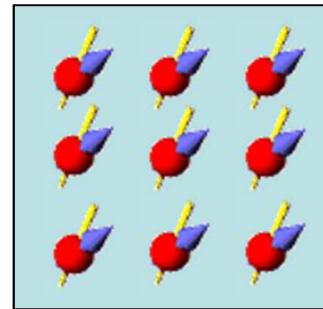


Hydrostatic Pressure and Oxygen Isotope Effects on the Static Stripe Order in $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$

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Outline

- **Introduction to the stripe order**
 - **Basic principles of the μ SR technique (pressure)**
 - **Stripe order and superconductivity in $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$ ($x = 1/8$) under hydrostatic pressure**
 - **Oxygen Isotope Effects (OIE's) on the static spin-stripe order**
 - **OIE's on the structural properties in the stripe phase**
 - **Conclusions**
-



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Zurich^{UZH}

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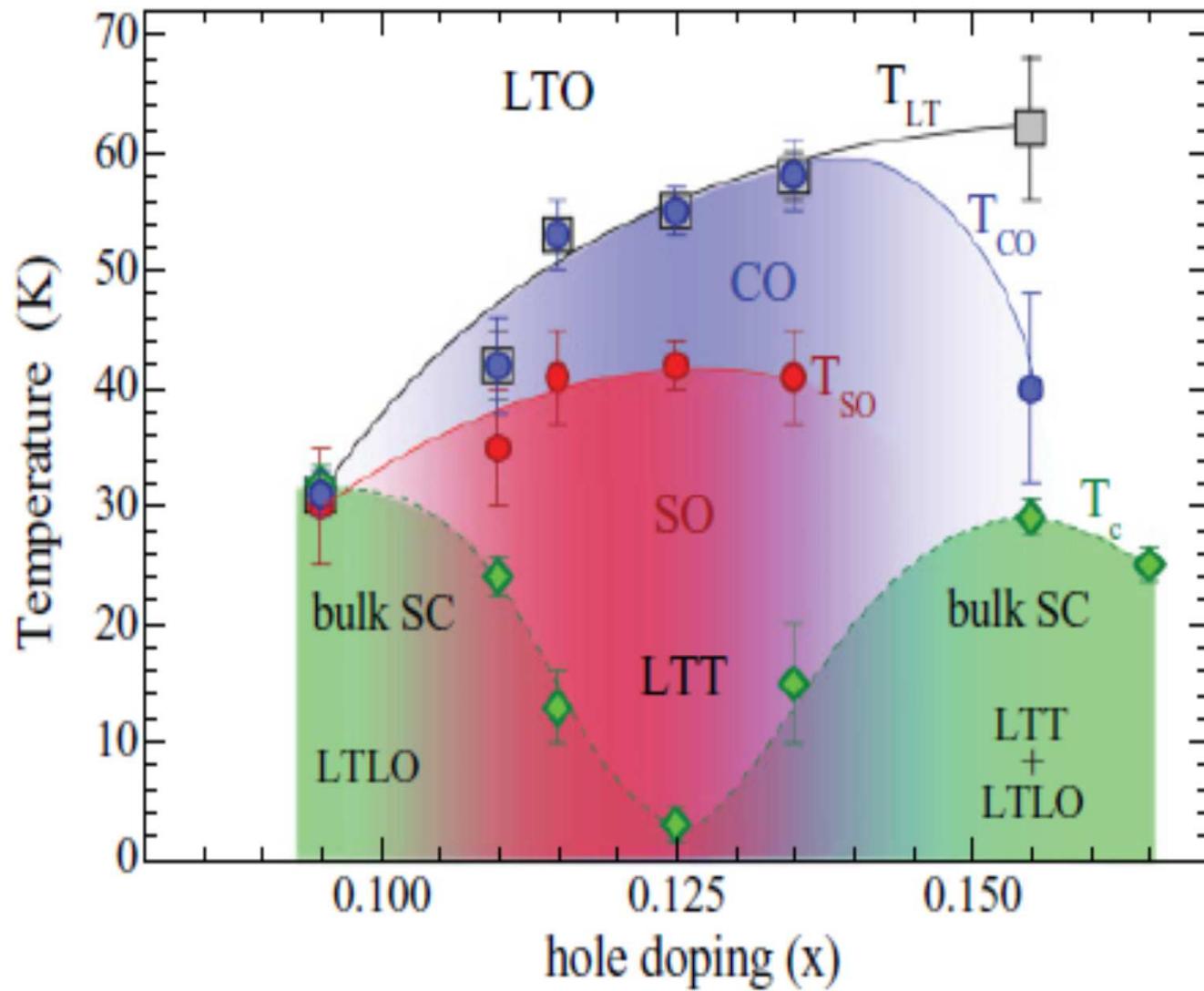
Denis Sheptyakov



Tbilisi State University

Alexander Shengelaya

Superconductivity in $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$

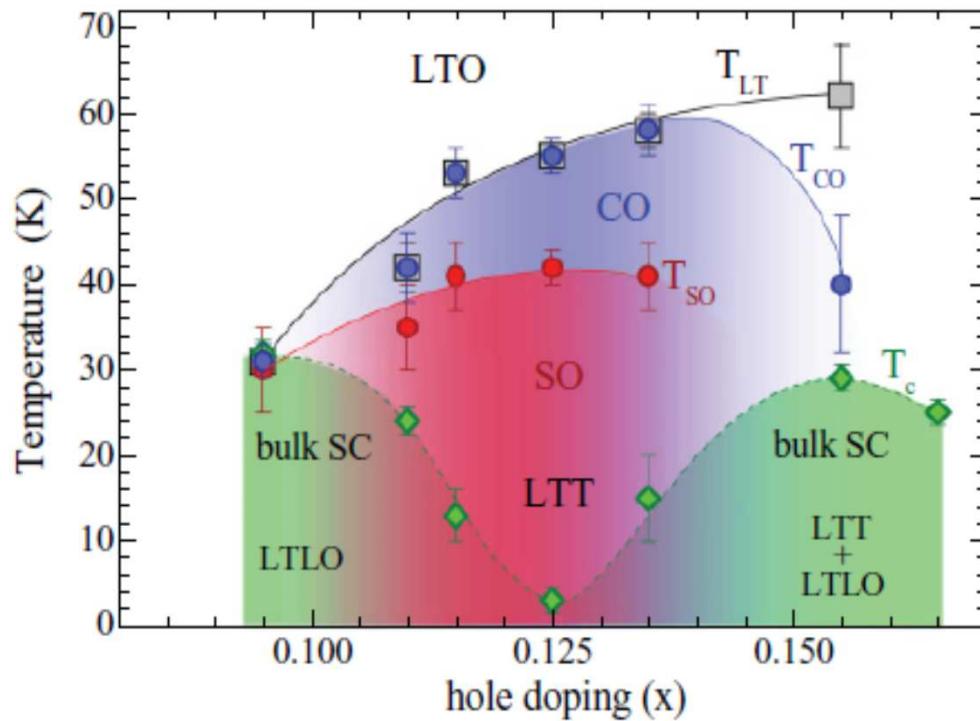


Moodenbaugh *et al*, Phys. Rev. B **38**, 4596 (1988).

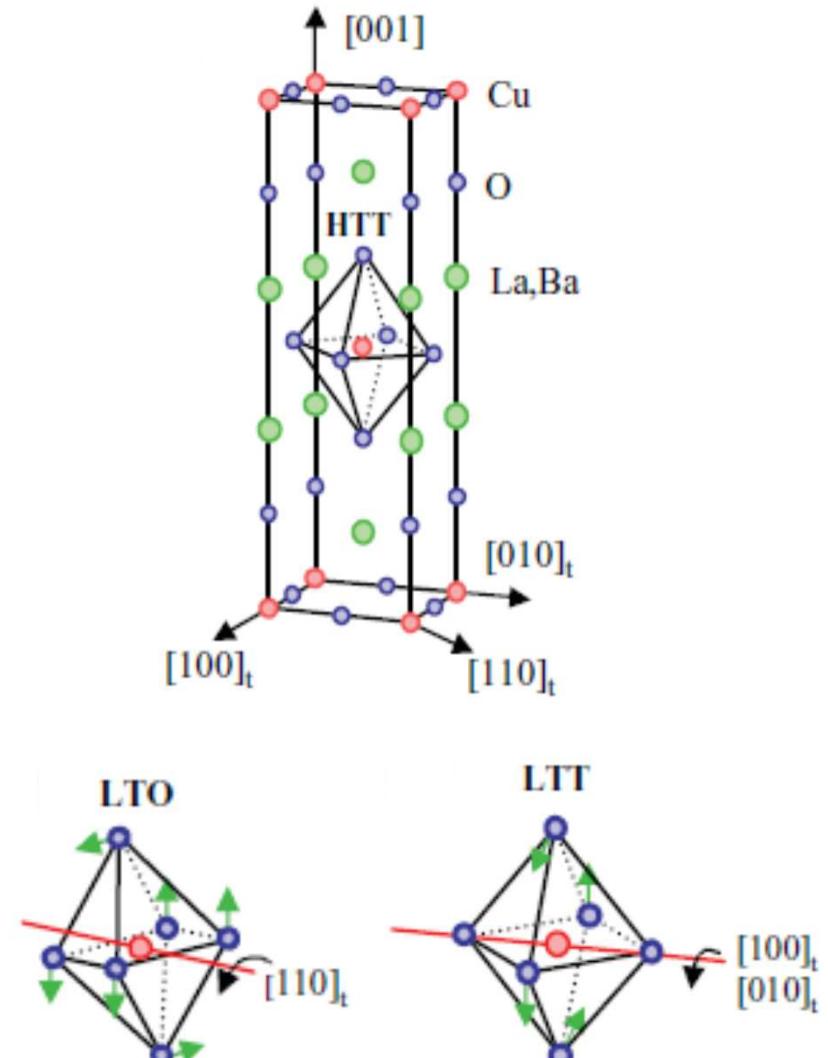
Axe *et al*, Phys. Rev. Lett. **62**, 2751 (1989).

Hücker *et al*, Phys. Rev. B **83**, 104506 (2011).

Structural phase transitions in $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$

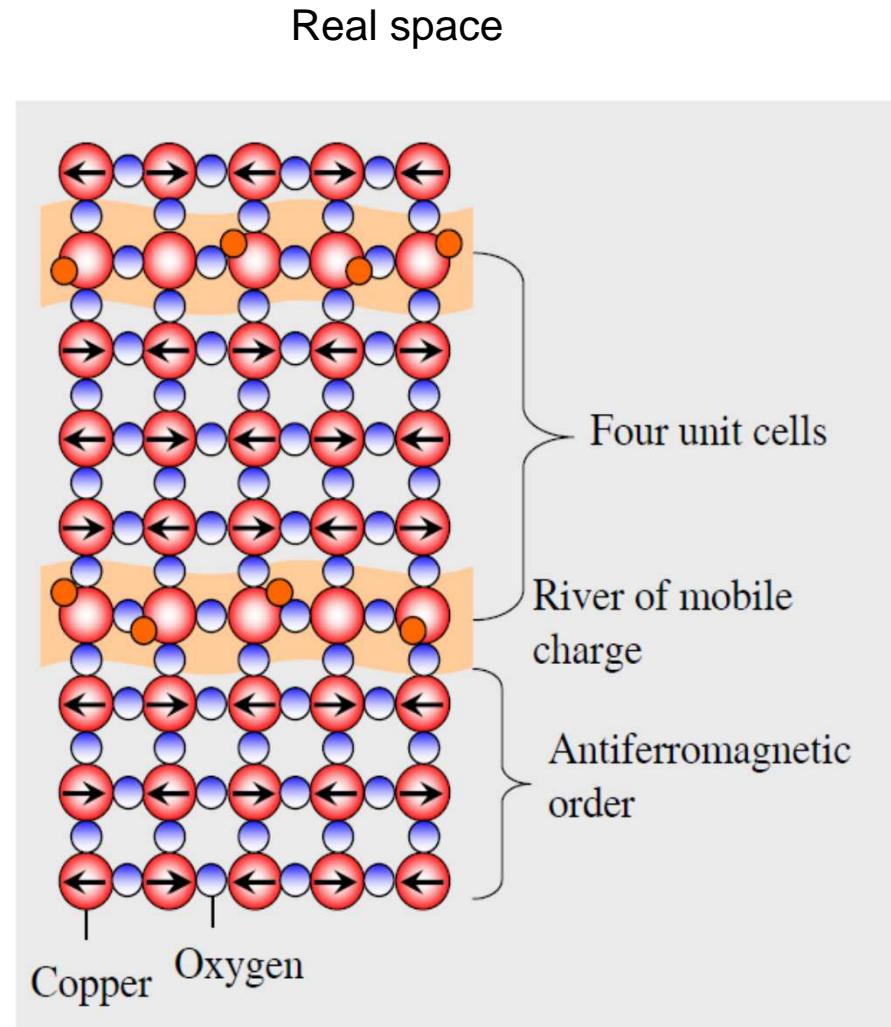
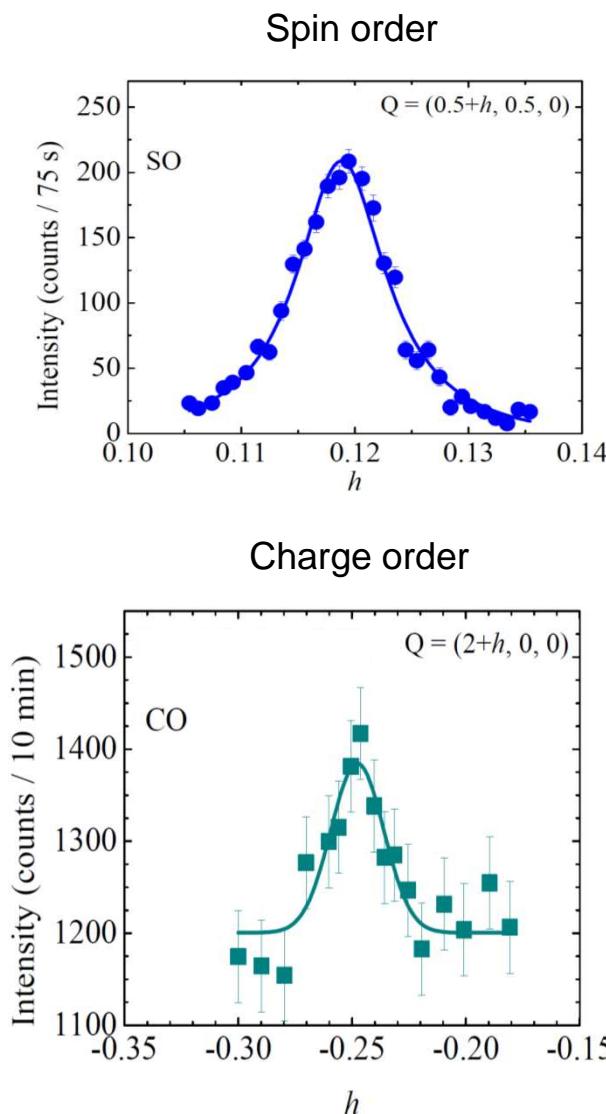


Hücker *et al*, Phys. Rev. B **83**, 104506 (2011).



Axe *et al*, Phys. Rev. Lett. **62**, 2751 (1989).
Hücker *et al*, Phys. Rev. B **83**, 104506 (2011).

Experimental evidence for static stripes in $\text{La}_{1.48}\text{Nd}_{0.4}\text{Sr}_{0.12}\text{CuO}_4$ Neutron Scattering



Guguchia, PhD thesis, University of Zürich (2013).

Tranquada *et al*, Nature (London) **375**, 561 (1995).

➤ What is microscopic origin of the stripe formation?

The stripe phase may be caused by electronic and/or electron-lattice interaction.

➤ Do stripes promote or inhibit superconductivity?

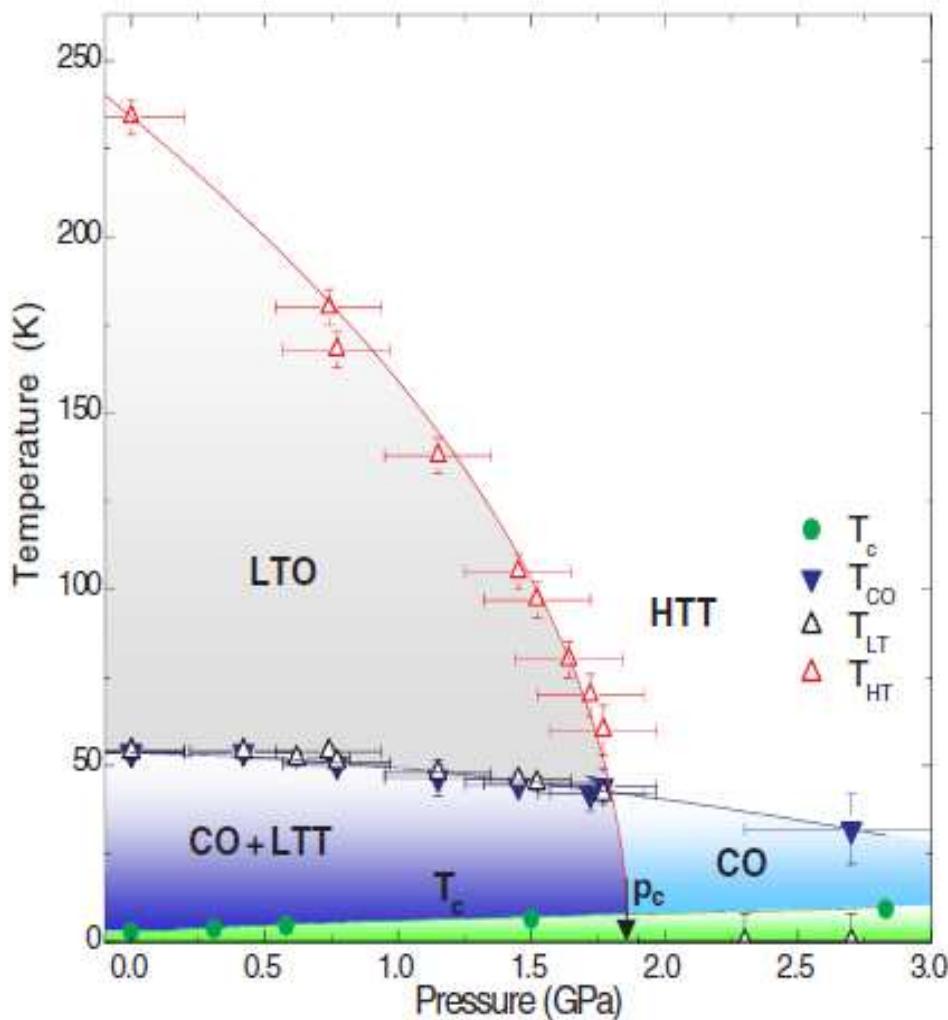
Zaanen and Gunnarson Phys. Rev. B **40**, 7391 (1989).

White and Scalapino, PRL **80**, 1272 (1998).

Emery and Kivelson, Physica C **209**, 597 (1993).

M. Vojta, Adv. Phys. **58**, 699 (2009).

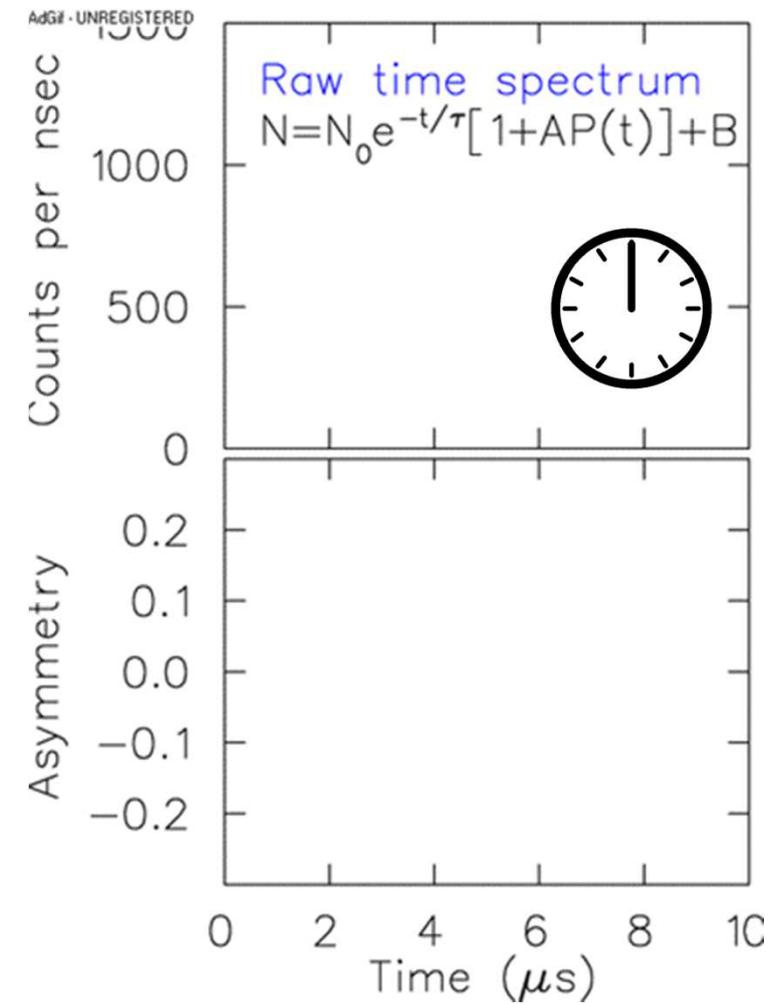
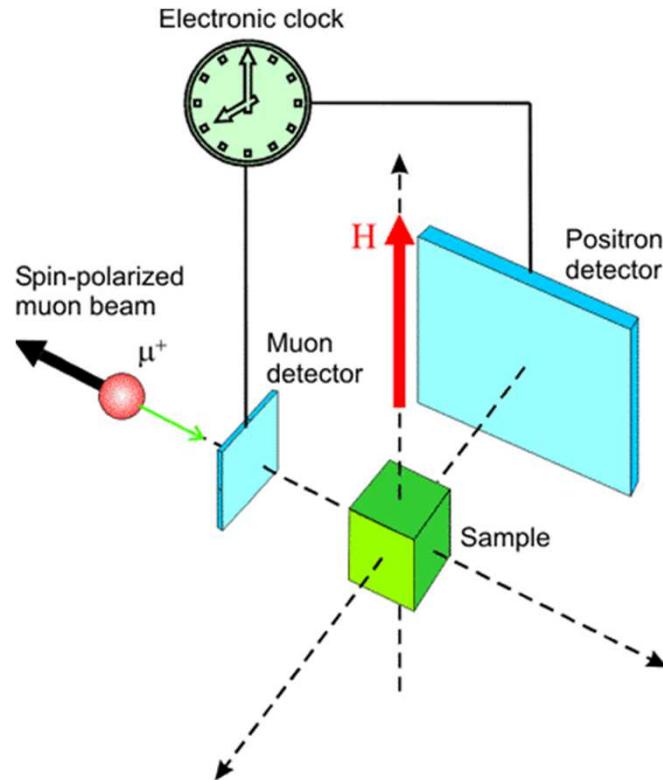
LTT structural phase under pressure



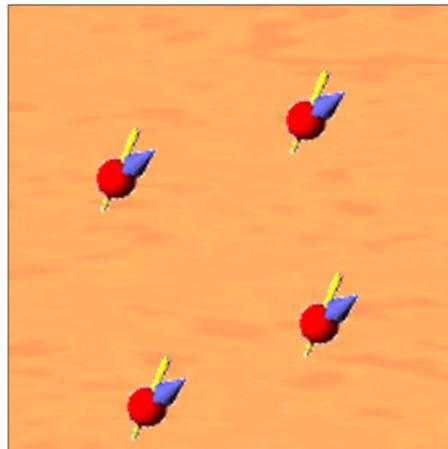
Hücker et al, PRL **104**, 057004 (2010).

Spin-stripe order vs hydrostatic pressure?

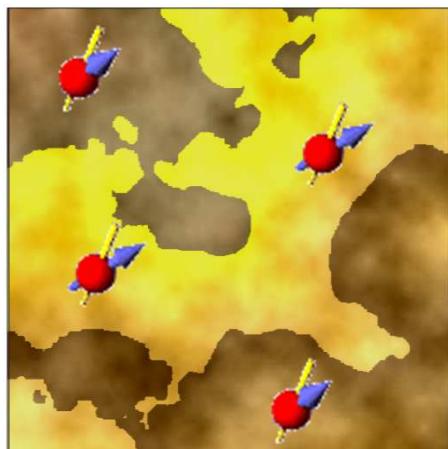
Muon-spin rotation (μ SR) technique



homogeneous



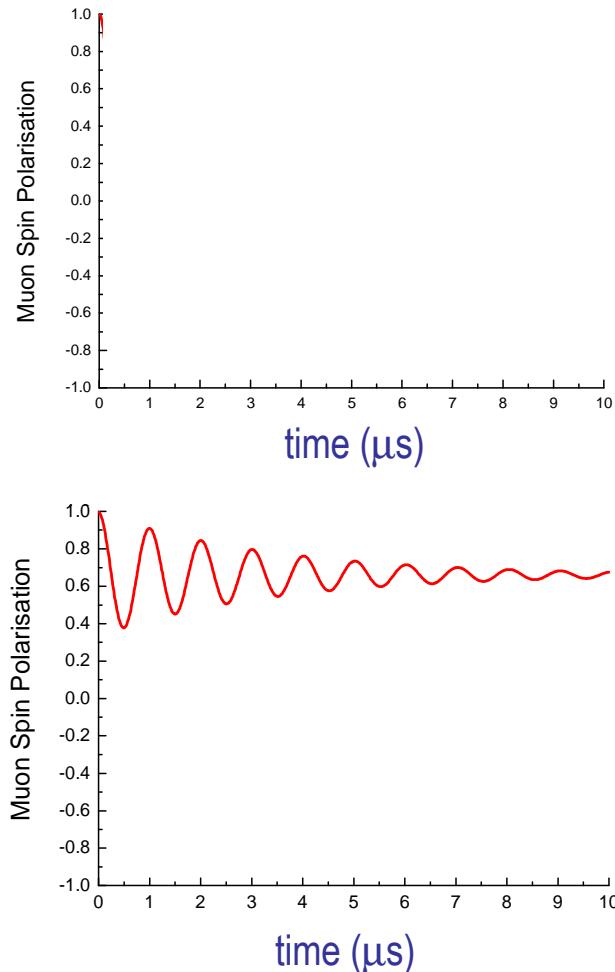
inhomogeneous

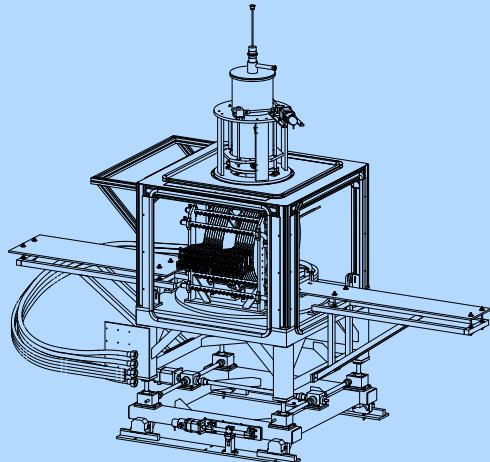


Courtesy of H. Luetkens

amplitude
frequency
- Damping

→ magnetic volume fraction
→ average local magnetic field
→ magnetic field distribution / magnetic fluctuations



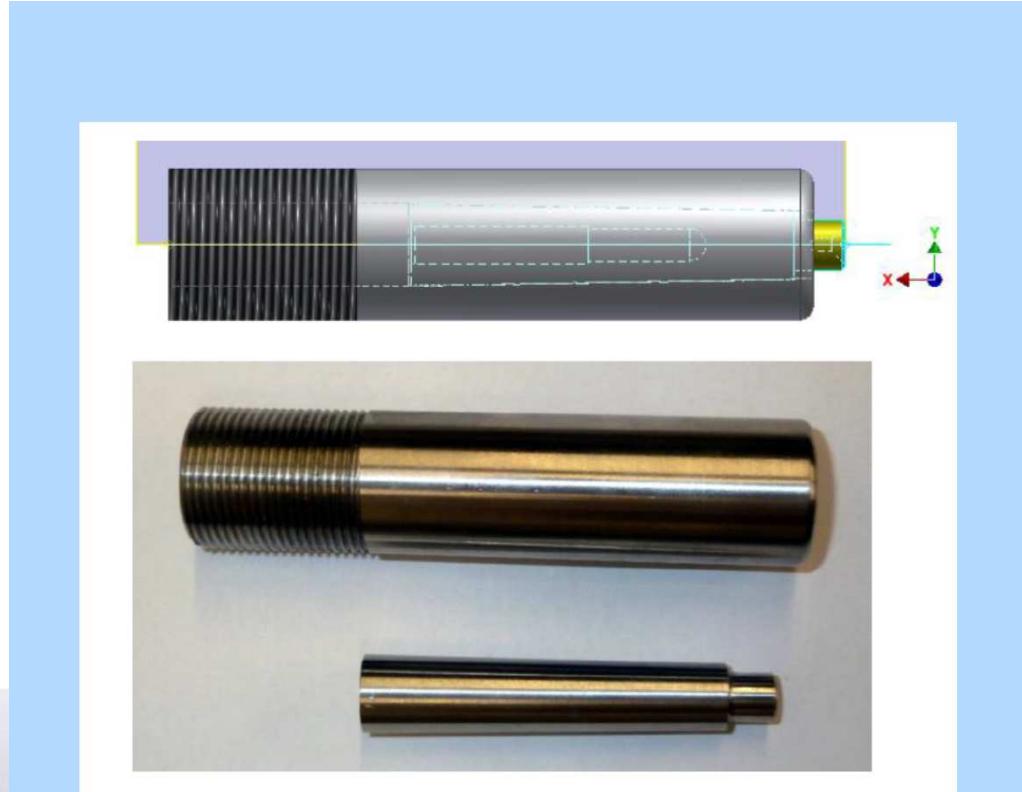


Collimation: 2 Pb collimators.
Cylindrical \varnothing 8, 10, 12, 16mm;
Rectangular 4x10mm.

Magnetic fields: Transverse or longitudinal to the muon-spin polarization, 0-0.66 T

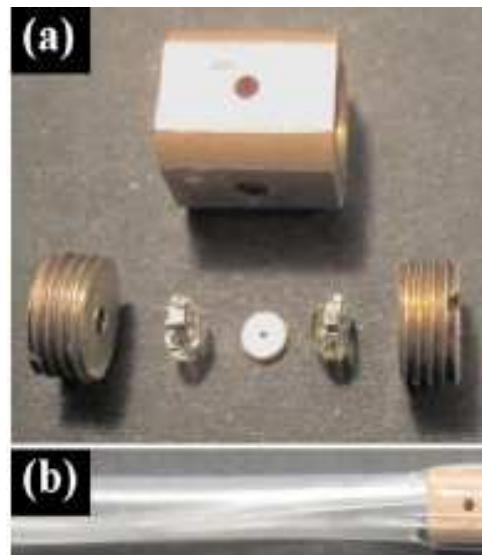
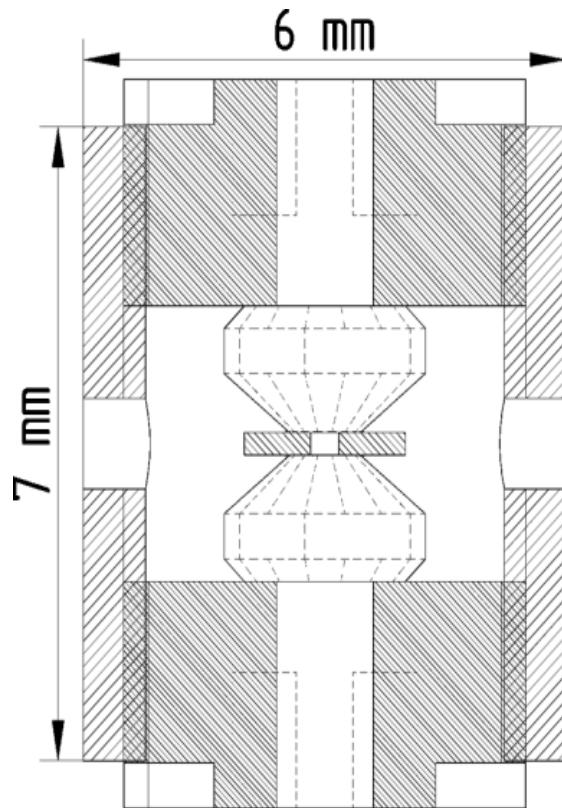
Cryostats:
Continuous flow (Janis),
 $\sim 2.6 < T < 300$ K
Closed cycle refrigerator, $11 < T < 475$ K
 N_2 flow cryostat, $80 < T < 500$ K
 3He cryostat, $0.3 < T < 300$ K

double-wall cells

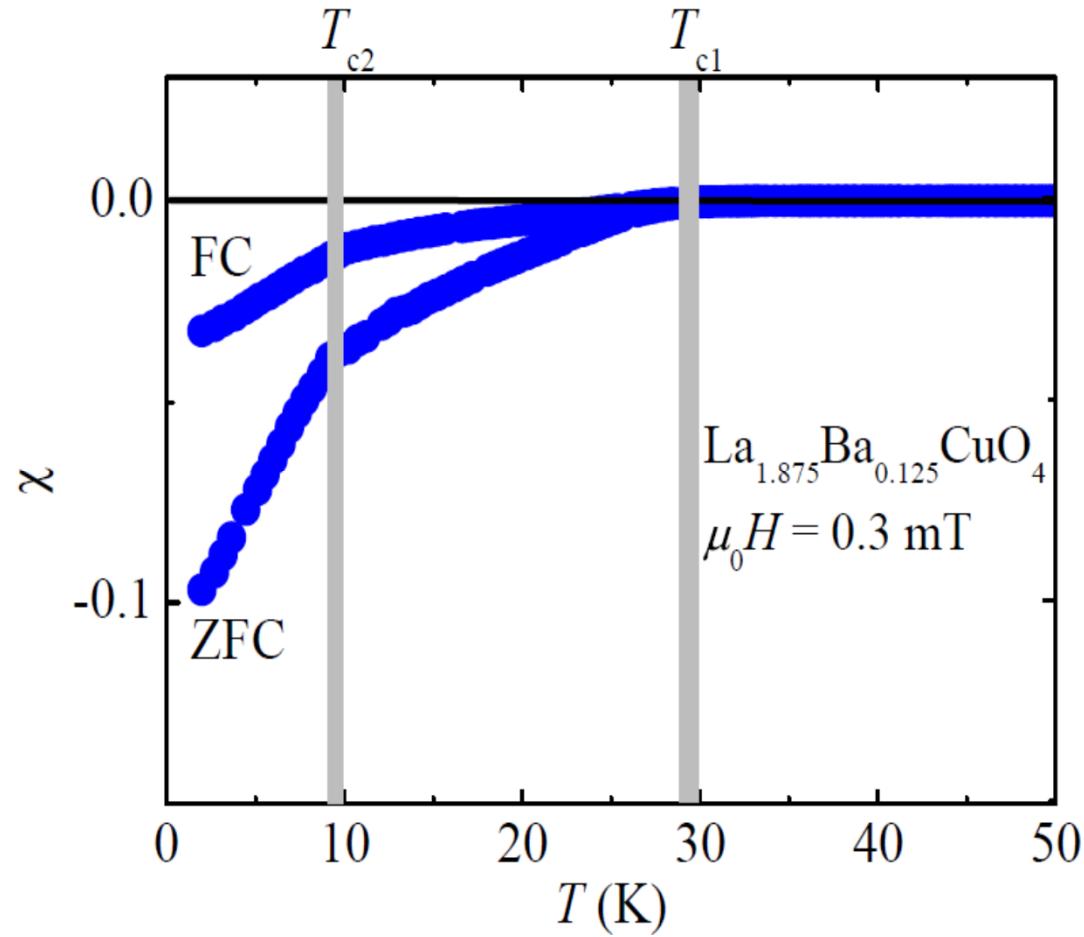


$P \approx 27 \text{ kbar}$

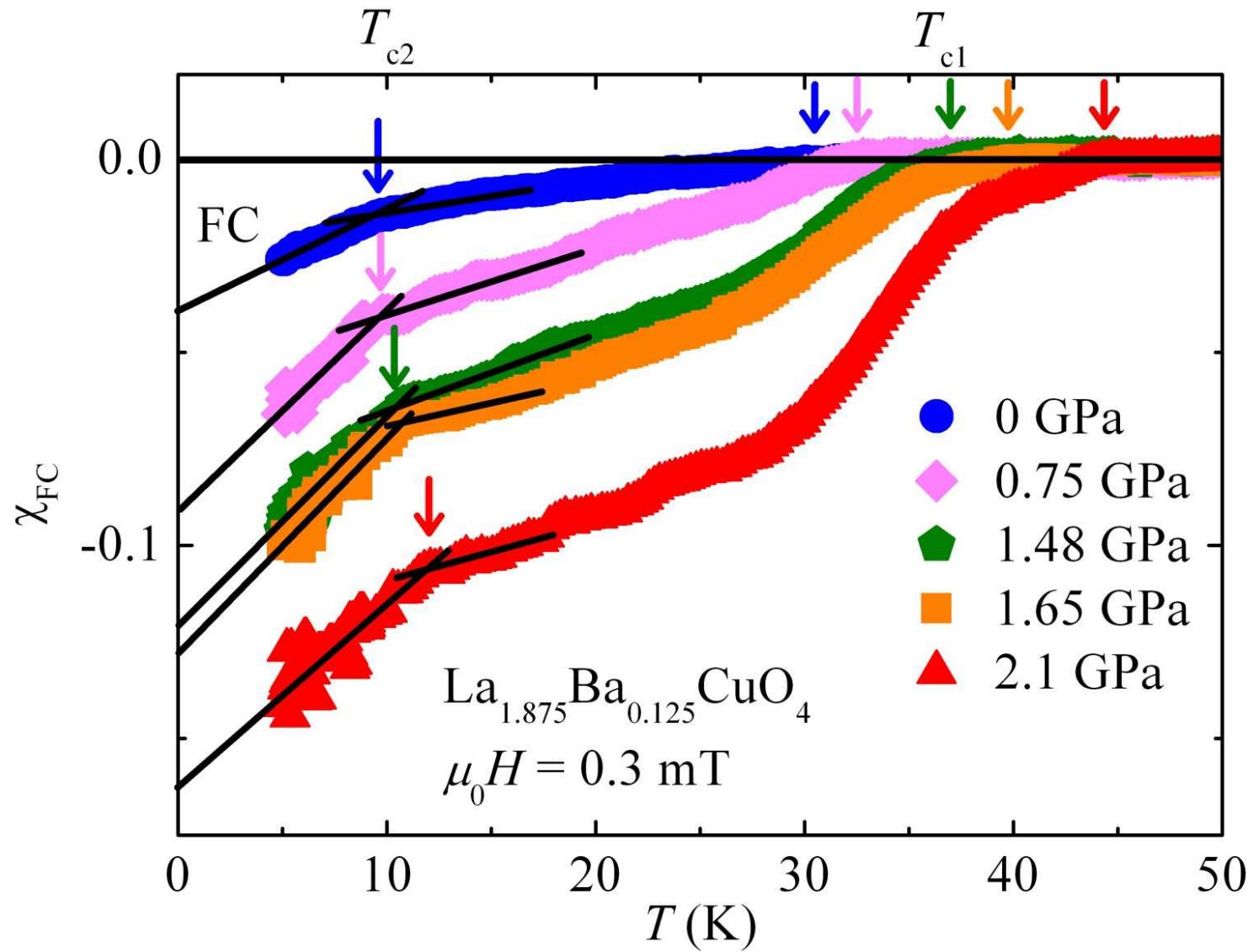
Fraction of the muons in
the sample $\sim 50 \%$

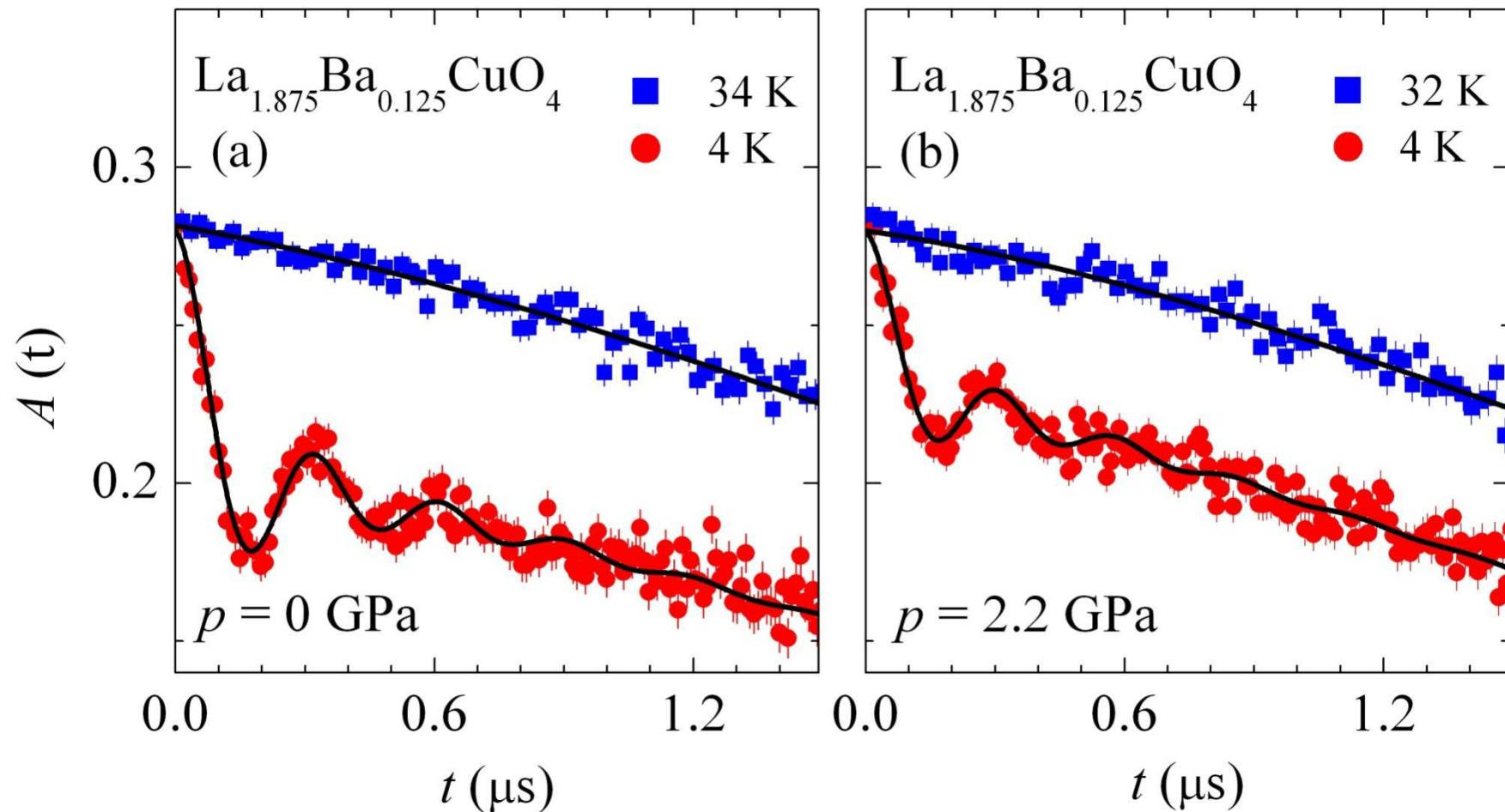


Guguchia and Maisuradze, University of Zurich.

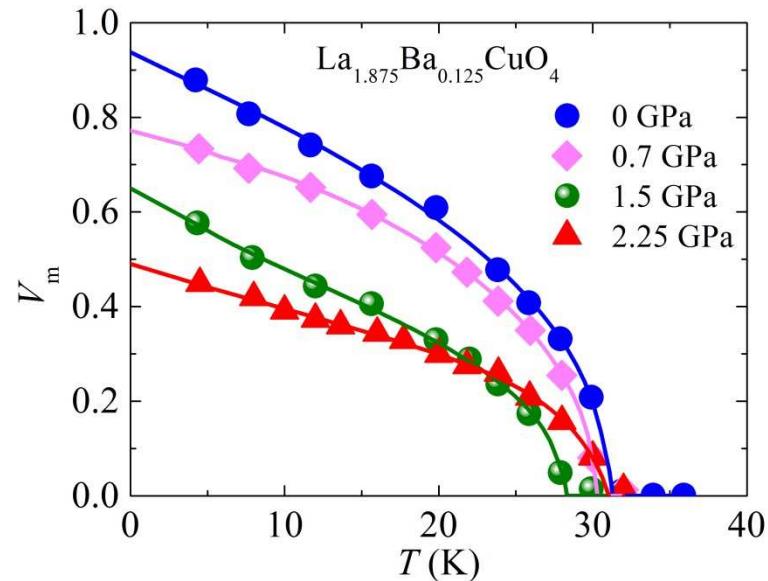
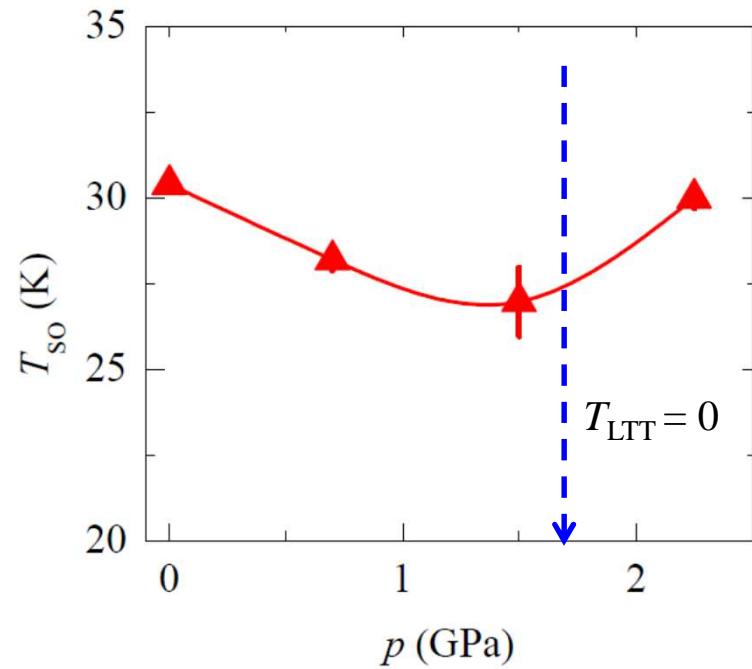
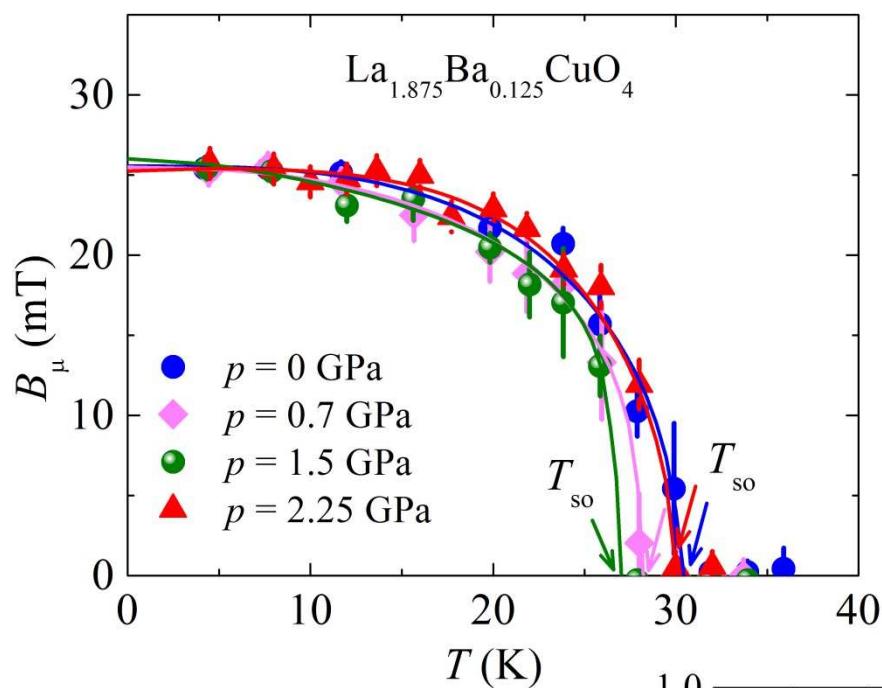


Superconducting properties of $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$

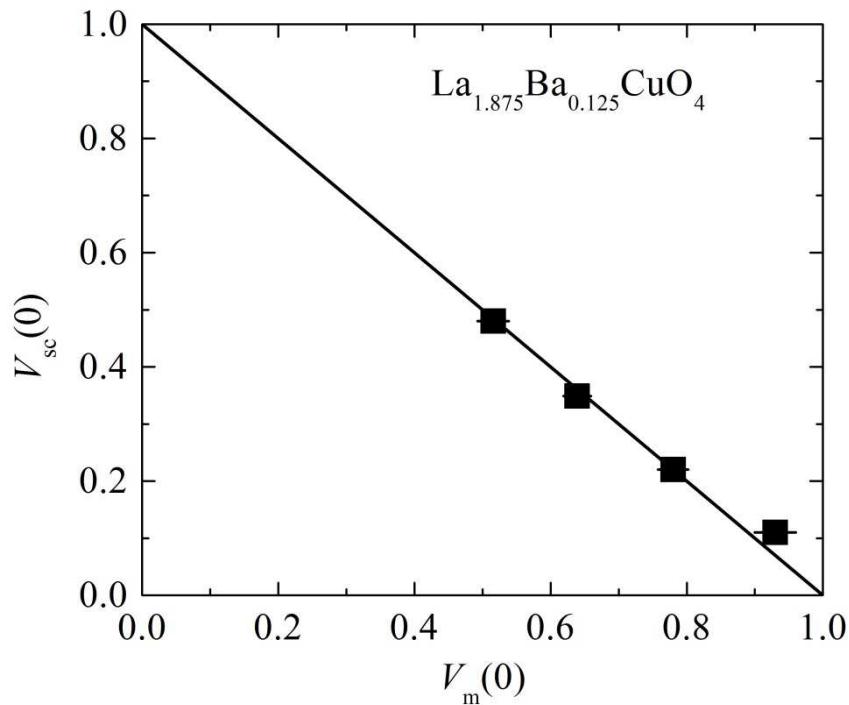
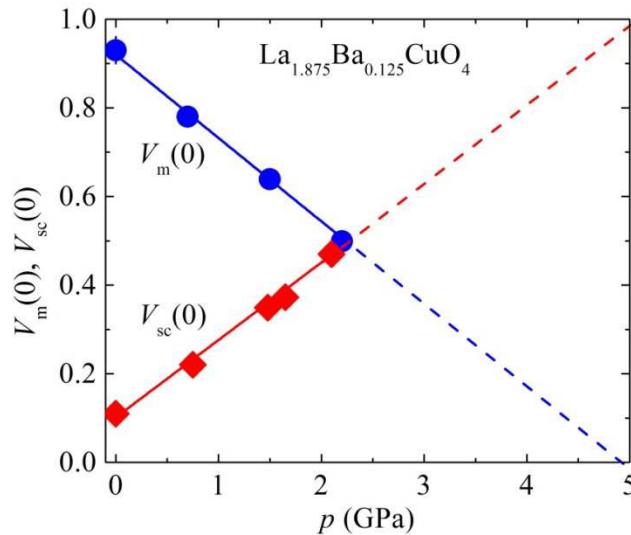




High pressure μ SR experiments on $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$



Phase diagrams



$$V_{sc}(0) + V_m(0) \approx 1$$

**Superconductivity and magnetism
are competing order parameters.**

Z. Guguchia et al., New Journal of Physics **15**, 093005 (2013).

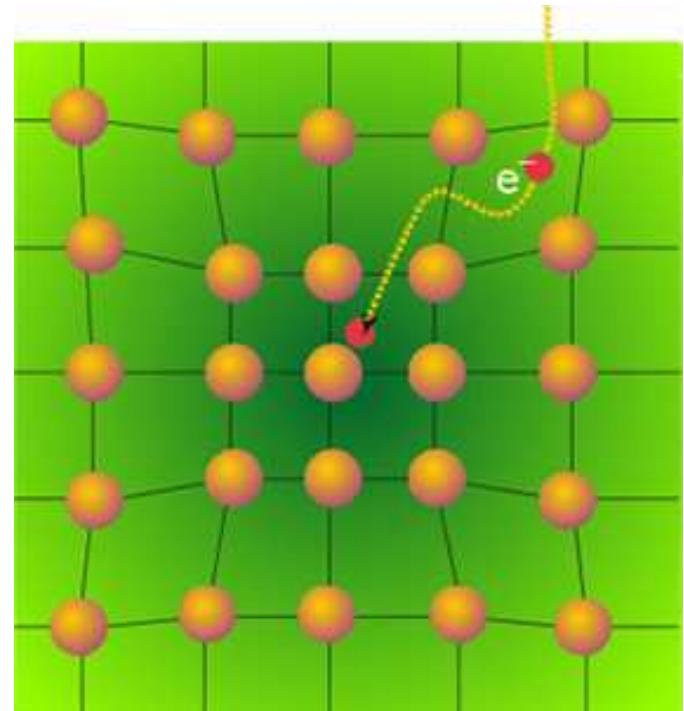
Electron-phonon interaction

Isotope effect:

$$T_c \propto M^{-\alpha},$$

$$\alpha = -d \ln T_c / d \ln M.$$

Ranges from 0.2-0.5 in elemental metals



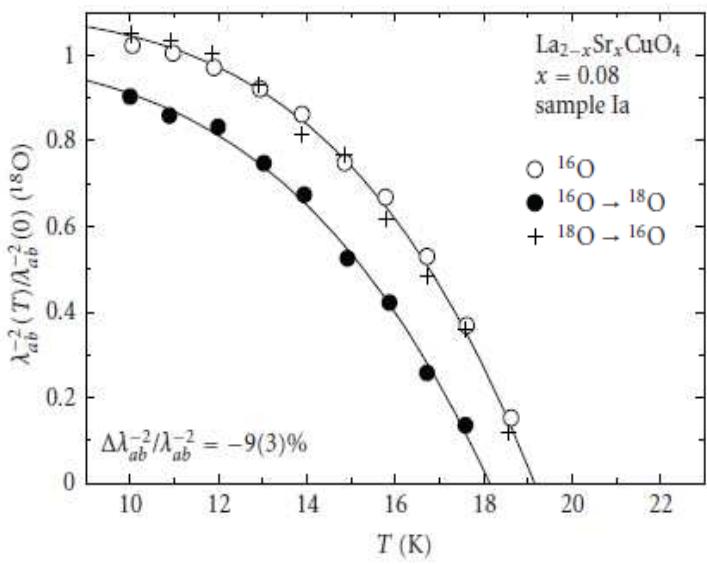
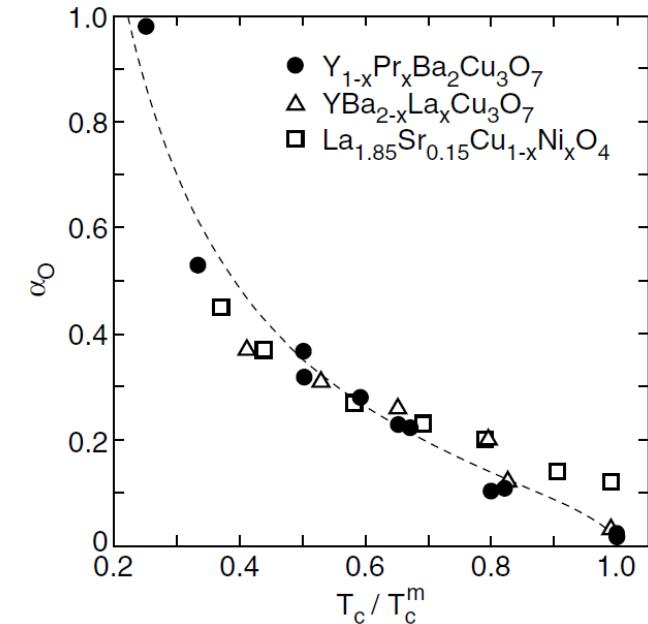
Weak coupling BCS predicts a value of $\alpha = 0.5$

C.A. Reynolds et. al., Phys. Rev. **78**, 487 (1950).

E. Maxwell, Phys. Rev. **78**, 477 (1950).

J. Bardeen et. al., Phys. Rev. **108**, 1175 (1957).

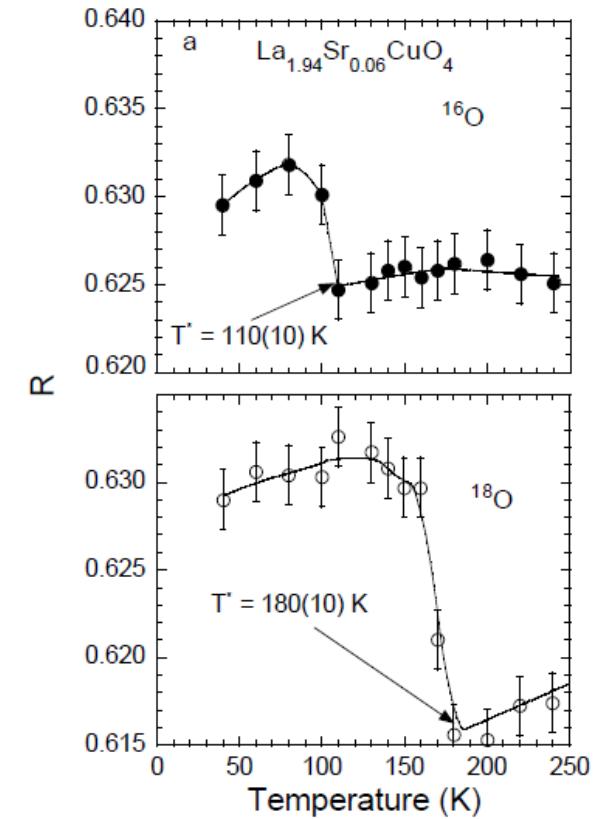
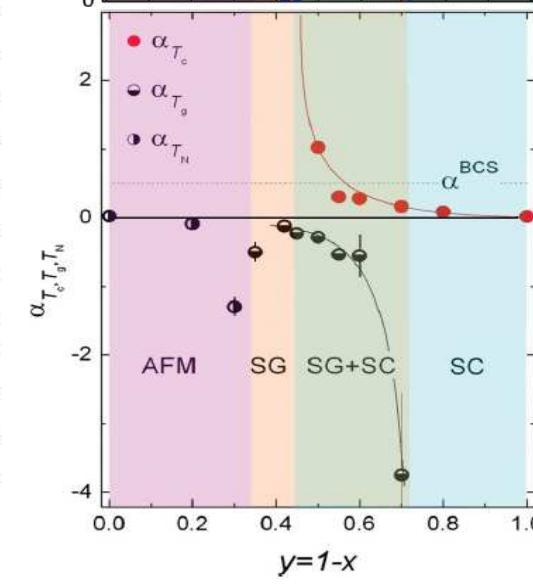
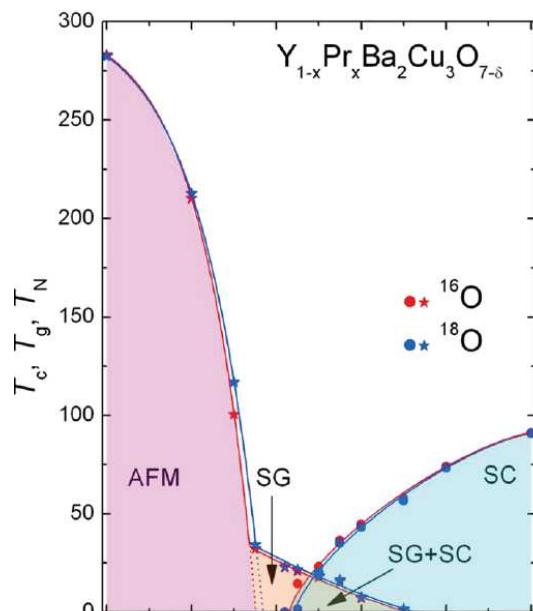
Unconventional Oxygen Isotope effects (OIE's) in cuprates



J. Hofer et. al., PRL **84**, 4192 (2000).

K.A. Müller, J. Phys. Condens. Matter **19**, 251002 (2007).

H. Keller et. al., Materials today **11**, 9 (2008).



Khasanov et. al., PRL **101**, 077001 (2008).

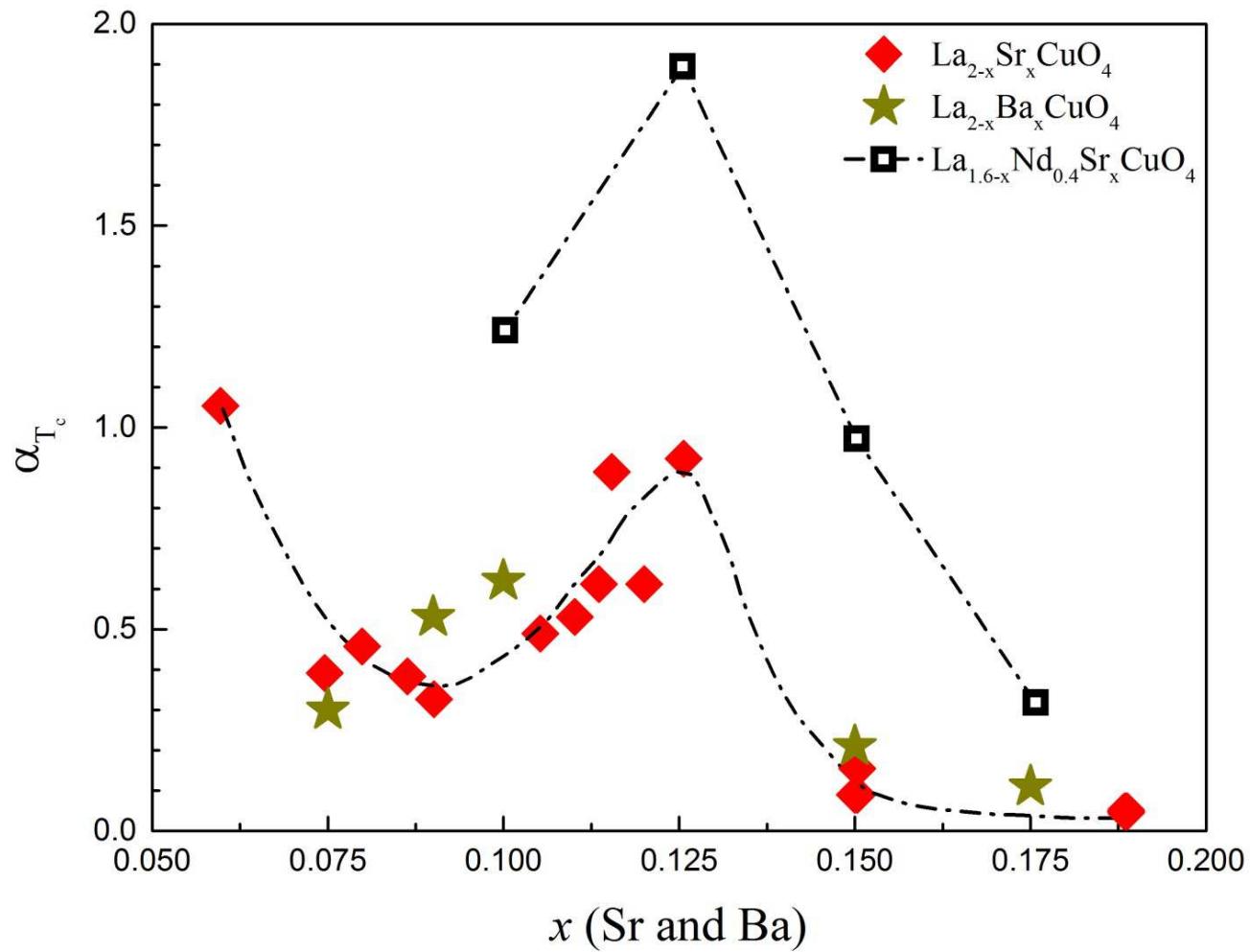
Shengelaya et. al, PRL **83**, 24 (1999).

Lanzara et. al., J. Phys. Condens. Matter **11**, L541 (1999).

Rubio Temprano et. al., PRL **84**, 1990 (2000).

Zhech et. al., Nature **371**, 681–683, 1994.

Isotope effect on T_c near 1/8



M.K. Crawford et. al., Science **250**, 1390 (1990).

J. Hofer et. al., PRL **84**, 4192 (2000).

B. Batlogg et. al., PRL **59**, 912 (1987).

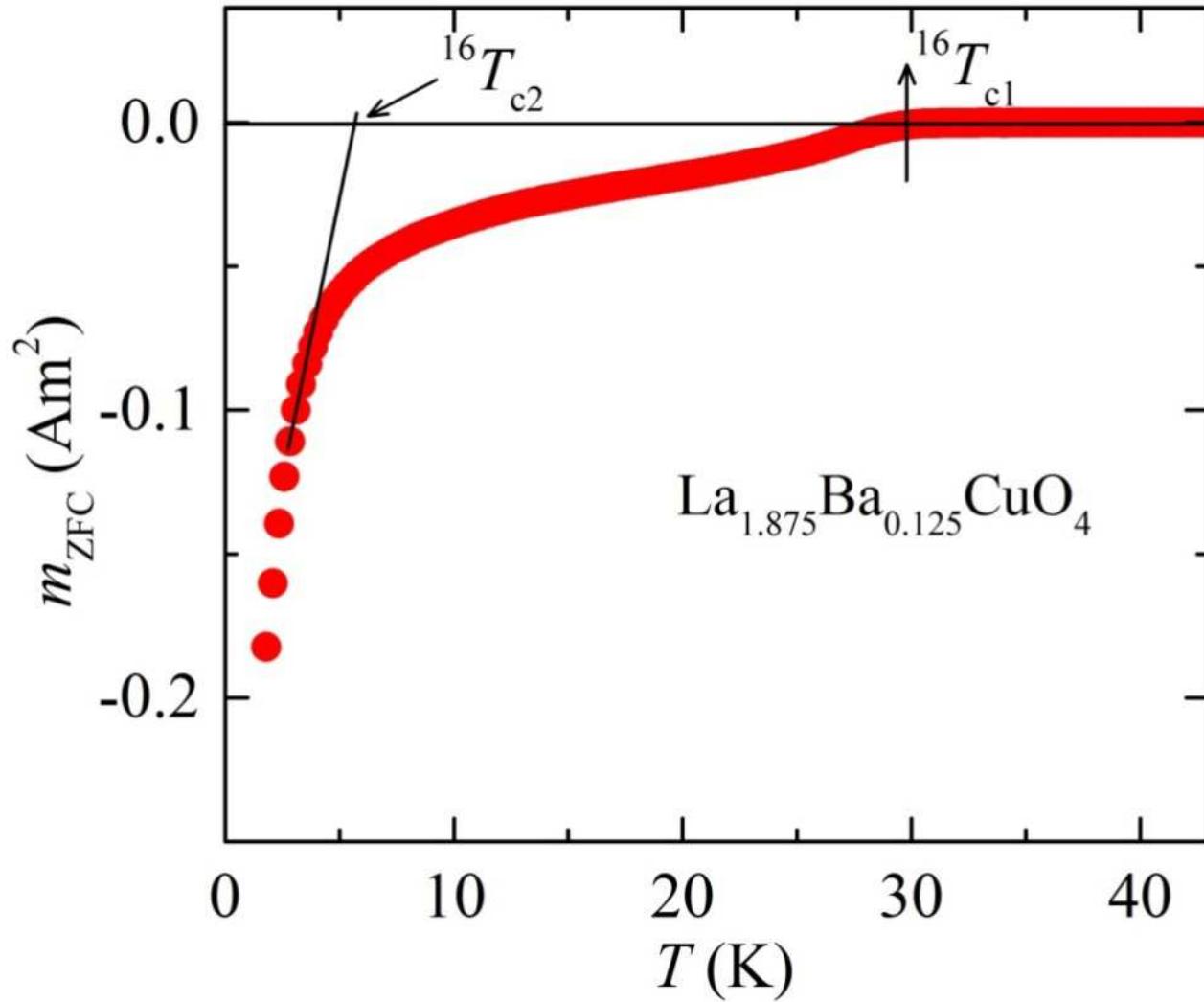
G.M. Zhao et. al., J. Phys.: Condens. Matter **10**, 9055 (1998).

J.P. Franck et. al., PRL **71**, 283 (1993).

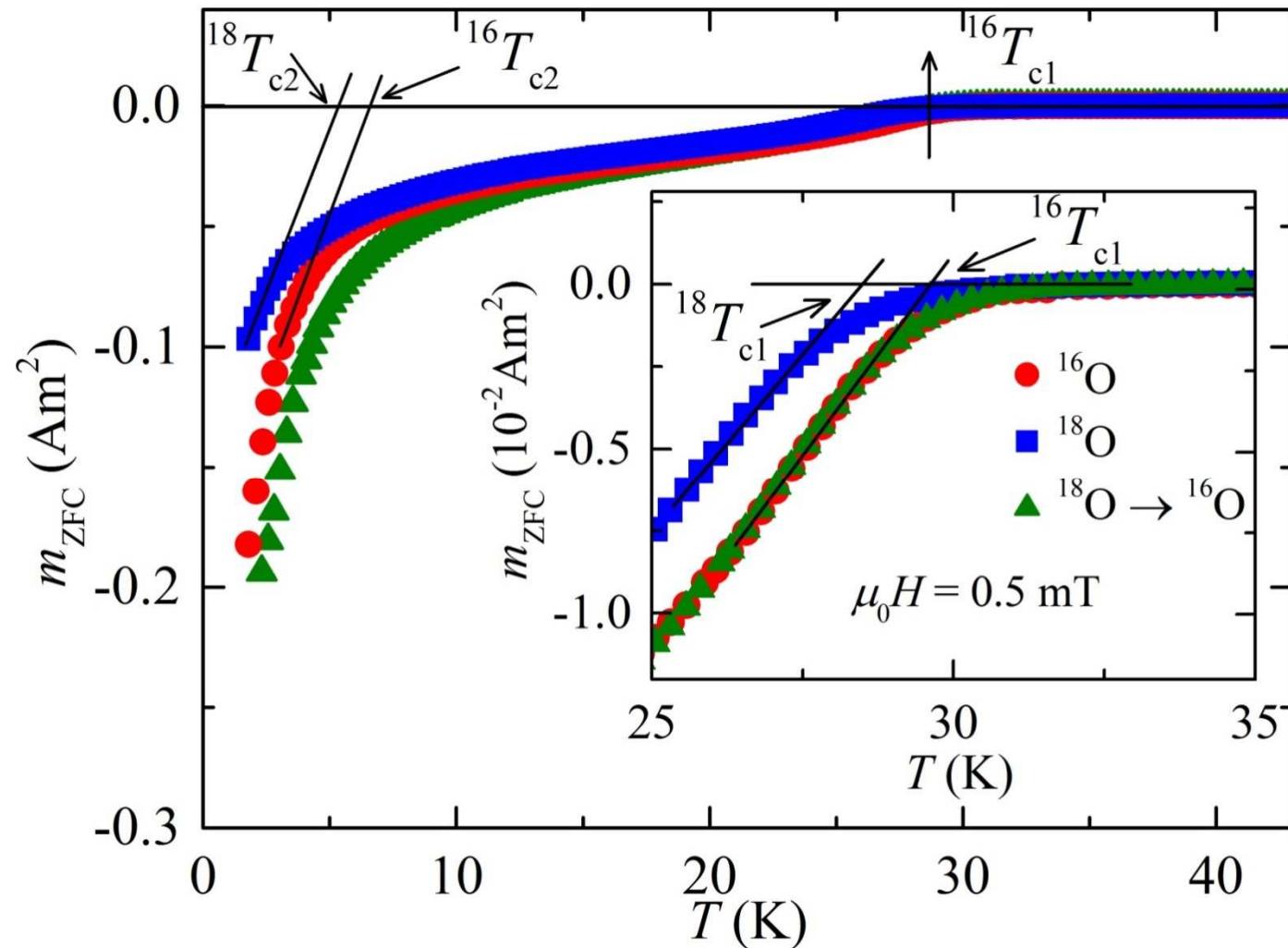
G.Y. Wang et. al., PRB **75**, 212503 (2007).

A. Bussmann-Holder et. al., PRL **67**, 512 (1991).

Magnetization experiments



Isotope effect on T_c in $\text{La}_{1.875}\text{Ba}_{0.125}\text{CuO}_4$



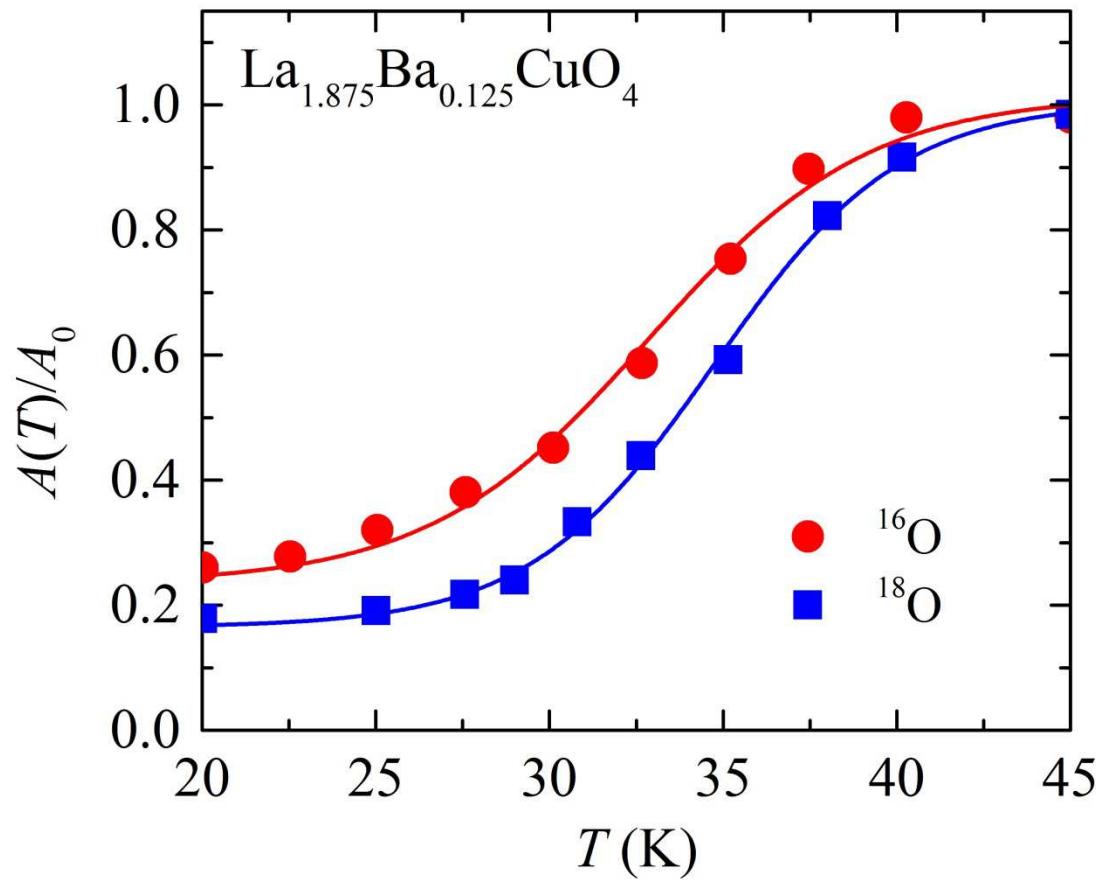
$$T_c \propto M^{-\alpha}.$$

$$^{16}T_{c1} = 29.7(1) \text{ K} \quad \text{and} \quad ^{18}T_{c1} = 28.3(1) \text{ K}.$$

$$\alpha = -d \ln T_c / d \ln M.$$

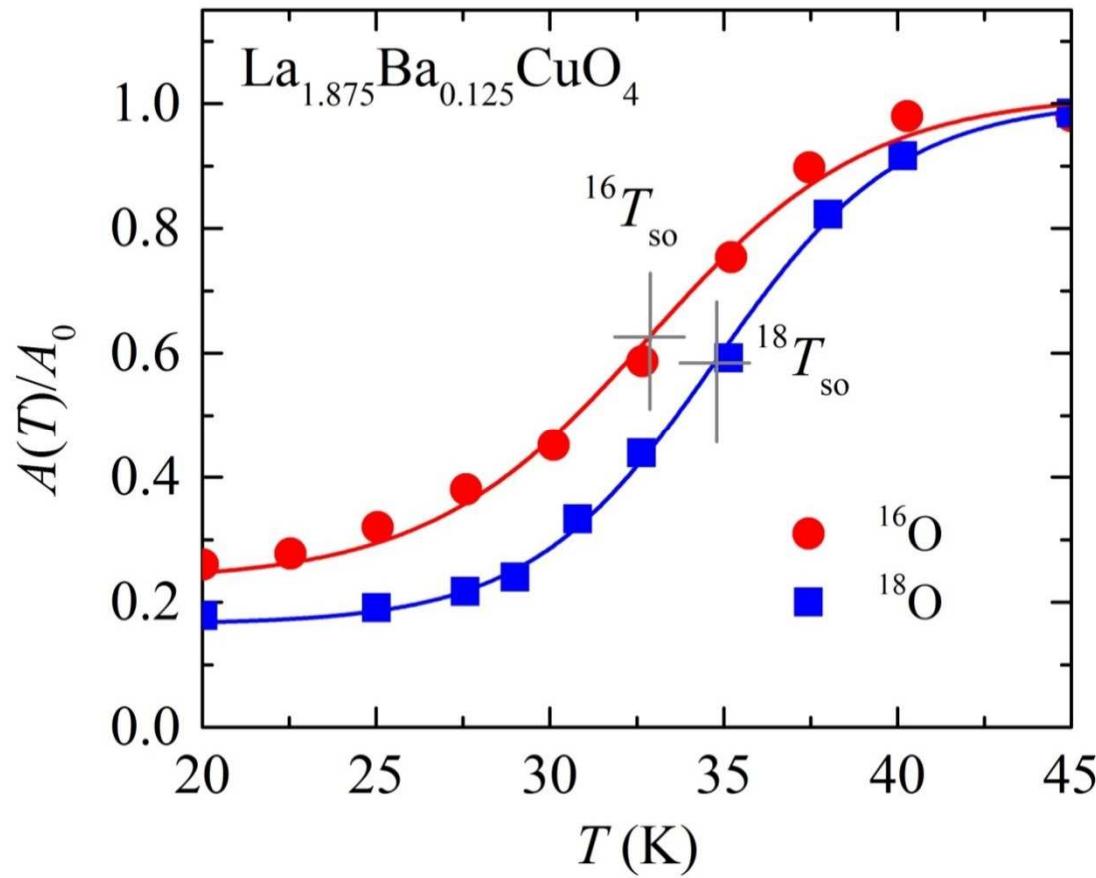
$$\alpha_{Tc1} = 0.46(6)$$

Oxygen Isotope effect on T_{so}



$$A(T) / A(0) = a \left[1 - \frac{1}{\exp[(T - T_{so}) / \Delta T_{so}] + 1} \right] + b$$

Oxygen Isotope effect on T_{so}

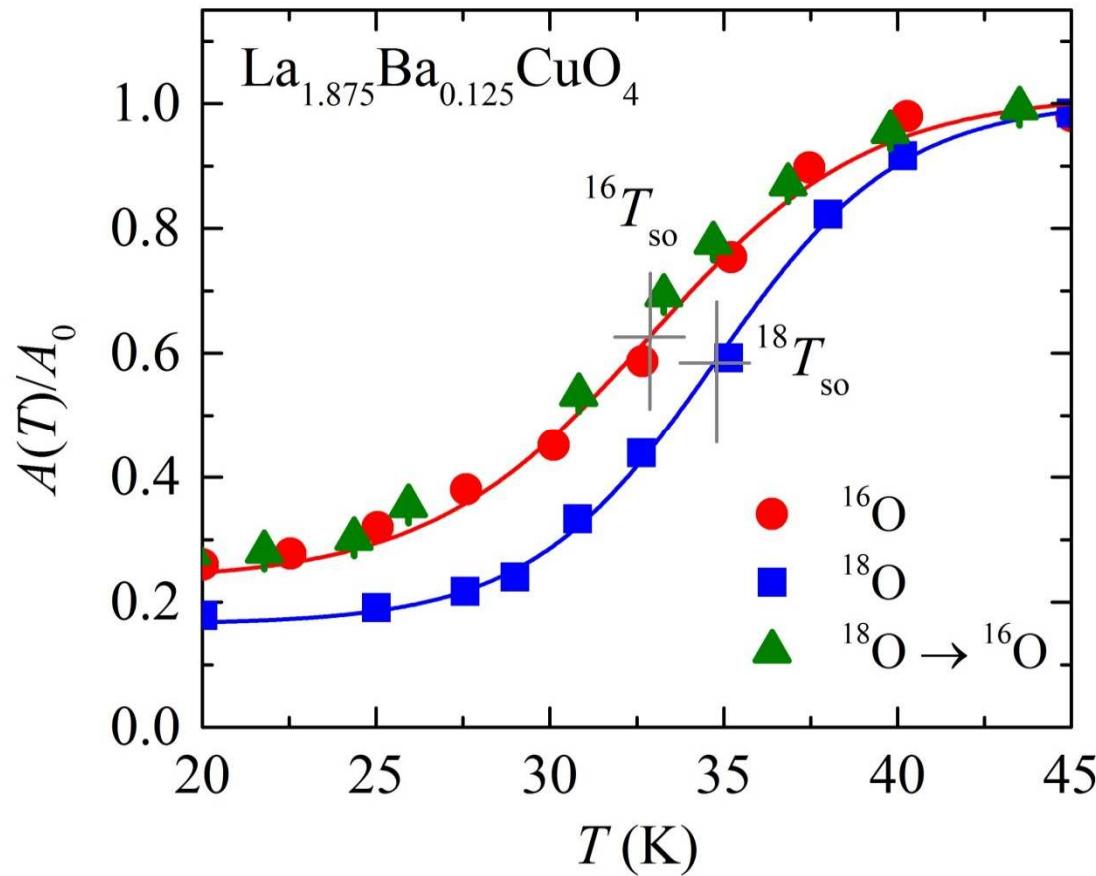


$$A(T)/A(0) = a \left[1 - \frac{1}{\exp[(T - T_{so})/\Delta T_{so}] + 1} \right] + b$$

$$^{16}T_{so} = 32.9(3) \text{ K} \quad \text{and} \quad ^{18}T_{so} = 34.8(2) \text{ K.}$$

$$\alpha_{T_{so}} = -0.56(9)$$

Oxygen Isotope effect on T_{so}

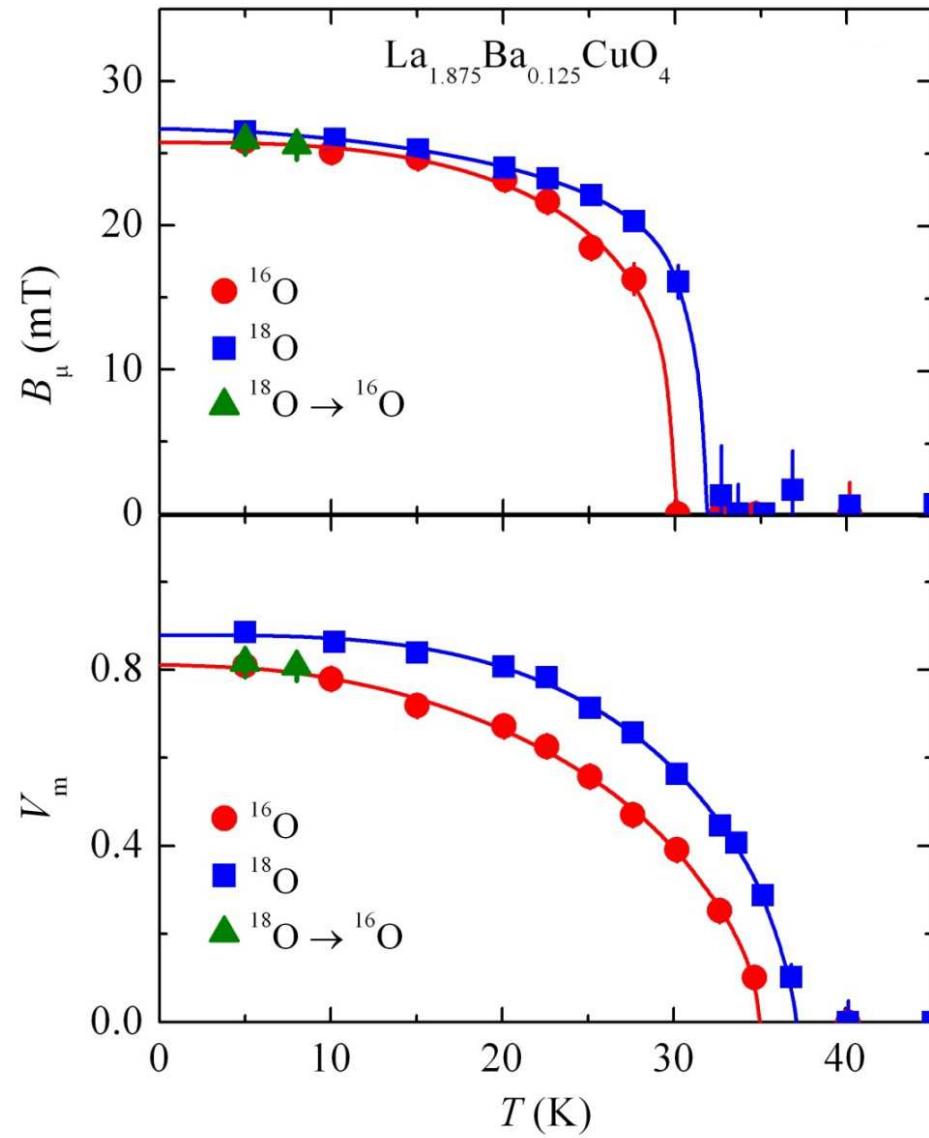
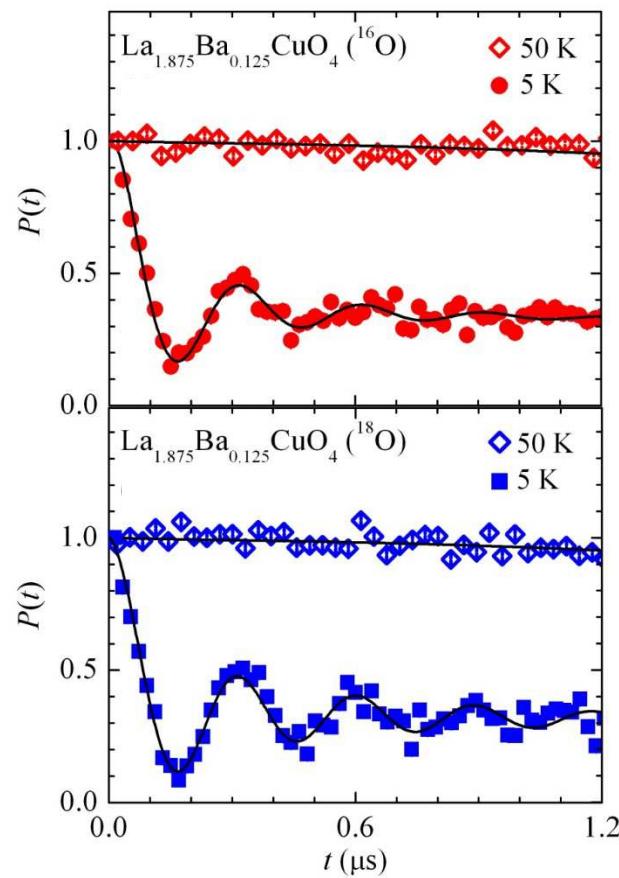


$$A(T)/A(0) = a \left[1 - \frac{1}{\exp[(T - T_{so})/\Delta T_{so}] + 1} \right] + b$$

$$^{16}T_{so} = 32.9(3) \text{ K} \quad \text{and} \quad ^{18}T_{so} = 34.8(2) \text{ K.}$$

$$\alpha_{T_{so}} = -0.56(9)$$

OIE effect on T_{so} and magnetic fraction V_m



Parameter	ΔT_{so}	$\alpha_{T_{\text{so}}}$	$\Delta V_{\text{m}}(0)$	$\alpha_{V_{\text{m}}}$
$A(T)$	1.9(4)	-0.56(9)
$B_\mu(T)$	1.7(5)	-0.55(11)
$V_{\text{m}}(T)$	2.2(3)	-0.61(7)	0.82(1)	-0.71(9)

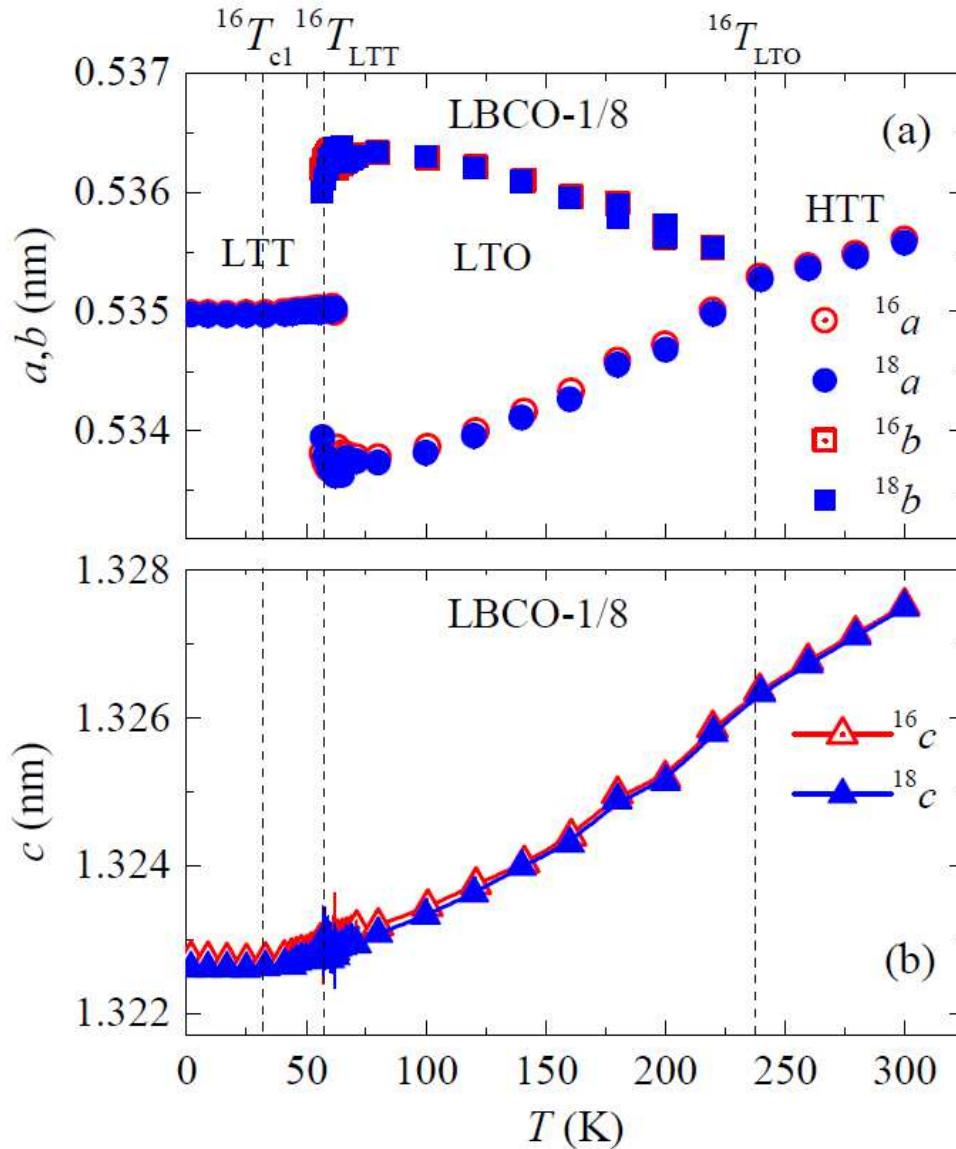
$$\langle \alpha_{T_{\text{so}}} \rangle = -0.57(6), \quad \alpha_{V_m} = -0.71(9).$$

Give evidence for stripe-lattice coupling in cuprates.

$$\langle \alpha_{T_{\text{so}}} \rangle = -0.57(6), \quad \alpha_{T_{c1}} = 0.46(6).$$

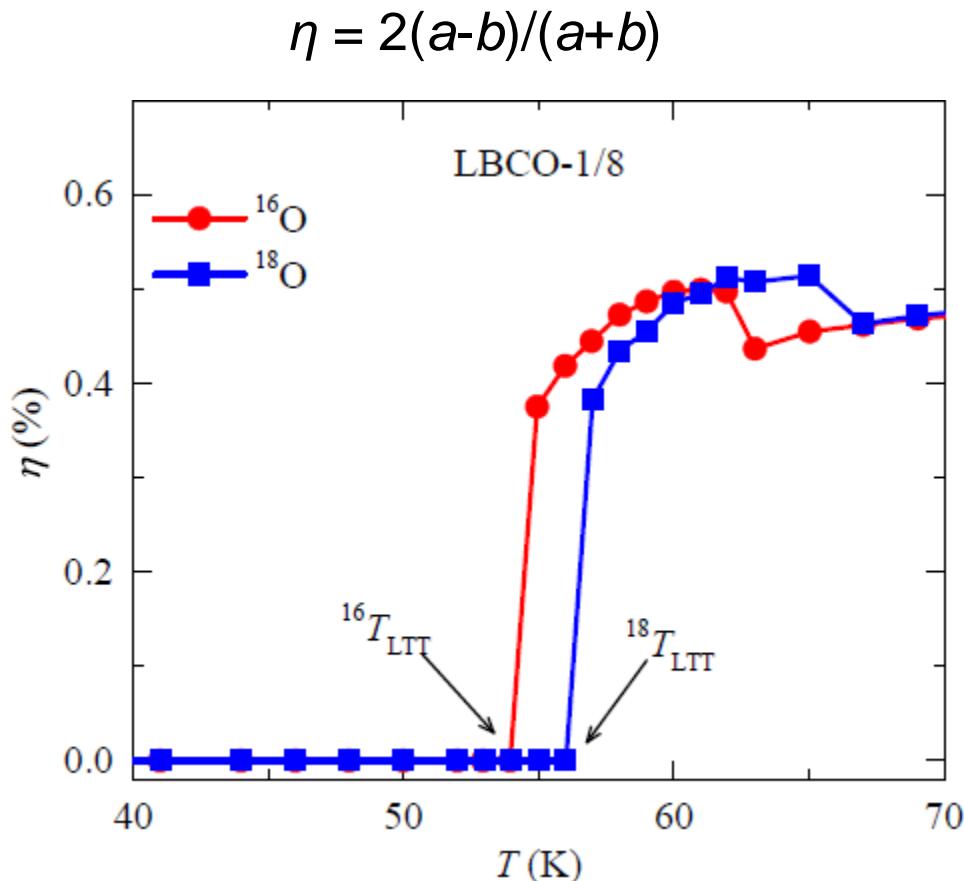
Superconductivity and stripe order are competing phenomena.

OIE effect on structural properties in the stripe phase



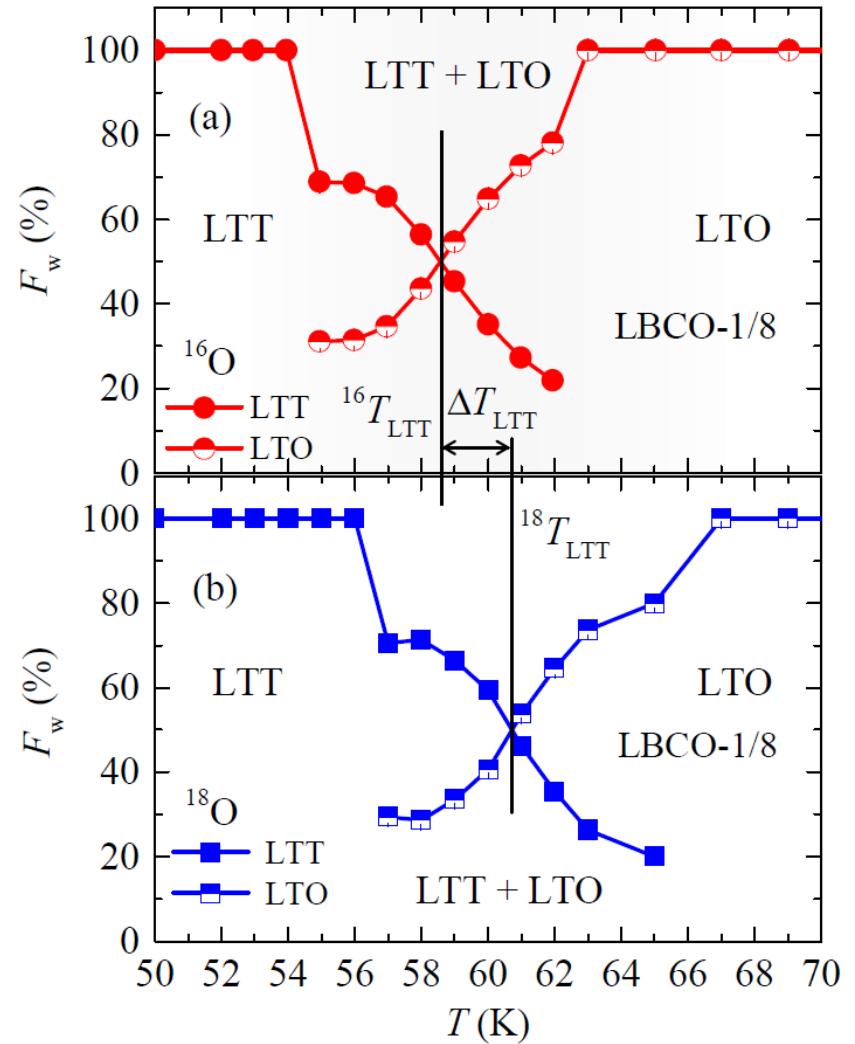
HTT – $I4/mmm$, LTO – $Bmab$, LTT – $p4/ncm$

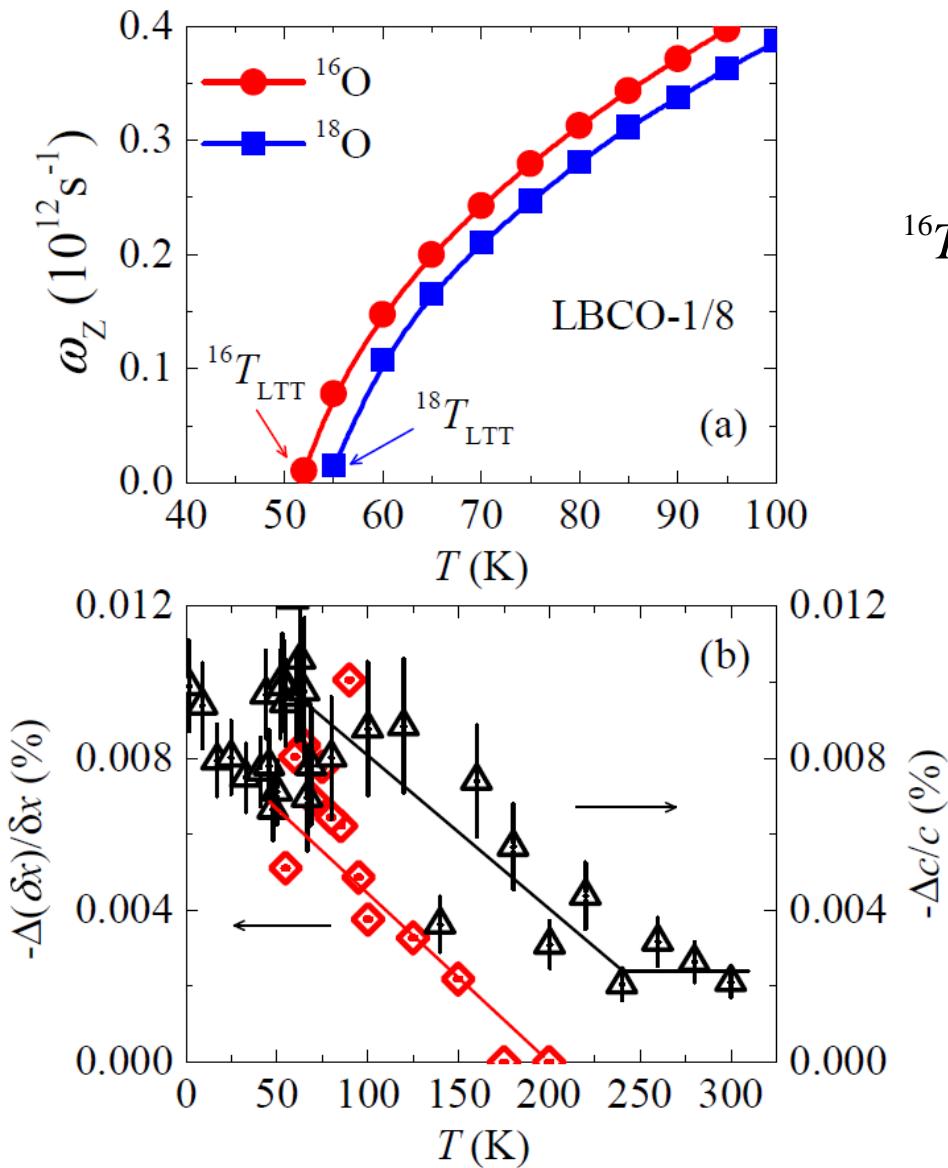
OIE effect on structural properties in the stripe phase



$$^{16}T_{LTT} = 54.5(3) \text{ K} \quad \text{and} \quad ^{18}T_{LTT} = 56.5(3) \text{ K}.$$

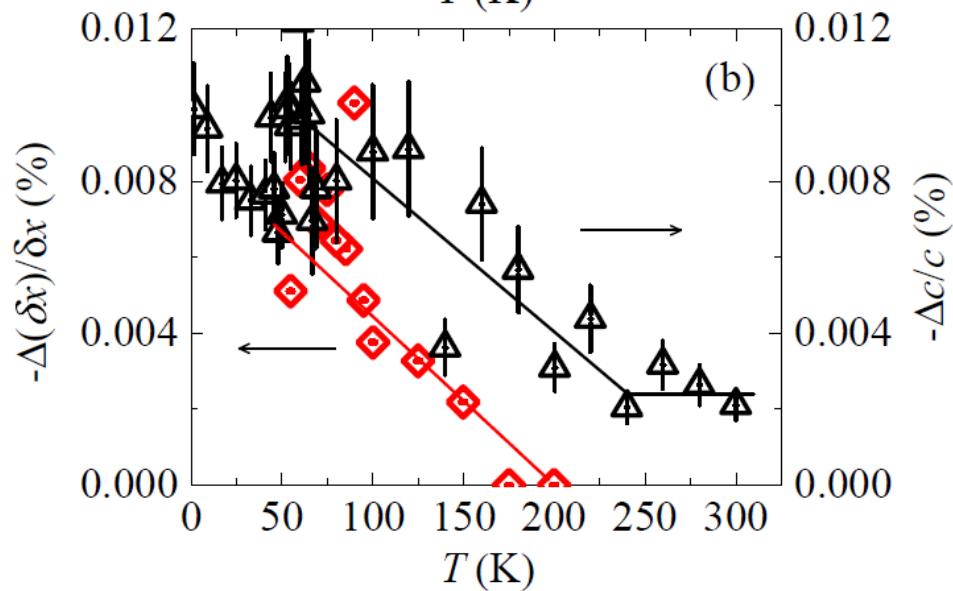
$$\alpha_{T_{LTT}} = -0.36(5).$$





$${}^{16}\text{T}_{\text{LTT}} = 52.1 \text{ K} \quad \text{and} \quad {}^{18}\text{T}_{\text{LTT}} = 54.8 \text{ K}.$$

$$\alpha_{\text{T}_{\text{LTT}}} = -0.49.$$



Conclusions

- Large negative OIE's were observed on T_{so} , V_m , T_{LTT} in $\text{La}_{2-x}\text{Ba}_x\text{CuO}_4$ ($x = 1/8$).
- Oxygen-isotope shifts of T_c and T_{so} , T_{LTT} are sign reversed. $V_{\text{sc}}(0) + V_m(0) \approx 1$. Stripe order and superconductivity are competing orders.
- The electron-lattice interaction is involved in the stripe formation and is a crucial factor controlling the competition between the stripe order and superconductivity.
- A purely electronic mechanism can not explain the present isotope and pressure experiments!