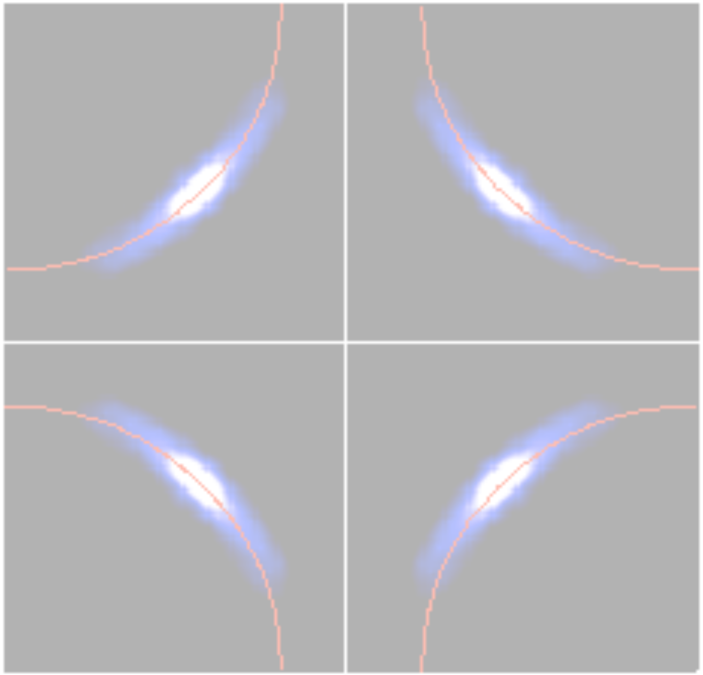
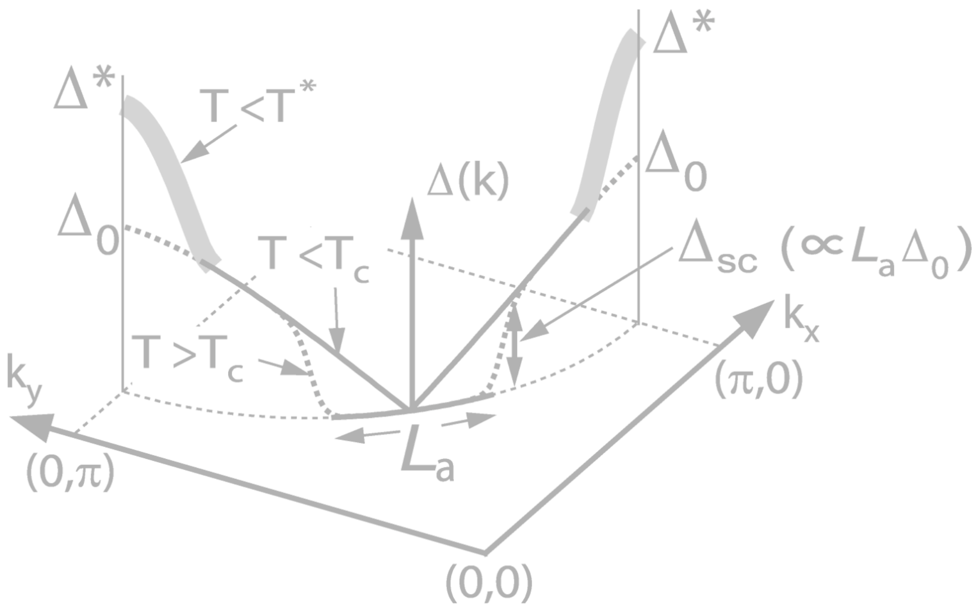
IMSS Symposium – Materials Structure Science using Synchrotron Radiation, Neutrons and Muons - October 16-17, 2008

Angle-resolved photoemission spectroscopy of high-temperature superconductors: Present status and outlook

Atsushi Fujimori
University of Tokyo





Collaborators

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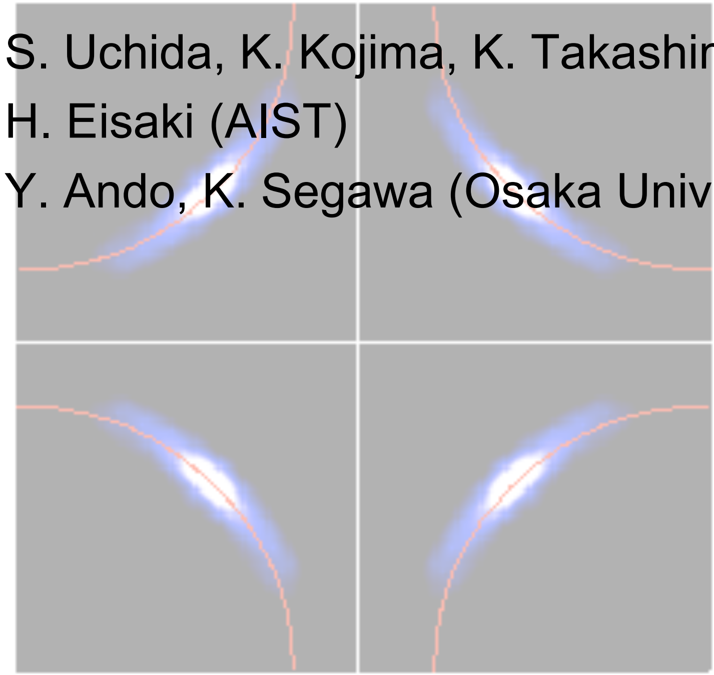
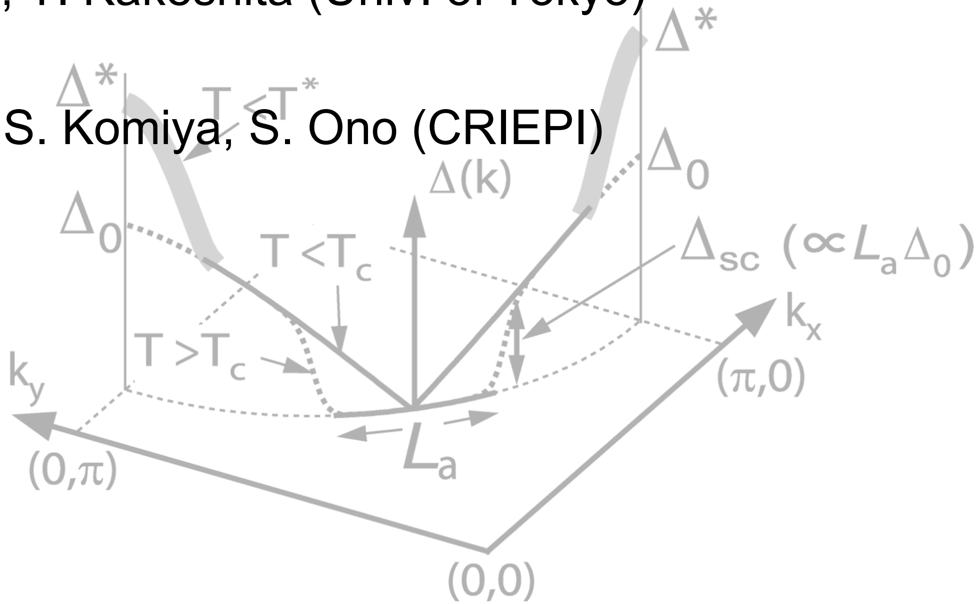
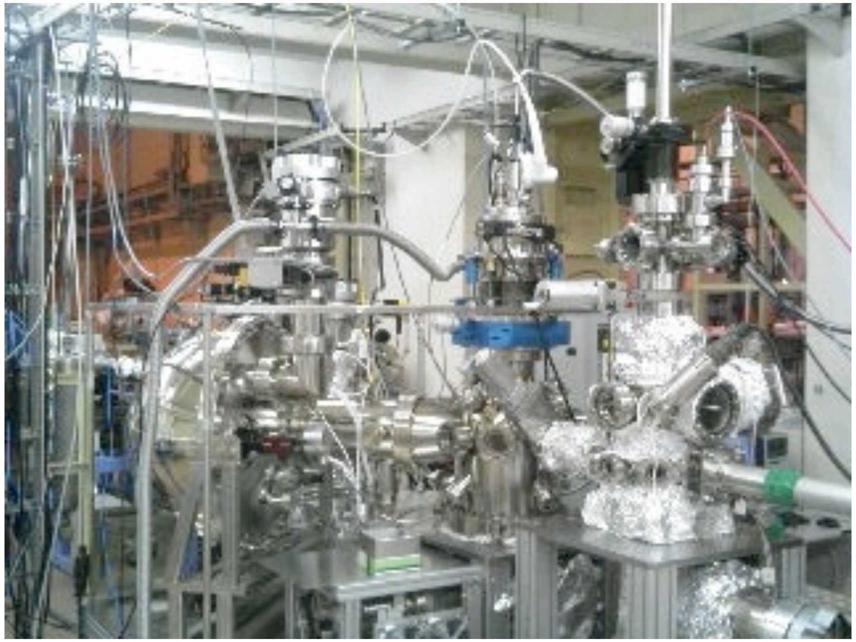


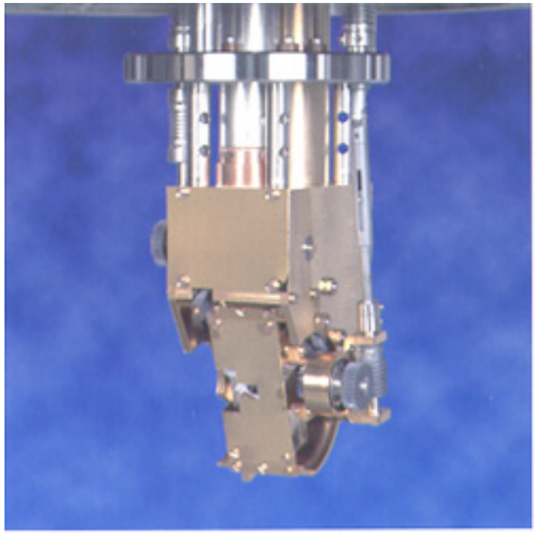


High-resolution ARPES station BL-28A at Photon Factory

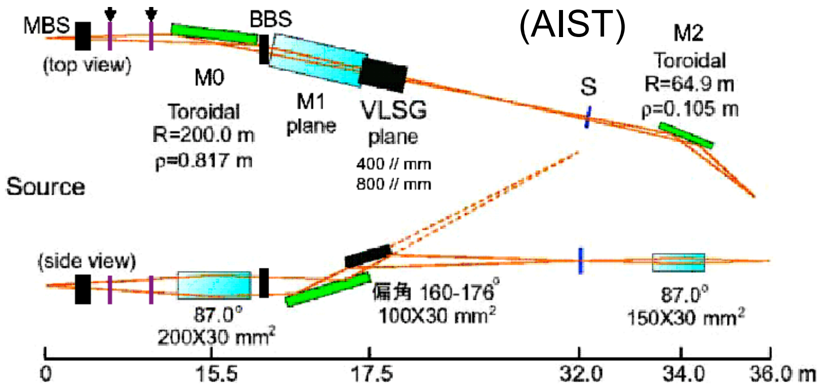
ARPES endstation



Sample manipulator with two-axis rotation



Y. Aiura (AIST)

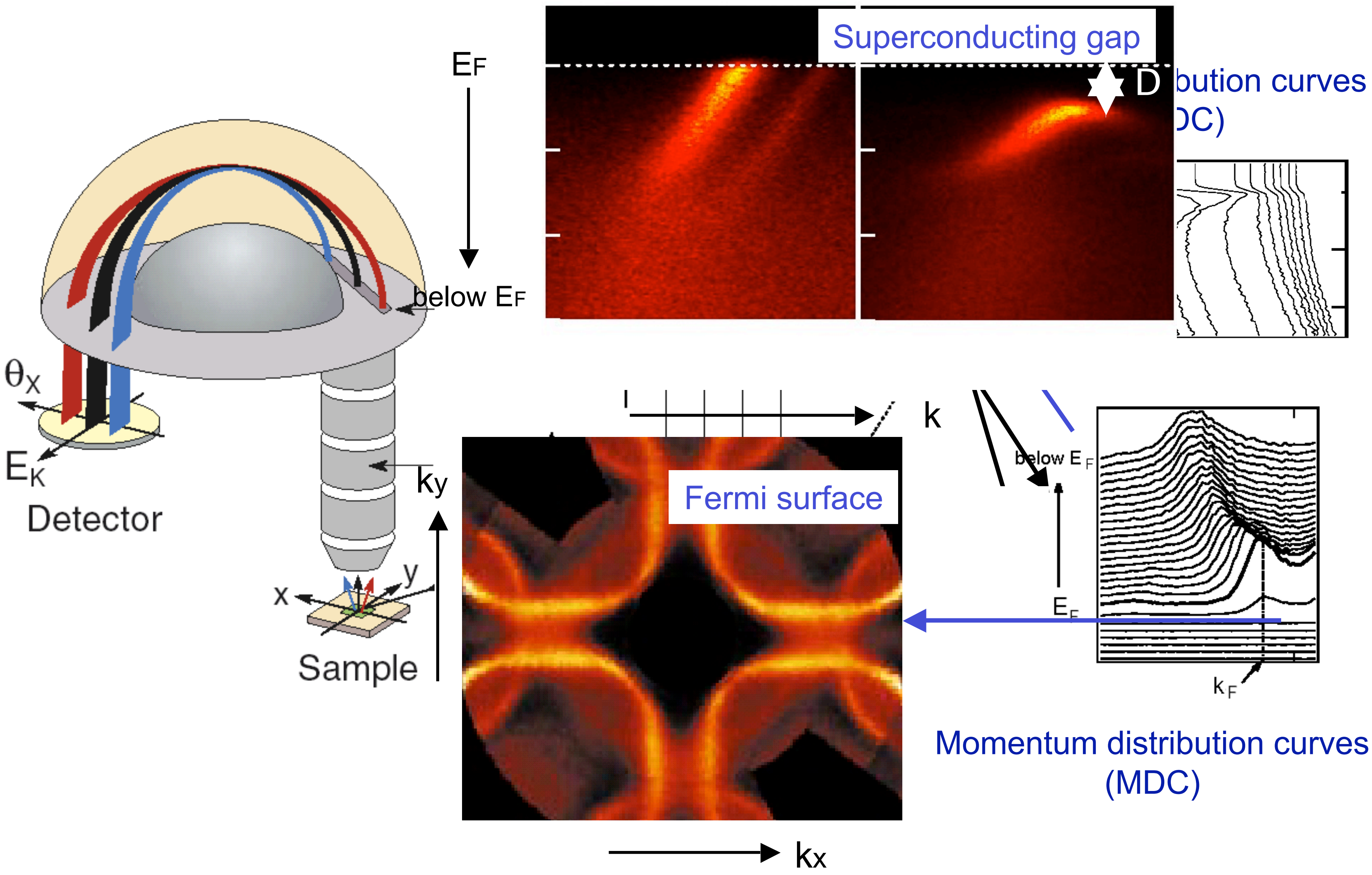


K. Amemiya (KEK-PF)

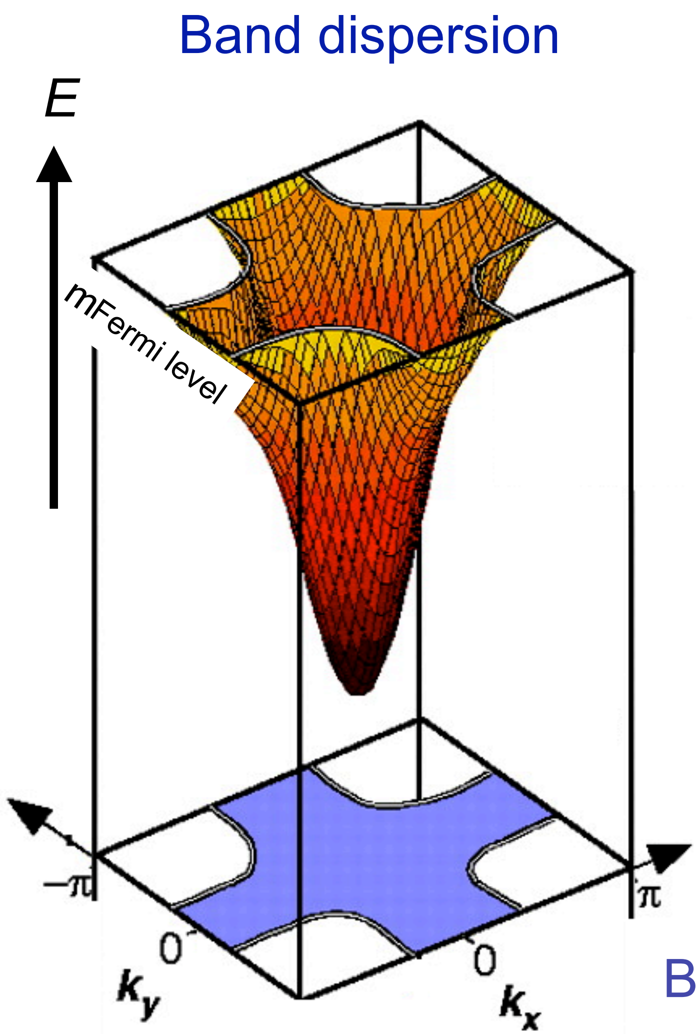
Staff: K. Ono, M. Kubota, N. Kamakura (KEK-PF)
User group: A. Fujimori, T. Takahashi, Y. Aiura,
T. Saitoh, K. Ozawa, ….

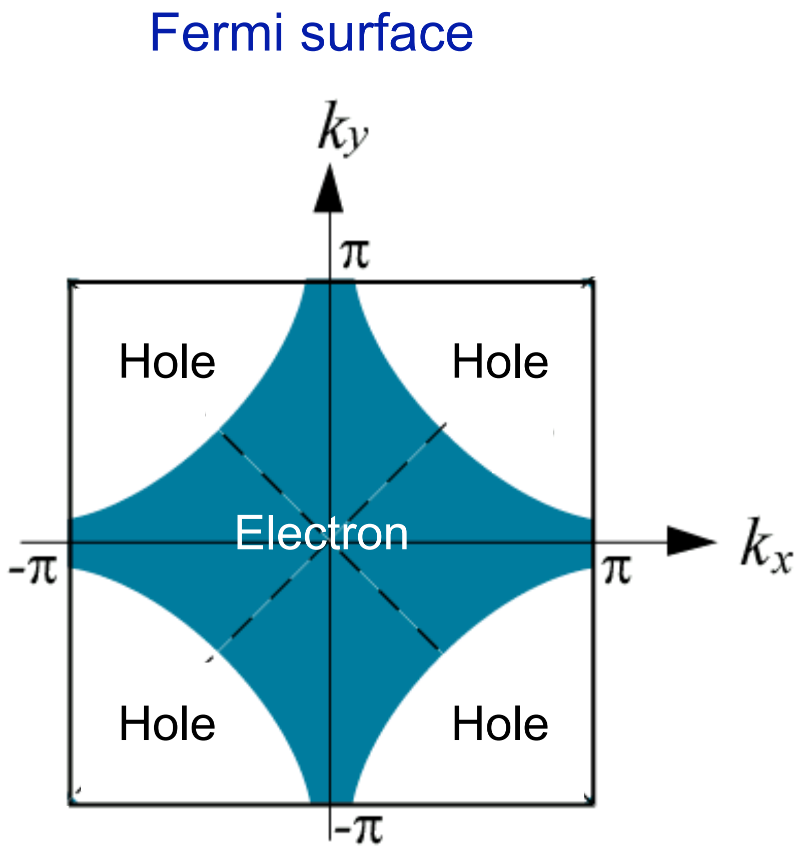
hn = 35-200 eV

Angle-Resolved Photoemission Spectroscopy （ARPES）



Band structure and Fermi surface in high-T_C cuprates

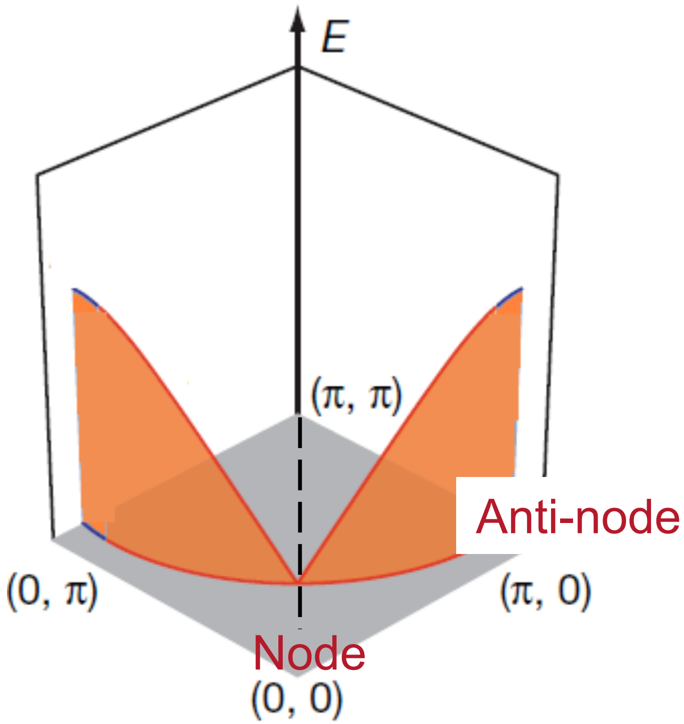




Band structure: $E(\boldsymbol{k}) = -2t(\cos k_xa + \cos k_ya) - 4t'\cos k_xa \cos k_ya - 2t''(\cos 2k_xa + \cos 2k_ya)$

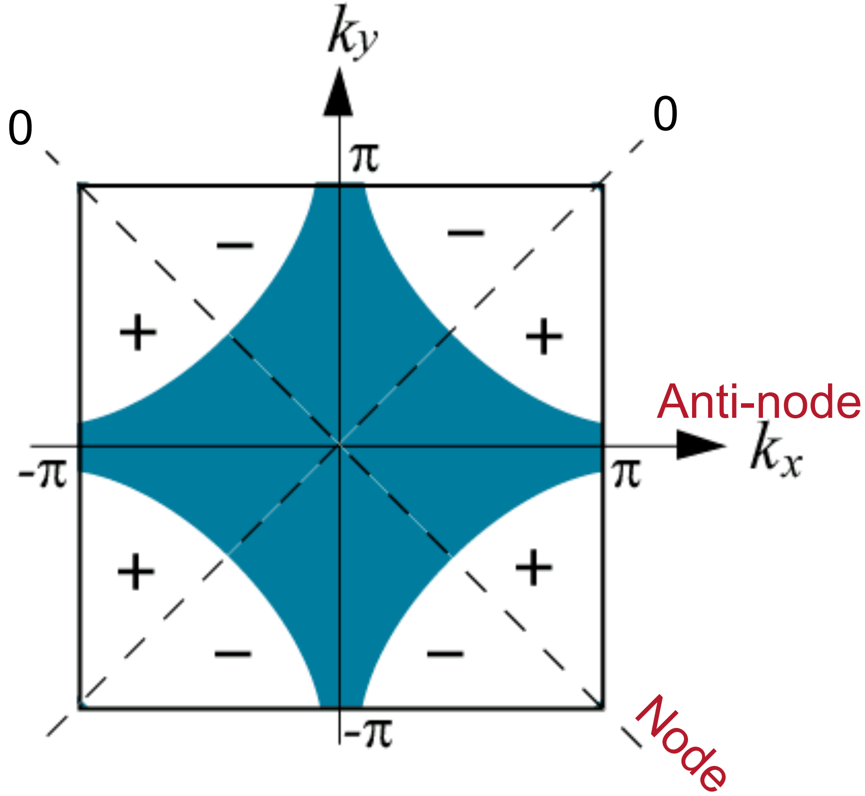
d-wave superconducting gap in high-T_C cuprates

d-wave superconducting gap



d_{x2-y2} symmetry

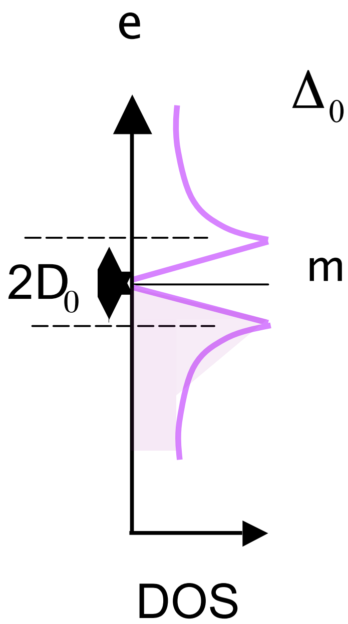
d-wave order parameter



Order parameter
$D(\boldsymbol{k}) = D_0(\cos k_x a - \cos k_y a)$

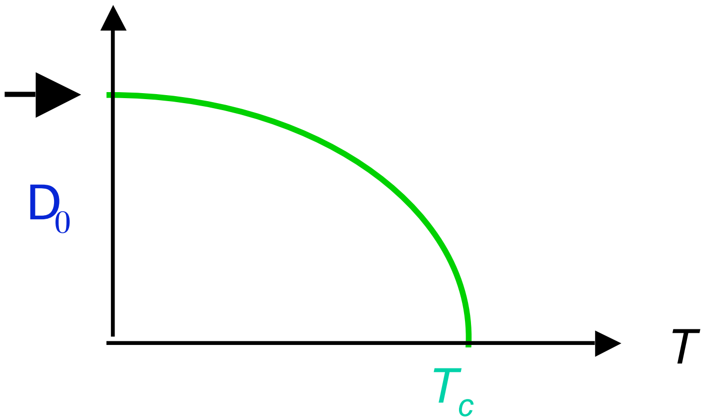
BCS theory of *d*-wave superconductor

Density of states



$$\Delta_0(0) = \frac{4.3 k_B T_c}{2}$$

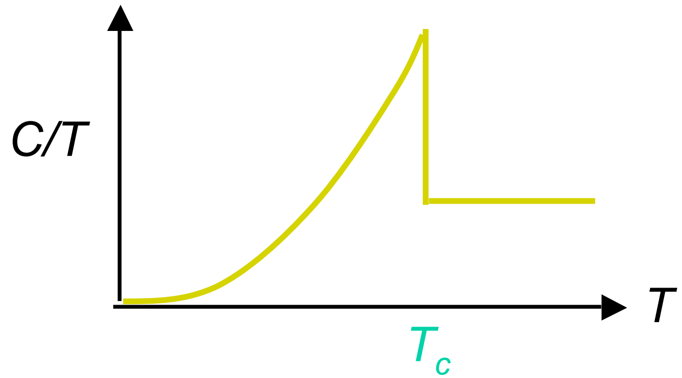
Superconducting gap $\Delta_0(T)$



$\Delta(\boldsymbol{k}) = \Delta_0(\cos k_x a - \cos k_y a)$

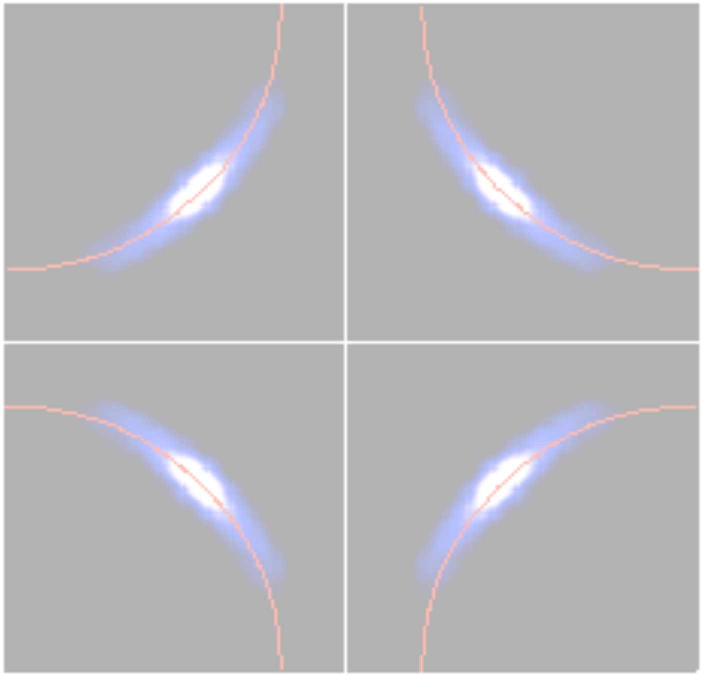
Superfluid density
= Fermi surface volume/m^*

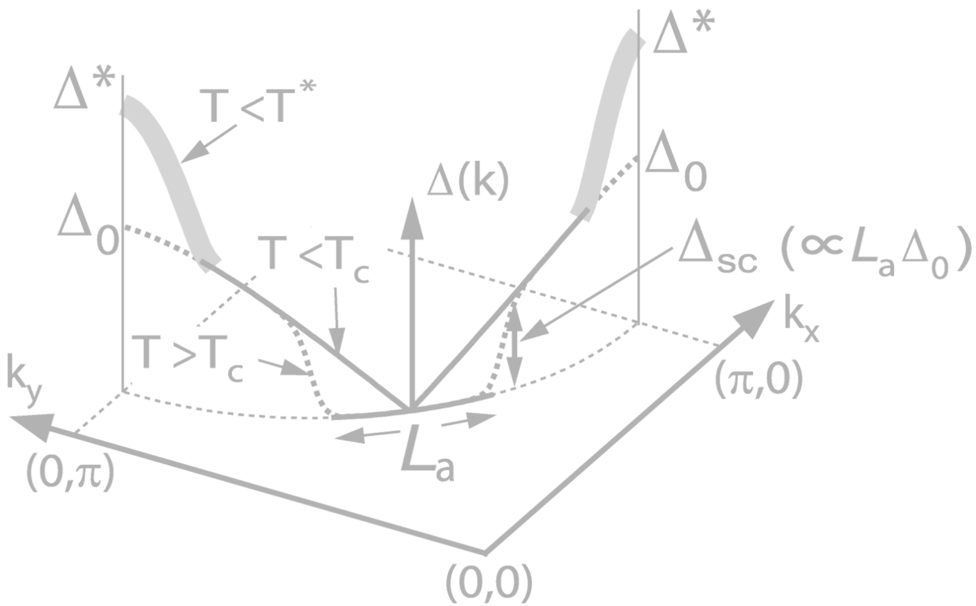
Electronic specific heat



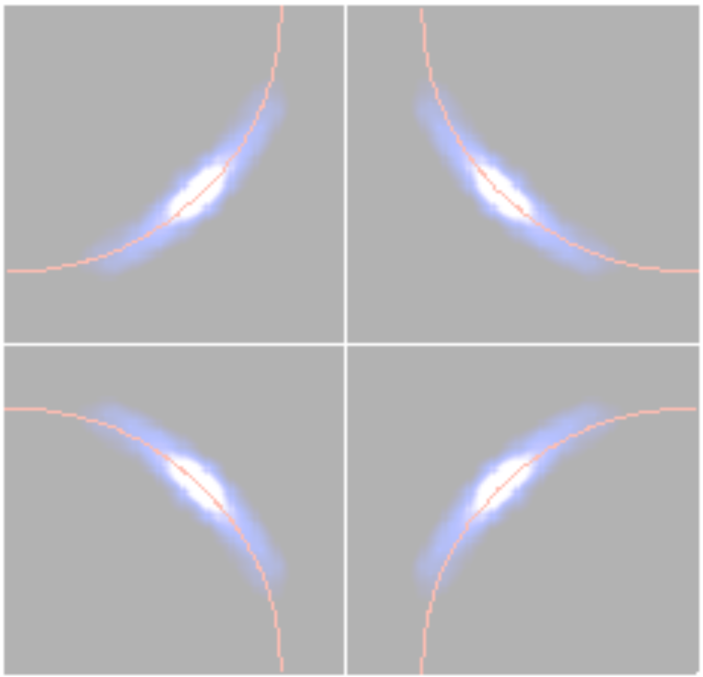
Outline

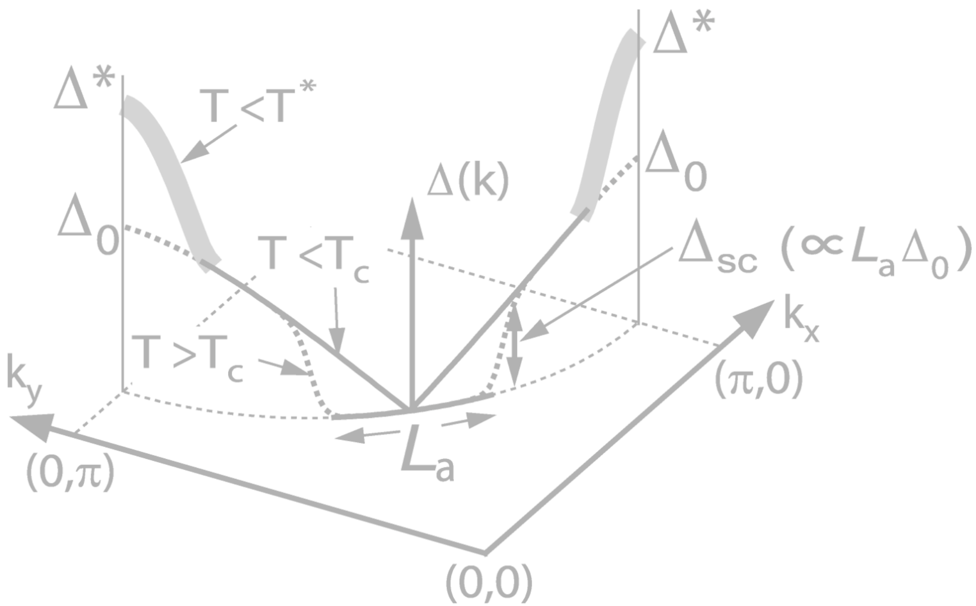
- Pseudogap, Fermi arc and superconducting gap
- Coupling of electron to Boson excitations





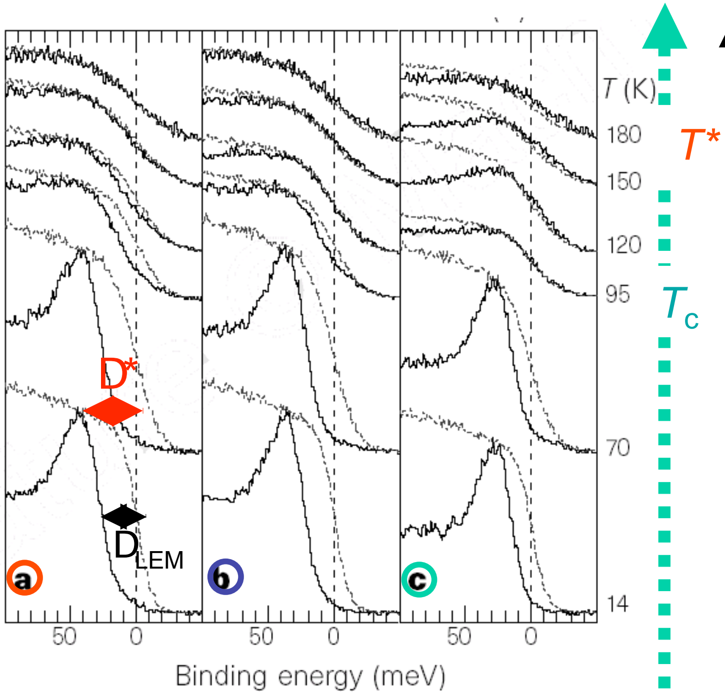
Pseudogap, Fermi arc and superconducting gap

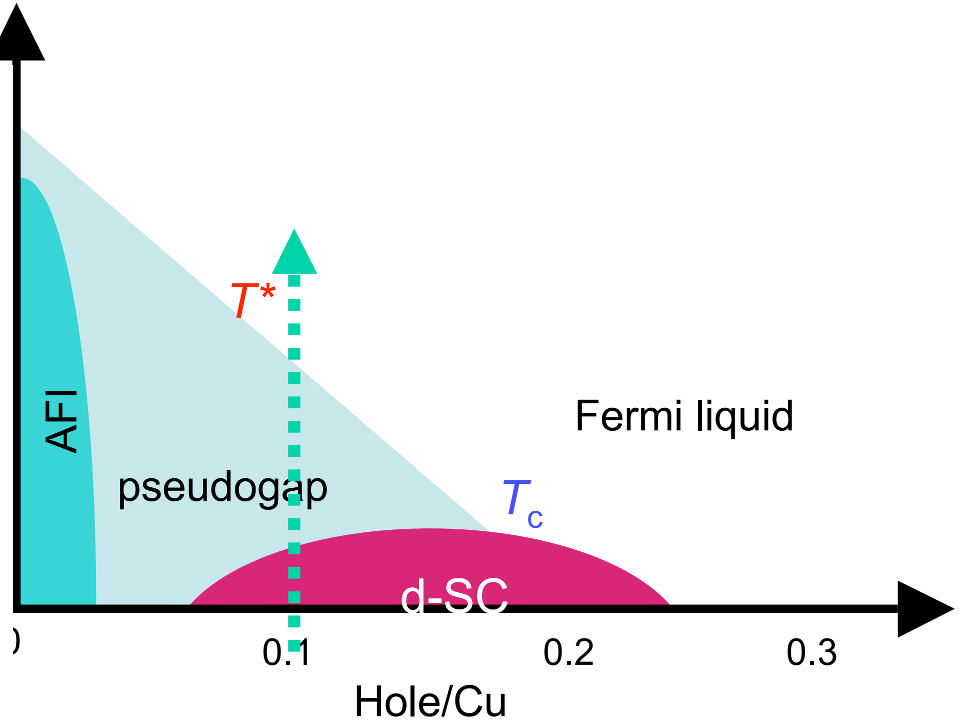




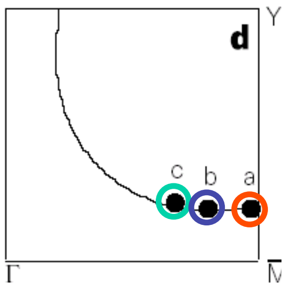
Temperature-dependent pseudogap opening

ARPES of underdoped Bi2212





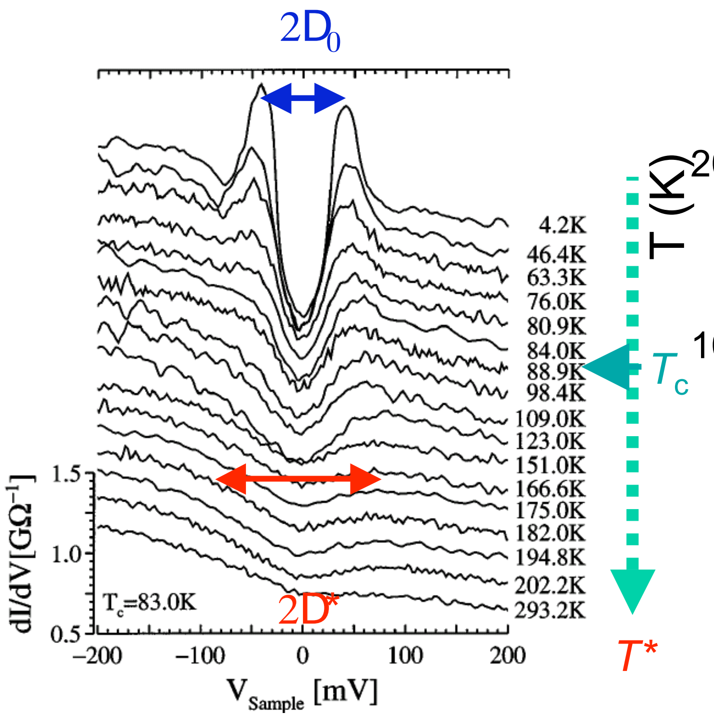
Temperature dependence of gaps

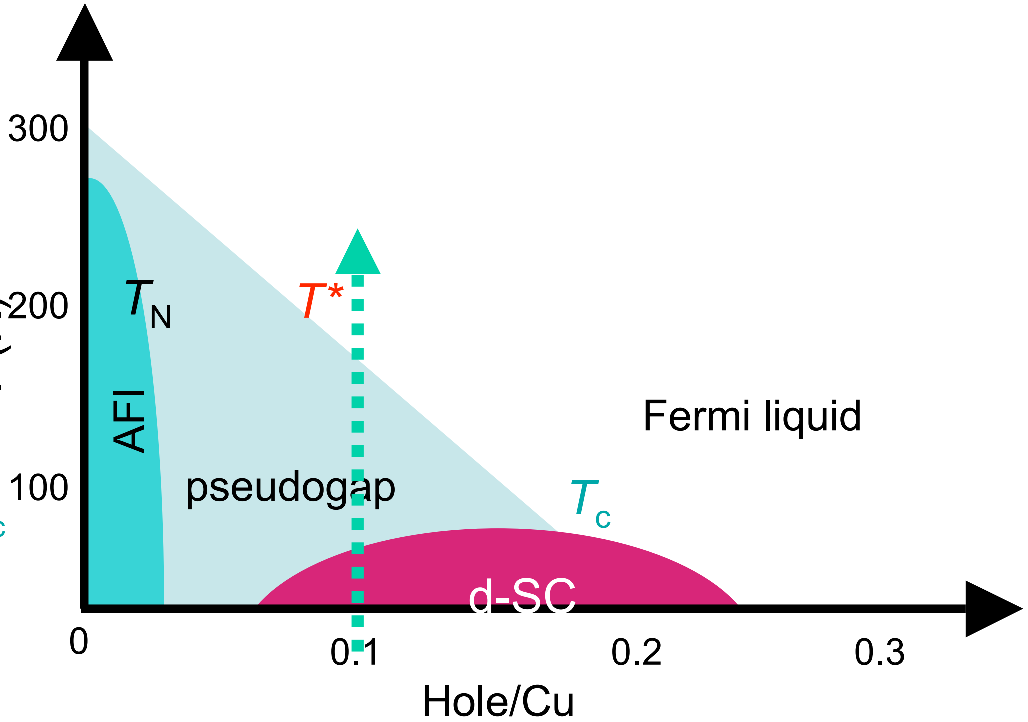


M. R. Norman et al. Nature '98

Temperature-dependent pseudogap opening

STM of underdoped Bi2212

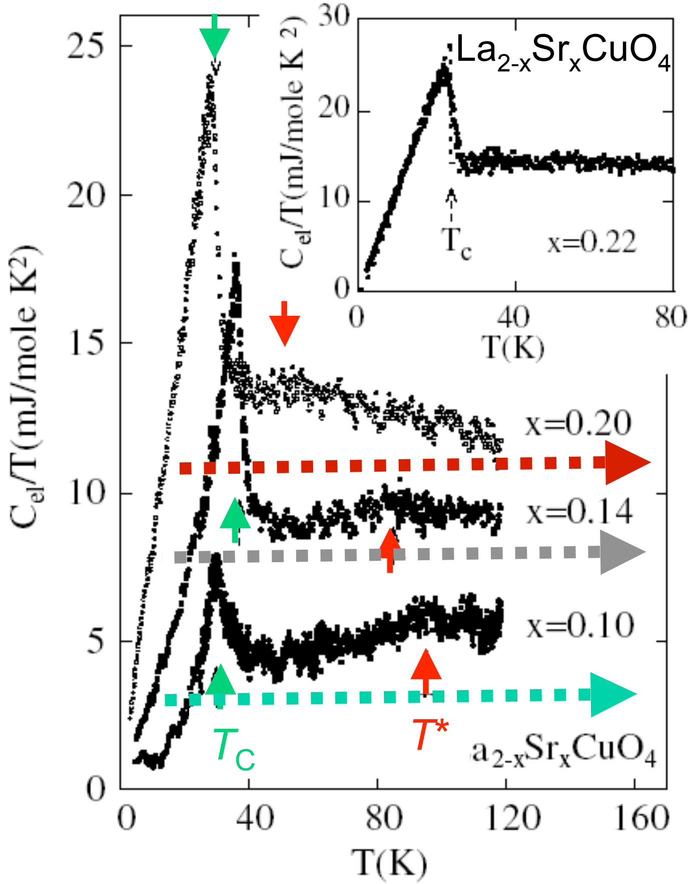


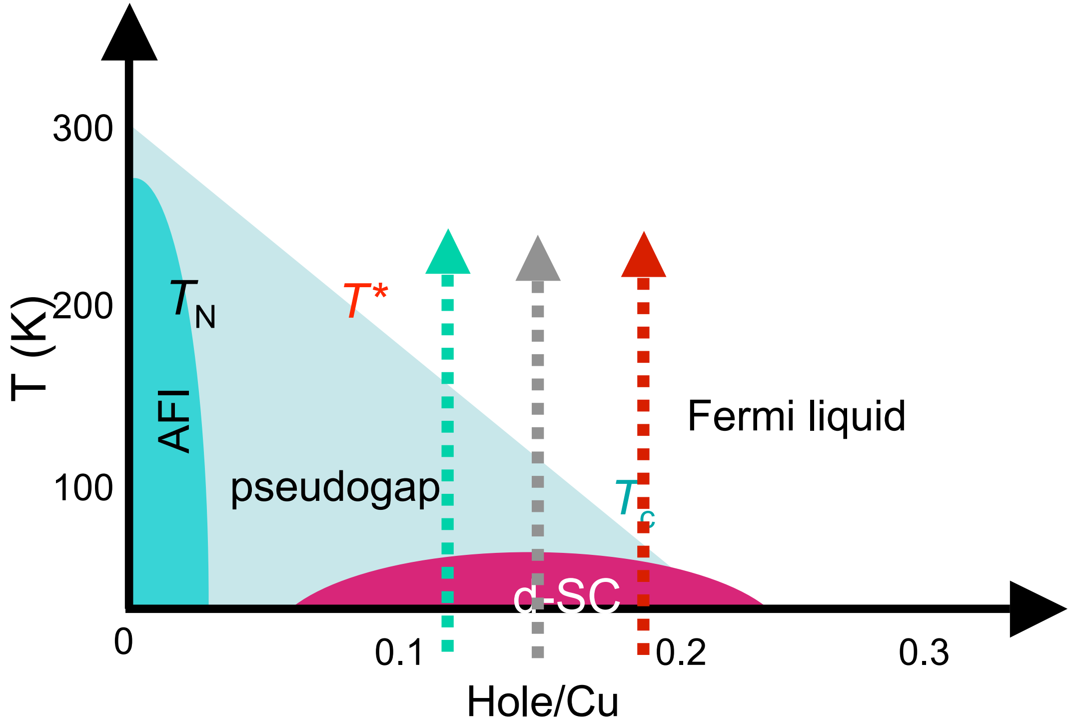


Ch. Renner et al., PRL, '98

Temperature-dependent pseudogap opening

Electronic specific heat

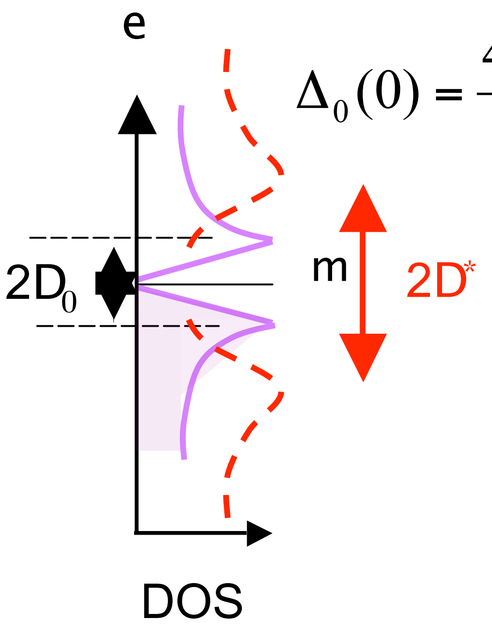




N. Momono et al., JPSJ '02
J. Loram et al., Physica C

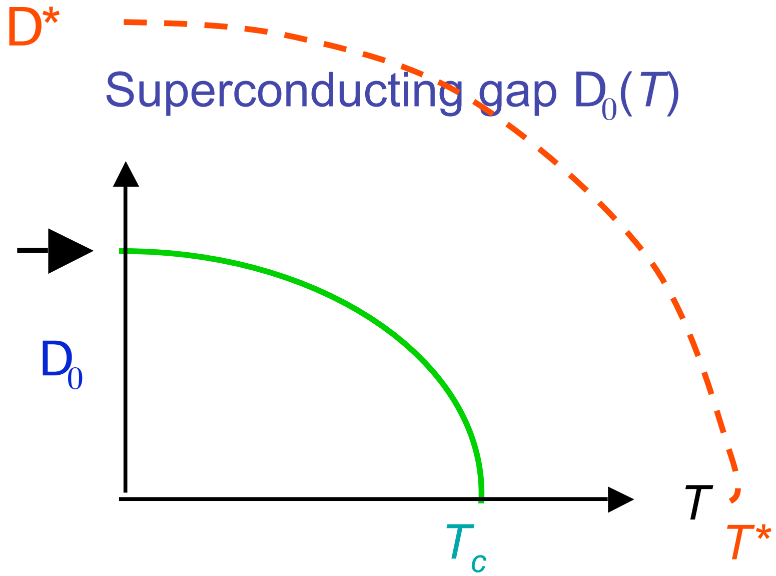
Pseudogap phenomena in high-T_c cuprates

Density of states

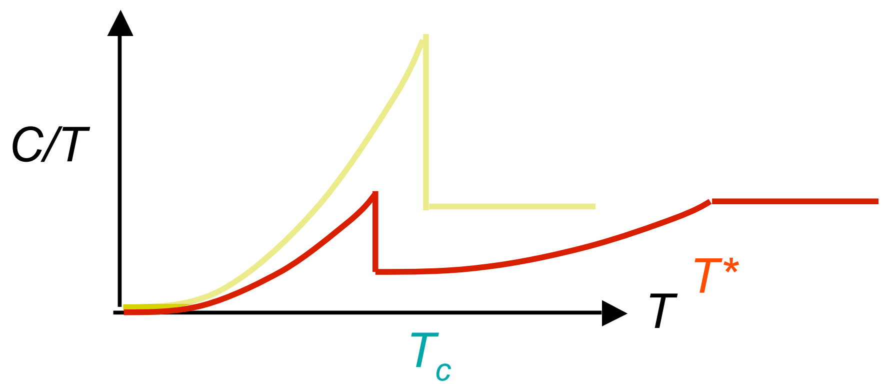


$$\Delta_0(0) = \frac{4.3k_BT_c}{2}$$

Superconducting gap $D_0(T)$



Electronic specific heat

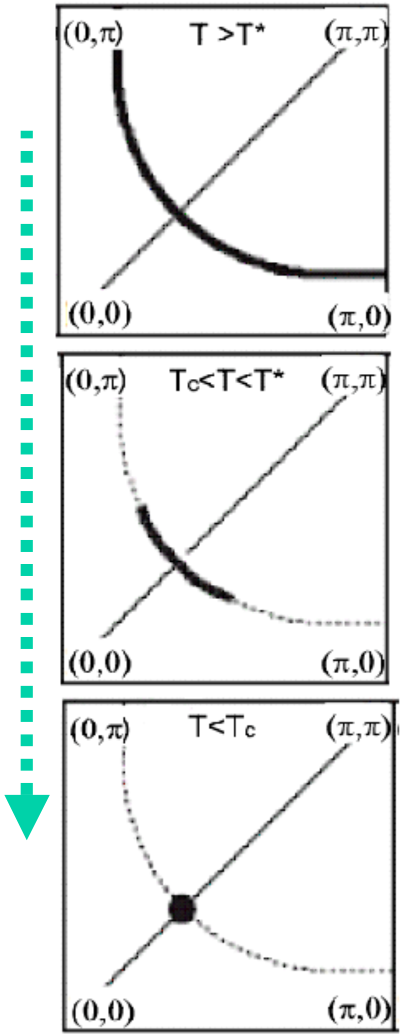


$D(\boldsymbol{k}) = D_0(\cos k_x a - \cos k_y a)$

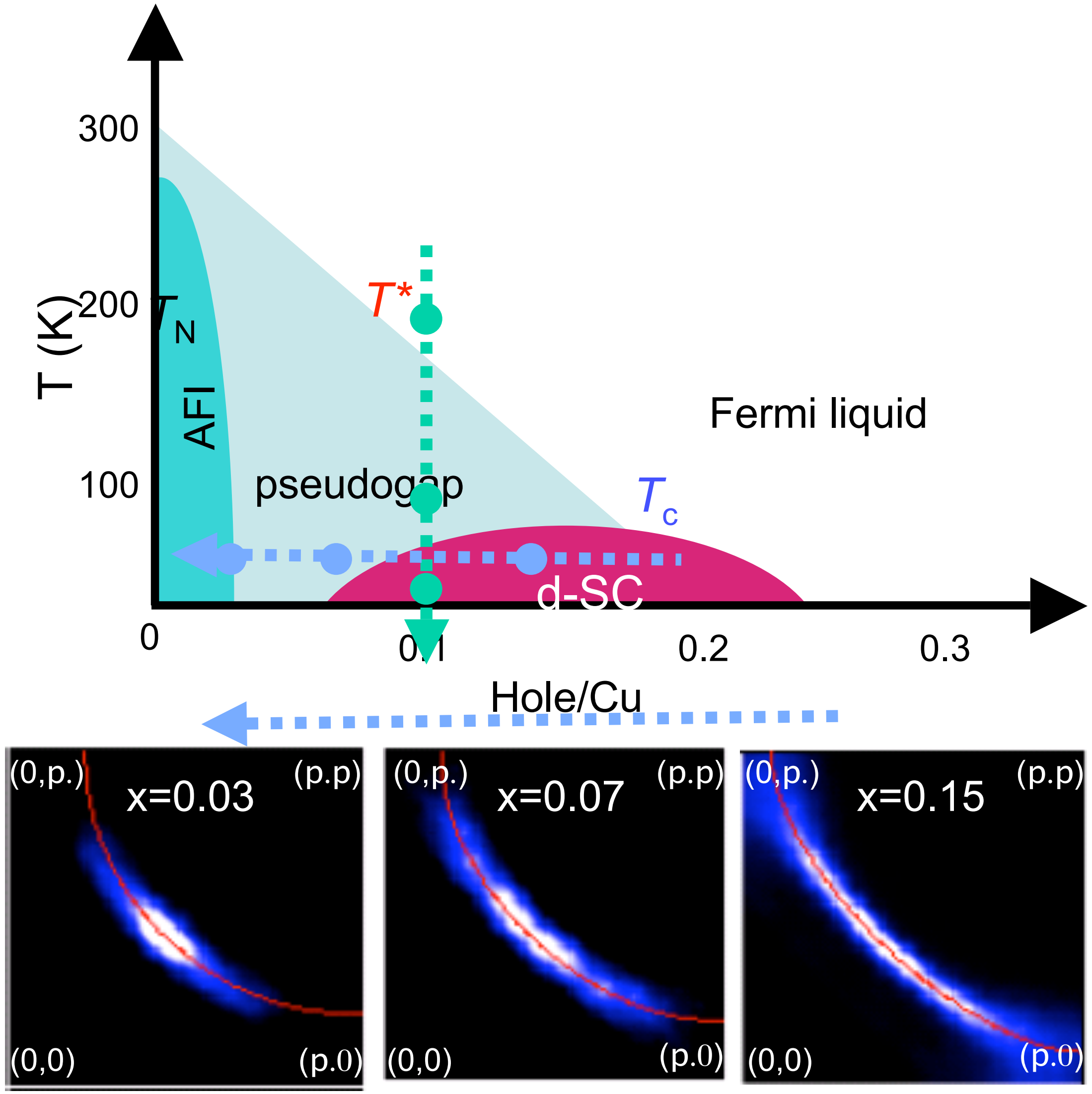
Superfluid density
<< Fermi surface volume/m^*

$\propto T_c$: Uemura relation

Pseudogap opening and Fermi "arc" formation



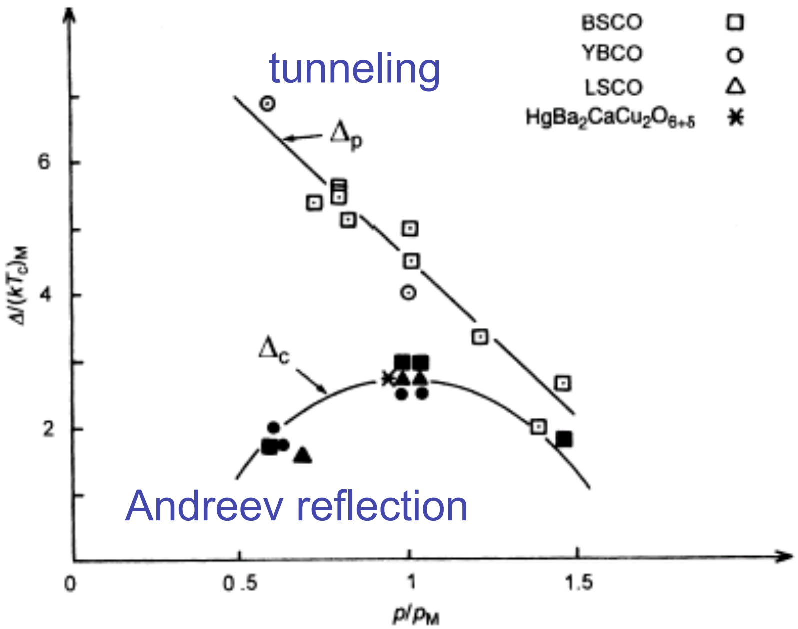
M. R. Norman et al. Nature '98



T. Yoshida et al., PRB'06

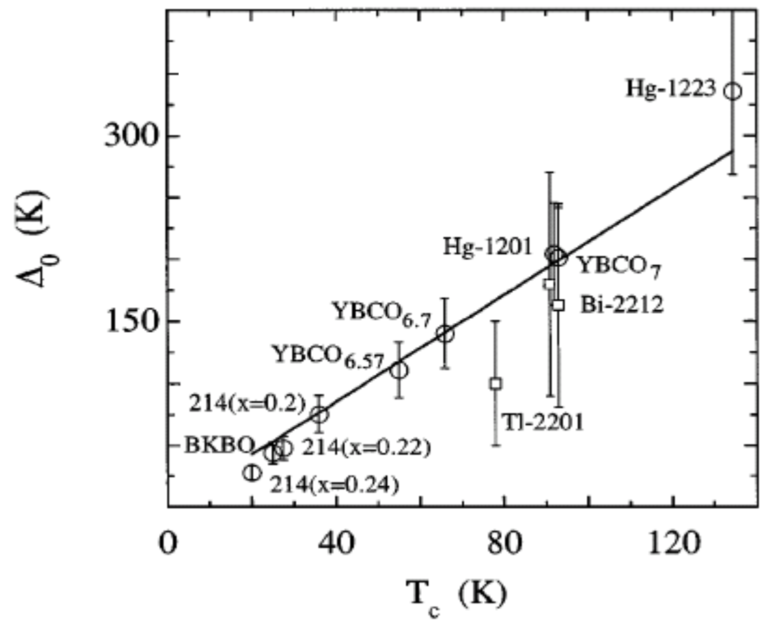
Distinct superconducting gap and pseudogap?

Andreev reflection



G. Deutcher, Nature '99

μon measurements of penetration depth



$$\frac{\lambda_{ab}^2(0)}{\lambda_{ab}^2(T)} \approx 1 - \frac{(2\ln 2)T}{\Delta_0}$$

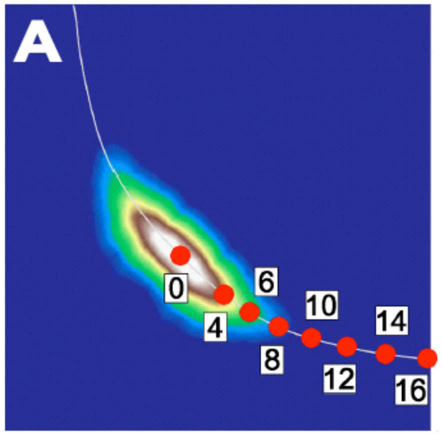
$$D(\boldsymbol{k}) = D_0(\cos k_x a - \cos k_y a)$$

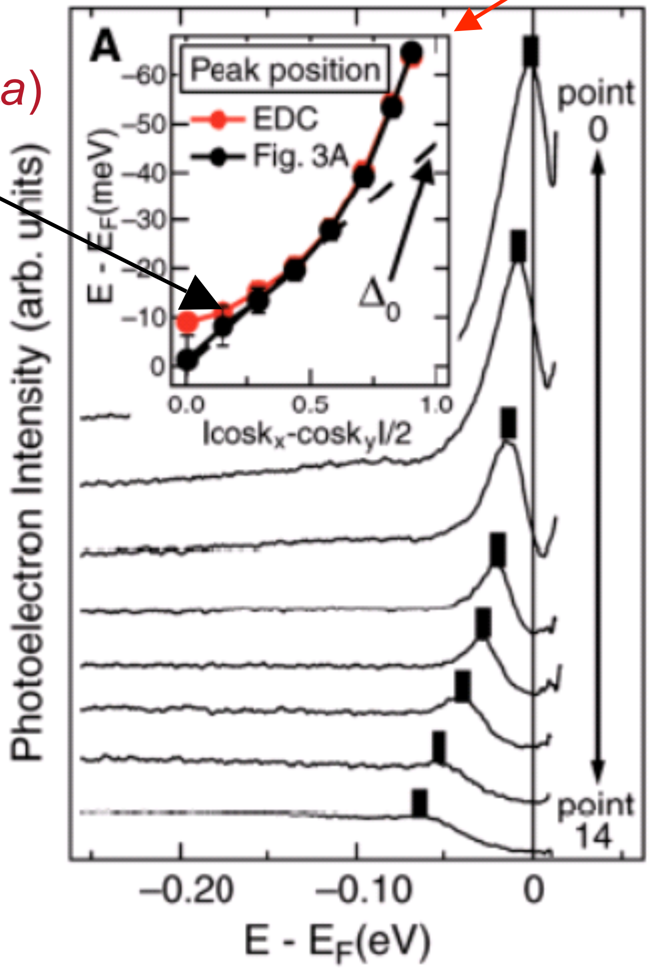
C. Panagopoulos, PRL '98

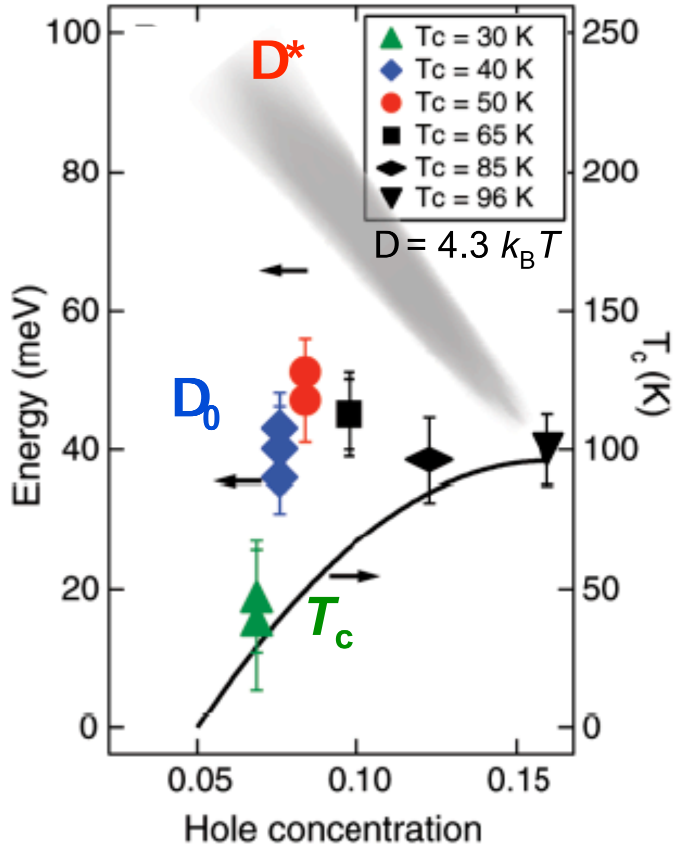
Two gap energy scales D^* and D_0 in underdoped Bi2212

$D(\boldsymbol{k}) = D_0(\cos k_x a - \cos k_y a)$
near node

D^*: larger gap near (p,0)



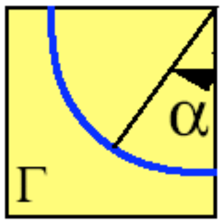


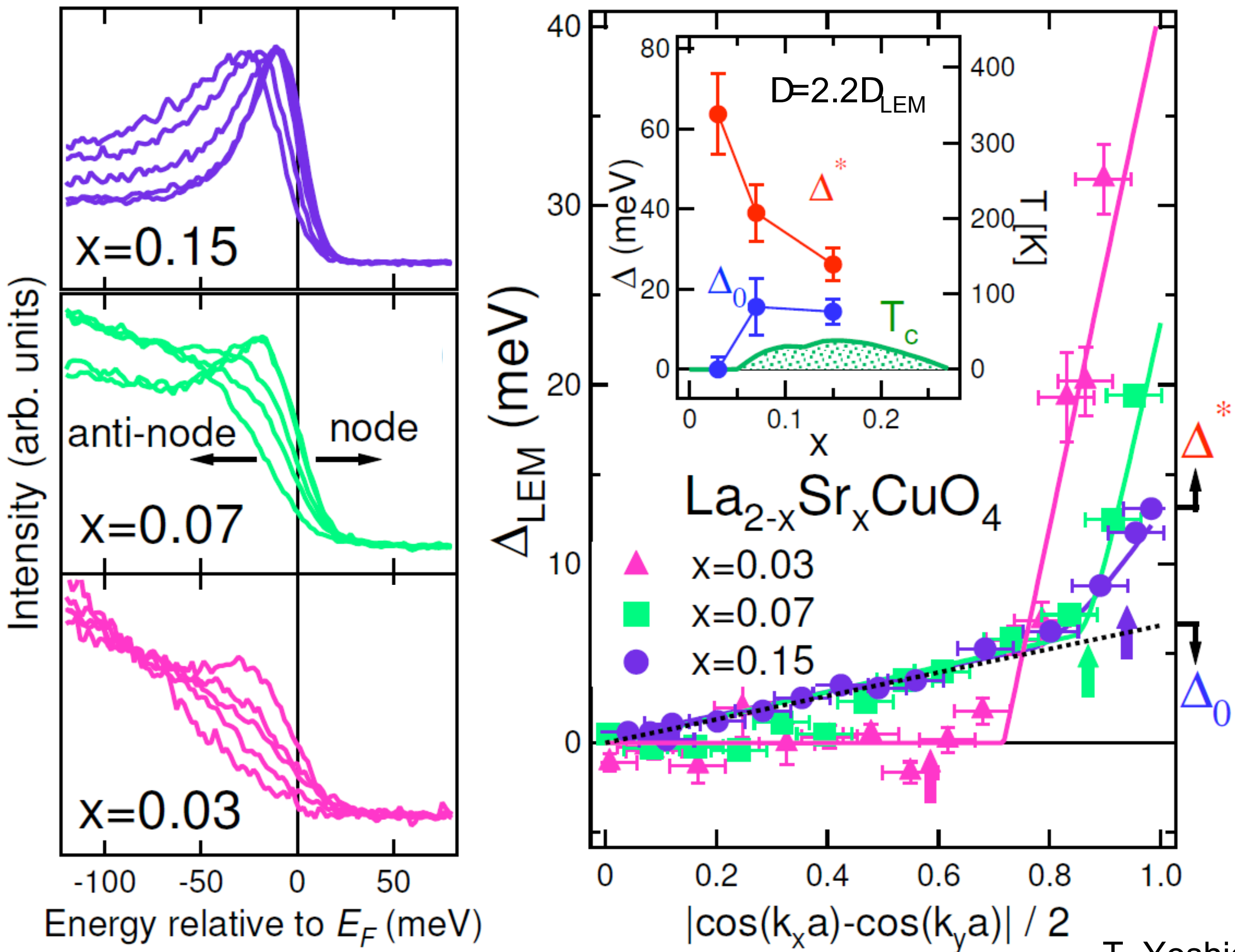


K. Tanaka et al., Science '06

Two gap energy scales D^* and D_0 in underdoped $La_{2-x}Sr_xCuO_4$

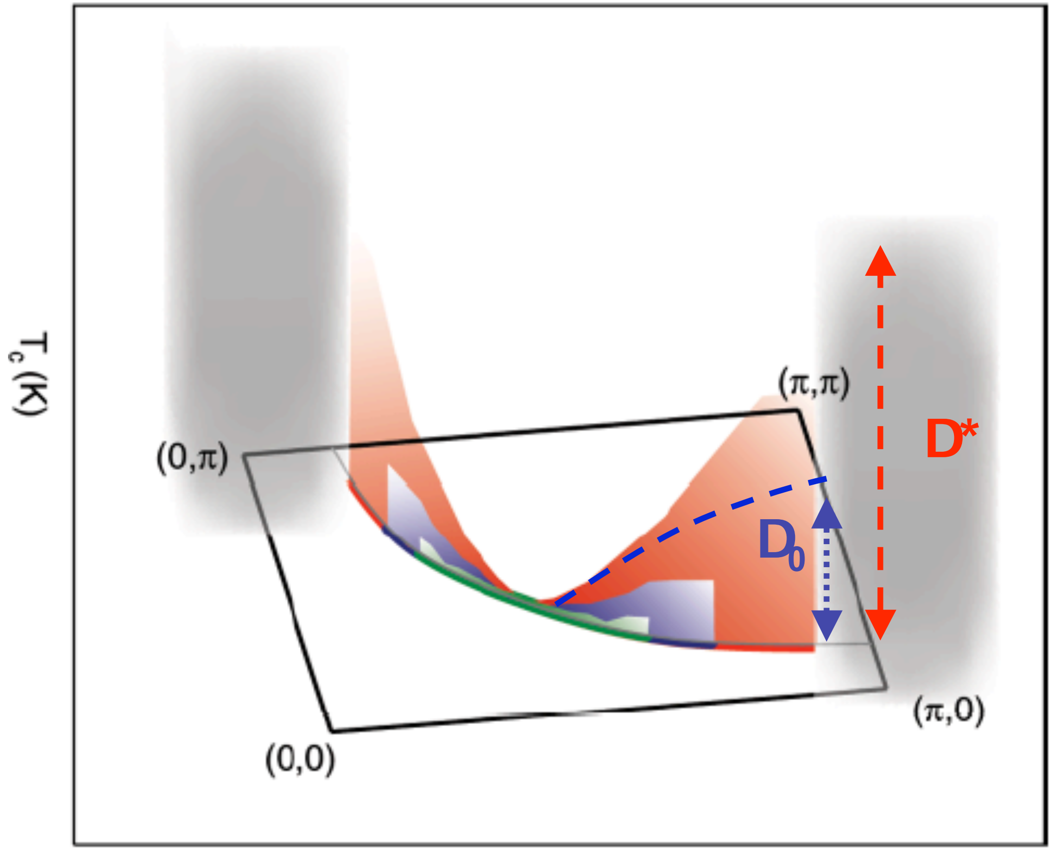
ARPES spectra on Fermi surface





T. Yoshida et al.

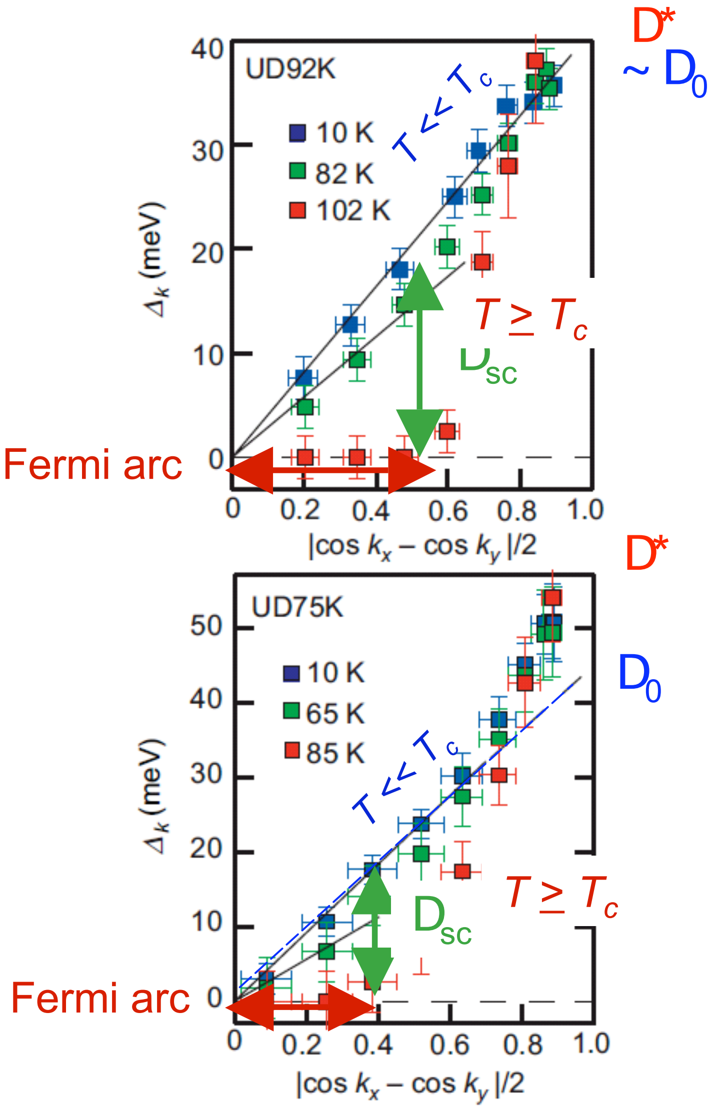
Two gap energy scales D^* and D_0 in underdoped cuprates

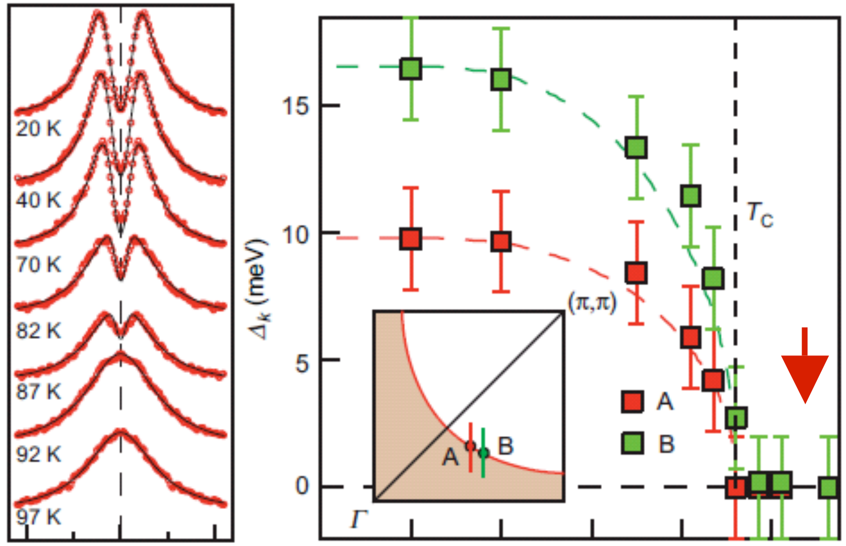


$D(k) = D_0(\cos k_x a - \cos k_y a)$ near node

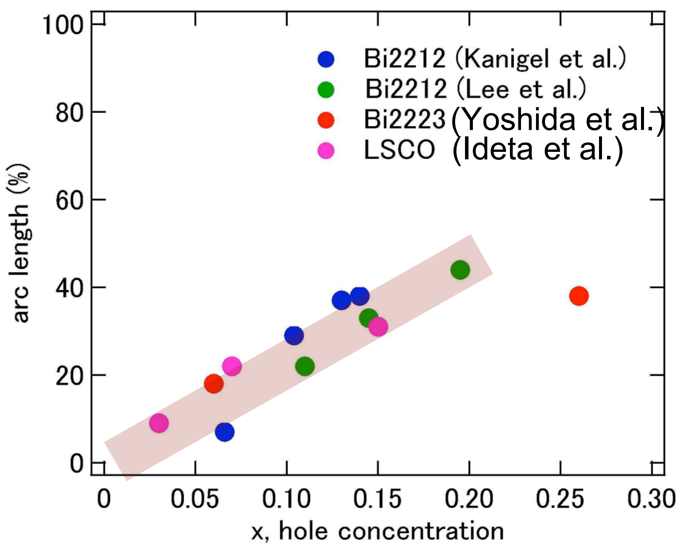
K. Tanaka et al., Science ‘06

Temperature dependence of superconducting gap/pseudogap in underdoped Bi2212





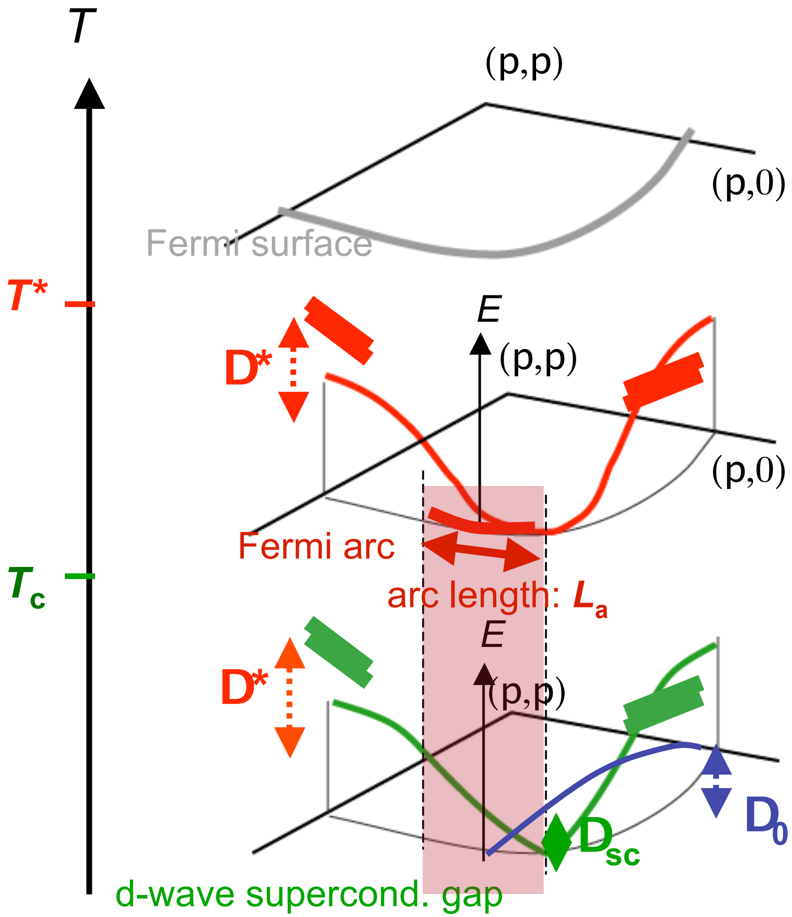
Universal Fermi arc length

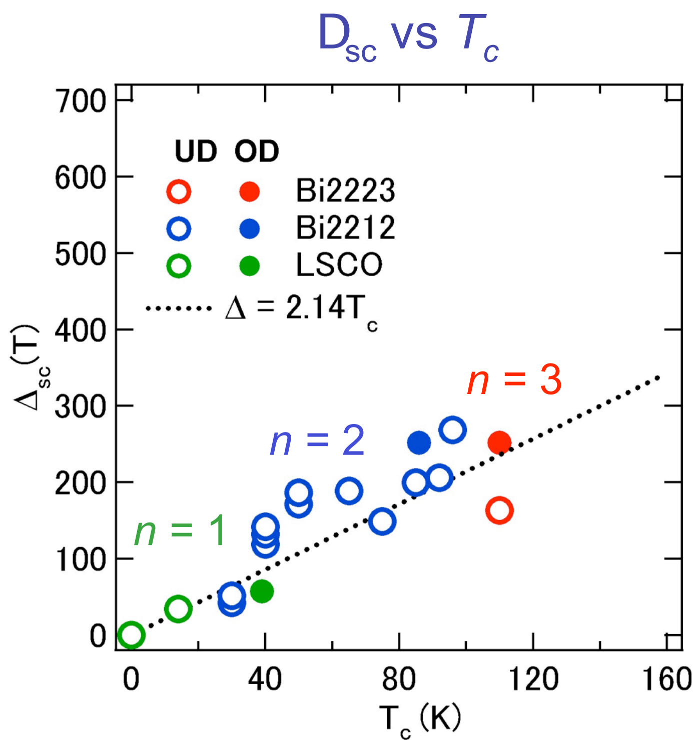


W.S. Lee et al., Nature '07

. Ideta et al

Superconducting gap D_{sc} *vs* T_c





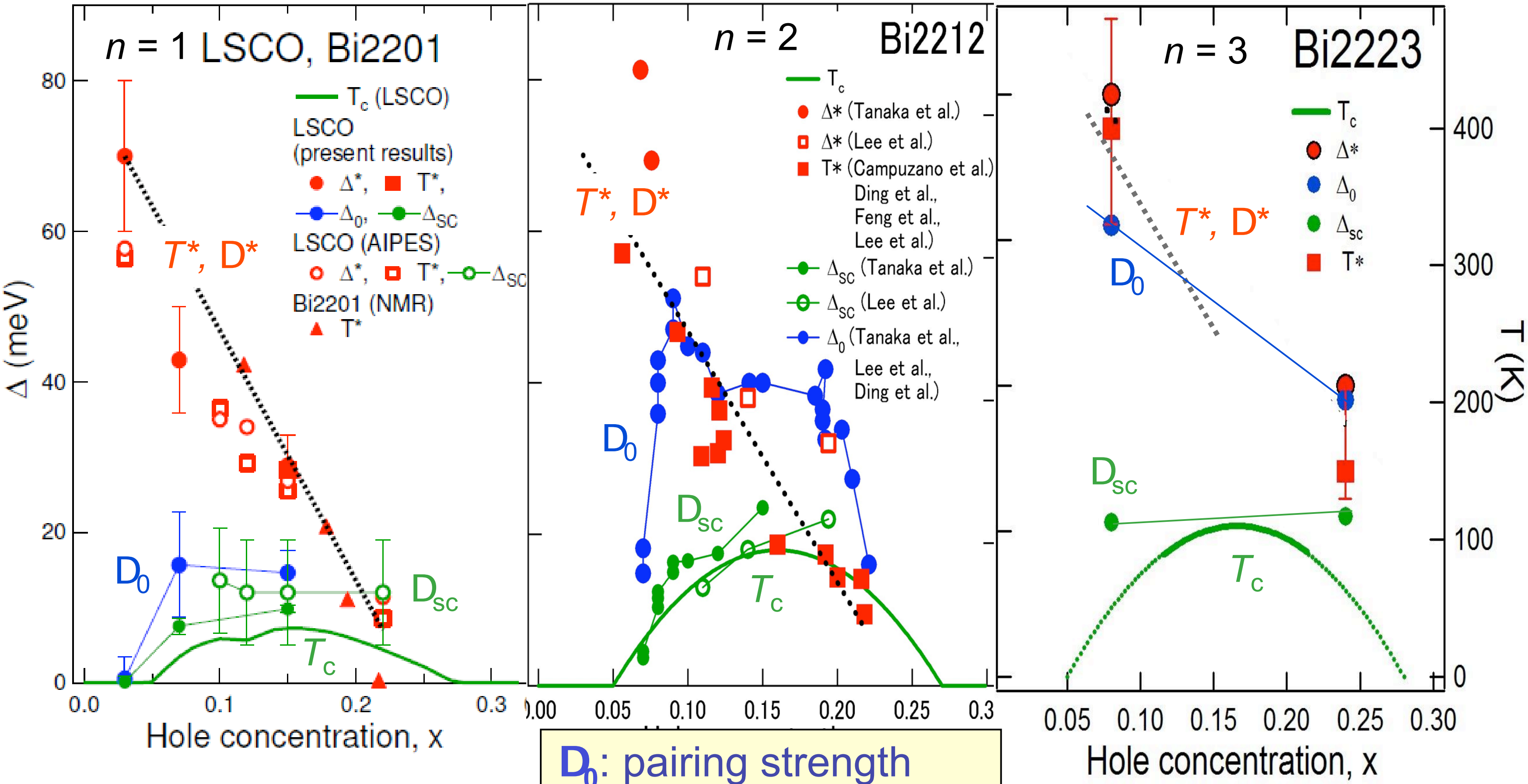
$2D_{sc}/k_B T_c \simeq 4.3$

$D_{sc} \sim D_0(a/2\sqrt{2})L_a$

S. Ideta et al

M. Oda et al, JPSJ ’00
P.A. Lee and X.G. Wen, PRL ’97

Superconducting gap/pseudogap in single, double and triple layer cuprates



D_0: pairing strength

L_a ~ superfluid density

$2D^*/k_B T^* \simeq 4.3$

$2D_{sc}/k_B T_c \simeq 4.3$

$D_{sc} \sim D_0 (a/2\sqrt{2}) L_a << D_0$

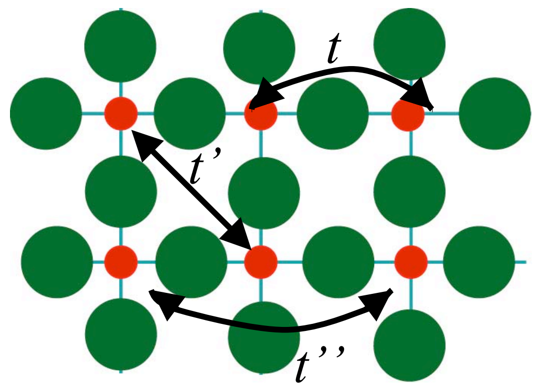
T. Yoshida et al.

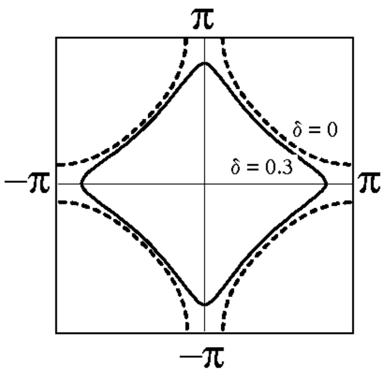
S. Ideta et al.

Dependence of D_0 and $T_{c,max}$ on the CuO_2-layer number

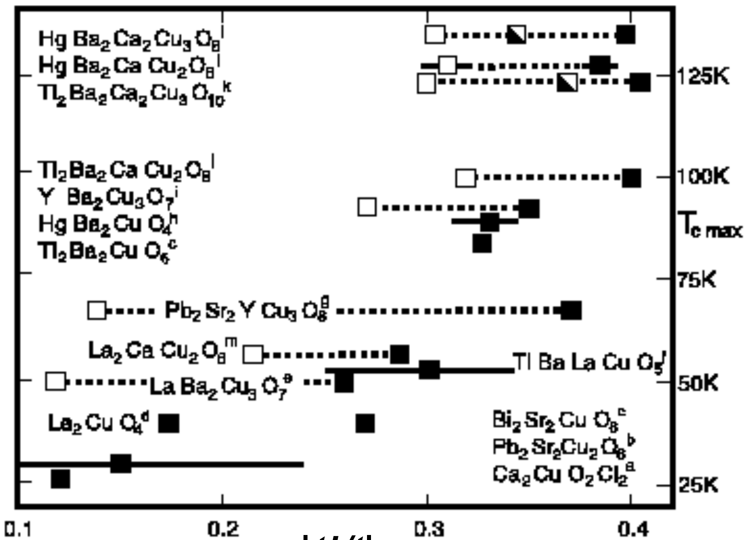
D*, *T**: *independent of* CuO_2-layer #
Property of a single CuO_2 layer (*U*, *J*, *t*, ….)

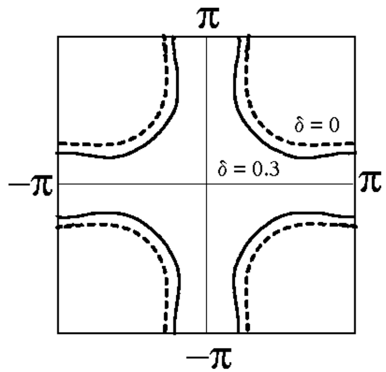
D_0, D_{sc}, T_c: *dependent on* CuO_2-layer #
Apical oxygen (*t'*, *t"*,…)
Out-of-plane disorder (Eisaki, Uchida)
Interlayer coupling – Copper pair tunneling





LSCO t'/t = -0.12, t"/t = 0.08





BSCCO t'/t = -0.34, t"/t = 0.23

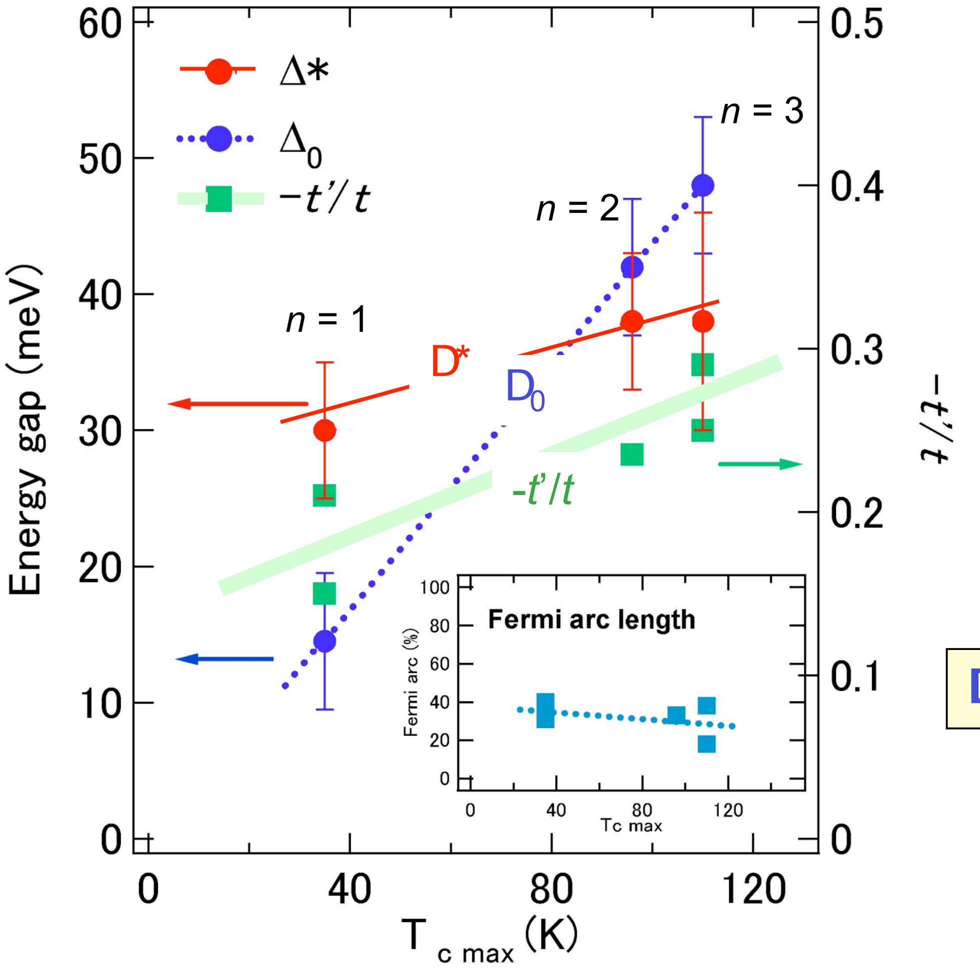
small ◄——— $|t'/t|$ ———► large

E. Pavarini et al., PRL '01

T.Tohyama and S. Maekawa, Supercond. Sci. Technol. '00

Dependence of $T_{c,max}$ on material parameters

Relationship for optimally-doped LSCO, Bi2212, Bi2223

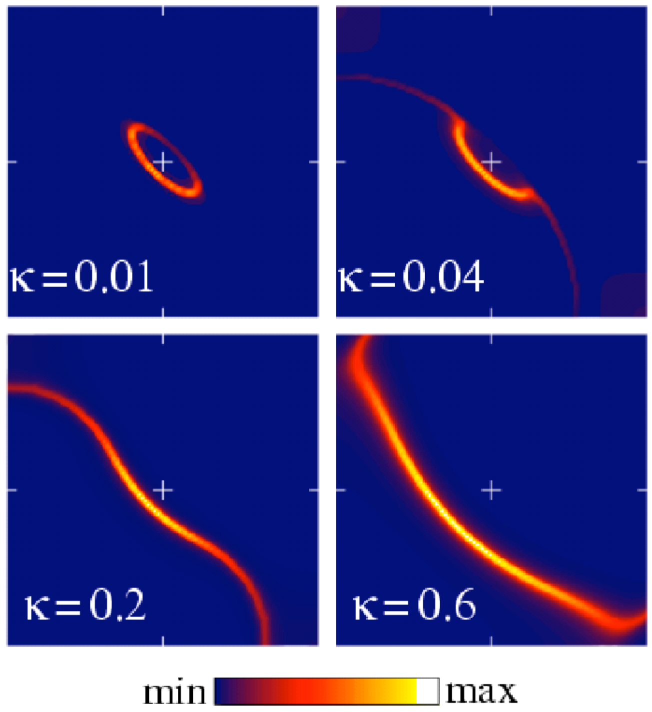


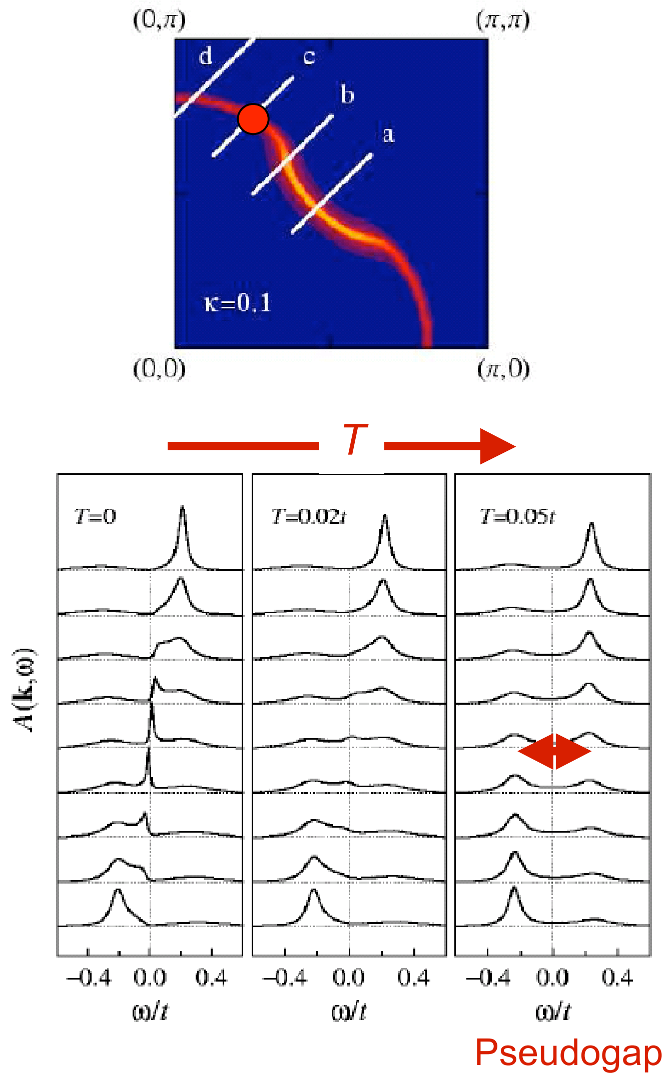
D_0: paring strength

S. Ideta

Possible origin of pseudogap?
(1) Antiferromagnetic fluctuations

Generalized *t-J* model calc

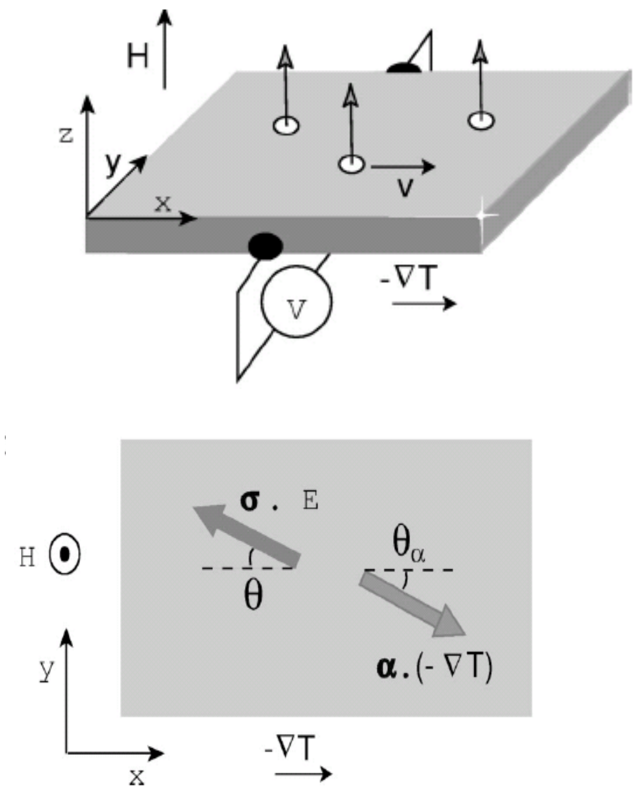


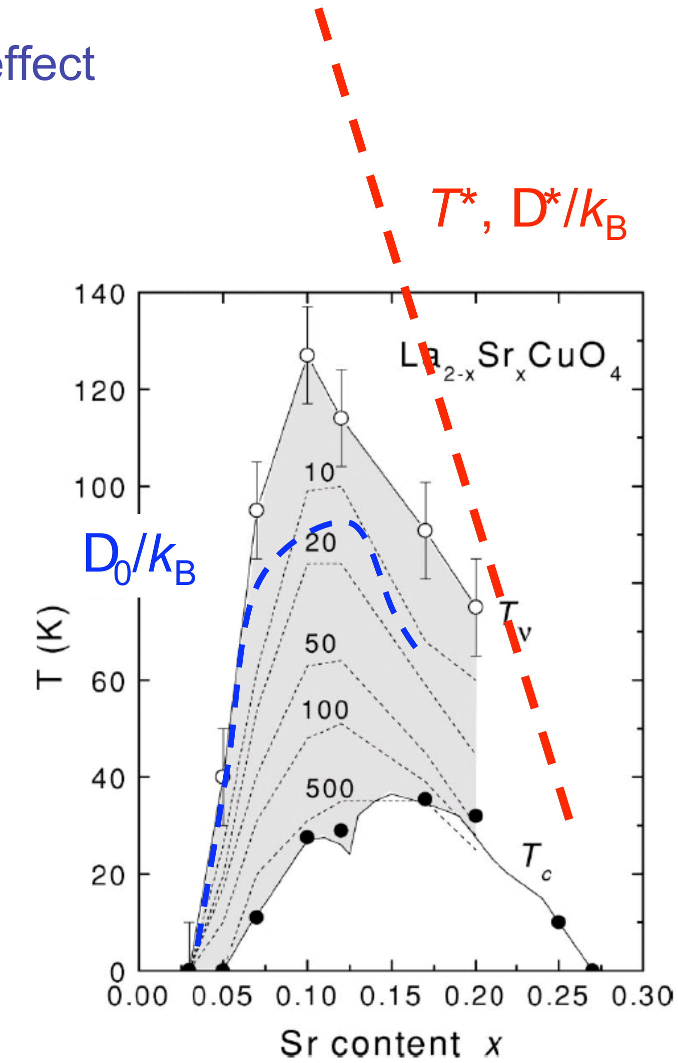


P. Prelovsek and A. Ramsak, PRB '02

Possible origin of pseudogap?
(2) *d*-wave pairing fluctuations

Nernst effect





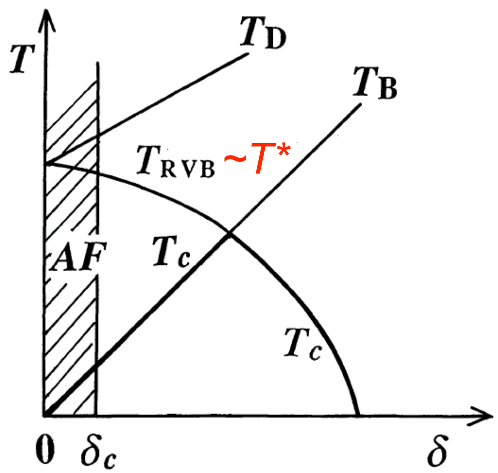
Signals too weak

Drops toward $x \rightarrow 0$ unlike T^*

Y. Wang et al. PRB '01

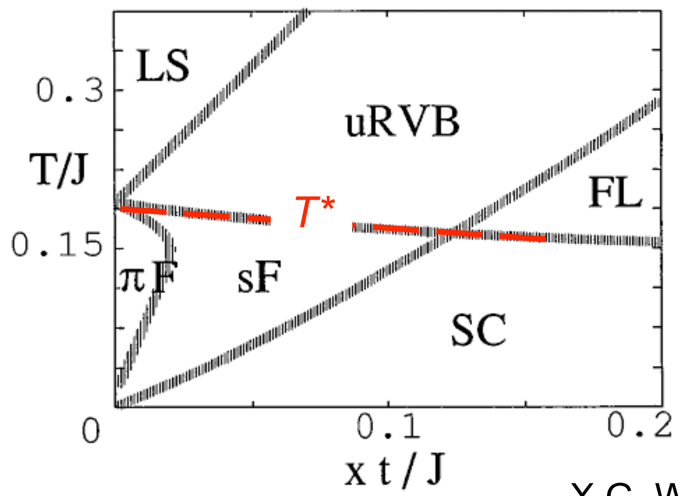
Possible origin of pseudogap?
(3) RVB - Resonating Valence Bonds

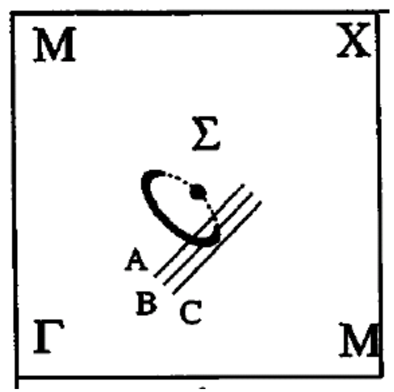
Slave-boson mean-field theories



H. Fukuyama
N. Nagaosa and P.A. Lee
G. Baskaran
G. Kotliar

SU(2)

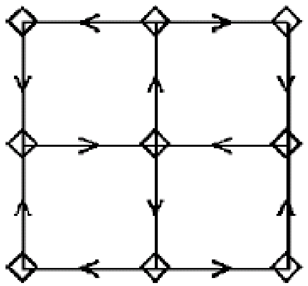


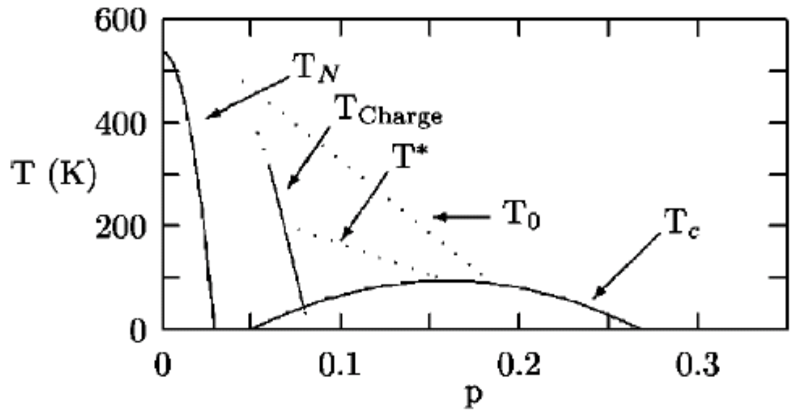


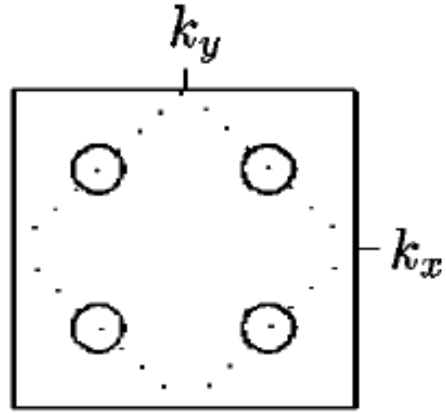
X.G. Wen and P.A. Lee, PRL '98

Possible origin of pseudogap?
(4) Time-reversal symmetry breaking

d-DW

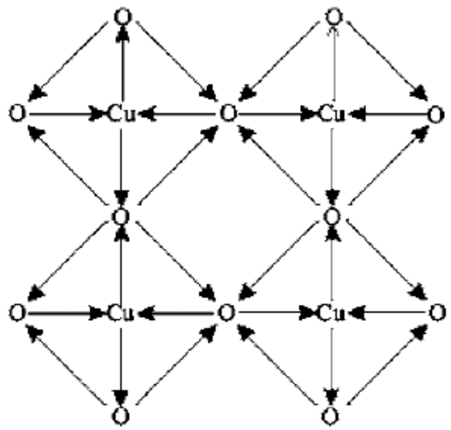


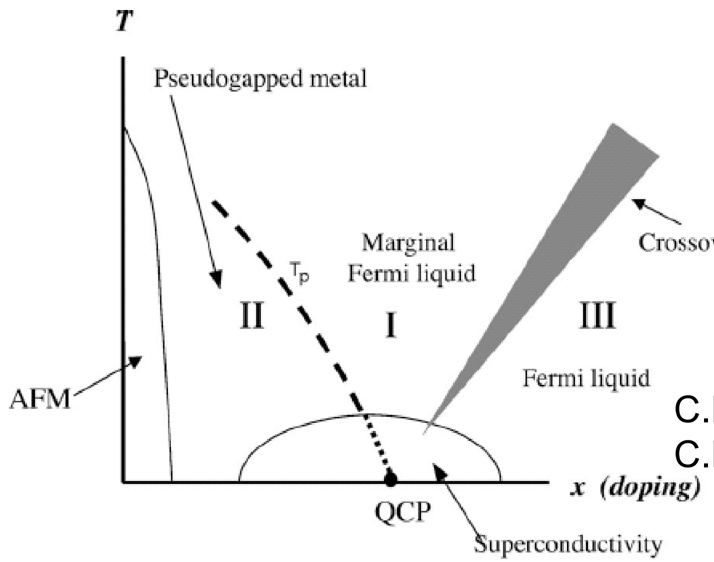




S. Chakraverty et al., PRB '01

Circulating current in *p*-*d* model





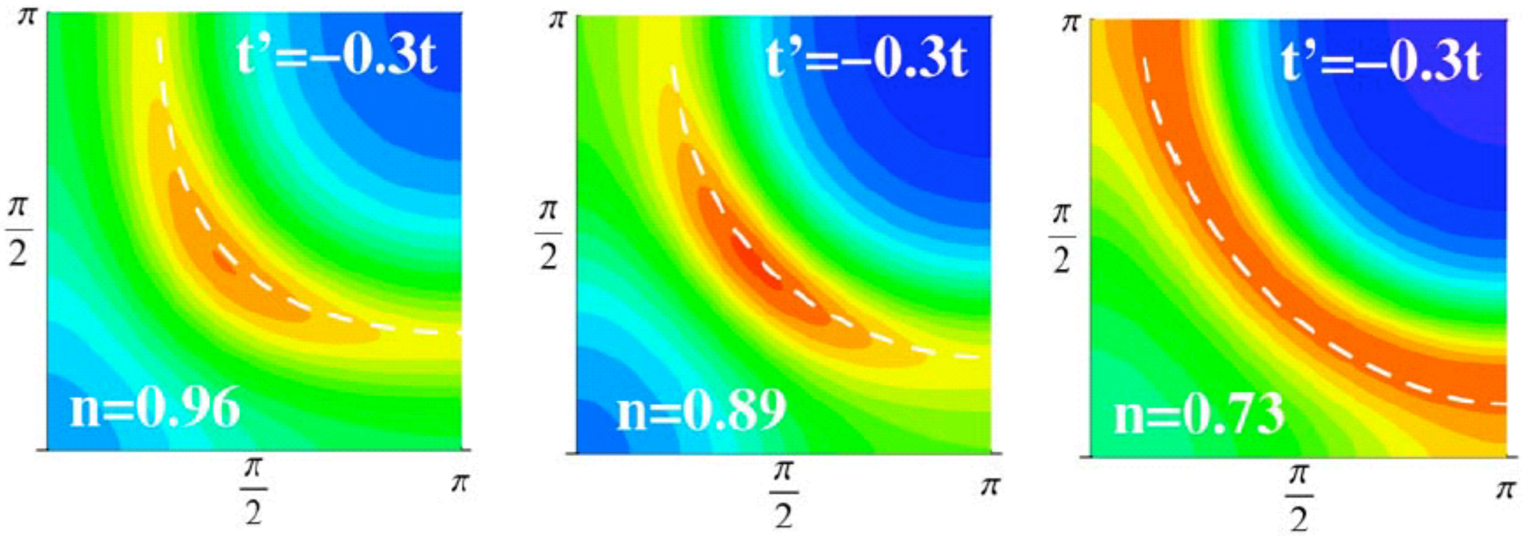
→ Fermi arc

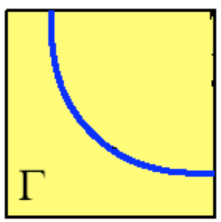
C.M. Varma PRB '06

C.M. Varma and L. Zhu, RL '07

Possible origin of pseudogap?
(5) *k*-dependent Mott transition

CDMFT calc

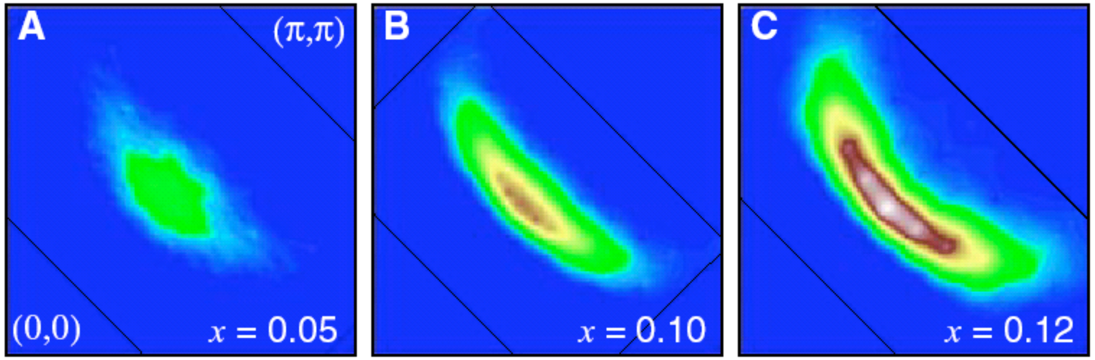




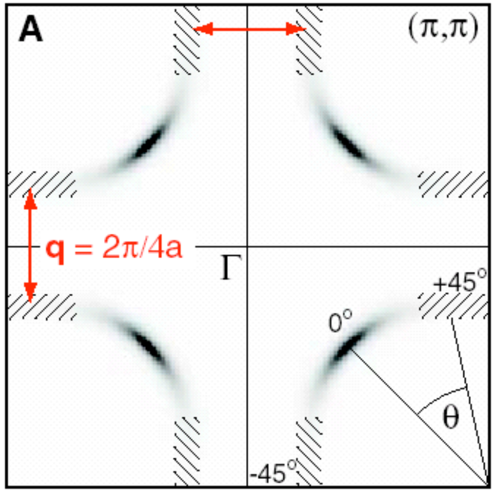
M. Civelli et al., PRL '05
Y.Z. Zhang and M. Imada, PRB '07

Possible origin of pseudogap?
(6) CDW, polaron effects

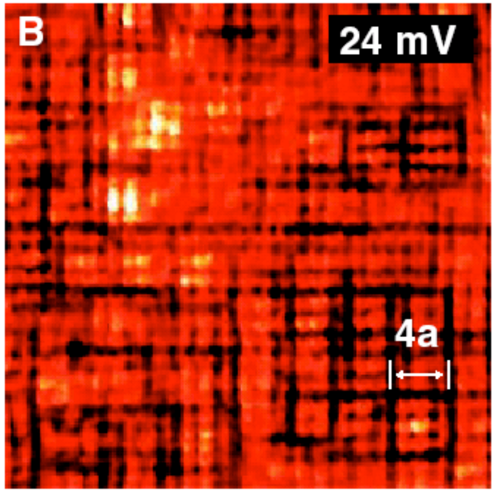
Fermi arc in $Na_xCa_{2-x}CuCl_2O_2$



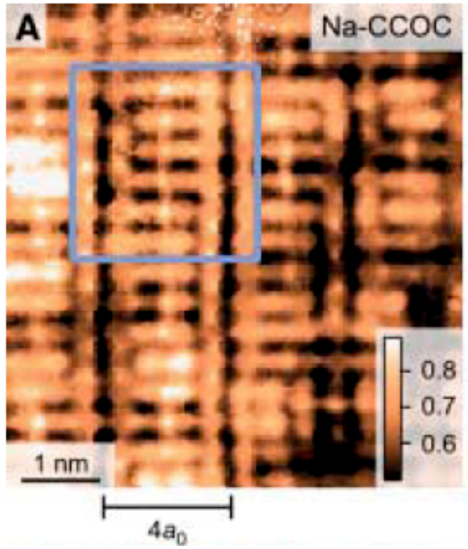
Fermi surface nesting?



Checkerboard pattern?



Cluster glass in STM?



K.M. Shen et al., Science '05 Y. Kohsaka et al., Science '07

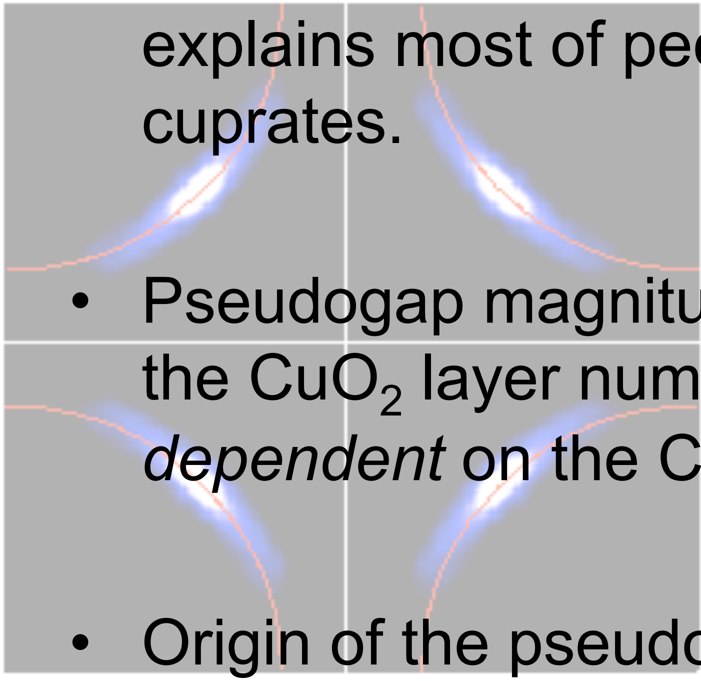
Short summary 1

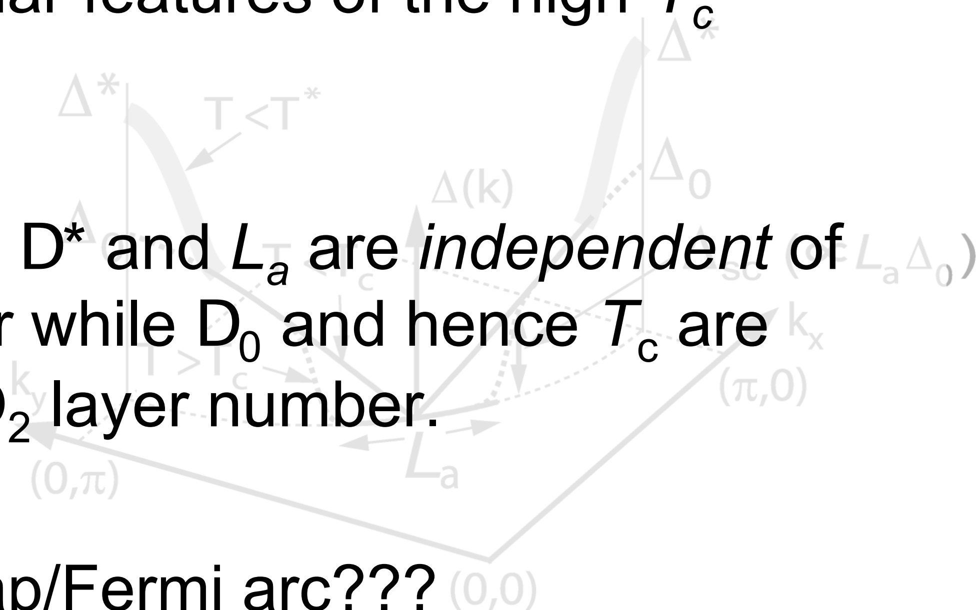
- Superconductivity in high-T_c cuprates occurs on the Fermi arc of length L_a.

  T_c is determined by the paring strength D_0 and the available electron density $\propto L_a$: $T_c \propto L_a D_0$., which explains most of peculiar features of the high-T_c cuprates.

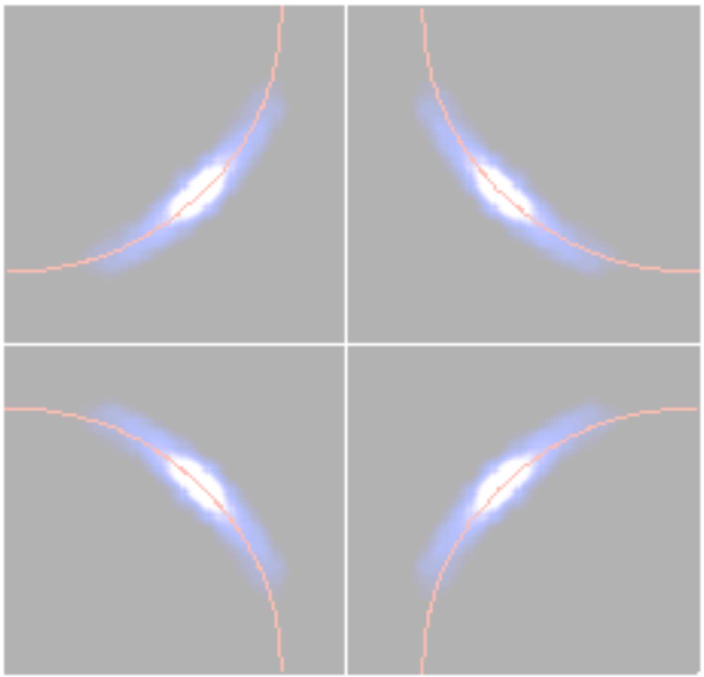
- Pseudogap magnitude D* and L_a are *independent* of the CuO_2 layer number while D_0 and hence T_c are *dependent* on the CuO_2 layer number.

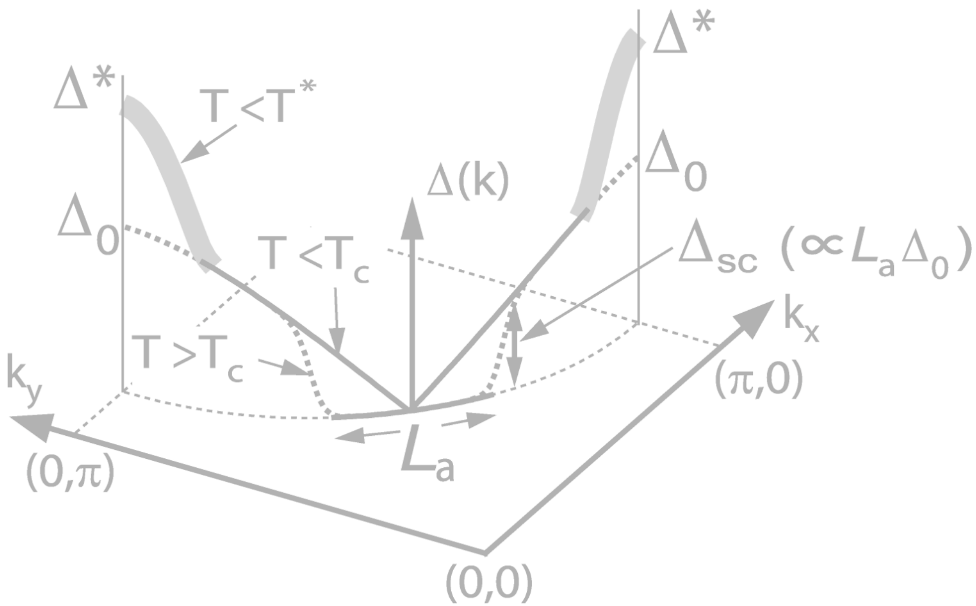
- Origin of the pseudogap/Fermi arc???





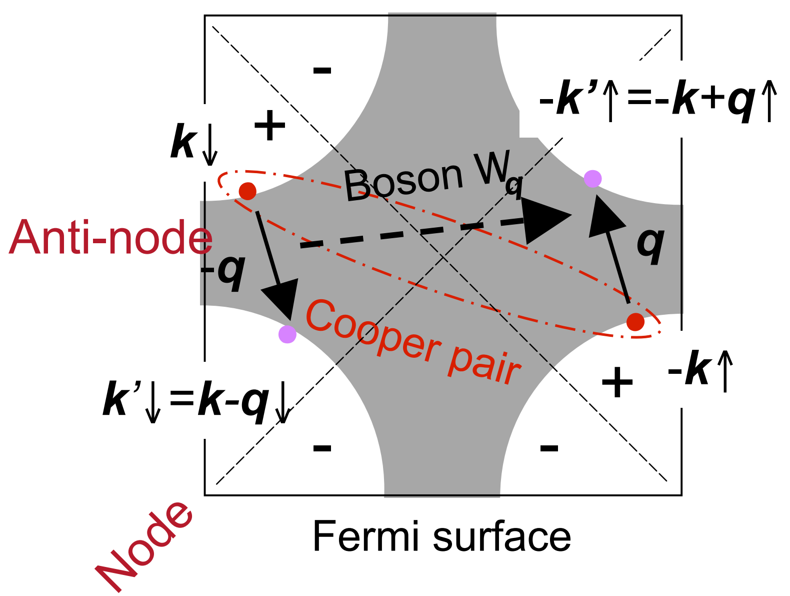
Coupling of electron to Boson excitations



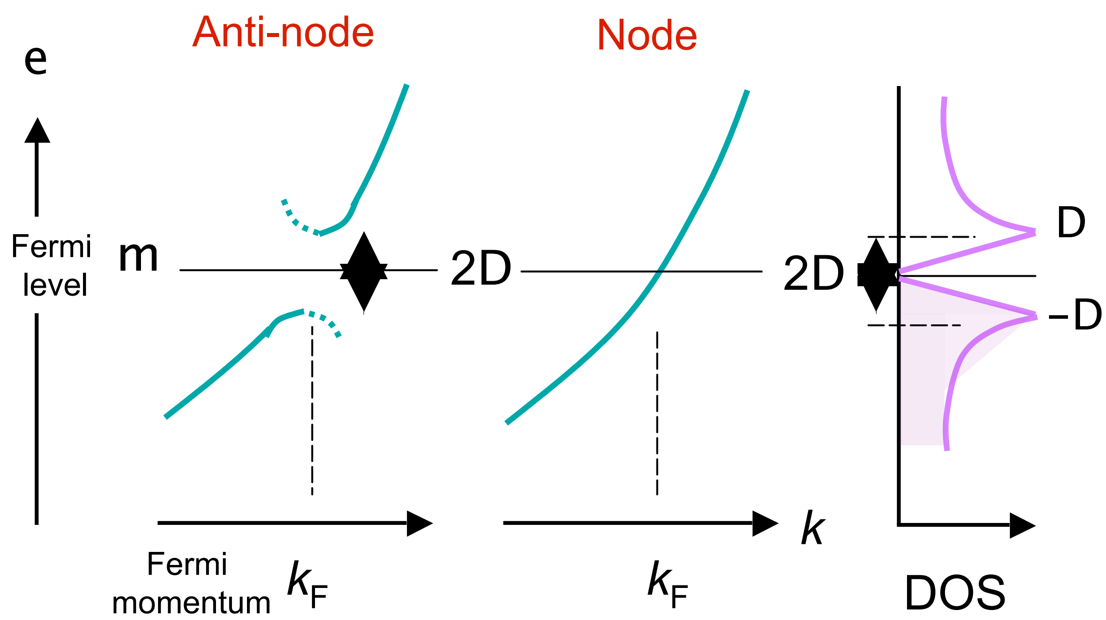


Boson-mediated *d*-wave superconductivity

Cooper pair formation



Superconducting gap + boson structure



$$\Psi_{\mathrm{BCS}} = \prod_{\mathbf{k}} (u_{\mathbf{k}} + v_{\mathbf{k}} a^{+}_{\mathbf{k},\uparrow} a^{+}_{-\mathbf{k},\downarrow}) |0\rangle$$

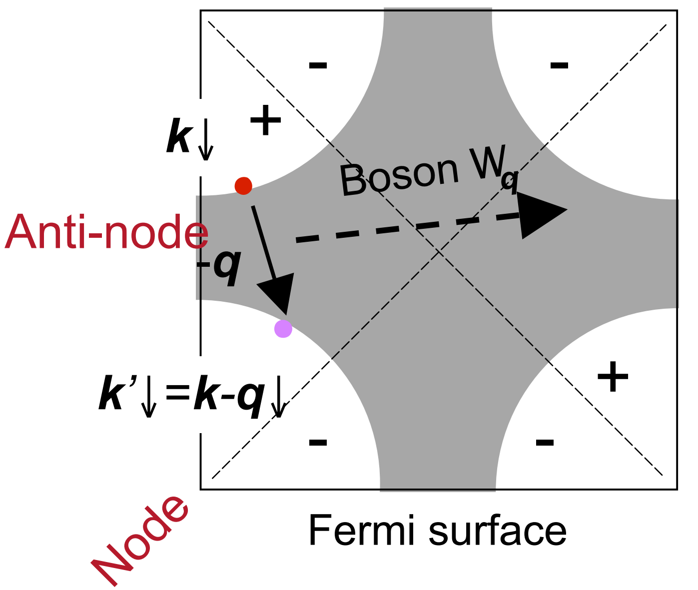
$$\varepsilon = \pm\sqrt{\varepsilon(\mathbf{k})^2 + \Delta(\mathbf{k})^2}$$

$$\Delta_k = \frac{1}{2}\sum_{k'>0}\frac{\Delta_{k'}}{\sqrt{\varepsilon_{k'}^2 + \Delta_{k'}^2}} V_{kk'}$$ Gap equation

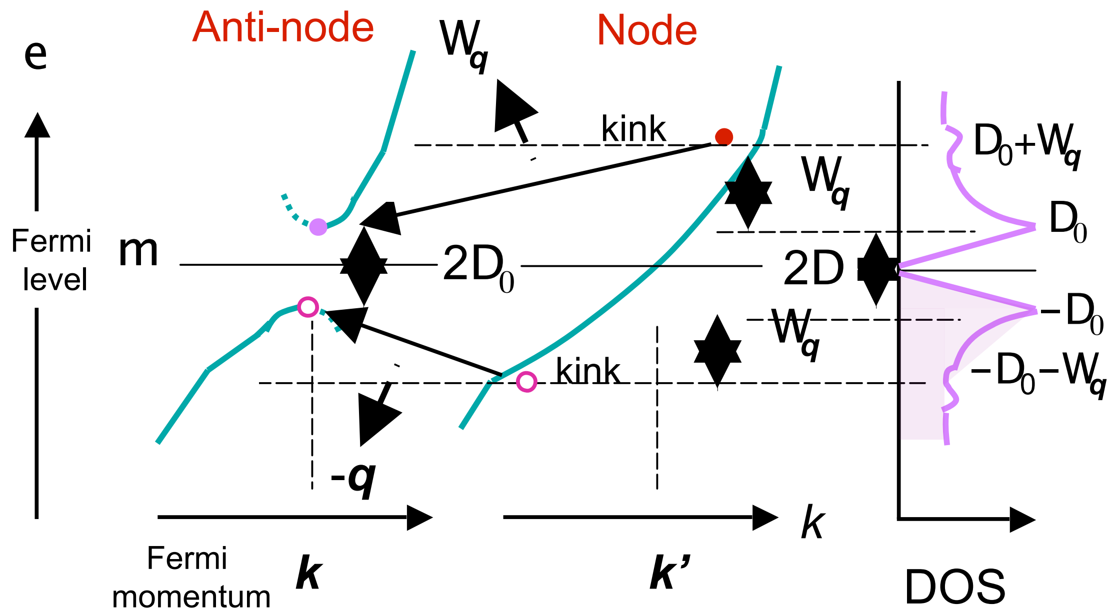
$D(\boldsymbol{k}) = D_0(\cos k_x a - \cos k_y a)$

Scattering of quasi-particle by Boson excitation

Electron-Boson coupling



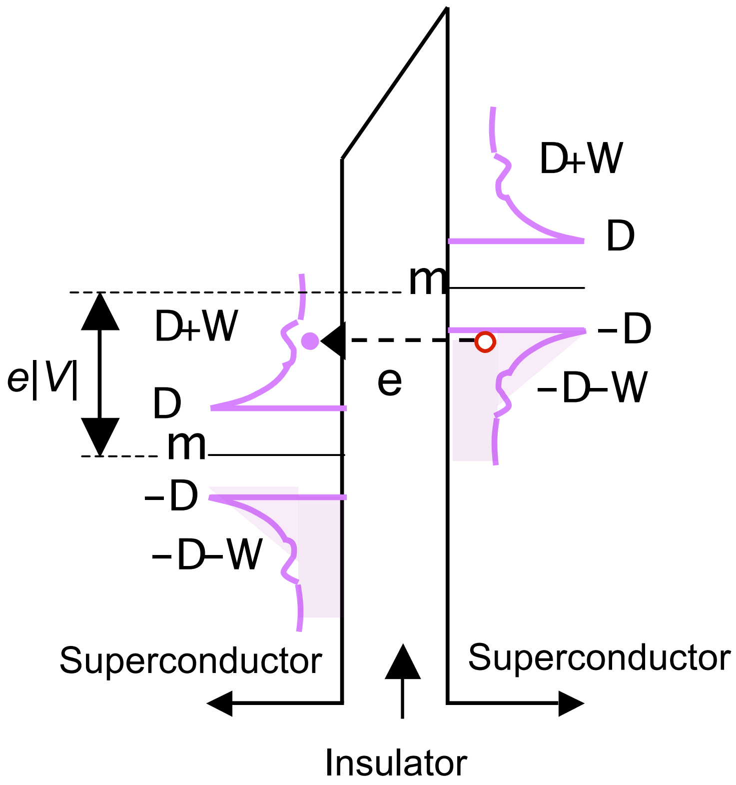
Superconducting gap + boson structure



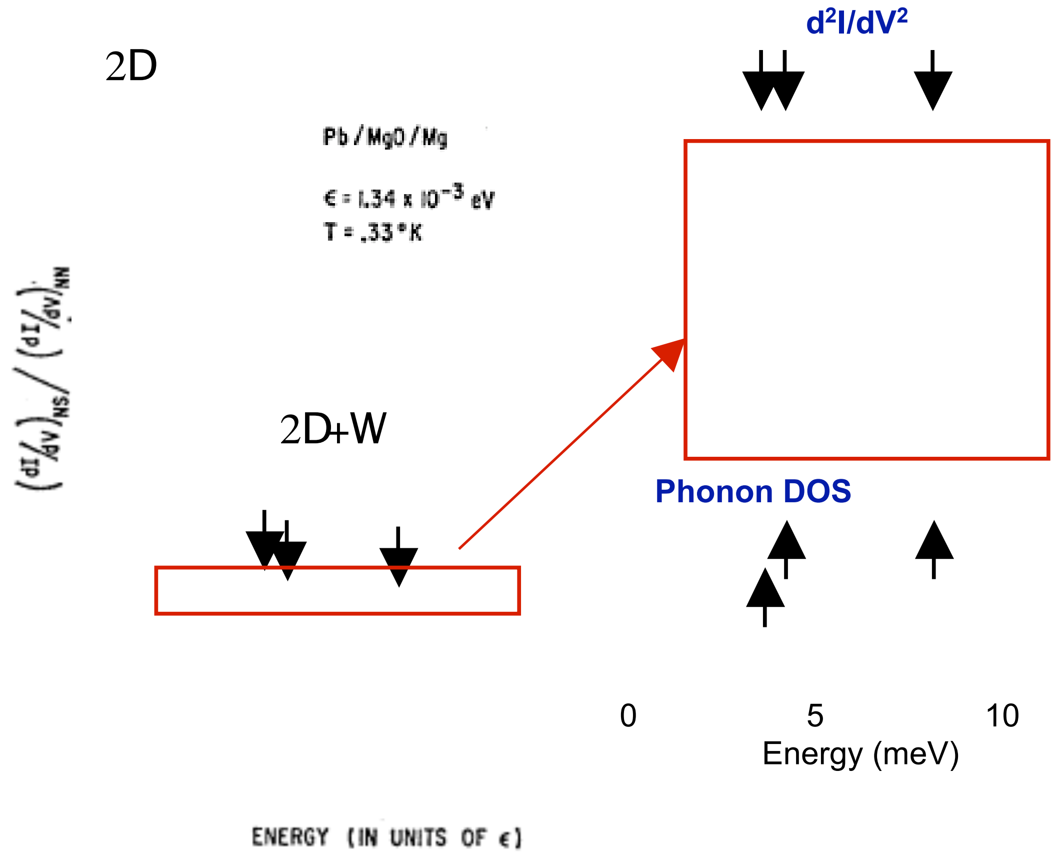
W_q: Boson energy

Evidence for electron-phonon coupling from tunneling spectroscopy

S/I/S tunneling barrier



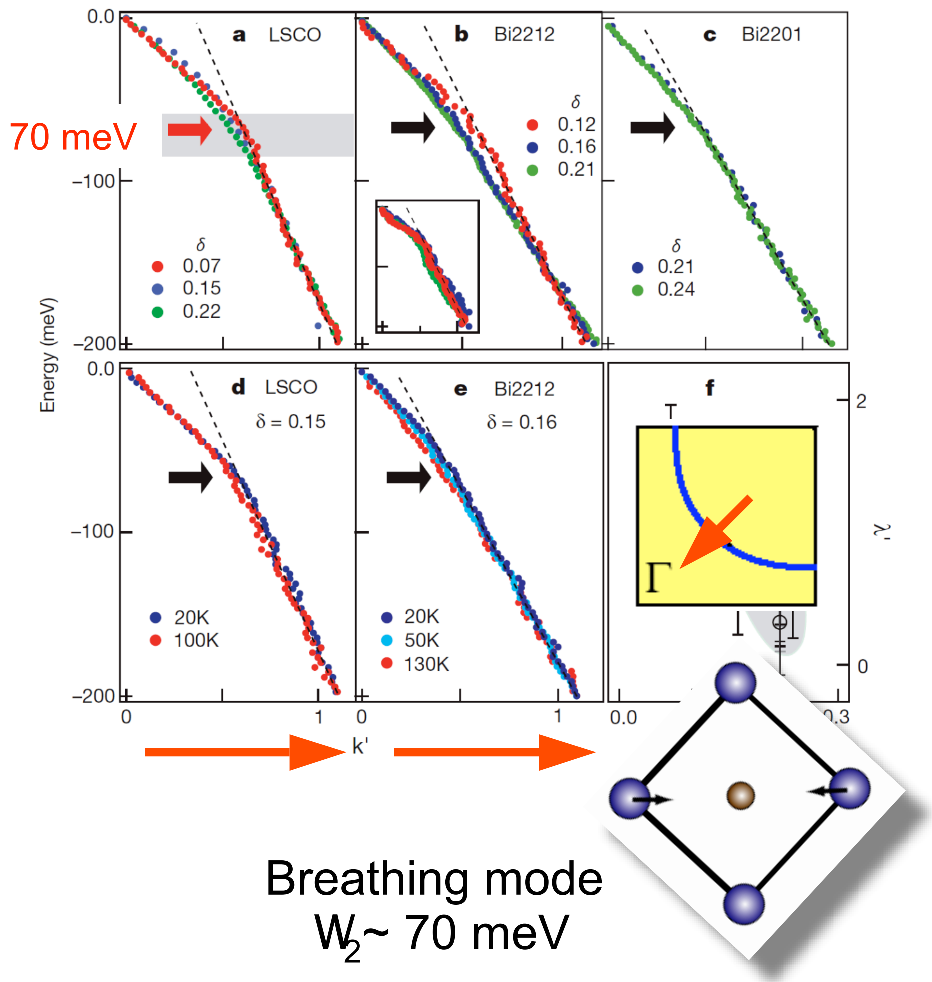
Tunneling spectrum of Pb/MgO/Pb junction



I. Giaever et al., PR '62   W.L. McMillan and J.M. Rowell, PRL '65

~70 meV kink in the nodal direction

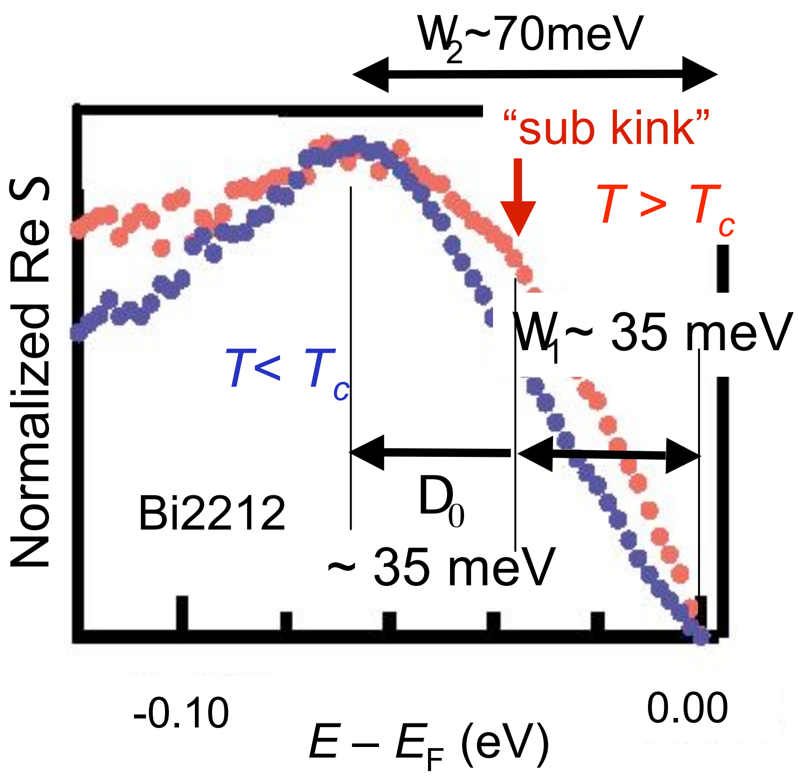
Previous interpretation



Breathing mode
W_2~ 70 meV

A. Lanzara et al., Nature '01

New interpretation



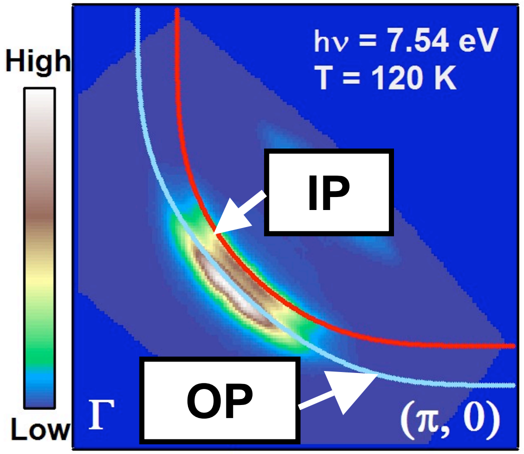
Boson energies

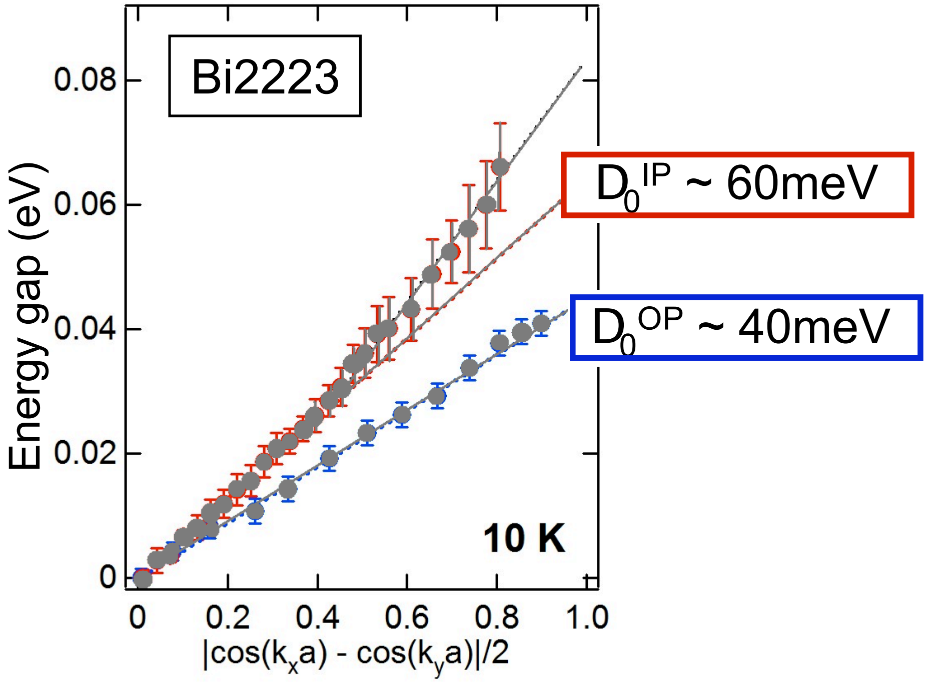
W_1 ~ 35 meV
W_2 ~ 70 meV

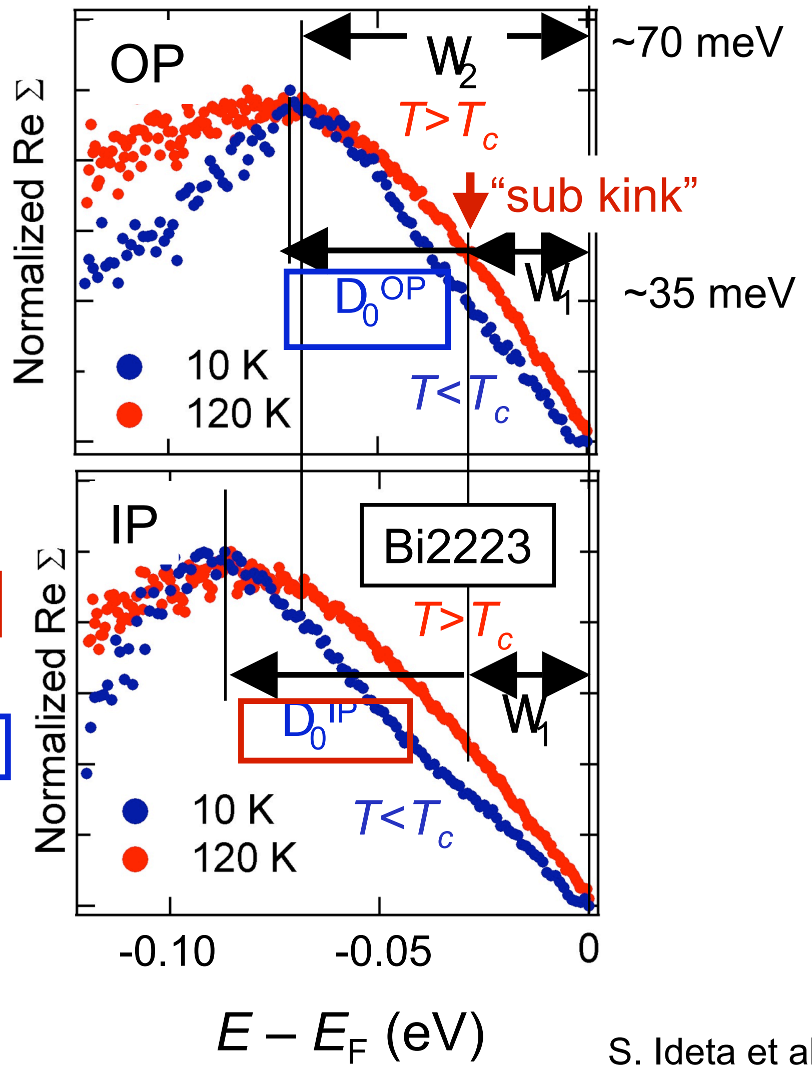
W. S. Lee et al., PRB '08

Theory: A. W. Sandvik et al., PRB '04

~95(!) meV kink in the trilayer cuprate Bi2223





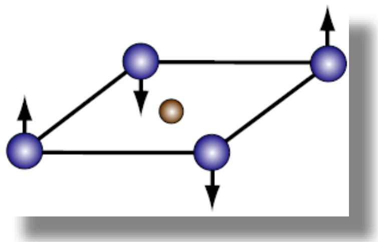


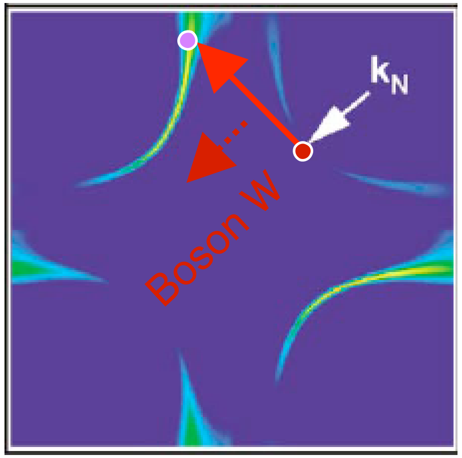
S. Ideta et al.

Phonon scenario of ARPES kinks

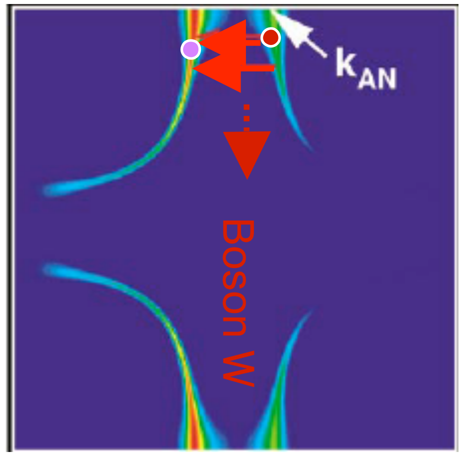
Nodal quasi-particle | Antinodal quasi-particle

Buckling mode
W_1 ~ 35 meV



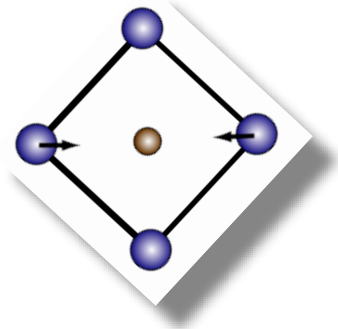


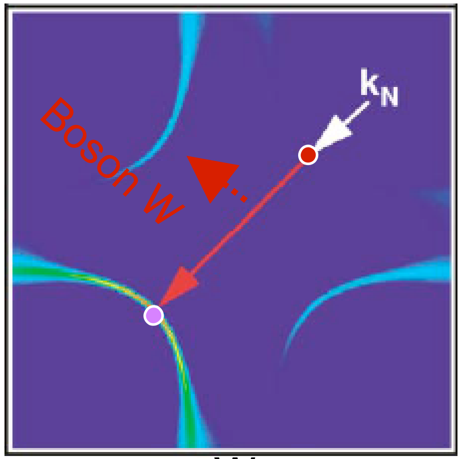
Kink at ~ W_1+D_0



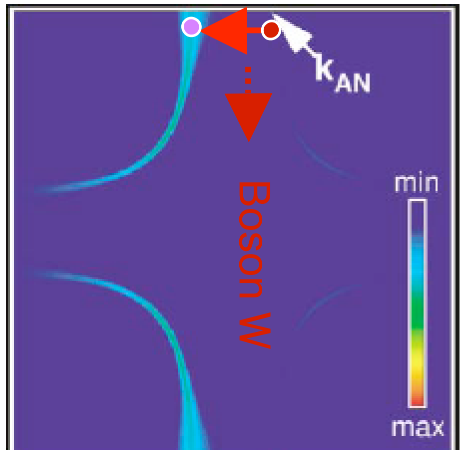
W_1+D_0

Breathing mode
W_2~ 70 meV





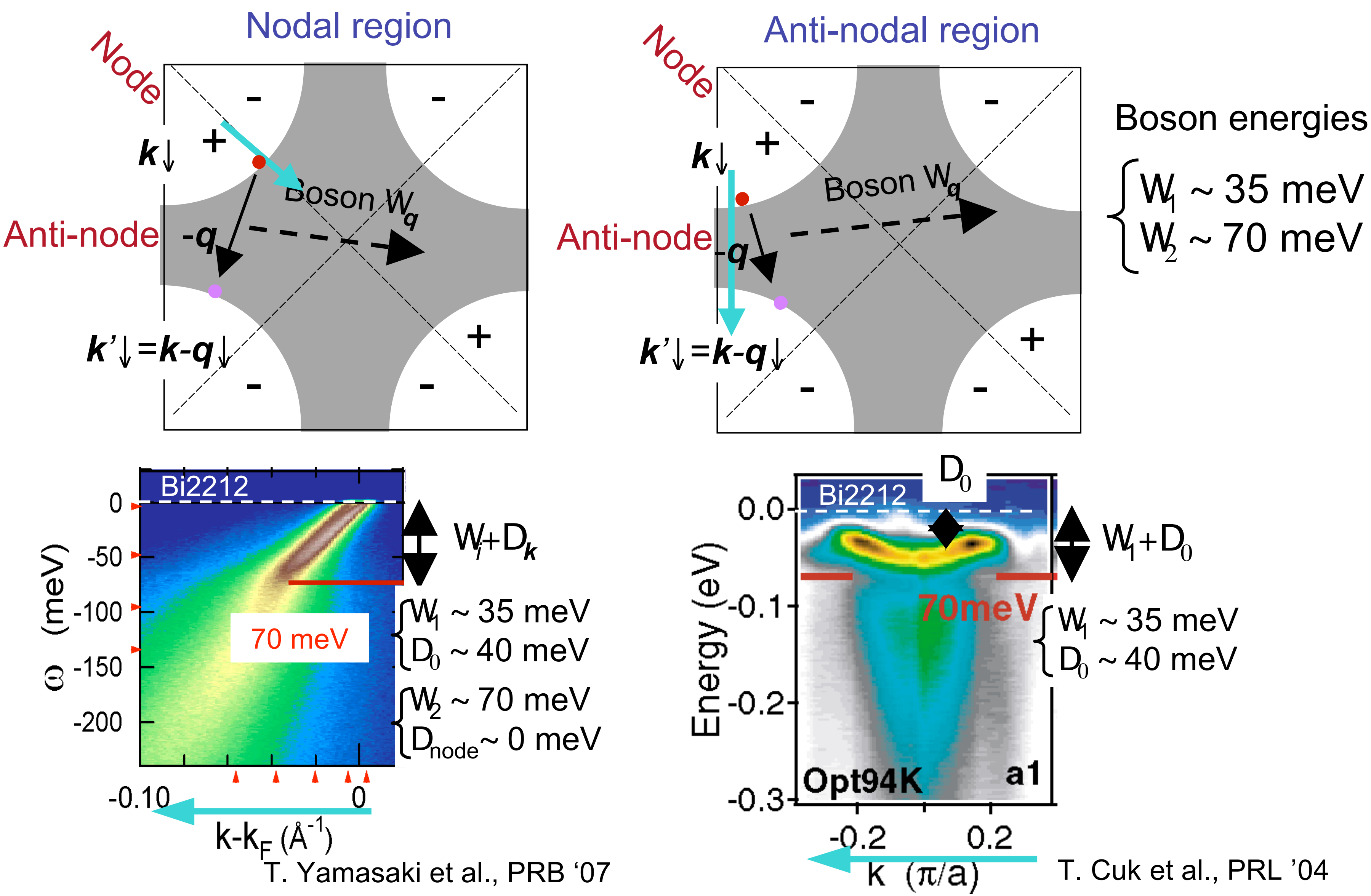
W_2



W_2+D_0 but weak

T. P. Deveraux et al. PRL '04

Kink in ARPES spectra

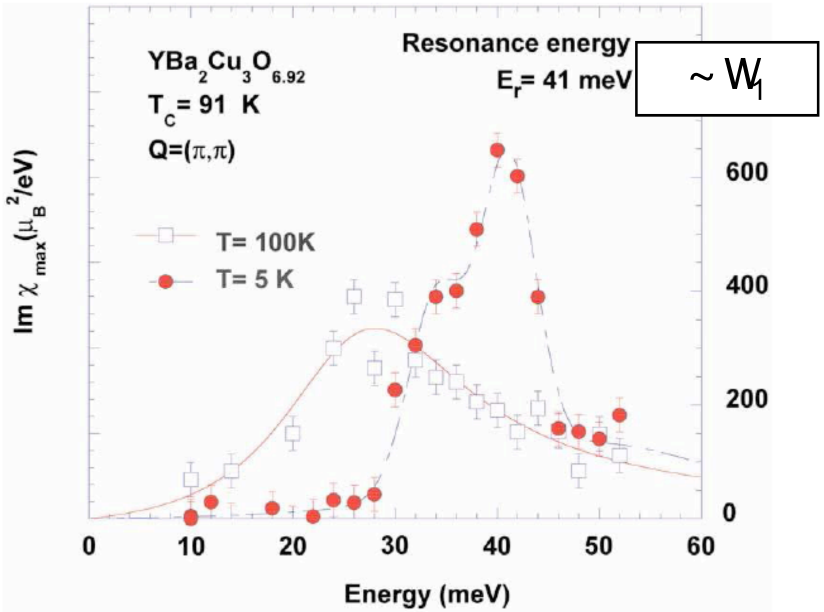


T. Yamasaki et al., PRB '07

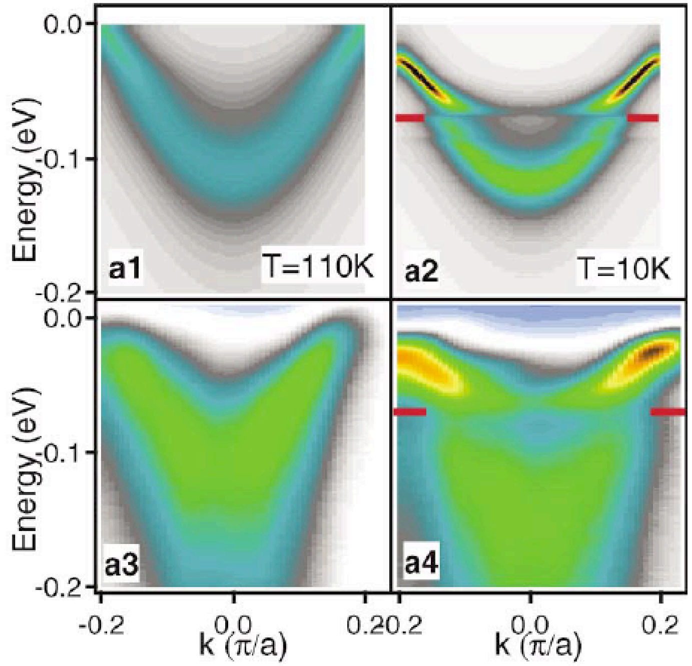
T. Cuk et al., PRL '04

Coupling to magnetic resonance at $W_1 \sim 40$ meV

Inelastic neutron scattering spectra



cf) Phonon scenario



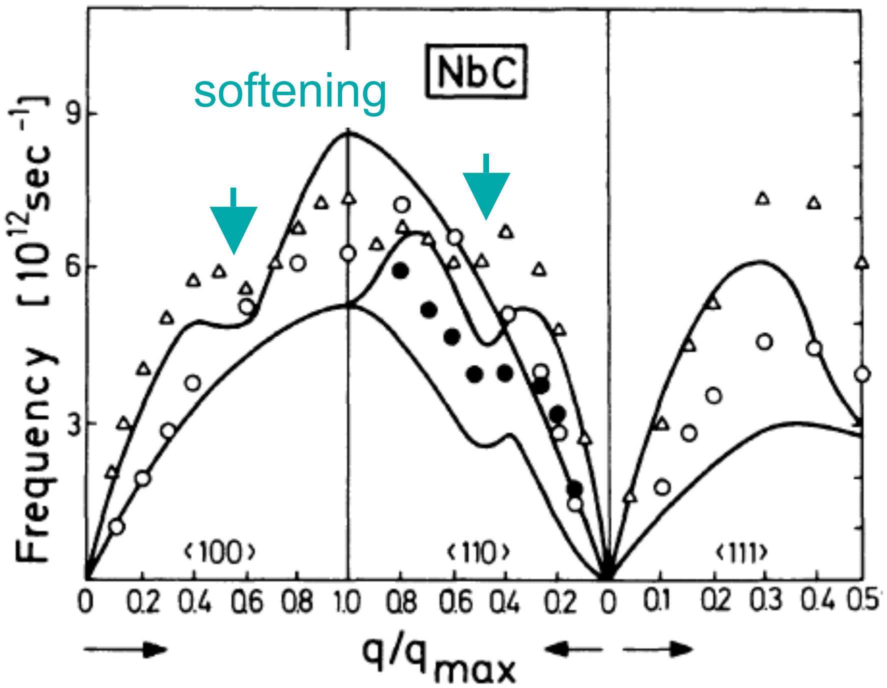
Broadening of Boson spectrum above T_c ➤ Smearing of ARPES kink around the anti-node ◀ Broadening of electronic spectrum above T_c

P. Bourges et al., in *High Temperature Superconductivity*,
ed. S.E. Barnes et al. (AIP '99)

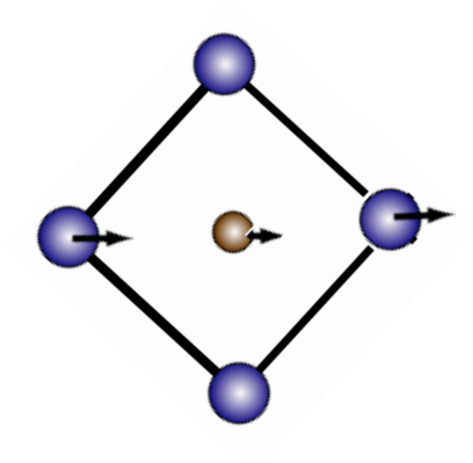
T. P. Deveraux et al. PRL '04

Phonon anomalies in conventional BCS superconductors

Phonon dispersions in NbC by neutron scattering

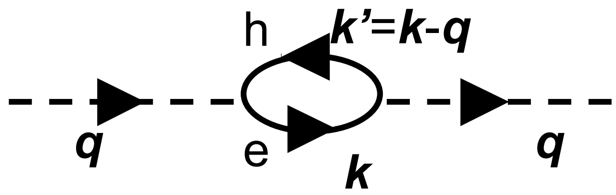


W. Hanke et al., PRL ‘76



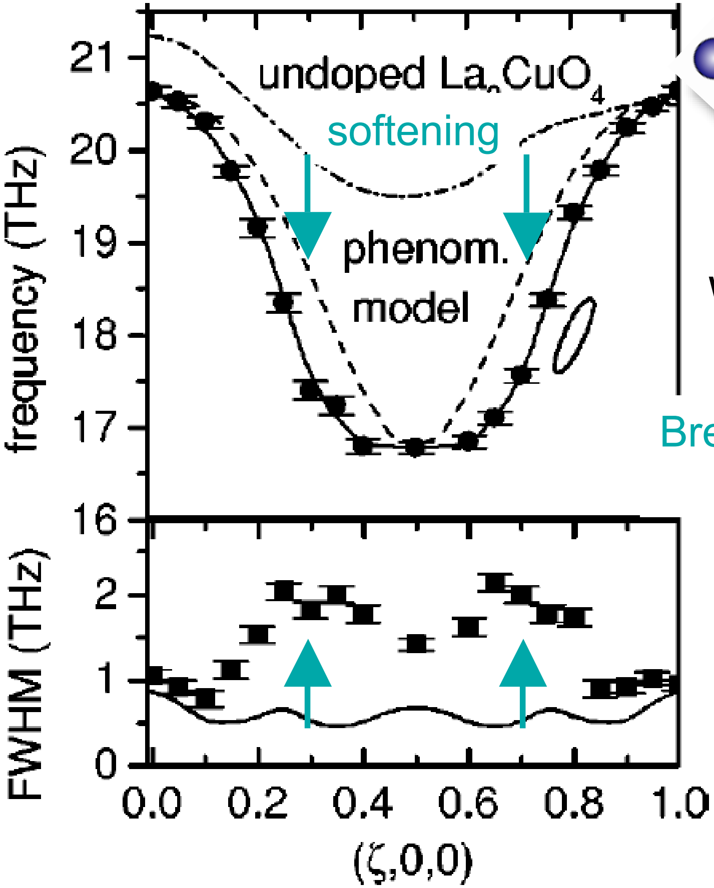
Breathing LA phonons:
q ~ (+p/2*a*,0,0)

W~ 15 meV

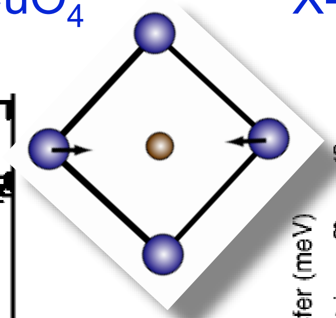


Corresponding W_2 ~ 70 meV phonon anomalies in high-T_c cuprates

Neutron scattering of $La_{2-x}Sr_xCuO_4$



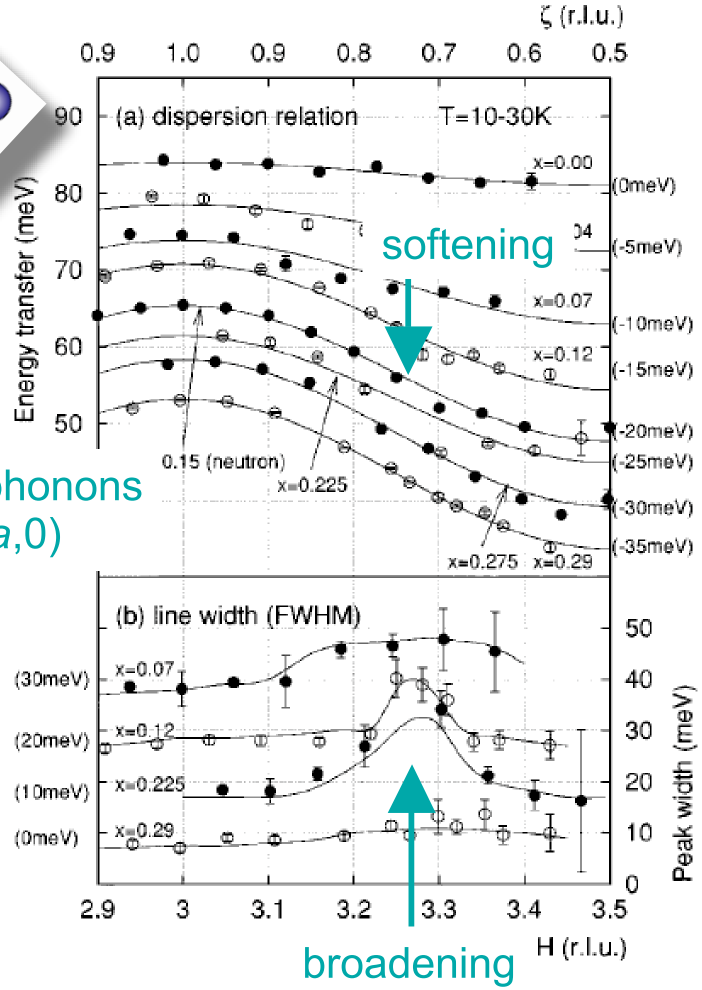
L. Pinchovius and M. Braden, PRB '99



W_2 ~ 70 meV

Breathing LO phonons
q ~ (±p/2*a*,0)

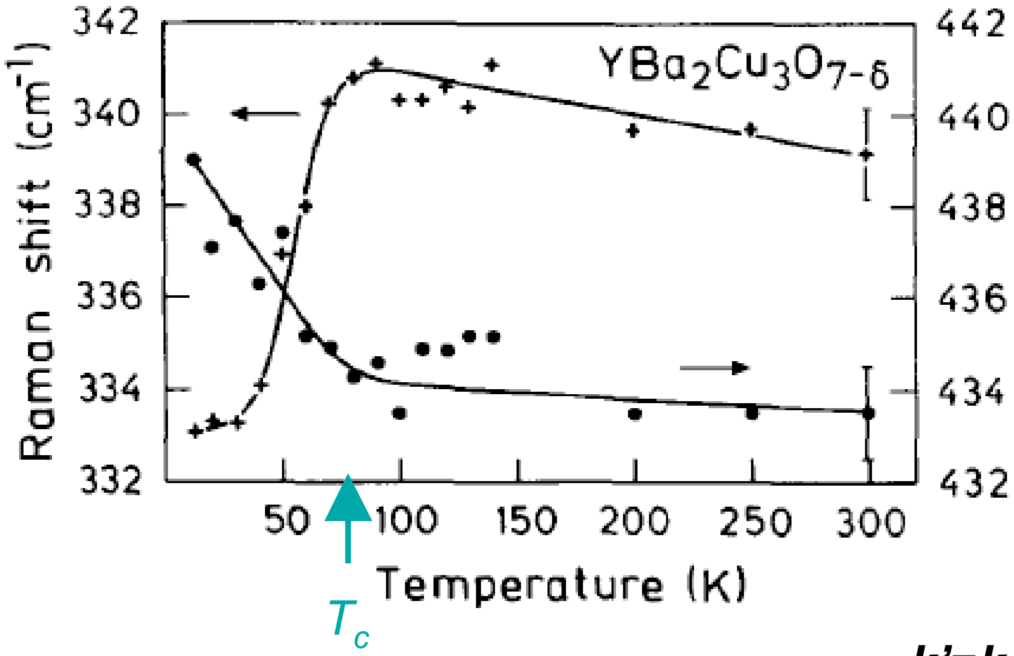
X-ray scattering of $La_{2-x}Sr_xCuO_4$

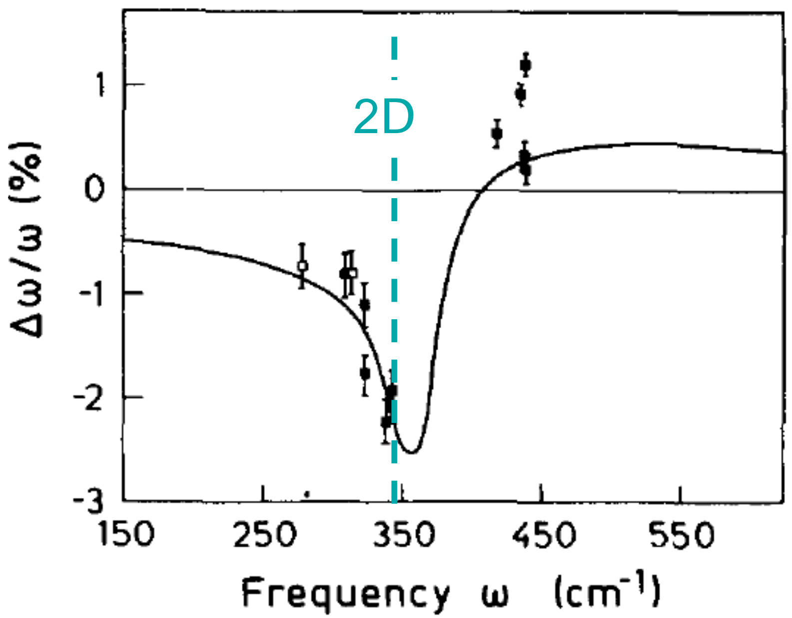


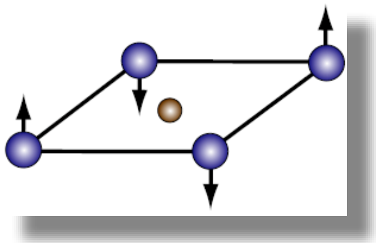
T. Fukuda et al., PRB '05

Corresponding W_1~ 35 meV phonon anomalies in high-T_c cuprates

Raman shifts in $YBa_2Cu_3O_{7-d}$

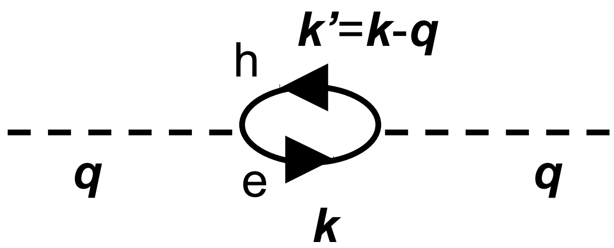






W_1 ~ 35 meV

etc



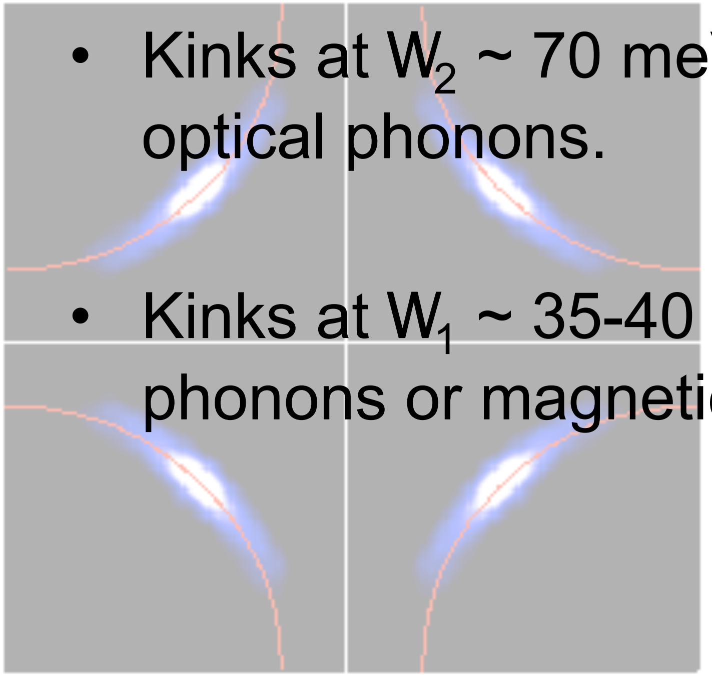
C. Thomsen et al., SSC '90

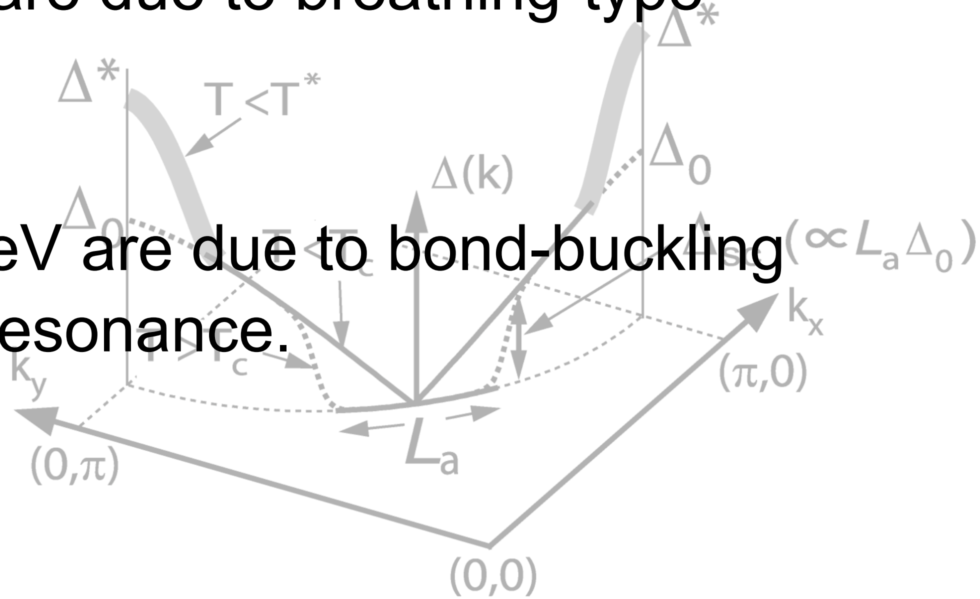
Short summary 2

- Electrons are coupled to Boson excitations, which yield kinks in ARPES spectra and may provide glue for Cooper pairing.

- Kinks at W_2 ~ 70 meV are due to breathing-type optical phonons.

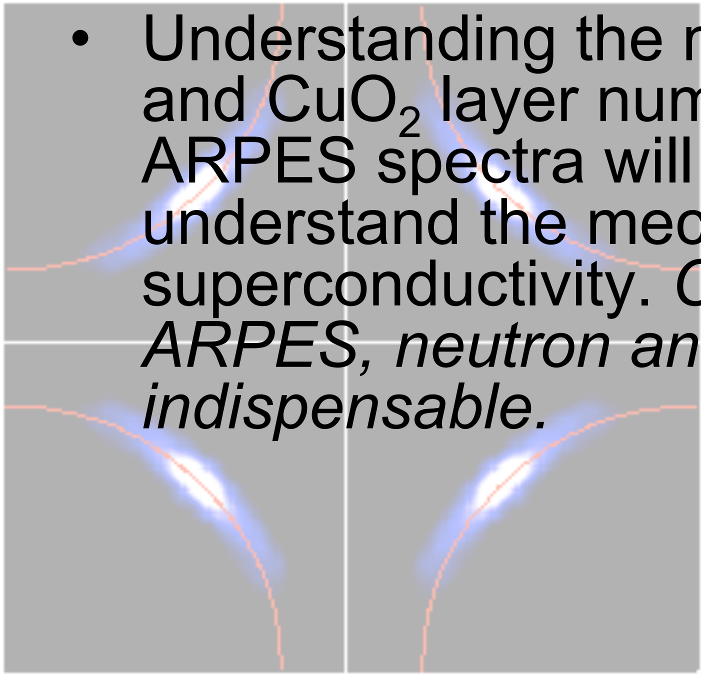
- Kinks at W_1 ~ 35-40 meV are due to bond-buckling phonons or magnetic resonance.





Outlook

- Understanding the origin of the pseudogap/Fermiarc and the CuO_2 layer number dependences of the pairing strength D_0 and hence of $T_{c.\mathrm{max}}$ will provide a key to elucidate the mechanism of high-T_c superconductivity.



- Understanding the momentum, temperature, doping, and CuO_2 layer number dependences of kinks in ARPES spectra will also provide a key to understand the mechanism of high-T_c superconductivity. *Close collaboration between ARPES, neutron and x-ray studies are indispensable.*