Title: Deconfined multi-criticality in quantum spin models and experiments

Speakers: Anders Sandvik

Collection: Quantum Criticality: Gauge Fields and Matter

Date: May 17, 2022 - 3:15 PM

URL: https://pirsa.org/22050035

Abstract: In the original field theoretical scenario of deconfined quantum criticality, the deconfined quantum-critical point (DQCP) separating antiferromagnetic (AFM) and singlet-solid phases of quantum magnets is generic, i.e., does not require fine-tuning. Recent numerical studies instead point to a fine-tuned multi-critical DQCP [1] that is also the end-point of a gapless spin liquid phase [2]. An example is the Shastry-Sutherland (SS) model, where a narrow spin liquid phase was recently detected [2,3], instead of the previously argued direct transition between plaquette singlet solid (PSS) and AFM phases. The multi-critical DQCP, followed by a direct transition without intervening spin liquid, can be reached when other interactions are included. Very recent NMR experiments on the SS compound SrCu2(BO3)2 under high pressures and high magnetic fields are consistent with this scenario [4]. Low-temperature (below 0.1 K) direct PSS to XY-AFM transitions were observed that become less strongly first-order at higher pressures. At the highest pressure, quantum-critical scaling of the spin-lattice relaxation was observed, indicating close proximity to a DQCP. This point may be the end-point of a not yet confirmed quantum spin liquid phase existing at slightly higher pressures.

[1] B. Zhao, J. Takahashi, and A. W. Sandvik, PRL 125, 257204 (2020).
[2] J. Yang, A. W. Sandvik, and L. Wang, PRB 105, L060409 (2022).
[3] L. Wang, Y. Zhang, and A. W. Sandvik, arXiv:2205.02476
[4] Y. Cui et al., arXiv:2204.08133.

Quantum Criticality: Gauge Fields and Matter, Perimeter Institute, May 16-20, 2022

Deconfined multi-criticality in models and experiments

Anders W Sandvik, Boston University

Topic

Ground state phases of the Shastry-Sutherland model
and related 2D S=1/2 models

+ new generic insights into deconfined quantum criticality

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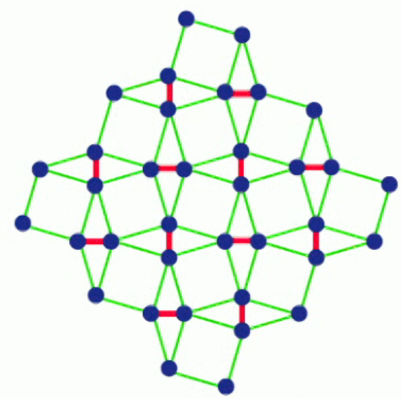

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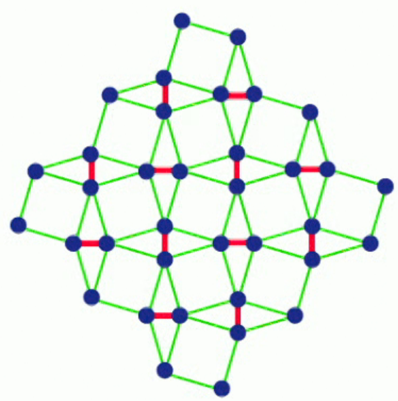

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Experiments: Weiqiang Yu, Yi Cui, (Renmin Univerity, Beijing) + many …

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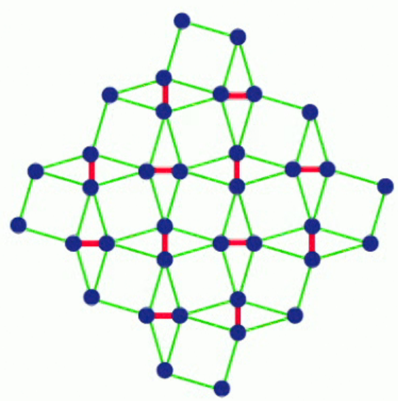

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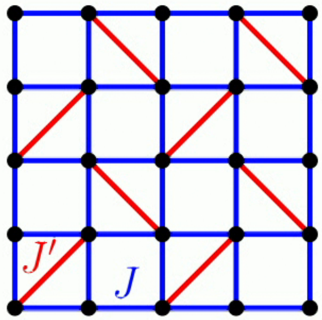
Shastry-Sutherland model

Shastry & Sutherland, 1982



$$H = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j + J' \sum_{\langle ij \rangle'} \mathbf{S}_i \cdot \mathbf{S}_j \qquad J, J' > 0 \qquad g = J/J'$$

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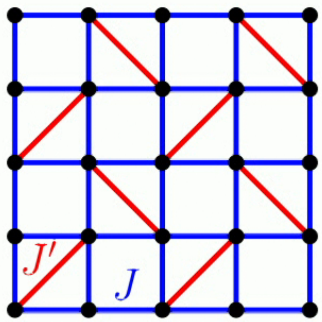

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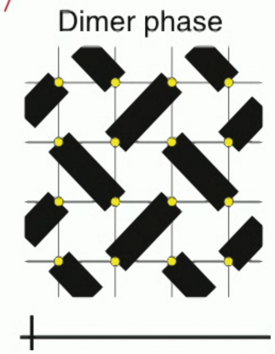
Exact dimer ground state for $g < g_{c1}$



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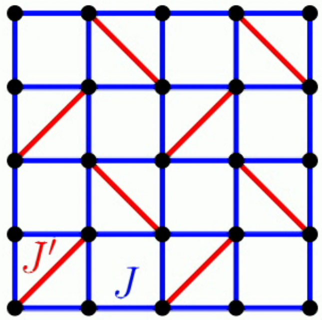

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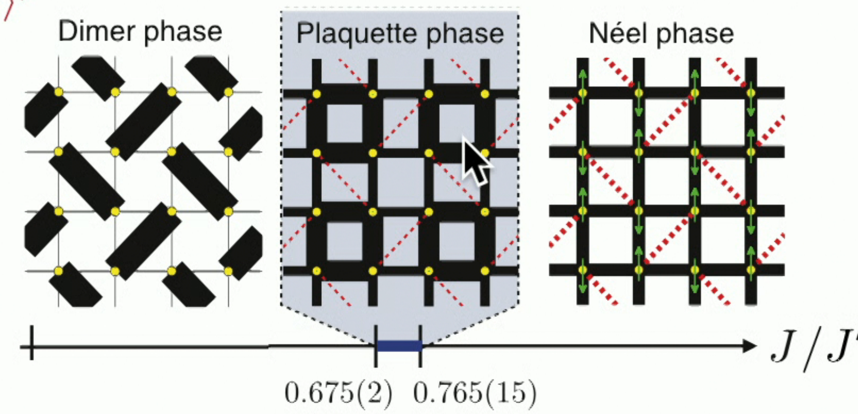

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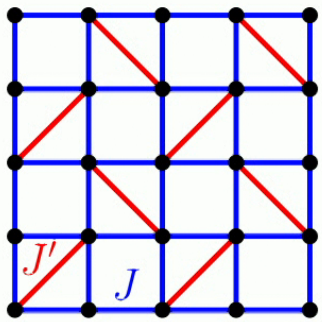

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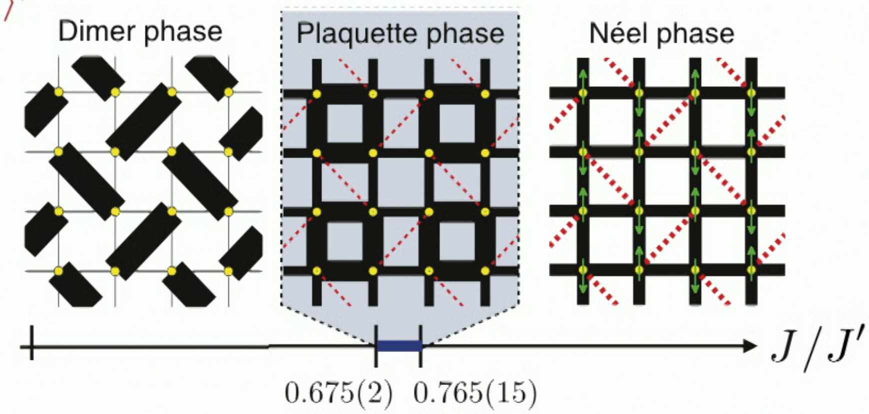

PEPS (tensor product): Corbotz & Mila PRB 2013

First-order plaquette - Neel transition

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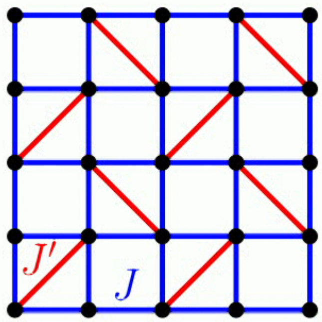

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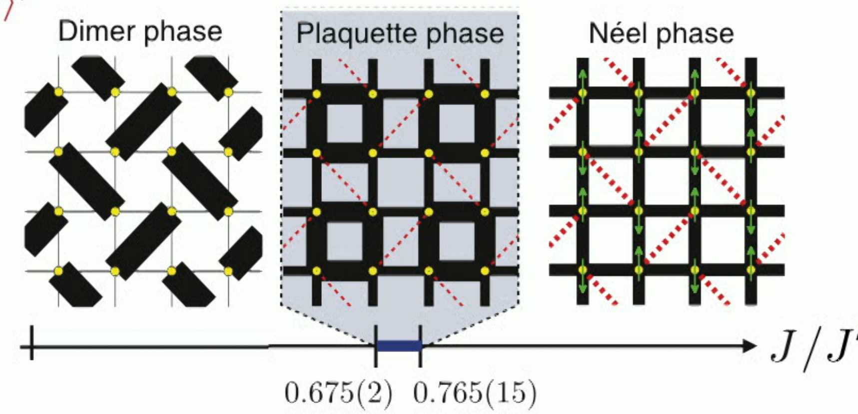

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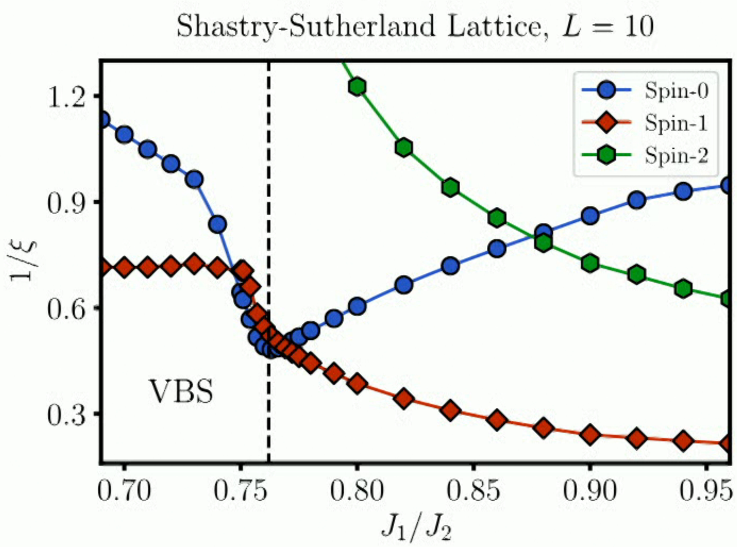

Lee, You, Schdev, Vishwanath, PRX 2019

	$L=6$	$L=8$	$L=10$	$L=12$
$(J_1/J_2)_{c1}$	0.682	0.677	0.675	0.675
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DMRG long cylinders

Argued continuous deconfined quantum-critical plaquette - Neel transition; emergent O(4) symmetry

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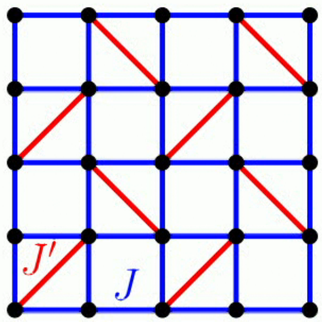

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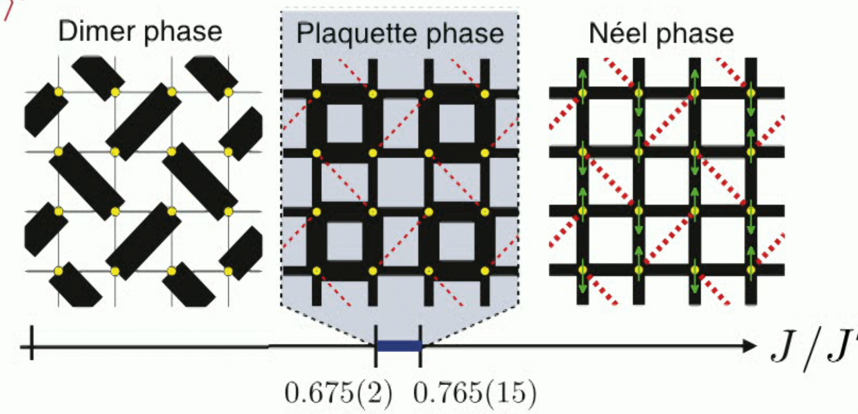

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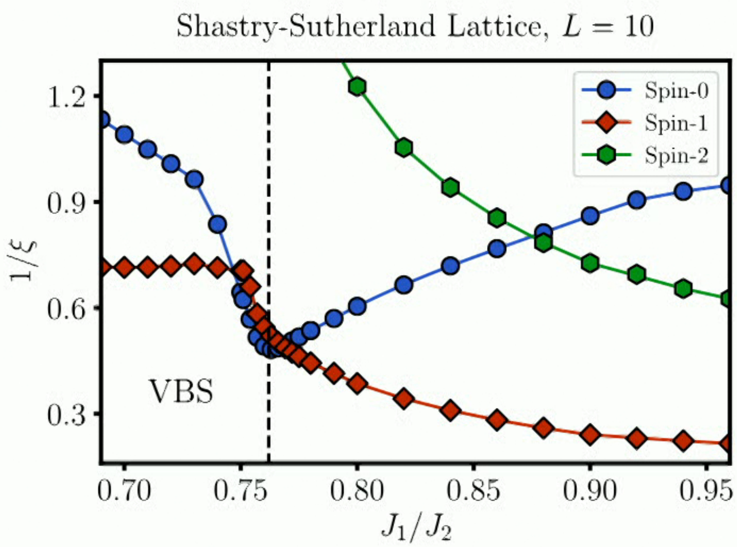

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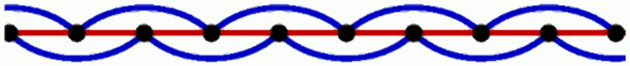
Here: Level crossing method to detect transitions

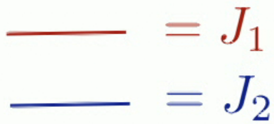
Yang, Wang, Sandvik, PRB 2022 (DMRG)

Wang, Zhang, Sandvik, arXiv:2205.02476 (exact diag.)

Level-crossing method

- Example: J_1-J_2 Heisenberg chain





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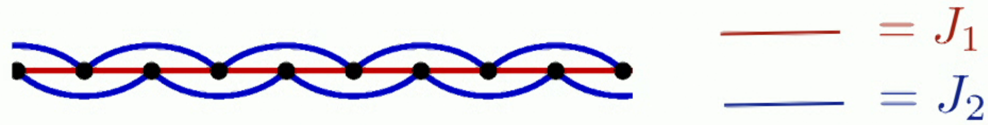

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dimerization transition at $g_c = 0.2411\ldots$

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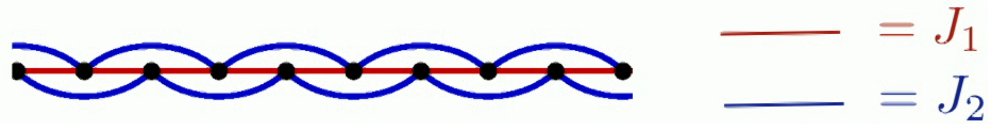

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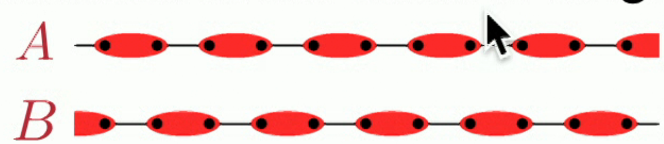

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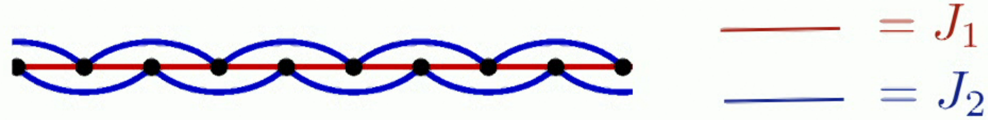

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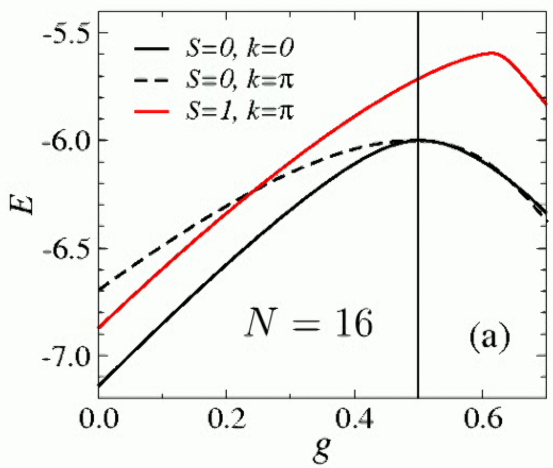

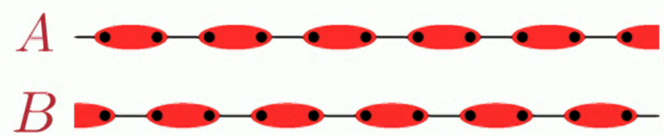

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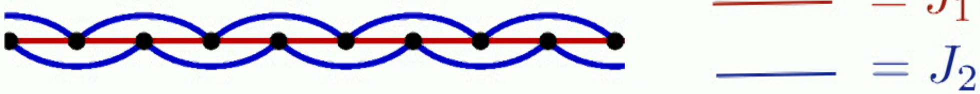

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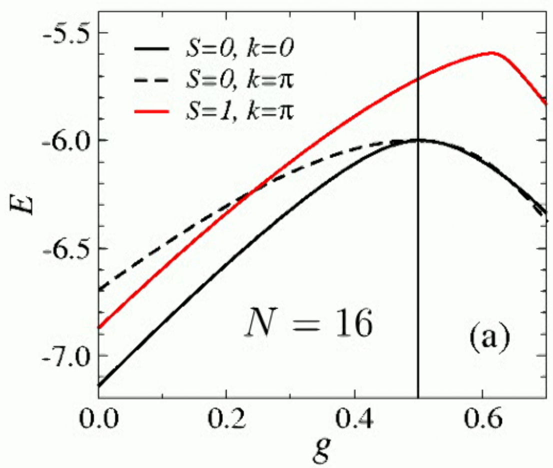

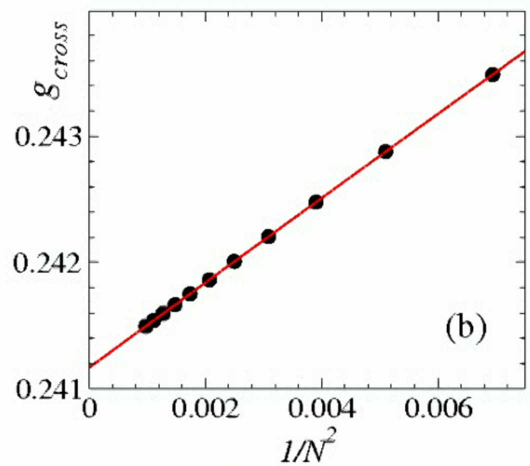

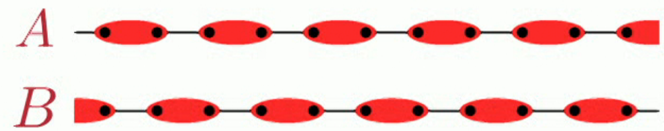

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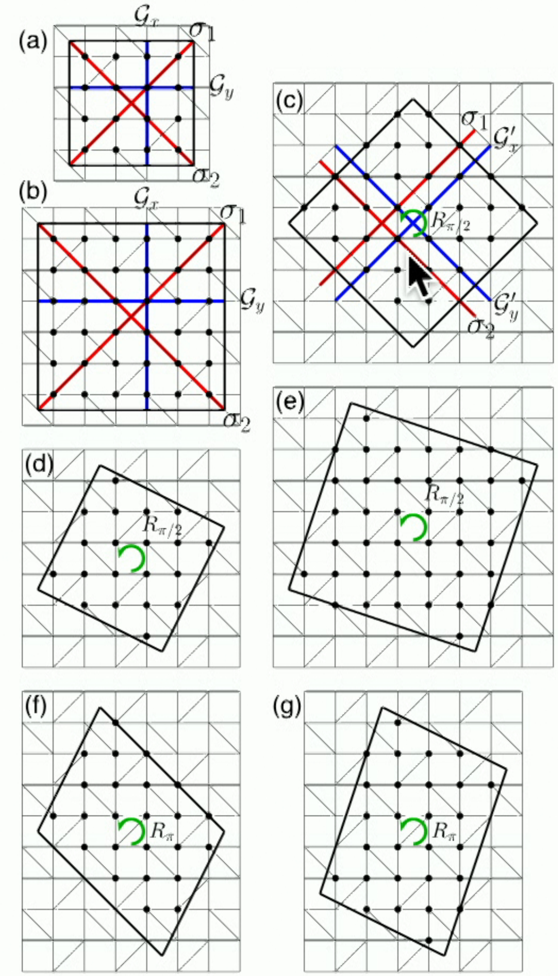
Nomura & Okamoto (Phys .Let. 1992)
Eggert (PRB 1996)
Sandvik (AIP Conf. Proc. 2010)

g_c=0.2411674(2)

Level crossings in the SS model. 1) Small clusters, exact diag

Wang, Zhang, Sandvik, arXiv:2205.02476



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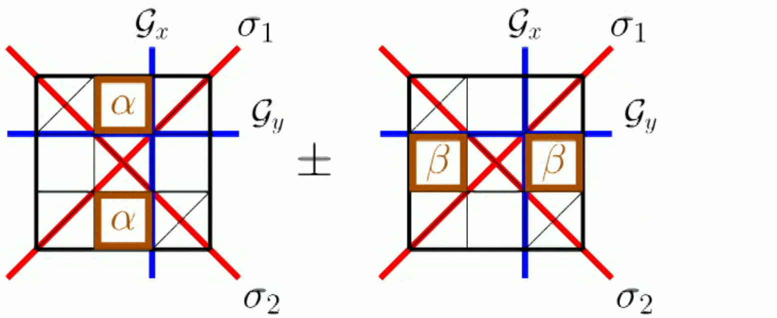

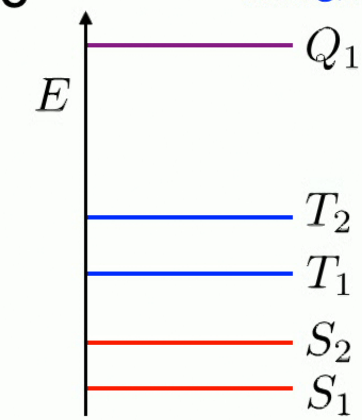

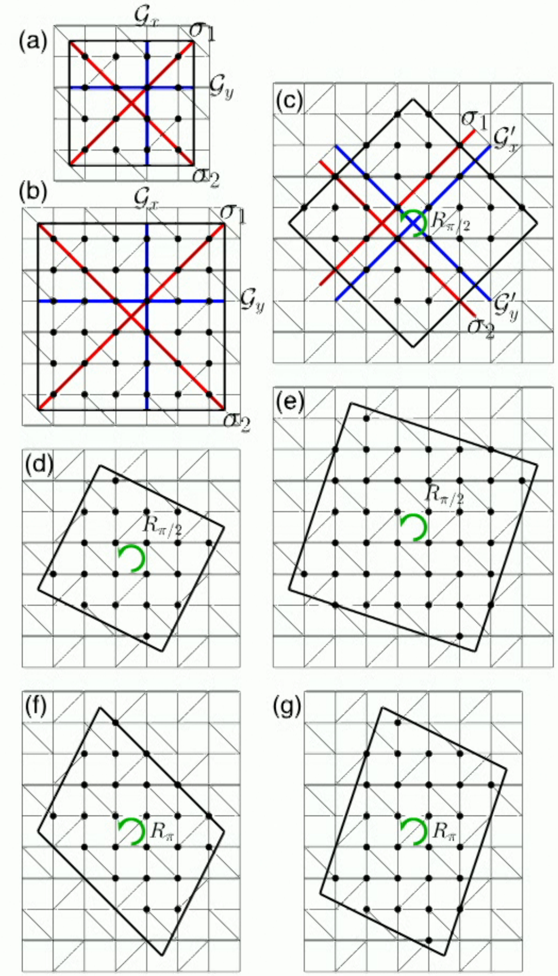

Singlets S_1, S_2. Triplets T_1, T_2. Quintuplet Q_1.

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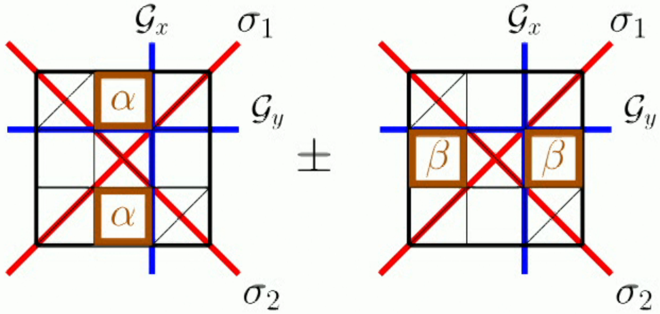

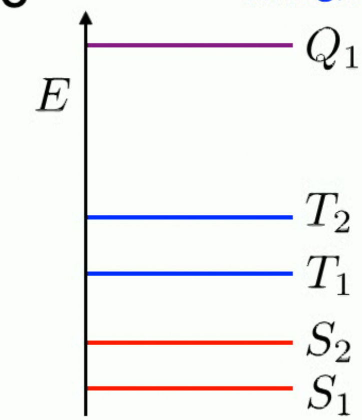

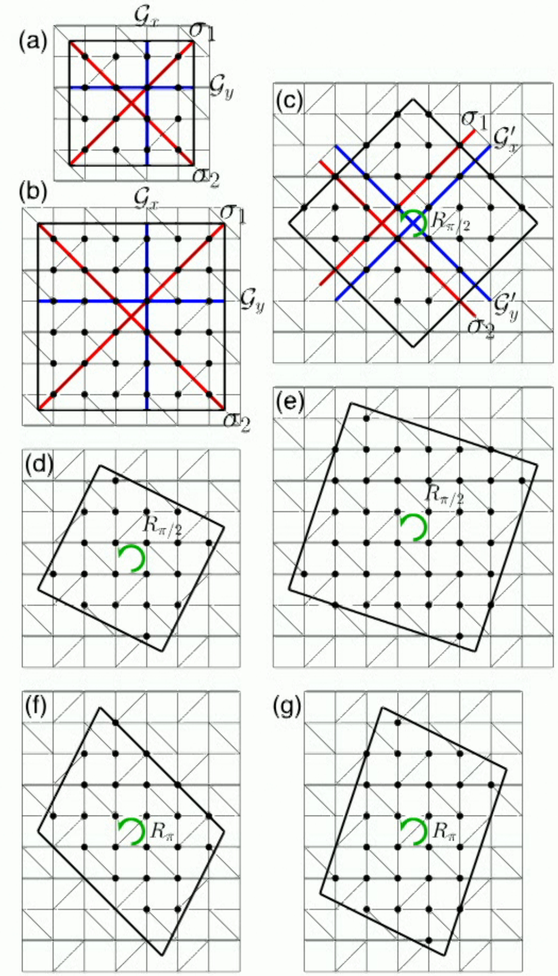

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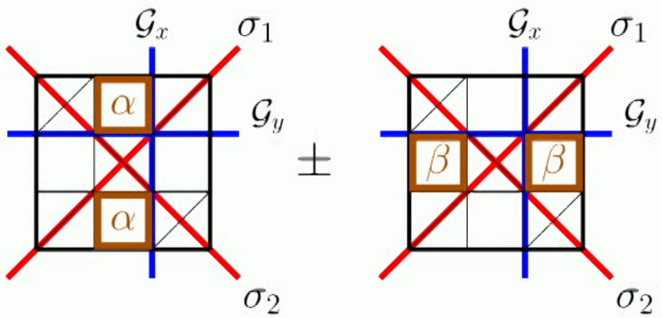

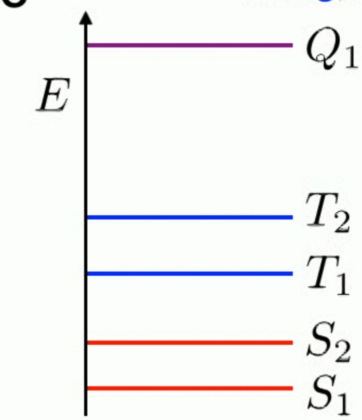

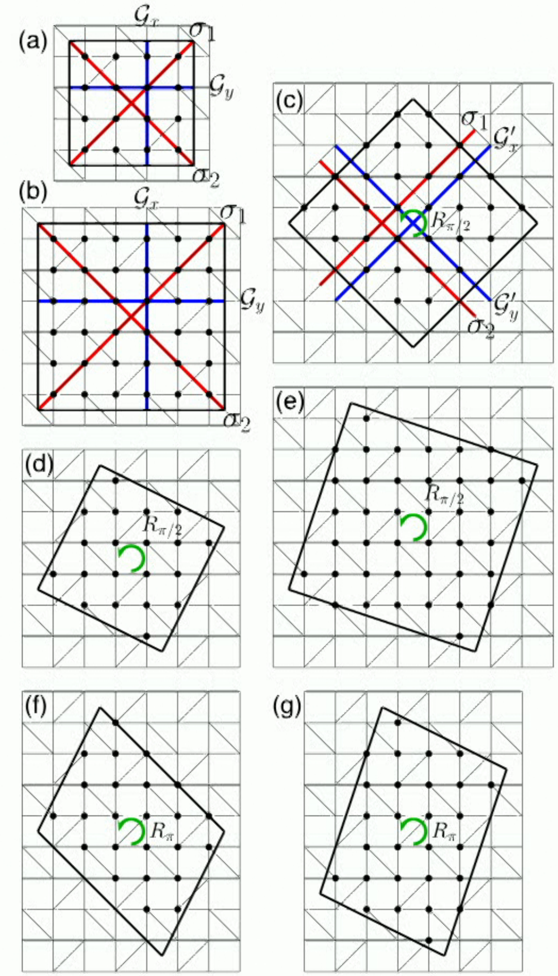

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<u>Gap criteria for PSS and AFM ordered phases</u>

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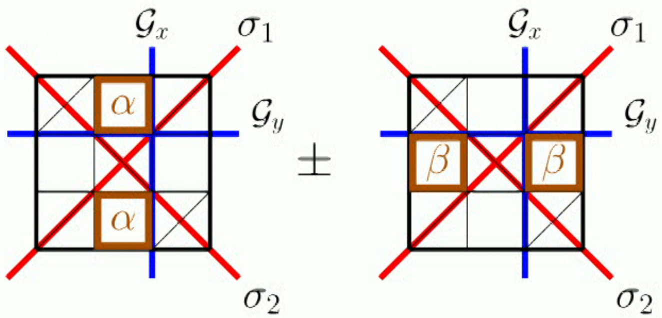

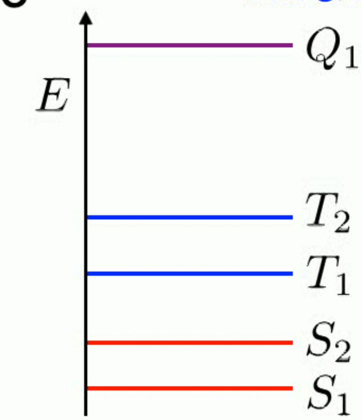

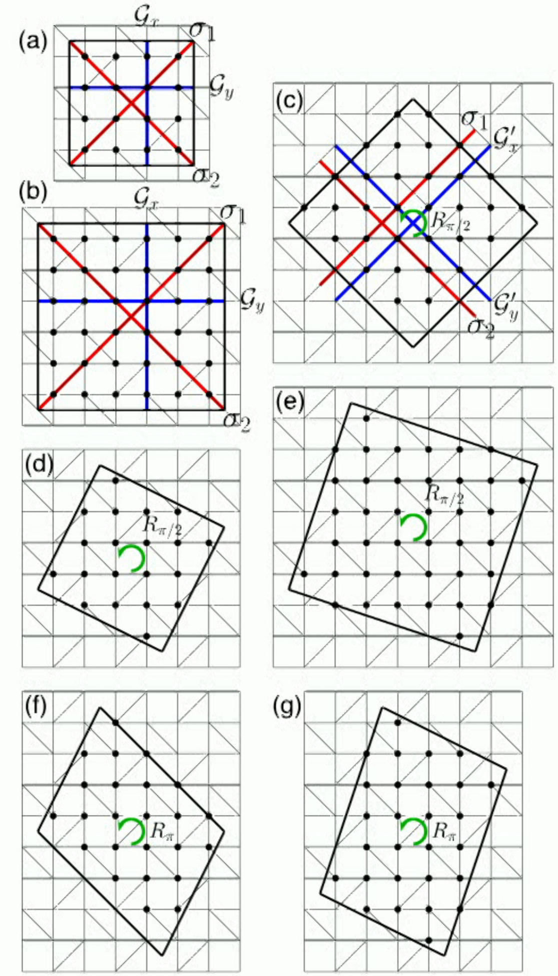

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Gap criteria for PSS and AFM ordered phases

PSS: $\Delta(S_2) < \Delta(T_1)$

AFM: $\Delta(Q_1) < \Delta(S_2), \quad \delta_T < \Delta(S_2)$

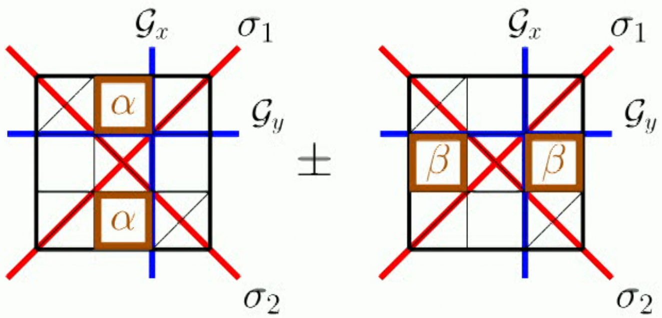
Anderson tower

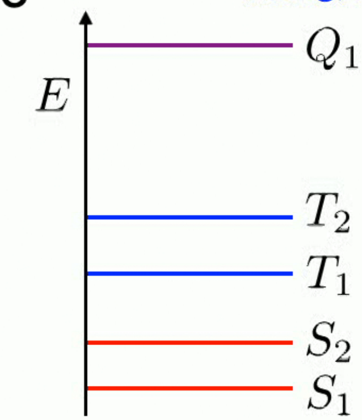
$E_S \propto S(S+1)/N$

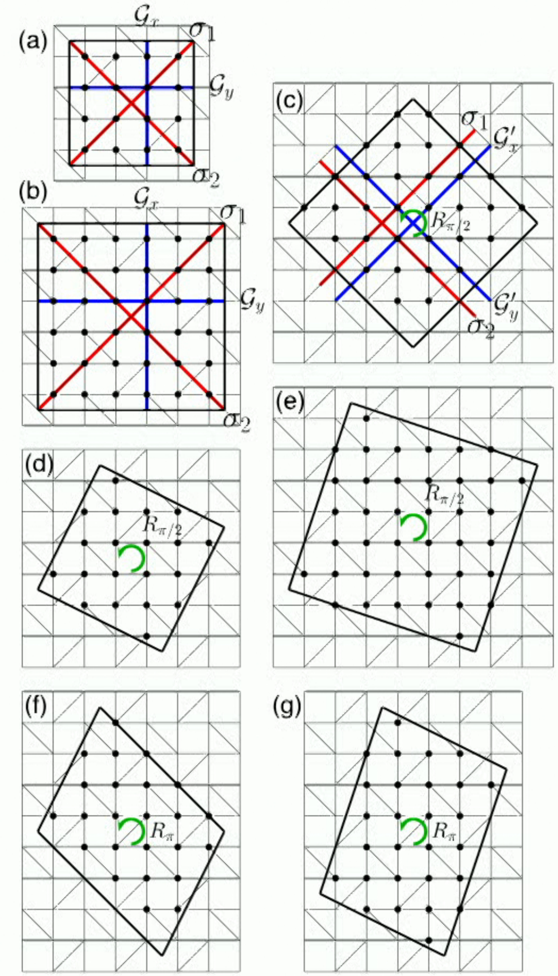
Level crossings in the SS model. 1) Small clusters, exact diag

Wang, Zhang, Sandvik, arXiv:2205.02476

quasi-degenerate singlet ground state
of the plaquette-singlet-solid (PSS)







Singlets S_1, S_2. Triplets T_1, T_2. Quintuplet Q_1.

Gaps: $\Delta(S_2) = E(S_2) - E(S_1) \quad \Delta(T_1) = E(T_1) - E(S_1)$

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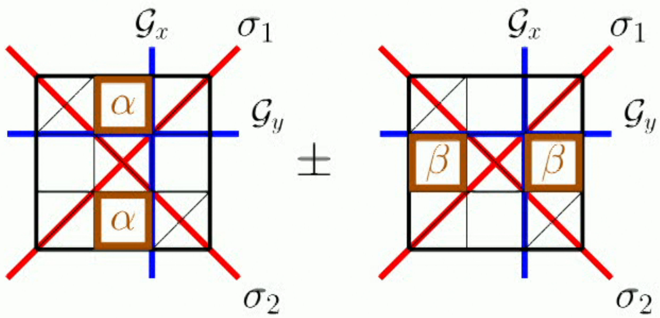

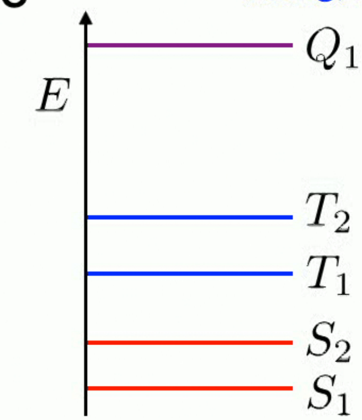

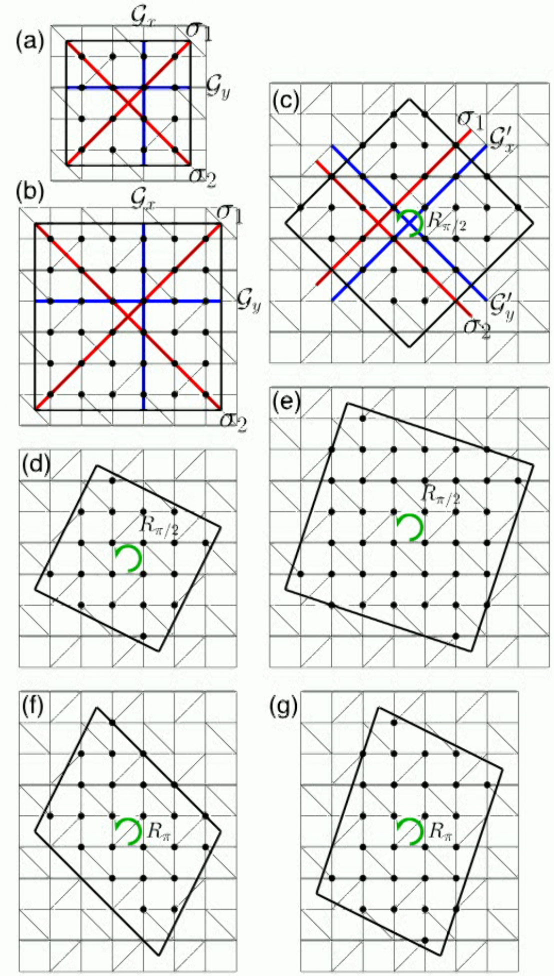

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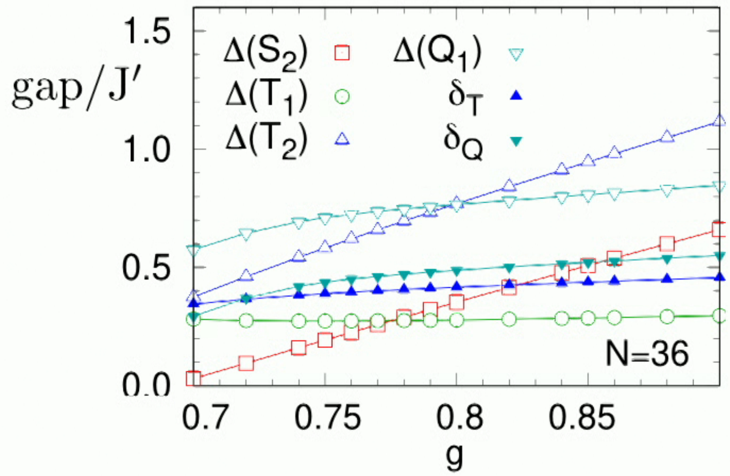
Gap crossings vs g to detect quantum phase transitions

Example, N=36: gaps versus g=J/J'

Size dependence of crossing points

$\Delta(T_1)$ crossing $\Delta(S_2)$ → g_{c1} (end of PSS phase)



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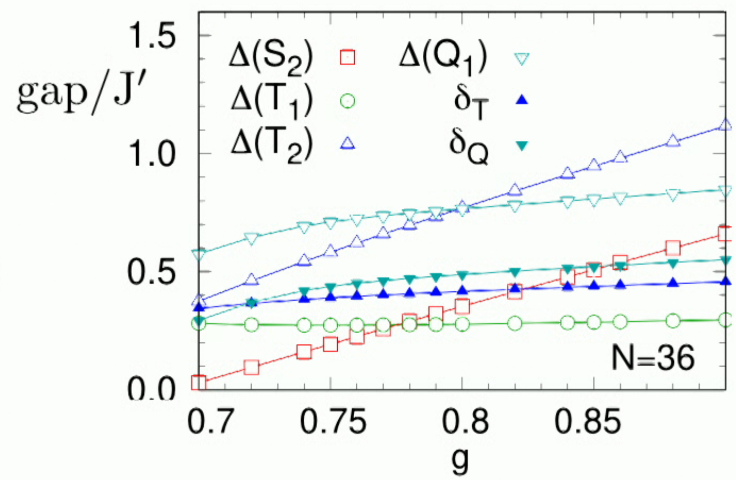

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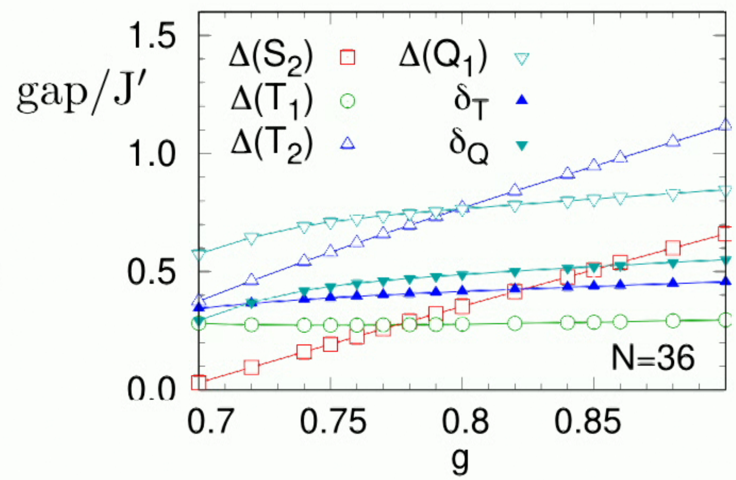

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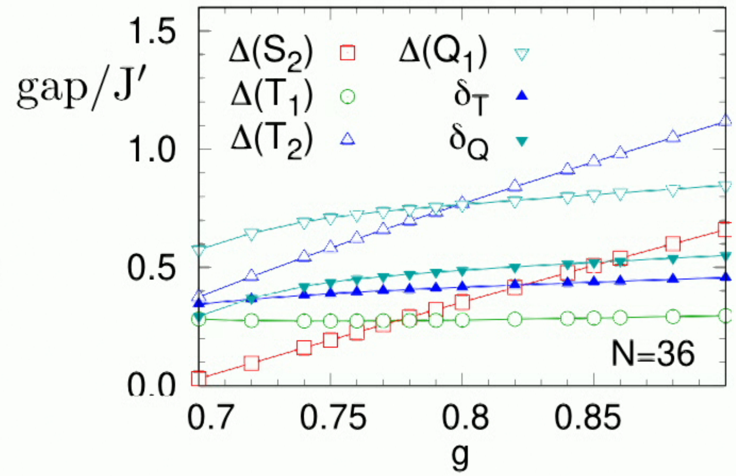

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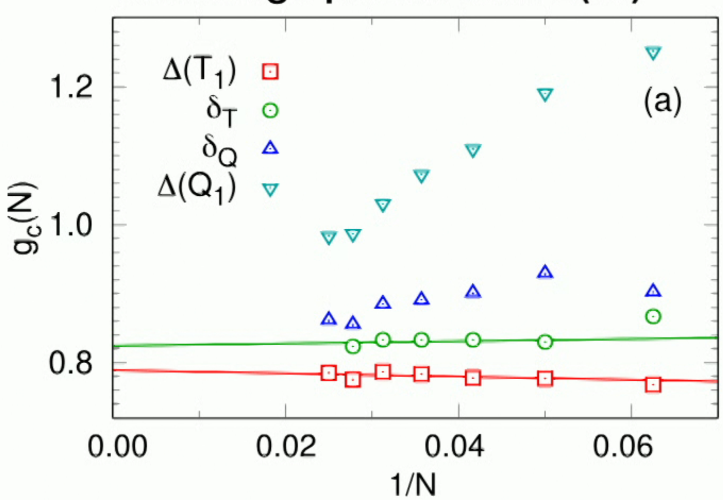

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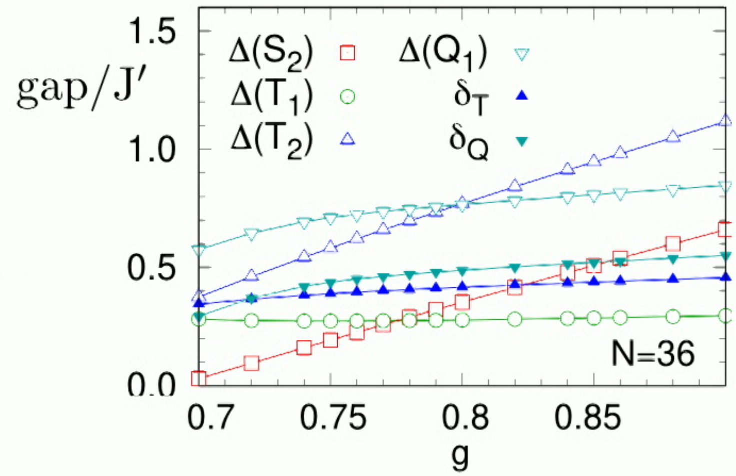

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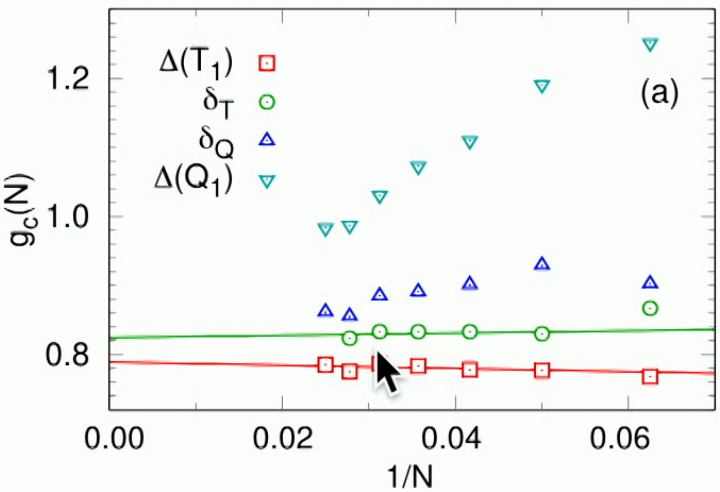

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shift all points equally for given N

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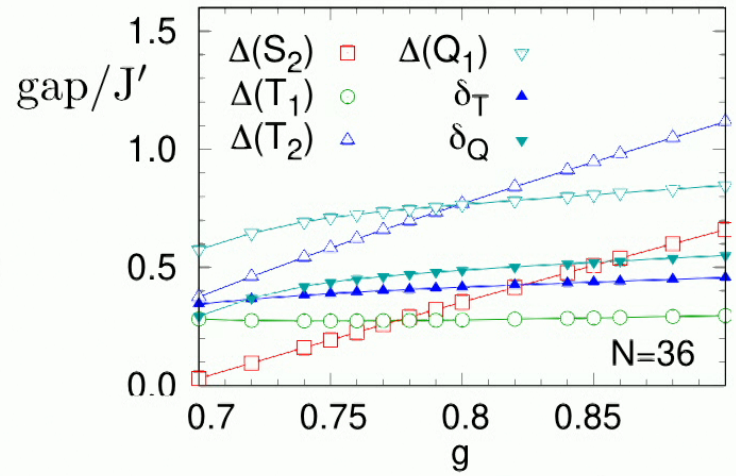

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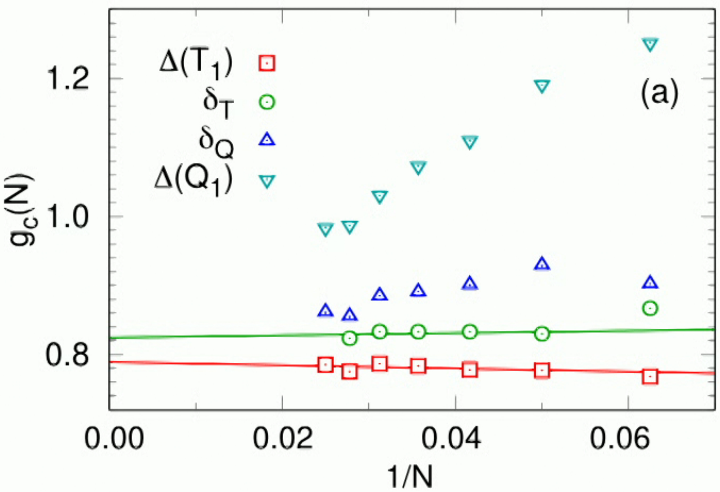

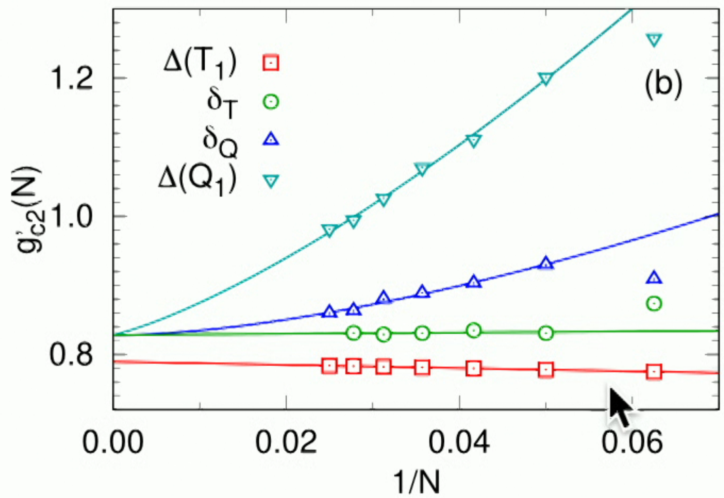

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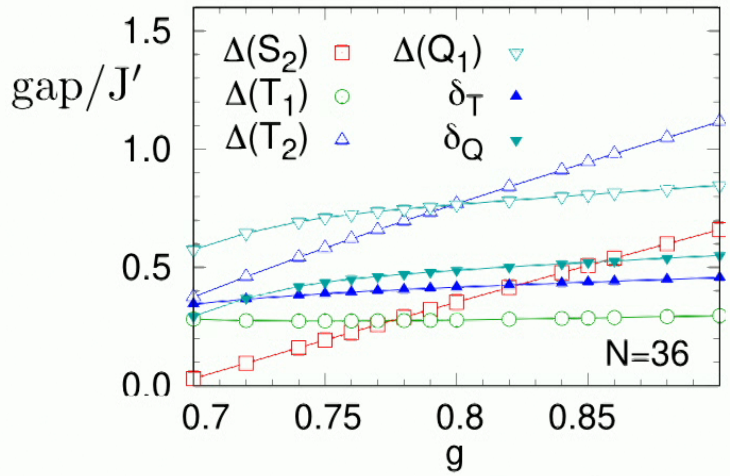

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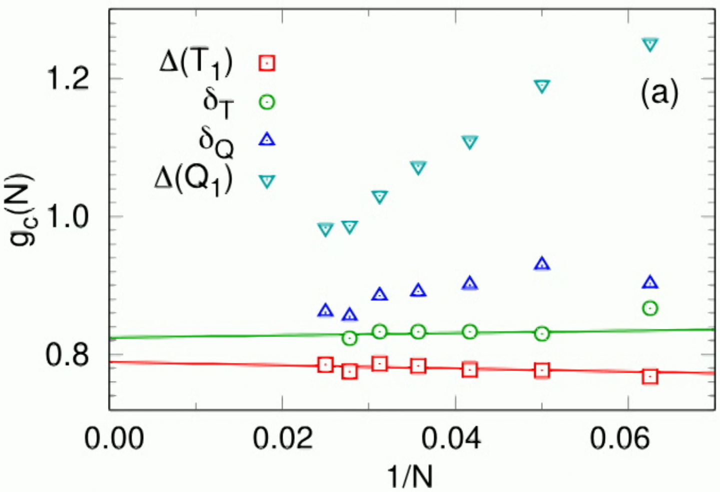

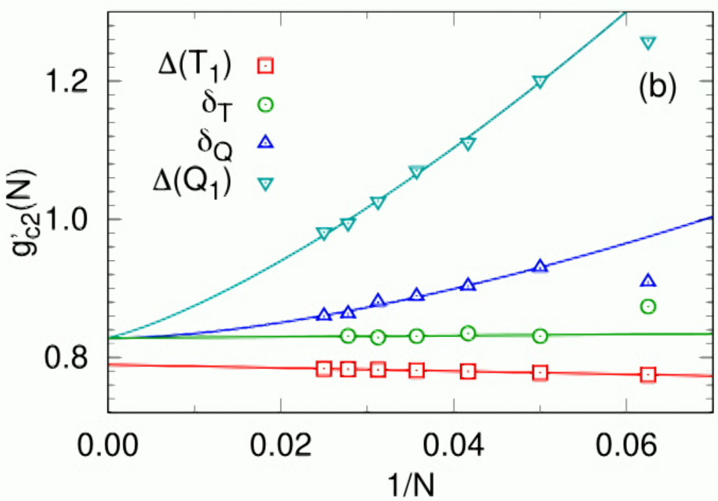

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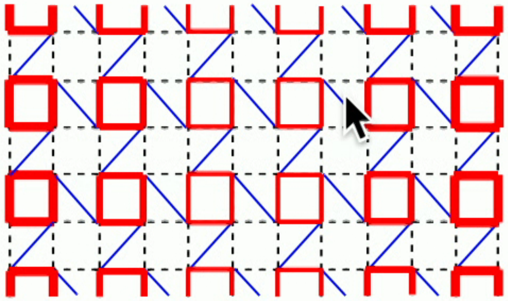
$g_{c1} < g_{c2}$: Other phase between PSS and AFM for $g \in [0.79, 0.82]$

Level crossings in the SS model. 2) DMRG, cylinders

Yang, Wang, Sandvik, PRB 2022

2L × L spins, open x boundaries, periodic y boundaries



PSS state is unique

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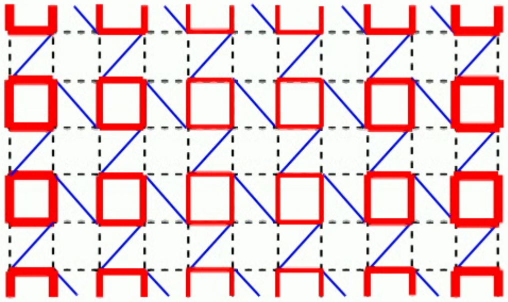

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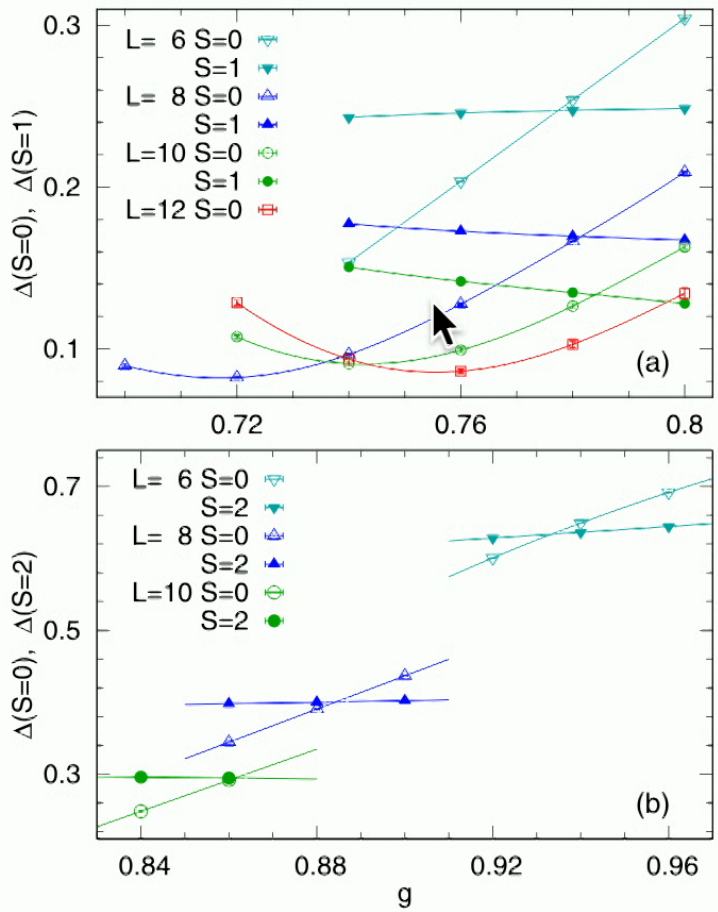

Second singlet is not degenerate ground state
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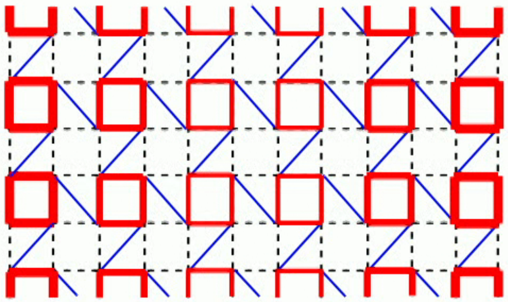

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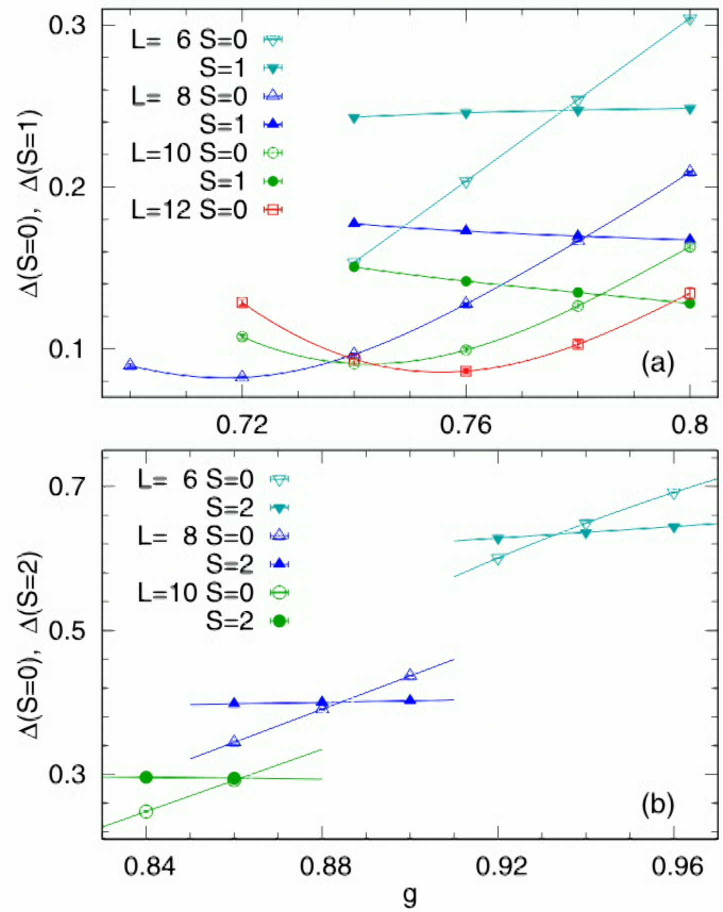

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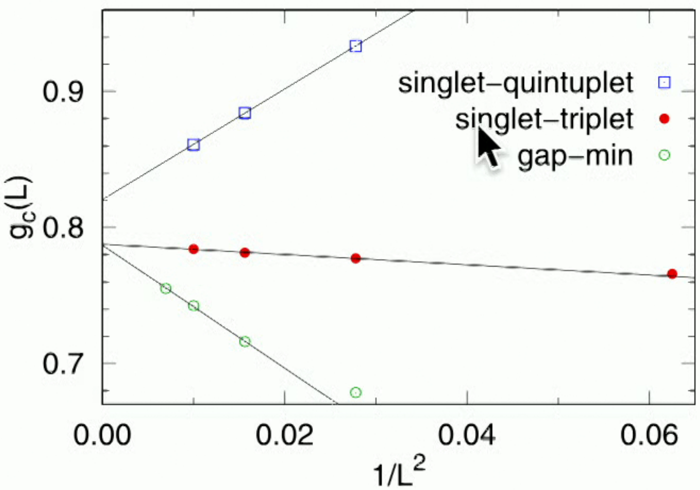

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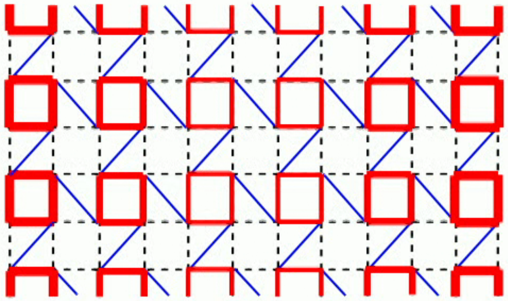

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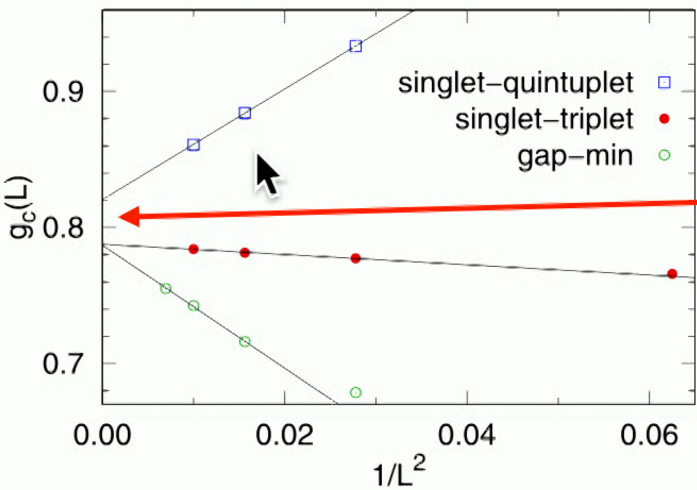
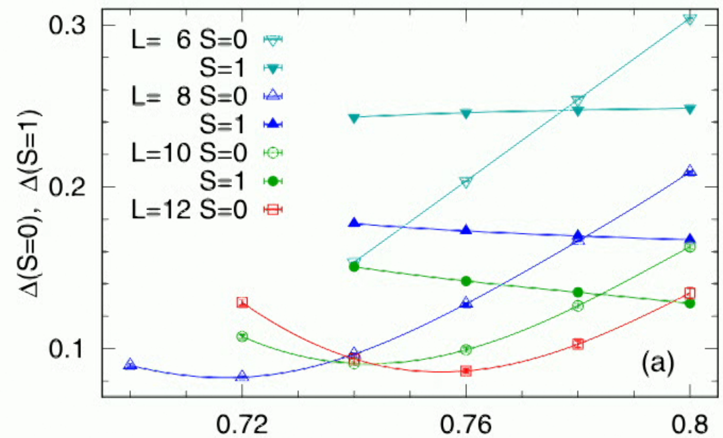
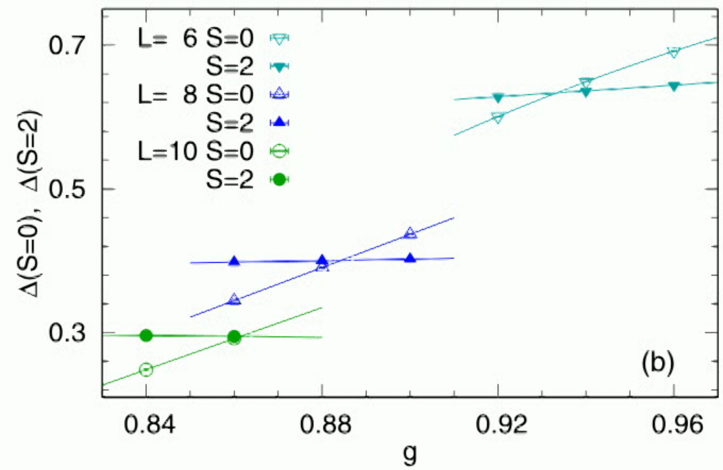


window between end of PSS and start of AFM agrees wits small-cluster Lanczos





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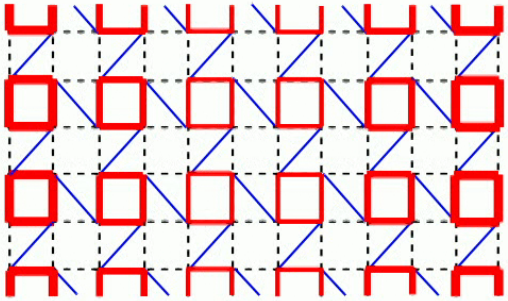

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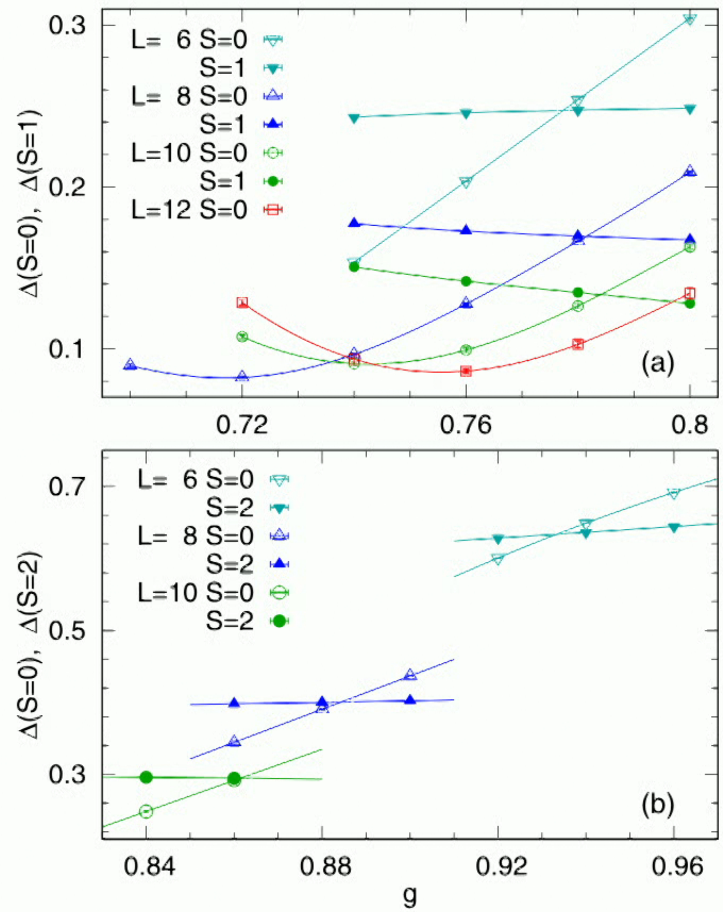

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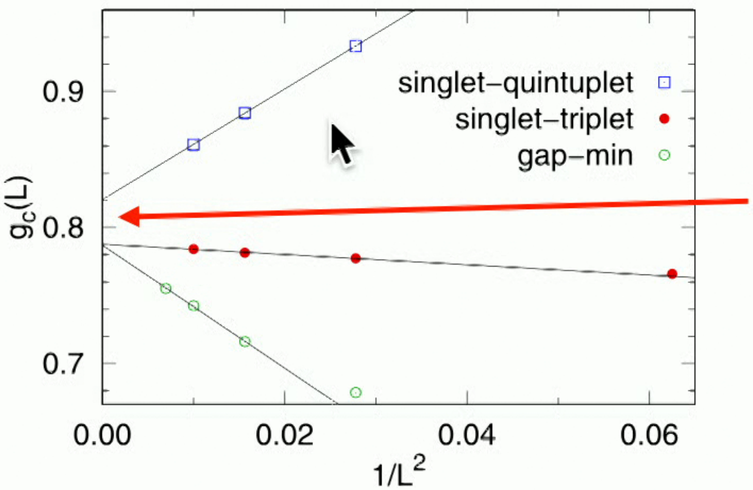

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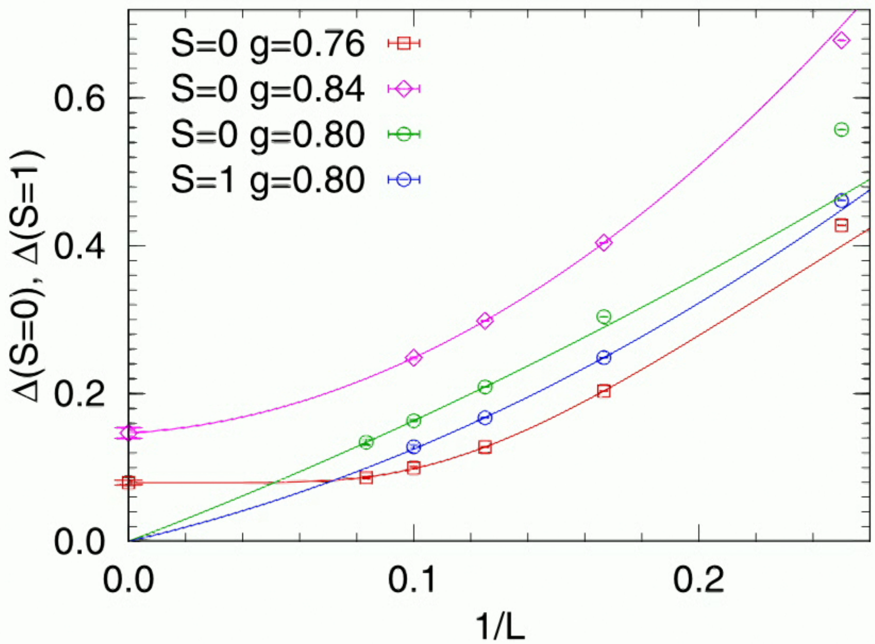
$1/L^2$ drifts of crossing points

SS model DMRG, spin liquid properties



Gaps in the spin liquid phase decay as 1/L (z=1)

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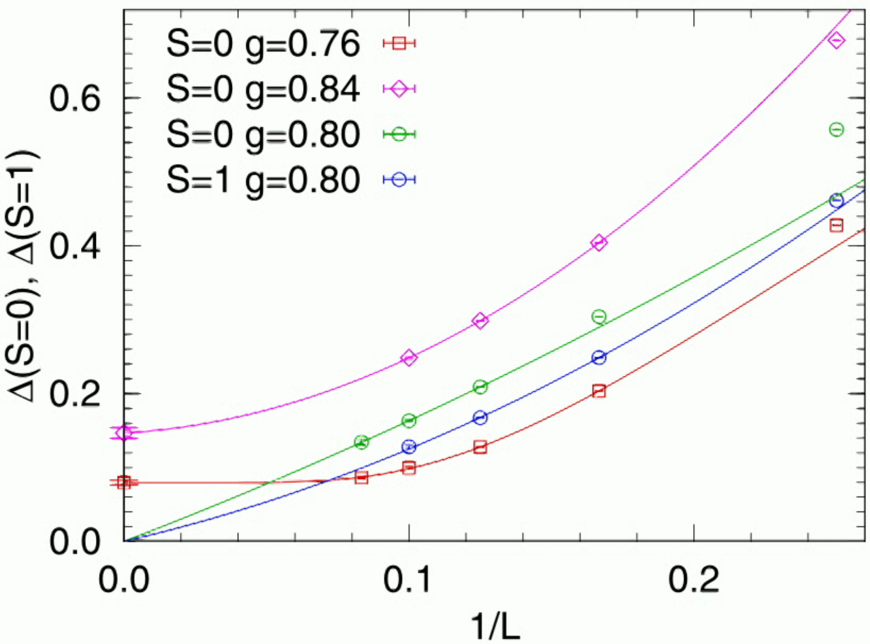

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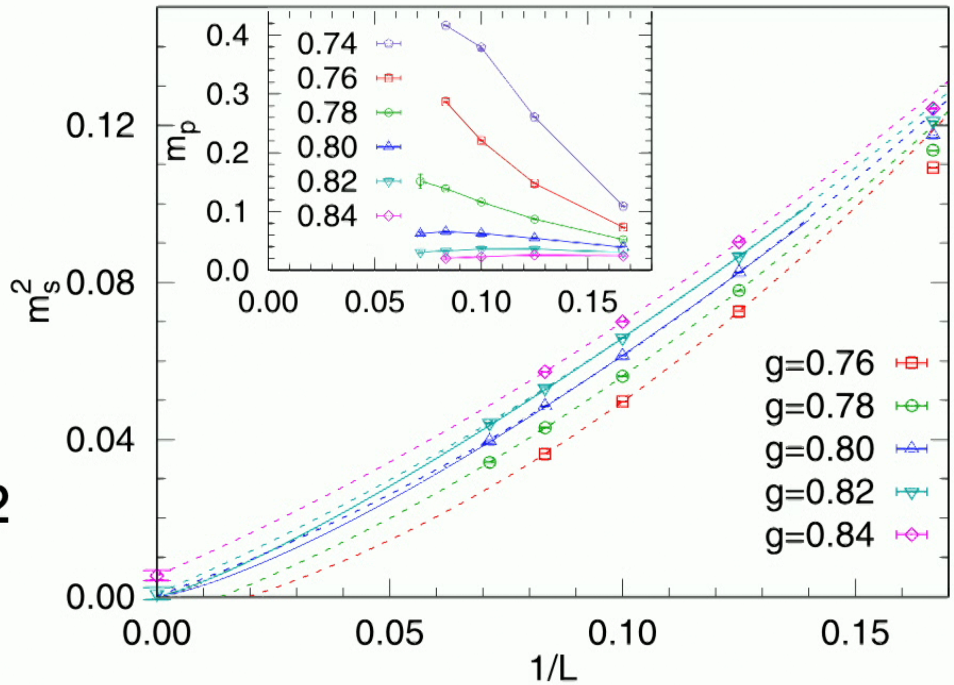
Spin correlations decay as $1/r^{1+\eta}$, $\eta \approx 0.2$



Checker-board J-Q (CBJQ) model, QMC

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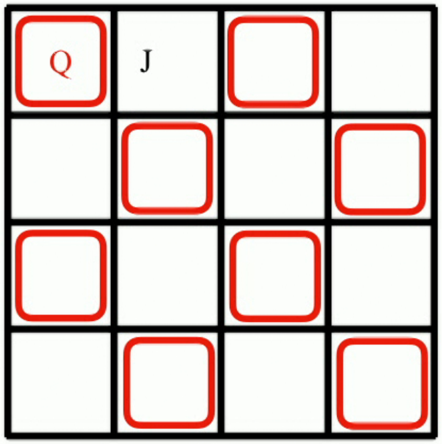

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$$P_{ij} = \frac{1}{4} - \mathbf{S}_i\cdot\mathbf{S}_j$$

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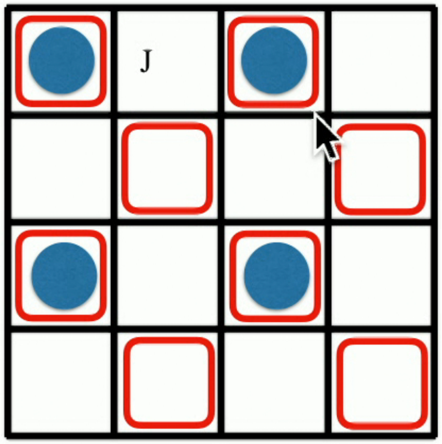

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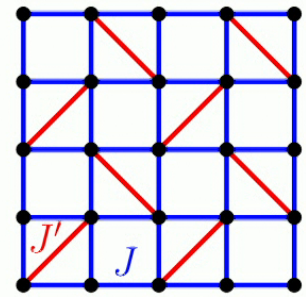

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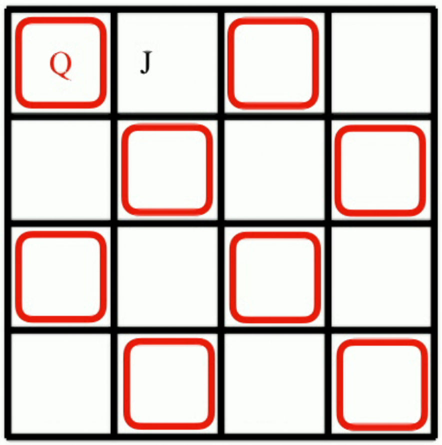

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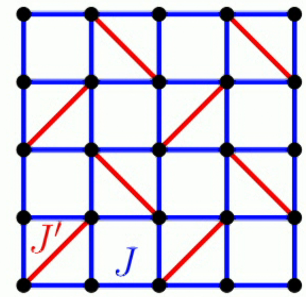

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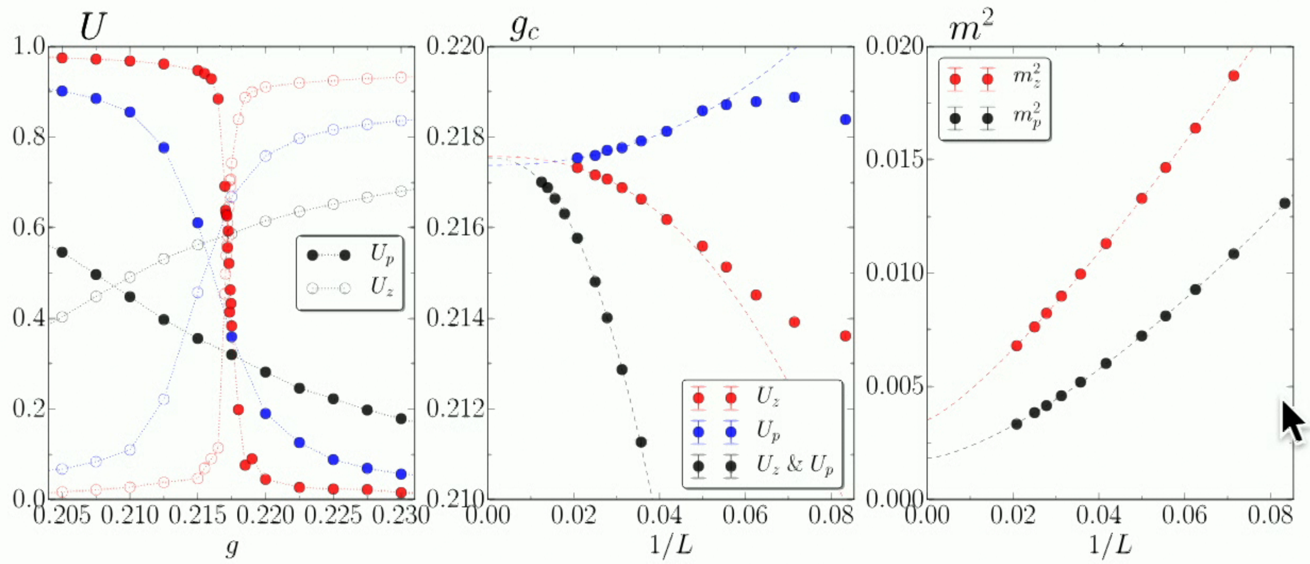

QMC simulations
- periodic L×L lattices
- periodic boundaries

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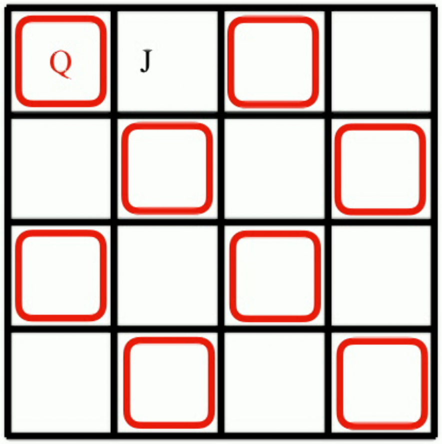

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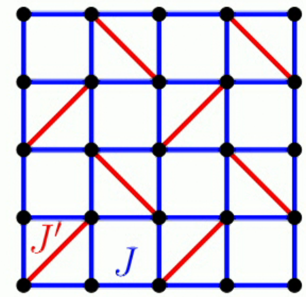

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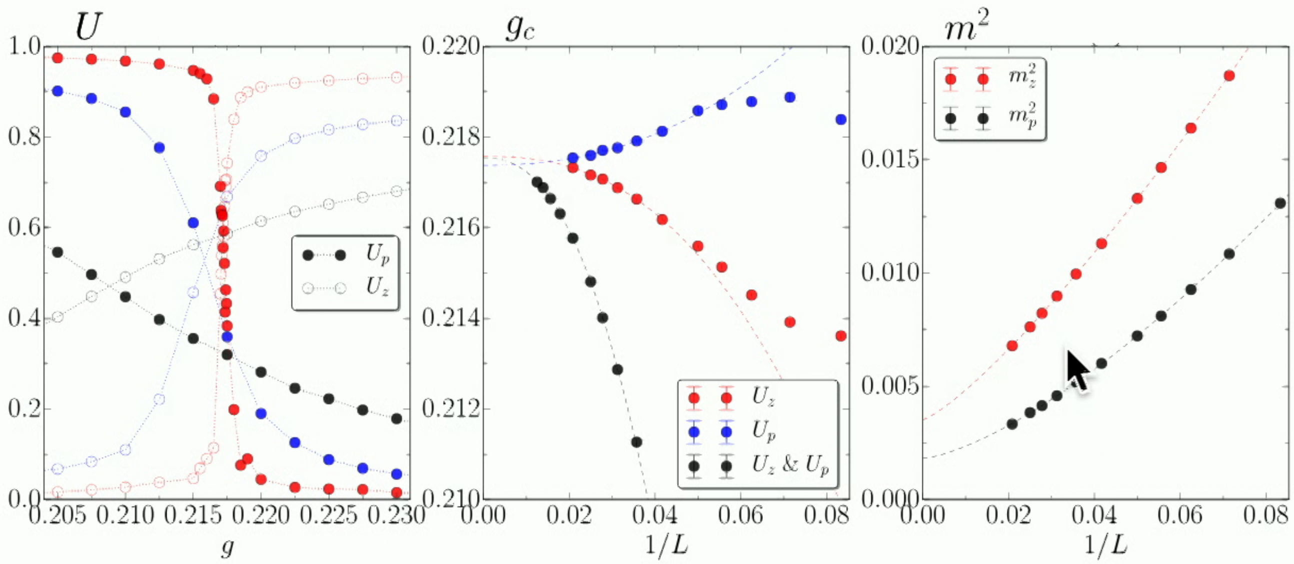

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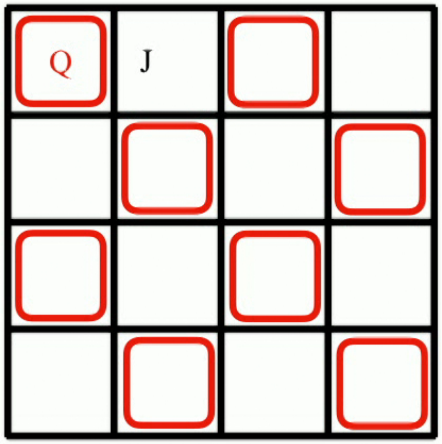

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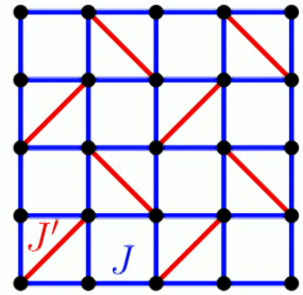

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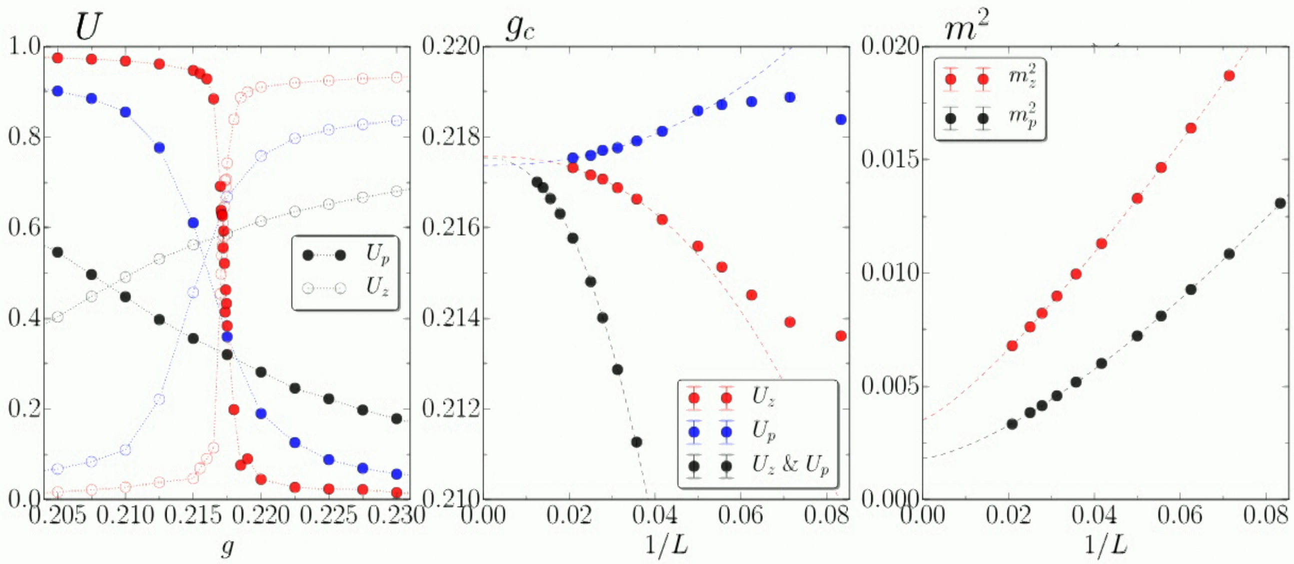

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First-order direct
PSS - AFM transition

Emergent O(4) symmetry of the coexistence state

Combined PS,AFM order parameter: (m_p, m_x, m_y, m_z)

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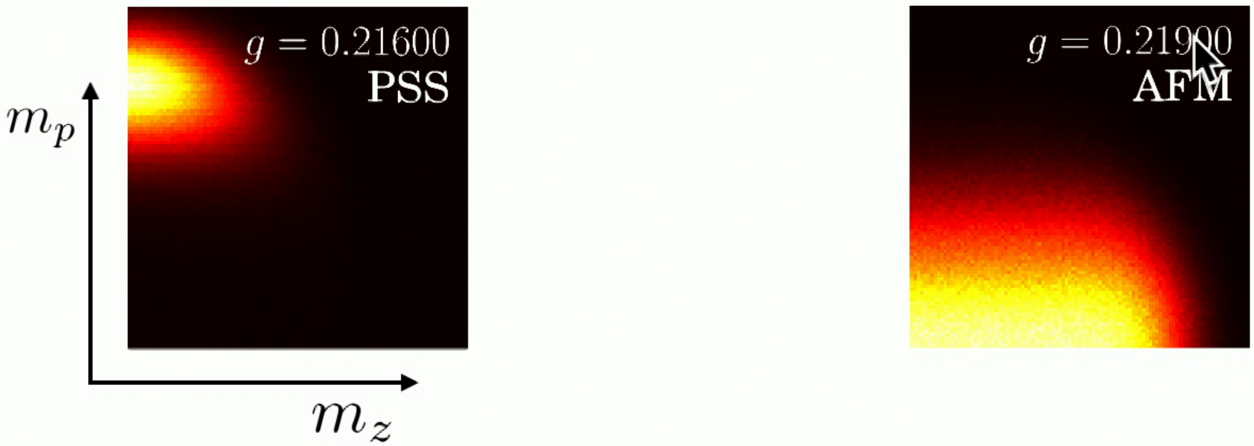
Distribution $P(m_p, m_z)$ (PS, AFM z-component), L=96



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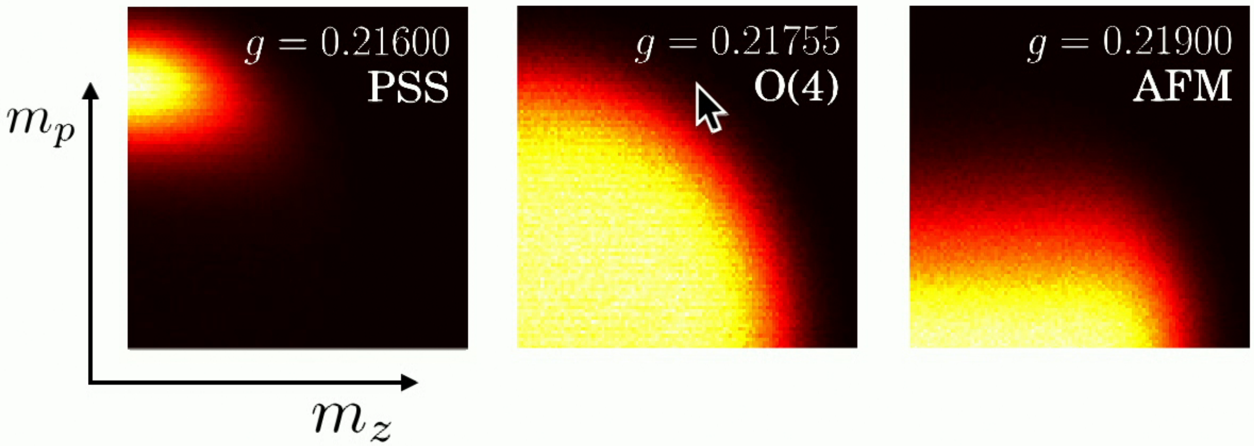

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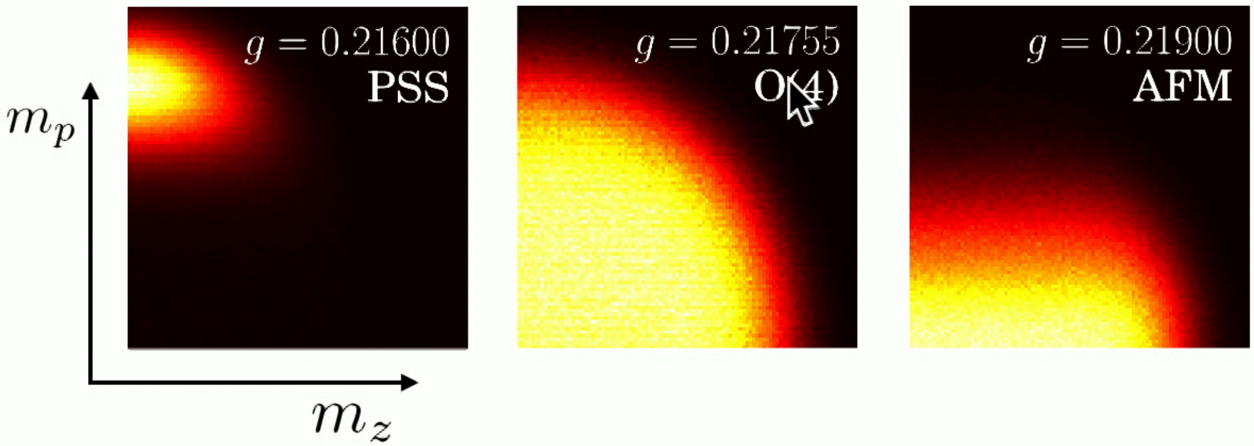
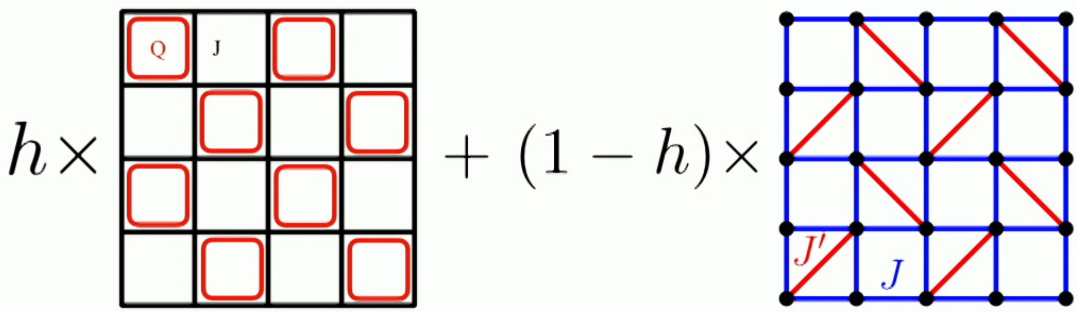


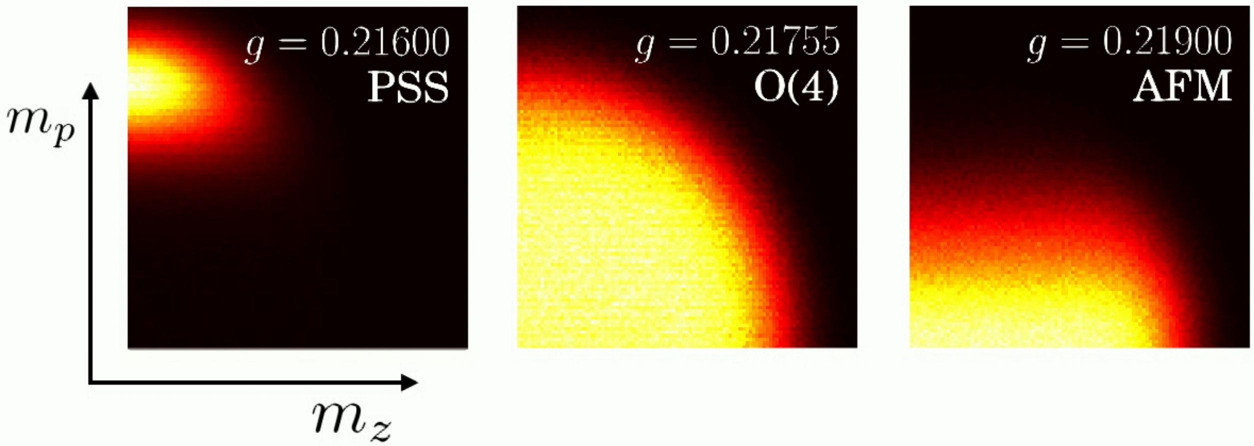
Combine CBJQ and SS models



Emergent O(4) symmetry of the coexistence state

Combined PS,AFM order parameter: (m_p,m_x,m_y,m_z)

Distribution $P(m_p,m_z)$ (PS, AFM z-component), L=96



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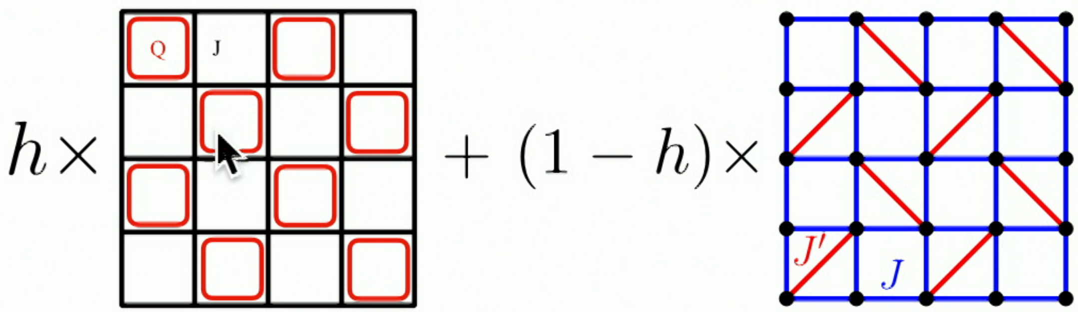

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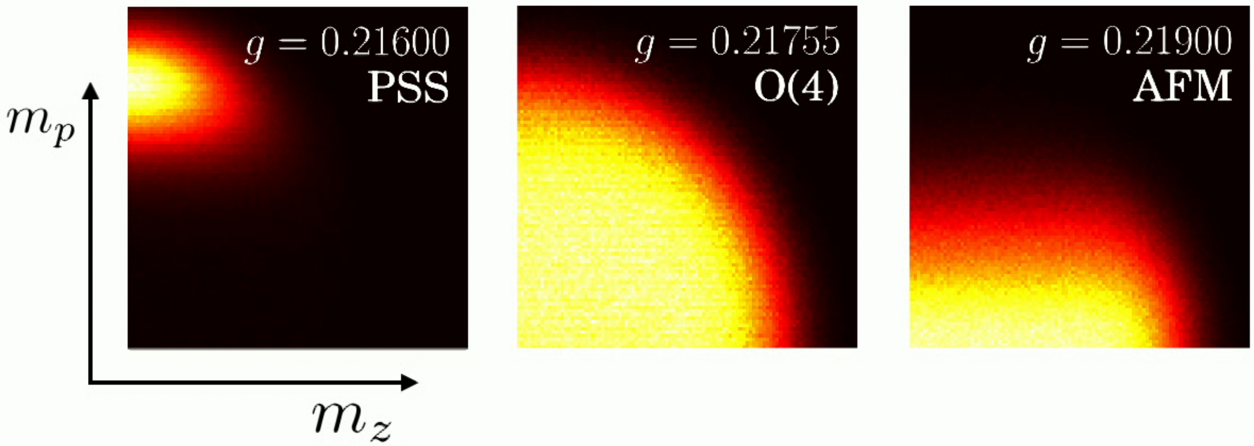
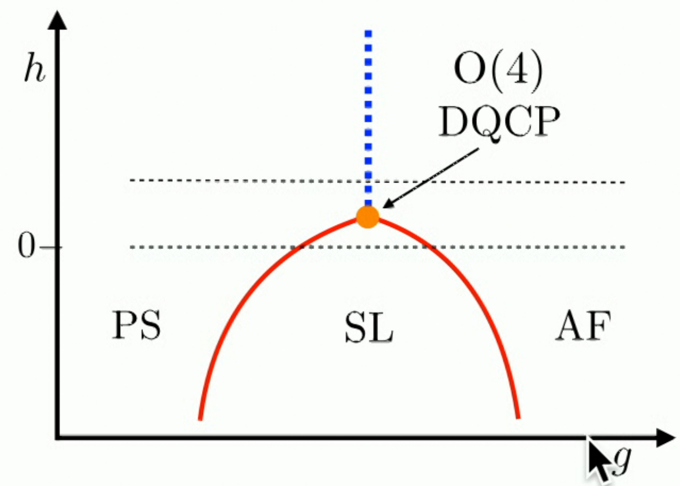


Multi-criticality scenario



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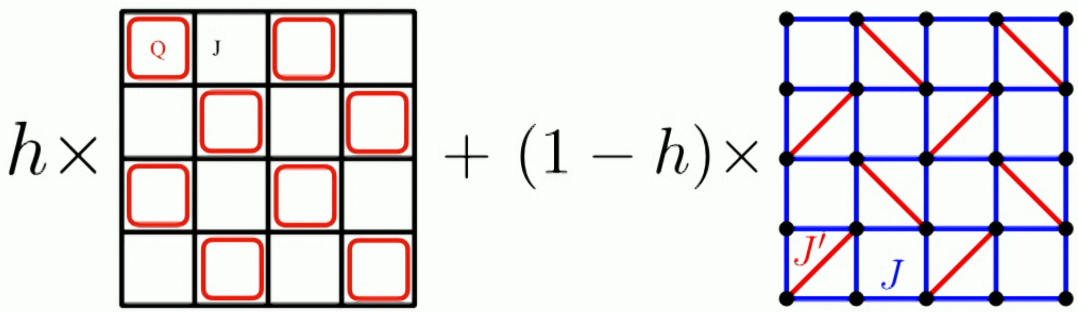

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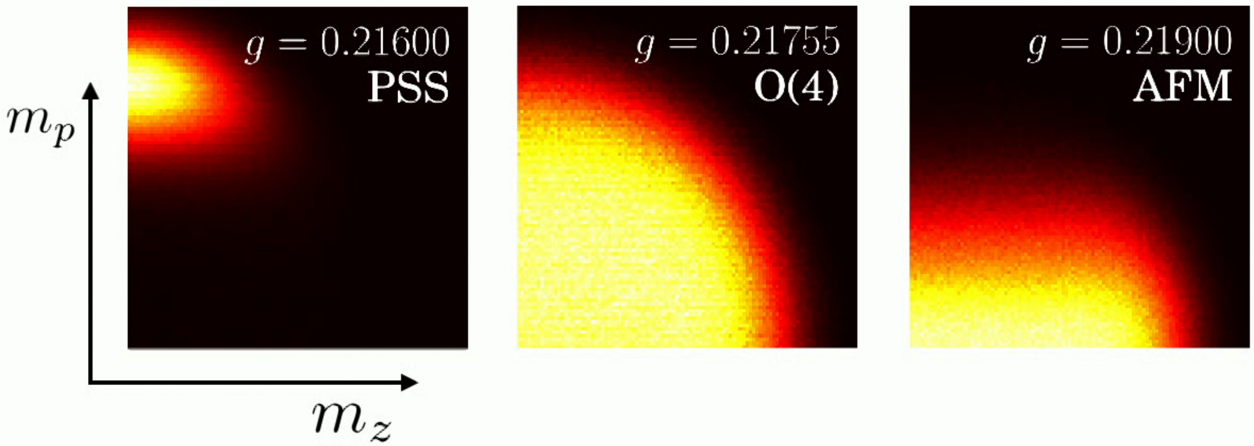

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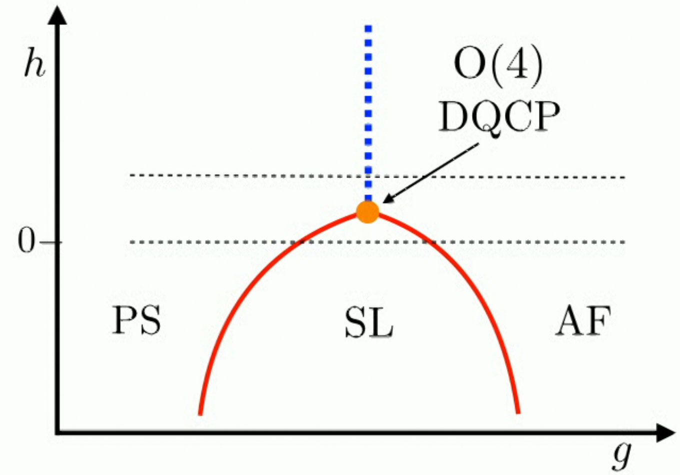

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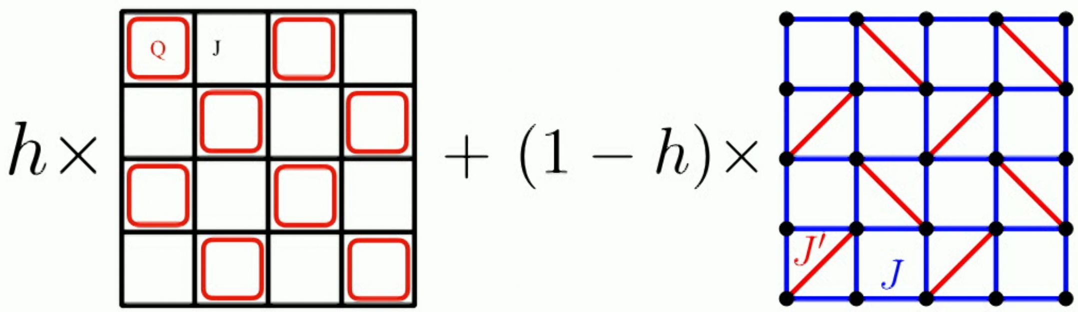

Also discussed in the context of Z_4 breaking VBS; SO(5) DQCP - identified new relevant operator

Zhao, Takahashi, Sandvik (PRL 2020)

Experiments: Shastry-Sutherland material $SrCu_2(BO_3)_2$

PHYSICAL REVIEW LETTERS **124,** 206602 (2020)

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

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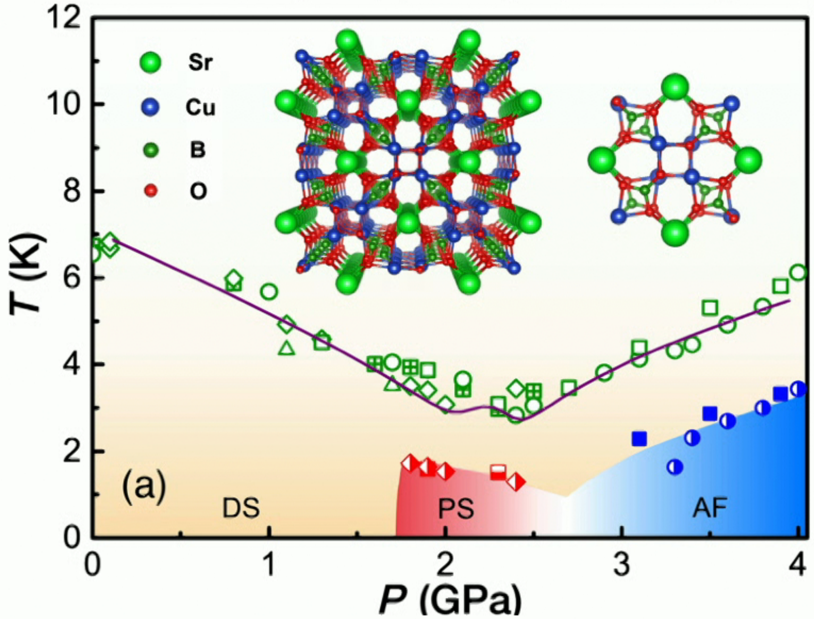

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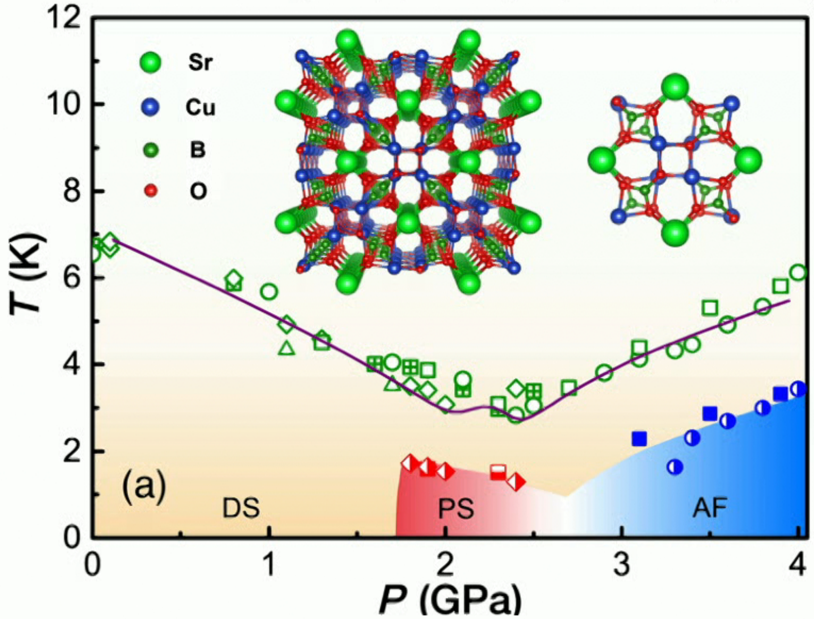

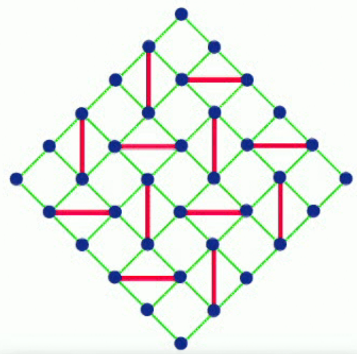

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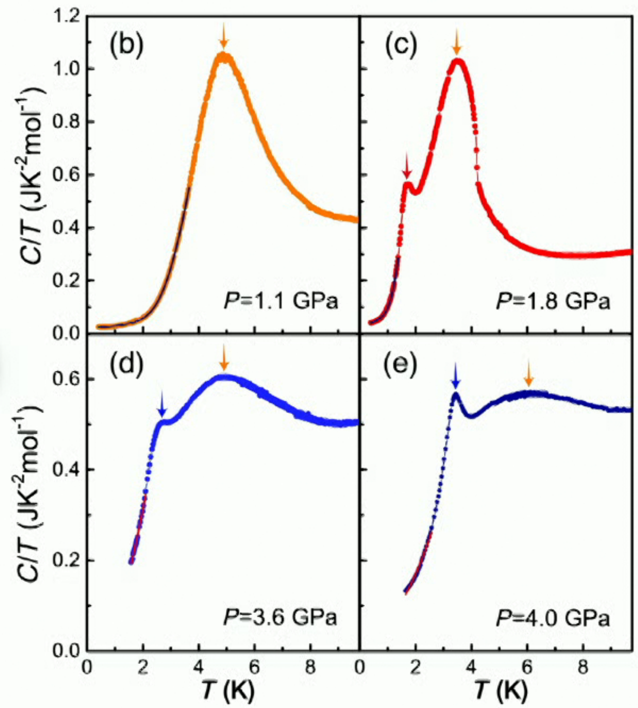

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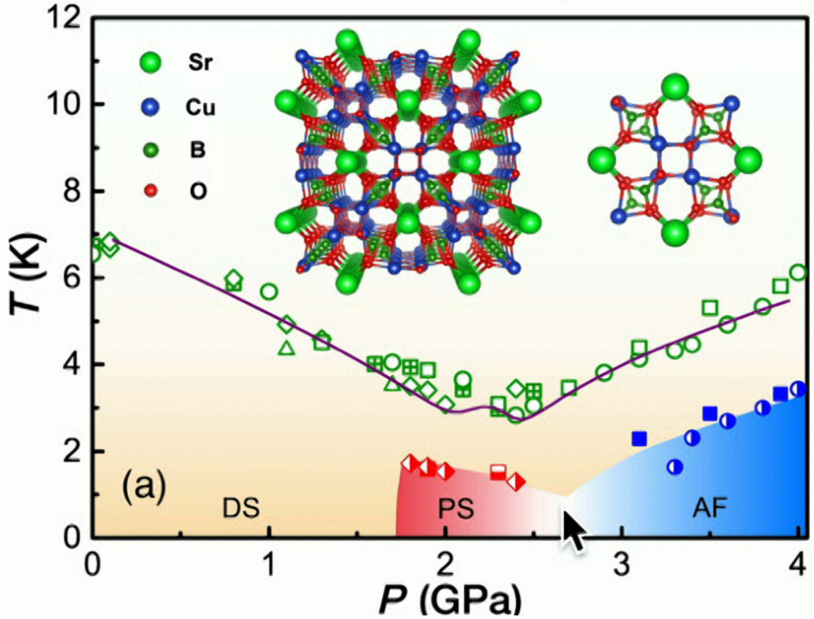

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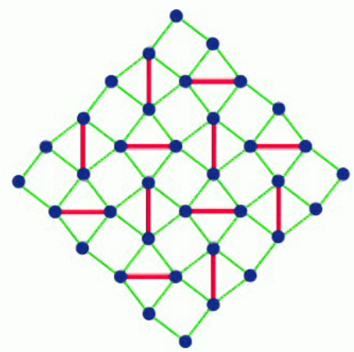
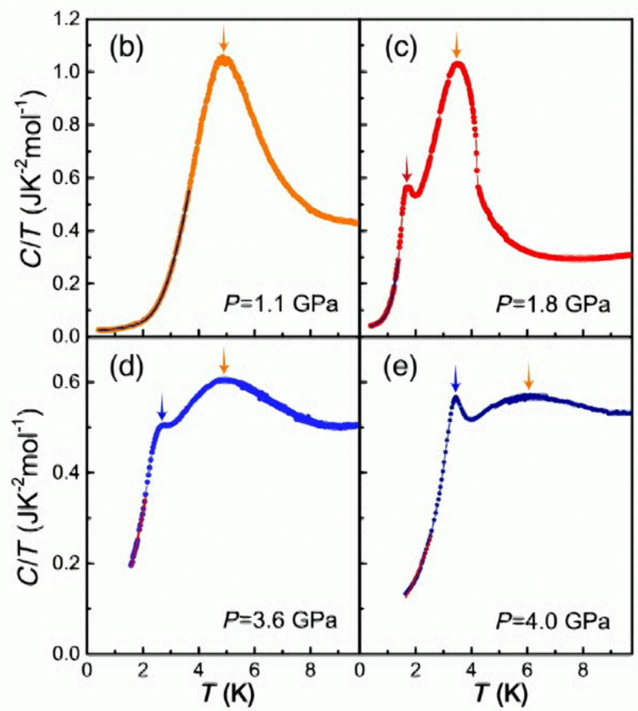


g=J/J' depends on the pressure

Spin liquid between PS and AFM?



arXiv:2204.08133v1 [cond-mat.str-el] 18 Apr 2022

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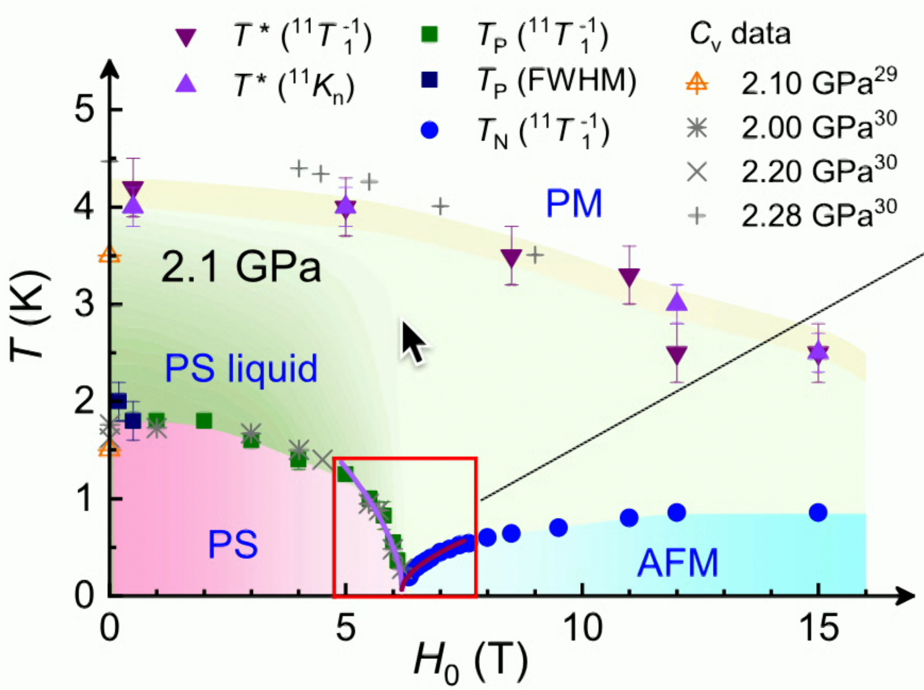
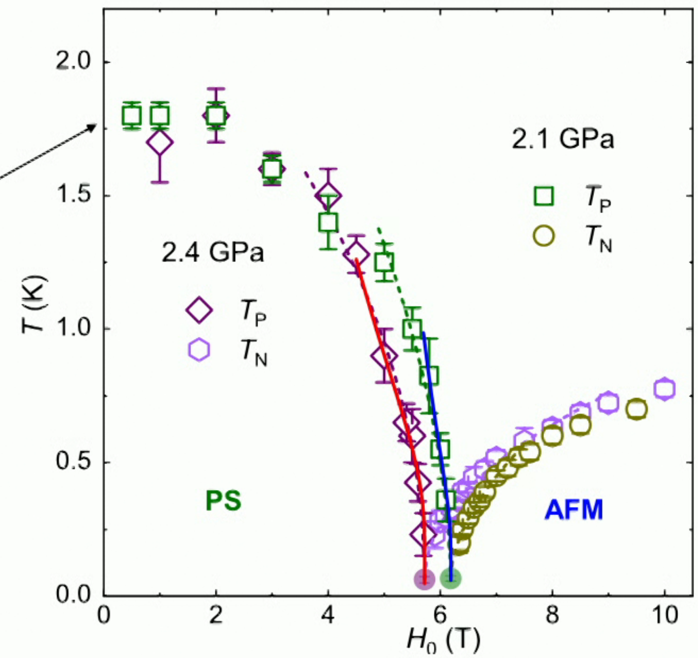
Suppression of PS phase by magnetic field, NMR (^{11}B) measurements





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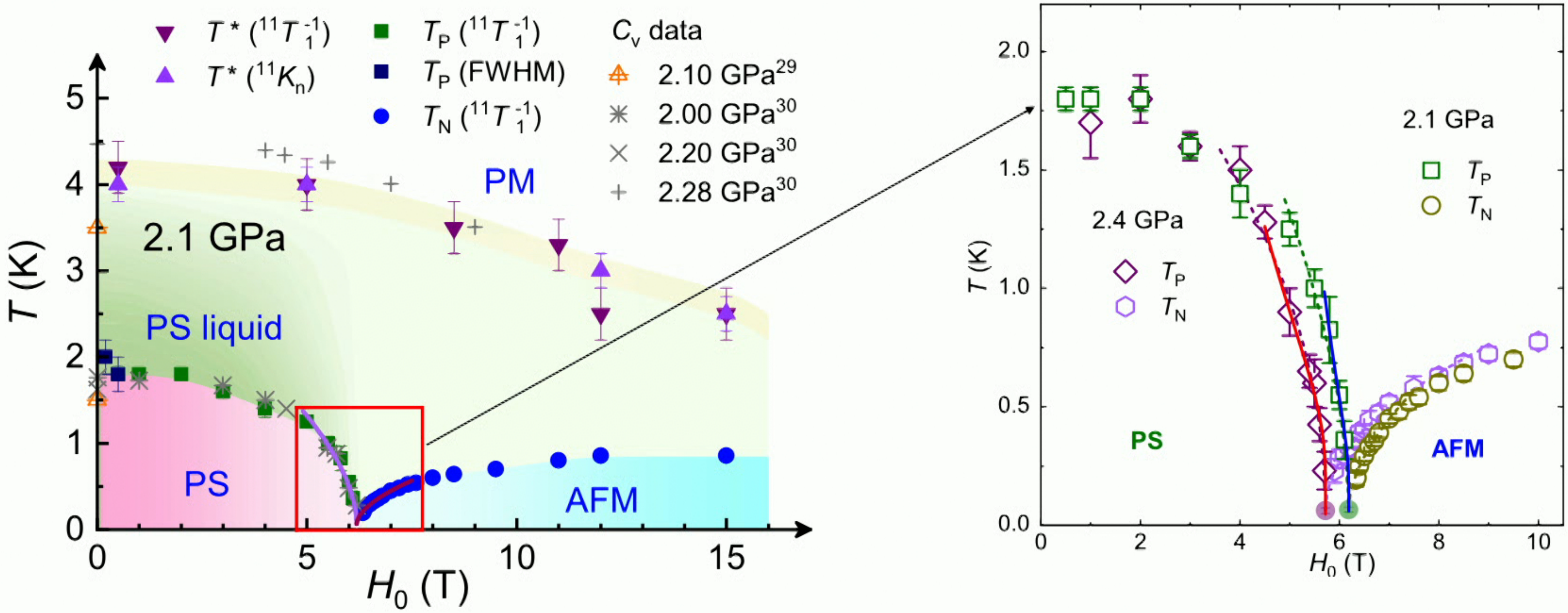
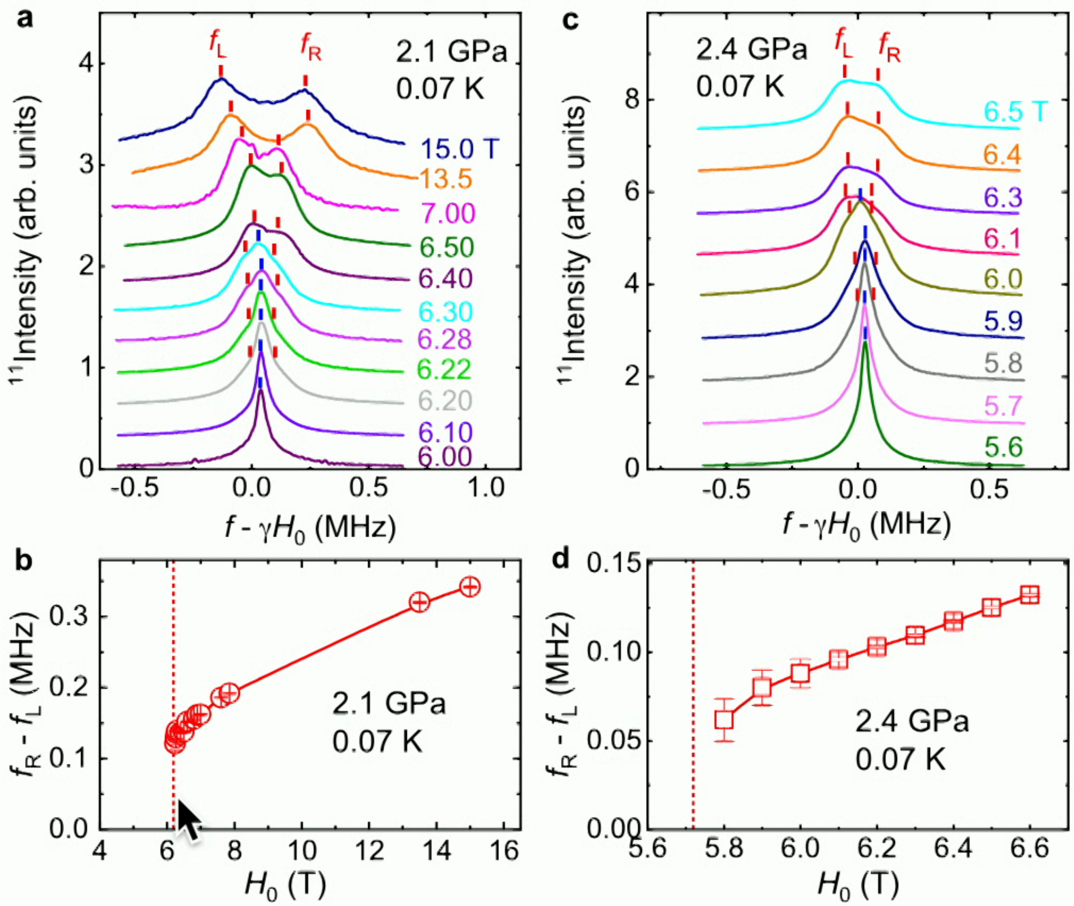


Common PS and AFM transition at T ~ 0.07 K, H_0 ~6 T

Proxy AFM order parameter: NMR line splitting



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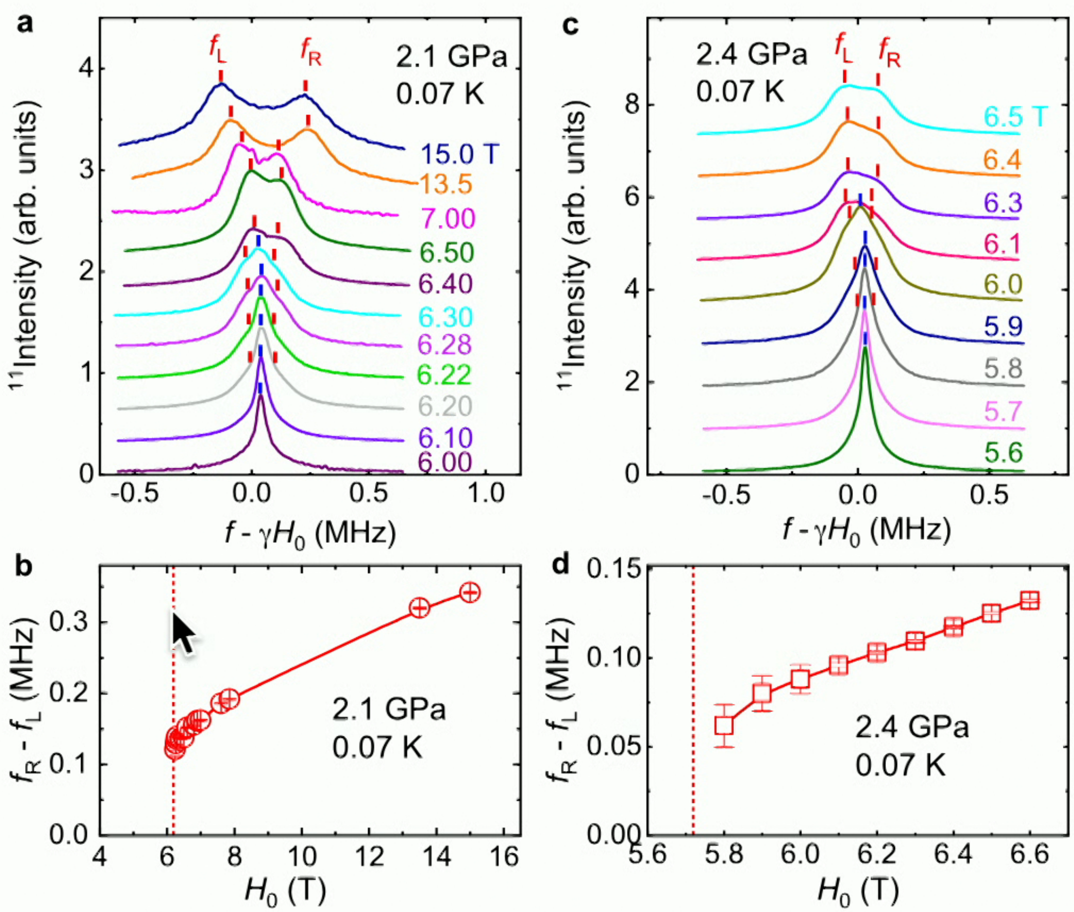

Transition point (dashed lines) determined more precisely from spin-lattice relaxation rate $1/T_1$

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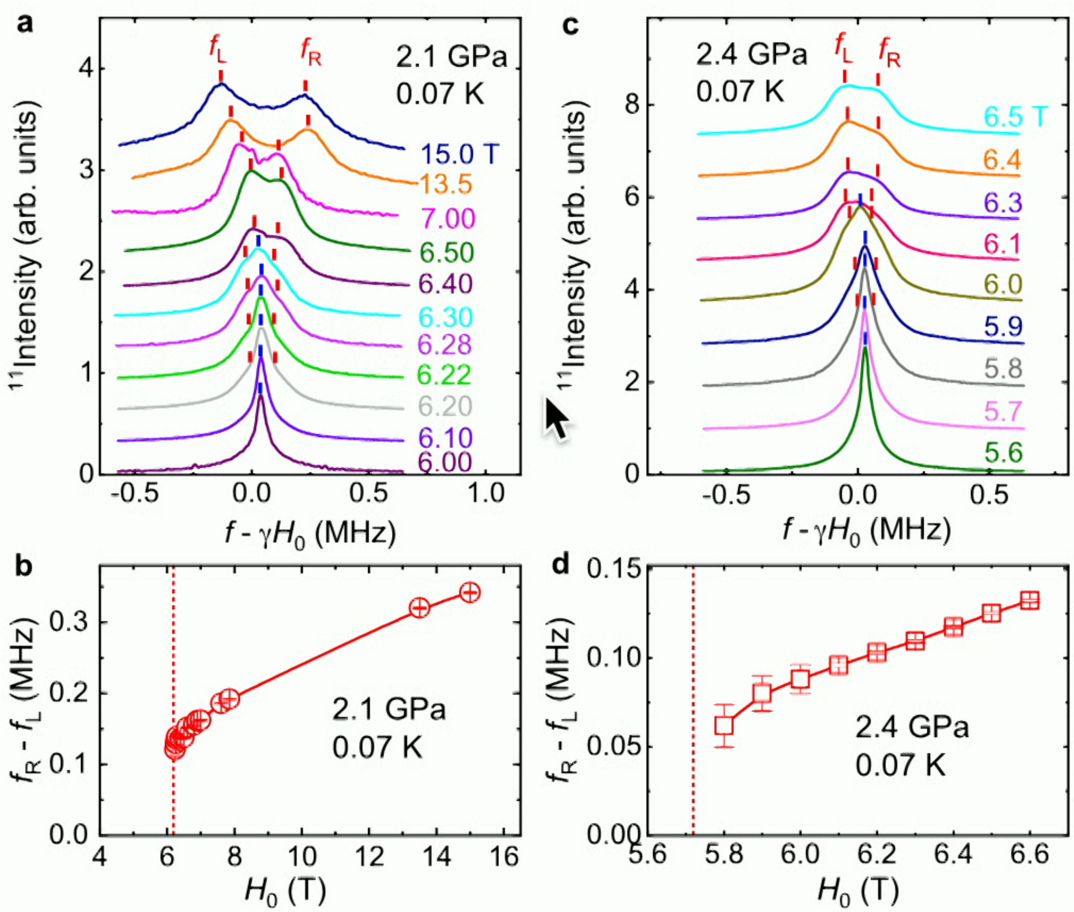

- **Phase coexistence at the low-T phase transition**
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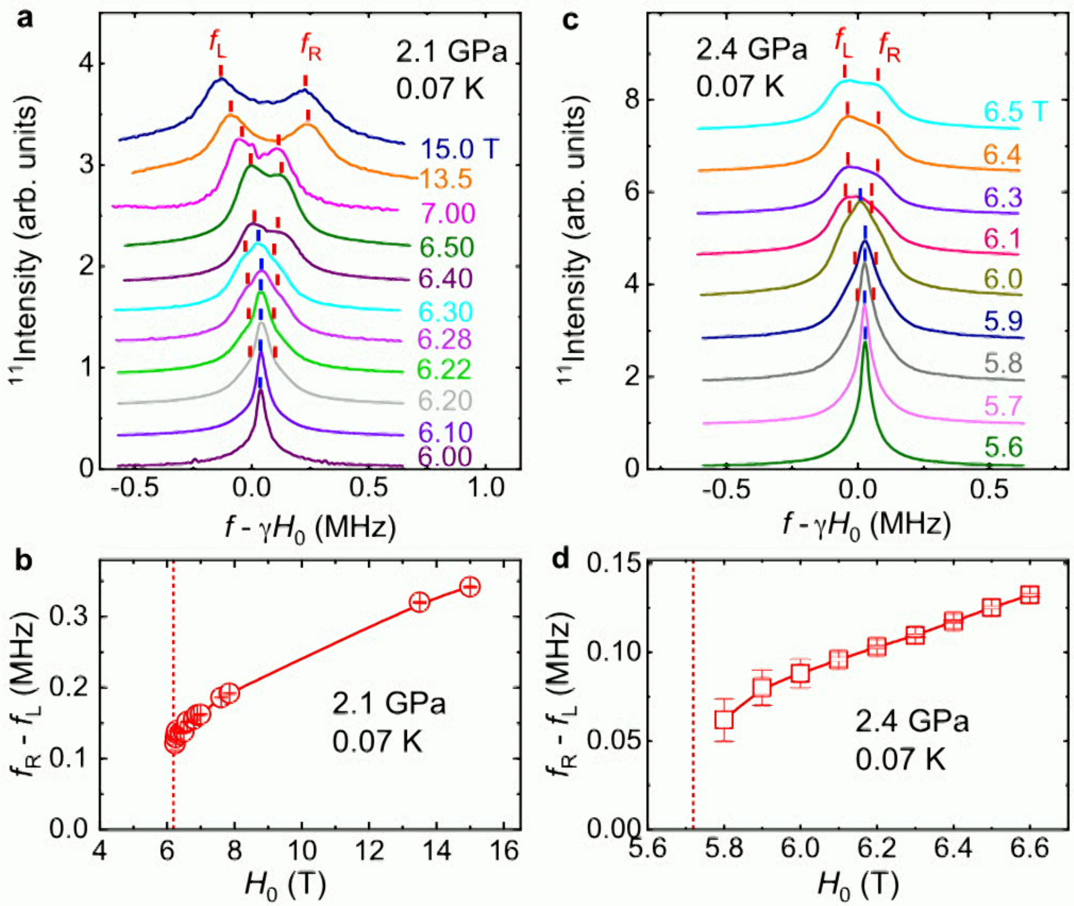

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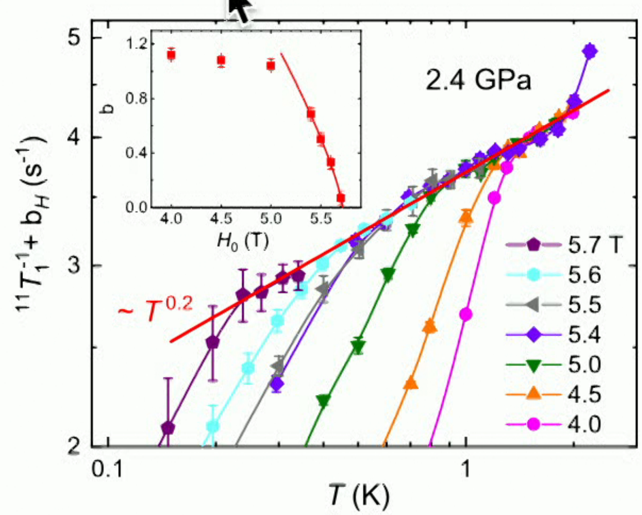
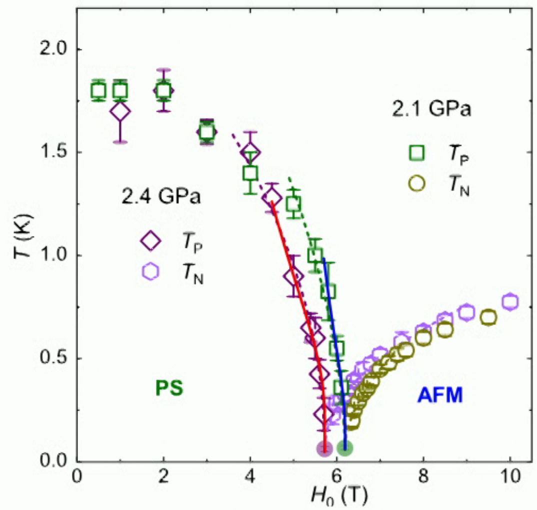
- Unusually low Tc for a first-order transition
- Quantum-critical T>0 scaling of spin-lattice relaxation at 2.4 GPa

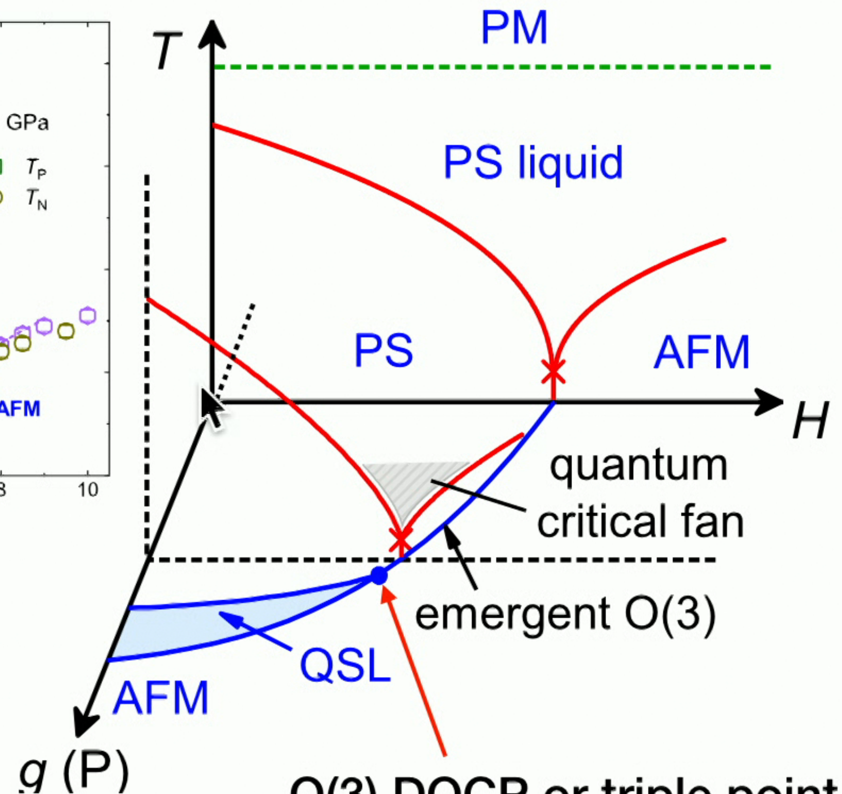


Theoretical scenario

Picture emerging from models and experiments

- Emergent O(3) symmetry (large length scale) on 1st-order PS-AFM line
- Only weak 3D effects





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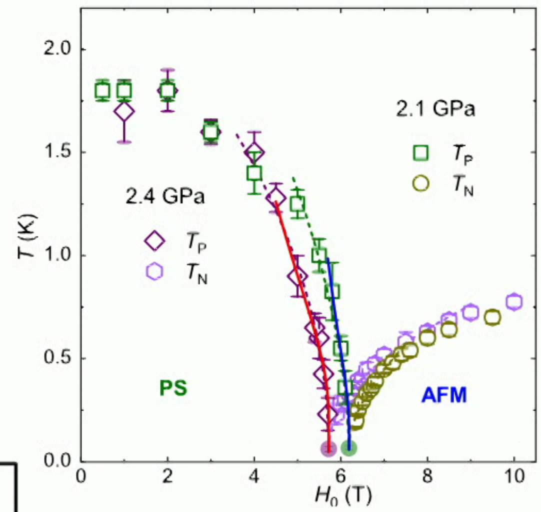
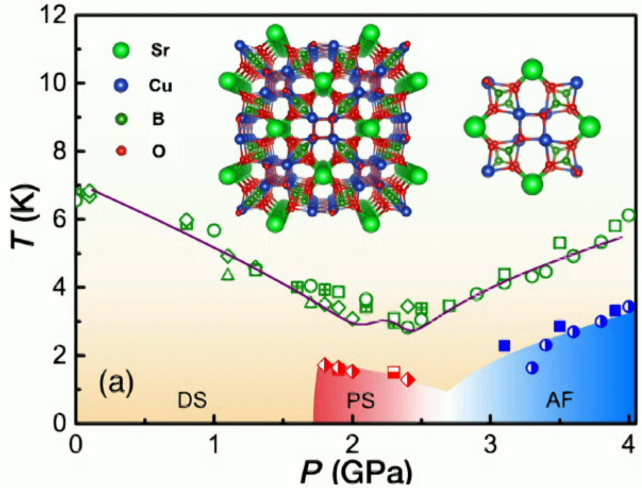
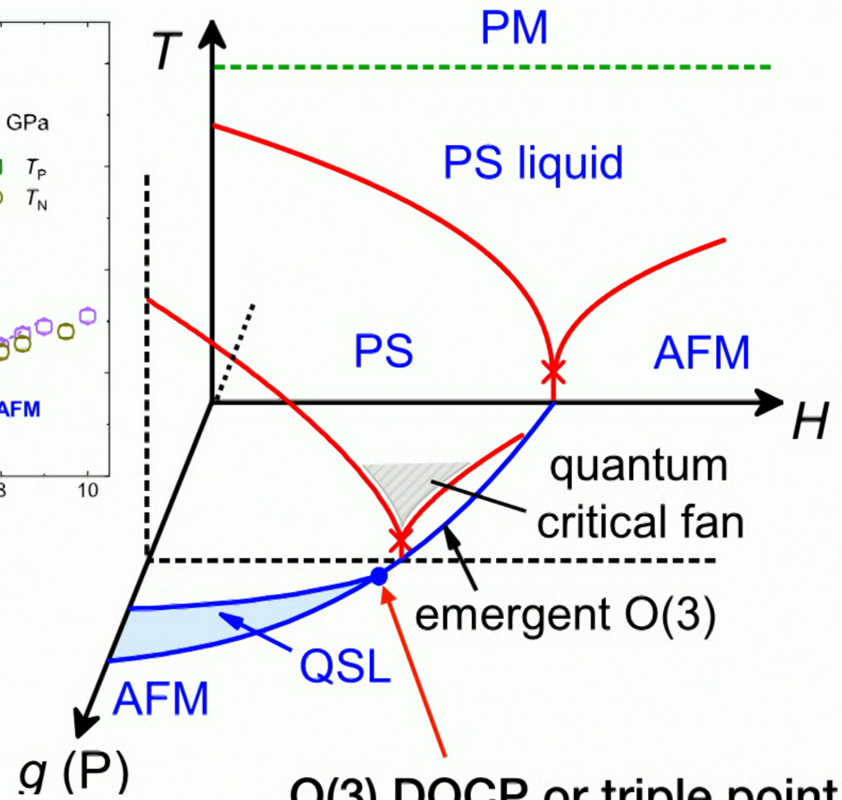
- At highest P, 2.4 GPa, influence of DQCP







Summary, conclusions

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NMR experiments match near-DQCP scenario

Is there a spin liquid?

- Not explicitly detected yet but there as a promising unexplored "whire region"

- SCBO single crystals are very clean, may be best spin liquid candidate