特定領域研究「新量子相の物理」

Quantum phases and their Dynamical responses

Quantum dynamics under time-dependent external fields

Seiji Miyashita
University of Tokyo

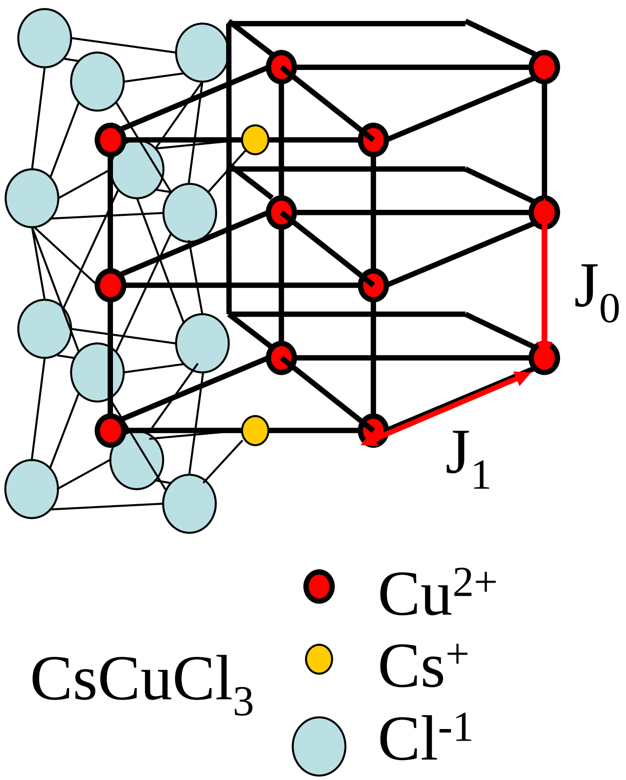
Quantum phases and their Dynamical responses

- New type magnetic states on frustrated lattices
- Gapless ferrimagnetic state
- Lattice gas model: solid, liquid, superliquid, supersolid
- Dynamical properties of peculiar states

Virtual interaction effects (Fluctuating media)

Many-body (ring) exchange model + phonon

Fluctuation induced phase transition in magnetization process of XY-Heisenberg antiferromagnets on the triangular lattice

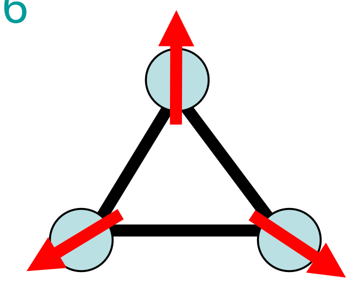


$CsCuCl_3$

CsCuCl3

H. Nojiri, T. Tokunaga and M. Motokawa
J. De Physique C8 49 (1988) 1456

H. B. Weber et al.
Phys. Rev. B54 (1996) 15924



Quantum fluctuation

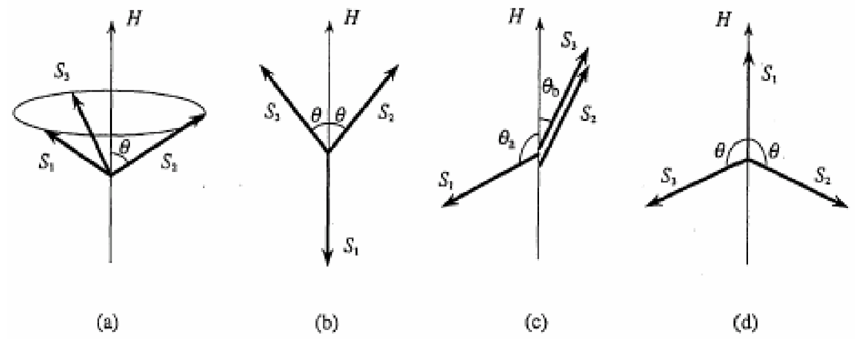
T. Nikuni and H. Shiba,
JPSJ 62 (1993) 3268, 64 (1995) 3471,
A. E. Jacobs, T, N and H.S.,
JPSJ 62 (1993) 4066.

Thermal fluctuation

S. Watarai, S. Miyashita and H. Shiba,
JPSJ 70 (2001) 532.

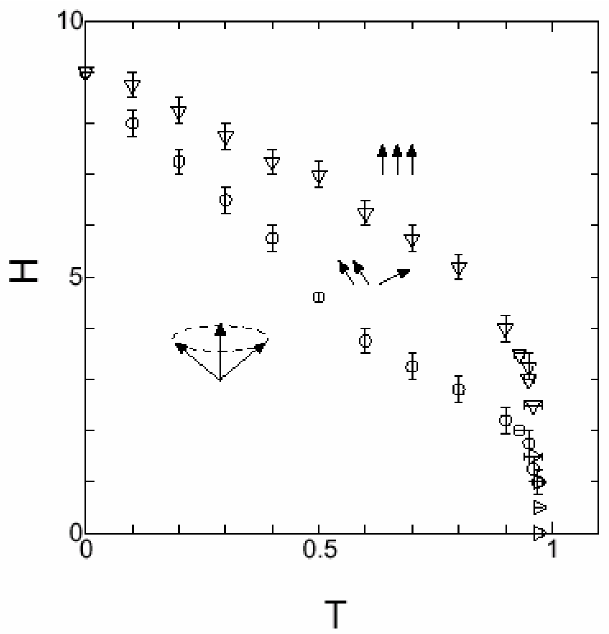
Classical XY-Heisenberg model

$$H = \sum_{<ij>} \overrightarrow{S_i} \cdot \overrightarrow{S_j} - D \sum_i (S_i^z)^2$$

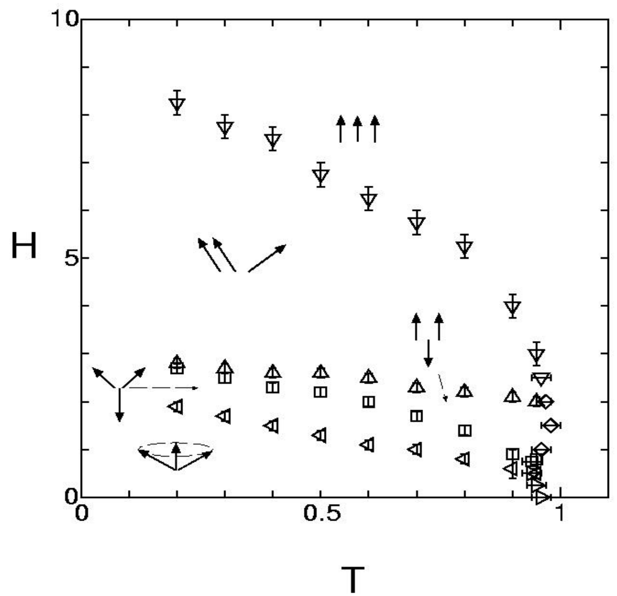


Entropy induced phase transition

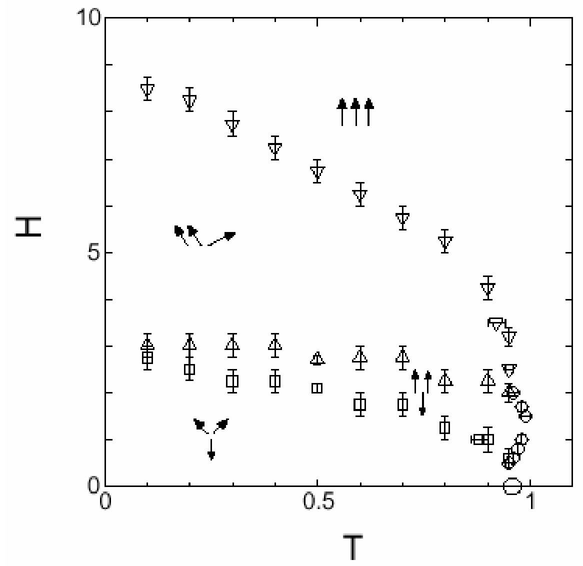
D=-0.1



D=-0.01

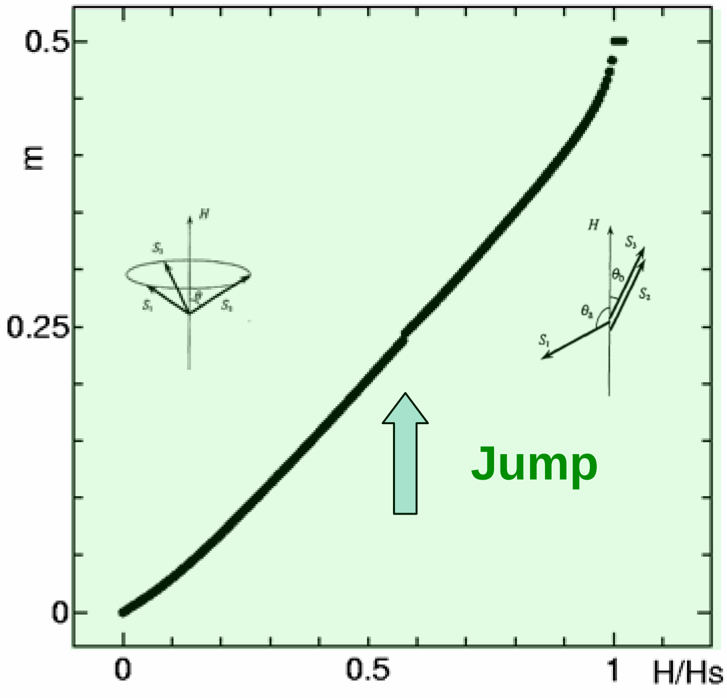


D=0

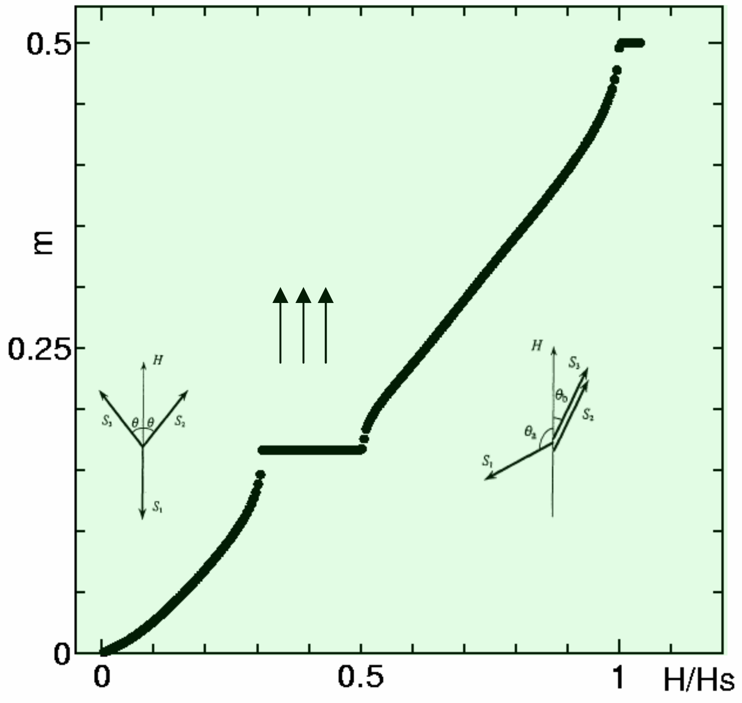


S. Watarai, S. Miyashita and H. Shiba: JPSJ 70 (2001) 532

2D XXZ Heisenberg model

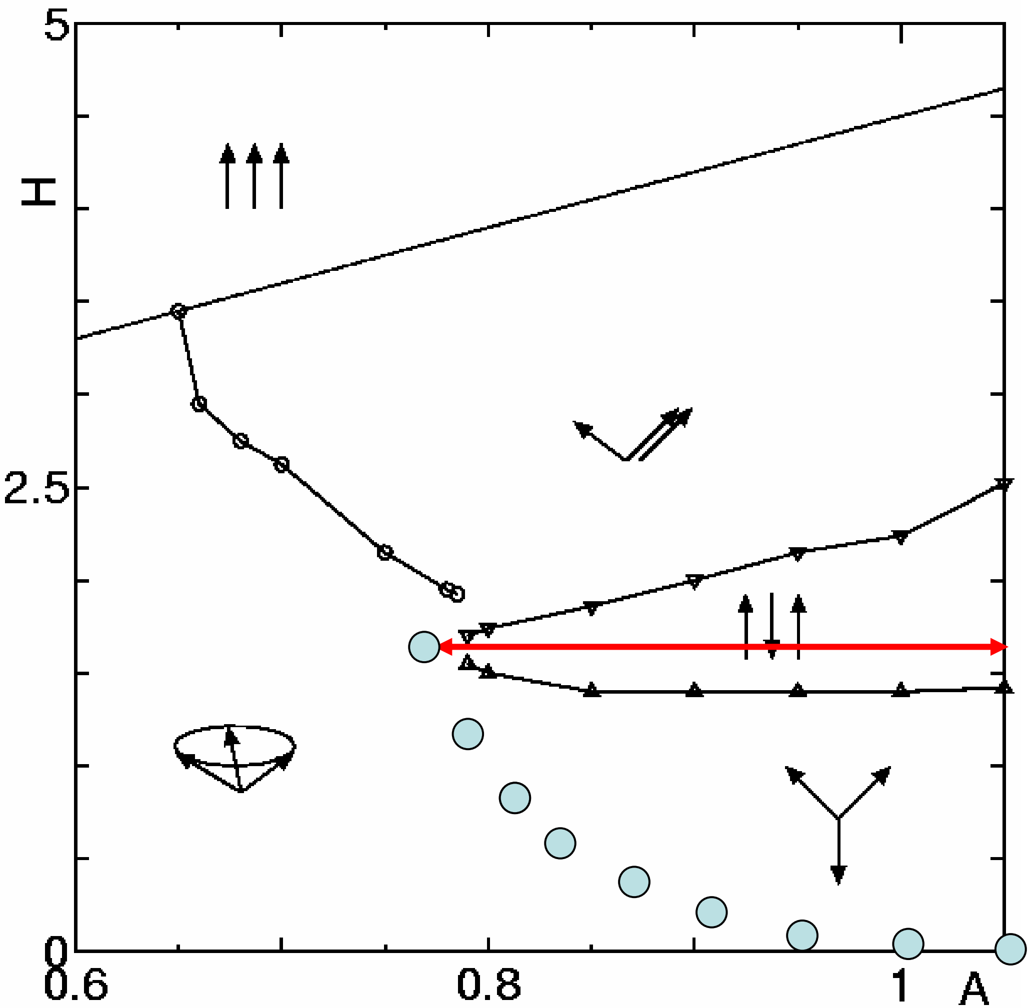


A=0.75



A=1

Phase diagram in (H,A)



1/3 plateau

$$A_C = 0.76 \pm 0.03$$

Quantum fluctuation chooses a configuration from degenerate states.
The choice depends on the spin anisotropy. The dependence is very similar to that of thermal fluctuation at finite temperatures.

This phase diagram is obtained from long range correlation of the chirality

A. Honecker, J. Richter, J. Phys. Condens. Matter 16 (2004) S749

Uniform nonzero magnetization in the ground state?

Ferri-magnetic state

- Lieb-Mattis type

  Localized magnetic moment

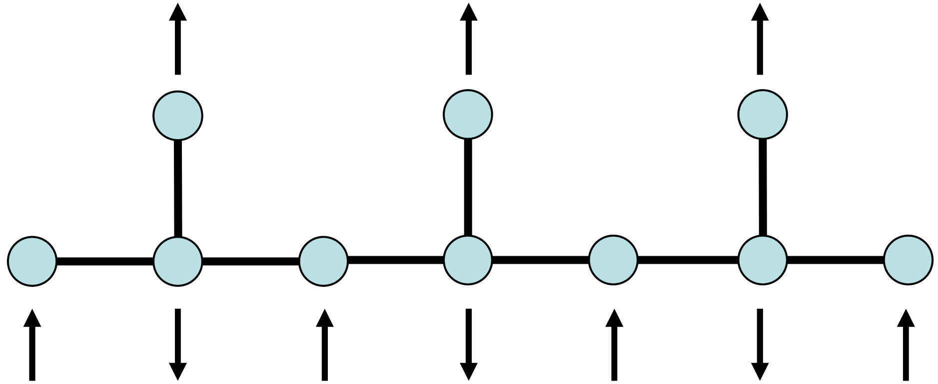
- Non-collinear type

  Uniform magnetic moment

M. Senda: Master thesis Osaka University 1998
N. Muramoto and M. Takahashi: JPSJ 68 (1999) 2098.
S. Yoshikawa and S. Miyashita: JPSJ Supple 2005

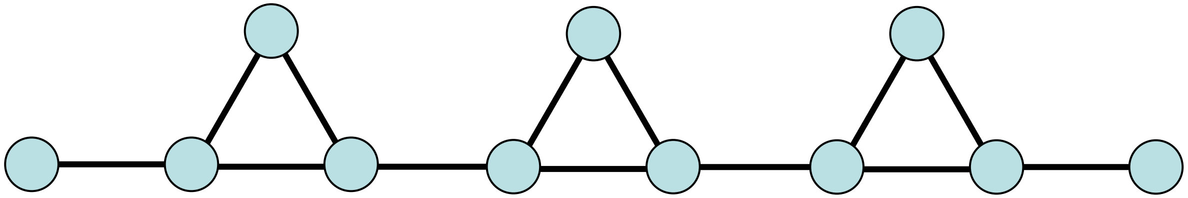
Attempt to find non-saturated ferrimagnetic state in Heisenberg model

- Lieb-Mattice ferri magnetism (LMFR)

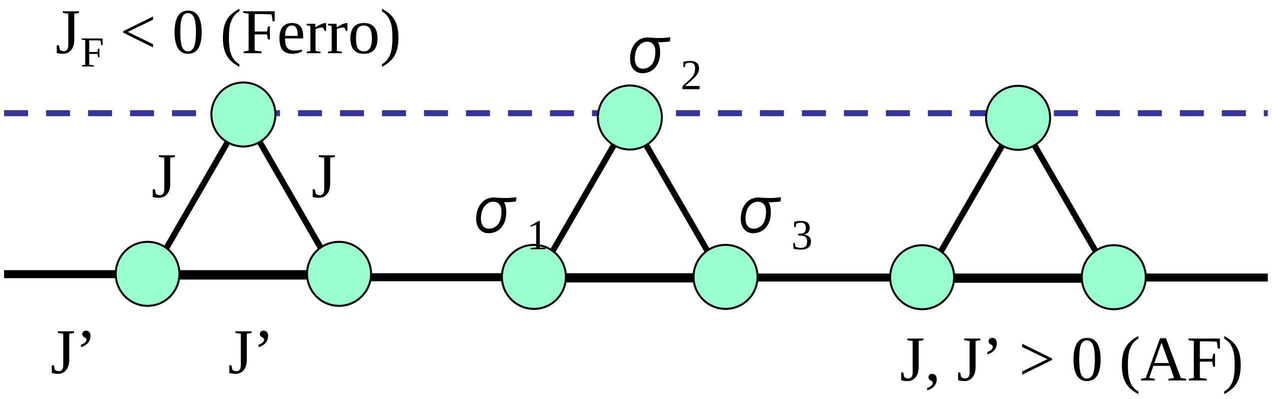


$M_G = |N_A - N_B|/2$

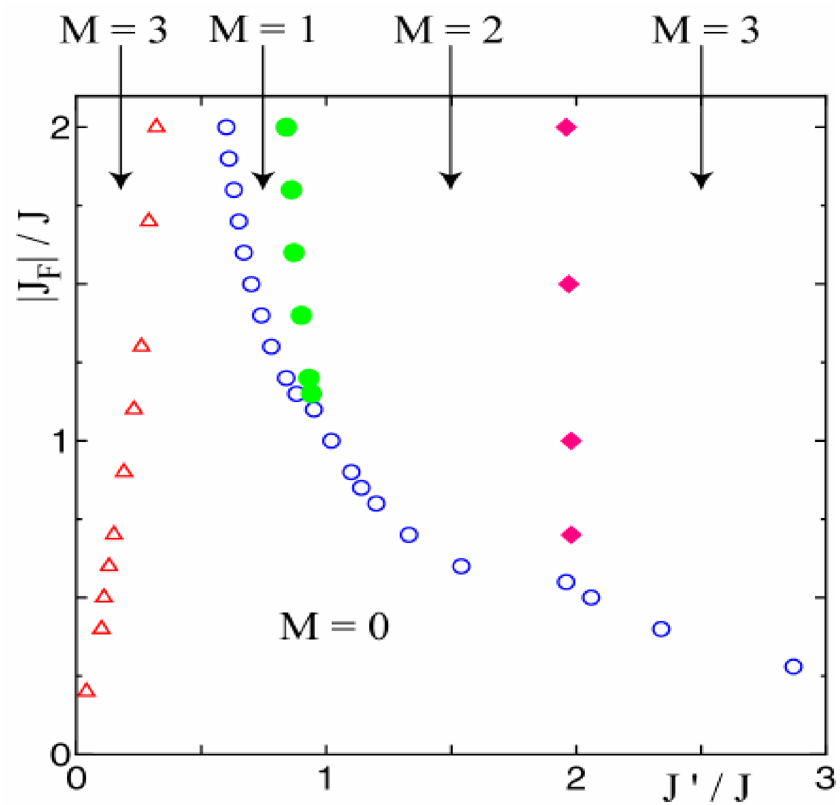
- Non Lieb-Mattice ferri magnetism (Non-LMFR, Non-collinear ferri)



Non-saturated magnetized state



N=18

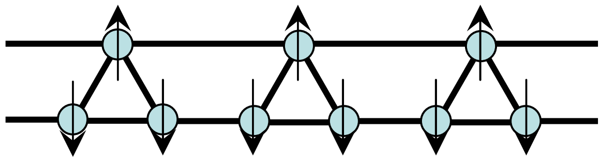


J >> J’ : LMFR

J << J’ : Non-LMFR

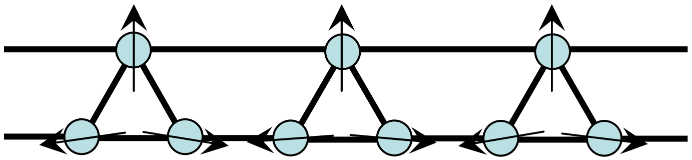
Magnetization processes

J >> J' : LMFR



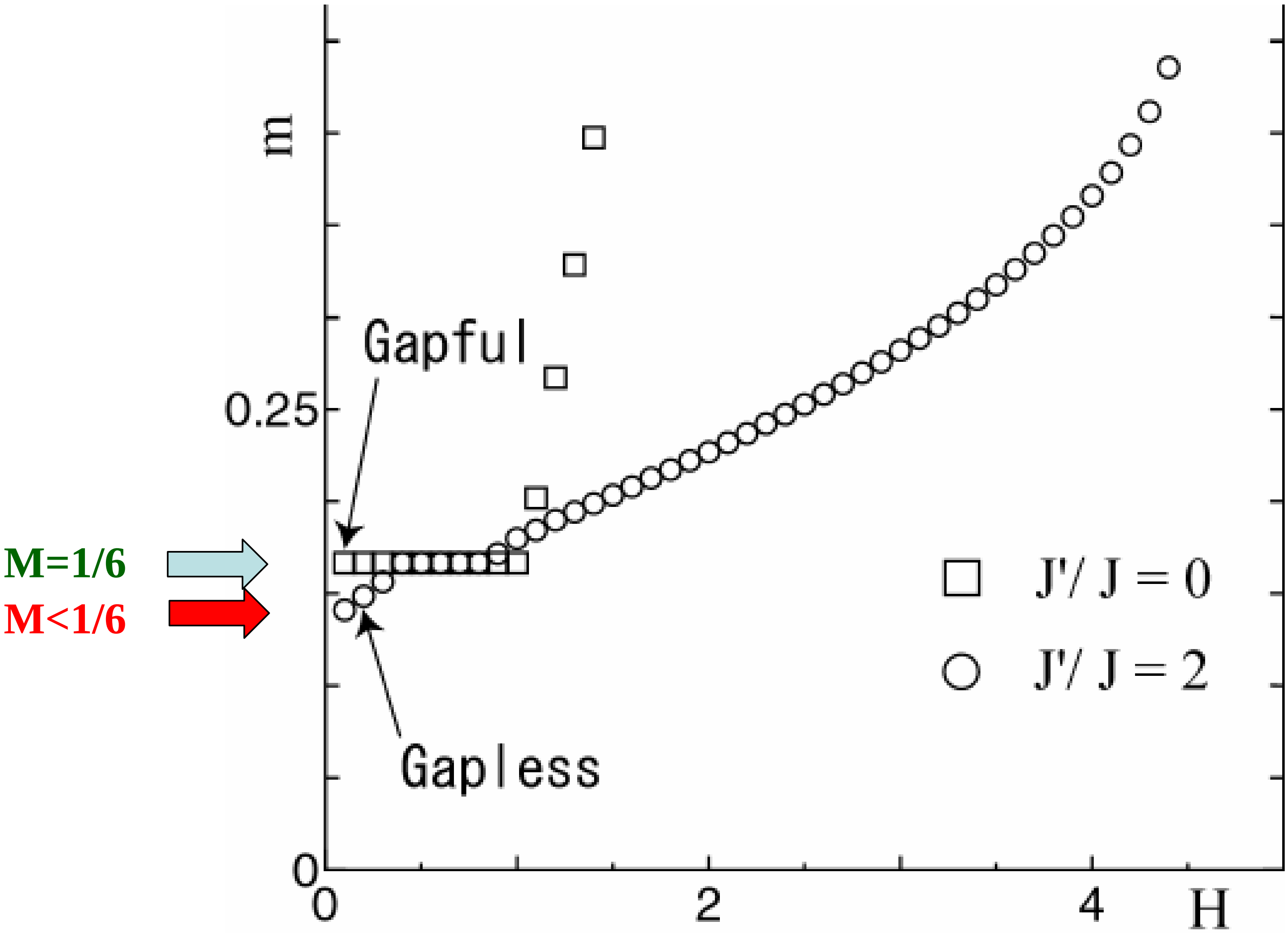
LM type:
Gapfull
Saturated magnetization

J << J' : Non-LMFR



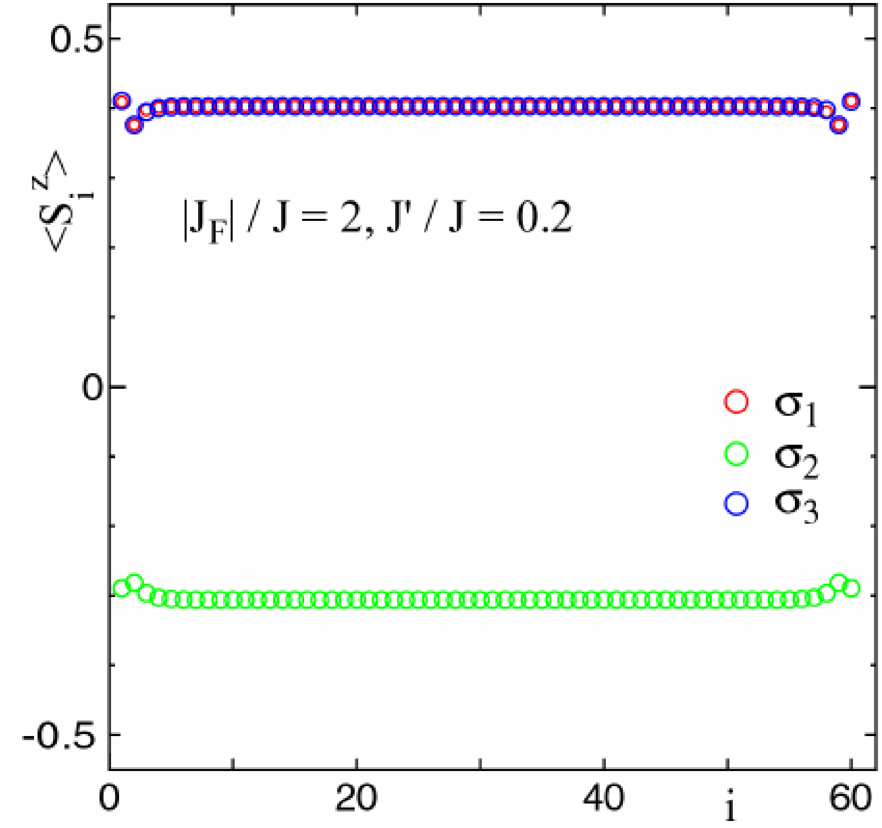
Non-collinear type
Gapless
Saturated magnetization
Smooth magnetization process

Magnetization processes

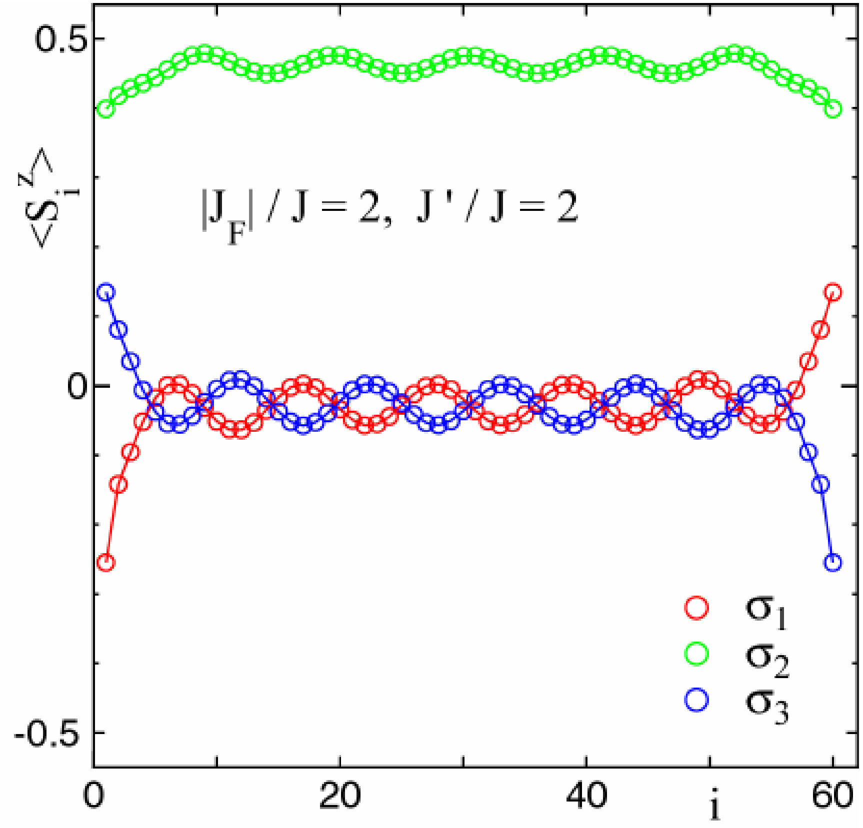


Local magnetic structures

LM phase

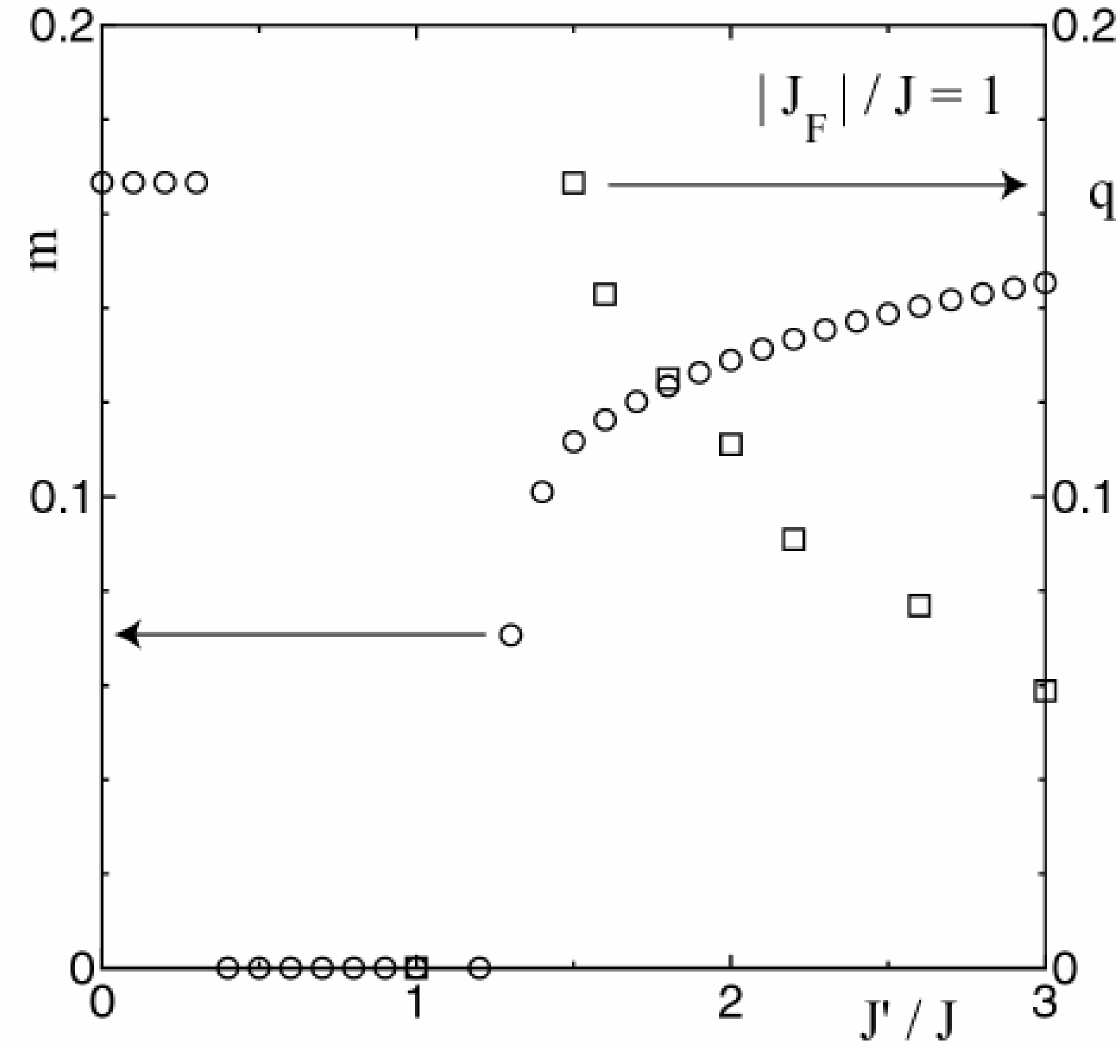


Non-collinear phase



3×60

Wave number of the moduration



$$\Delta m = M_{\text{Saturate}} - m$$

$$q \propto \Delta m, \qquad q_{\text{F}}\,?$$

Supersolid

Quantum Lattice gas

T. Matsubara and H. Matsuda: PTP 16 (1956) 569.

$$H = -\sum_{<ij>}\left[J\left(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+\right) - J_z\sigma_i^z\sigma_j^z\right]$$

Frustration among interaction

S. Miyashita: JJAP Supple. 26 (1987) 26

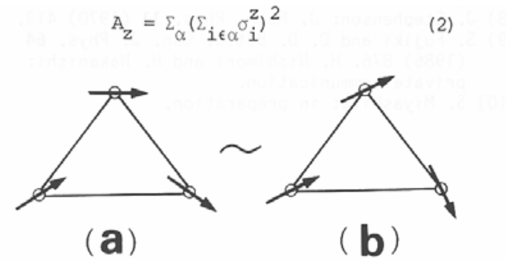


Fig. 1. Non-collinear ground state configurations for the classical system corresponding to (1).

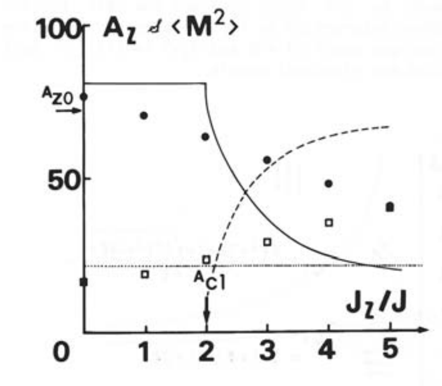
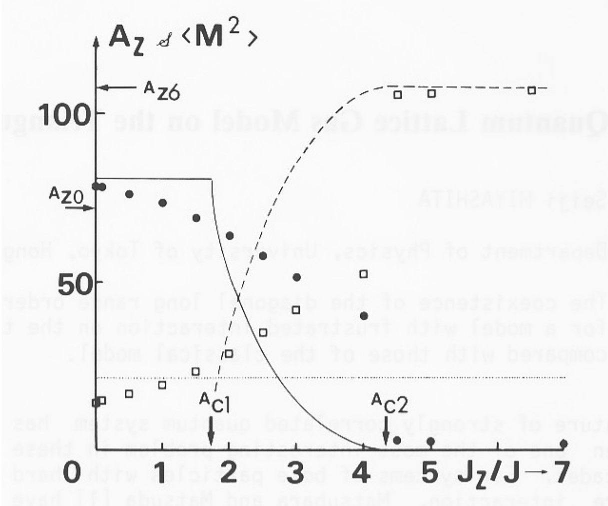


Fig. 2. The ratio J_z/J dependences of A_z (□) and $\langle M^2\rangle$ (●). A_{zo} denotes the maximum value of A_z in the M_z=0 subspace. A_{c1} denotes the critical value in the classical system.

Nearest neighbor



NN+NNN

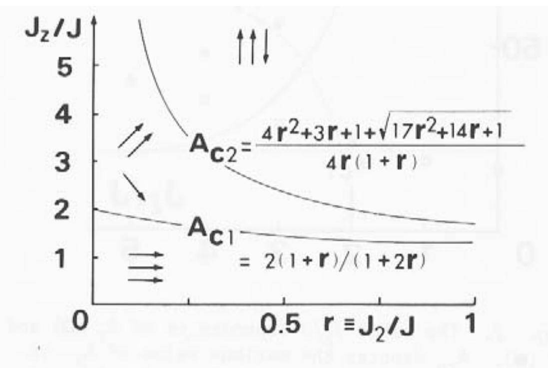


Fig. 3. The ground state phase diagram for the classical model corresponding to (1).

classical

Supersolid

$$H = -t\sum_{<ij>}\left(a_i^{+}a_j + a_j^{+}a_i\right) + V\sum_{<ij>} n_i n_j$$

Condensation of Defect:
A.F. Andreev and I. M. Lifshitz:
Sov. Phys. JETP 29 (1969) 1107.
Solid + vacancies = mass flow (torsional oscillator:
E. Kim and M. H. W. Chan: Nature 427 (2004) 225 :
superliquid of vacancies=super-solid?
Collected motion reduces the energy

M. Boninsegni: J. Low Temp. Phys. 132 (2003) 39.
Triangular lattice GFMC: repulsion
n=1/3 solidation, superfluid=0
near n=1/3 coexist? Supersolid.

M. Boninsegni and N. Prokof'ev:
Phys. Rev. Lett. **95**, 237204 (2005)

M. Boninsegni

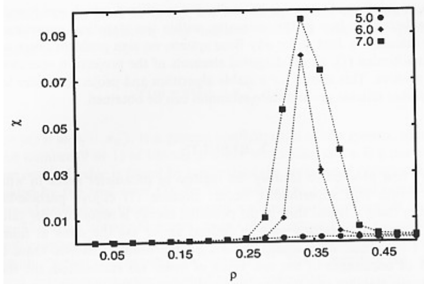


Fig. 1. GFMC results for the commensurate crystal order parameter χ, defined in the text, on a 324-site triangular lattice, for various values of the NN interaction V. Dashed lines are guides to the eye. Only results for $0 \leqslant \rho \leqslant 0.5$ need be shown, owing to the particle-hole symmetry featured by (1), as explained in the text.

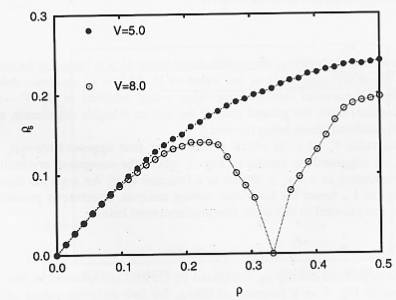
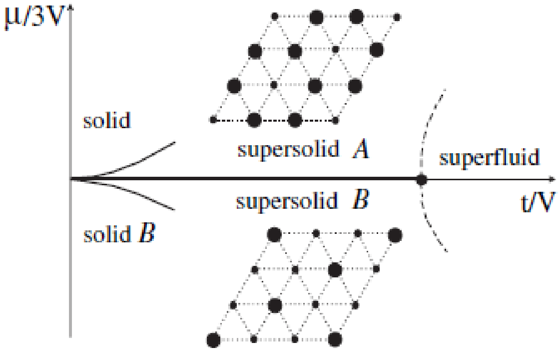


Fig. 4. Superfluid density ρ_S as a function of the filling ρ, computed by GFMC on a a 144-site triangular lattice, at $V = 5.0$ and $V = 8.0$. Statistical errors are smaller than the sizes of the symbols. Dashed lines are guides to the eye. At $V = 8.0$, the superfluid density is found to vanish at commensurate filling. This is observed at all values of $V \gtrsim 5.75$.



Conditions for Supersolid

P. Sengupta, et al. PRL 94 (2005) 207202.

Square lattice: condition for supersolid
NOT ½ filling, zV > U (soft core),
Only NN

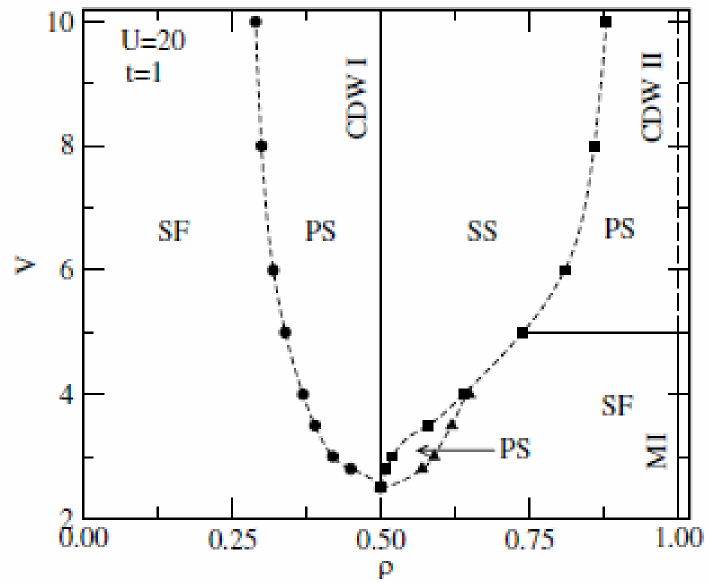
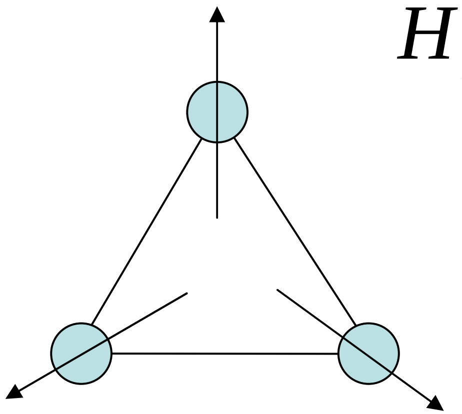


FIG. 1. The ground state phase diagram of the 2D extended Bose-Hubbard model (1) in the $V - \rho$ plane for $U/t = 20$ and densities $\rho \leq 1$, showing superfluid (SF) phases, checkerboard solids formed by single bosons (CDW I) and pairs of bosons (CDW II), a Mott-insulating phase (MI), phase separation (PS), and finally a supersolid phase (SS).

Ordering on fluctuating media

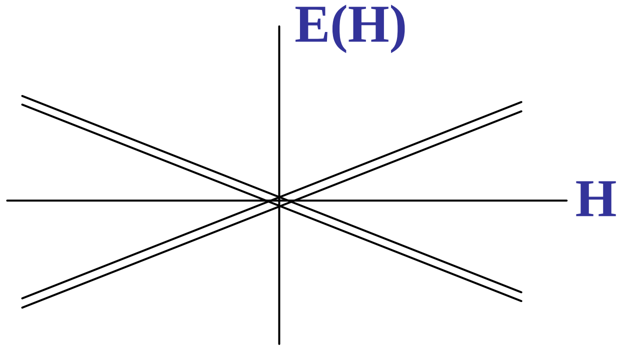
- Characteristic response of the peculiar state
- Virtual process
- Spin-crossover

Energy structure and dynamical property

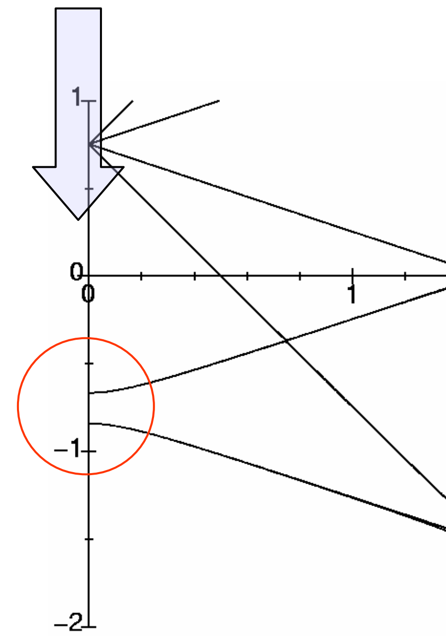


$$H_D = \vec{D} \cdot \left(\vec{S}_i \times \vec{S}_j \right)$$

$$\left[H, M_z \right] \neq 0$$



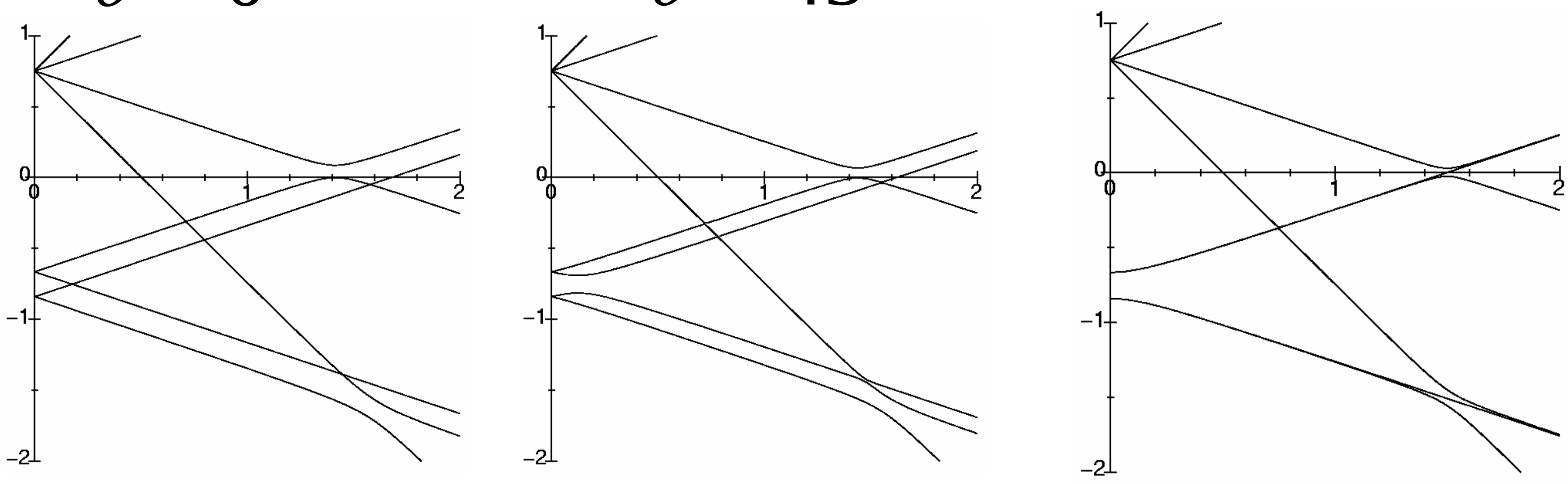
Extra-degeneracy
+
Dzyloshinskii-Moriya interaction

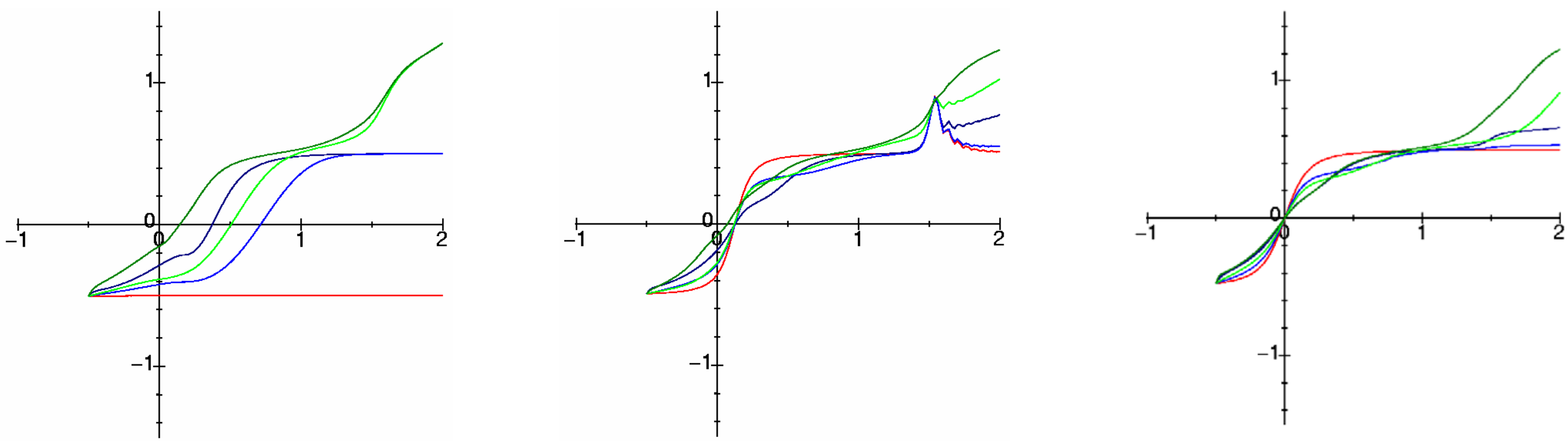


SM, &. N. Nagaosa, Prog. Theor. Phys. 106 (2001) 533
N. P. Konstantinidis and D. Coffey, PRB 68 (2003) 180504
I.Chiorescu, W. Wernsdorfer, A. Mueller, SM, and B. Barbara: PRB 67 (2003) 020402

Angle dependence of the energy levels

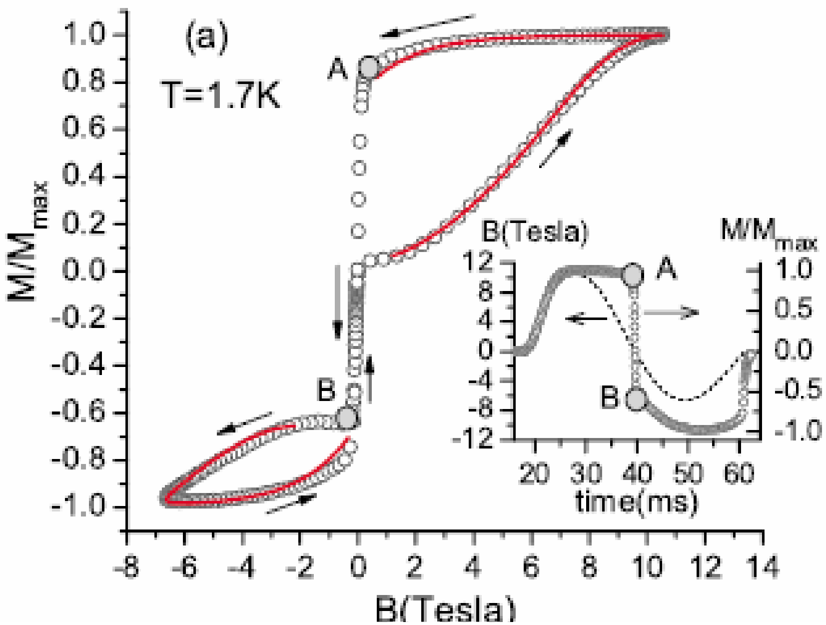
$\theta = 0^\circ$ $\theta = 45^\circ$ $\theta = 90^\circ$

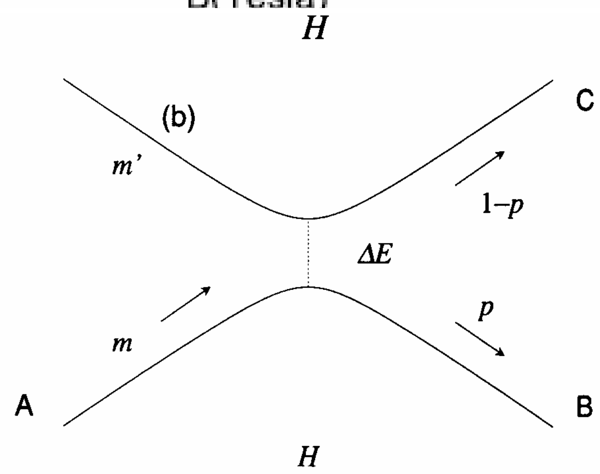


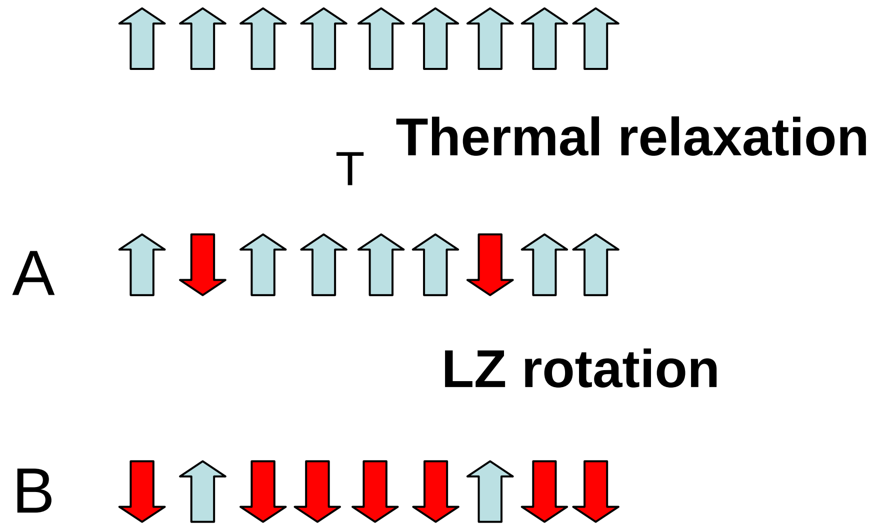


H. De Raedt, SM, K. Michielsen, M. Machida: PRB 70 (2004)064401

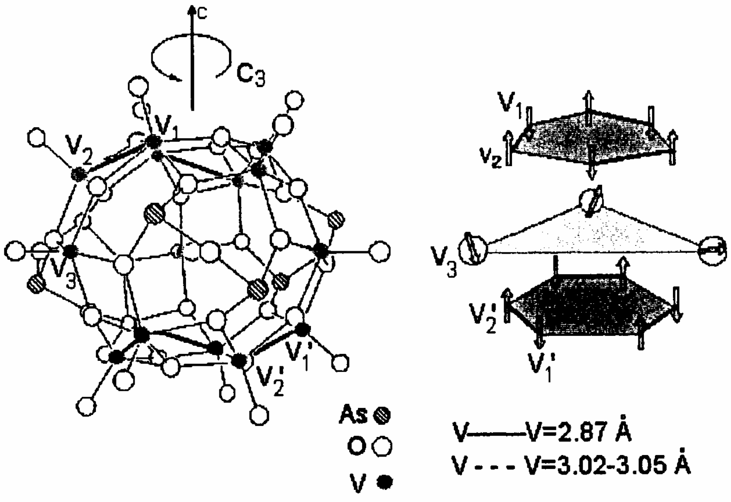
Thermal relaxation and LZ transition



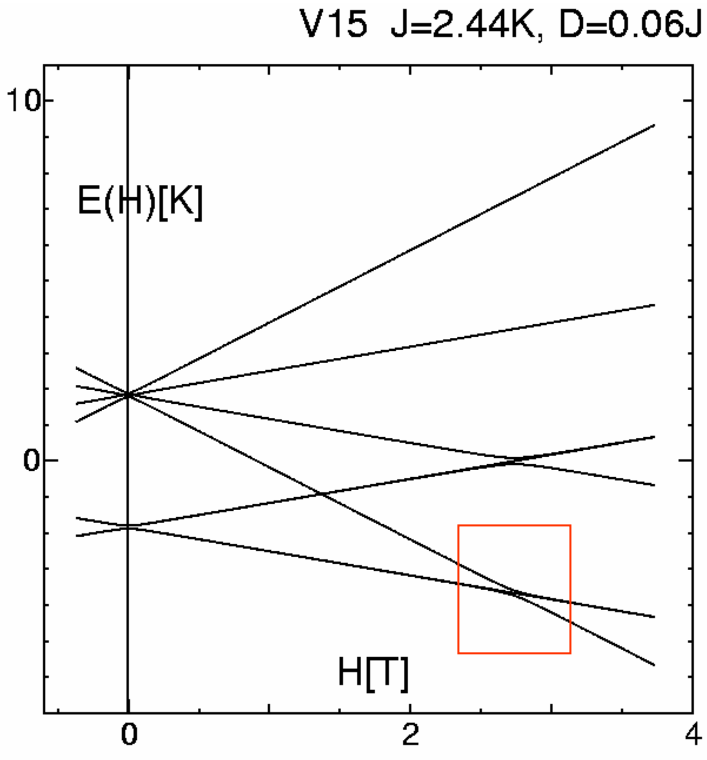


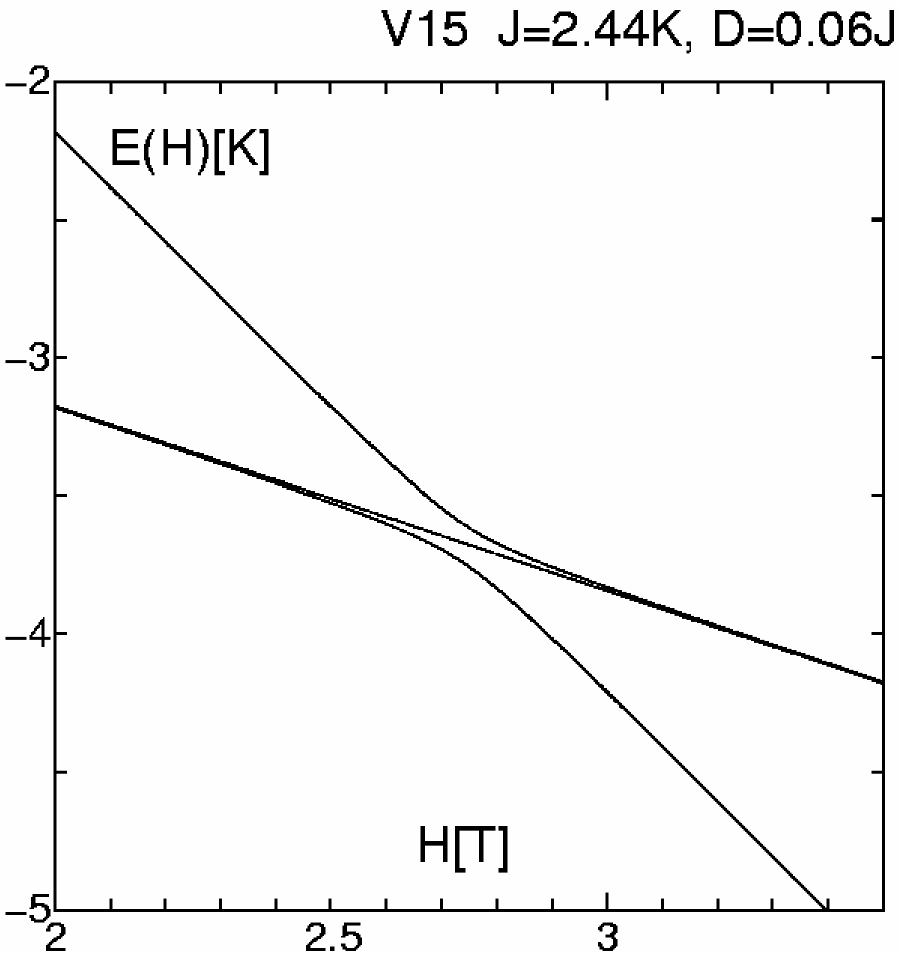


Effects of the energy level structure



Transition from 1/2 ⟺ 3/2





Half jump at level crossing

Up sweep ΔS=1/2

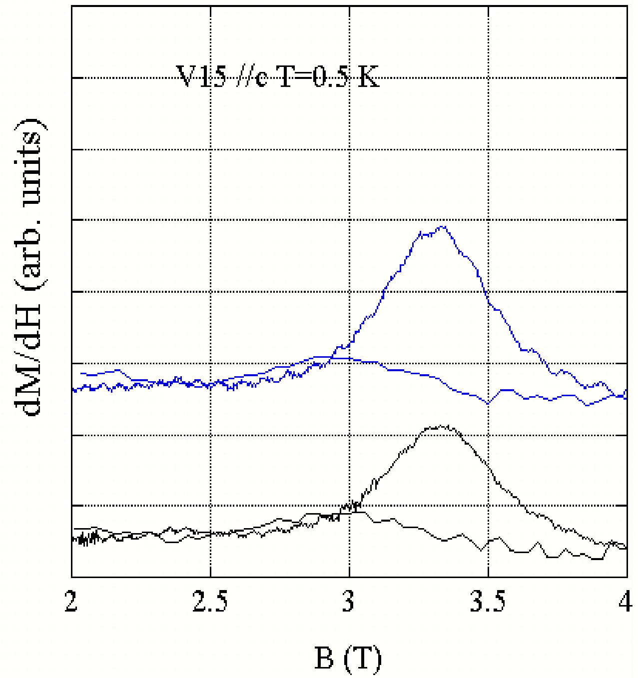
S=1/2 to S=1 **Half jump**

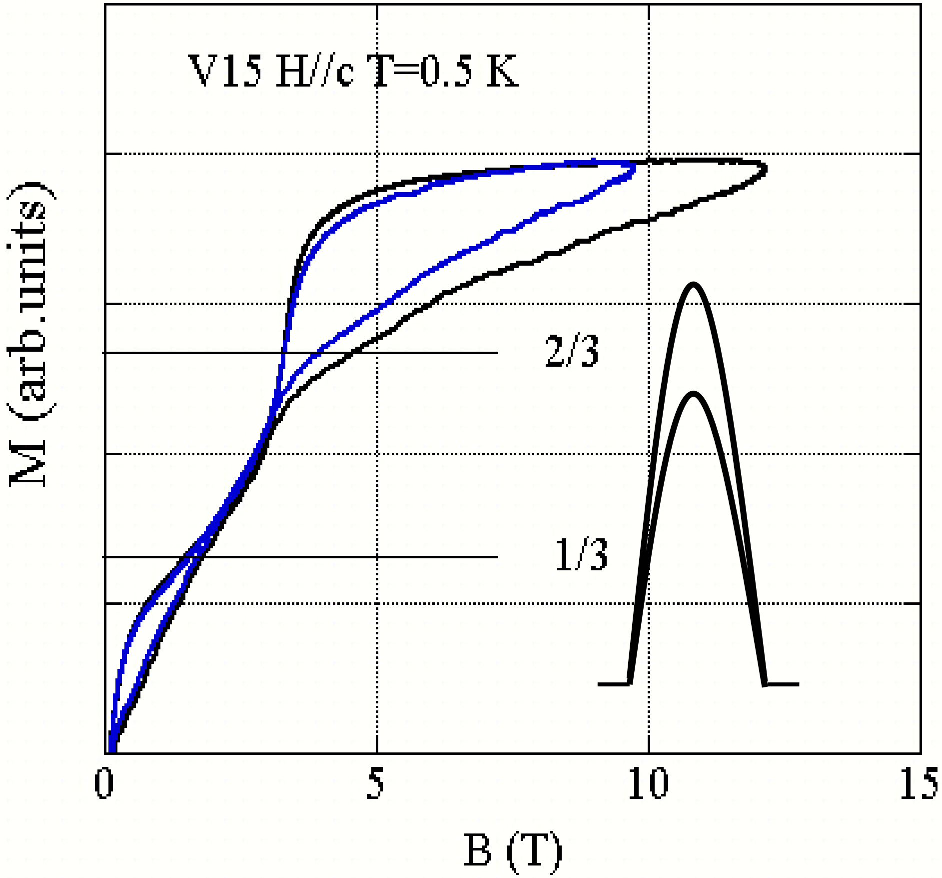
Down sweep ΔS=1

S=3/2 to S=1/2 **Full jump**

Saturate in a certain time

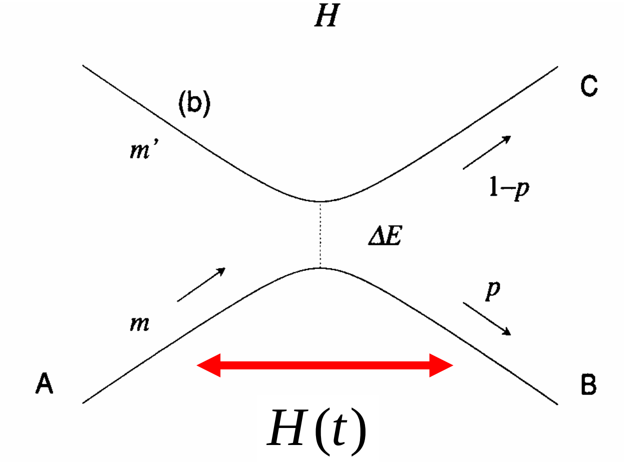
H. Nojiri
Pulse magnetic field
V15, V3, Cu3





Resonance on the AC field
Non-trivial Resonance

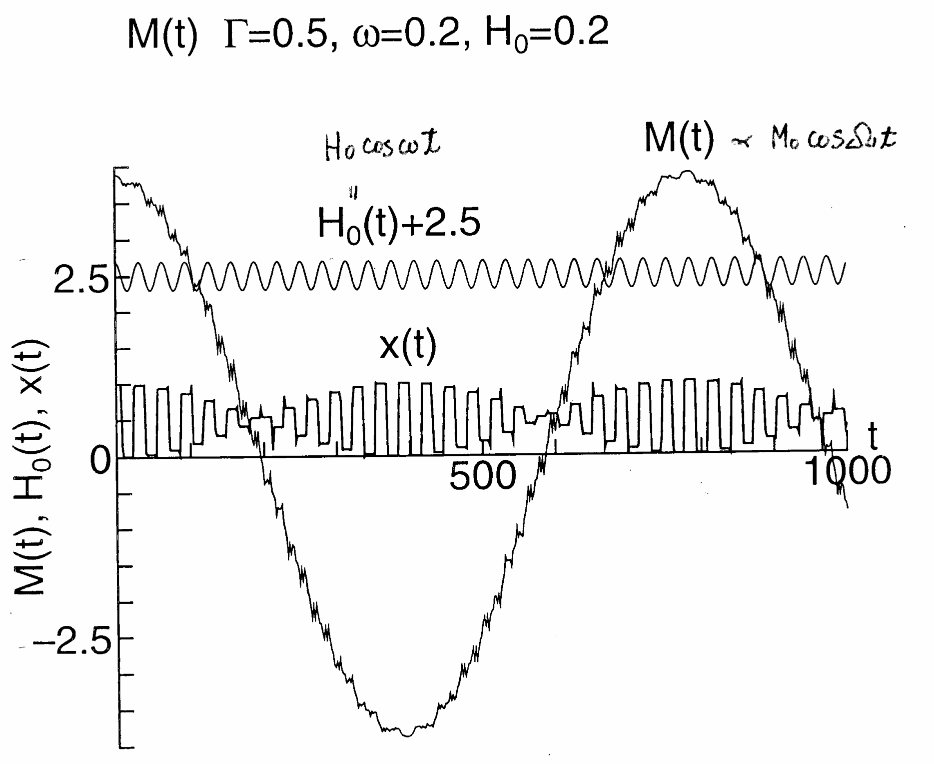
$$H(t) = -h_W \cos(\omega t) \sum_i S_i^z$$



$$M(t) = M_0 \cos(\Omega t + \delta),$$

$$\Omega = \frac{\omega}{\pi} \sqrt{2p(1-\cos\alpha)}$$

$$p = 1 - \exp\left(-\frac{\pi(\Delta E)^2}{4c\Delta M} \right)$$



Y. Kayamuma, PRB 47 (1993) 9940
SM, K. Saito, H. De Daedt,
Phys. Rev. Lett. 80 (1998) 1525.

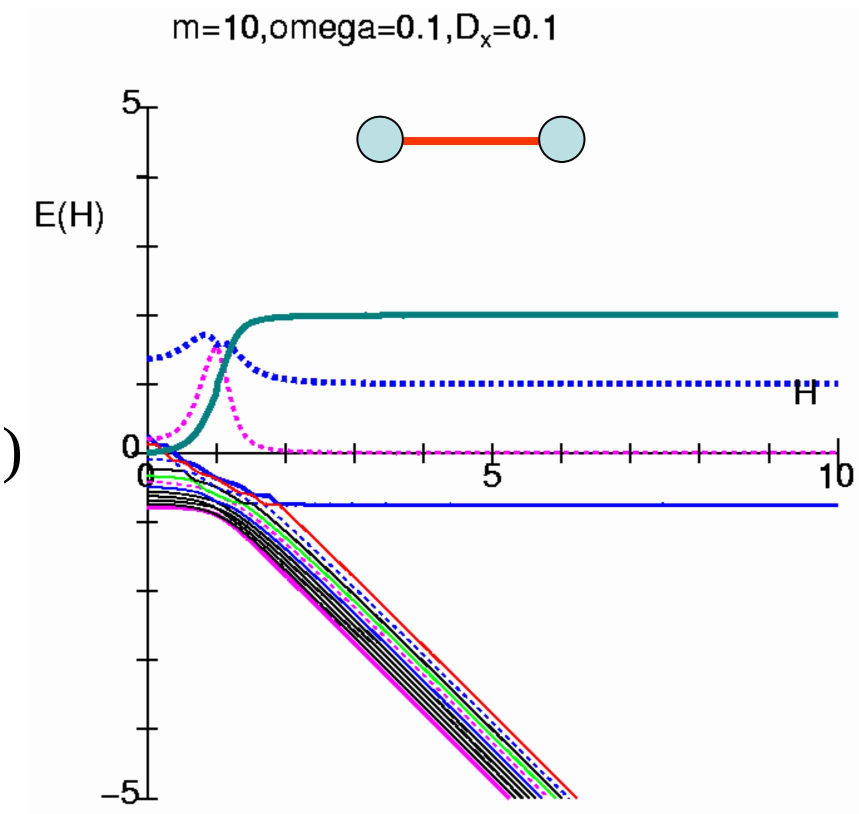
Fluctuation induced DM for a dimer

$$H = J\vec{S}_1 \cdot \vec{S}_2 + \vec{d} \cdot \left(\vec{S}_1 \times \vec{S}_2\right) + H\left(S_1^z + S_1^z\right) + \frac{k}{2}x^2 + \frac{1}{2m}p^2$$

$$\vec{d} = \vec{d}_0 x \qquad [x, p] = i\hbar \quad \langle x \rangle = 0$$

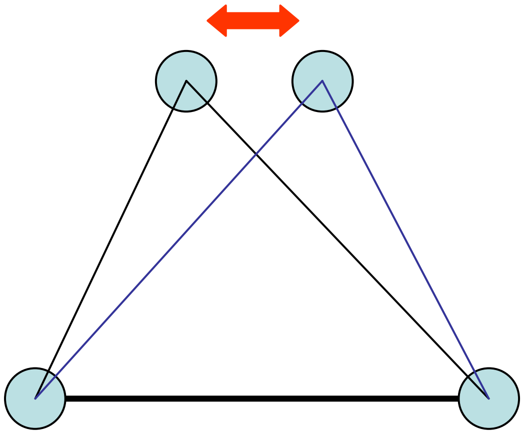
$$H = H_{\mathrm{Spin}} + H_{\mathrm{SP}} + H_{\mathrm{Phonon}}$$

$$\begin{cases} H_{\mathrm{Spin}} = J\vec{S}_1 \cdot \vec{S}_2 \\ H_{\mathrm{SP}} = \sum_k \left(\alpha_k a_k^+ + \alpha_k^+ a_k\right)\vec{D} \cdot (\vec{S}_1 \times \vec{S}_2) \\ H_{\mathrm{Phonon}} = \sum_k \omega_k a_k^+ a_k \end{cases}$$

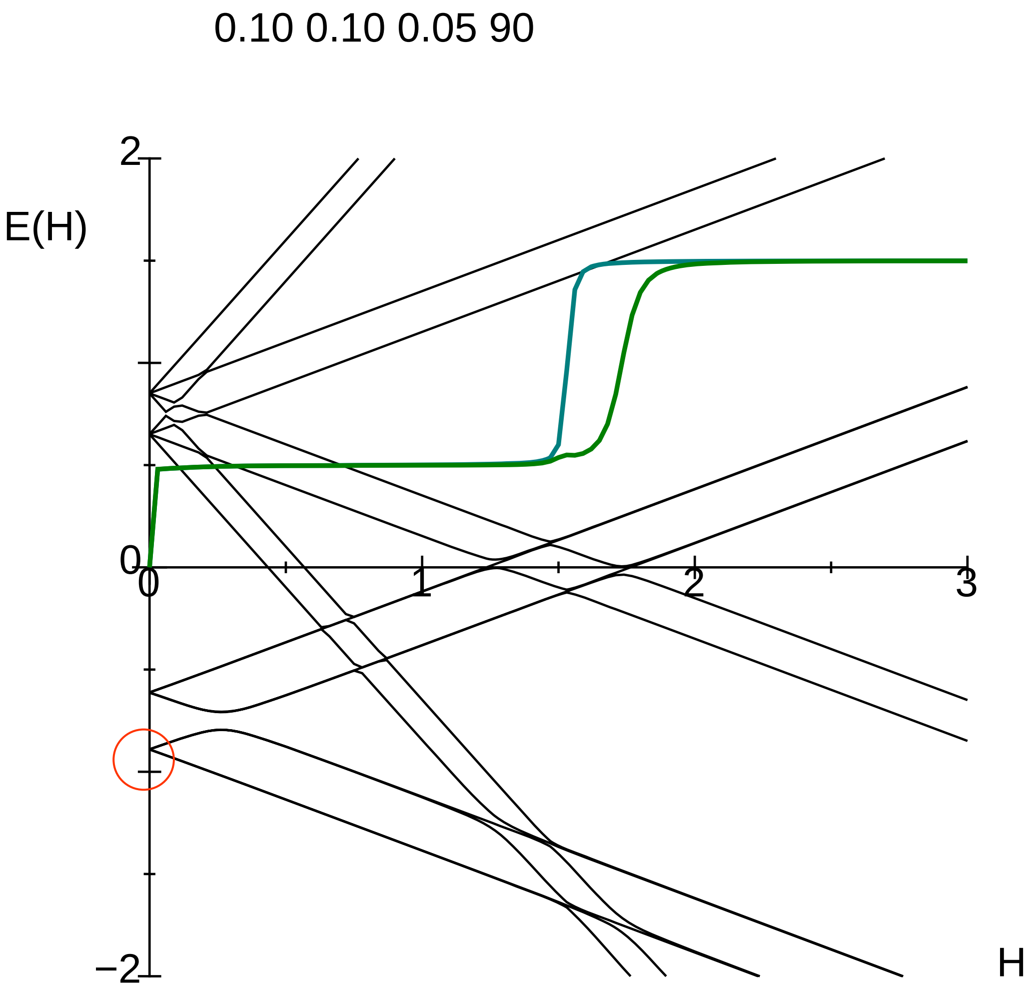


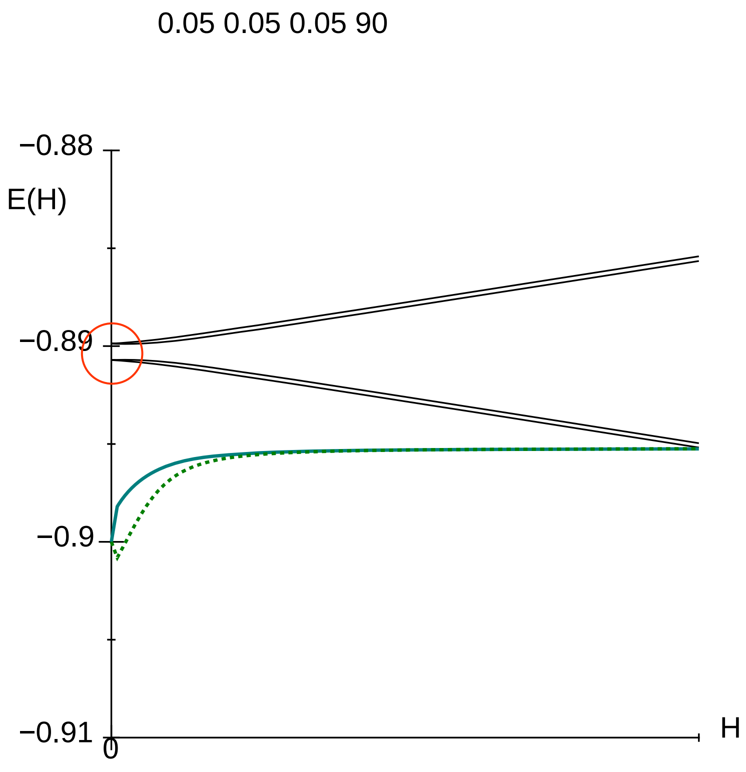
Effect of bond fluctuation
A minimal model

$$H = \sum_{<ij>} \left(J_{ij} + \sigma^{z} \Delta J_{ij} \right) \vec{S}_i \cdot \vec{S}_j + \sigma^{z} \sum_{<ij>} \vec{D}_{ij} \cdot \vec{S}_i \times \vec{S}_j + a\sigma^{x}$$



Small energy split at H=0

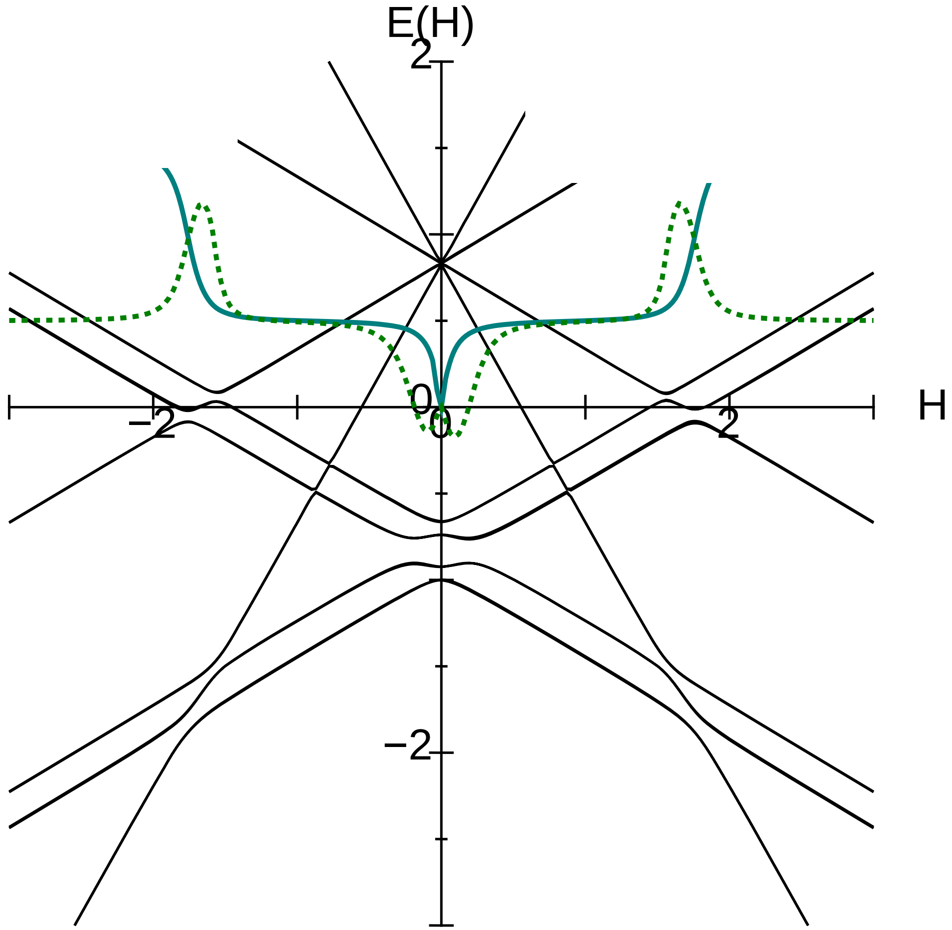




θ =90°

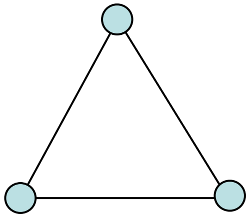
Effect of scalar chirality

$$\alpha \vec{S}_1 \cdot \left(\vec{S}_2 \times \vec{S}_3 \right)$$



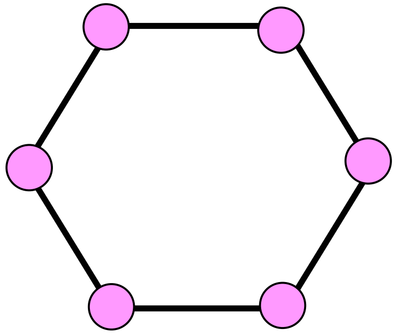
α ＝０．１

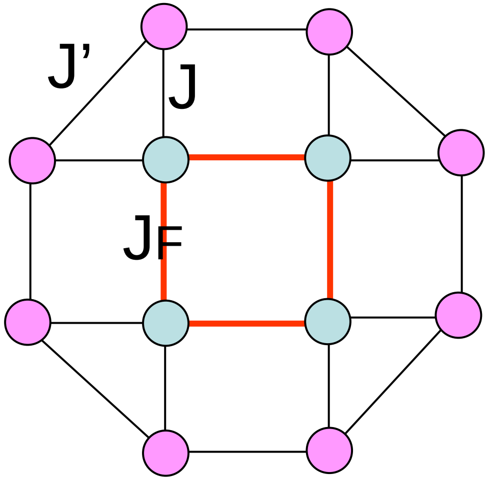
Types of microscopic spin states



- Triangle lattice and odd rings
- Even rings
- New types of microscopic spin state

  Non-collinear ferrimagnetism

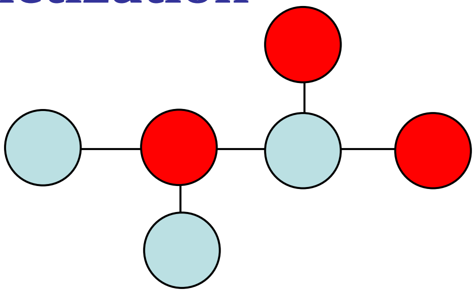




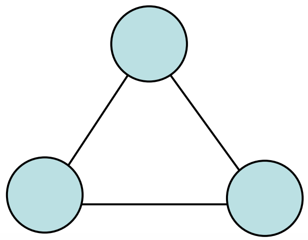
Ferrimagnetism

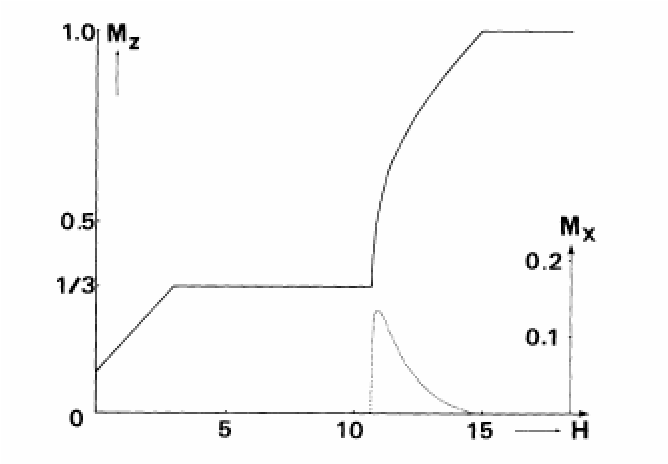
Ground state with non-saturated magnetization

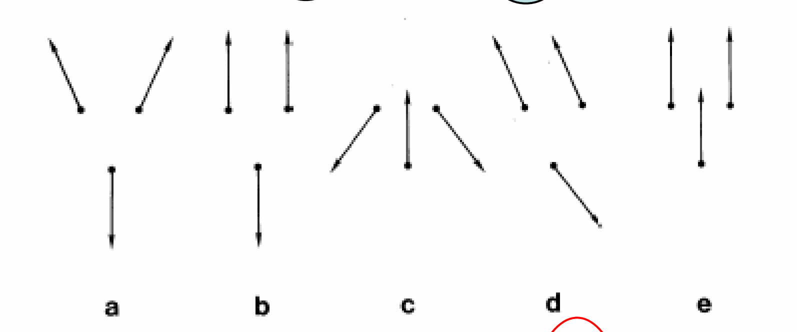
Lieb-Mattis type: no-frustration



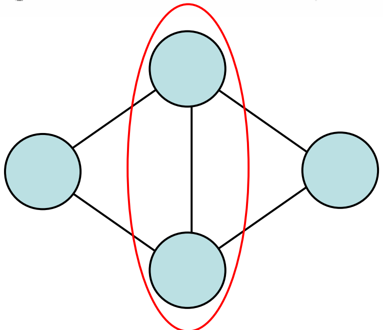
Non-colliear type: frustration



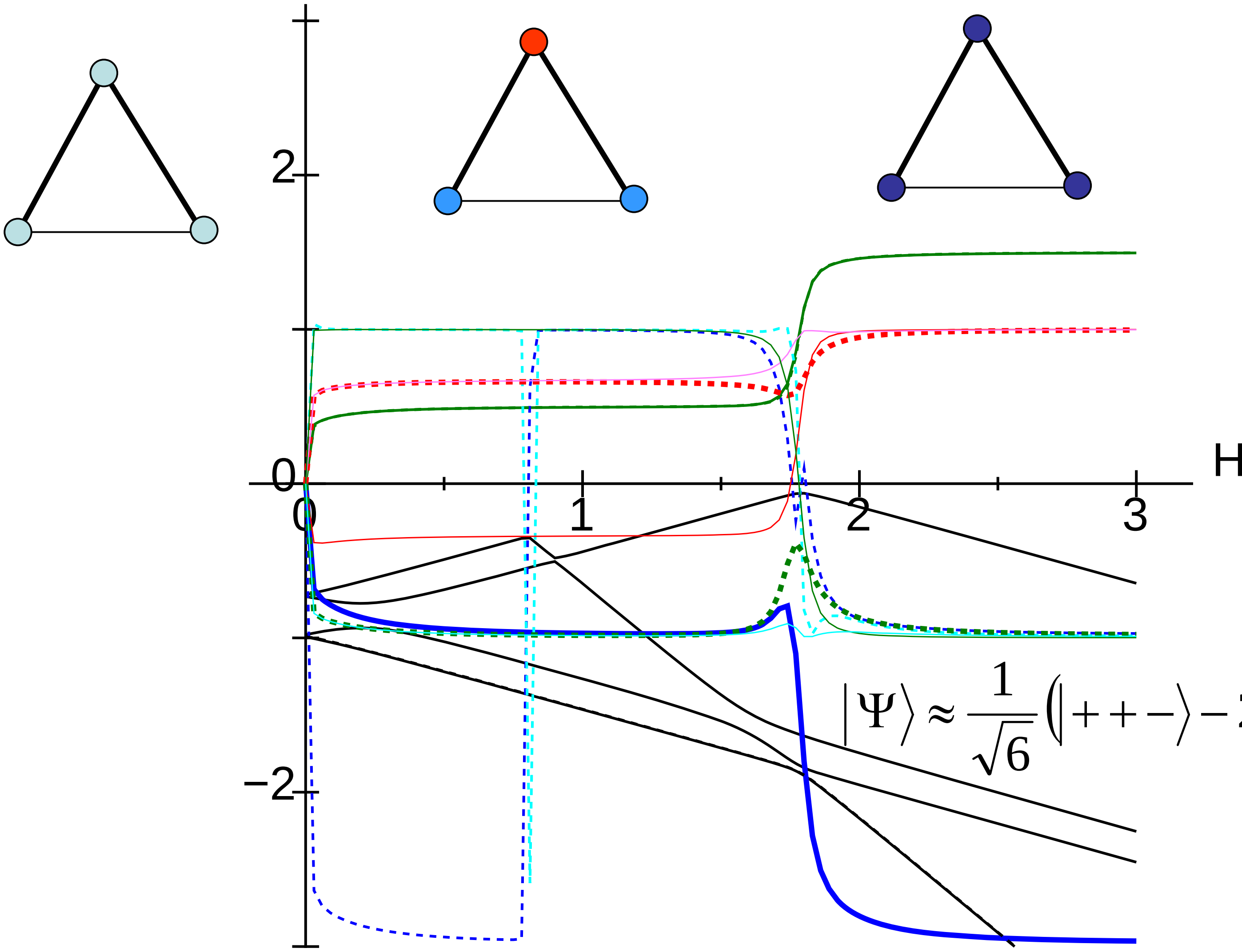




Another type: frustration+dimerization

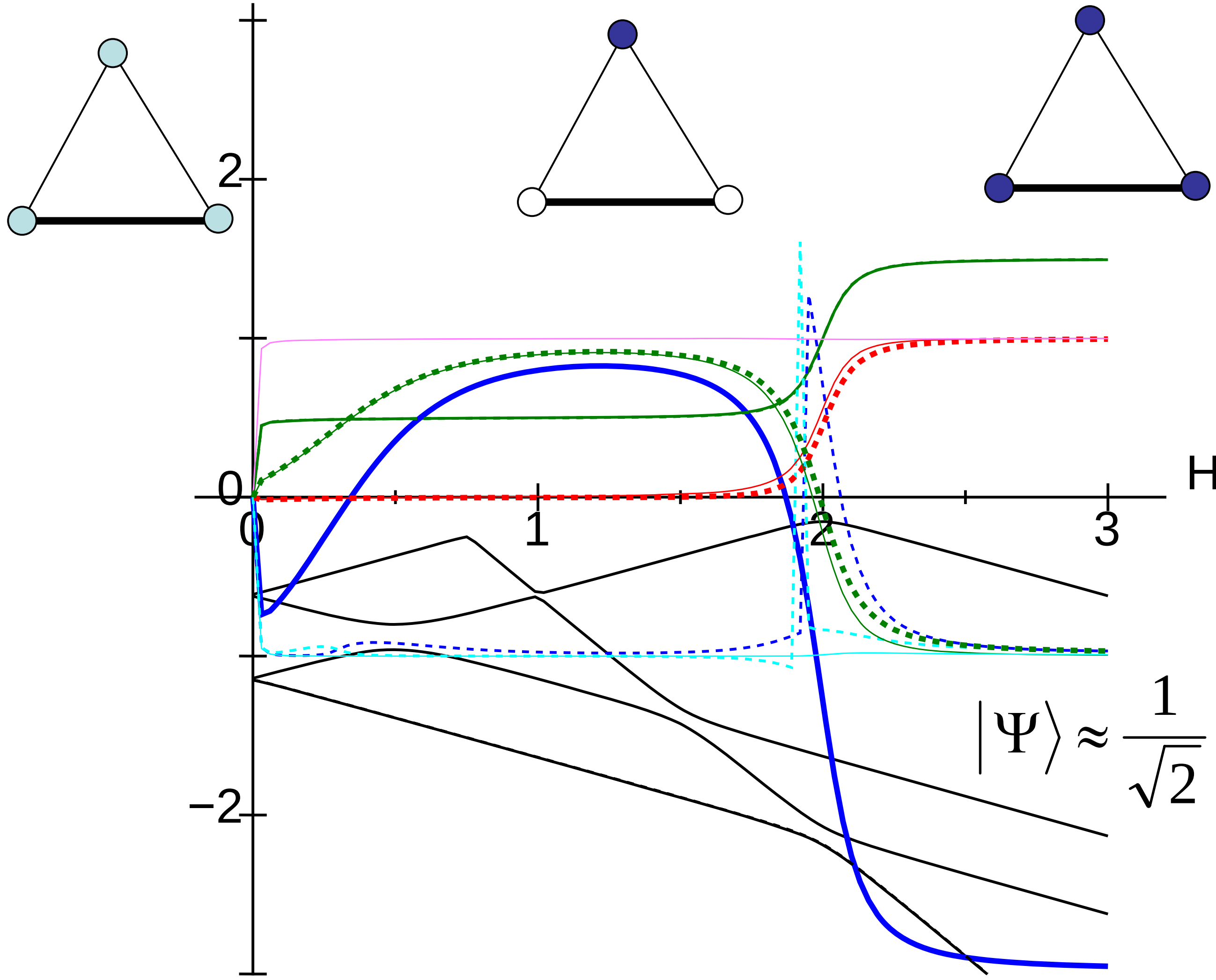


2 strong bonds



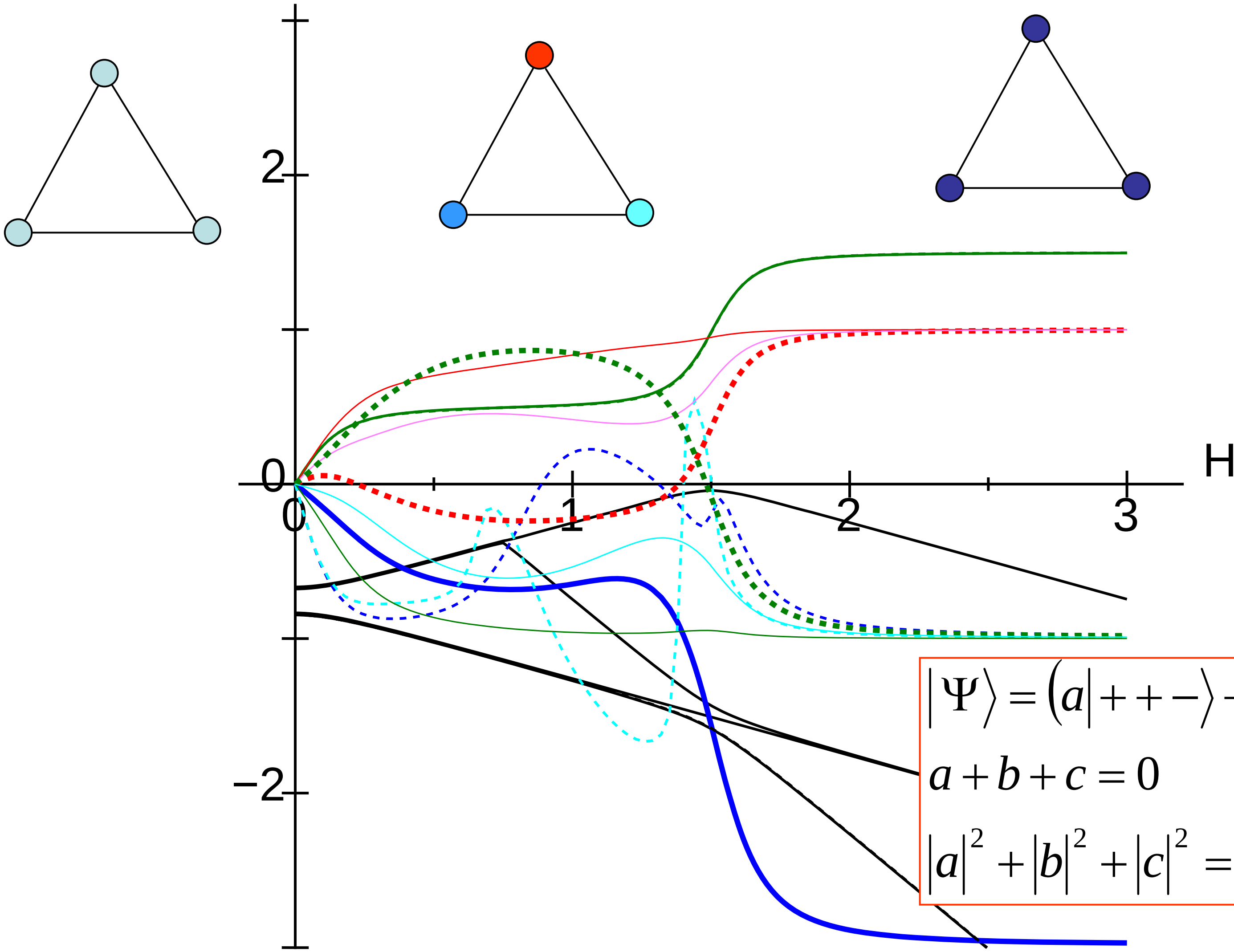
$$|\Psi\rangle \approx \frac{1}{\sqrt{6}}\left(|{+}{+}{-}\rangle - 2|{+}{-}{+}\rangle + |{-}{+}{+}\rangle\right)$$

1 strong bond



$$|\Psi\rangle \approx \frac{1}{\sqrt{2}}\left(|++-\rangle - |-++\rangle\right)$$

Local magnetization : the uniform case



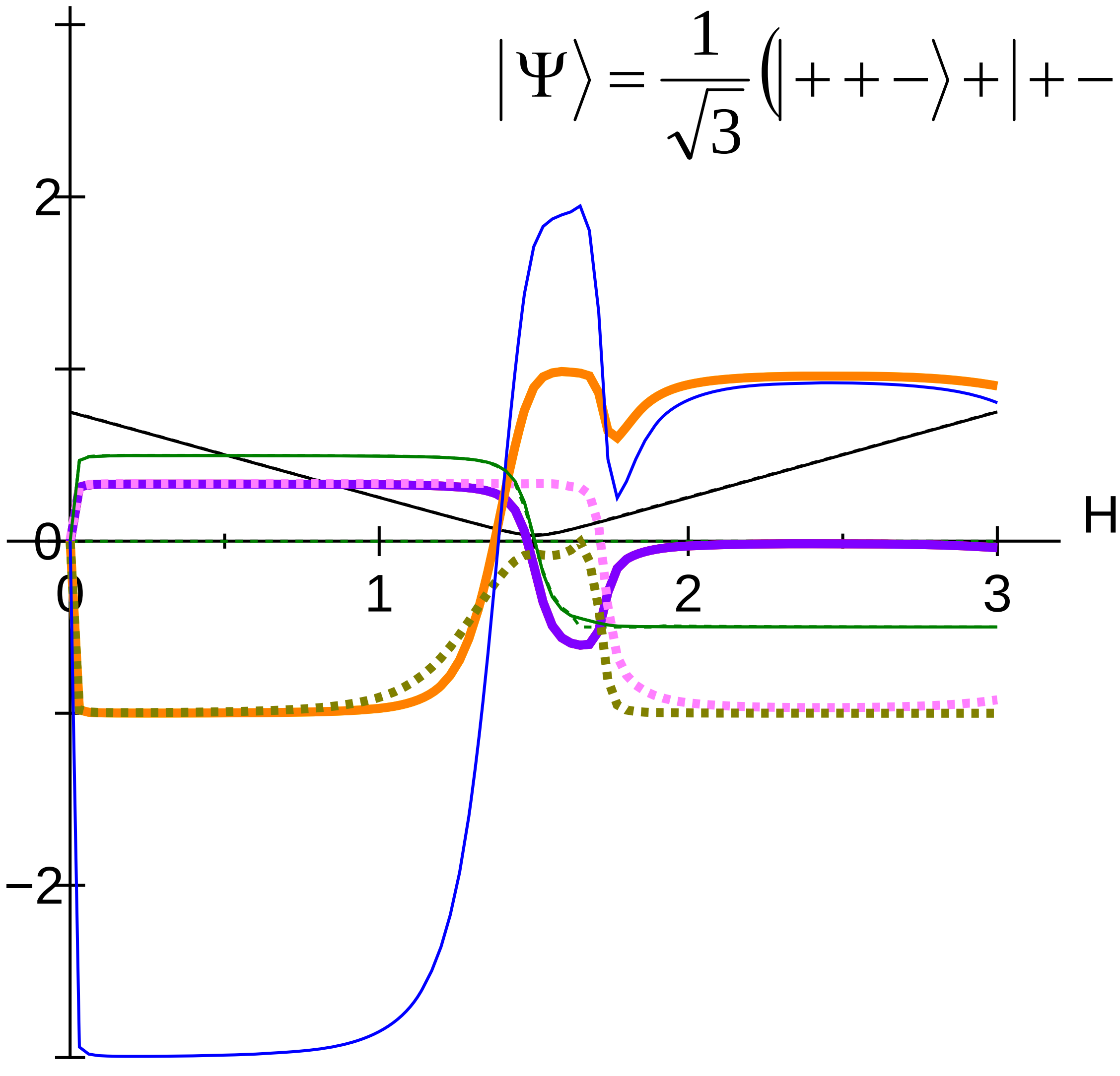
$$|\Psi\rangle = \left(a|++-\rangle + b|+-+\rangle + c|-++\rangle\right)$$

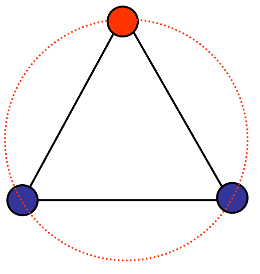
$$a + b + c = 0$$

$$|a|^2 + |b|^2 + |c|^2 = 1$$

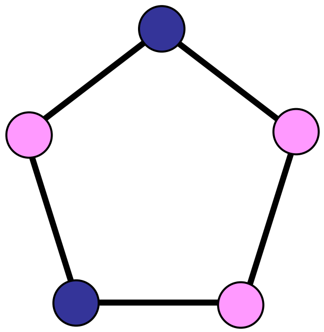
Spin wave type

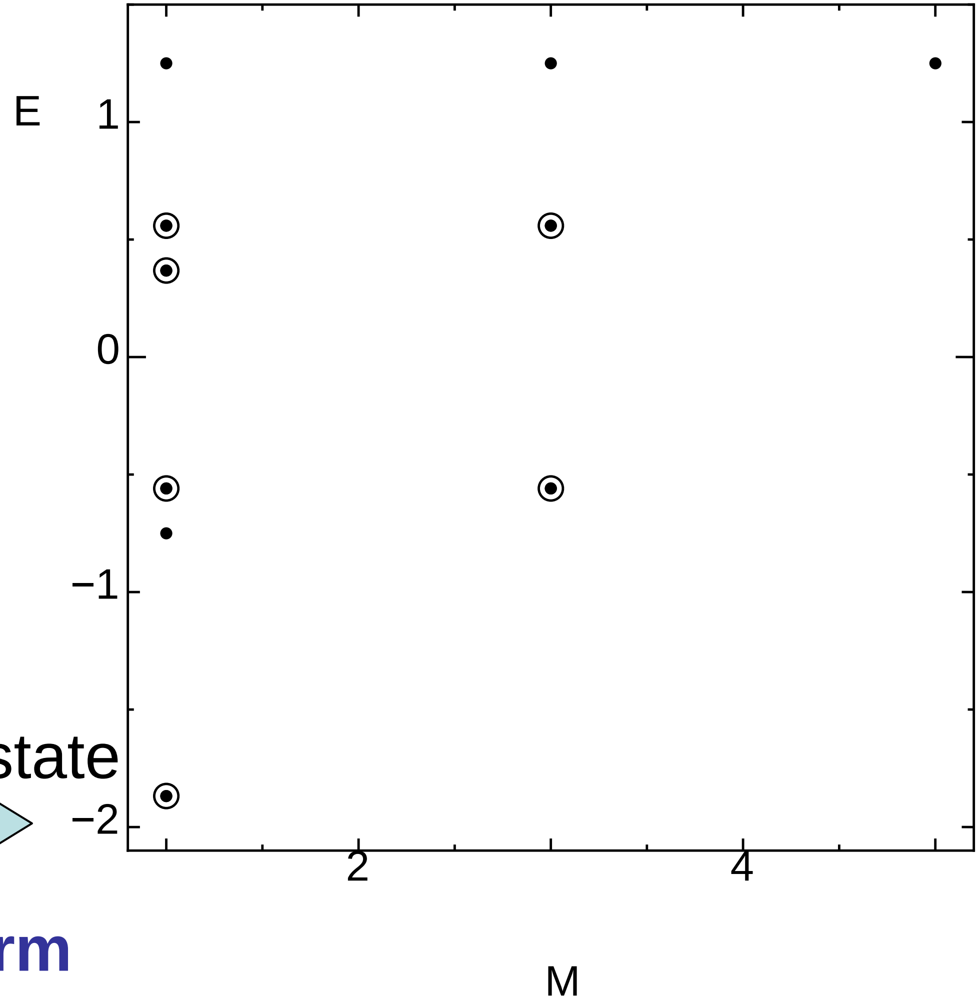
$$|\Psi\rangle = \frac{1}{\sqrt{3}}\left(|++-\rangle + |+-+\rangle + |-++\rangle\right)$$





Odd ring N=5

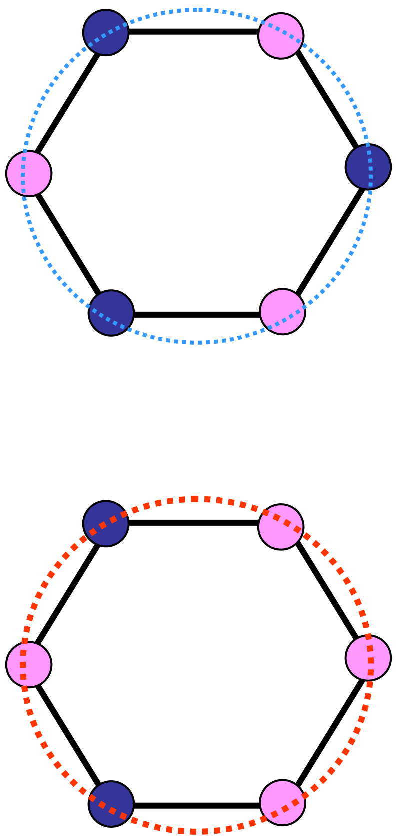


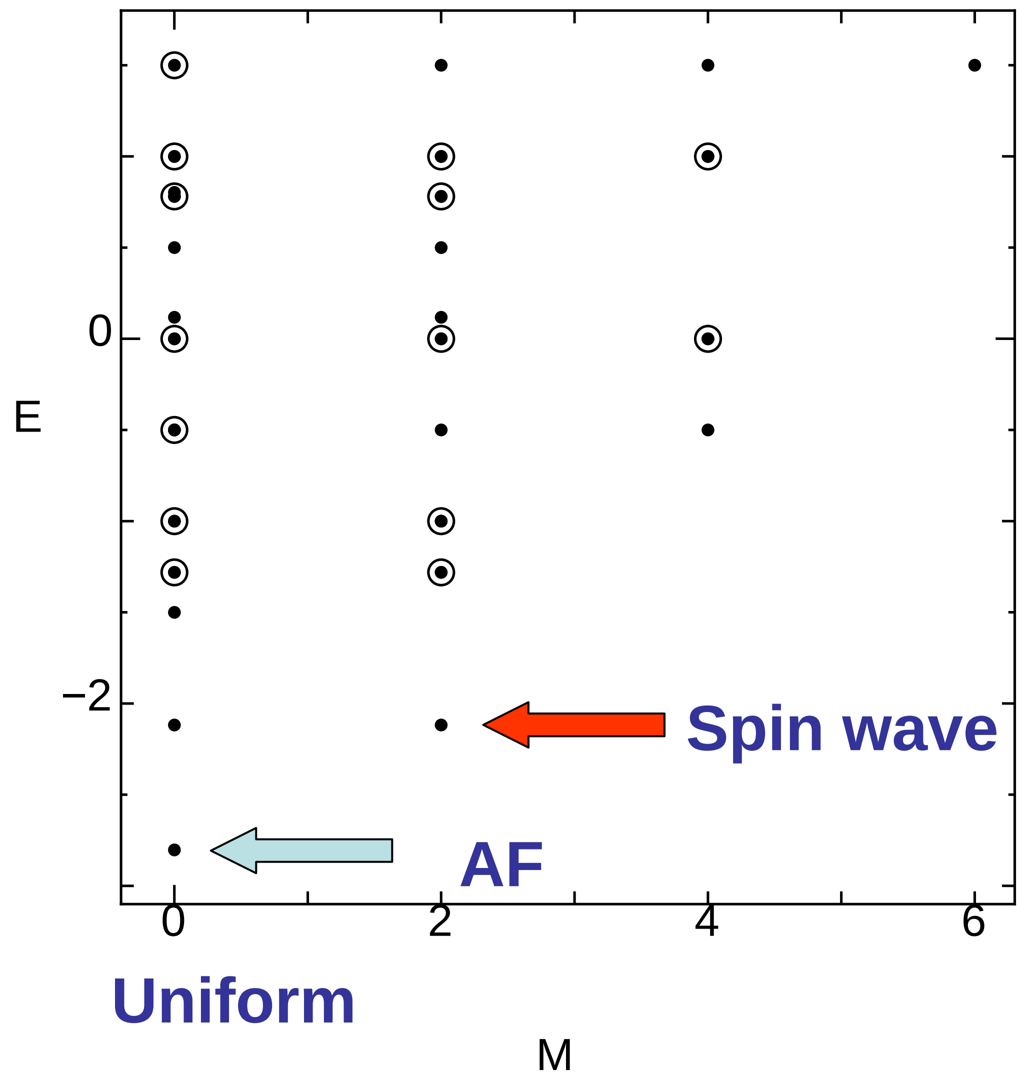


Degenerate ground state

Non-uniform

Even spin case   N=6

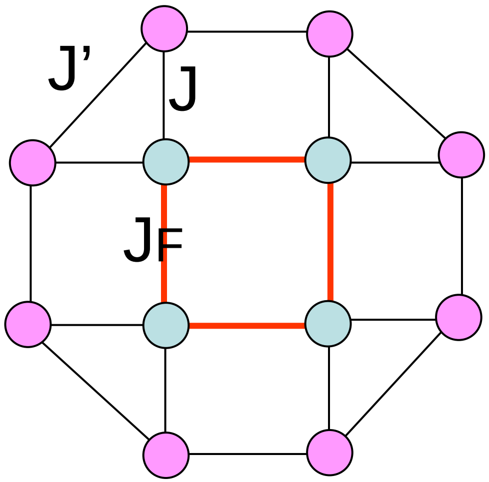




Uniformly fluctuating magnetic state?

Spin wave type $$|\Psi\rangle = \frac{1}{\sqrt{3}}\left(|++-\rangle + |+-+\rangle + |-++\rangle\right)$$

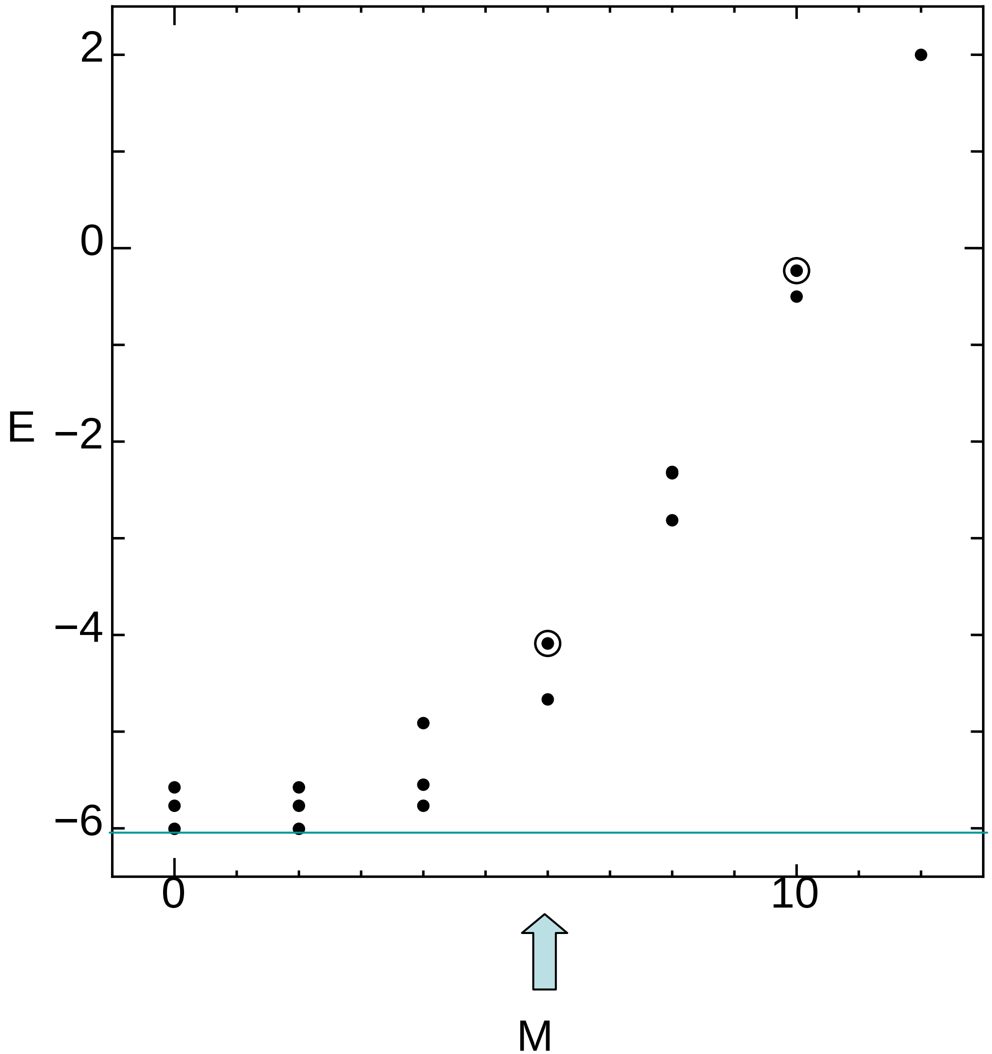
Non-collinear ferrimagnetic state: ground state

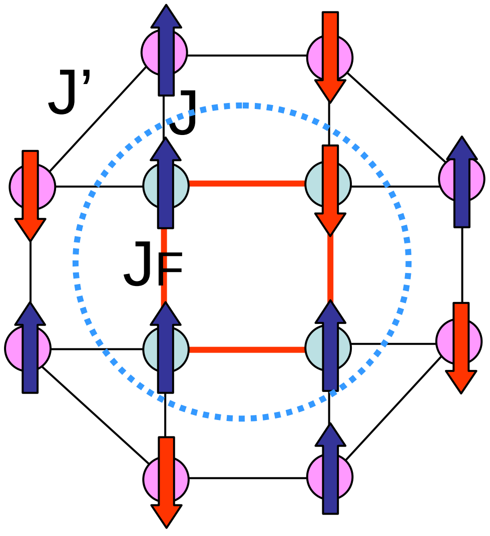


J >> J' : LMFR

J << J' : Non-LMFR

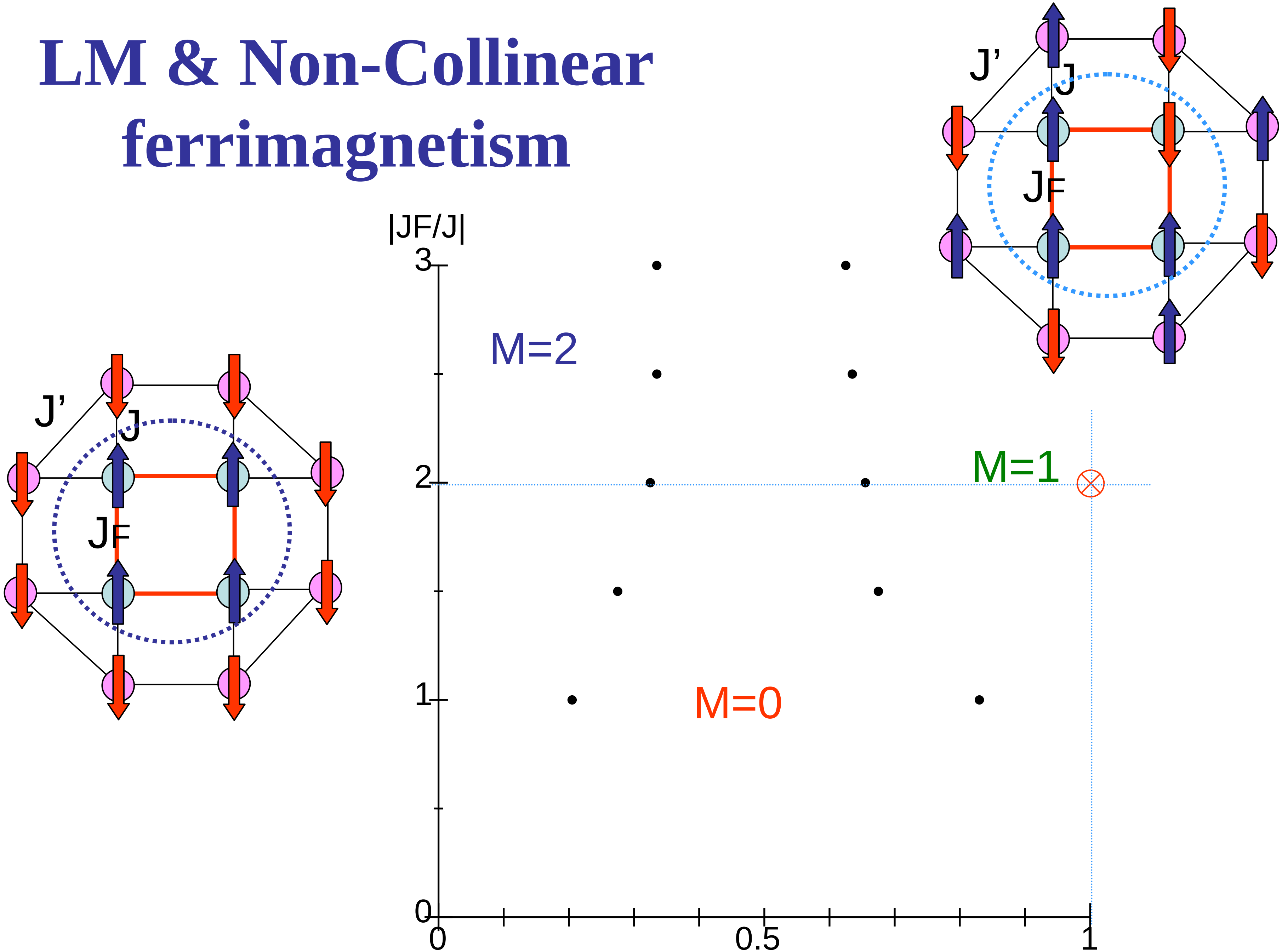
N=12 Non-collinear Ferrimagnetism





$J=J'=1,\ J_F=2$

LM & Non-Collinear ferrimagnetism



Quantum phases and their Dynamical properties

- New type magnetic states on frustrated lattices
- Characteristic properties of peculiar states

Dynamical properties

Virtual interaction effects (Fluctuating media)

Supersolid

Many-body (ring) exchange model

phonon