Quantum antiferromagnetism and superconductivity

Subir Sachdev

Talk online at http://sachdev.physics.harvard.edu

- **Objective:** Study dynamics of entangled many body quantum states similar to those found in correlated electron materials.

- **Approach:** Test theoretical understanding of quantum phases and quantum phase transitions of model Hamiltonians by using tunable realizations in optical lattices of cold atoms

- **Entanglement of spins**

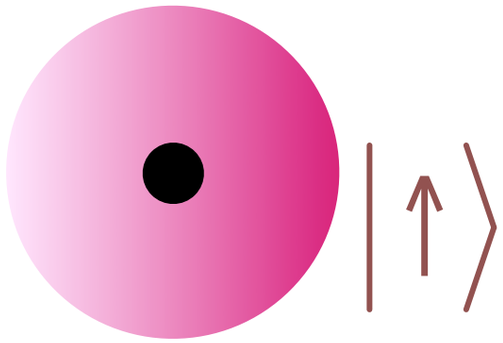
- **Entanglement of valence bonds**

- **Entanglement of spins**

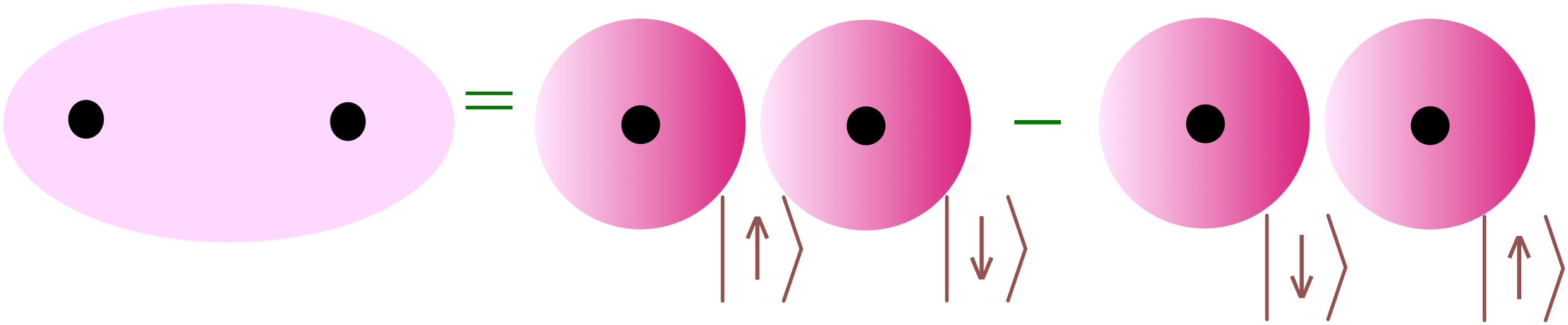
- **Entanglement of valence bonds**

Entanglement of spins

Hydrogen atom:



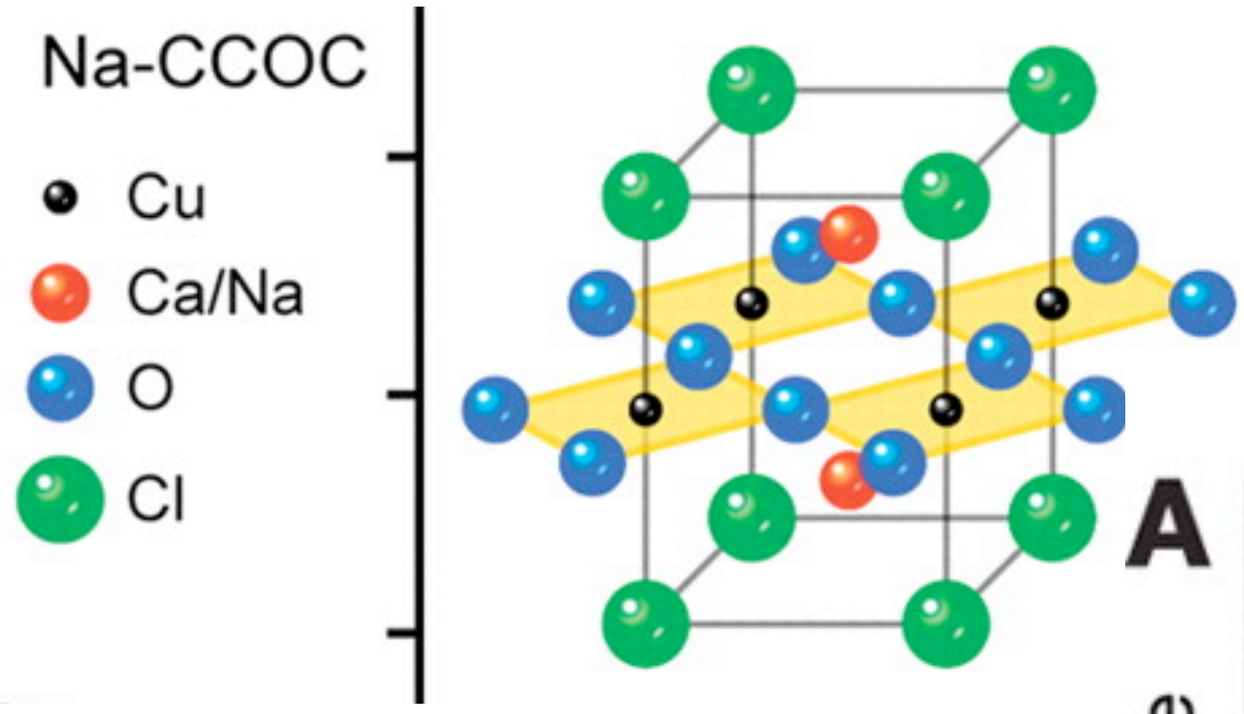
Hydrogen molecule:

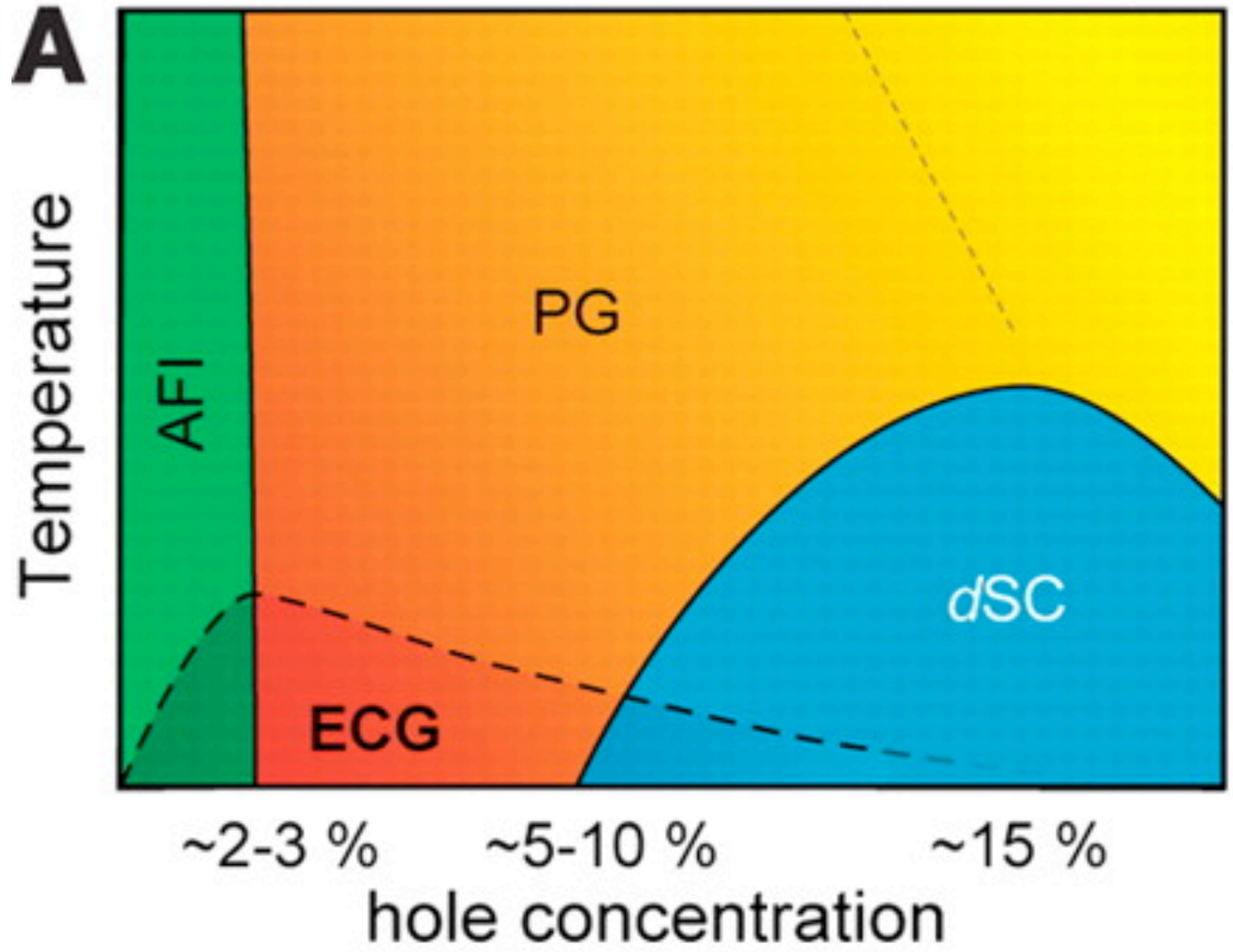


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

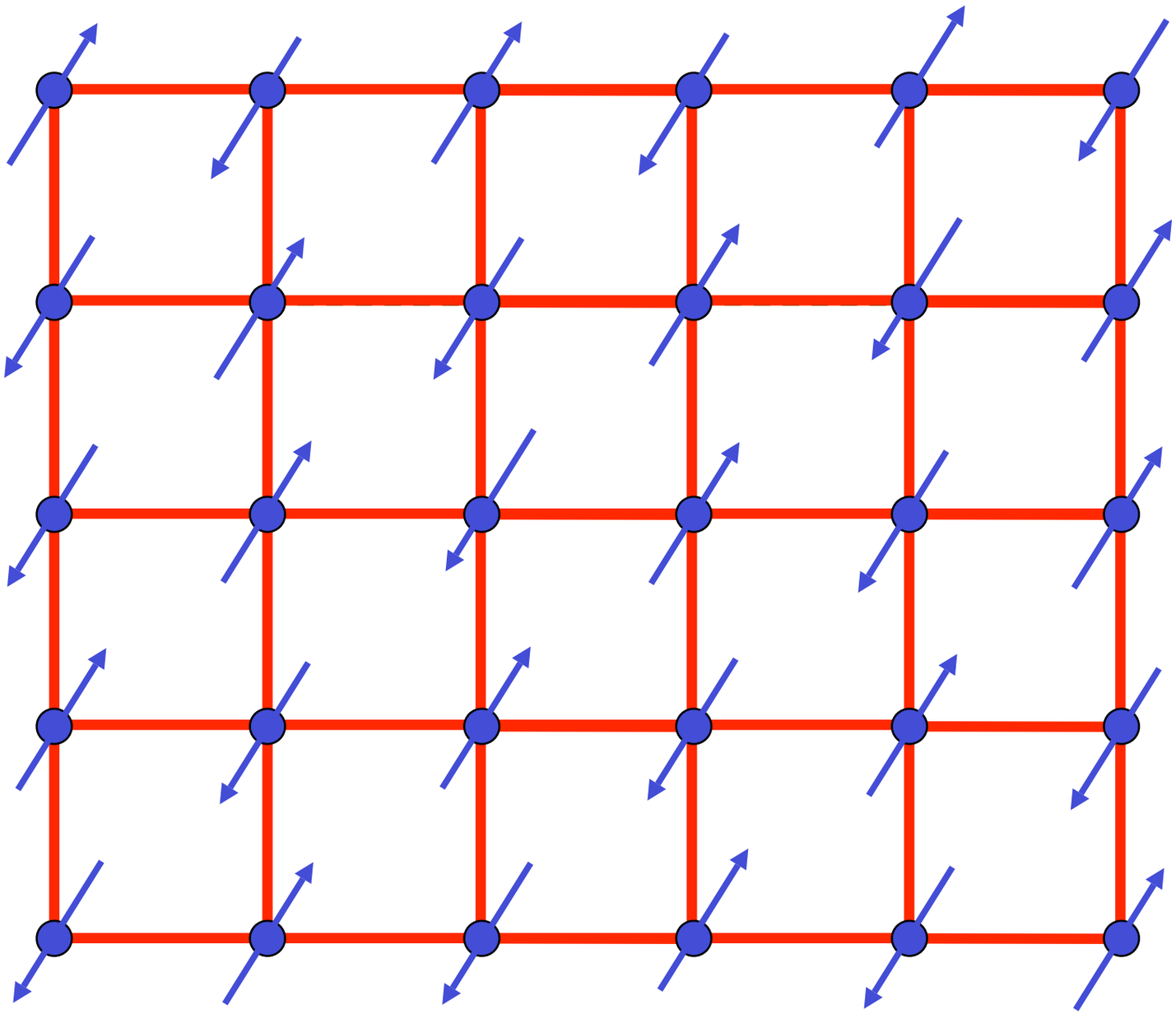
Superposition of two electron states leads to non-local correlations between spins

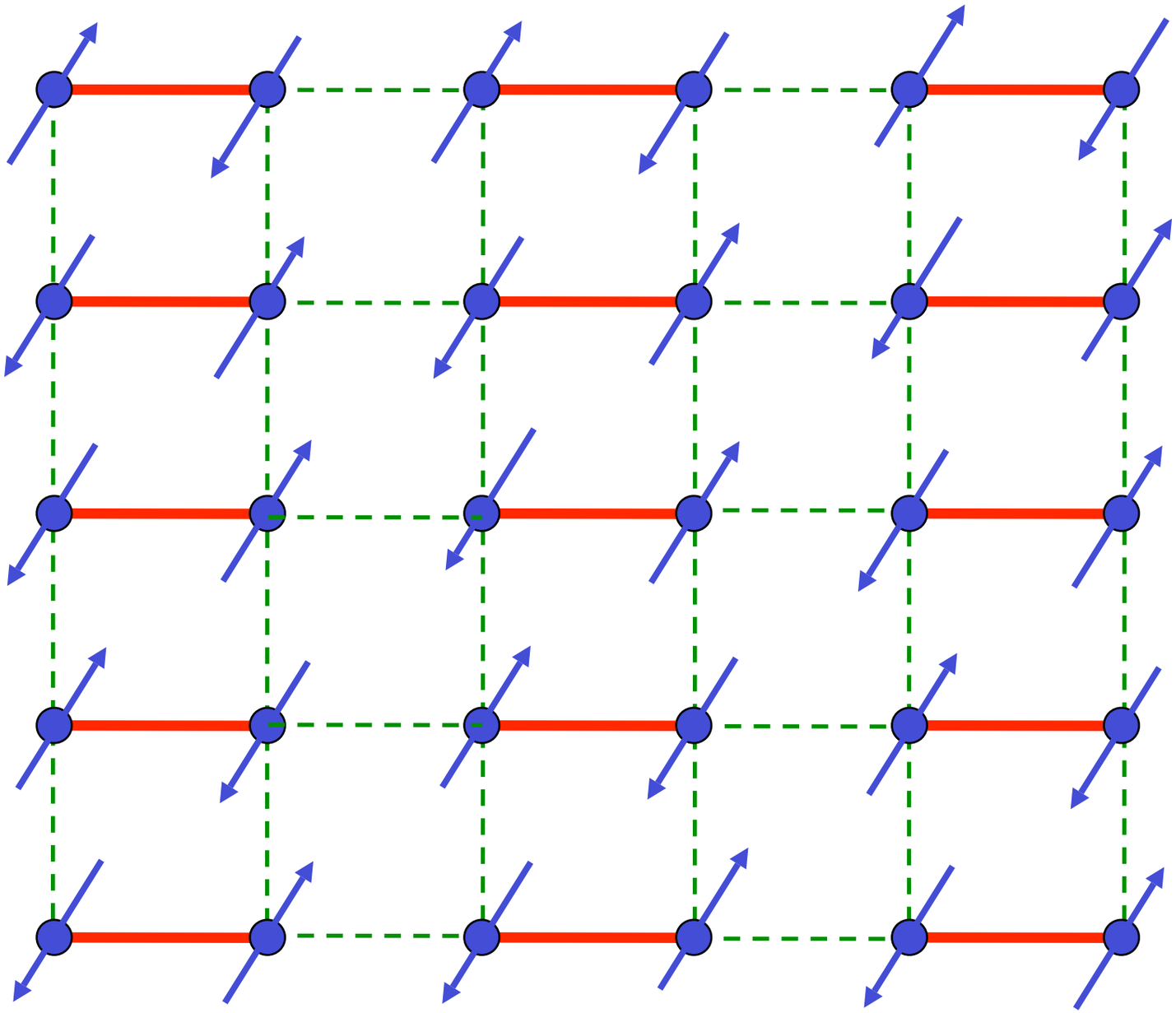
The cuprate superconductors



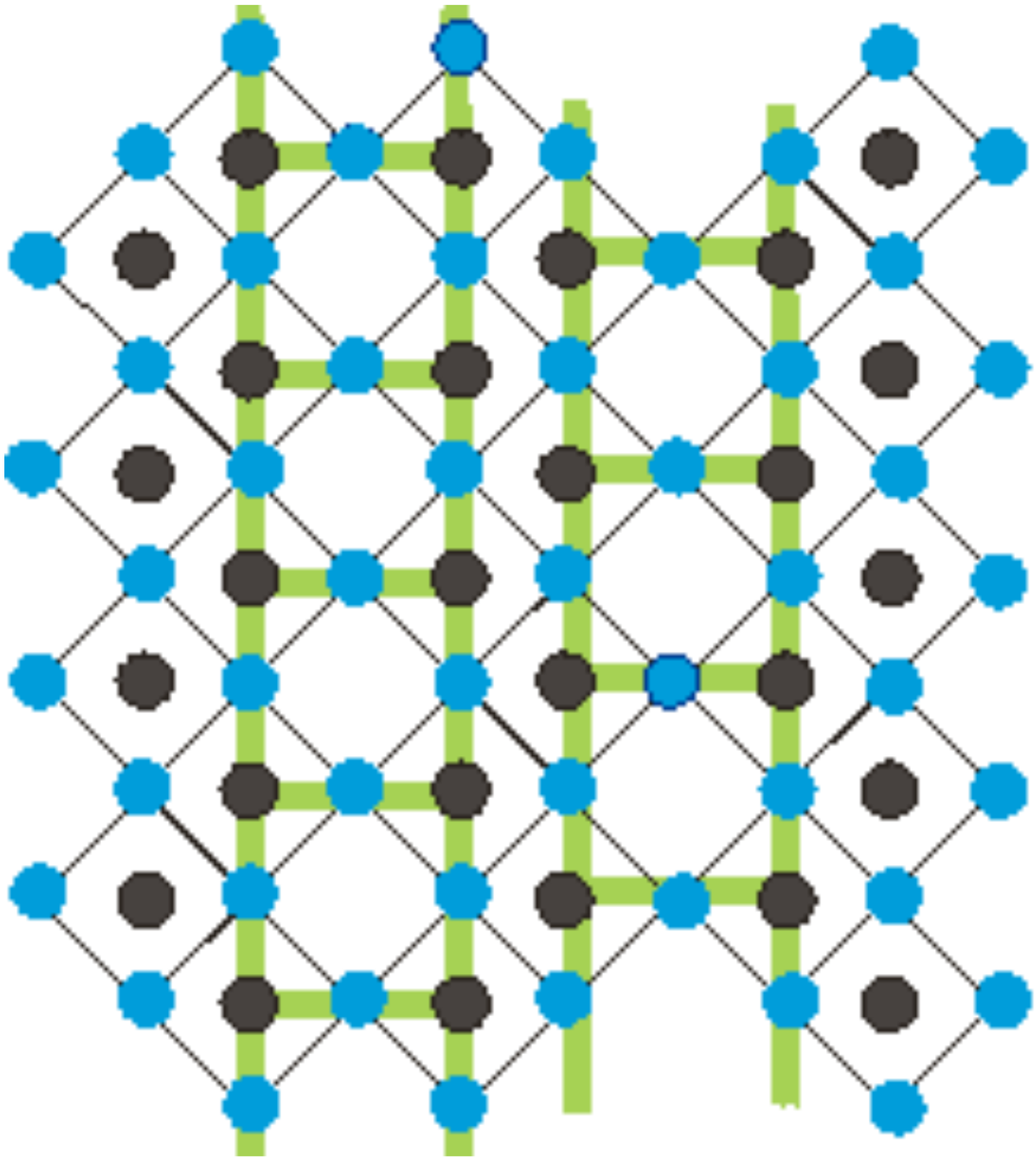


Antiferromagnetic (Neel) order in the insulator



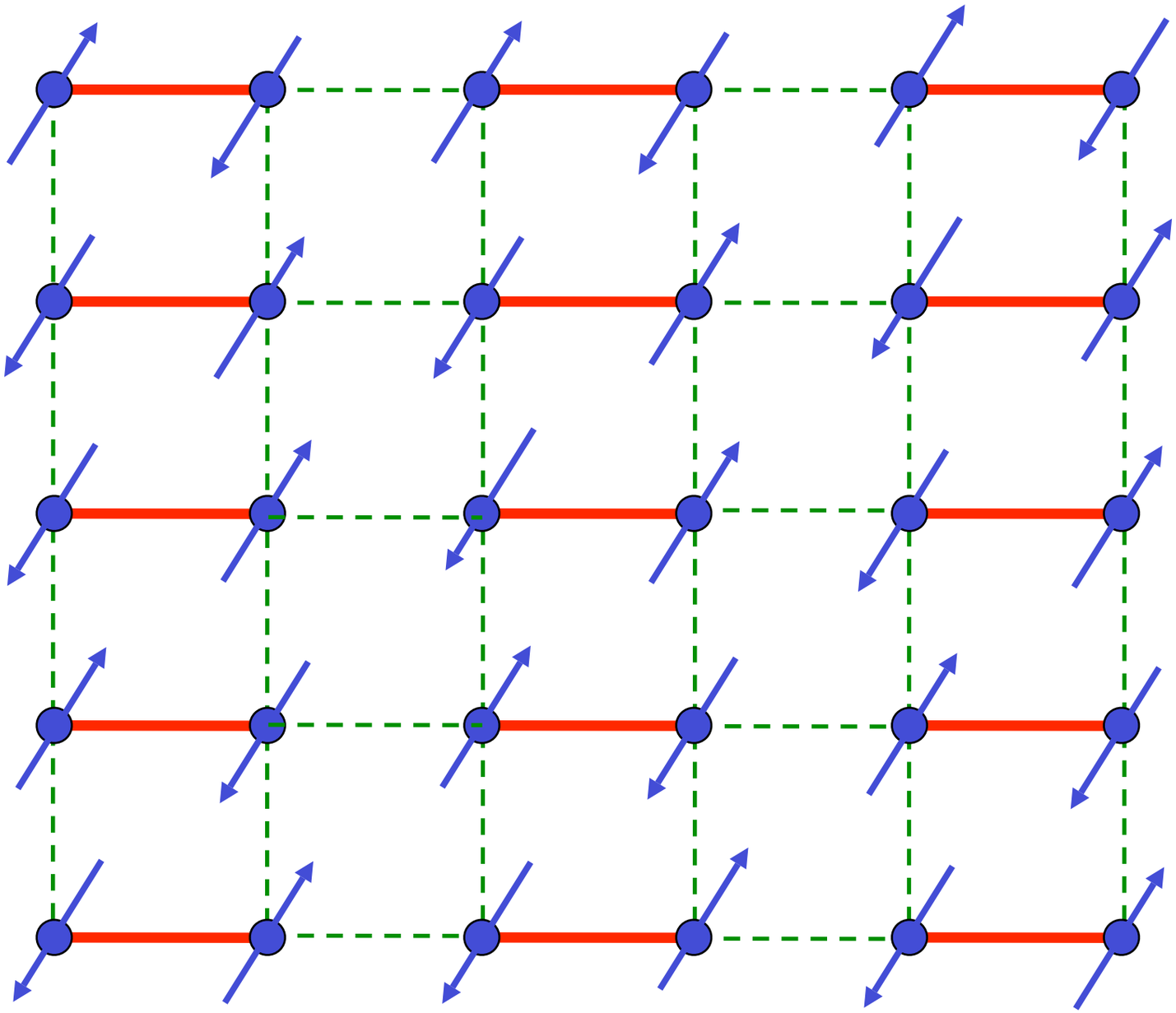


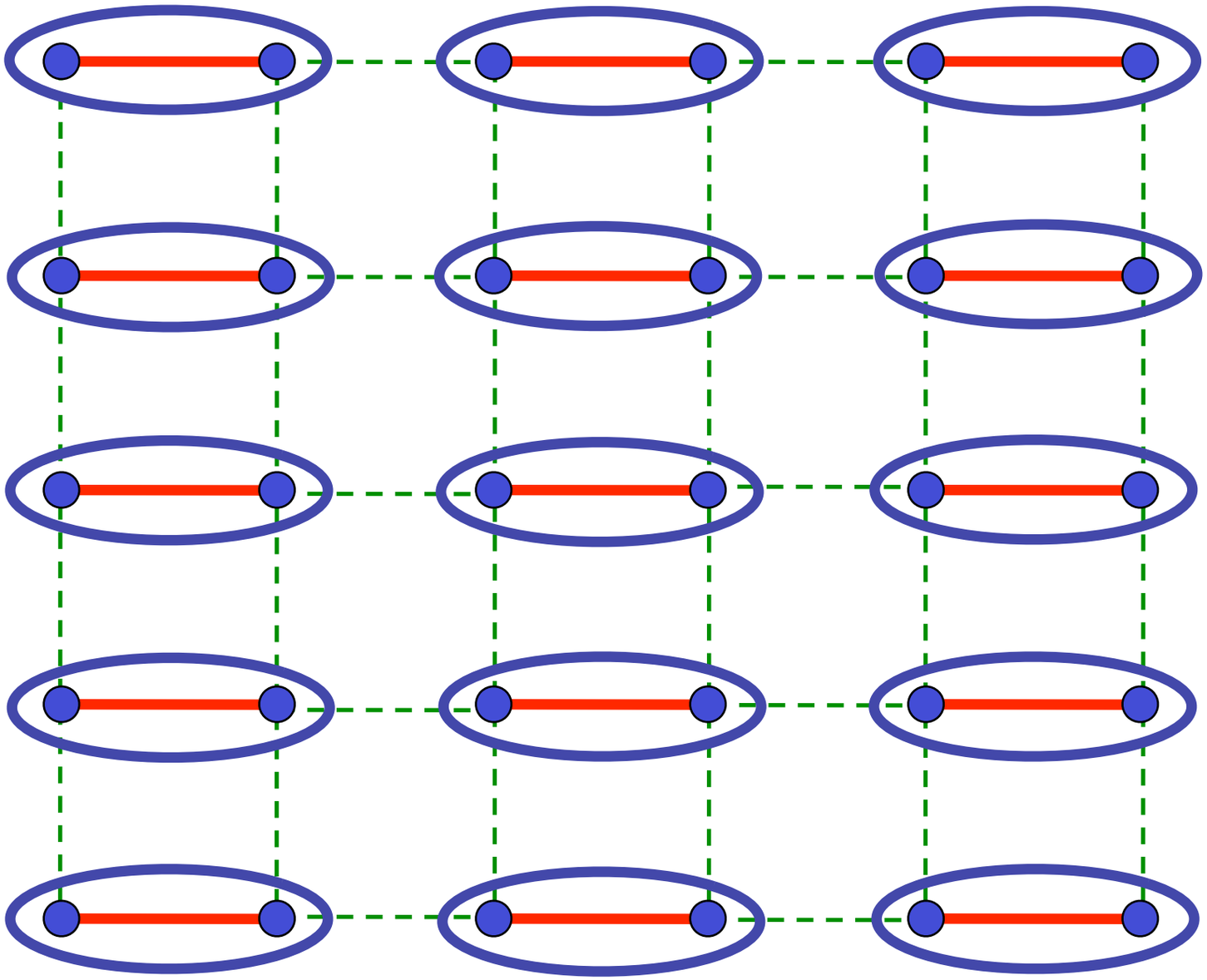
$SrCu_2O_3$



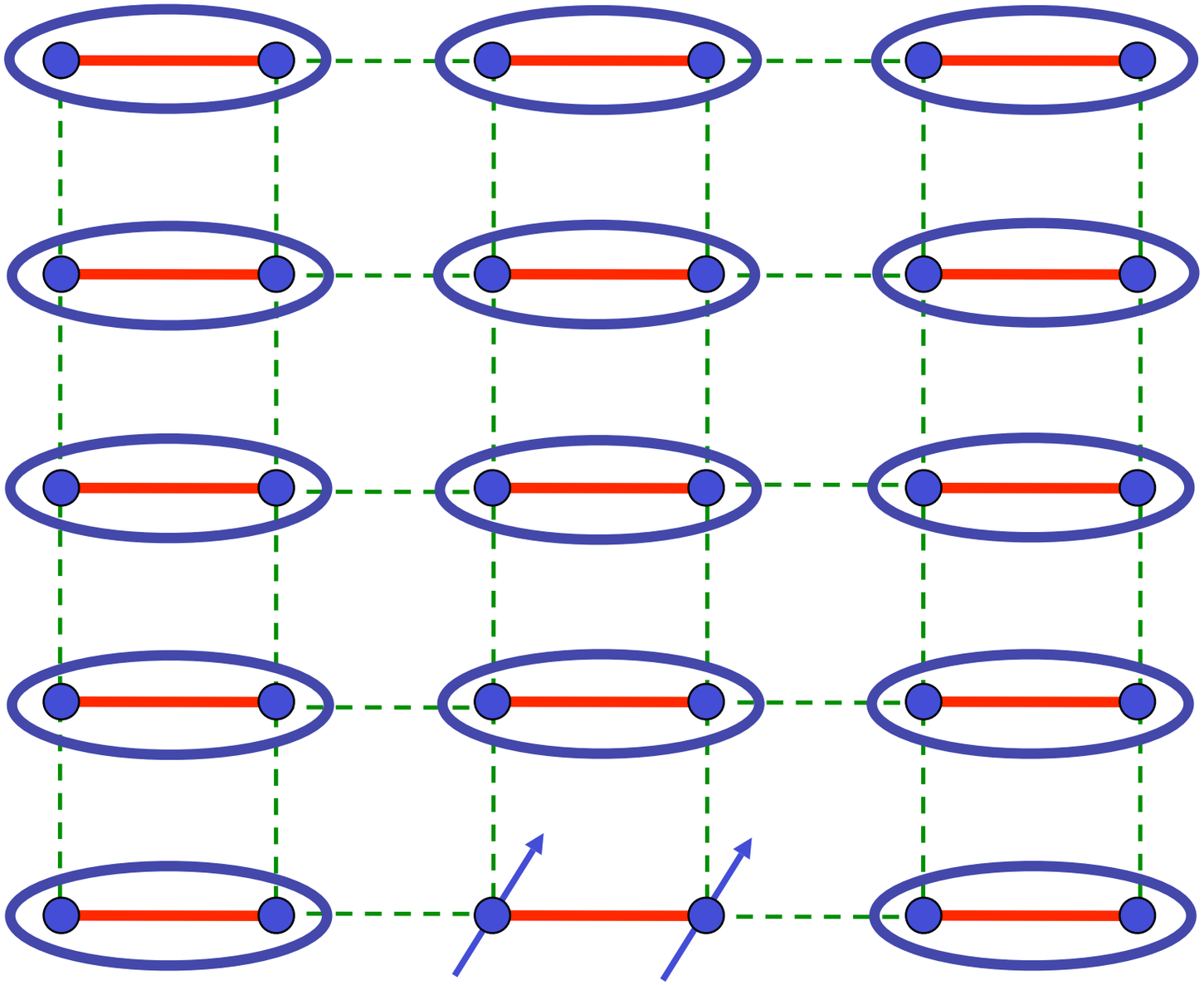
Oxygen

Copper



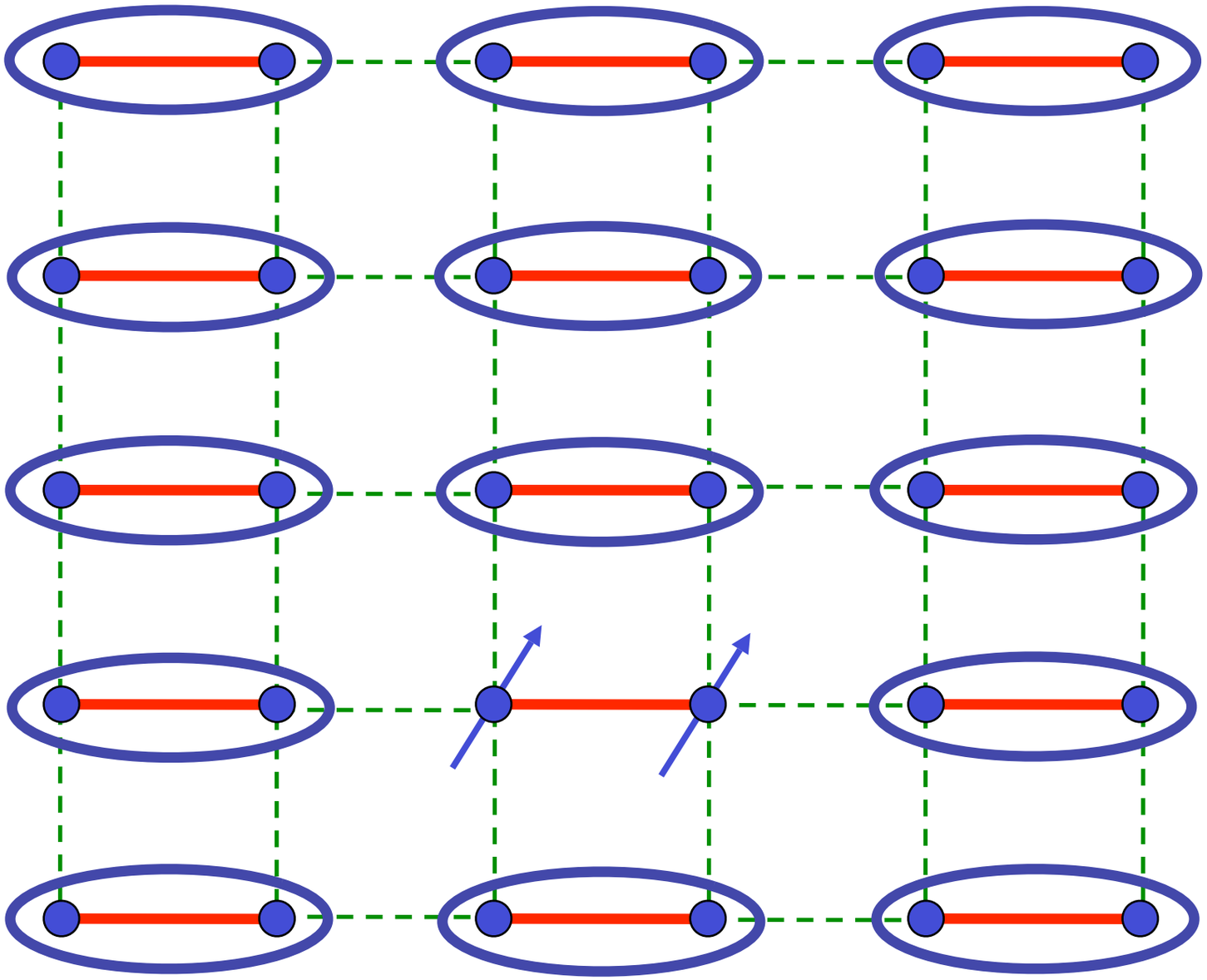


$$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$



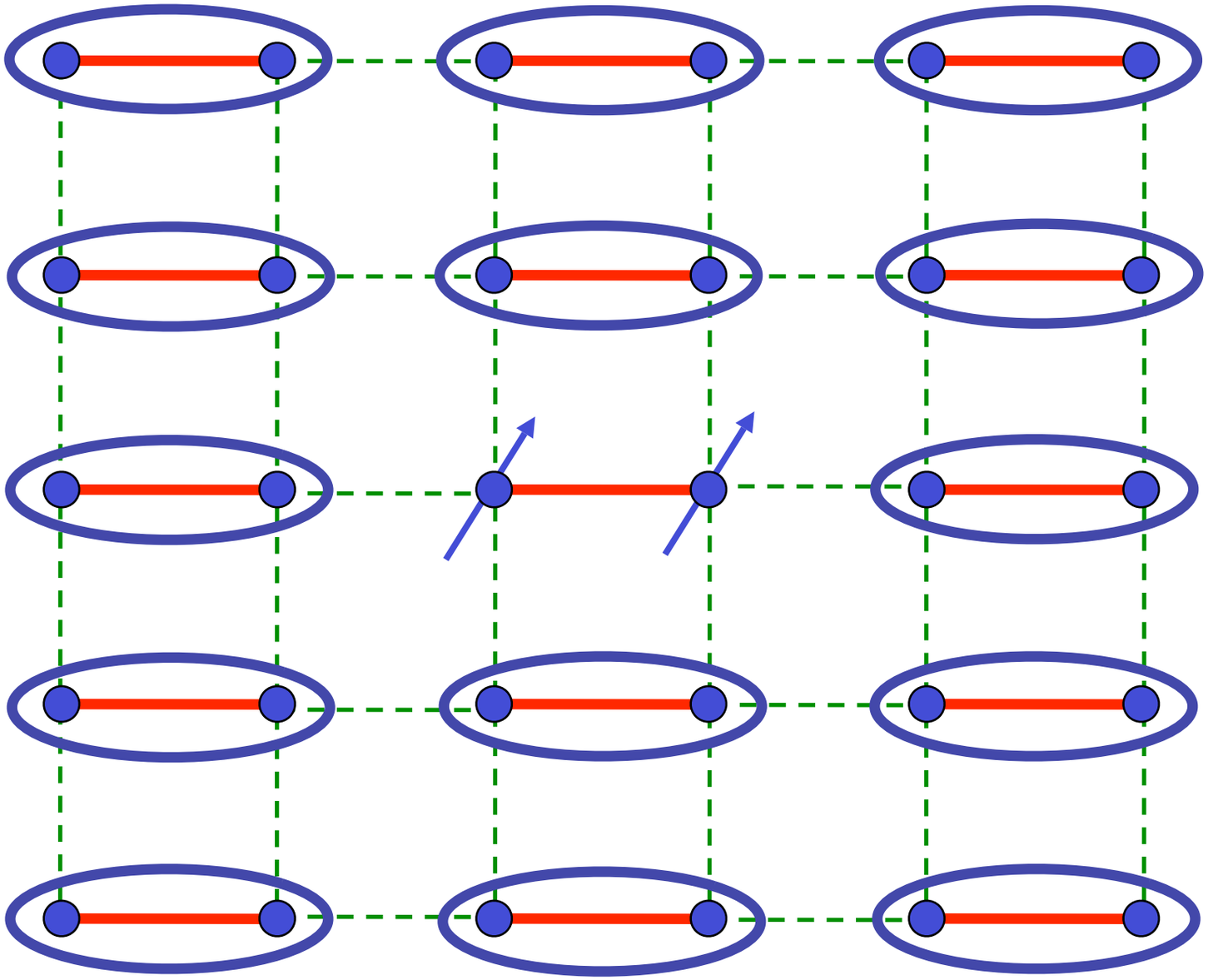
$$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

Excitation: S=1 ***triplon***



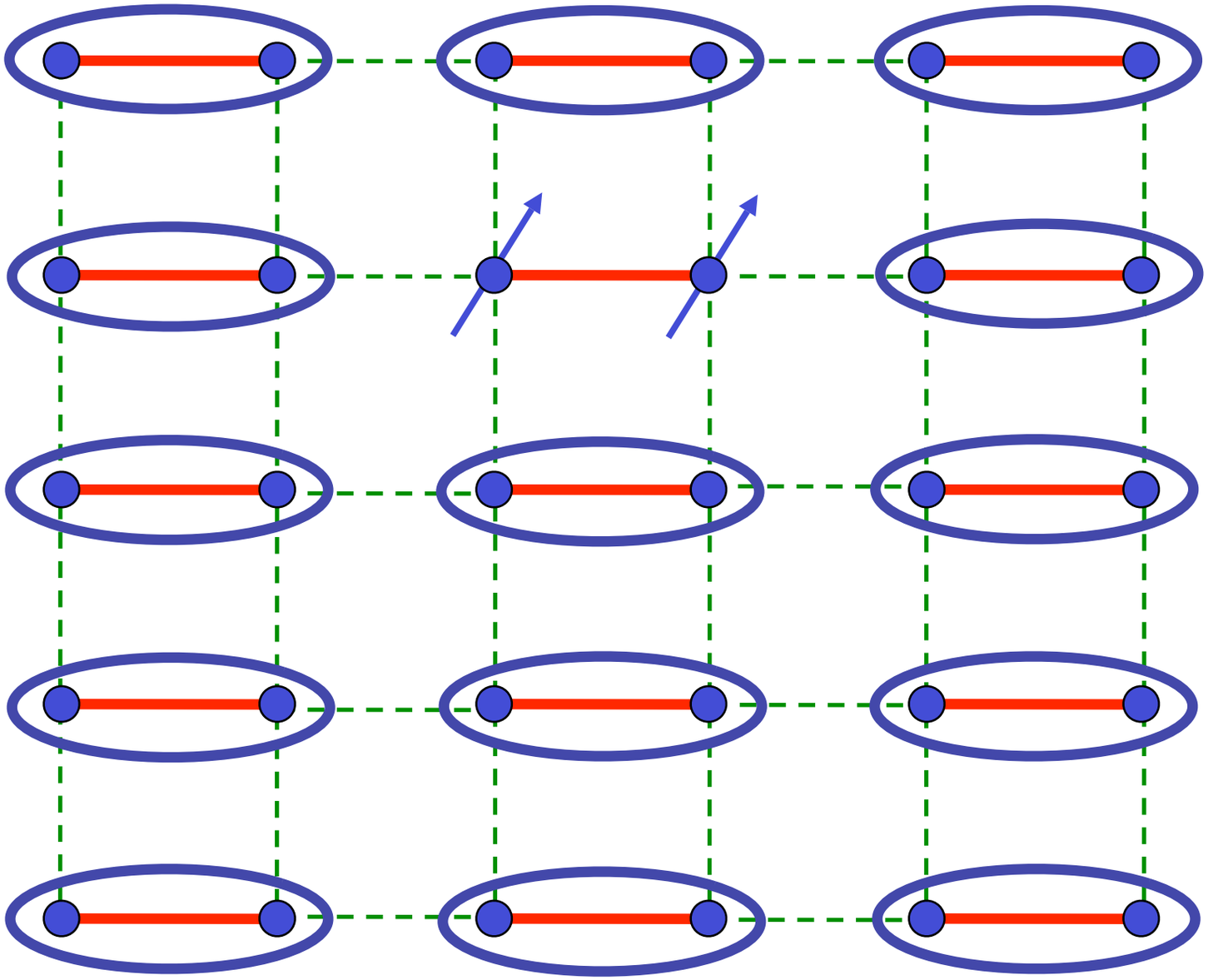
$$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

Excitation: S=1 ***triplon***



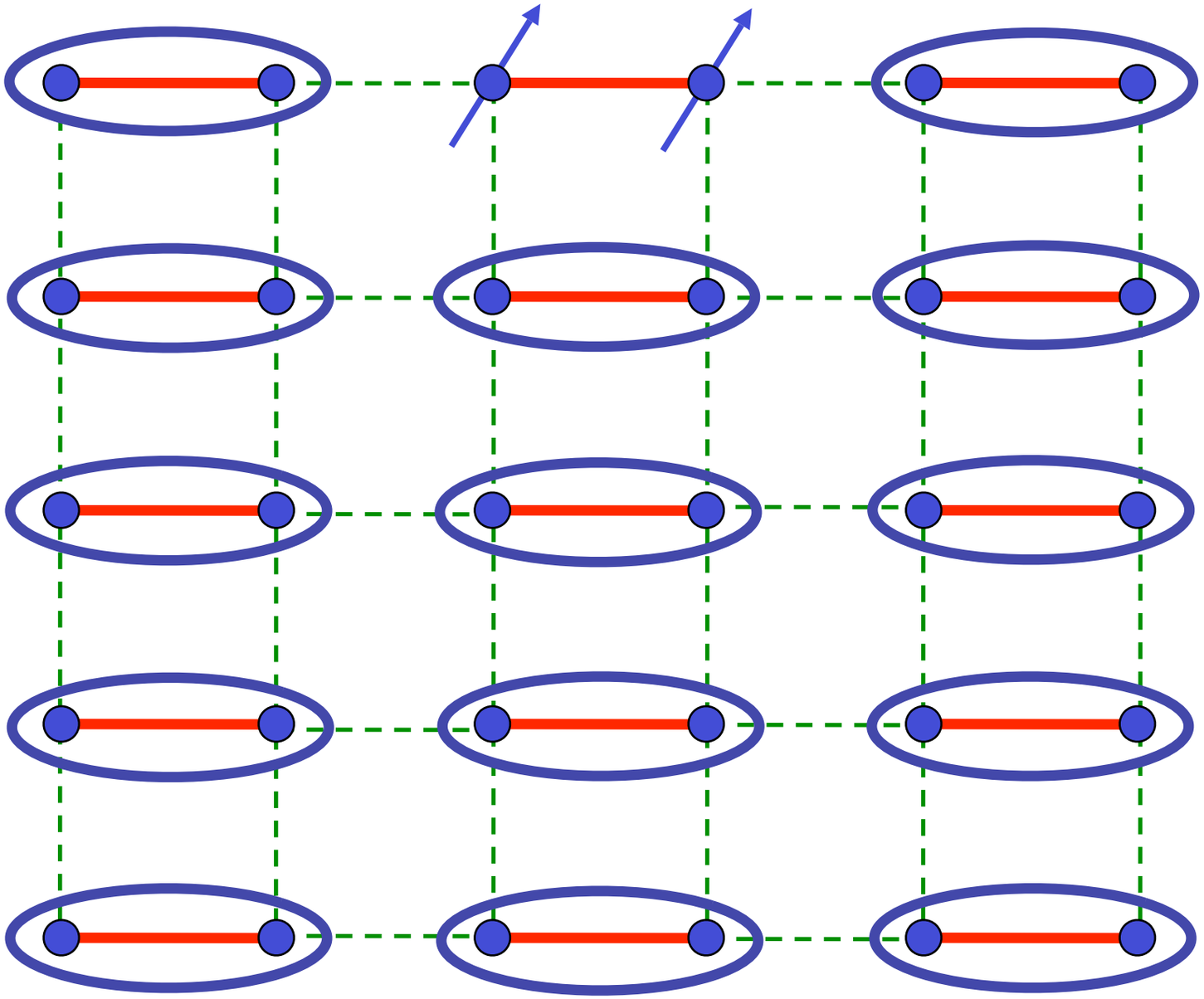
$$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

Excitation: S=1 ***triplon***



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

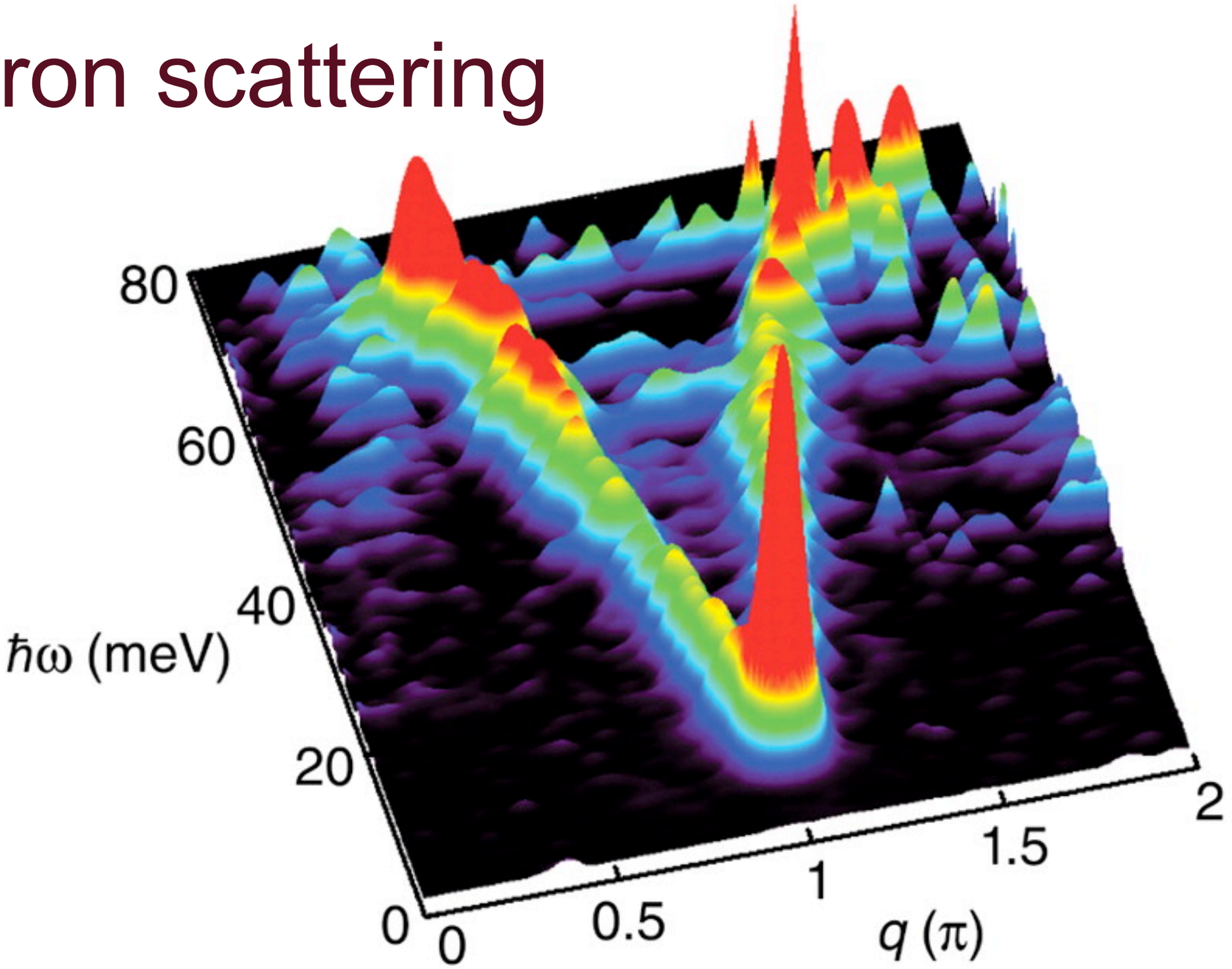
Excitation: S=1 ***triplon***



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

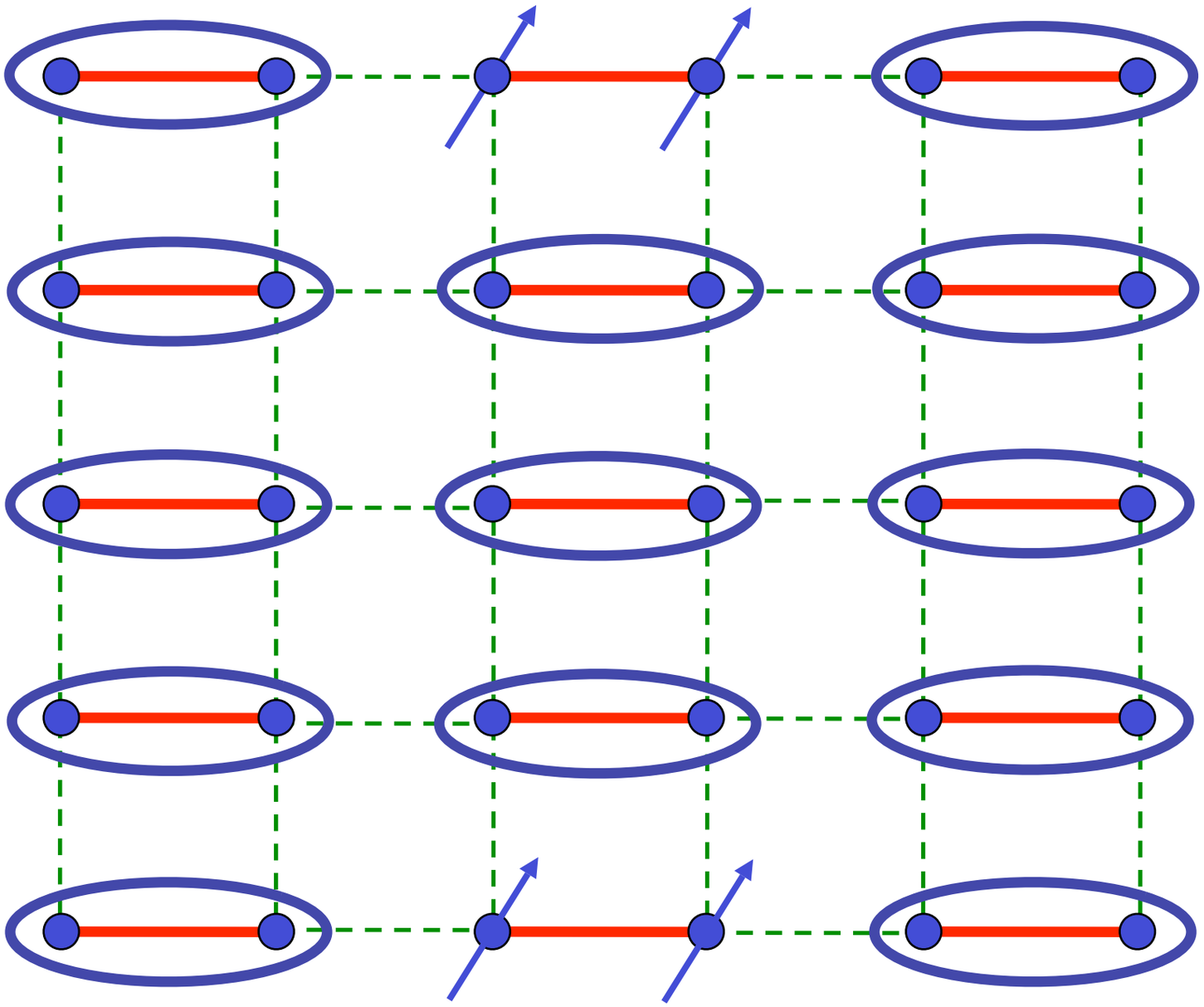
Excitation: S=1 ***triplon***

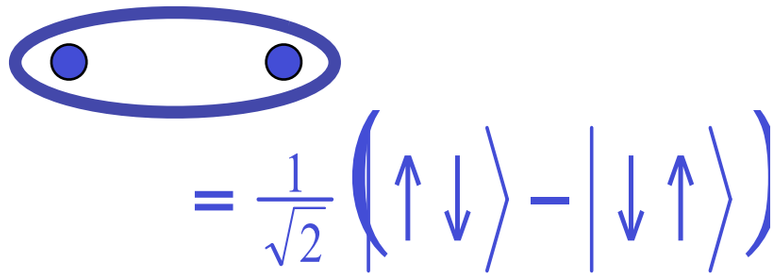
Neutron scattering



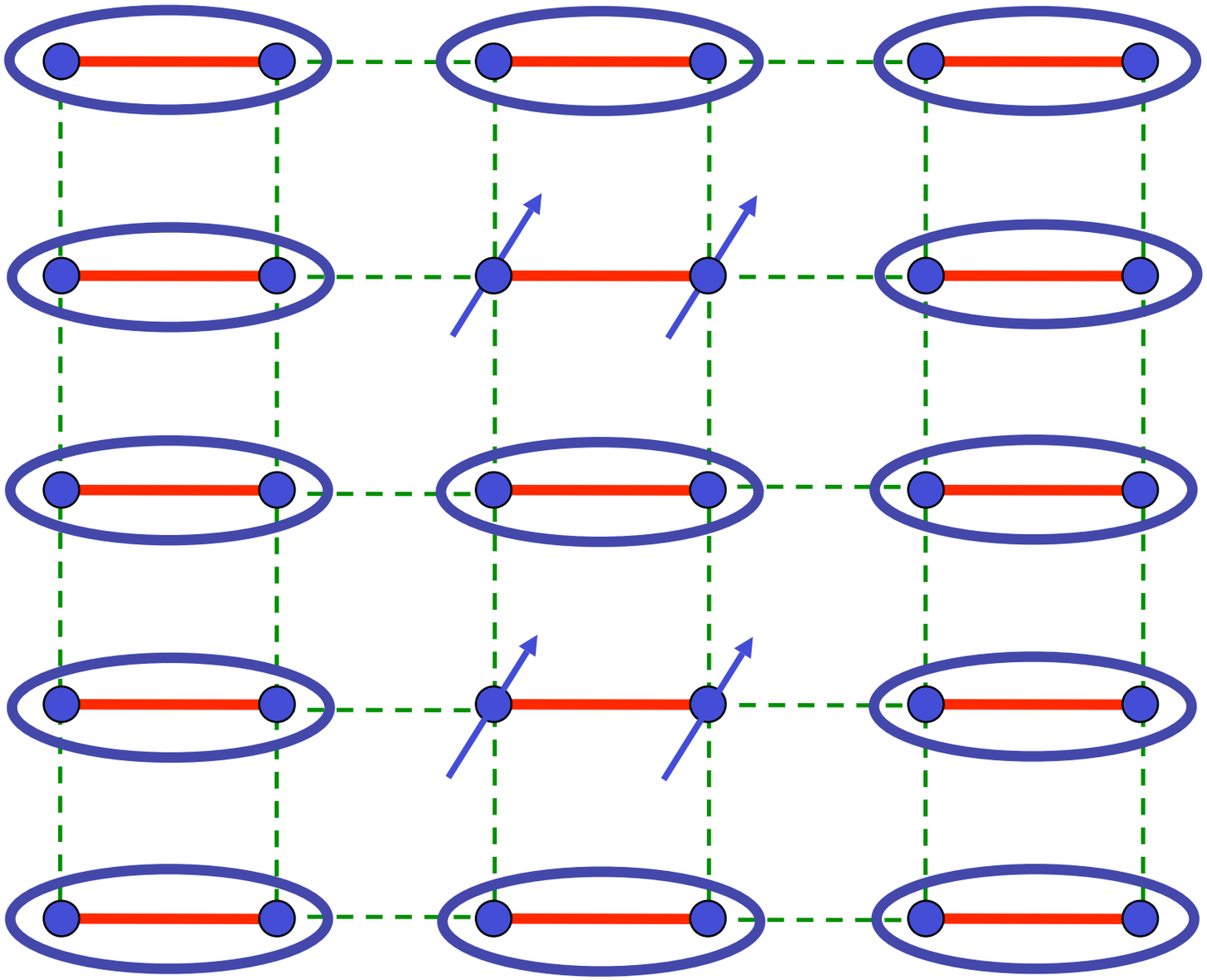
G. Xu, C. Broholm, Yeong-Ah Soh, G. Aeppli, J. F. DiTusa, Y. Chen, M. Kenzelmann, C. D. Frost, T. Ito, K. Oka, and H. Takagi, Science **317**, 1049 (2007).

Collision of triplons



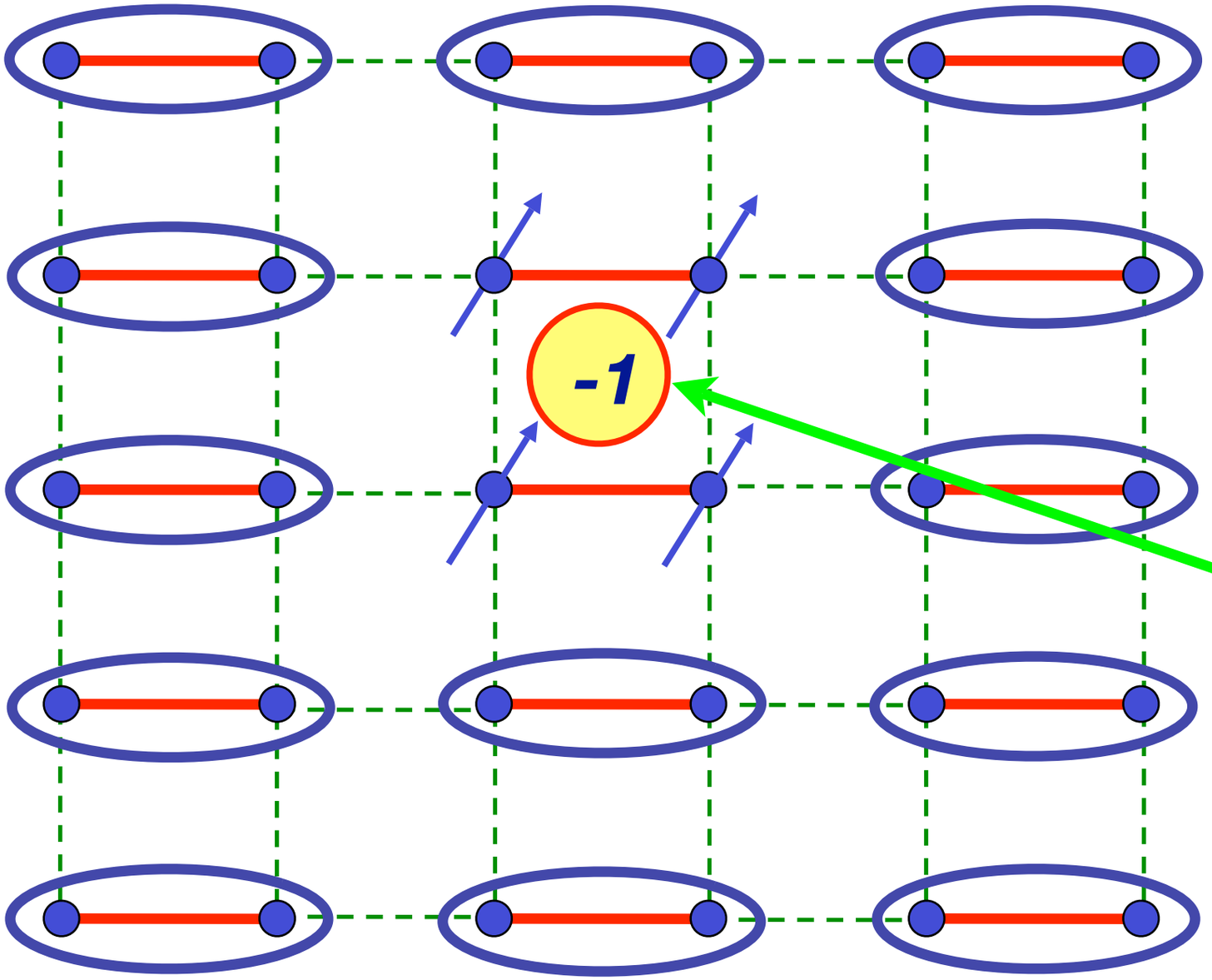


Collision of triplons



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

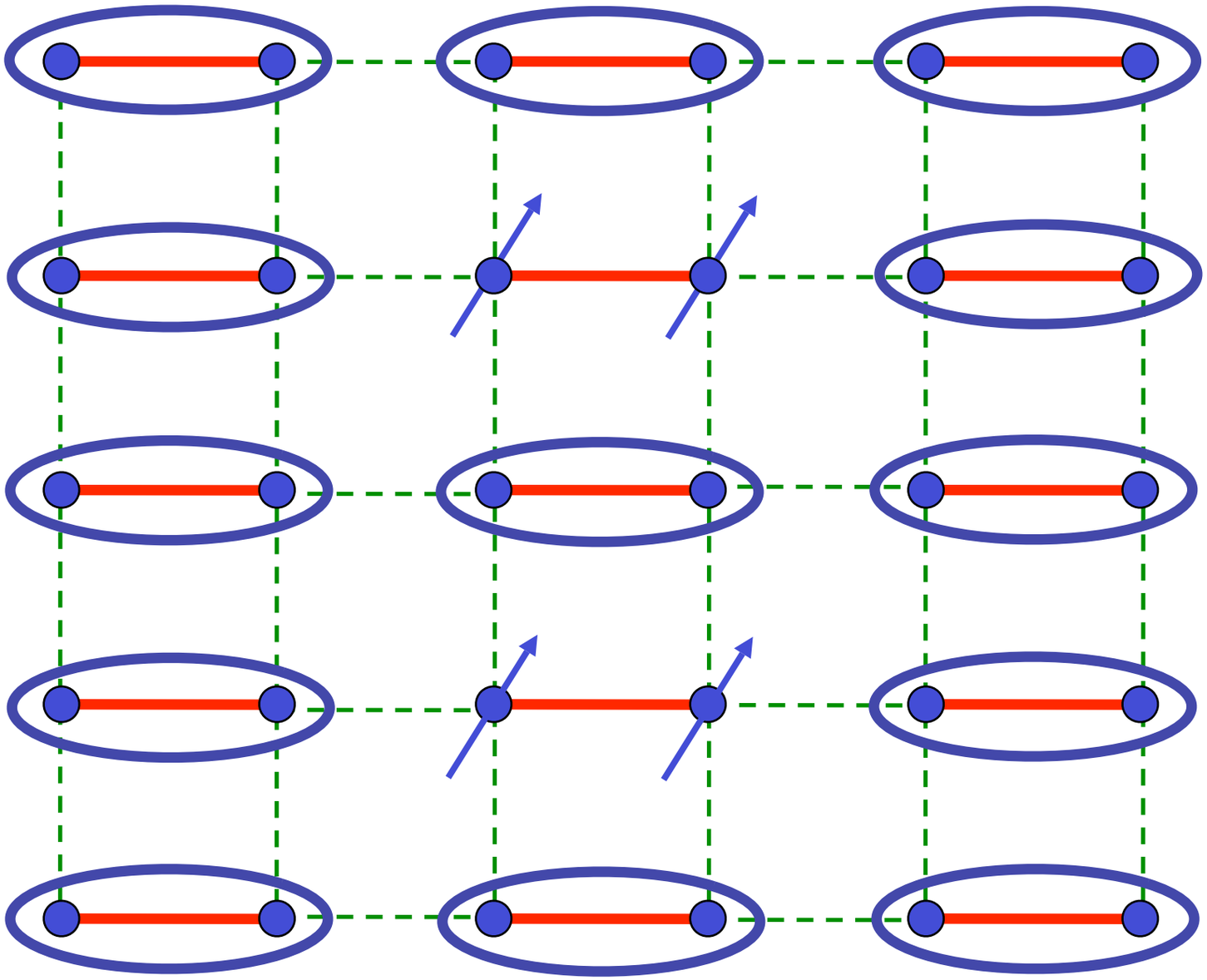
Collision of triplons



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

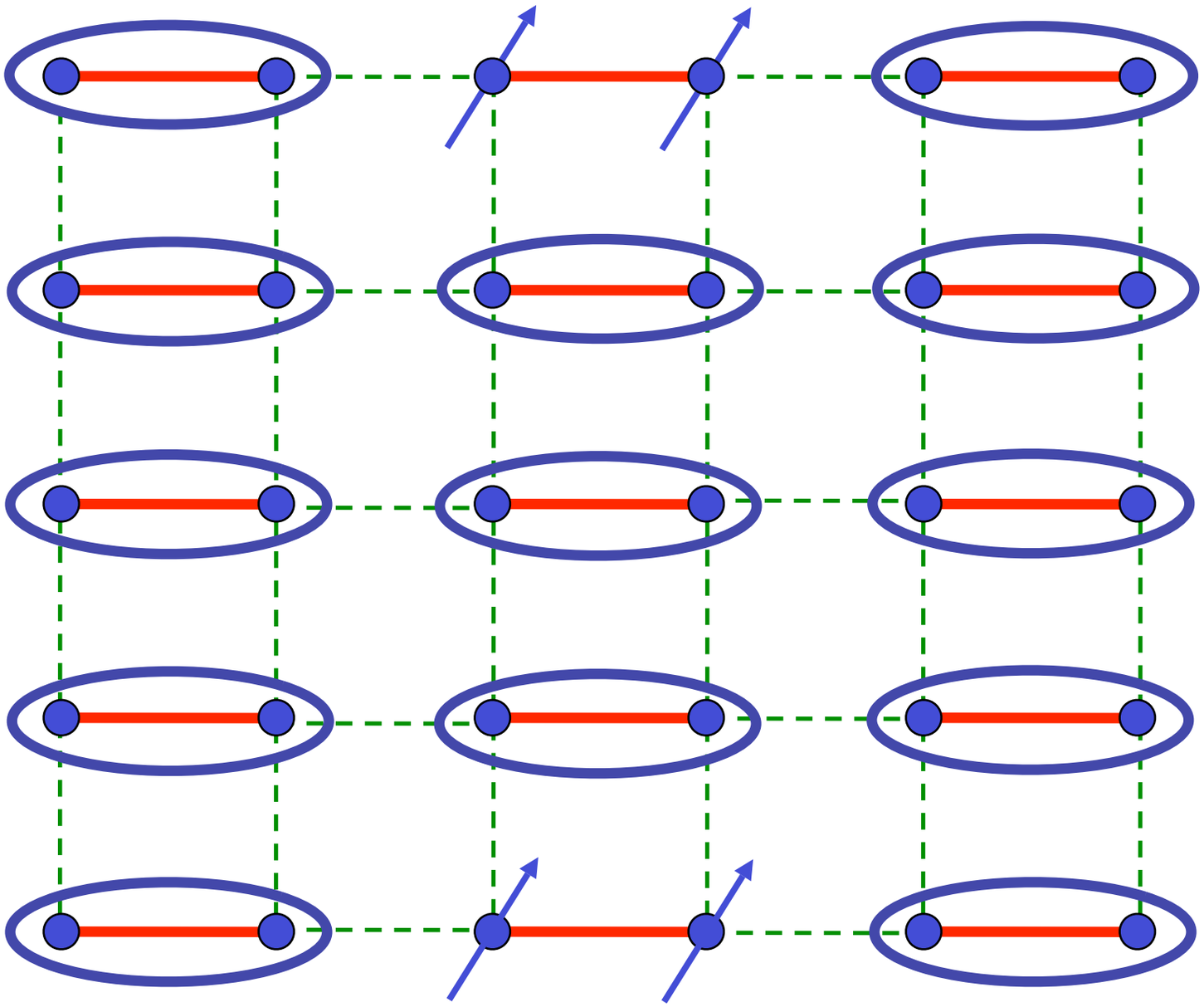
Collision S-matrix

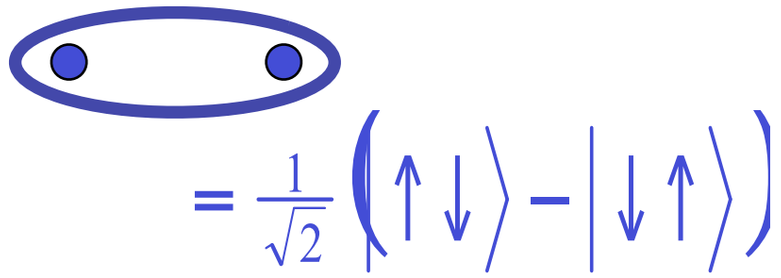
Collision of triplons



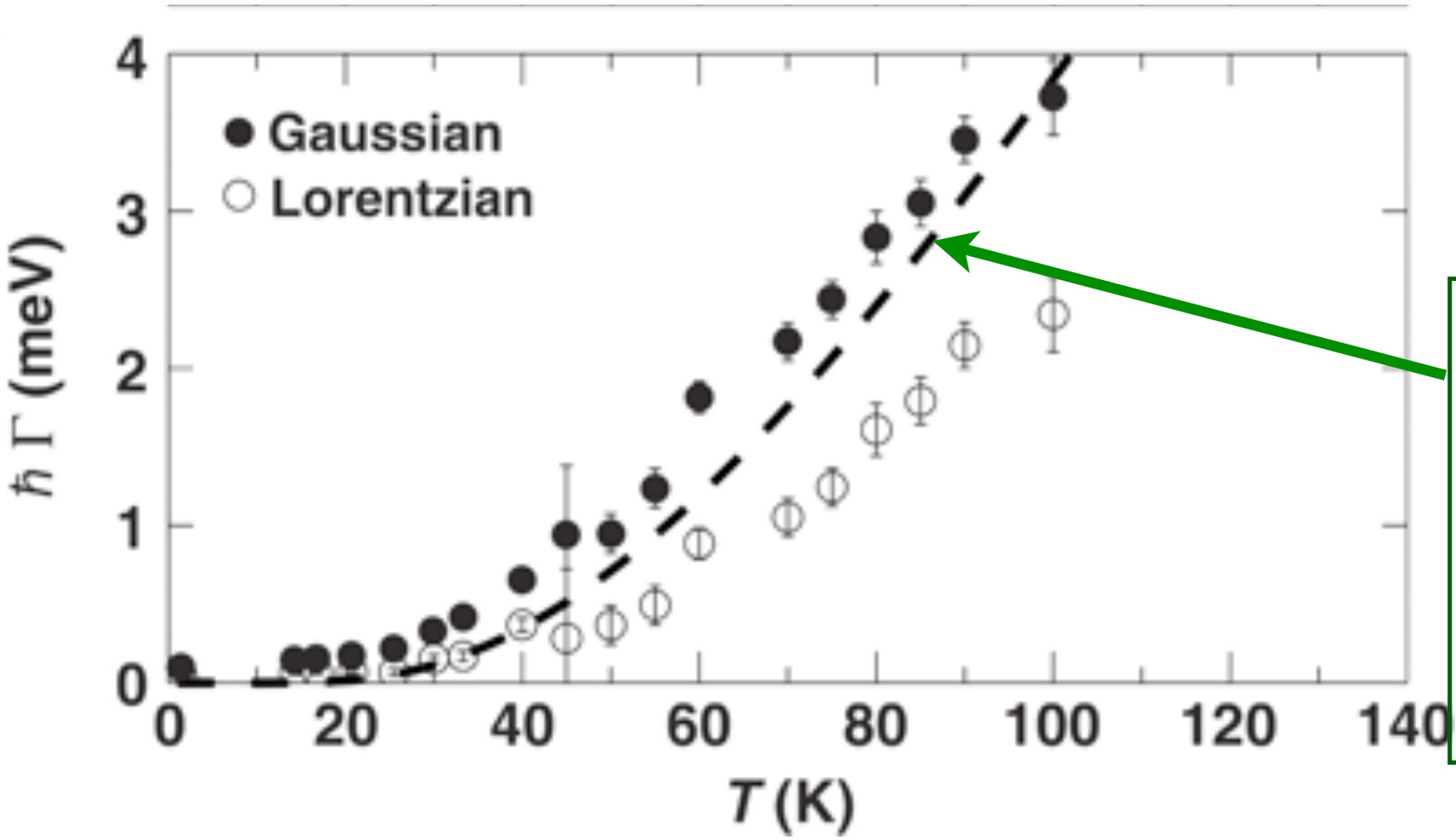
$$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

Collision of triplons





Neutron scattering linewidth



Parameter free prediction by K. Damle and S. Sachdev, Phys. Rev. B **57**, 8307 (1998) from multiple collisions with universal, quantum *S*-matrices

G. Xu, C. Broholm, Yeong-Ah Soh, G. Aeppli, J. F. DiTusa, Y. Chen, M. Kenzelmann, C. D. Frost, T. Ito, K. Oka, and H. Takagi, Science **317**, 1049 (2007).

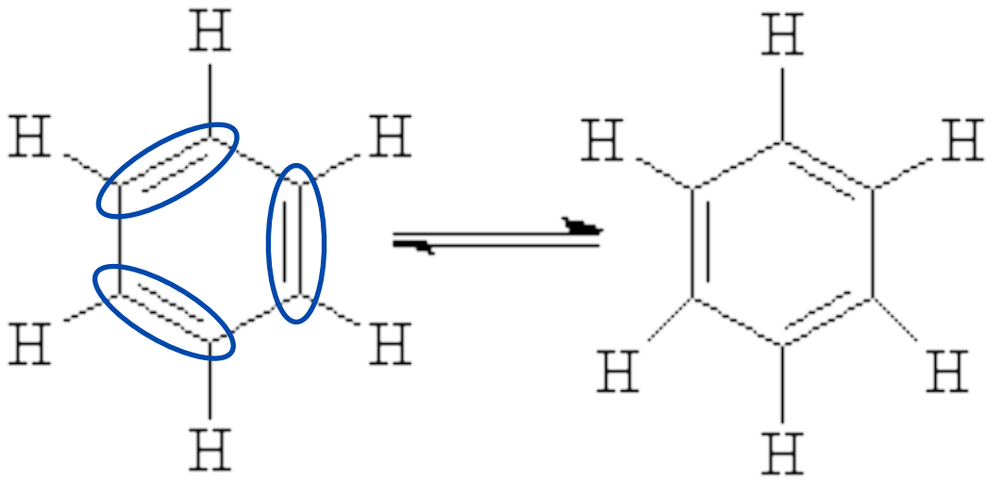
- **Entanglement of spins**

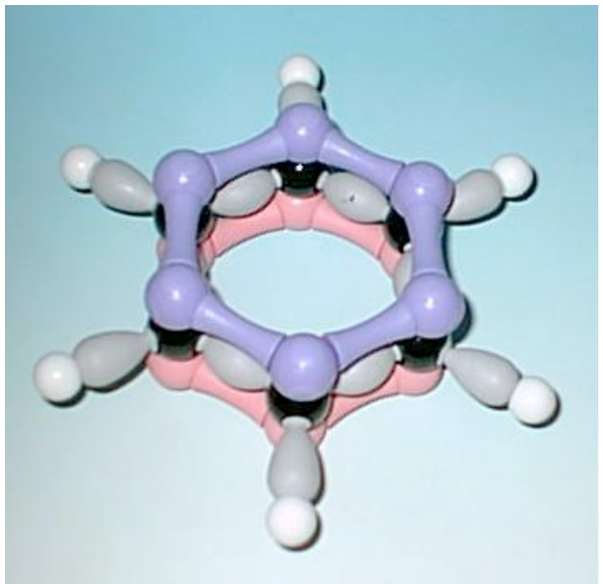
- **Entanglement of valence bonds**

- **Entanglement of spins**

- **Entanglement of valence bonds**

Entanglement of valence bonds

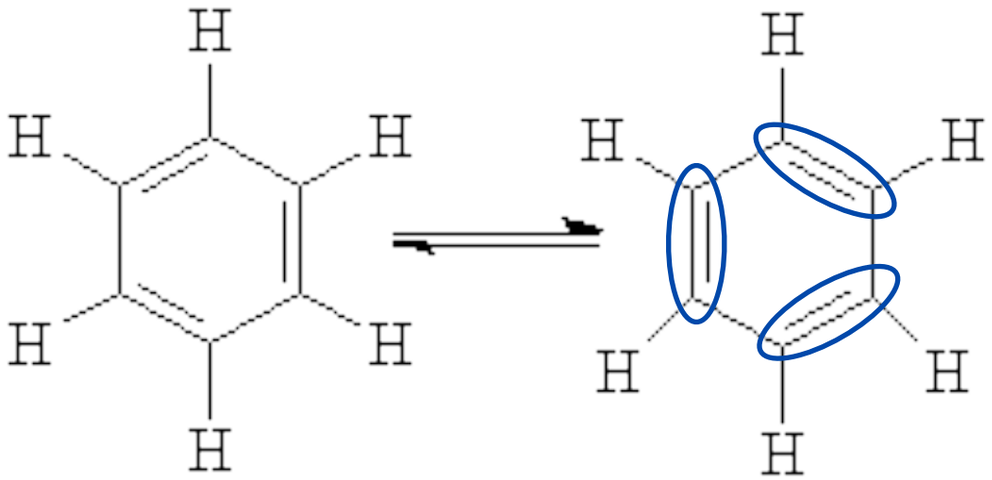


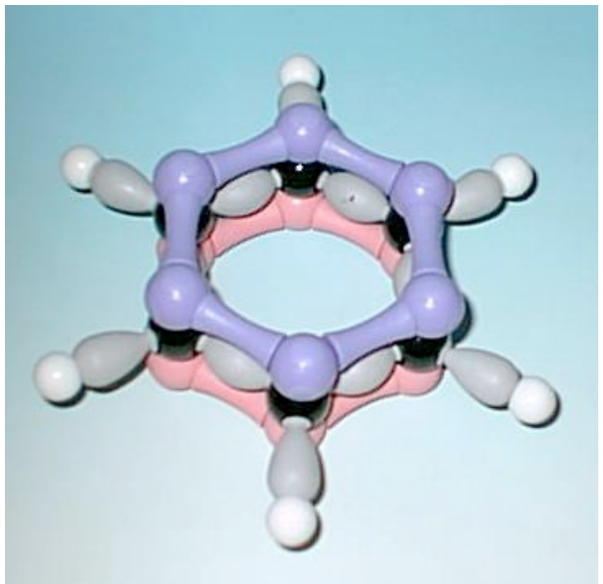


Resonance in benzene leads to a symmetric configuration of valence bonds

(*F. Kekulé, L. Pauling*)

Entanglement of valence bonds

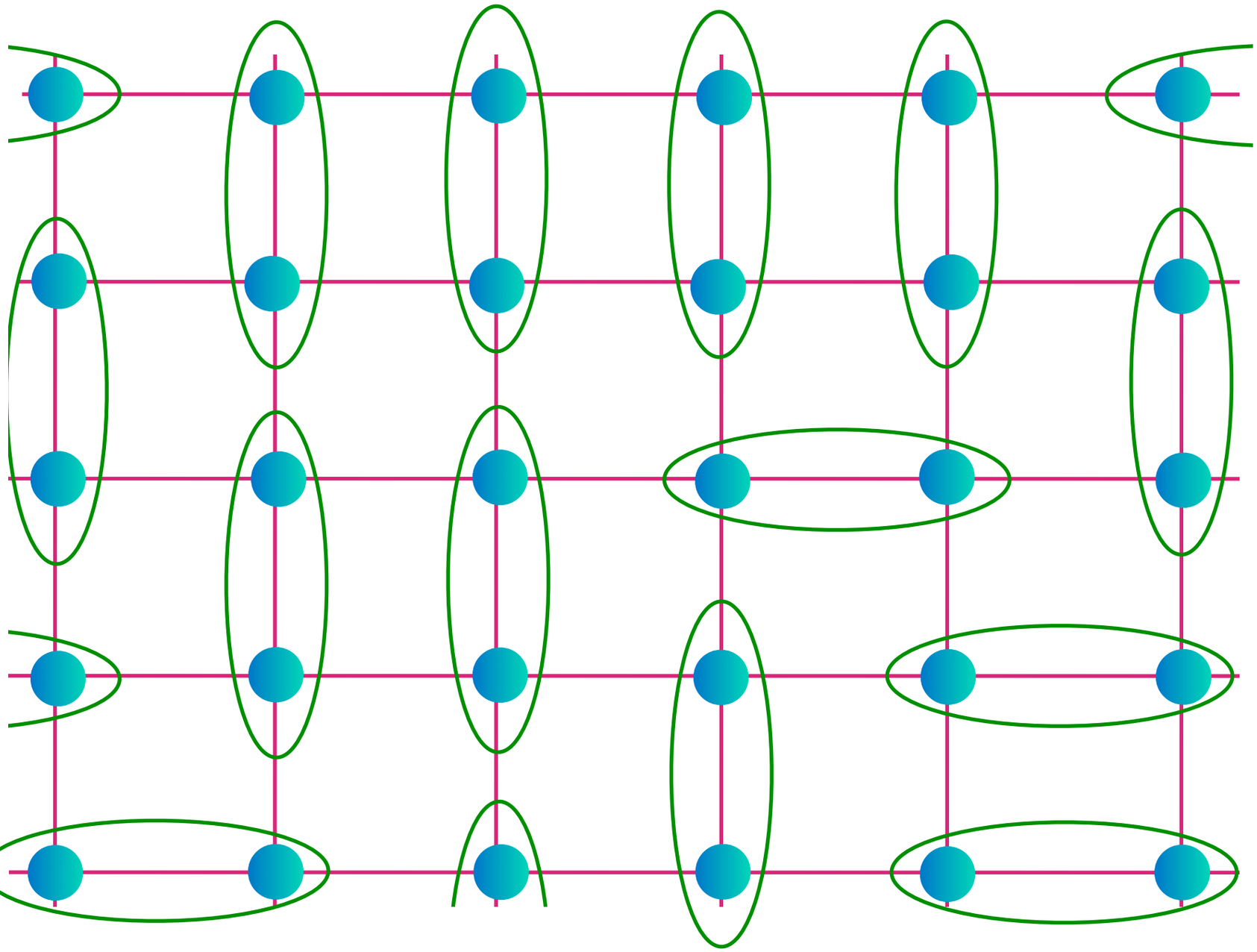


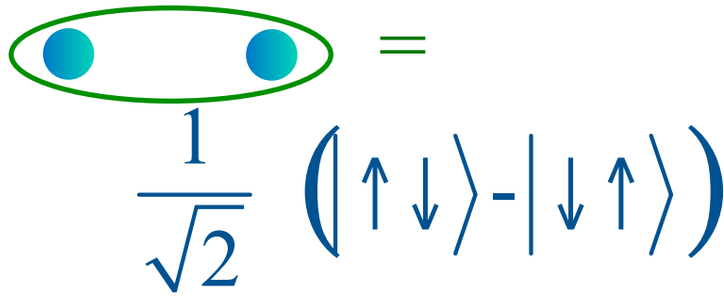


Resonance in benzene leads to a symmetric configuration of valence bonds

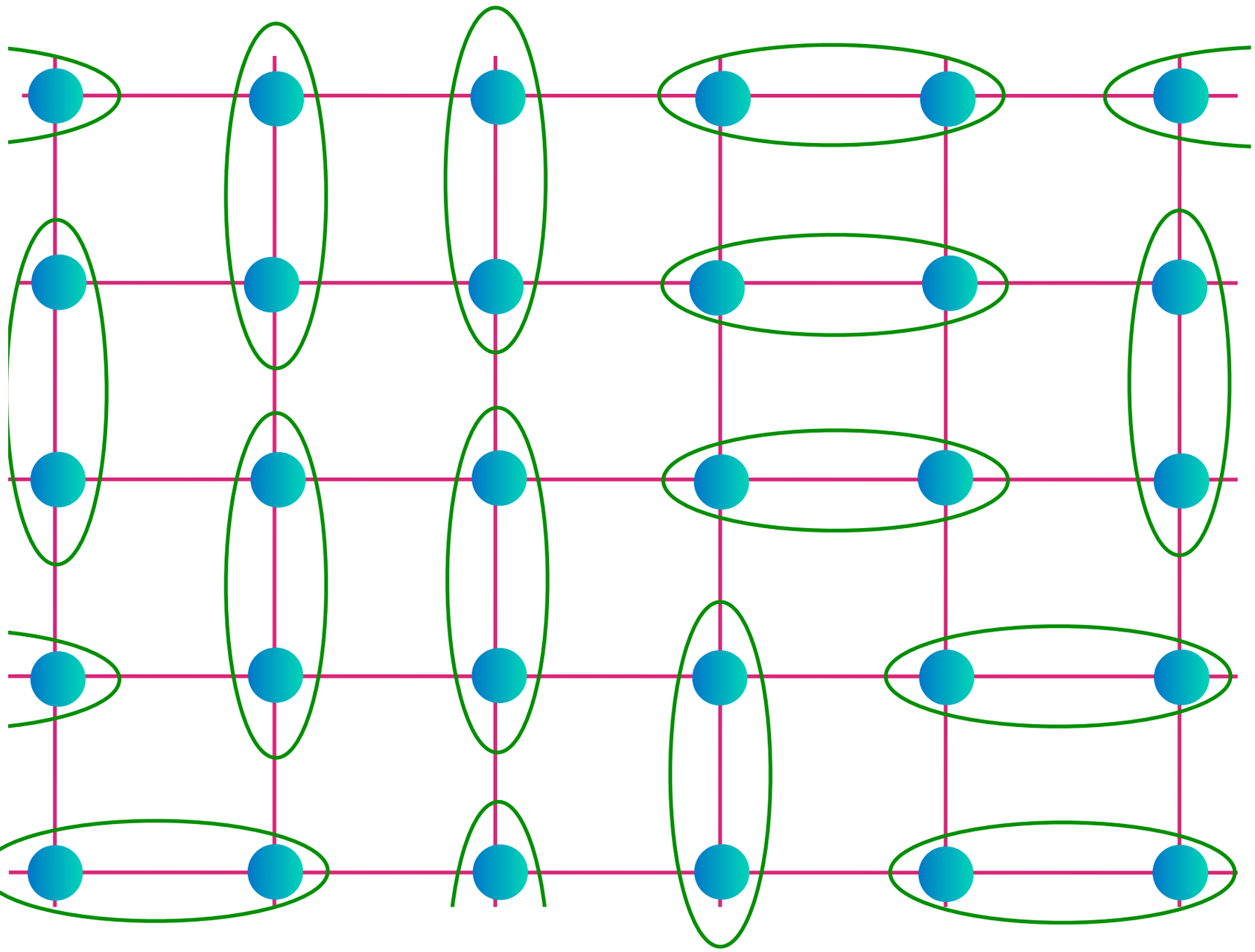
(*F. Kekulé, L. Pauling*)

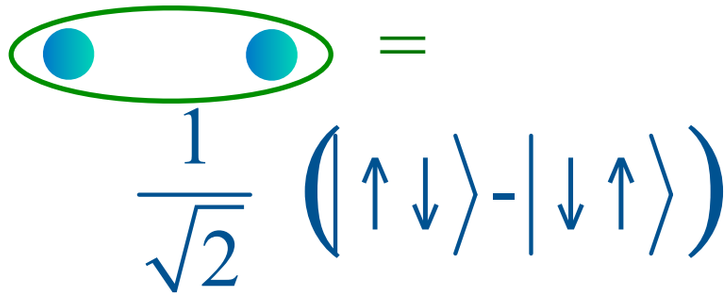
Valence bond entanglement in quantum spin systems



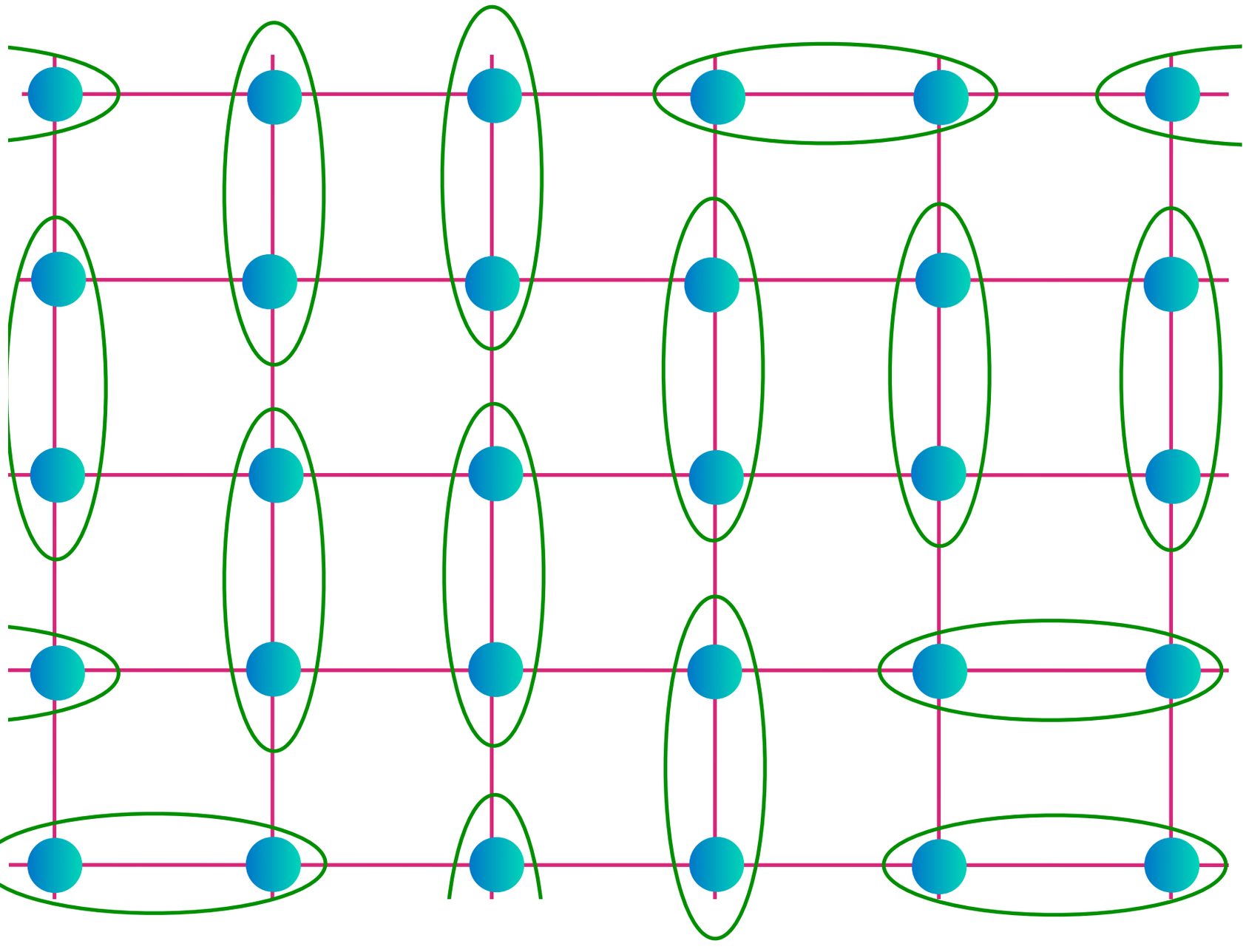


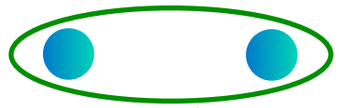
Valence bond entanglement in quantum spin systems





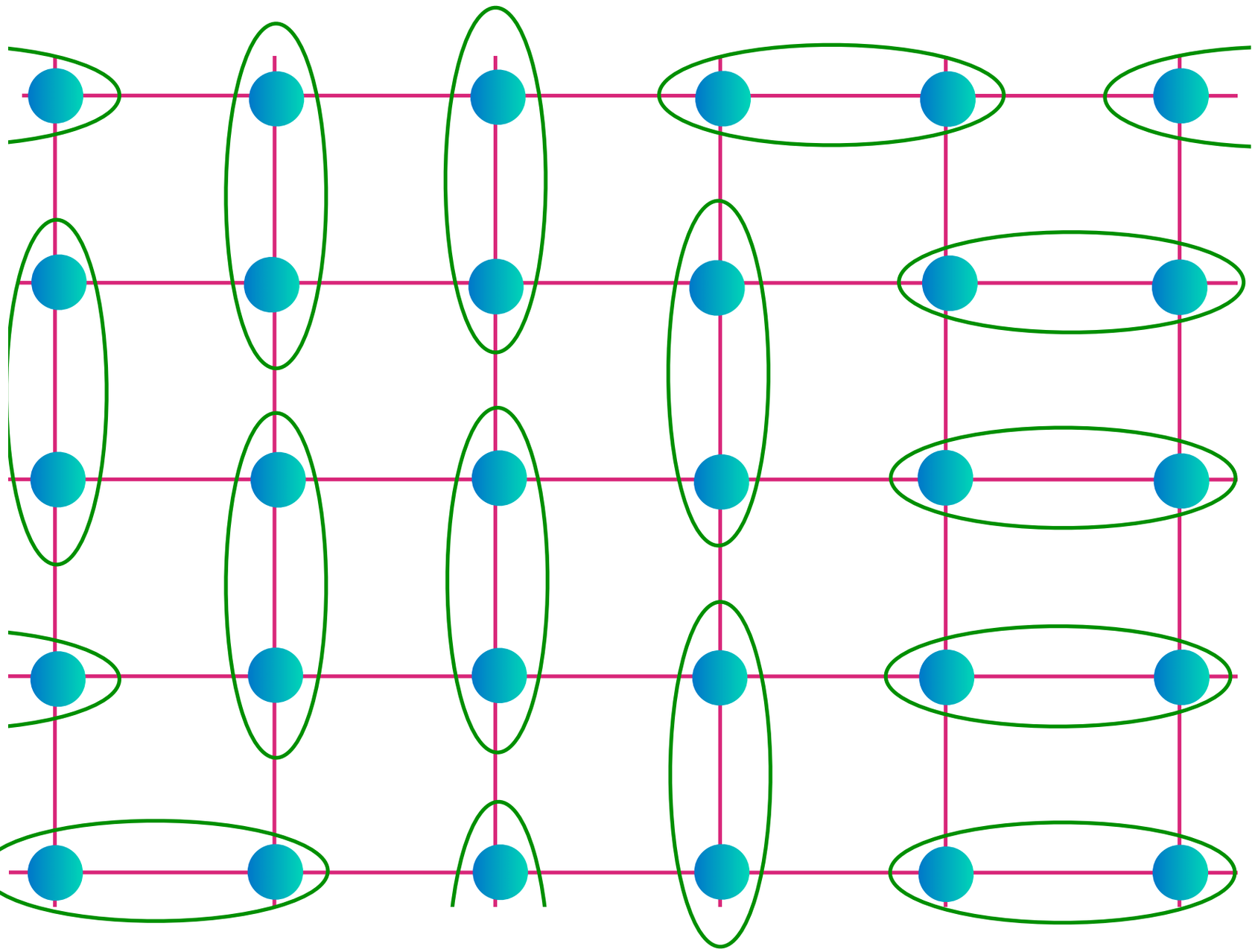
Valence bond entanglement in quantum spin systems

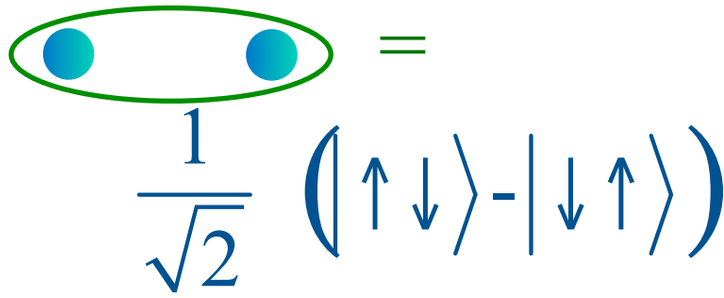




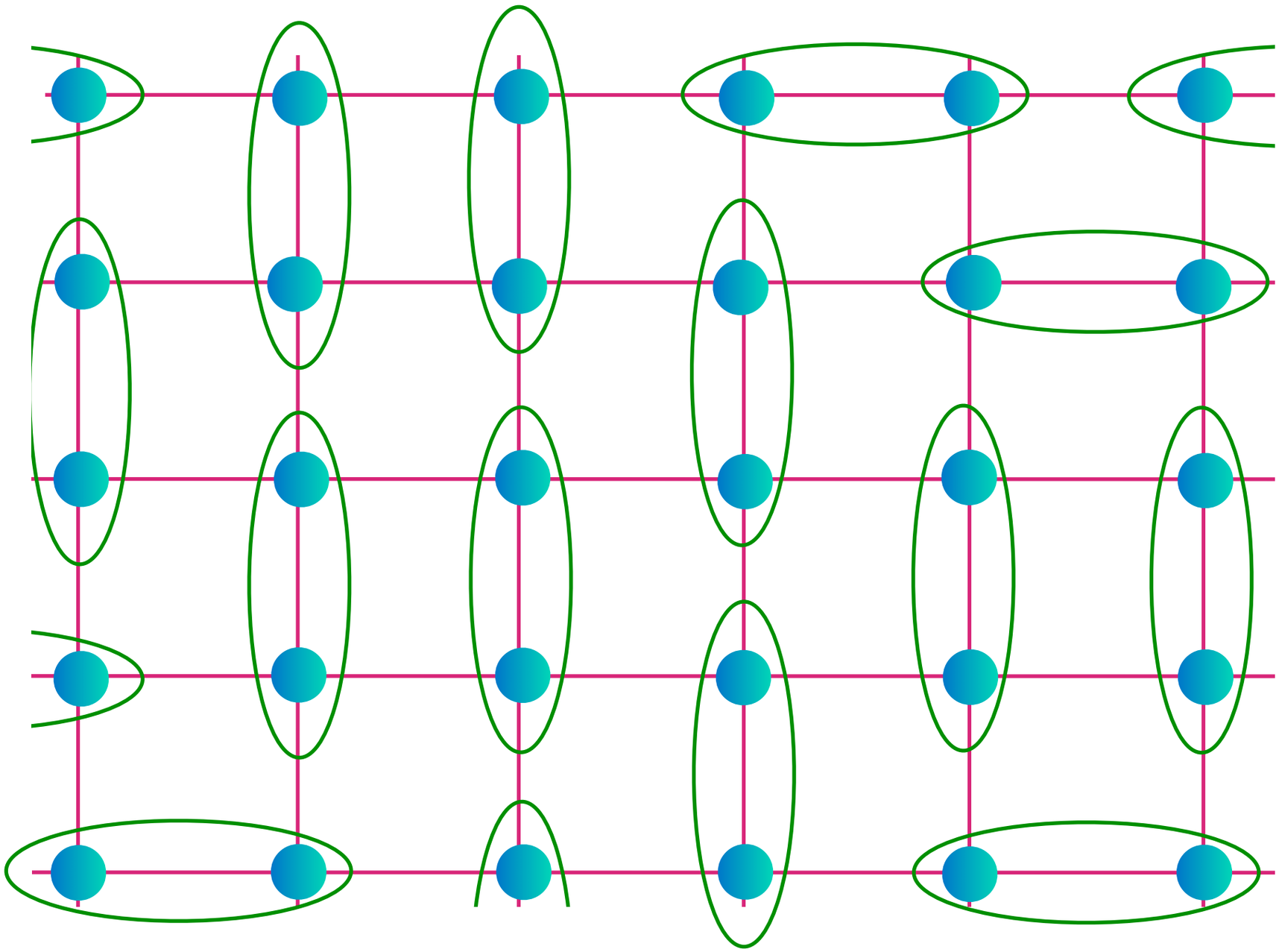
$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

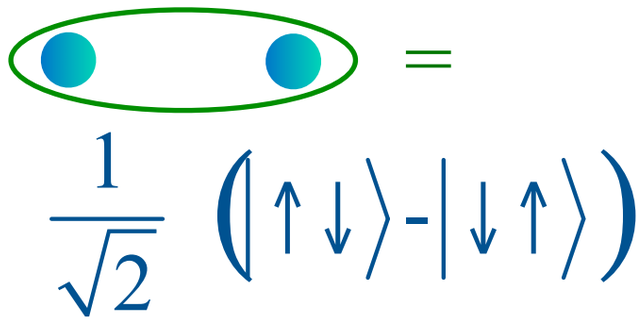
Valence bond entanglement in quantum spin systems





Valence bond entanglement in quantum spin systems

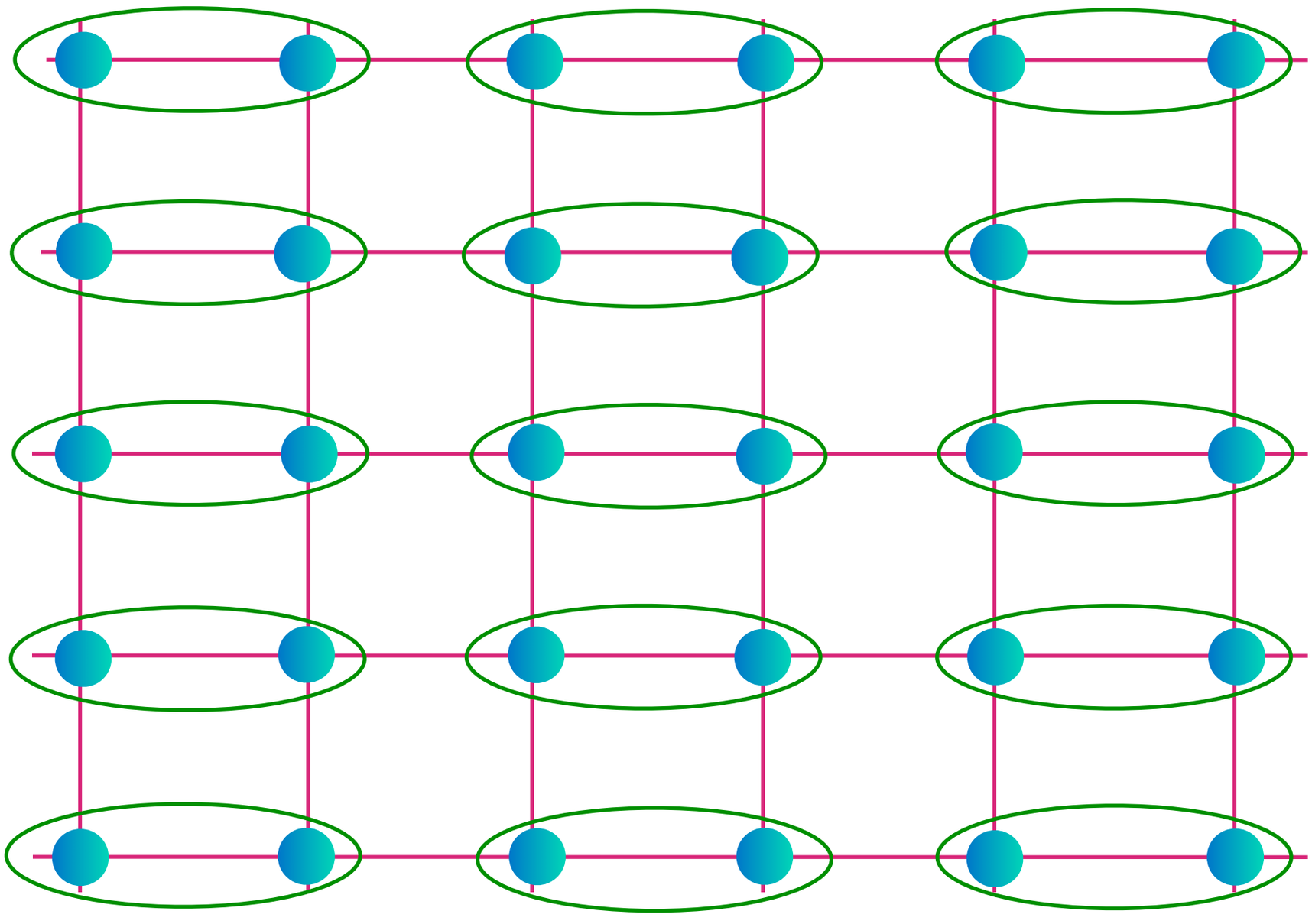


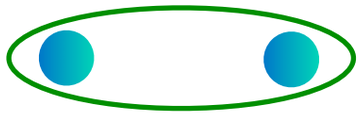


Resonating valence bond (RVB) liquid

P. Fazekas and P.W. Anderson, *Phil Mag* **30**, 23 (1974).

Valence bond entanglement in quantum spin systems



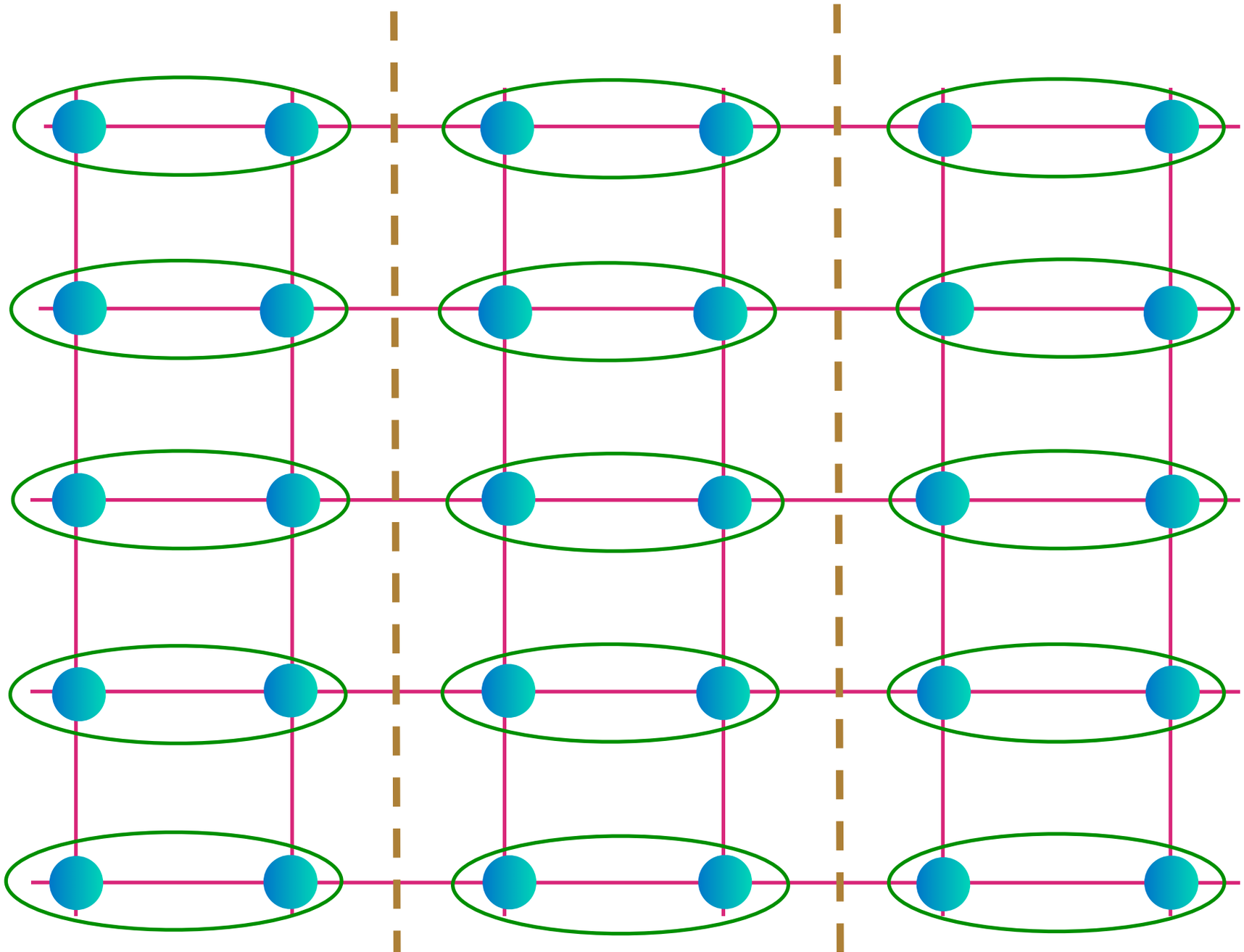


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

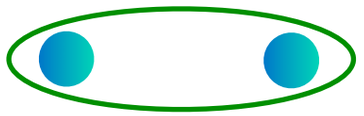
Valence Bond Solid (VBS)

N. Read and S. Sachdev, *Phys. Rev. Lett.* **62**, 1694 (1989).
R. Moessner and S. L. Sondhi, *Phys. Rev.* B **63**, 224401 (2001).

Valence bond entanglement in quantum spin systems



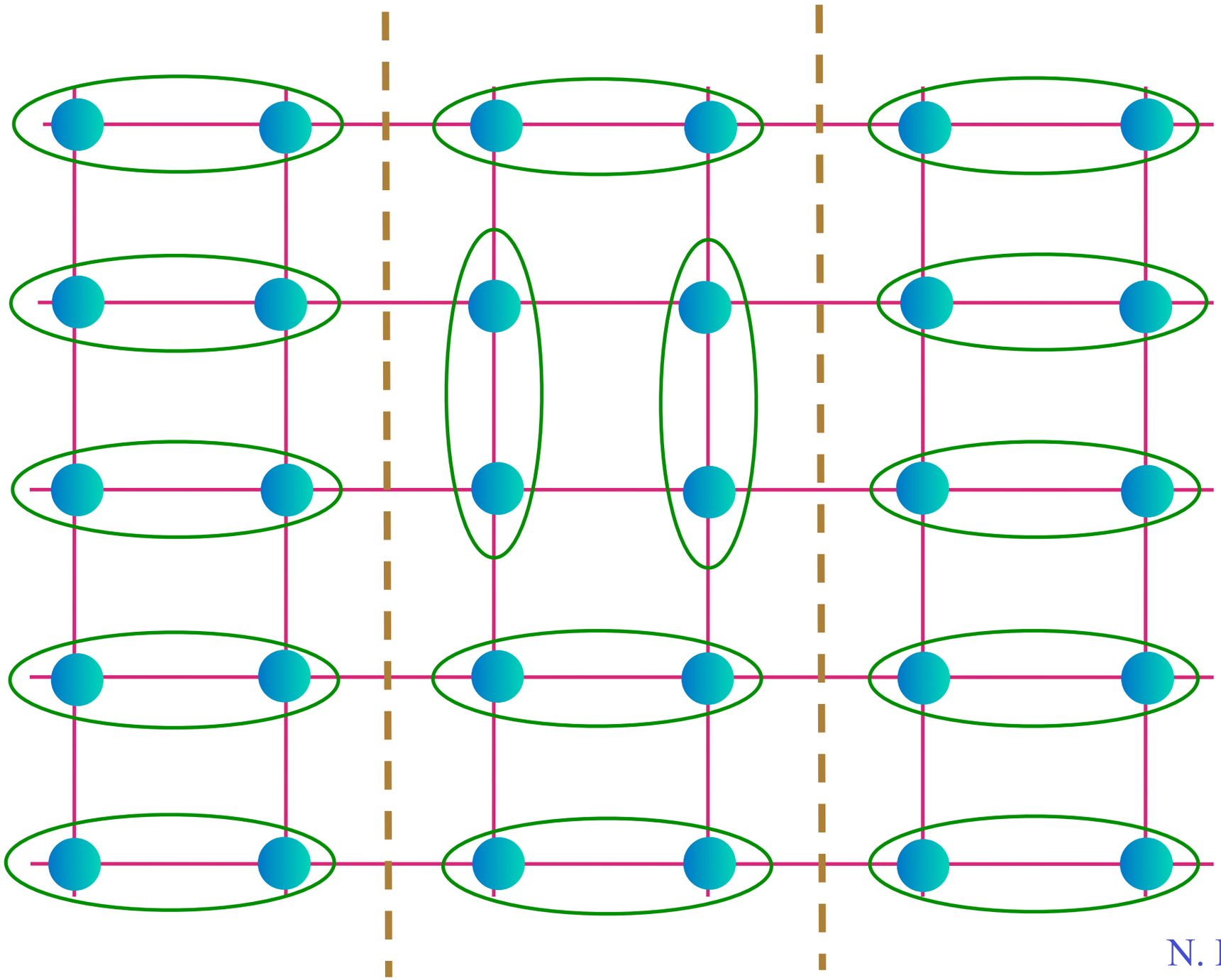
Valence Bond Solid (VBS)



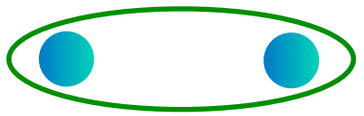
$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

N. Read and S. Sachdev, *Phys. Rev. Lett.* **62**, 1694 (1989).
R. Moessner and S. L. Sondhi, *Phys. Rev.* B **63**, 224401 (2001).

Valence bond entanglement in quantum spin systems



Valence Bond Solid (VBS)

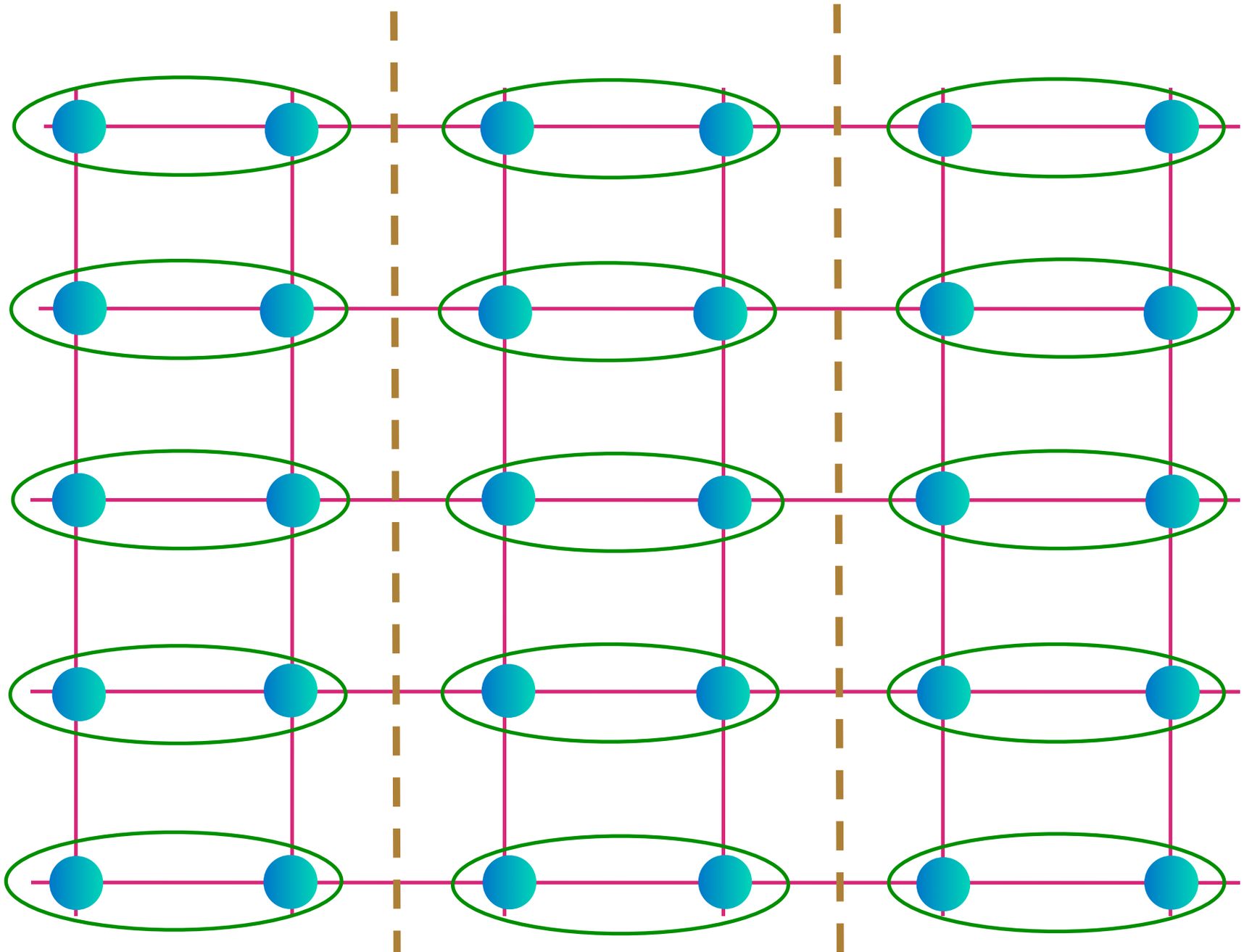


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

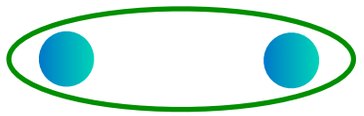
N. Read and S. Sachdev, *Phys. Rev. Lett.* **62**, 1694 (1989).

R. Moessner and S. L. Sondhi, *Phys. Rev.* B **63**, 224401 (2001).

Valence bond entanglement in quantum spin systems



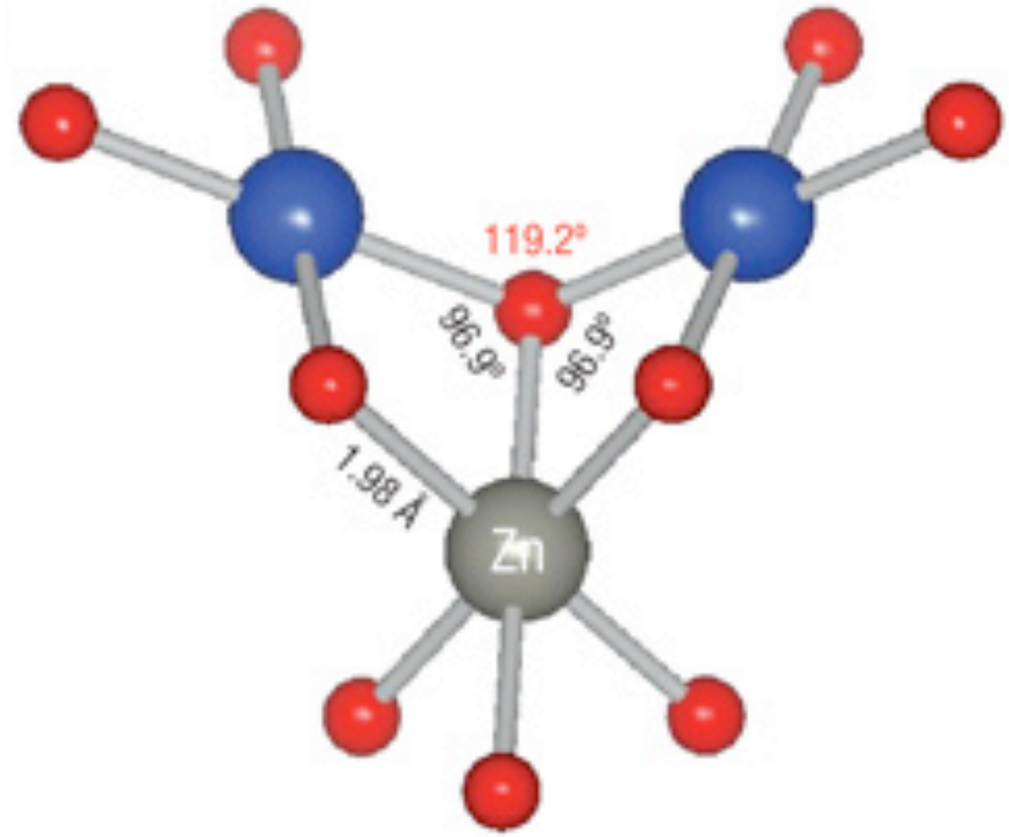
Valence Bond Solid (VBS)

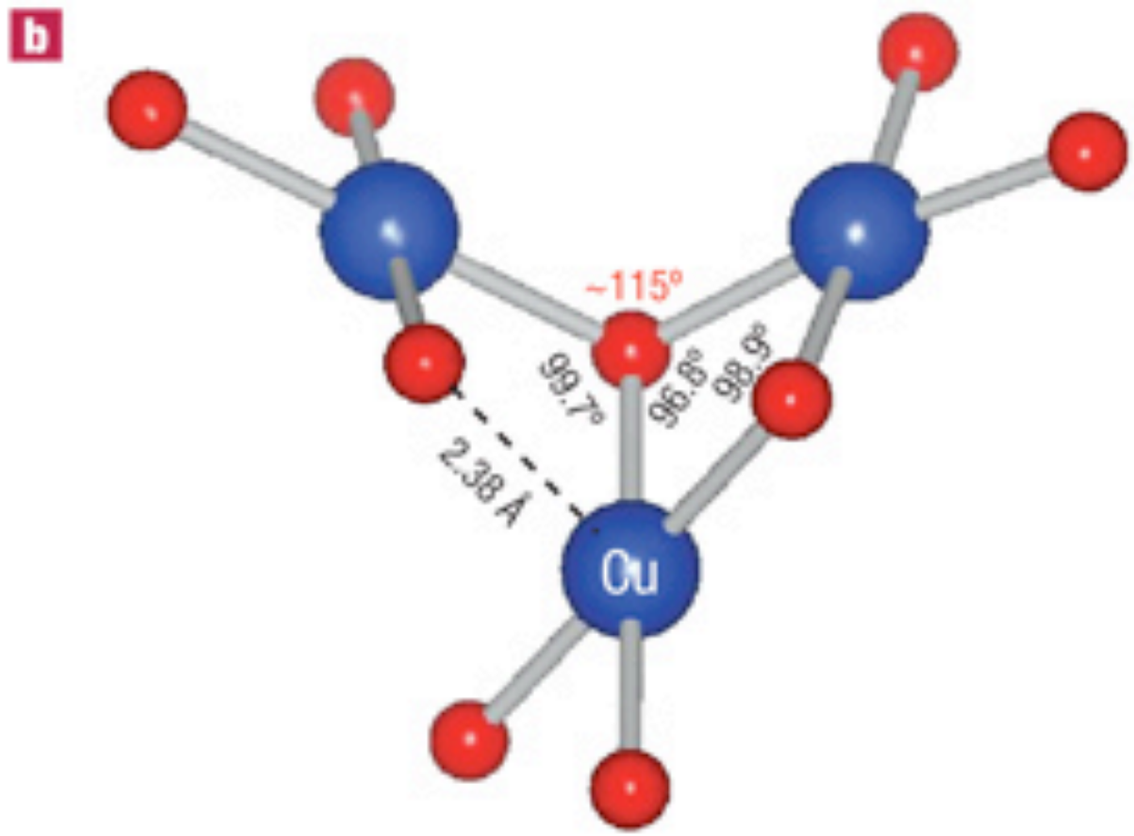


$$= \frac{1}{\sqrt{2}} \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

N. Read and S. Sachdev, *Phys. Rev. Lett.* **62**, 1694 (1989).
R. Moessner and S. L. Sondhi, *Phys. Rev.* B **63**, 224401 (2001).

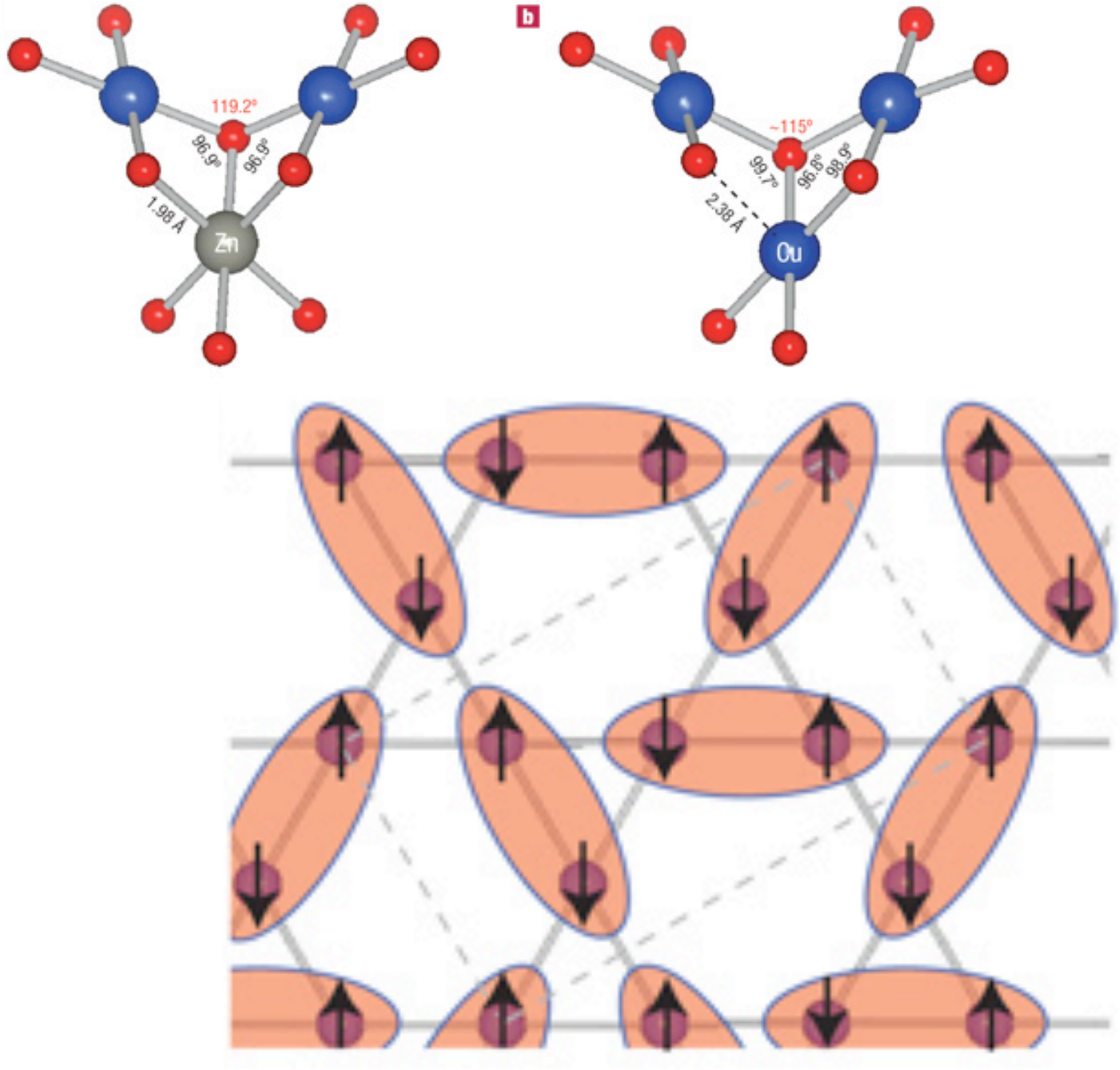
$Zn_xCu_{4-x}(OD)_6Cl_2$





S.-H. Lee, H. Kikuchi, Y. Qiu, B. Lake, Q. Huang, K. Habicht, K. Kiefer Nature Materials online, 26 Aug 2007

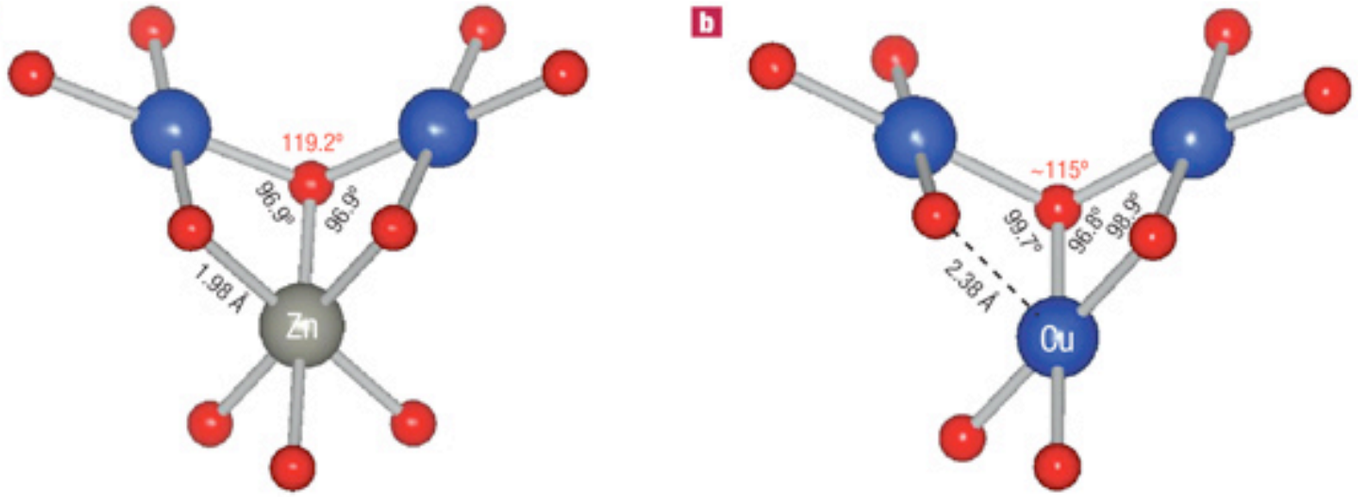
$Zn_xCu_{4-x}(OD)_6Cl_2$

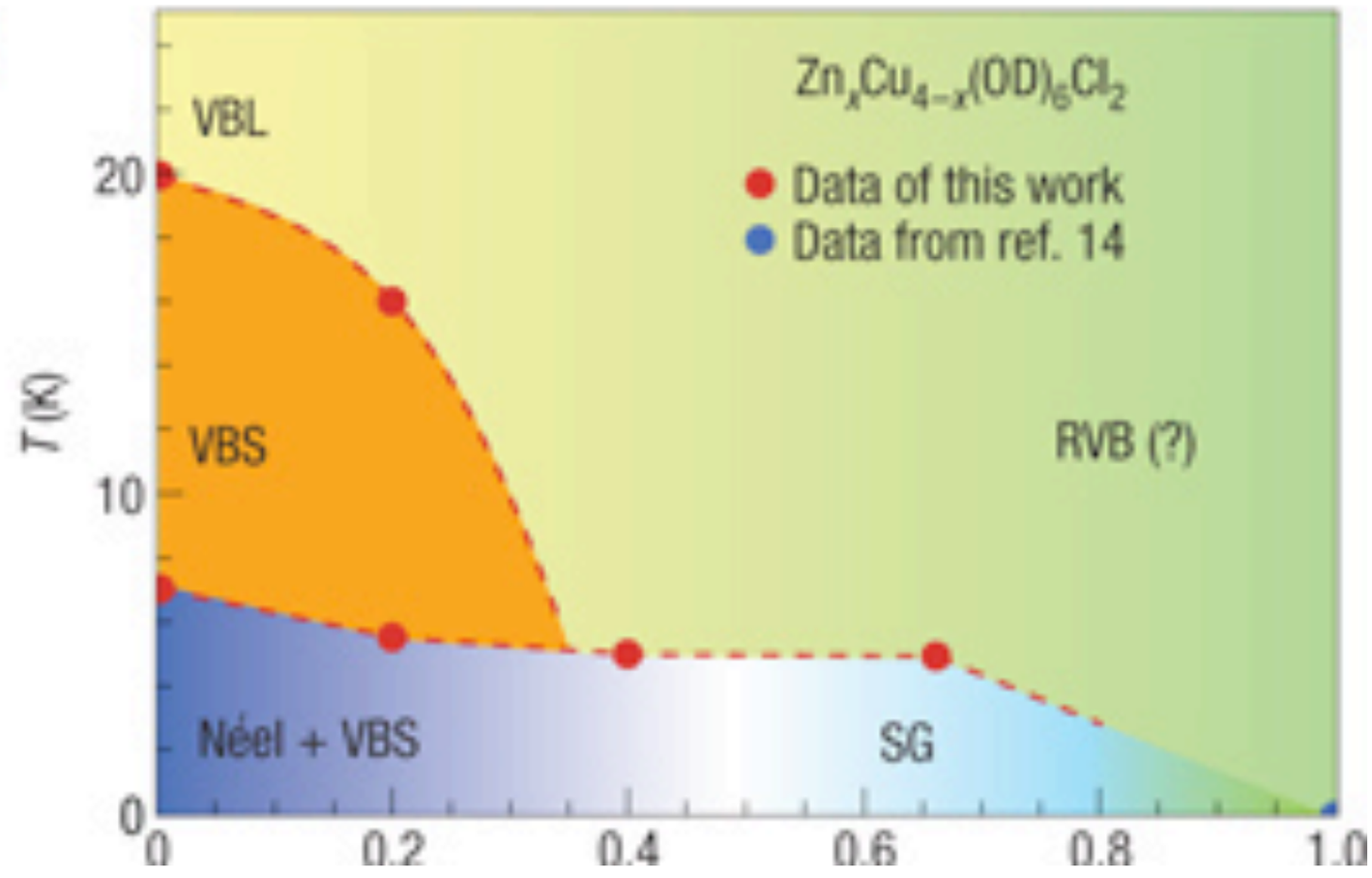


Spins on layered kagome lattices

S.-H. Lee, H. Kikuchi, Y. Qiu, B. Lake, Q. Huang, K. Habicht, K. Kiefer Nature Materials online, 26 Aug 2007

$Zn_xCu_{4-x}(OD)_6Cl_2$: Antiferromagnetism to bond order

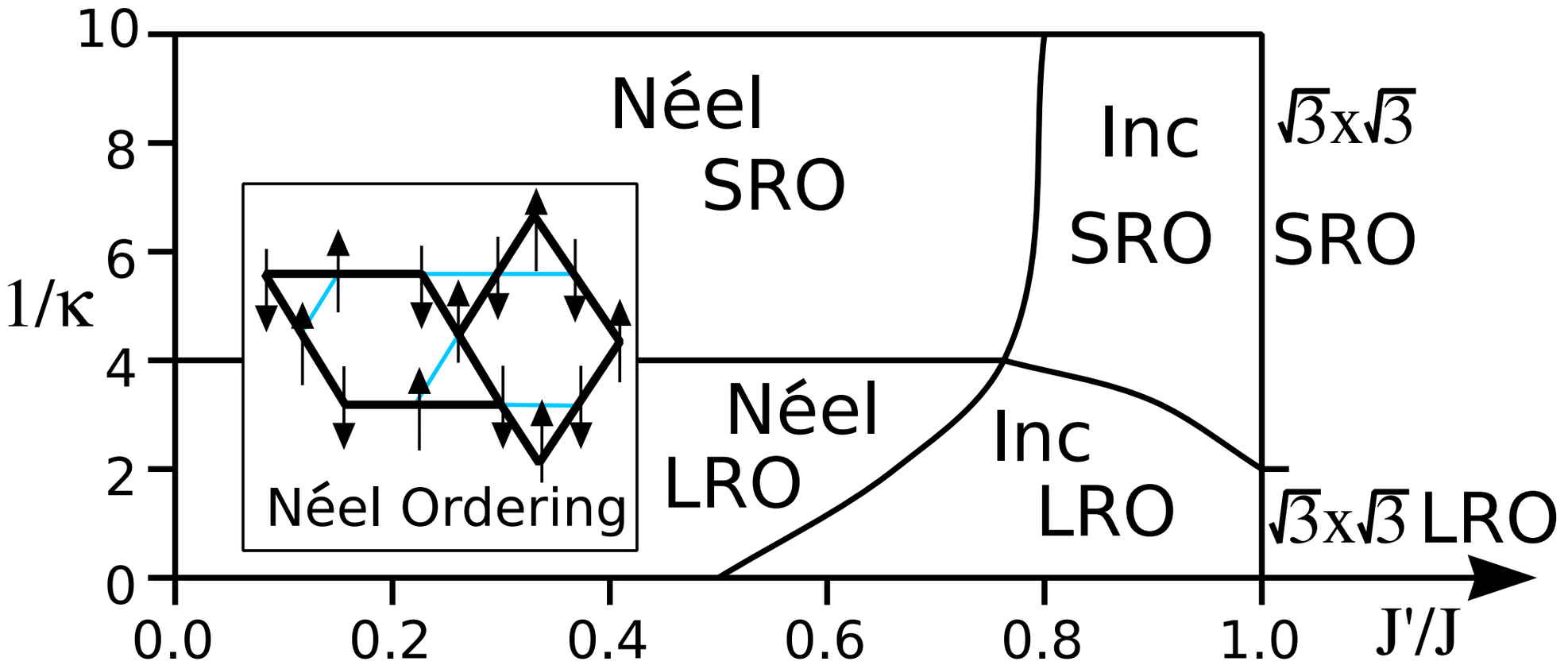


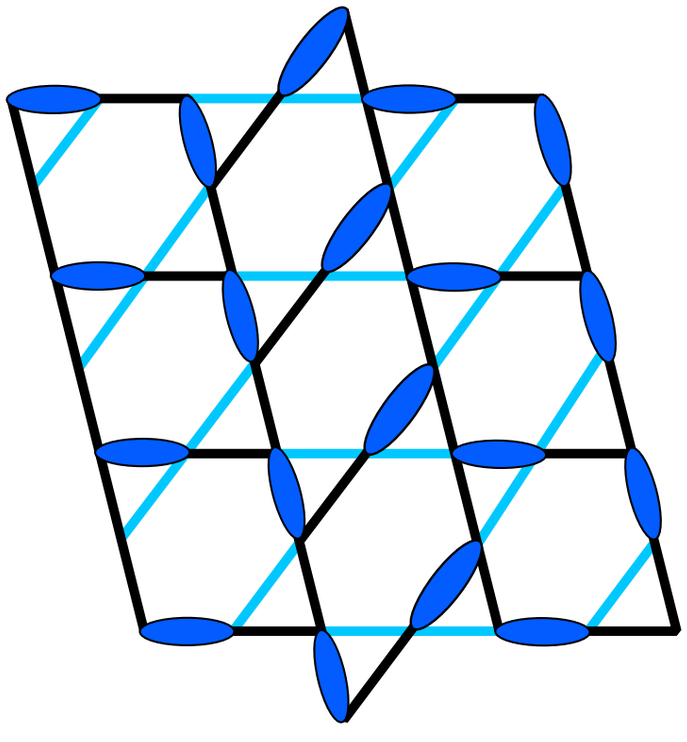


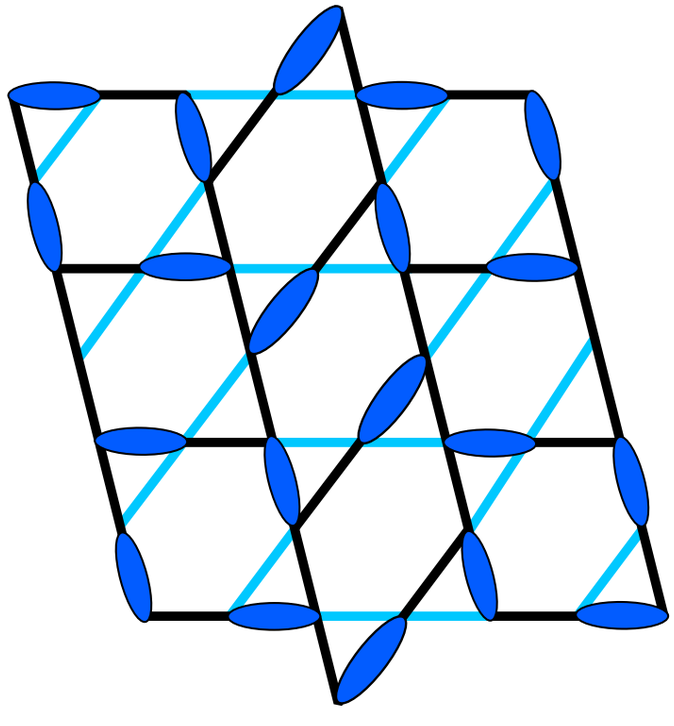
VBS and RVB states

S.-H. Lee, H. Kikuchi, Y. Qiu, B. Lake, Q. Huang, K. Habicht, K. Kiefer Nature Materials online, 26 Aug 2007

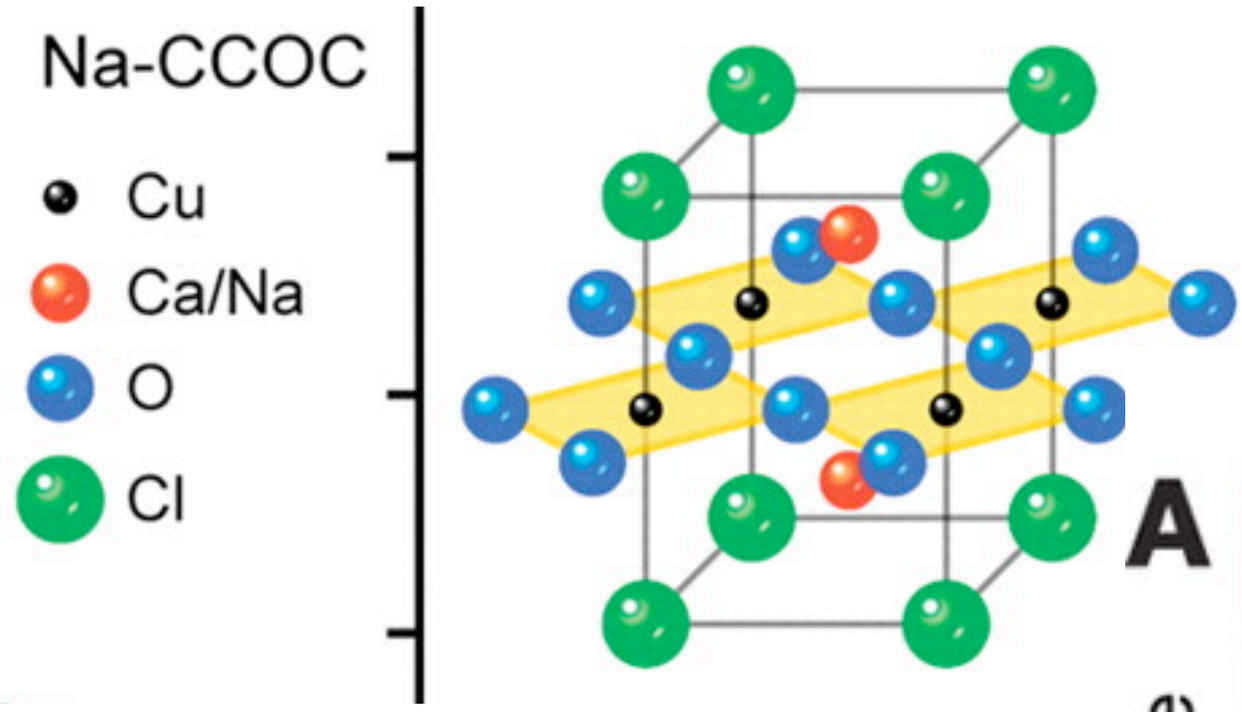
Theoretical modeling: M. J. Lawler, L. Fritz, Y. B. Kim, and S. Sachdev, arXiv:0709.4489



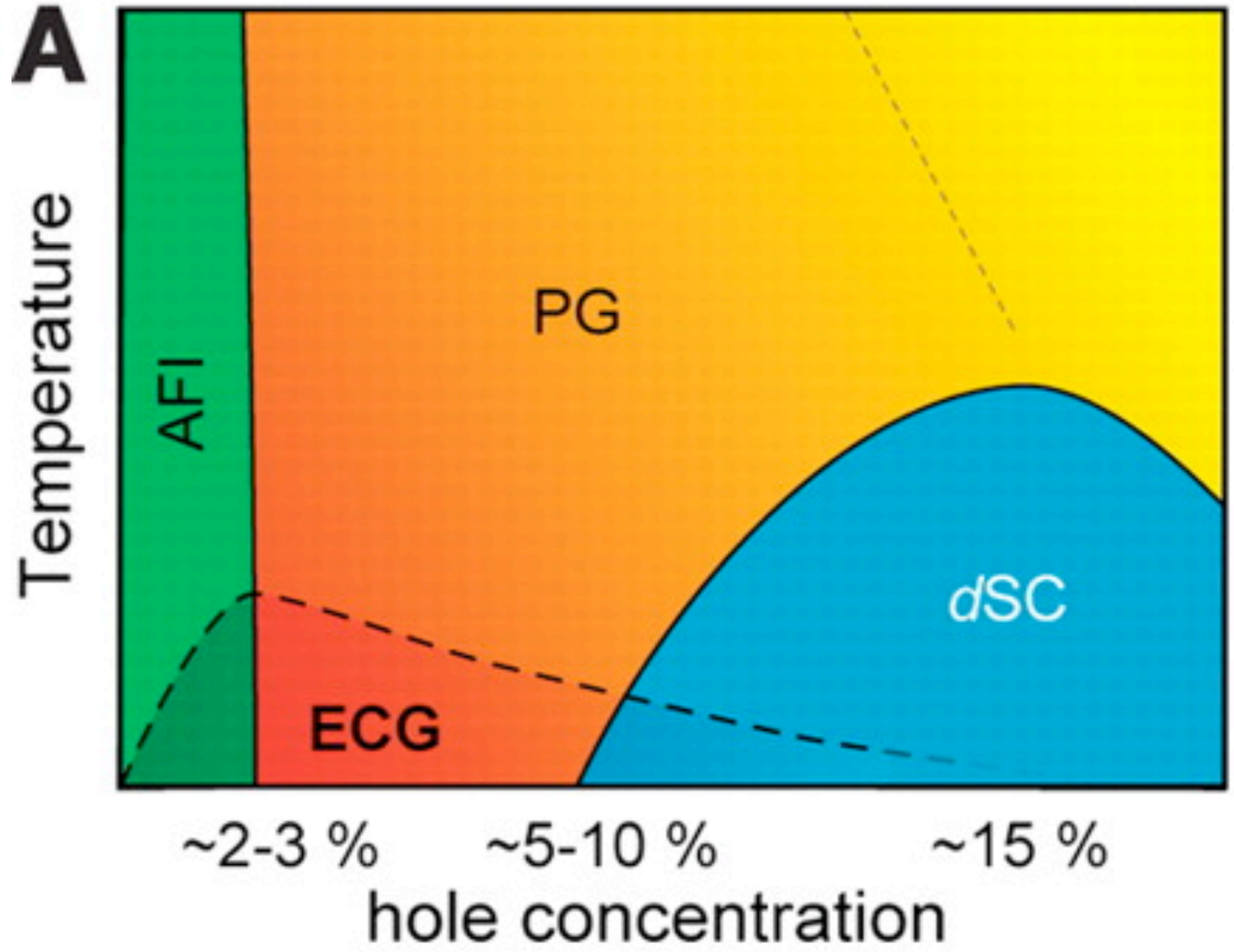




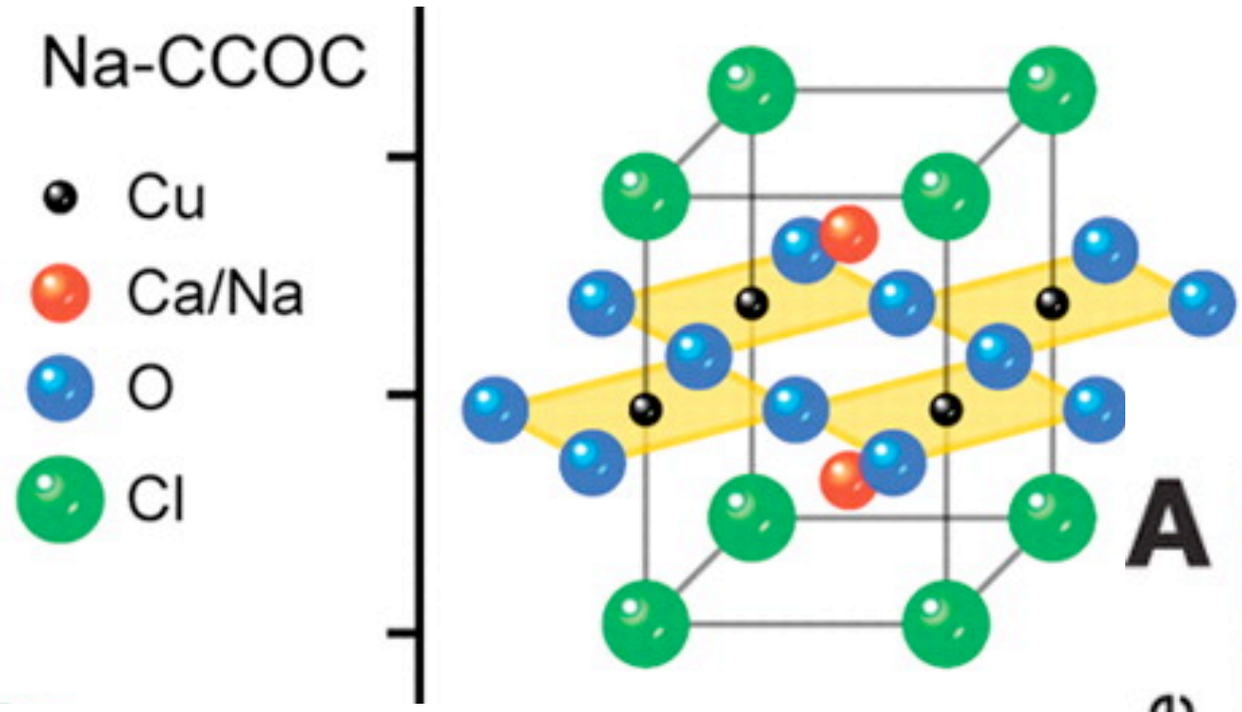
Antiferromagnetism to bond order in the cuprate superconductors



Scanning tunneling microscopy by group of Seamus Davis

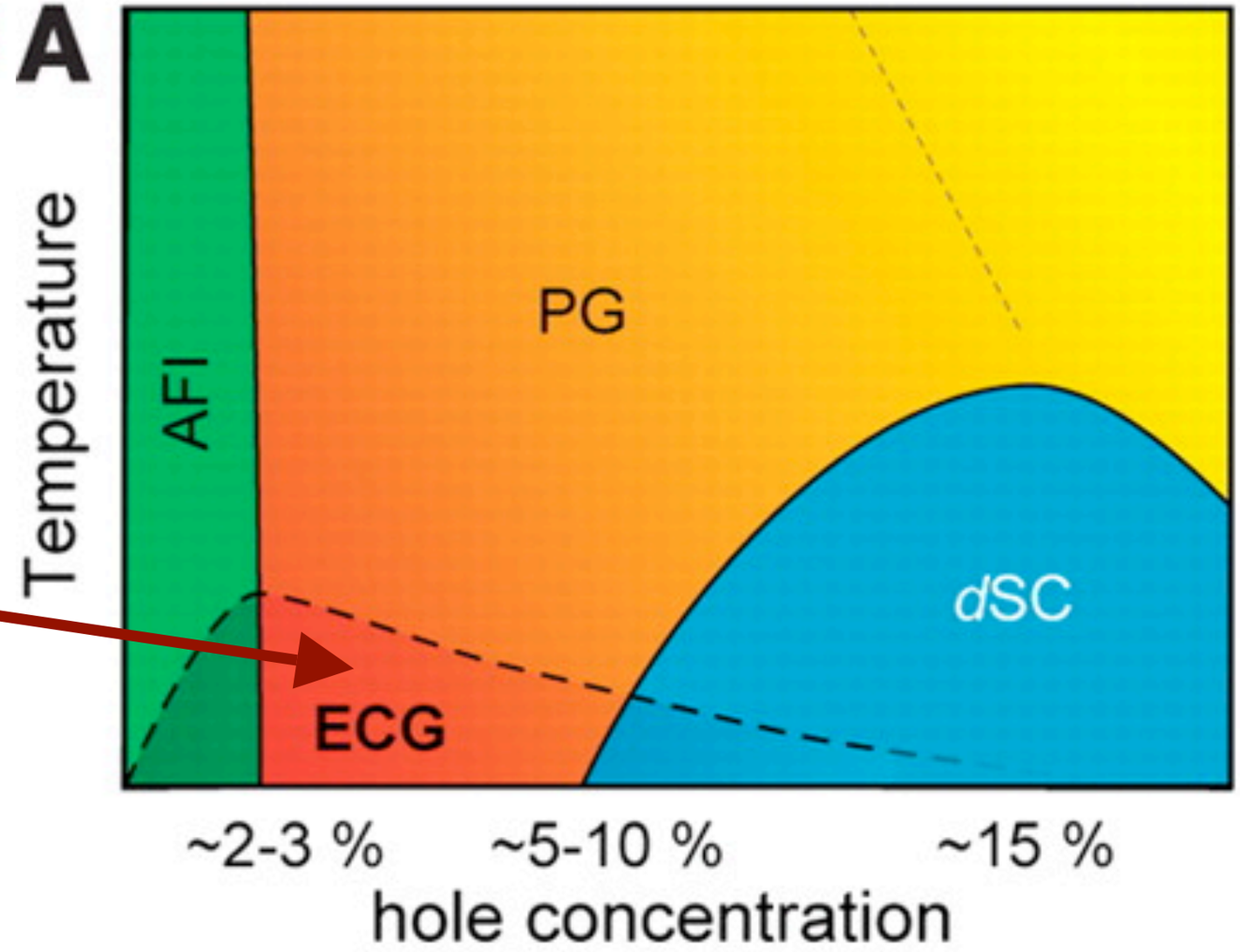


Antiferromagnetism to bond order in the cuprate superconductors



A

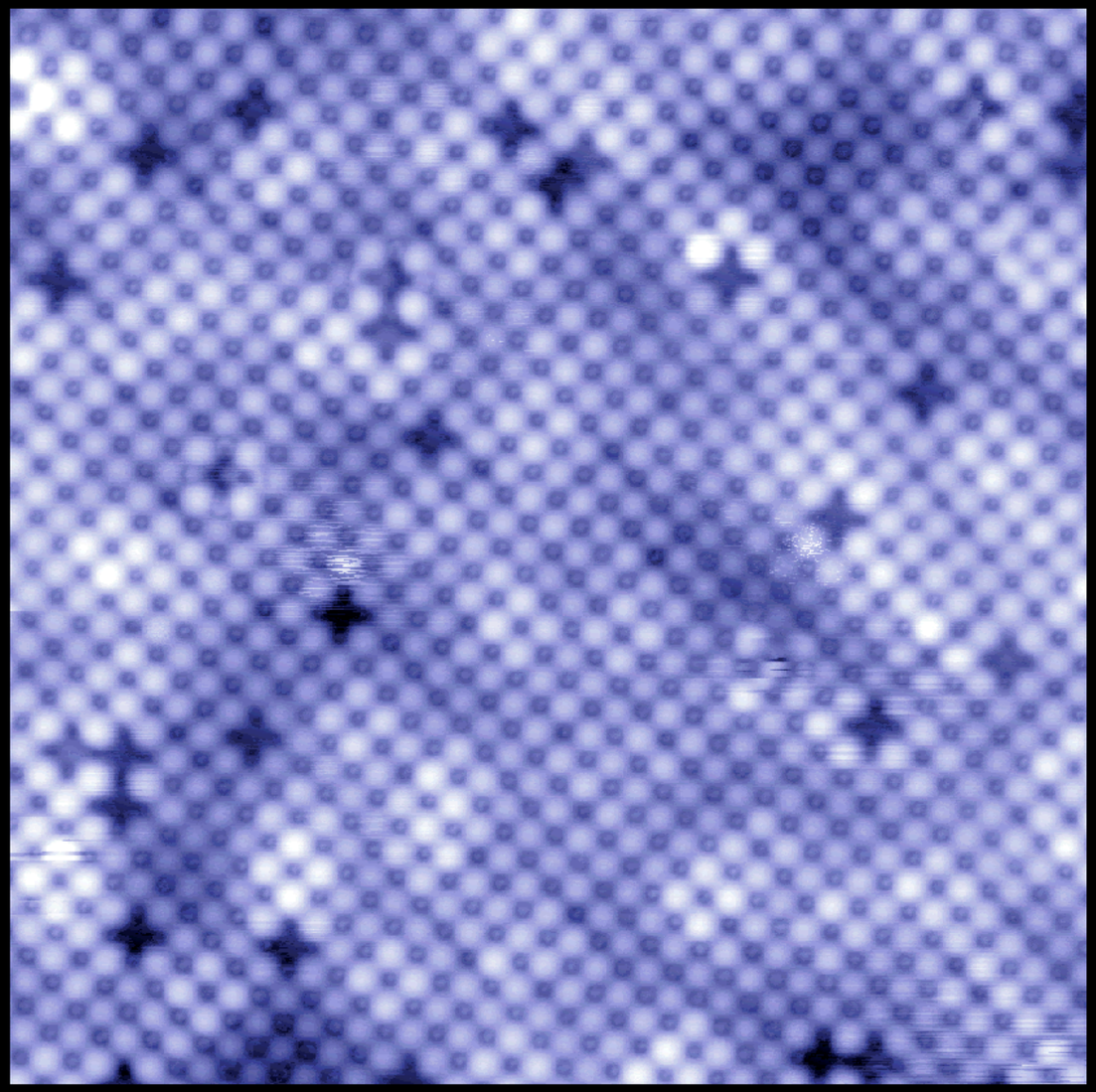
Scanning tunneling microscopy by group of Seamus Davis



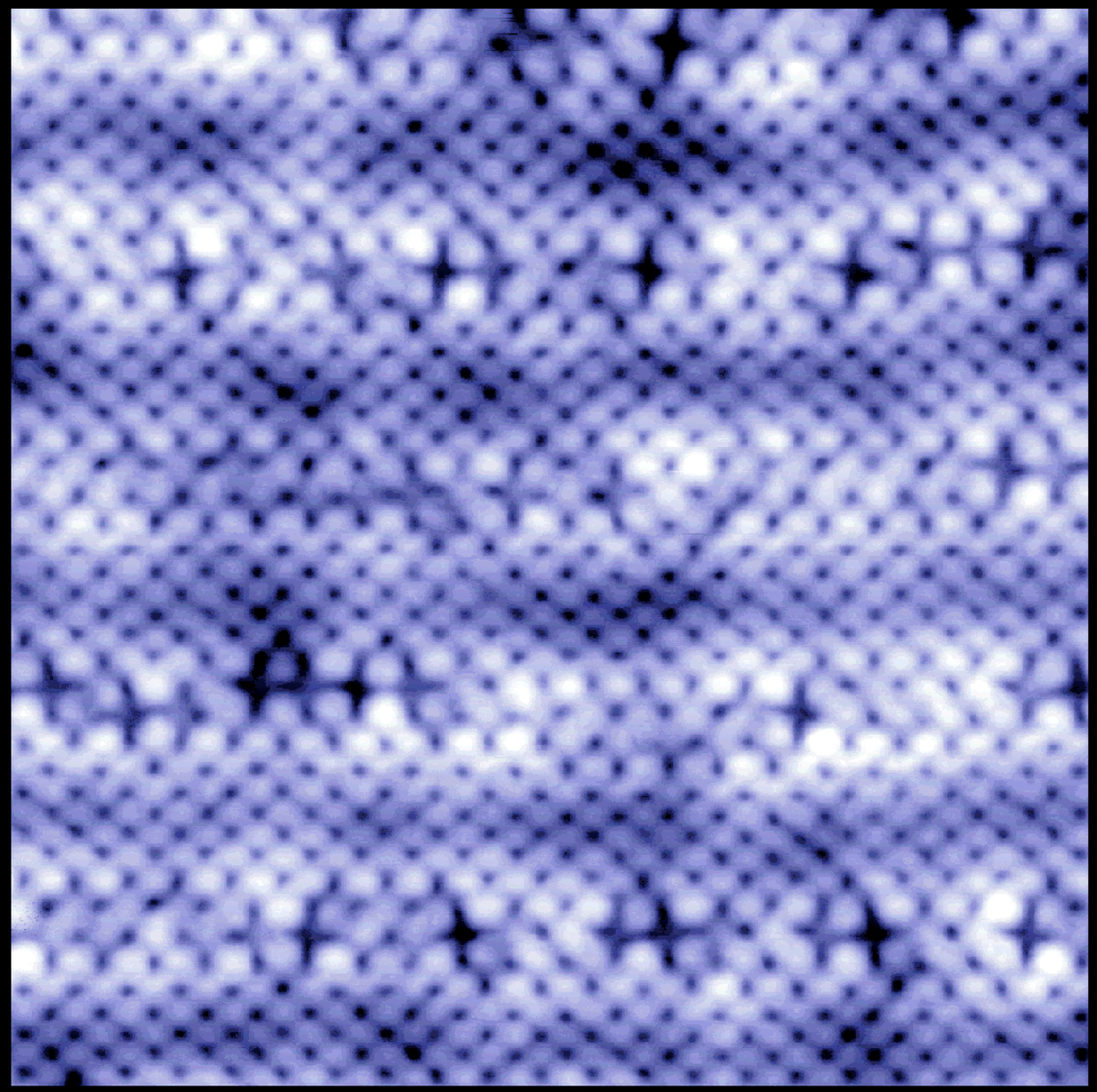
"Glassy" Valence Bond Solid (VBS)

R-map at E=150meV

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



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

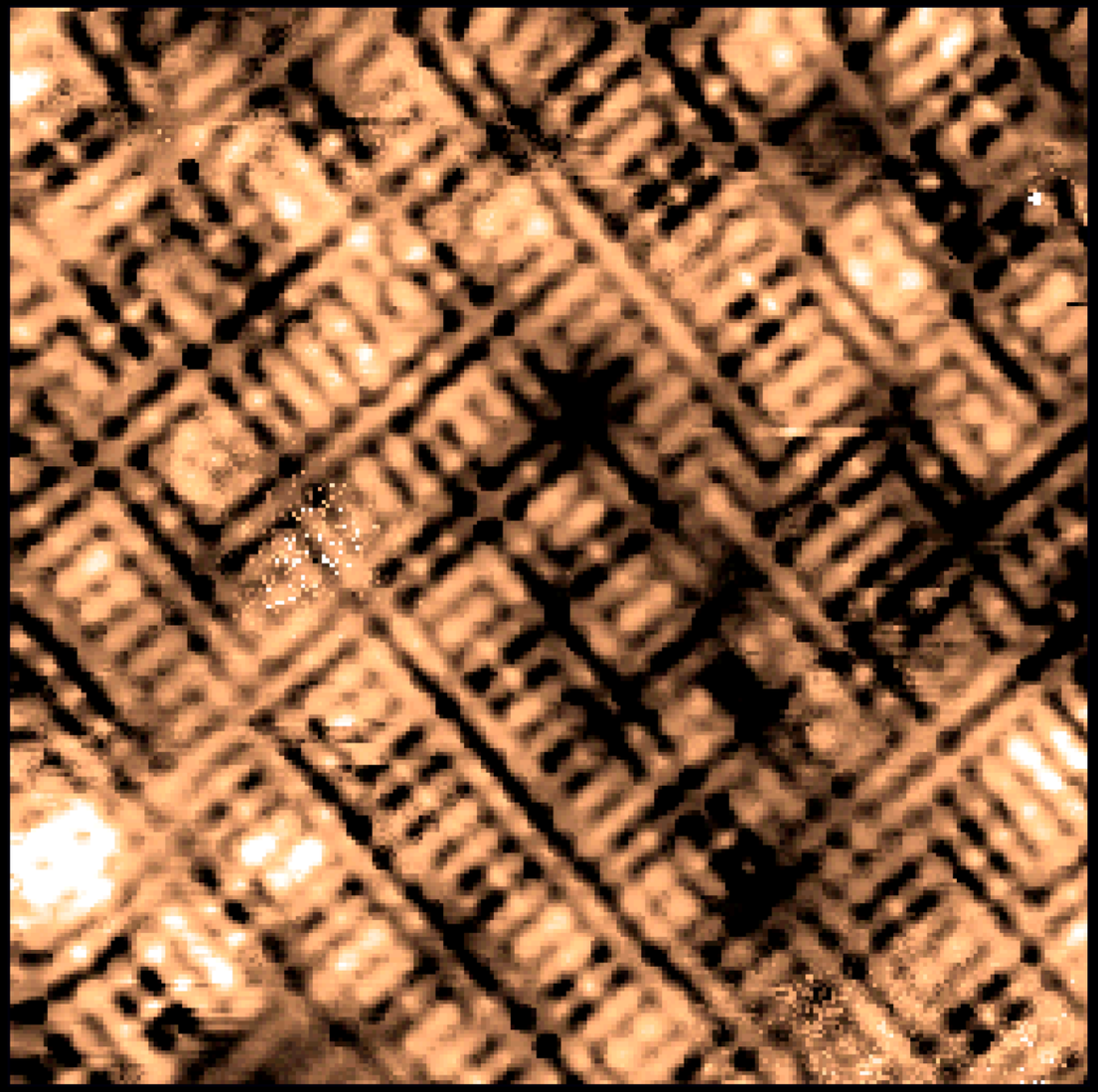


12 nm

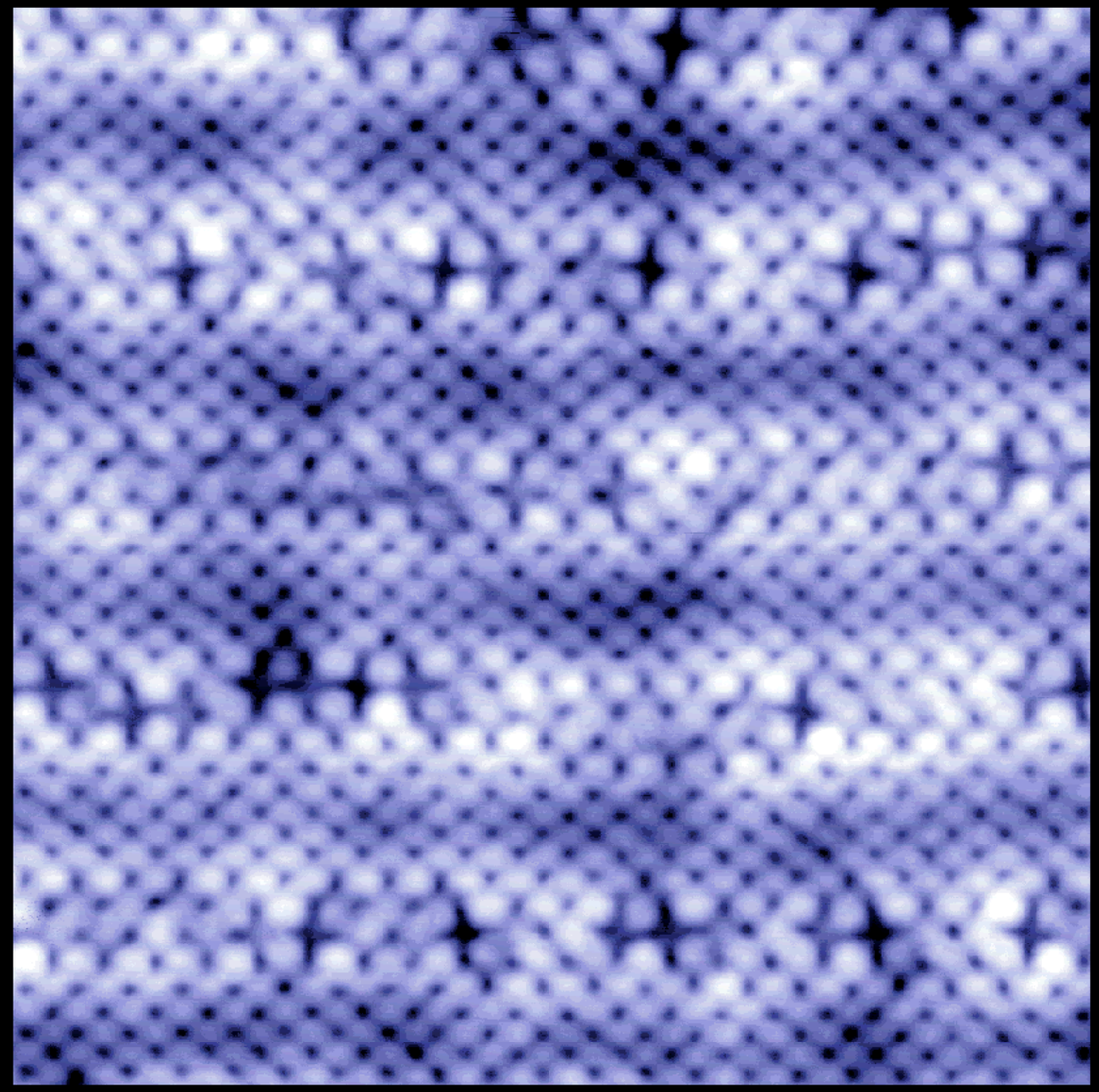
Y. Kohsaka et al. **Science 315**, 1380 (2007)

R-map at E=150meV

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



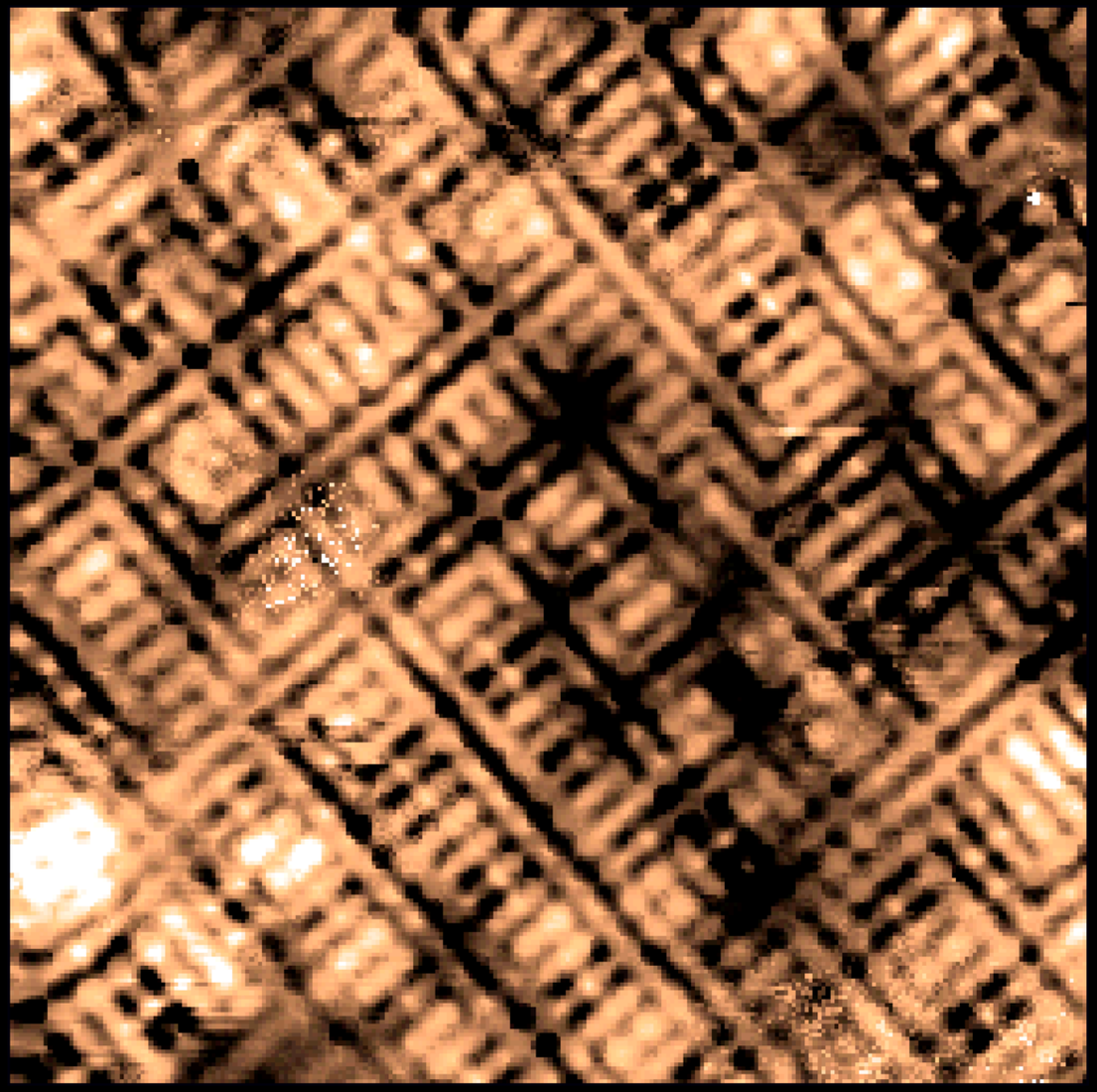
$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$



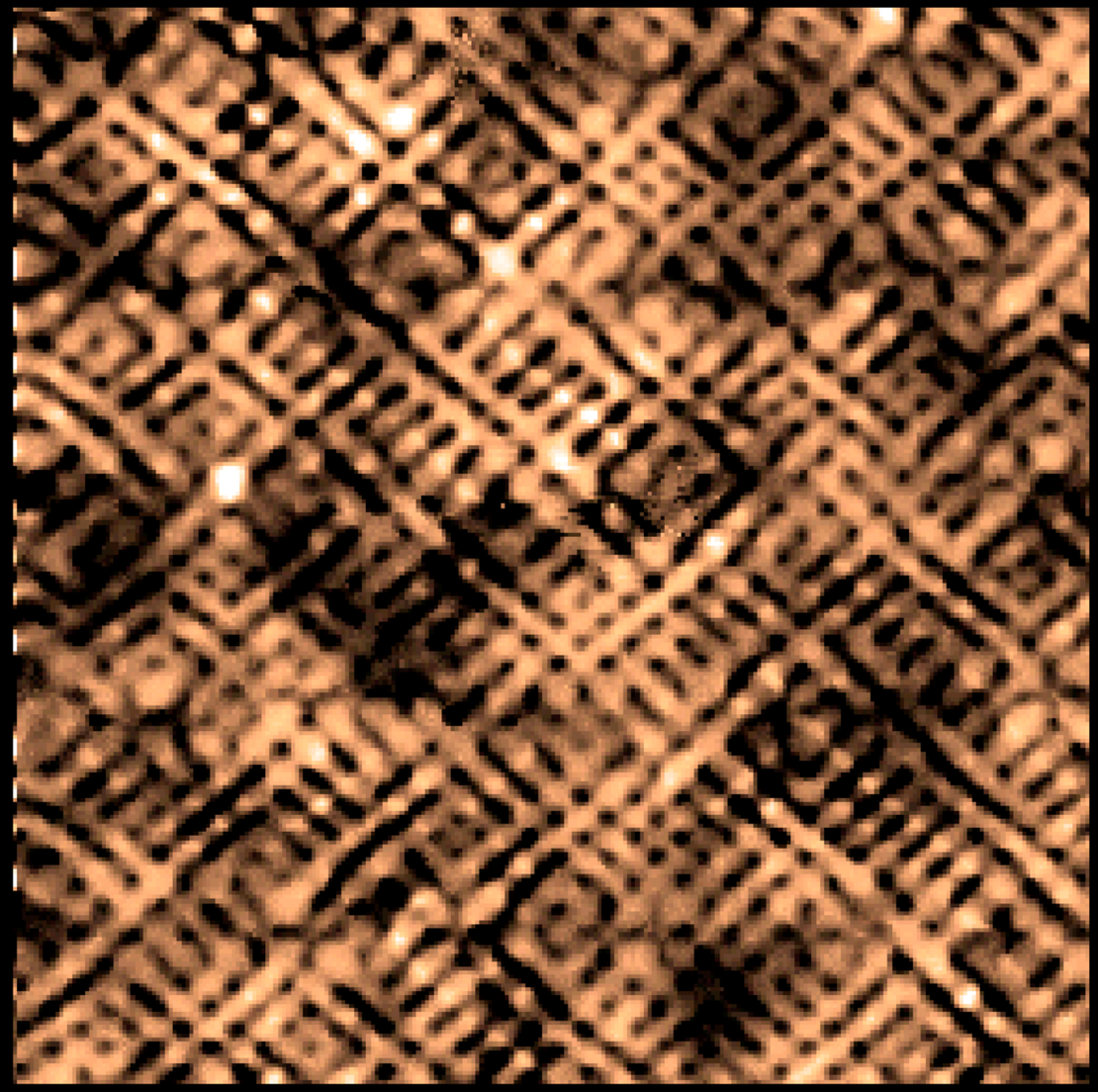
Y. Kohsaka et al. Science 315, 1380 (2007)

R-map at E=150meV

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



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

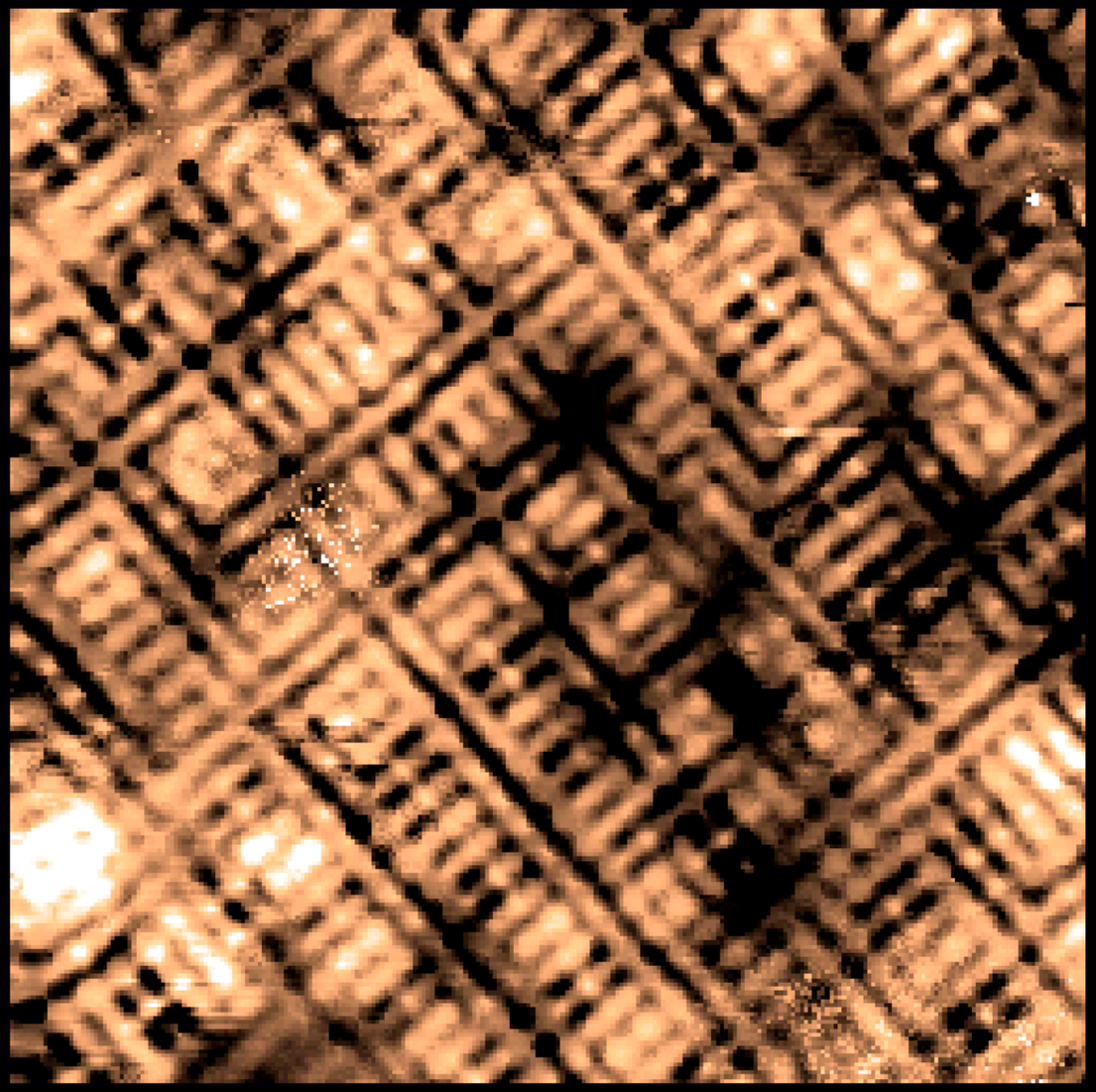


12 nm

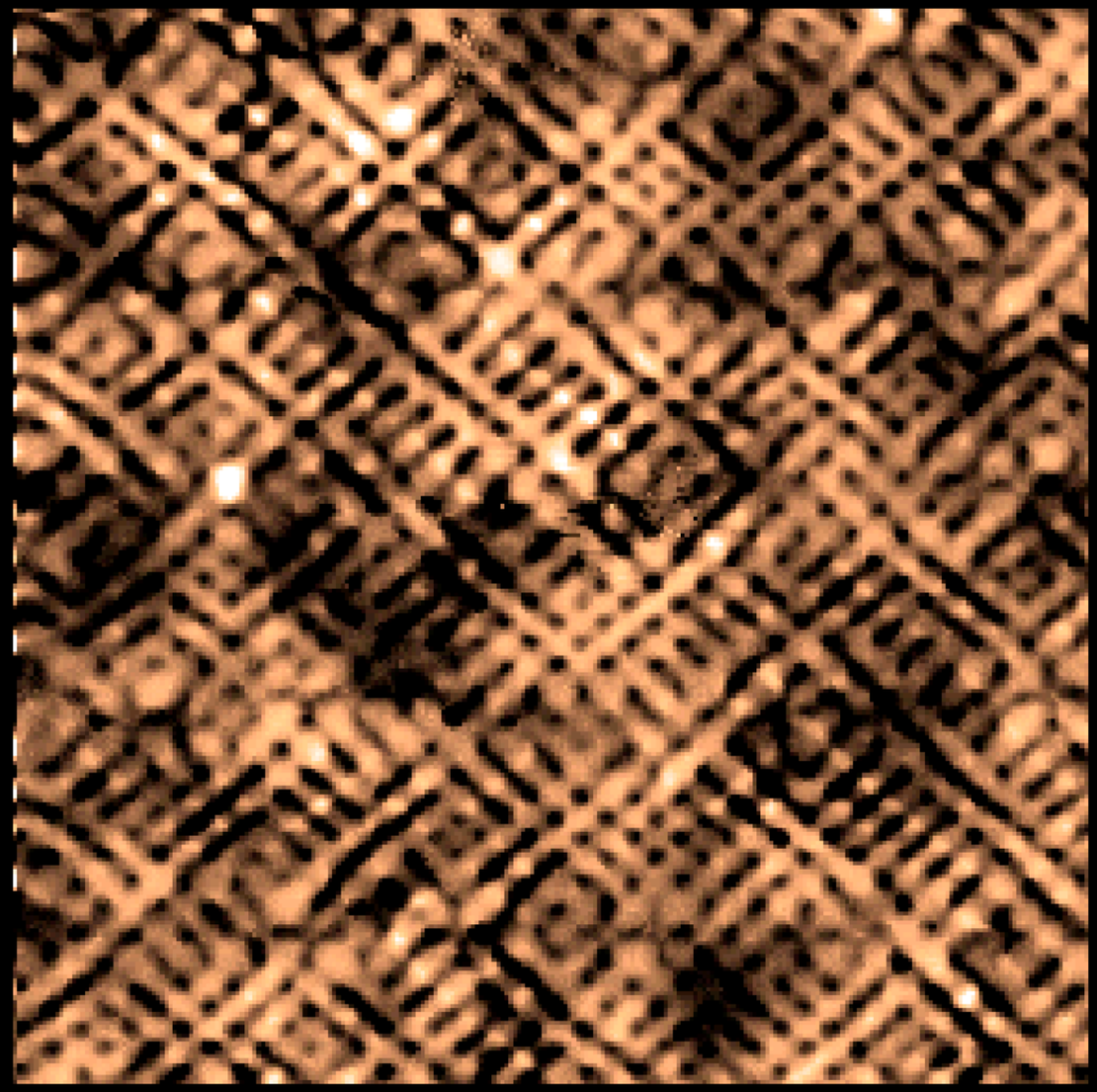
Y. Kohsaka et al. *Science* **315**, 1380 (2007)

R-map at E=150meV

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



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



12 nm

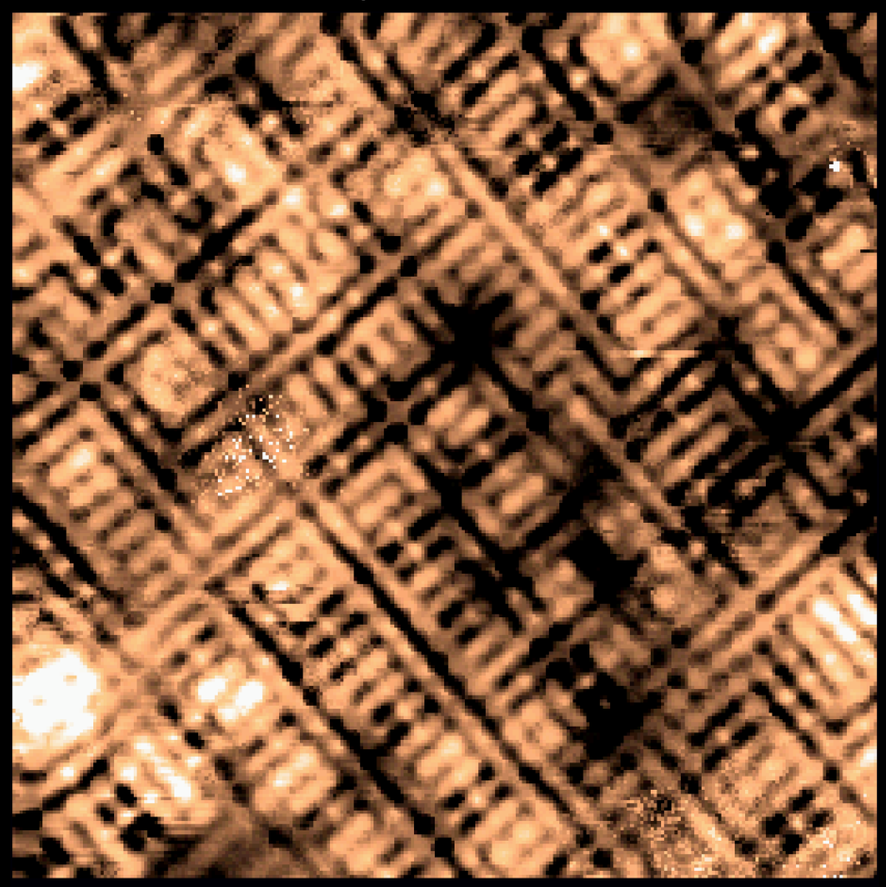
Indistinguishable bond-centered TA contrast

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)

R map (150 mV)



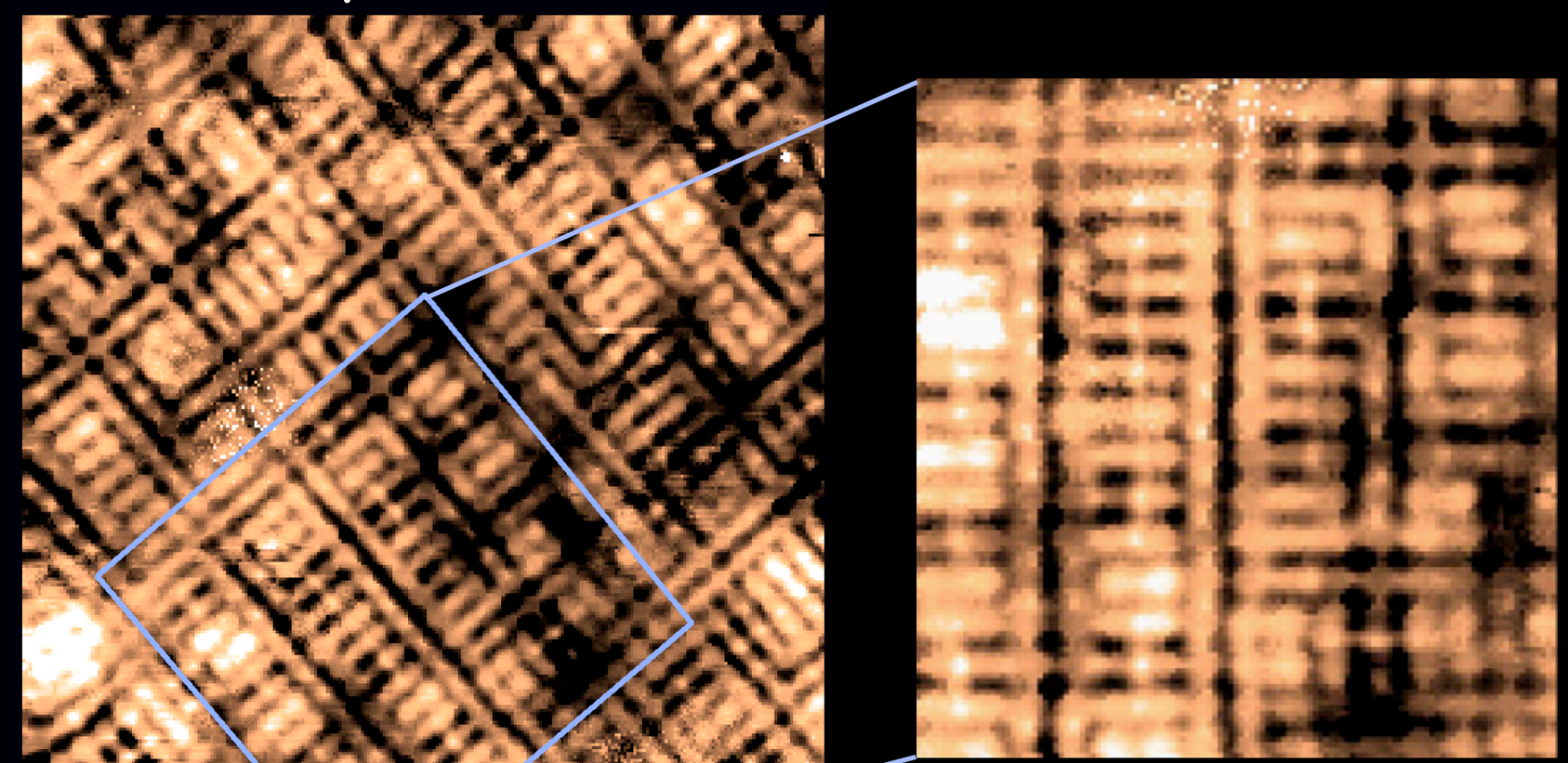
12 nm

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$, 4 K

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

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

R map (150 mV)



12 nm

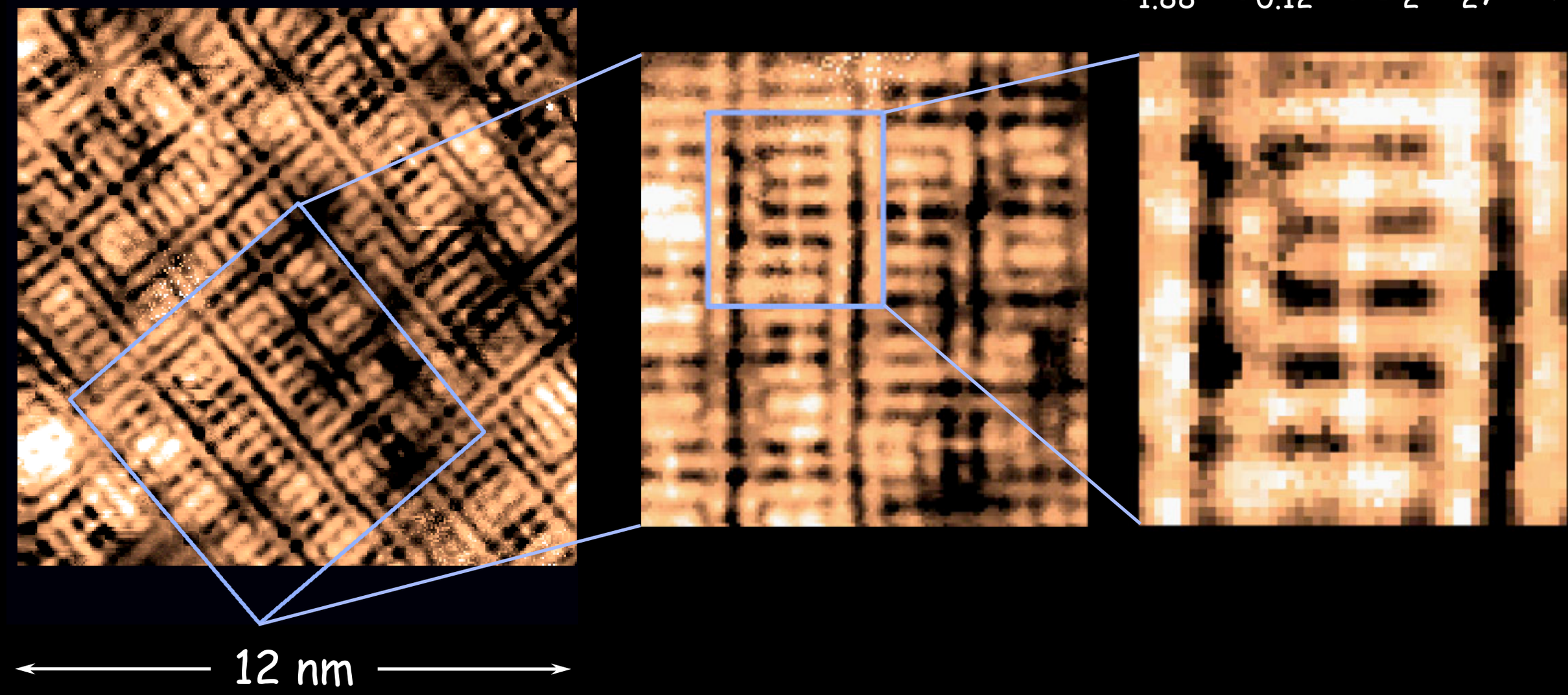
$Ca_{1.88}Na_{0.12}CuO_2Cl_2$, 4 K

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

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

R map (150 mV)

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$, 4 K

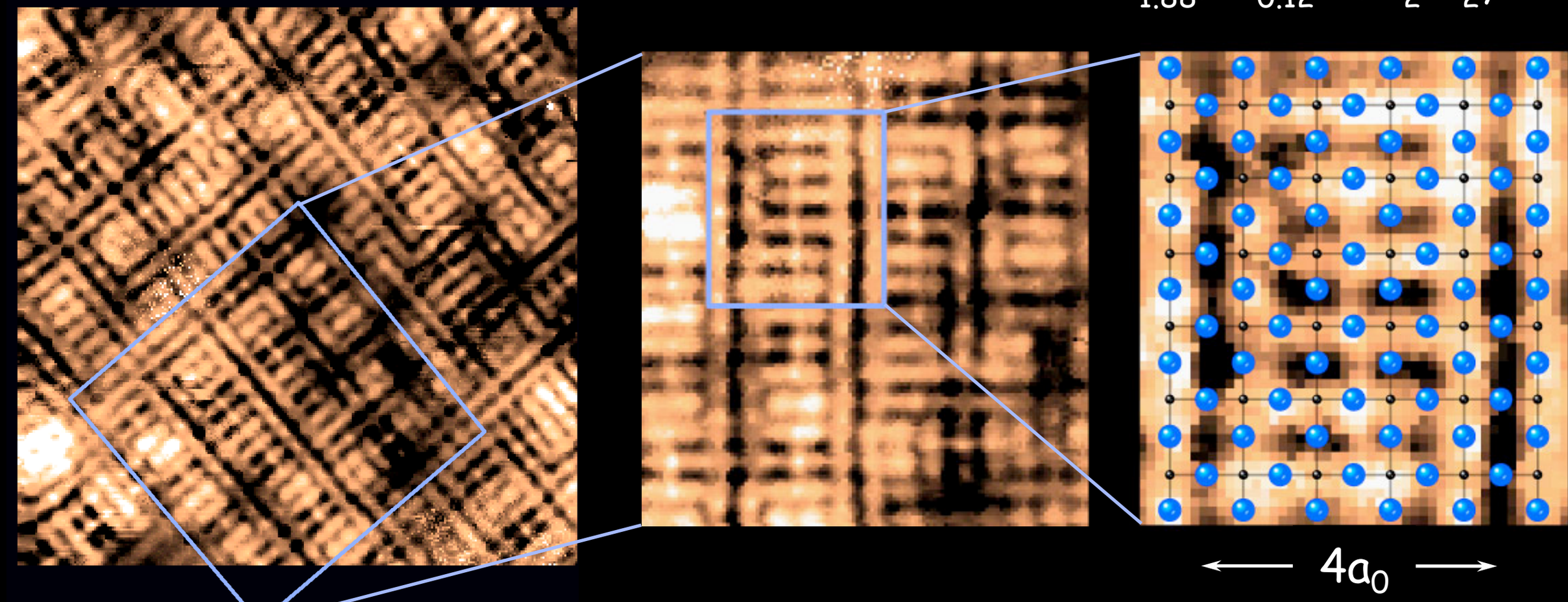


Y. Kohsaka et al. Science 315, 1380 (2007)

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

R map (150 mV)

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$, 4 K

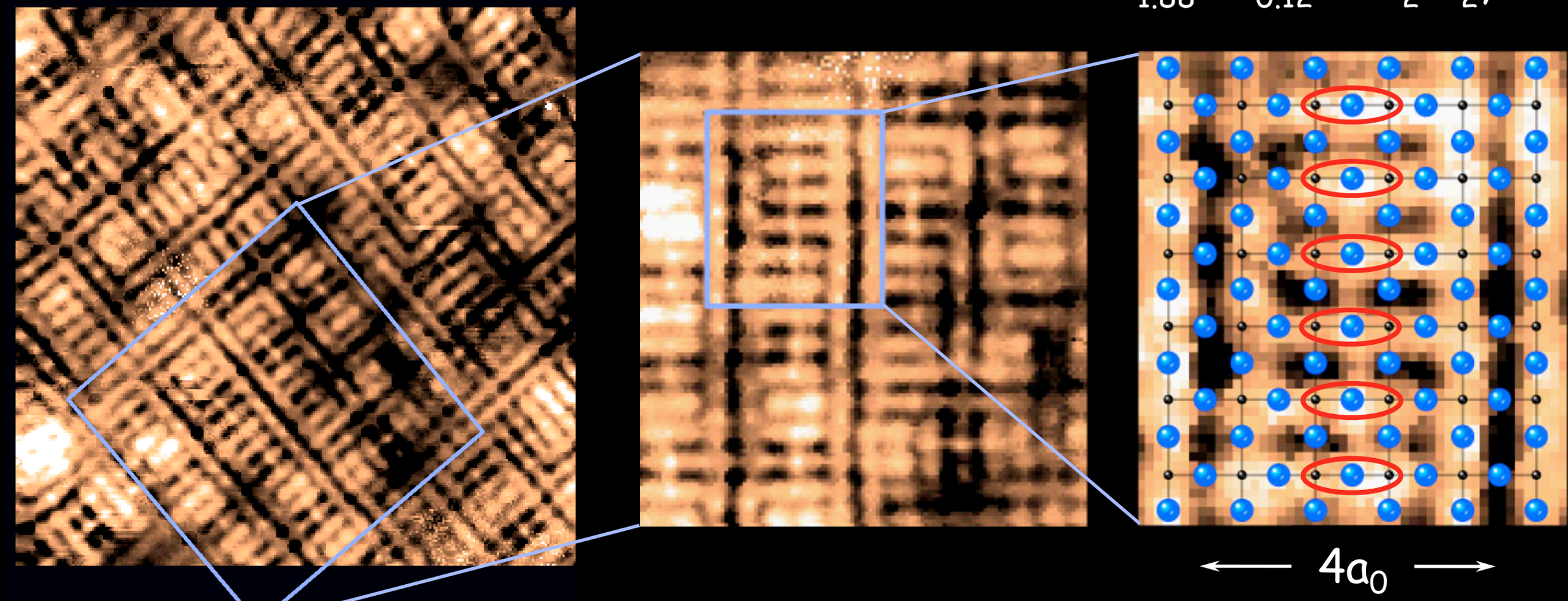


Y. Kohsaka et al. Science 315, 1380 (2007)

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

R map (150 mV)

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$, 4 K



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

Plan

- Theoretical models of spin and valence bond entanglement being compared to experiments in condensed matter

- Studies of optical lattices of atoms should lead to more sensitive tests at shorter times and distances