A quantum magnetic analog to the critical point of water

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Thermal Critical Points and Quantum Critical End Point in the Frustrated Bilayer Heisenberg Antiferromagnet

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A quantum magnetic analogue to the critical point of water

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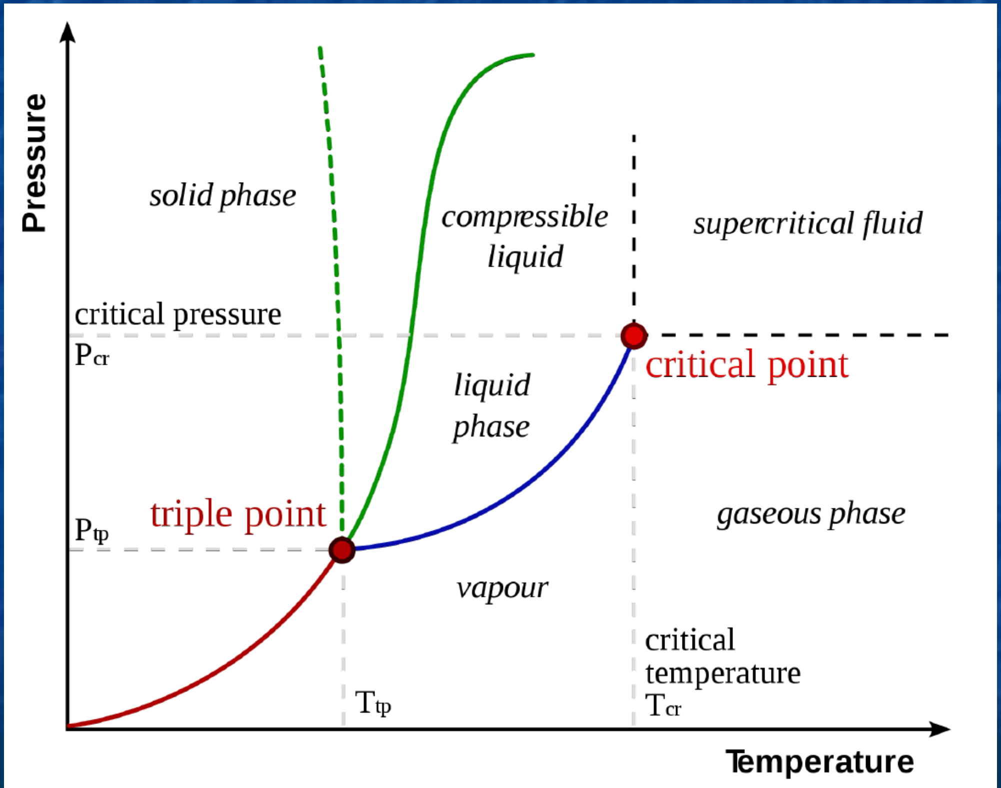
$SrCu_2(BO_3)_2$ under pressure

The critical point of water

1822: Baron Cagniard de la Tour

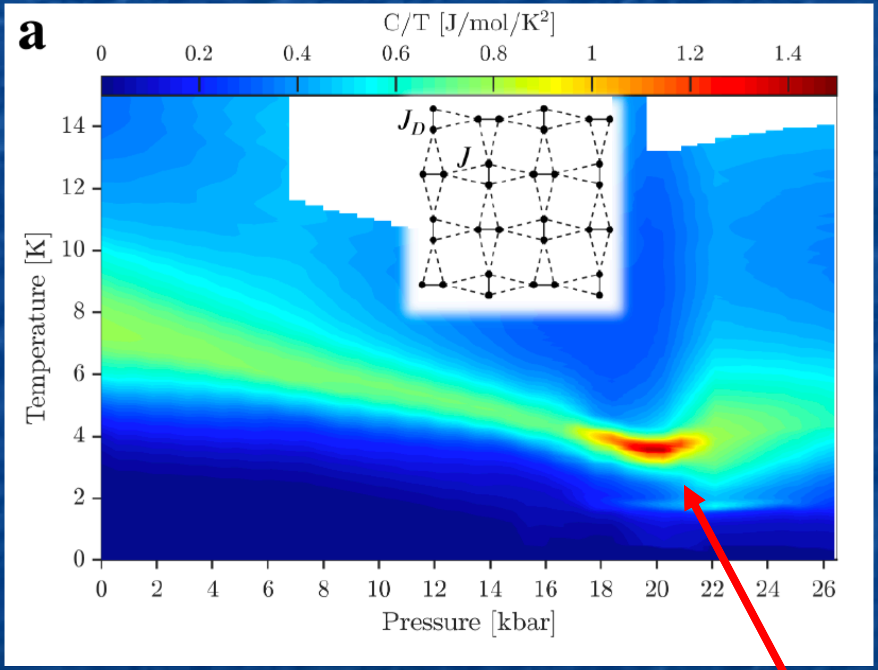


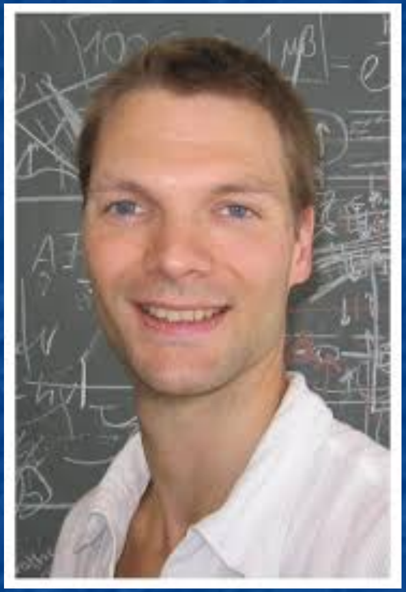
T_c=374° C
P_c=218 bar

Figure from Wikipedia

$SrCu_2(BO_3)_2$

2019: H. Rønnow and collaborators

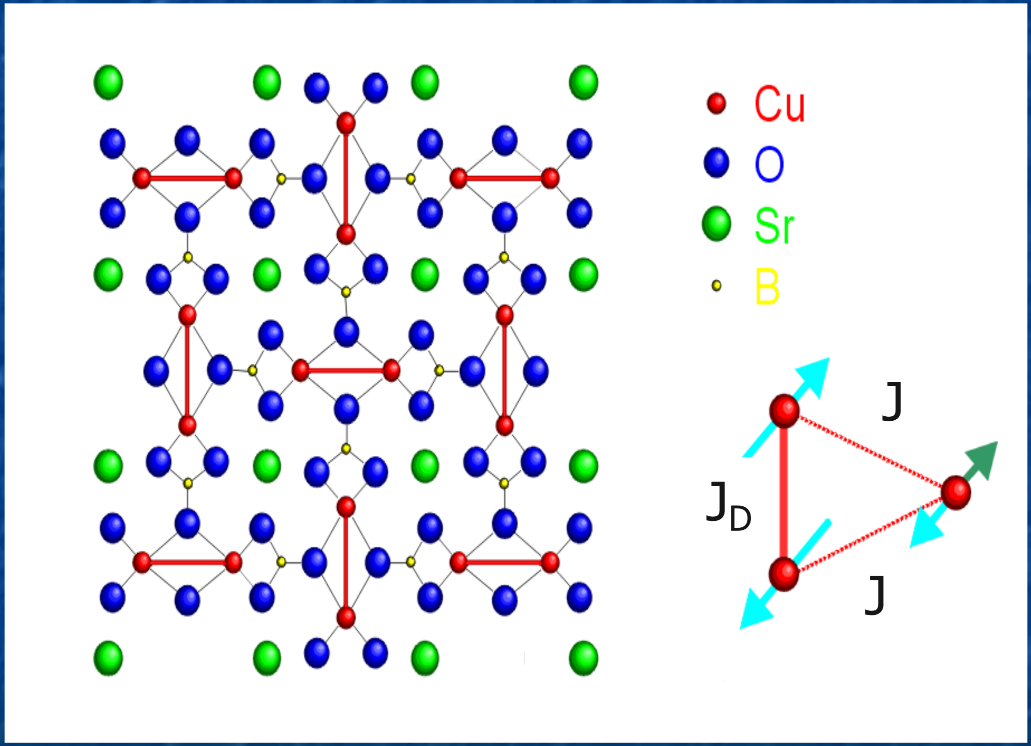




FM: Critical point around P=19 kbar and T=3.3K

$SrCu_2(BO_3)_2$

Smith and Keszler, JSSC 1991



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

$J_D \approx 85$ K

$J/J_D \approx 0.63$

Orthogonal dimer model <=> Shastry-Sutherland

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

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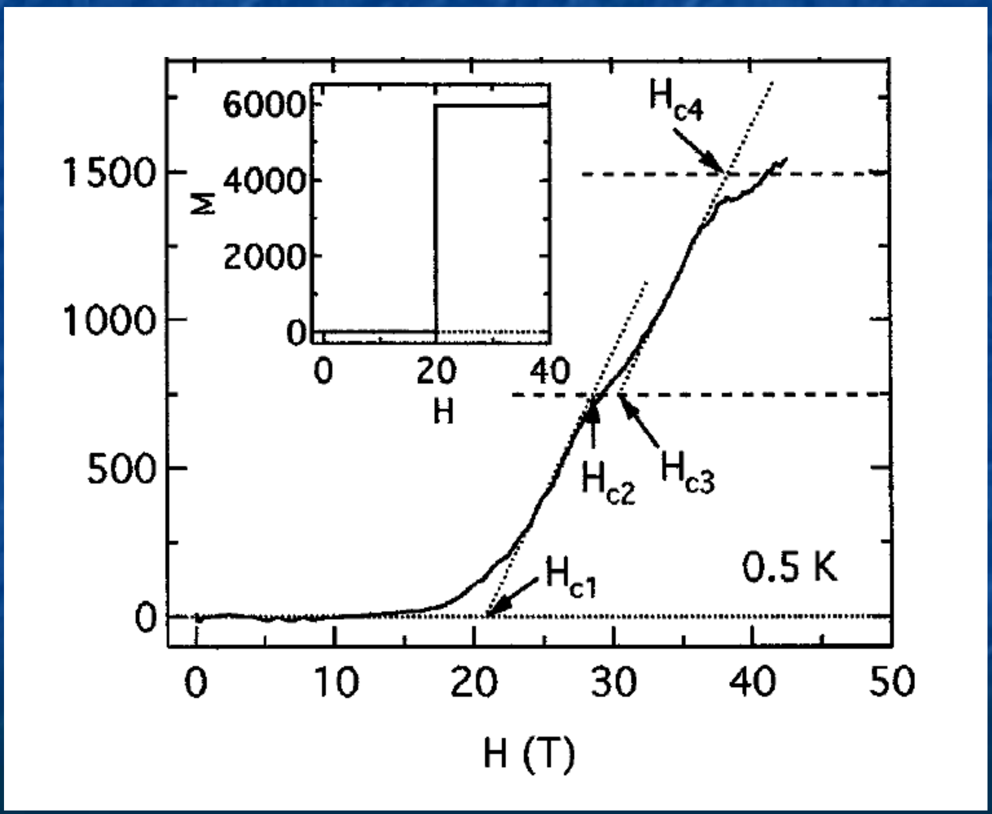

Anomalies

- M=0
- M=1/8
- M=1/4

and many more...

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

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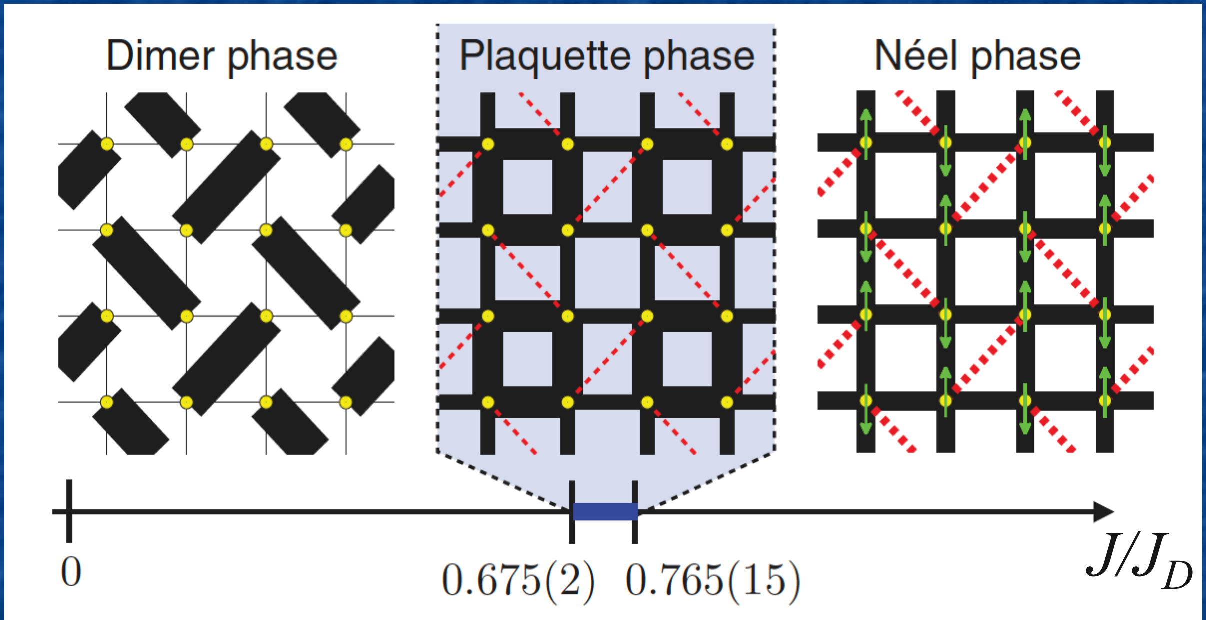

Early results:
Koga & Kawakami, 2000
Läuchli et al, 2002

iPEPS with various setups and
bond dimension up to 10

$SrCu_2(BO_3)_2$ under pressure

- Pressure: expected to change J/J_D and found to increase it
- NMR (Waki et al, 2007): intermediate phase around 24 kbar
- Confirmed later on by magnetization (Haravifard et al, 2016) neutron scattering (Zayed et al, 2017), ESR (Sakurai et al, 2018), and specific heat (Guo et al, 2020)

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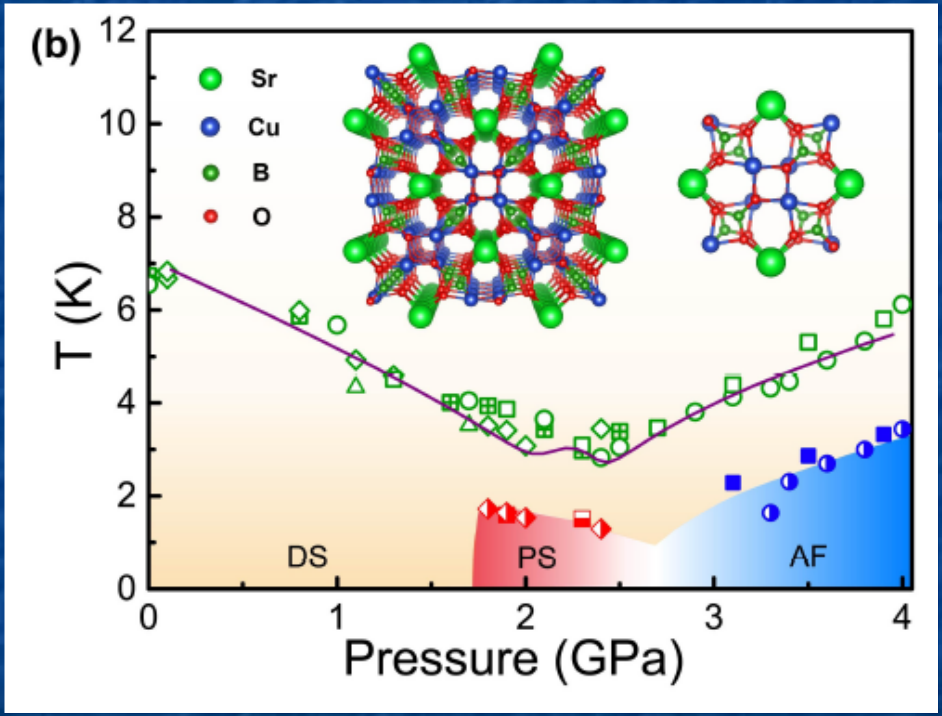
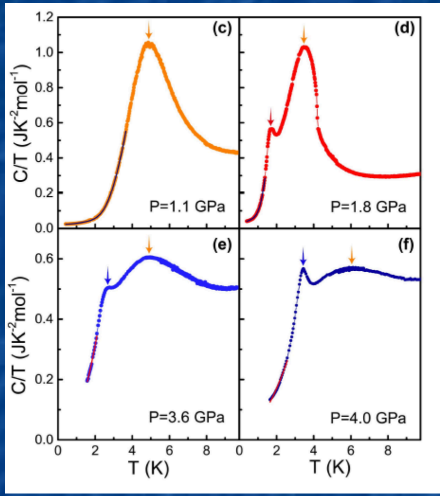
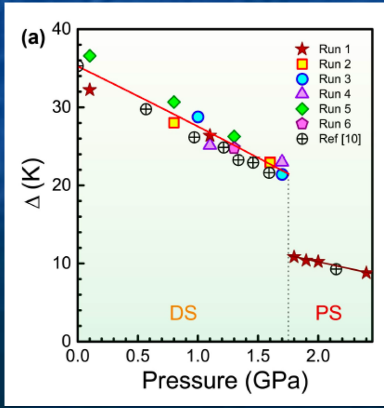
Quantum Phases of $SrCu_2(BO_3)_2$ from High-Pressure Thermodynamics

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,‡]



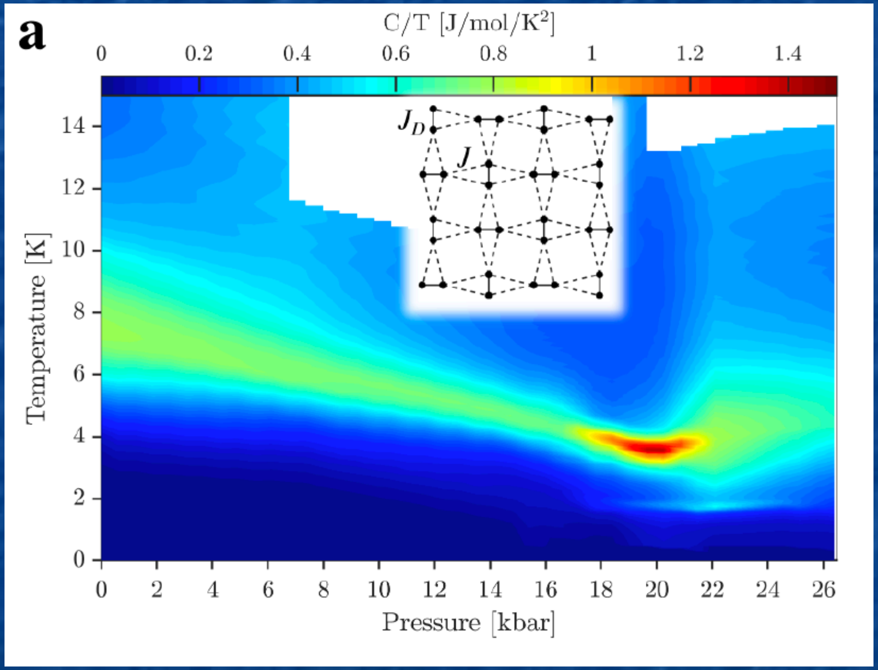


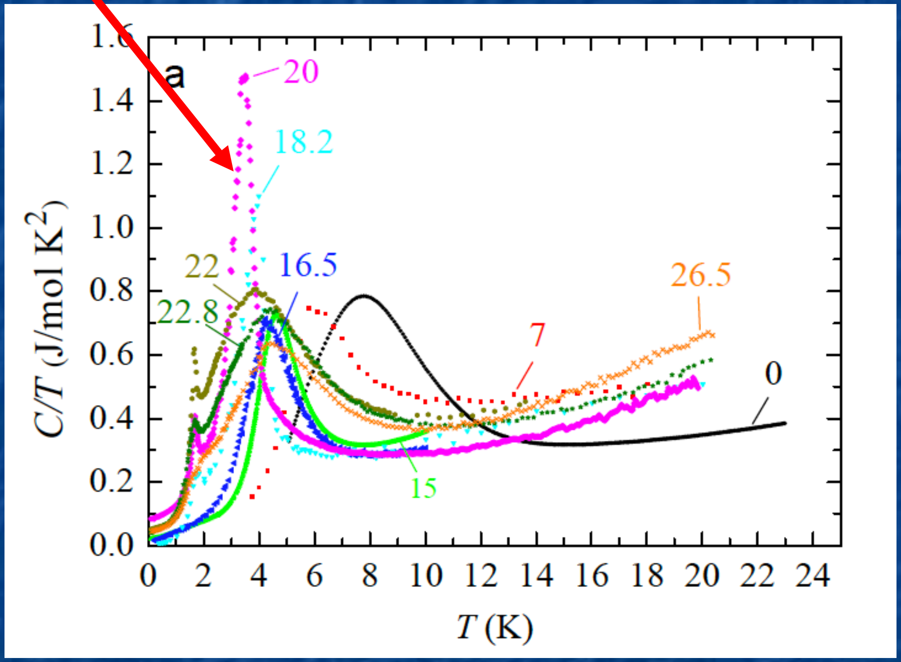


Intermediate phase with critical temperature around 2K

$SrCu_2(BO_3)_2$

Extremely narrow peak between 18 and 20 kbar





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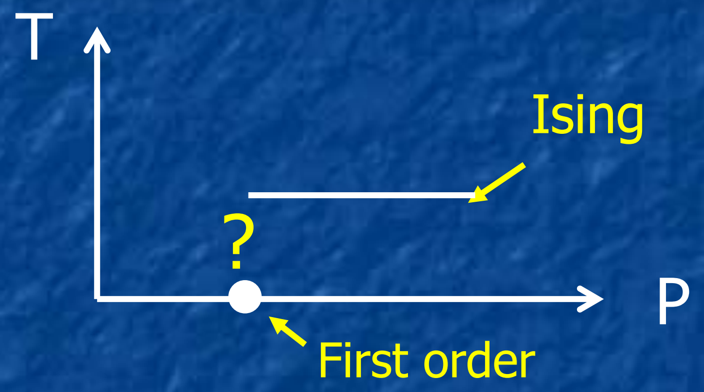
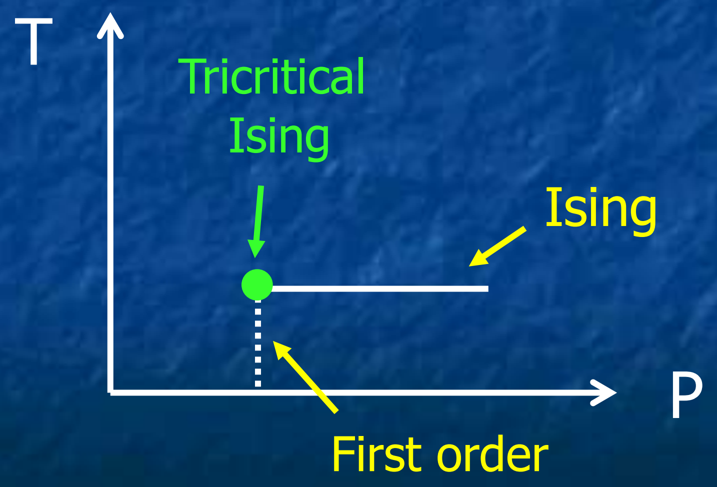
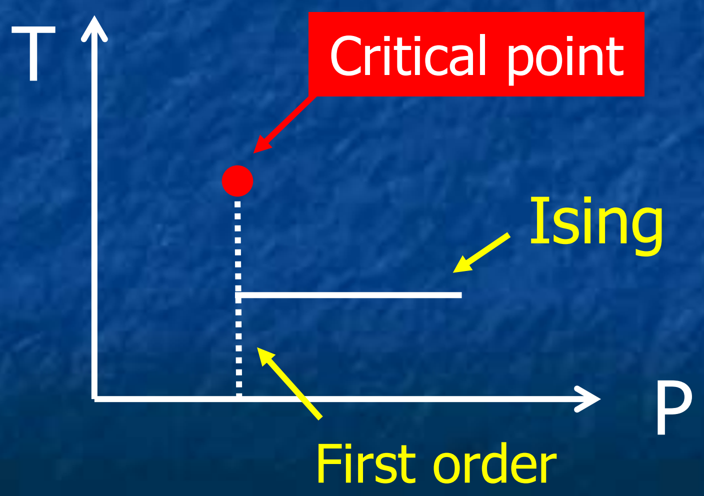
NB: transition into plaquette phase at much lower T, around 2K

First-order vs Ising

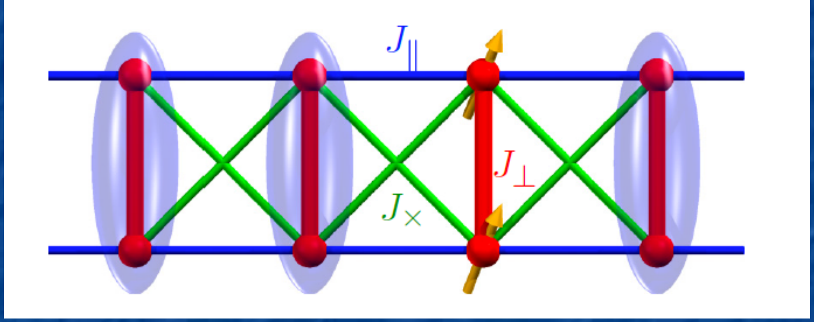






Fully frustrated dimer models

- Example: fully-frustrated ladder



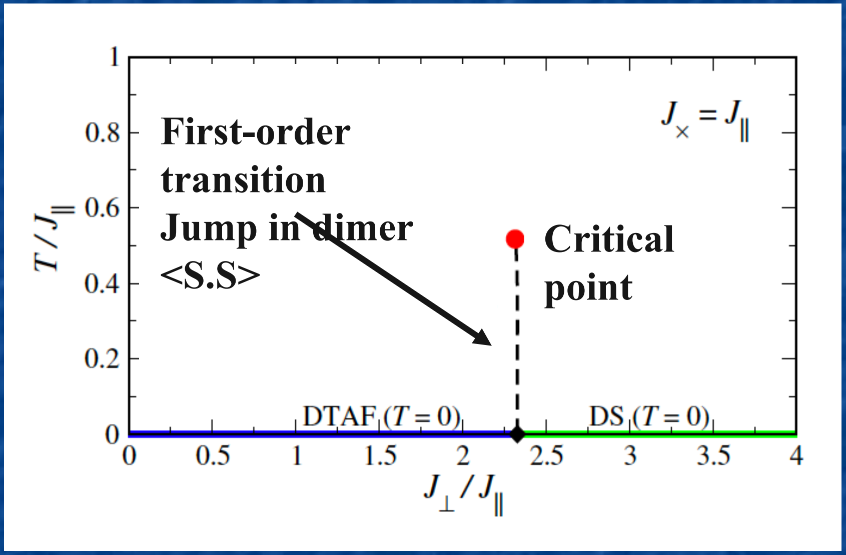
$$J_\times = J_\parallel$$

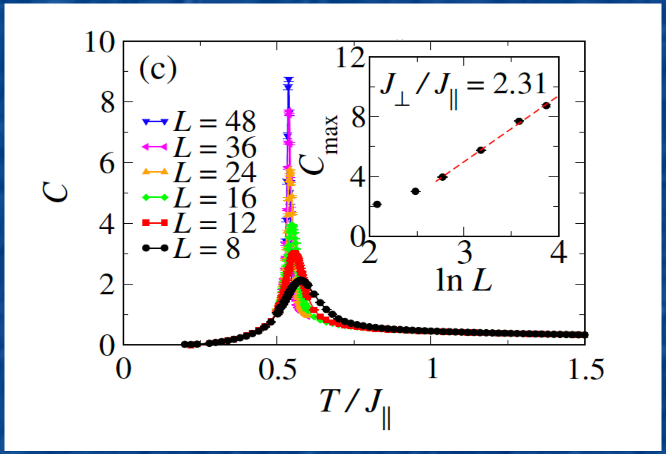
$$H = J_\parallel \sum_{i=1}^{L} \vec{T}_i \cdot \vec{T}_{i+1} + J_\perp \sum_{i=1}^{L} \left(\frac{1}{2} \vec{T}_i^2 - S(S+1) \right)$$

$\vec{T}_i = \vec{S}_i^1 + \vec{S}_i^2$ Total spin on a rung is a good quantum number

Fully Frustrated Bilayer

QMC simulations in dimer basis (Stapmans,…,Wessel, PRL 2018)





Ising 2D: $\alpha = 0$, C α ln L

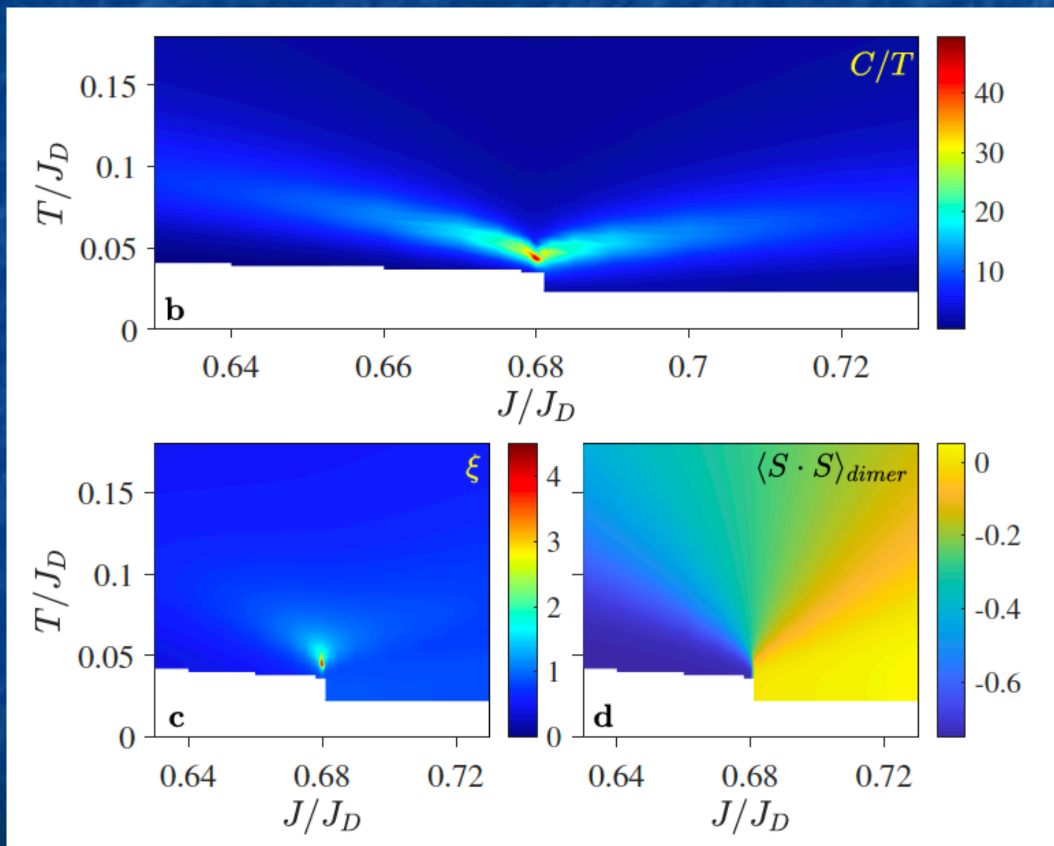
Square lattice of dimers with fully frustrated couplings

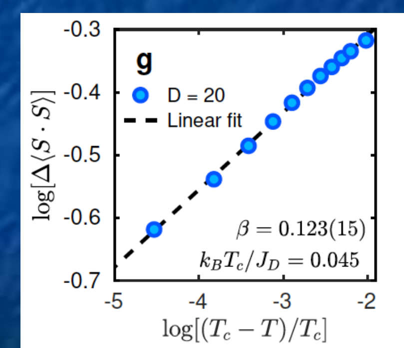
→ Large intra-dimer coupling: dimer singlets

→ Larger inter-dimer coupling: dimer triplets and S=1 square lattice AF

iPEPS for Shastry-Sutherland

Ising critical point





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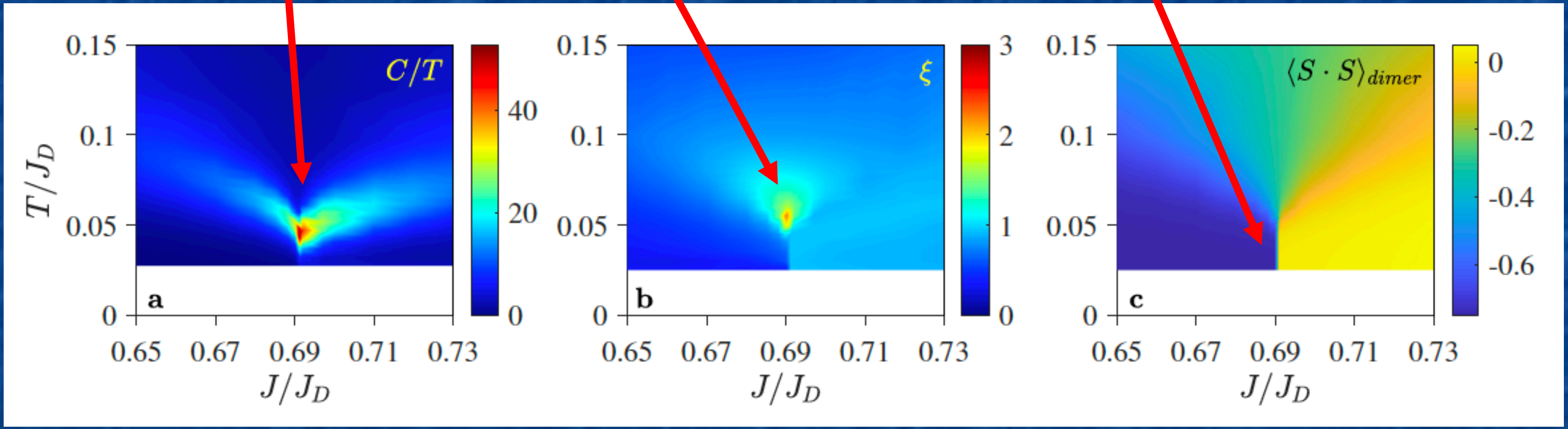
Shastry-Sutherland with intra-dimer DM interaction

Ising critical point

Jump in dimer <S.S>



More realistic model for $SrCu_2(BO_3)_2$

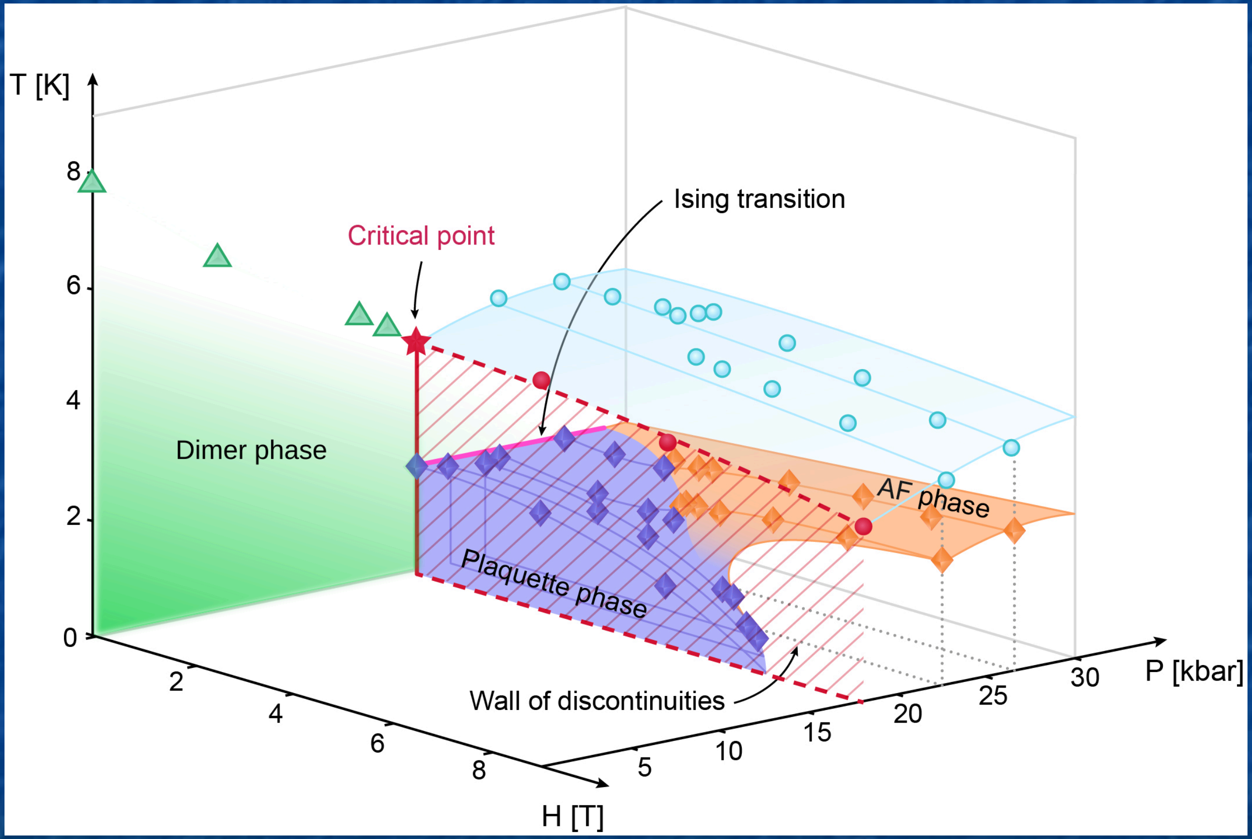
Effect of magnetic field

- First-order transition between two gapped phases

  → should be insensitive to magnetic field
- Transition between plaquette and Néel phases

  → Néel phase should be favored by magnetic field

(P,T,H) phase diagram



J. Larrea … P. Corboz … H. Ronnow, FM, unpublished

Conclusion

- $SrCu_2(BO_3)_2$ is one of the most interesting quantum antiferromagnets ever synthetized

  → Spin gap

  → Unique series of plateaus at 1/8, 2/15, 1/6, 1/4, 1/3, 1/2 (and maybe 2/5)

  → Topological magnetic excitations in a small field

  → Probably spin nematic and spin supersolid phases

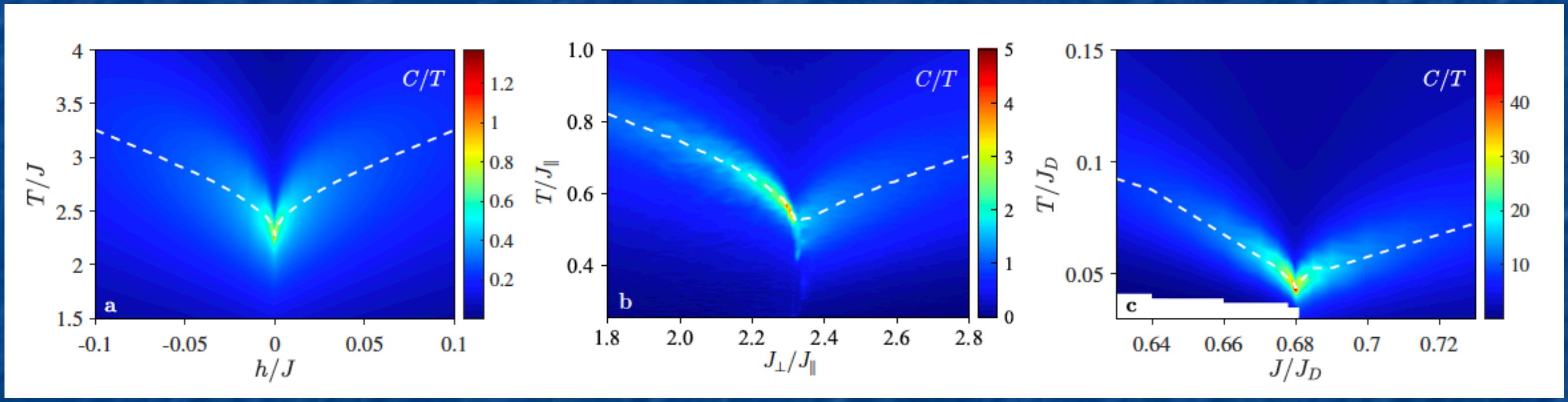
  → A critical point analogous to that of water

- Main challenge: most of the action takes place above 27 Tesla or above 20 kbar at very low temperature

Perspectives

- Check the presence of first-transition line below T=3.3K
- Probe the supercritical regime above T_c present in that and related models

Ising in a field FFB Shastry-Sutherland



First order quantum transitions not so boring after all !