The saga of the Shastry-Sutherland compound $SrCu_2(BO_3)_2$

F. Mila
Ecole Polytechnique Fédérale de Lausanne
Switzerland

Collaborators

Theorists

S. Miyahara (Fukuoka), F. Becca (Trieste)
M. Moliner, (Lausanne), I. Rousochatzakis (Loughborough)
K. Schmidt and C. Boos (Erlangen), J. Dorier (Lausanne)
S. Manmana (Göttingen), A. Honecker (Cergy-Pontoise)
P. Corboz, S. Crone and I. Niesen (Amsterdam)
D. Badrtdinov and V. Mazurenko (Ekaterinburg)
B. Normand (PSI), S. Wessel (Aachen)

Experimentalists

M. Takigawa, Y. Matsuda (ISSP, Tokyo)
C. Berthier, M. Horvatic (Grenoble)
S. Haravifard (Duke)
H. Rønnow (Lausanne), C. Rüegg (PSI)

Scope

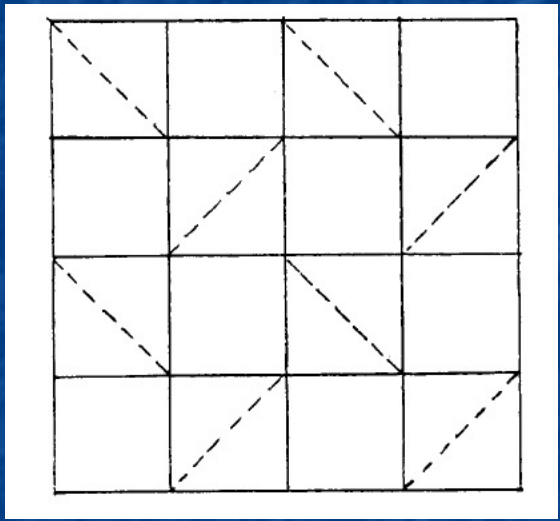
- The pioneers
  Shastry-Sutherland 1981, Smith-Keszler 1991
- Magnetization plateaus of $SrCu_2(BO_3)_2$
  Kageyama et al 1999, Kodama et al 2002, …
- Intermediate phase of $SrCu_2(BO_3)_2$ under pressure
  Waki et al 2007, Radtke et al 2014, …
- Topological magnons
  Romhanyi et al 2015, McClarty et al 2017
- Plaquette-AF transition
  Lee et al 2019, Guo et al 2020
- First-order transition and critical point
  Larrea et al 2021
- Bound states, impurities, combining magnetic field with pressure, spin supersolid, spin nematic, …

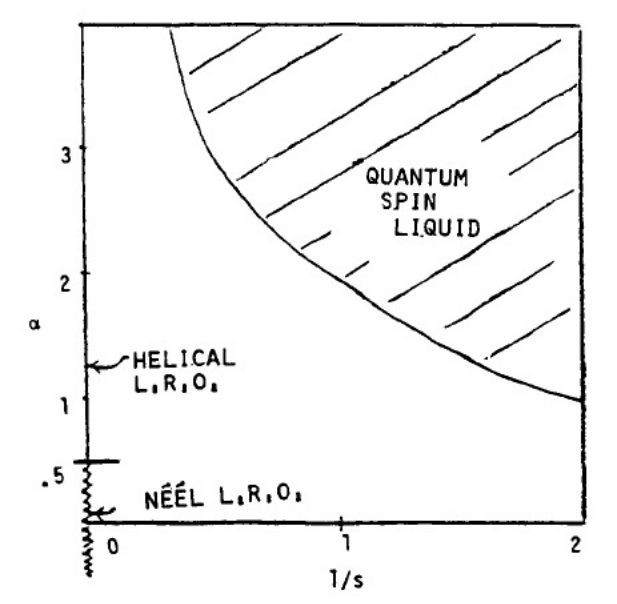
Physica 108B (1981) 1069-1070
North-Holland Publishing Company

EXACT GROUND STATE OF A QUANTUM MECHANICAL ANTIFERROMAGNET

B. Sriram Shastry and Bill Sutherland

Department of Physics, University of Utah, Salt Lake City, UT 84112





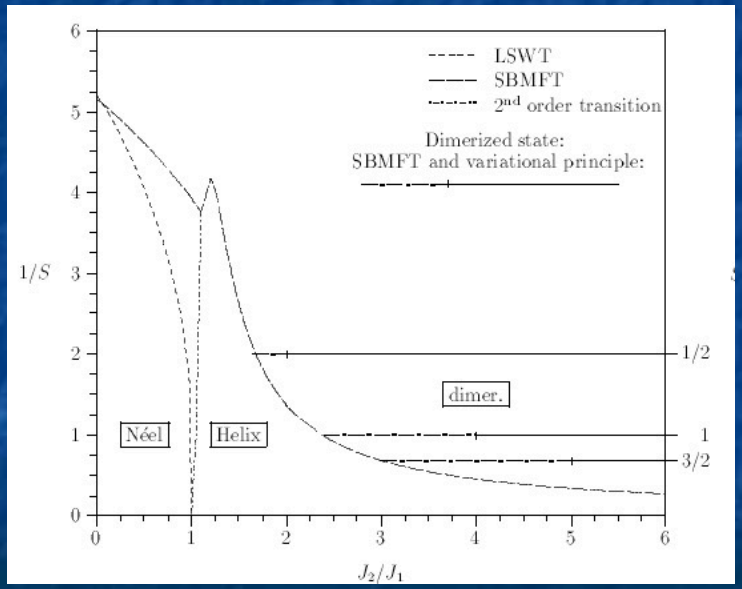
EUROPHYSICS LETTERS 10 April 1996

Europhys. Lett., **34** (2), pp. 145-150 (1996)

First-order transition between magnetic order and valence bond order in a 2D frustrated Heisenberg model

M. Albrecht and F. Mila

Laboratoire de Physique Quantique, Université Paul Sabatier - 31062 Toulouse, France

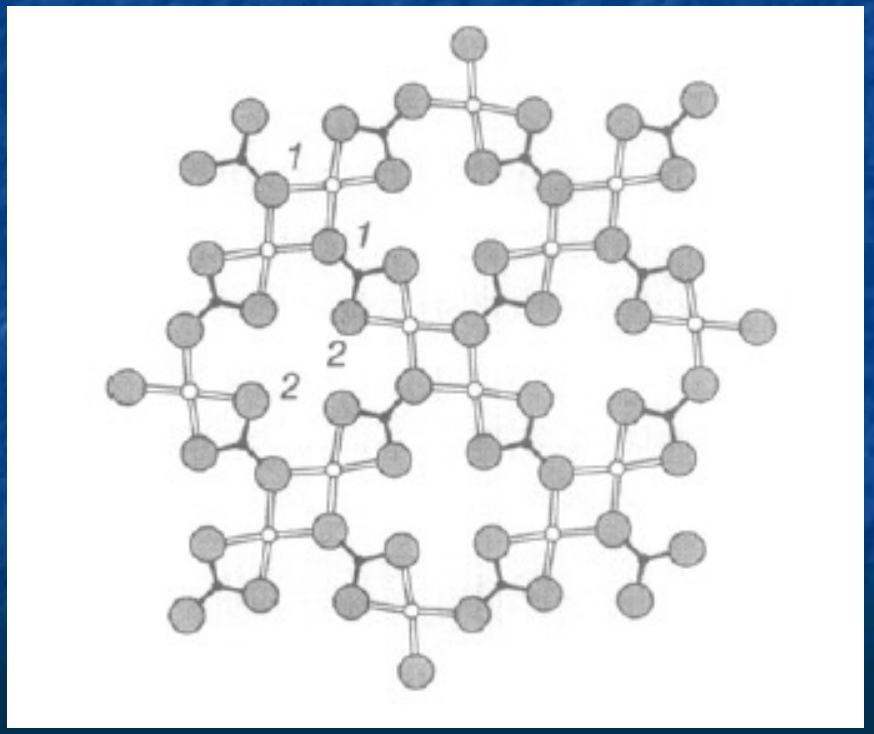


JOURNAL OF SOLID STATE CHEMISTRY 93, 430–435 (1991)

Synthesis, Structure, and Properties of the Orthoborate $SrCu_2(BO_3)_2$

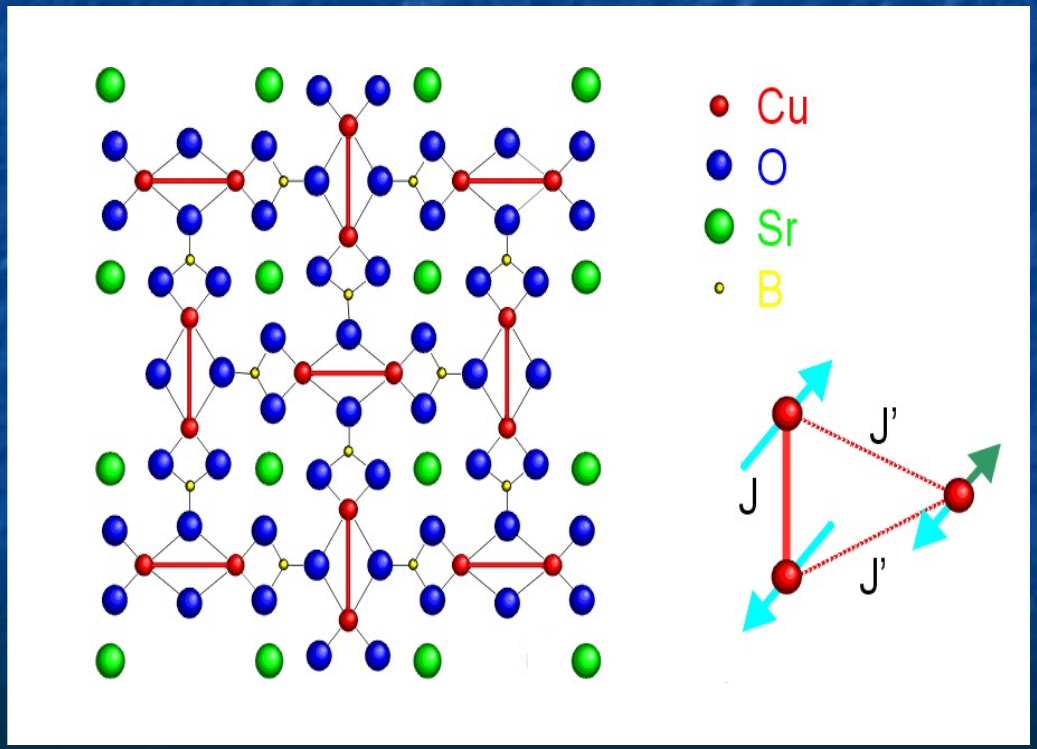
ROBERT W. SMITH AND DOUGLAS A. KESZLER*

Department of Chemistry and Center for Advanced Materials Research, Oregon State University, Gilbert Hall 153, Corvallis, Oregon 97331-4003



$SrCu_2(BO_3)_2$

Smith and Keszler, JSSC 1991

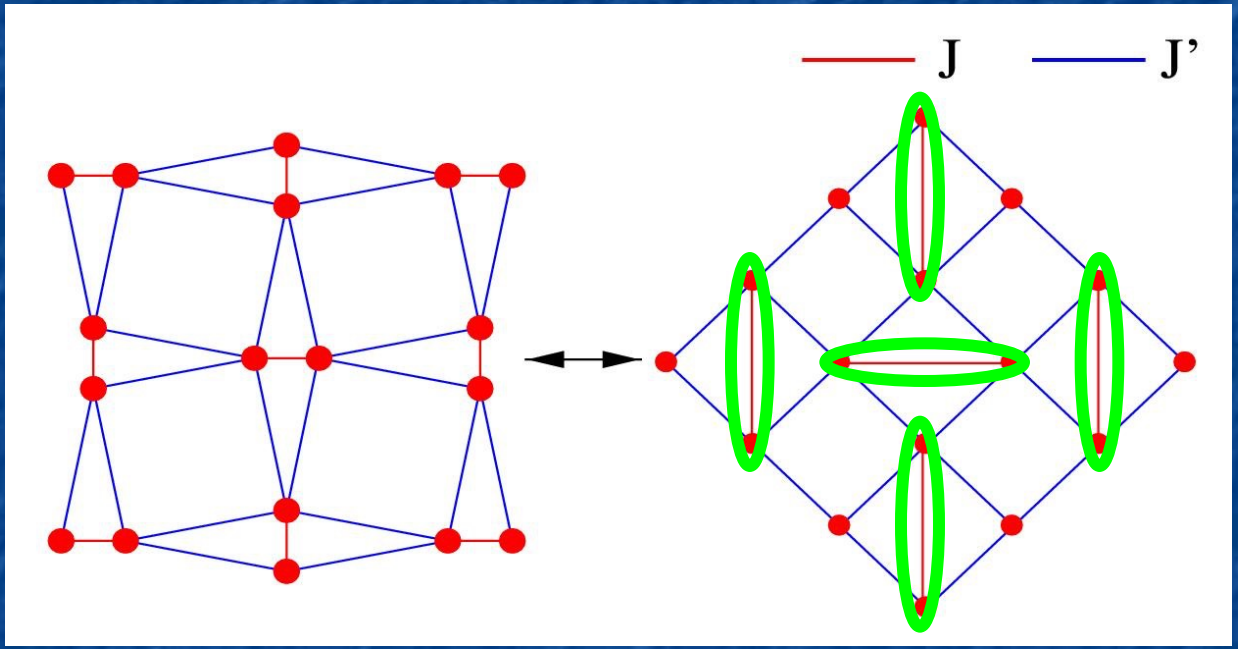


Cu^{2+} -> Spin 1/2

J ≈ 85 K

J'/J ≈ 0.63

Shastry-Sutherland model



Ground-state = Product of singlets on J-bonds

Shastry and Sutherland, ’81

→ Spin gap, and plateau at 0

Scope

- The pioneers

  Shastry-Sutherland 1981, Smith-Keszler 1991

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  Lee et al 2019, Guo et al 2020

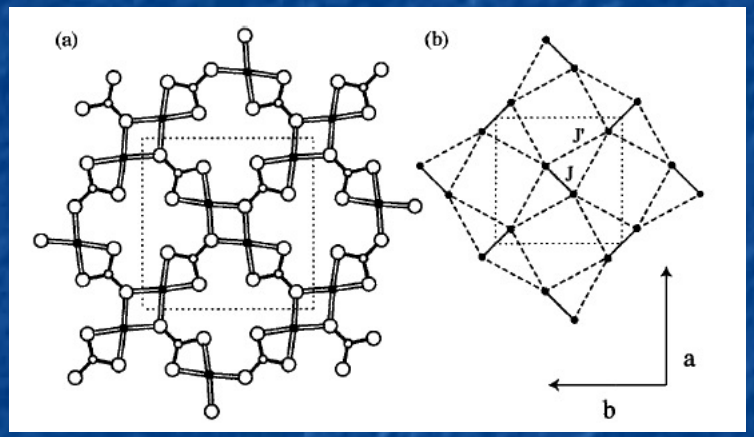
- First-order transition and critical point

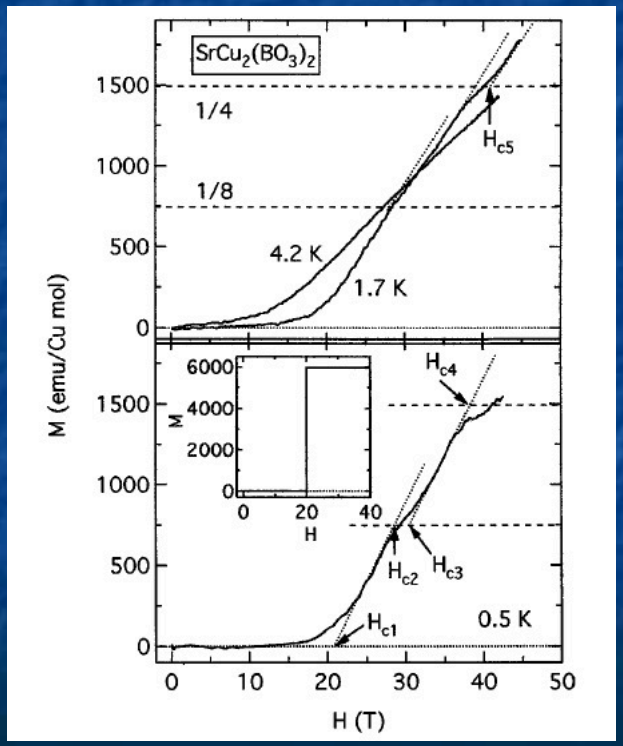
  Larrea et al 2021

- Bound states, impurities, combining magnetic field with pressure, spin supersolid, spin nematic, …

Exact Dimer Ground State and Quantized Magnetization Plateaus in the Two-Dimensional Spin System $SrCu_2(BO_3)_2$

H. Kageyama,[1,2,*] K. Yoshimura,[1,3,†] R. Stern,[3] N. V. Mushnikov,[2] K. Onizuka,[2] M. Kato,[1] K. Kosuge,[1] C. P. Slichter,[3] T. Goto,[2] and Y. Ueda[2]

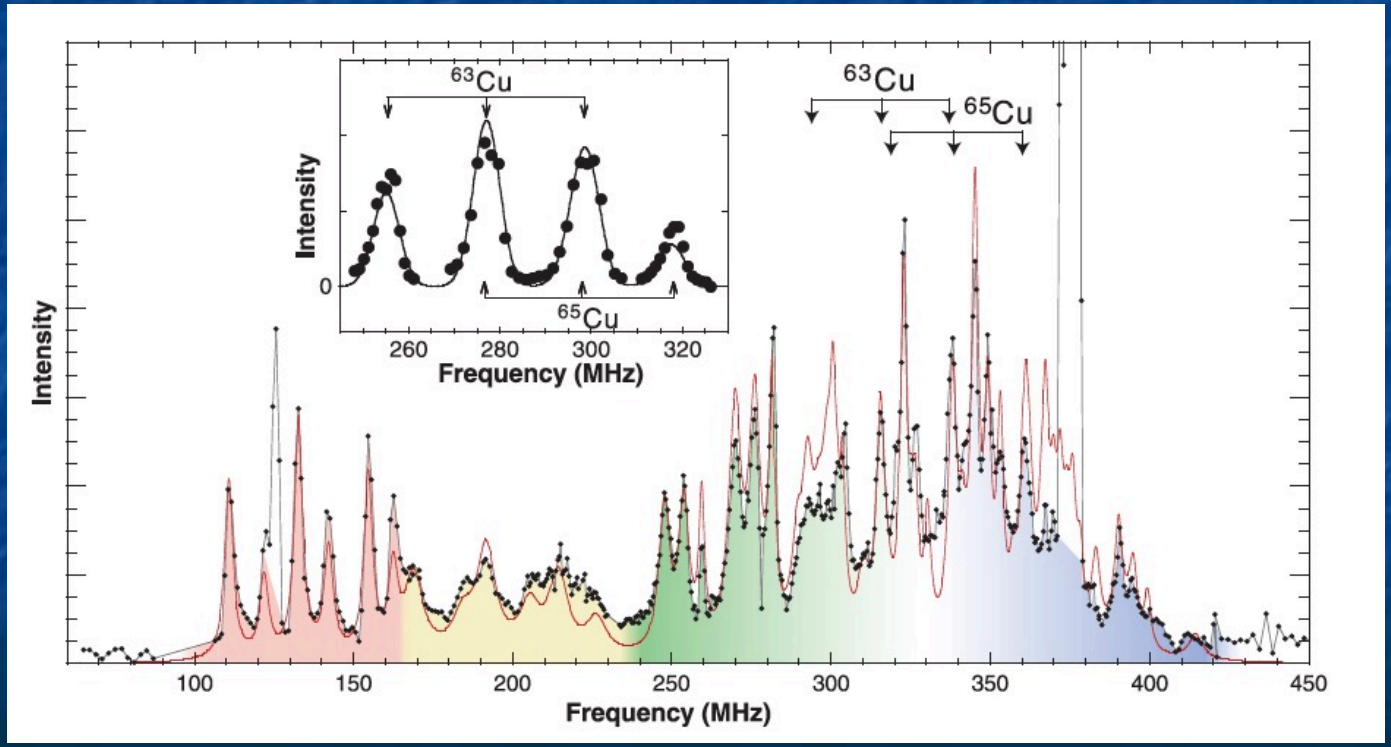




Magnetic Superstructure in the Two-Dimensional Quantum Antiferromagnet $SrCu_2(BO_3)_2$

K. Kodama,[1] M. Takigawa,[1]* M. Horvatić,[2] C. Berthier,[2,3]
H. Kageyama,[1] Y. Ueda,[1] S. Miyahara,[1,4] F. Becca,[4] F. Mila[4]

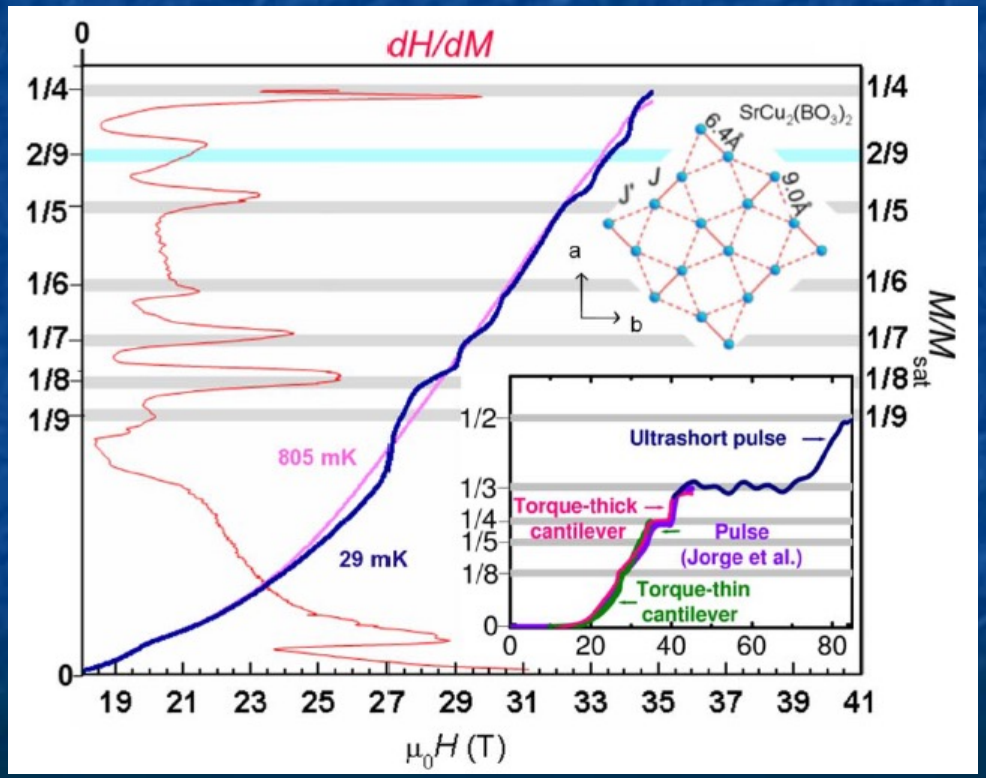
SCIENCE VOL 298 11 OCTOBER 2002



Fractalization drives crystalline states in a frustrated spin system

Suchitra E. Sebastian[a,1], N. Harrison[b], P. Sengupta[c], C. D. Batista[c], S. Francoual[b], E. Palm[d], T. Murphy[d], N. Marcano[a], H. A. Dabkowska[e], and B. D. Gaulin[e]

www.pnas.org/cgi/doi/10.1073/pnas.0804320105 PNAS | December 23, 2008 | vol. 105 | no. 51 | 20157–20160

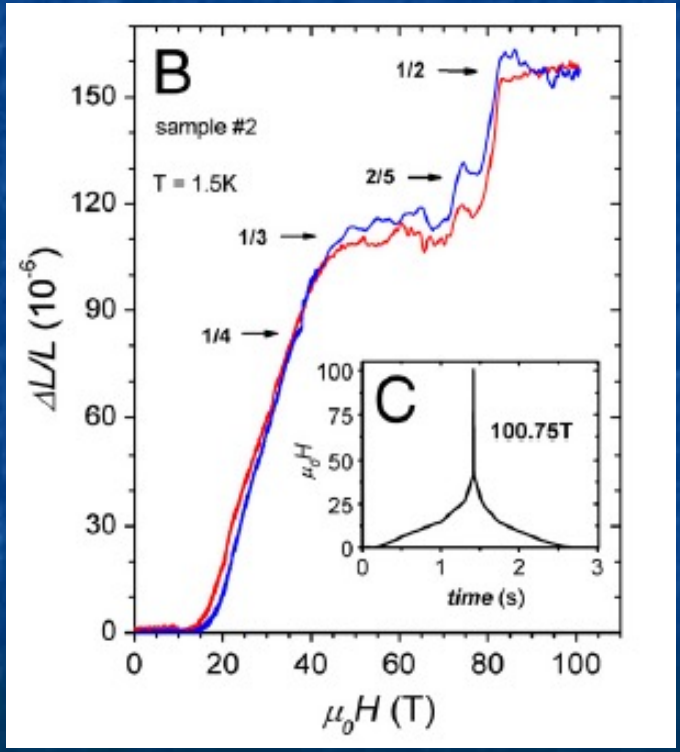


1/9, 1/8, 1/7, 1/6,
1/5, 2/9, 1/4

Magnetostriction and magnetic texture to 100.75 Tesla in frustrated $SrCu_2(BO_3)_2$

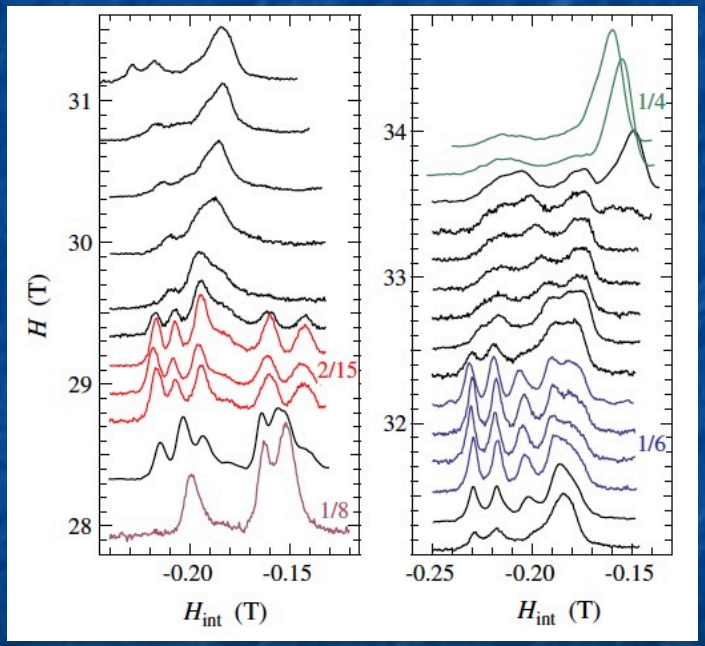
Marcelo Jaime[a,b,1], Ramzy Daou[c,d], Scott A. Crooker[a,b], Franziska Weickert[b], Atsuko Uchida[a,b], Adrian E. Feiguin[e], Cristian D. Batista[f], Hanna A. Dabkowska[g], and Bruce D. Gaulin[g,h]

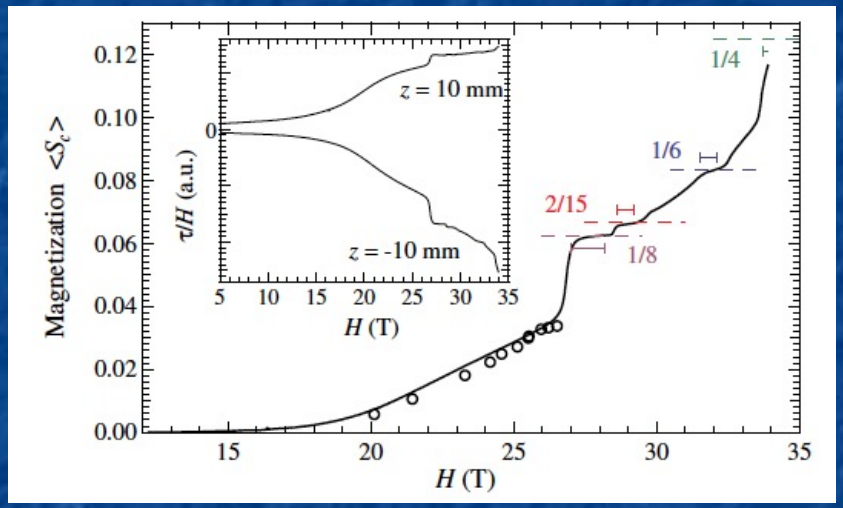
PNAS | July 31, 2012 | vol. 109 | no. 31



Incomplete Devil's Staircase in the Magnetization Curve of $SrCu_2(BO_3)_2$

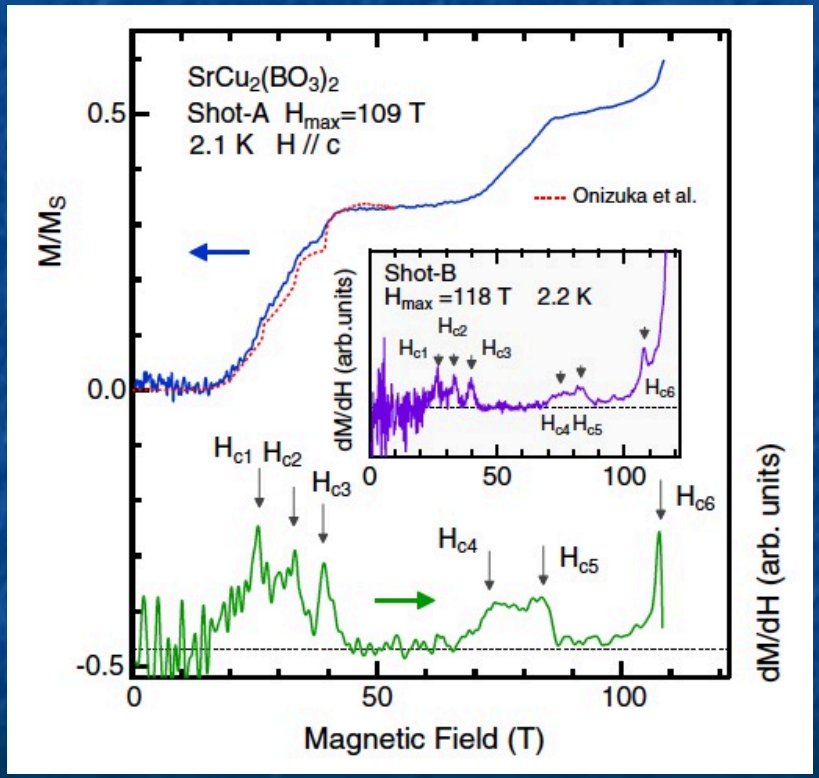
M. Takigawa,[1,*] M. Horvatić,[2] T. Waki,[3] S. Krämer,[2] C. Berthier,[2] F. Lévy-Bertrand,[2,†] I. Sheikin,[2] H. Kageyama,[4] Y. Ueda,[1] and F. Mila[5]





Magnetization of $SrCu_2(BO_3)_2$ in Ultrahigh Magnetic Fields up to 118 T

Y. H. Matsuda,[1,*] N. Abe,[1] S. Takeyama,[1] H. Kageyama,[2] P. Corboz,[3] A. Honecker,[4,5] S. R. Manmana,[4] G. R. Foltin,[6] K. P. Schmidt,[6] and F. Mila[7]



Summary on plateaus

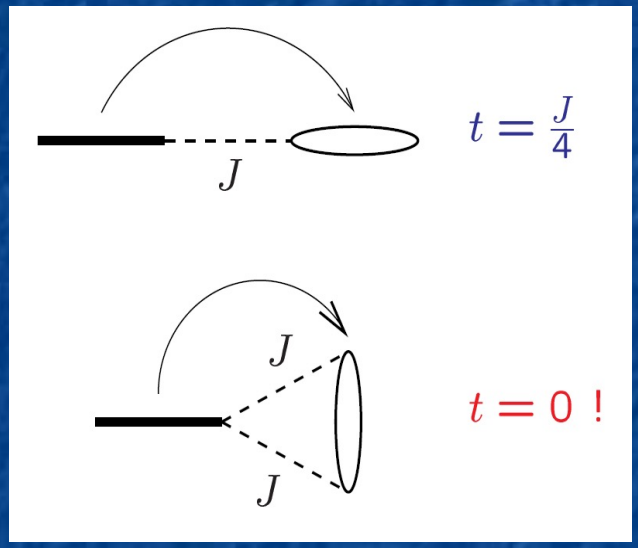
Improbable sequence of plateaus

1/8 2/15 1/6 1/4 1/3 2/5 1/2

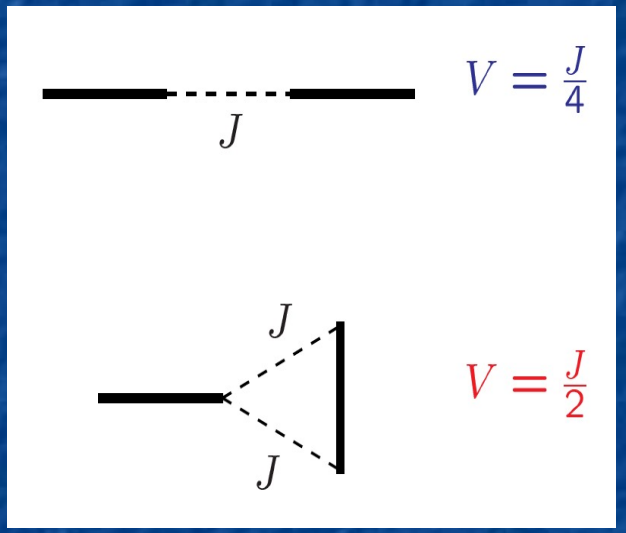
Theory?

Effect of frustration

Triplet Hopping



Triplet Repulsion



- Kinetic energy << potential energy
- Long-range repulsion

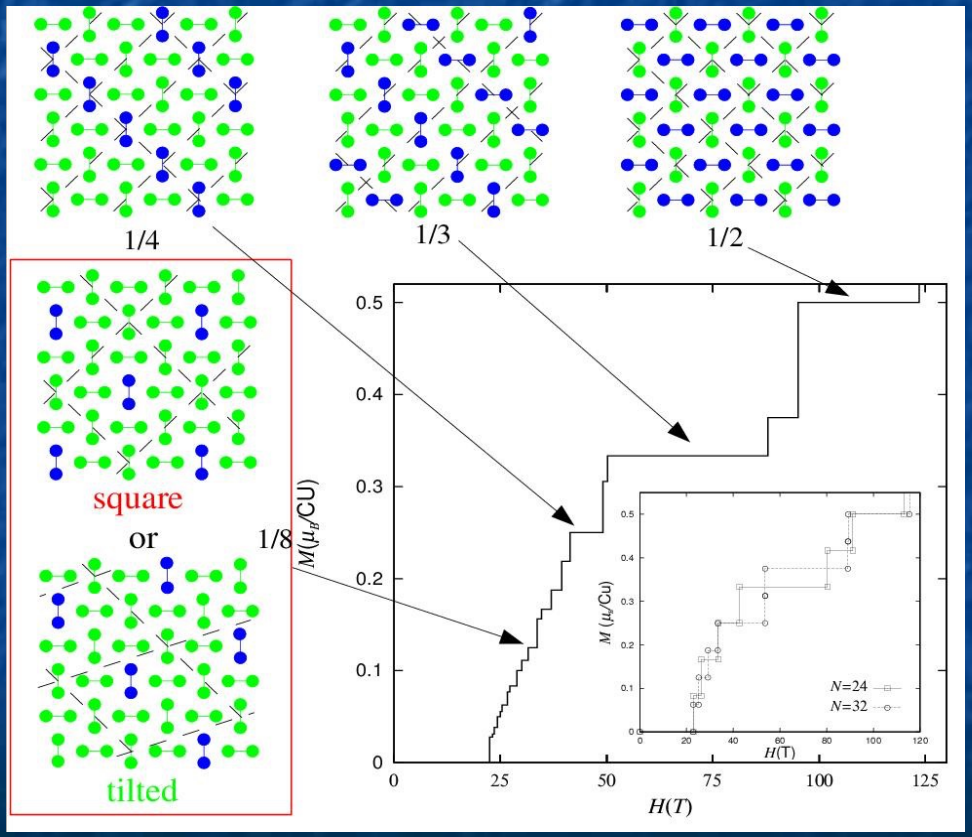
  → Crystals of triplets with high commensurability

  → Magnetization plateaux

PHYSICAL REVIEW B VOLUME 61, NUMBER 5 1 FEBRUARY 2000-I

Superstructures at magnetization plateaus in $SrCu_2(BO_3)_2$

Shin Miyahara and Kazuo Ueda



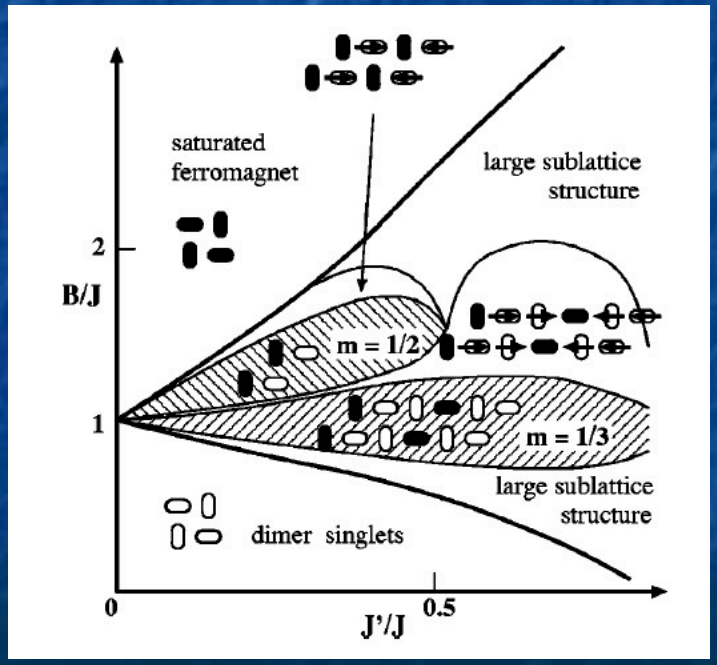
- Simple ansatz for long-range triplet-triplet interaction
- Many plateaus

PHYSICAL REVIEW B VOLUME 62, NUMBER 22 1 DECEMBER 2000-II

Magnetization plateaus of the Shastry-Sutherland model for $SrCu_2(BO_3)_2$: Spin-density wave, supersolid, and bound states

Tsutomu Momoi*
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

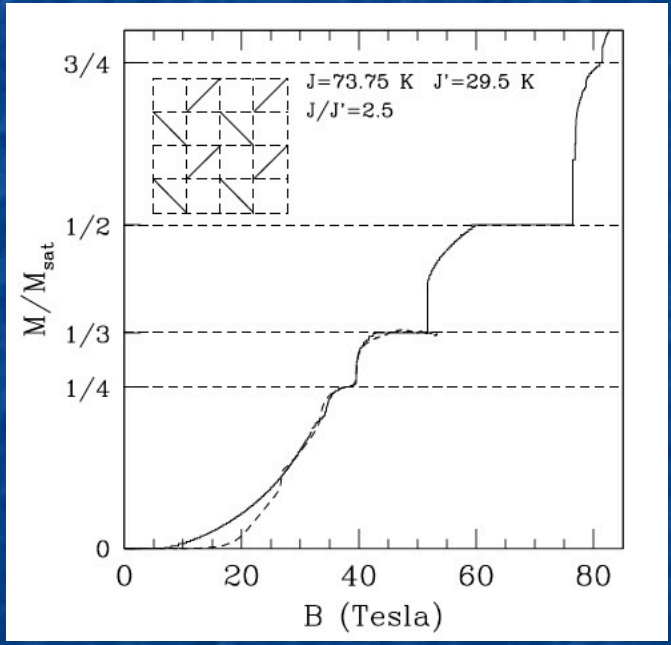
Keisuke Totsuka
Department of Physics, Kyushu University, Hakozaki, Higashi-ku, Fukuoka-shi 812-8581, Japan
(Received 1 June 2000)



VOLUME 87, NUMBER 9 PHYSICAL REVIEW LETTERS 27 AUGUST 2001

Magnetization Plateaus of $SrCu_2(BO_3)_2$ from a Chern-Simons Theory

G. Misguich,[1] Th. Jolicoeur,[2] and S. M. Girvin[3,4]

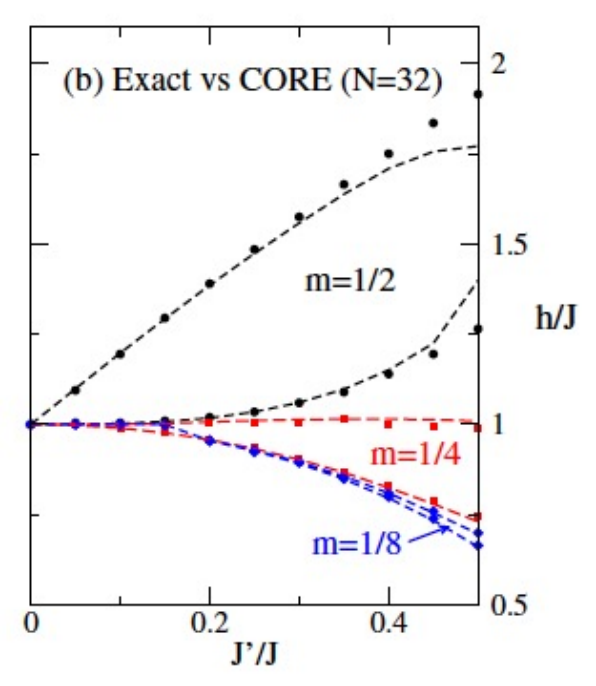


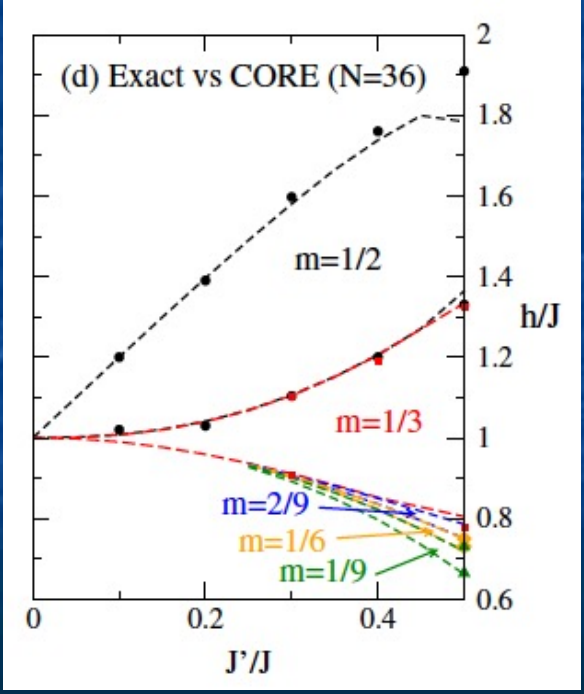
PRL 101, 227201 (2008) PHYSICAL REVIEW LETTERS week ending 28 NOVEMBER 2008

Effective Theory of Magnetization Plateaux in the Shastry-Sutherland Lattice

A. Abendschein[1,2] and S. Capponi[1,2,*]

Effective model with CORE (Contractor Renormalization)
Exact diagonalization on small clusters



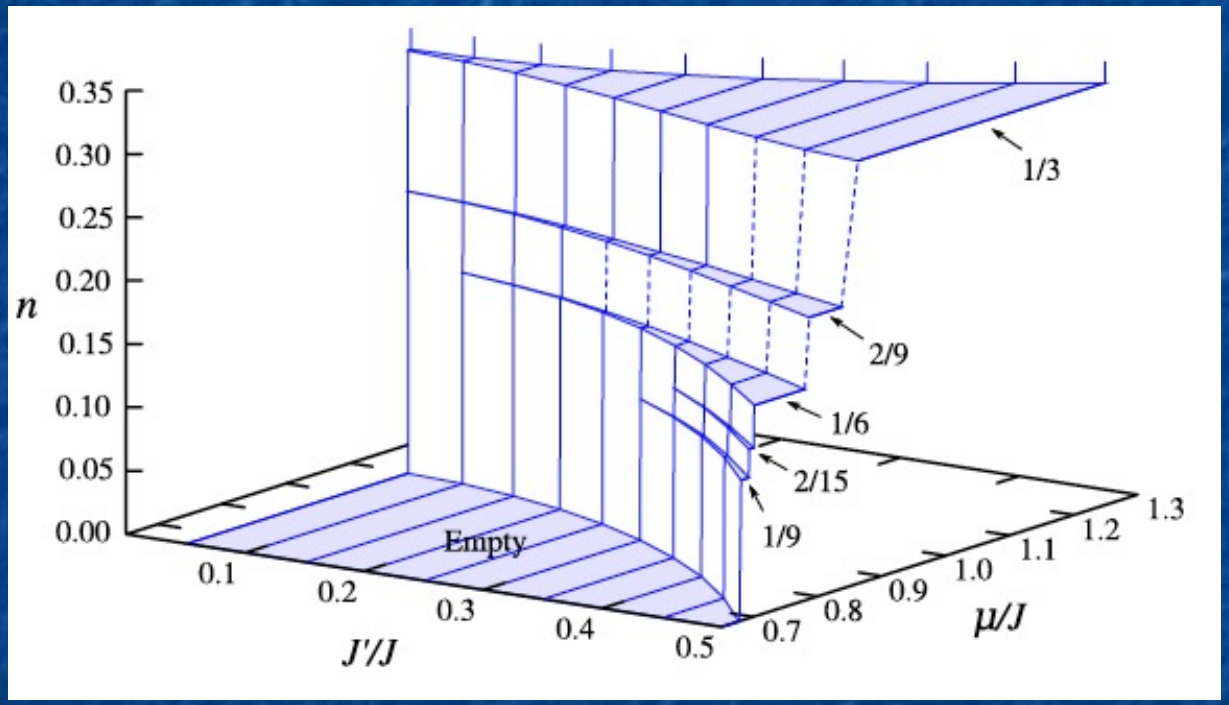


- Large finite-size effects
- No 2/15 plateau

PRL 101, 250402 (2008) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2008

Theory of Magnetization Plateaux in the Shastry-Sutherland Model

J. Dorier,[1] K. P. Schmidt,[2,*] and F. Mila[1]



No 1/8 plateau

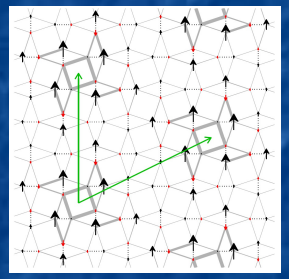
Expansion in J'/J up to 0.5 using p-CUT
(perturbative continuous unitary transformation)

PRL 112, 147203 (2014) PHYSICAL REVIEW LETTERS week ending 11 APRIL 2014

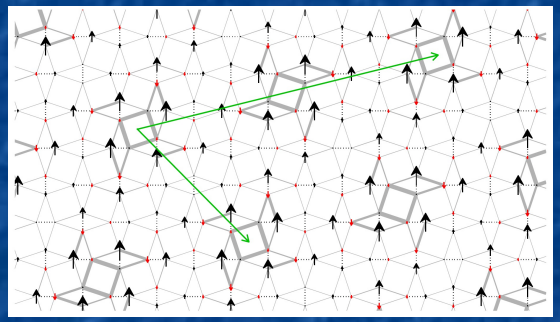
Crystals of Bound States in the Magnetization Plateaus of the Shastry-Sutherland Model

Philippe Corboz[1] and Frédéric Mila[2]

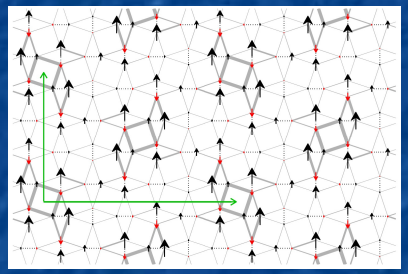
1/8

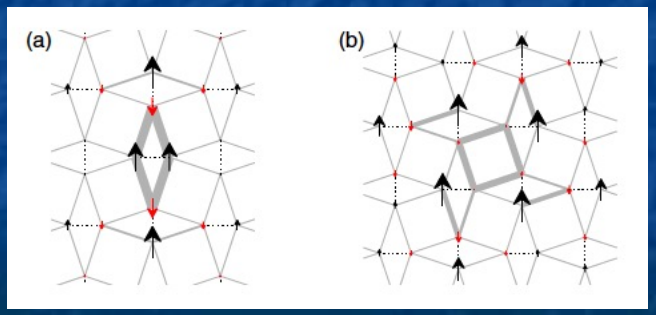


2/15



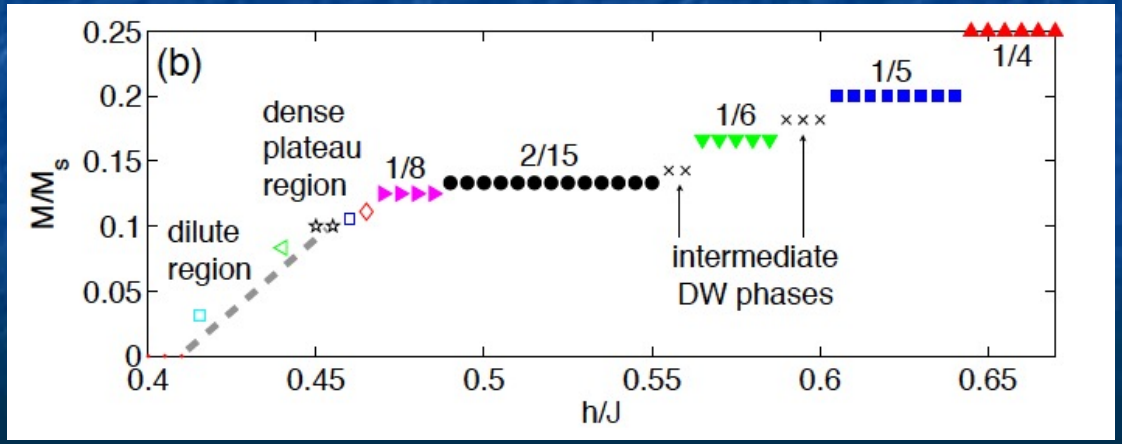
1/6





Triplet

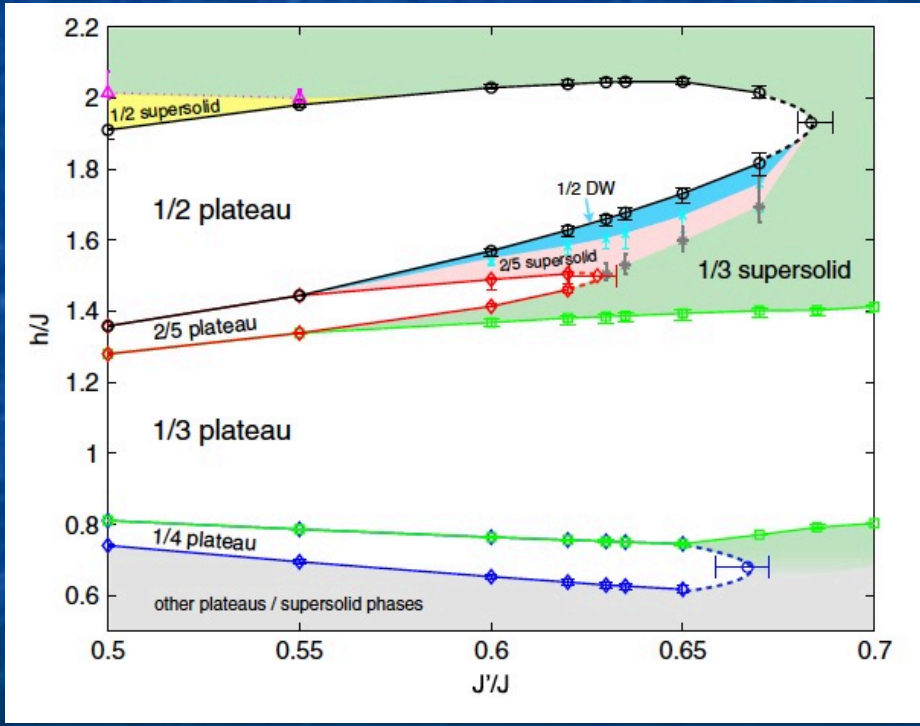
Spin-2 bound state



Method: iPEPS (tensor networks)

Magnetization of $SrCu_2(BO_3)_2$ in Ultrahigh Magnetic Fields up to 118 T

Y. H. Matsuda,[1,*] N. Abe,[1] S. Takeyama,[1] H. Kageyama,[2] P. Corboz,[3] A. Honecker,[4,5] S. R. Manmana,[4] G. R. Foltin,[6] K. P. Schmidt,[6] and F. Mila[7]



Scope

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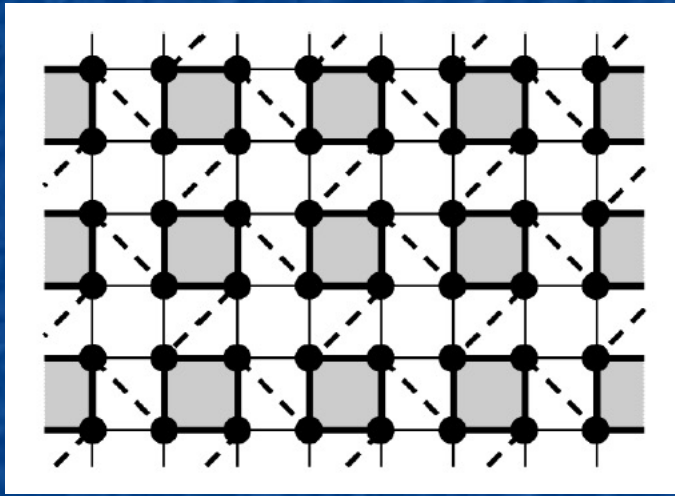
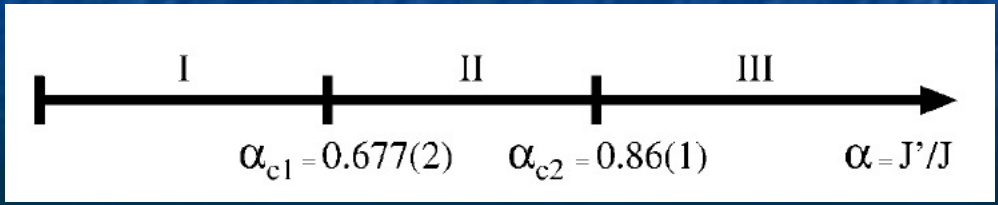
  Lee et al 2019, Guo et al 2020
- First-order transition and critical point
  Larrea et al 2021
- Bound states, impurities, combining magnetic field with pressure, spin supersolid, spin nematic, …

VOLUME 84, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 2000

Quantum Phase Transitions in the Shastry-Sutherland Model for $SrCu_2(BO_3)_2$

Akihisa Koga and Norio Kawakami
Department of Applied Physics, Osaka University, Suita, Osaka 565-0871, Japan
(Received 6 December 1999)





Series expansions

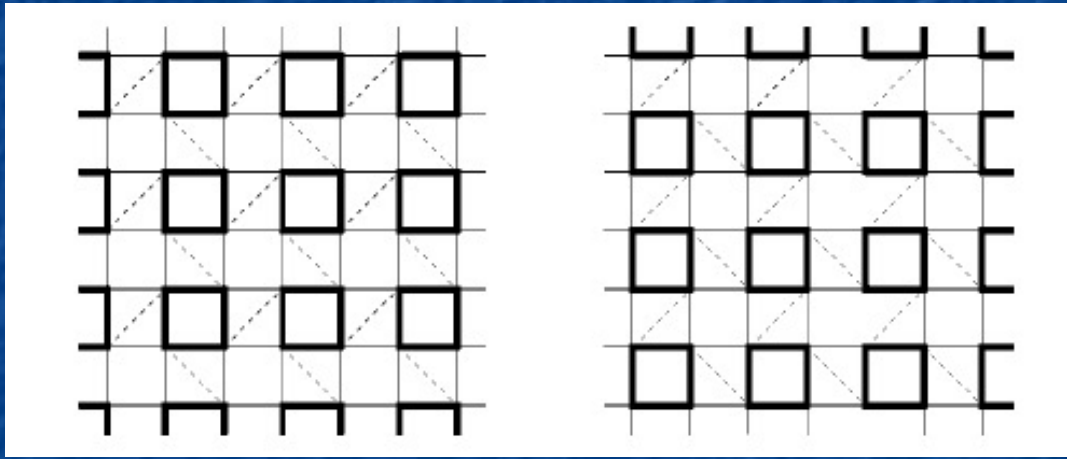
↓

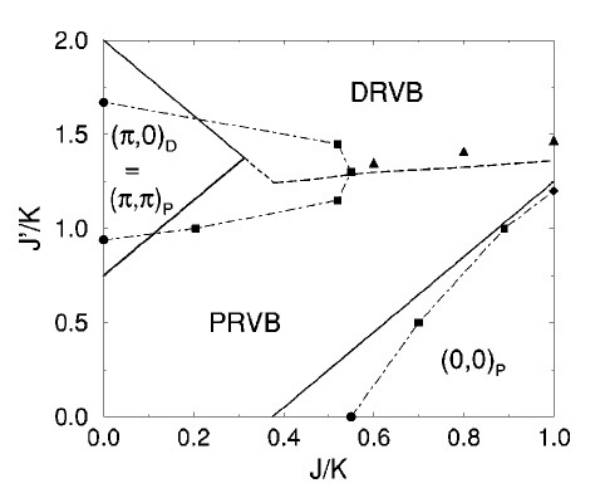
Intermediate plaquette phase

PHYSICAL REVIEW B **66**, 014401 (2002)

Phase diagram of the quadrumerized Shastry-Sutherland model

Andreas Läuchli, Stefan Wessel, and Manfred Sigrist
Institut für Theoretische Physik, ETH-Hönggerberg, CH-8093 Zürich, Switzerland
(Received 5 February 2002; published 20 June 2002)





Exact diagonalizations → two-fold degenerate plaquette phase

PHYSICAL REVIEW B **87**, 115144 (2013)

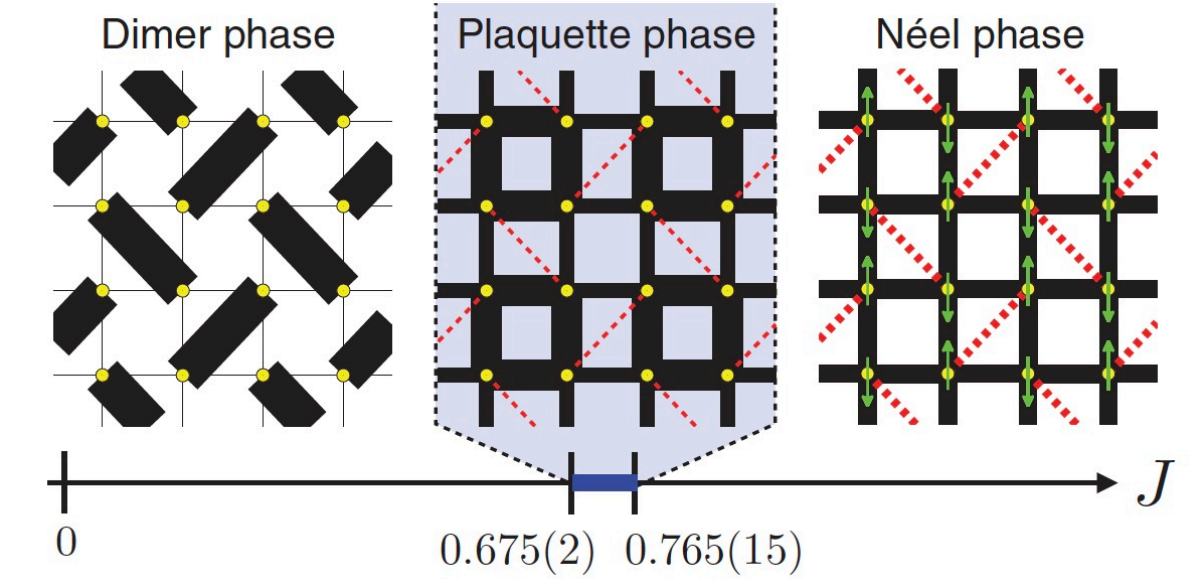
Tensor network study of the Shastry-Sutherland model in zero magnetic field

Philippe Corboz[1] and Frédéric Mila[2]

[1]*Theoretische Physik, ETH Zürich, CH-8093 Zürich, Switzerland*

[2]*Institut de théorie des phénomènes physiques, École Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland*

(Received 13 December 2012; revised manuscript received 27 February 2013; published 27 March 2013)



iPEPS with various setups and bond dimension up to 10

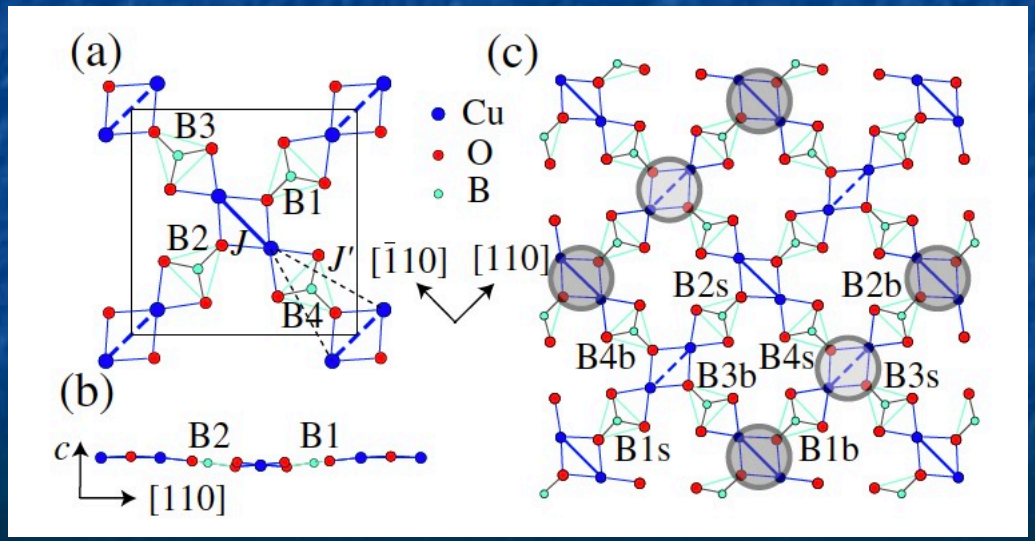
Journal of the Physical Society of Japan
Vol. 76, No. 7, July, 2007, 073710

A Novel Ordered Phase in $SrCu_2(BO_3)_2$ under High Pressure

Takeshi WAKI[1*], Koichi ARAI[1†], Masashi TAKIGAWA[1‡], Yuta SAIGA[1,2], Yoshiya UWATOKO[1], Hiroshi KAGEYAMA[3], and Yutaka UEDA[1]

[1]*Institute for Solid State Physics, The University of Tokyo, Kashiwa, Chiba 277-8581*
[2]*Graduate School of Science and Engineering, Saitama University, Saitama 338-8570*
[3]*Department of Chemistry, Graduate School of Science, Kyoto University, Kyoto 606-8502*

(Received May 2, 2007; accepted May 31, 2007; published July 10, 2007)



Intermediate phase under pressure, but two types of Cu sites

↓

NOT the plaquette phase

nature COMMUNICATIONS

ARTICLE

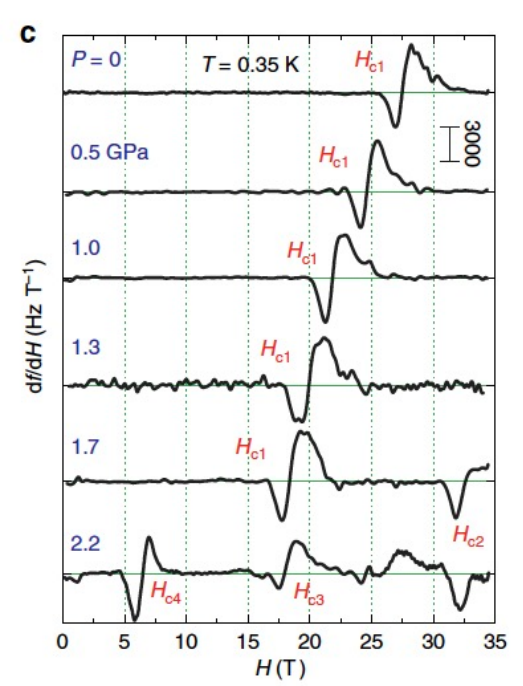
Received 17 Jun 2015 | Accepted 16 May 2016 | Published 20 Jun 2016

DOI: 10.1038/ncomms11956 OPEN

Crystallization of spin superlattices with pressure and field in the layered magnet $SrCu_2(BO_3)_2$

S. Haravifard[1,2,3], D. Graf[4], A.E. Feiguin[5], C.D. Batista[6,7,8], J.C. Lang[3], D.M. Silevitch[2,9], G. Srajer[3], B.D. Gaulin[10], H.A. Dabkowska[10] & T.F. Rosenbaum[2,9]

Second derivative of magnetization



Magnetic field response under pressure

↓

Confirmation of a phase transition around 2GPa

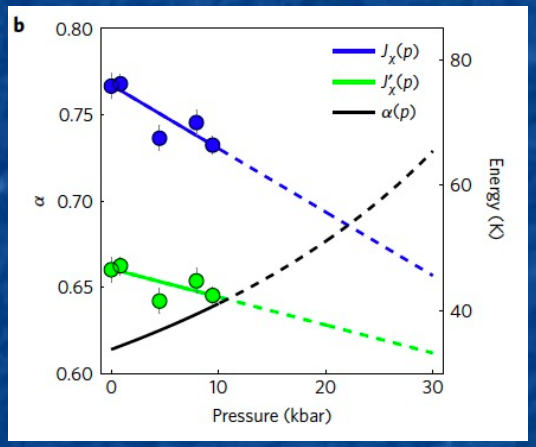
LETTERS
PUBLISHED ONLINE: 17 JULY 2017 | DOI: 10.1038/NPHYS4190
nature physics

4-spin plaquette singlet state in the Shastry–Sutherland compound $SrCu_2(BO_3)_2$

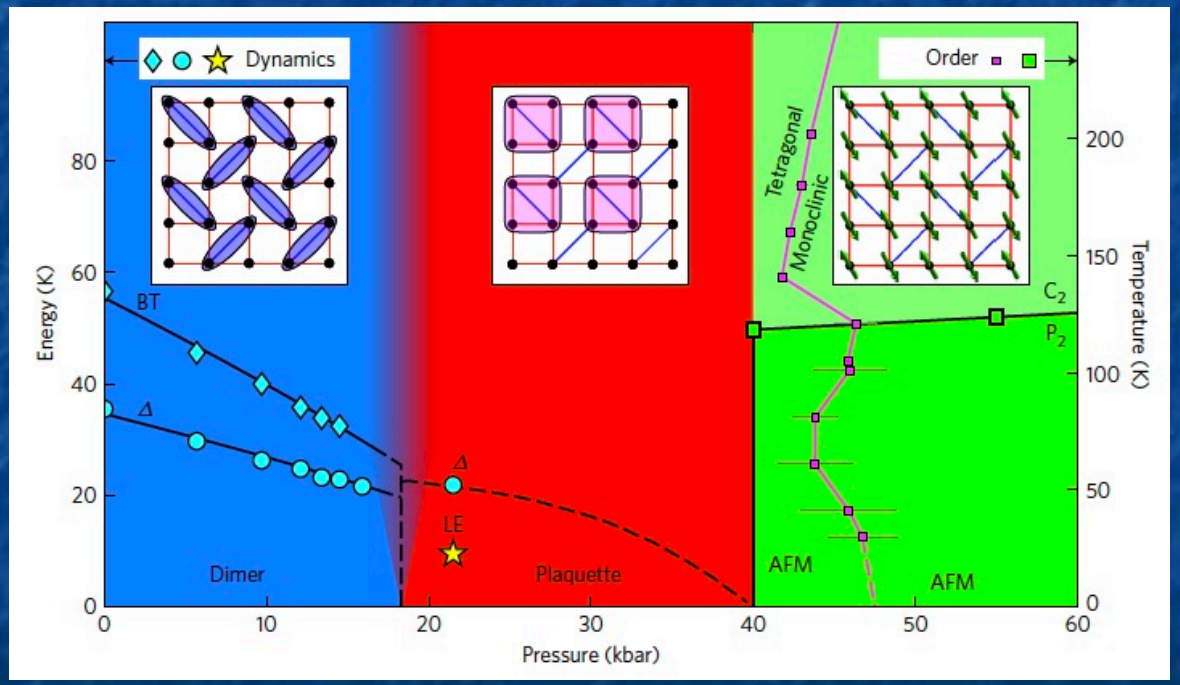
M. E. Zayed[1,2,3*], Ch. Rüegg[2,4,5], J. Larrea J.[1,6], A. M. Läuchli[7], C. Panagopoulos[8,9], S. S. Saxena[8], M. Ellerby[5], D. F. McMorrow[5], Th. Strässle[2], S. Klotz[10], G. Hamel[10], R. A. Sadykov[11,12], V. Pomjakushin[2], M. Boehm[13], M. Jiménez-Ruiz[13], A. Schneidewind[14], E. Pomjakushina[15], M. Stingaciu[15], K. Conder[15] and H. M. Rønnow[1]

Neutron scattering

Susceptibility



J'/J increases



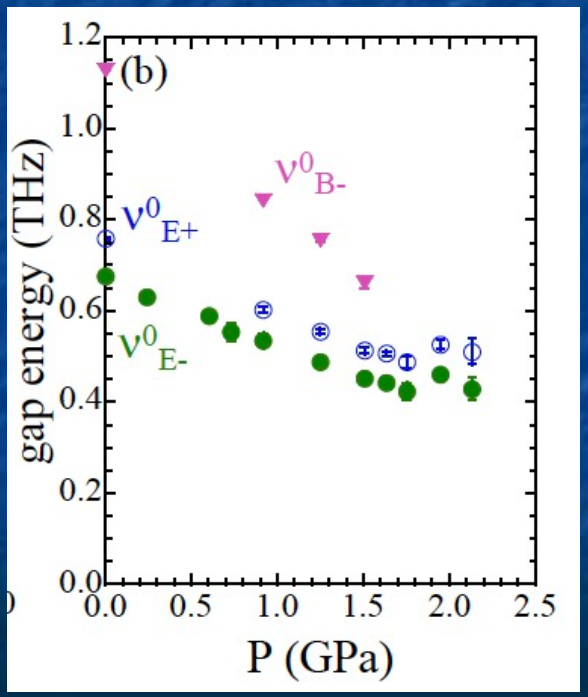
The intermediate phase is a full plaquette phase!

Journal of the Physical Society of Japan 87, 033701 (2018) Letters
https://doi.org/10.7566/JPSJ.87.033701

Direct Observation of the Quantum Phase Transition of $SrCu_2(BO_3)_2$ by High-Pressure and Terahertz Electron Spin Resonance

Takahiro Sakurai[1]*, Yuki Hirao[2], Keigo Hijii[3], Susumu Okubo[3], Hitoshi Ohta[3], Yoshiya Uwatoko[4], Kazutaka Kudo[5], and Yoji Koike[6]

ESR



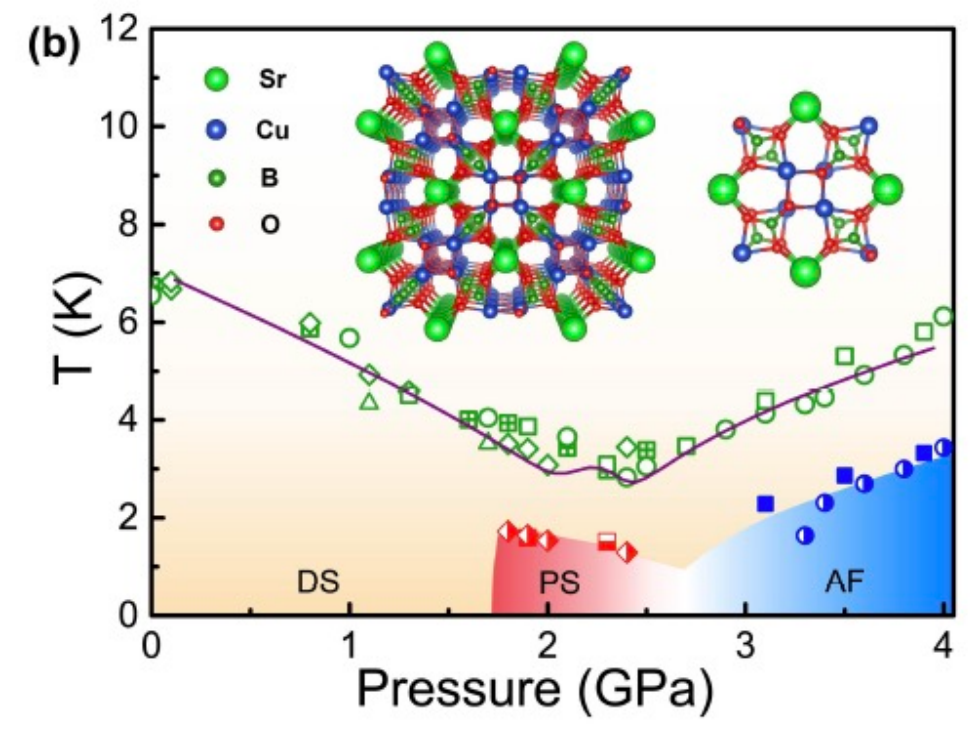
The gap levels off around 1.8 GPa

↓

Confirmation of a phase transition around 1.8 GPa

Quantum Phases of $SrCu_2(BO_3)_2$ from High-Pressure Thermodynamics

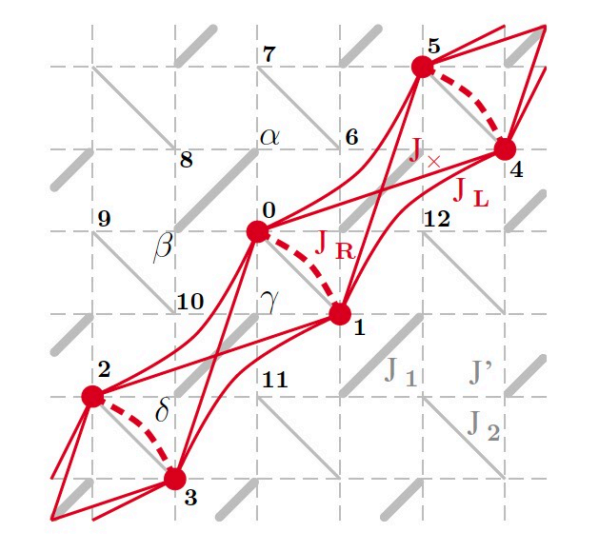
Jing Guo,[1] Guangyu Sun,[1,2] Bowen Zhao,[3] Ling Wang,[4,5] Wenshan Hong,[1,2] Vladimir A. Sidorov,[6] Nvsen Ma,[1] Qi Wu,[1] Shiliang Li,[1,2,7] Zi Yang Meng,[1,8,7,*] Anders W. Sandvik,[3,1,†] and Liling Sun[1,2,7,‡]

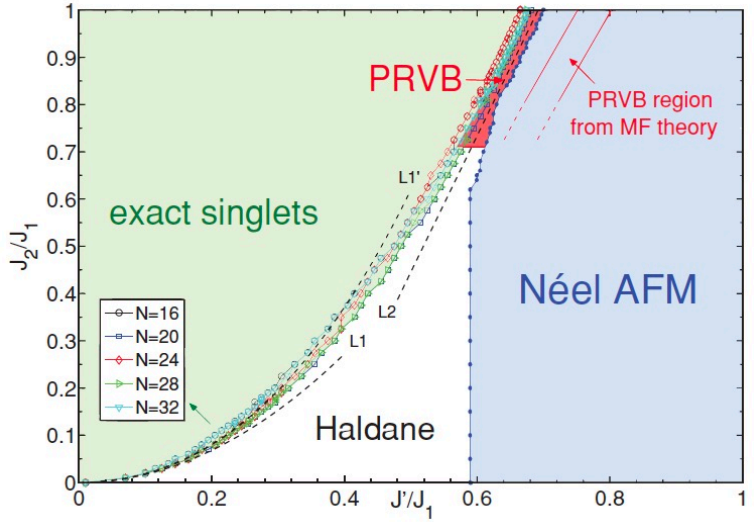


PHYSICAL REVIEW B **83**, 140414(R) (2011)

Emergence of one-dimensional physics from the distorted Shastry-Sutherland lattice

M. Moliner,[1,*] I. Rousochatzakis,[2,†] and F. Mila[3,‡]





J2 ≪ J1 → effective fully frustrated ladder

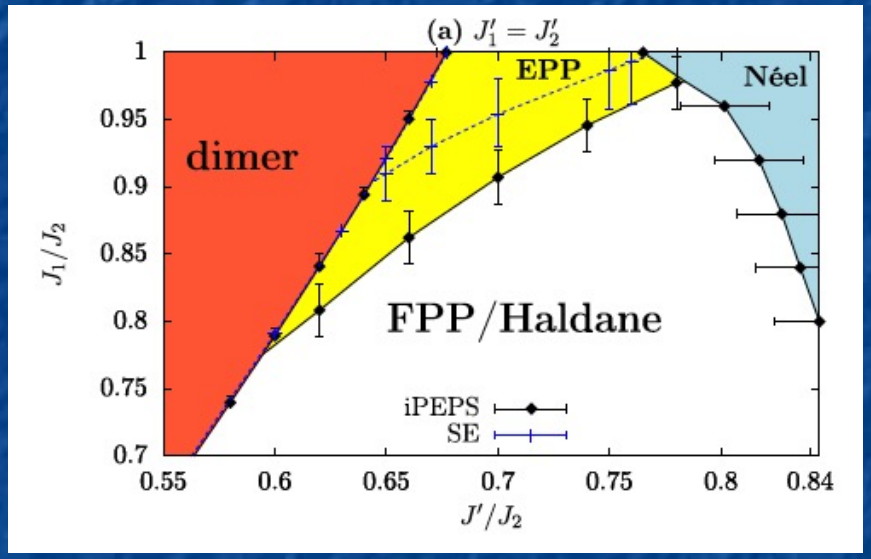
→ Haldane phase

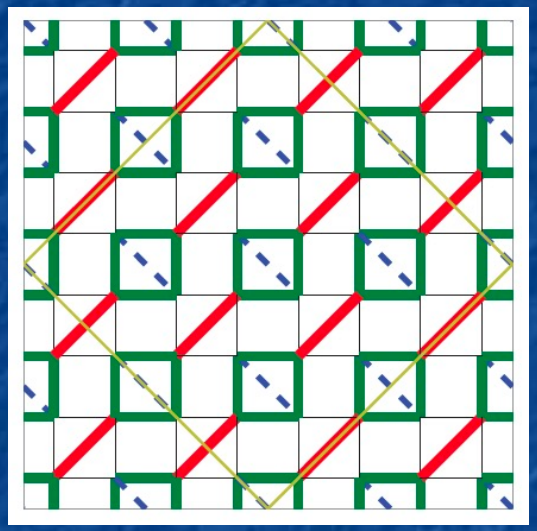
PHYSICAL REVIEW B **100**, 140413(R) (2019)

Rapid Communications

Competition between intermediate plaquette phases in $SrCu_2(BO_3)_2$ under pressure

C. Boos,[1,2,*] S. P. G. Crone,[3] I. A. Niesen,[3] P. Corboz,[3] K. P. Schmidt,[1,†] and F. Mila[2,‡]





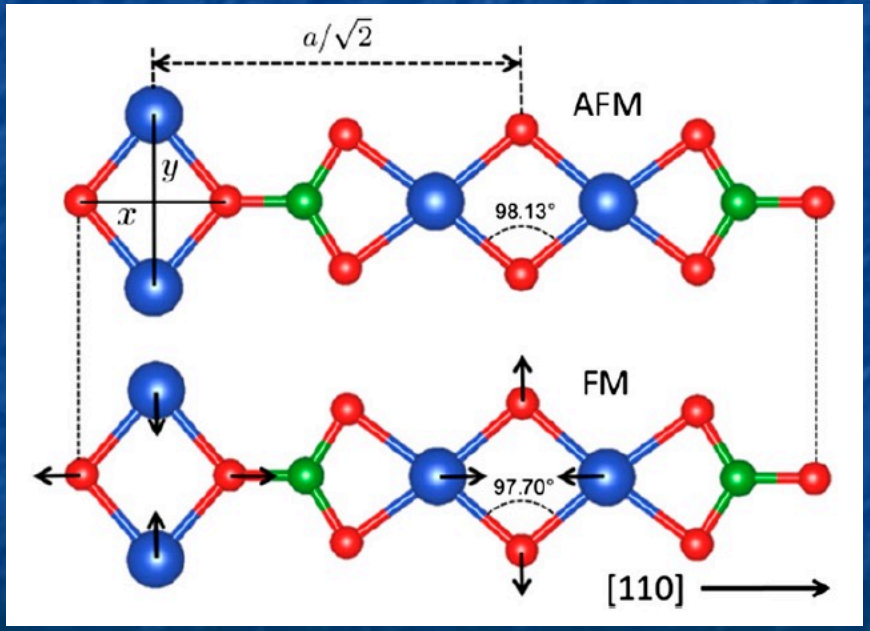
Haldane and full plaquette phases are adiabatically connected

→ single alternative to plaquette phase

Magnetic nanopantograph in the $SrCu_2(BO_3)_2$ Shastry–Sutherland lattice

Guillaume Radtke[a], Andrés Saúl[b,c,1], Hanna A. Dabkowska[d], Myron B. Salamon[e,f], and Marcelo Jaime[f]

PNAS | February 17, 2015 | vol. 112 | no. 7 | 1971–1976



Scope

- The pioneers

  Shastry-Sutherland 1981, Smith-Keszler 1991
- Magnetization plateaus of $SrCu_2(BO_3)_2$

  Kageyama et al 1999, Kodama et al 2002, …
- Intermediate phase of $SrCu_2(BO_3)_2$ under pressure

  Waki et al 2007, Radtke et al 2014, …
- Topological magnons

  Romhanyi et al 2015, McClarty et al 2017
- Plaquette-AF transition

  Lee et al 2019, Guo et al 2020
- First-order transition and critical point

  Larrea et al 2021
- Bound states, impurities, combining magnetic field with pressure, spin supersolid, spin nematic, …

nature COMMUNICATIONS

ARTICLE

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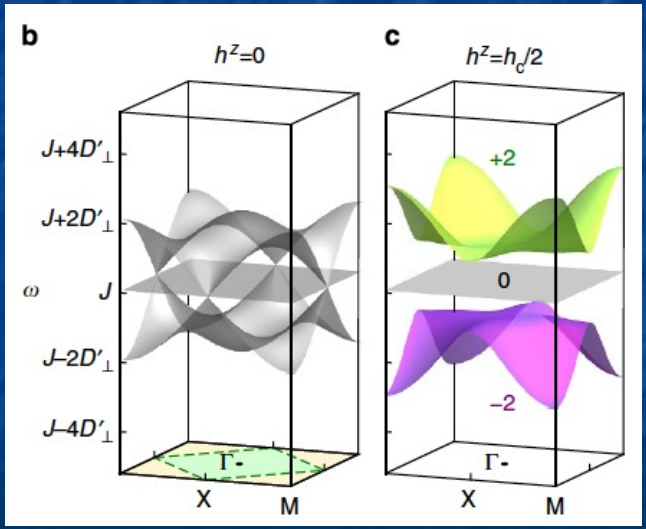
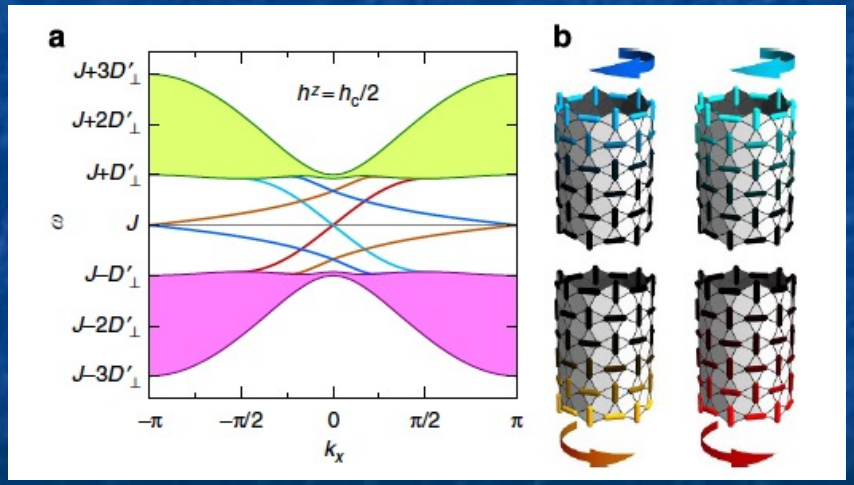
DOI: 10.1038/ncomms7805

Hall effect of triplons in a dimerized quantum magnet

Judit Romhányi[1], Karlo Penc[2] & R. Ganesh[1]



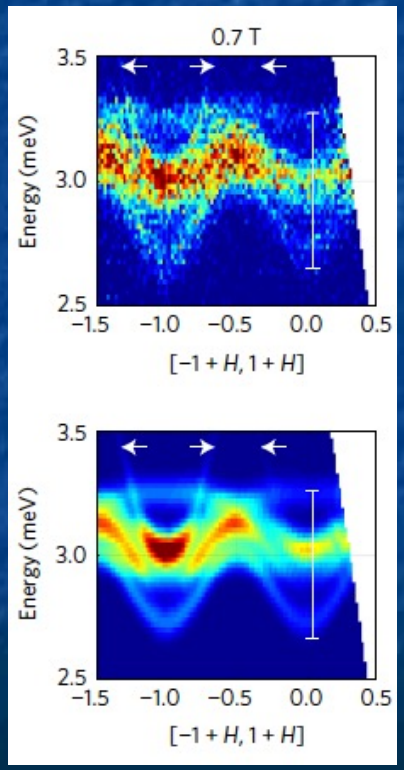


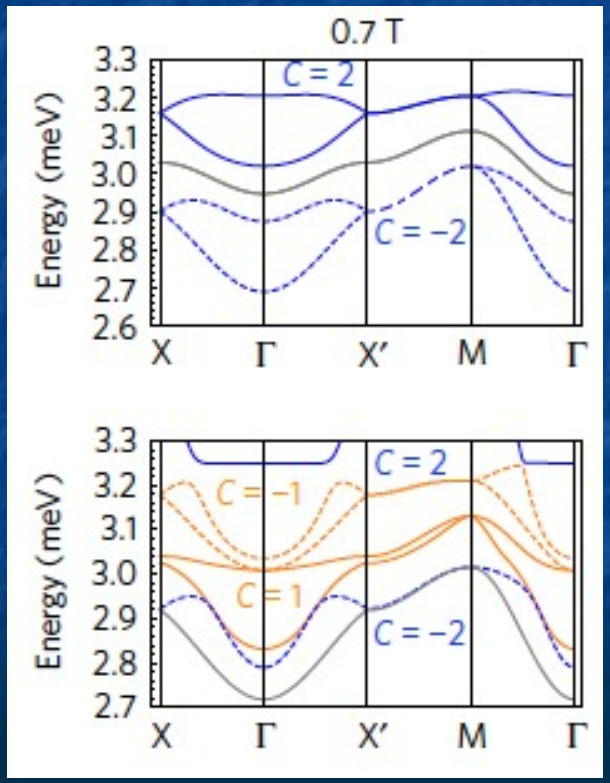
DM interactions + small magnetic field

LETTERS
PUBLISHED ONLINE: 8 MAY 2017 | DOI: 10.1038/NPHYS4117
nature physics

Topological triplon modes and bound states in a Shastry–Sutherland magnet

P. A. McClarty[1,2]*, F. Krüger[1,3]*, T. Guidi[1], S. F. Parker[1], K. Refson[1,4], A. W. Parker[5], D. Prabhakaran[6] and R. Coldea[6]





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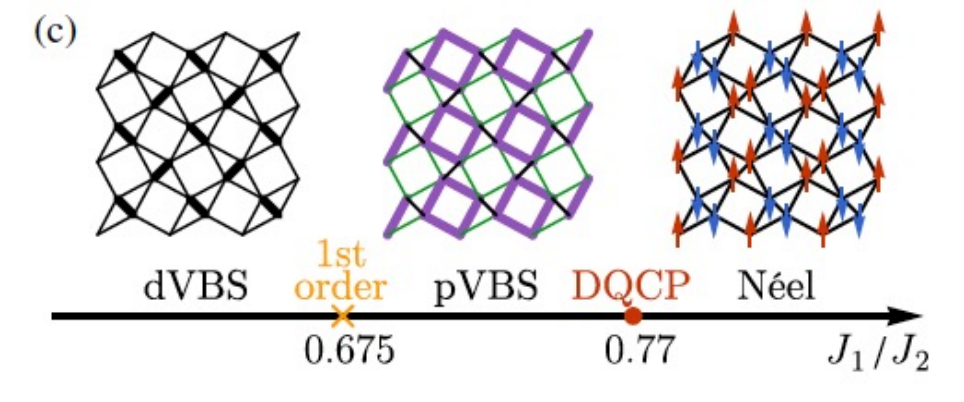
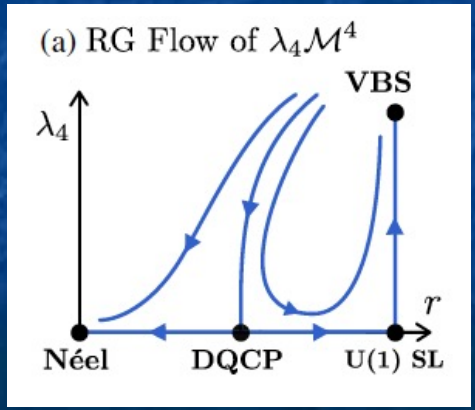
Signatures of a Deconfined Phase Transition on the Shastry-Sutherland Lattice: Applications to Quantum Critical $SrCu_2(BO_3)_2$

Jong Yeon Lee,[1] Yi-Zhuang You,[1,2] Subir Sachdev,[1] and Ashvin Vishwanath[1]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics, University of California, San Diego, California 92093, USA*





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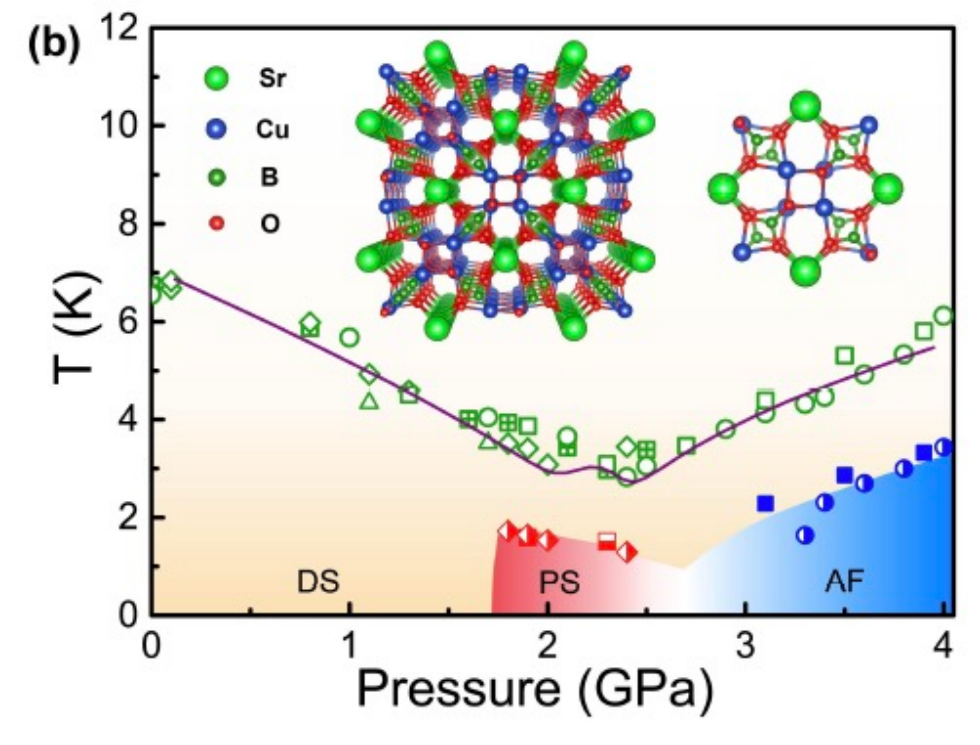
Jing Guo,[1] Guangyu Sun,[1,2] Bowen Zhao,[3] Ling Wang,[4,5] Wenshan Hong,[1,2] Vladimir A. Sidorov,[6] Nvsen Ma,[1] Qi Wu,[1] Shiliang Li,[1,2,7] Zi Yang Meng,[1,8,7,*] Anders W. Sandvik,[3,1,†] and Liling Sun[1,2,7,‡]



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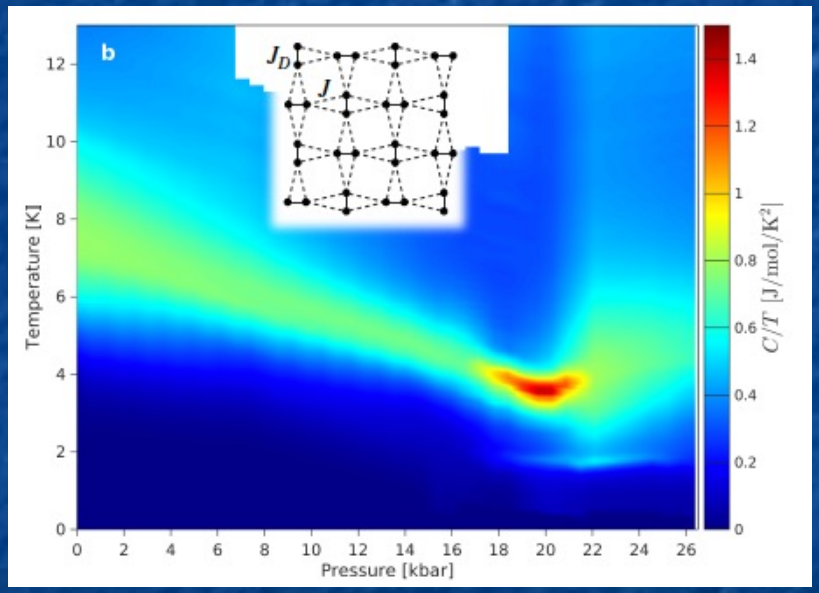
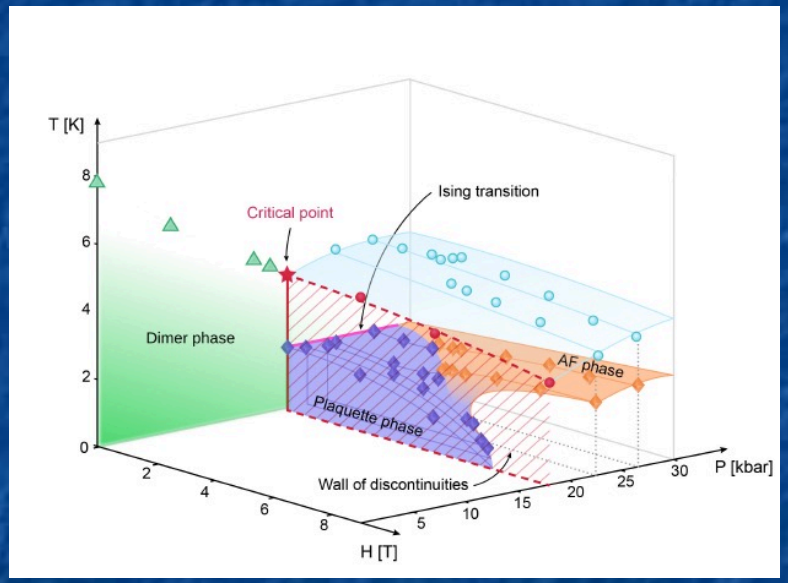
  Larrea et al 2021
- Bound states, impurities, combining magnetic field with pressure, spin supersolid, spin nematic, …

A quantum magnetic analogue to the critical point of water

J. Larrea Jiménez,[1,2] S. P. G. Crone,[3] E. Fogh,[2] M. E. Zayed,[4] R. Lortz,[5] E. Pomjakushina,[6] K. Conder,[6] A. M. Läuchli,[7] L. Weber,[8] S. Wessel,[8] A. Honecker,[9] B. Normand,[10,2] Ch. Rüegg,[10,11,2,12] P. Corboz,[3] H. M. Rønnow,[2] and F. Mila[2]





What else?

- Bound states
- Impurity effects
- Spin supersolid phases
- …

$SrCu_2(BO_3)_2$ is the most interesting quantum magnet ever synthetized!