Novel Dynamic Scaling Regime in Hole-Doped La_2CuO_4

Ying Chen

Los Alamos National Laboratory

Collaborators:

Wei Bao	Los Alamos National Laboratory
Emilio Lorenzo	CNRS, Grenoble, France
Yiming Qiu	National Institute of Standards and Technology
Seunghun Lee	National Institute of Standards and Technology
Sungil Park	National Institute of Standards and Technology
John Sarrao	Los Alamos National Laboratory

Outline

Introduction

- ✓ Magnetic and transport properties of hole doped La_2CuO_4 (Sr, Ba, Li)
- ✓ Theoretical phase diagram of 2D Heisenberg antiferromagnet (HAF)

Spin dynamics of 2D paramagnetic state of $La_2Cu_{1-y}Li_yO_4$ at T<<J

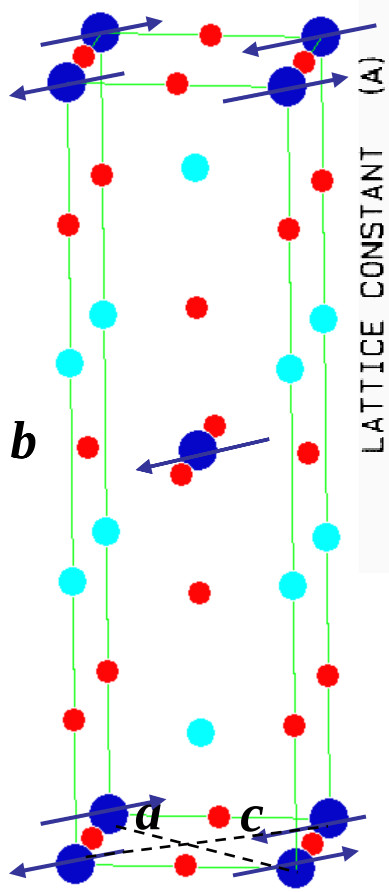
- ✓ $S(\mathbf{q},\omega)$ peaks sharply at (π,π) in Cu-O plane and flat out of the plane
- ✓ $S(\mathbf{q},\omega)$ crosses over from ω/T scaling at high temperatures to a novel low temperature regime characterized by a constant energy scale
- ✓ The observed crossover possibly corresponds to the theoretically expected quantum critical to quantum disordered crossover for 2D Heisenberg antiferromagnet

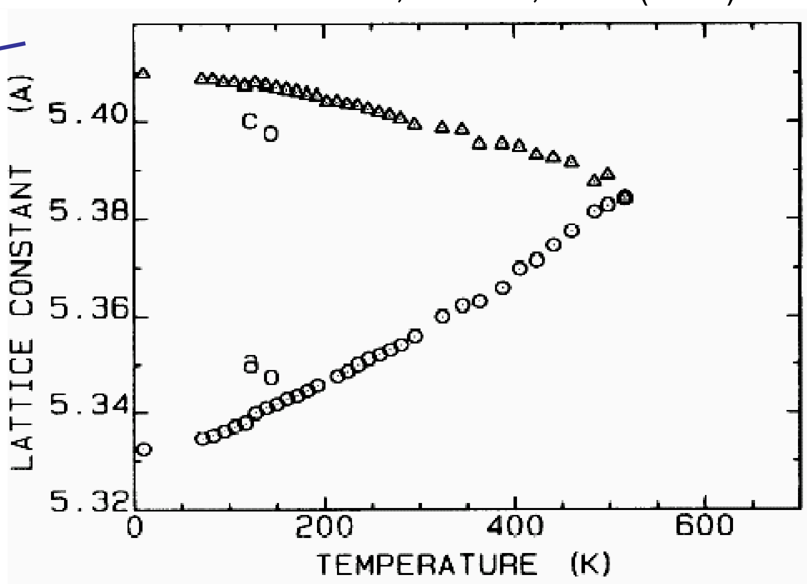
Summary

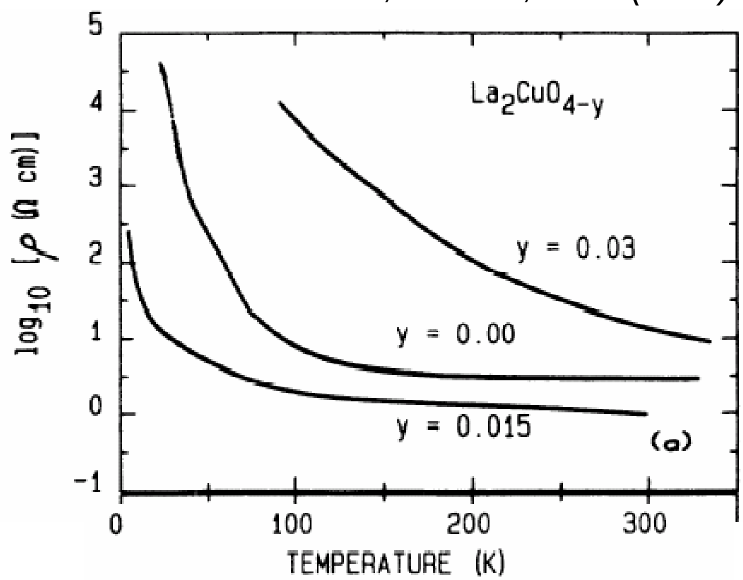
La_2CuO_4

Vaknin et al., PRL *58*, 2802 (1987)

Johnston et al., PRB 36, 4007 (1987)







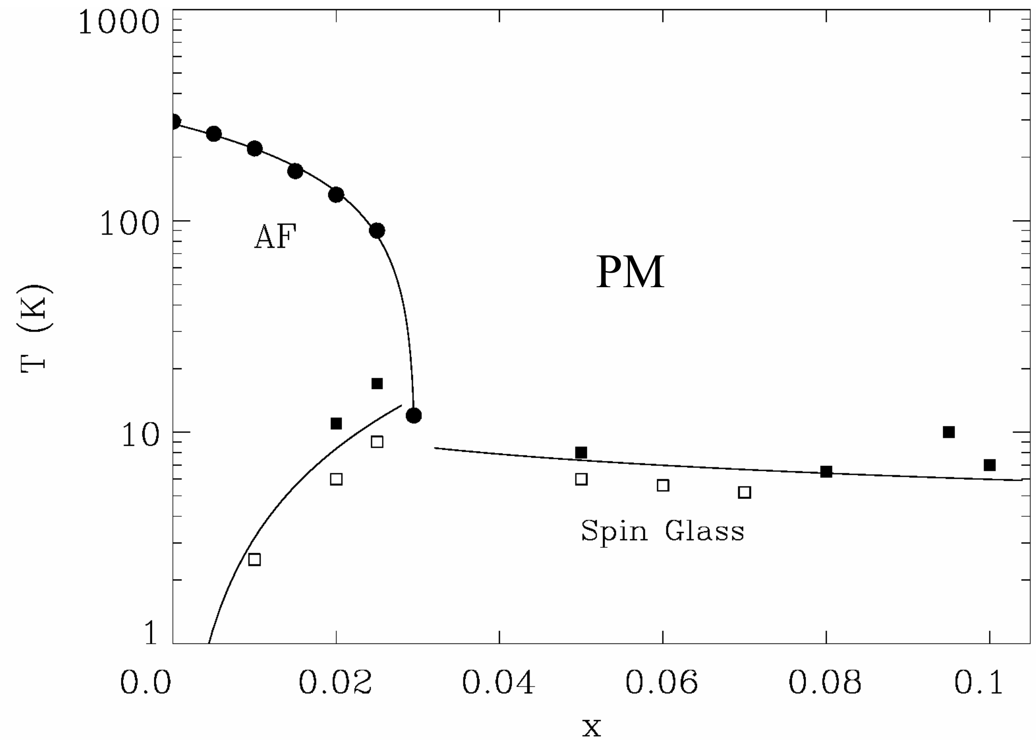
Tetragonal: $(\pi\pi0)$
Orthorhombic: (100) and (001)

✓ La_2CuO_4: insulator, 3D AF order below $T_N \approx 325$ K

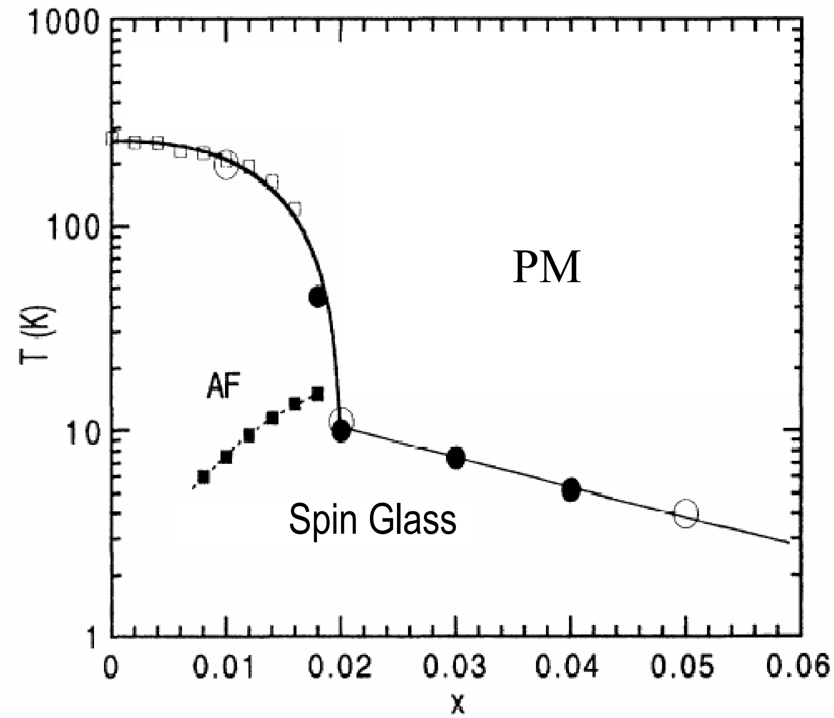
Shirane et al., PRL 59 1613 (1987)

Suppress Néel order by holes

$La_2Cu_{1-x}Li_xO_4$



$La_{2-x}Sr_xCuO_4$

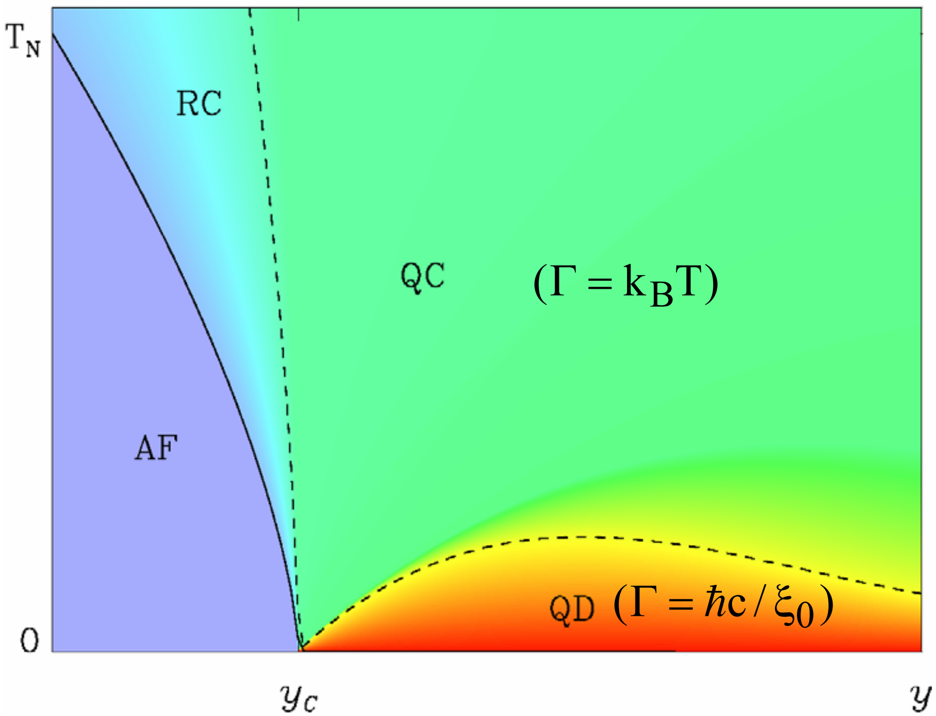


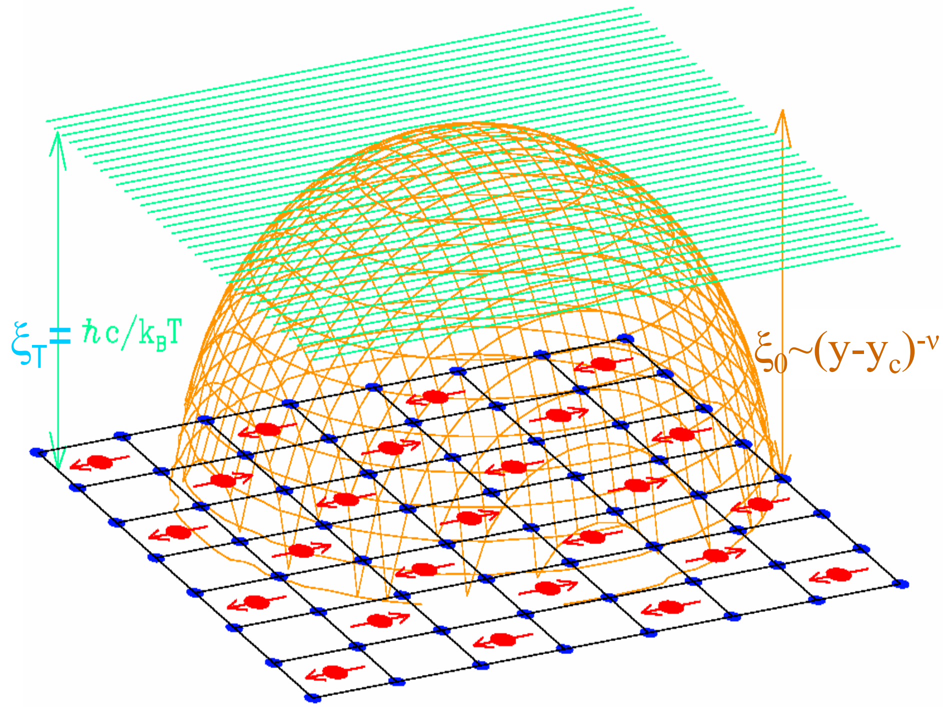
Sarrao et al. PRB 54 12014(1996); Heffner et al., Physica B (2002)
Sasagawa et al., PRB 66, 184512 (2002)

Chou et al., PRL 71, 2323 (1993)

✓ The 3D long range AF order in La_2CuO_4 can be suppressed by 2-3% hole doping using Sr or Li, thus allowing experimental investigation of the quantum spin dynamics of the 2D paramagnetic state of hole-doped La_2CuO_4 in a wide temperature range $T_{sf}<T<<J/k_B\sim1000$ K

Theoretical phase diagram





$$\text{QC}: \quad \xi_T < \xi_0 \qquad \Gamma = \hbar c / \xi_T = k_B T \qquad T > Tx = hc/k_B \xi_0$$

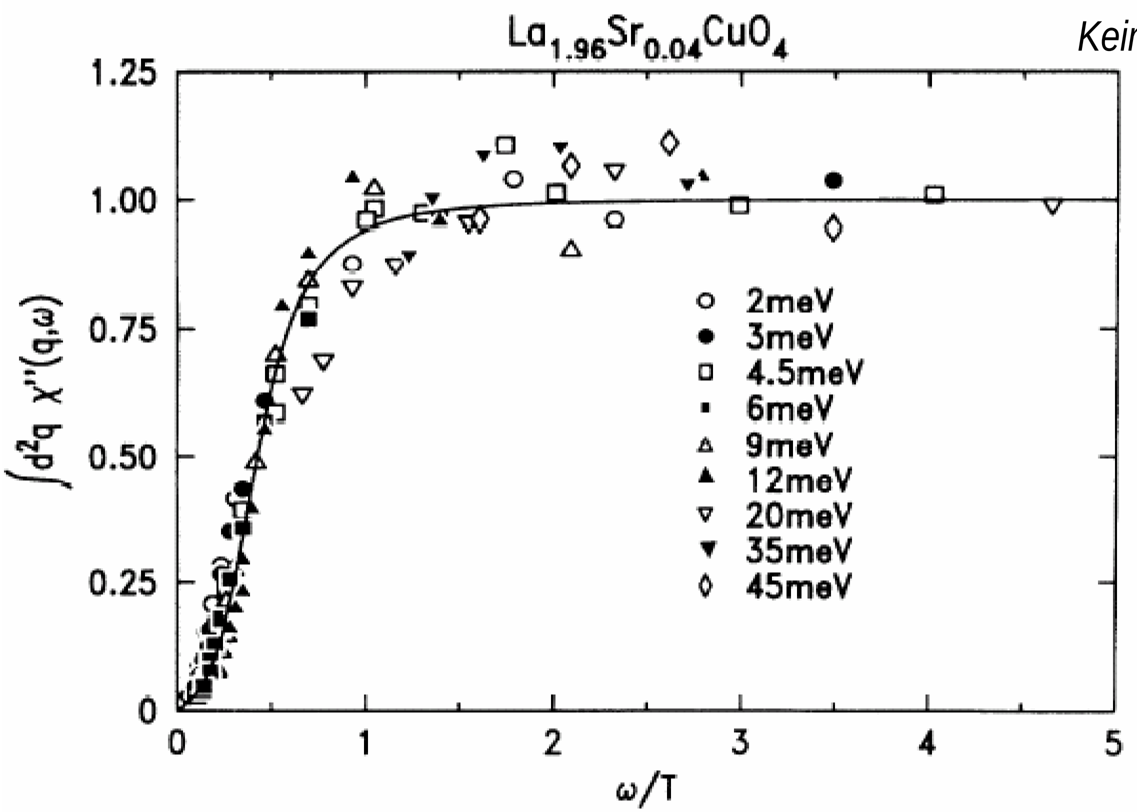
$$\text{QD}: \quad \xi_0 < \xi_T \qquad \Gamma = \hbar c / \xi_0 \qquad T < Tx$$

✓ A crossover from the quantum critical (QC) regime, where the energy scale is $k_B T$, to the quantum disordered (QD) regime, where the energy scale is constant, is predicted for $y > y_c$ of 2D Heisenberg antiferromagnet

Sachdev, Science 288, 475 (2000); Chakravarty, et al., PRL 60, 1057 (1988)

Quantum critical ω/T scaling

Keimer et al., PRL 67, 1930 (1991)



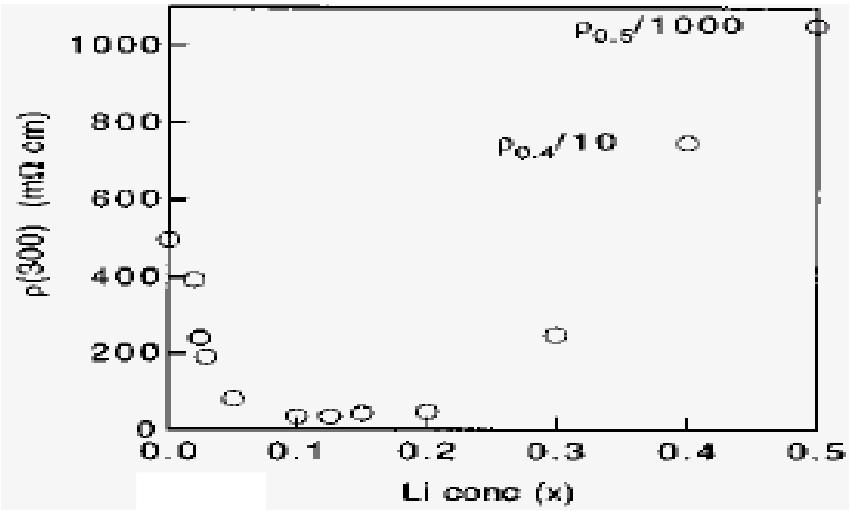
✓ The ω/T scaling has been observed in Sr and Ba doped La_2CuO_4 as a consequence of quantum criticality

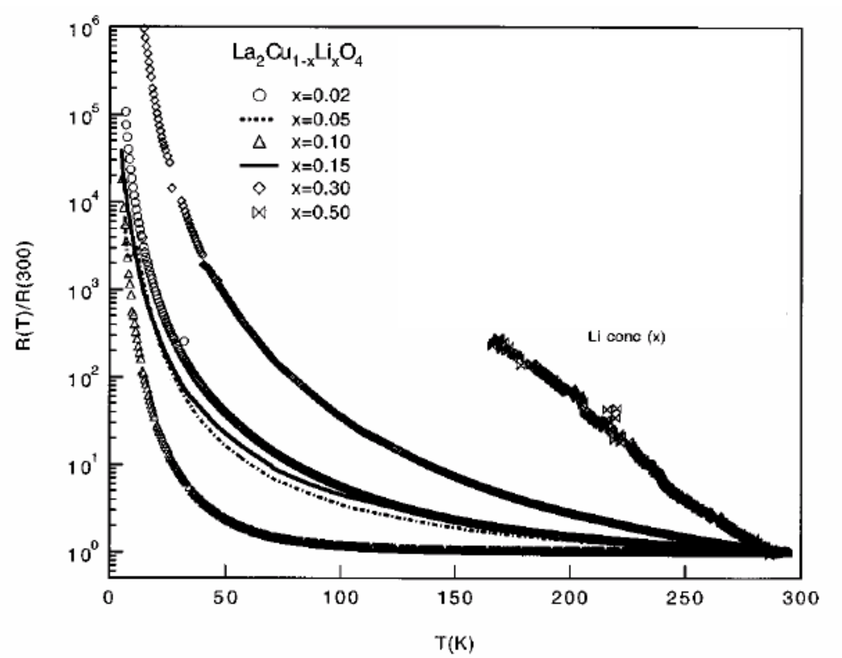
Aeppli, Science(1997); Keimer, PRL (1991); Hayden, PRL(1991)

Direct observation of quantum critical to quantum disordered crossover in Li doped La_2CuO_4

Transport properties

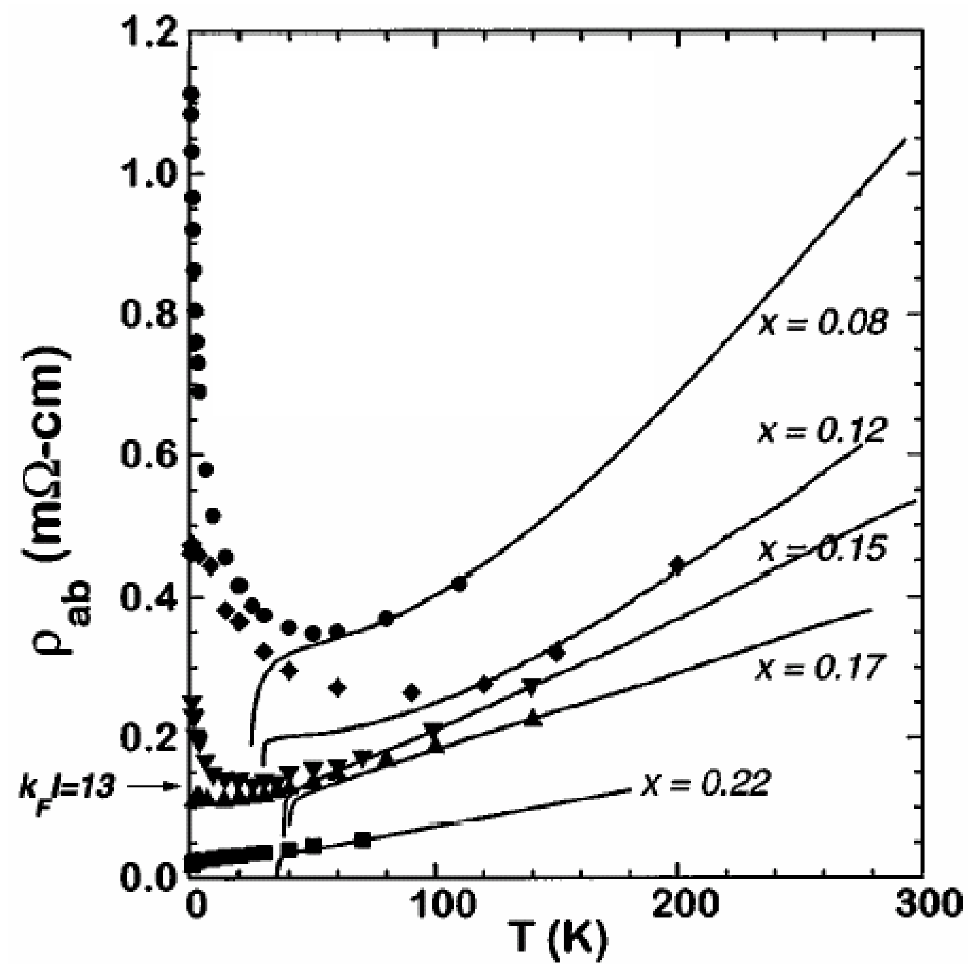
$La_2Cu_{1-x}Li_xO_4$





Sarrao et al., PRB 54,12014 (1996)

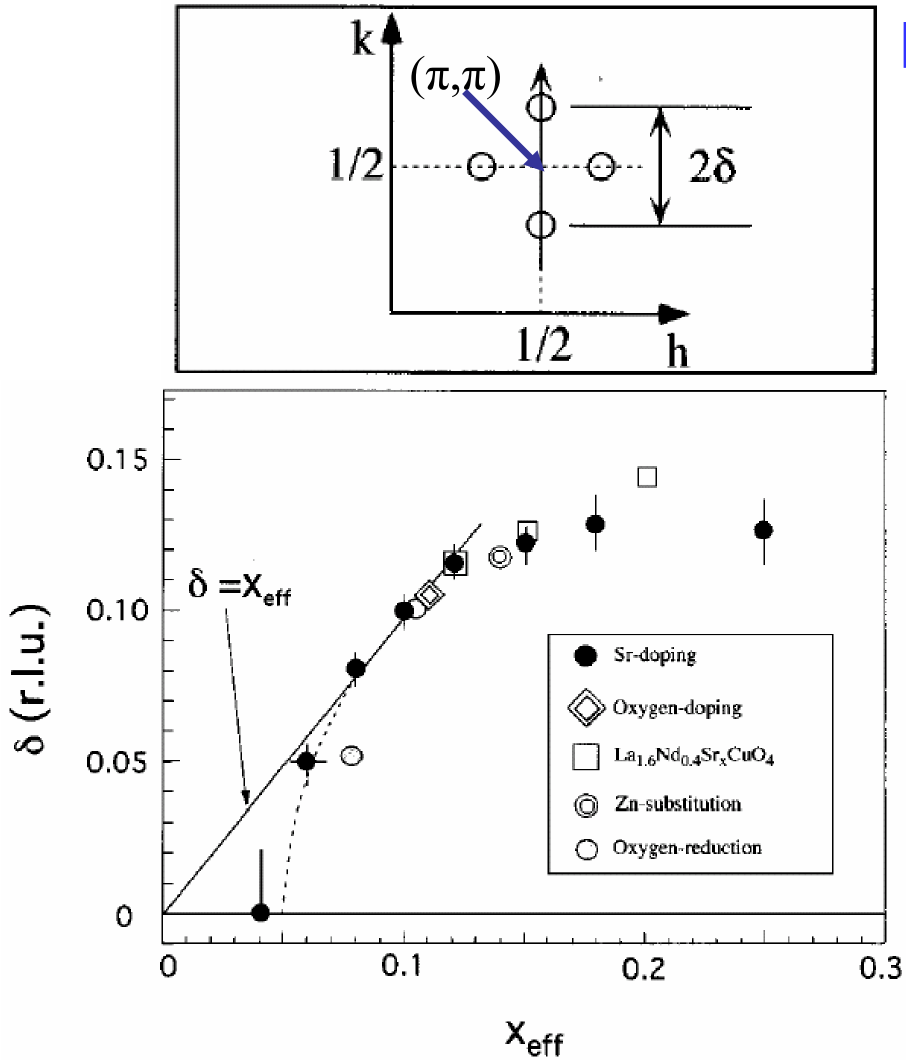
$La_{2-x}Sr_xCuO_4$



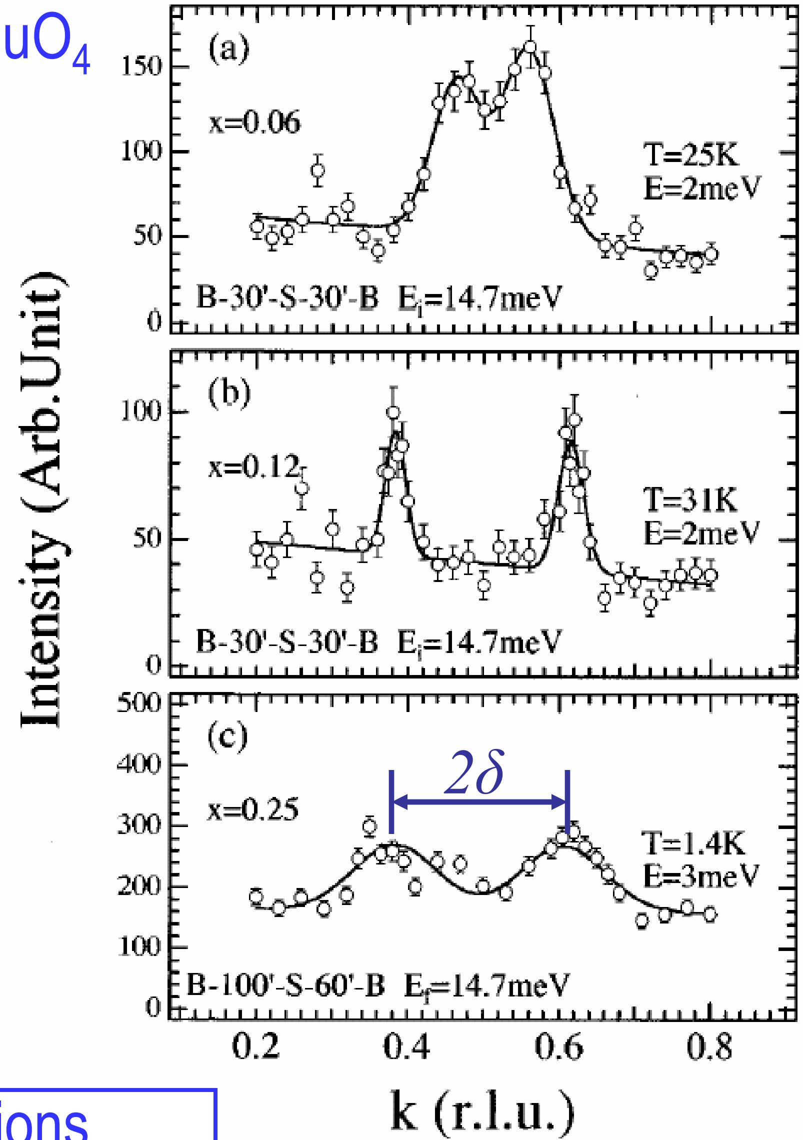
Boebinger et al., PRL 77, 5417 (1996)

✓Sr doping creates a more mobile holes than Li doping

Incommensurate magnetic correlations



$La_{2-x}Sr_xCuO_4$

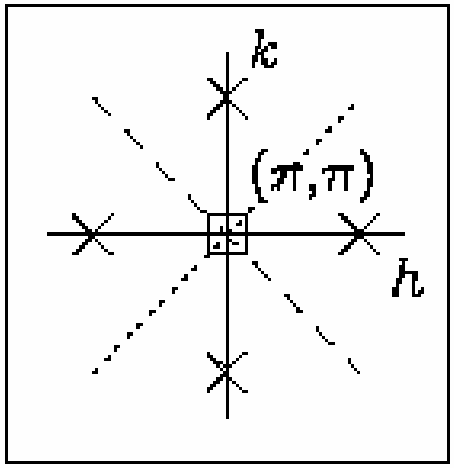


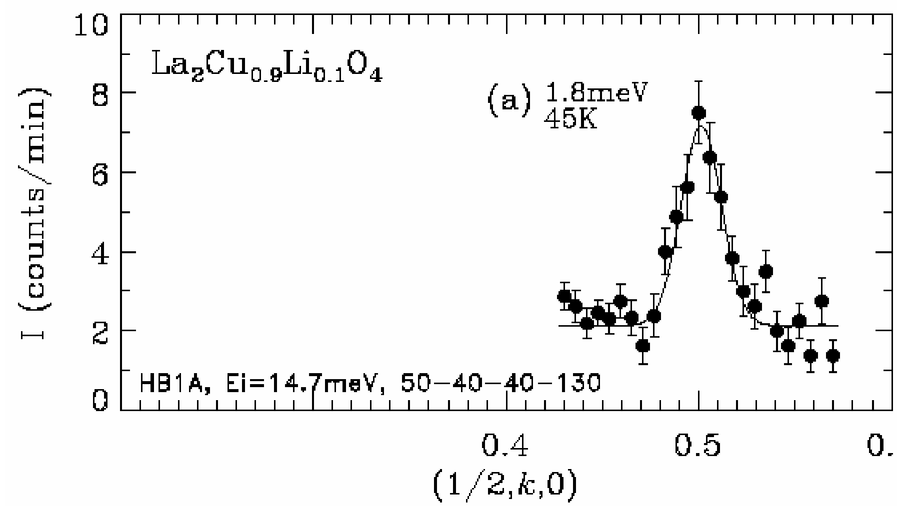
✓ Incommensurate dynamic magnetic correlations in $La_{2-x}Sr_xCuO_4$ *S.-W. Cheong et al., PRL 67,1791 (1991)*

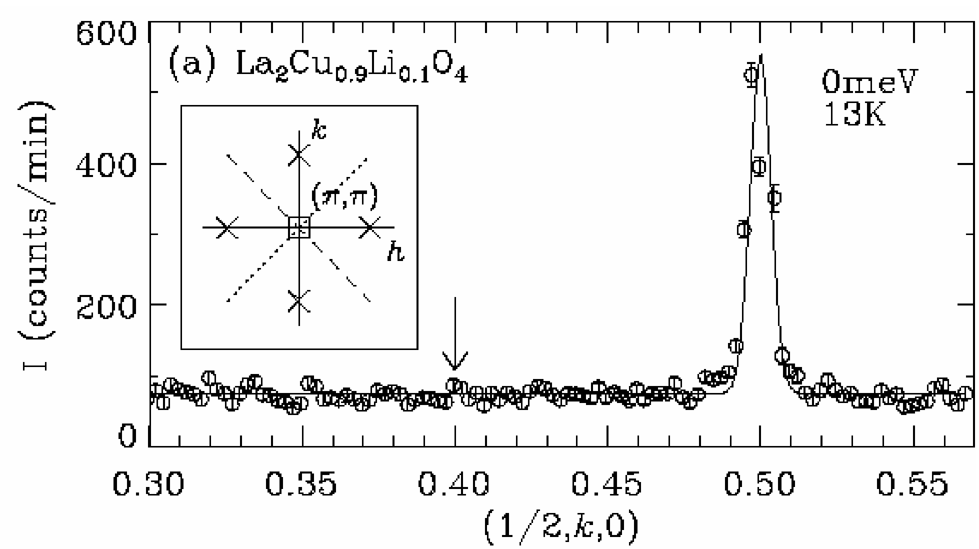
Yamada, PRB 57,6165 (1998)

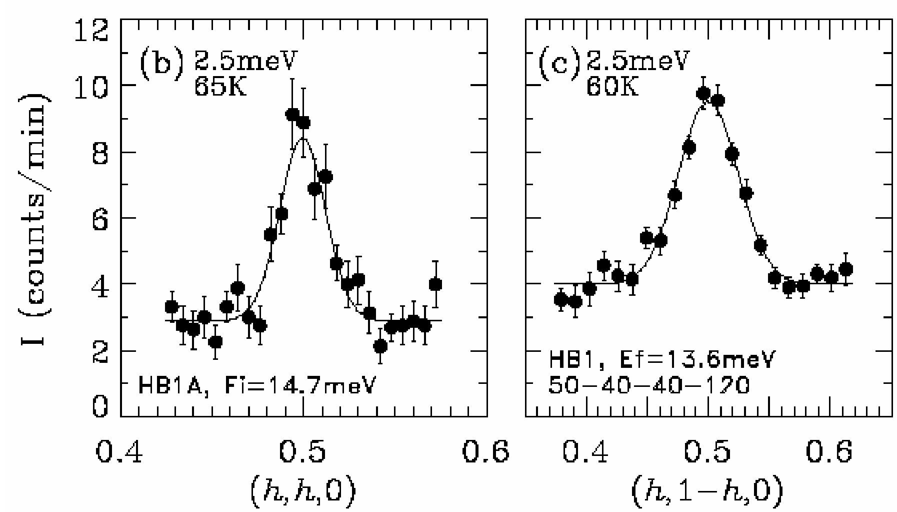
Commensurate magnetic correlations

$La_2Cu_{1-x}Li_xO_4$





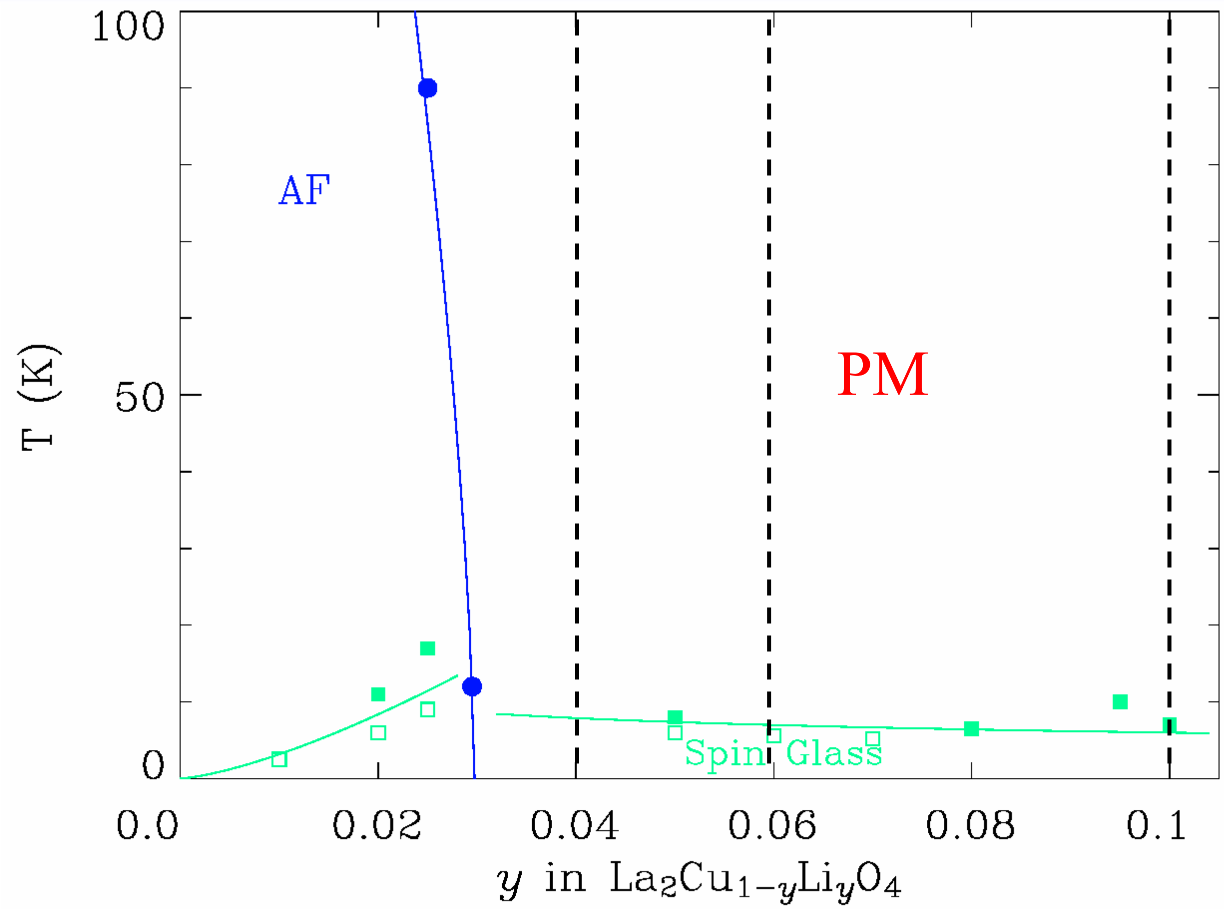




✓ Commensurate dynamic magnetic correlations in $LaCu_{1-x}Li_xO_4$

Bao et.al., PRL 84, 3978 (2000)

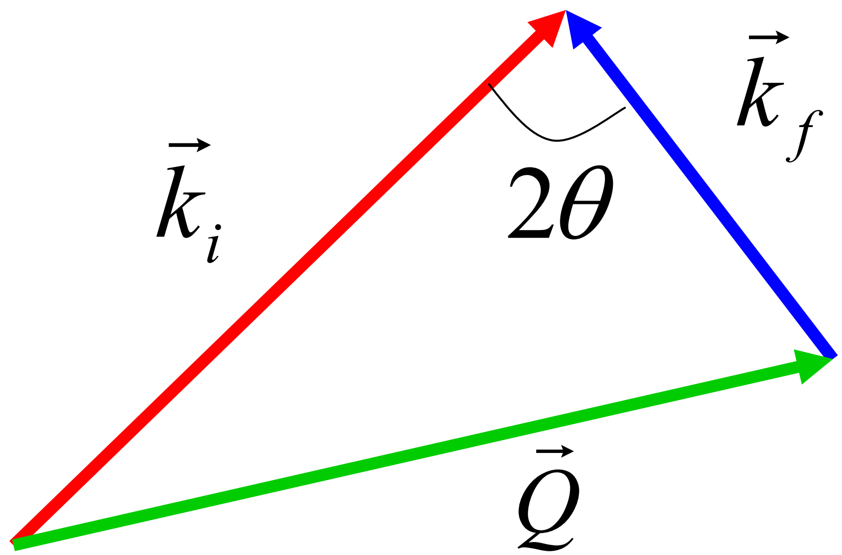
Phase diagram of $La_2Cu_{1-x}Li_xO_4$



Sarrao et al. PRB 54 12014(1996); Heffner et al., Physica B (2002); Sasagawa et al., PRB 66, 184512 (2002)

✓ Cold neutron inelastic scattering study of the quantum spin dynamics of 2D paramagnetic state of $La_2Cu_{1-x}Li_xO_4$ (x=0.04, 0.06 and 0.1)

Magnetic neutron scattering



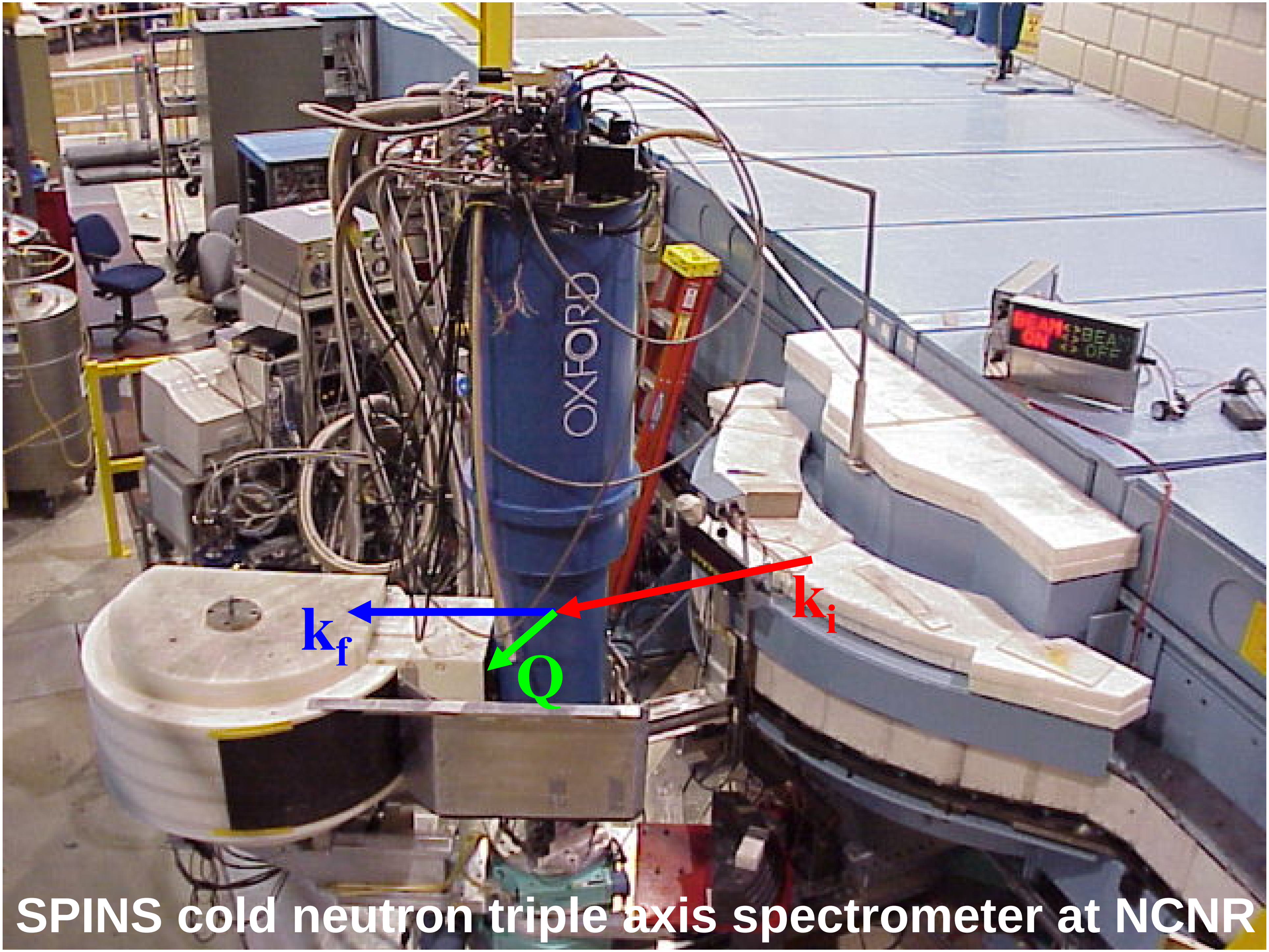
$$\vec{Q} = \vec{k}_i - \vec{k}_f$$
$$\hbar\omega = E_i - E_f$$

The scattering cross section is proportional to the *Fourier transformed dynamic spin correlation function*,

$$\mathbf{S}^{\alpha\beta}(\vec{Q},\omega) = \frac{1}{2\pi\hbar}\int dt\; e^{-i\omega t}\,\frac{1}{N}\sum_{\vec{R}\vec{R}'} e^{i\vec{Q}\bullet(\vec{R}-\vec{R}')} < S^{\alpha}_{\vec{R}}(t)\, S^{\beta}_{\vec{R}'}(0) >$$

Fluctuation-Dissipation theorem:

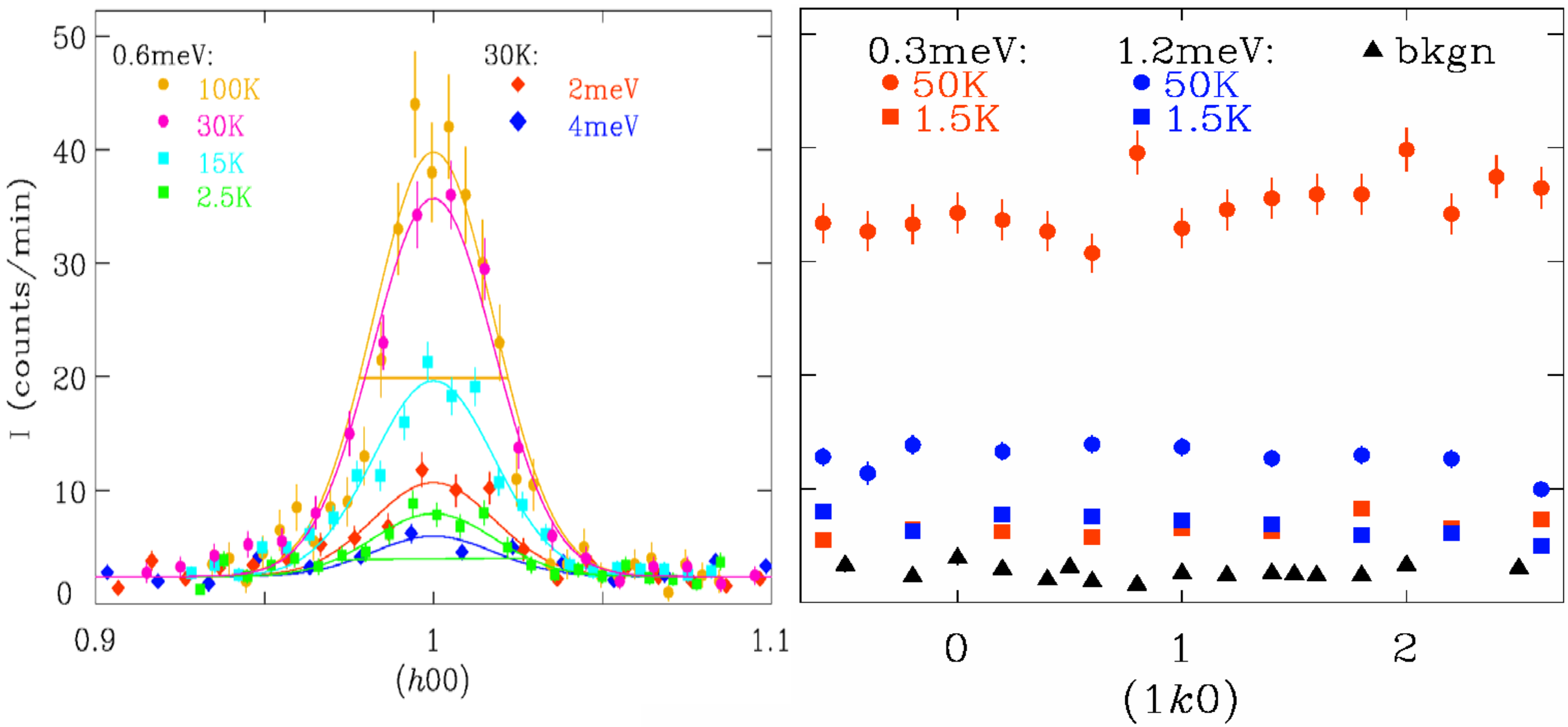
$$\chi''(\vec{Q},\omega) = \pi\left(1 - e^{-\hbar\omega/k_B T}\right)\mathbf{S}(\vec{Q},\omega)$$



SPINS cold neutron triple axis spectrometer at NCNR

Spatial spin correlations

$La_2Cu_{0.94}Li_{0.06}O_4$

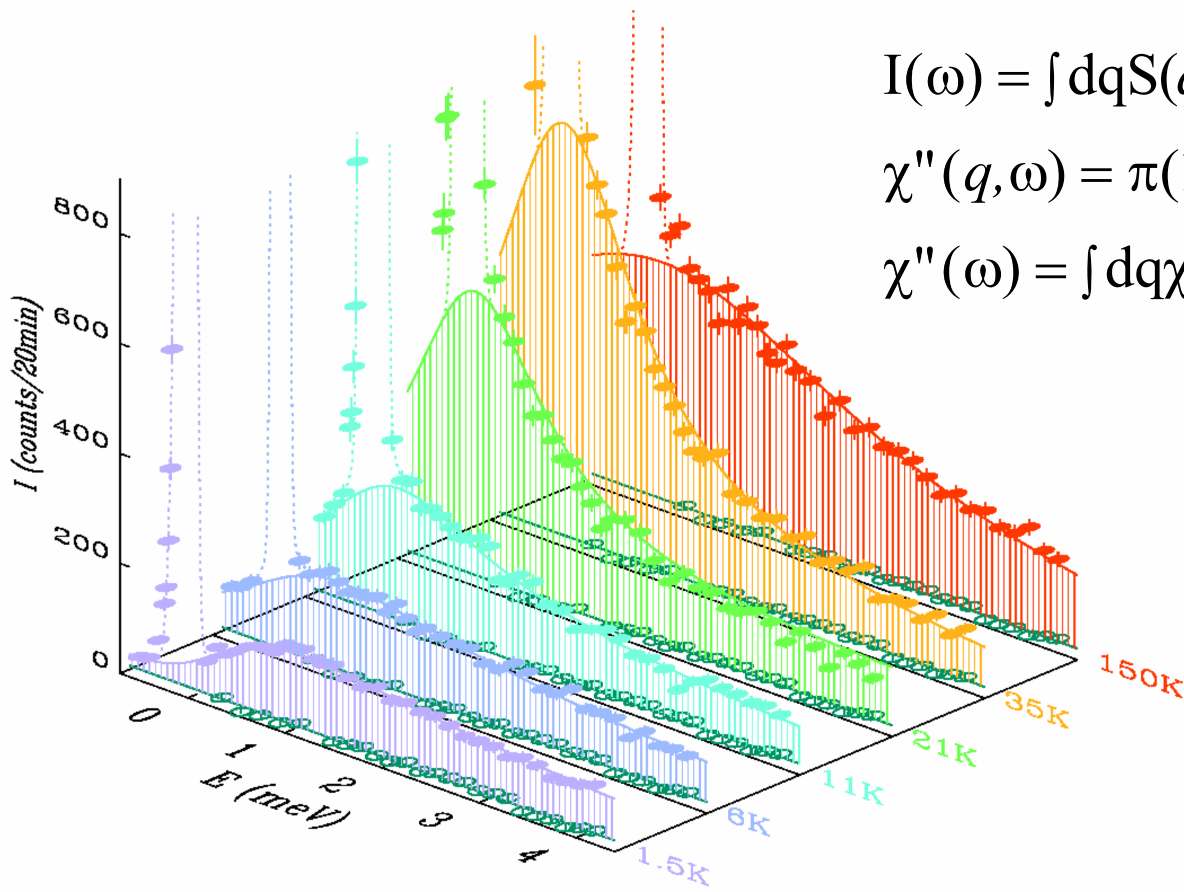


- ✓ Resolution-limited in plane peak at q=(100)=(π,π)
- ✓ In-plane correlation length, ξ, ≥40Å; mean distance of Li, d, ≈15 Å
- ✓ Flat along out-of-plane (k) direction; 2D dynamic spin correlations

Spin excitation spectra S(ω,q)

$La_2Cu_{0.94}Li_{0.06}O_4$

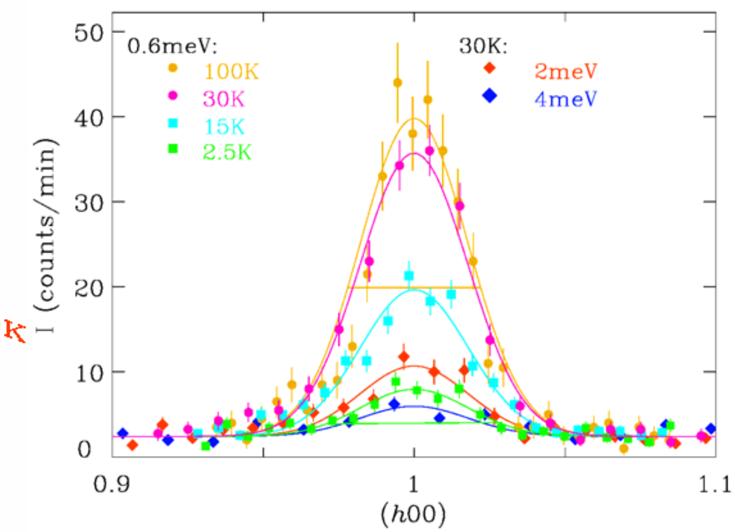
q=(100)=(π,π)



$$I(\omega) = \int dq S(q,\omega)$$

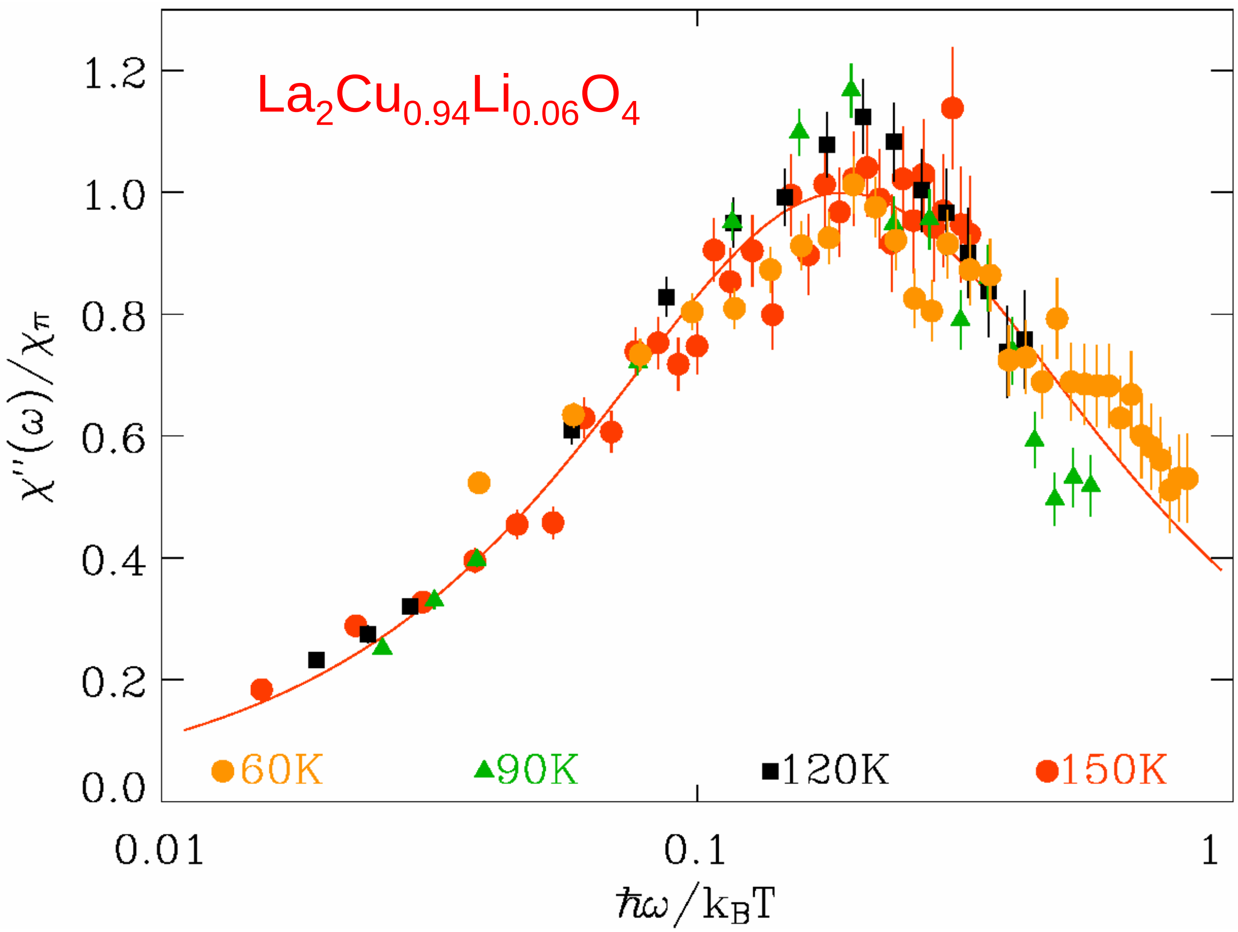
$$\chi''(q,\omega) = \pi(1-e^{-\hbar\omega/k_B T})S(q,\omega)$$

$$\chi''(\omega) = \int dq\chi''(q,\omega) = c(1-e^{-\hbar\omega/k_B T})I(\omega)$$



✓ Low energy magnetic neutron scattering intensity first enhanced, then suppressed upon cooling

ω/T scaling at high T



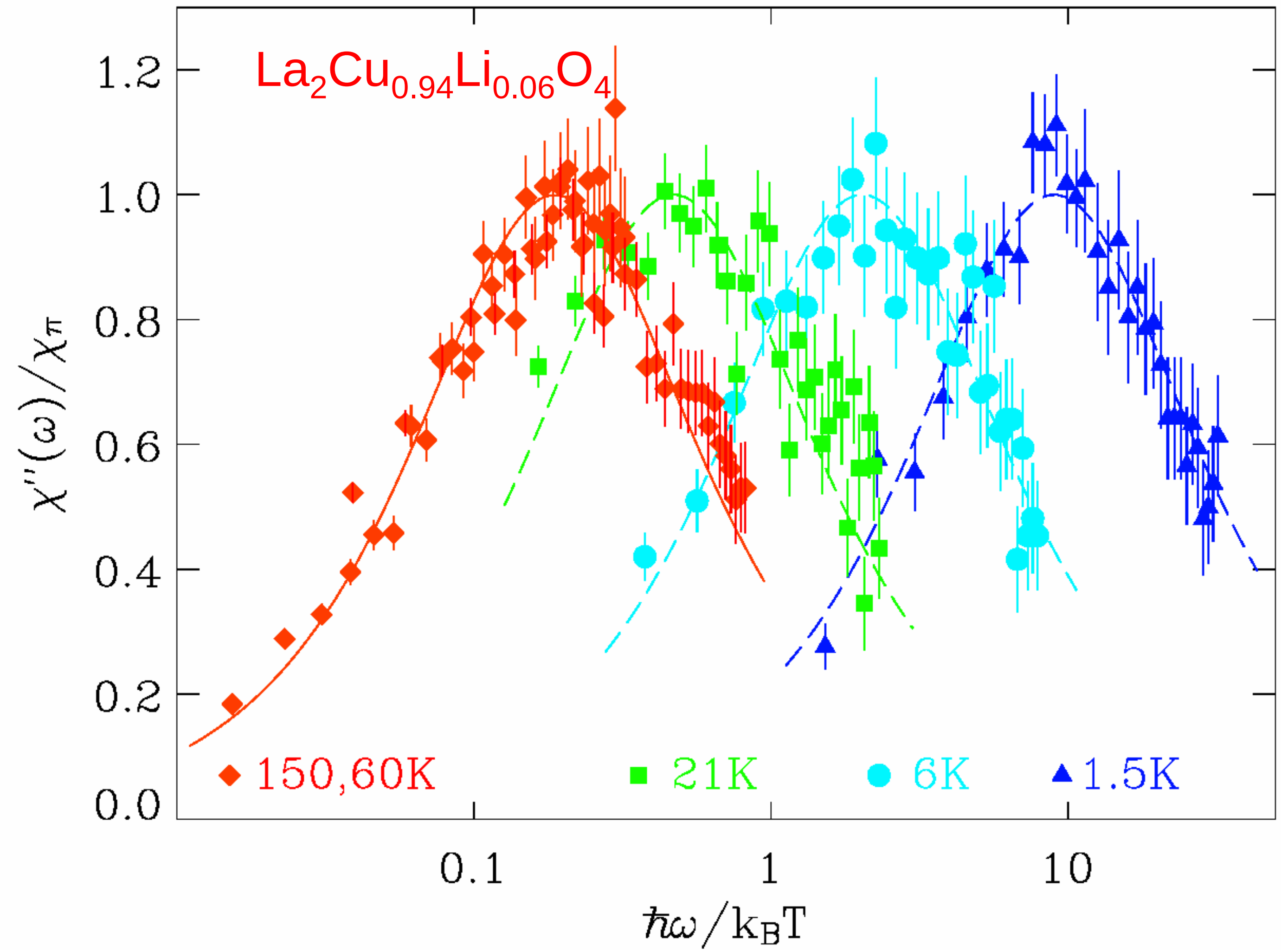
$$\chi''(\omega)/\chi_\pi = f(\hbar\omega/k_B T)$$

$$f(x) = \frac{0.18x}{0.18^2 + x^2}$$

$$\Gamma = 0.18 k_B T$$

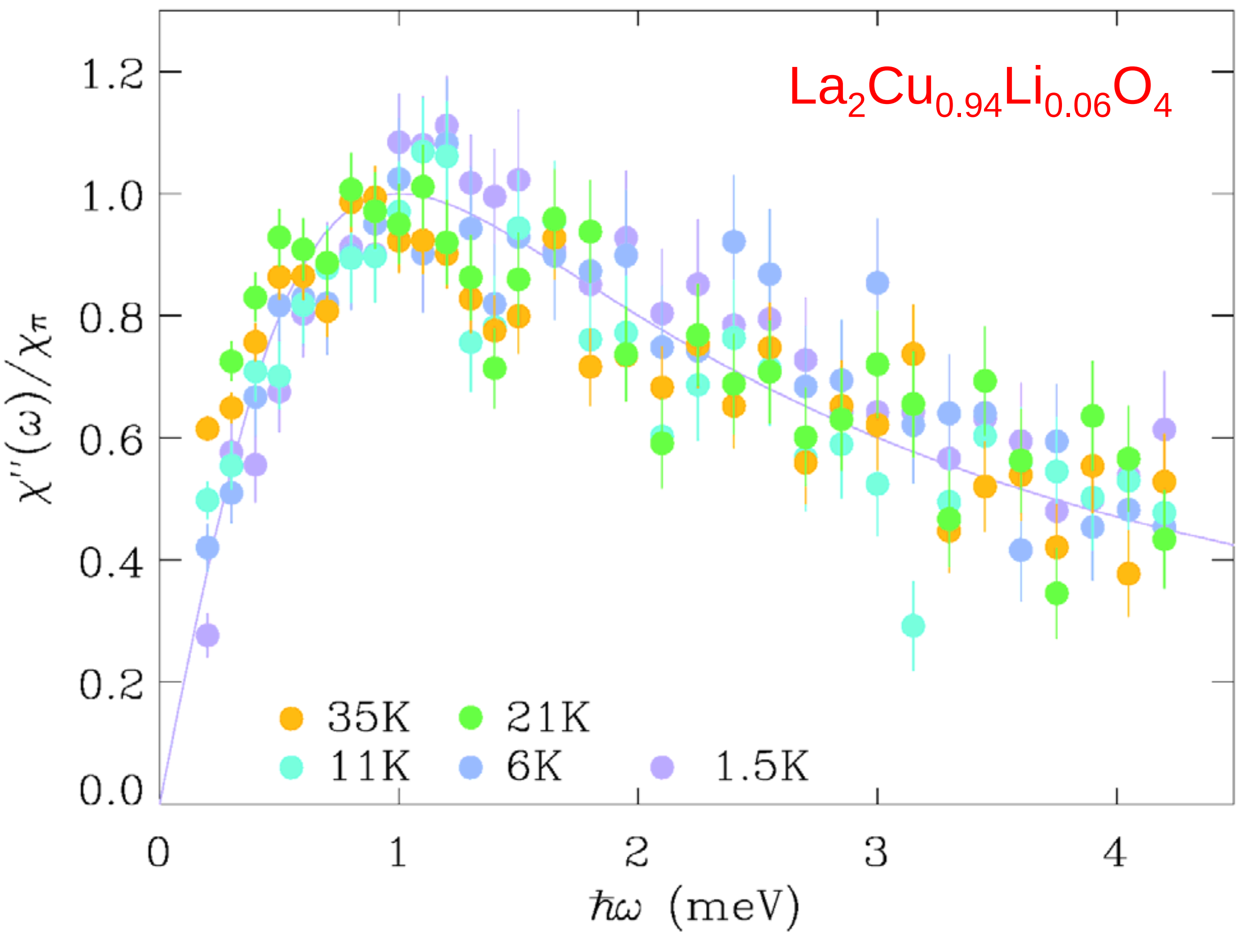
✓ Data taken above 50 K fall onto a single ω/T scaling curve

Departure from ω/T scaling at low T



✓ ω/T scaling becomes invalid below 50 K

Constant energy scale at low T



$$\chi''(\omega)/\chi_\pi = g(\hbar\omega/\Gamma_0)$$

$$g(x) = \frac{x}{1 + x^2}$$

$$\Gamma_0 \approx 1 meV$$

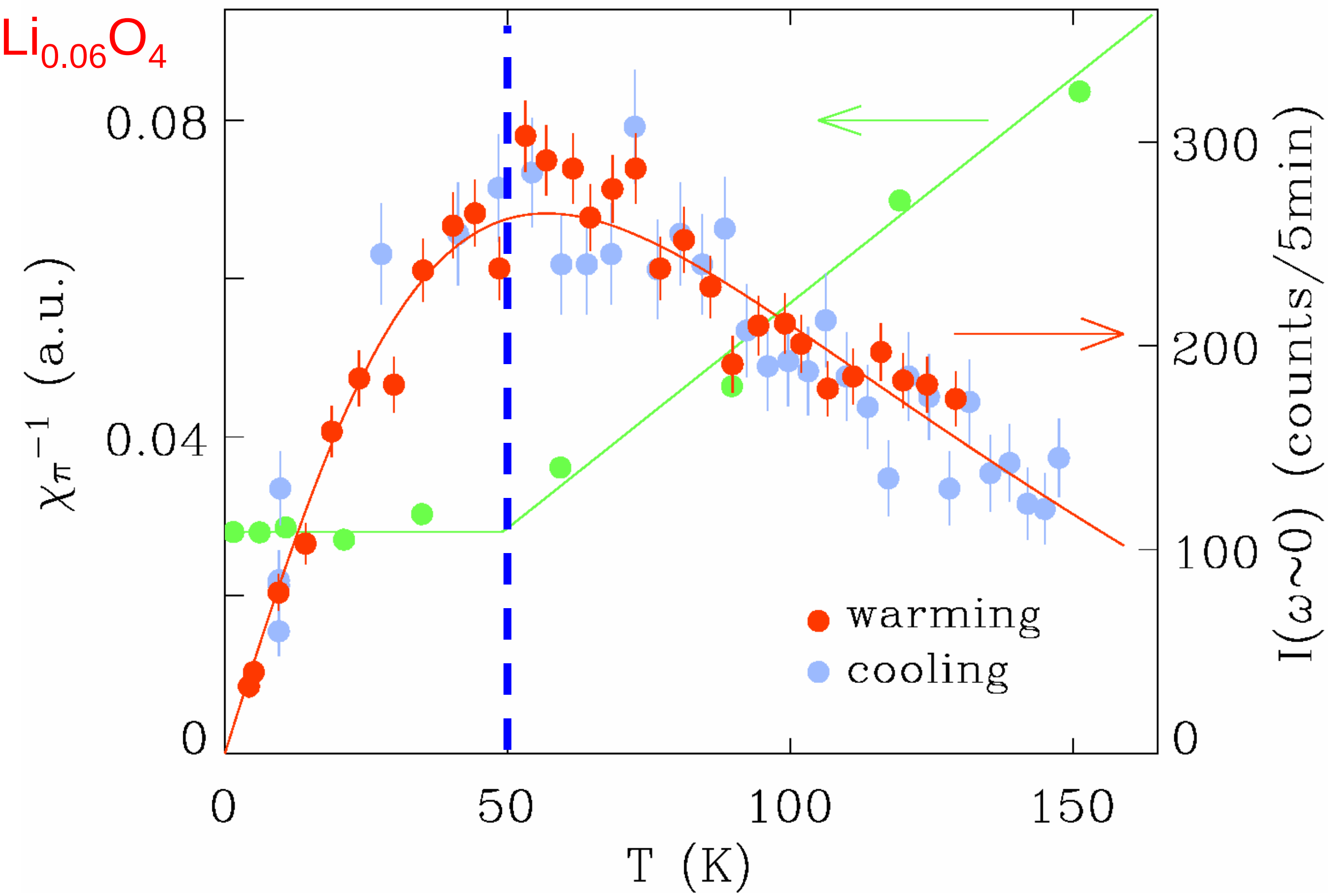
✓ Energy scale, Γ, saturates to a finite value at low temperatures

$$\Gamma = 0.18 k_B T \qquad T > 50\ \mathrm{K}$$

$$\Gamma \approx 1\mathrm{meV} \qquad T < 50\ \mathrm{K}$$

Temperature dependence of χ_π, $I(\omega\sim0)$

$La_2Cu_{0.94}Li_{0.06}O_4$



$$\chi_\pi^{-1} \propto T, \qquad T > T_x$$

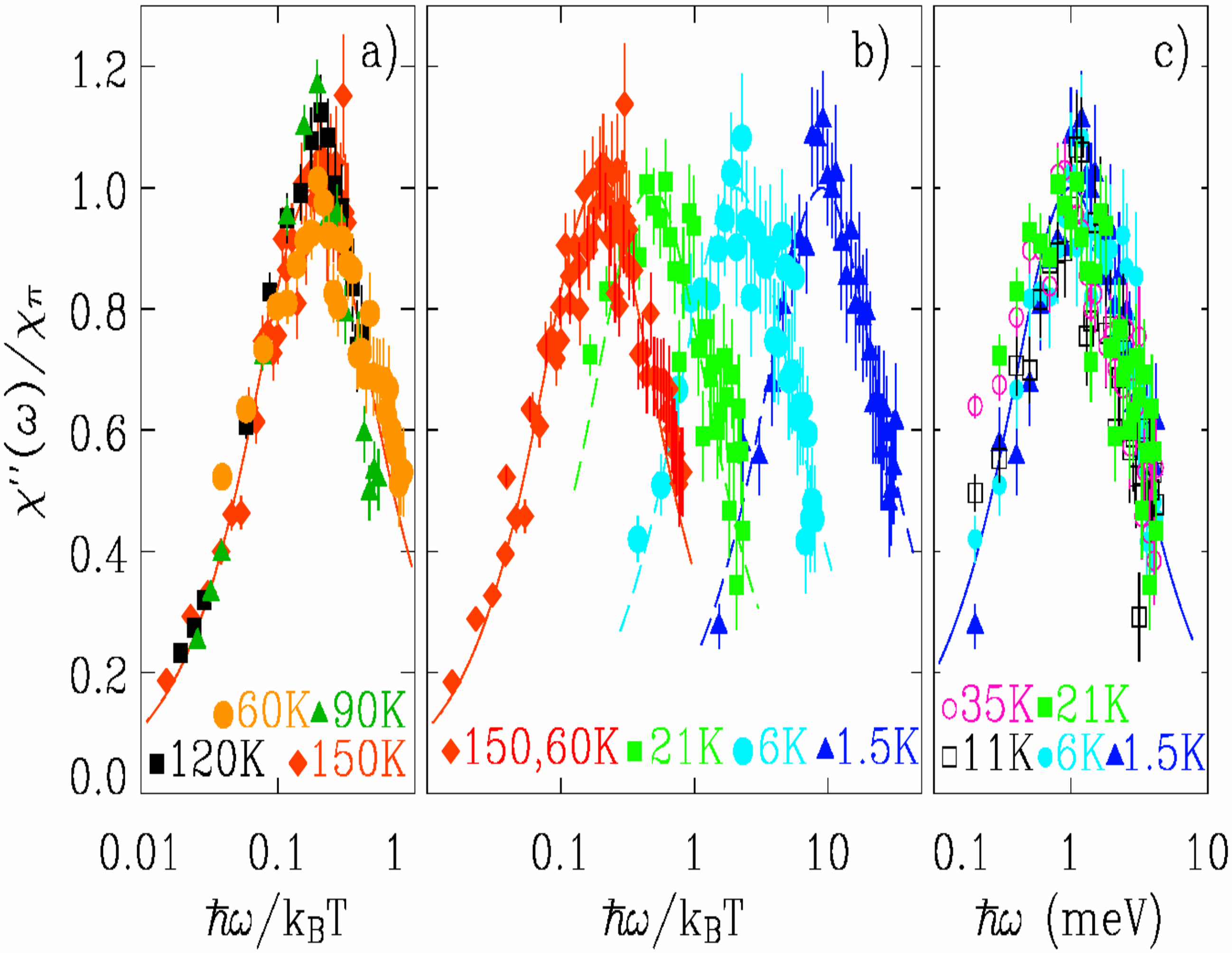
$$\chi_\pi^{-1} \sim \text{const.}, T < T_x$$

$$I(\omega \to 0) \propto T^{-1}, \; T > T_x$$

$$I(\omega \to 0) \propto T, \qquad T < T_x$$

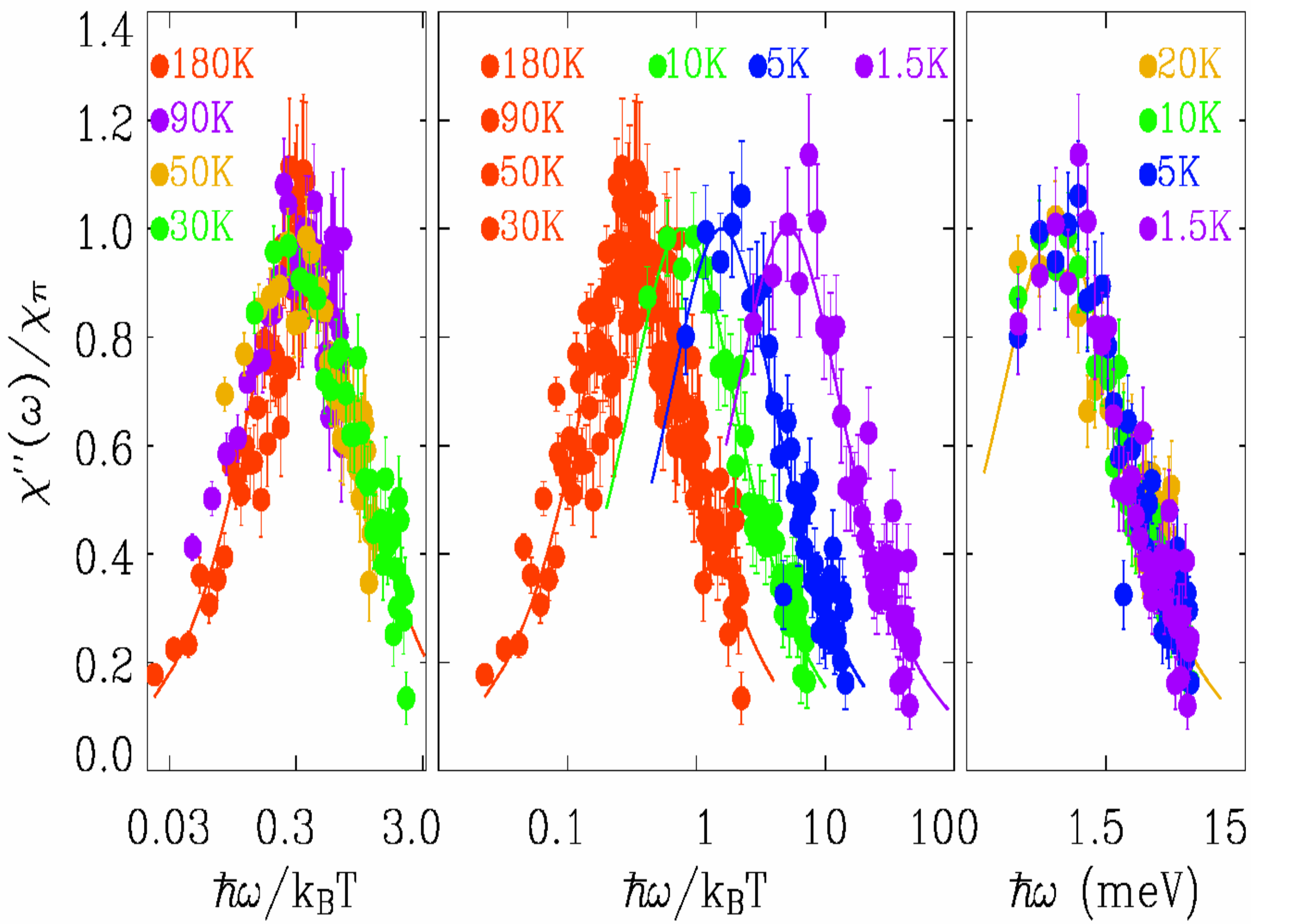
✓ Different scaling regimes below and above $T_x \approx 50K$

Scaling plot: $La_2Cu_{0.94}Li_{0.06}O_4$



- ✓ T>50K: ω/T quantum critical scaling regime
- ✓ T<50K: a novel regime with a constant energy scale

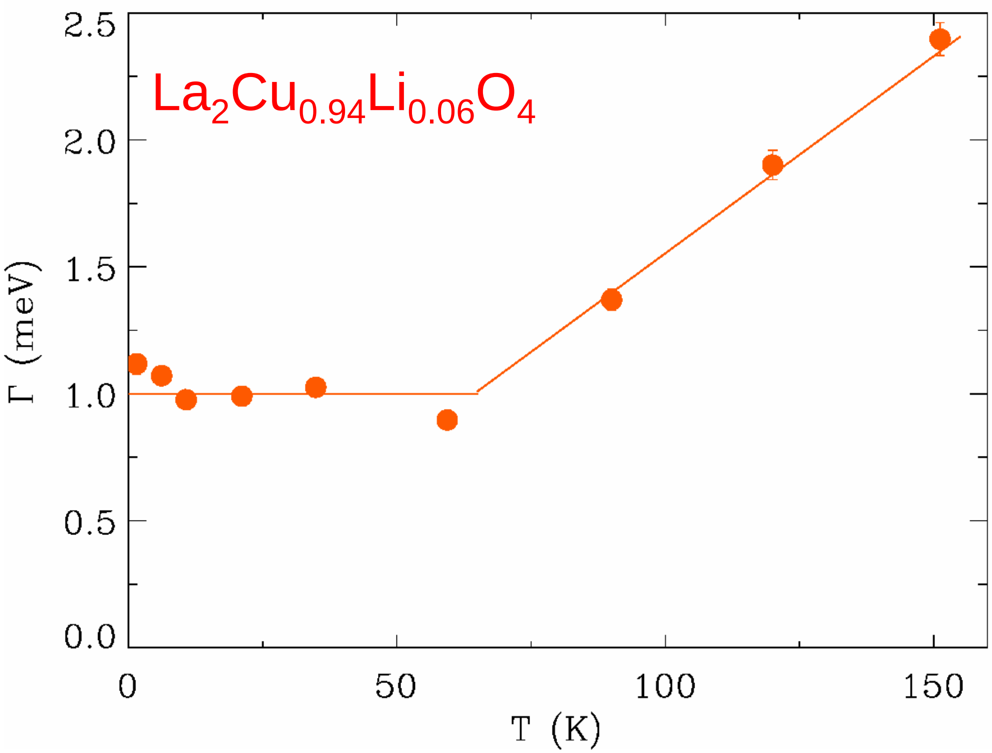
Scaling plot: $La_2Cu_{0.9}Li_{0.1}O_4$

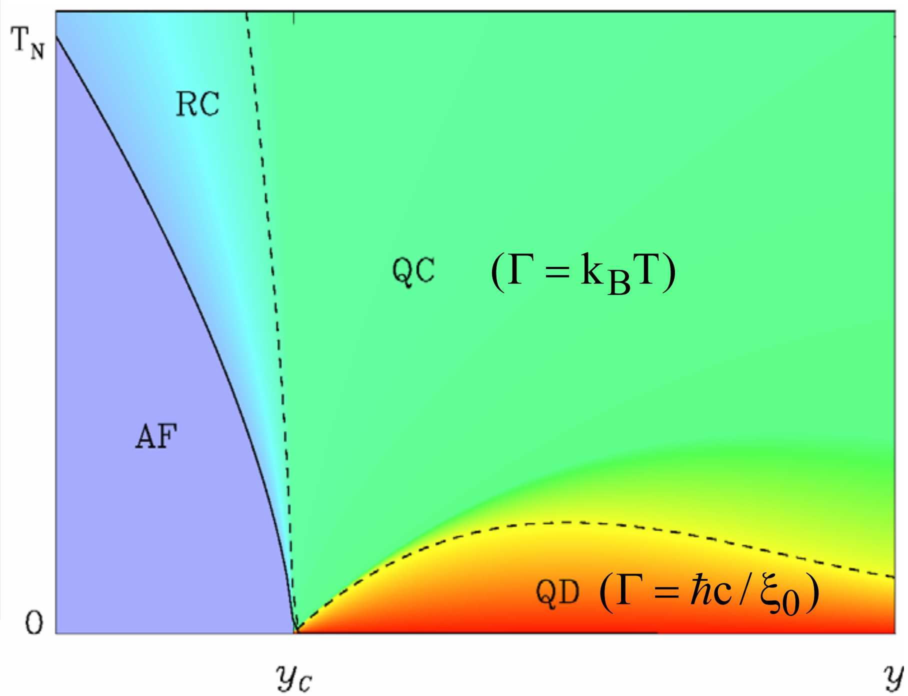


✓ T>30K: ω/T quantum critical scaling regime

✓ T<30K: a novel regime with a constant energy scale

The novel low temperature regime





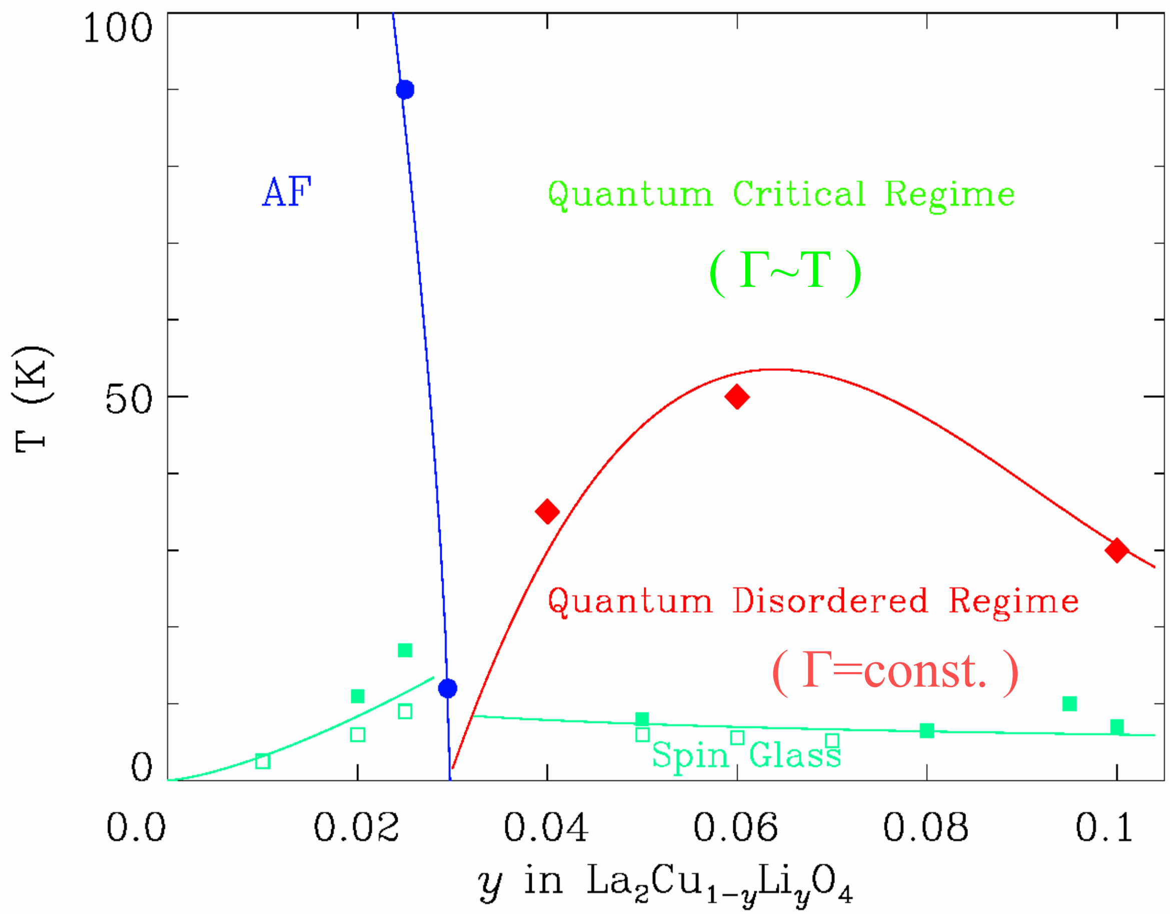
✓The observed crossover is not related to the spin glass transition

✓The low temperature regime may be the QD regime of 2D Heisenberg AF

✓ Gapless $\chi''(\omega)$: possible role of spin-charge scattering

Sachdev et al., PRB 51, 14874 (1995); Liu and Su, Phys. Lett. 200, 393 (1995).

Experimental phase diagram $La_2Cu_{1-y}Li_yO_4$



✓ A crossover from ω/T scaling to a novel constant energy scale regime upon cooling in all samples with T_x =35, 50 and 30 K for y=0.04, 0.06 and 0.1

Summary

✓ First observation of a crossover in spin dynamics from the quantum critical ω/T scaling to a new low temperature regime with a constant energy scaling upon cooling in $La_2Cu_{1-y}Li_yO_4$ (y=0.04, 0.06 and 0.1)

✓ Gapless $\chi''(\omega)$: possible coupling between doped holes and spin dynamics in doped cuprates

✓Magnetic phase separation: the 2D (π,π)-correlated spin component not frozen

W. Bao Y. Chen et al., Phys. Rev. Lett. ***91,*** *127005 (2003)*
W. Bao et al., Phys. Rev. Lett. ***84****,3978 (2000)*