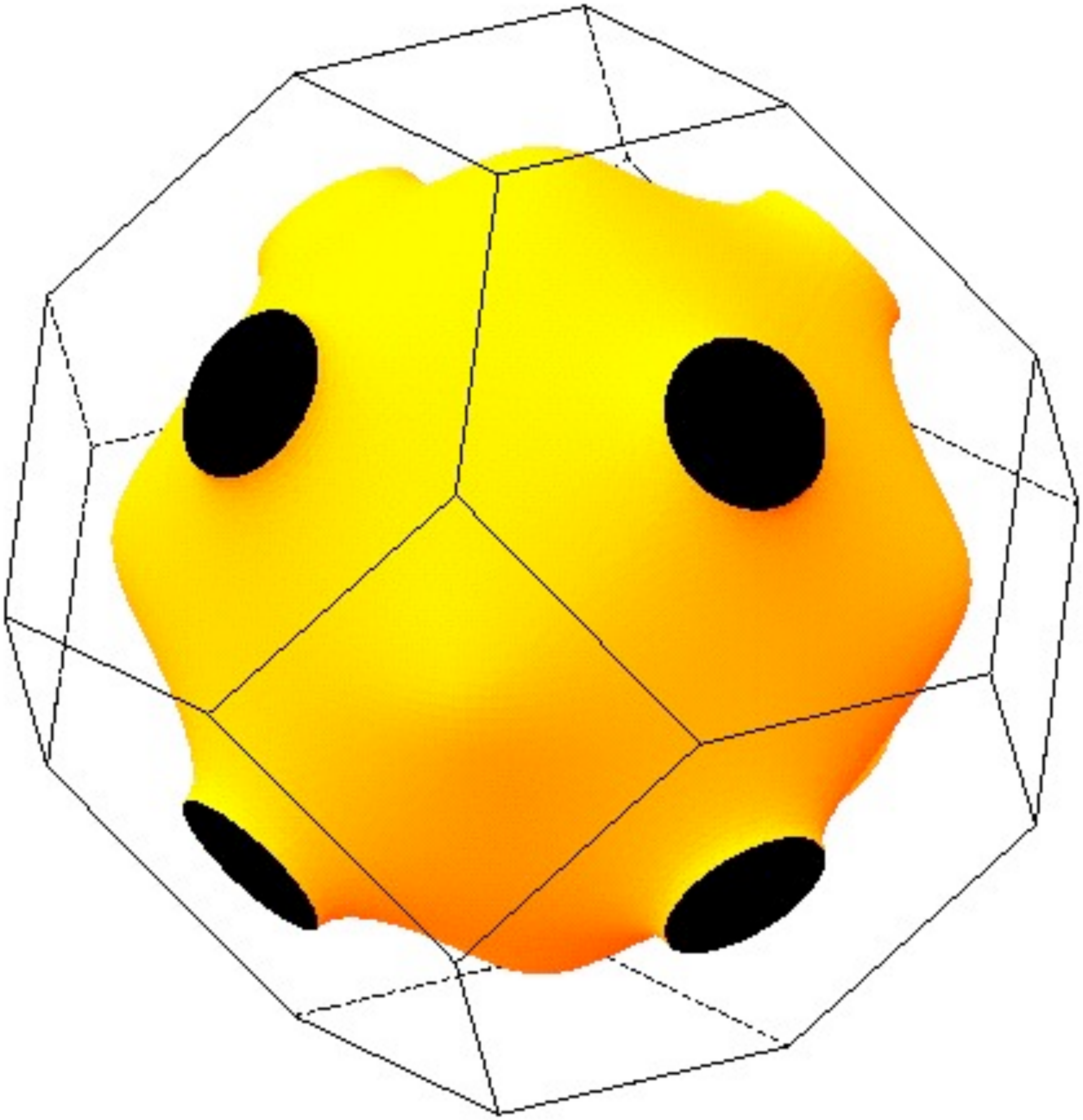
Metals, Insulators, Superconductors,.......

S. Sachdev

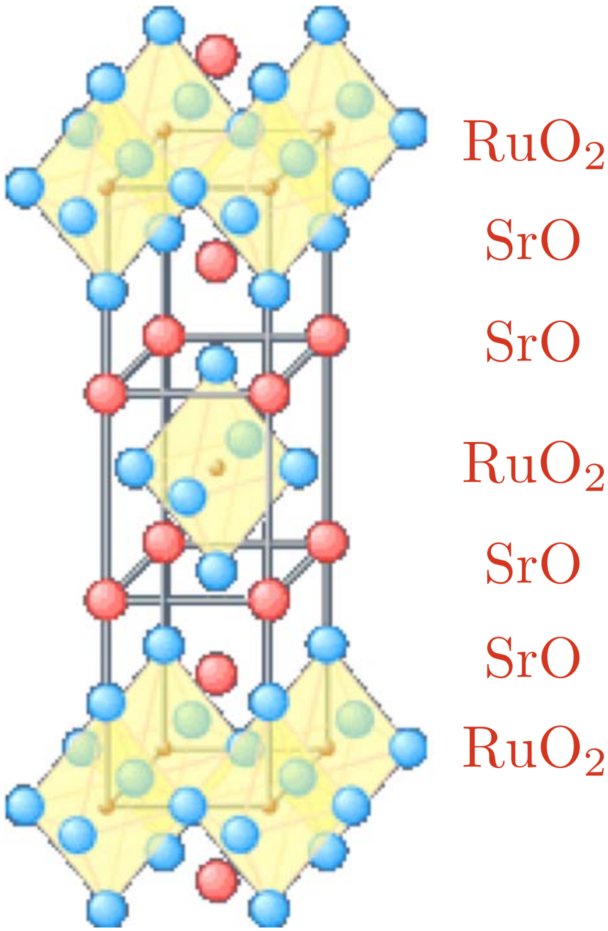
http://qpt.physics.harvard.edu/p168.pdf

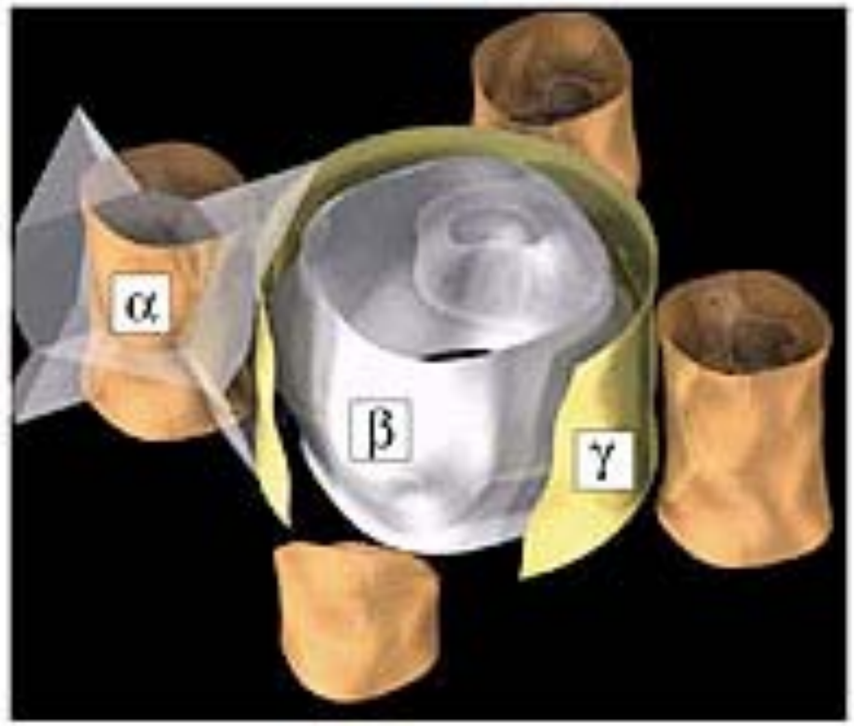
Metals



Fermi surface of Cu

Sr_2RuO_4





de Hass-van Alphen oscillations

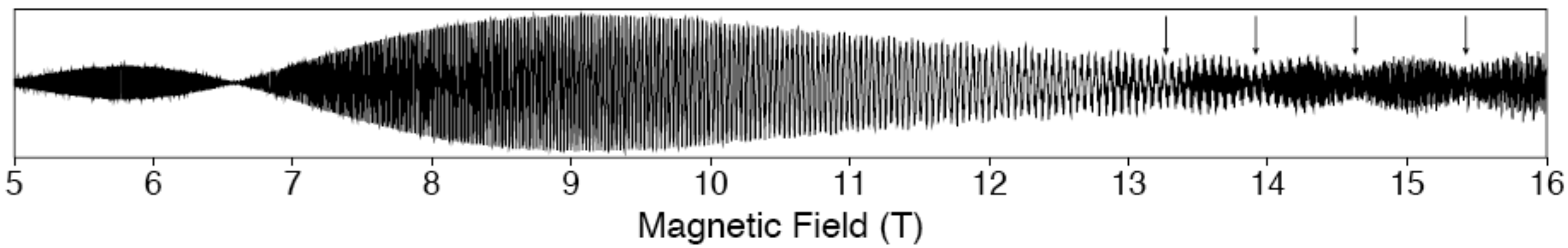


FIG. 1. Example of a dHvA field sweep on Sr_2RuO_4, for $\theta = 9.8°$ off the c axis in the [001] → [110] rotation study. The vertical axis is the pickup signal (in arbitrary units) at the second harmonic of the excitation frequency. At high fields, beats in the β oscillations are visible, as indicated by arrows.

$$\text{Period of oscillation in } 1/H = \frac{2\pi e}{\hbar c} \frac{1}{\text{extremal area}}$$

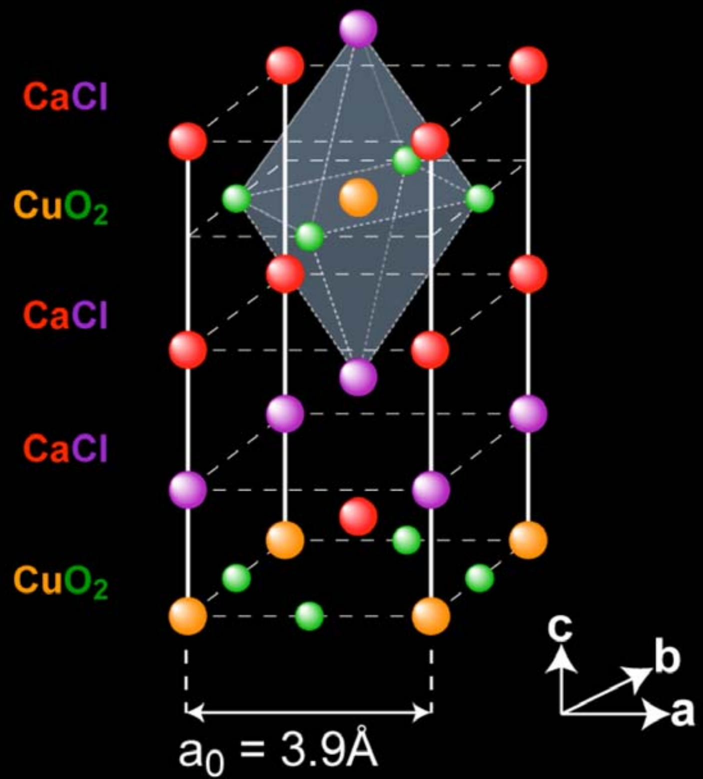
Luttinger relation:

$$2 \times \frac{\text{Volume enclosed by Fermi surface}}{8\pi^3}$$
$$= \text{density of electrons modulo}(2 \times \text{volume of Brillouin zone})$$

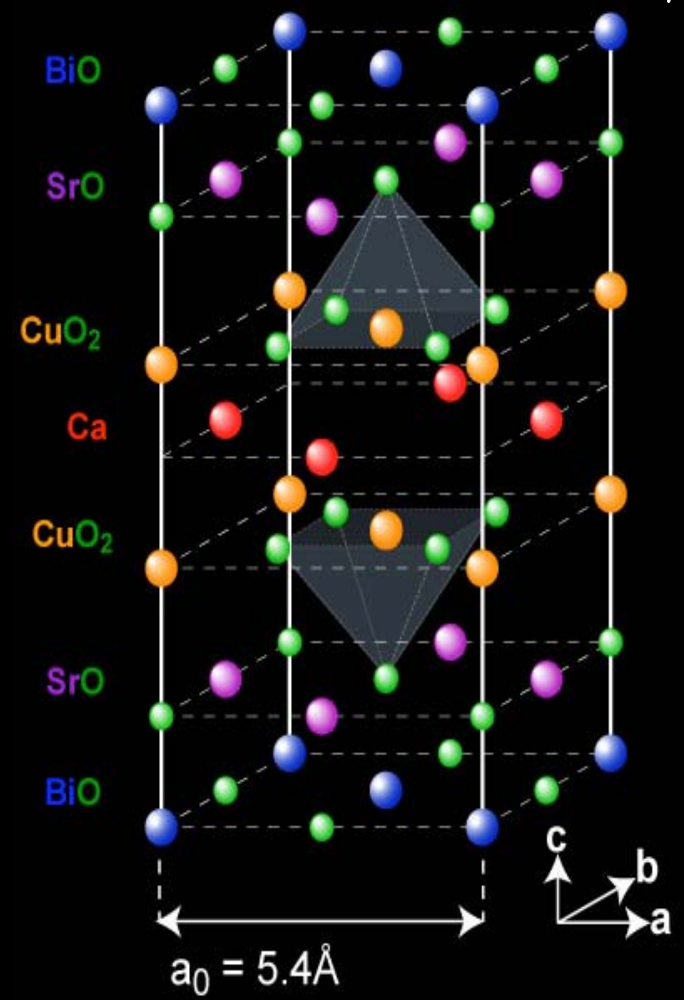
Insulators

Antiferromagnetism in the cuprate superconductors

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



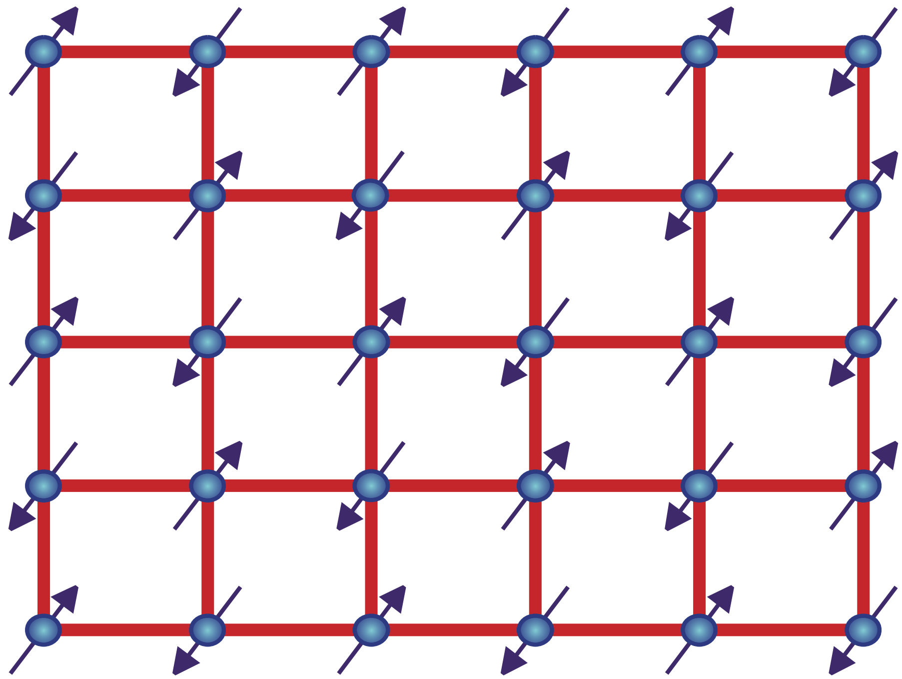
$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$



S=1/2 Heisenberg antiferromagnets on the square lattice

$$H = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - Q \sum_{\langle ijkl \rangle} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \tfrac{1}{4}\right) \left(\mathbf{S}_k \cdot \mathbf{S}_l - \tfrac{1}{4}\right)$$

For small Q

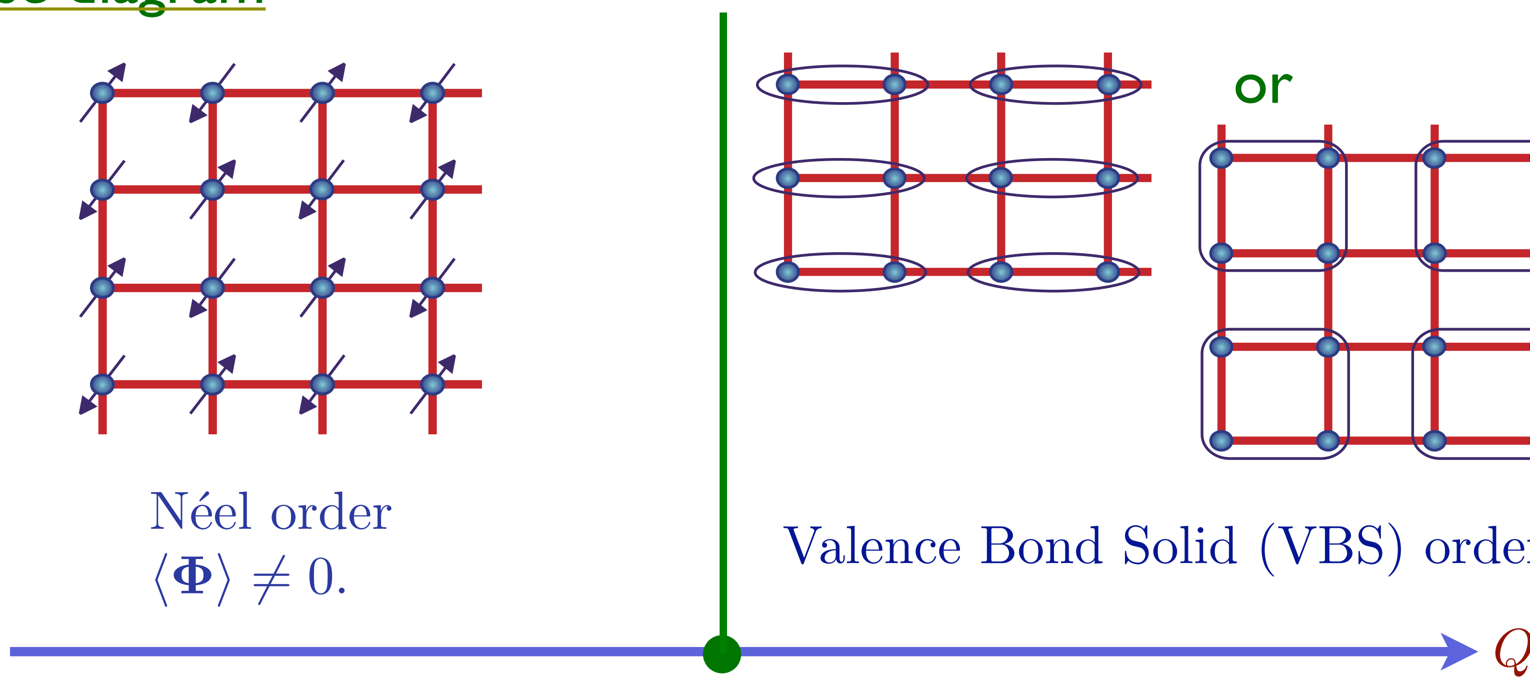


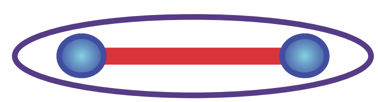
Order parameter $\mathbf{\Phi} = (-1)^i \boldsymbol{S}_i$

S=1/2 Heisenberg antiferromagnets on the square lattice

$$H = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - Q \sum_{\langle ijkl \rangle} \left(\mathbf{S}_i \cdot \mathbf{S}_j - \tfrac{1}{4}\right)\left(\mathbf{S}_k \cdot \mathbf{S}_l - \tfrac{1}{4}\right)$$

Phase diagram




$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

S=1/2 Heisenberg antiferromagnets on the square lattice

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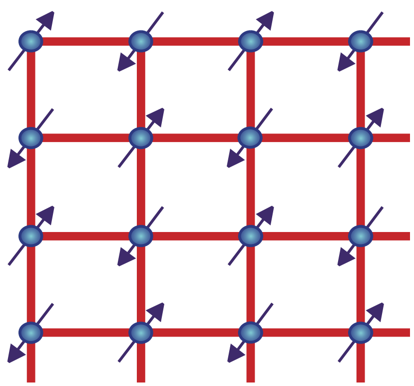
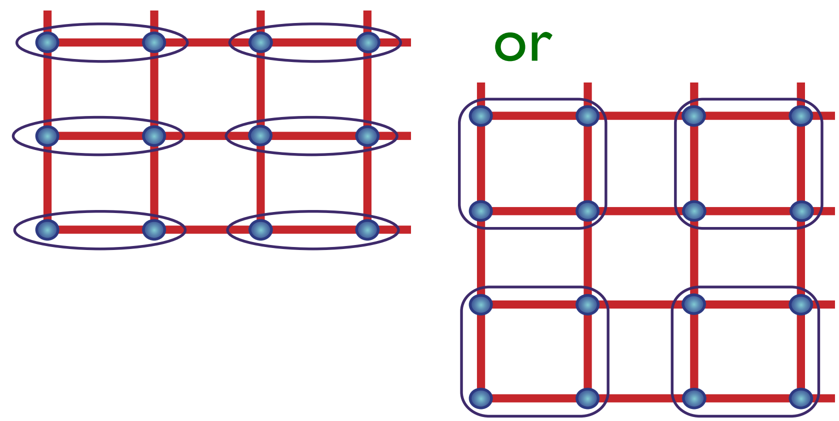
Phase diagram





Higgs phase: Néel order
$\langle z_\alpha \rangle \neq 0$, $\langle \mathbf{\Phi} \rangle \neq 0$.

"Coulomb" phase: VBS order,
Monopole $\langle V \rangle \neq 0$

s_c $\quad$ s

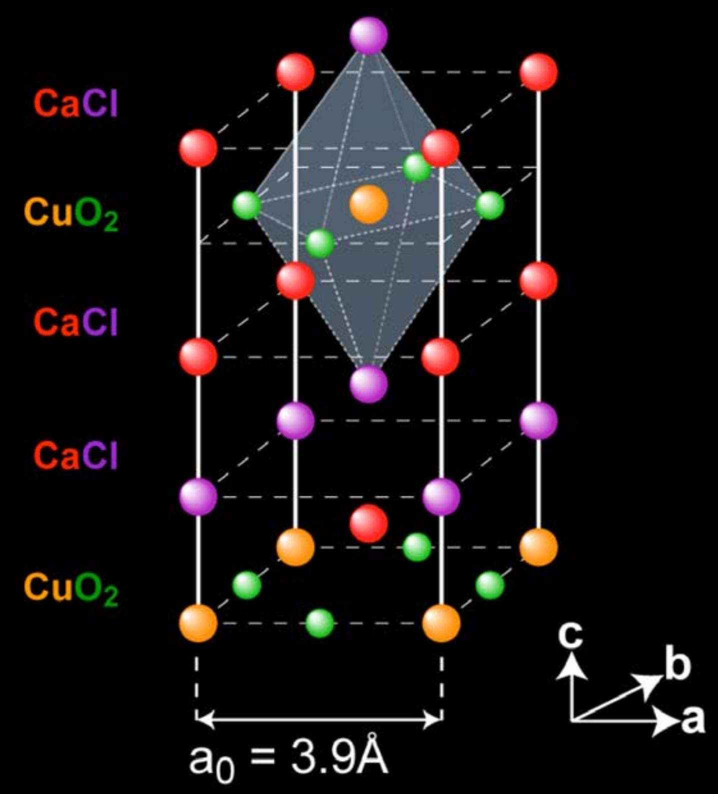
$$\mathcal{S}_z = \int d^2 r d\tau \left[|(\partial_\mu - iA_\mu) z_\alpha|^2 + s|z_\alpha|^2 + u(|z_\alpha|^2)^2 + \frac{1}{2e_0^2} (\epsilon_{\mu\nu\lambda} \partial_\nu A_\lambda)^2 \right]$$

Similar phase diagram for $\mathcal{N} = 4$ supersymmetric quantum electrodynamics with 2 matter hypermultiplets

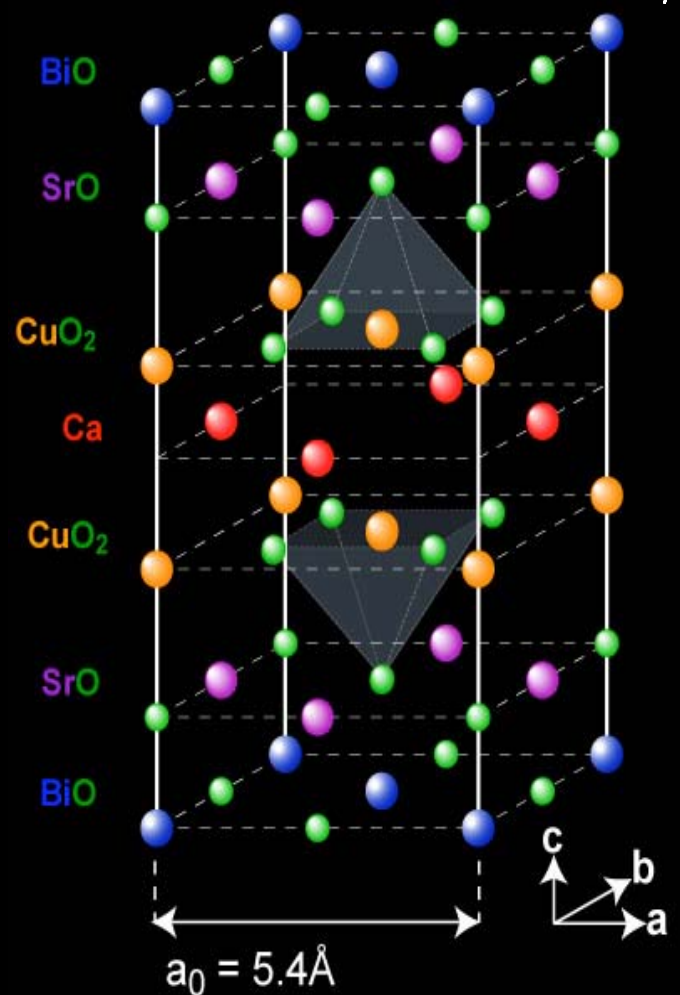
Superconductors

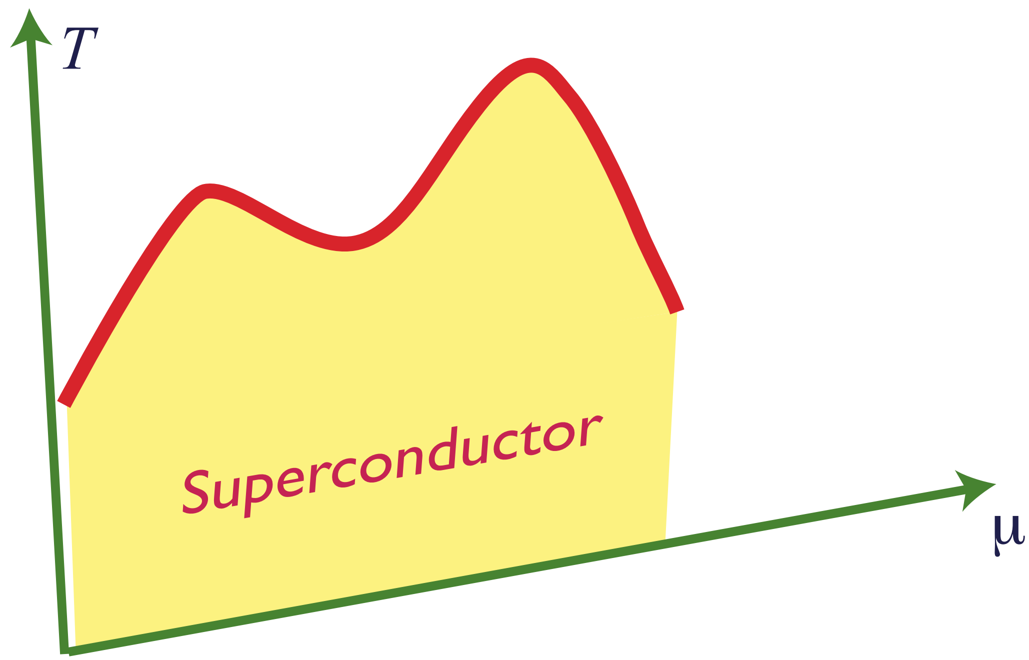
Dope the antiferomagnets with charge carriers of density *x* by applying a chemical potential μ

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$

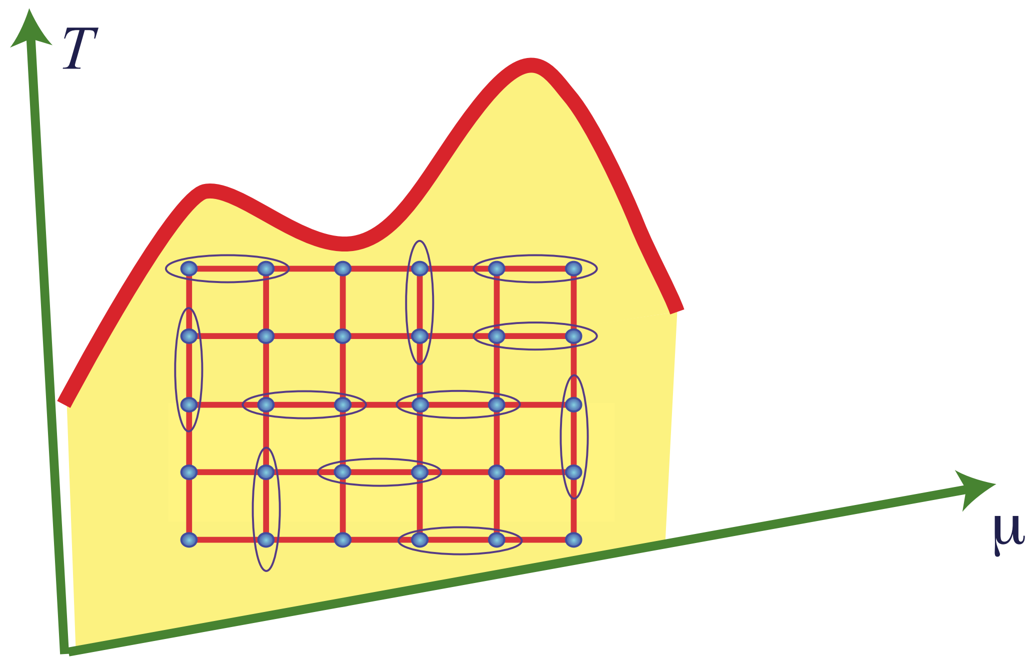


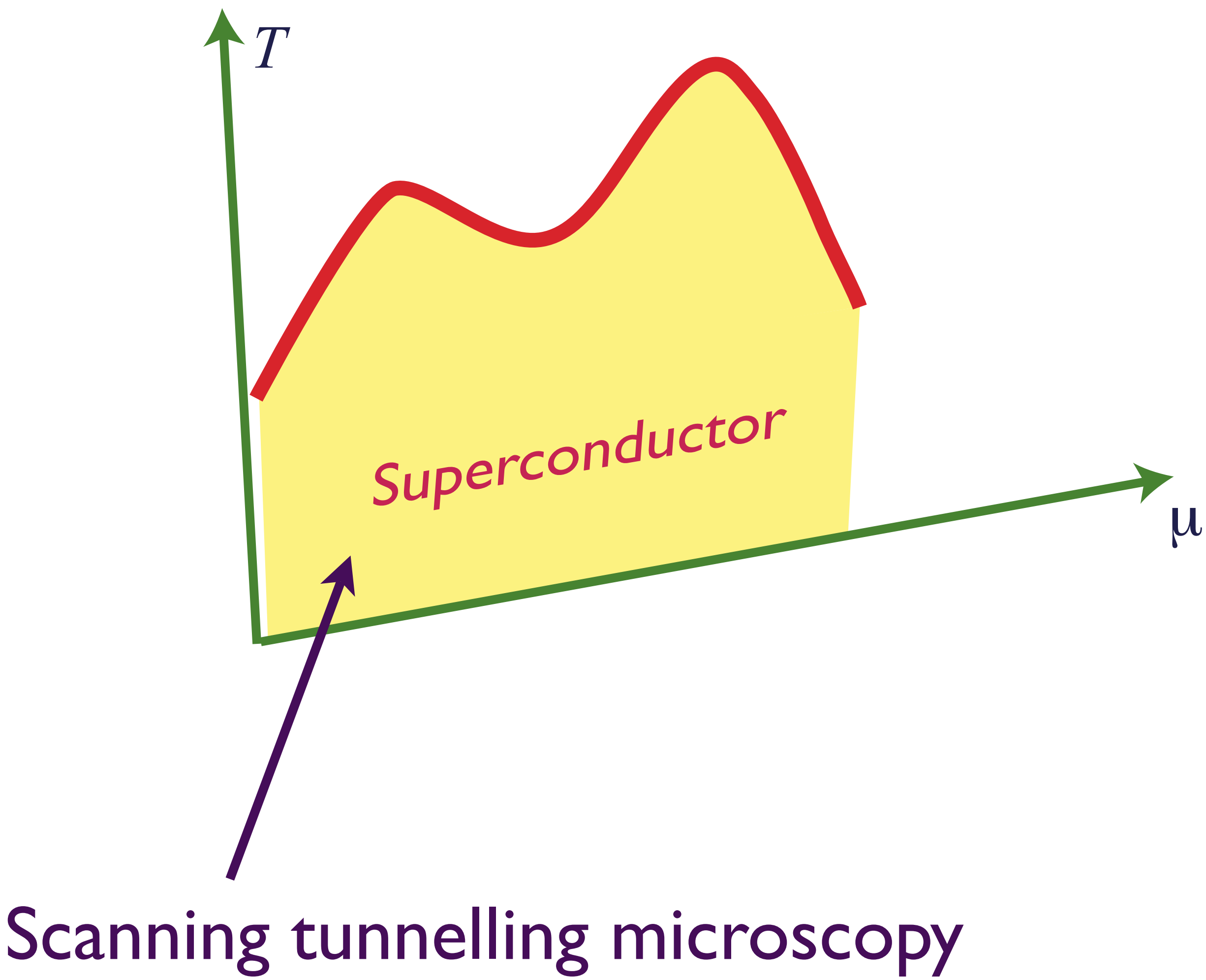
$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$





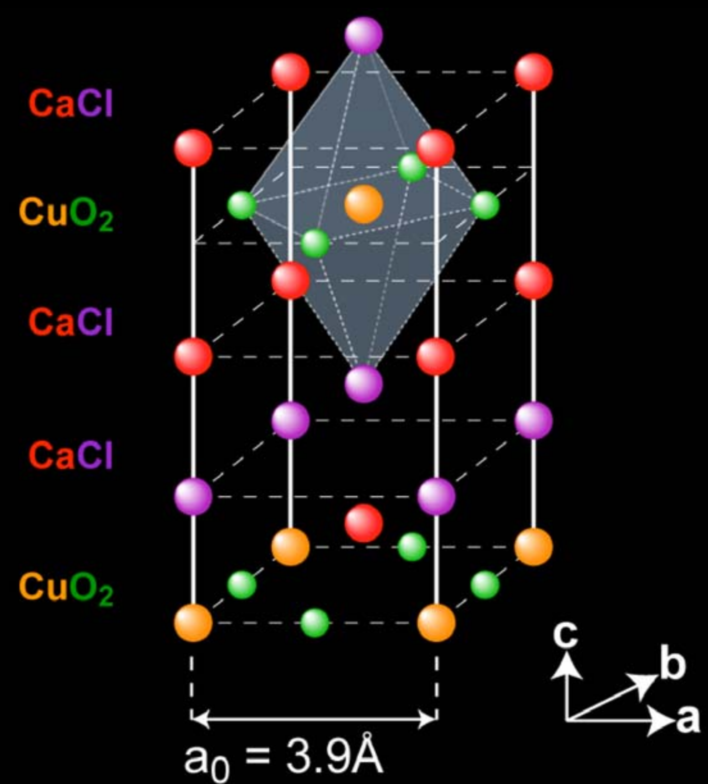
T
Superconductor
μ


T
μ

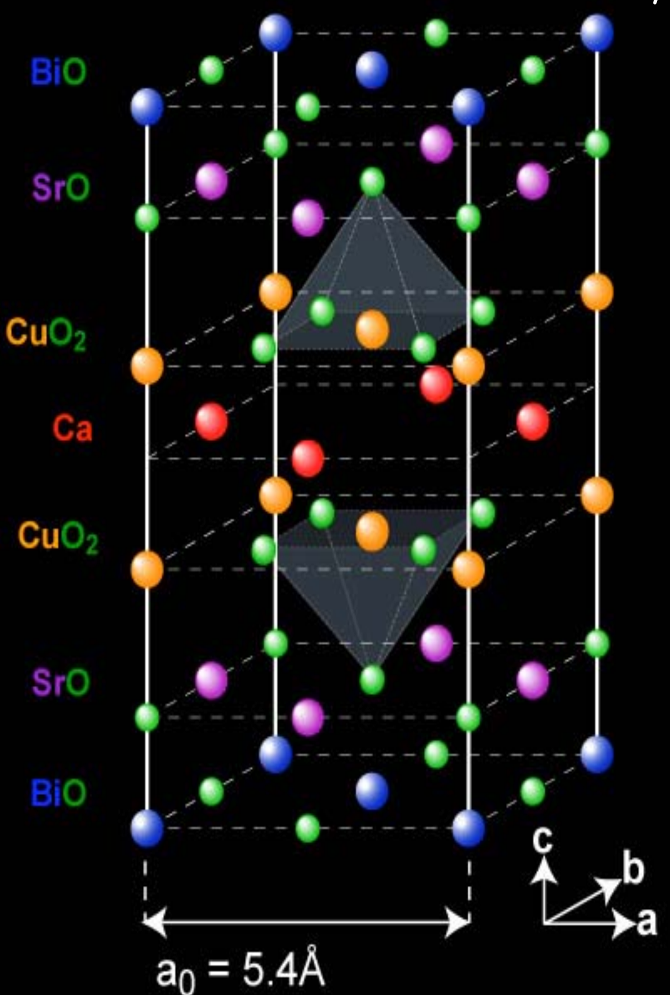

T
Superconductor
μ
Scanning tunnelling microscopy

STM studies of the underdoped superconductor

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$

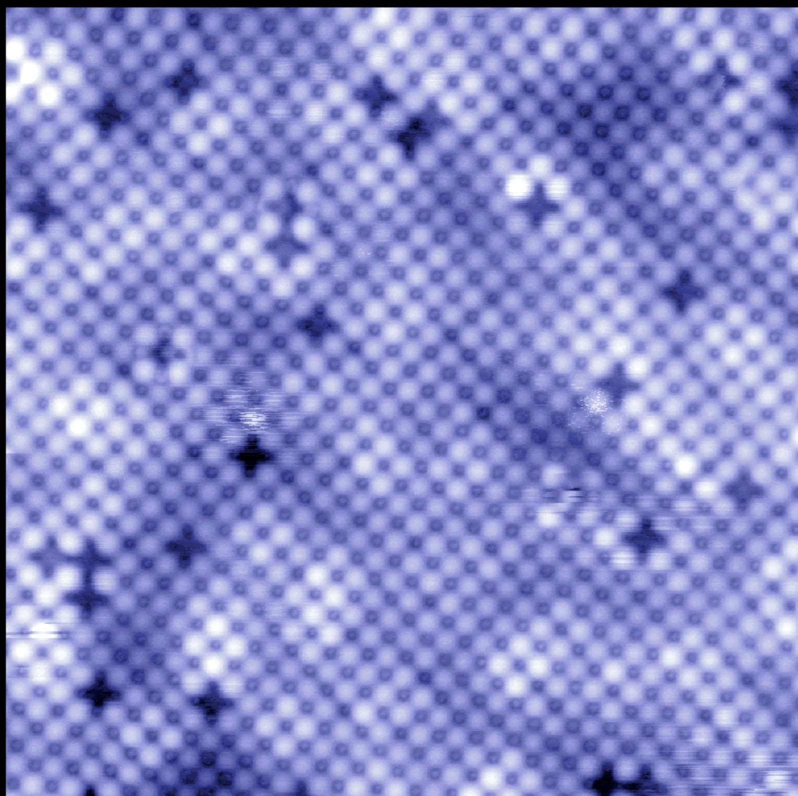


$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$

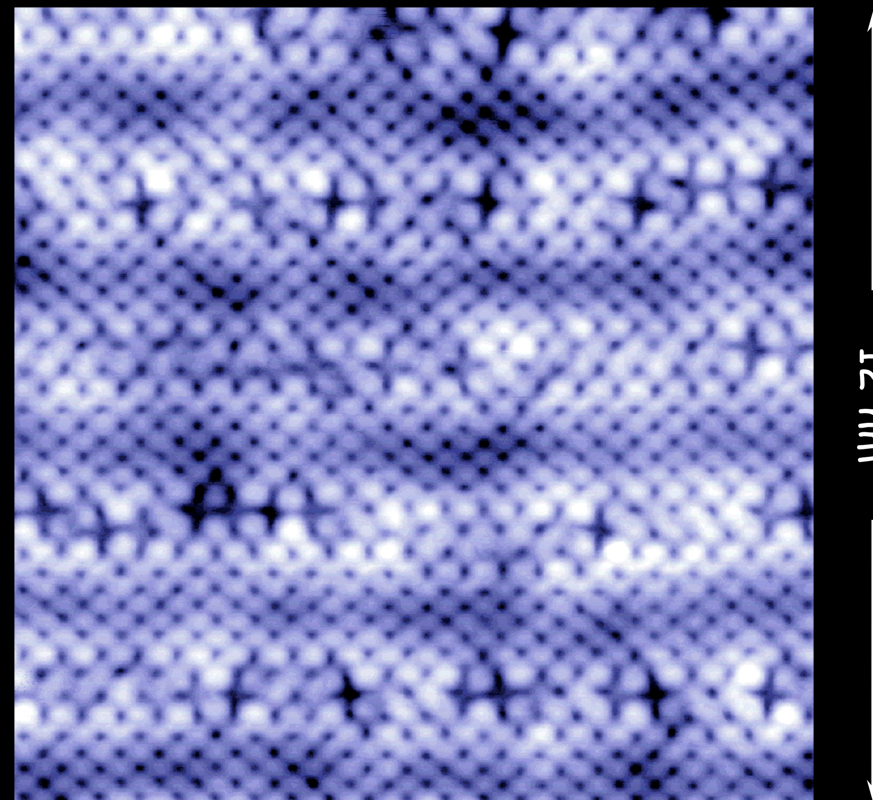


Topograph

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$

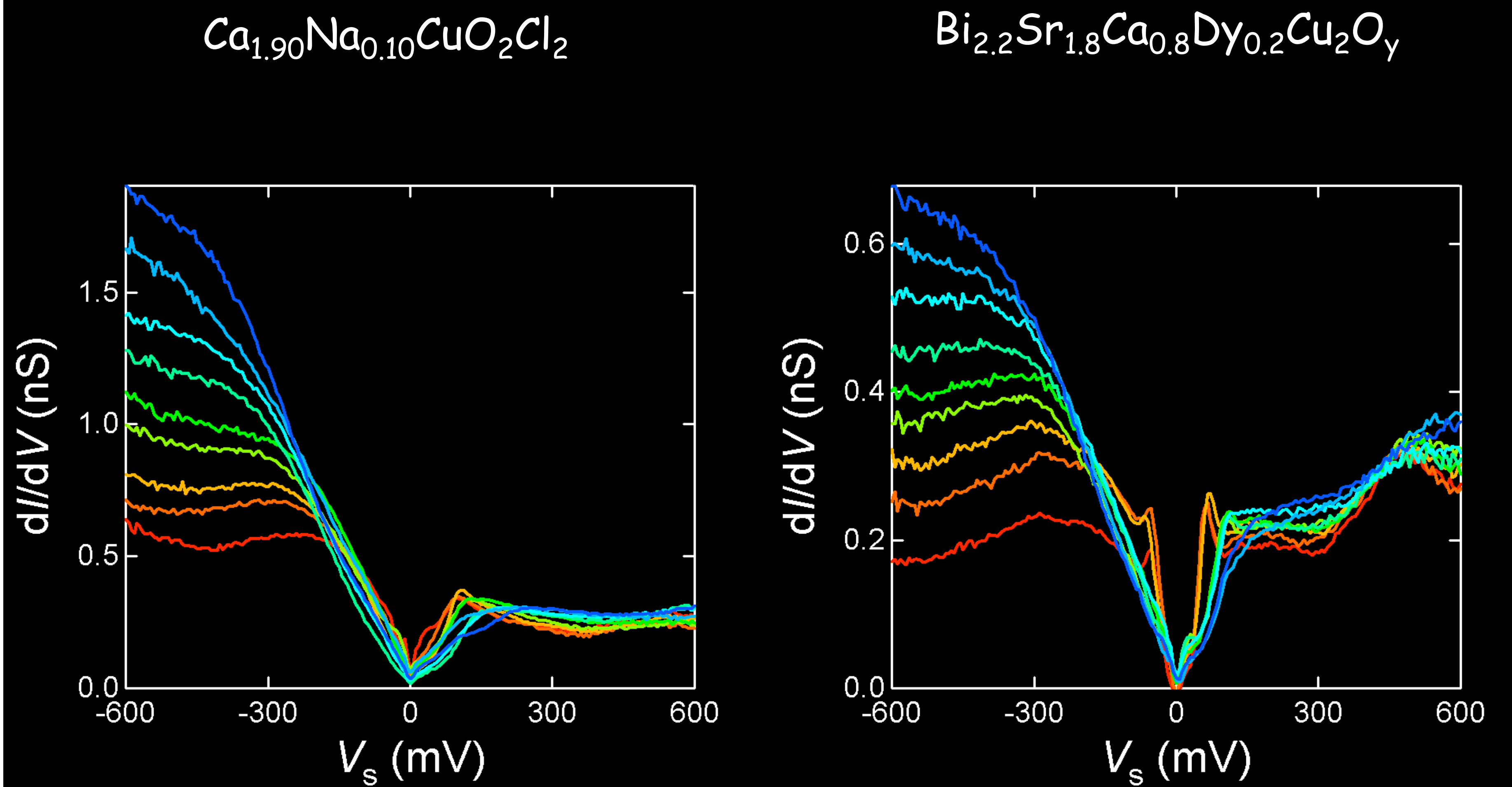


$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$



Y. Kohsaka et al. Science 315, 1380 (2007)

dI/dV Spectra

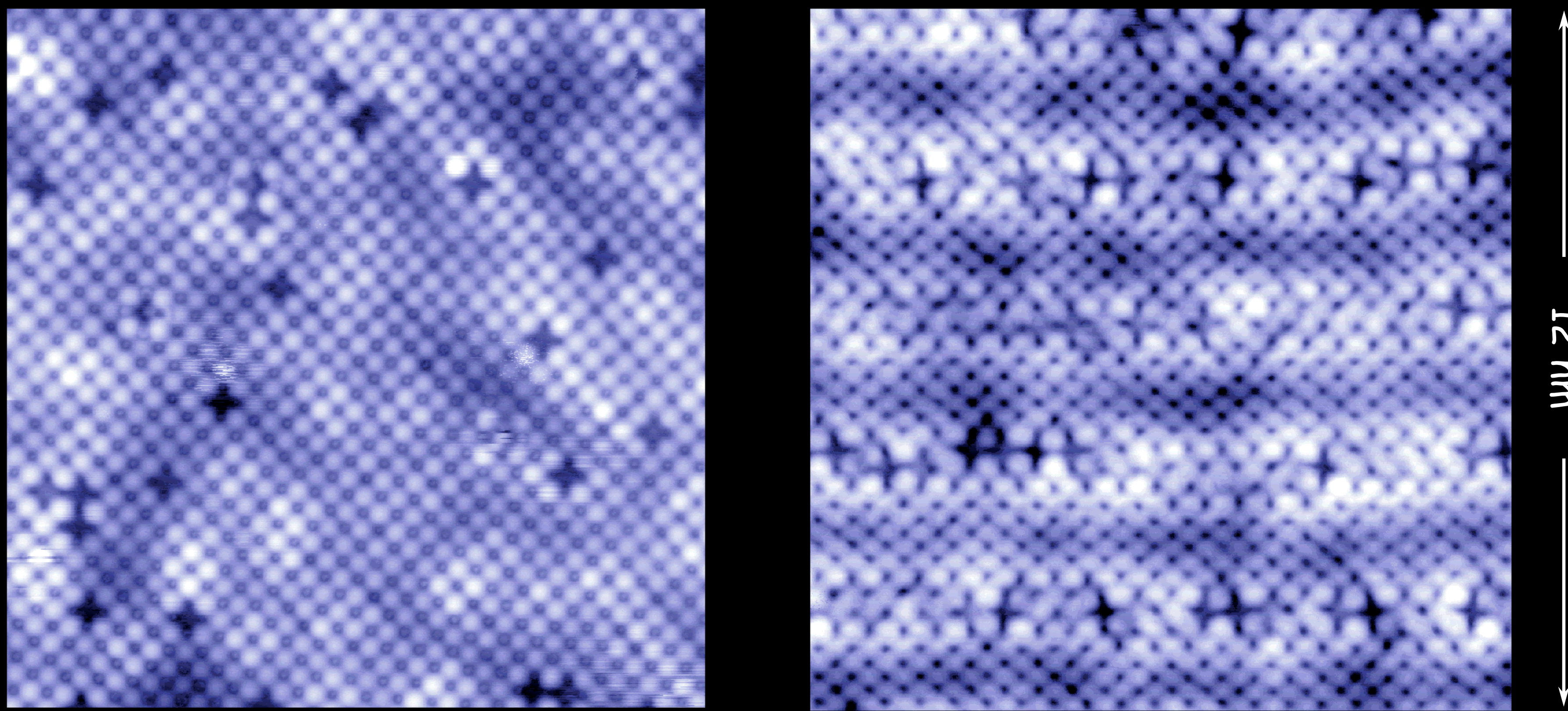


Intense Tunneling-Asymmetry (TA)
variation are highly similar

Y. Kohsaka et al. Science 315, 1380 (2007)

Topograph

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$ $Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$



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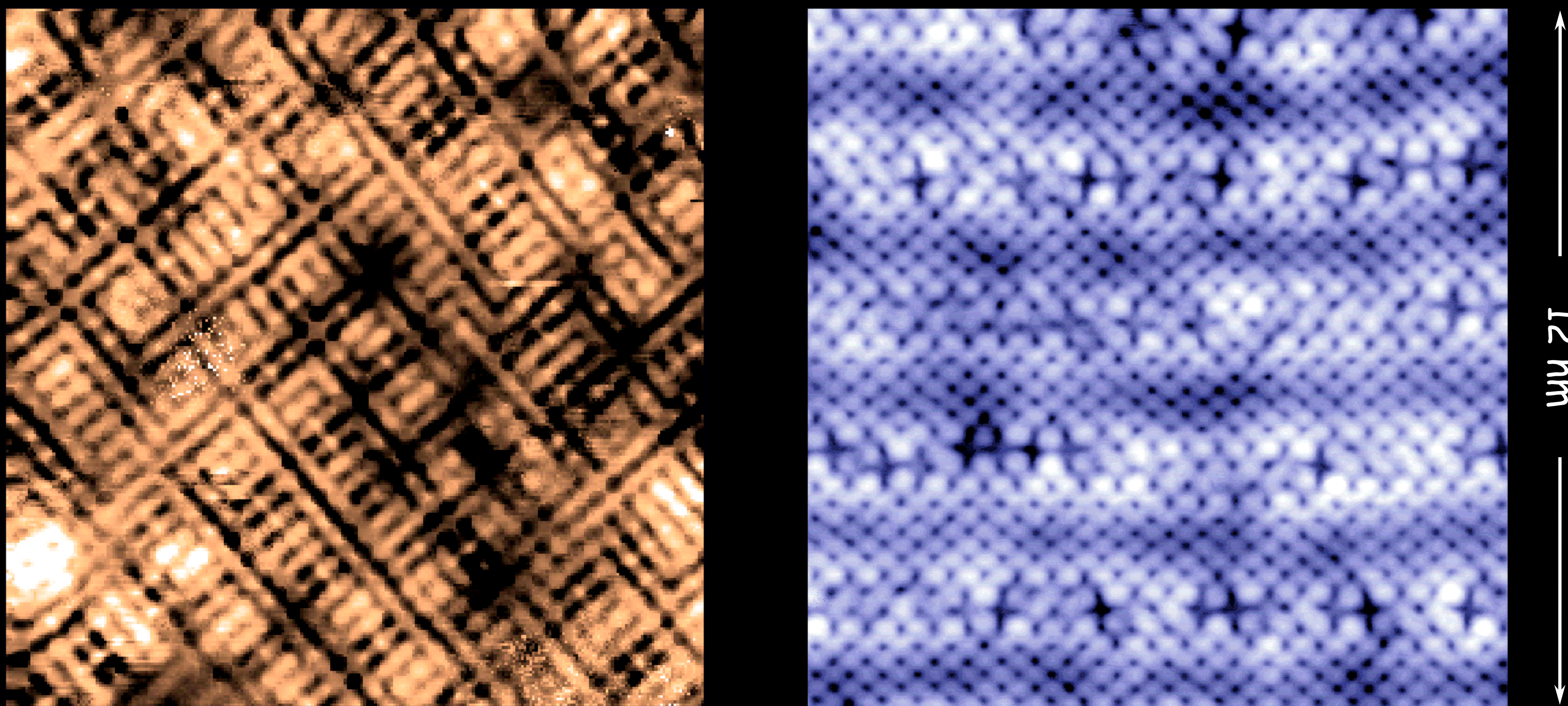
Tunneling Asymmetry (TA)-map at E=150meV

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$ $Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$



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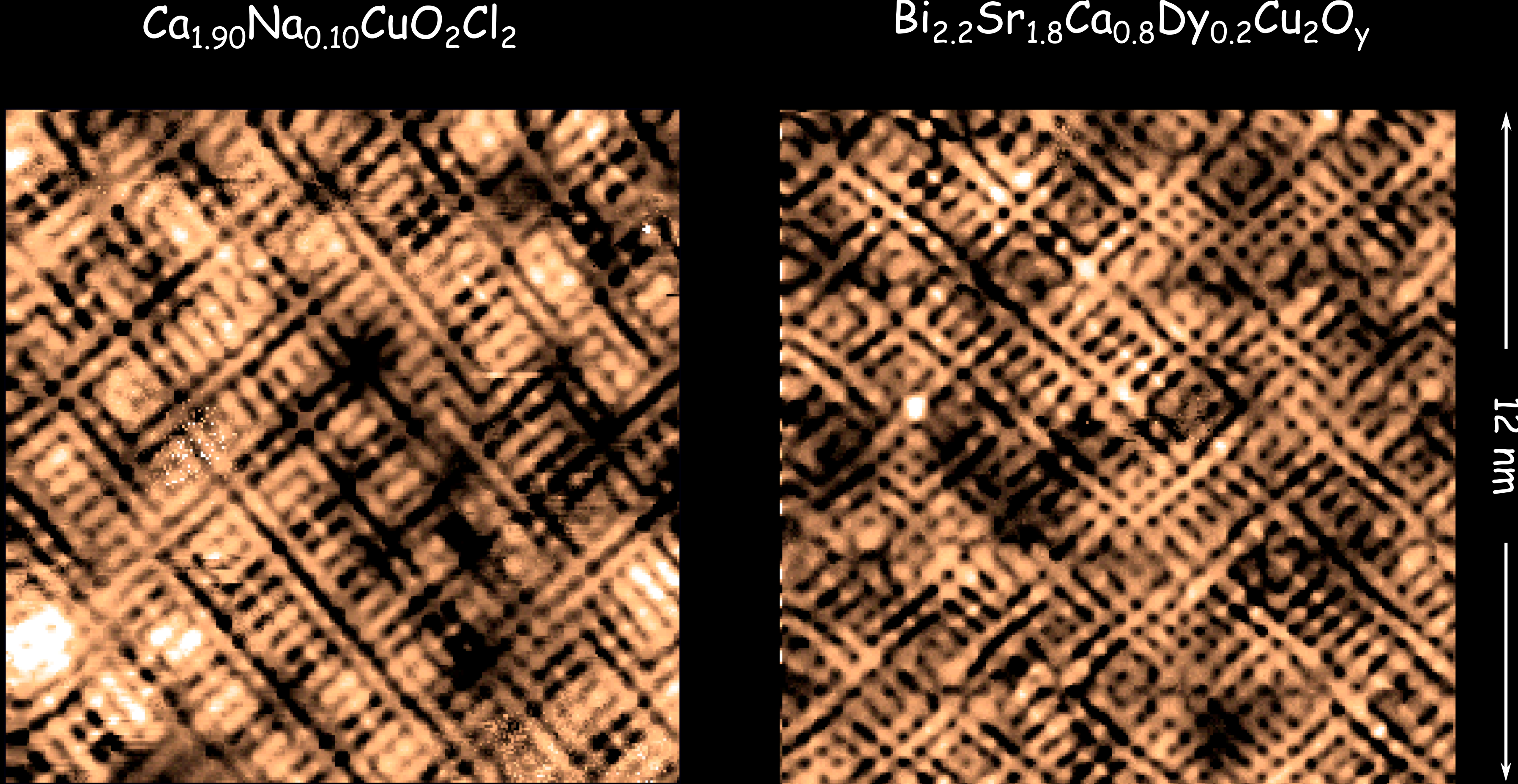
Tunneling Asymmetry (TA)-map at E=150meV



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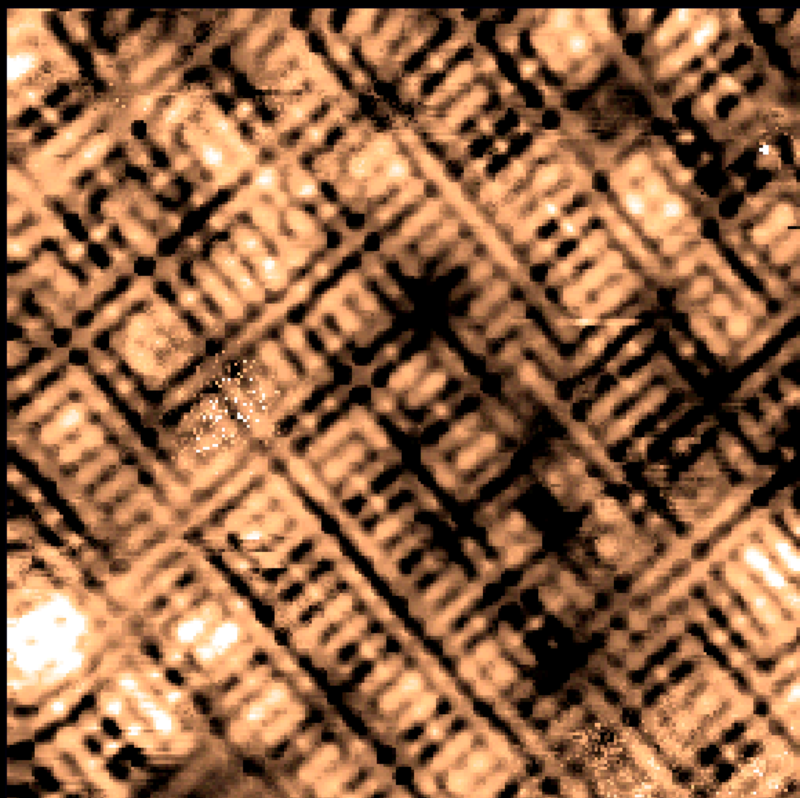

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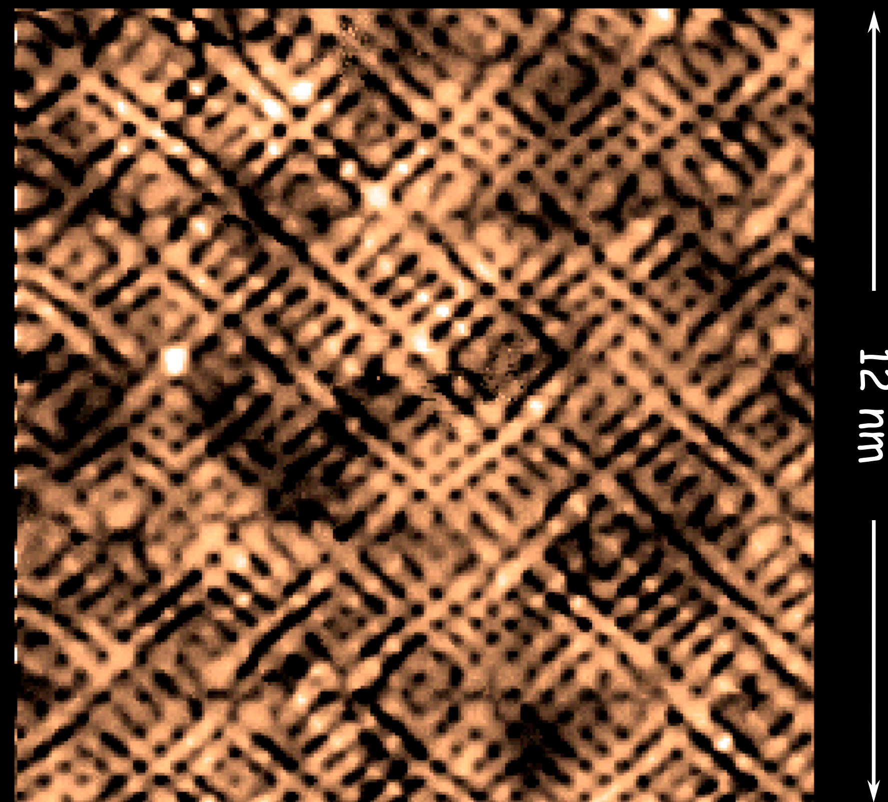
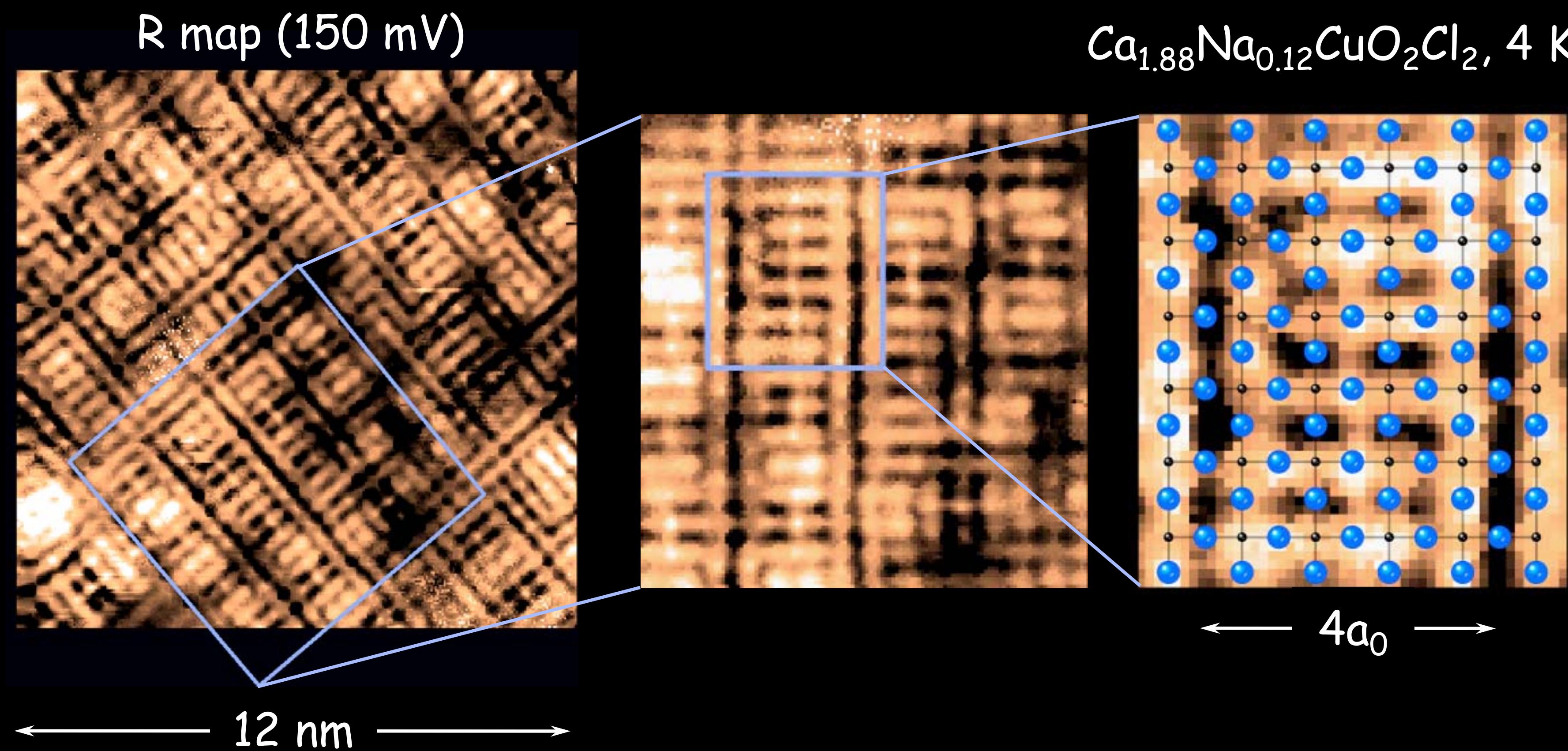


Indistinguishable bond-centered TA contrast

with disperse $4a_0$-wide nanodomains

Y. Kohsaka et al. *Science* 315, 1380 (2007)

TA Contrast is at oxygen site (Cu-O-Cu bond-centered)



Y. Kohsaka et al. Science 315, 1380 (2007)

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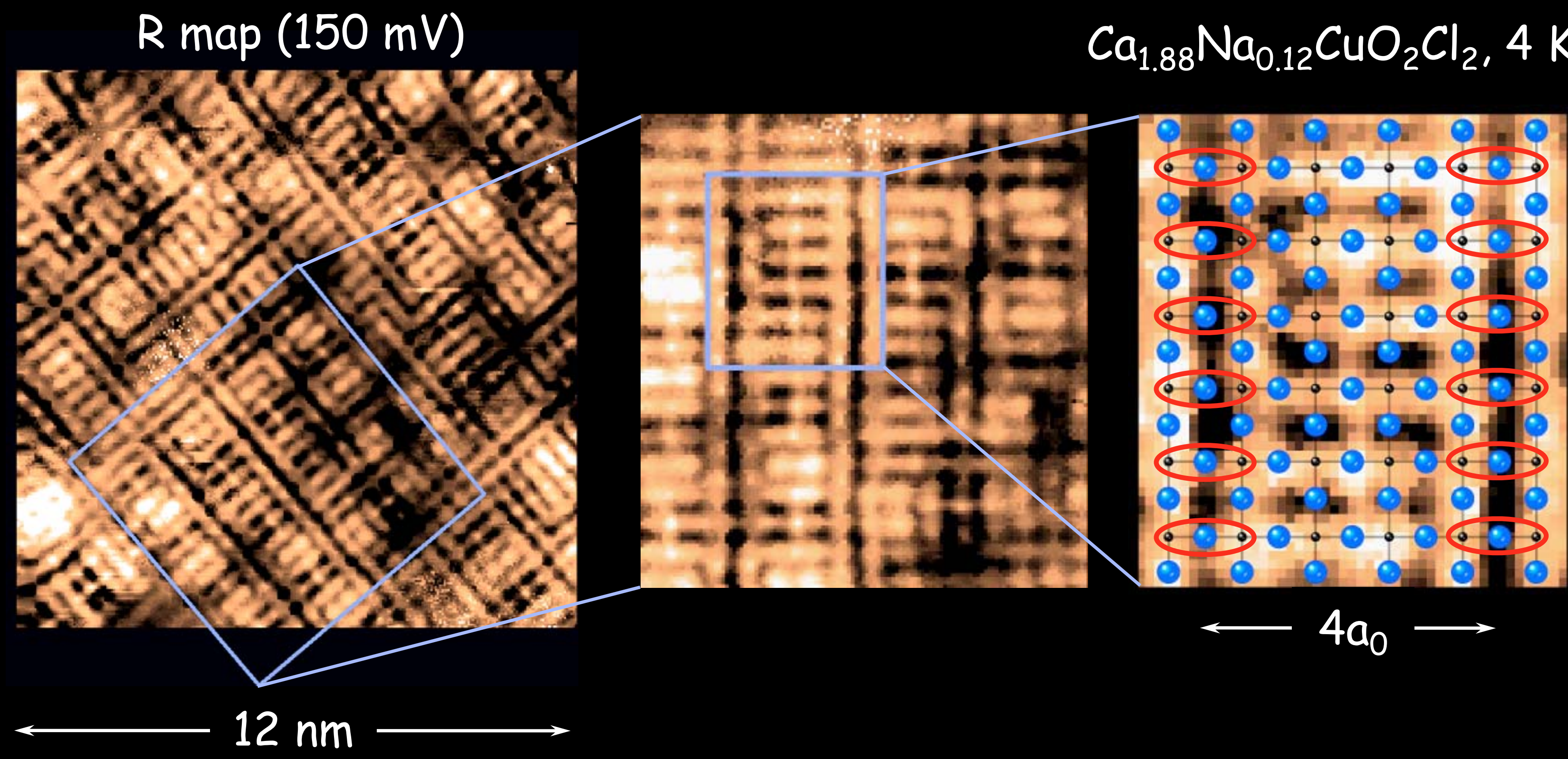

Evidence for VBS order - a valence bond supersolid

S. Sachdev and N. Read, Int. J. Mod. Phys. B 5, 219 (1991).

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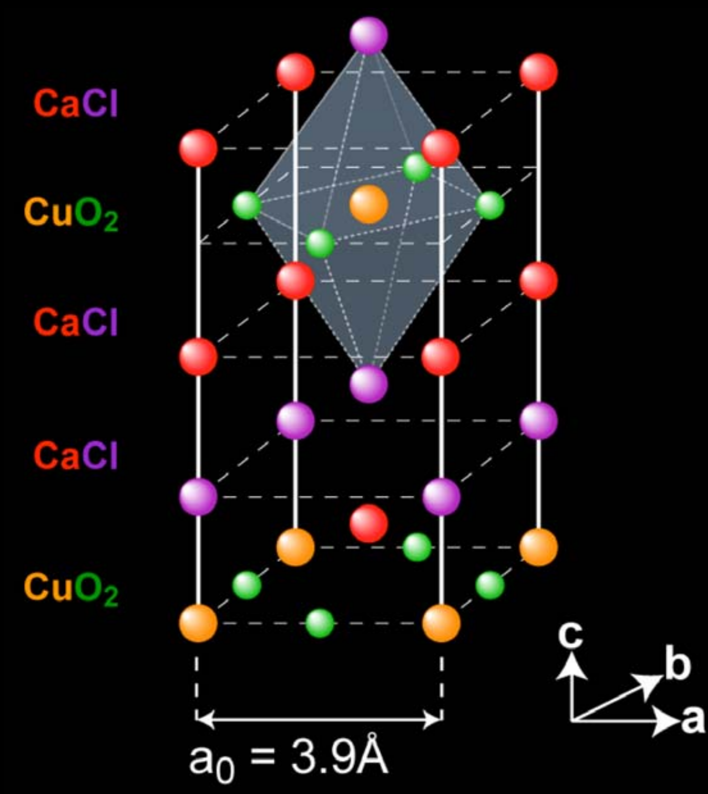
High field "normal state" of the cuprate superconductors

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



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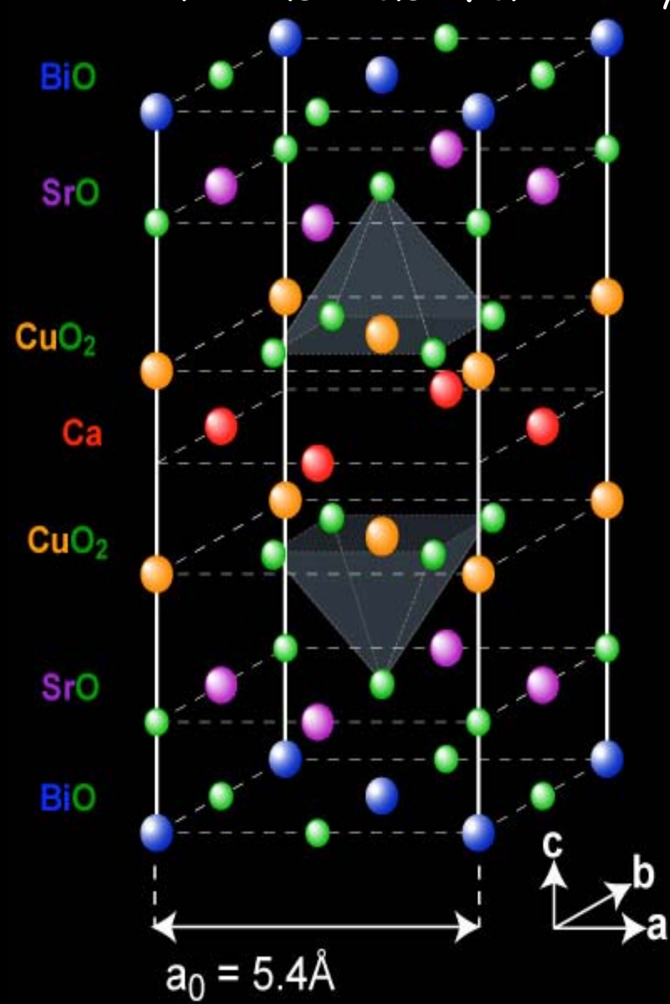
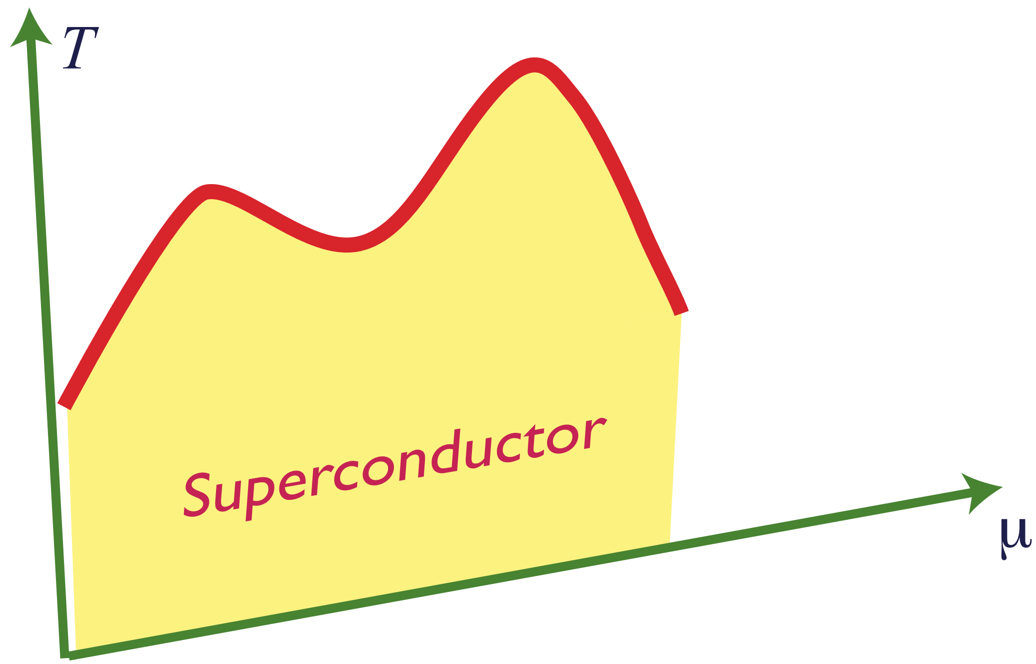
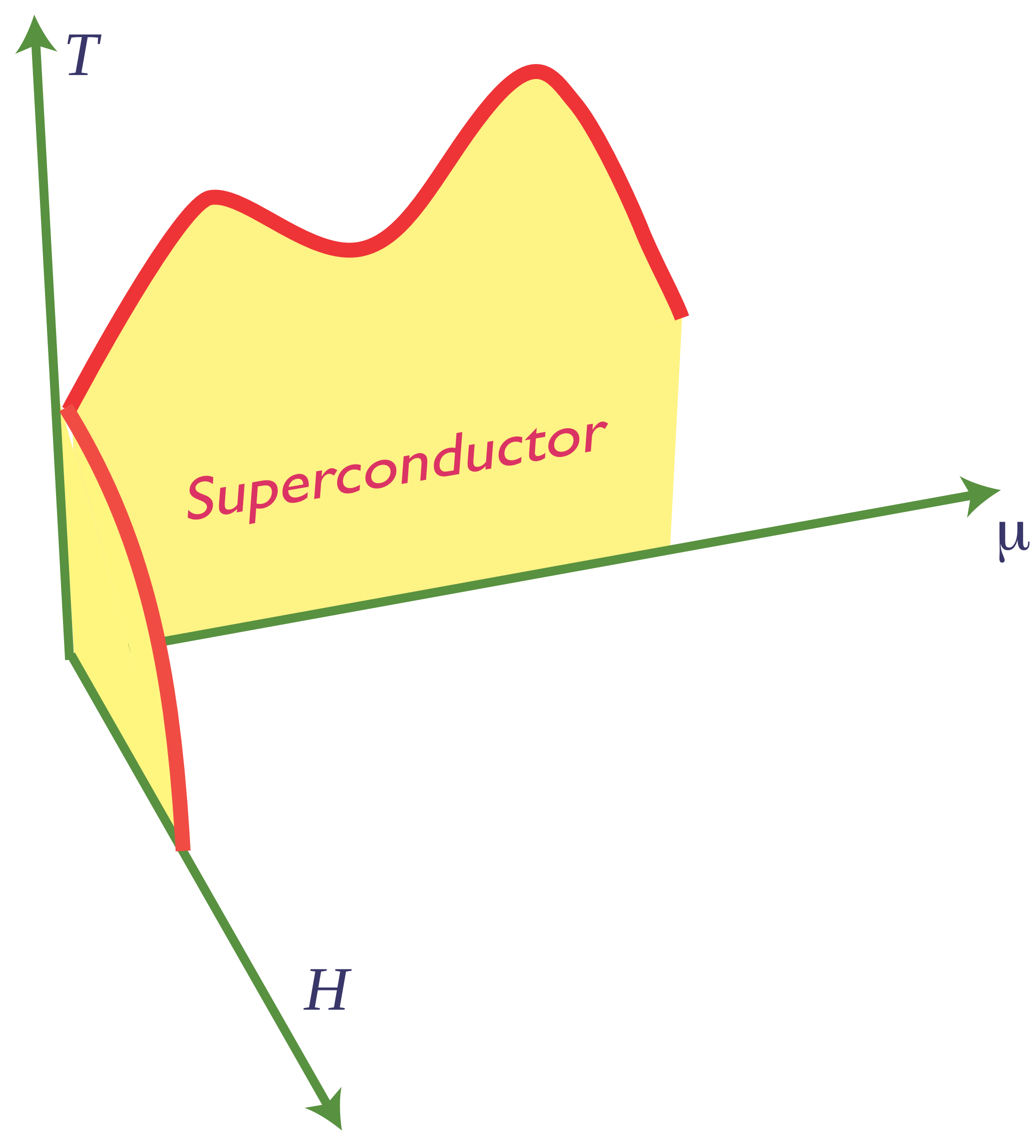
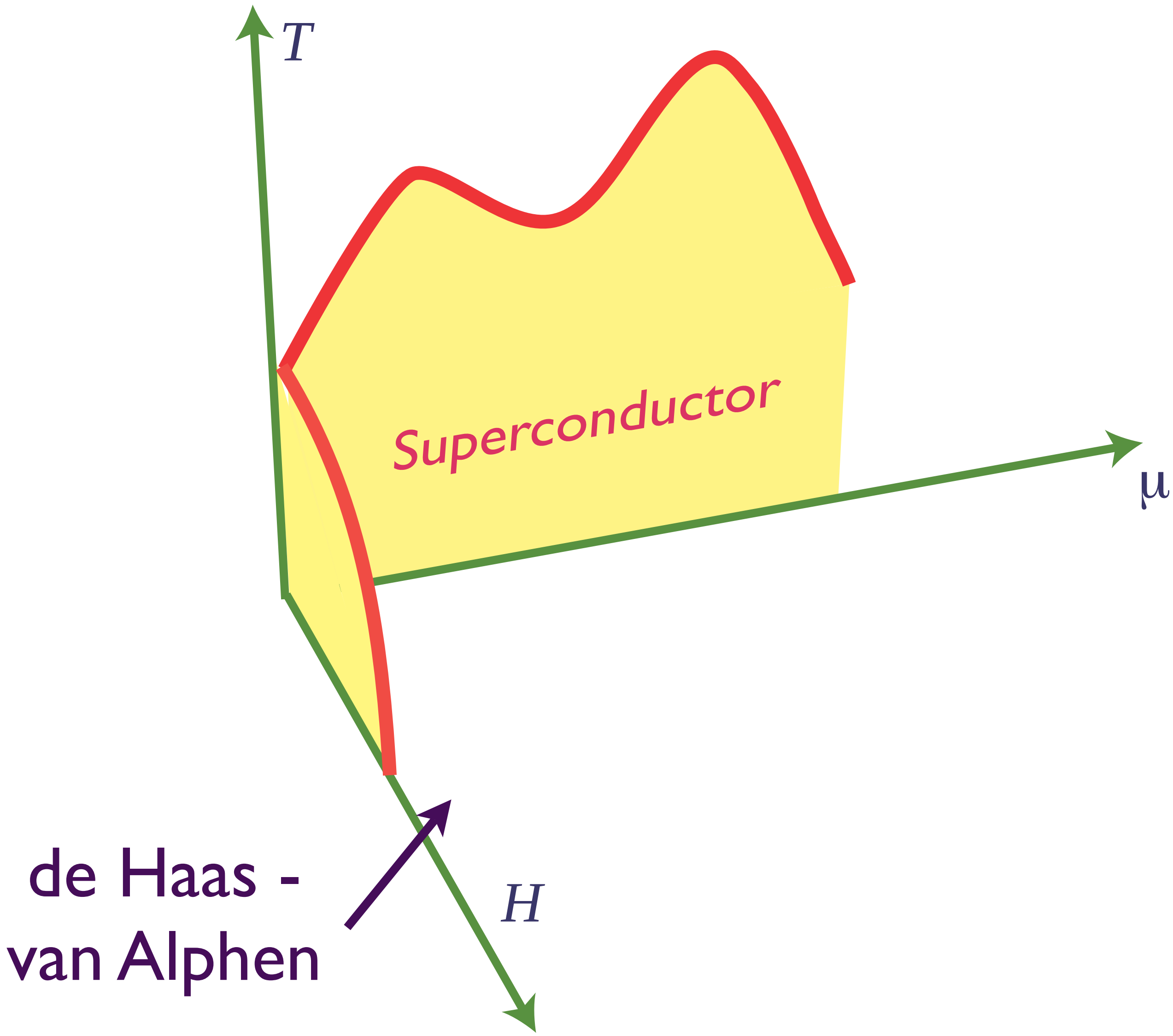


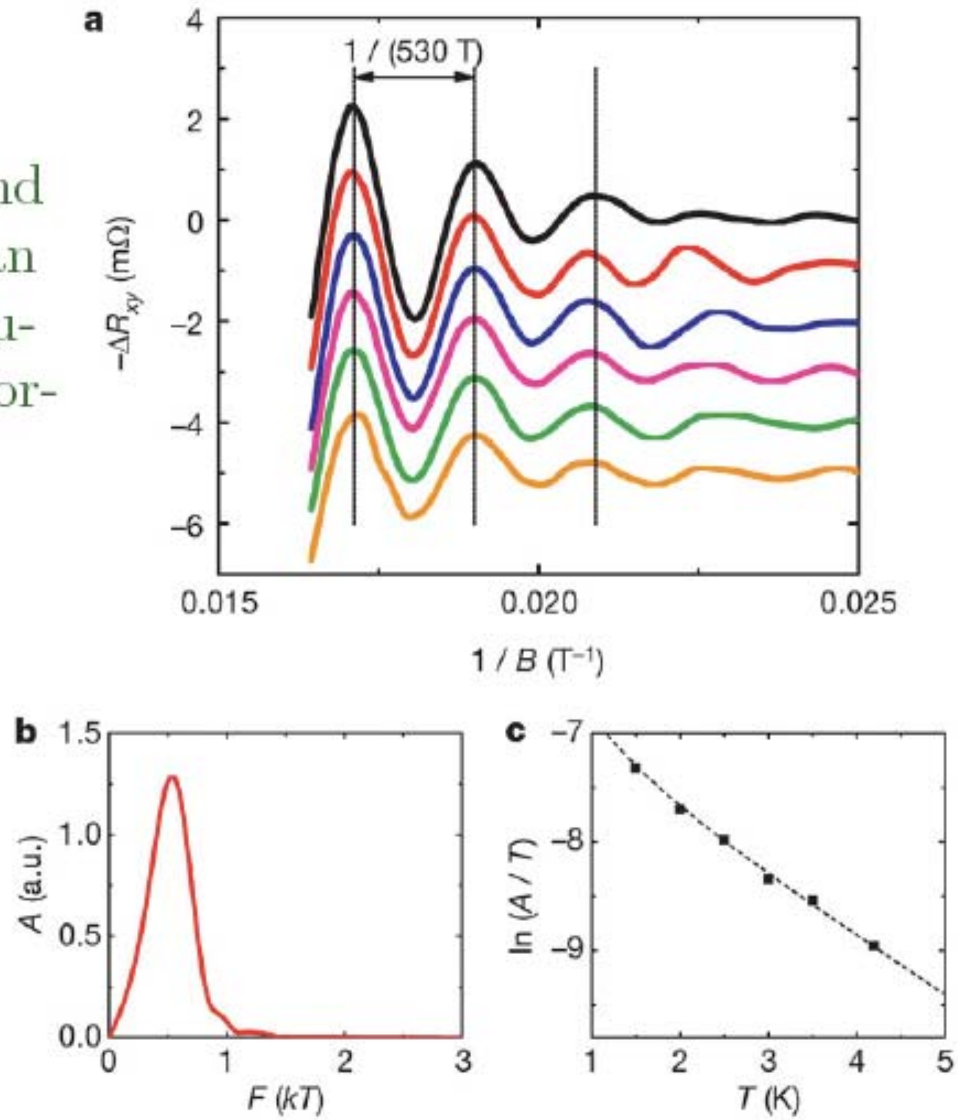

T
Superconductor
μ



T
Superconductor
μ
H


T
Superconductor
μ
H
de Haas -
van Alphen

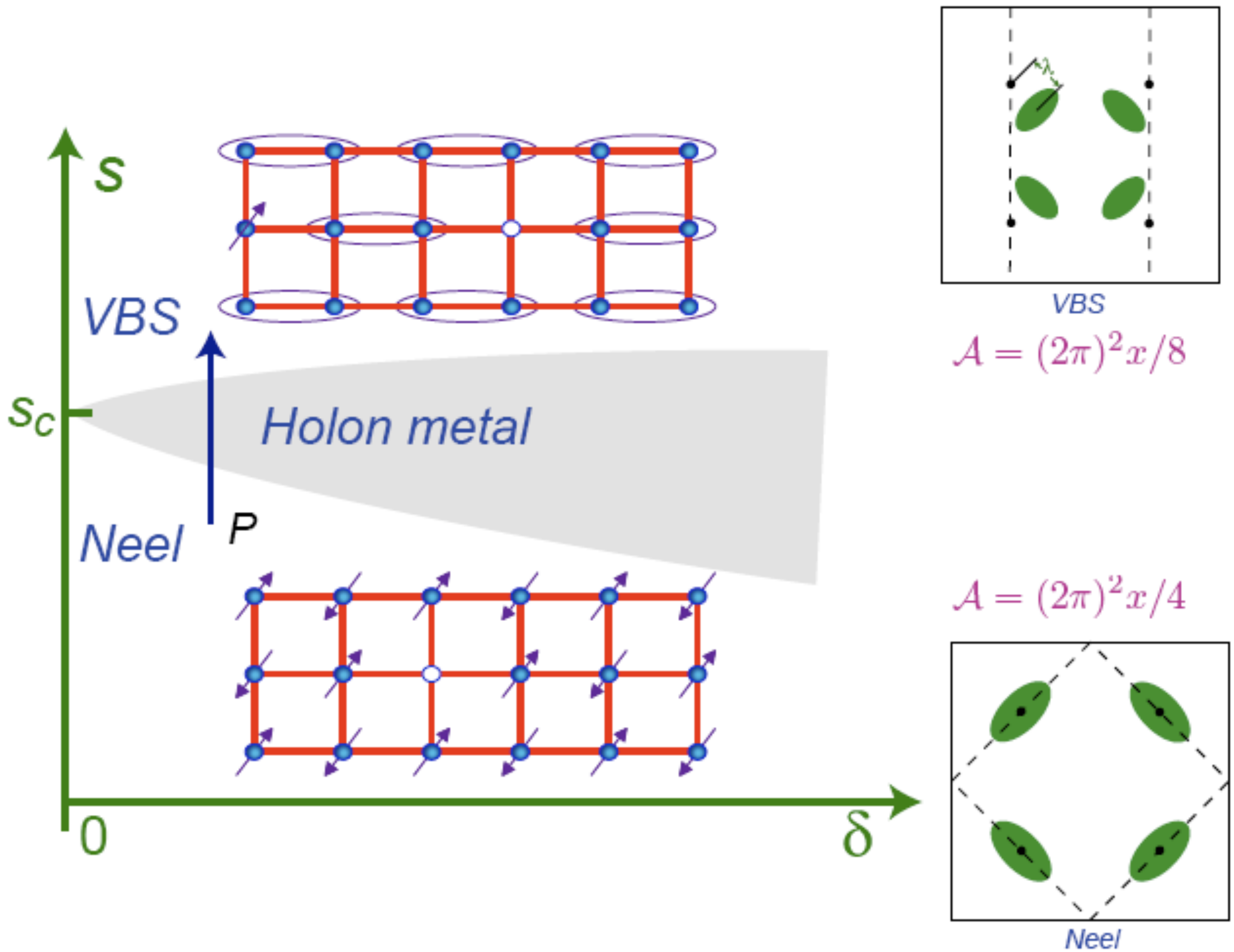
Quantum oscillations and the Fermi surface in an underdoped high T_c superconductor (ortho-II ordered $YBa_2Cu_3O_{6.5}$).



N. Doiron-Leyraud, C. Proust, D. LeBoeuf, J. Levallois, J.-B. Bonnemaison, R. Liang, D. A. Bonn, W. N. Hardy, and L. Taillefer, *Nature* **447**, 565 (2007)

Period of oscillations indicates a carrier density which is the density of holes, and violates the Luttinger count

Phase diagram of lightly doped antiferromagnet



R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, Physical Review B **75** , 235122 (2007)