# Discussion of Electronic Nematic State

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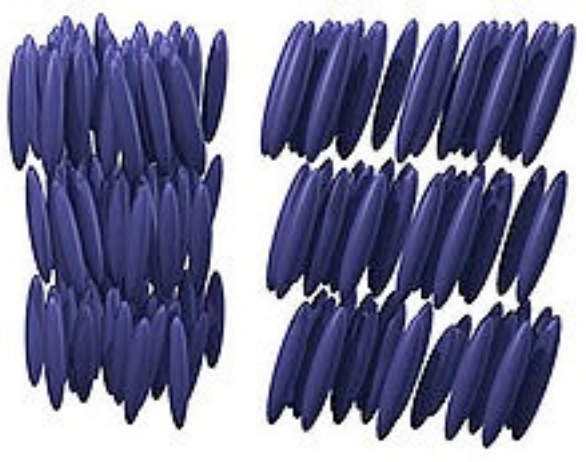
# Introduction: What is Nematic phase

- The word “Nematic” originally comes from Liquid Crystal (LCs 液晶).
- Liquid crystal is the a state of matter that have properties between those of conventional liquid and a solid crystal.
- Within a nematic phase, rod-shaped molecule have no position order, but they self align to have long-range directional order. (LCD)



- A smectic phase happens below temperature of nematic phase, by forming well-defined layer. Smectics are positional ordered in one direction.

# Analogy: What is Electronic Nematic phase

- With weak interaction, electron can be considered as quantum gas of quasiparticle -- fermi-liquid, homogeneous and isotropic. Analog to liquid.
- Sufficient strong interaction, electrons crystallize, freezing into an insulating state, exhibits density modulations. Analog to crystals.
- View from symmetry-breaking
- **<u>Definition</u>**:
  **(1)**Liquid phase breaks no spatial symmetry.
  **(2)**Nematic phase breaks rotation symmetry, but leaves both translation and reflection symmetry unbroken.
  **(3)**Smectic phase breaks translation symmetry in only one direction.
  **(4)**Crystalline phase breaks translation symmetry.

# Define Electronic Nematic phase order parameter

$$\mathcal{N} = \frac{\rho_{xx} - \rho_{yy}}{\rho_{xx} + \rho_{yy}}$$

$$\mathcal{Q}_{\mathbf{k}} \equiv \frac{S(\mathbf{k}) - S(\mathcal{R}[\mathbf{k}])}{S(\mathbf{k}) + S(\mathcal{R}[\mathbf{k}])},$$

where R is rotation by π/2, and

$$S(\mathbf{k}) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} S(\mathbf{k},\omega)$$

$$\mathcal{N} = \frac{\langle \vec{\sigma}_{\vec{R}} \cdot \vec{\sigma}_{\vec{R}+\hat{x}} \rangle - \langle \vec{\sigma}_{\vec{R}} \cdot \vec{\sigma}_{\vec{R}+\hat{y}} \rangle}{\langle \vec{\sigma}_{\vec{R}} \cdot \vec{\sigma}_{\vec{R}+\hat{x}} \rangle + \langle \vec{\sigma}_{\vec{R}} \cdot \vec{\sigma}_{\vec{R}+\hat{y}} \rangle}$$

etc...

# Mechanism of Electronic Nematic

- Analog to liquid crystal: How point-like shapeless electron behaves stripe-like nematic order.

# Mechanism of Electronic Nematic: Two perspectives

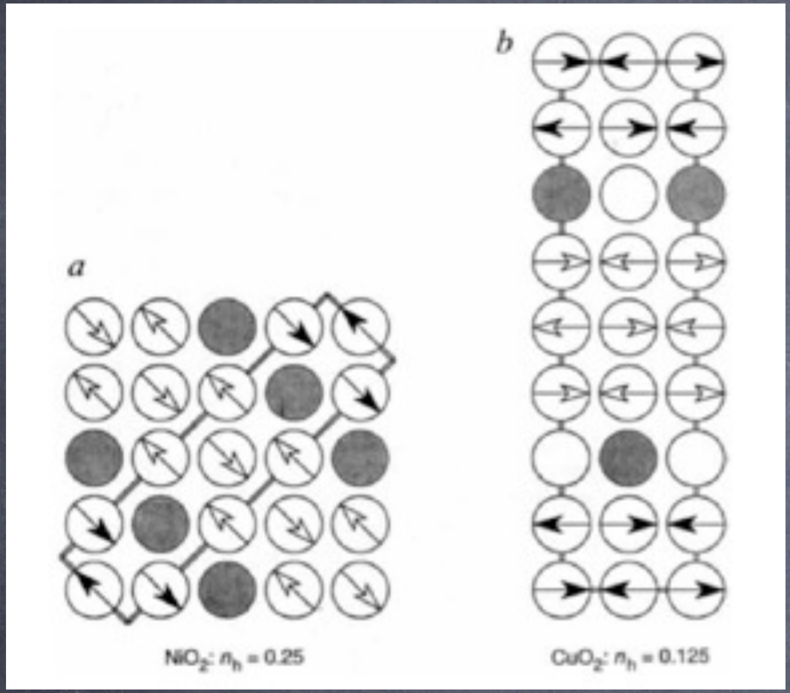
- Strong correlated system: nematic state derives from melting of smectic state.
- Fermi-liquid-like perspective: Pomeranchuk instability breaks symmetry of fermi surface defined by quasiparticles.

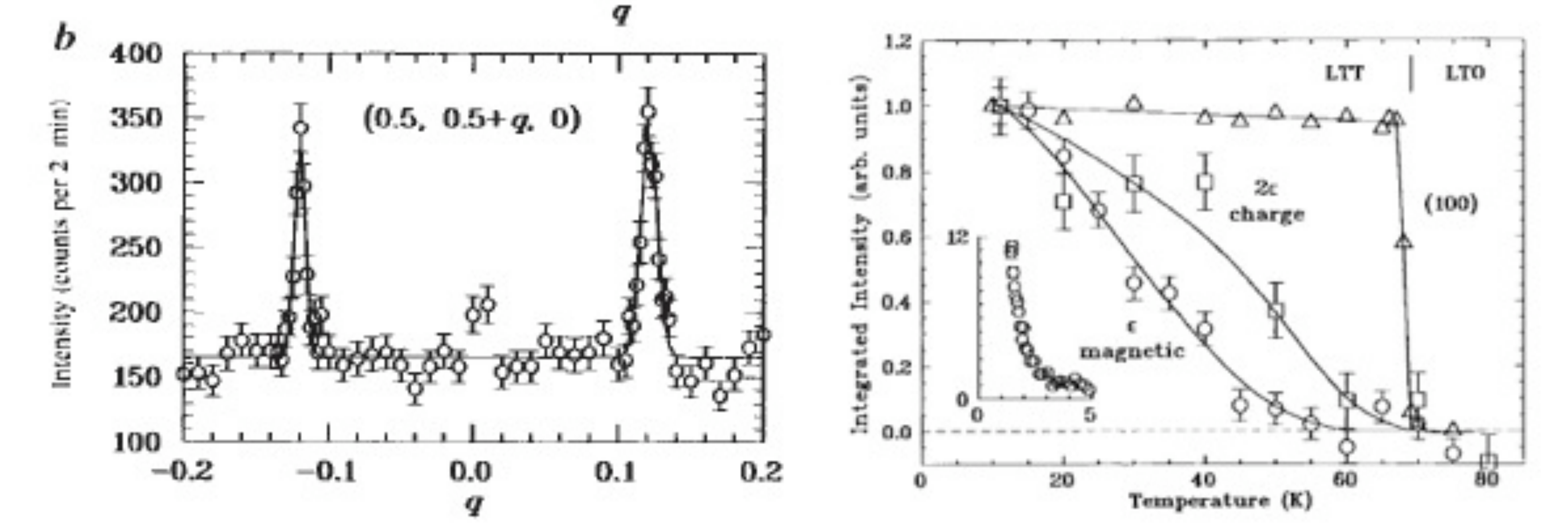
# Mechanism ——A melting process: what is electronic stripe order

- **CONDITION** Coulomb interactions are sufficiently weak (dielectric constant is large enough)
  **RESULT** System lower its energy by locally phase separating into small regions of hole-rich and hole-poor material (charge density inhomogeneous)

- Considering quantum dynamical process, heavily-doped material: creating small dipolar regions does NOT involve large motion of charge. ***Local, low-energy collective modes***: Classical dipolar becomes Local dipolar modes. (measured by antiferromagnetic correlation length etc.)

# Electronic stripe order
# Experiment evidence: High Tc cuprate SC





LEFT: Scans of superlattice peaks incommensurate with the crystal lattice, HOWEVER consistent with the proposed spin and charge stripes. $La_{1.48}Nd_{0.4}Sr_{0.12}CuO_4$ at 11K.

a, Idealized diagram of spin and charge stripe pattern in $NiO_2$ plane

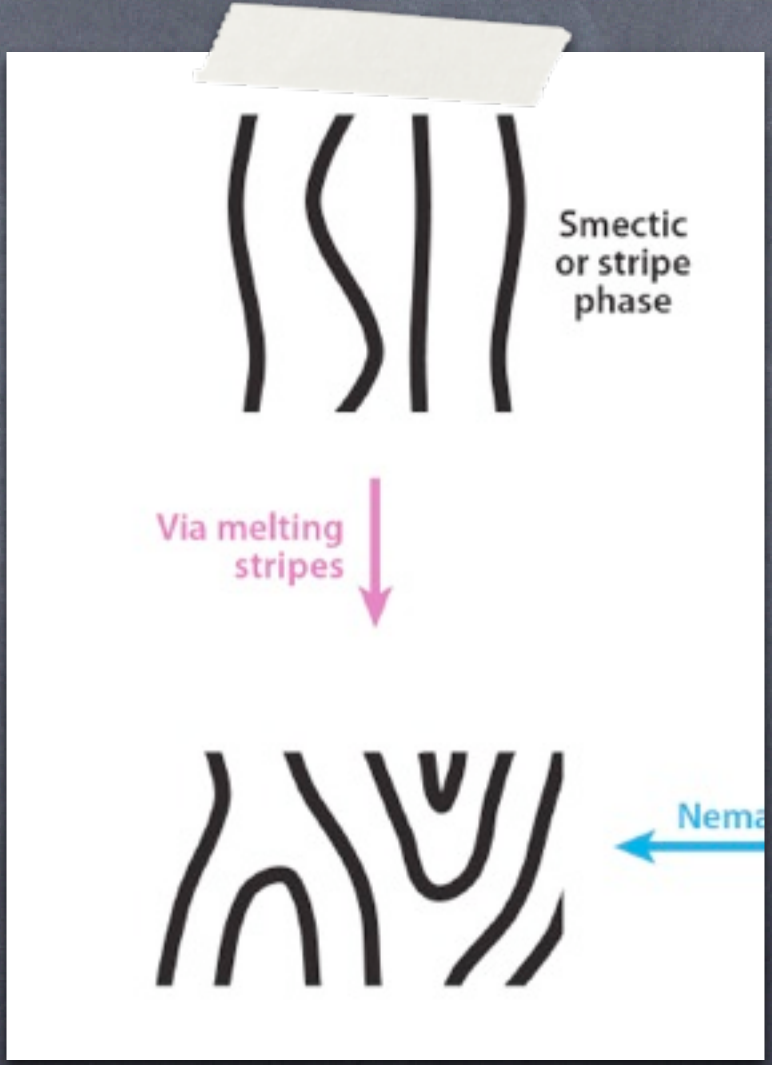
b, Hypothesized stripe pattern in $CuO_2$ place of $La_2CuO_4$

RIGHT: Temperature dependence of peak intensities. Results show for the magnetic (0.5,0.5-ε,0) (circle), charge-related (0,2-2ε,0) (squares).

*Nature* **375**, 561 - 563 (15 June 1995)

# Mechanism of Electronic Nematic Outline: a melting process

- Similar to the theory developed in complex classical fluids.
- Keyword: dislocations — — topological defects of strips
- Take place via thermal phase transition or quantum phase transition.



# Mechanism —— melting process : A simple model of 2-D stripe array

Consider an isolated metallic stripe in a Mott insulator

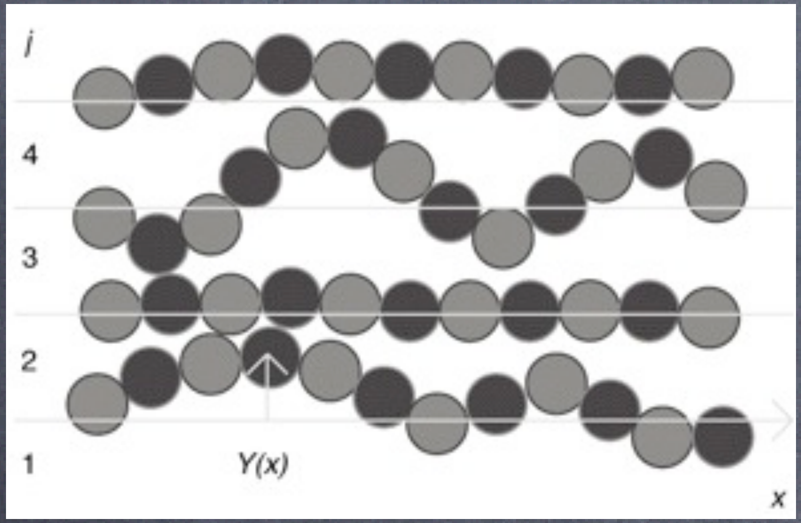


**Figure: Schematic representation of a smectic stripe phase. The circles represent periodic structures along the stripes, which are forced out of phase by the transverse fluctuations.**

Interactions between stripes typically drive a transition to an insulating ordered charge-density-wave (CDW) state at low temperature.

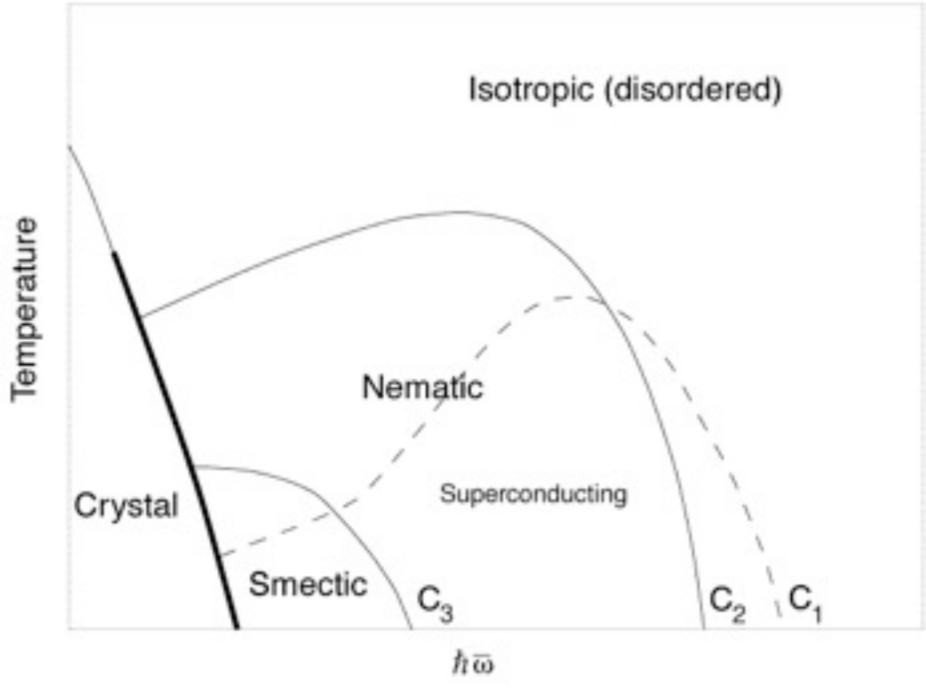
$$H_c = \sum_j \int \mathrm{d}x V(\Delta_j Y)\cos[\sqrt{2\pi}(\Delta_j \phi) - 2k_{\mathrm{F}}(\Delta_j L)] \qquad (4)$$

**The coupling Hamiltonian between the CDWs on neighboring stripes**

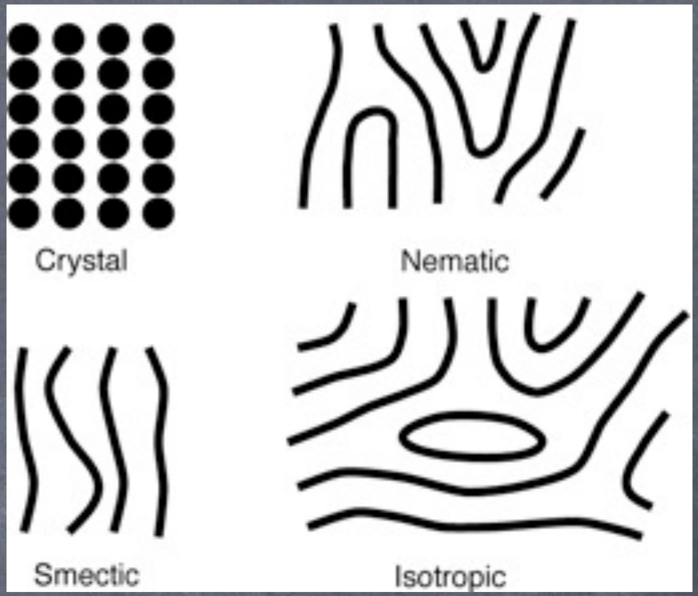
**“ϕ” defines the phase of the CDW**
**“L” is the arc-length, that is the distance measured along the stripe j.**

*Nature 393, 550-553 (11 June 1998)*

# Mechanism —— melting process
# A simple model of 2-D stripe array: Results discussion



**Phase diagram: Here "hω" is a measure of magnitude of transverse zero-point fluctuations of the stripes**



- Low " **hω**" the phases of CDWs on neighboring strips are locked, the transverse stripe fluctuations become the phonons of fully ordered crystal.
- $$\langle J \rangle \approx J_0 \exp\{(\alpha^2/2)\langle[\Delta_j Y]^2\rangle\} \qquad (8)$$
  Effective Josphenson Coupling.
  Hence the superconducting coupling is strongly enhanced by the transverse stripe fluctuations.

# Mechanism ——A melting process: General consideration

- The theory of quantum smectic-nematic phase transition by a dislocation proliferation mechanism remains an open problem.
- Since the degrees of freedoms are electrons, from which these nano-structures form, electron nematic is typically an anisotropic metal.
- Similarly, nematic order can also arise from thermal or quantum melting a frustrated quantum antiferromagnet.

# Mechanism ——Pomeranchuk instability: Fermi-liquid-like perspective

- Classic result due to Pomeranchuk (1958), that shows a Fermi liquid is thermodynamically stable. However if some conditions are violated a thermodynamic (Pomeranchuk) instability occurs.

- Along with Pomeranchuk instability, the system must undergo a quantum phase transition in which the symmetries of the Fermi liquid state are lowered.

- The anisotropic nature of nematic ground state leads to a transport anisotropy, which is tuned by magnitude of the order parameter.

- No suitable quantitative theory for these problems yet. Hartree-Fock theory is not reliable in strong correlation regimes. There are conflicting results on some subjects.

# How to detect Electronic Nematic Order or Fluctuation

- difficulty and ambiguousness

# How to detect Electronic Nematic Order/Fluctuation
## Strategies

- Generally, we are interested in electronic liquid-crystal states and their associated fluctuations, but the results are also easily generalized to other forms of order.

- Although nematic order involves the spontaneous breaking of a spatial symmetry, true macroscopic measurements of spontaneous nematic symmetry breaking are not possible.

- The ordered phase may be induced by making small changes to the chemical composition of material, applying pressure or magnetic fields, etc.

- Almost all tests of nematic order necessarily involve the observation of an **unreasonably** large, and **strongly** T-dependent, anisotropy in electronic response to a **small** symmetry-breaking field.

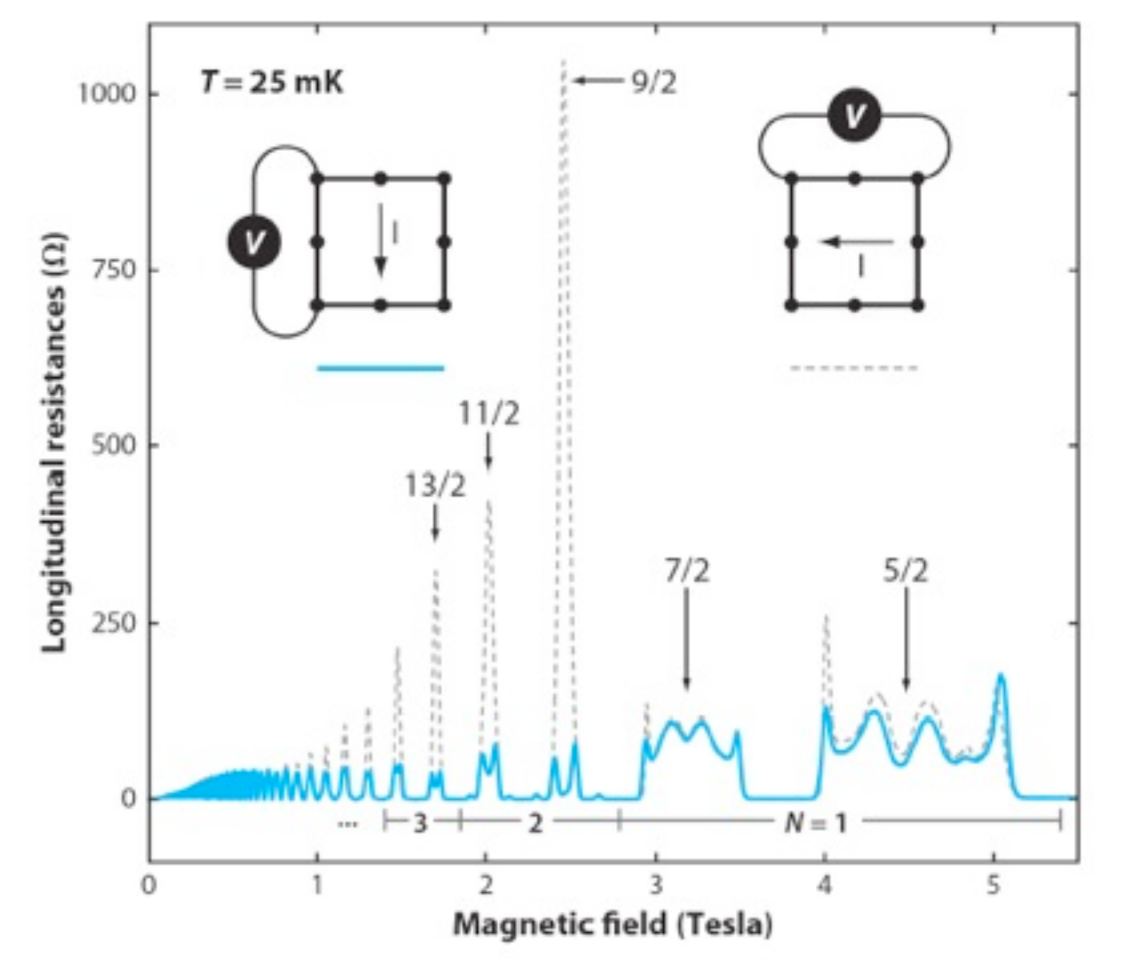
# How to detect Electronic Nematic Order/Fluctuation

## Strategies

- Typically, the best way to detect both the broken-symmetry state and the relevant fluctuations is by appropriate dynamical structure factor S(q,ω).
- Indeed x-ray and neutron scattering studies have provided the best evidence of ordered and fluctuating stripe phases.
- However, in many interesting materials, appropriate crystals are not available. Here, probes of local order, such as NMR, NQR, uSR, STM techniques may be the best available.
- In a pure quantum system, the order-parameter fluctuations are not static. Unless something is done to pin these fluctuation, they are invisible to local probes.
- Pinning such as boundaries, vortices, crystal-field effects, weak quenched disorder , etc.

# GaAs/GaAlAs Experiment facts:
# Evidence of existence of electronic nematic phase

- Two-dimensional electron systems.
- Best known for their display of fractional quantized Hall (FQH) effect, when a large magnetic field is applied perpendicularly.

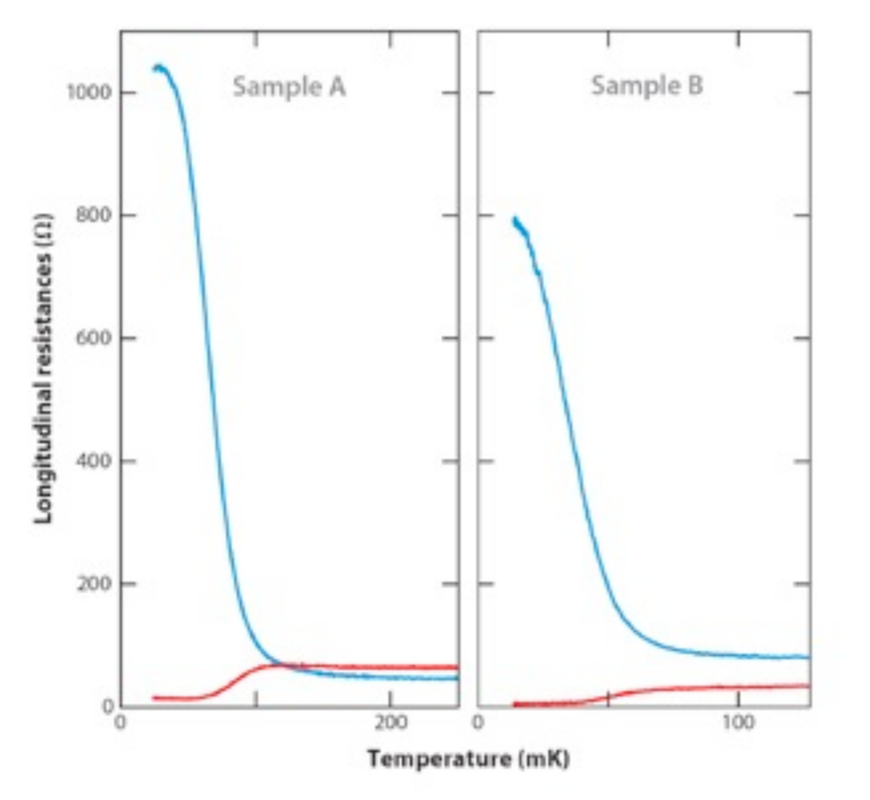


Substantial resistance anisotropy was observed by a perpendicular magnetic field to 2-D plane.

At Landau level filling factor v=9/2, 11/2, 13/2 etc. T=25mK

*1999 Phys. Rev. Lett. 82 394-397*

# GaAs/GaAlAs Experiment facts:
# Evidence of existence of electronic nematic phase



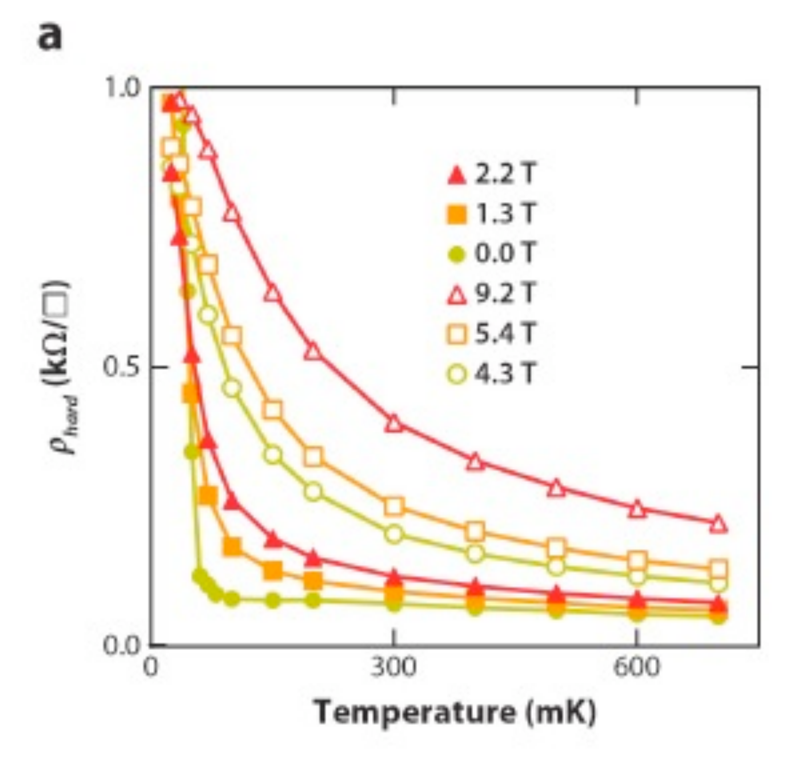
- The anisotropy subsides rapidly with increasing T, and is essentially absent above T=150mK
- This effect is largely independent of temperature and magnetic field.

- Hard transport direction lies along <1$\underline{1}$0> , stripes tend to lie along <110>.
- In-plane field along <110> interchange hard and easy transport direction.

# GaAs/GaAlAs Experiment facts:
# Evidence of existence of electronic nematic phase

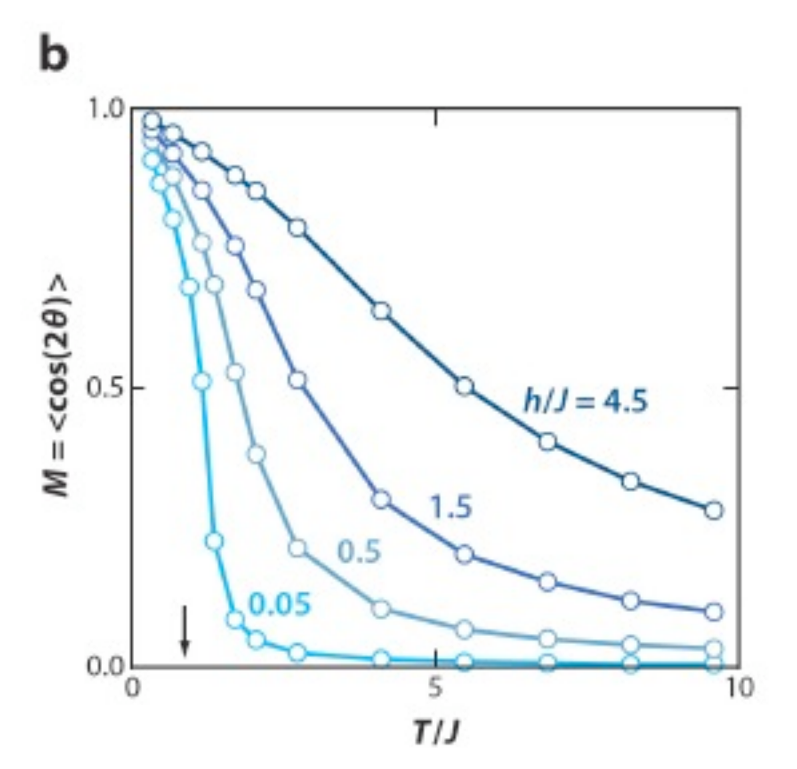
- Hartree-Fork theories of CDW formation estimated that CDWs would form at temperature is few Kelvin.
- Interesting possibility is that local stripe order may appear within small domains. Thermal fluctuations prevent long range orientational order.
- In this view, a in-plane magnetic field would order domains and thereby induce resistive anisotropy at elevated temperature.

# GaAs/GaAlAs Experiment facts:
# Evidence of existence of electronic nematic phase

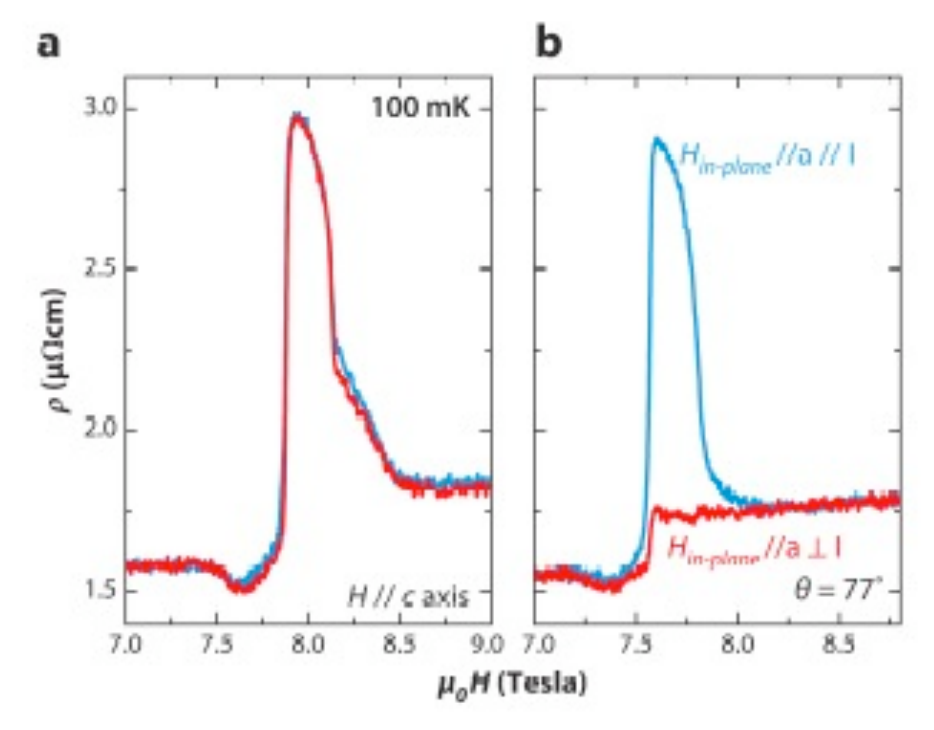


- In-plane field dramatically increases the temperature range of resistive anisotropy
- Importantly, no significant anisotropy at v=3/2, which discounts that in-plane field itself creating an anisotropy.

- reminiscent of how a ferromagnet responds to an external magnetic field.
- Results of Monte Carlo calculation on a 2D XY model with varying symmetry breaking potential.



# Bilayer ruthenate $Sr_3Ru_2O_7$ Experiment facts: Metamagnetism and Nematicity

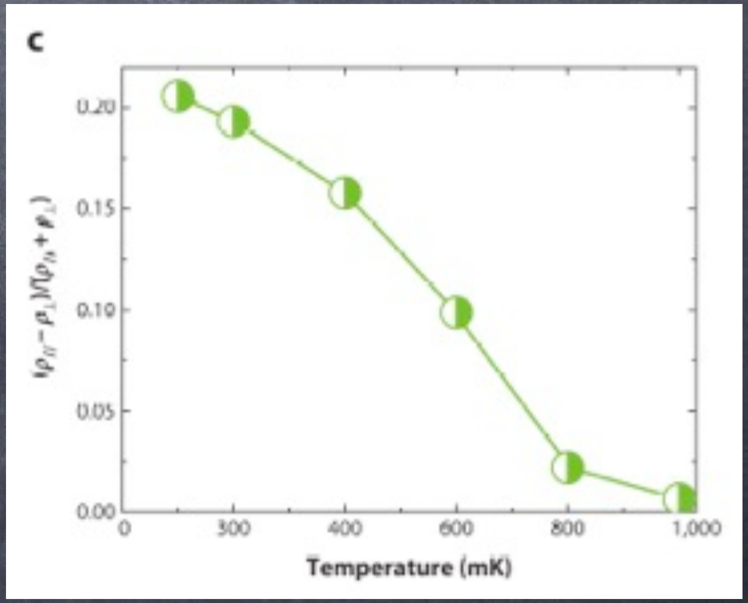


- Applied by magnetic field along c-axis (perpendicular to conduction layer), it displays a standard metallic magnetoresistance.

- However, if sample is tilted slightly to provide an in-plane field component, resistivity becomes strongly anisotropic.

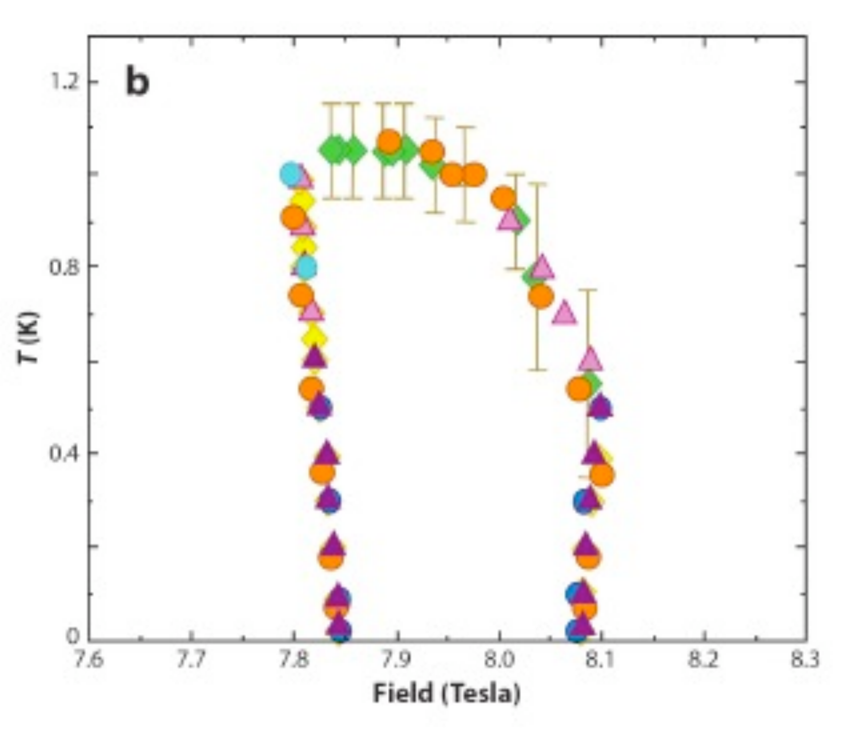
- $Sr_3Ru_2O_7$ hosts a symmetry broken nematic phase between 7.8T and 8.1T. With domain formation masking the anisotropy.

- Providing an in-plane field component aligns these domains and reveals full effects of symmetric breaking.



*2007 Science 315 214-17*

# Bilayer ruthenate $Sr_3Ru_2O_7$ Experiment facts: Metamagnetism and Nematicity



- Existence of a fully bounded thermodynamic phase.
- Magnetocaloric and specific heat show the boundary represent thermodynamic phase transition
- Within the resolution of neutron scattering, it is isotropic in the plane.
- Unusually, the entropy within the phase is higher than adjacent fluids.

- Open questions like: Entropy and scale of resistive anisotropy.

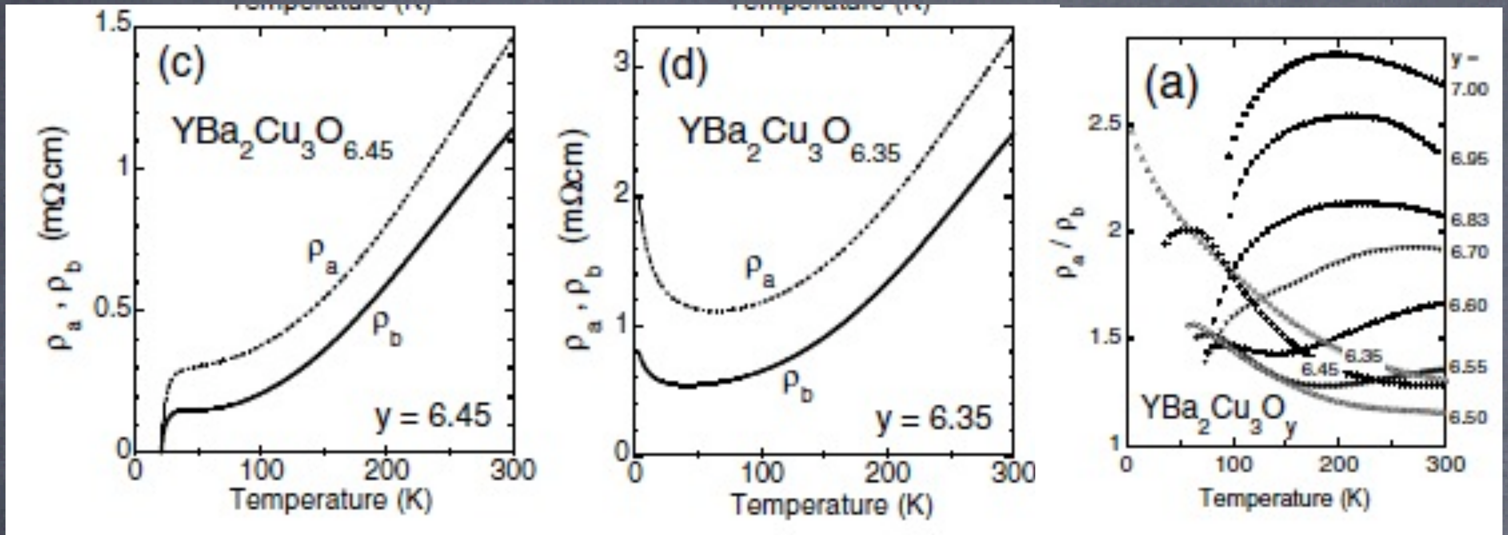
# Cuprate high Tc superconductors experiment facts: Transport anisotropies

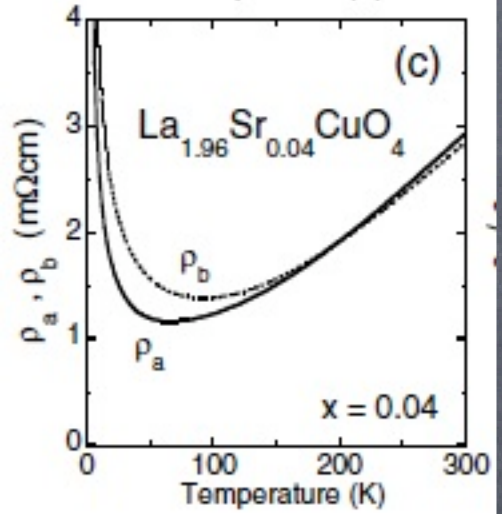
- Ex. $YBa_2Cu_3O_{6+x}$, $La_{2-x}Sr_xCuO_4$(non-sc), are orthorhombic.
  ***Good***: orthorhombicity exerts a symmetry breaking field.
  ***Bad***: macroscopic anisotropy is to be expected as a consequence of orthorhomicity itself.

- Same logic as before,
  small and weakly T dependent anisotropies at High T → consequence of crystal structure.
  Large magnitude, strongly T depend below a well defined crossover T → associated with onset of electronic nematic order.

- However, it is hard to say how large an observed anisotropy must be in order to accepted as “large” response to orthorhomicity, without a quantitative theory.

# Cuprate high Tc superconductors experiment facts: Transport anisotropies

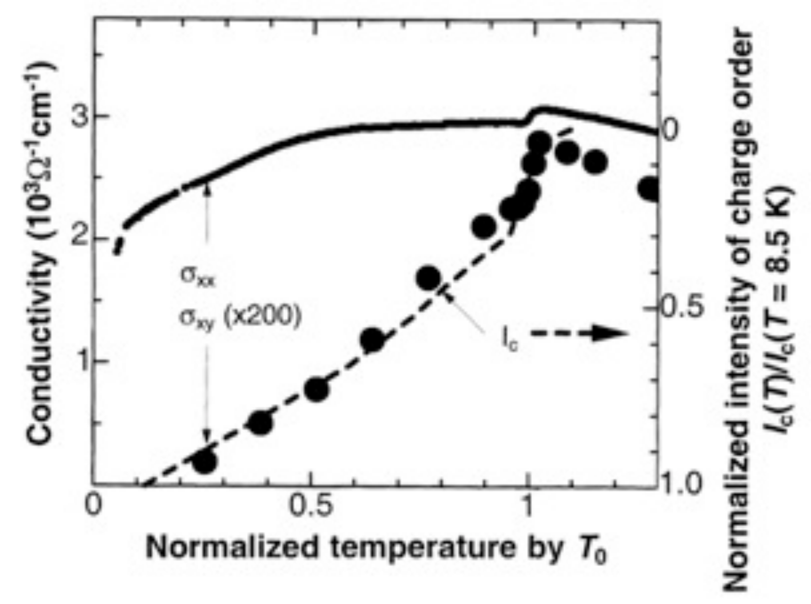




- Resistivity anisotropies as large as factor of 2 have been observed in detwinned single crystals.
- More recently neutron scattering study of magnetic structure of $YBa_2Cu_3O_{6+x}$ revealed order one anisotropy below well-defined ordering T~150K. [2008 Science 319 597-600]
- More subtle investigations of orientational symmetry breaking can be undertaken by studying the transport in a magnetic field

*2002 Phys. Rev. Lett. 88 137005*

# Cuprate high Tc superconductors experiment facts: Transport anisotropies

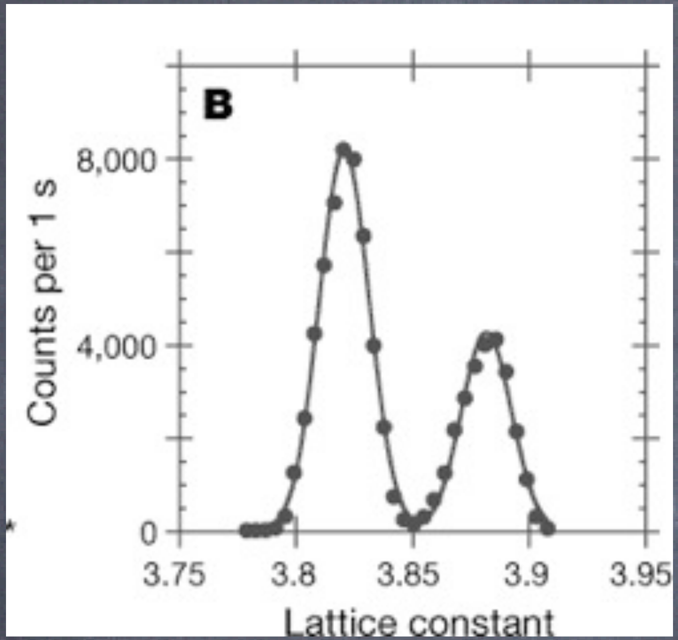


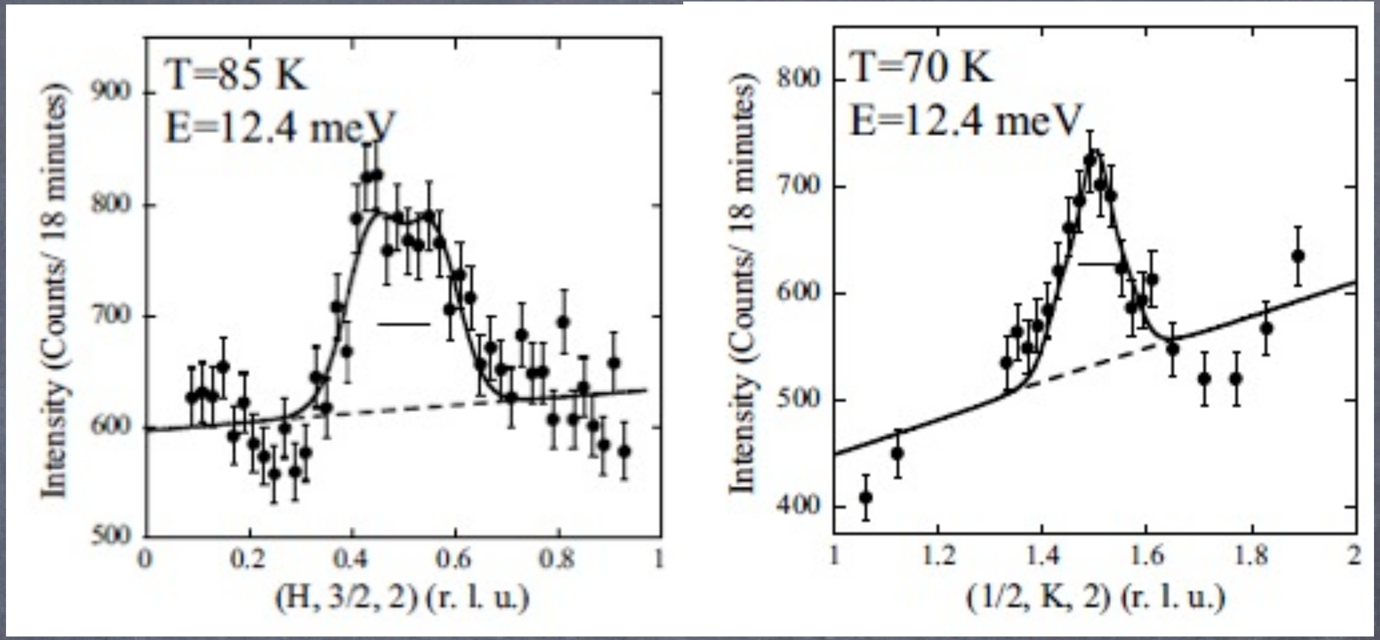
- A magnetic field perpendicular to the CuO2 planes in order to break fourfold symmetry of crystal structure. $La_{2-x-y}Nd_ySr_xCuO_4$
- $\sigma_{xx}$ keeps large value even at the lowest T, reduction of $\sigma_{xy}$ demonstrates that charge order suppresses transverse motion of carriers.

- Remarkable anisotropy of resistivity tensor was also observed by an in-plane magnetic field in $YBa_2Cu_3O_{6+x}$. x=0.32 and 0.3
- Results were interpreted as evidence for nematic stripe order. HOWEVER, alternative explanations of anisotropy associated with spin-orbit coupling in antiferromagnetic phase.

*1999 Science 286, 265     1999 Phys. Rev Lett 83, 2813*

# Cuprate high Tc superconductors experiment facts: Anisotropic diffraction patterns





- Microscopic approach, directly measure the order parameter. $\mathcal{Q}_{\mathbf{k}} \equiv \frac{S(\mathbf{k}) - S(\mathcal{R}[\mathbf{k}])}{S(\mathbf{k}) + S(\mathcal{R}[\mathbf{k}])}$,
- Well-developed structure was observed in inelastic spectrum at vector $\mathbf{Q}_S$ ~ (0.5+0.1, 0.5) and $\mathbf{Q}'_S$ ~ (0.5, 0.5+0.1). Associated with ordering vectors perpendicular to the chain direction. Order parameter ψ~1. (left-YBCO)
- Two barely resolved incommensurate peaks at the stripe-order wave vector was observed. However a single sharp peak at chain direction.(right-YBCO)

*2000 Nature 404, 729   Cond-Mat/0308168*

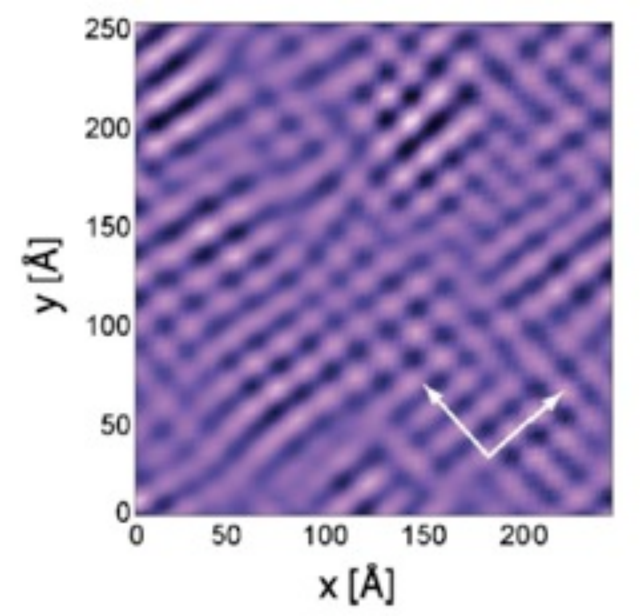
# Cuprate high Tc superconductors experiment facts: STM imaging of nematic order

- Because STM is a local but spatially resolved probe, it is actually the optimal probe of nematic order.

- A filtered version of the local-density-of-states map $N_f(r,E)$ of $Bi_2Sr_2CaCu_2O_{8+\delta}$, by

$$N_f(\mathbf{r},E)=\int d\mathbf{r}'f(\mathbf{r}-\mathbf{r}')N(\mathbf{r}',E),$$

$$f(\mathbf{r})\propto\Lambda^2e^{-r^2\Lambda^2/2}[\cos(\pi x/2a)+\cos(\pi y/2a)].$$

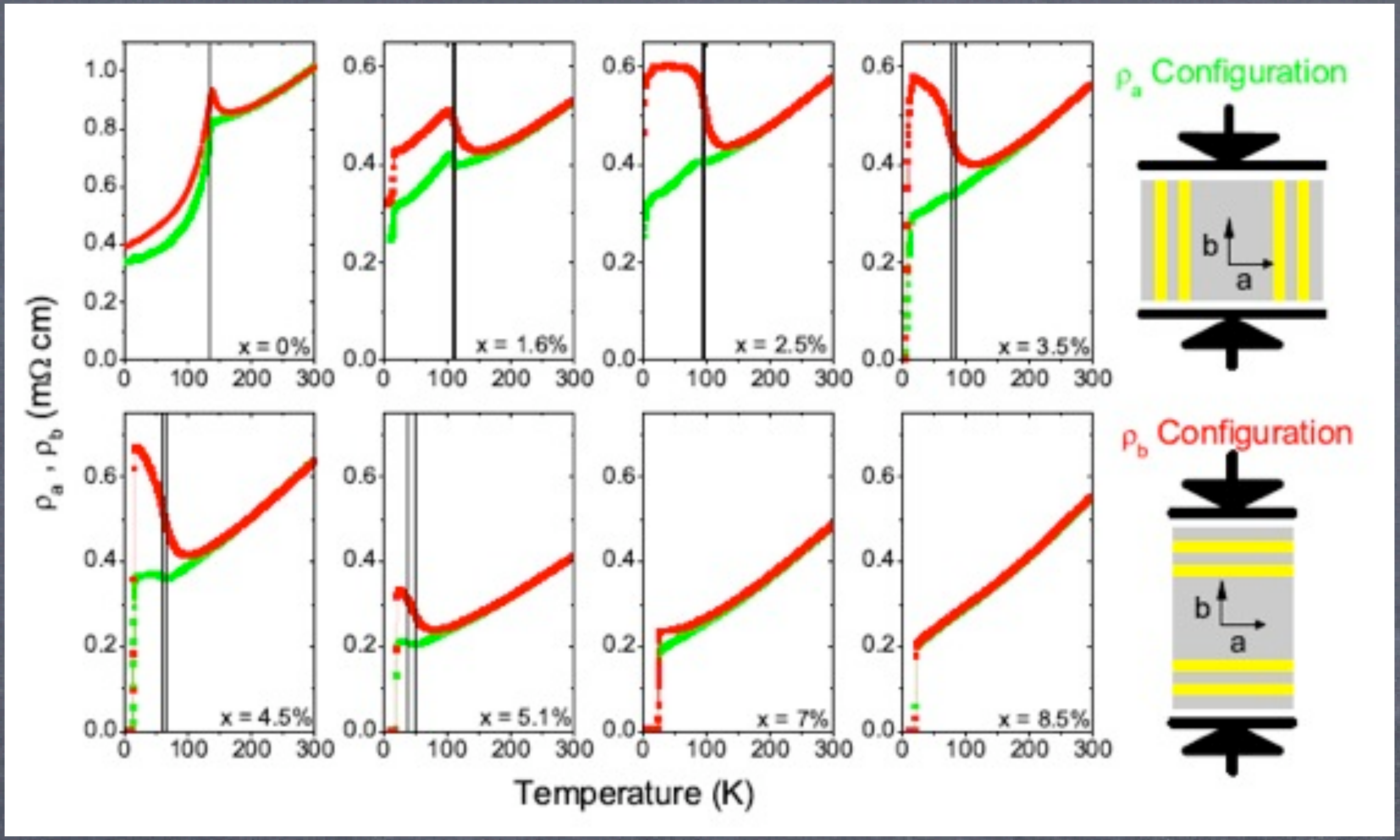


- The filtered image shows only the portion associated with pinned stripes.

- This particular method of analysis builds directly on: the nematic as a melted stripe-ordered state.

*Phys. Rev. B 67, 014533*

# Iron-pnictide high Tc superconductors experiment briefing



- Pressure serves as a symmetry-breaking field.
- Quantitive theory is desperately needed concerns the relation between transport properties and nematic order.

# Conclusion and Prospect

- A relative clear picture of nematic state mechanism as melted stripe order. Although microscopic mechanism of stripe order is not clear.
- Nematic detection: macroscopic isotropic → **unreasonably** large, and **strongly** T-dependent, anisotropy in electronic response to a **small** symmetry-breaking field.
- Accumulated experiments facts help us to build insights and intuition.
- It appears structural distortion is a consequence of electron nematicity, maybe important related to iron-pnictide sc.