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ICTP 40th Anniversary

SMR.1572 - 13

Workshop on
Novel States and Phase Transitions in Highly Correlated Matter

12 - 23 July 2004

Physics of lightly doped cuprate revealed from $Ca_{2-x}Na_xCuO_2C1_2$

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Trieste2004

Physics of lightly doped cuprate revealed from $Ca_{2-x}Na_xCuO_2Cl_2$

Hide TAKAGI (University of Tokyo & RIKEN)

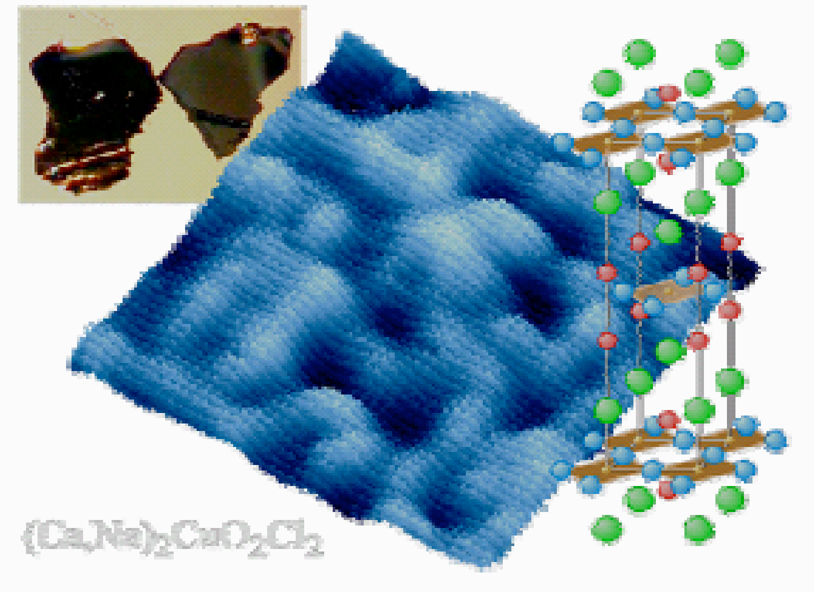
With Y.Kohsaka, K.Waku and T. Sasagawa (Tokyo)

T.Hanaguri &K.Iwaya (RIKEN)

C. Lupien & J.C.S Davis (Cornell)

K. Shen & Z.X.Shen (Stanford)

M.Azuma & M Takano (Kyoto)



Supported by CREST-JST

OUTLINE

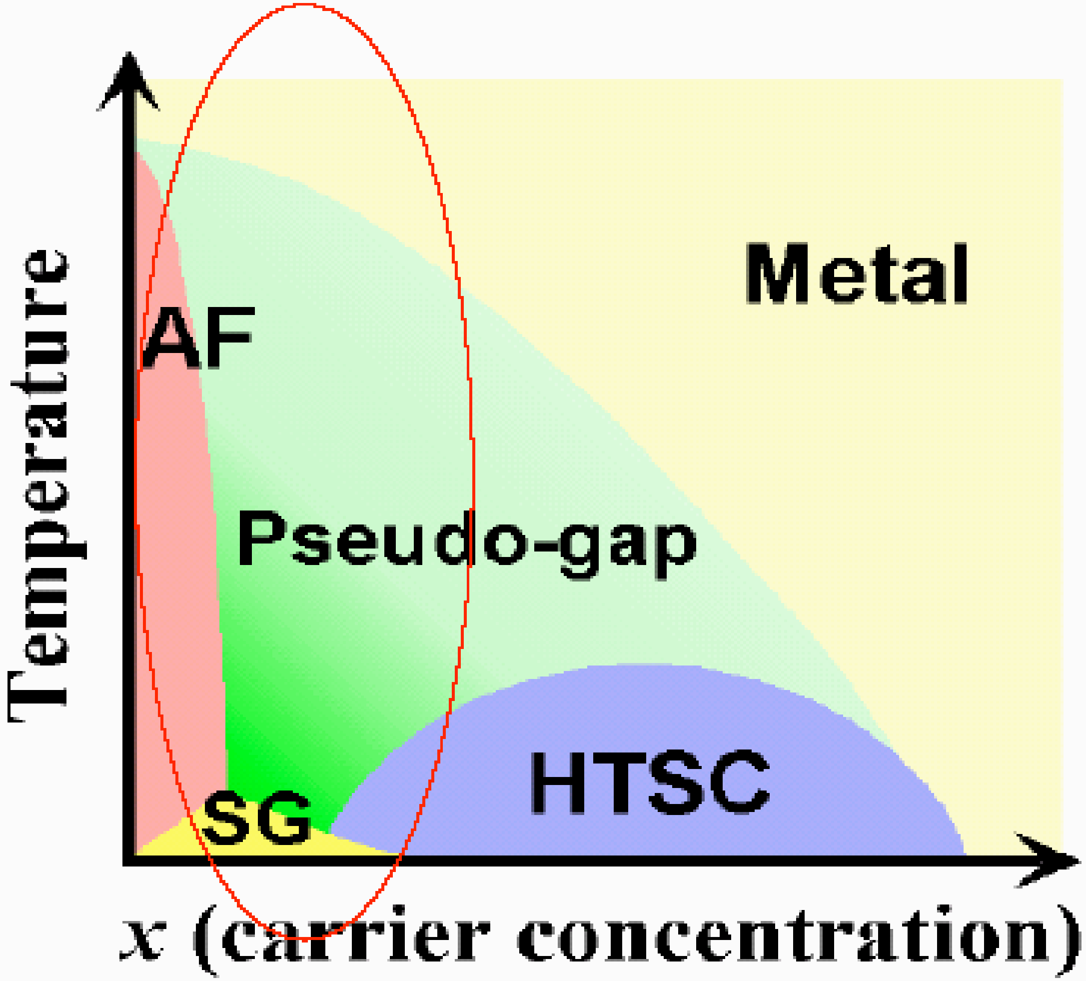
1. Introduction – why oxychlorides?
2. Phase diagram and transport of $Ca_{2-x}Na_xCuO_2Cl_2$
3. Pseudogap observed by optics and ARPES
3. STM/STS observation of nano-scale heterogeneity "Kishimen"
4. 4a x 4a checkerboard LDOS modulation
5. Implication to pseudogap physics
6. Remarks on FAQs

<u>Friday morning</u>

Geometrical frustration in spinel oxides

(+ electron-phonon interaction in cuprates)

Need for real/k-space spectroscopy (STM/STS, ARPES) on "lightly doped " cuprates



electronic evolution from Mott ins. to d-wave SC?

- Fermi Surface evolution
- Pseudogap

Mottness vs. Cooperness?

Hidden order?

- ***charge ordering (stripe, checkerboard)***
- **DDW**

Electronic phase separation

real space physics important

BSCCO, favorite of STM/ARPES community, chemically unstable near Ins.

M^{2}S 2000 (Houston), conference summary

Materials & Properties

Hidenori TAKAGI

Department of Advanced Materials Science, University of Tokyo, 7-3-1 Hongo, Tokyo 1

mainly because of the difficulty in obtaining clean surfaces. We should pay more attention to developing materials suitable for such surface sensitive experiments. This is particularly true for the heavily underdoped region, where high-quality Bi single crystals are hard to come by. The exploration of the heavily underdoped region becomes increasing important to establish the connection between the parent Mott insulator and the key features outlined above.

$(Ca,Na)_2CuO_2Cl_2$ - Ideal system for STM &ARPES

- *Excellent cleave*

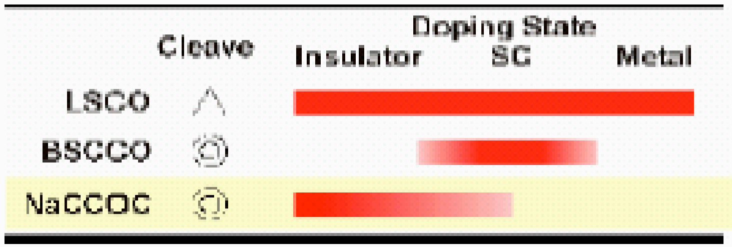
  only Bi and oxychloride

- *Undistorted CuO_2 monolayer*

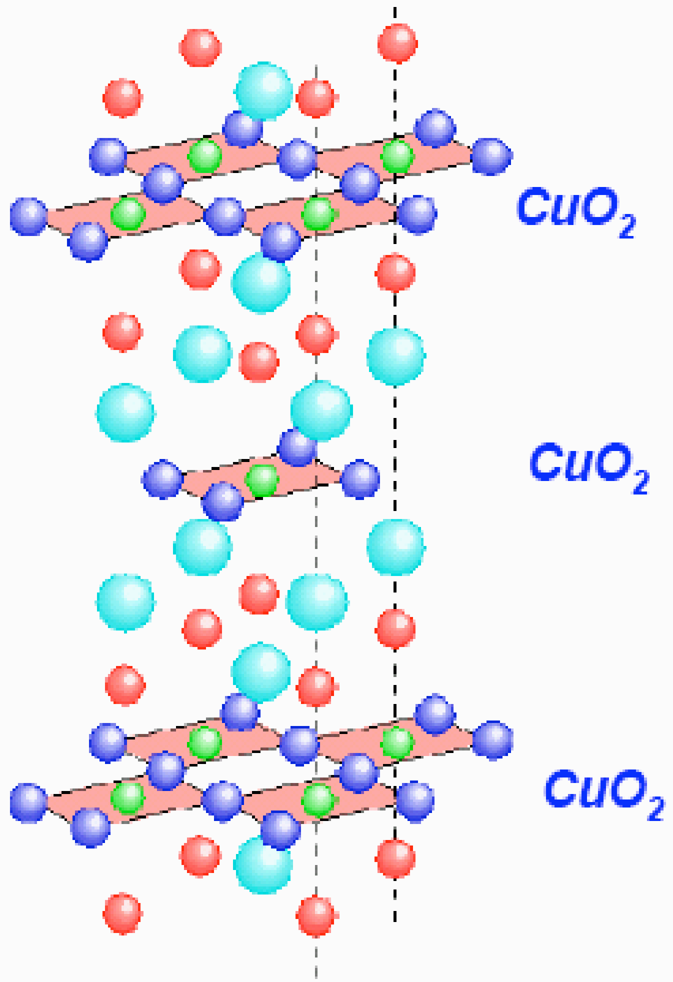
  remains tetragonal down to low T

- *Phase exists from Ins. to UD SC*

Z. Hiroi *et al.*, Nature 371, 139 (1994).



$(Ca,Na)_2CuO_2Cl_2$



Parent compound $Ca_2CuO_2Cl_2$

ARPES Ins. standard

F.Ronning, Z.X.Shen *et al.* Science 282, 2067 (98)

Mott gap with d-wave like dispersion

High quality surface due to easy cleavage

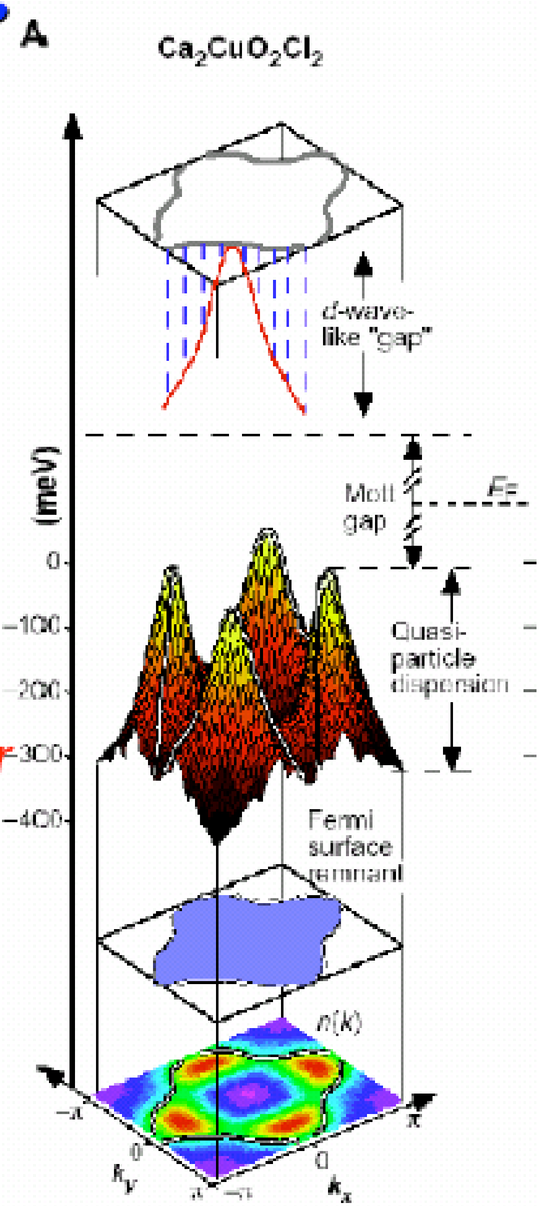
⟶

Evolution of d-wave Mott Ins into SC?

Bad news:Na-doped phase formed only under High Pressure

Na-doping requires high pressure synthesis ***under several GPa***

No doped single crystal available



Single Crystal Growth under High Pressure

Y. Kohsaka *et al.*, J. Am. Chem. Soc., 124, 12275 (2002).

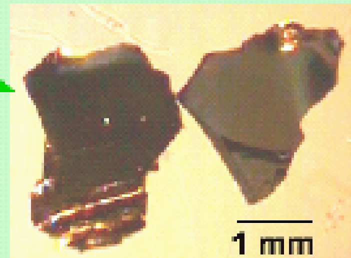
Cubic-Anvil type HP apparatus
"Elephant"

5.5 GPa in a volune of 1cm^3

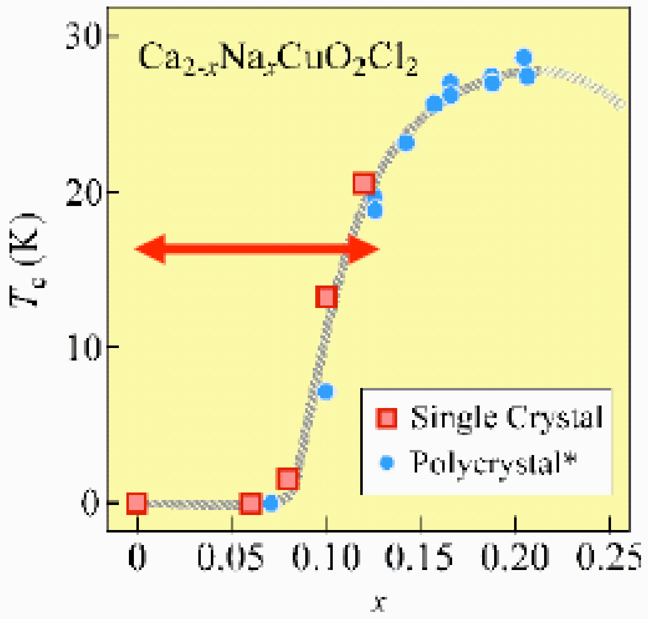
$Ca_2CuO_2Cl_2$ Powder
NaCl (flux, Na source)
$NaClO_4$ (O_2 & Na source)

2 ~ 5.5 GPa
1230 ~ 970℃ / 30 hrs

$(Ca,Na)_2CuO_2Cl_2$ Crystals

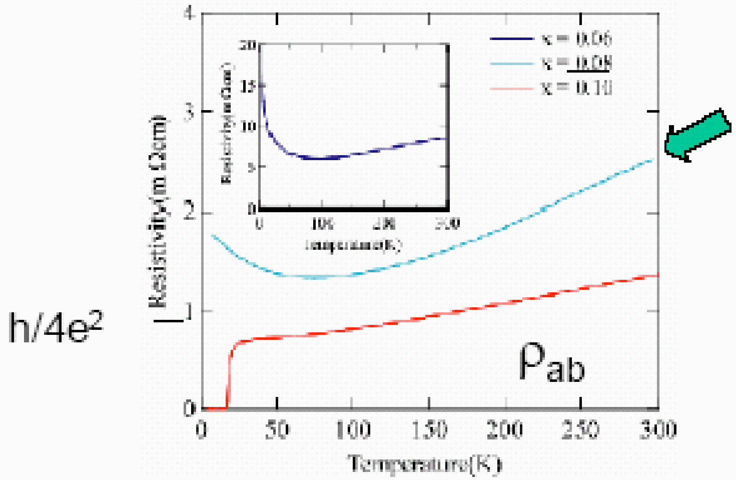


Phase Diagram and transport properties of $Ca_{2-x}Na_xCuO_2Cl_2$ Single Crystals

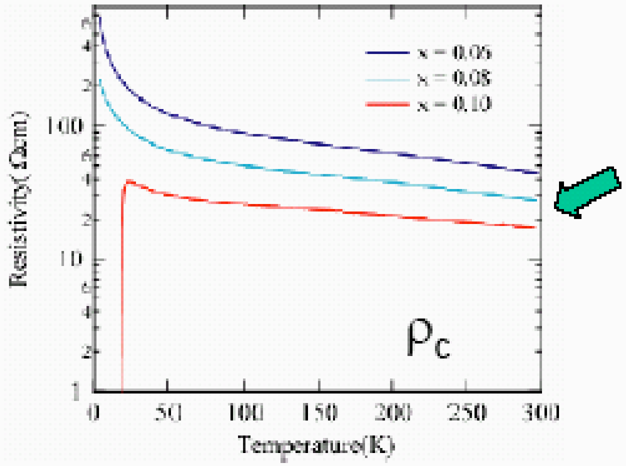


single crystals from x=0 to x=0.12

highly anisotropic, $\rho_c/\rho_a >>10^4$

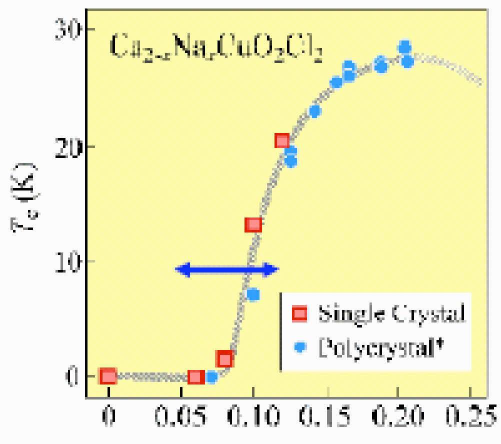


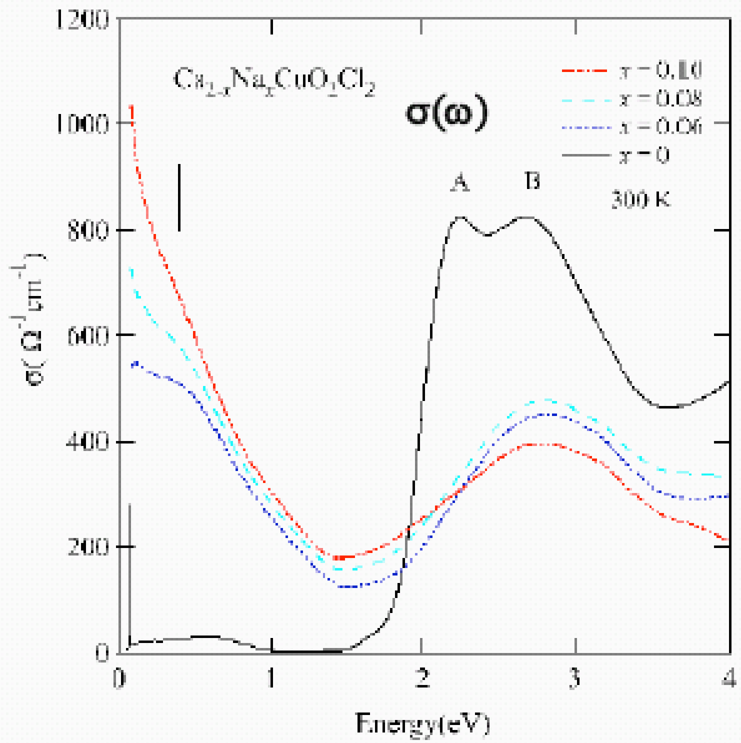
M-I (likely S-I) transition around x=0.08

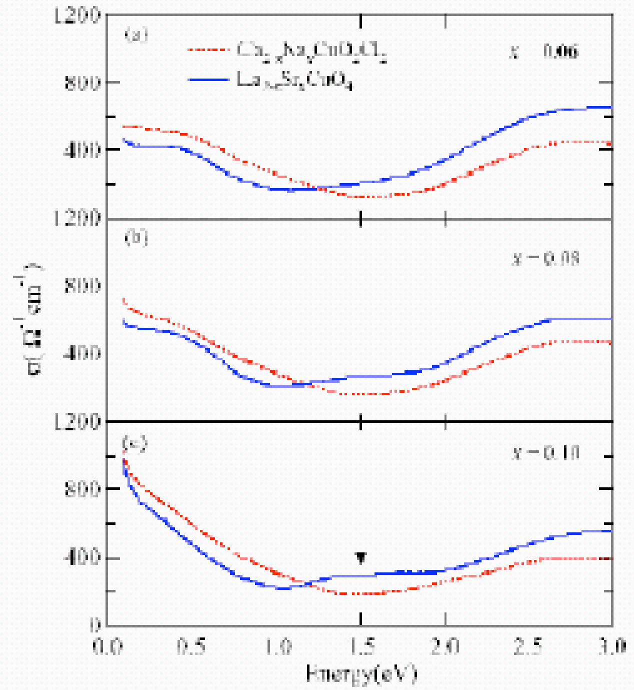


K.Waku et al., submitted to PRB

Evolution of optical conductivity in $Ca_{2-x}Na_xCuO_2Cl_2$





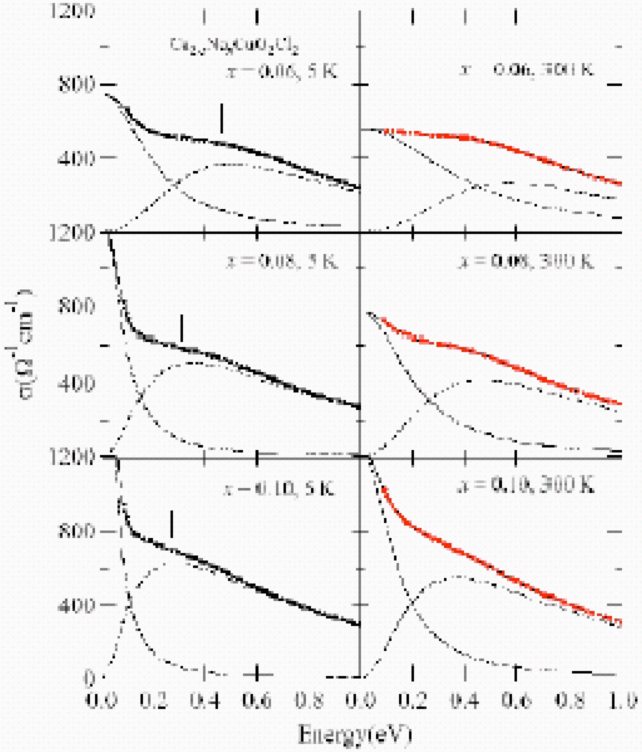


K. Waku et al. PRB submitted

Pseudogap signature in optical conductivity

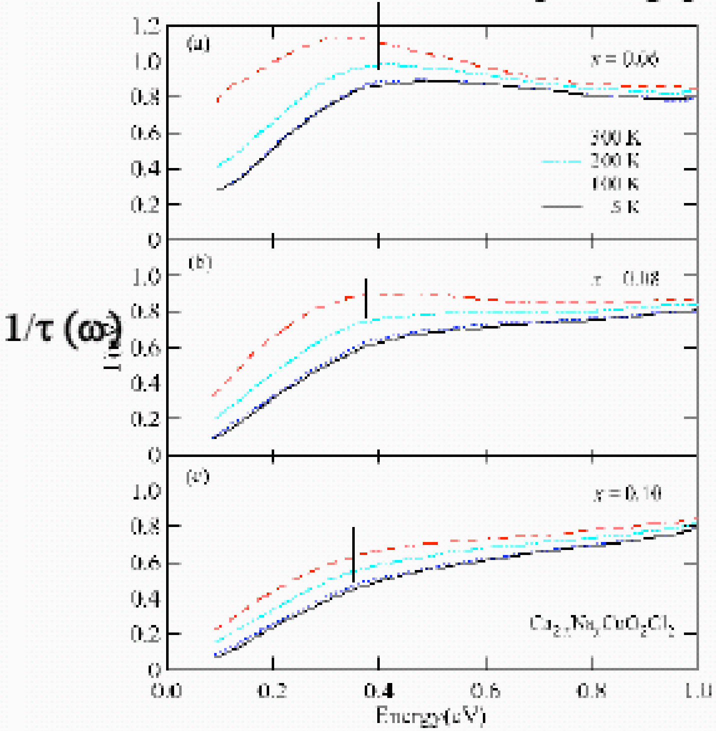
Two component

Drude + Mid IR absorption



One component "Generalized Drude"

"knee" = pseudogap signature



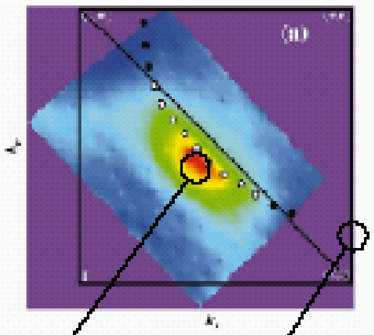
Drude-like nodal + (pseudo)gapped antinodal?

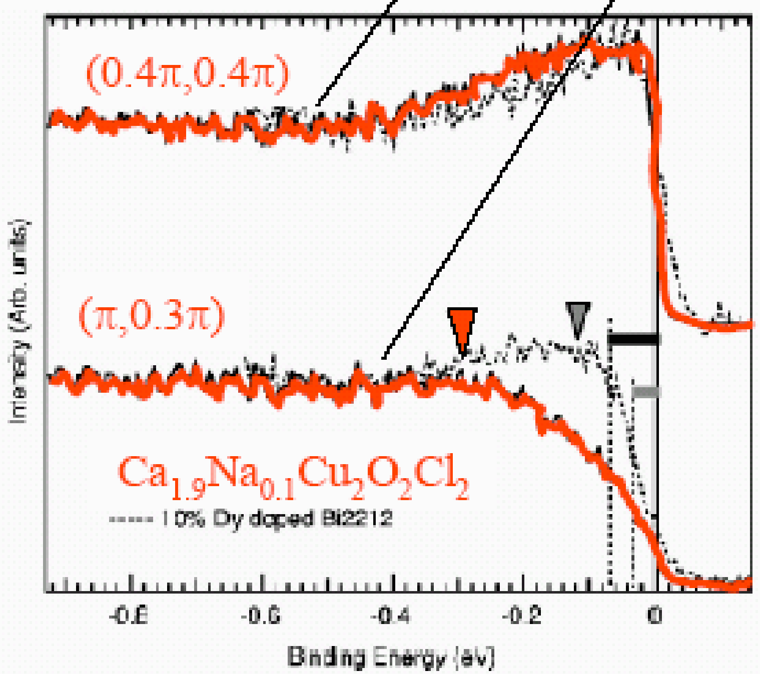
Softening of Mid-IR

all doped single crystals have pseudogap siganature 0.2-0.3 eV in optical conductivity

Large Pseudogap at antinodal region observed by APPES

Fermi arc





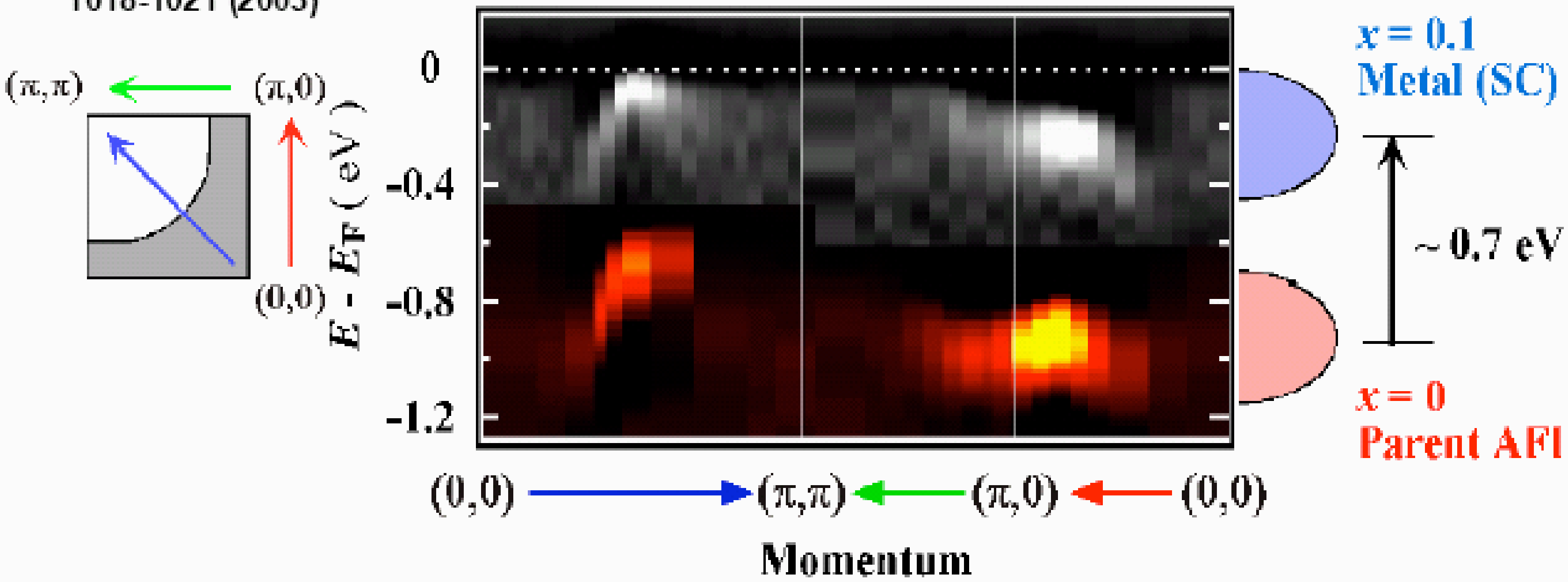
0.1-0.2 eV gap at antinodal region

Y.Kohsaka *et al*. JPSJ (2003):F. Ronning, *et al*., Phys. Rev. B 67, 165101 (2003).

Fingerprint of Mott insulator in metallic phase -Chemical Potential Shift

Y.Kohsaka *et al.* J. Phys. Soc. Jpn. 72, 1018-1021 (2003)

ARPES With Z.X.Shen (Stanford)



Fingerprints of the parent AFI

(1) Shadow Band near (π/2, π/2)

(2) Large Pseudo Gap around (π,0)

gap originates from d-wave dispersion of Mott gap

Real space image of "pseudo-gapped" $Ca_{1.90}Na_{0.10}CuO_2Cl_2$

Y. Kohsaka et al., PRL in press

(100) square lattice with 3.9A spacing, cleaved surface:ionic CaCl layer

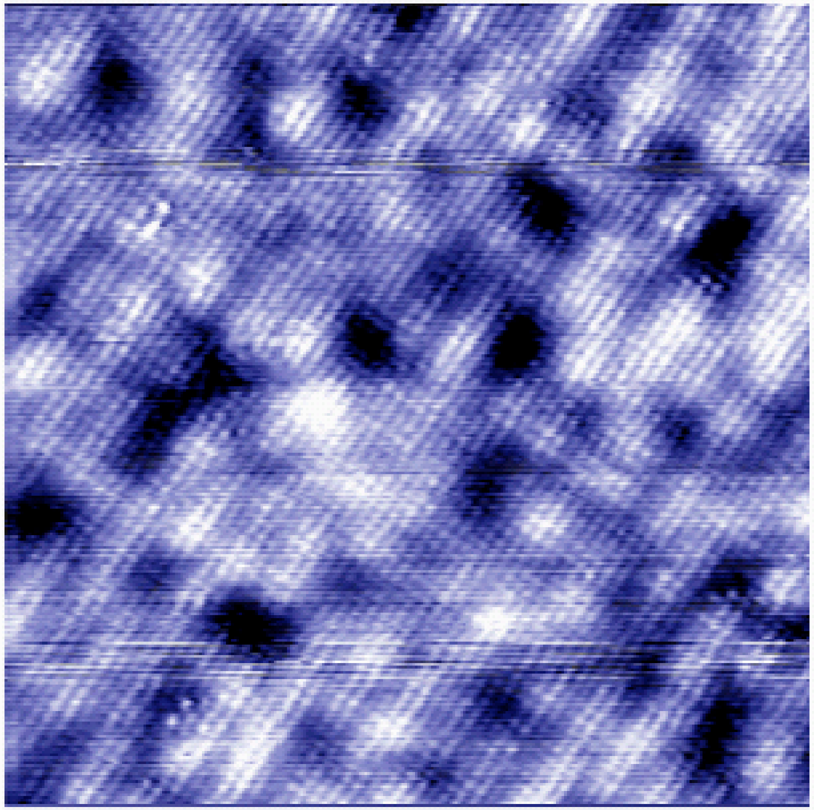
$P \sim 10^{-11}$ Torr, $T = 7$K

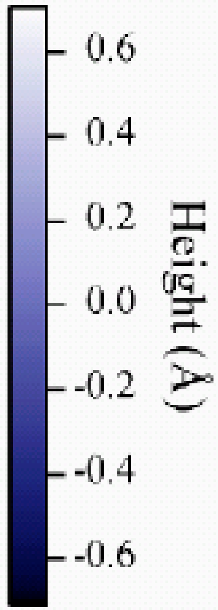
(010)

$x \sim 0.10$

Sample bias voltage: V_s = -250mV

Tunneling current: $I_t \sim$ 0.01nA





nano-scale structure with preferred orientation

- bright rivers or patches with ~4a width along (100) "Kishimen" (Japanese fettuccine)

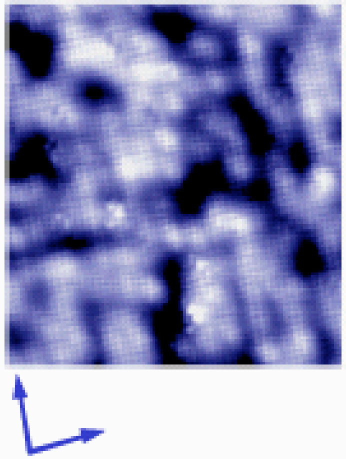
not topographic effect but LDOS variation ("electronic" heterogeneity)

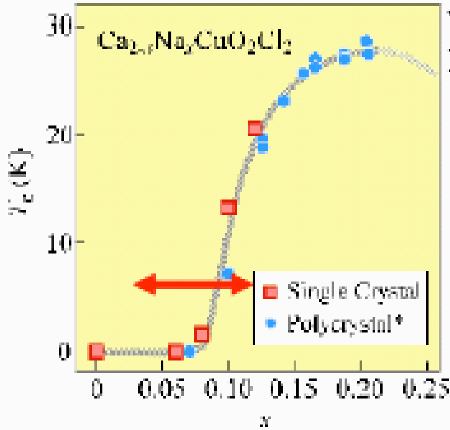
Doping dependence of real space images

Why organized?

Why screening so poor?

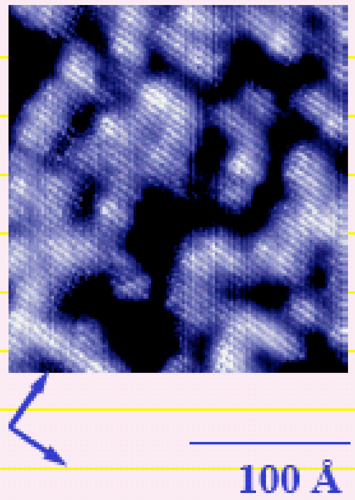
x = 0.08 (S-I transition)





Y. Kohsaka et al., PRL in press

x = 0.06 (insulator)

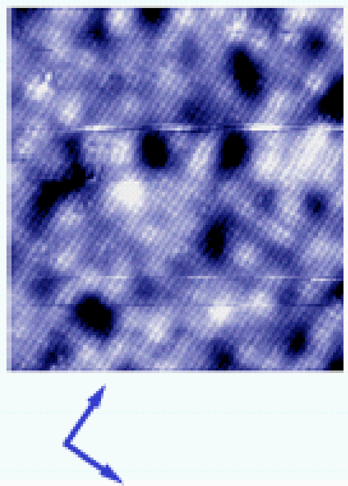


Kishimen robust

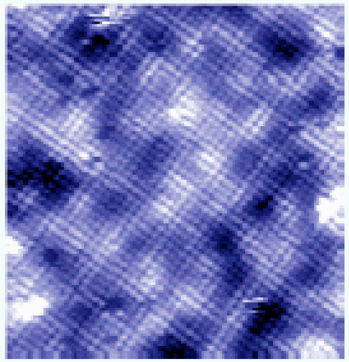
but contrast becomes less pronounced with x

Real space physics
Important for M-I

x = 0.10 (T_c = 13 K)



x=0.12 (Tc=21 K)



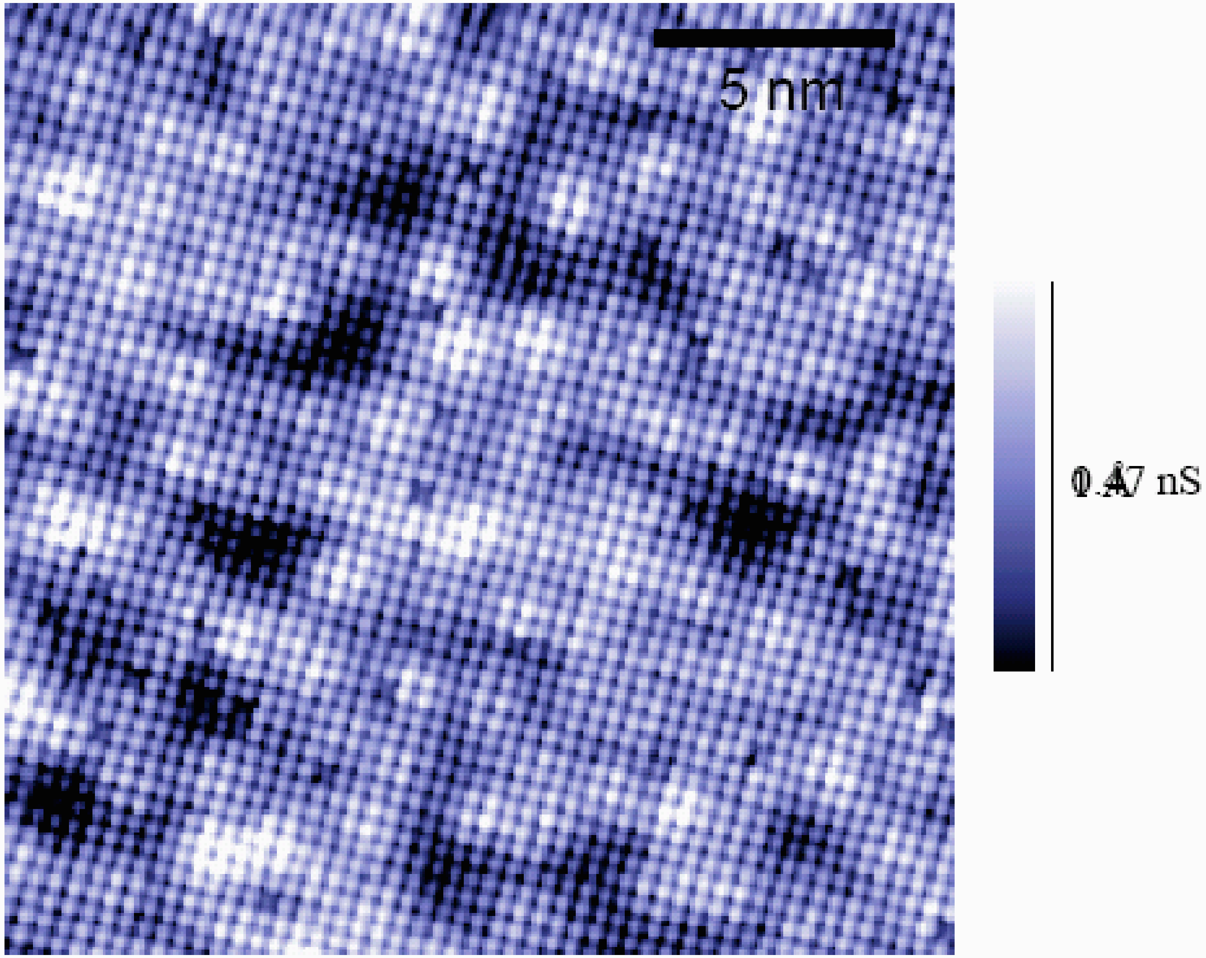
Checkerboard LDOS modulation in $Ca_{2-x}Na_xCuO_2Cl_2$ (x=0.1)

Hanaguri et al., Nature in press

Topograph / dI/dV @24mV

$T < 250$ mK

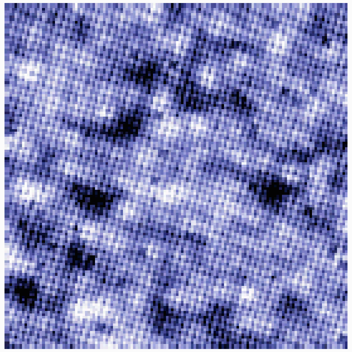
$V_{sample} = 200$ mV
$I_t = 100$ pA / 500 pA



“4a x 4a” checkerboards in $Ca_{2-x}Na_xCuO_2Cl_2$ (x=0.1)

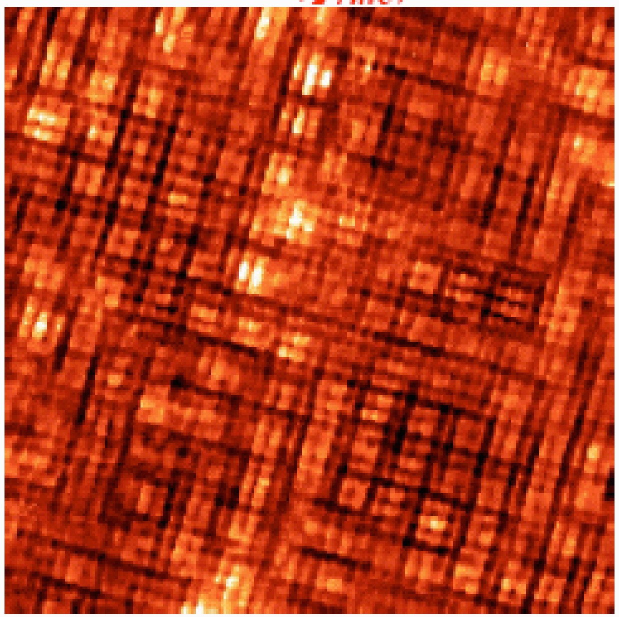
Hanaguri et al., Nature in press

Topograph

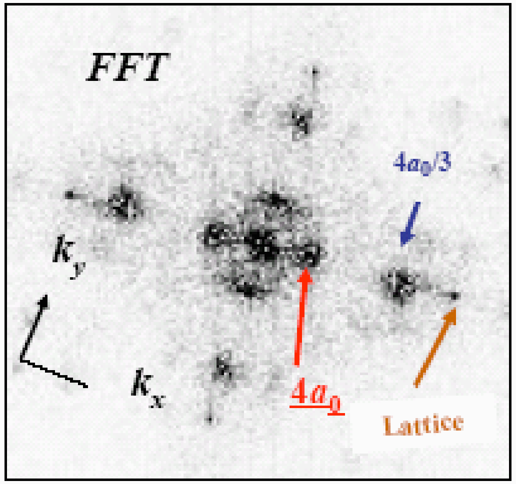


Relative change of normalized LDOS at a specific V

$dI/dV|_{+24meV}$



periodicity: 4a x 4a



canceled by normalization in dI/dV

Kishimen =
“Checker board” + nano-scale variation of potential
(likely impurity)

"4a x 4a" checkerboards in $Ca_{2-x}Na_xCuO_2Cl_2$ (x=0.1)

Hanaguri et al., Nature in press

Topograph

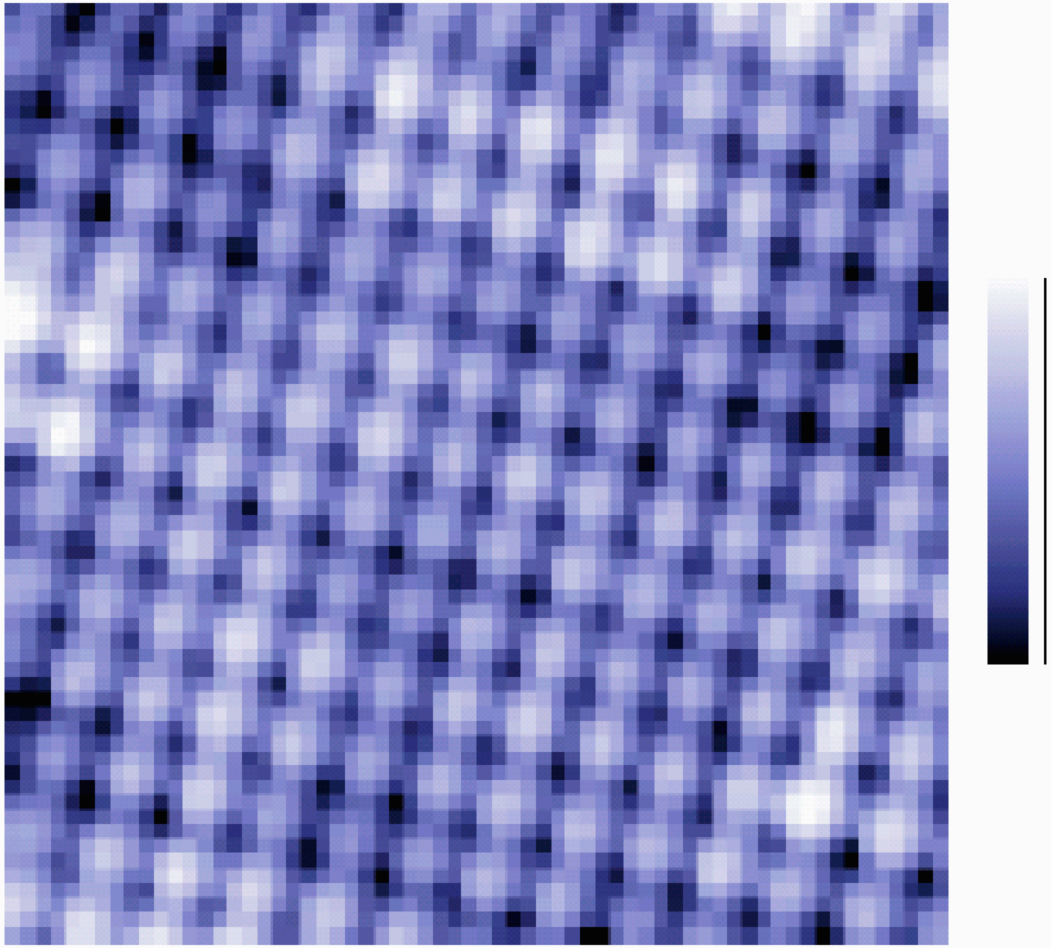
dI/dV_{25mV}

$T < 250$ mK

$V_{sample} = 200$ mV

$I_t = 100$ pA

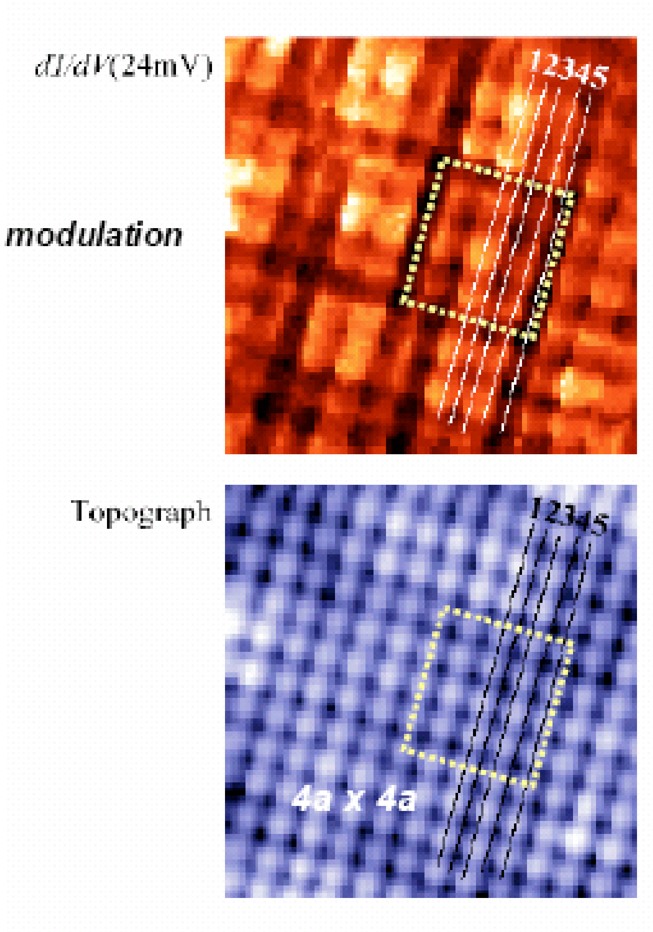
$I_t = 5$ pA

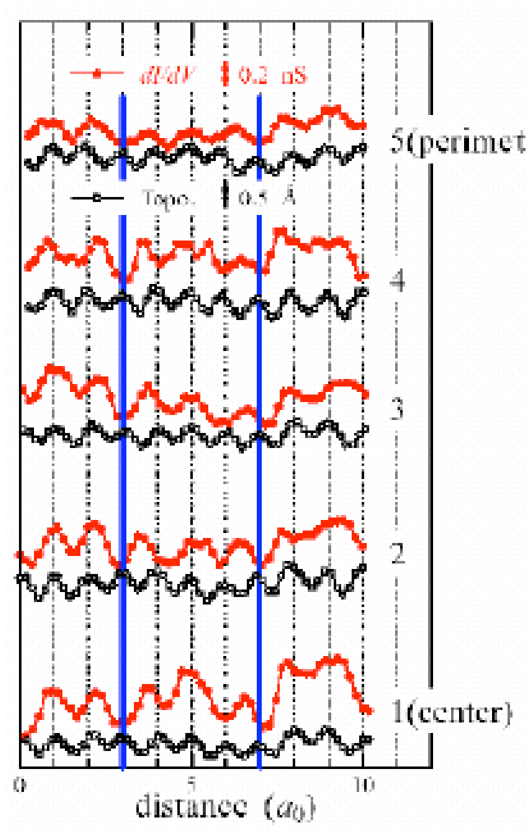


4a x 4a checkerboard CDW formation in $Ca_{2-x}Na_xCuO_2Cl_2$ (x=0.1)

Hanaguri et al., Nature in press

LDOS modulation

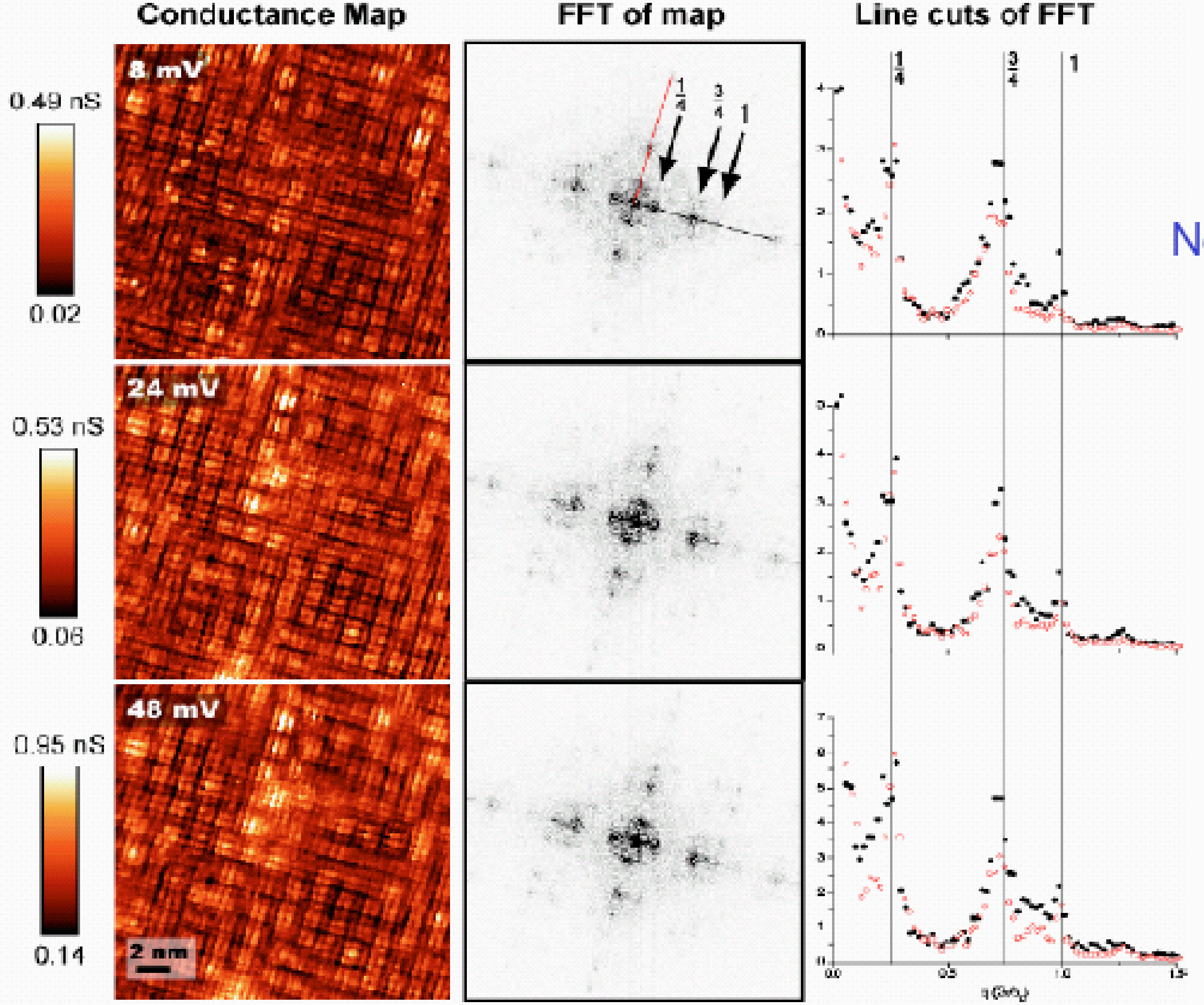




3LDOS peaks for 4 a_0

—— *4/3a_0 in FFT*

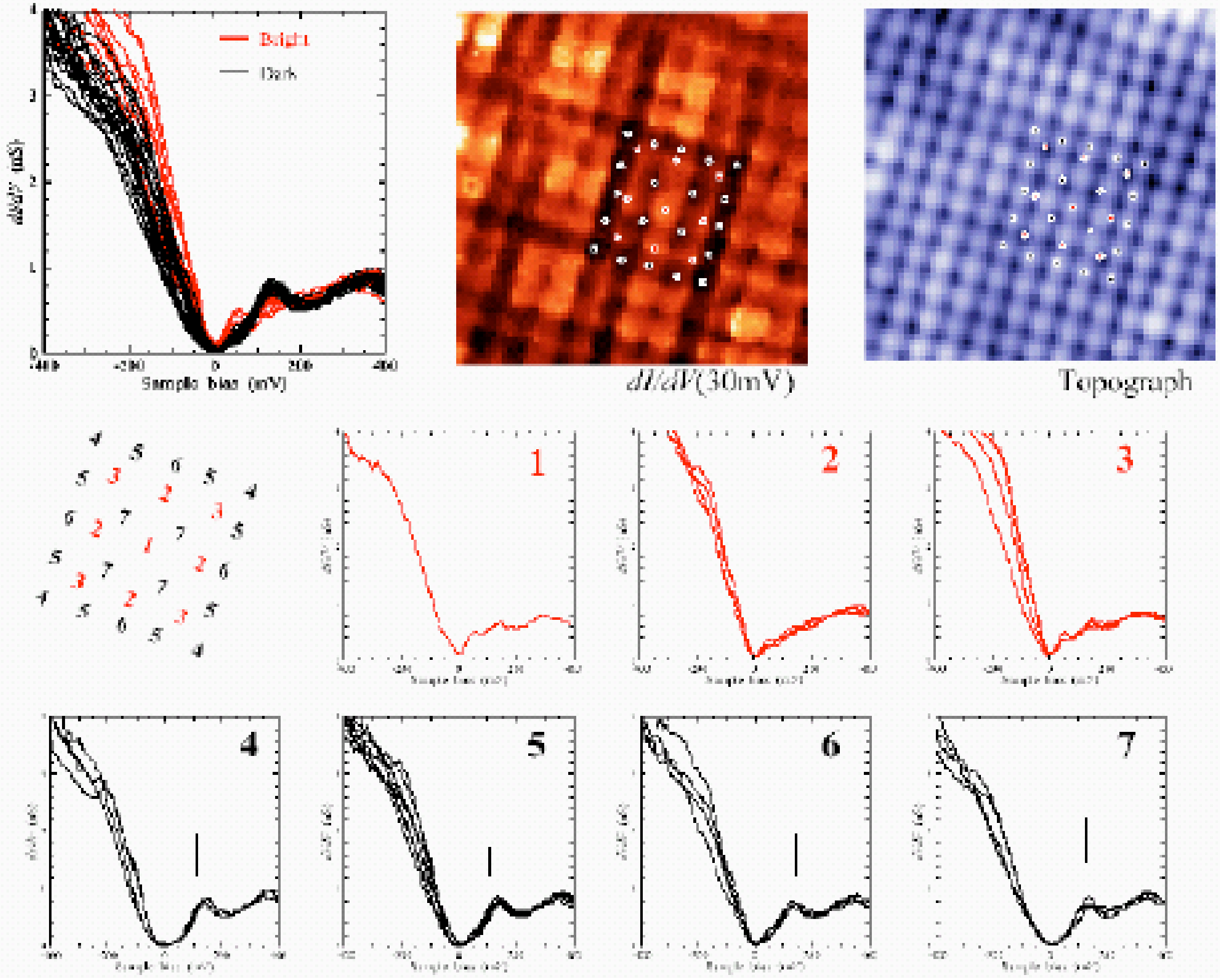
Energy dependence of periodicity



Non-dispersive

T. Hanaguri *et al.*, Submitted to *Nature*

Energy scale for 4a x 4a CDW – 100-200 meV

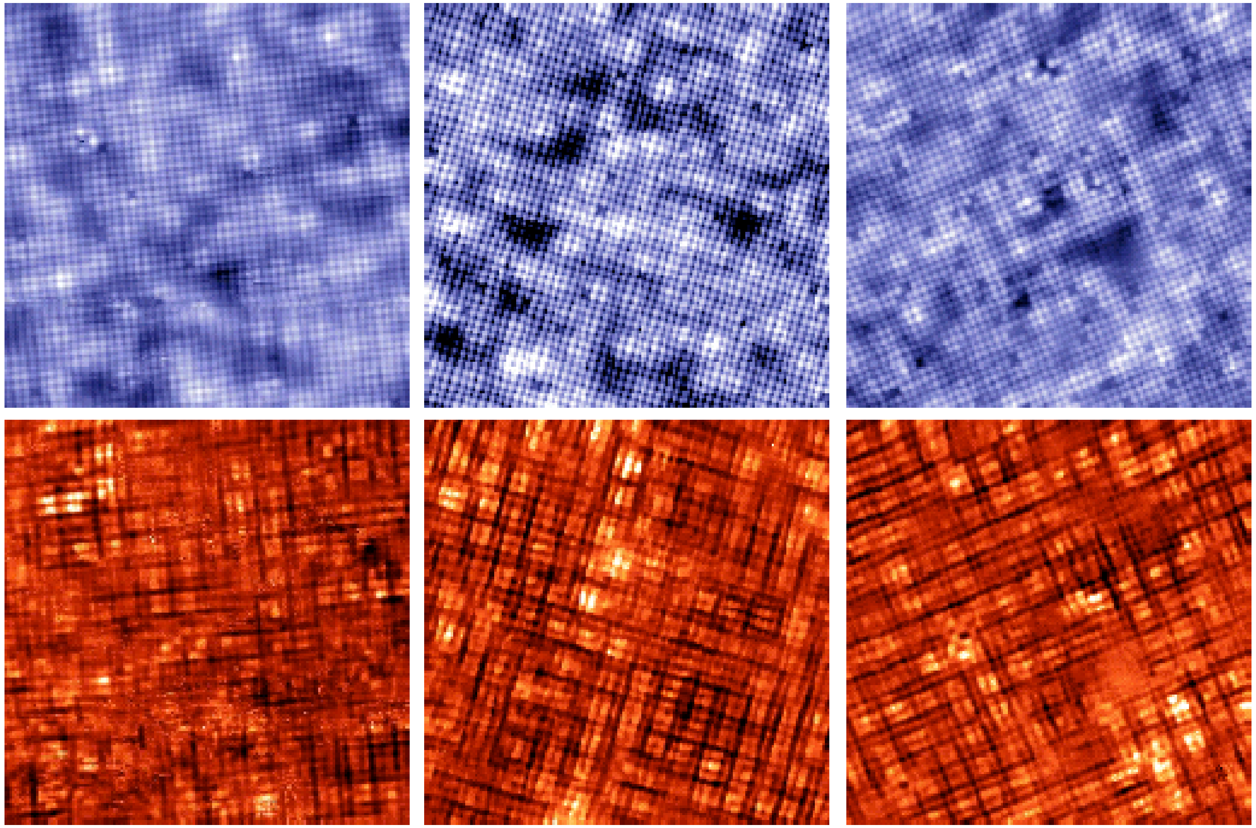


Checkerboard robust against doping

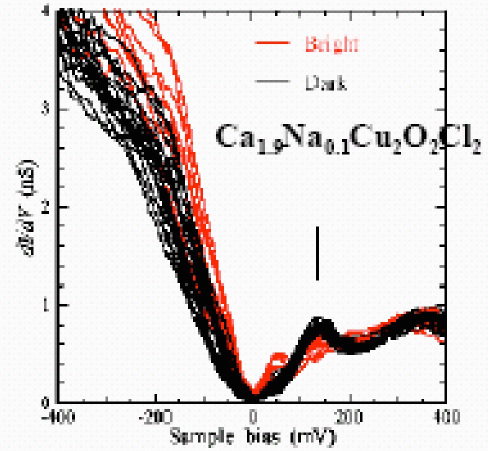
$x \sim 0.08$ (MIT) | $x \sim 0.10$ (SC) | $x \sim 0.12$ (SC)

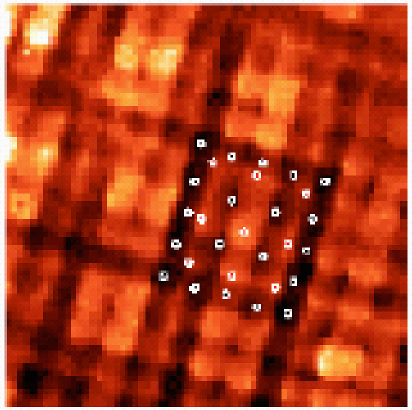
Topo.

$dI/dV|_{24mV}$



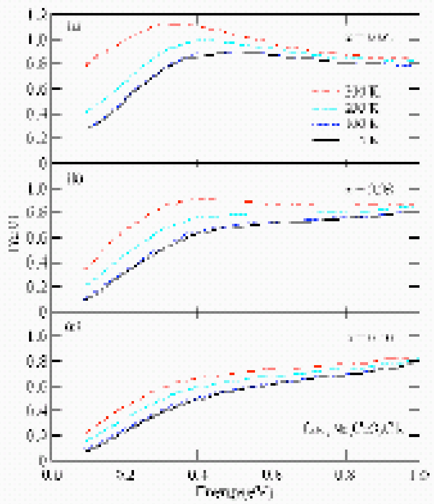
Checkerboard responsible for pseudogap ?
- comparable E - scale





dI/dV(30mV)

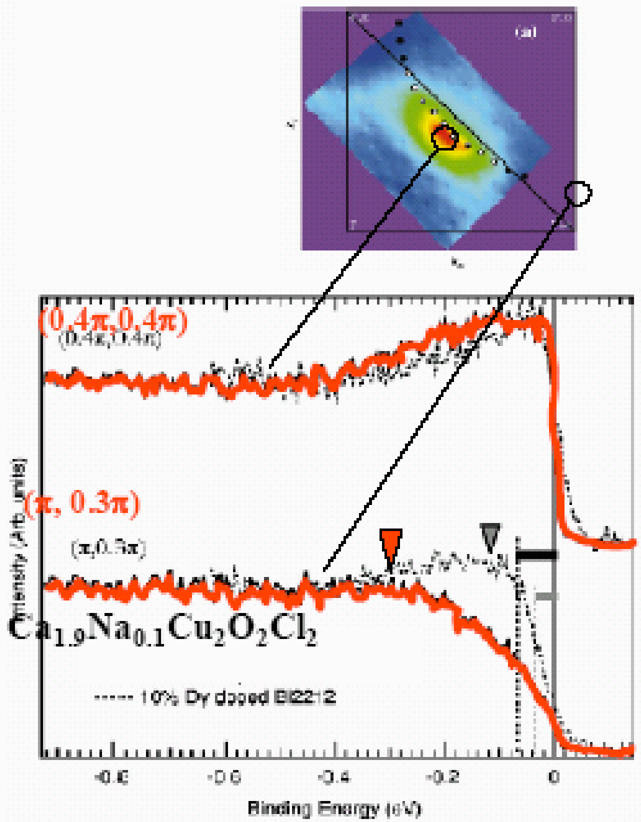
LDOS modulation on 100-200meV scale



σ(ω)

ARPES

pseudo gap of
0.1 -0.2 eV

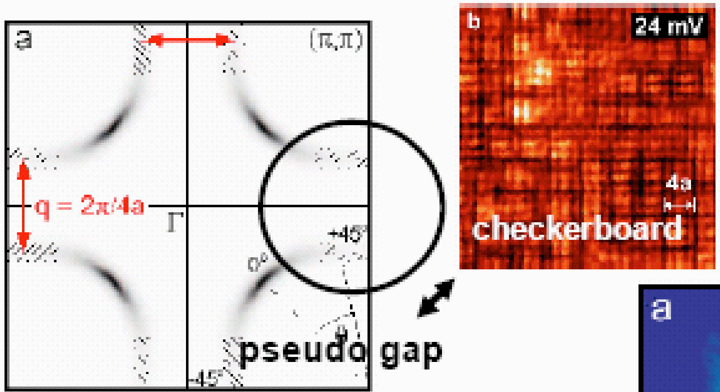


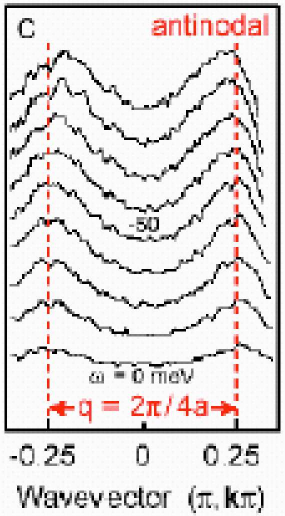
F. Ronning, *et al.*, Phys. Rev. B 67, 165101 (2003).

FS nesting in anti-nodal region gives 4a periodicity

Kyle Shen & Z.X.Shen

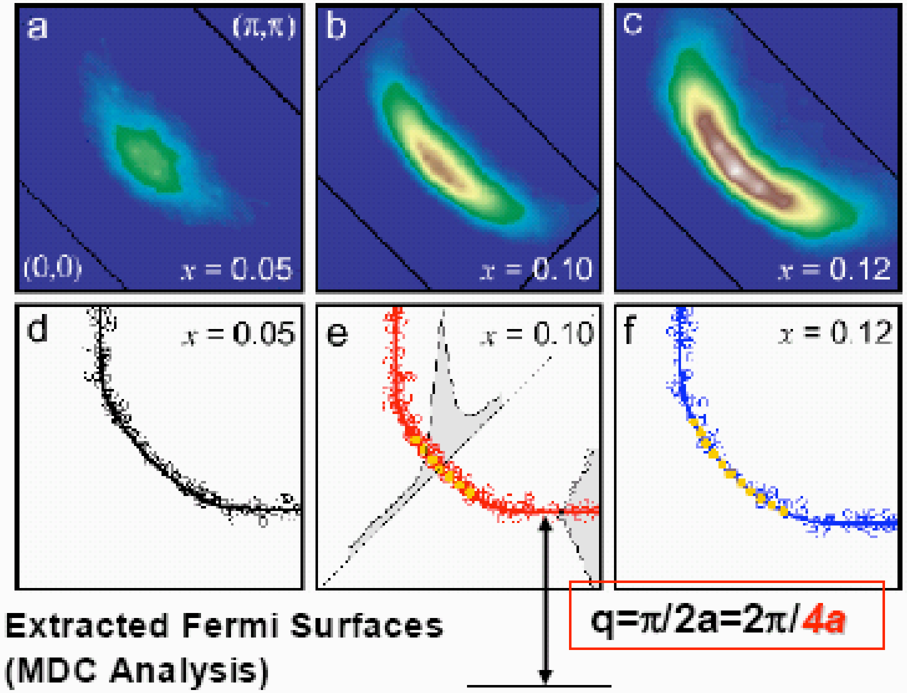
Support for the link between the checkerboard and antinodal pseudogap





MDC Analysis

Spectral Weight Map (+/- 10 meV)



Extracted Fermi Surfaces (MDC Analysis)

metallicity maintained by nodal QP

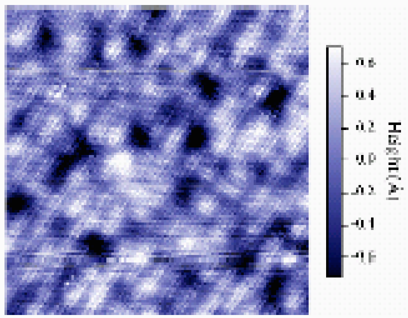
Picture emerged: STM/STS + ARPES

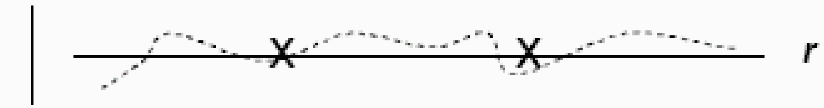
- 4a x 4a checkerboard likely (hidden) order behind pseudogap formed around $(\pi,0)$

- 4a periodicity originates from FS nesting around $(\pi,0)$

- Nodal FS arc appears to protect antinodal nesting **checkerboard stable over a wide concentration range**

so homogeneous on inhomogeneous background - "Kishimen"





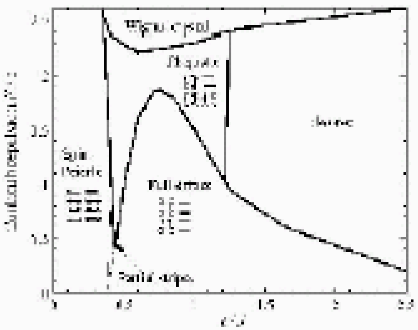
–Connection to SC gap? previous talk

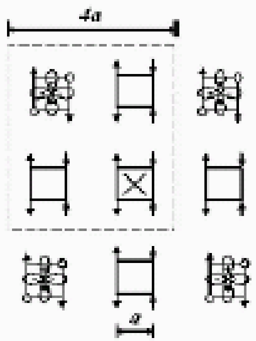
possible scenario for chaecerboard: charge ordering (Wigner crystallization)

- bulk compositions close to "1/8" = 0.125

  Charge ordering at "X=1/8" = 2 holes / 16 (4x4) sites (possibly 1/16) ?

- Wigner crystallization of holes or hole pairs proposed





M. Vojta, PRB **66**, 104505 (2002).
J. Zaanen & O. Gunnarsson PRB **40**, 7391 (1989).
H.-D. Chen *et al.*, PRL **89** 137004 (2002).
D.-H. Lee *et al.*, Preprint
*****

- link with FS nesting at antinodal region ??

  Can these picture give stable 4a nesting?

  importance of k-space (FS) physics (nodal vs. antinodal)

  real space and k-space pictures should be unified

FAQs:

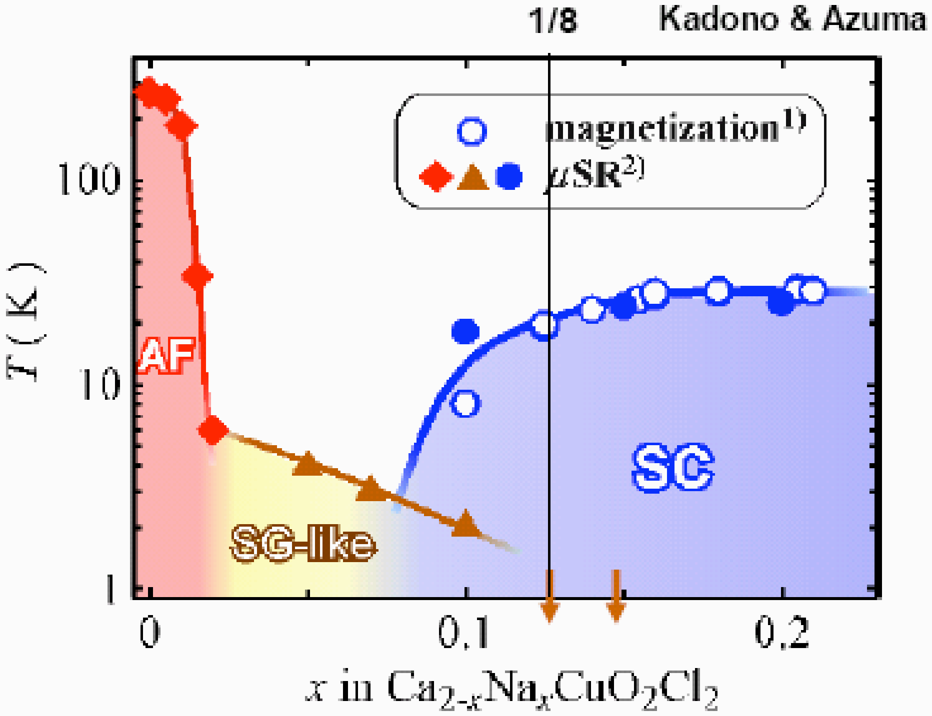
Charge ordering at "X=1/8" = 2 holes / 16 (4x4) sites (possibly 1/16) ??

-Any singularity at 1/8? *(real space ordering of "1/8" holes)*

within the available data we have, no pronounced anomaly in Tc and T_{SG} observed.

"1/8" anomaly very weak in the other systems except for LBCO

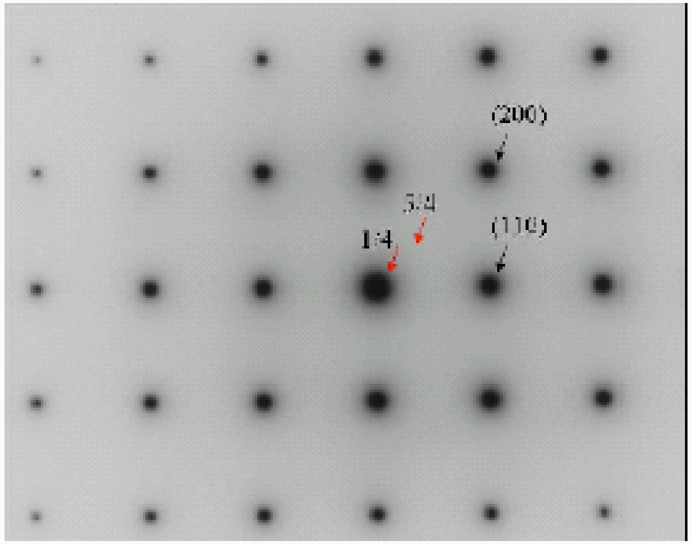
need detailed study



FAQs :

Bulk evidence? - Search for diffraction evidence for charge ordering

Electron Diffraction @ 30 K (with M. Uchida, NIMS)



- charge (lattice) modulation very weak

-x-ray diffraction using synchrotron source now in progress

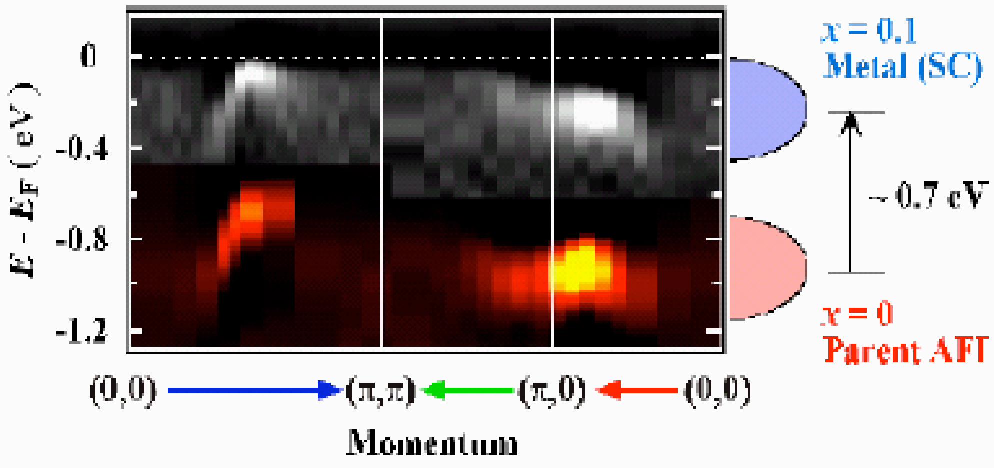
(La214 CO peak not in electron diffraction but in x-ray)

- NMR signal extremely broad around M-I and sharpens in SC phase (Zheng & Kitaoka, Osaka)

FAQs: Mottness vs Charge orderness

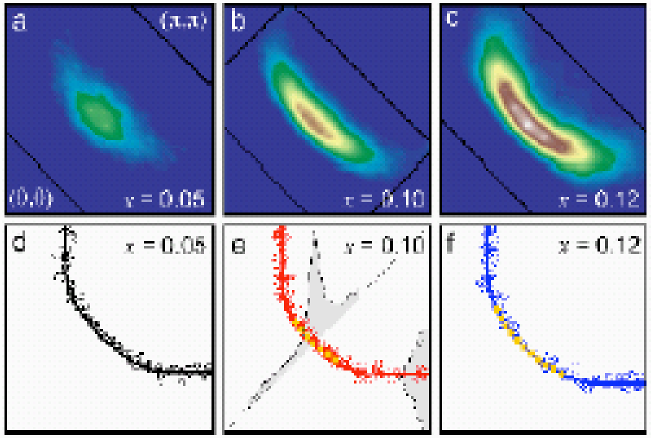
Mottness irrelvant to pseudogap?

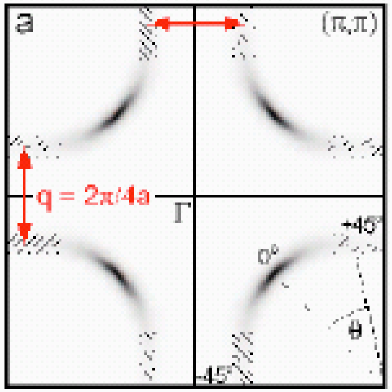
Chemical potential shift high energy phenomena??



Until last year

Mott gap with d-wave like dispersion





Charge ordering

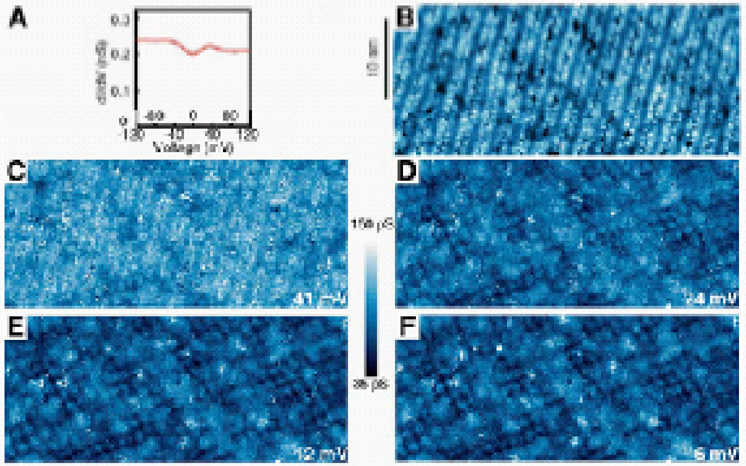
FS nesting at antinodal region

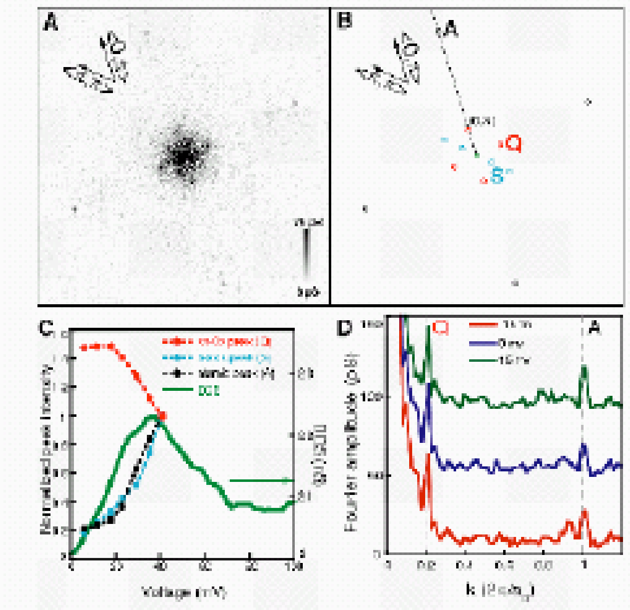
FAQs :

Universal among cuprates?

Vershinin, Yazdani et al. Bi in the high T pseudo gap state

dispersionless ~4.7 a self organization of electrons





Davis G (McElroy et al.)

underdoped Bi

not specific to oxychlorides

link between quasi-particle scattering and 4a checkeboard?

Summary

- $Ca_{2-x}Na_xCuO_2Cl_2$ as a key material for high-T_c physics

- Discovery of 4a x 4a checkerboard CDW

  Previously observed "Kishimen" is a superposition of checkerboard and nano-inhomogeneity

- E-scale of a few 100 meV suggests intimate link to the pseudo-gap physics

- Antinodal FS nesting gives 4a periodicity (ARPES)

- Bulk evidence for CDW not yet observed (exploration in progress)

- Evolution of antinodal CDW state into d-wave SC preventing or helping somehow?