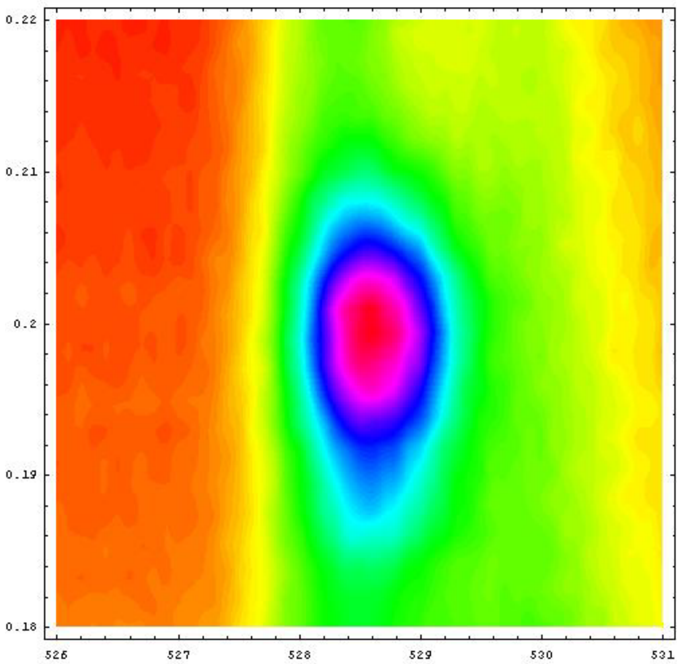
Quantum melting of the Wigner crystal in the "spin ladder" material $Sr_{14-x}Ca_xCu_{24}O_{41}$

And thoughts on RSXS, CES, etc…

Peter Abbamonte, *UIUC*



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Shin-ichi Uchida, *University of Tokyo*
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Adrian Gozar, *Brookhaven National Laboratory*
Paul Evans, *University of Wisconsin*
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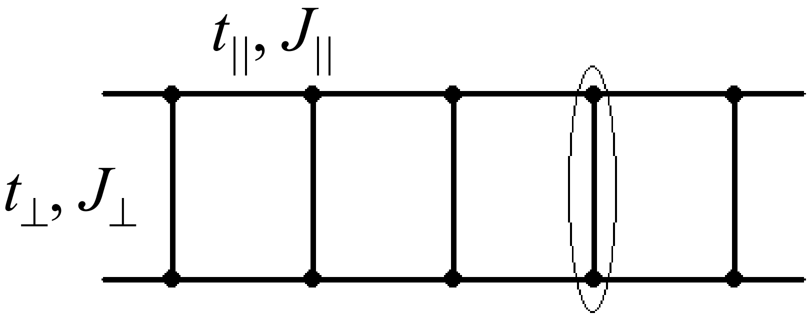
The “Spin Ladder”

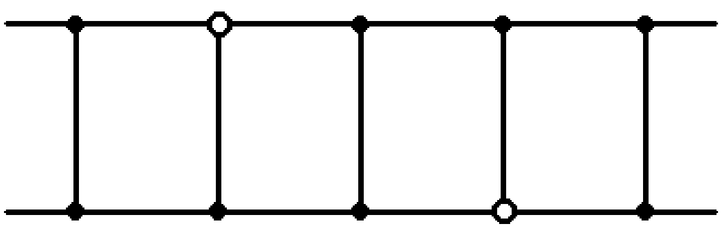
E. Dagotto, J. Riera, and D. Scalapino, *Phys. Rev. B*, **45**, 5744 (1992)
E. Dagotto and T. M. Rice, *Science*, **271**, 618 (1996)



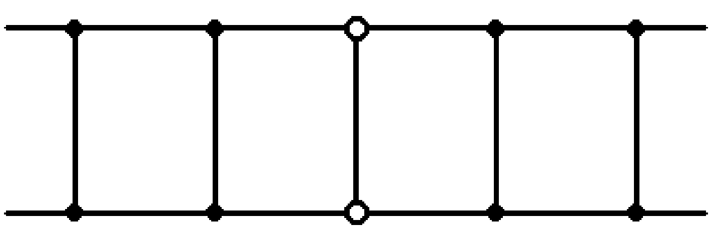
- Spin liquid (exponential decay in correlation)

$$J_{\perp} >> J_{||}$$

- Singlets across the rungs



- Doped hole breaks a singlet (costs $\sim J_{\perp}$)

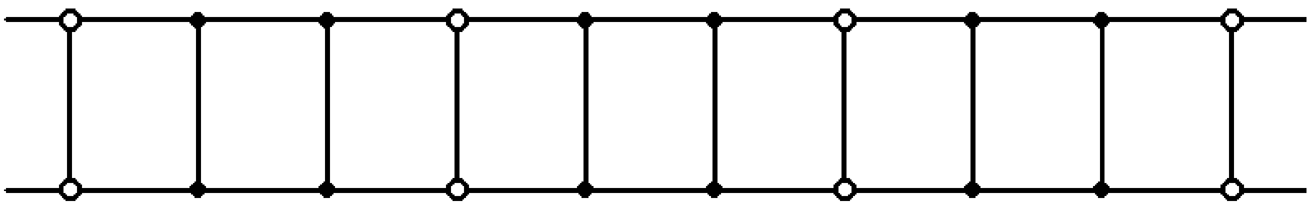


- Holes bind into pairs
- Superconductivity without phonons,
  $\Delta \sim d_{x2\text{-}y2}$ [M. Sigrist, *PRB*, **49**, 12058 (1994)]

Spin ladders

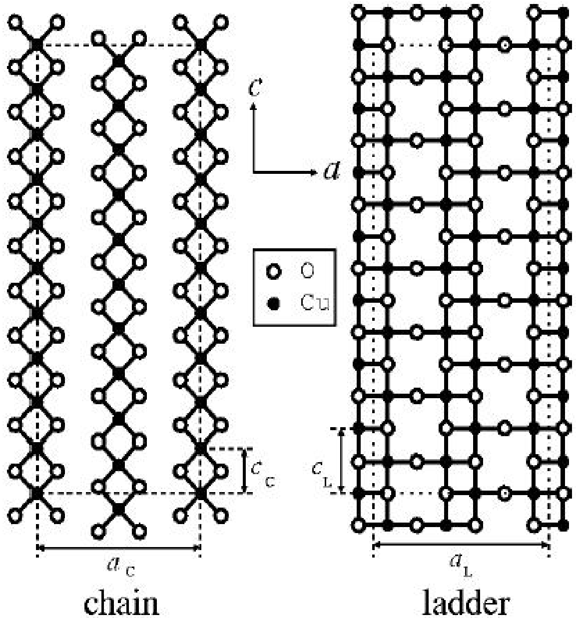
E. Dagotto, J. Riera, and D. Scalapino, *Phys. Rev. B*, **45**, 5744 (1992)
S. White, I. Affleck, and D. Scalapino, *Phys. Rev. B*, **65**, 165122 (2002)
S. Carr, A. Tsvelik, *Phys. Rev. B*, **65**, 195121 (2002)

Unstable to the formation of "charge density waves"



- δ rational $\Rightarrow$ holes "crystallize" into insulating CDW
- δ irrational $\Rightarrow$ metal with dynamic CDW correlations $\sim 1/|n-n'|^{K+\rho}$
- Reminiscent of : $\rightarrow$ *CDW vs. SC ground states in* TaS_2
  $\rightarrow$ *ordered stripes vs. SC in High* T_c

$Sr_{14-x}Ca_xCu_{24}O_{41}$

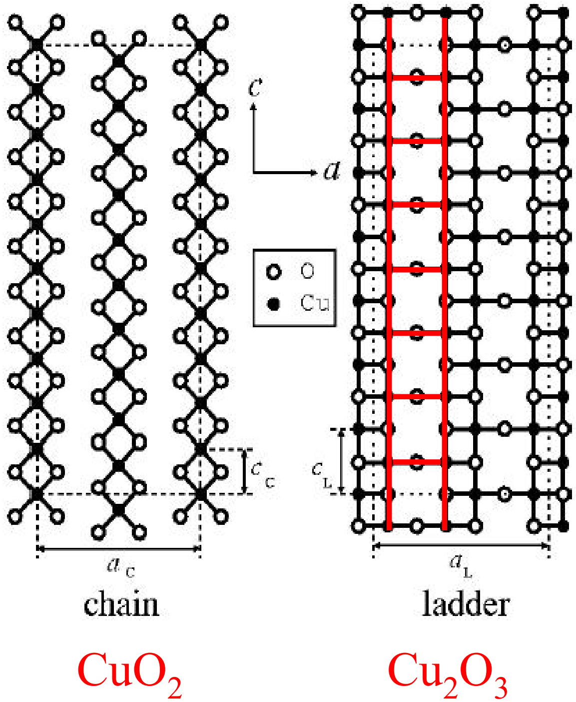


CuO_2 Cu_2O_3

- Incommensurate structure – no unit cell
- Sr^{2+} , $O^{2-} \Rightarrow Cu^{2.25+}$
  isoelectronic to perovskite cuprates
- 6 holes / formula unit
- ladder has larger electronegativity:
  5 holes on chain, 1 hole on ladder [1]
- $\delta_{chain} = 0.5$, $\delta_{ladder} = 0.071$
- Ca: holes move chain $\rightarrow$ ladder

[1]Osafune, *PRL*, **78**, 1980 (1997); Nücker, *PRB*, **62**, 14384 (2000)

$Sr_{14-x}Ca_xCu_{24}O_{41}$



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[1] Osafune, *PRL*, **78**, 1980 (1997); Nücker, *PRB*, **62**, 14384 (2000)

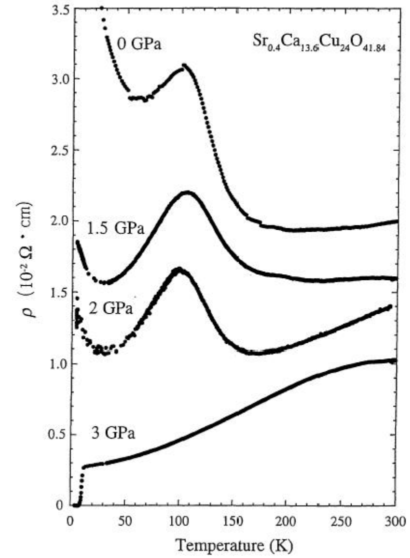
$Sr_{14-x}Ca_xCu_{24}O_{41}$

- **$x = 13.6 \Rightarrow$ superconductivity $T_c = 12$ K at $P = 3$ GPa [2]**

- **$x = 0 \Rightarrow$ insulating with a CDW [3]**

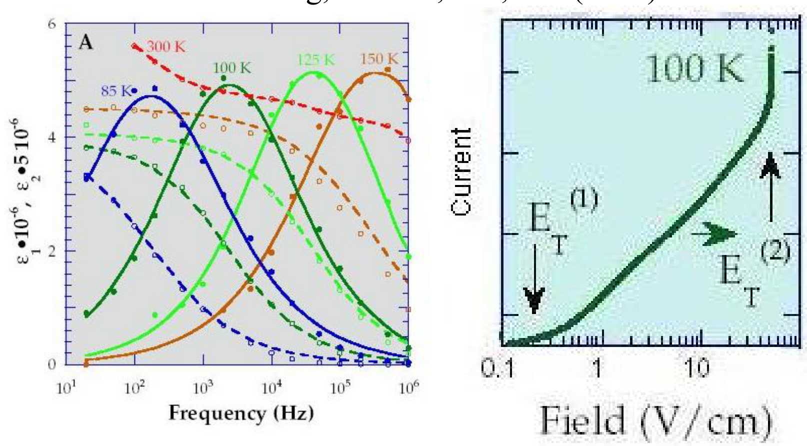
- **$m^* \sim 50$ ($10^3 - 10^4$ more typical) [4]**

- **Can tune between CDW and SC in one system**



M. Uehara, *et. al.*, *J. Phys. Soc. Jpn.*, **65** 2764 (1996)

[3]Blumberg, *Science*, **297**, 584 (2002)



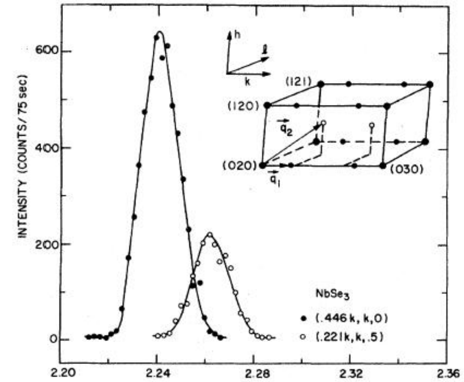
[2]Uehara, *J. Phys. Soc. Jap.*, **65**, 2764 (1996); Gorshunov, *PRB*, **66**, 60508 (2002); [4]Vuletić, *PRL*, **90**, 257002 (2003)

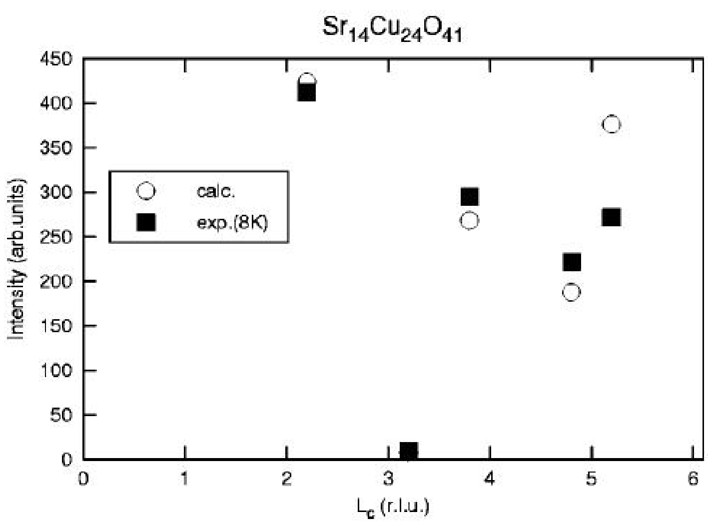
X-ray diffraction

R. M. Fleming, D. E. Moncton, and D. B. McWhan, *Phys. Rev. B*, **18**, 5560 (1978)

1. modulation wavelength (commensurate?)
2. coherence length
3. form factor (sinusoidal?)
4. Δ(T) (mean field or no?)

$NbSe_3$





T. Fukuda, *PRB*, **66**, 12104 (2002)
D. E. Cox, *PRB*, **57**, 10750 (1998)

l_c	L	(l,m)
1.5	15	(-2,5)
2.2	22	(-2,6)
3.2	32	(-1,6)
3.8	38	(1,4)
4.8	48	(2,4)
5.2	52	(1,6)

S. van Smaalen, *PRB*, **67**, 26101 (2003)
Etrillard, *Physica C*, **403**, 290 (2004)

Conclusion: no evidence for a structural CDW in $Sr_{14}Cu_{24}O_{41}$

Two types of CDWs

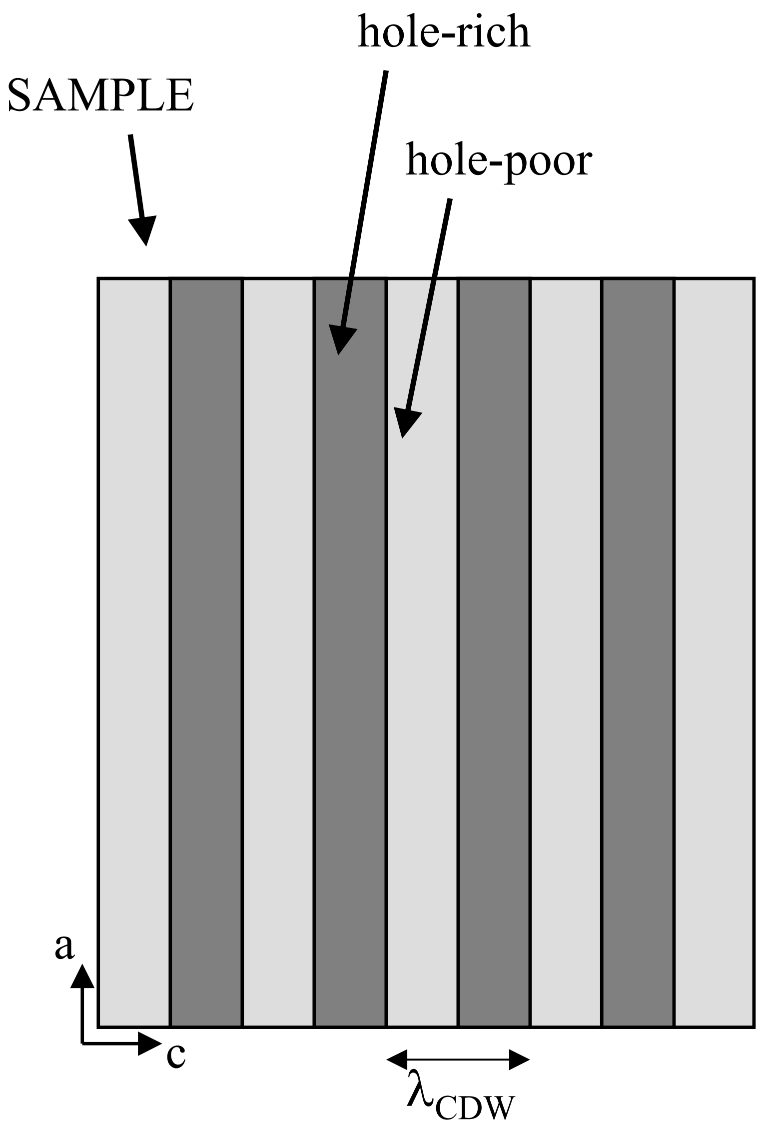
	Peierls CDW	***Wigner crystal*** [E. Wigner, *Phys. Rev.*, **46**, 1002 (1934)]
Examples	$NbSe_3$, $K_{0.3}MoO_3$	^4He surface, 2DEG, (Mott state!)
Mechanism	H_{ep}	Coulomb
Effective mass	$\sim 10^3 - 10^4$	???
Charge modulation	$\sim Z = 10^1 - 10^2$	~ 0.1
Cross section	$\sim Z^2 \sim 10^2 - 10^4$	$\sim 10^{-2}$
Bottom line	Easy to measure	Harder to measure by 10^{-5}

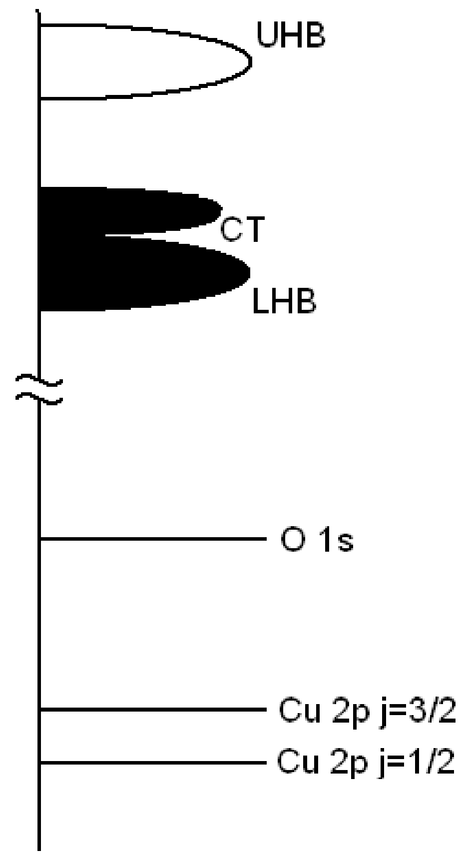
CDW predicted is *Wigner*, not Peierls (viz. "hole crystal")

Could $Sr_{14}Cu_{24}O_{41}$ contain a Wigner crystal?

Resonant soft x-ray scattering (RSXS)

P. Abbamonte, L. Venema, A. Rusydi, G. A. Sawatzky, G. Logvenov, and I. Bozovic, *Science*, **297**, 581 (2002)





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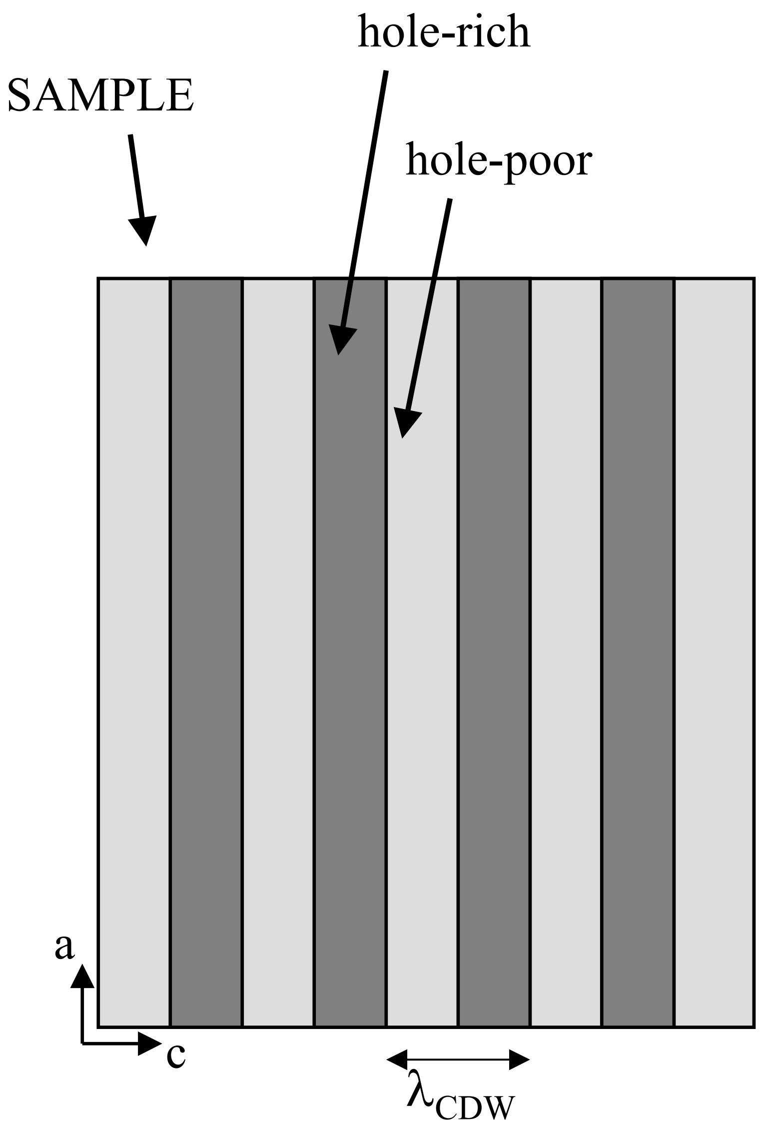

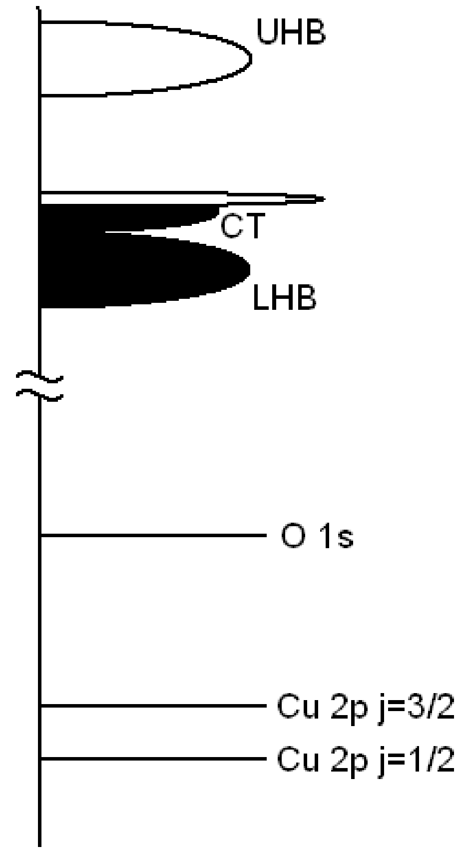

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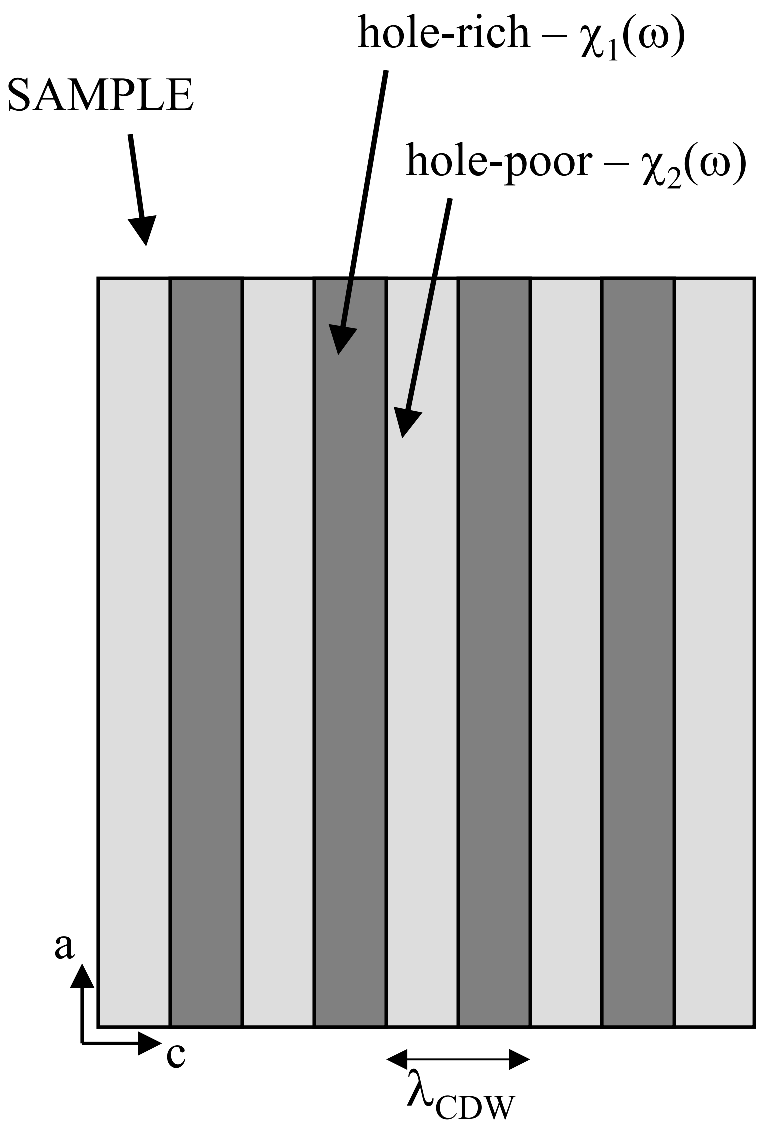
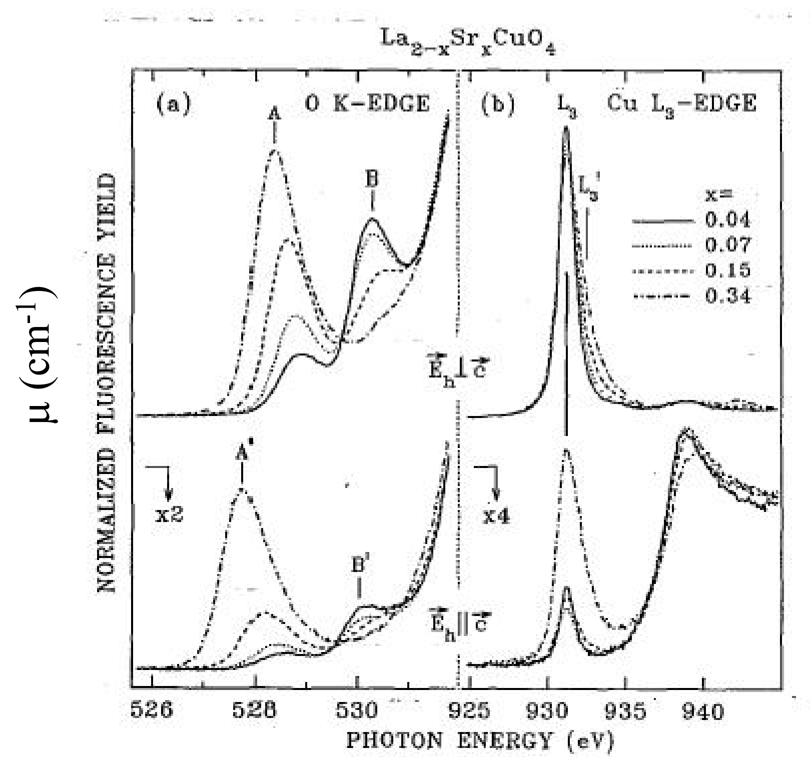


P. Abbamonte, L. Venema, A. Rusydi, G. A. Sawatzky, G. Logvenov, and I. Bozovic, *Science*, **297**, 581 (2002)



C. T. Chen, *et. al.*, PRL, **66**, 104 (1991)

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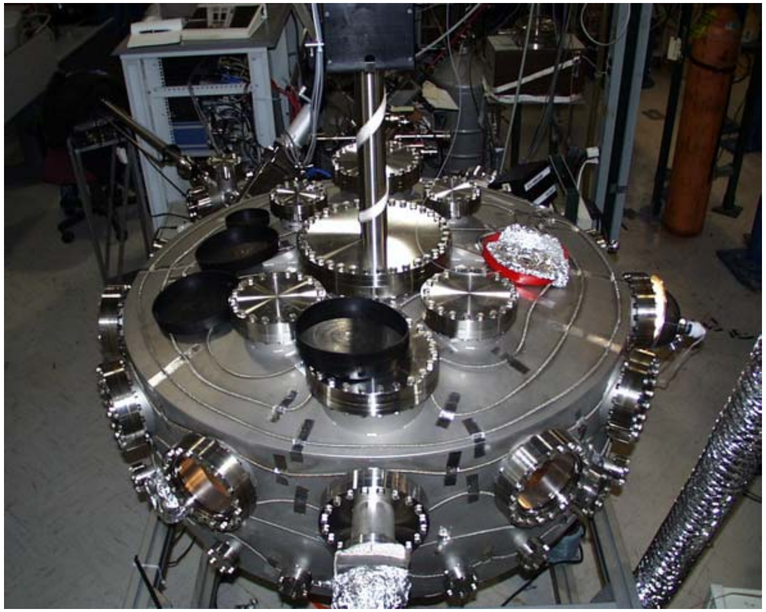
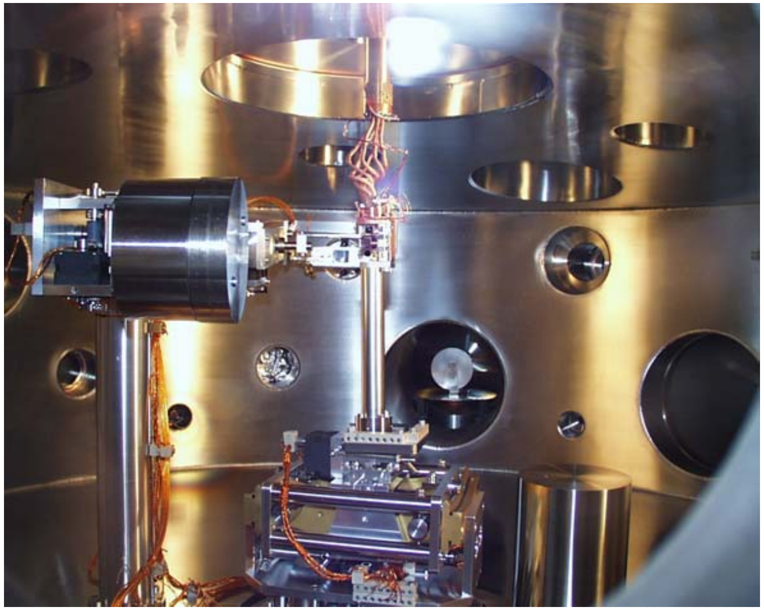




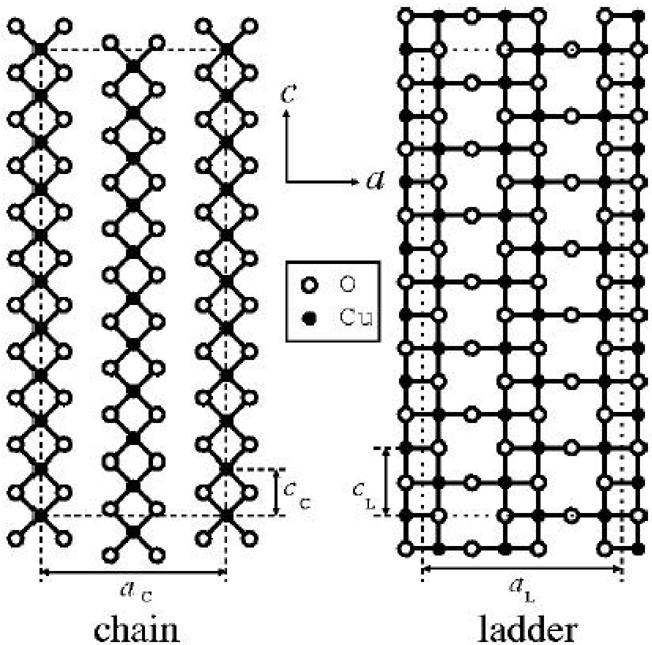
- 1.2 m vacuum chamber
- 4 circle geometry
- Multilayer fluorescence rejection
- Channeltron / Au·CsI cathode

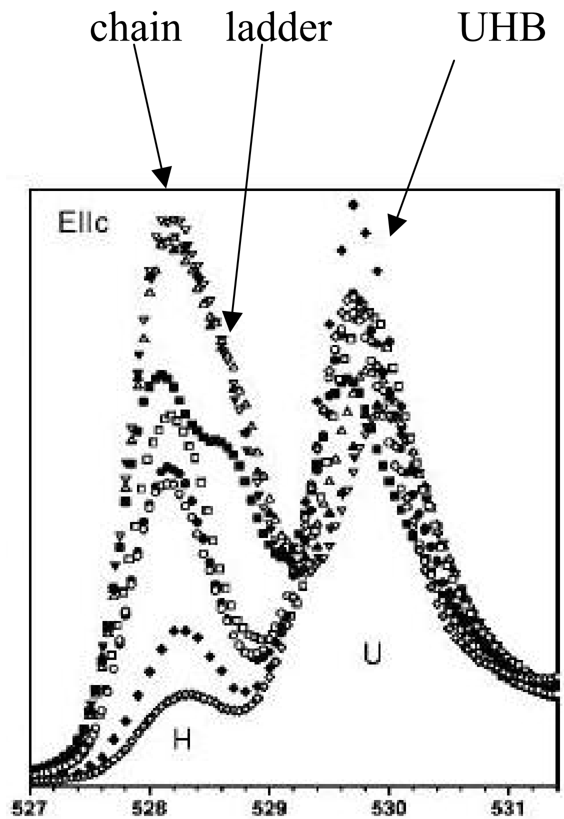
- He flow cryostat
- 5 Tesla magnet (vertical field)
- Base pressure = 5×10^{-10} mbar
- National Synchrotron Light Source, X1B

MOMENTUM-RESOLVED UNOCCUPIED DENSITY OF STATES

Similar to:
- *Inverse ARPES, but bulk-sensitive*
- *Fourier STM at V<0, but can do T dependence*

Edge structure in $Sr_{14-x}Ca_xCu_{24}O_{41}$





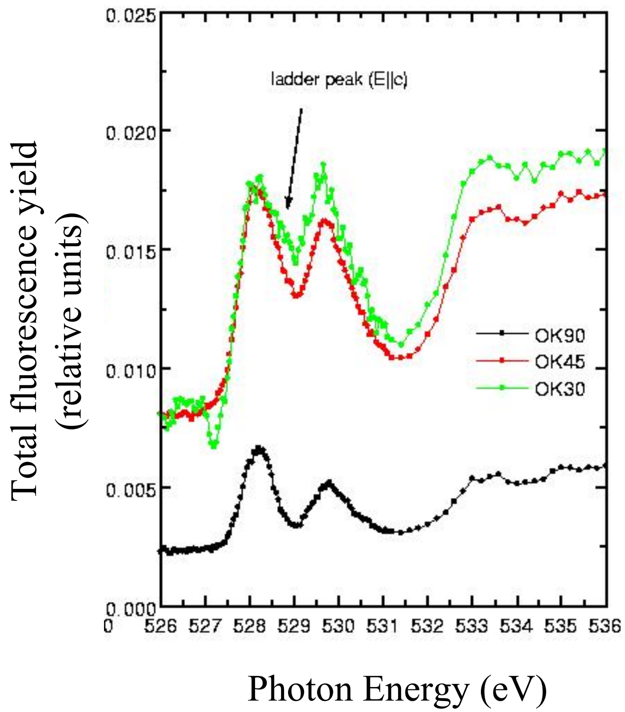
N. Nücker, *et. al*., *PRB*, **62**, 14384 (2000)

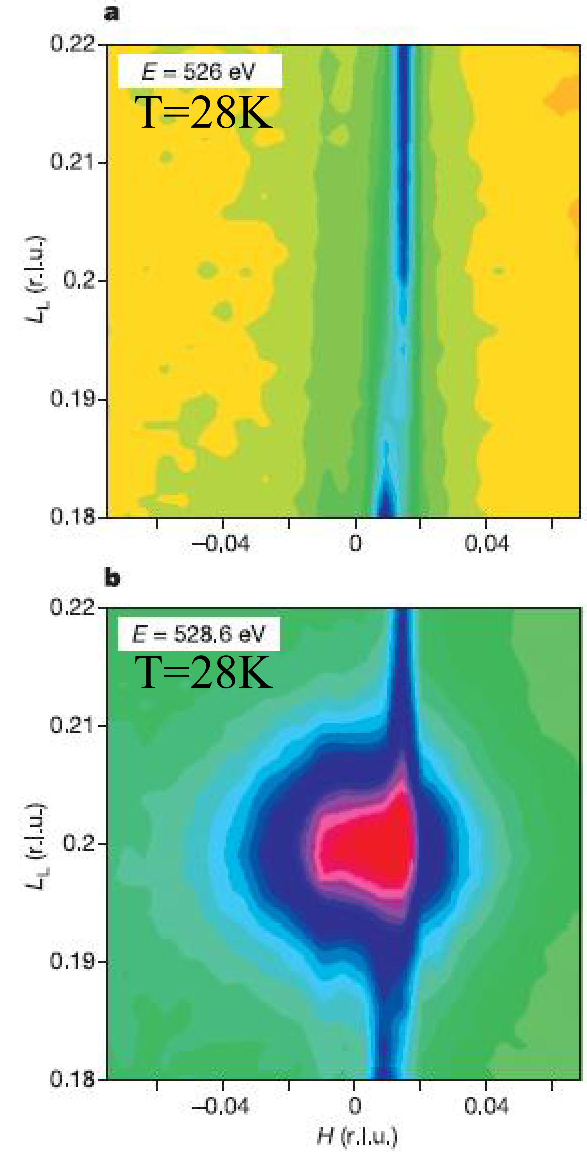
$$\mathbf{Q} = \left(\frac{2\pi}{a} H, \frac{2\pi}{b} K, \frac{2\pi}{c} L \right)$$

Examples: (1/2, 0, 0) ⇔ (π, 0)

(1/2, 1/2, 0) ⇔ (π, π)

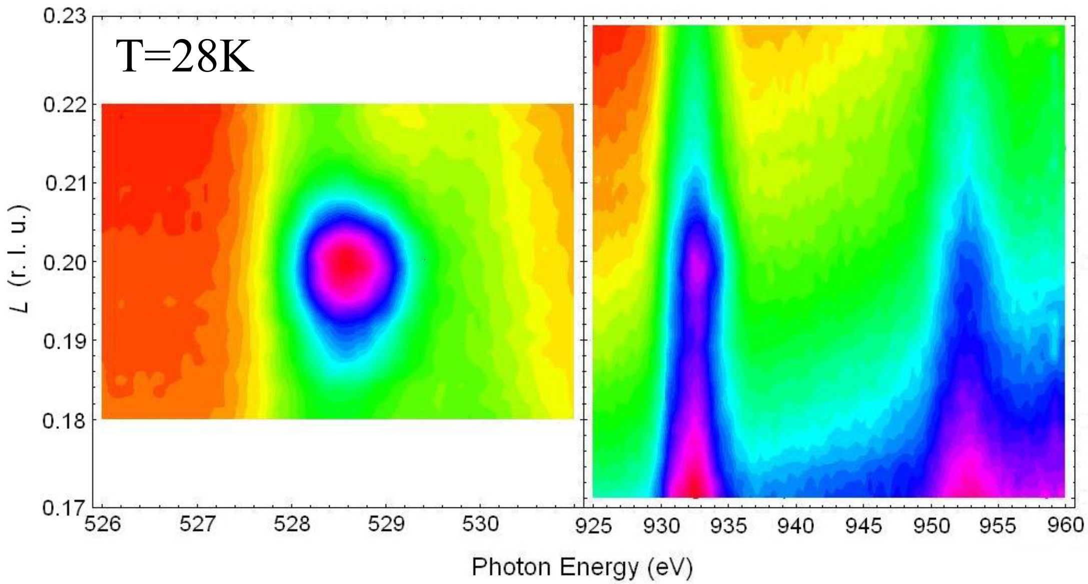
Valence modulation in $Sr_{14}Cu_{24}O_{41}$



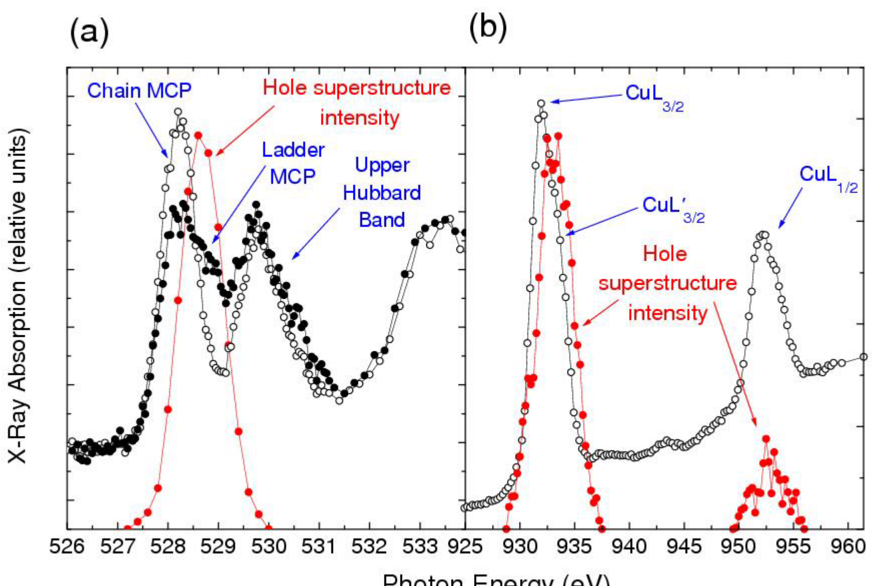


- $L = 0.200 \pm 0.009$ r. l. u. $\Rightarrow \lambda = 5.00 \pm 0.24\, c_L$.
- *Does not index to 27.3 Å unit cell.*
- $\xi_c = 255$ Å, $\xi_a = 274$ Å
- No measurable off-resonant signal $\Rightarrow$ mainly electronic (not structural) phenomenon

Resonance properties



- Disappears of O_K prepeak – *cannot be structural*
- Visible at Cu$L_{2,3}$ – still at L=0.2
- Coherent, bulk phenomenon
- No harmonic at L=0.4 – sinusoidal

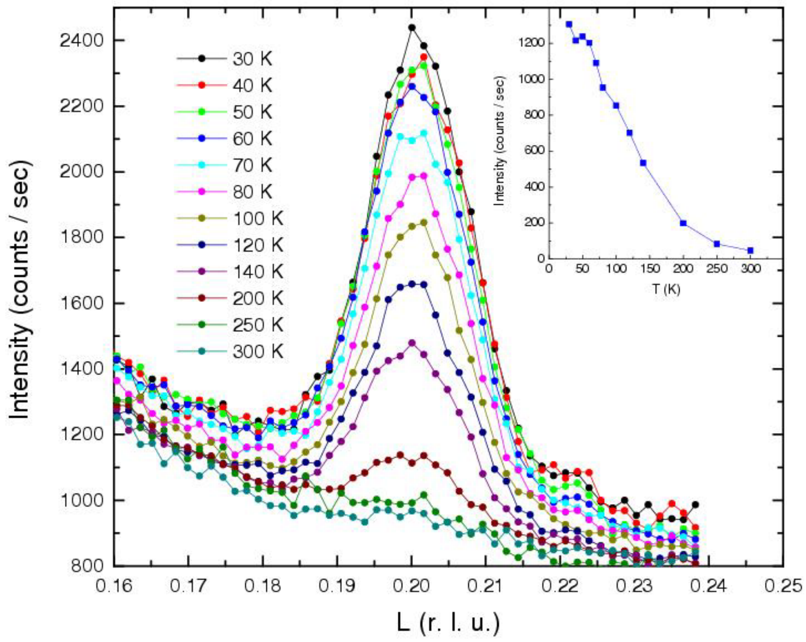


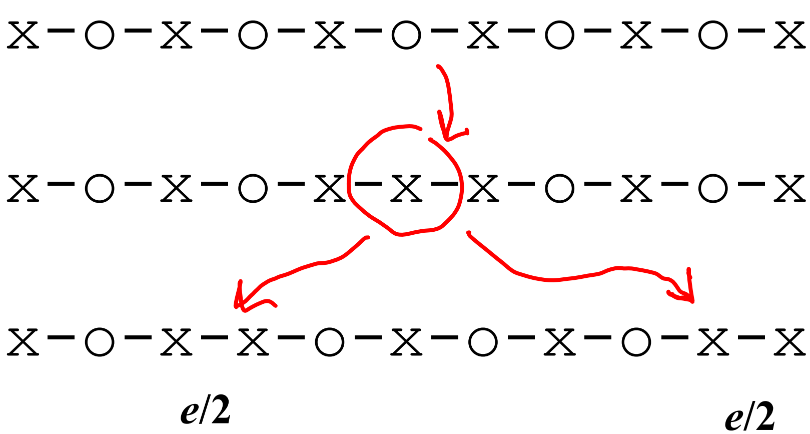
- Resonates *only* with ladder feature
- Resonates at CuL_3', not L_3 (just electrostatic)

Seems to contain a Wigner crystal

P. Abbamonte, A. Rusydi, *et. al.*, *Nature*, **431**, 1078 (2004)

Discommensuration and "Solitons"

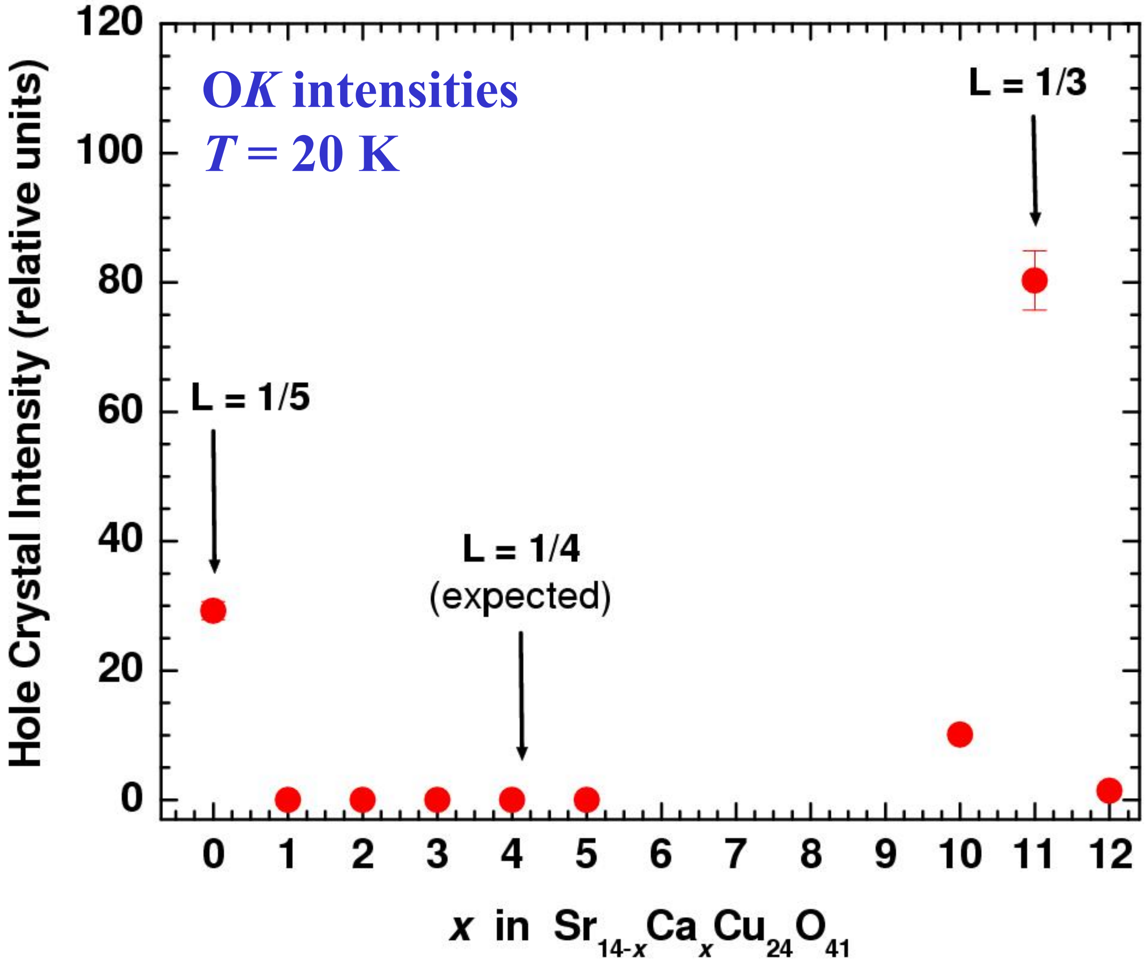




Hubbard, *PRB*, **17**, 494 (1978)
Su, *PRL*, **43**, 1698 (1979)
M. J. Rice, *Phys. Lett.*, **71A**, 152 (1979)

Vary the Ca

Evolution with carrier density



Forms only on rational fractions.

Interpolate for 1/4:

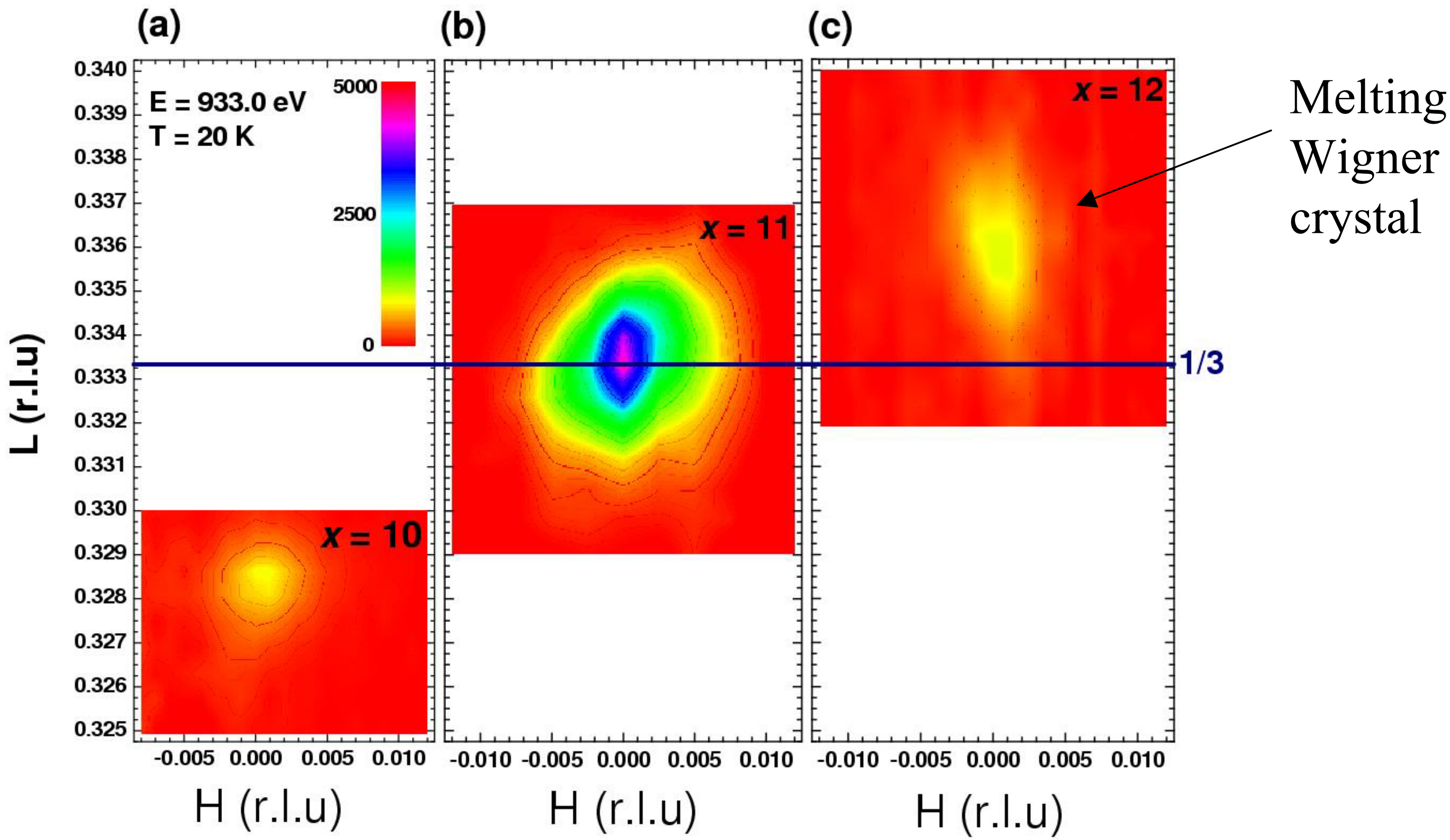
$$L(x) = 1/5 + 2x / 165$$

$$x(1/4) = 4.125$$

$$\Delta L = 2\ \Delta x/165 = 0.013$$

$$R_c \sim 1/\Delta L = 77\ c_L$$

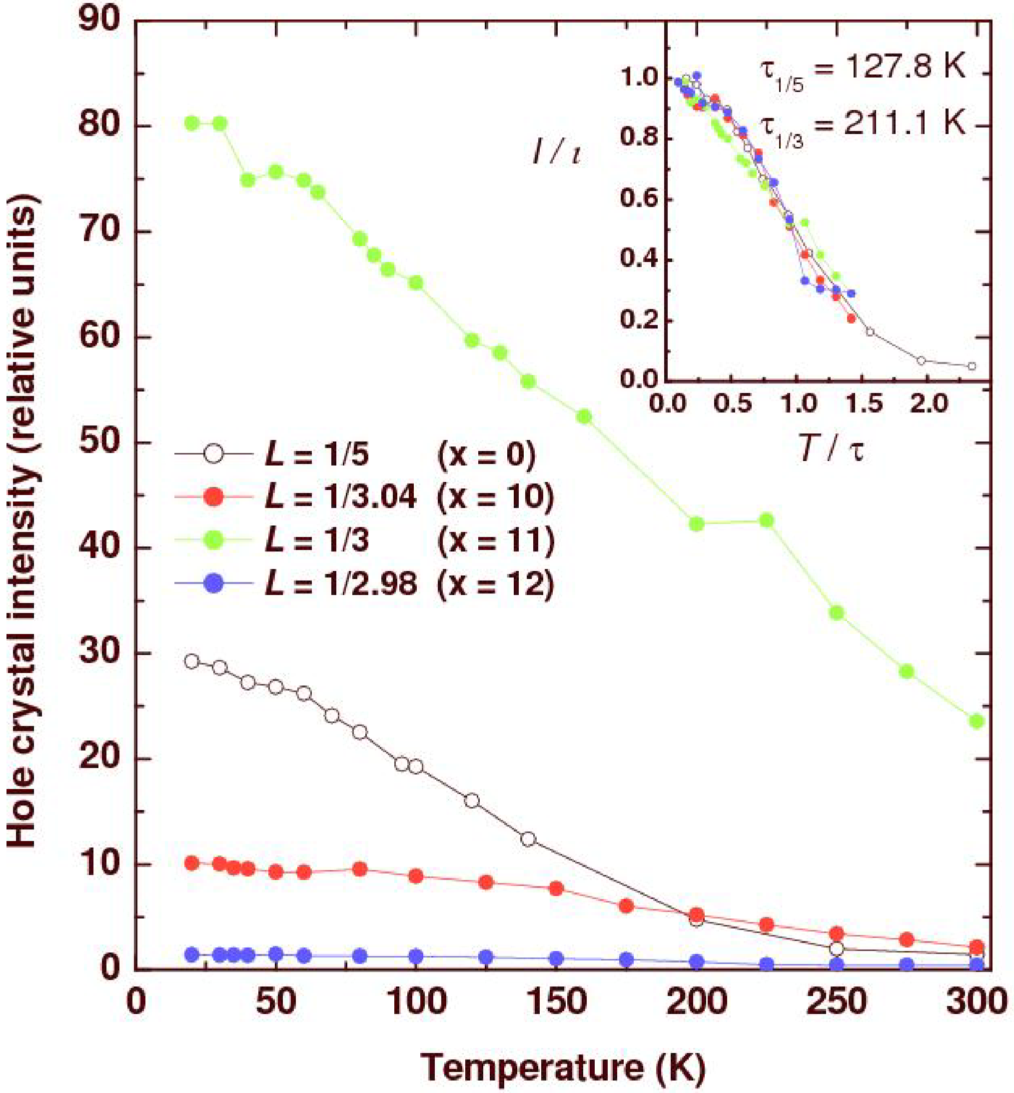
Evolution with carrier density



$\xi_c = (1580 \pm 70)$ Å and $\xi_a = (1615 \pm 70)$ Å

Interaction strength grows with decreasing hole spacing

Temperature scaling



$$\frac{\tau_{1/3}}{\tau_{1/5}} = 1.652 = \frac{5}{3}$$

$$\boldsymbol{U \sim 1/R}$$

Retrospective

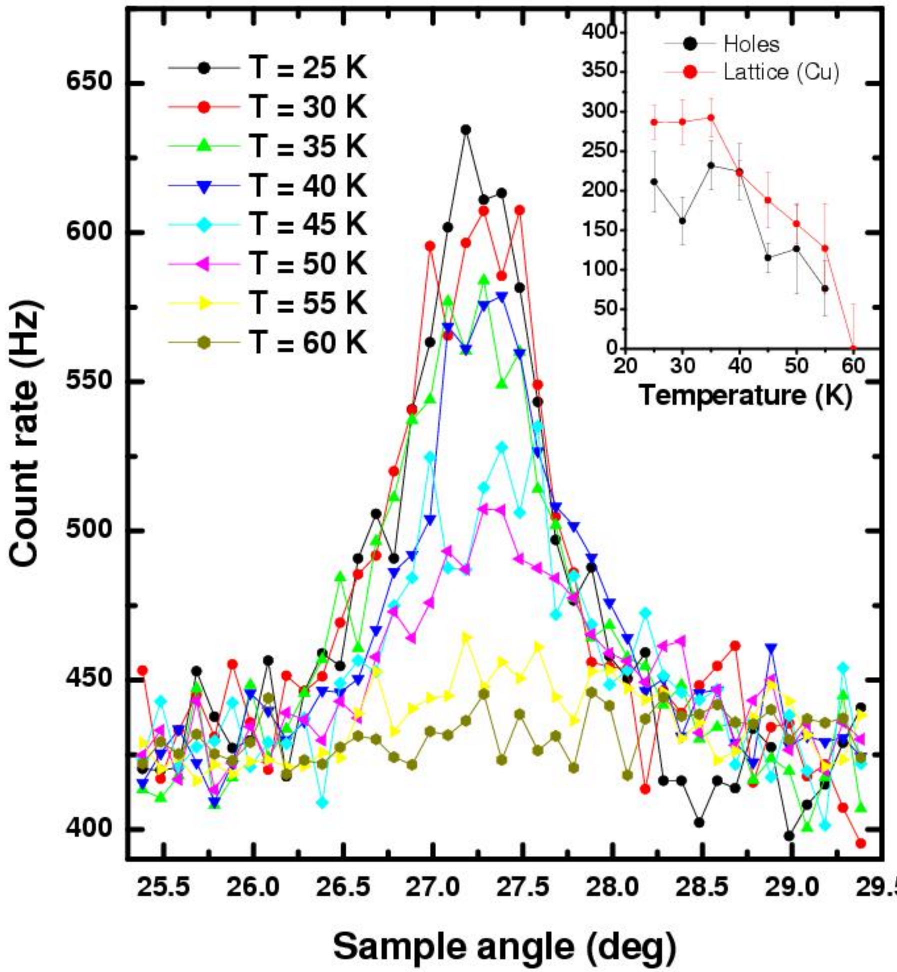
- CDW in $Sr_{14-x}Ca_xCu_{24}O_{41}$ is electronic – not Peierls
- Forms only on rational wave vectors L = 1/5, 1/3
- Melts at $T = 0$ for incommensurate filling
- Interaction strength grows with decreasing hole separation
- Temperature curves collapse; $\tau_{1/3} / \tau_{1/5} = 5/3$

Questions:

- Kinetics of melting? Fractionally charged solitons?
- What determines ΔL?
- Why the scaling?
- Why no $L = 1/4$?
- Relation to metal-insulator transition, superconductivity?

Temperature dependence (OK)

Stripes in $La_{2-x}Ba_xCuO_4$



RSXS Scientific Purpose

Detecting & studying hidden order parameters

(key question: are there many?)

Warning: $\chi(\mathbf{q}) = -\frac{r_e \lambda^2}{\pi} n(\mathbf{q})$ $\mathbf{D}^{(1)} = D_0 \frac{k^2 e^{ikr}}{4\pi r} \epsilon_f \cdot \epsilon_i \int d\mathbf{x}' \, e^{i\mathbf{q}\cdot\mathbf{x}'} \chi(\mathbf{x}')$

RSXS Instrumentation Lessons

- Analyzer optics. Multilayers don't (really) work.
- Detectors (channeltron w/CsI has QE ~ 25%)
- Angular flexibility. Two axes wont do it (Kappa?). *All the way to 180 degrees!*
- High energy capability. Need 3.3 keV to get to (200)
- System for centering. Can't just call Huber.
- T < 10 K. Is it even possible?!
- Stick to different materials to avoid cold welding. Stainless / ZrCu.
- Vacuum lubricants (Tiodize, MoS_2, etc.)
- Balance carefully!
- Separate detector and step motor feed throughs to avoid cross-talk