Neutron and x-ray scattering studies of superconductors

lecture 2: unconventional superconductors

- magnetic neutron scattering continued
- resonant inelastic x-ray scattering from magnons and paramagnons
- resonant elastic x-ray scattering from charge density waves

lecture 3: cuprate and nickelate superlattices

- orbital occupation
- magnetic order
- charge density waves

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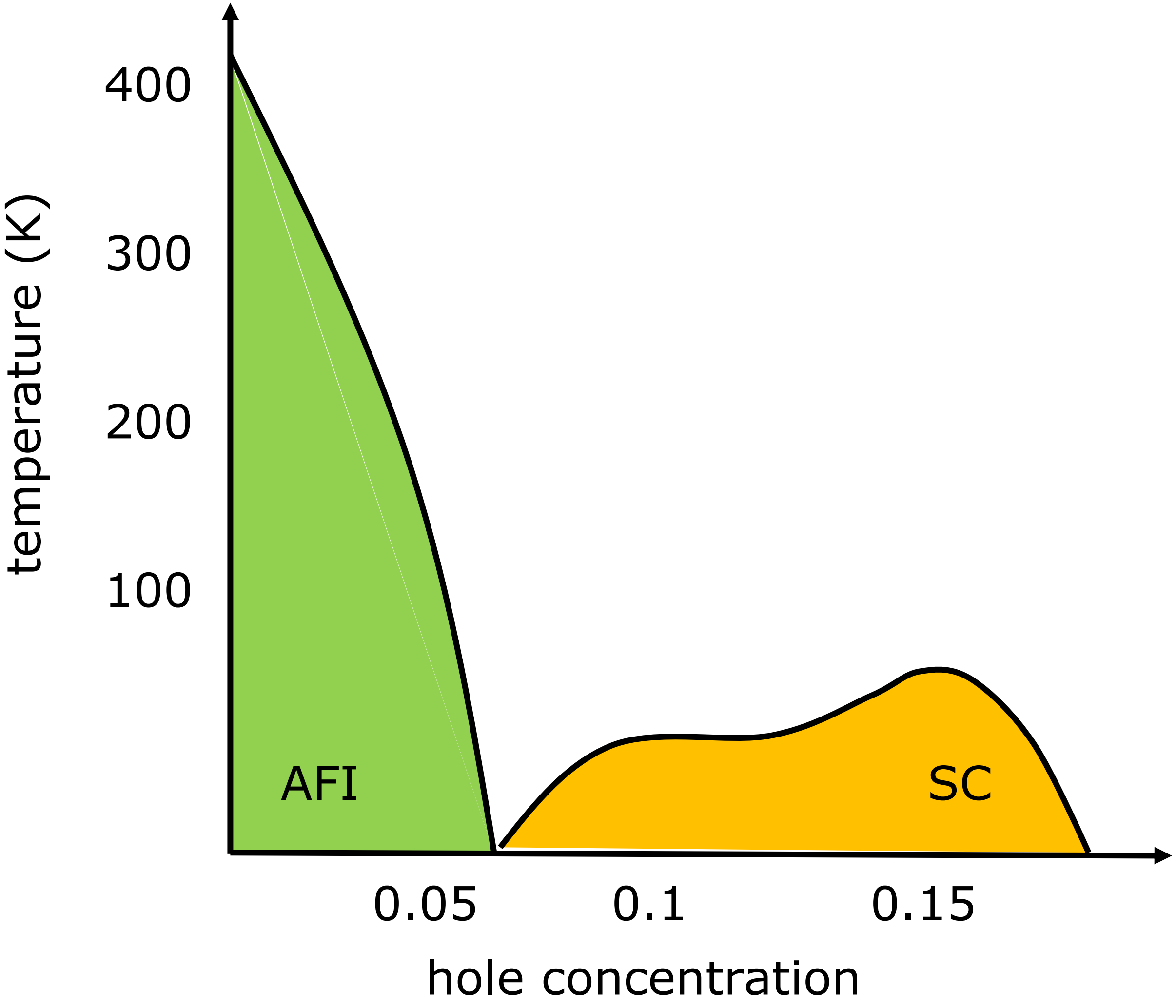
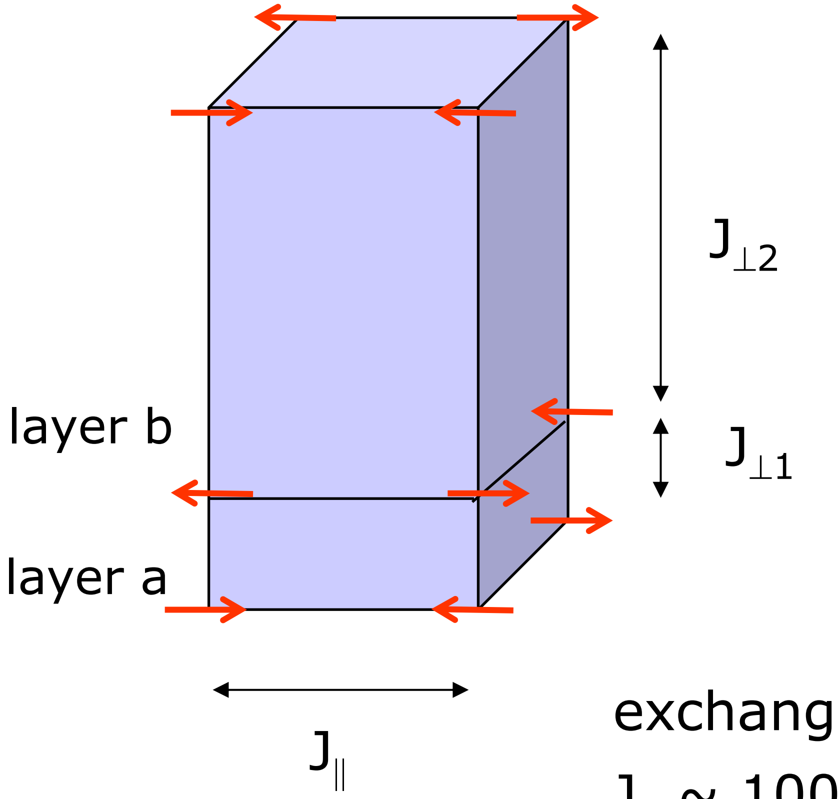
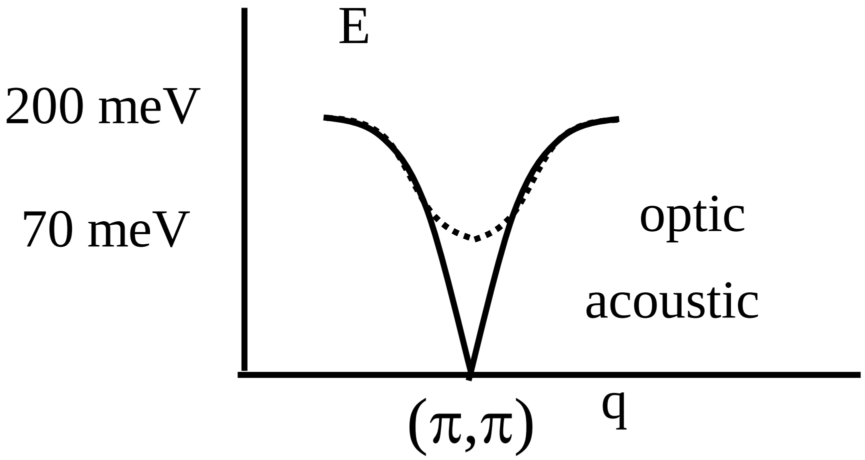
Phase diagram of $YBa_2Cu_3O_{6+x}$



$YBa_2Cu_3O_6$ magnons

$$H = \Sigma_{ij} (J_\parallel S_i^{(a,b)} \bullet S_j^{(a,b)}) + \Sigma_i (J_{\perp 1} S_i^{(a)} \bullet S_i^{(b)} + J_{\perp 2} S_i^{(b)} \bullet S_i^{(a)})$$





exchange parameters from magnon dispersions

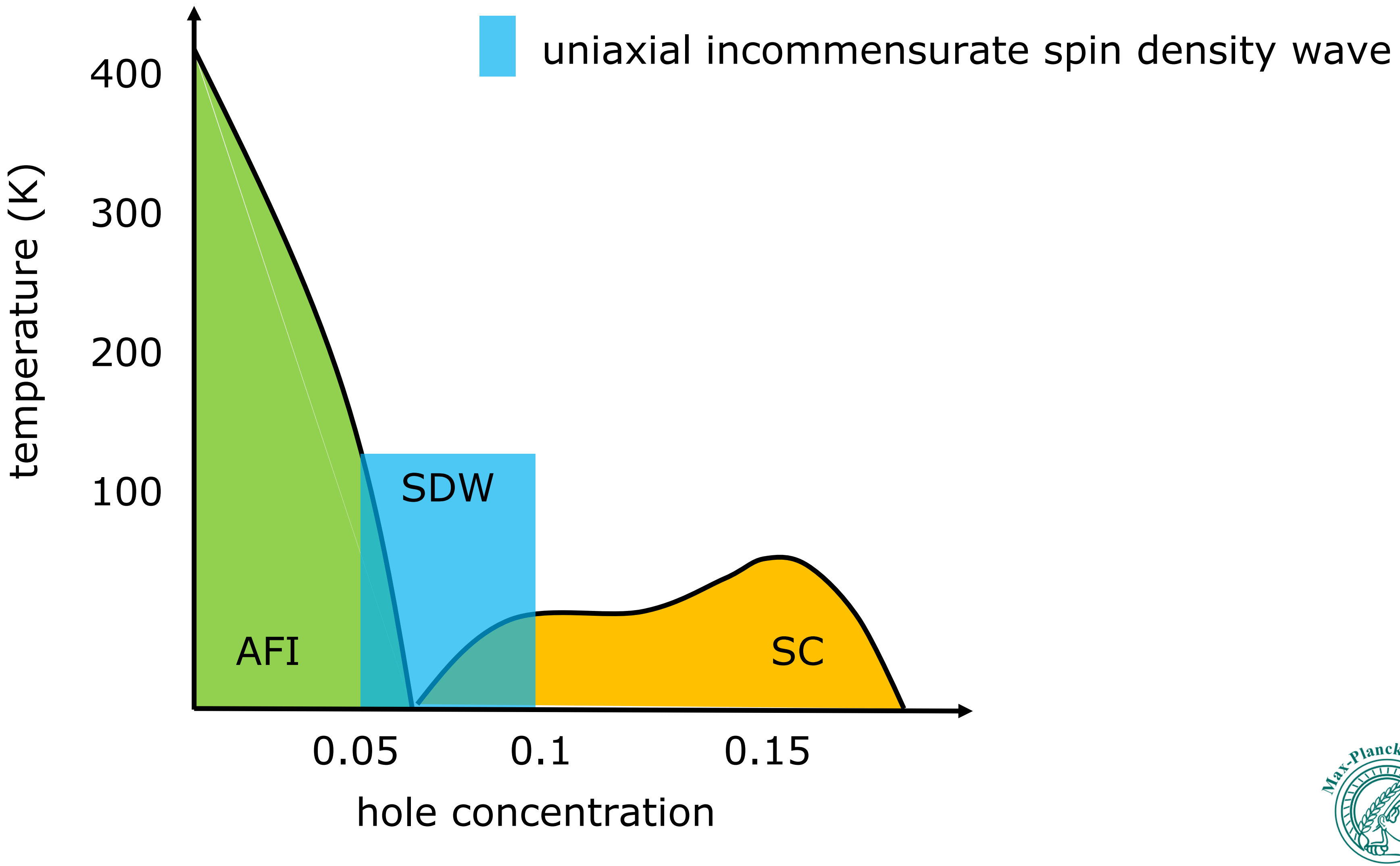
$J_\parallel \sim 100$ meV

$J_{\perp 1} \sim 10$ meV

$J_{\perp 2} \sim 0.01$ meV

Tranquada et al., PRB 1989
Reznik et al., PRB 1996

Competing order in $YBa_2Cu_3O_{6+x}$



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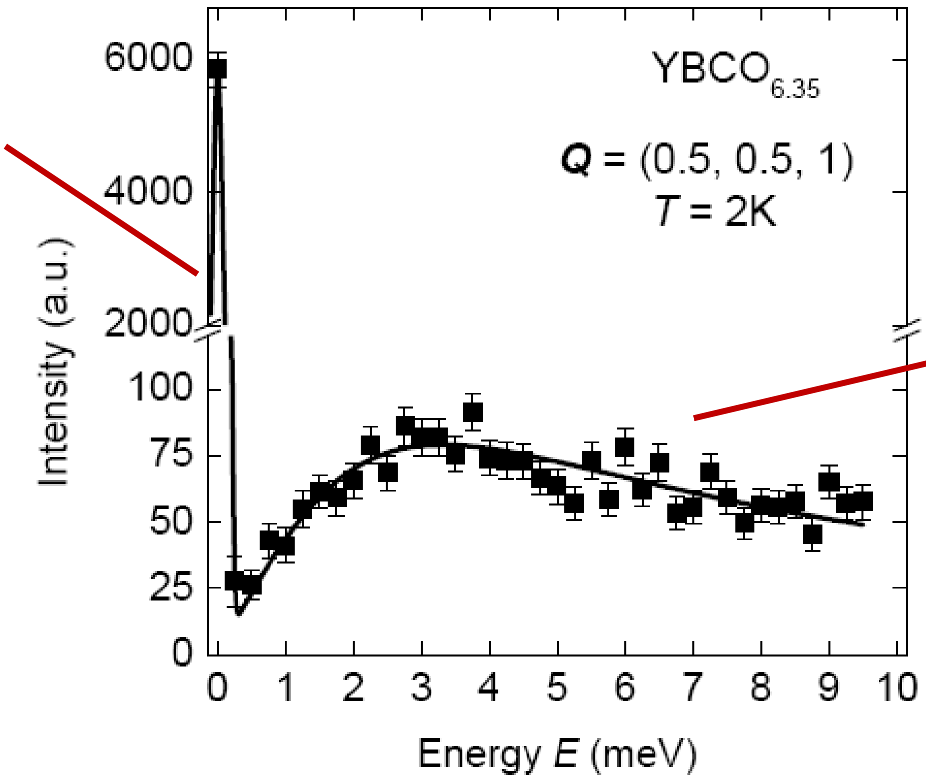
Lightly doped YBCO

$YBCO_{6.35}$ $T_c = 10$ K p ~ 0.06

quasielastic peak



spin excitations

Haug et al.
NJP 2010

analogous to Bragg peak, spin waves of antiferromagnetic Mott insulator

but centered on incommensurate wave vector

Low-energy spin fluctuations

neutron scattering

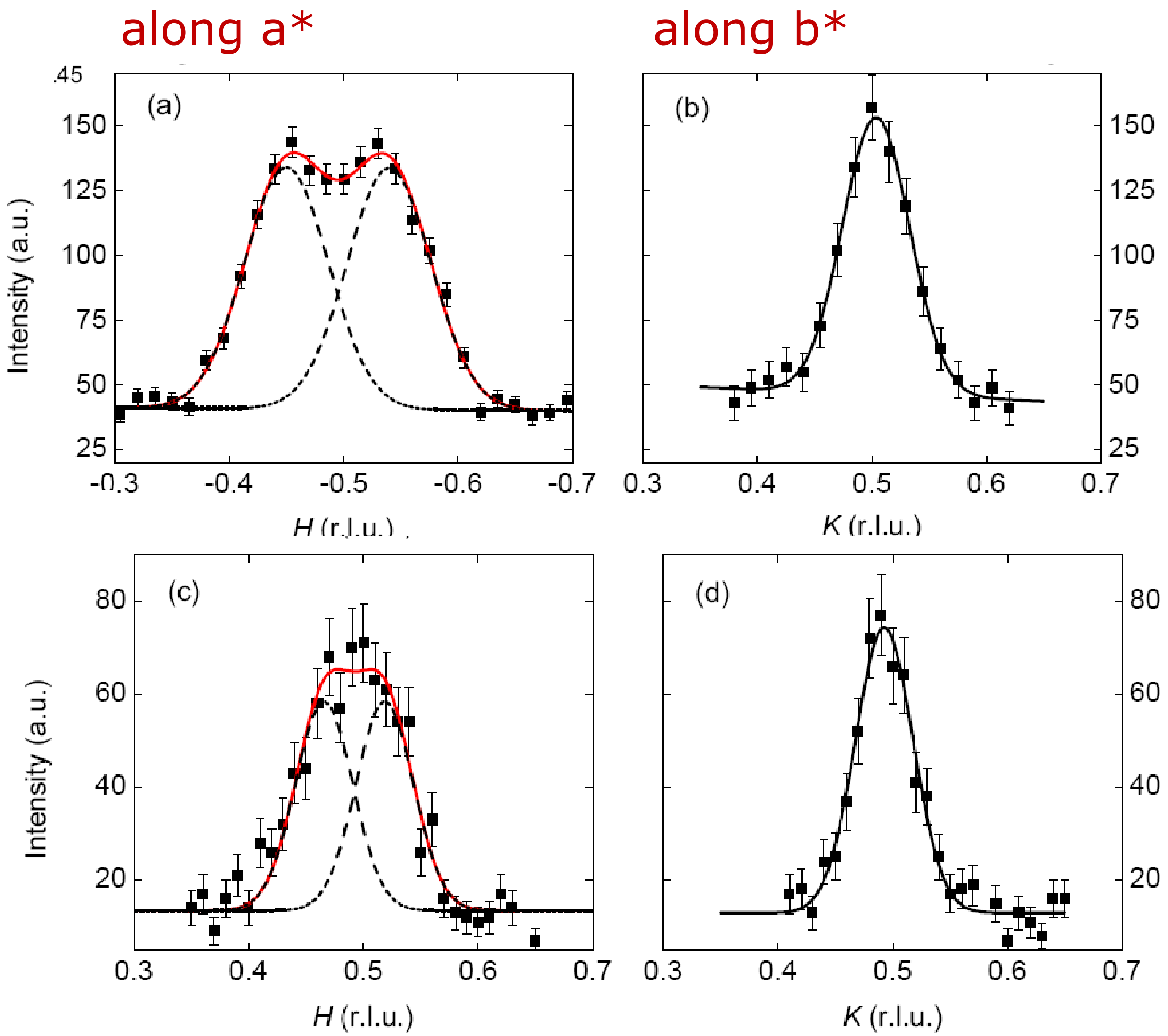
YBCO$_{6.45}$

T_c = 35 K

YBCO$_{6.35}$

T_c = 10 K

Haug et al.
NJP 2010



uniaxial incommensurate magnetic order

in lightly doped, weakly metallic YBCO → “spin density wave”

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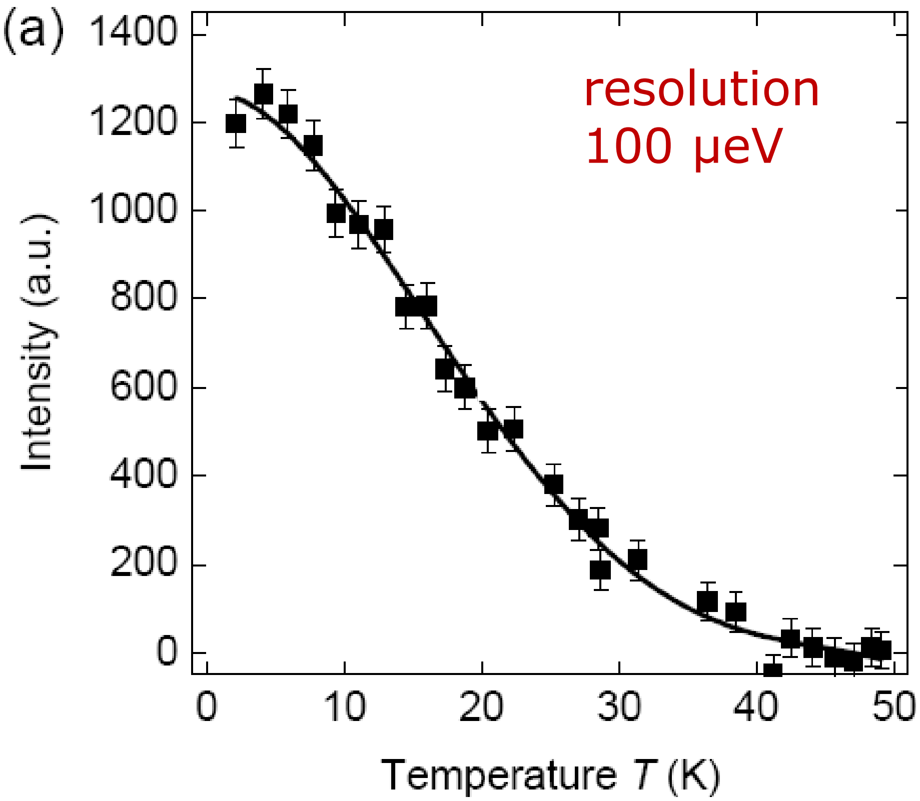
Temperature dependence

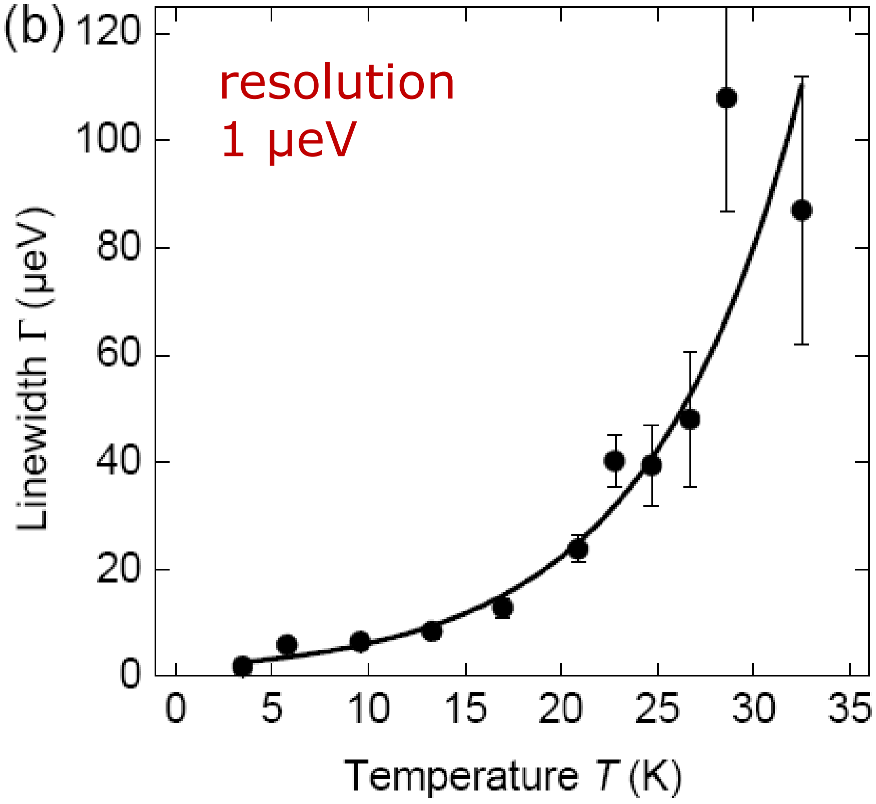
conventional triple-axis

quasielastic neutron scattering



neutron spin-echo spectroscopy

→ energy width Γ of quasielastic peak



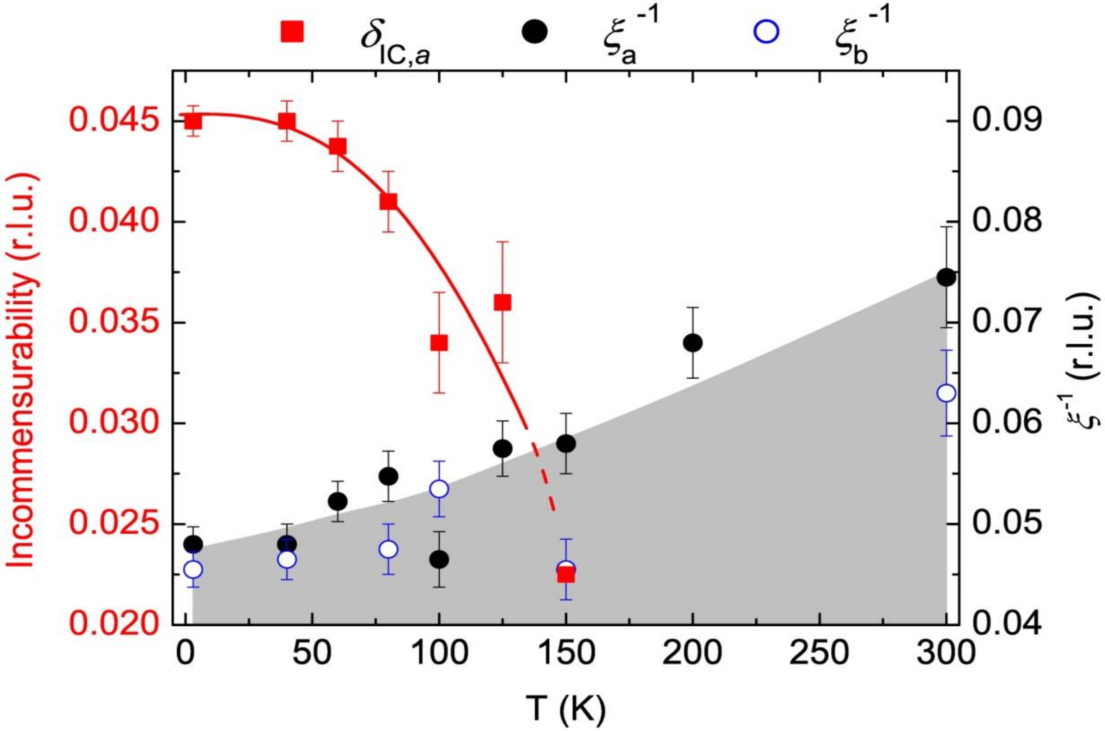
energy width Γ of quasielastic peak narrows continuously as T → 0

generic behavior in 2D Heisenberg systems

disorder also contributes → “cluster spin glass”

Electronic nematic state in YBCO

inelastic neutron scattering



Hinkov et al.
Science 2008

spontaneous onset of incommensurability upon cooling below ~150 K

→ orientational symmetry broken

but no static magnetic order → translational symmetry unbroken

electronic analog of nematic liquid crystal

Fradkin, Kivelson et al.
Yamase, Metzner et al.
Ando et al.
McKenzie et al. …

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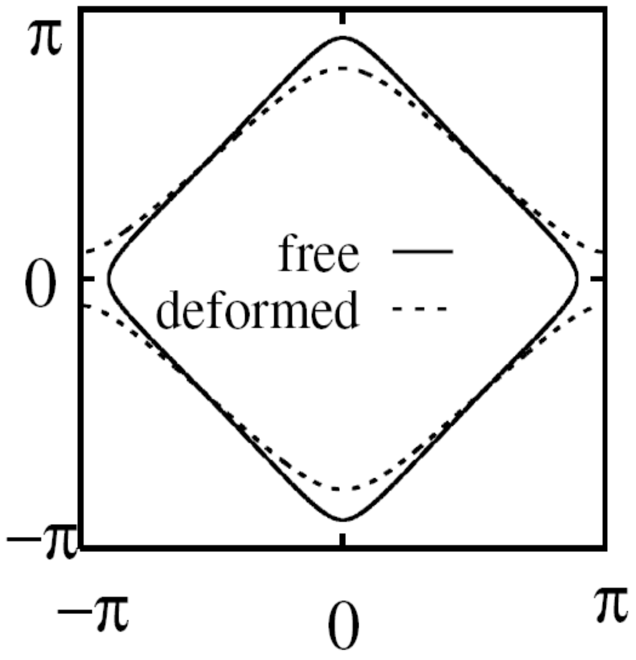
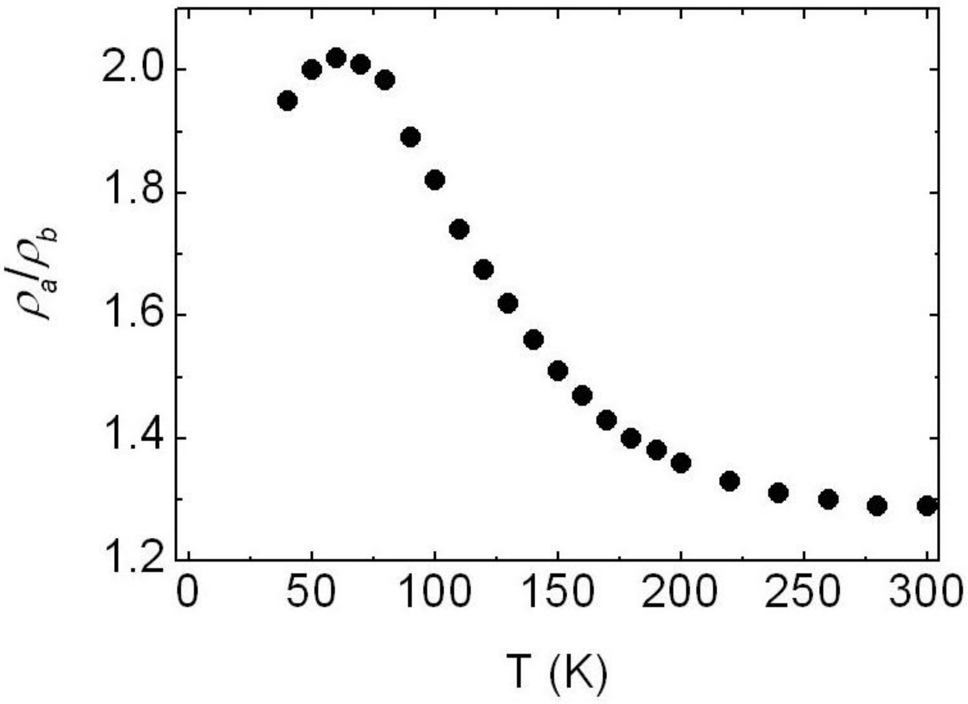
Electronic nematic state in YBCO





possible route towards nematicity:

Pomeranchuk instability

resistivity, Nerst effect anisotropies

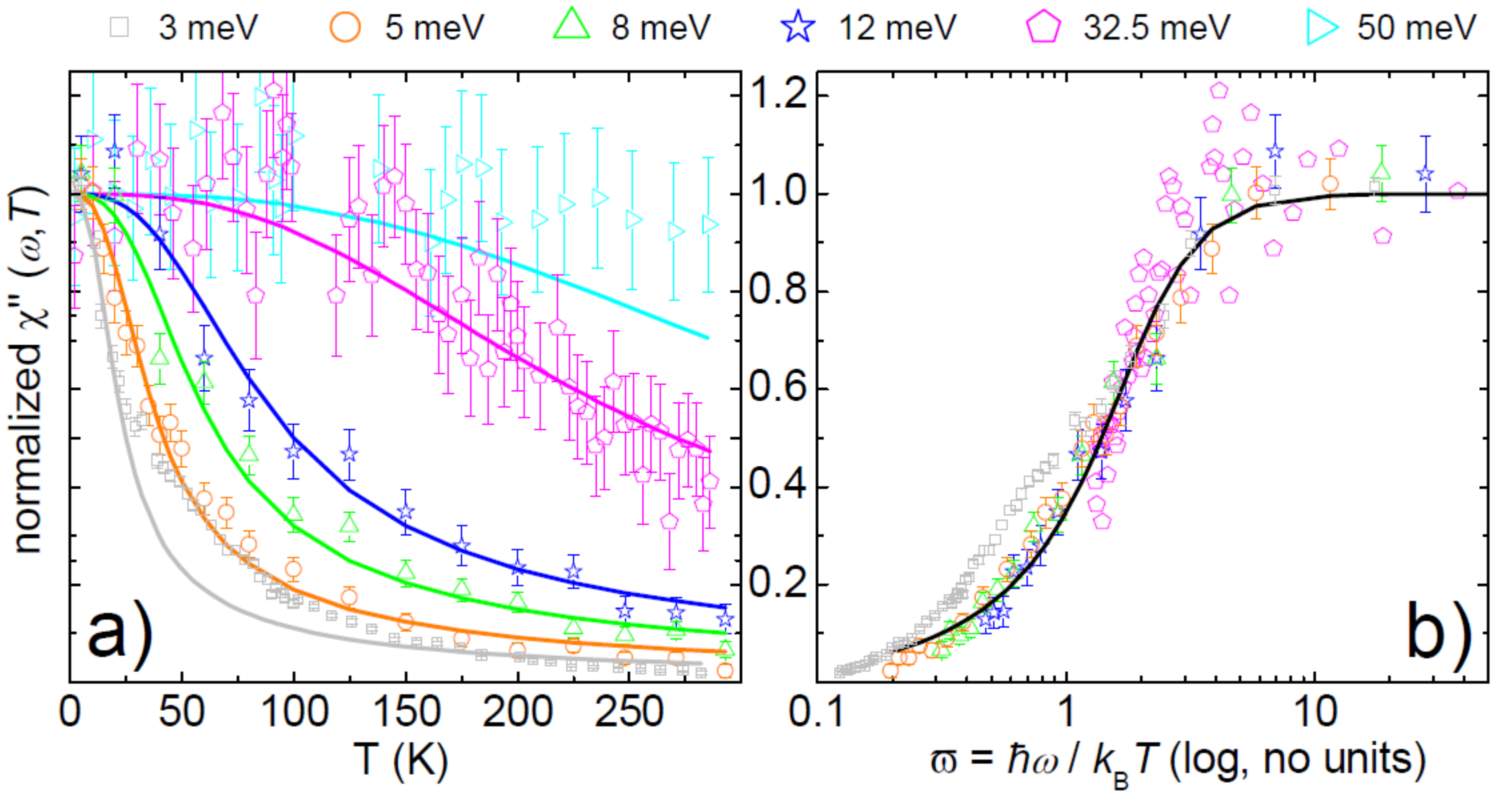
turn up at similar temperature

Halboth & Metzner, PRL 2000
Yamase & Kohno, JPSJ 2000

Ando et al., PRL 2002
Daou et al., Nature 2010

Quantum critical point

$YBa_2Cu_3O_{6.45}$ T = 2K   (in IC-SDW state)

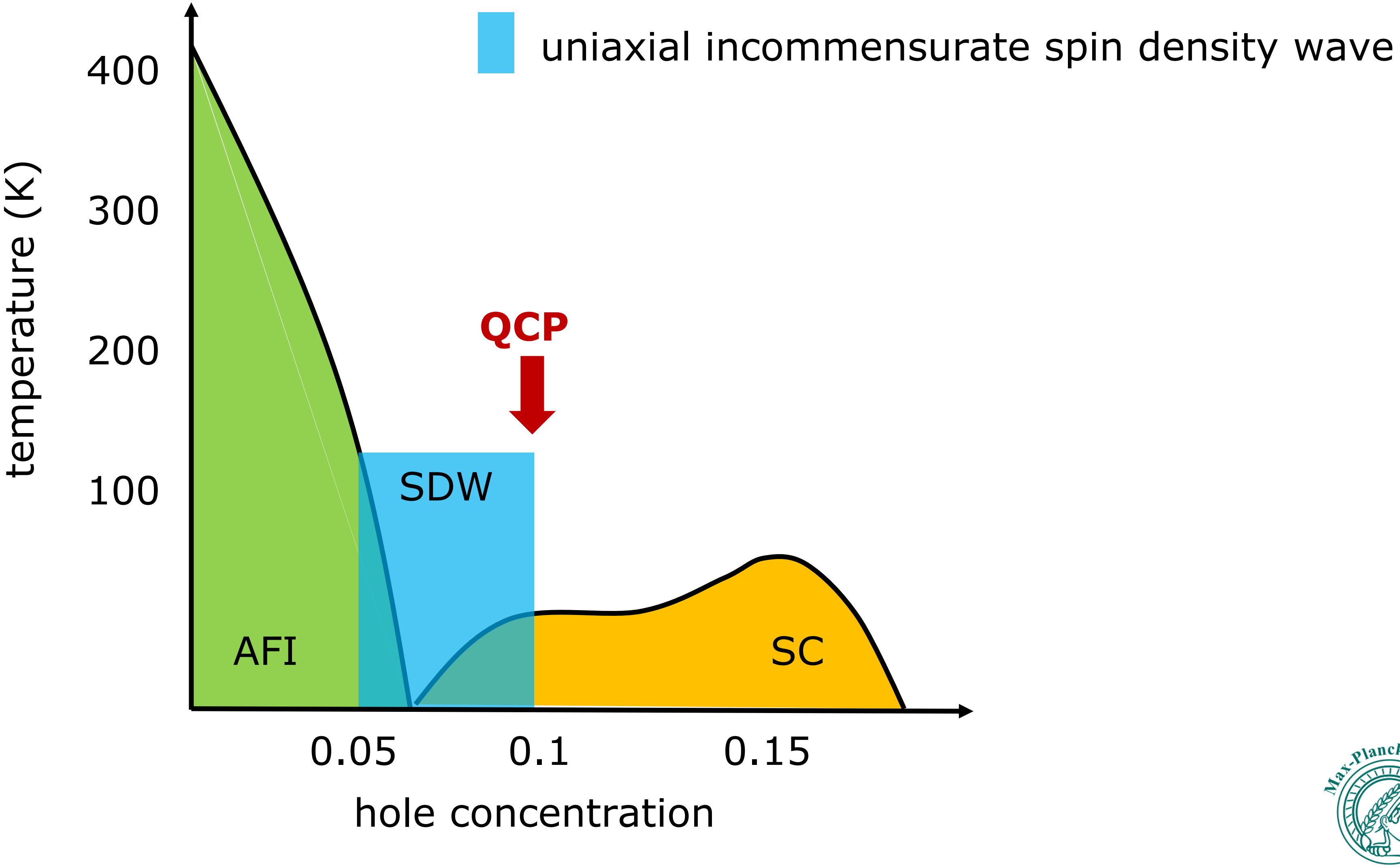


Hinkov et al.

ω/T scaling of χ´´

evidence of **quantum critical point** where magnetic order disappears

Competing order in $YBa_2Cu_3O_{6+x}$



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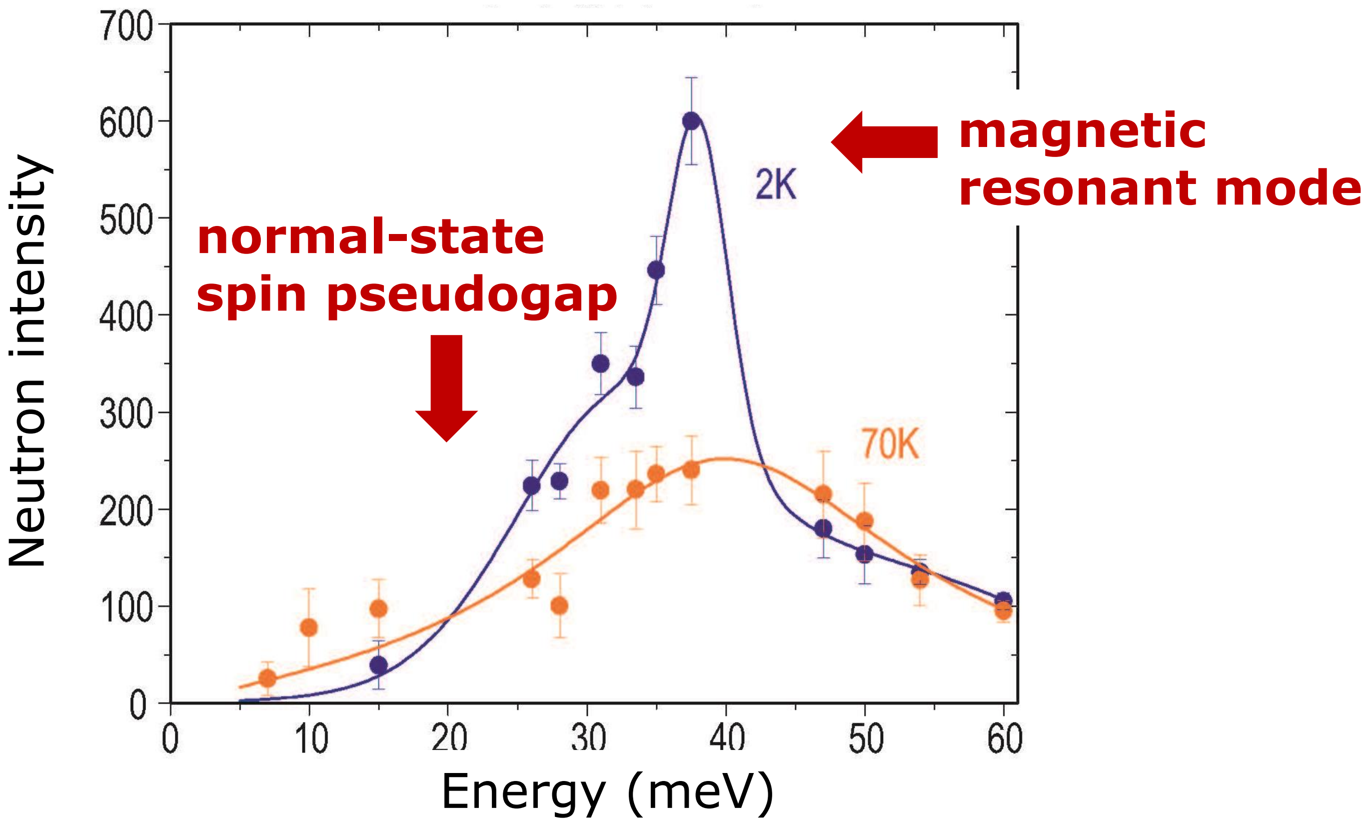
Beyond the QCP

YBCO$_{6.6}$ T_c = 61 K p ~ 0.11

no static magnetic order

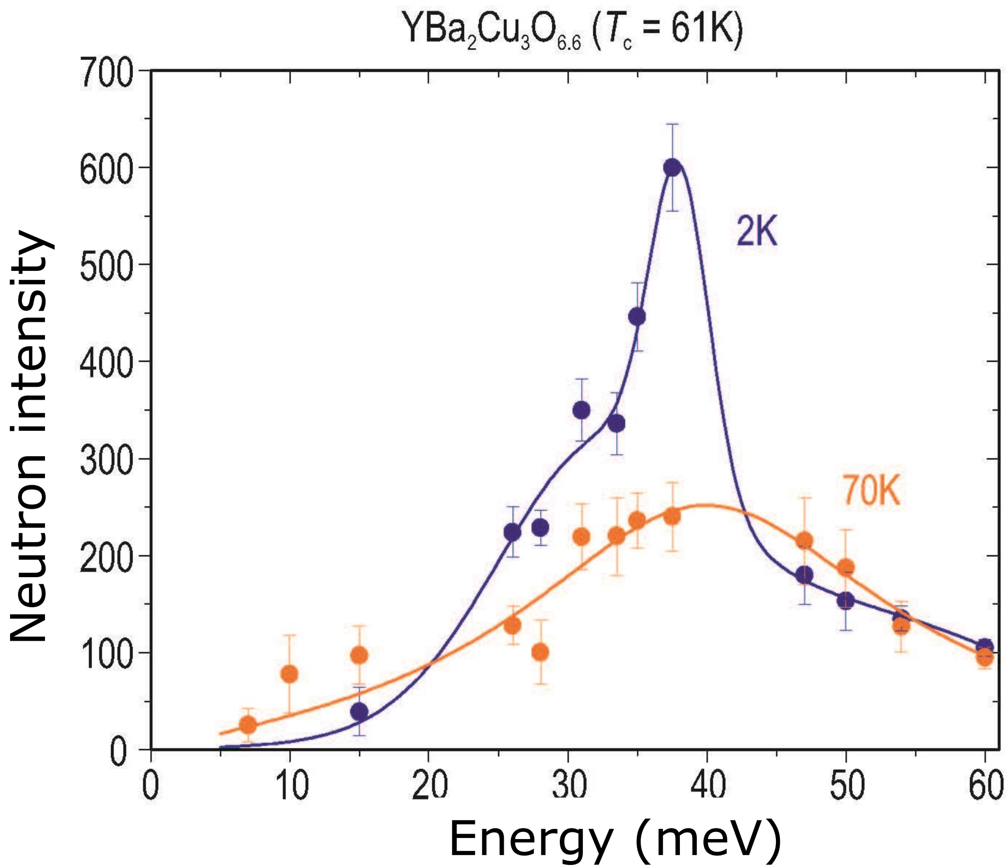


normal-state spin pseudogap

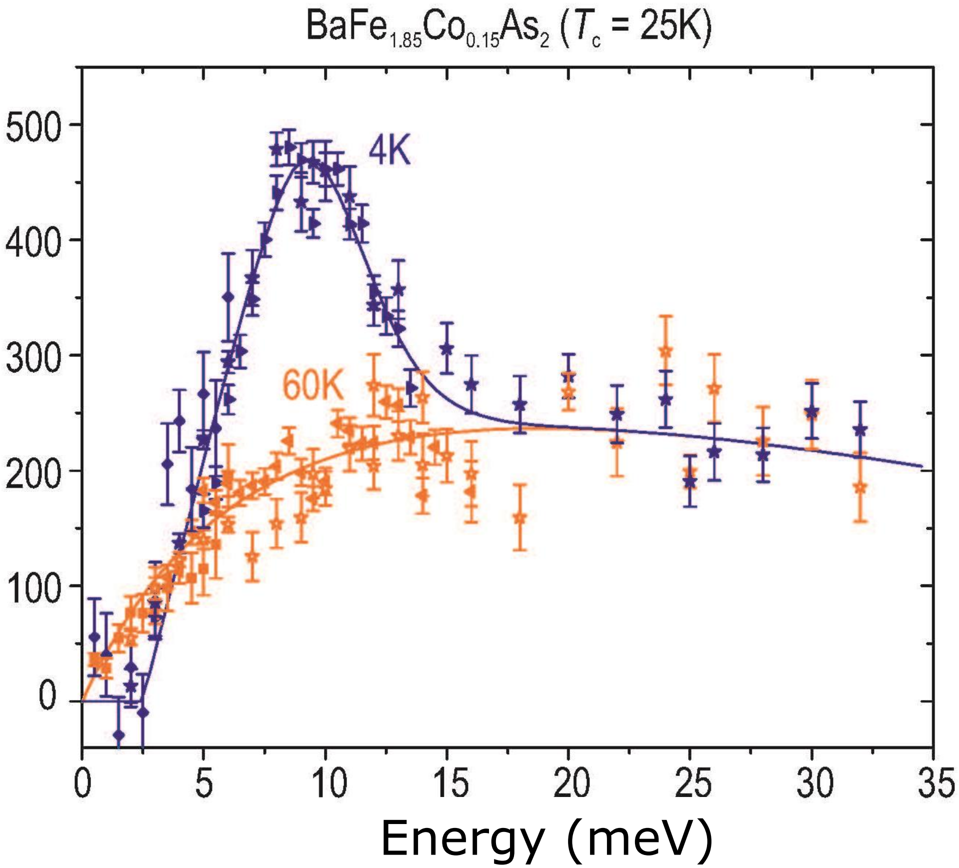
magnetic resonant mode

Suchaneck et al., PRL 2010
see also Fong et al., PRB 2000; Dai et al., PRB 2000

Magnetic resonant mode



Suchaneck et al., PRL 2010



Inosov et al., Nature Phys. 2010

Christianson et al., Lumsden et al …

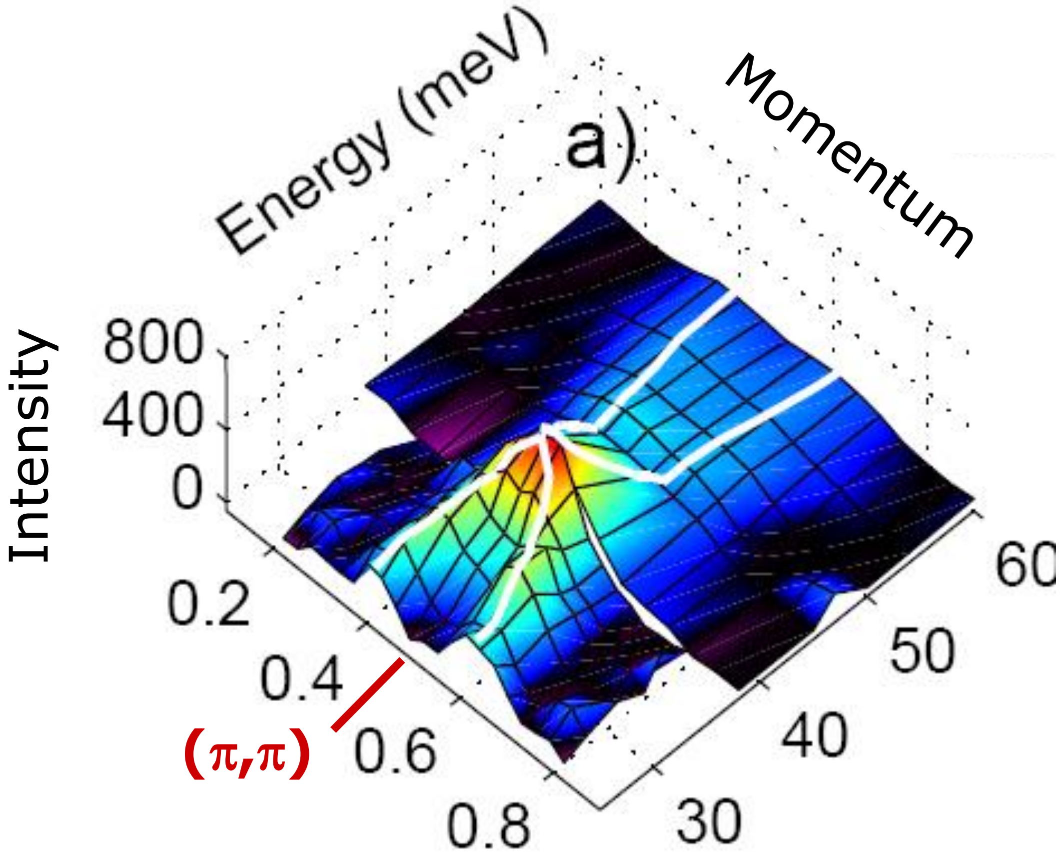
strong feedback effect of the pairing interaction on bosonic spectrum

similar amplitude, *T*-dependence in two families of high-T_c superconductors

Magnetic resonant mode

$YBa_2Cu_3O_{6.6}$

T_c = 62 K



Hinkov et al.
Nature 2004
Nature Phys. 2007

Mook et al.
Dai et al. …

hour-glass dispersion

- magnon-like dispersion at high energies
- “inverted” dispersion at low energies

Inelastic magnetic neutron scattering

$$\frac{d^2\sigma}{d\Omega\, dE} = 2(\gamma r_0)^2 \frac{k_f}{k_i} N \left|F(\mathrm{Q})\right|^2 e^{-2W} \frac{1}{\pi(g\mu_{\mathrm{B}})^2} \frac{1}{1-e^{-\hbar\omega\beta}} \chi''(\mathrm{Q},\omega)$$

itinerant electrons electrons → Lindhard function & RPA

$$\chi_0(q,\omega) = \sum_k \frac{f(E_{k+q\uparrow}) - f(E_{k\downarrow})}{\hbar\omega - (E_{k+q} - E_k - \Delta) + i\varepsilon}$$

band dispersions

$$\chi(q,\omega) = \frac{\chi_0(q,\omega)}{1 - J(q)\chi_0(q,\omega)}$$

RPA expression

J(q) peaked at *q* = *(π,π)*

INS from superconductors

coherence factor

$$\chi(q,\omega) = \Sigma_k \{ \tfrac{1}{2} \left(1 + \frac{\varepsilon_k \varepsilon_{k+q} + \Delta_k \Delta_{k+q}}{E_k E_{k+q}}\right) \frac{f(E_{k+q}) - f(E_k)}{\omega - (E_{k+q} - E_k) + i\delta}$$

scattering of
thermally excited pairs

$$+ \tfrac{1}{4} \left(1 - \frac{\varepsilon_k \varepsilon_{k+q} + \Delta_k \Delta_{k+q}}{E_k E_{k+q}}\right) \frac{1 - f(E_{k+q}) - f(E_k)}{\omega + (E_{k+q} + E_k) + i\delta}$$

pair annihilation

$$+ \tfrac{1}{4} \left(1 - \frac{\varepsilon_k \varepsilon_{k+q} + \Delta_k \Delta_{k+q}}{E_k E_{k+q}}\right) \frac{f(E_{k+q}) + f(E_k) - 1}{\omega - (E_{k+q} + E_k) + i\delta} \}$$

pair creation

$$E_k = \sqrt{\varepsilon_k^2 + \Delta_k^2}$$

Fong et al., PRL 1995
Monthoux & Scalapino, PRL 1994

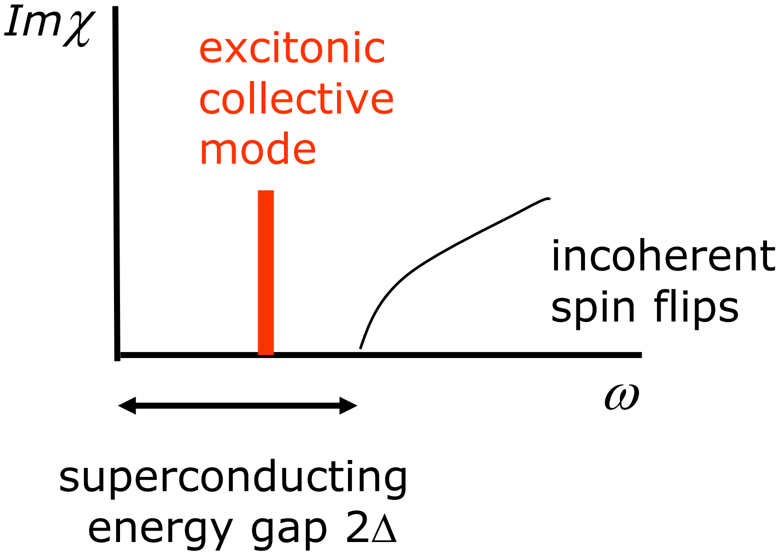
χ'' → 0 at $q = (\pi,\pi)$ in s-wave superconductor

resonant mode implies **sign change** in superconducting gap function

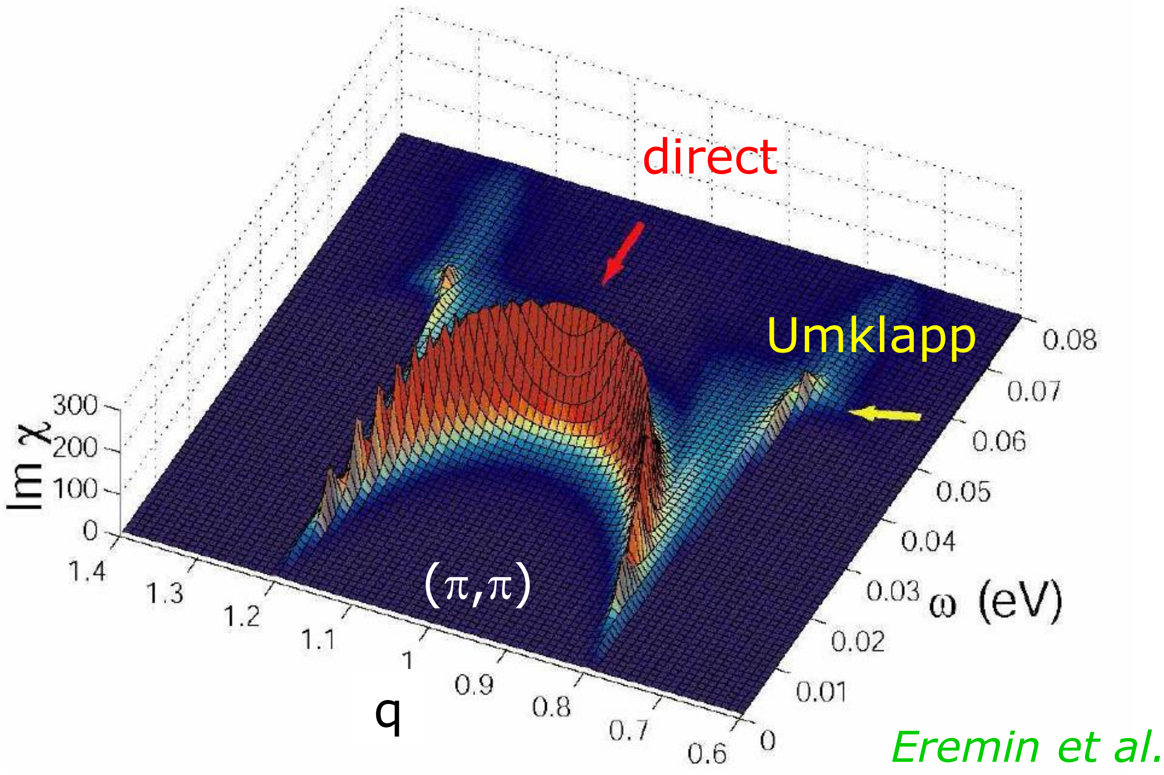
d-wave in cuprates, $s_\pm$ in iron pnictides

Magnetic resonant mode

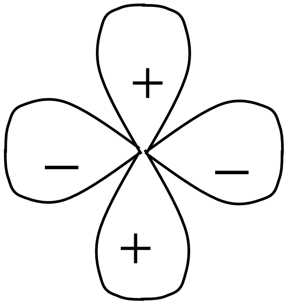
spin excitations of a d-wave superconductor



RPA reproduces lower branch of hour-glass dispersion



Eremin et al. PRL 2005



dispersion of resonant mode

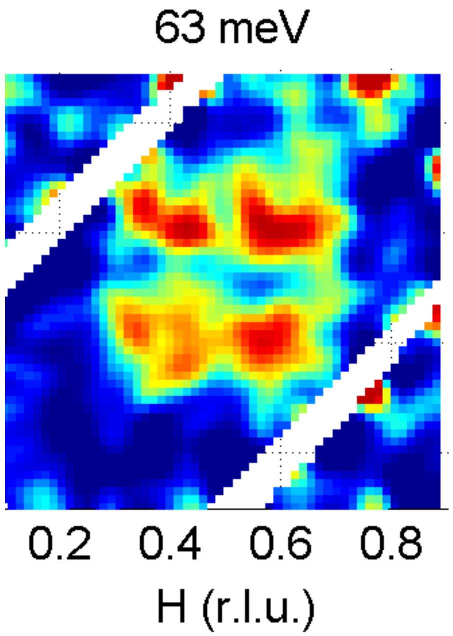
momentum-space signature of Cooper-pair wave function

Universal high-energy spin excitations

underdoped cuprates

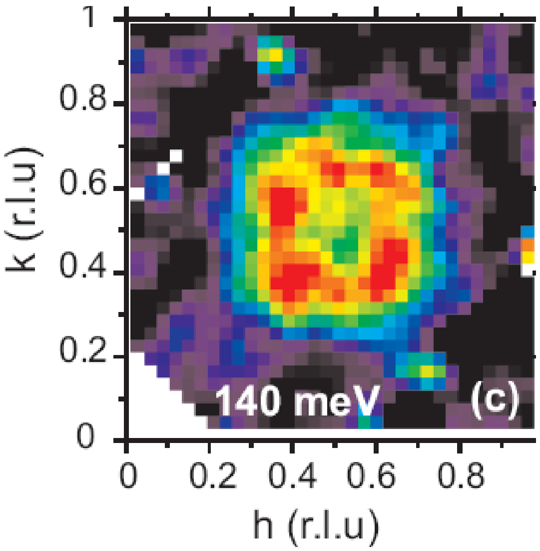
high-energy excitations weakly dependent on temperature, doping, structural details

$YBa_2Cu_3O_{6.6}$



Hinkov et al.
Nature Phys. 2007

$La_{1.91}Sr_{0.09}CuO_4$

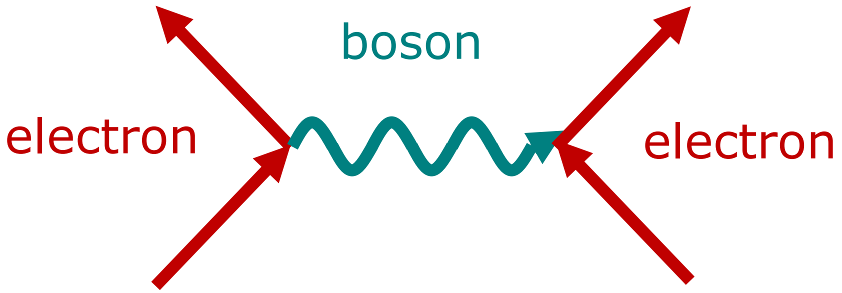


Lipscombe et al.
PRL 2009

Understanding unconventional superconductors

experimental observations

- gapped, non-critical spin fluctuations
- feedback effect of superconductivity on spin fluctuation spectra
- fermionic quasiparticles, at least at low temperature



→ quantify strength of spin fluctuation mediated pairing interaction

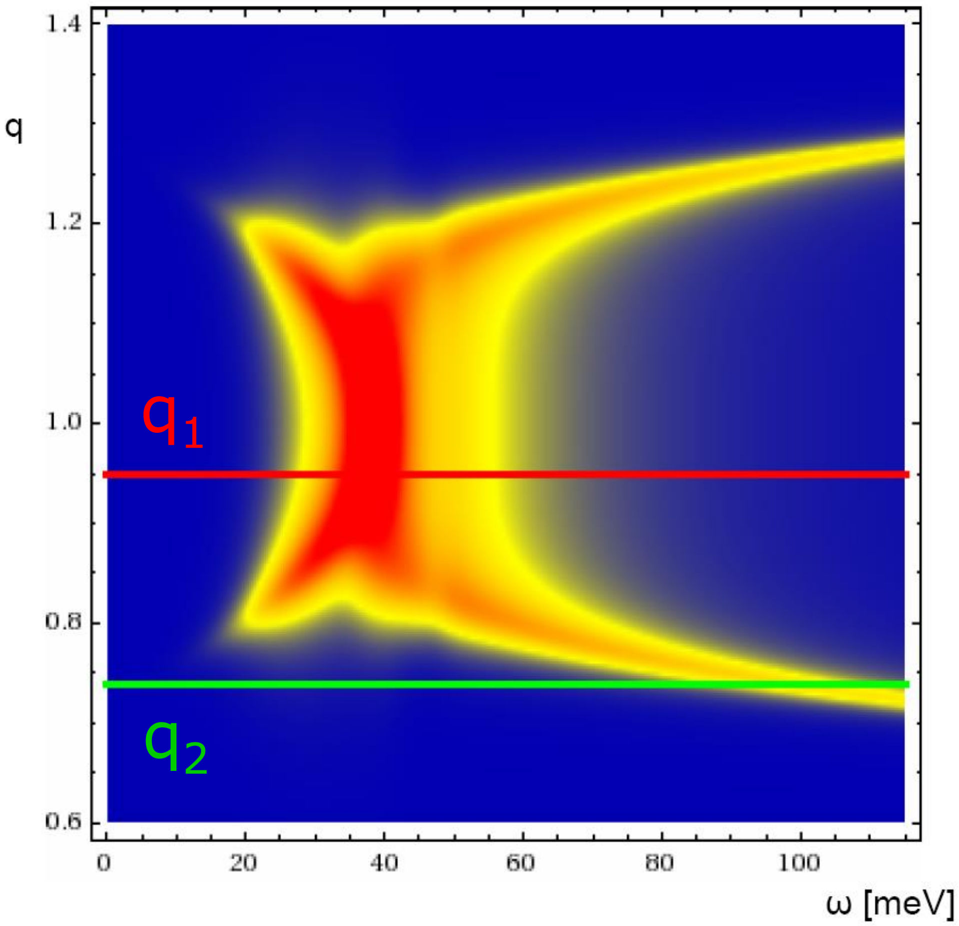
→ calculate T_c, energy gap, … → guideline for materials design

Eliashberg theory is the only method that is currently available.

Joint analysis ARPES – INS

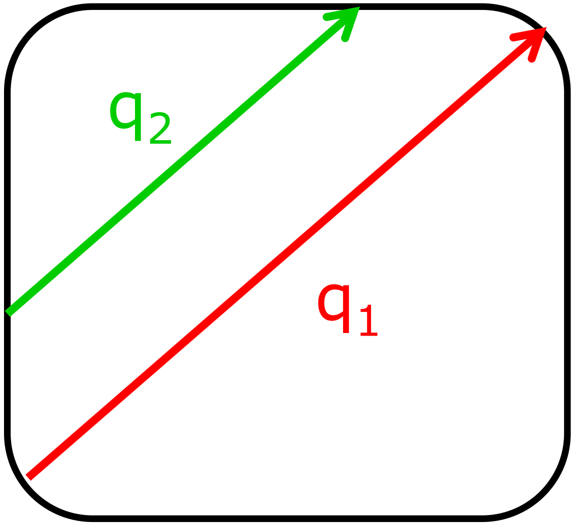
anomalous spin excitations

from neutron scattering

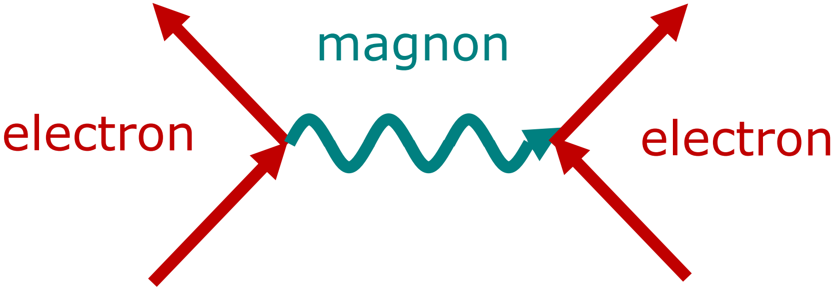


electronic band dispersions

from photoemission



quantitative cross-correlation



Eliashberg theory

- compare INS & ARPES spectra

  of underdoped $YBa_2Cu_3O_{6.6}$ (T_c = 62 K)

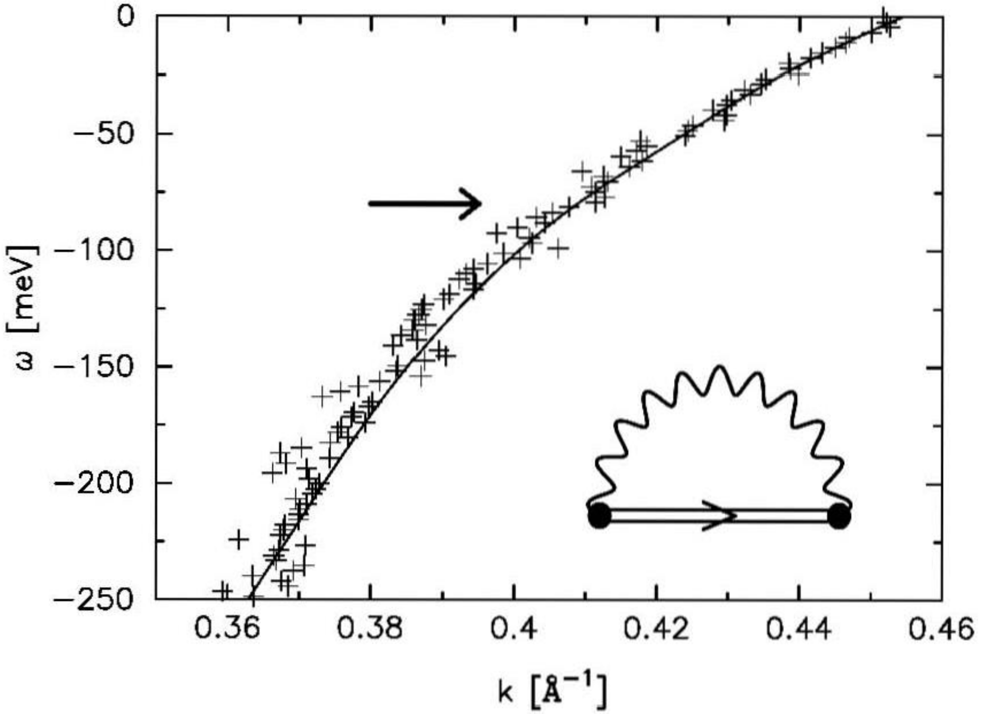
  → spin-fermion coupling constant

- mean-field superconducting gap equation

  → T_c ~ 170 K

Dahm et al., Nature Phys. 2009

ARPES dispersion



spin fluctuations have sufficient strength to mediate high-temperature superconductivity

… but what about optimal doping?

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