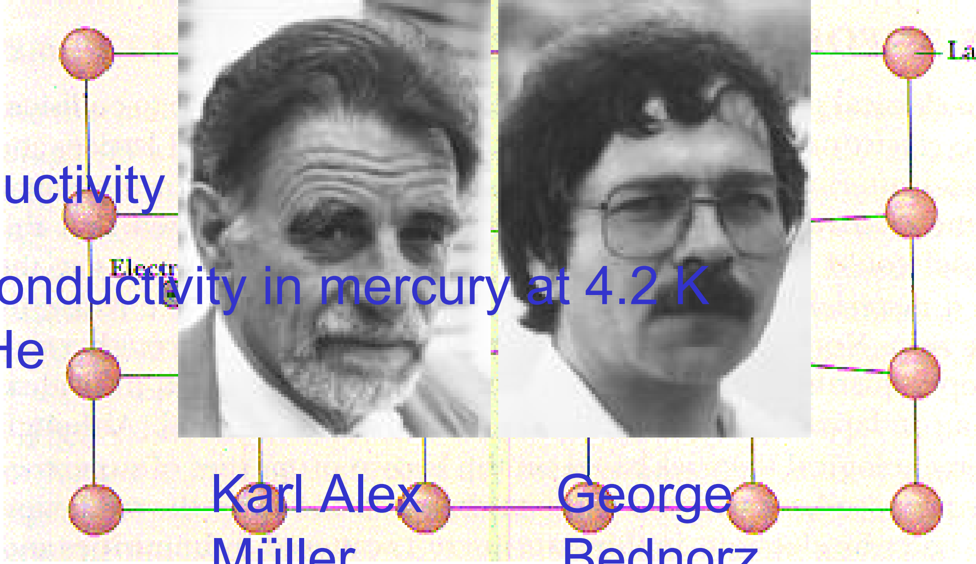
Seeing Stripes:
Competition and Complexity in High Temperature Superconductors

John Tranquada

BROOKHAVEN
NATIONAL LABORATORY

Advanced Photon Source
Argonne National Laboratory
December 1, 2004



1957

986

1911

scovery of superconductivity

Kamerlingh Onnes

$La_{2-x}Ba_xCuO_4$

Discovered superconductivity in mercury at 4.2 K

First to condense He

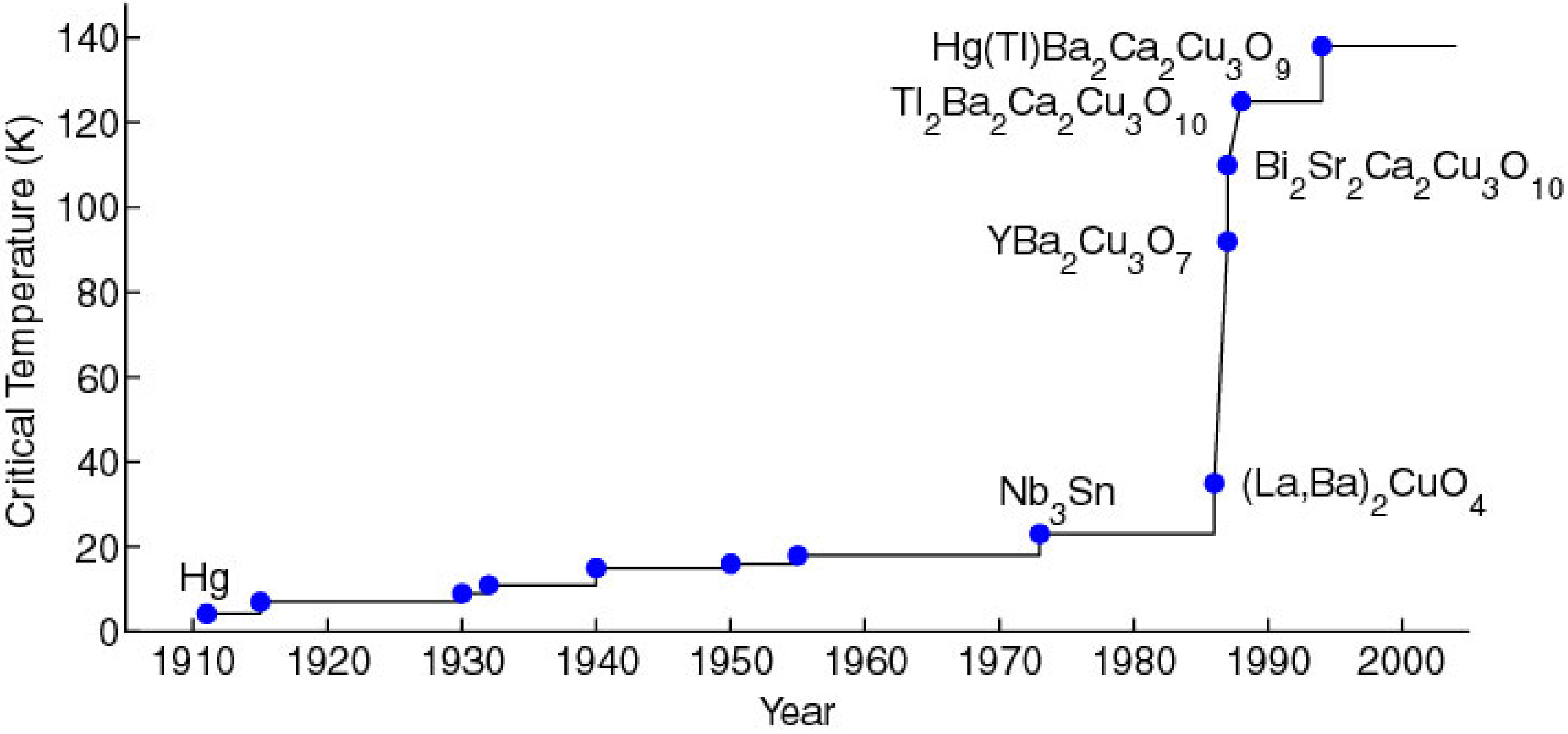
Bardeen

Cooper

Schrieffer

Karl Alex
Müller

George
Bednorz



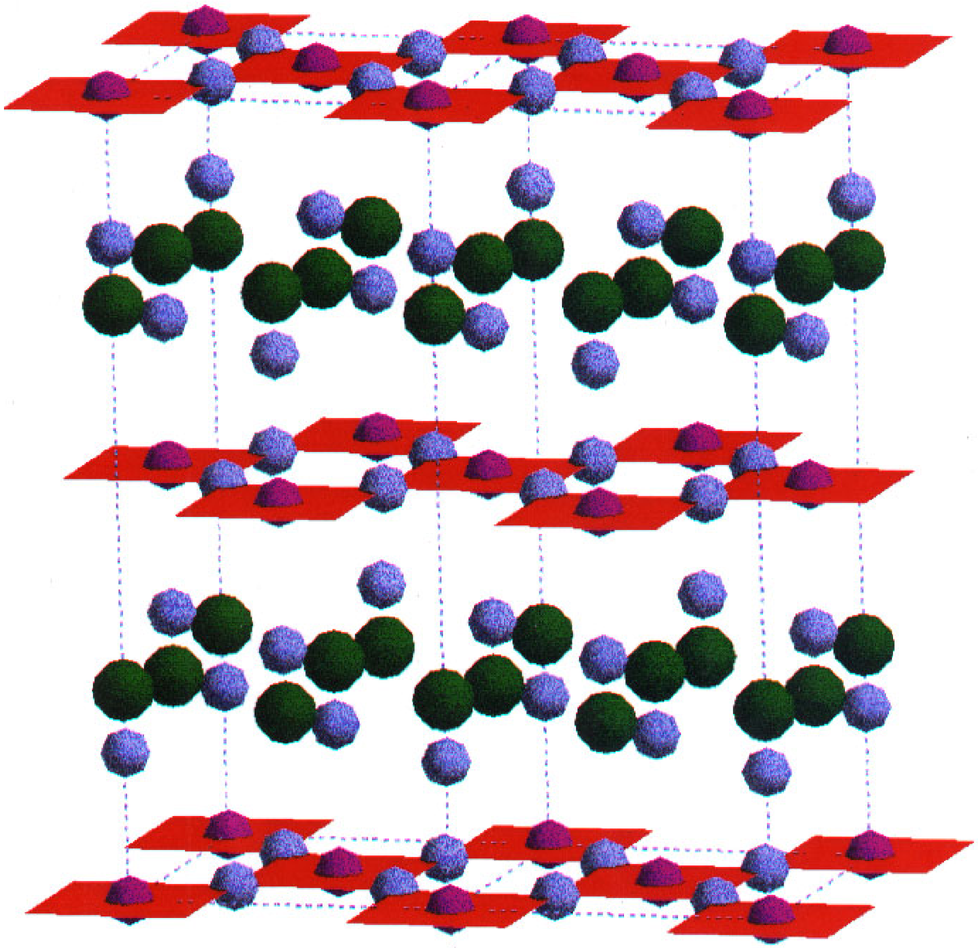
First report of high T_c superconductivity

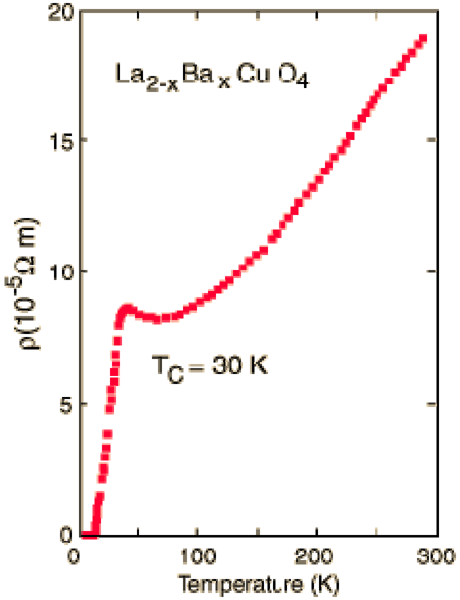
Z. Phys. B – Condensed Matter 64, 189–193 (1986)

Possible High T_c Superconductivity in the Ba – La – Cu – O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986





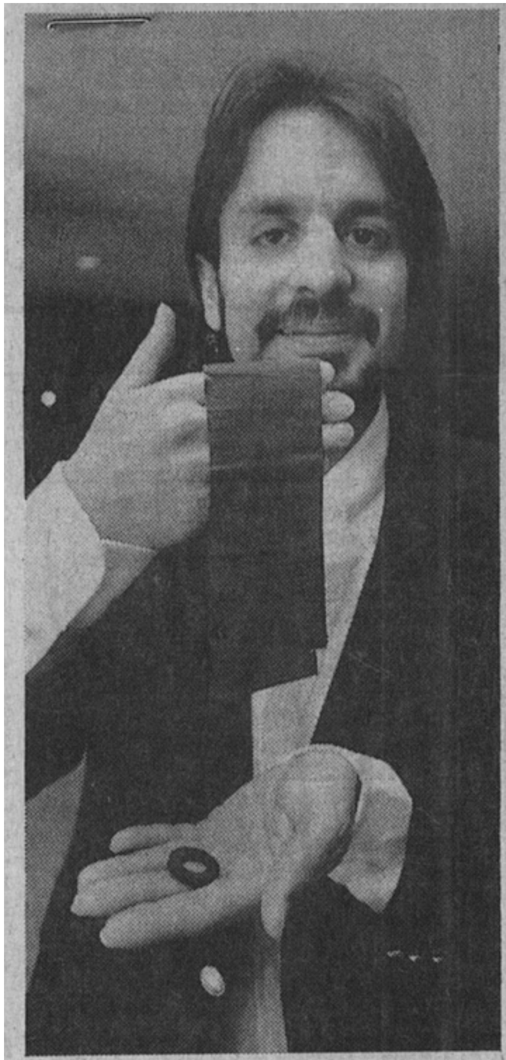
$La_{2-x}Ba_xCuO_4$

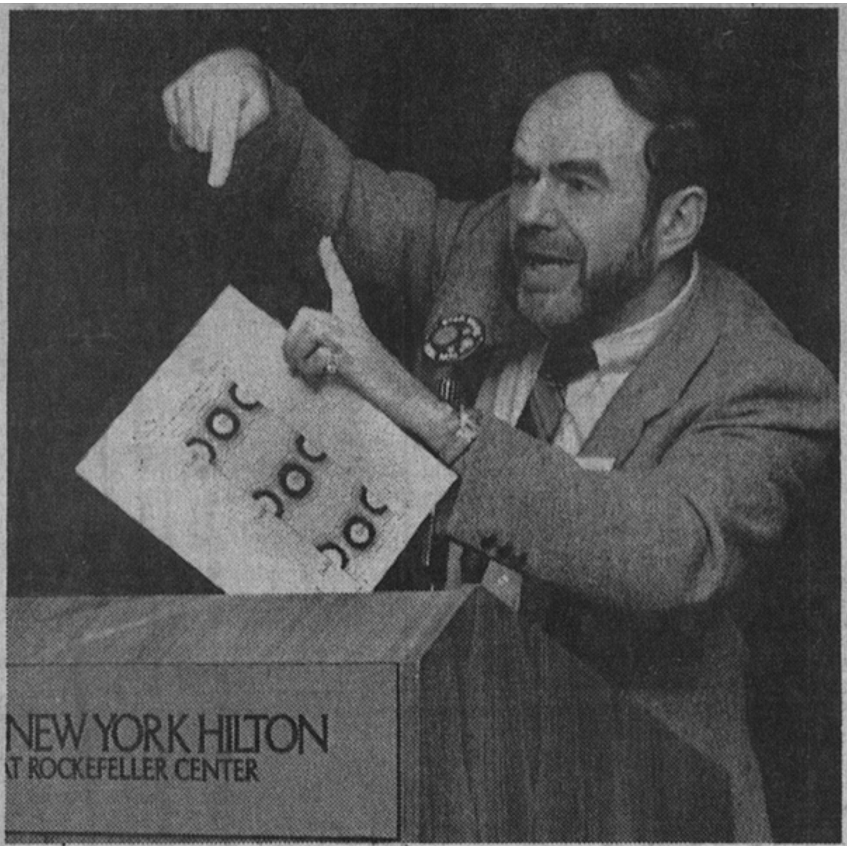
New York Times, front page March 20, 1987

American Physical
Society, March Mtg.

Post-deadline session
Wed. evening
7 pm until dawn

`Woodstock'
for Physics





The New York Times/Marilynn K. Yee

Dr. Robert J. Cava of Bell Laboratories, left, showing two examples of a new superconducting material — a sheet of vinyl-like tape and a washer-size semiconducting ring — at a conference of scientists yesterday at the New York Hilton. Arthur Freeman of Northwestern University, above, held a diagram of the molecular structure of the material.

Discoveries Bring a 'Woodstock' for Physics

By JAMES GLEICK

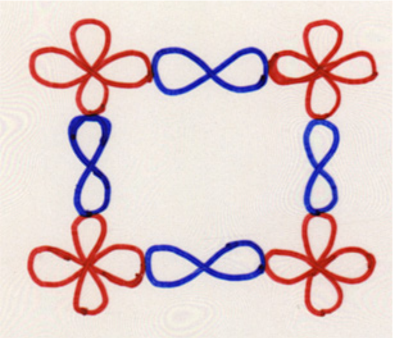
No sooner was a breakthrough announced than it was obsolete, and only the coming of dawn yesterday

the crowd had filled all 1,200 seats, and nearly 1,000 more physicists jammed the aisles and pressed against the walls. Outside, hundreds more strained to get in.

said Theodore H. Geballe of Stanford University.

The fast-breaking research on superconductors, materials that carry

La_2CuO_4



Conduction band formed by hybridization of Cu $3d_{x2-y2}$ and O $2p_{\sigma}$

1 unpaired electron per Cu atom

Band structure theory:
predicts a metal---half-filled band

Experiment:
Correlated insulator with band gap of 1.8 eV

Hole-doping in $La_{2-x}Sr_xCuO_4$

Valence counting: $La_2CuO_4 = (La^{3+})_2(Cu^{2+})(O^{2-})_4$

$(6+) + (2+) + (8-) = 0$

Copper Oxide Plane: $(CuO_2)^{2-}$

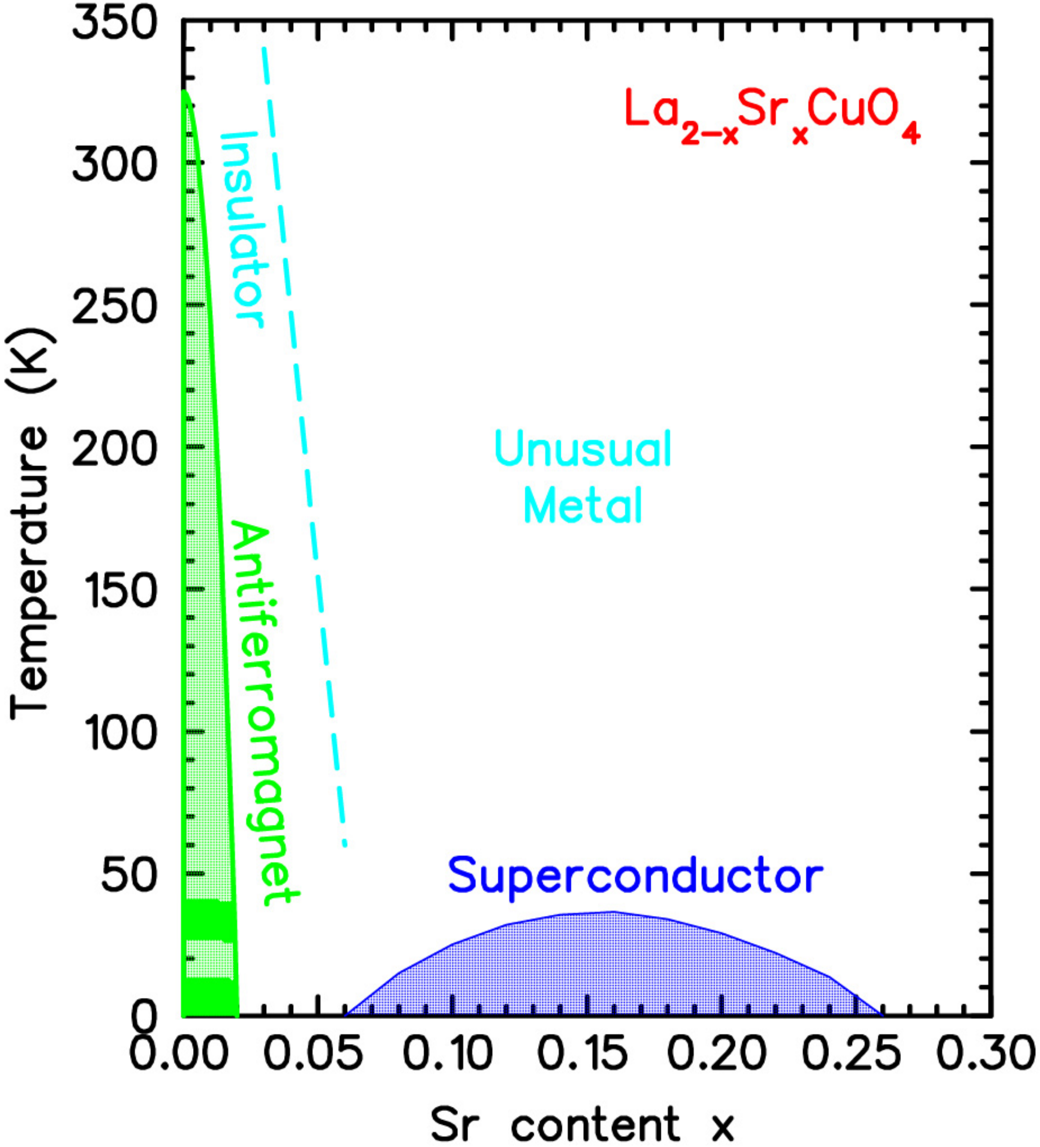
Doping: $La^{3+} \rightarrow Sr^{2+}$ or Ba^{2+}

Fewer electrons to give to oxygens

Holes (missing electrons) go into CuO_2 planes

Density of holes/Cu = x

Typical Phase Diagram: $La_{2-x}Sr_xCuO_4$

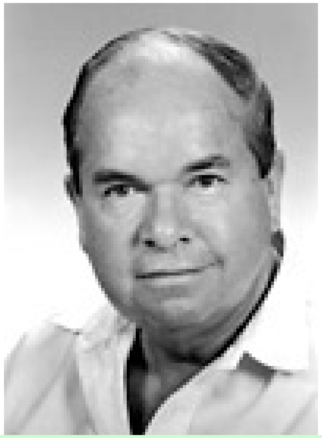


Questions

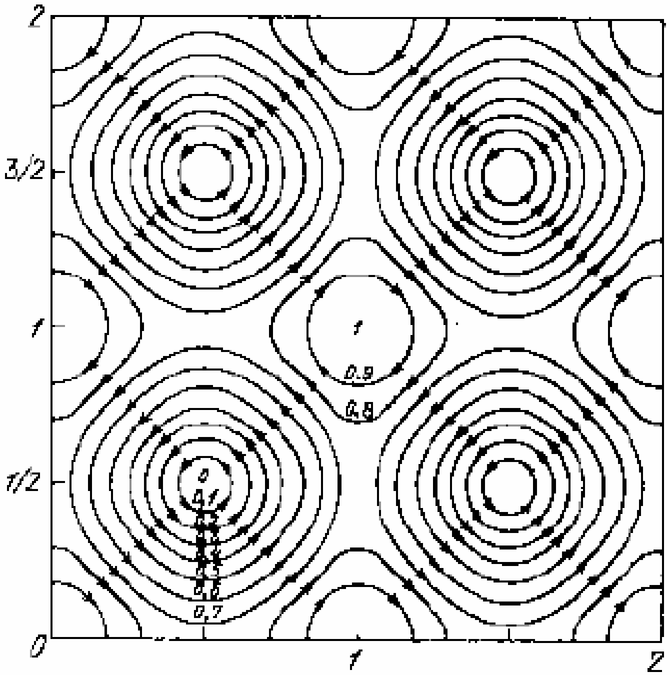
- What is the role of antiferromagnetism?
- What happens when holes are doped into an antiferromagnetic insulator?
- How does a doped antiferromagnet evolve into a superconductor?

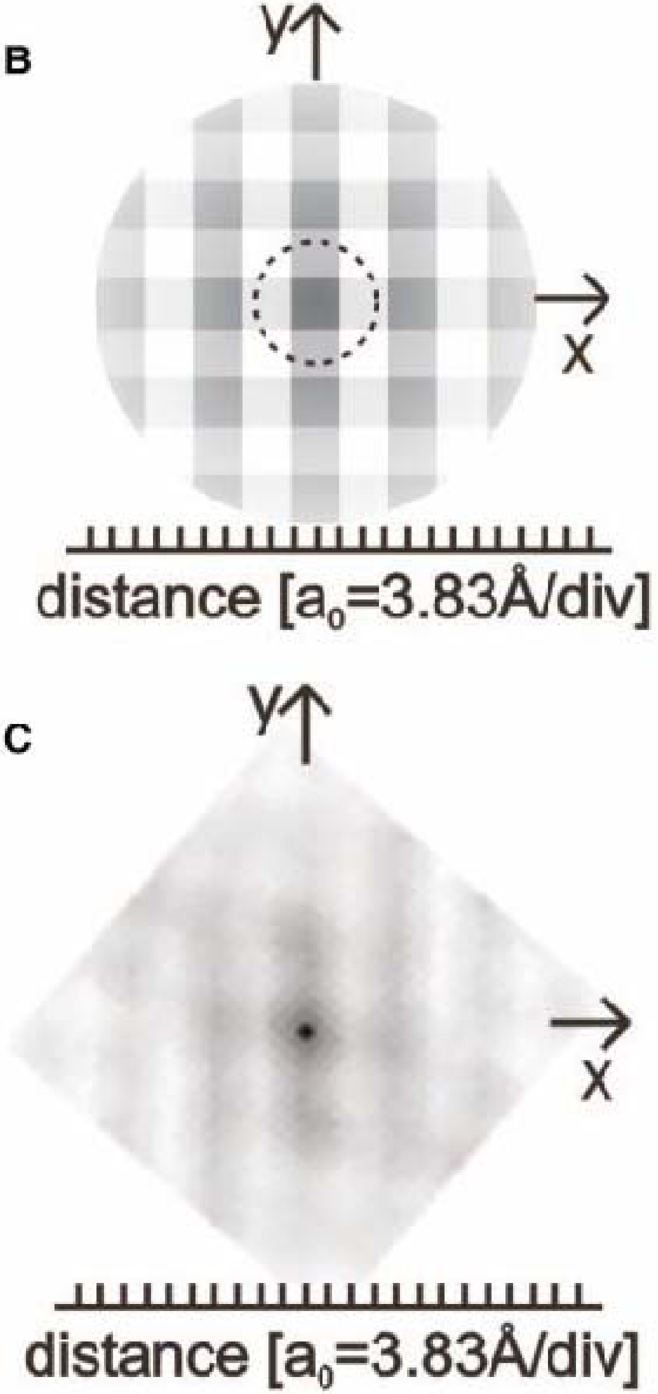
Cuprates are type-II superconductors

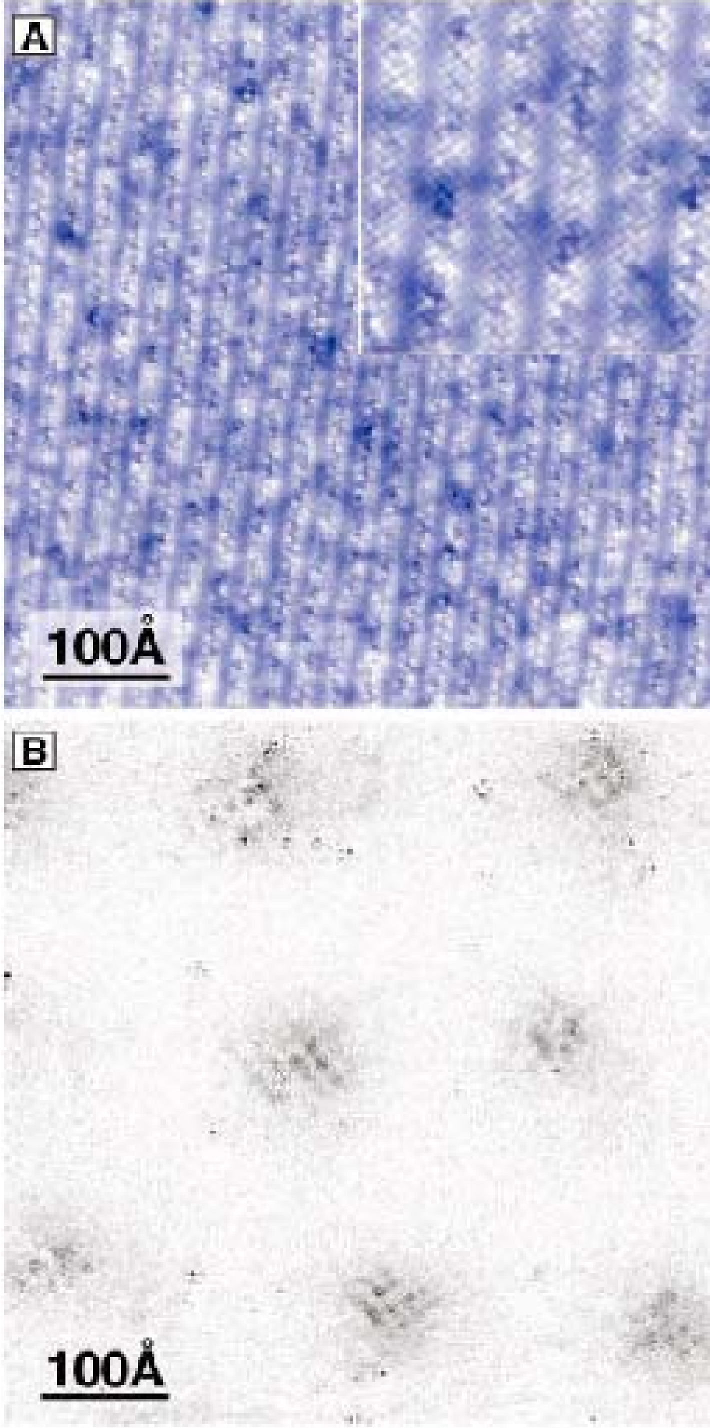
- Superconductors expel magnetic fields
- A strong enough magnetic field will kill superconductivity
- Type II superconductor: Above a threshold, magnetic field can penetrate in quantized amounts screened by superconducting vortices
  - ☐ Vortex core is "normal" (non-superconducting)



Alexei Abrikosov
2003 Nobel Prize




B
y
x
distance [a_0=3.83Å/div]
C
y
x
distance [a_0=3.83Å/div]


A
100Å
B
100Å

period = 4a

Competing Order

- What is the nature of the competing order?
- How is the competing order related to the superconducting state?
- Does the competing state only compete with superconductivity?

Charge stripes are the answer

- Holes doped into an antiferromagnet segregate into stripes
  - Domains of antiferromagnetism survive
- Static ordering of stripes competes with superconductivity
- Quantum-disordered stripes coexist with superconductivity
  - Stripes may be essential to the mechanism of superconductivity (Emery, Kivelson, Fradkin and others)
- All of this is contrary to the standard model of electronic states that underlies the BCS theory of superconductivity

Antiferromagnetism

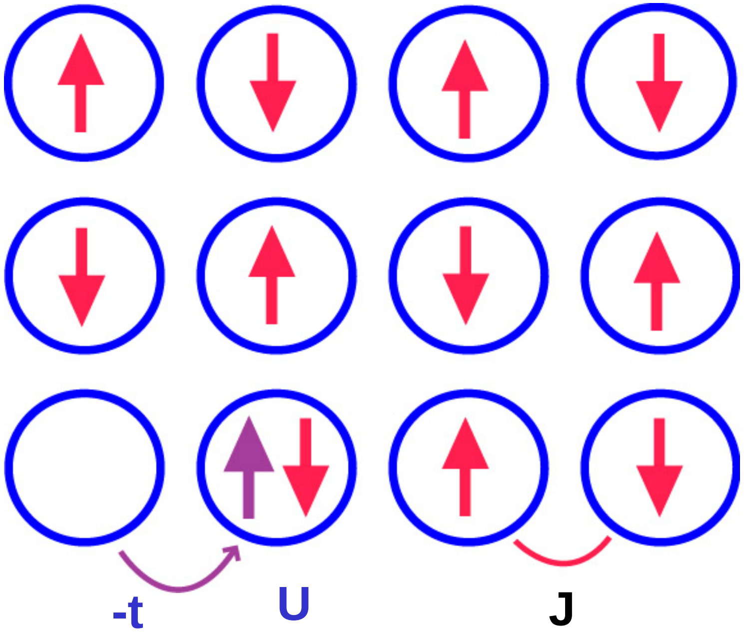
1/2-Filled Hubbard Model

1 orbital/site

1 electron/orbital

t = kinetic energy

U = onsite Coulomb repulsion



Coulomb repulsion
+
Pauli exclusion
⇓
Antiferromagnetic superexchange

$\mathbf{J} = 4\mathbf{t}^2/\mathbf{U}$

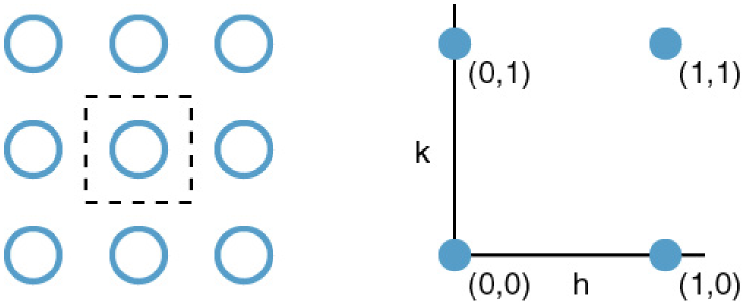
P.W. Anderson (1959)

Antiferromagnetic order doubles unit cell

Real space

Reciprocal space

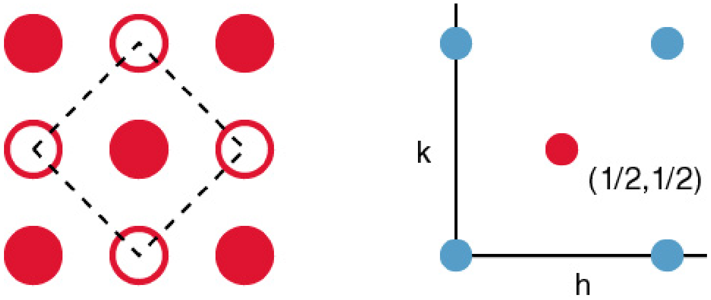
Crystal structure



Q = (h, k, l)

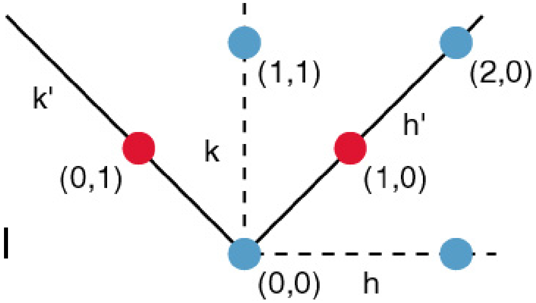
in units of (2π/a,2π/b,2π/c)

Magnetic structure

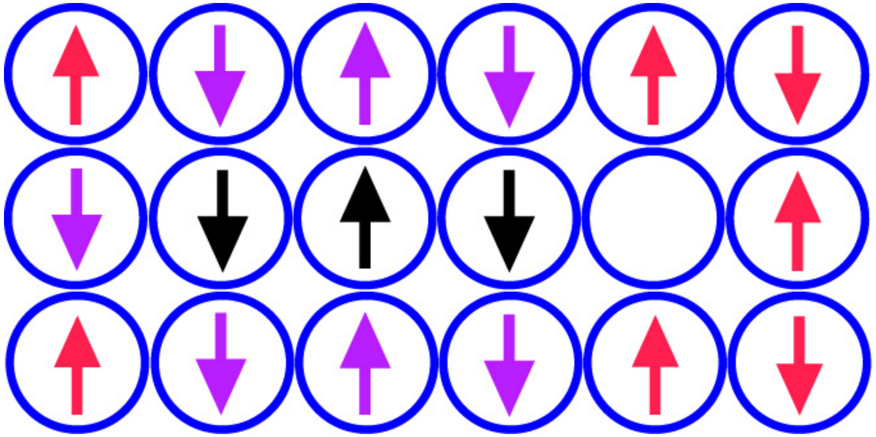


Octahedral tilt pattern in LTO is same as AF order; however, structure factor for tilted octahedra at Q = (1/2,1/2,L) is zero if L = 0.

Coordinates must rotate by 45° to describe orthorhombic cell



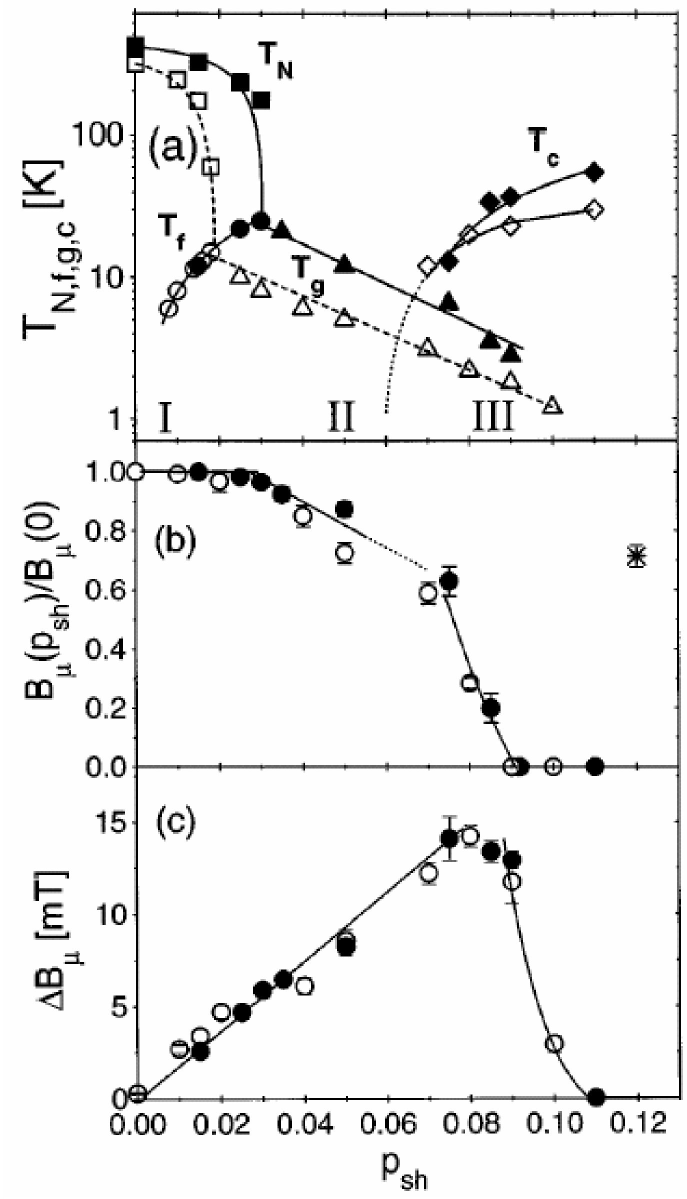
Competing Interactions



Motion of hole   lowers kinetic energy

but   costs superexchange energy

Local Magnetism Survives Doping



Phase diagram for $La_{2-x}Sr_xCuO_4$ and $Y_{1-2x}Ca_{2x}Ba_2Cu_3O_6$

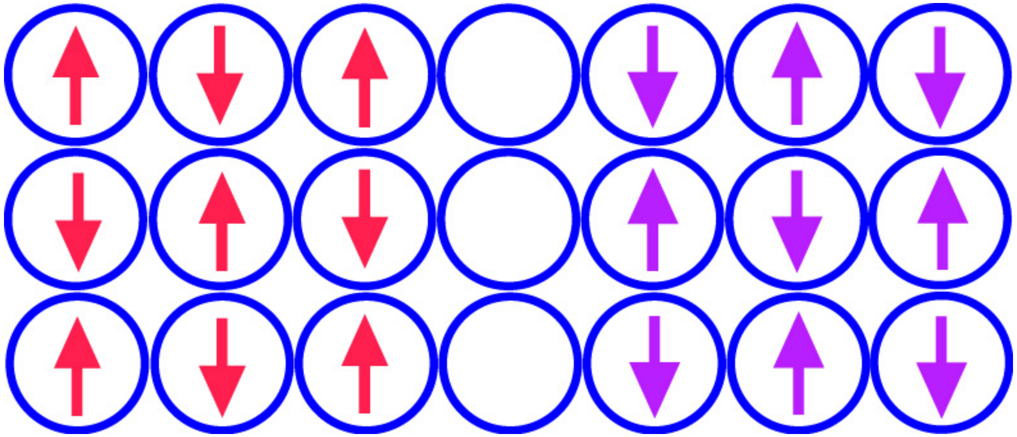
$p_{sh} = x$

Local magnetic field at T = 1 K measured by muon spin rotation

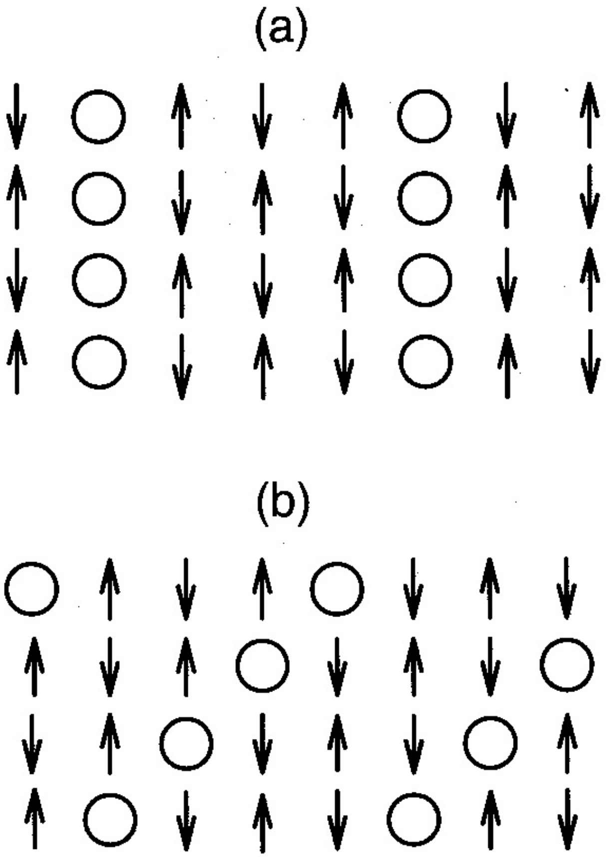
Niedermayer, Budnick, et al.
PRL **80**, 3843 (1998)

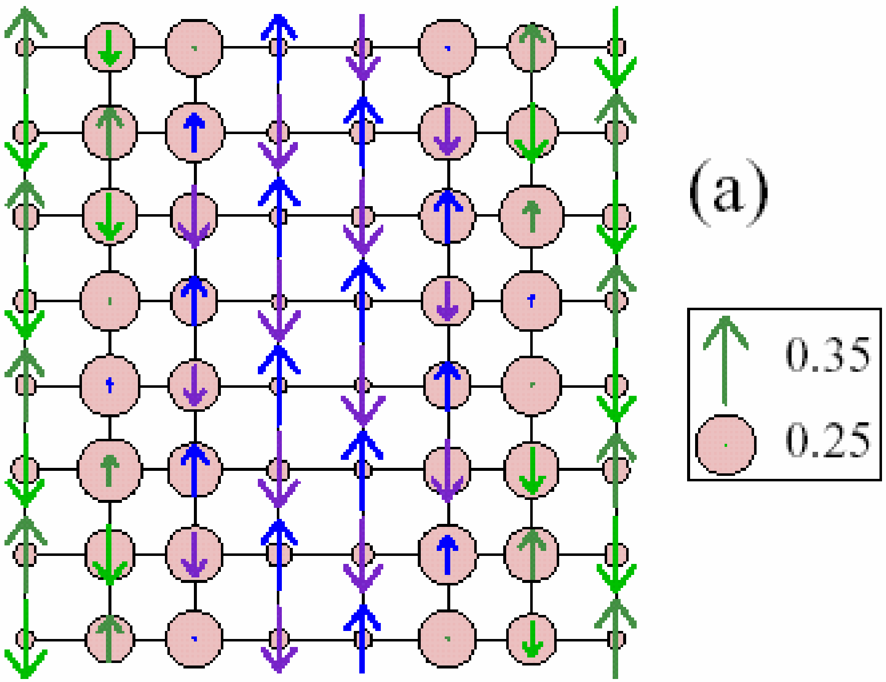
Hole segregation to antiphase domain walls

2D
extrapolation



Early stripe predictions





Zaanen and Gunnarson
Phys. Rev. B **40**, 7391 (1989)

Hubbard model
Mean-field solution

White and Scalapino,
PRL 80, 1272 (1998)

t-J model
Density matrix renormalization group

Alternative: Frustrated Phase Separation

Analysis of t-J model by Emery and Kivelson:

Holes tend to phase separate!

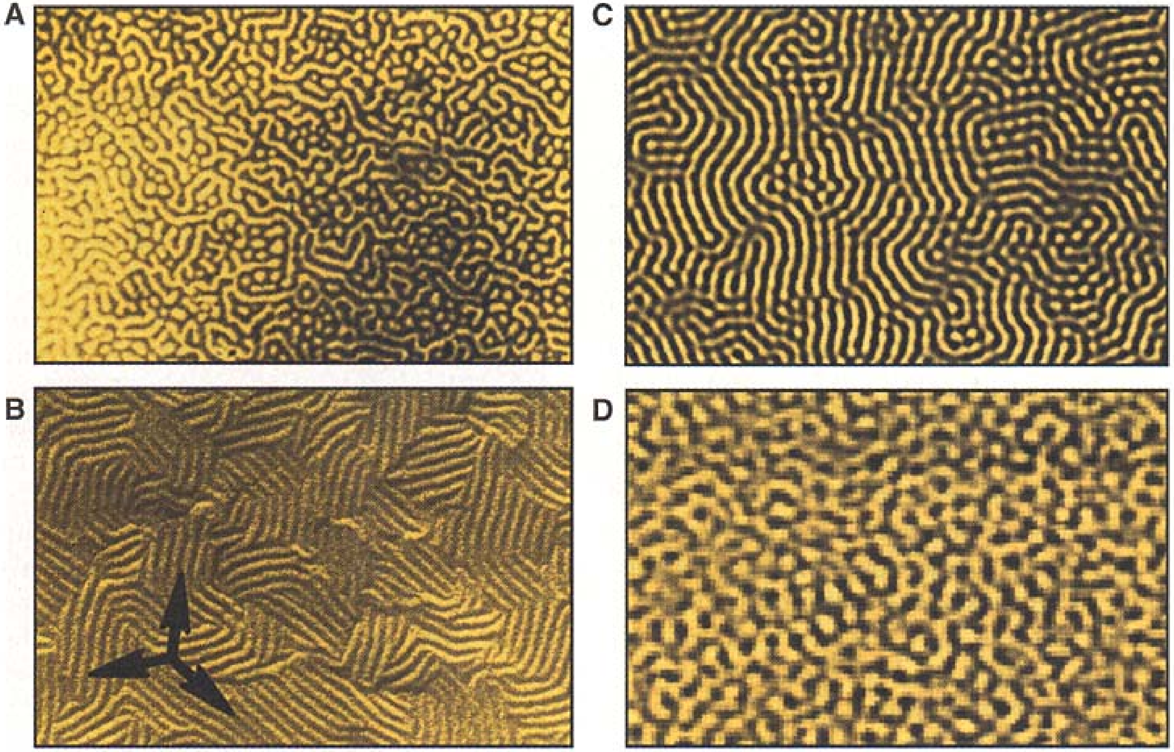
t-J model lacks long-range part of Coulomb interaction

Long-range Coulomb repulsion frustrates phase separation

Competing interactions result in striped and checkerboard phases

Löw, Emery, Fabricius, and
Kivelson, PRL **72**, 1918 (1994)

Examples of Stripe Phases



Type 1 superconductor foil
In a magnetic field

d = 7 μm

Chemical reaction-diffusion
system

d = 0.25 mm

d = 24 nm

Mixture of 2 phospholipids

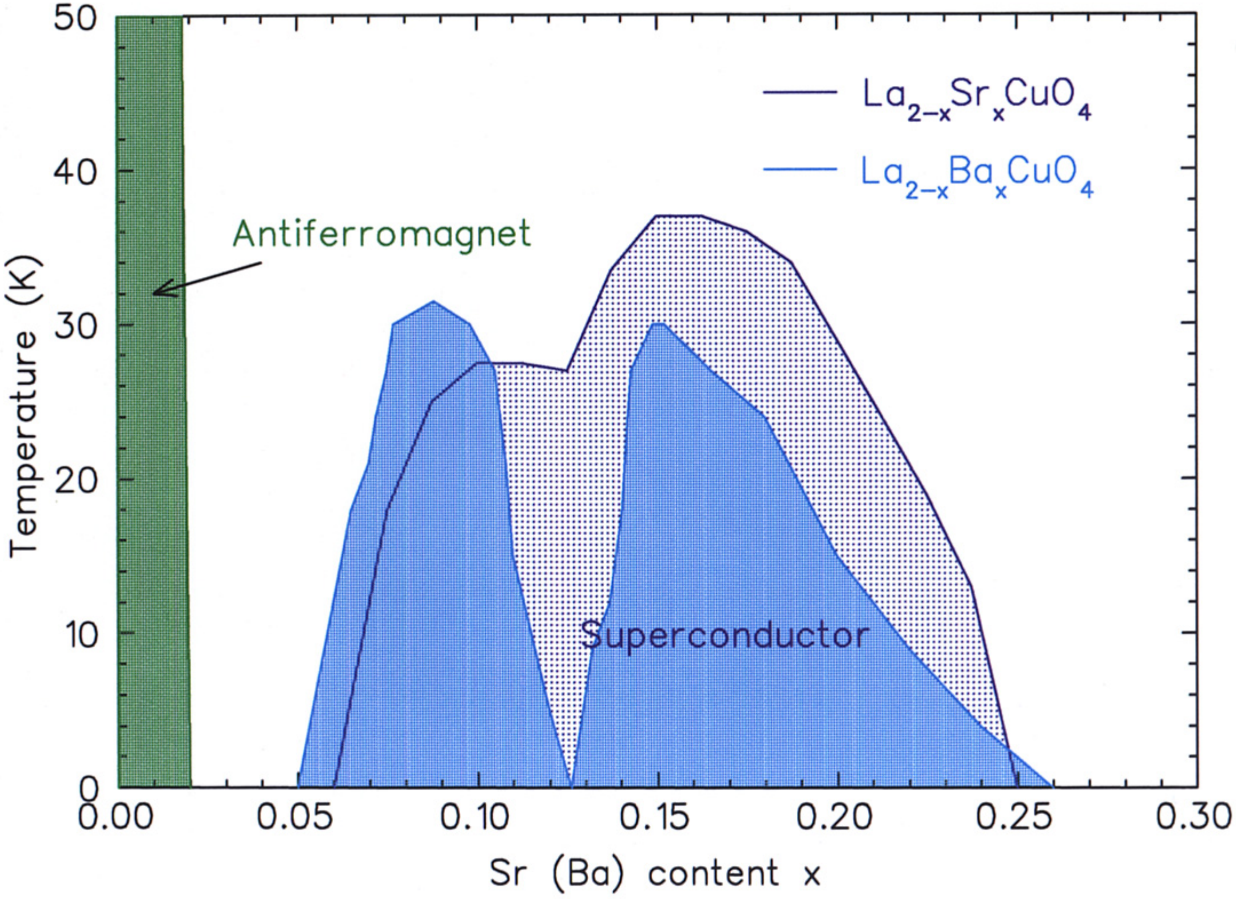
d = 1 cm

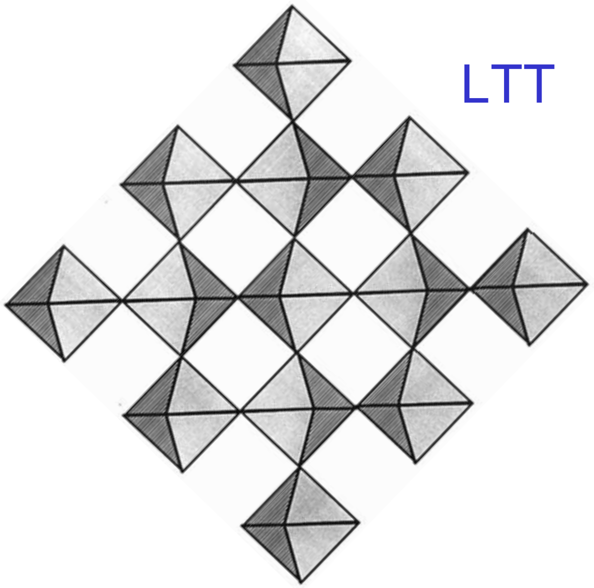
Rayleigh-Bénard convection
In CO_2 gas

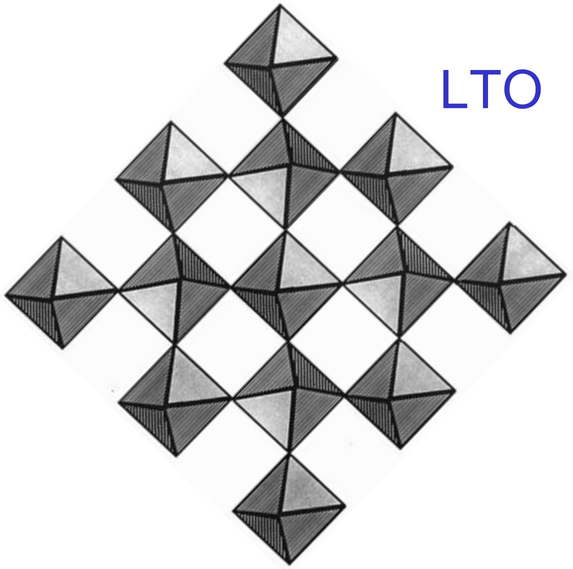
Seul and Andelman, Science **267**, 476 (1995)

Stripe ORDER seen only in special cases

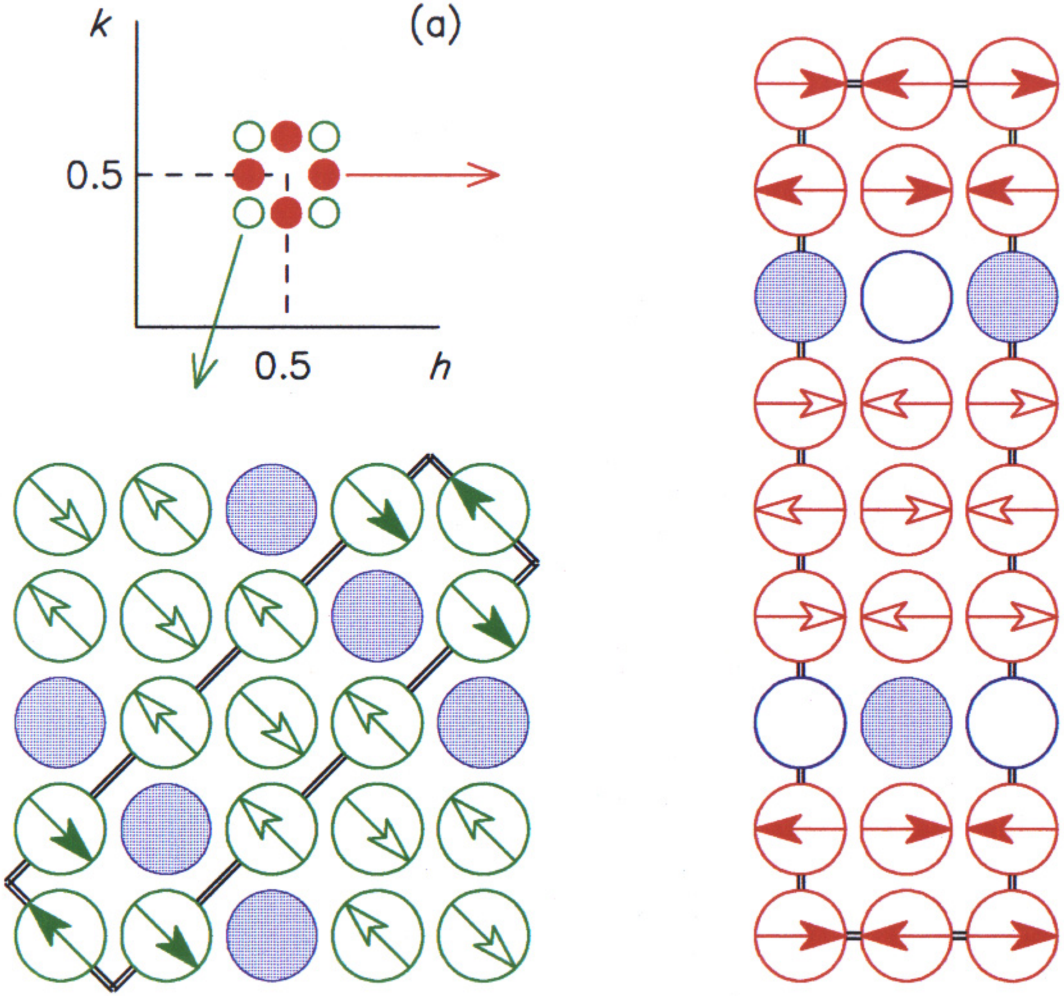
1/8 problem







Charge and spin stripe order



(b) NiO_2: $n_h = 0.25$

(c) CuO_2: $n_h = 0.125$

Discovered by
Neutron Diffraction
in

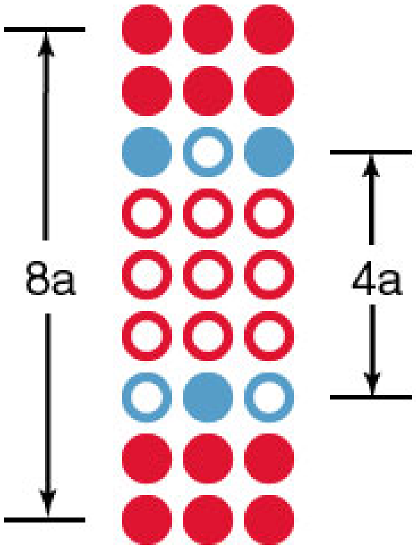
$La_{2-x}Sr_xNiO_{4+\delta}$
(1994)

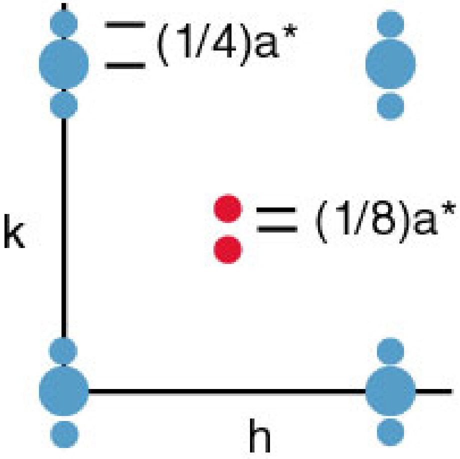
and in

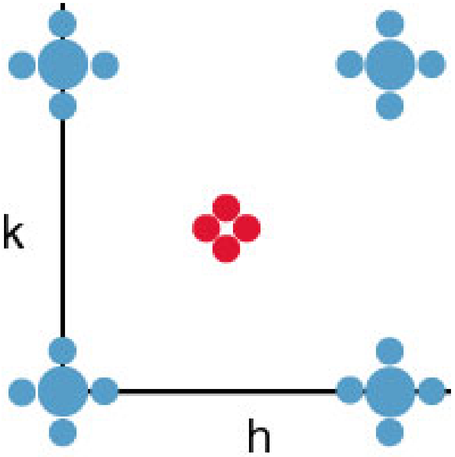
$La_{1.6-x}Nd_{0.4}Sr_xCuO_4$
(1995)

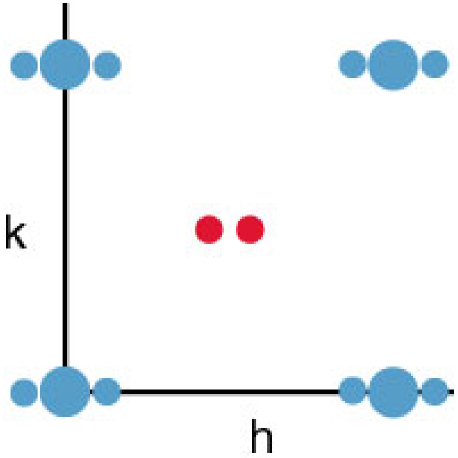
$La_{1.875}Ba_{0.125}CuO_4$
Fujita et al. (2004)

Horizontal and vertical stripes

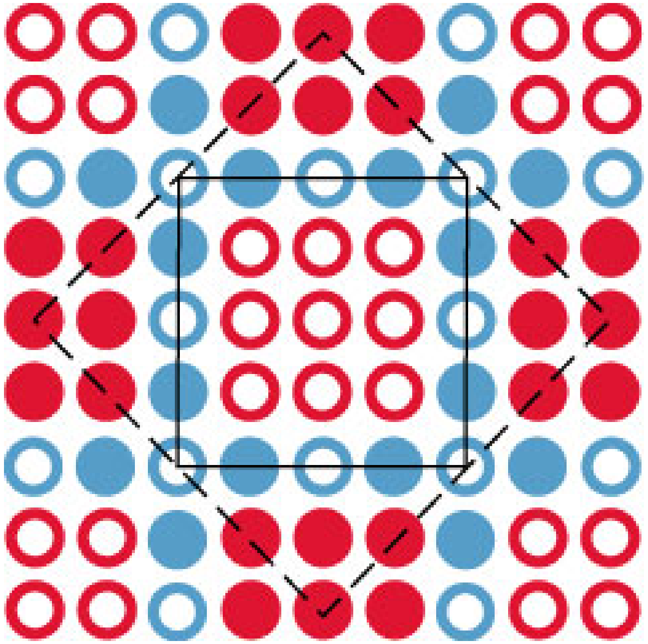


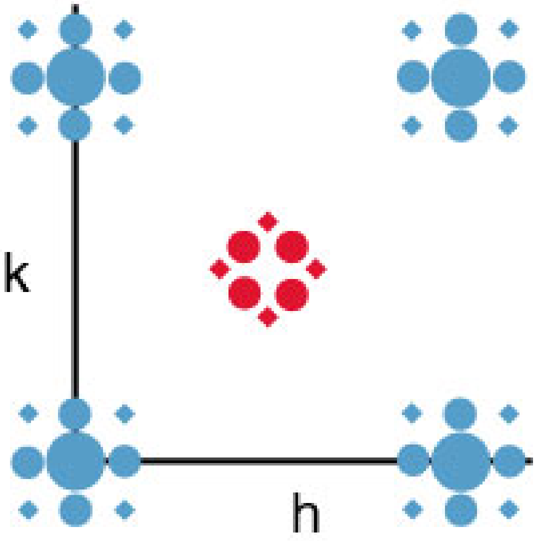






Diffraction from a grid





Modulation amplitude and diffraction intensities

Bond-length variation in stripe-ordered phase

$La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ $La_2NiO_{4.133}$

$\Delta d_{Cu\text{-}O} \approx 0.01$ Å $\Delta d_{Ni\text{-}O} \approx 0.04$ Å

Intensity of superlattice peak / Intensity of fundmental Bragg peak

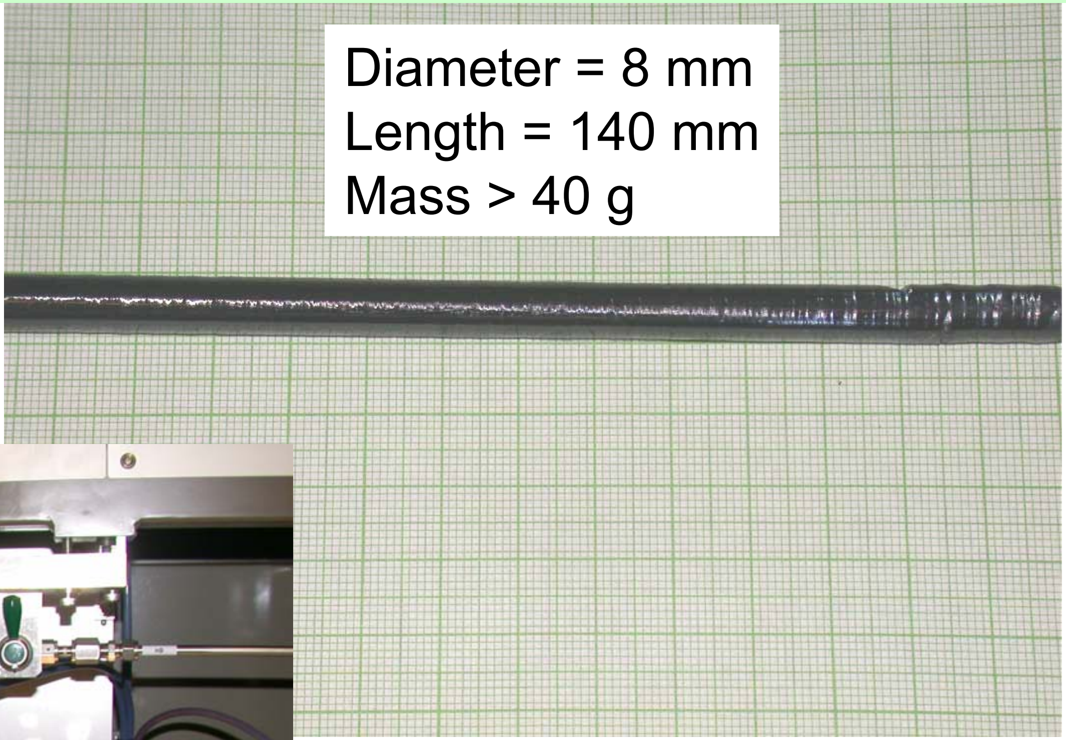
	cuprate	nickelate
Neutrons	10^{-6}	10^{-4}
X-rays	10^{-8}	10^{-6}

Relevance of stripes

- Charge stripes have period ~ 4a (near optimum doping)
  - Compatible with STM observations
- Stripe order competes with superconductivity
- Are there fluctuating stripes in good superconductors?
  - Stripe ORDER is hard enough to see!
  - Dynamic stripes are even more challenging
- Useful signature: spin fluctuations
  - Test: Is spectrum of spin fluctuations in a stripe-ordered sample similar to that in a good superconductor?

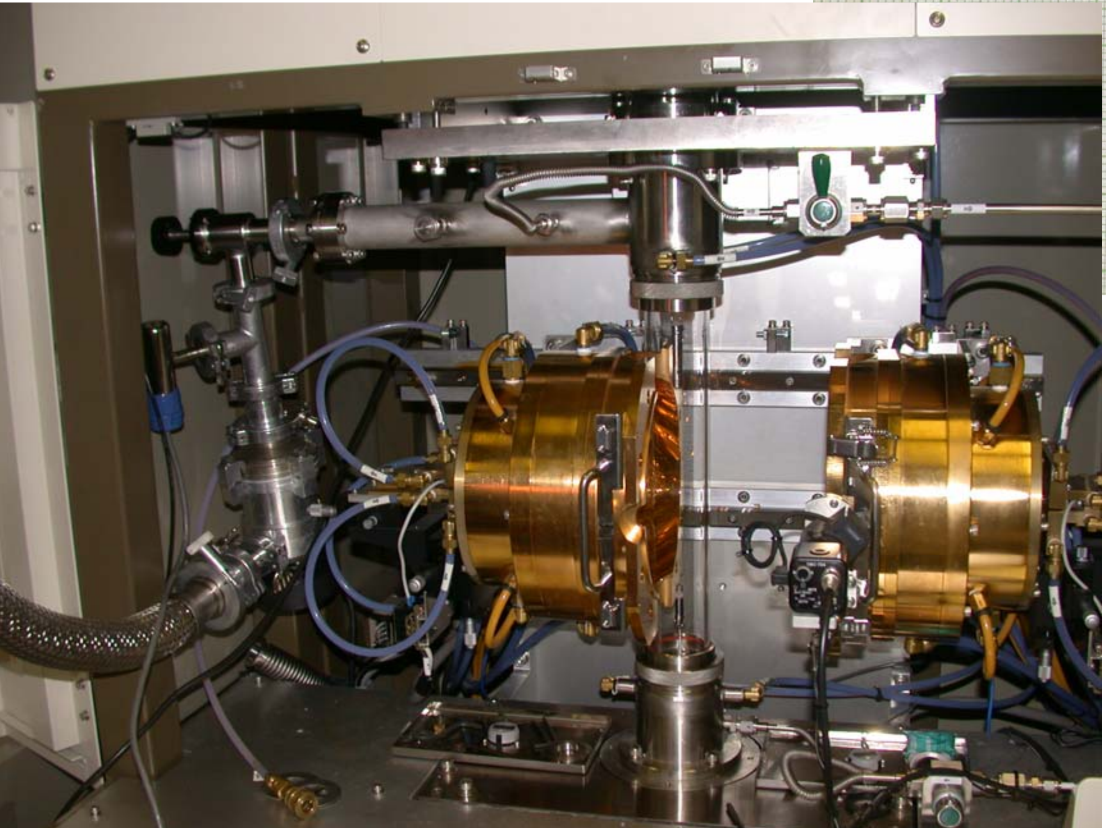
Growth of large crystals of $La_{1.875}Ba_{0.125}CuO_4$

Grown by Genda Gu, BNL
In collaboration with
Fujita and Yamada, Tohoku U.



Diameter = 8 mm
Length = 140 mm
Mass > 40 g

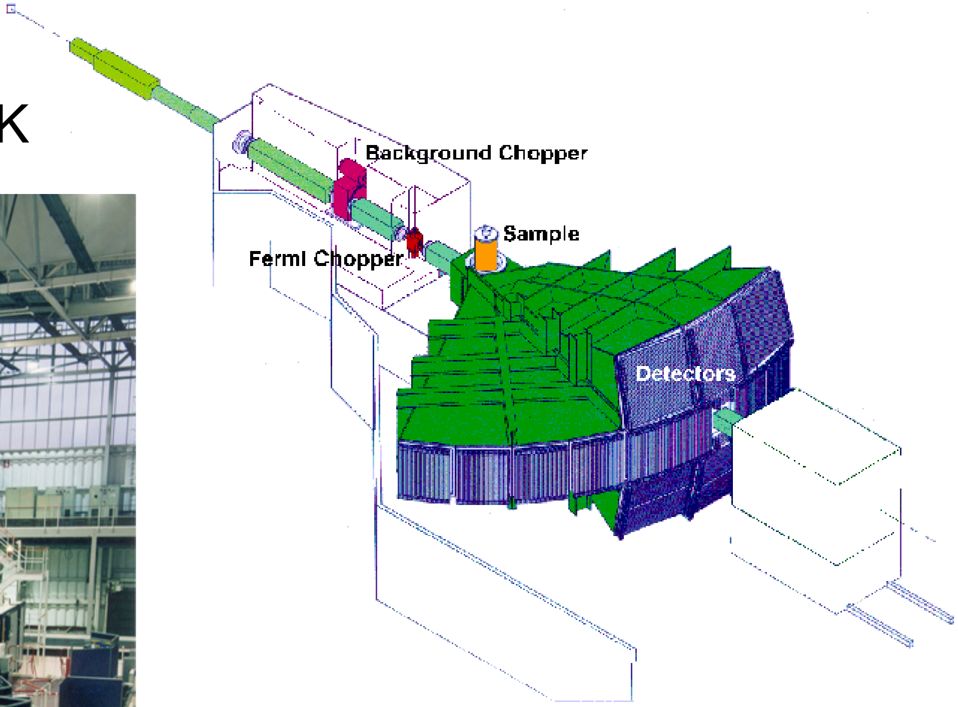
Infrared Image Furnace



QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Neutron scattering study on MAPS at ISIS

ISIS at Rutherford-Appleton Lab, UK



MAPS

Time-of-flight spectrometer
for study of inelastic scattering

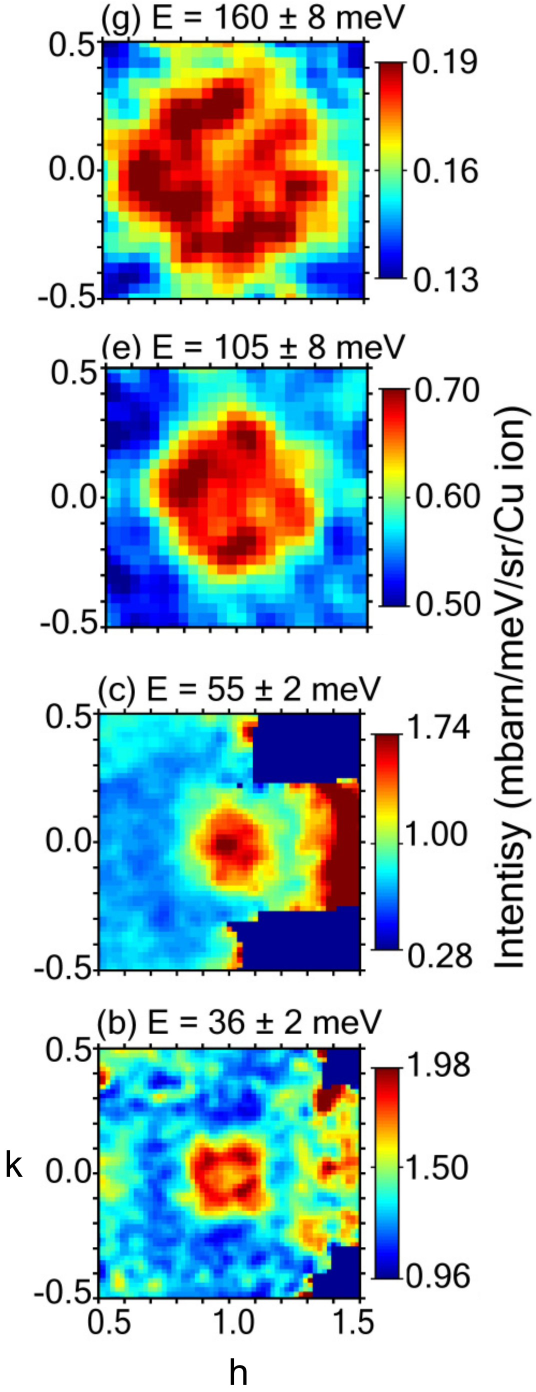
Area detector: ~150,000 pixels

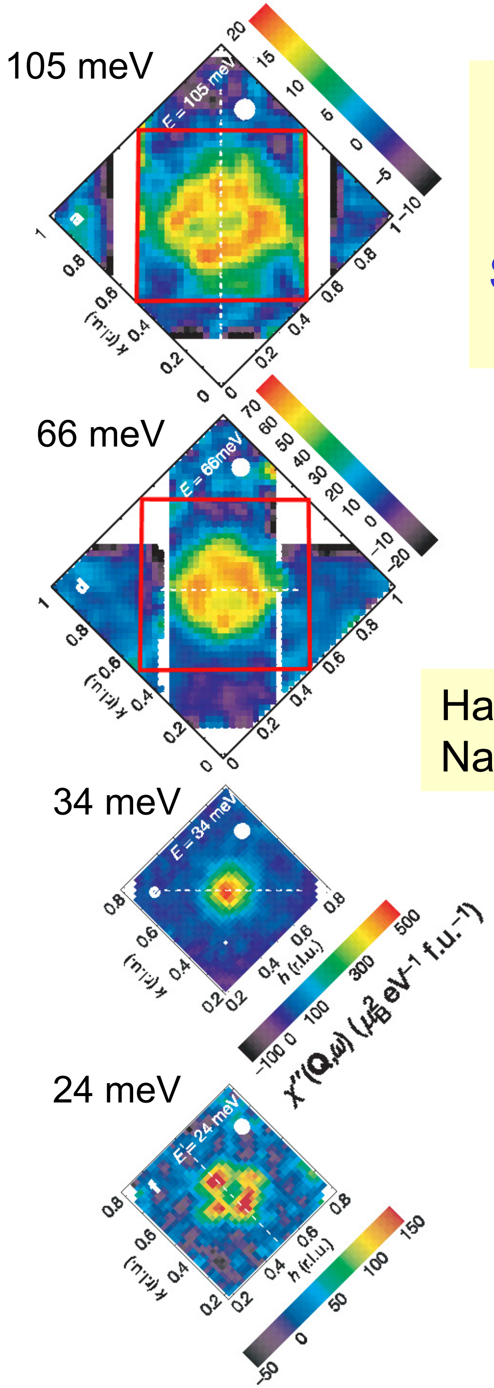
Toby Perring, Hyungje Woo

$La_{2-x}Ba_xCuO_4$

x = 1/8

Normal state with Stripe order



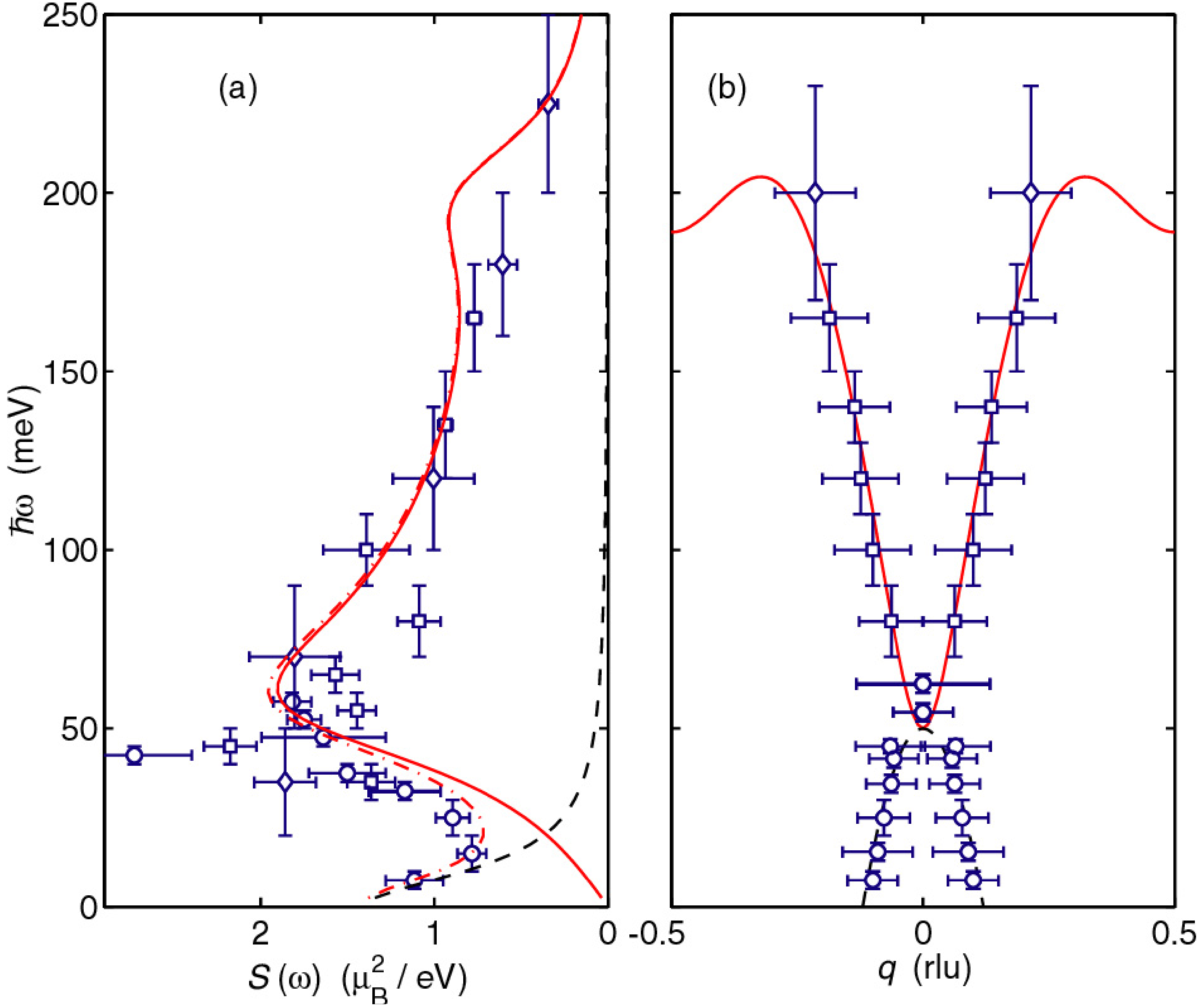


$YBa_2Cu_3O_{6.6}$

Superconducting state

Hayden et al.,
Nature **429**, 531 (2004)

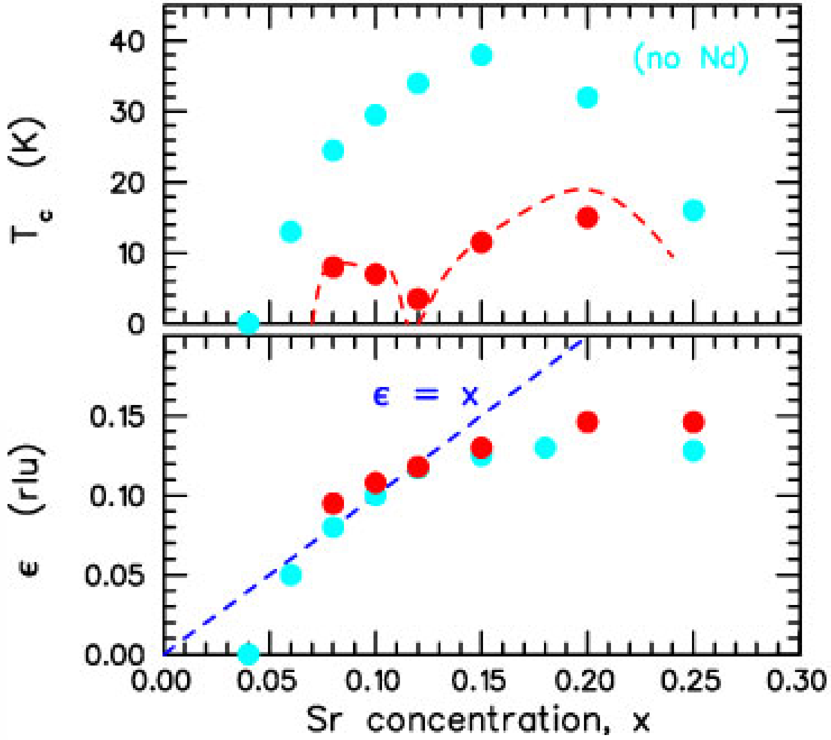
Evidence for spin gap

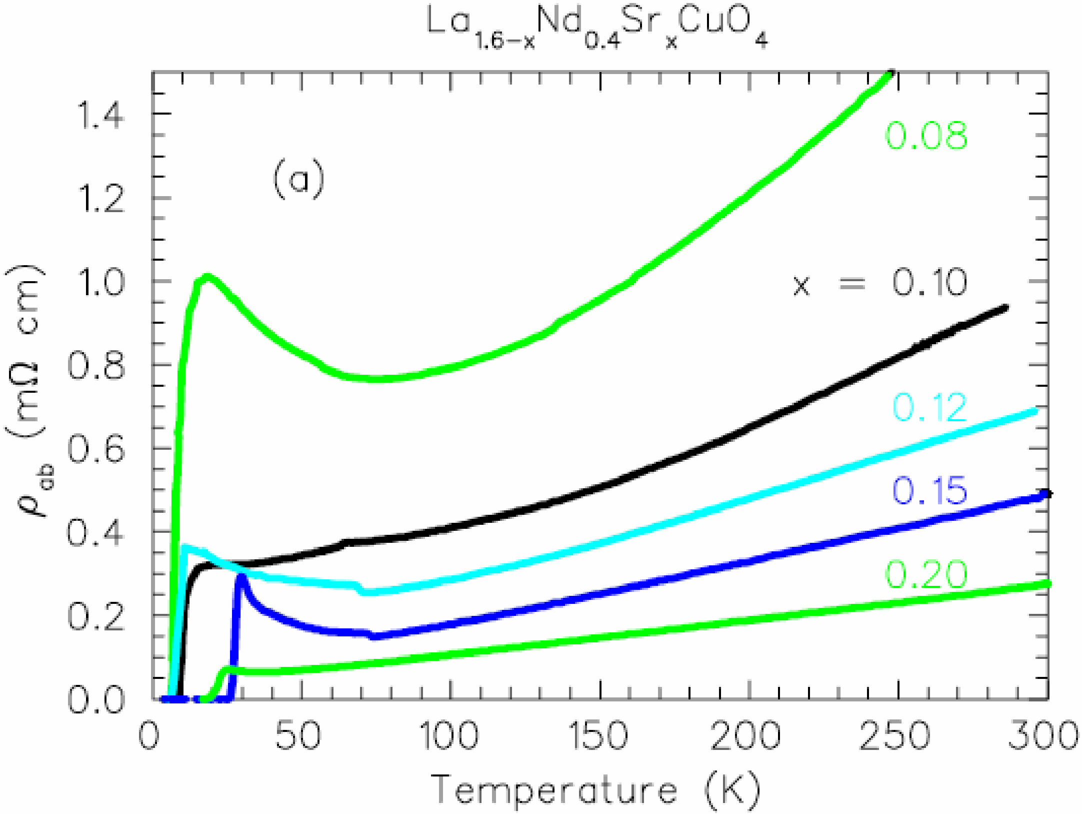


Conclusions

- Doped 2D antiferromagnets have a tendency to form stripes
- Stripe order has been observed in a few special cuprates
- Stripe order competes with superconducicitivity
- Magnetic spectrum of ordered stripes is similar to that of a good superconductor
  - Suggests presence of dynamic stripes in superconductors
    - Implies novel mechanism for superconductivity in cuprates

Stripes in $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$

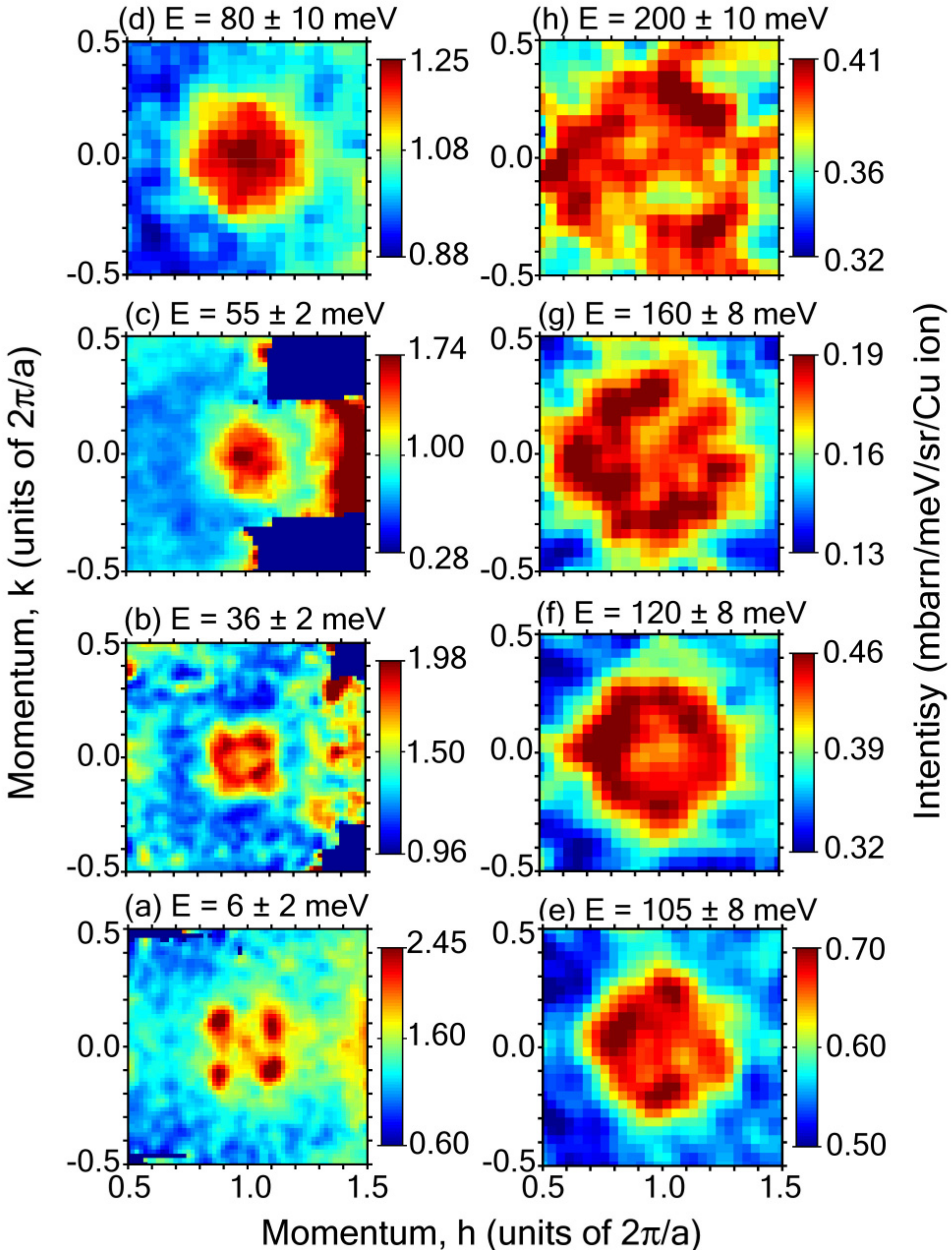


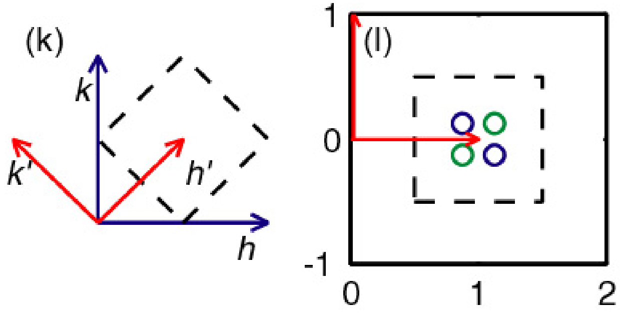


Constant-energy slices through magnetic scattering

T = 12 K

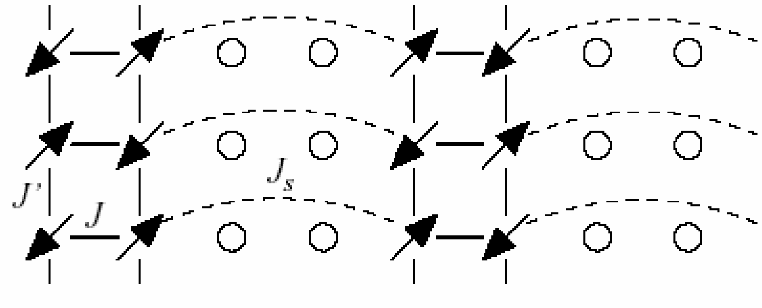
$T_c <$ 6 K

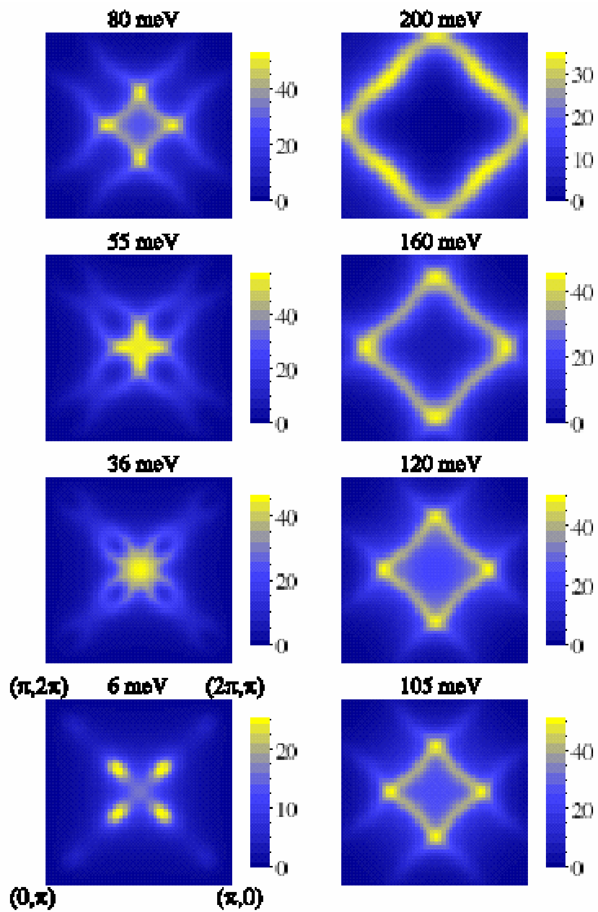


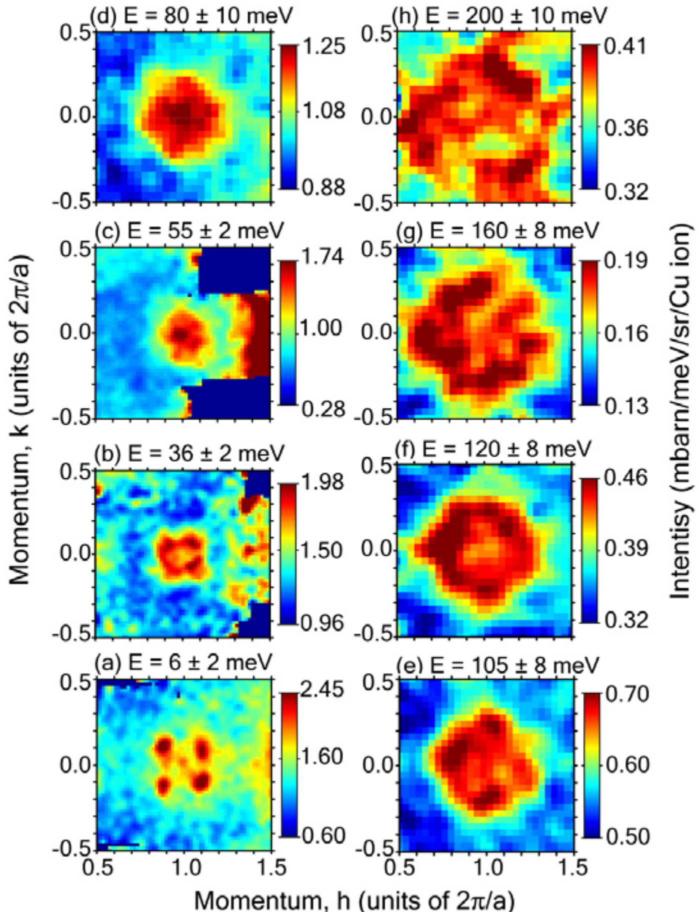


Model: Weakly-coupled spin ladders

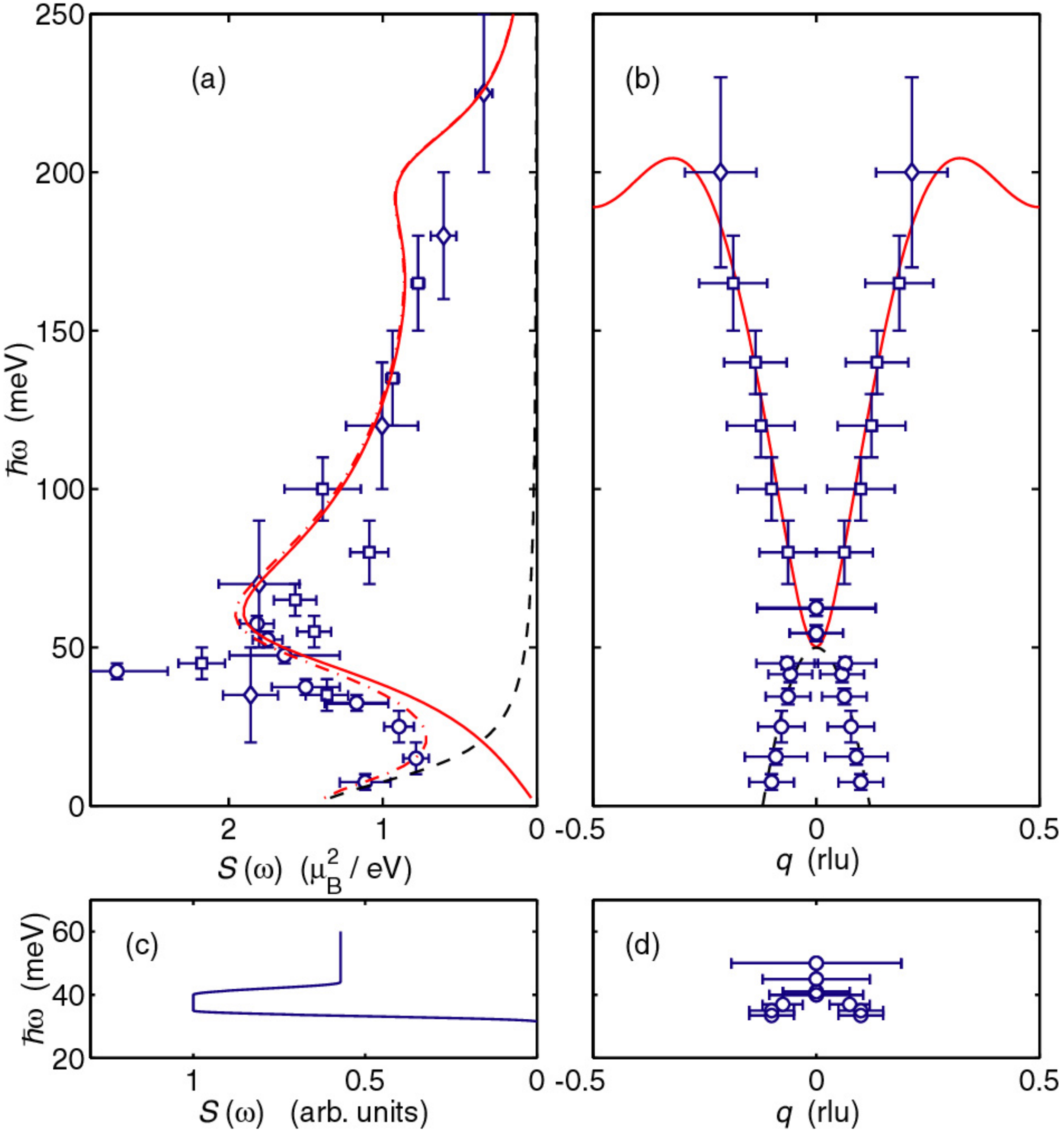
Vojta and Ulbricht, PRL (2004)







Evidence for spin gap



What does this have to do with superconductivity?

Conclusions

- Charge inhomogeneity in cuprates is a natural and generic response to the competition between kinetic, exchange, and Coulomb energies
- Charge stripes define magnetic clusters (spin ladders) that exhibit gapped, quantum magnetic excitations
- The resulting spin gap may set the pairing scale for superconductivity

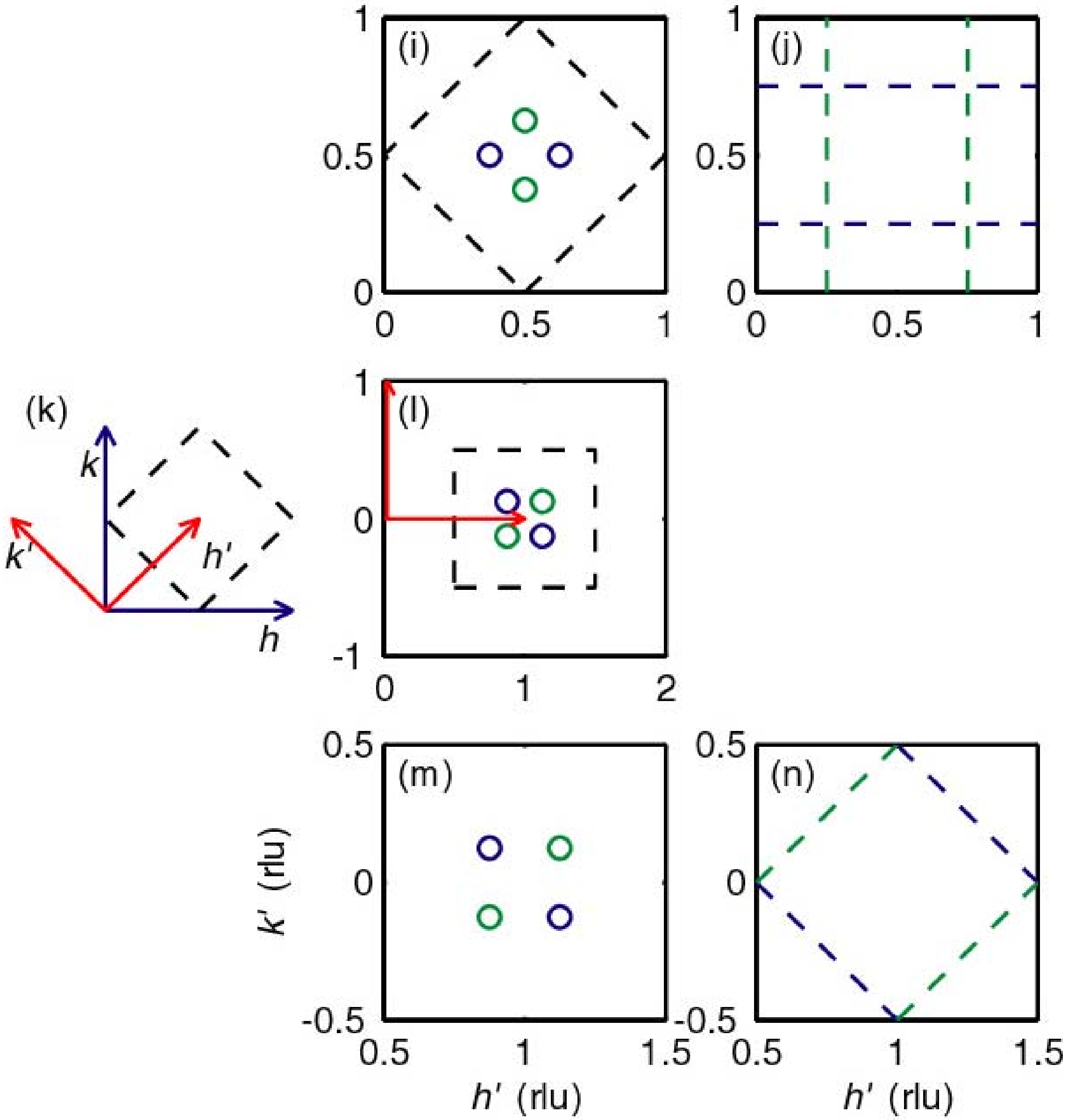
Standard model of electronic structure

- Local-Density Approximation for electron-electron interactions
  - Interactions treated in mean field
  - Only effect is to shift bands in energy
- Landau's Fermi-Liquid Theory
  - Map quasiparticles (dressed excitations) to a gas of free electrons (for ω,T ⌫ 0)
  - Very successful at describing the transport properties of metals

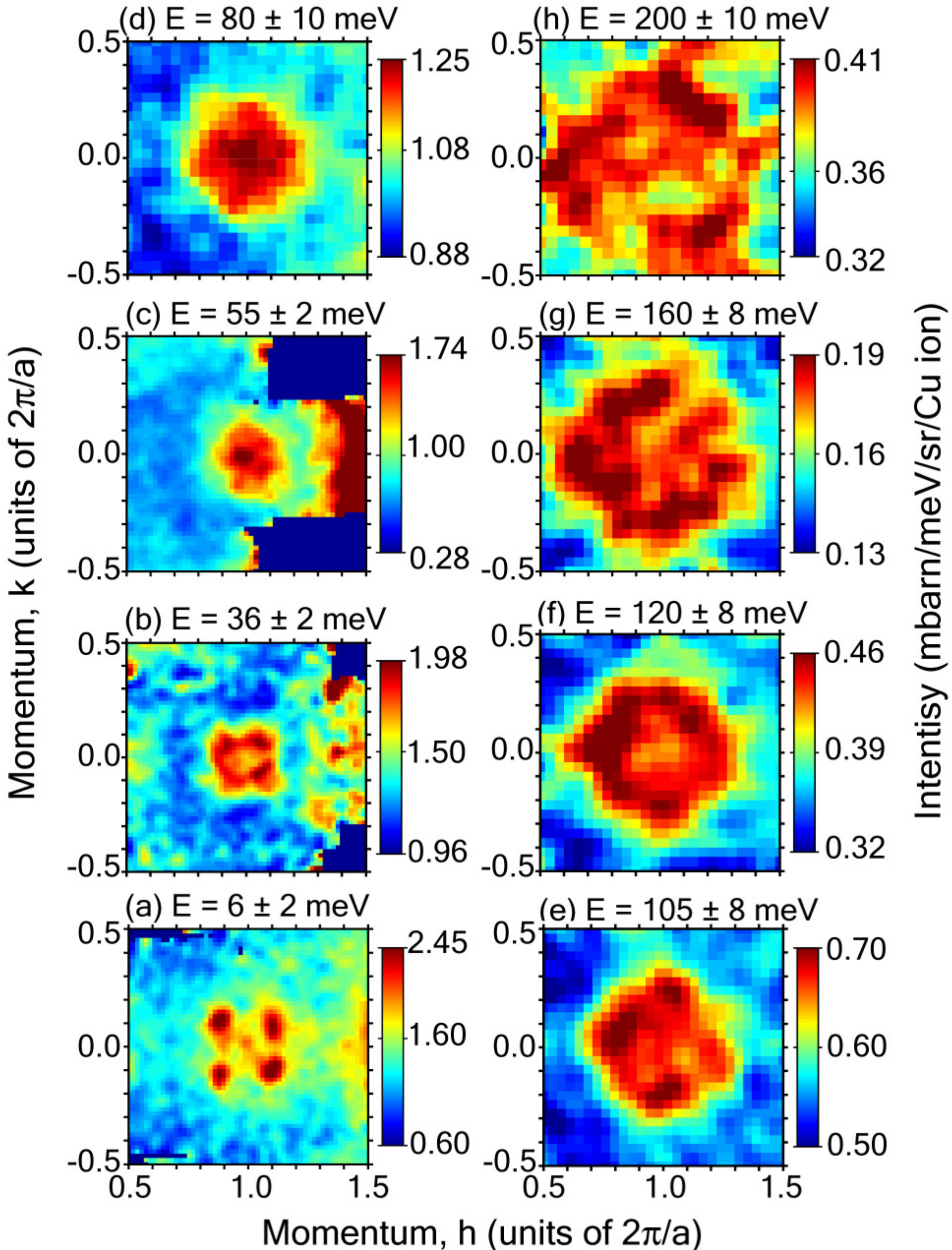
Key Question

- Does charge inhomogeneity (stripes)
  - Help superconductivity?
  - Or compete with superconductivity?
- Obvious that stripe order competes with superconductivity
  - Symbiotic interaction requires dynamic stripes

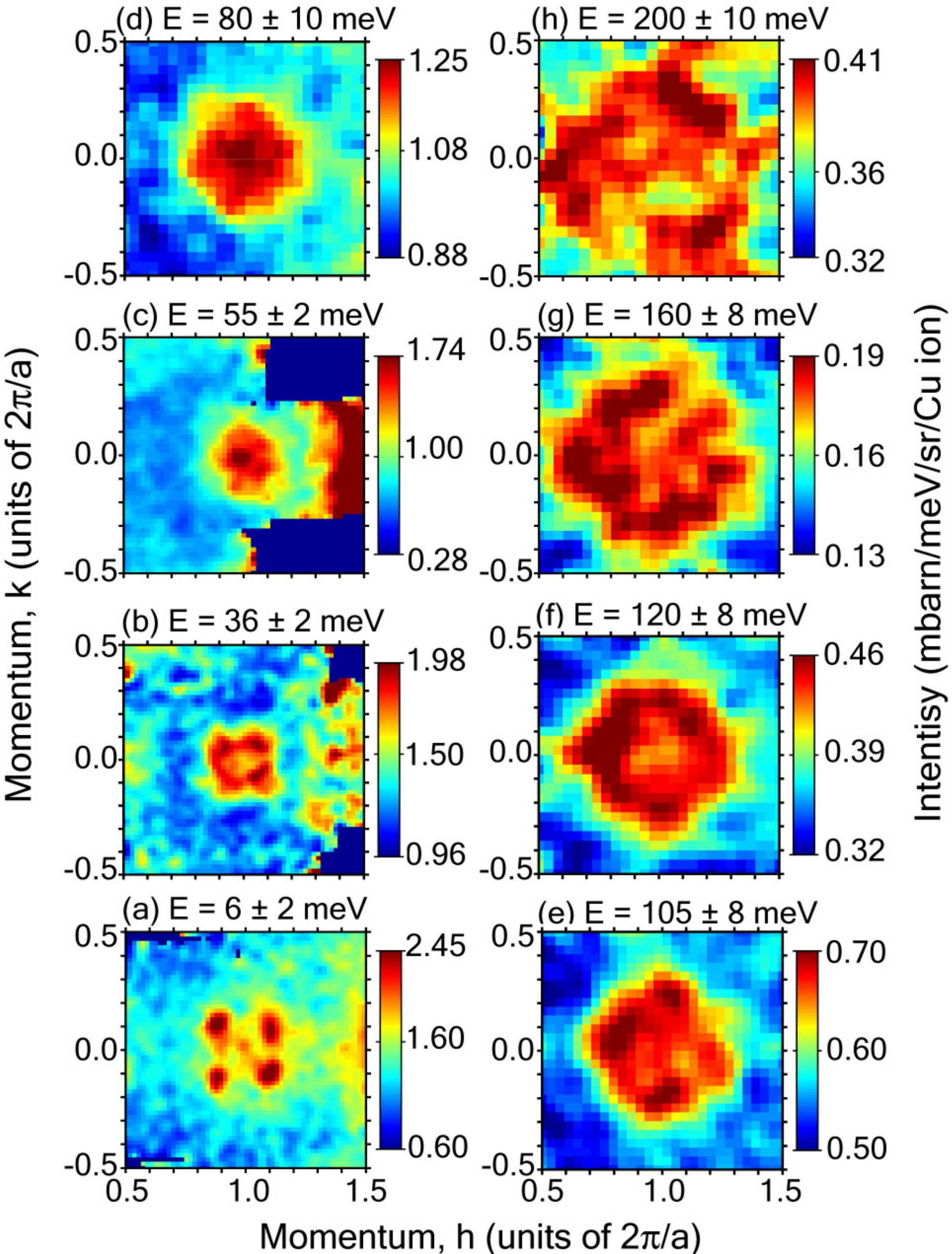
Expected scattering patterns in reciprocal space

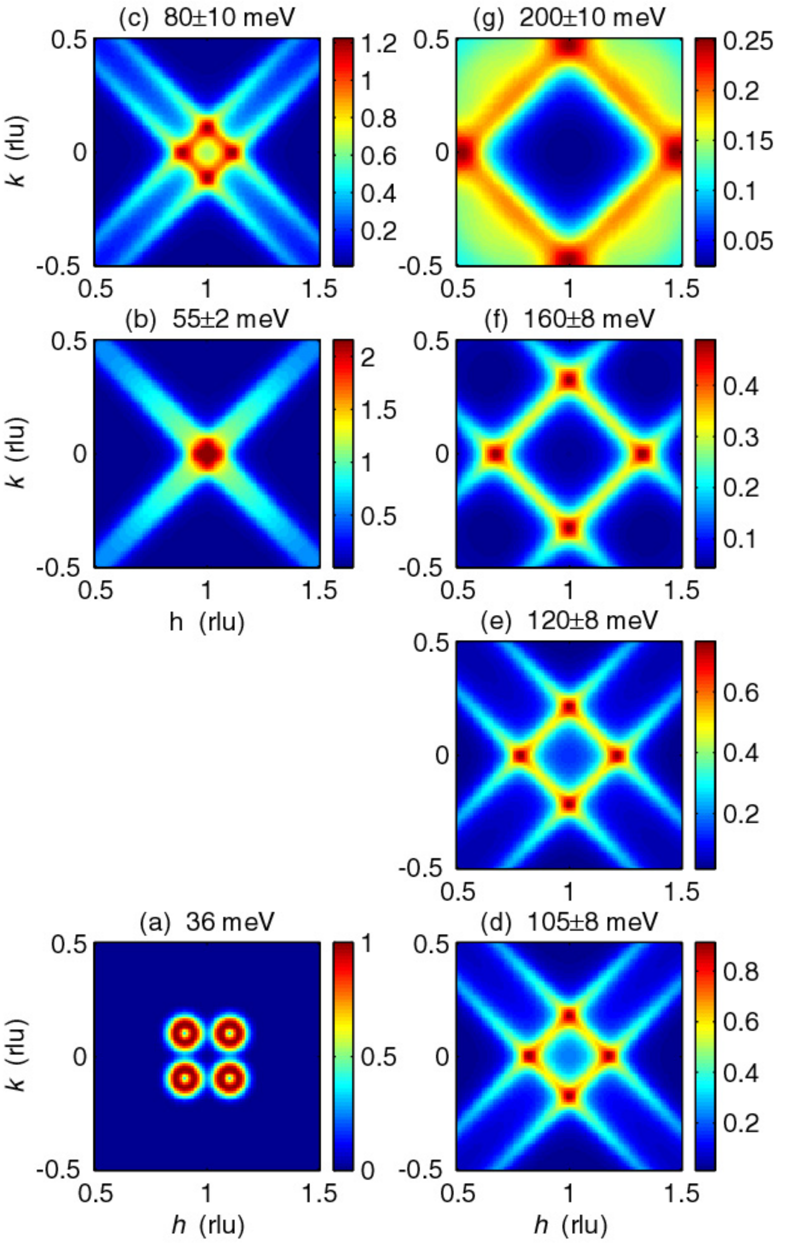


Constant-energy slices through magnetic scattering



Comparison with models





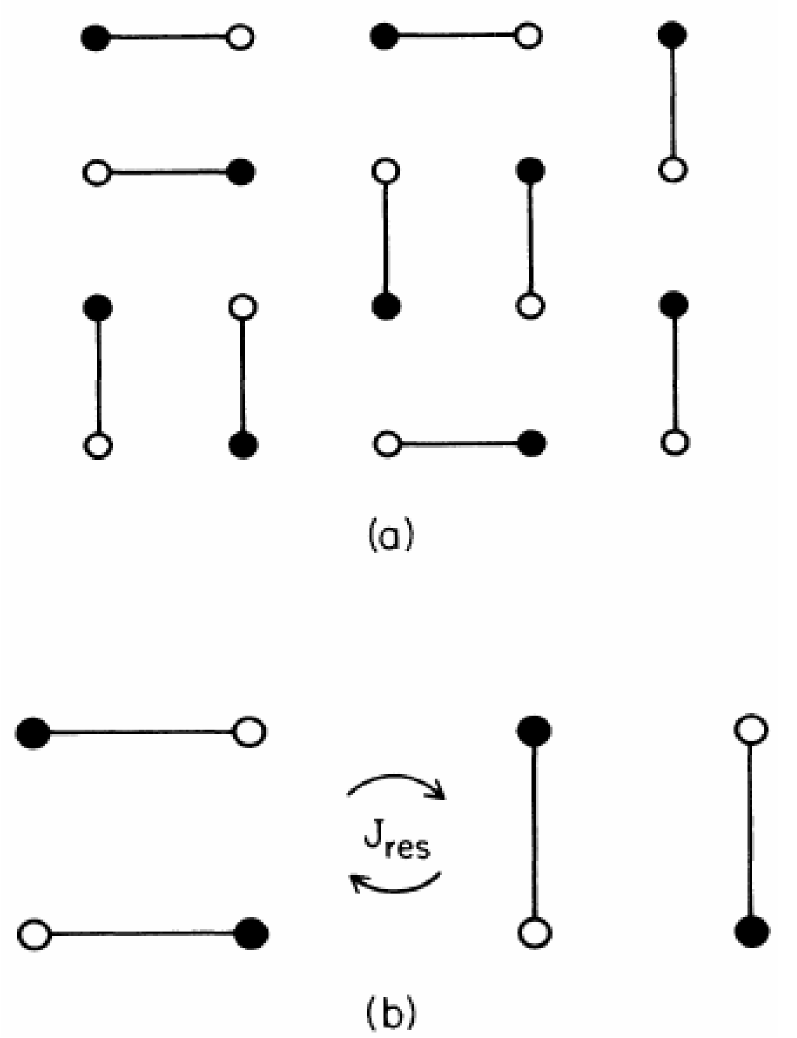
Mechanism of High Temperature Superconductivity in a Striped Hubbard Model

E. Arrigoni, E. Fradkin, and S. A. Kivelson

cond-mat/0309572

It is shown, using asymptotically exact methods, that the two dimensional repulsive Hubbard model with strongly modulated interactions exhibits high temperature superconductivity. Specifically, the explicit modulation, which has the same symmetry as period 4 bond-centered stripes, breaks the system into an alternating array of more and less heavily hole doped, nearly decoupled two-leg ladders. It is shown that this system exhibits a pairing scale determined by the spin-gap of the undoped two-leg ladder, and a phase ordering temperature proportional to a low positive power of the inter-ladder coupling.

Resonating Valence Bond (RVB) picture



PW Anderson, 1987

La_2CuO_4: 2D CuO_2 planes, S = 1/2 per Cu,

+ magnetic frustration(?)

⇒ Quantum Spin Liquid

Kivelson, Rokhsar, and Sethna, 1987

Considered local-singlet RVB

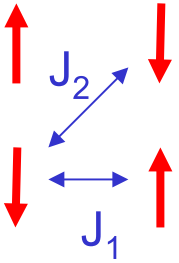
Existence of a spin gap leads to Bose condensation of doped holes

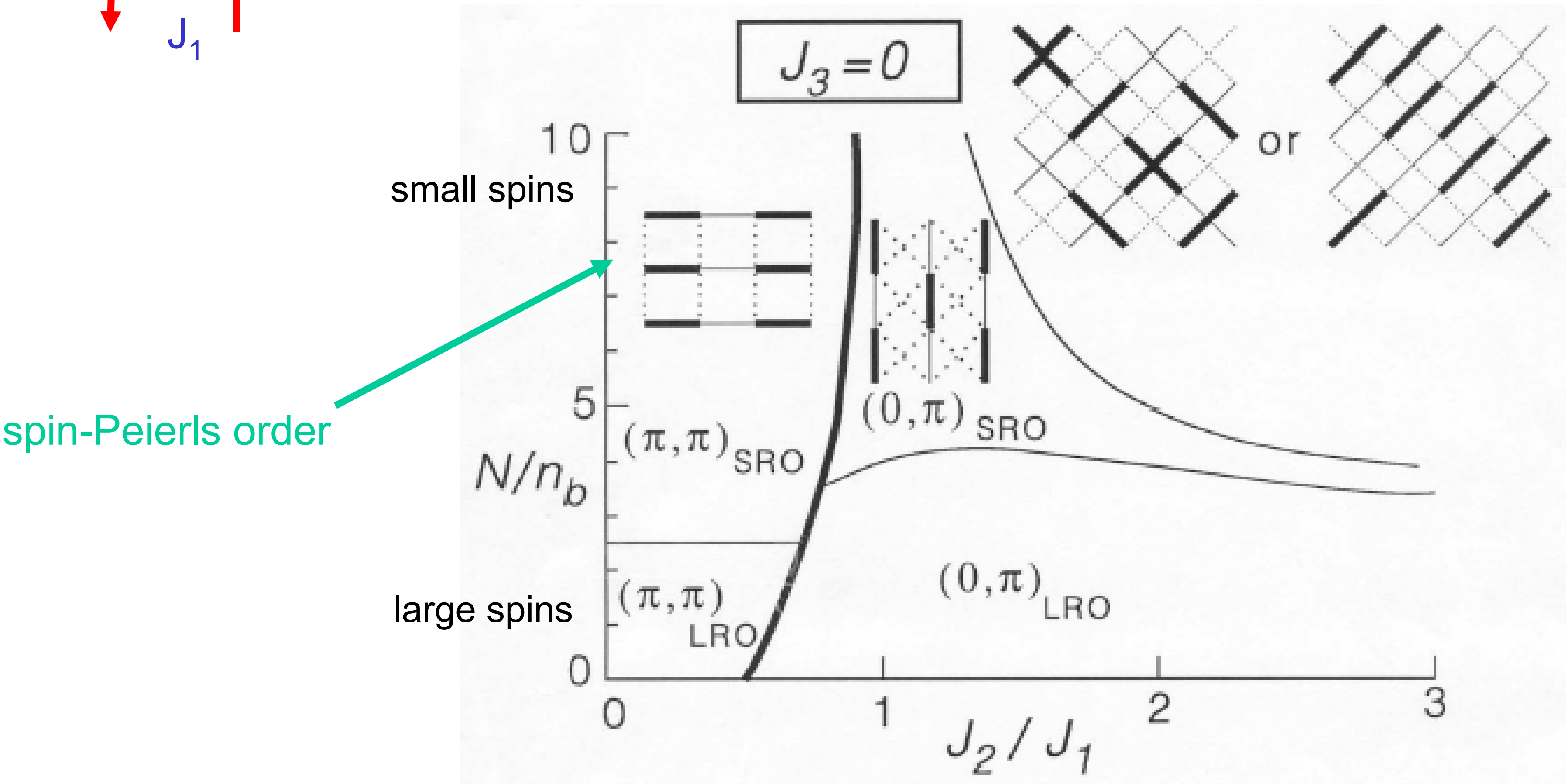
Requires dynamic modulation of superexchange by phonons

Reality: Cu-O bonds are stiff

Frustrated 2D Antiferromagnet

Sachdev and Read, 1991





small spins

large spins

spin-Peierls order

Why cuprates are exciting

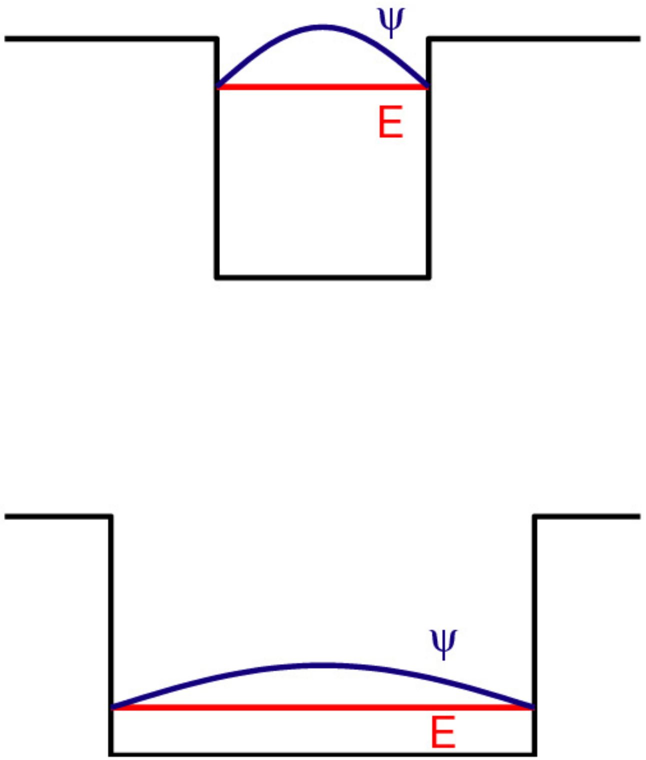
- Standard models fail
  - ☐ Band theory of electronic structure violated
    - Electronic states become localized (not extended) due to strong electron-electron interactions
  - ☐ BCS pairing mechanism is invalid
    - Electrons pair, but not due to electron-phonon interaction
- New many-body physics
  - ☐ Competing interactions of simple form give complex behavior

Kinetic energy and delocalization

$$KE = p^{2} / 2m$$

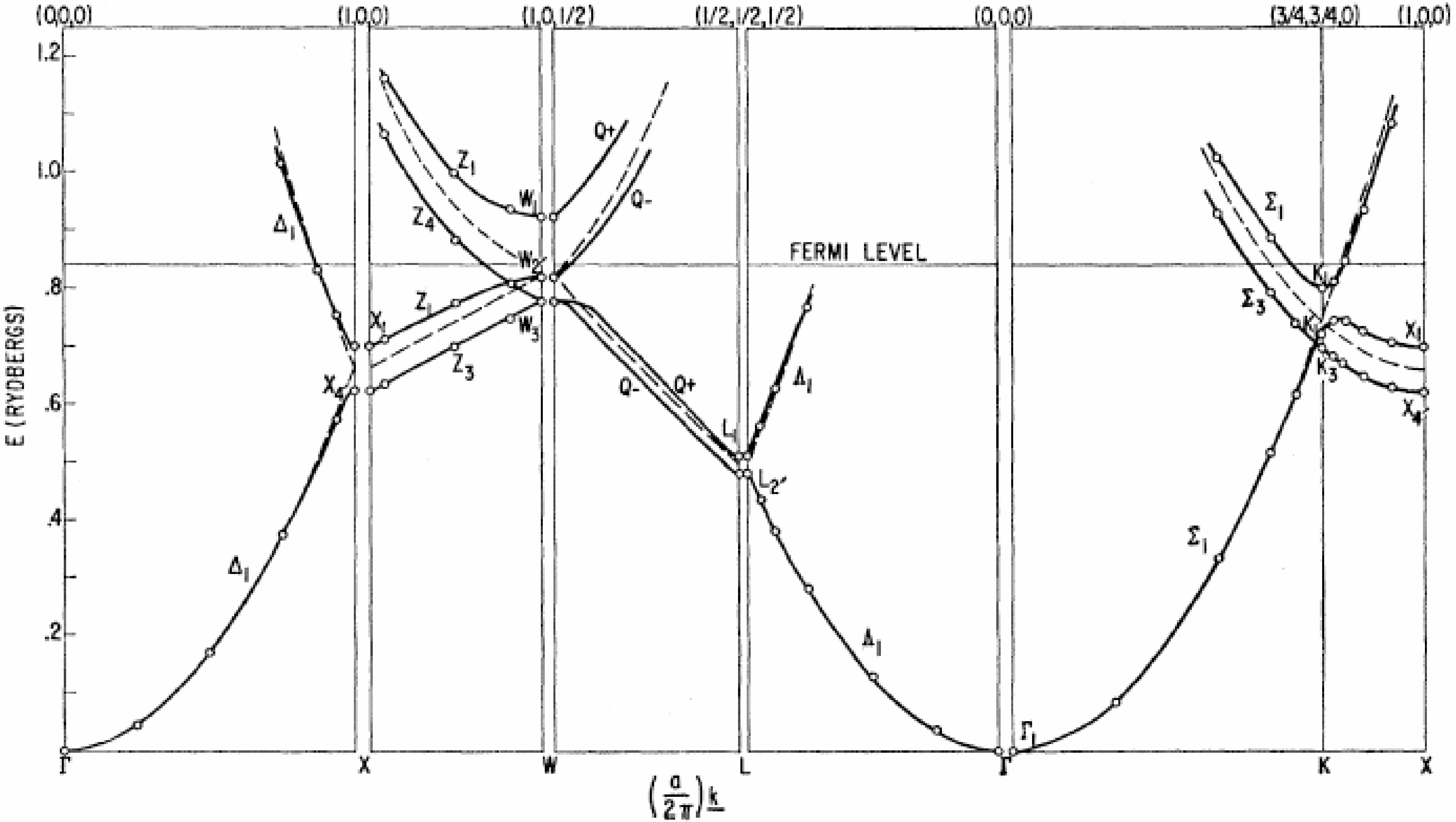
$$= h^{2}k^{2} / 2m$$

$$k = 2\pi / \lambda$$



Conduction electrons in a crystal will delocalize to minimize their kinetic energy

Band Structure of Aluminum



– – – – Free electron dispersion + lattice symmetry

—— Calculation by KKR method

B. Segal, Phys. Rev. **124**, 1797 (1961)

What are the magnetic excitations of stripes?