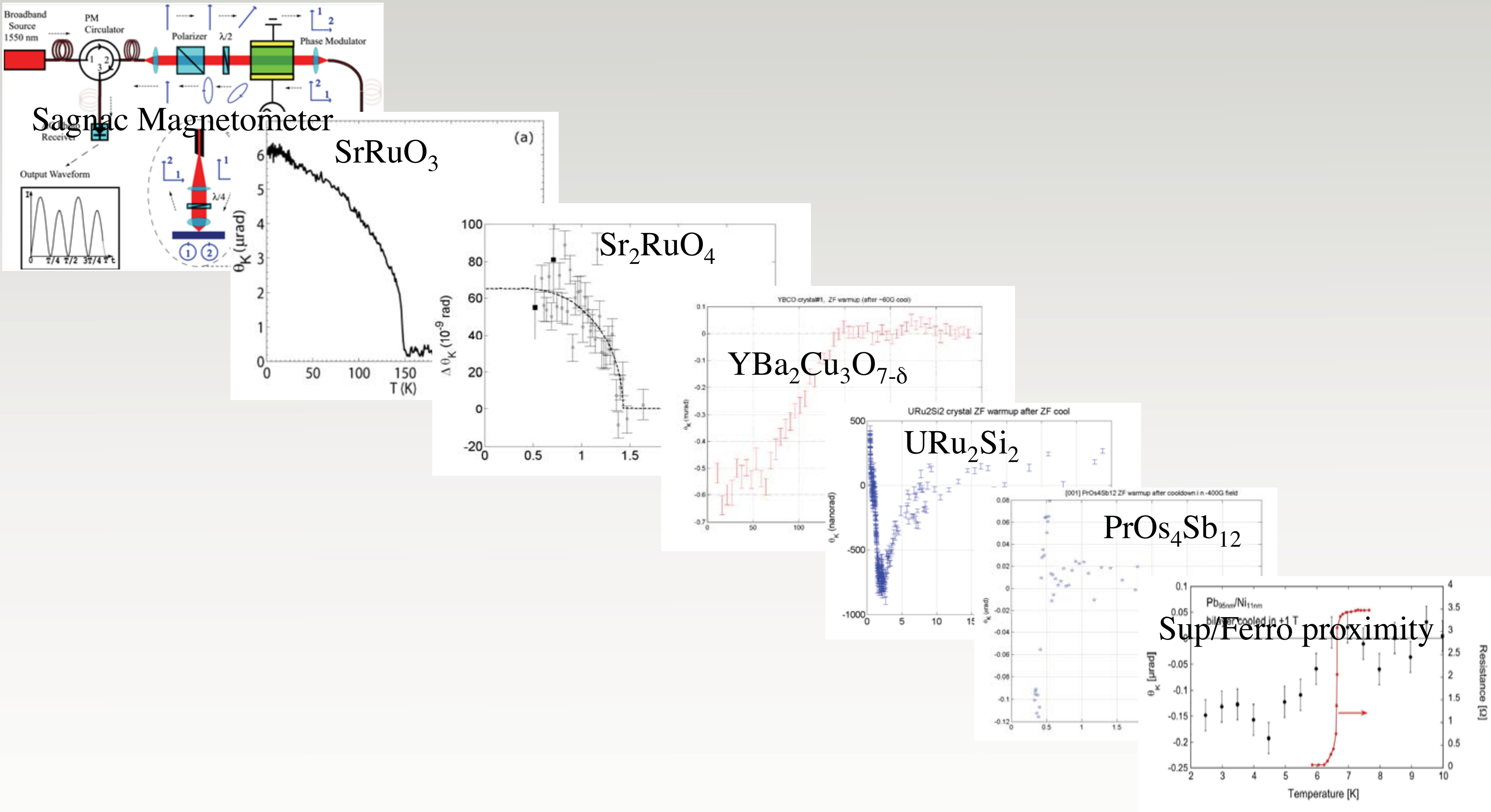
FIG. 4: Unpolarized inelastic neutron scattering measurements of the IC magnetic fluctuations around $Q_{IC} = Q_{AF} \pm (\delta, 0)$: a) Temperature dependence of the spin susceptibility at an energy of 4 meV: $Im\chi(Q_{IC}, \hbar\omega = 4\text{meV})$. The inset represents the location of the different magnetic response in the a-b plane: **Q**=0 AFO and IC spin fluctuations are shown in red and black, respectively. b) Temperature dependence of the IC parameter δ. In a) and b), the vertical dashed line indicates $\sim T_{mag}$. c) Typical H-scans across IC spin excitations at $\hbar\omega$=4 meV. The figure shows the imaginary part of the dynamical magnetic susceptibility $Im\chi(Q, \hbar\omega)$ at 30 K (full circles) and at 150 K (open triangles). d) Schematic picture of the CuO_2 plane for a hole doping of 1/12 based on the bond centered stripes model discussed in ref. [12].

Summary

- Kerr effect seems to measure charge ordering indirectly!
- Charge ordering is a pronounced effect in all high Tc superconductors.
- Charge (followed by spin) ordering is the last effect before superconductivity.
- There are several magnetic effects, some may occur through phase transitions above Tc.

➔Study the general problem of charge order coupled to other order parameters!

Thank you!


Sagnac Magnetometer
SrRuO3
Sr2RuO4
YBa2Cu3O7-δ
URu2Si2
PrOs4Sb12
Sup/Ferro proximity