Quantum Materials Symposium 2016 (QMS16), Muido, Korea, Feb 22-26, 2016

Suppressed antiferromagnetism and expanded superconducting phase in "protect-annealed" electron-doped cuprates

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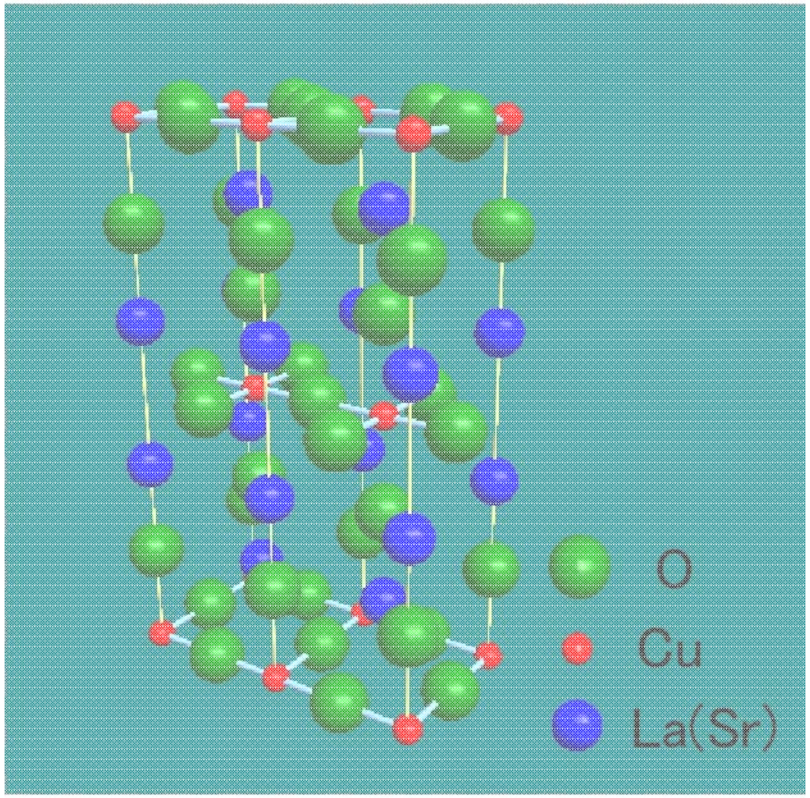
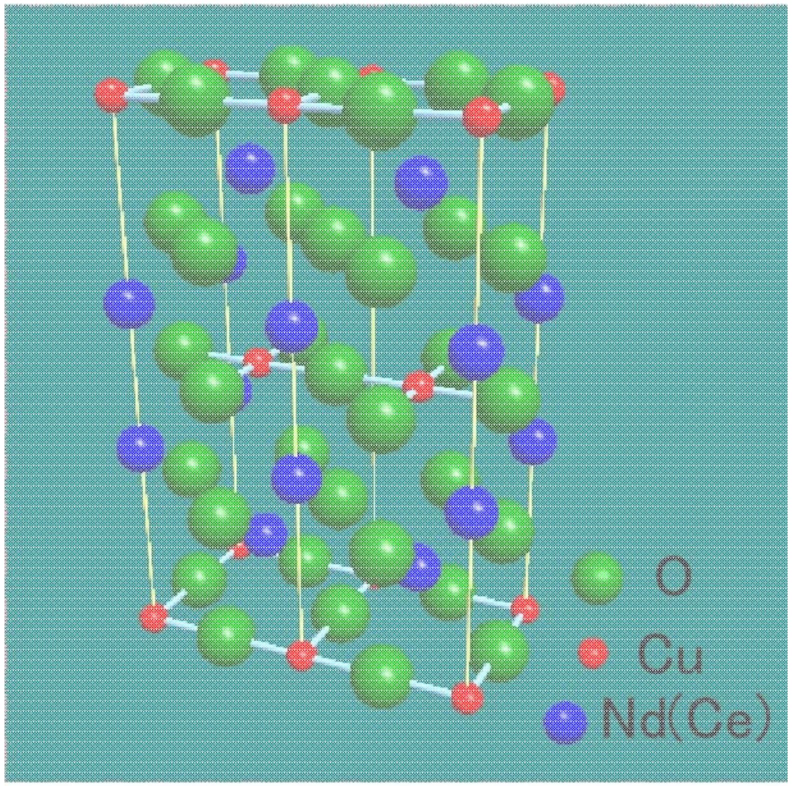
University of Tokyo





Collaborators

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T. Yoshida (Kyoto U)

Bulk single crystals

T. Adachi (Sophia U), Y. Koike (Tohoku U)

Thin films

Y. Krockenberger, H. Yamamoto (NTT)

VUV ARPES

A. Ino, H. Anzai, M. Arita, H. Namatame, M. Taniguchi (HiSOR)

Laser ARPES

S. Shin, Y. Ohta (ISSP)

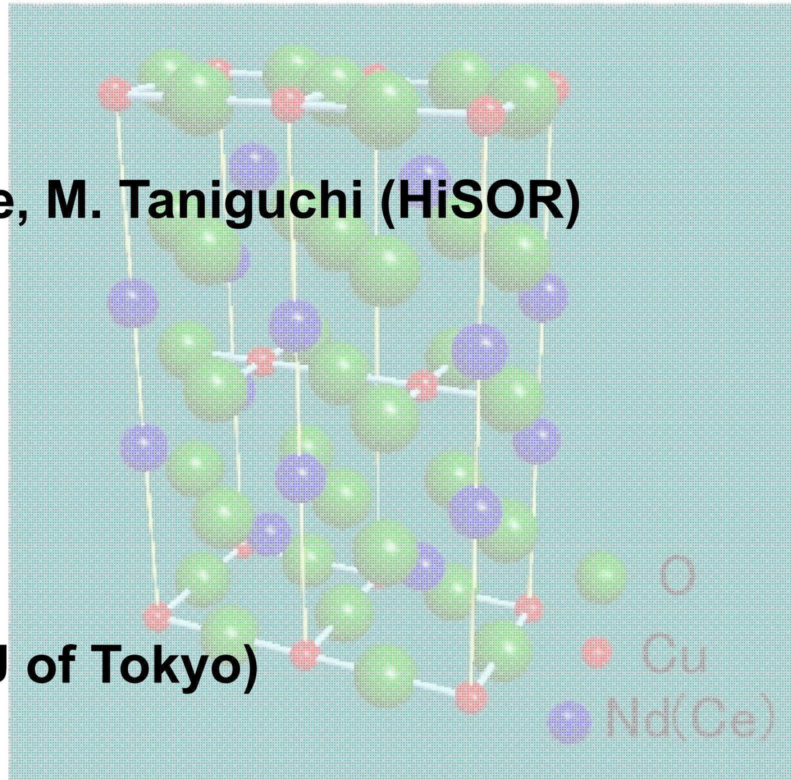
XAS

H. Wadati, S. Shin (ISSP)

Discussion

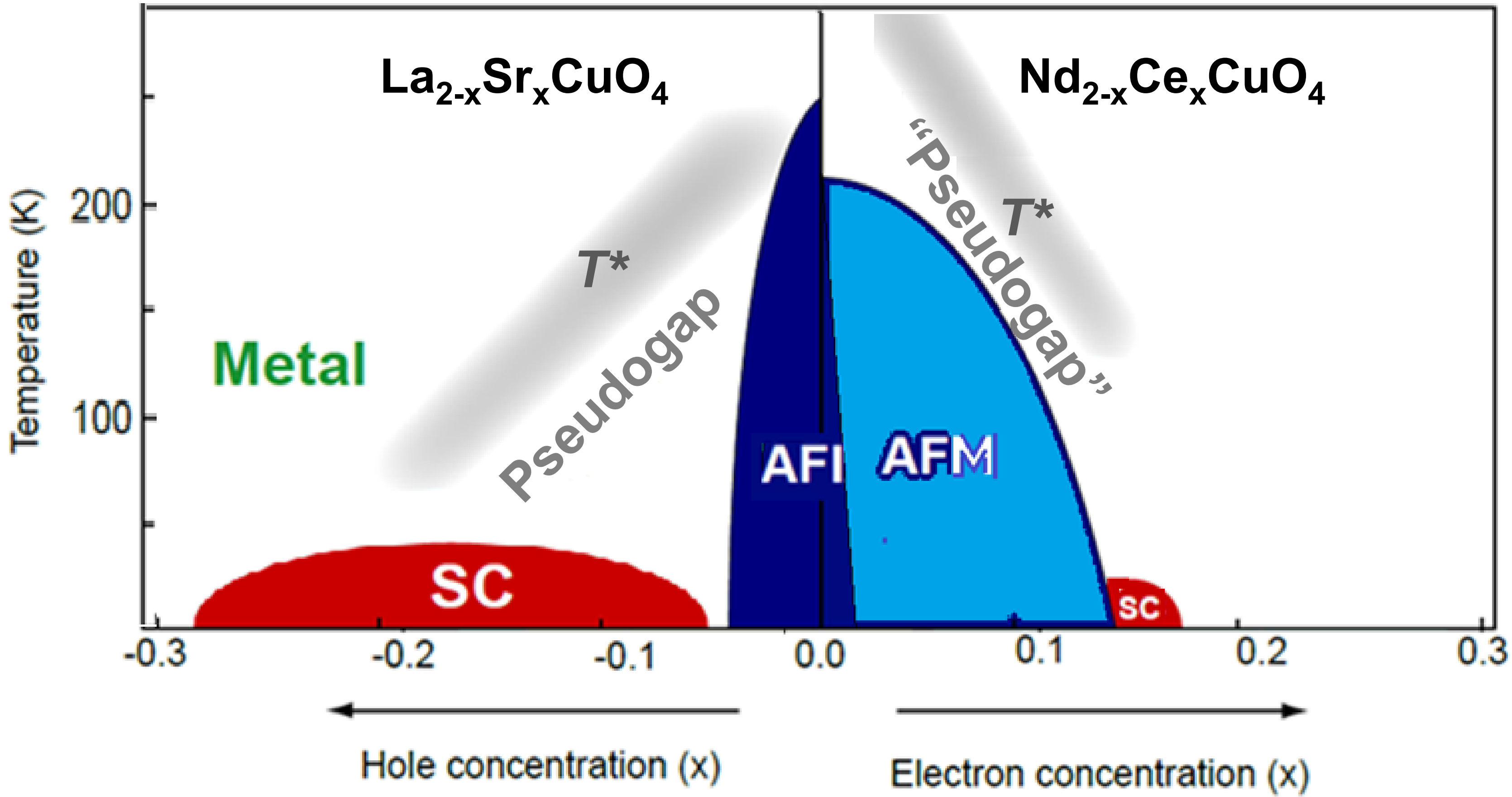
T. Saha-Dasgupta (SNBC), M. Ogata (U of Tokyo)

C. M. Varma (UC Riverside)



Phase diagrams of cuprate superconductors

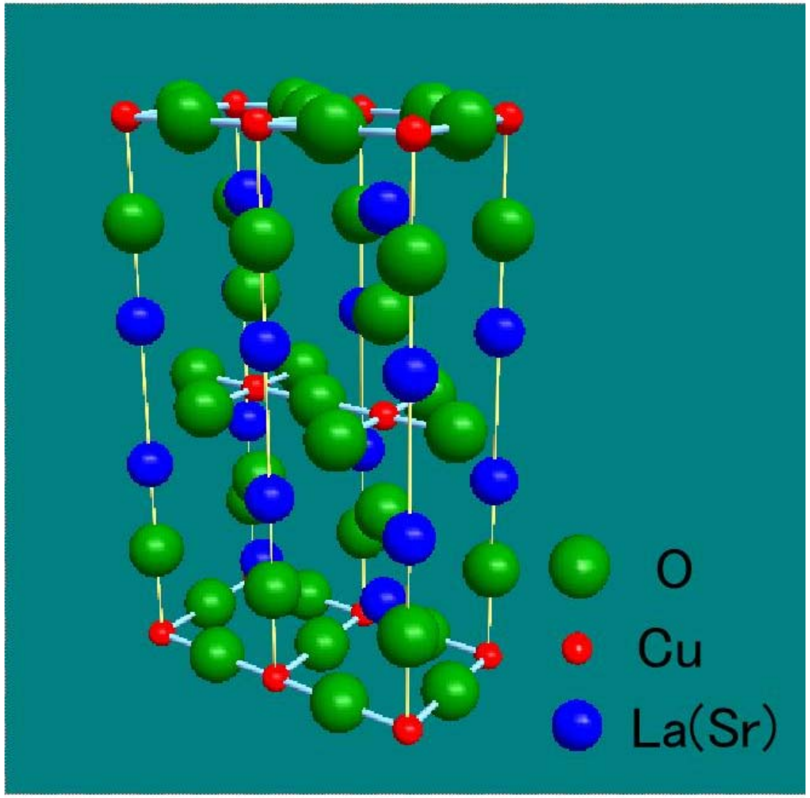
Hole-doped **Electron-doped**



Crystal structures of cuprate superconductors

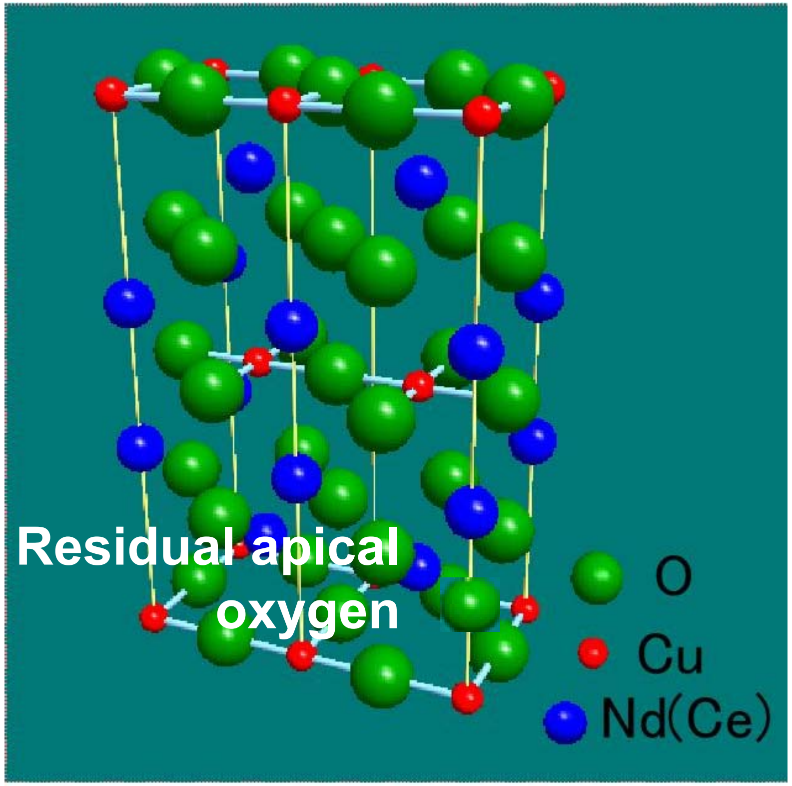
Hole-doped

$La_{2-x}Sr_xCuO_4$



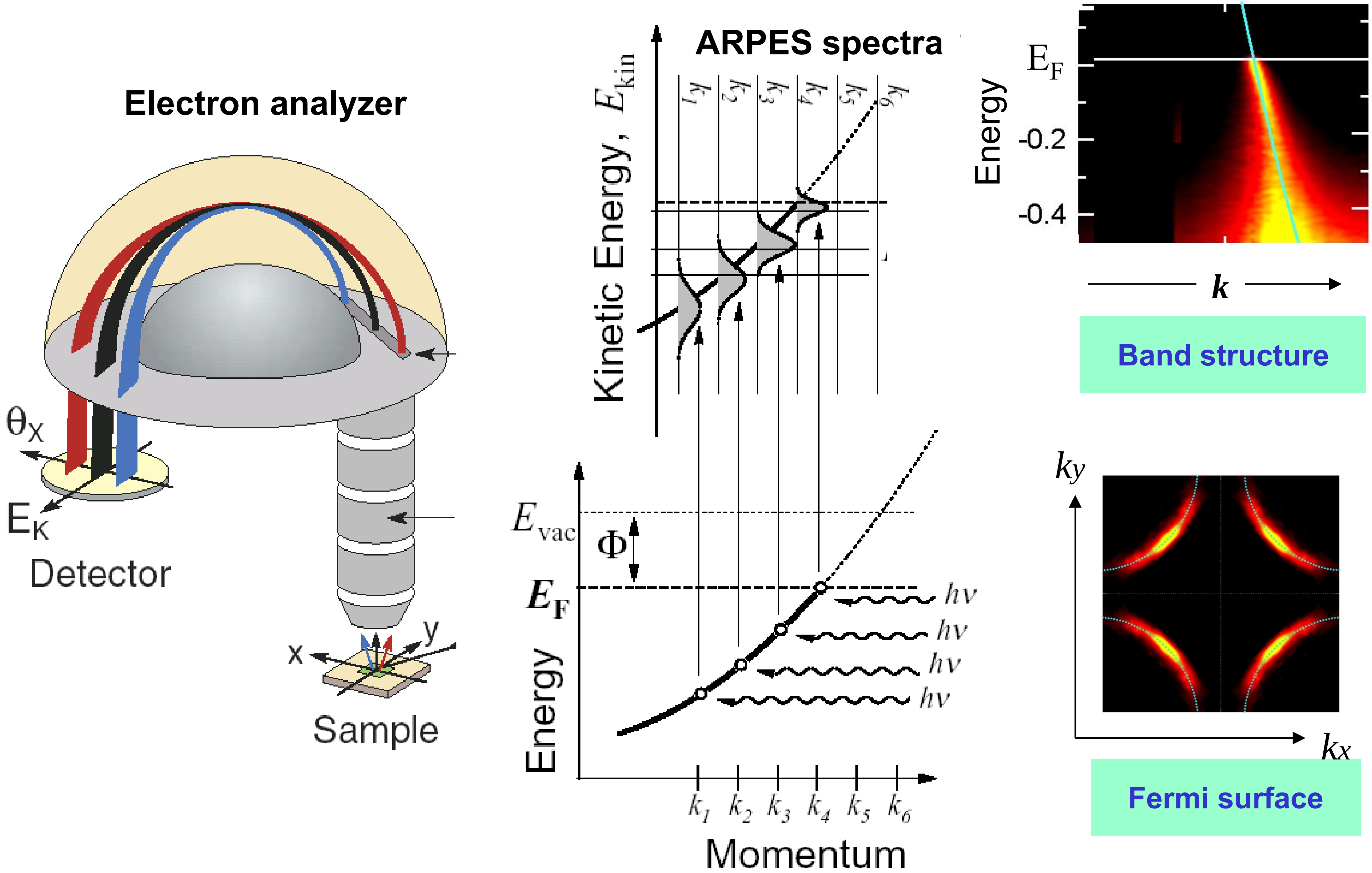
Electron-doped

$Nd_{2-x}Ce_xCuO_4$



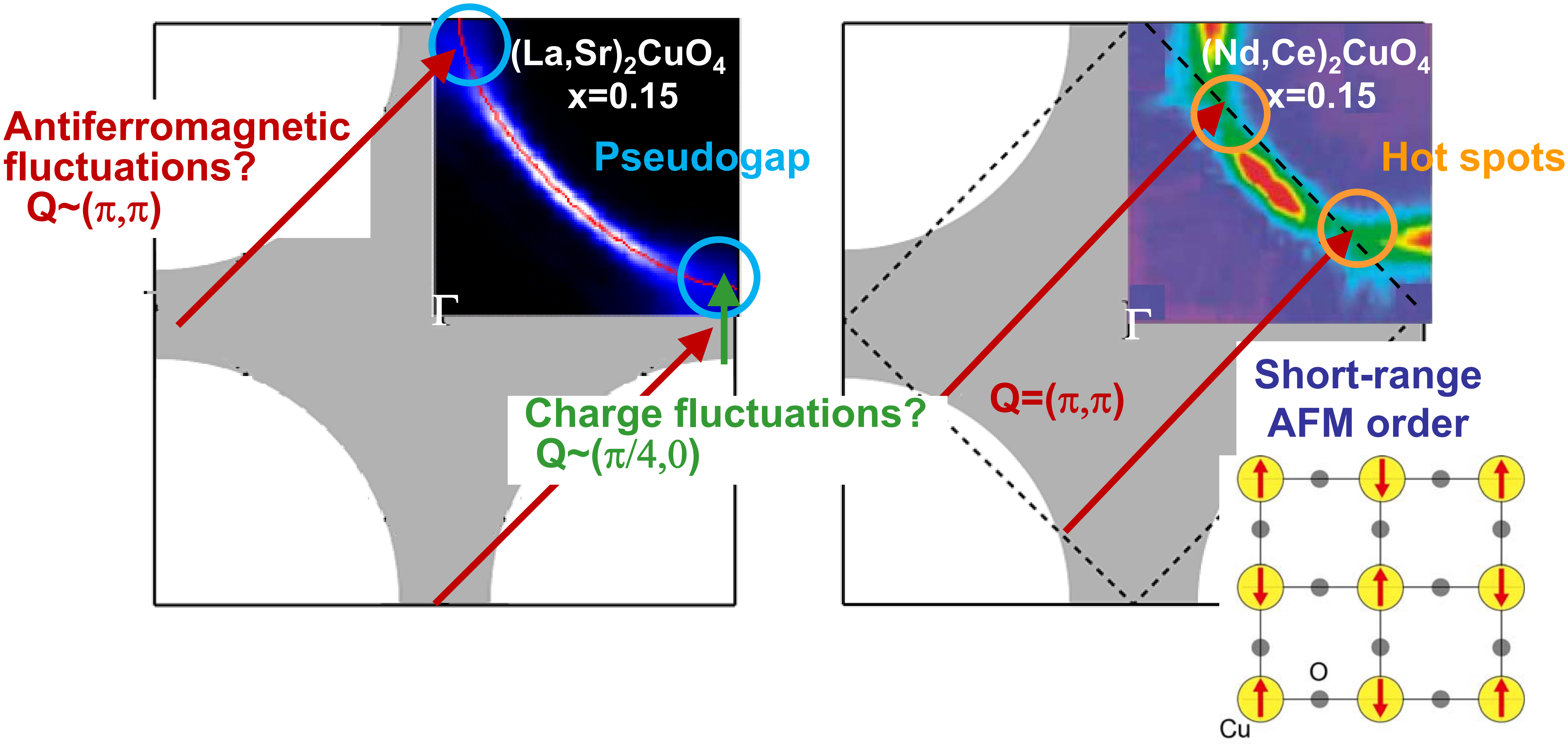
T' structure - No apical oxygen

Angle-Resolved Photoemission Spectroscopy
ARPES



Pseudogaps in cuprate superconductors

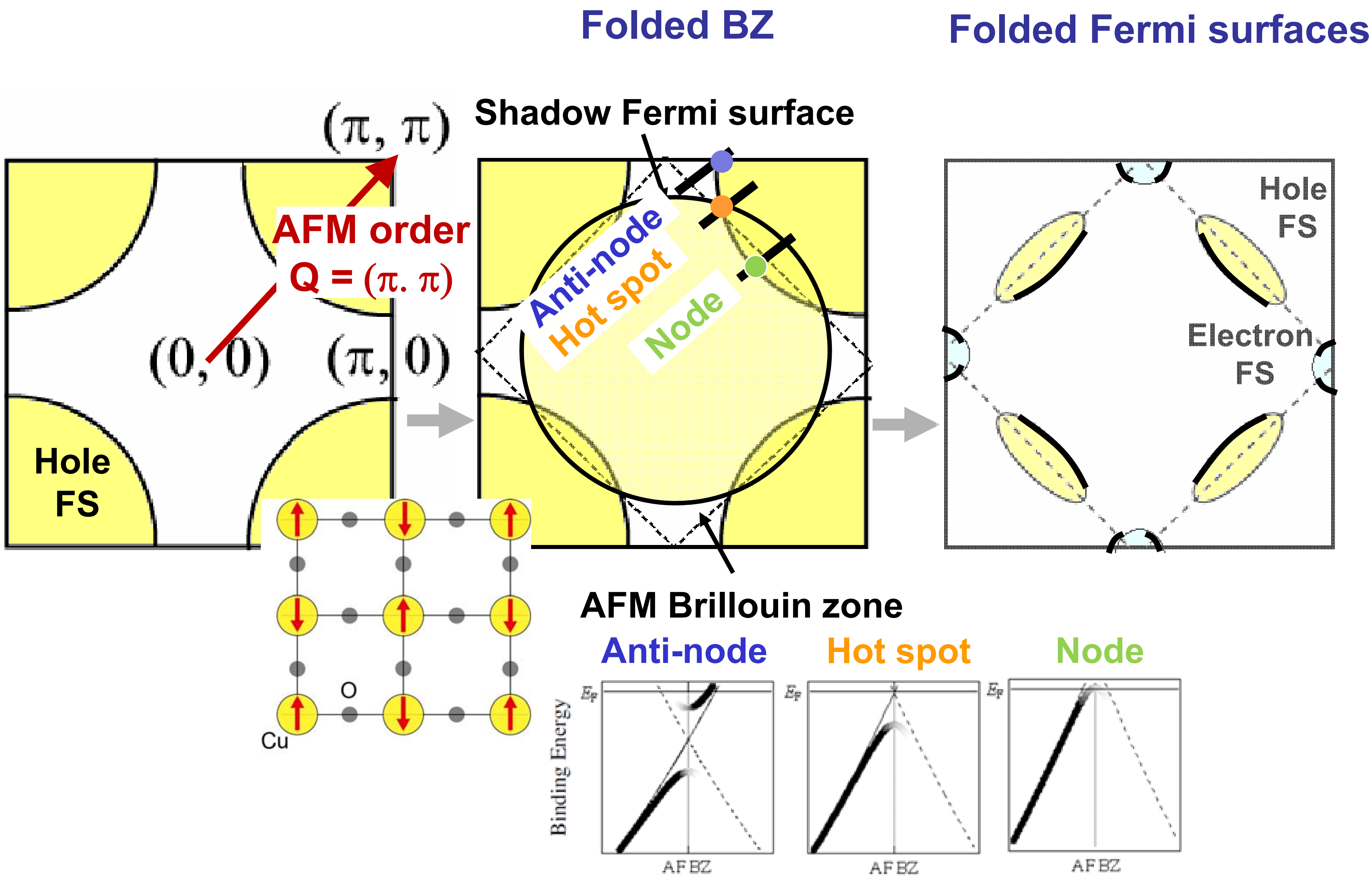
Hole-doped | **Electron-doped**



T. Yoshida *et al.*, PRB 2006

P. Armitage *et al.*, PRL 2002

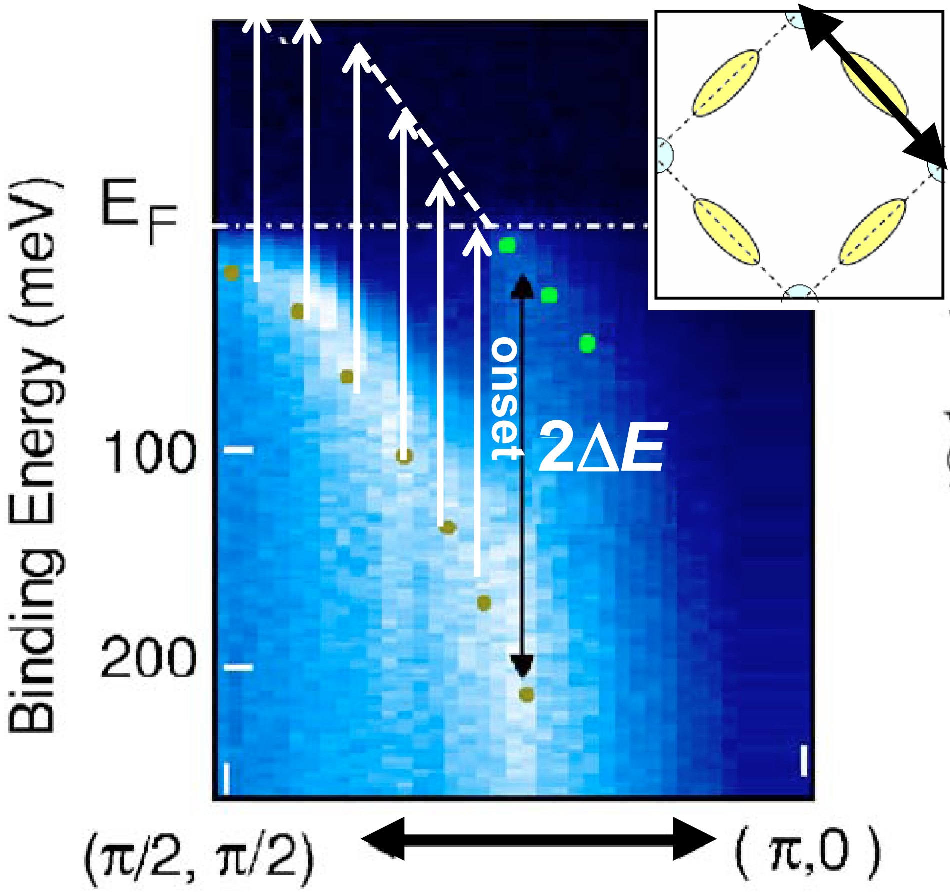
Folded Fermi surfaces in electron-doped cuprates



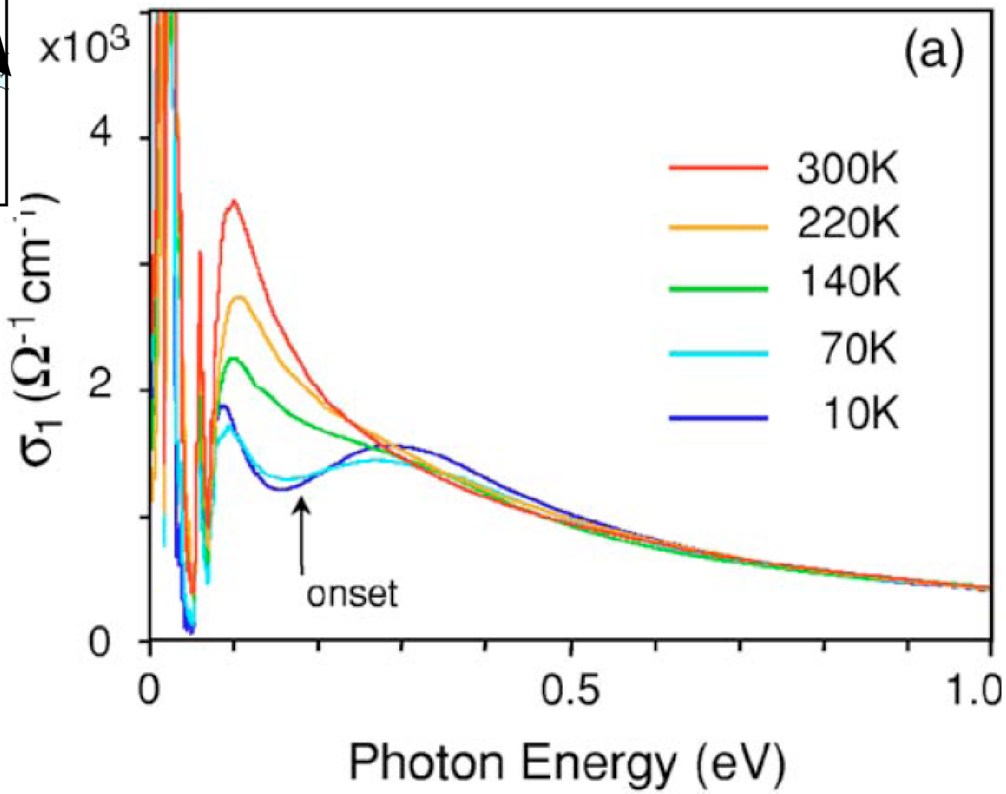
Effects of AFM correlation in $Sm_{2-x}Ce_xCuO_4$ (x=0.14)

$$H=\begin{pmatrix}\varepsilon_0+\Delta E-4t'\cos(k_xa)\cos(k_ya) & -2t\{\cos(k_xa)+\cos(k_ya)\} \\ -2t\{\cos(k_xa)+\cos(k_ya)\} & \varepsilon_0-\Delta E-4t'\cos(k_xa)\cos(k_ya)\end{pmatrix}$$

Splitting on the AFM BZ boundary

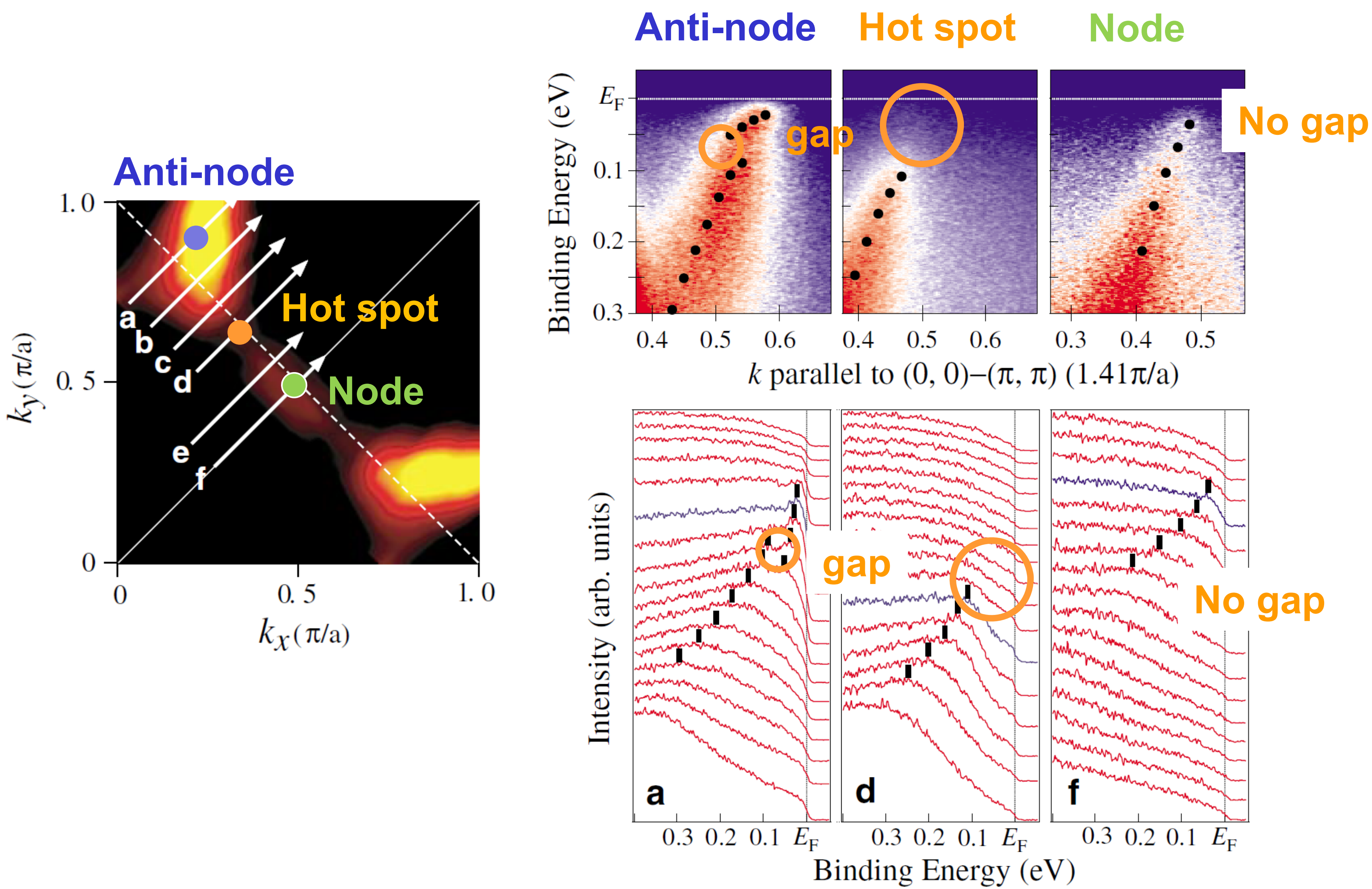


Pseudogap in optical conductivity



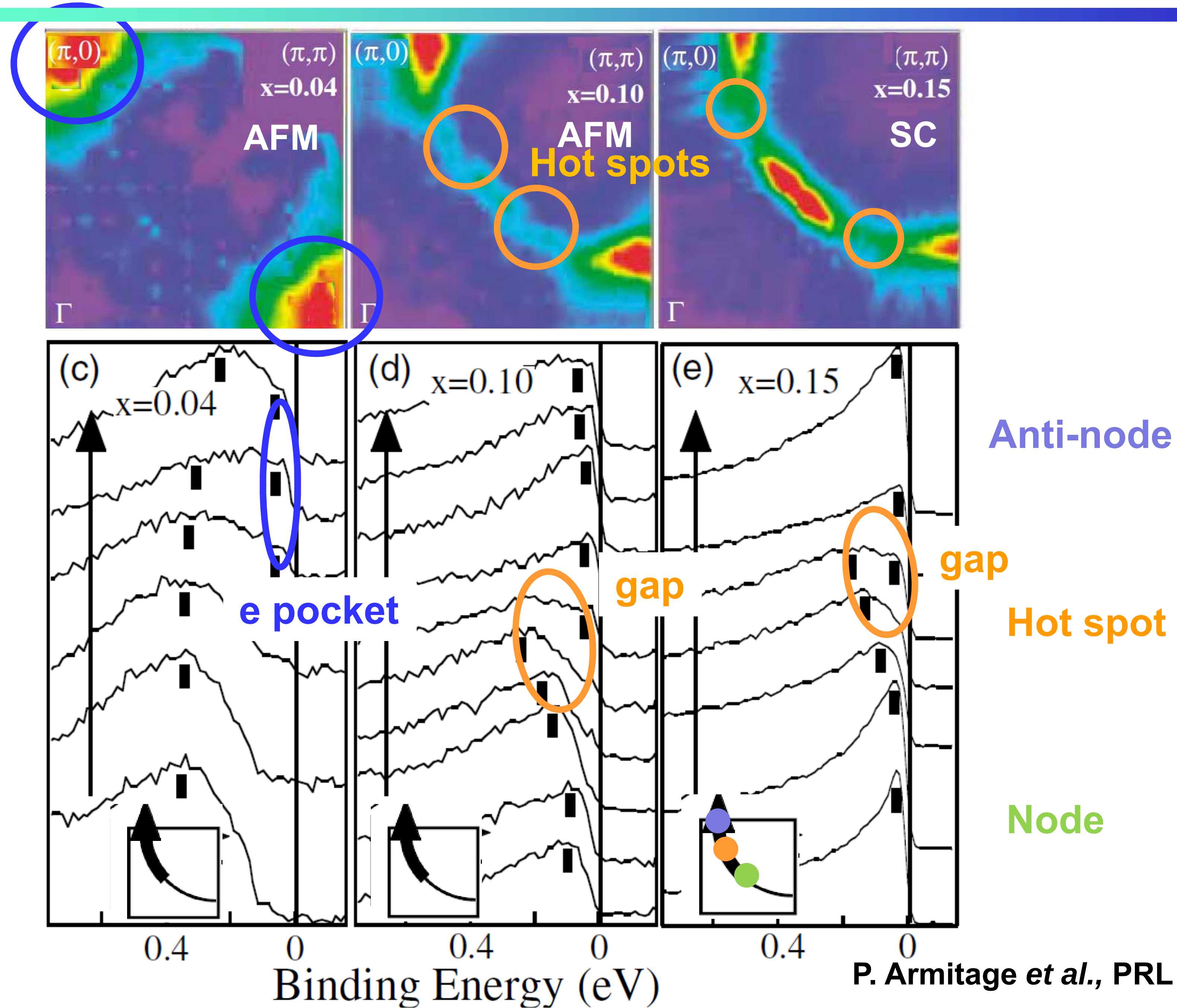
S. R. Park et al., PRB 2007

ARPES spectra of electron-doped superconductor $Nd_{1.87}Ce_{0.13}CuO_4$



H. Matsui *et al.*, PRL (2005)

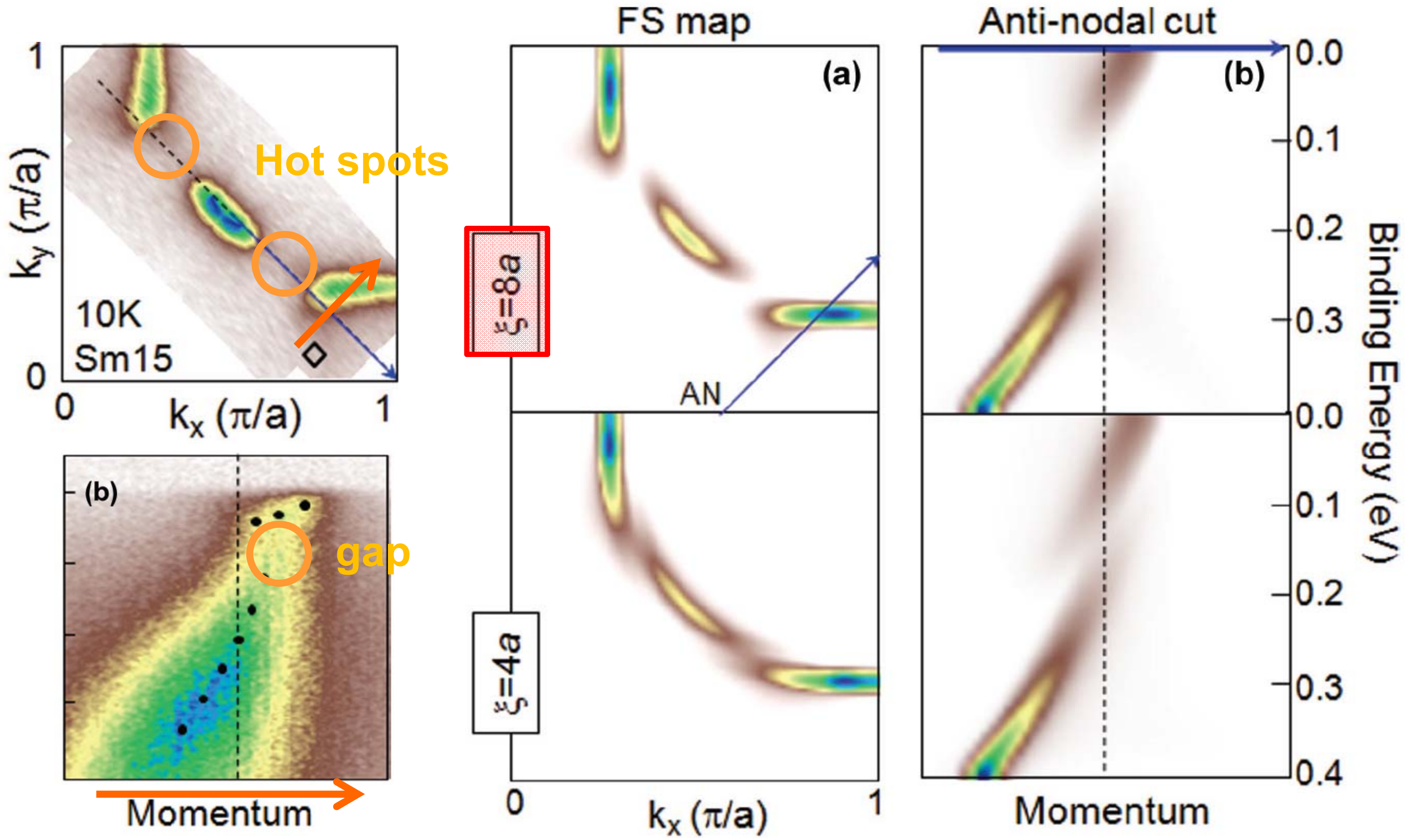
ARPES spectra of electron-doped superconductor $Nd_{2-x}Ce_xCuO_4$



P. Armitage *et al.*, PRL (2002)

AFM correlation length ξ in $Sm_{1.85}Ce_{0.15}CuO_4$ by deduced by ARPES and simulations

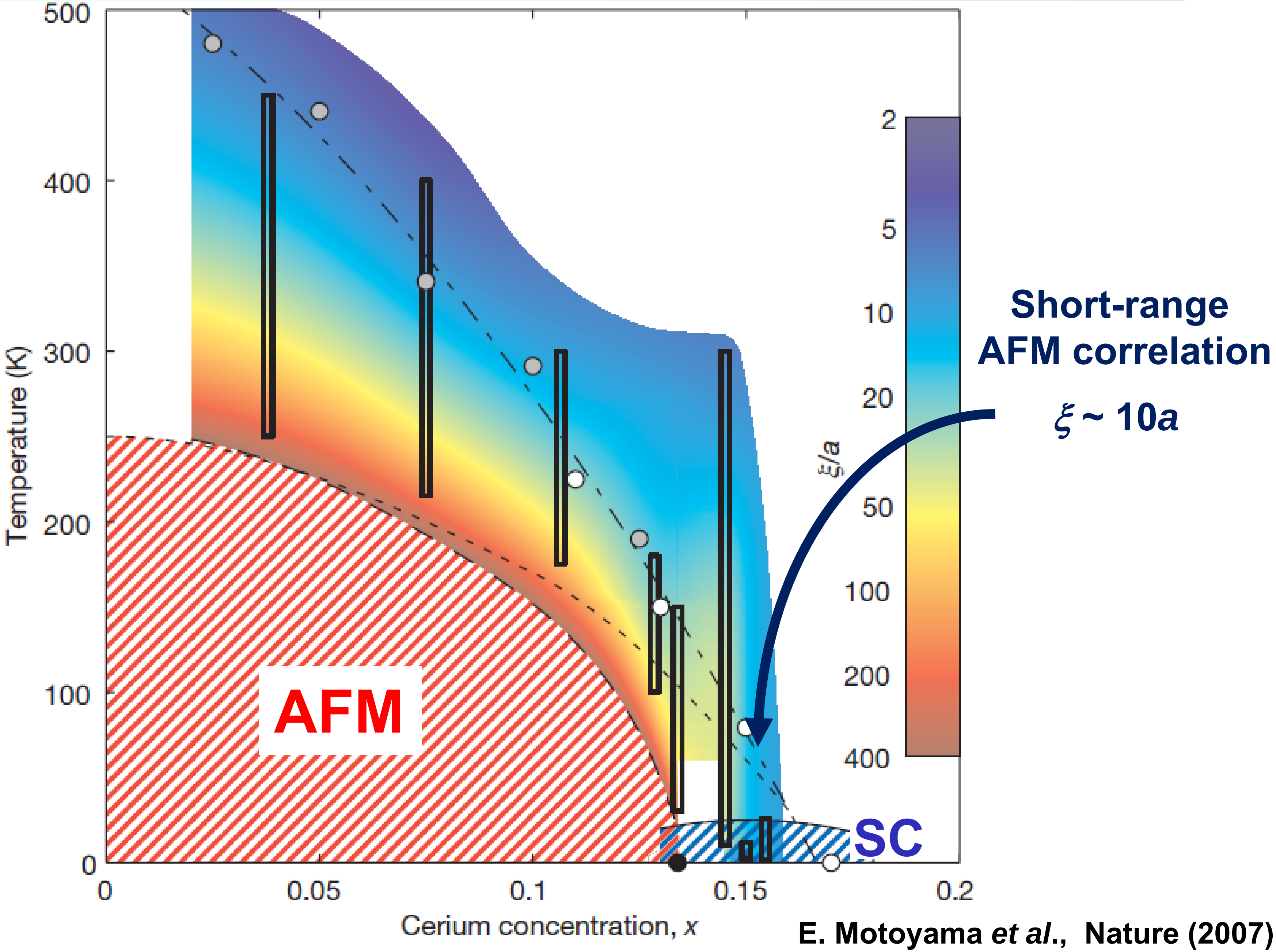
Experiment | **Theory: AFM phase fluctuation model**



Short- range AFM correlation

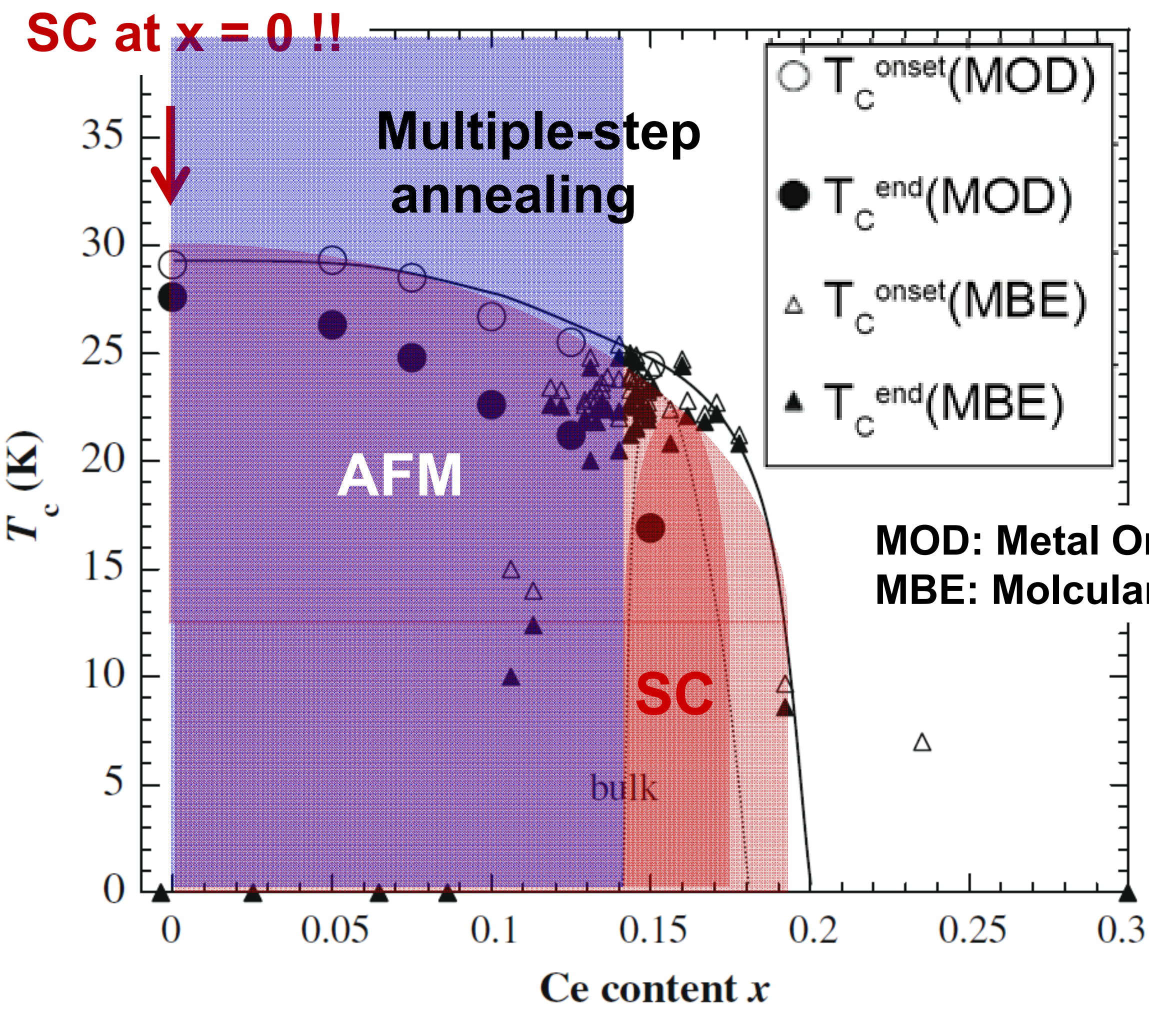
S.R. Park *et al.*, PRB (2013)

AFM correlation length ξ in $Nd_{2-x}Ce_xCuO_4$ measured by inelastic neutron scattering



E. Motoyama *et al*., Nature (2007)

Expanded superconducting region in $Nd_{2-x}Ce_xCuO_4$ thin films by special annealing

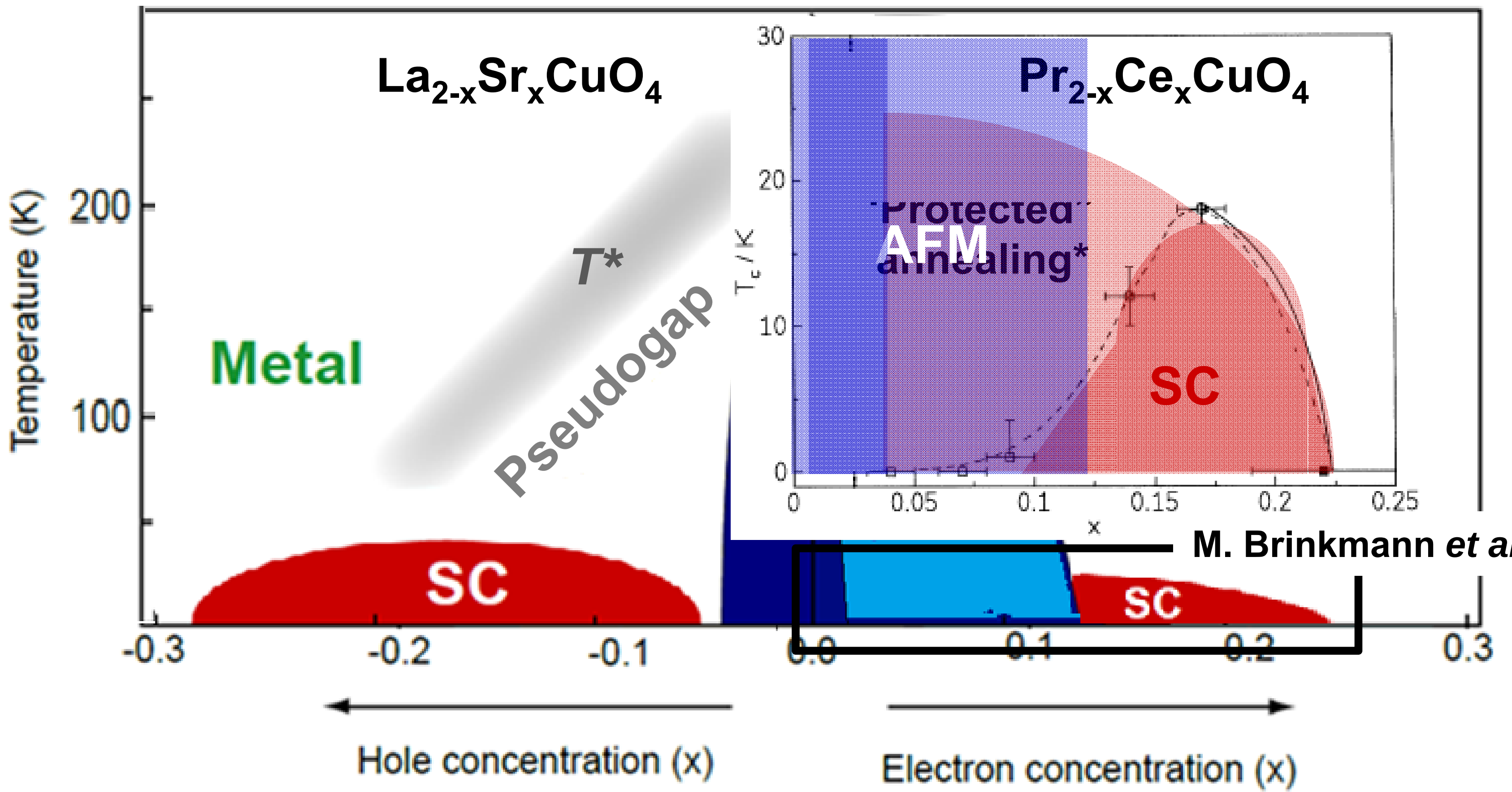


MOD: Metal Organic Decomposition
MBE: Molcular Beam Epitaxy

O. Matsumoto *et al*., Physica C (2009)

Extended superconducting region in electron-doped superconductors

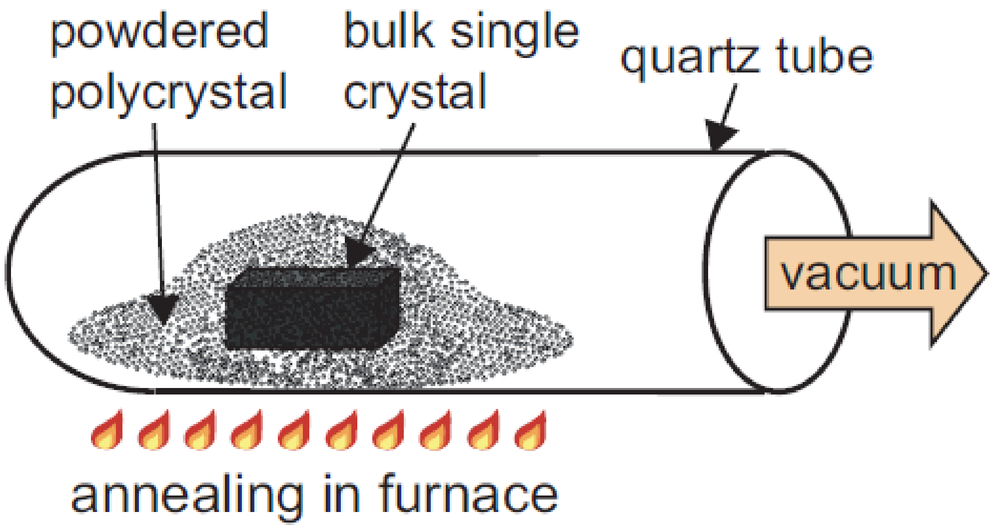
Hole-doped **Electron-doped**



M. Brinkmann *et al.*, PRL (1995)

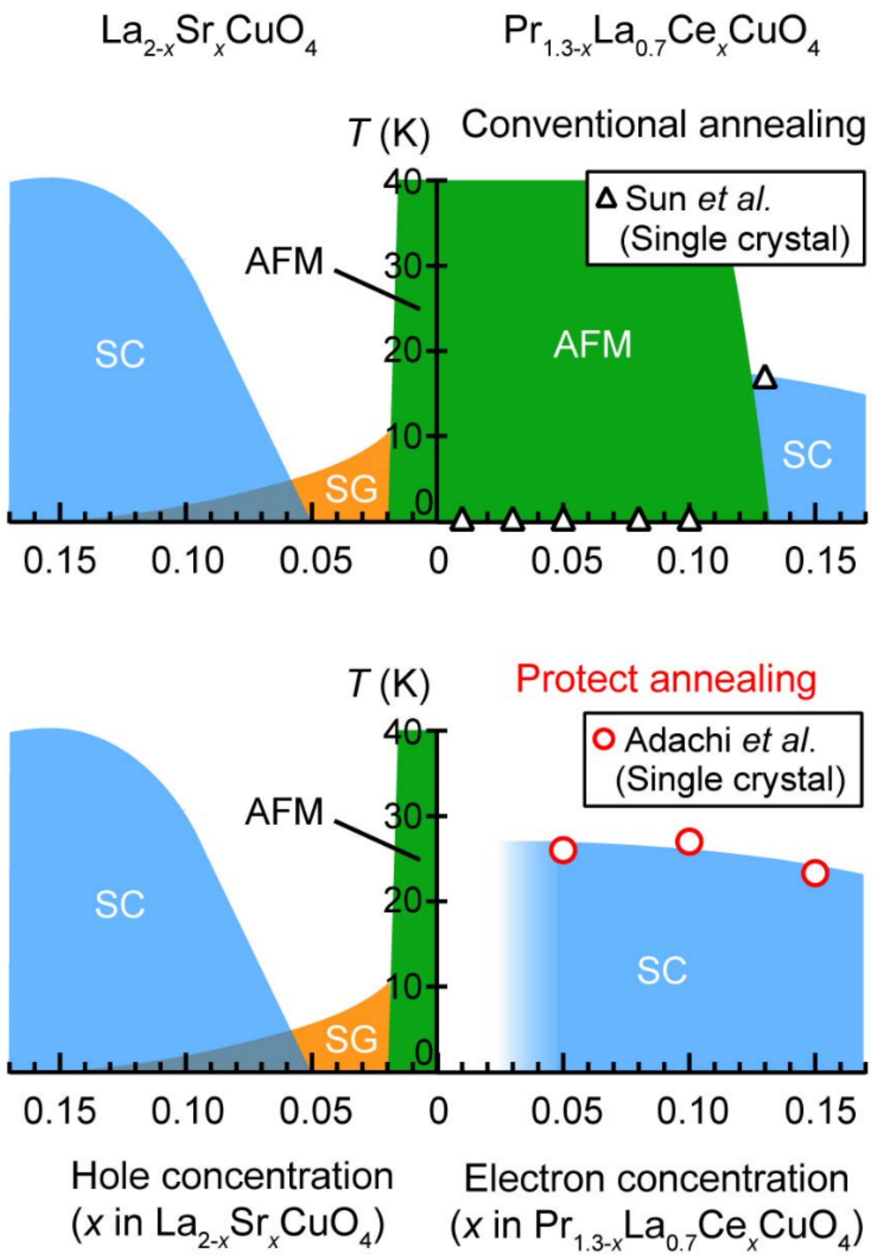
*Thin plates sandwiched by polycrystals of the same composition

Extended superconducting region in "protect-annealed" single crystals



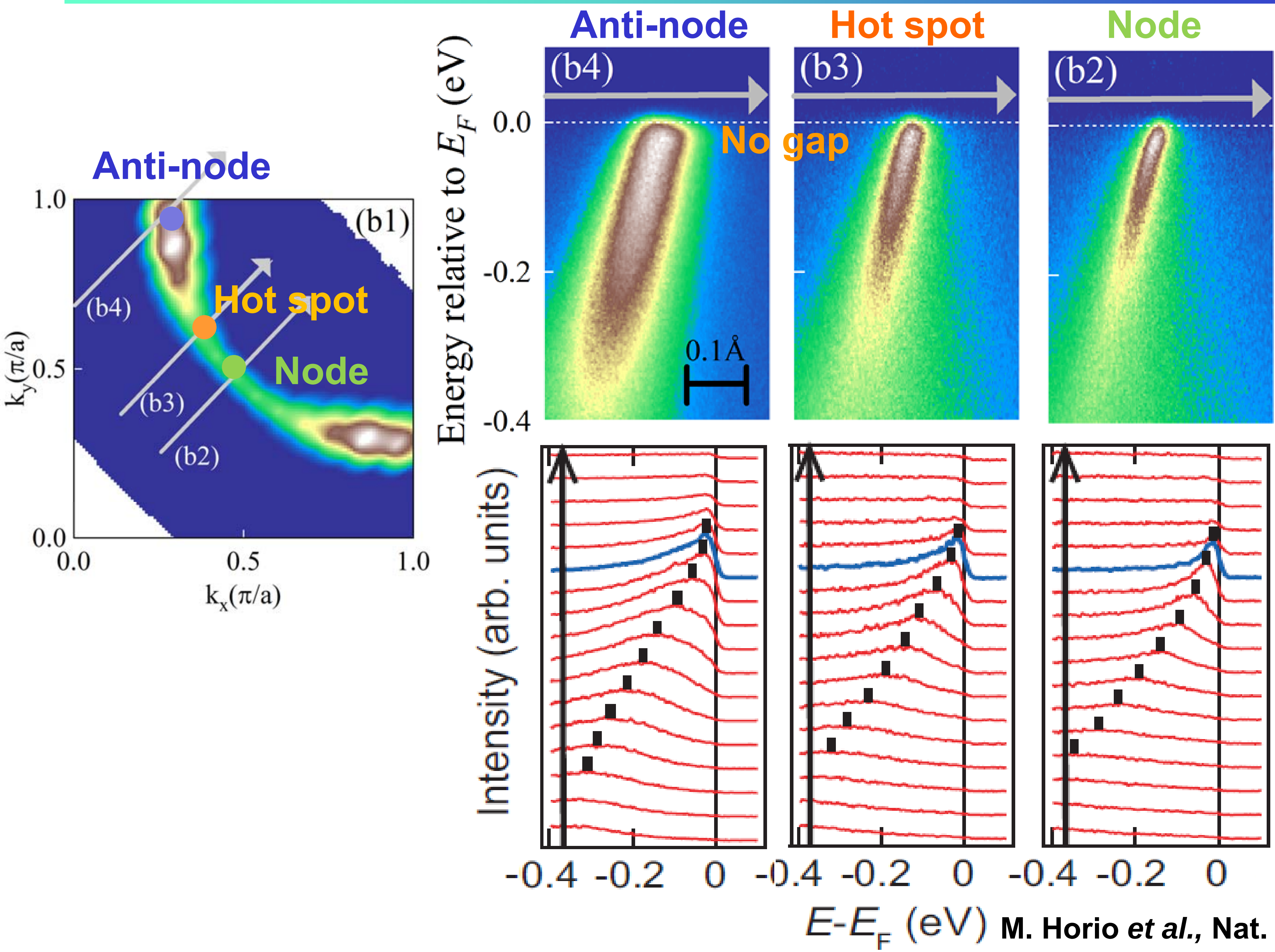
Excess oxygen is supposed to be removed during the annealing.

$O_{4.04} \rightarrow O_{3.99}$



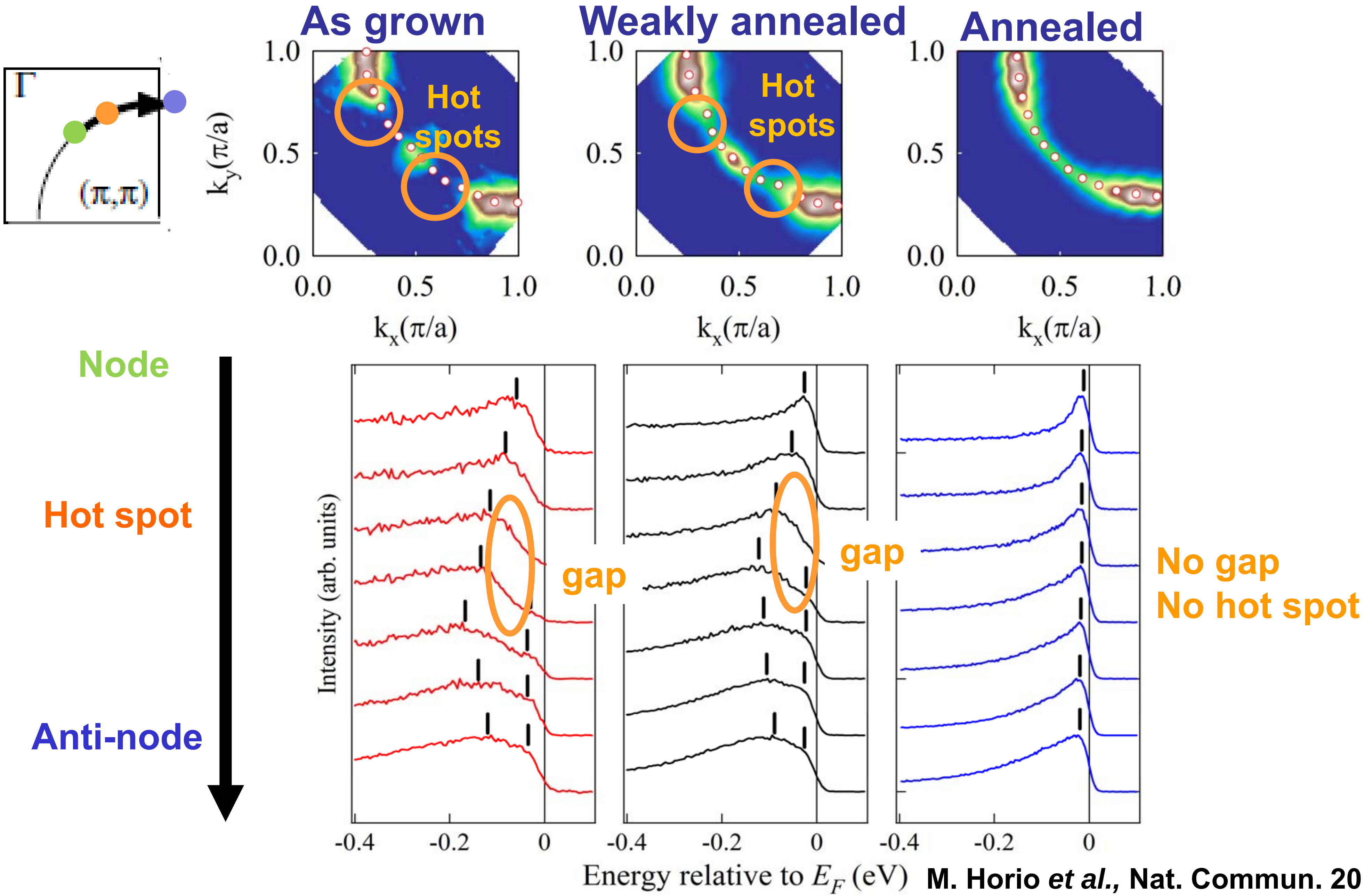
T. Adachi *et al*., J. Phys. Soc, Jpn. 82, 063713 (2013).

ARPES spectra of "protect-annealed" $Pr_{1.2}La_{0.7}Ce_{0.1}CuO_4$



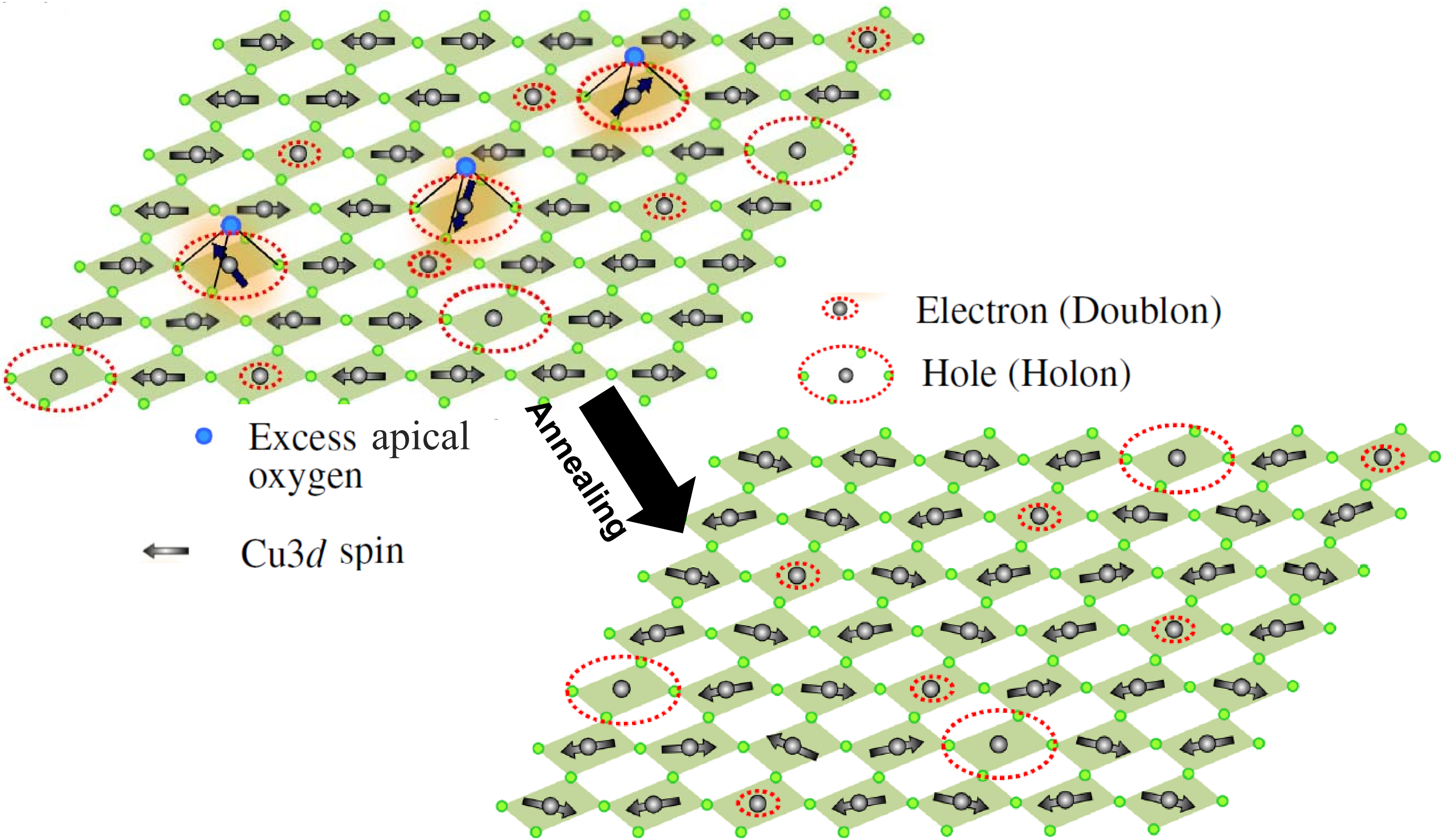
M. Horio *et al.*, Nat. Commun. 2016

Annealing effect on the quasi-particle and Fermi surface in $Pr_{1.2}La_{0.7}Ce_{0.1}CuO_4$



M. Horio *et al.*, Nat. Commun. 2016

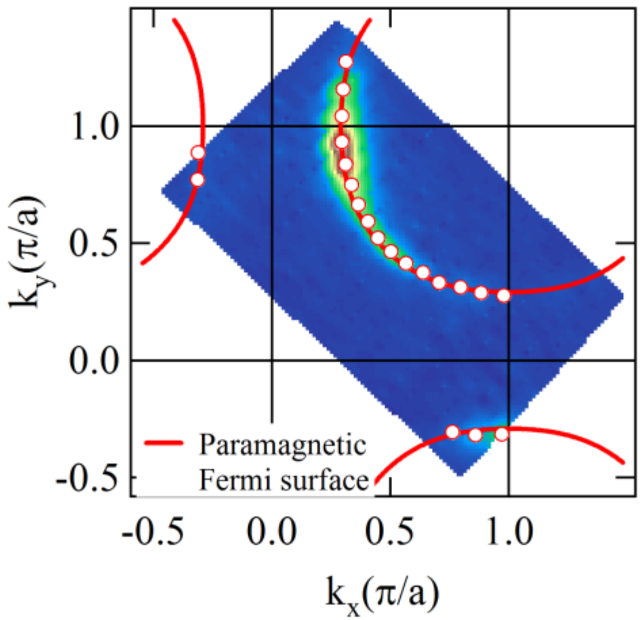
Complete removal of apical oxygen by annealing

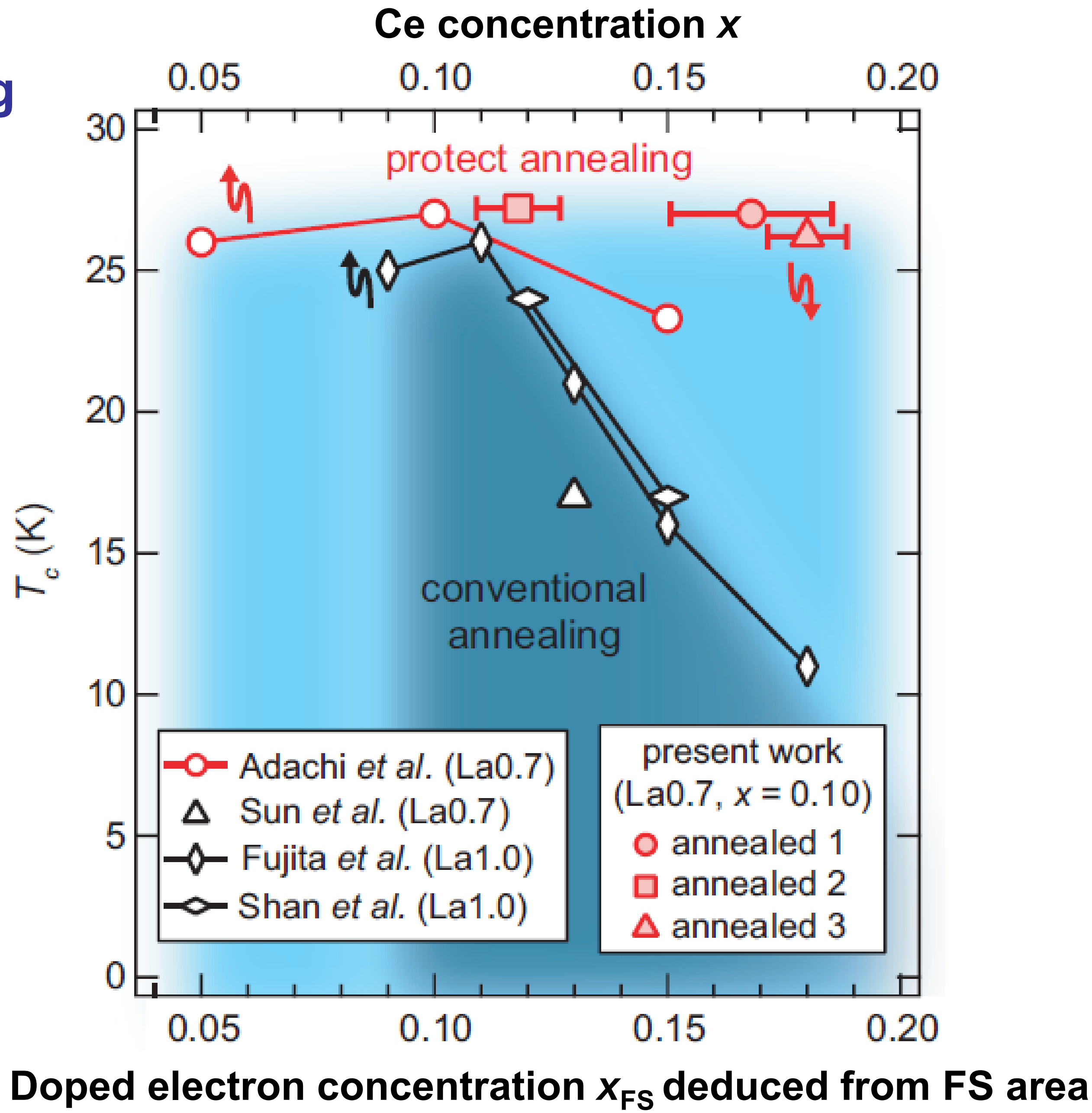


T. Adachi et al., JPSJ '13

T_c vs Ce content x or electron concentration x_{FS} deduced from Fermi-surface area

Fermi surface mapping of $Pr_{1.3-x}La_{0.7}Ce_xCuO_4$

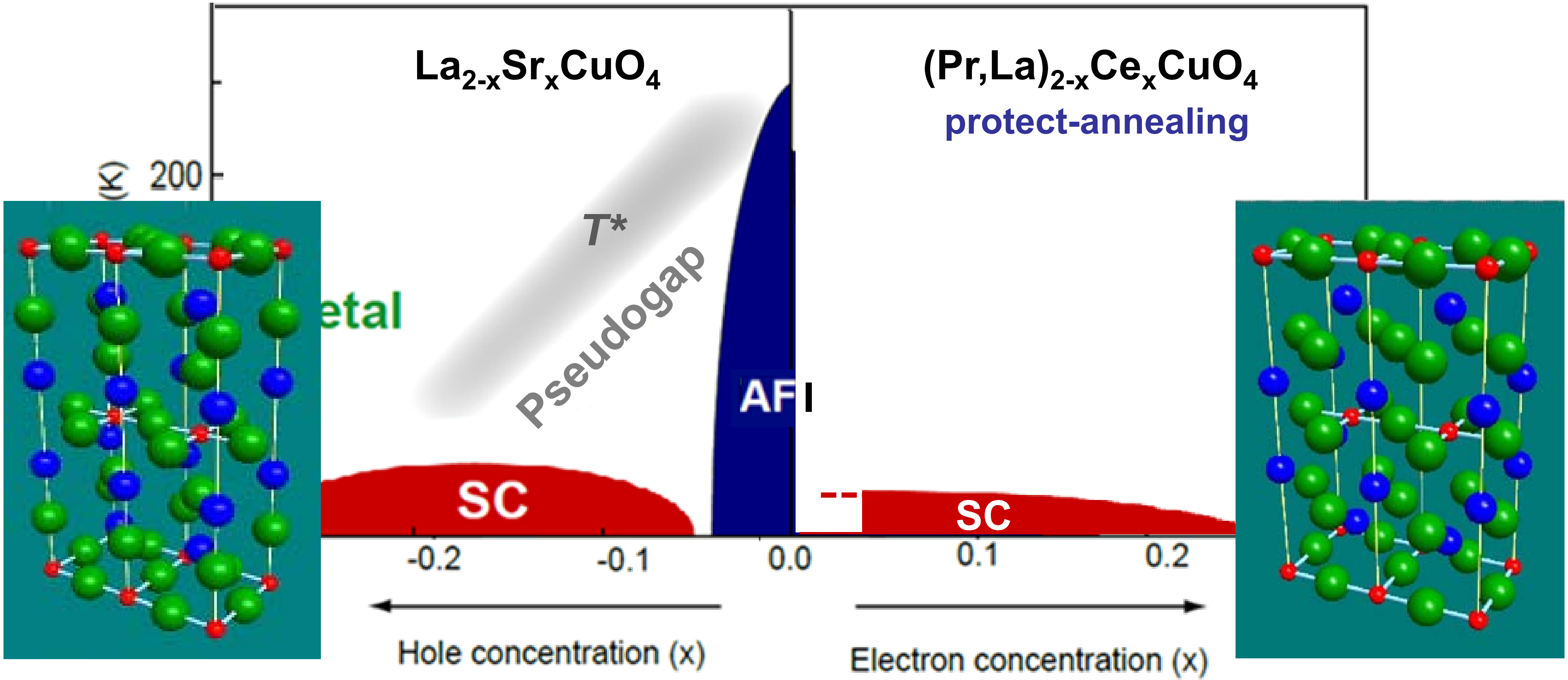




M. Horio *et al.*, Nat. Commun. 2016

Phase diagrams of cuprate superconductors

Hole-doped | **Electron-doped**



Optical gap E_{gap} ~ 2.0 eV > E_{gap} ~ 1.5 eV S. Uchida et al., PRB '91

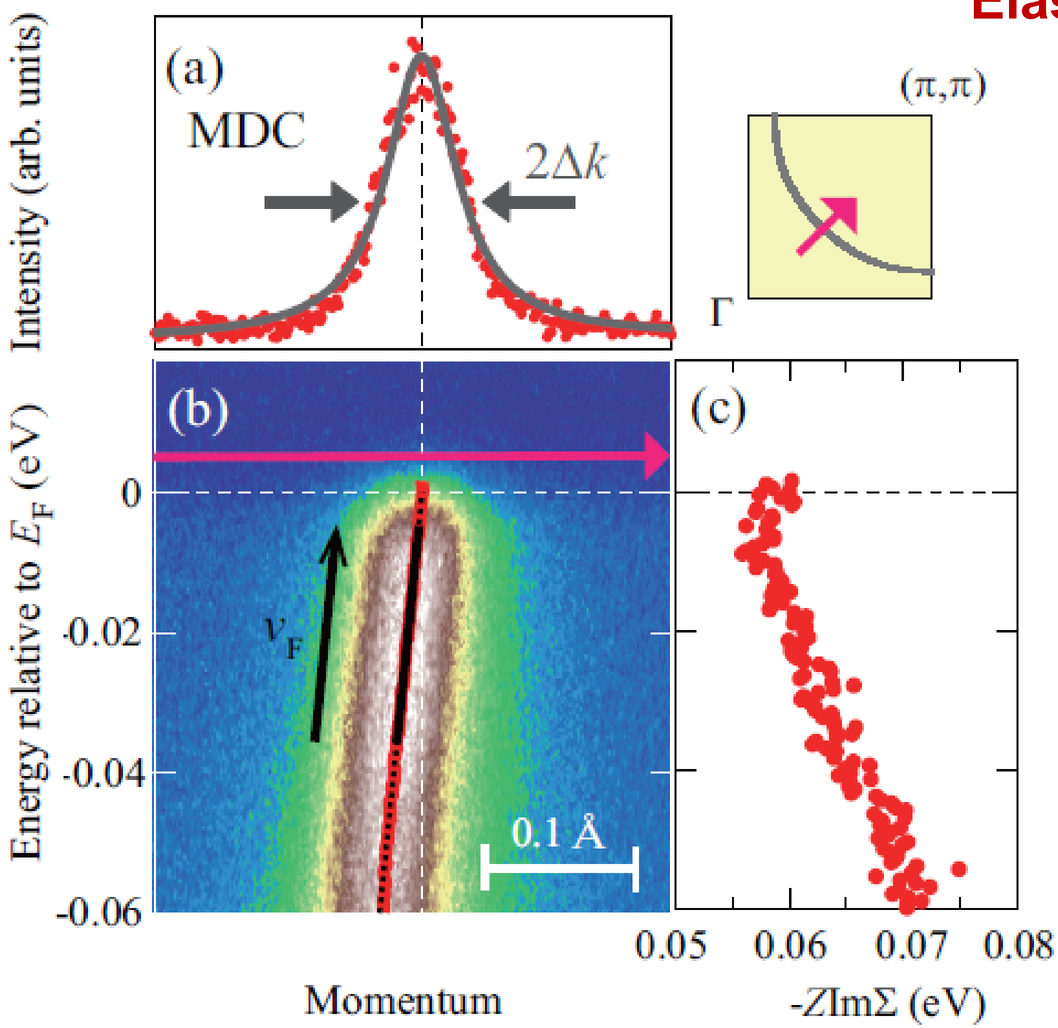
Charge-transfer energy $\varepsilon_d - \varepsilon_p$ ~ 2.8 eV > $\varepsilon_d - \varepsilon_p$ ~ 1.6 eV

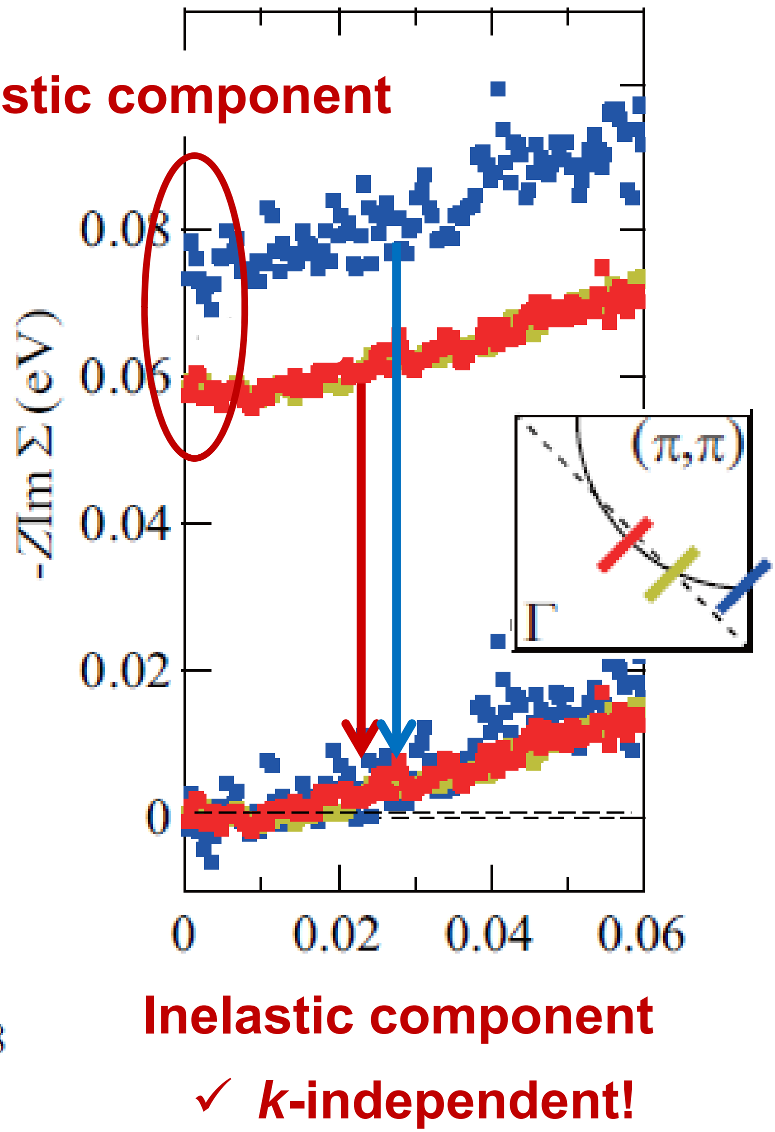
Mott insulator **Slater insulator?**

H. Das and T. Saha-Dasgupta, PRB (2009)
C. Weber *et al.*, Nat. Phys., PRB (2010)

Scattering rate $\Gamma(\varepsilon) \equiv -Z\,\mathrm{Im}\Sigma(\varepsilon)$ of quasi-particle

$$\Gamma(\varepsilon) \equiv -Z\mathrm{Im}\Sigma(\epsilon) = v_F \Delta k(\epsilon)$$

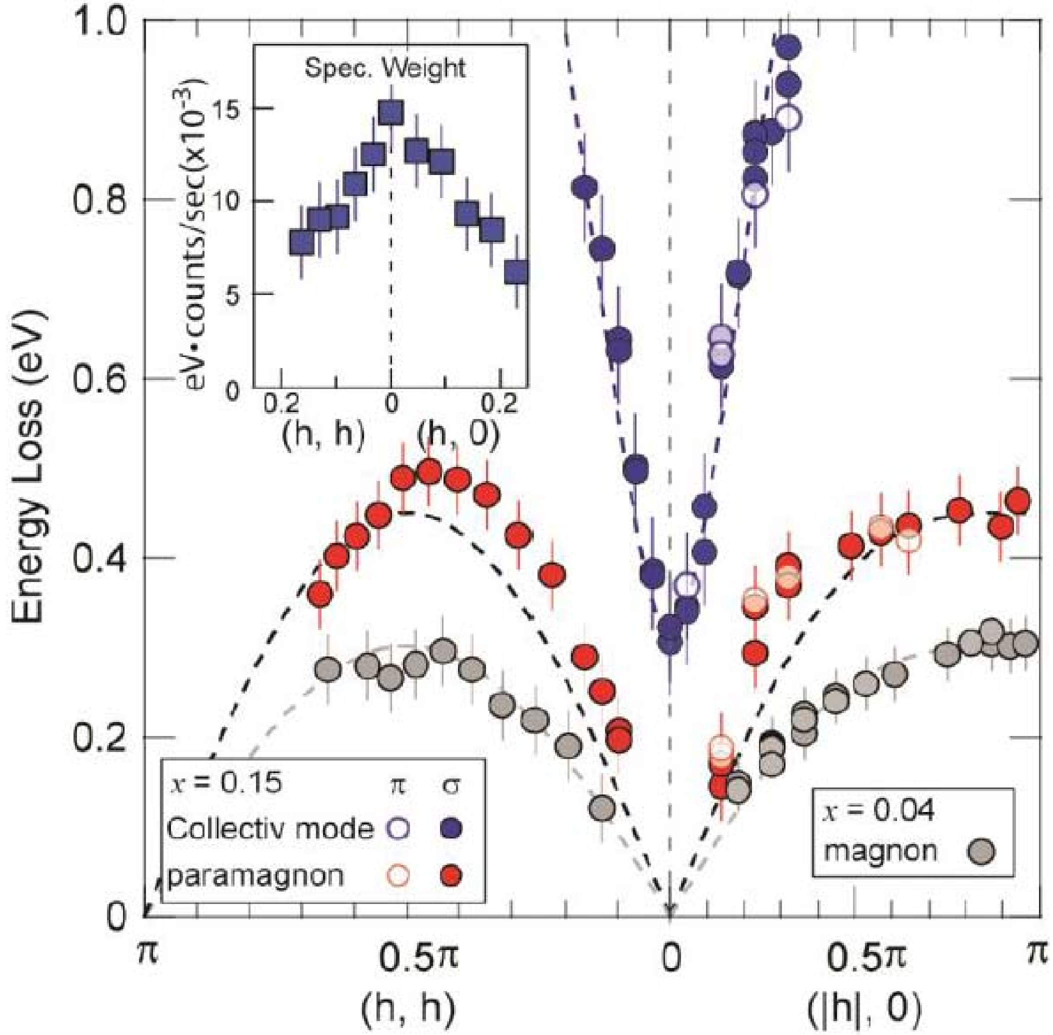




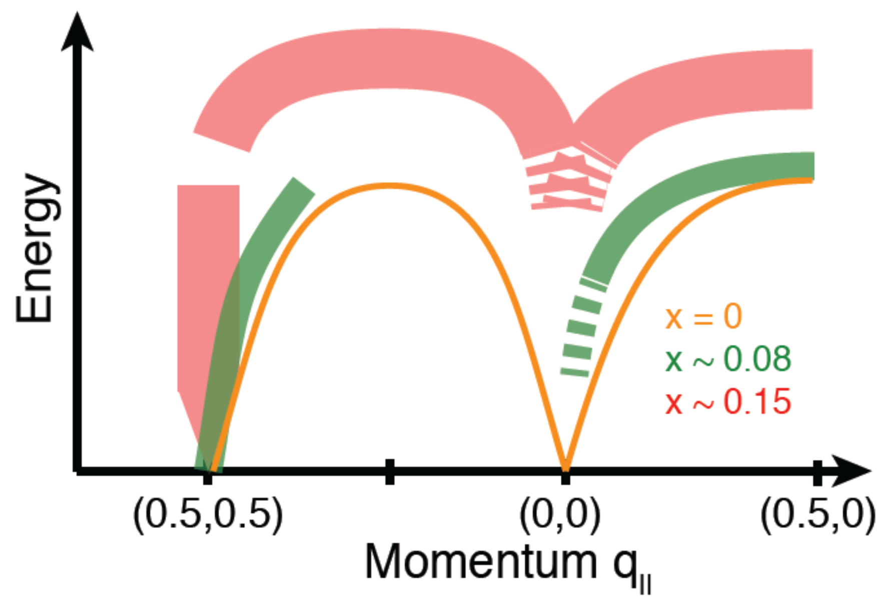
M. Horio *et al.*, Nat. Commun. 2016

High energy spin excitations in $Nd_{2-x}Ce_xCuO_4$

Cu $L_{2,3}$-edge RIXS



W-S. Lee *et al*., Nat. Phys. (2014)



K. Ishii, M. Fujita et *al*., Nat. Commun. (2014)

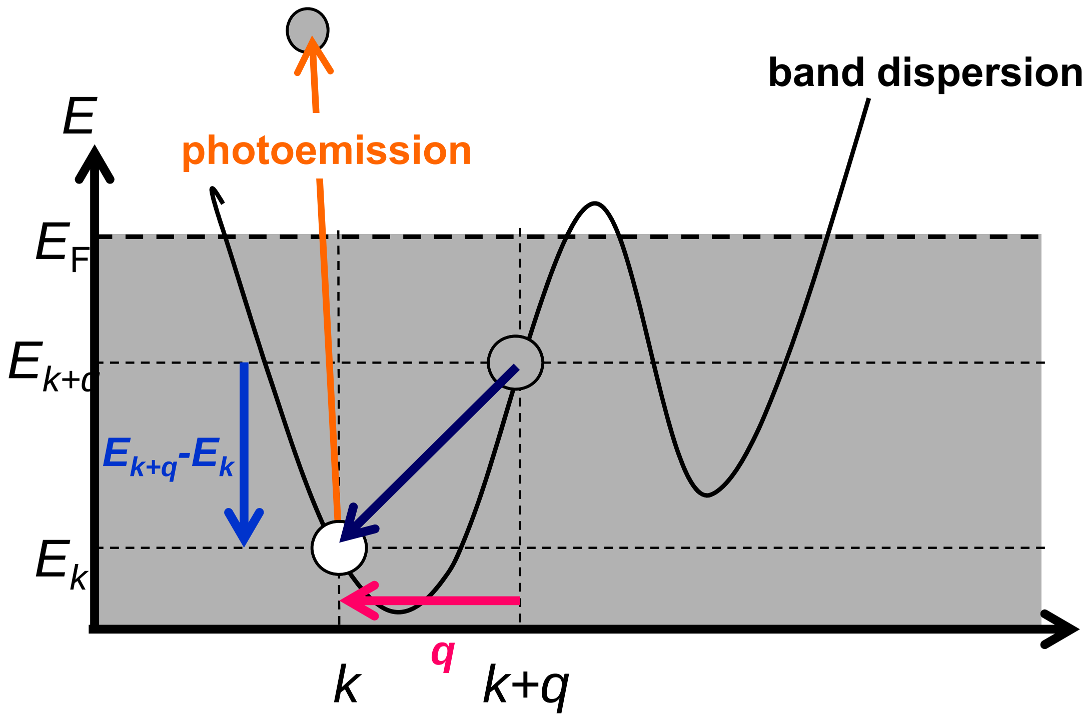
Simulation of scattering rate by spin fluctuations

$$\mathrm{Im}\Sigma_{\boldsymbol{k}}(\epsilon = E_{\boldsymbol{k}}) \propto \sum_{\boldsymbol{q},\omega} \mathrm{Im}\chi(\boldsymbol{q},\omega)\mathrm{Im}\frac{f(E_{\boldsymbol{k}+\boldsymbol{q}})}{E_{\boldsymbol{k}+\boldsymbol{q}} - E_{\boldsymbol{k}} - \omega + i\delta}$$

$$\mathrm{Im}\chi(\boldsymbol{q},\omega) \propto \frac{\omega}{\{1+(\boldsymbol{q}-\boldsymbol{Q}_{\mathrm{AFM}})^2\xi^2\}^2 + (\omega/\omega_{\mathrm{SF}})^2}$$ **: Spin fluctuation spectrum**

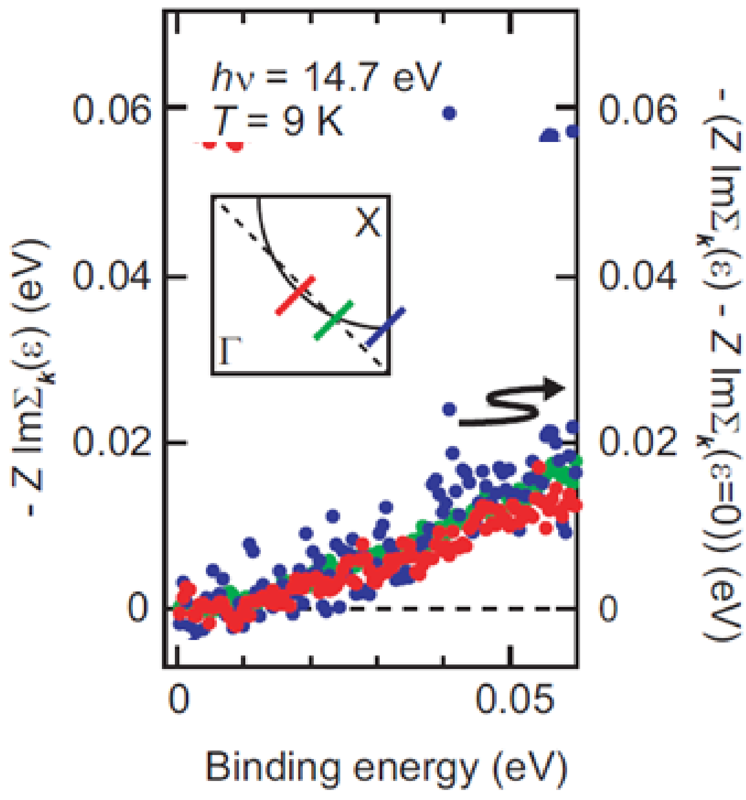
$\boldsymbol{Q}_{\mathrm{AFM}} = (\pi,\pi)$, ξ: **AFM correlation length**

ω_{SF}: **AFM fluctuation energy (=6 meV, Fujita *et al.* PRL '08)**

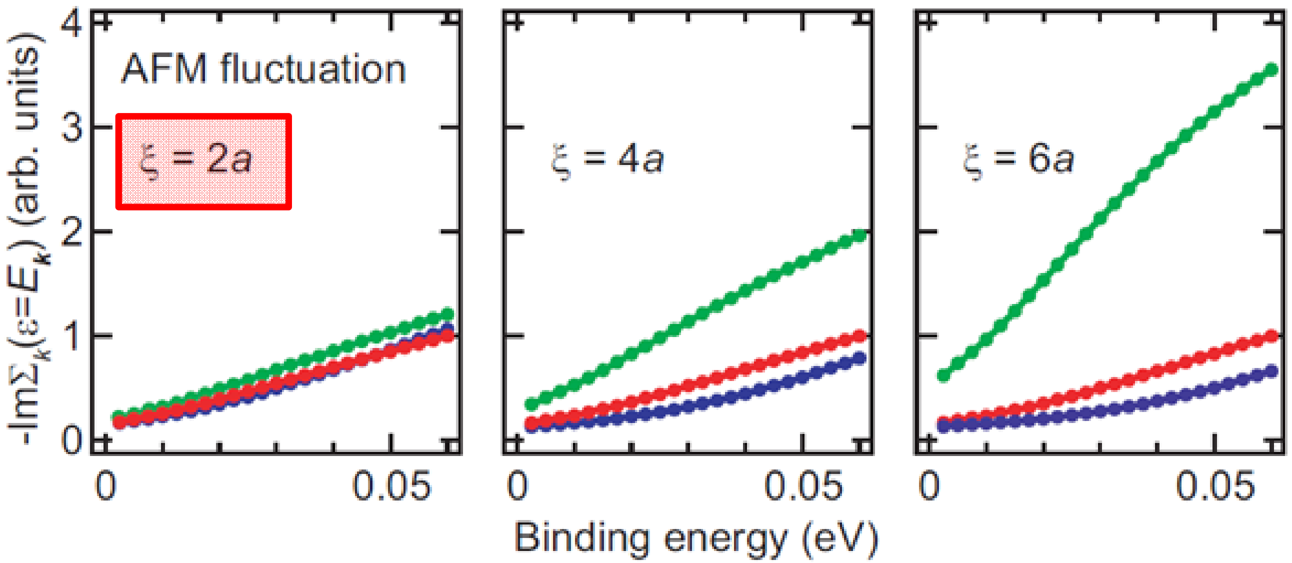


Inelastic scattering rate in $Pr_{1.2}La_{0.7}Ce_{0.1}CuO_4$

Experiment



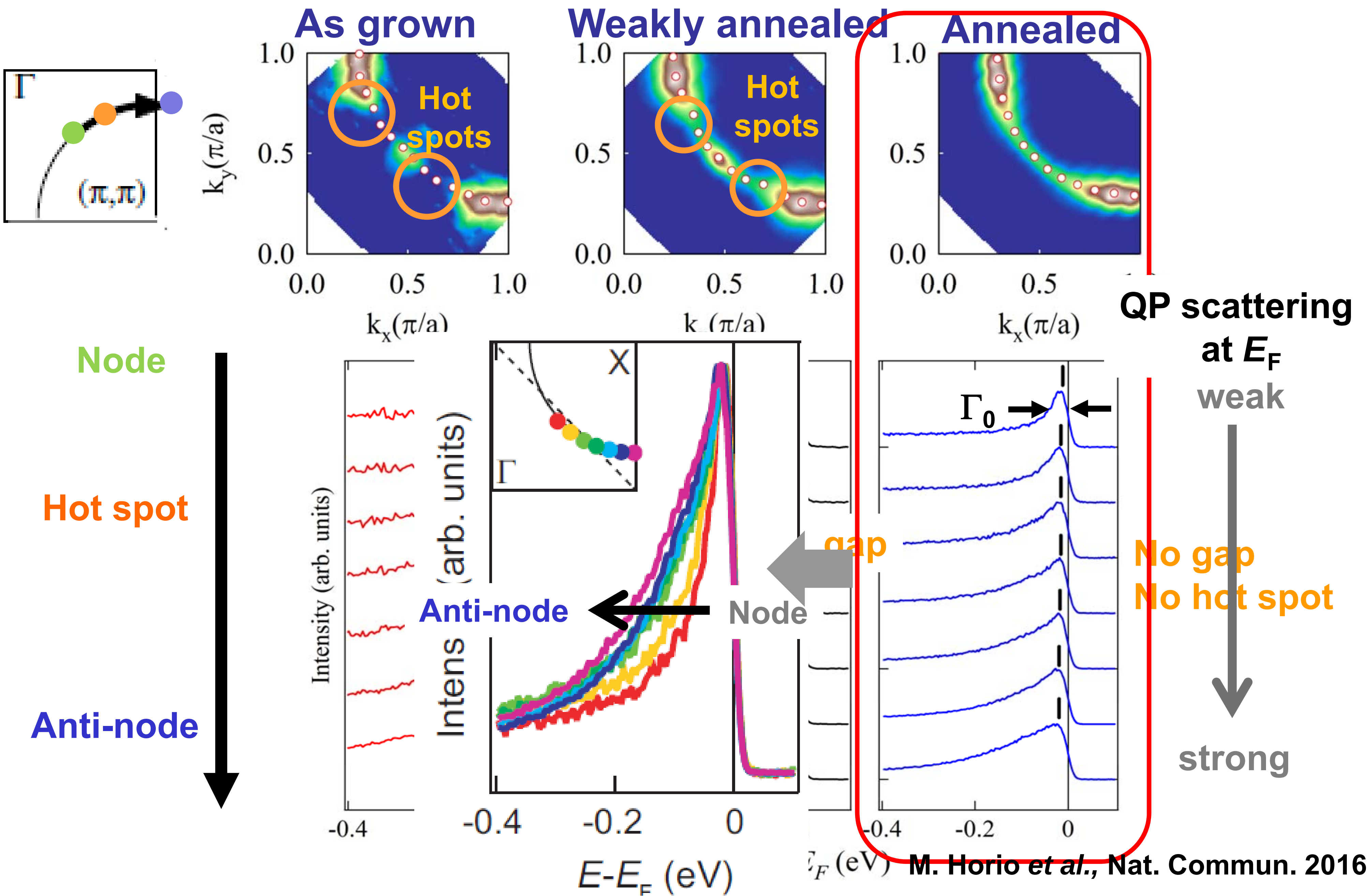
Simulations with AFM fluctuations



✓ **AFM fluctuations are very short-ranged and/or the spin moment is much reduced.**

M. Horio *et al.*, Nat. Commun. 2016

Elastic scattering rate Γ_0 of quasi-particle

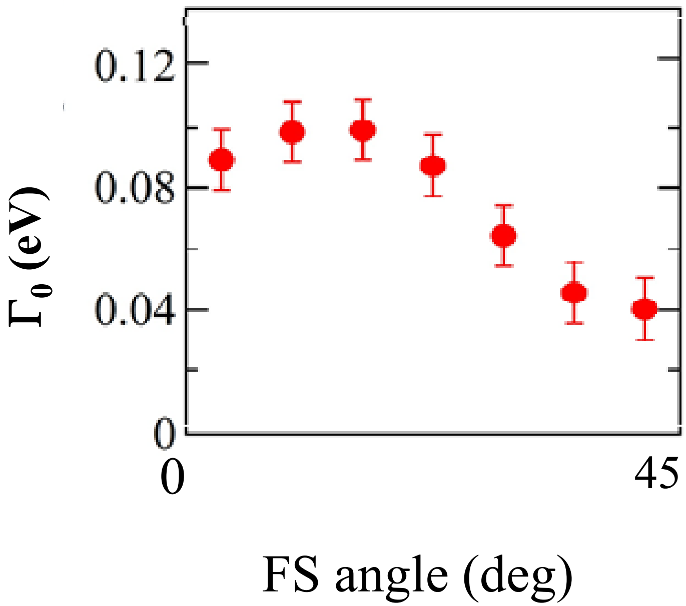


M. Horio *et al.*, Nat. Commun. 2016

Elastic scattering rate Γ_0 of quasi-particle

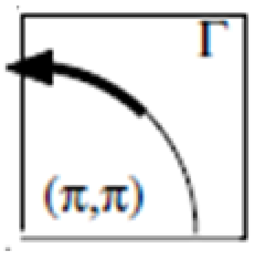
Hole-doped

Optimally doped Bi2212



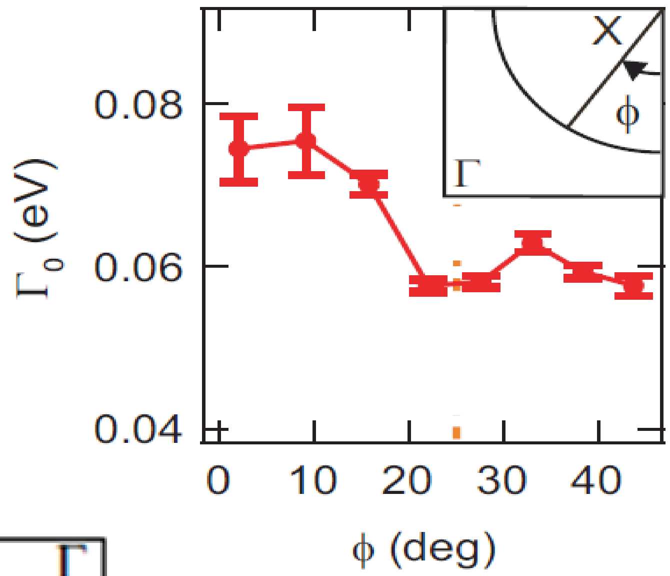
Anti-node ← **Node**

T. Valla *et al.*, PRL (2000)



Electron-doped

Annealed $Pr_{1.2}La_{0.7}Ce_{0.1}CuO_4$



Anti-node ← **Node**

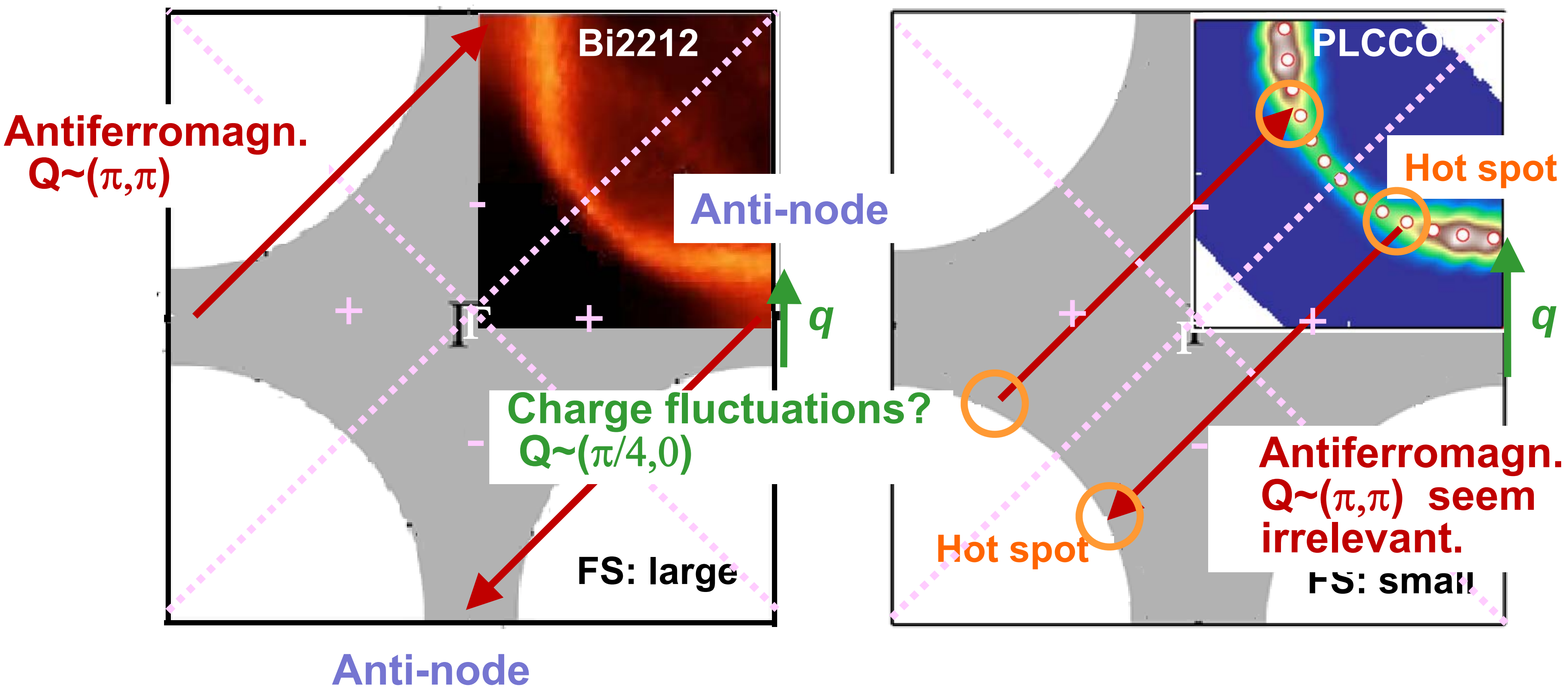
M. Horio *et al.*, Nat. Commun. 2016

Elastic scattering rate Γ_0 is higher in the antinodal region.

→ Common scattering mechanism for hole- and e-doped HTSC?

QP scattering in annealed electron-doped and hole-opt/overdoped superconductors

Hole-doped | **Electron-doped**
Optimally doped | **Protect-annealed**

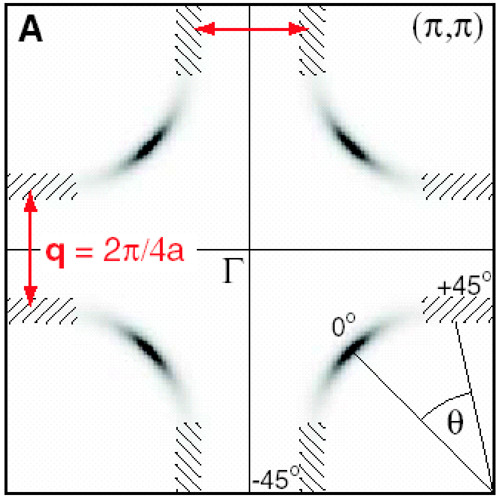


Nesting *q* → Charge modulation, Lattice distortion

A. Koitzsch *et al.*, PRB (2004)

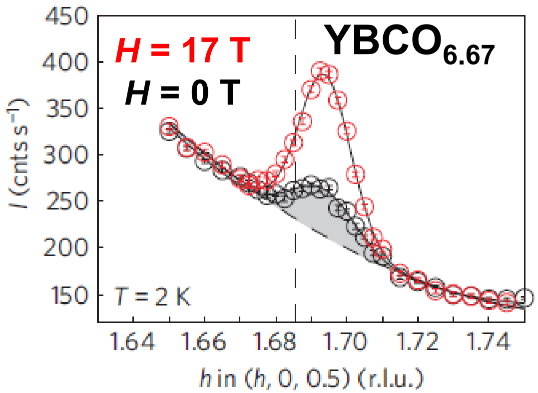
Charge order/CDW in hole-doped cuprates

Nested Fermi surface by ARPES

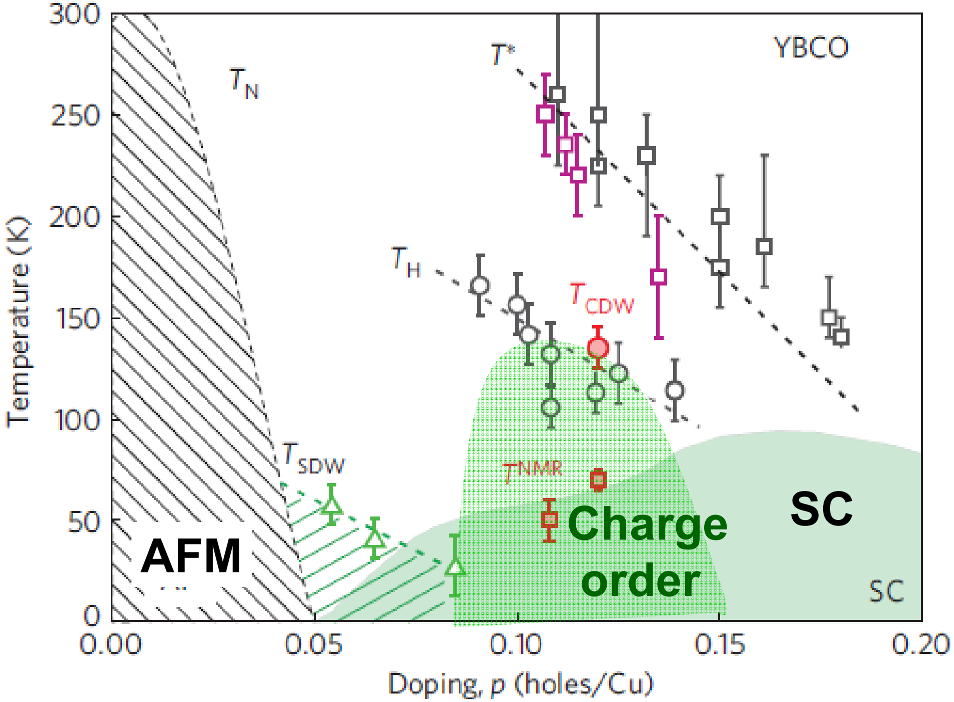


K.M. Shen *et al.*, Science '05

Incommensulate x-ray diffraction peak



Phase diagram



$R_H < 0$ at $T < T_H$ due to FS reconstruction

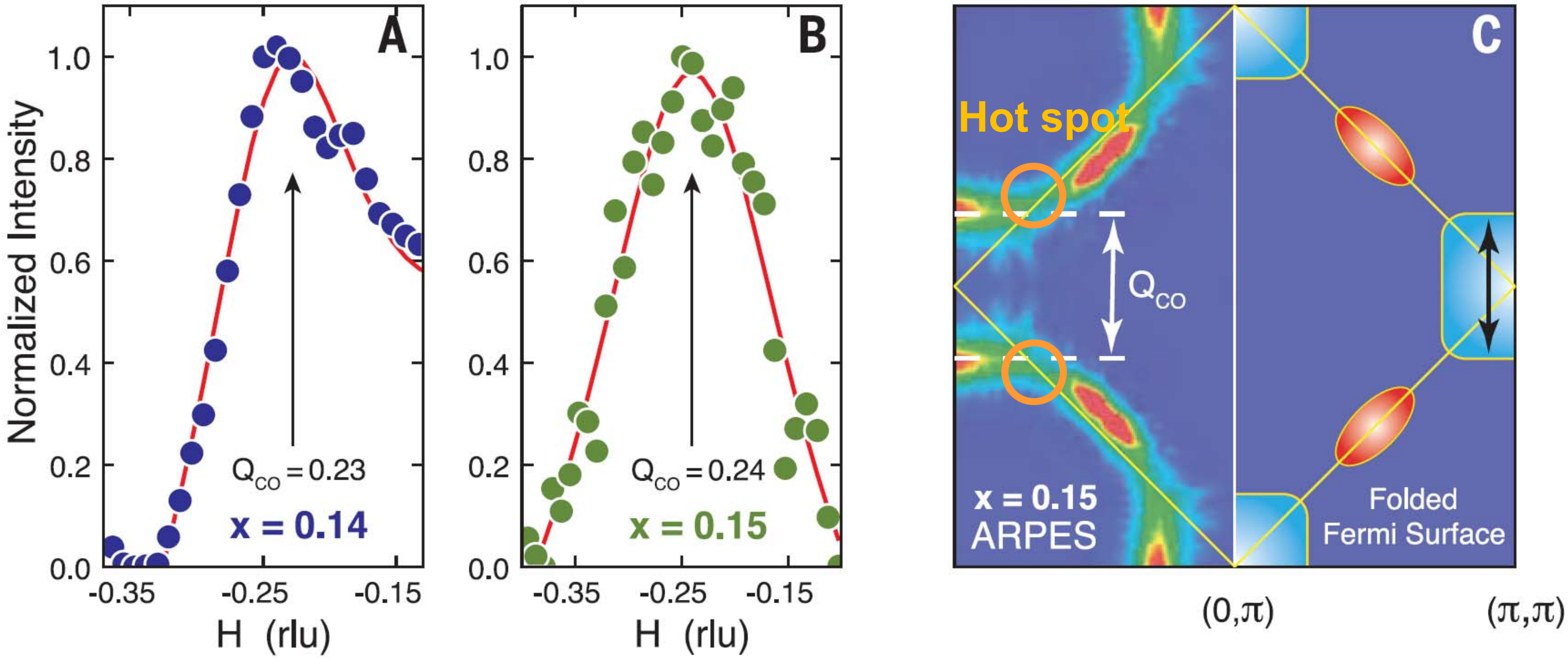
J. Chang *et al.*, Nat. Phys. '12

Possible charge order in electron-doped cuprates

Soft X-ray diffraction in $Nd_{2-x}Ce_xCuO_4$

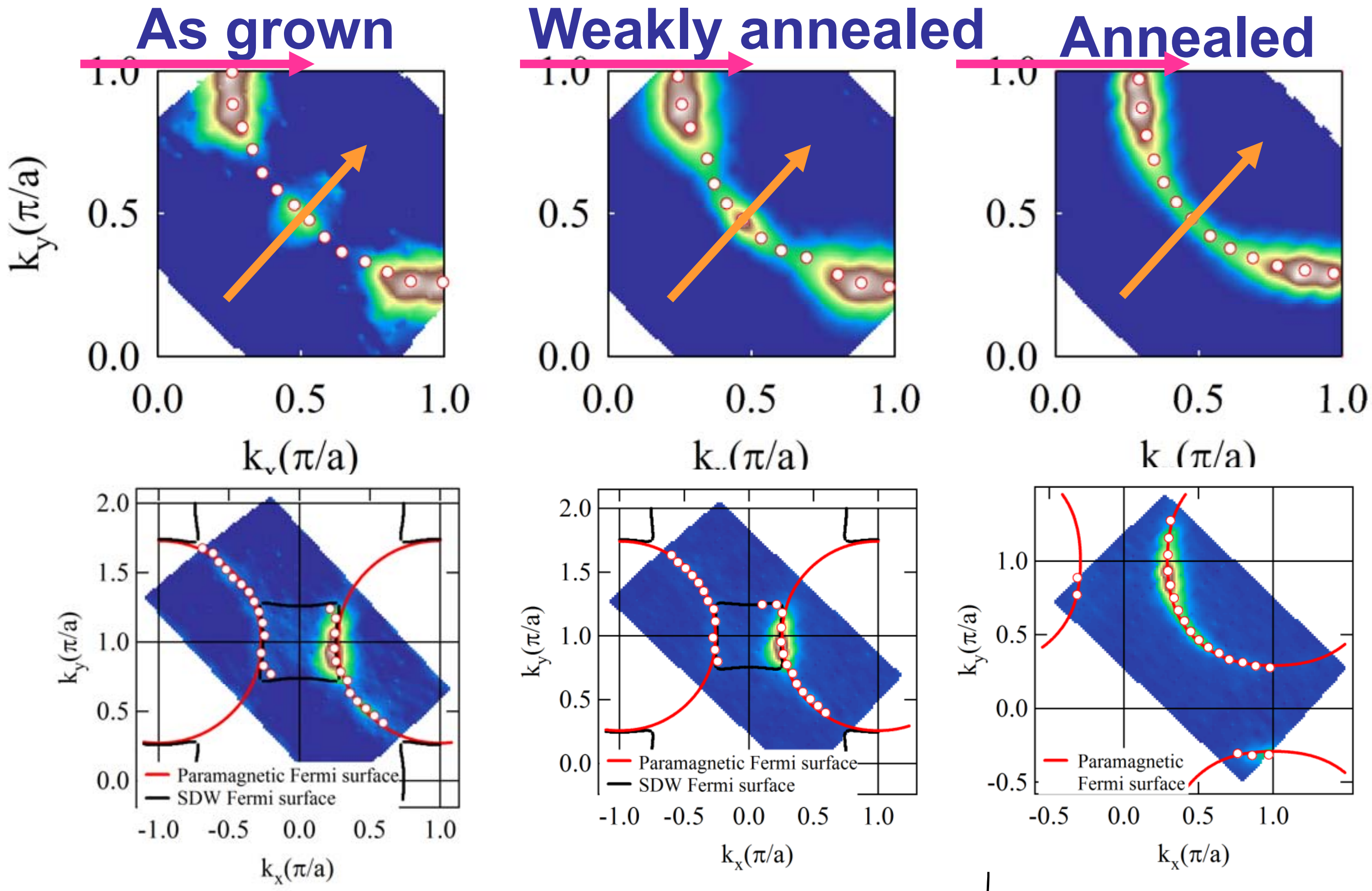
Incommensurate peak

Nesting between Fermi surfaces
Nesting between hot spots?



E. H. da Silva Neto *et al.*, Nature (2015)

Annealing effect on the Fermi surface of $Pr_{1.2}La_{0.7}Ce_{0.1}CuO_4$



M. Horio *et al.*

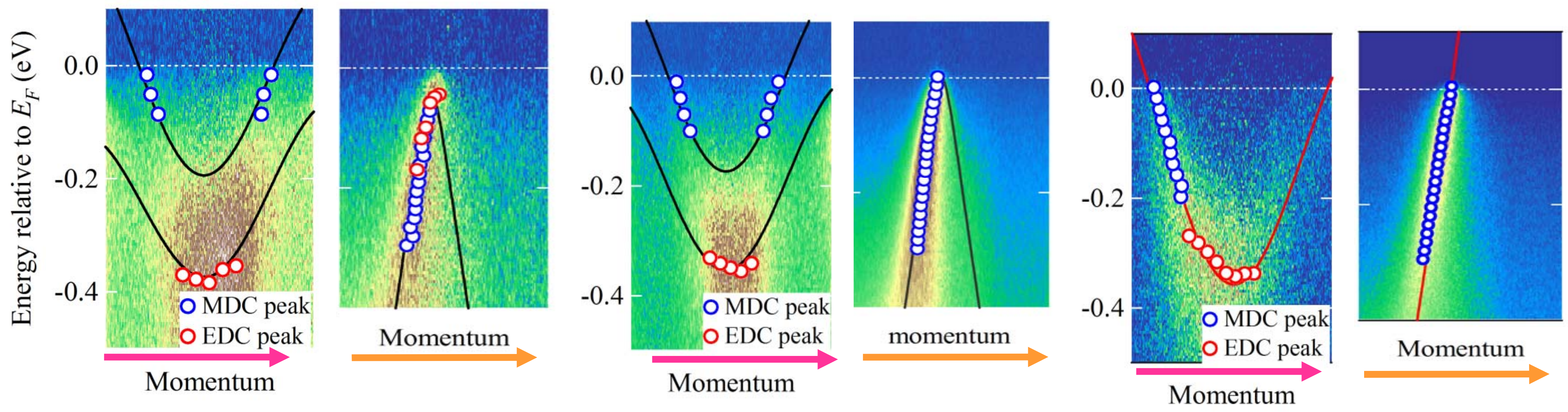
Antiferromagnetic **Paramagnetic**

$$H = \begin{pmatrix} \Delta E - 4t'\cos(k_x a)\cos(k_y a) & -2t\{\cos(k_x a) + \cos(k_y a)\} \\ -2t\{\cos(k_x a) + \cos(k_y a)\} & -\Delta E - 4t'\cos(k_x a)\cos(k_y a) \end{pmatrix}$$

$$\varepsilon_{\mathbf{k}} = -2t(\cos k_x a + \cos k_y a) - 4t'\cos k_x a \cos k_y a$$

Annealing effect on the band dispersions in $Pr_{1.2}La_{0.7}Ce_{0.1}CuO_4$

As grown | **Weakly annealed** | **Annealed**



M. Horio *et al.*

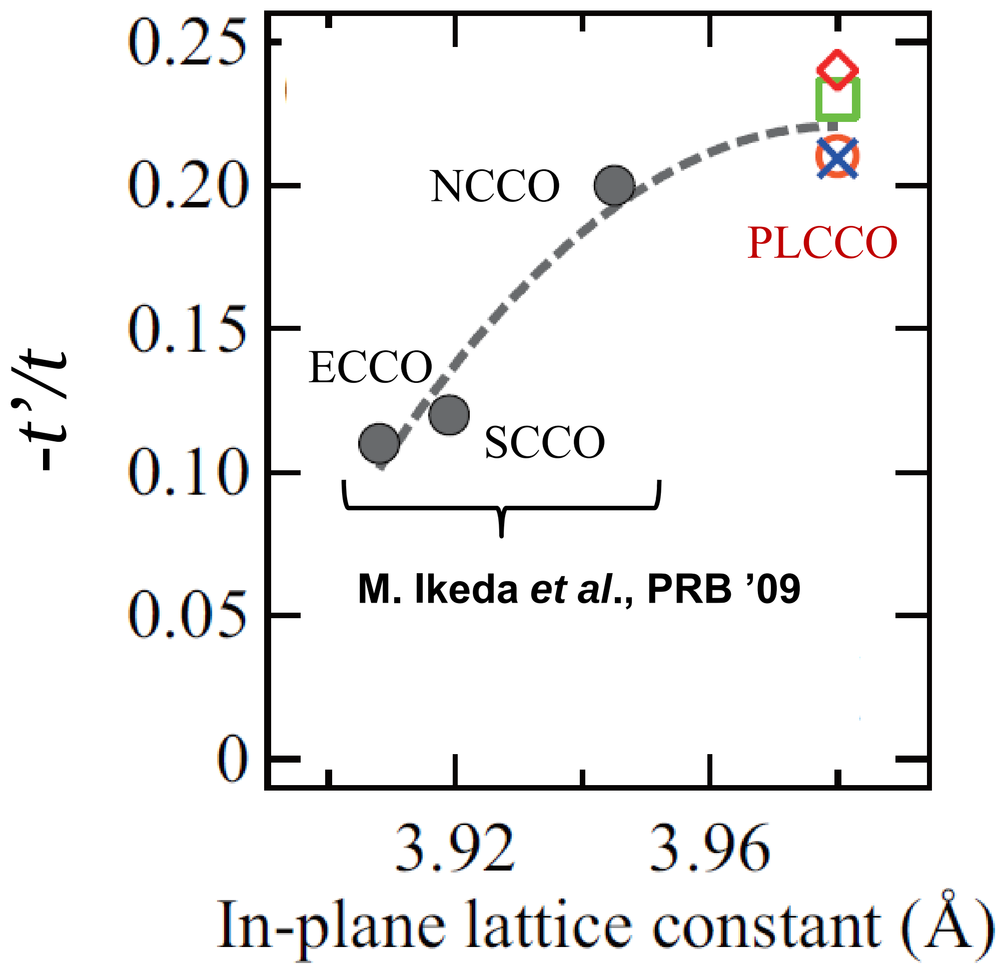
Antiferromagnetic | **Paramagnetic**

$$H = \begin{pmatrix} \Delta E - 4t' \cos(k_x a)\cos(k_y a) & -2t\{\cos(k_x a) + \cos(k_y a)\} \\ -2t\{\cos(k_x a) + \cos(k_y a)\} & -\Delta E - 4t' \cos(k_x a)\cos(k_y a) \end{pmatrix}$$

$$\varepsilon_{\mathbf{k}} = -2t(\cos k_x a + \cos k_y a) - 4t' \cos k_x a \cos k_y a$$

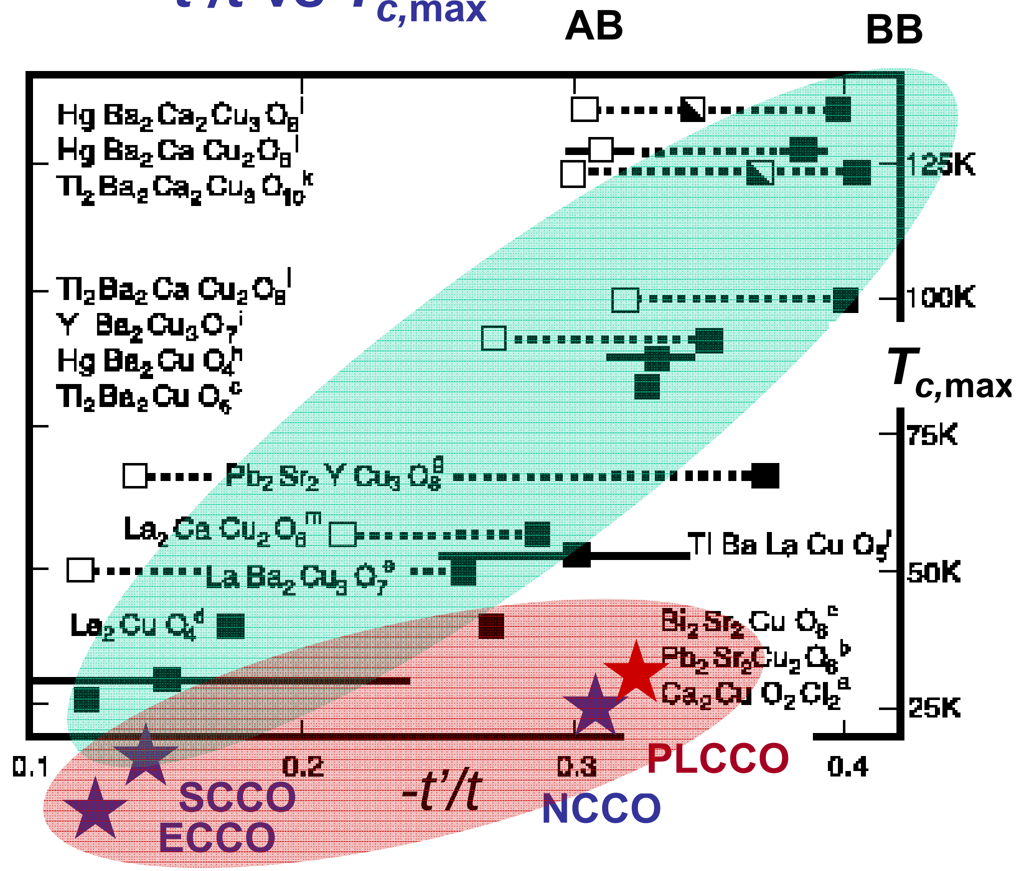
Fermi surface curvature *t'/t*

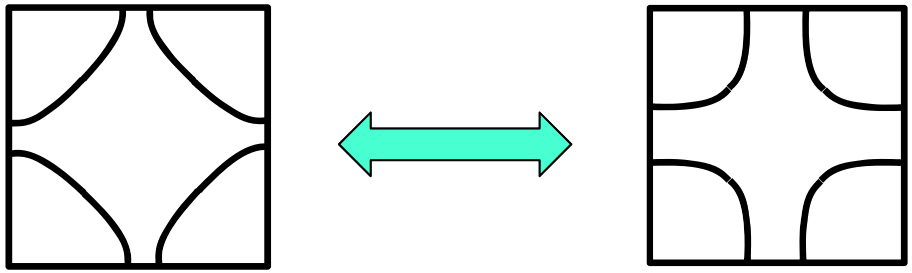
t'/t vs lattice constant



M. Horio *et al.*, Nat. Commun. 2016

t'/t vs $T_{c,max}$





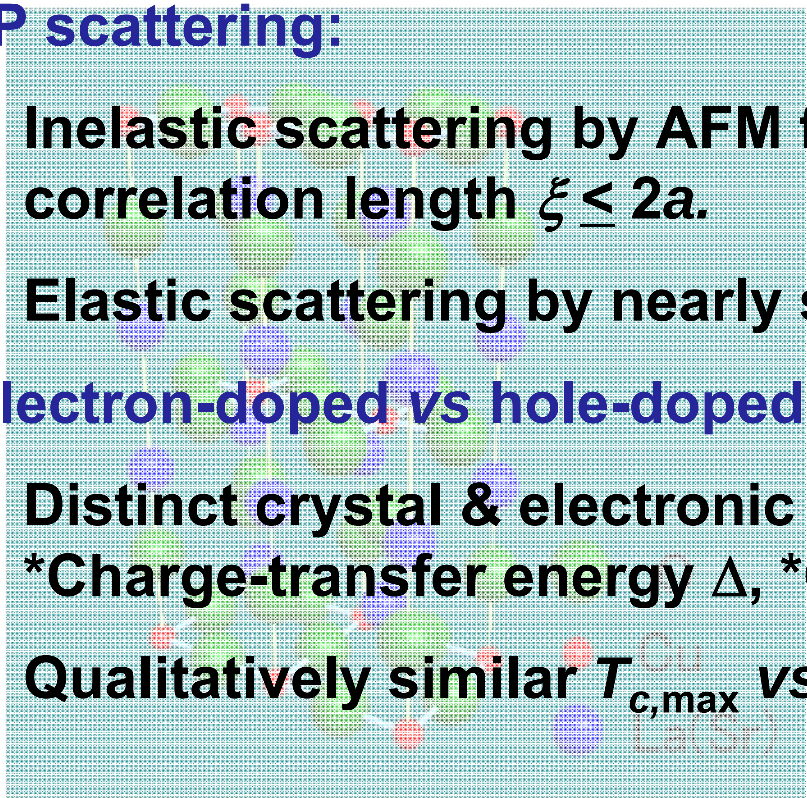
E. Pavarini *et al.*, PRL '01

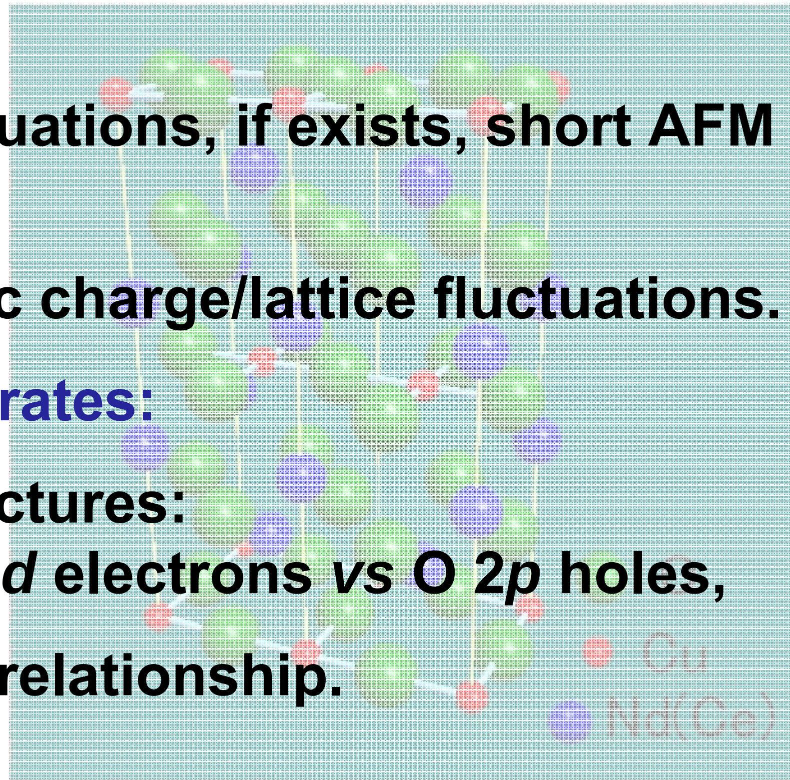
Summary

Effects of "protect" annealing:

- **Pseudogap of the AFM origin is suppressed.**
- **Superconducting region is expanded from *n* < 0.1 to *n* ~ 0.2 with constant T_c ~ 27 K, leading to a new phase diagram.**

QP scattering:





- **Inelastic scattering by AFM fluctuations, if exists, short AFM correlation length $\xi \leq 2a$.**
- **Elastic scattering by nearly static charge/lattice fluctuations.**

Electron-doped *vs* hole-doped cuprates:

- **Distinct crystal & electronic structures:**
  ***Charge-transfer energy Δ, *Cu 3*d* electrons *vs* O 2*p* holes,**
- **Qualitatively similar $T_{c,max}$ *vs* *t'/t* relationship.**