Randomness-induced ordering behavior of the frustrated $s=1/2$ J_1-J_2 Heisenberg model on the square lattice with ferromagnetic and antiferromagnetic J_1

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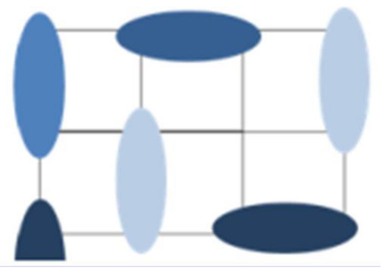
Introduction

- Randomness
- Frustration
- Quantum Fluctuation

[1] K. Watanabe *et al.*, J. Phys. Soc. Jpn. **83**, 034714 (2014).
[2] H. Kawamura *et al.*, J. Phys. Soc. Jpn. **83**, 103704 (2014).
[3] K. Uematsu *et al.*, J. Phys. Soc. Jpn. **86**, 044704 (2017).

Random singlet (RS) state

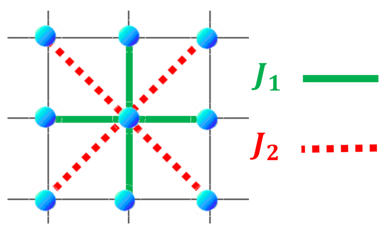
- No magnetic LRO
- Gapless
- T-linear specific heat
- Orphan spins
- Stabilized in the random model on the triangular-,[1] kagome-,[2] and J_1-J_2 honeycomb lattice[3]



Motivation

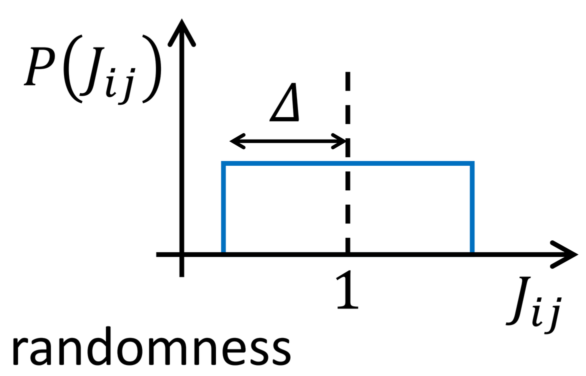
How ubiquitous the RS state is ? $\Rightarrow$ We investigate the random J_1-J_2 model on the square lattice.

- Other lattices
- Tune both randomness and frustration



Model

$$\mathcal{H} = J_1 \sum_{\langle i,j\rangle} J_{ij}\boldsymbol{S}_i\cdot\boldsymbol{S}_j + J_2 \sum_{\langle\langle i,j\rangle\rangle} J_{ij}\boldsymbol{S}_i\cdot\boldsymbol{S}_j$$

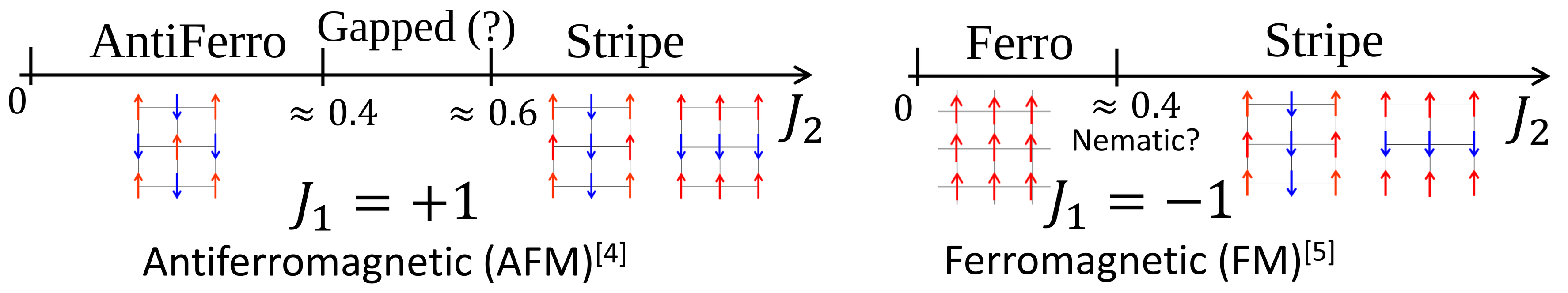


$J_1=\pm1,\ J_2\geq0$: frustration, $\quad 0\leq\varDelta\leq1$: randomness

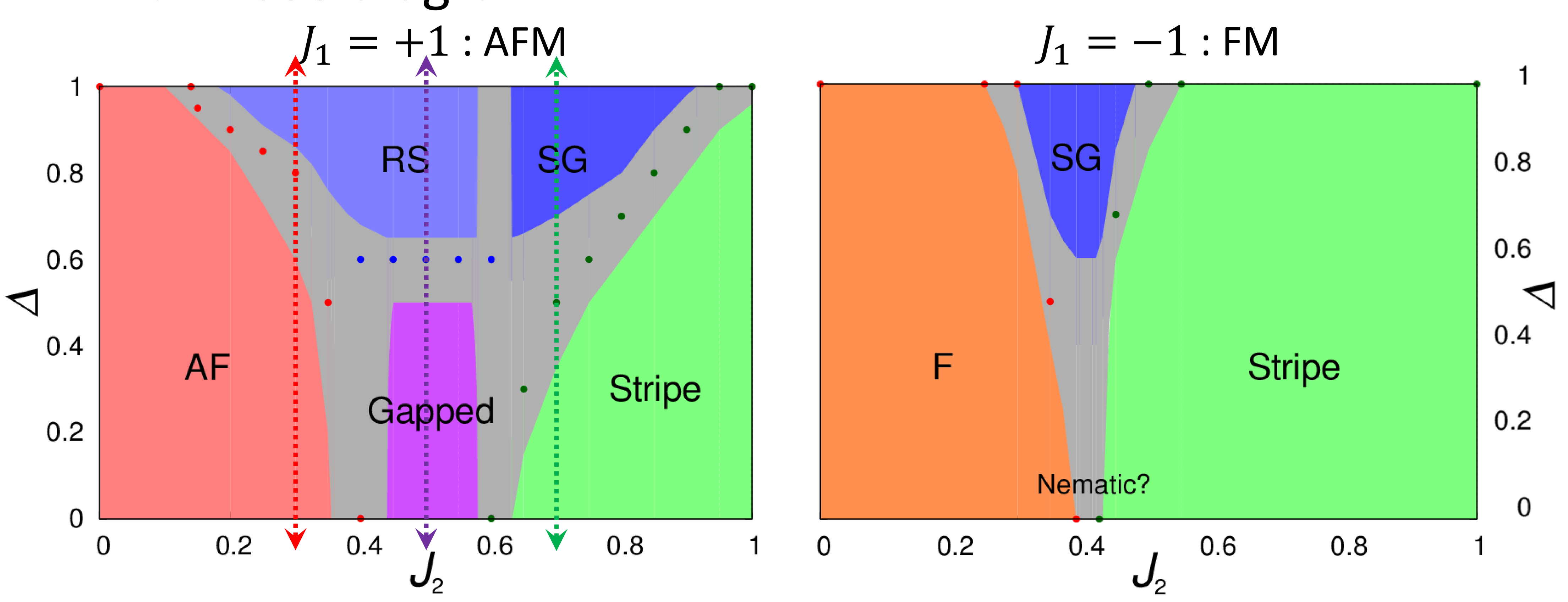
Method : Exact diagonalization ($T=0$) and Hams-de Raedt method ($T\neq0$)

Previous studies of $\varDelta=0$[4,5]

[4] J. Richter *et al.*, Eur. Phys. J. B **73**, 117 (2010).
[5] J. Richter *et al.*, Phys. Rev. B **81**, 174429 (2010).

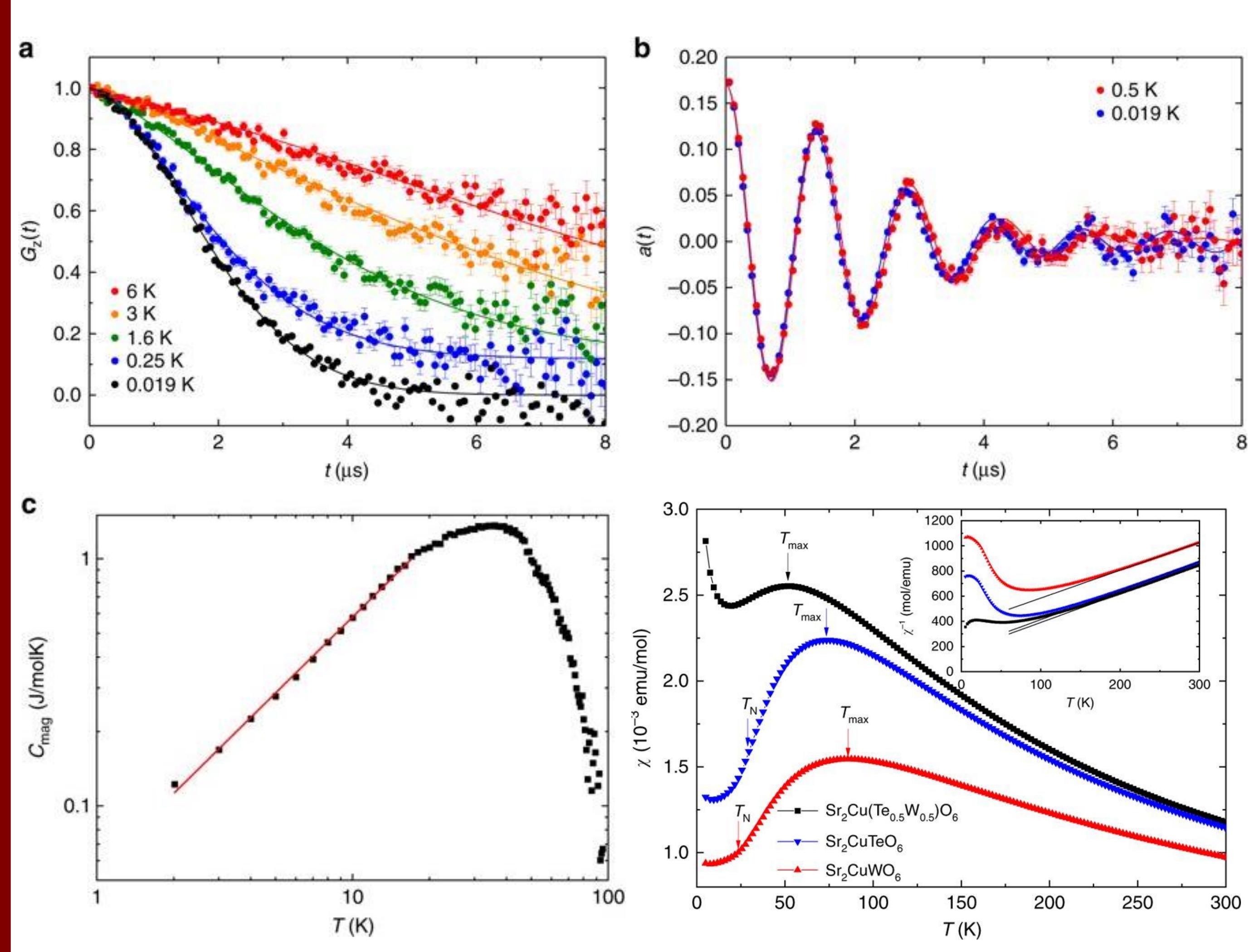


$T=0$ Phase diagram



Relation to experiment - $Sr_2Cu(Te_{0.5}W_{0.5})O_6$[6]

[6] O. Mustonen *et al.*, Nat. Commun. **9**, 1085 (2018).



- Mixed crystal of two square-lattice AFMs: Sr_2CuTeO_6 ($J_2/J_1=0.03, T_N=29K$) and Sr_2CuWO_6 ($J_2/J_1=7.92, T_N=24K$)

$\Rightarrow$ The $J_2/J_1\approx0.5$ region could be reached by $Sr_2Cu(Te_{1-x}W_x)O_6$ with significant quenched disorder in the magnetic interactions.

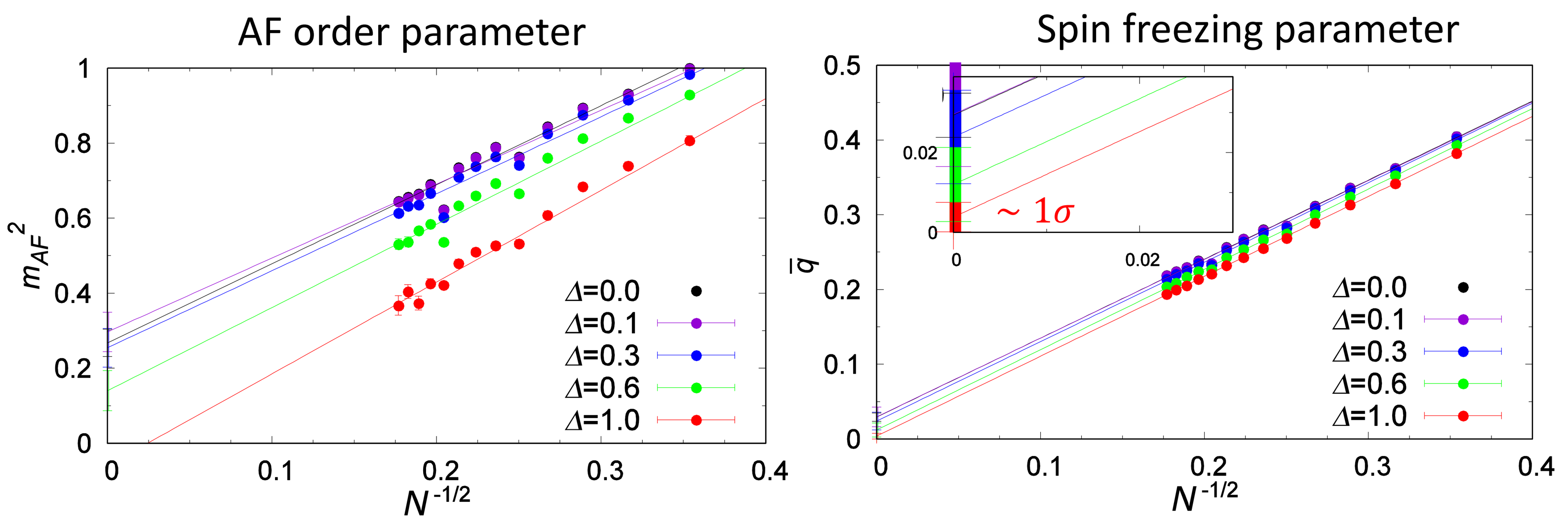
- Spins remain entirely dynamic down to 19 mK.
- T-linear specific heat at low temperatures.
- Curie-tail-like susceptibility at low temperatures.

J_2 and $\varDelta$ dependence of order parameters ($J_1=+1$: AFM)

AF-RS transition ($J_2=0.3$)

$$m_{AF}^2=\frac{1}{2}\frac{1}{\frac{N}{4}\left(\frac{N}{4}+1\right)}\times\langle(\textstyle\sum_{i\in A}\boldsymbol{S}_i)^2+(\sum_{i\in B}\boldsymbol{S}_i)^2\rangle$$

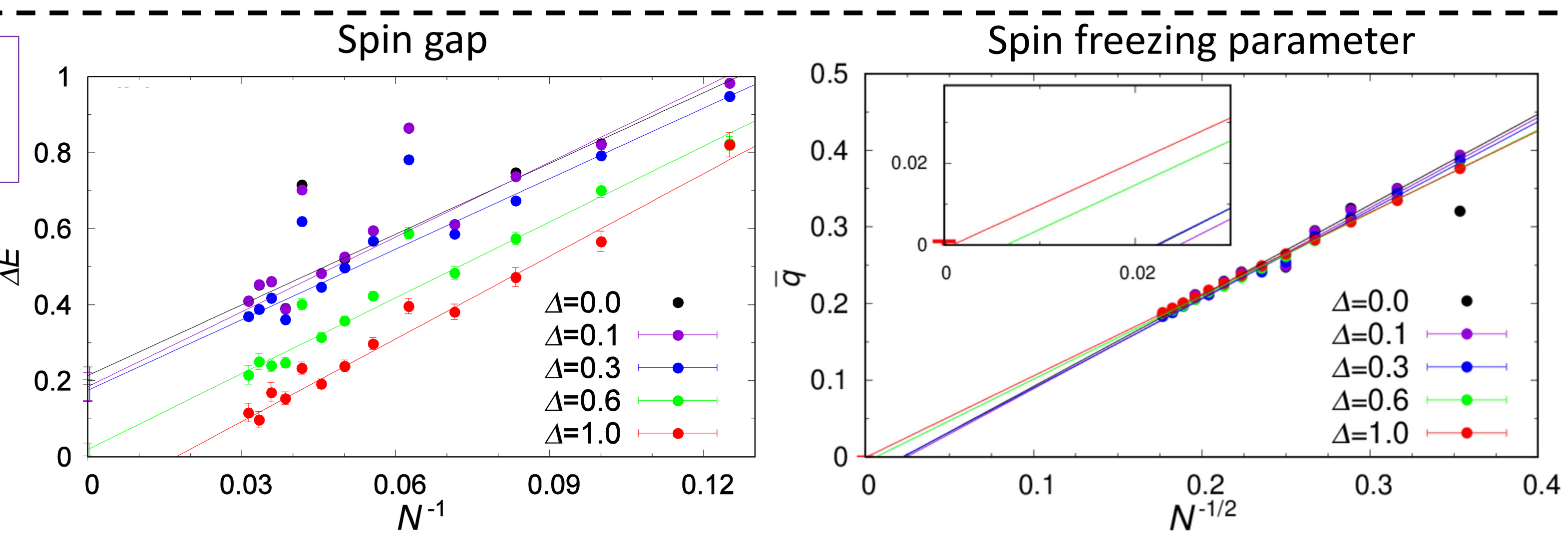
No magnetic order for $\varDelta\gtrsim0.8$.



Gapped-RS transition ($J_2=0.5$)

$$\bar{q}=\frac{1}{N}\sqrt{\textstyle\sum_{i,j}\langle\boldsymbol{S}_i\cdot\boldsymbol{S}_j\rangle^2}$$

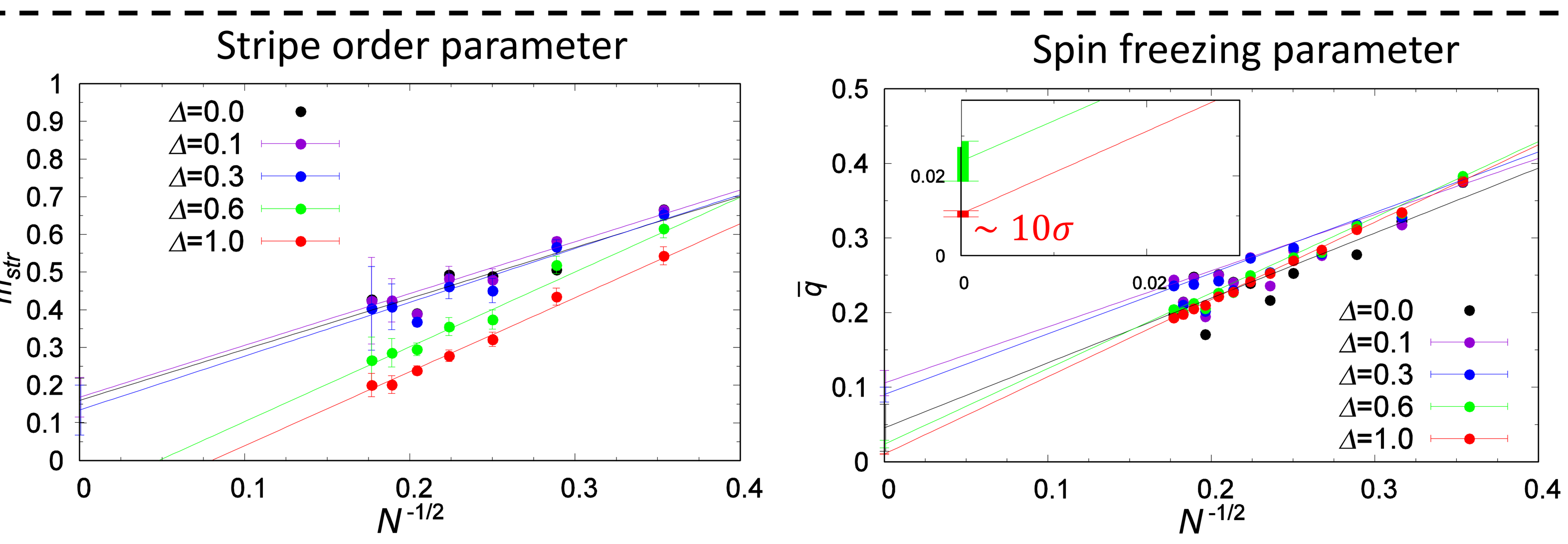
Gapless and nonmagnetic for $\varDelta\gtrsim0.6$.



Stripe-SG transition ($J_2=0.7$)

$$m_{str}^2=\frac{1}{3}\frac{1}{2}\frac{1}{\frac{N}{4}\left(\frac{N}{4}+1\right)}\sum_{\nu=1,2,3}\times\left\langle\left(\textstyle\sum_{i\in A_\nu}\boldsymbol{S}_i\right)^2+\left(\sum_{i\in B_\nu}\boldsymbol{S}_i\right)^2\right\rangle$$

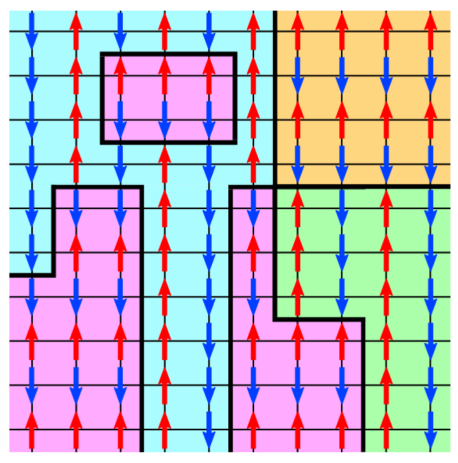
Spin-glass (SG) order for $\varDelta\gtrsim0.5$.



Realization mechanism of the SG state

- Local J_{ij} favors either vertical or horizontal stripes.

$\Rightarrow$ Stripe-ordered clusters are randomly generated to minimize the energy.



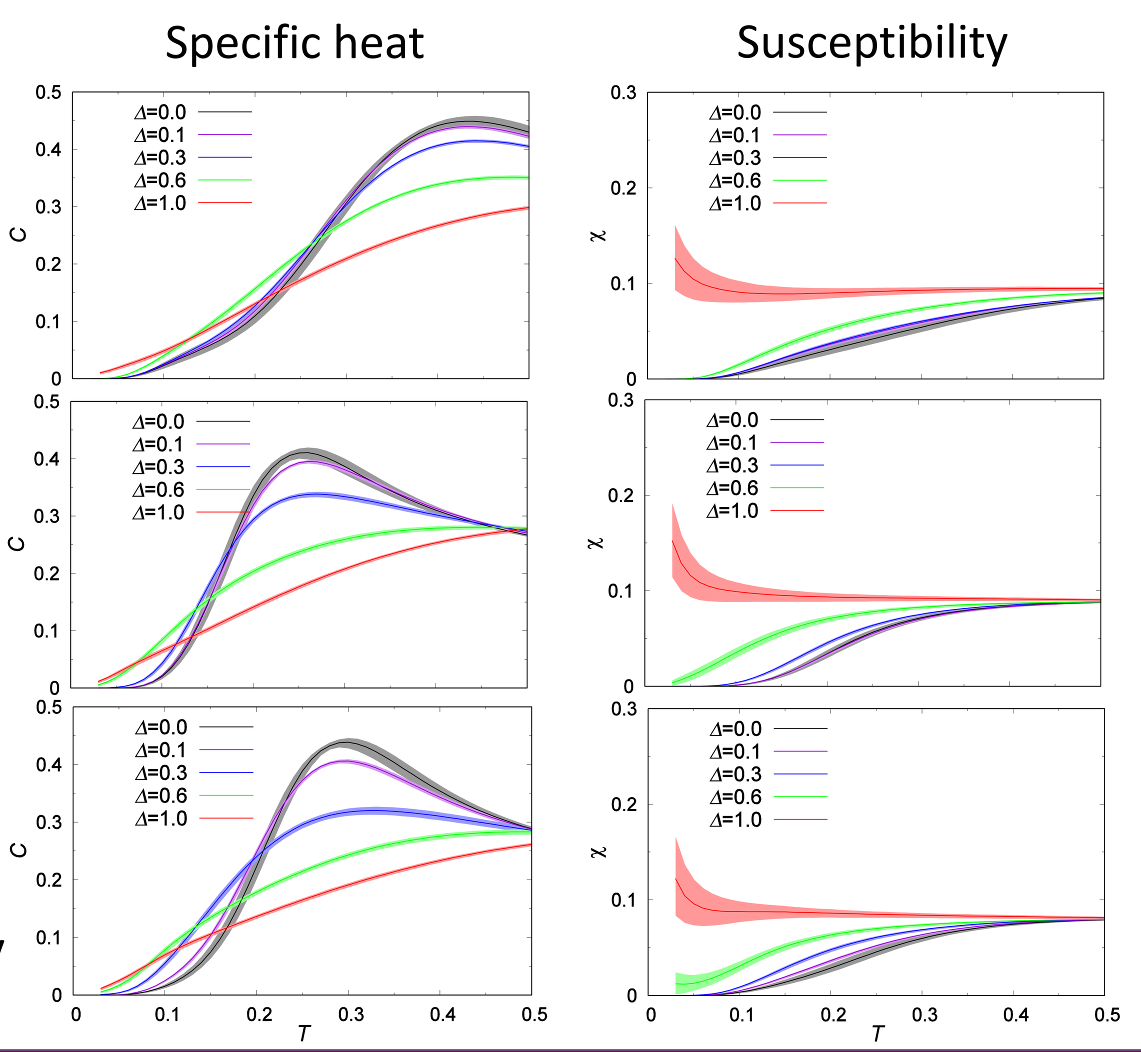
Finite-temperature properties (J_1 : AFM)

AF-RS transition ($J_2=0.3$)

Gapped-RS transition ($J_2=0.5$)

Stripe-SG transition ($J_2=0.7$)

T-linear specific heat and Curie-tail-like susceptibility for $T\lesssim0.1$.



Summary and discussion

By using the ED method, we get the $T=0$ phase diagram of the frustrated $s=1/2$ J_1-J_2 Heisenberg model on the square lattice with FM and AFM J_1 in the randomness ($\varDelta$) v.s. frustration (J_2) plane

- For sufficiently strong frustration and randomness, the RS state and the SG state are stabilized.
- In the ferromagnetic model, the RS state is absent in this parameter region.

$\Rightarrow$ The AFM character is essential to stabilize the RS state.

- The SG state realized in both of the FM and AFM model might be stabilized by employing the two degrees of freedom of the stripe order adjusted to randomness.
- The RS state and the SG state is indistinguishable by the specific heat and the susceptibility in the perfectly equilibrated system.

$\Leftarrow$ In the experiment, the SG state is distinguishable from the RS state by the cusp-like susceptibility accompanying the nonequilibrium effect.