Multiple-*Q* states and skyrmion lattice of the triangular-lattice Heisenberg model under magnetic fields with an incommensurate helical structure

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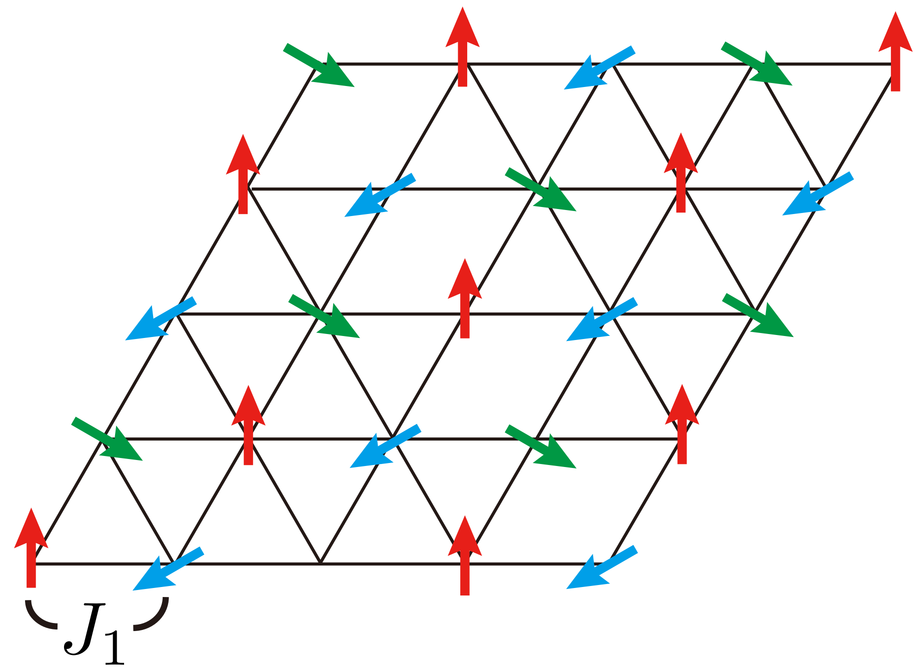
Triangular-lattice Heisenberg antiferromagnets

$$\mathcal{H} = -J_1 \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

$$\vec{S}_i = (S_{i,x}, S_{i,y}, S_{i,z})$$

- Nearest neighbor model: $J_1 < 0$

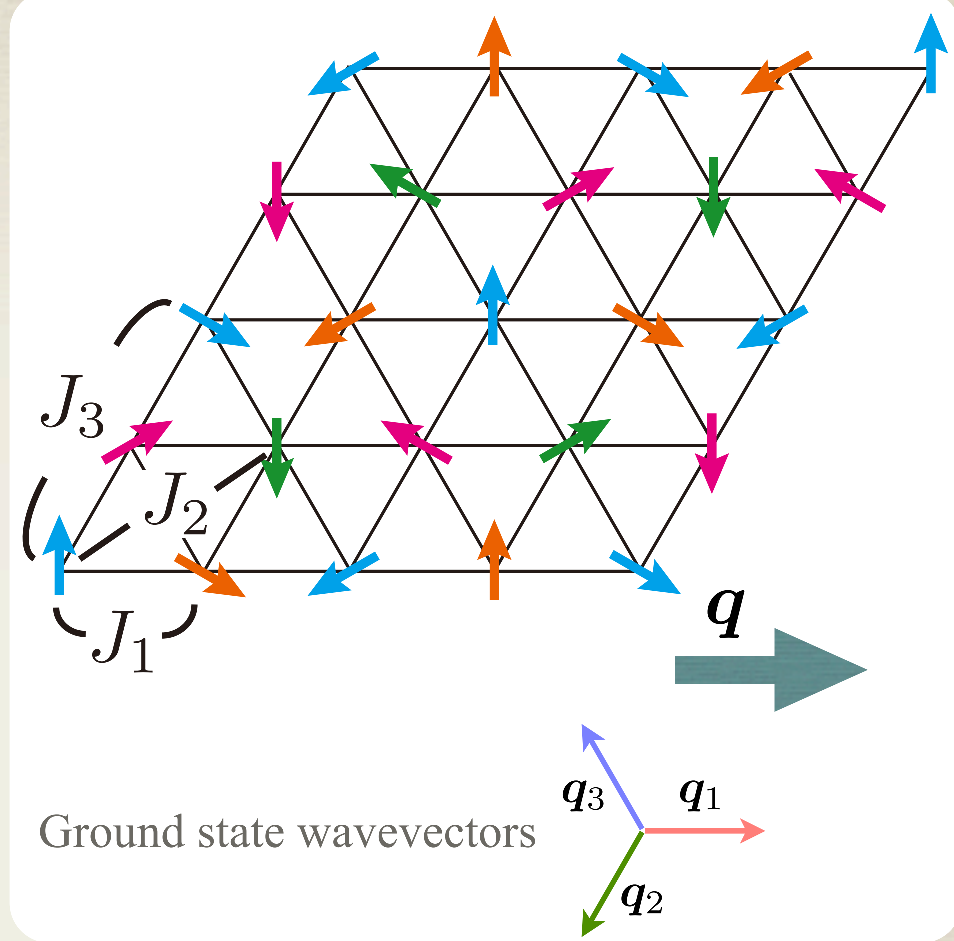
  The ground state is the 120° structure



Triangular-lattice Heisenberg antiferromagnets

$$\mathcal{H} = -J_1 \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j \; -J_2 \sum_{\langle i,j \rangle_2} \vec{S}_i \cdot \vec{S}_j - J_3 \sum_{\langle i,j \rangle_3} \vec{S}_i \cdot \vec{S}_j$$

$\vec{S}_i = (S_{i,x}, S_{i,y}, S_{i,z})$ $J_2, J_3 < 0$: antiferromagnetic



- Nearest neighbor model: $J_1 < 0$

  The ground state is the 120° structure

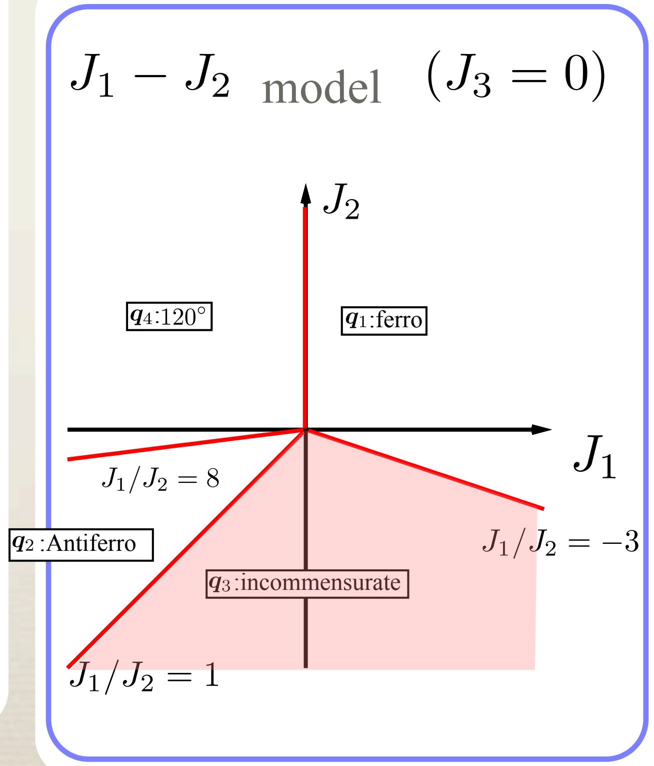
- Effects of further neighbor interactions

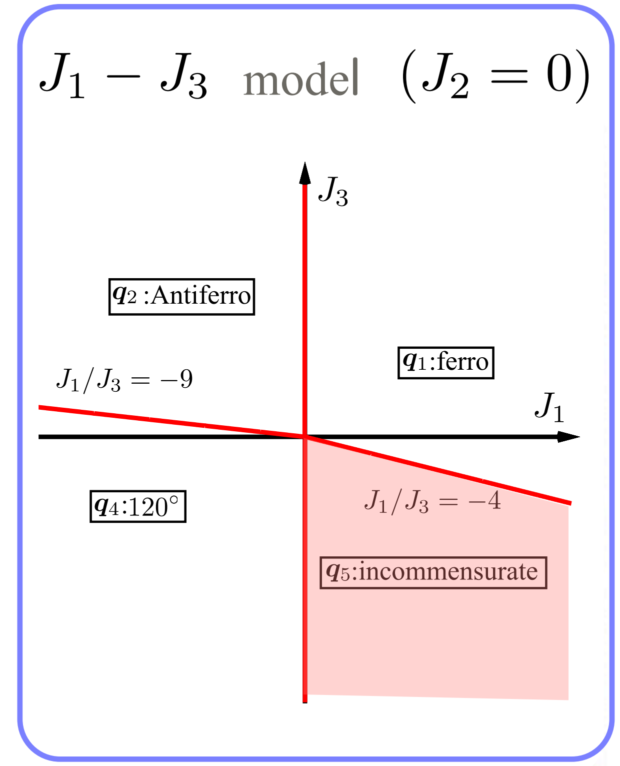
Large antiferromagnetic J_2, J_3

The ground state is an incommensurate spiral

Three-fold degeneracy
with respected to the choice of
three equivalent directions on the lattice

c.f. $NiGa_2S_4$: $J_1/J_3 \simeq -0.2$
$J_1 > 0$: Ferromagnetic



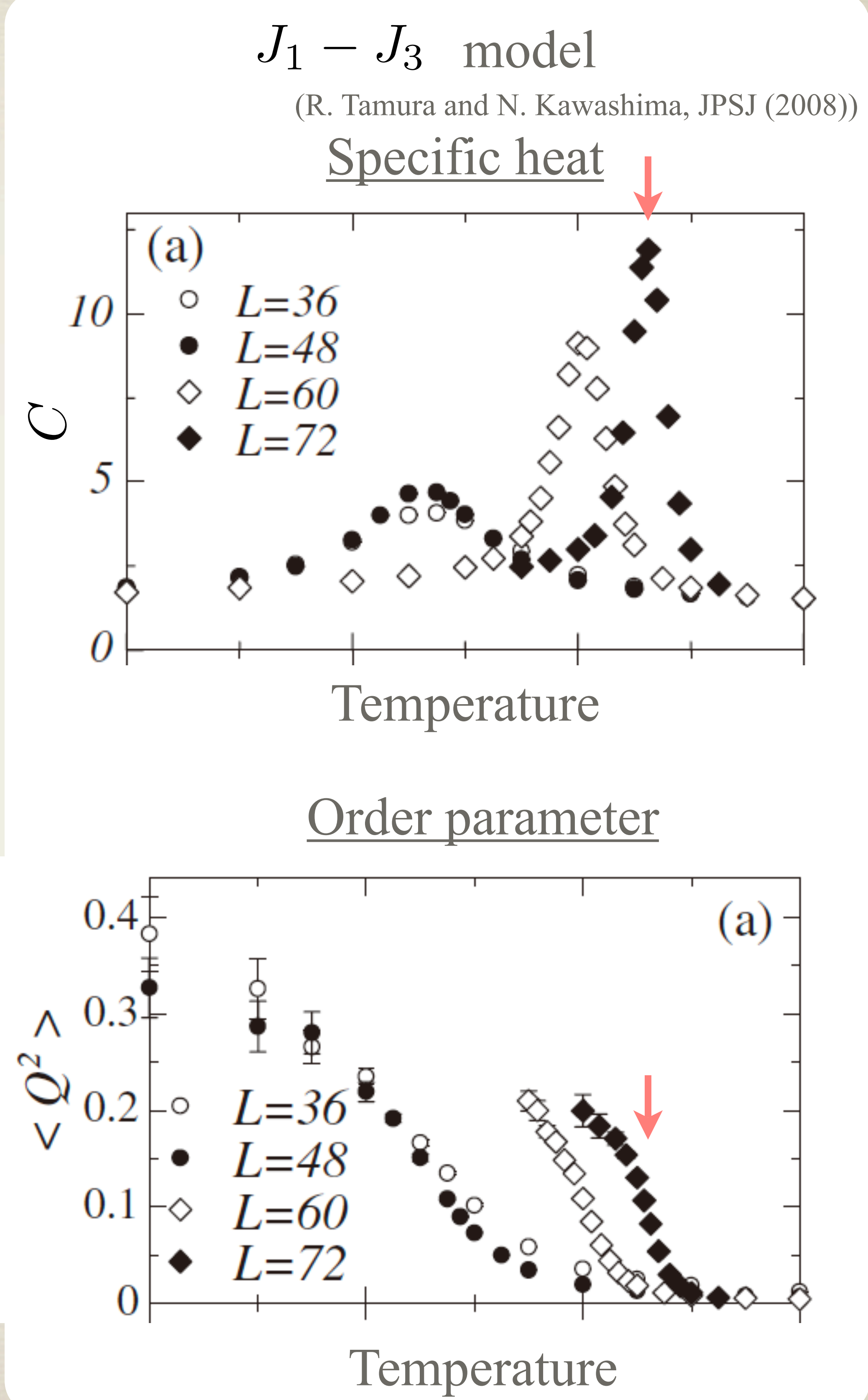


Ordering due to the three-fold degeneracy

1. Phase transition associated with breaking of the three-fold lattice symmetry

(R. Tamura and N. Kawashima, 2008)

- In zero magnetic fields, the ordered state is a single-q spiral state.



Ordering due to the three-fold degeneracy

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(R. Tamura and N. Kawashima, 2008)

- In zero magnetic fields, the ordered state is a single-q spiral state.

2. Possibility of multiple-q states

Multiple-q state：

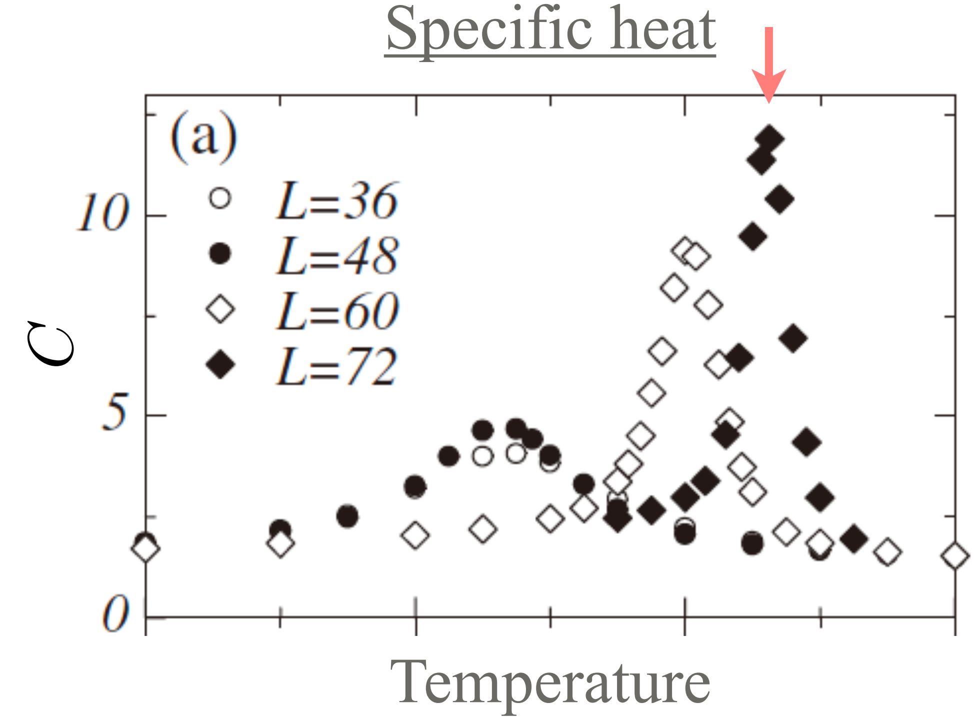
More than one wavevectors coexist

➡ It might be realize under applied fields.

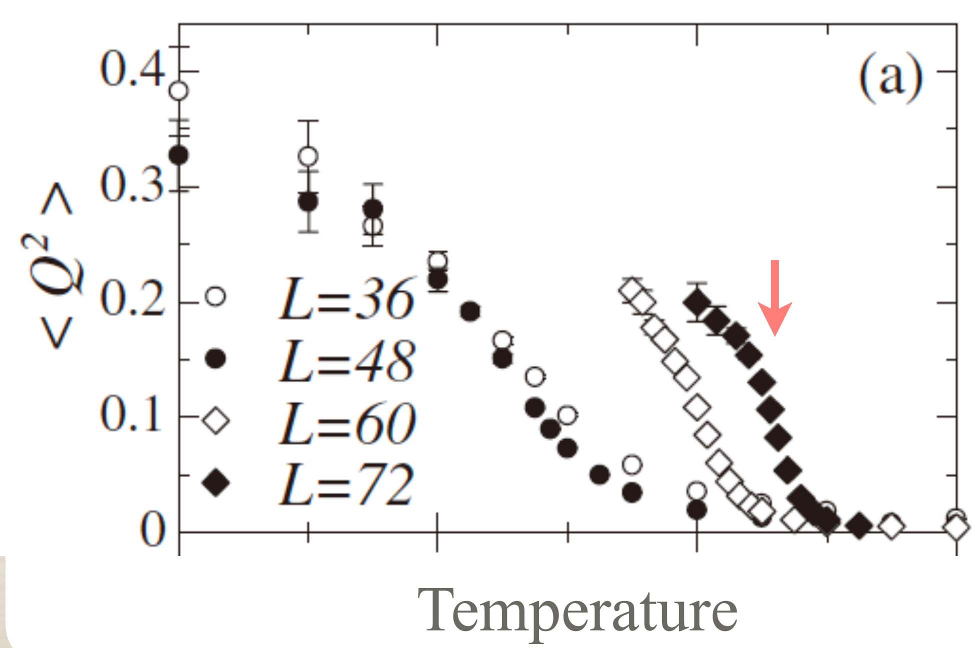
$J_1 - J_3$ model

(R. Tamura and N. Kawashima, JPSJ (2008))

Specific heat



Order parameter



Model and methods

Triangular-lattice *J_1-J_3* (or *J_1-J_2*) model:

$$\mathcal{H} = -J_1 \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j - J_2 \sum_{\langle i,j \rangle_2} \vec{S}_i \cdot \vec{S}_j - J_3 \sum_{\langle i,j \rangle_3} \vec{S}_i \cdot \vec{S}_j - H \sum_i S_{i,z}$$

$J_2, J_3 < 0$ ：antiferromagnetic

Purpose：

To clear the ordering of the triangular-lattice Heisenberg model with an incommensurate ground state under magnetic fields

Question： Are multiple-*q* states stabilized under applied fields?

Methods： Mean-field analysis

Monte Carlo simulations

Model and methods

Triangular-lattice J_1-J_3 (or J_1-J_2) model:

$$\mathcal{H} = -J_1 \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j \; -J_2 \sum_{\langle i,j \rangle_2} \vec{S}_i \cdot \vec{S}_j - J_3 \sum \vec{S}_i \cdot \vec{S}_j \; -H \sum S_{i,z}$$

Answer：

・Several types of multiple-q states are indeed stabilized under magnetic fields.

・One of them corresponds to the so called "*skyrmion lattice*" state.

Purpose：

To clear the o

model wi

Question： Are multiple-q states stabilized under applied fields?

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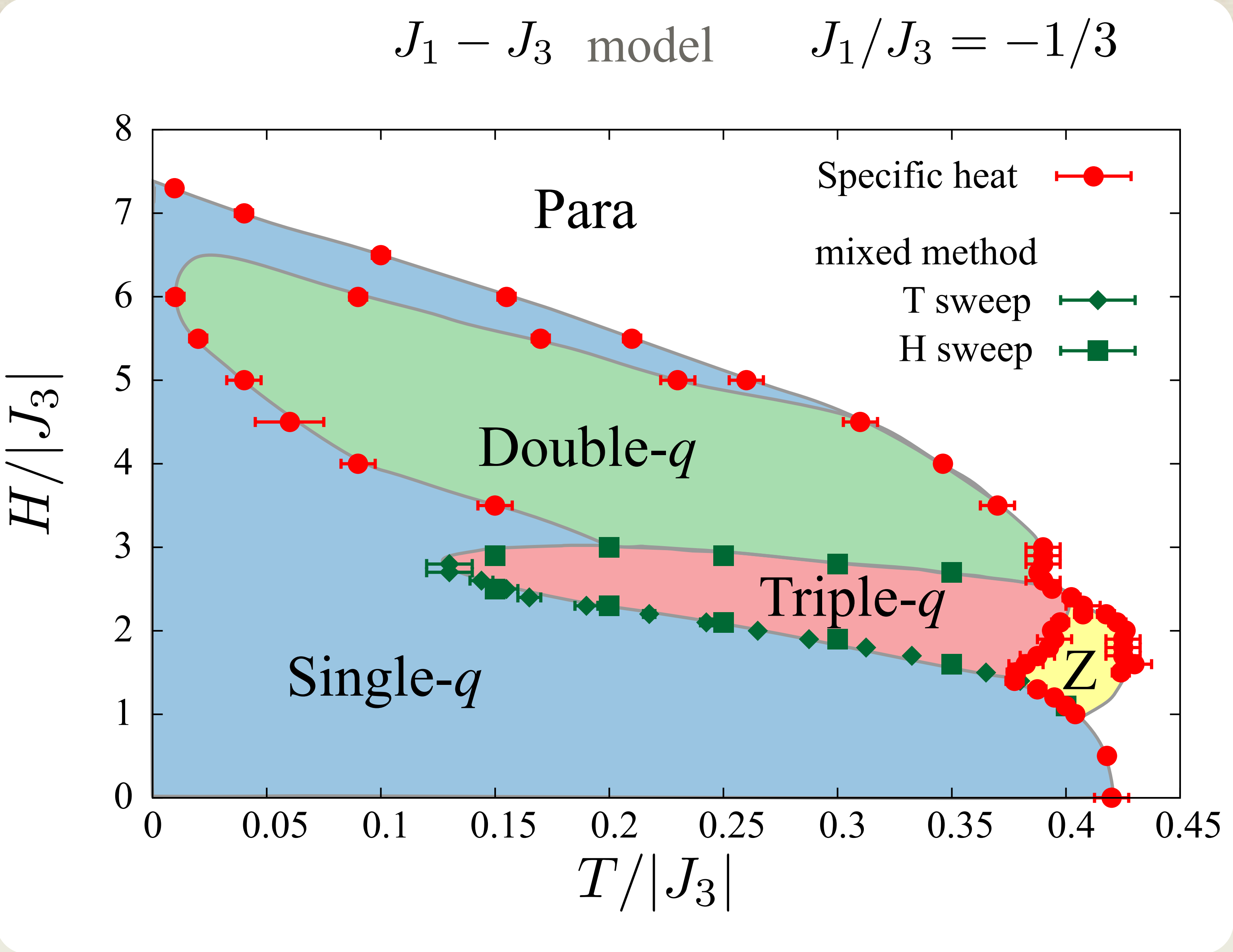
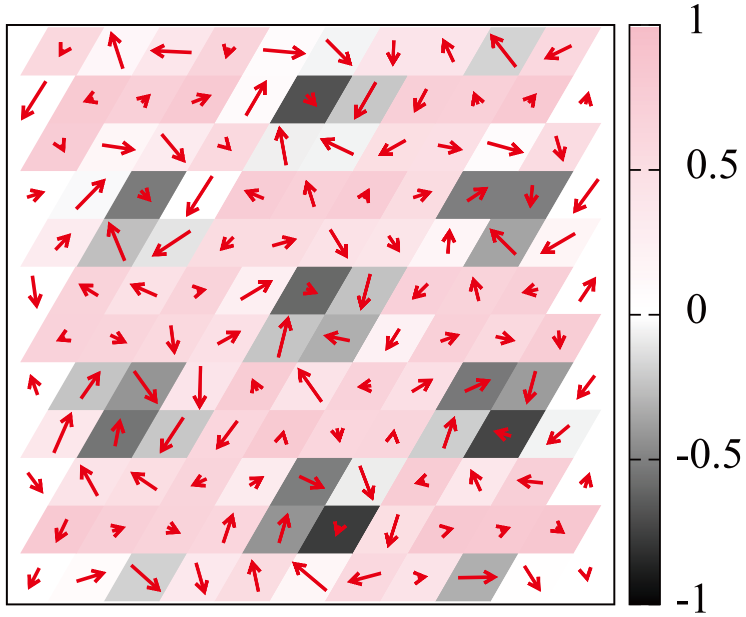
Phase diagram



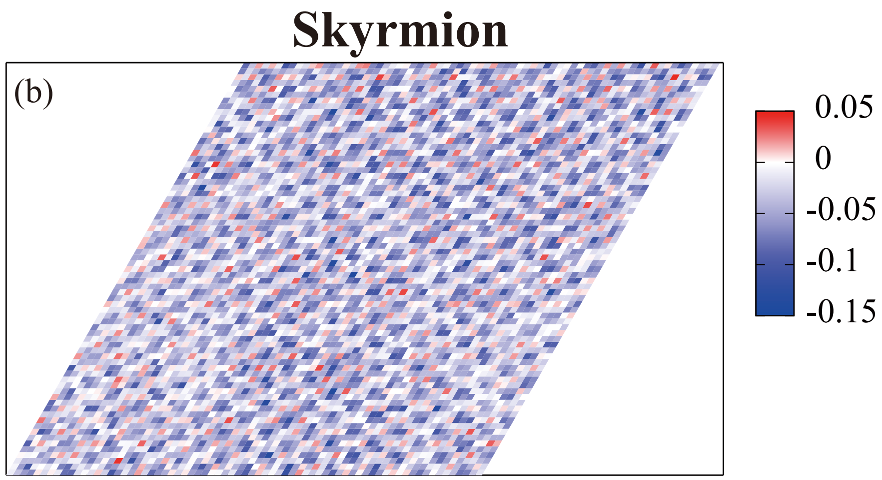
- In addition to the single-q state, the double-q and the triple-q states are stabilized under magnetic fields.
- Triple-q phase and Z phase are related to the skyrmion lattice

Triple-q phase: the skyrmion lattice

Snapshot

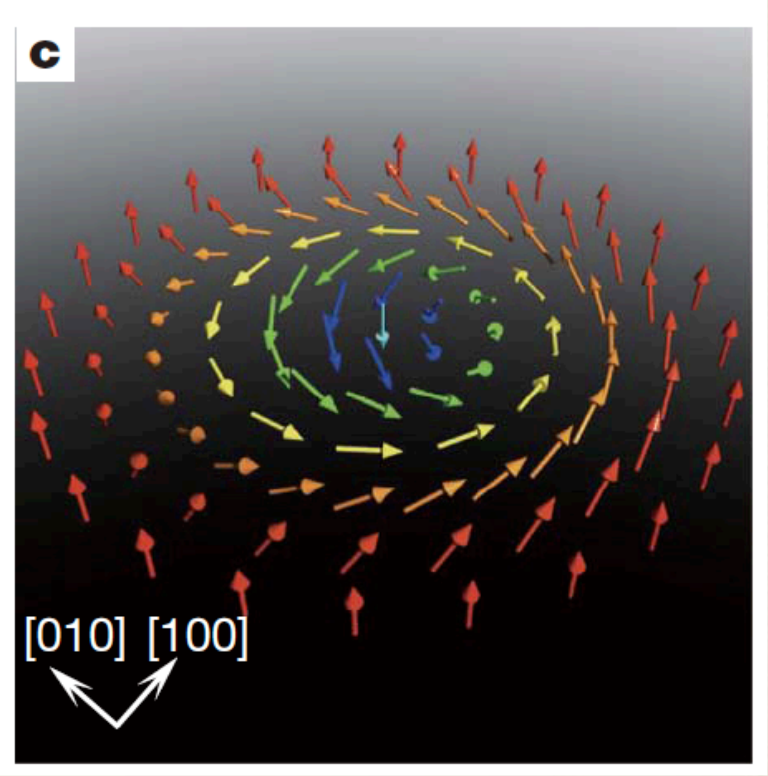


Skyrmion density

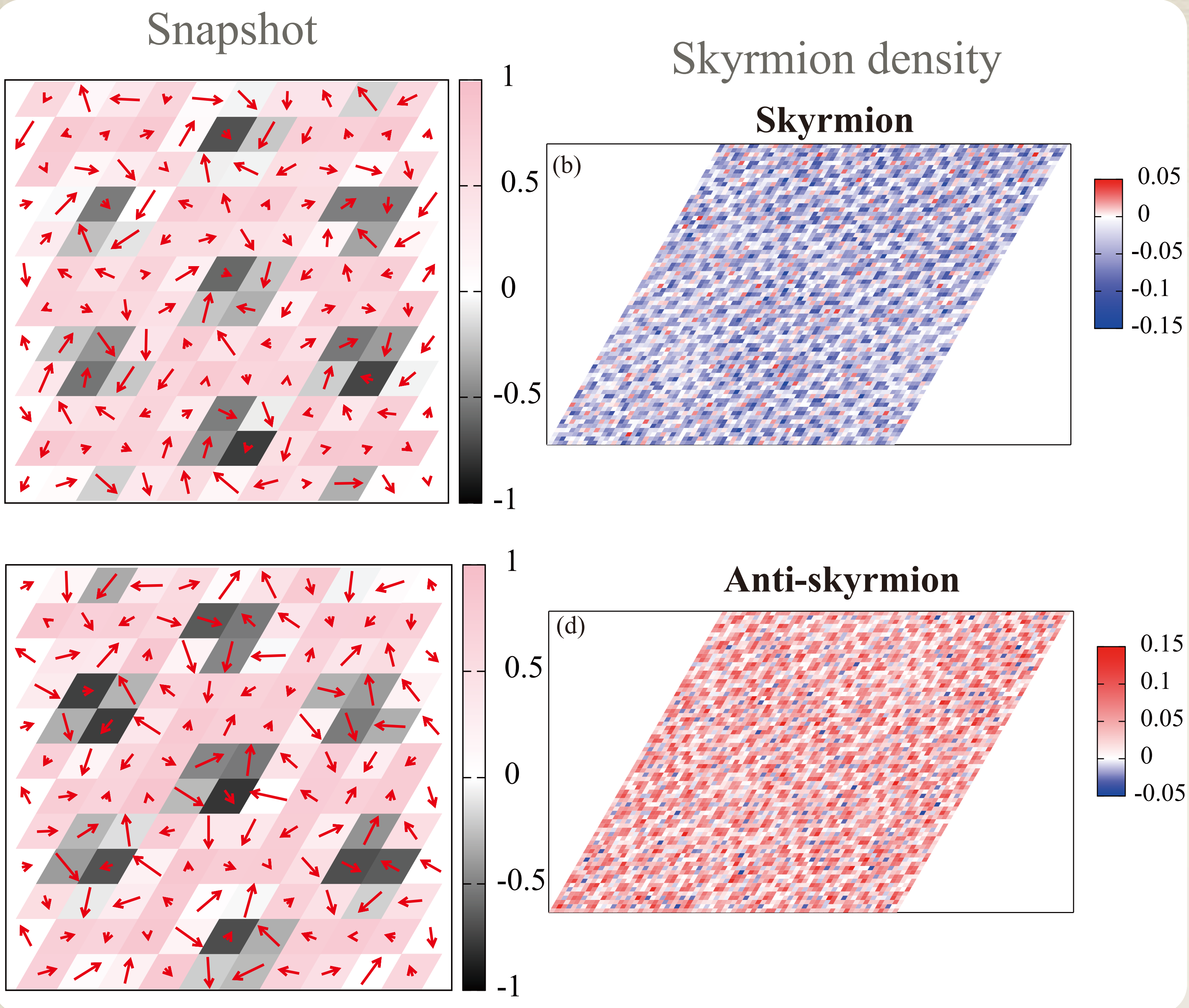


Skyrmion

X. Z. Yu et al., Nature (2010)



Triple-*q* phase: the skyrmion lattice



Skyrmion

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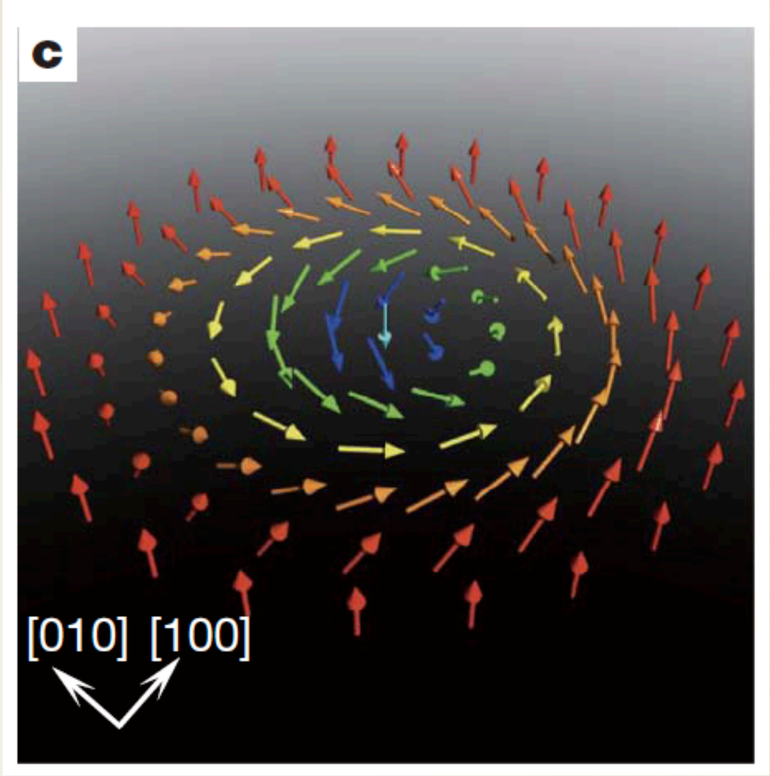
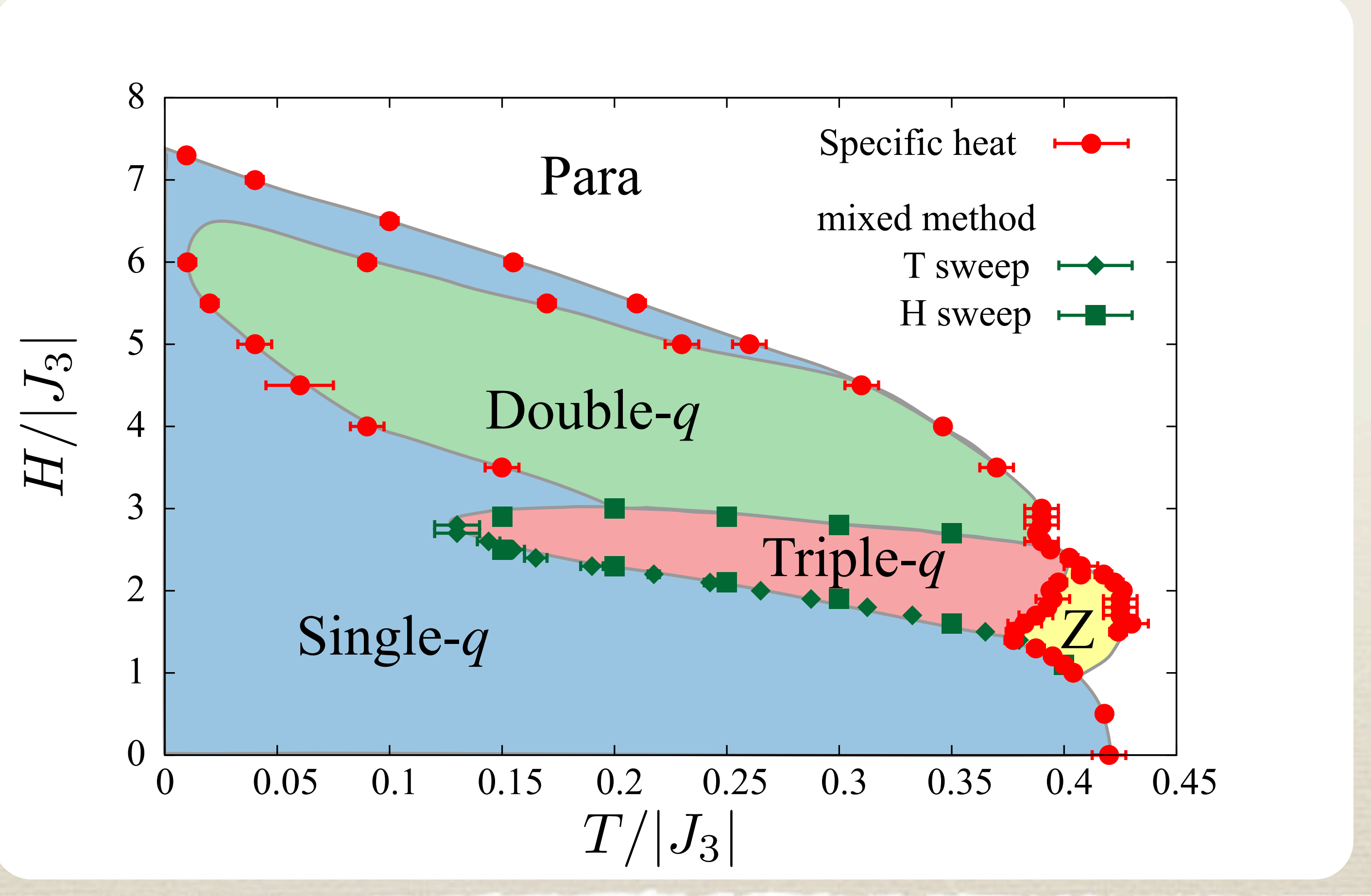


Both skyrmion and the anti-skyrmion lattices are possible.

Z phase:
A domain state of skyrmion and anti-skyrmion lattices

Summary

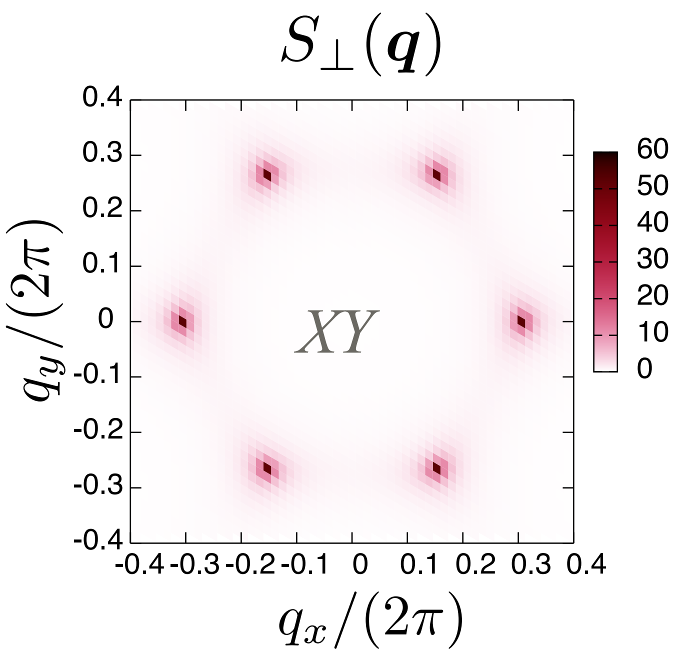
- We investigated the ordering of the classical Heisenberg model on the triangular-lattice with an incommensurate helical spin structure under magnetic fields.
  - In addition to the standard single-*q* phase, the double-*q* and the triple-*q* phases are stabilized under applied fields.
  - The spin structure in the triple-*q* phase is the skyrmion lattice.
  - A domain state of skyrmion and anti-skyrmion lattices also appears.

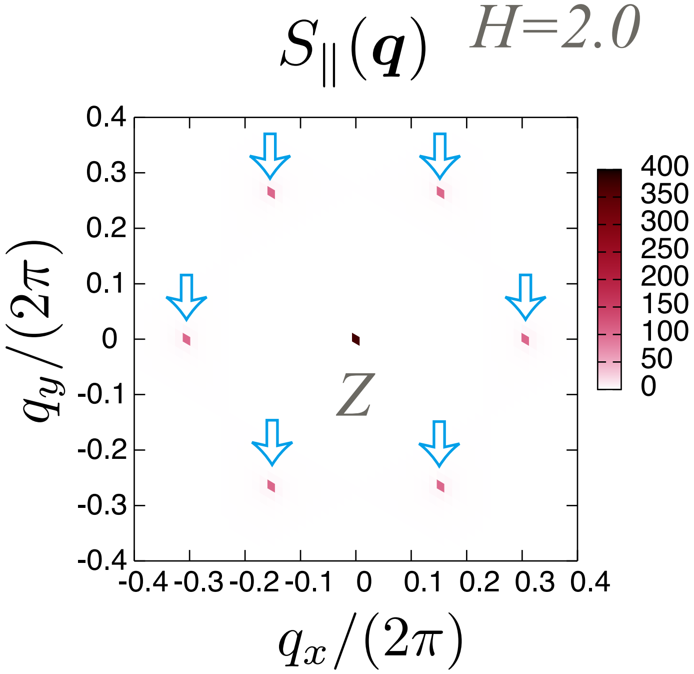


“Z” Phase

A domain state of skyrmion and anti-skyrmion lattices

Spin structure factor T=0.41 H=2.0



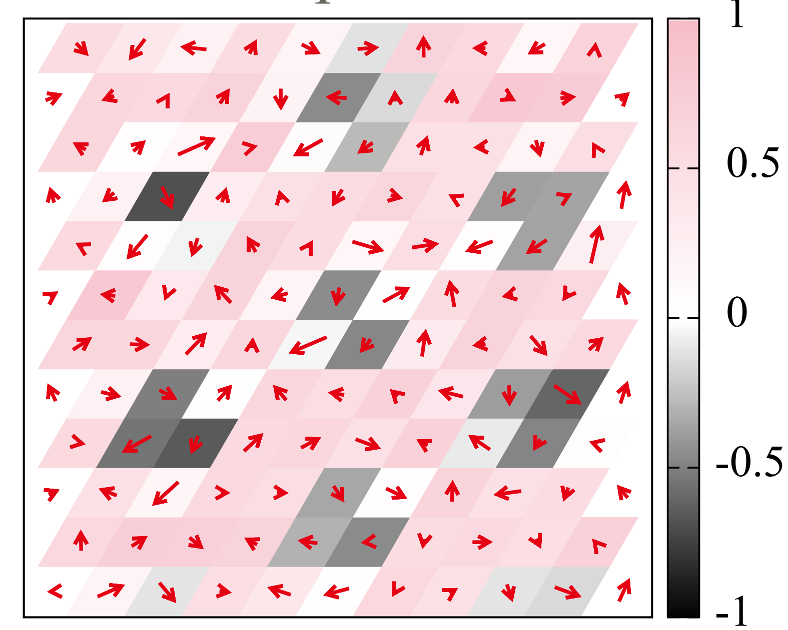


XY: broad peaks ⟷ *Z*: sharp peaks

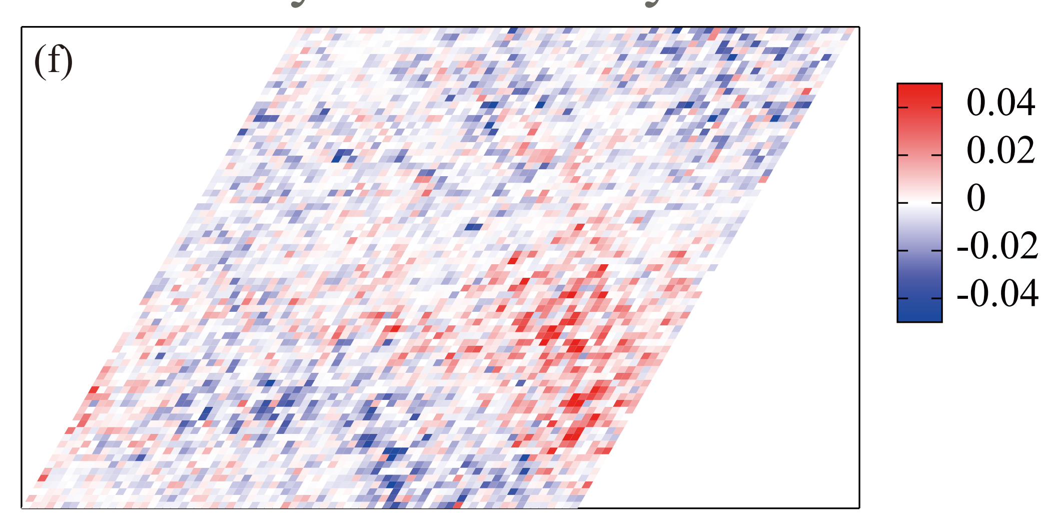
Only the *Z* component retains a quasi-long-range order similar to the triple-*q* phase.

- A domain state of skyrmion and anti-skyrmion lattices

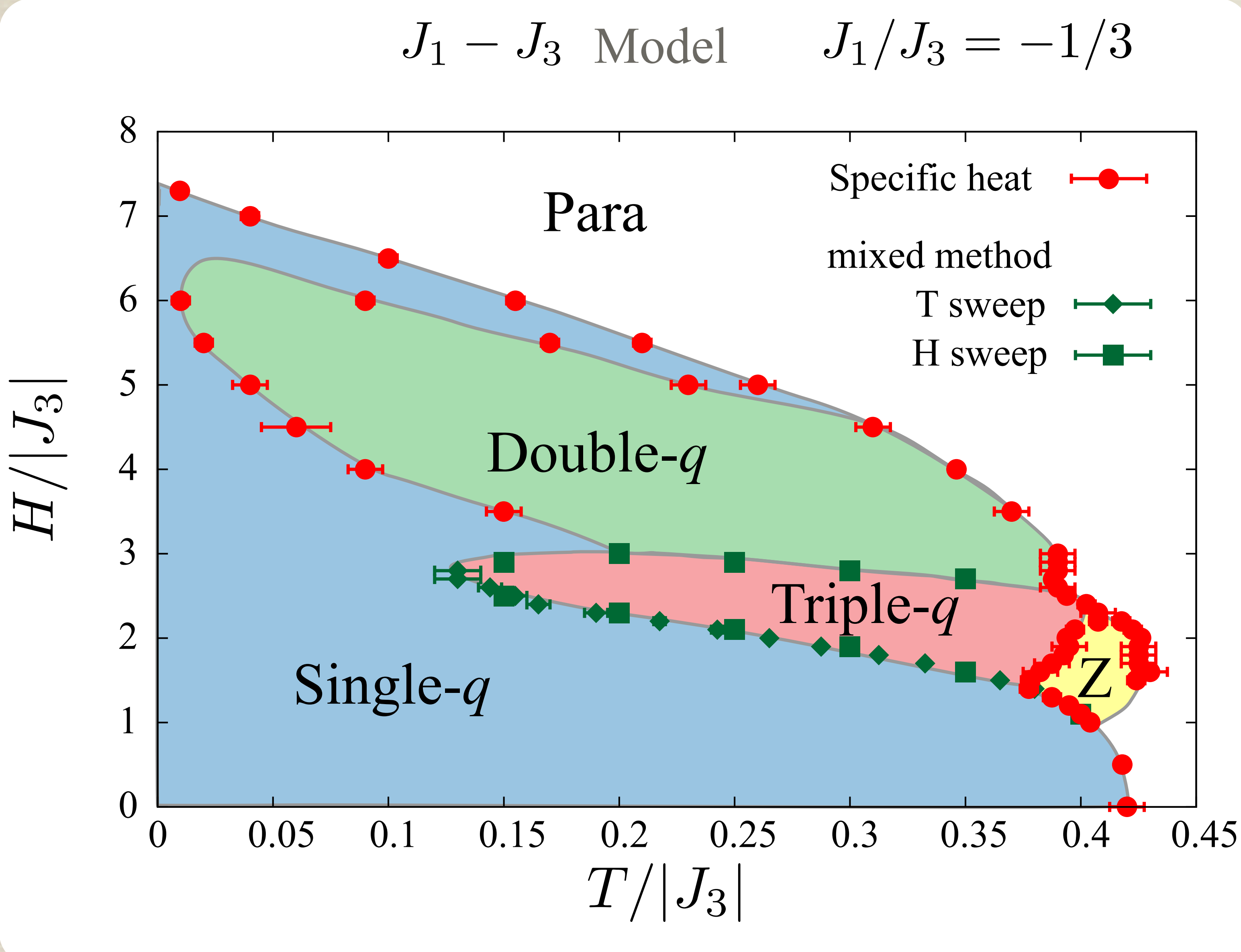
Snap shot

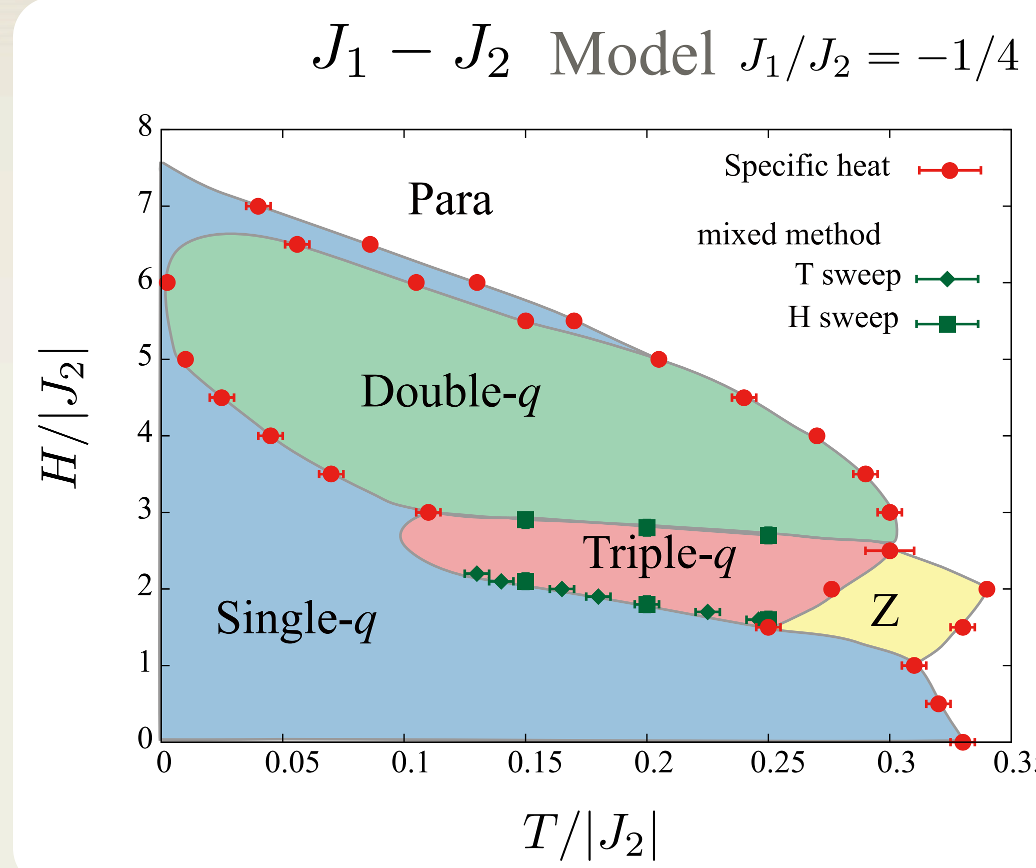


Skyrmion density



Phase diagram





- In addition to the single-q state, the double-q and the triple-q states are stabilized under magnetic fields.
- A similar phase diagram is obtained also for the J_1-J_2 model