Antiferromagnets on the kagomé lattice

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Outline

- Spin-1/2 Heisenberg model on kagomé lattice
  - Gap (?) and homogeneous susceptibility: Ph. Sindzingre Paris
  - Dynamical Spin Susceptibility: A. Laeuchli EPFL
- The J_1-J_2 model on the kagomé lattice :
  - a new chiral low temperature phase
  - the role of vortices on the low temp. properties

J.-C. Dommenge (Rutgers), L. Messio & P. Viot (Paris)

J|A|C|S
COMMUNICATIONS

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A Structurally Perfect $S = {}^1/_2$ Kagomé Antiferromagnet

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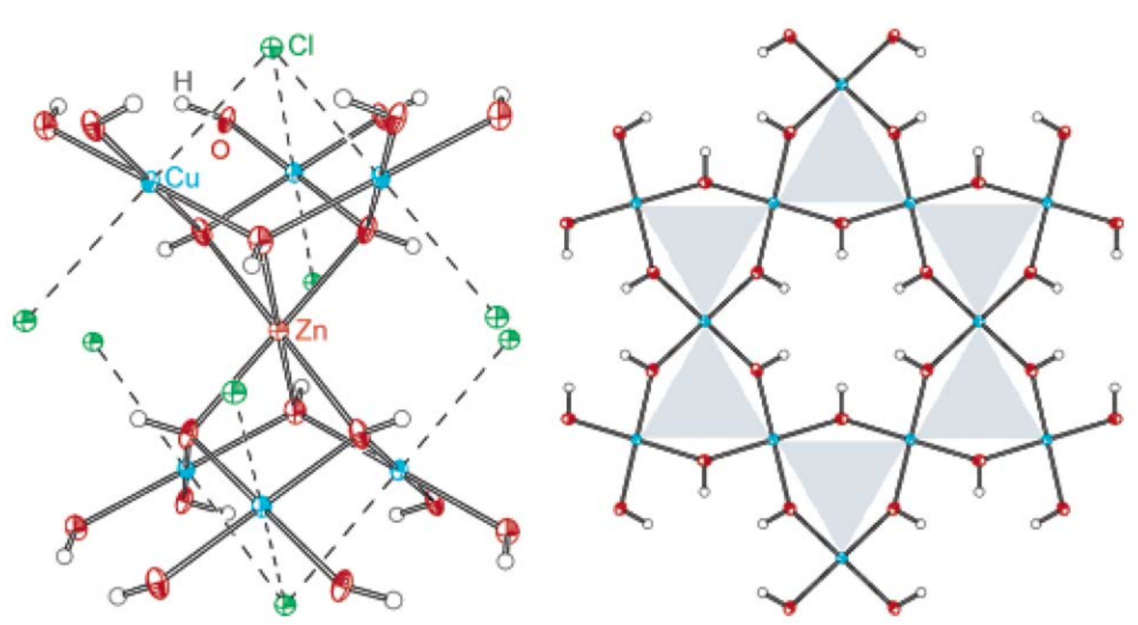

Figure 1. Crystal structure of Zn−paratacamite (**1**), $Zn_{0.33}Cu_{3.67}(OH)_6Cl_2$.

PRL 98, 077204 (2007) PHYSICAL REVIEW LETTERS week ending 16 FEBRUARY 2007

Quantum Magnetism in the Paratacamite Family: Towards an Ideal Kagomé Lattice

P. Mendels,[1] F. Bert,[1] M. A. de Vries,[2] A. Olariu,[1] A. Harrison,[2] F. Duc,[3] J. C. Trombe,[3]
J. S. Lord,[4] A. Amato,[5] and C. Baines[5]

PRL 98, 107204 (2007) PHYSICAL REVIEW LETTERS week ending 9 MARCH 2007

Spin Dynamics of the Spin-1/2 Kagome Lattice Antiferromagnet $ZnCu_3(OH)_6Cl_2$

J. S. Helton,[1] K. Matan,[1] M. P. Shores,[2] E. A. Nytko,[2] B. M. Bartlett,[2] Y. Yoshida,[3] Y. Takano,[3] A. Suslov,[4] Y. Qiu,[5]
J.-H. Chung,[5] D. G. Nocera,[2] and Y. S. Lee[1]

Ground state and excitation properties of the quantum kagomé system $ZnCu_3(OH)_6Cl_2$ investigated by local probes.

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^{63}Cu and ^{35}Cl NMR Investigation of the $S = \frac{1}{2}$ Kagomé Lattice System $ZnCu_3(OH)_6Cl_2$

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(Dated: April 3, 2007)

Quantum spin liquid states in the two dimensional kagomé antiferromagnets, $Zn_xCu_{4-x}(OD)_6Cl_2$

S.-H. Lee[*], H. Kikuchi[†], Y. Qiu[‡], B. Lake[§+], Q. Huang[‡], K. Habicht[§] and K. Kiefer[§]

Low temperature magnetization of the S=1/2 kagome antiferromagnet $ZnCu_3(OH)_6Cl_2$

F. Bert,[1] S. Nakamae,[2] F. Ladieu,[2] D. L'Hôte,[2] P. Bonville,[2] F. Duc,[3] J.-C. Trombe,[3] and P. Mendels[1]
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(Dated: July 16, 2007)

$ZnCu_3(OH)_6Cl_2$

- Curie-Weiss temperature Θ_{cw}= -300 K
- J ≅ 175 K

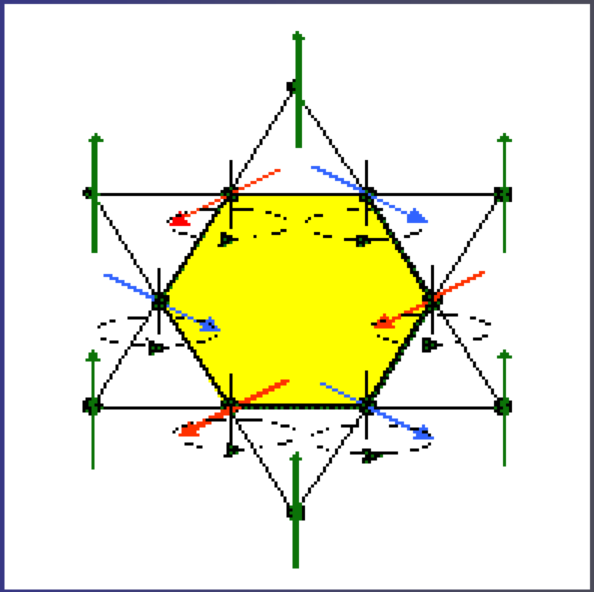
- No magnetic order down to 50 mK
- Dynamical features down to 50 mK
- No observable gap down to 0.1 meV
- No SG transition

A spin liquid phase down to T ≤ J/1000

Classical Heisenberg Hamiltonian on the kagomé lattice

$$H = \sum S_i . S_j$$

$$= \frac{1}{2} \sum_{\alpha} S_{\alpha}^{2} + C$$



An infinite number of soft modes, an infinite T=0 degeneracy

Therm. fluct. select coplanar configurations at very low T

J. Chalker, et al 92, Huse & Rutemberg 92 , Reimers & Berlinsky 93

Quantum Heisenberg Hamiltonian on the kagomé lattice

- V. Elser ‘89, C. Zeng & V.E. ‘90, P. Leung & V.E ‘93
- J. Chalker and J. Eastmond, ‘92
- P. Chandra & P. Coleman, Rutgers group, ‘93
- N. Elstner & A.P. Young, ‘94
- Paris Group: 95, 97, 99… 07

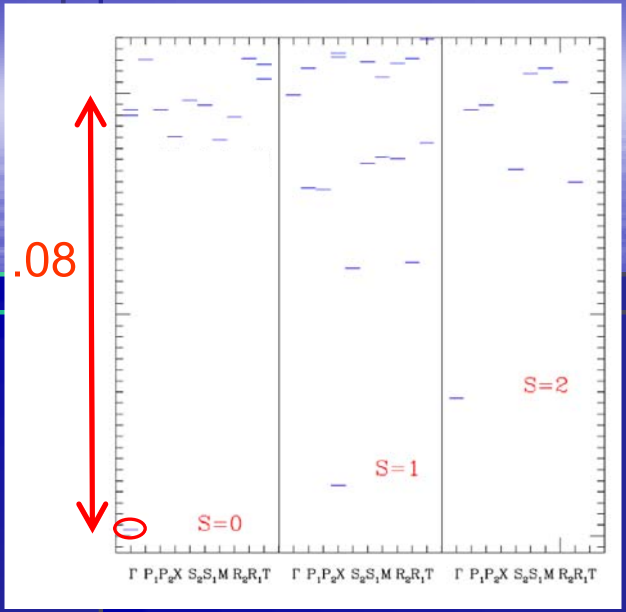
No Local order parameter

‘Short’ range correlations

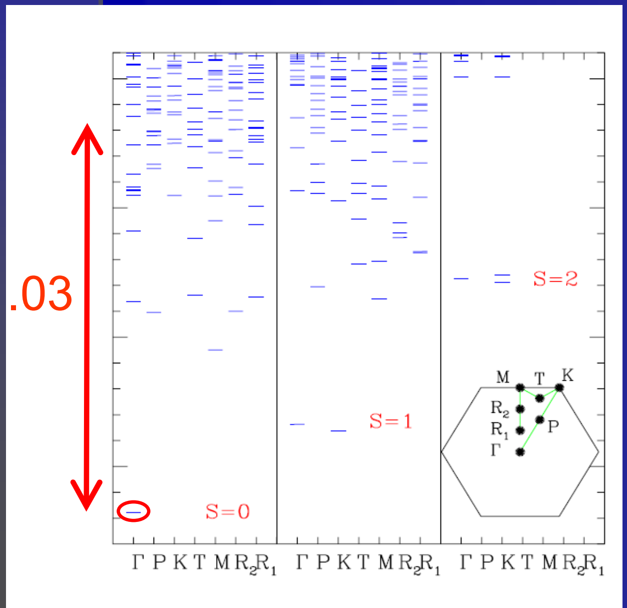
- Dimer approach: Leung & Elser, F. Mila’s group ‘98, ‘01…

Spectra of $\mathbf{H} = \Sigma\, \mathbf{S_i . S_j}$ (per spin)

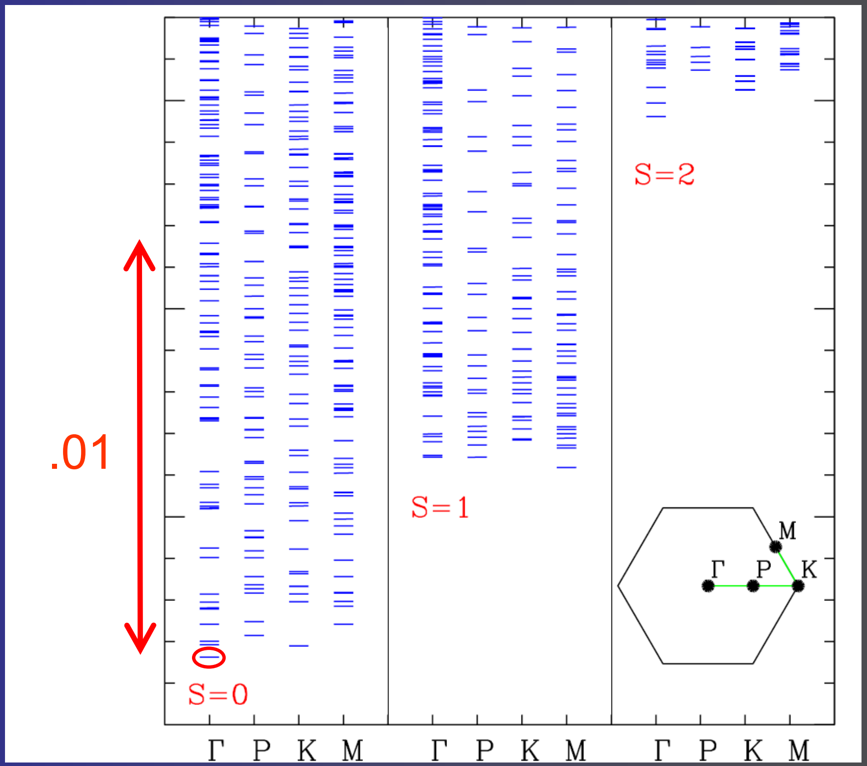
Square N=36



triangular N=36



Kagomé N=36



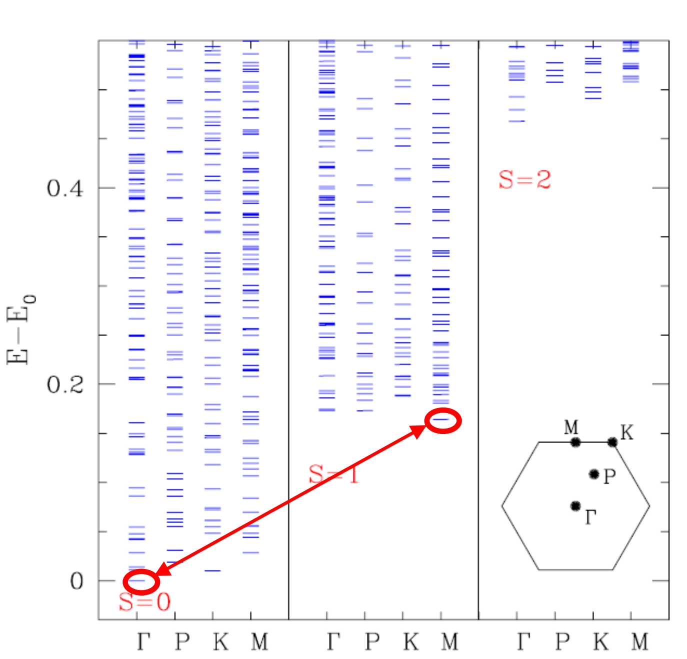
Extremely high density of low lying excitations

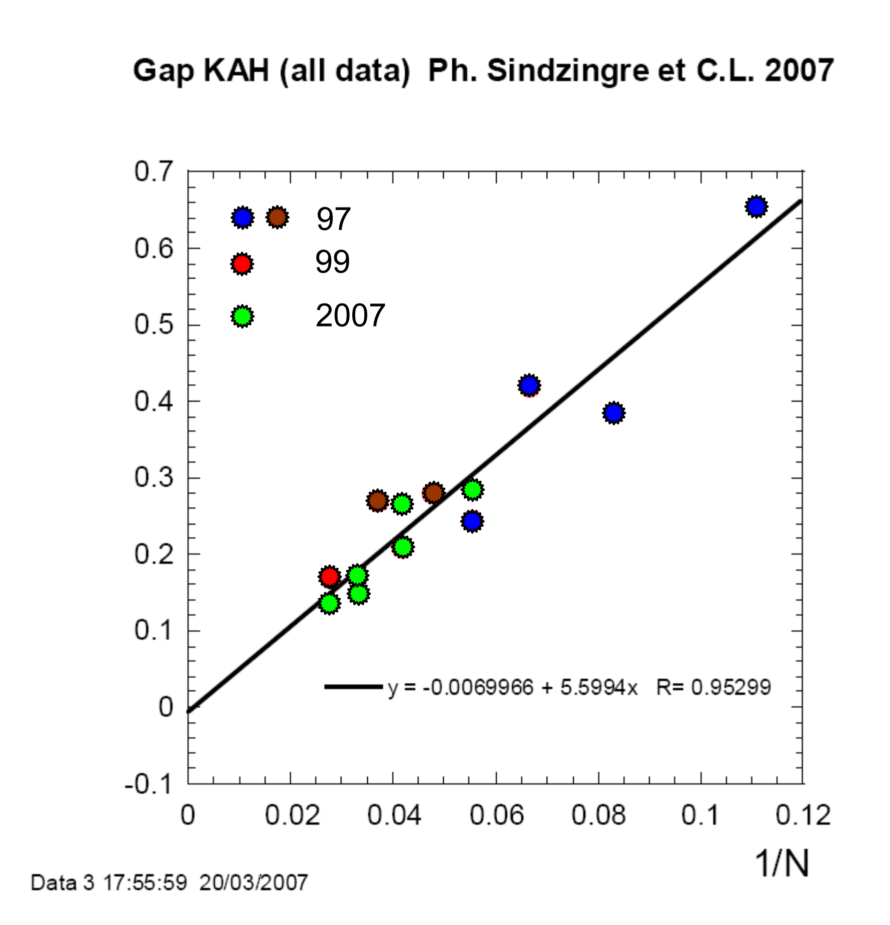
-> Extra low temperature dynamics

Is the S=1/2 KAH gapped ?

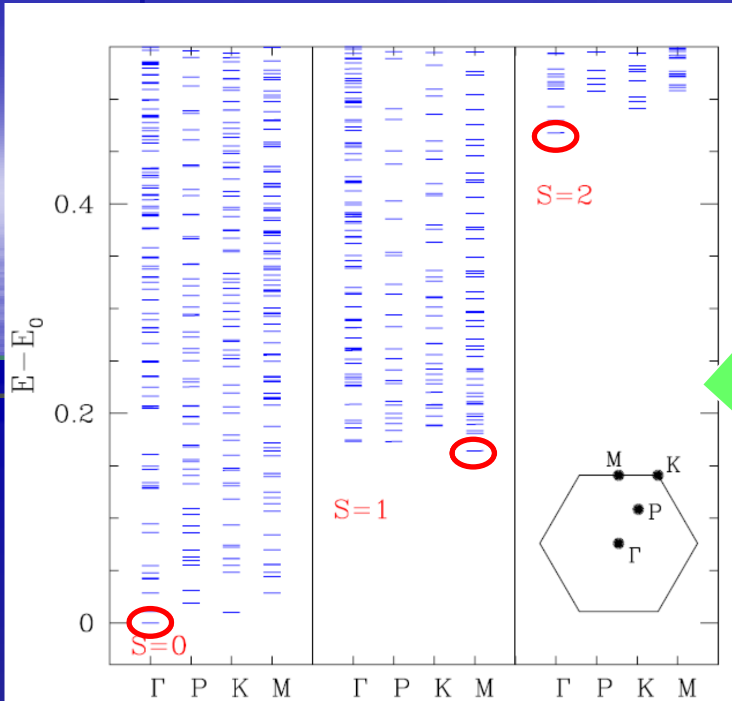
(standard analysis)

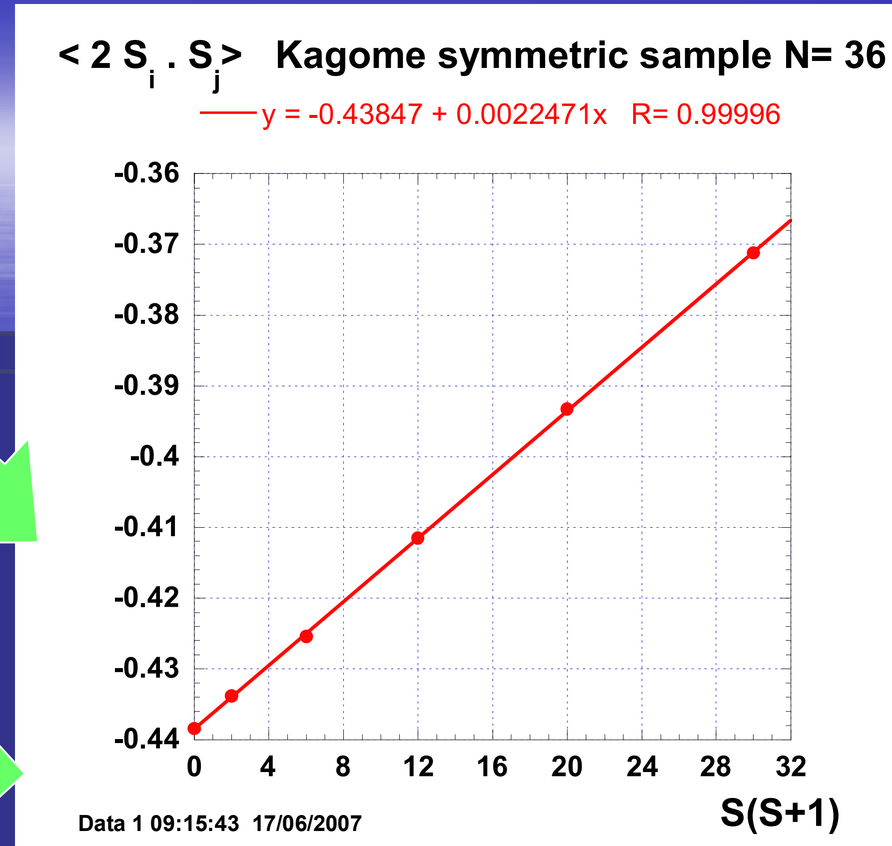
$$H = \Sigma S_i . S_j$$

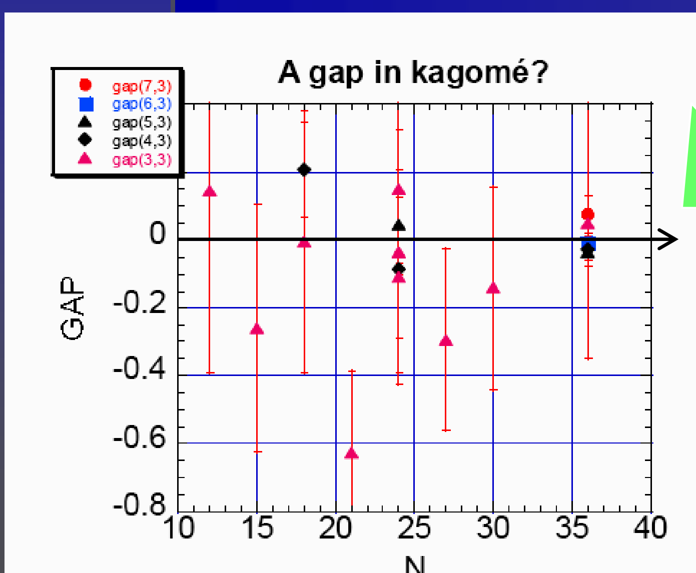




Gap = 0 +/- 0.027







Gap = 0 +/- 0.01

To be read:

Gap ∈ [0 .. 0.01] with proba. 2/3

Is the S=1/2 KAH gapped ?

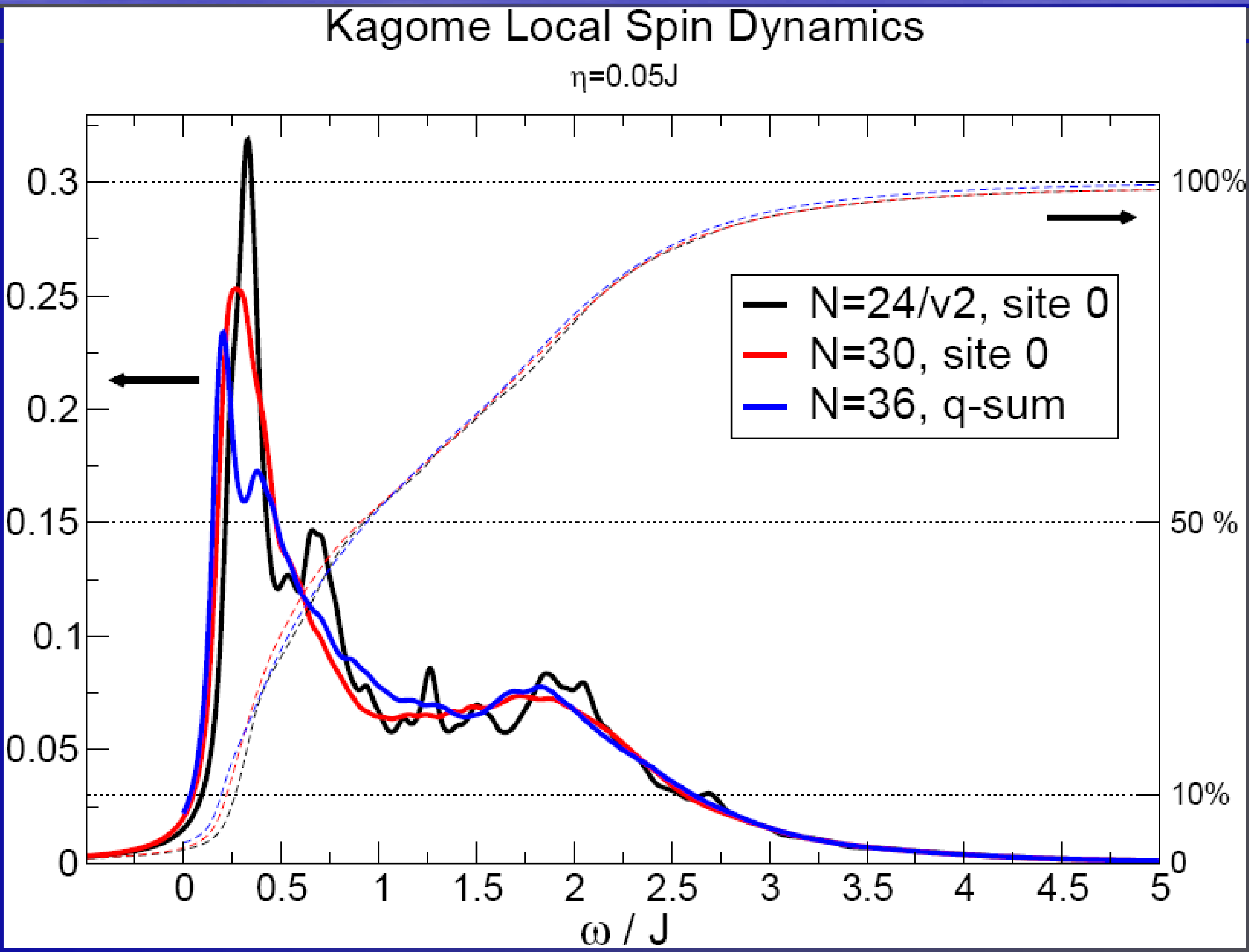
(refined analysis)

- *Spin Gap* $\in$ [0 .. 0.01]
- $J\,\chi\,(T \sim 0.01J) = 0.09 \pm 0.015$

If $C = 0.5,\ J = 175\ K$,

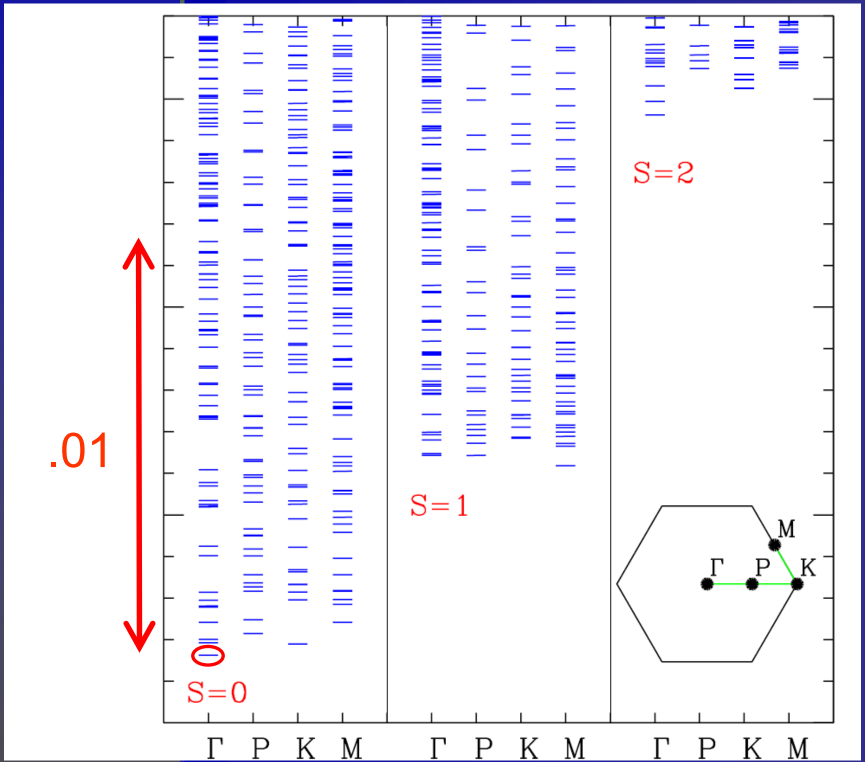
$\chi\,(T \sim 0.01J) = 0.001\ cm^3/mole$

Dynamical Structure Factor
Andreas Laeuchli 2007



Nature of the low temperature phase?

Kagomé N=36



- Valence Bond Crystal ?

  Zeng & Elser 1990, Syromyatnikov & Maleyev, Nikolic & Senthil, misguich & Sindzingre 2006, Singh & Huse 2007

- Z2 Spin Liquids?

  Sachdev 92, Wang & Vishnawath 2006

- U(1) Spin Liquid ?

  Hastings 2001,
  Ran, Hermele, Lee & Wen
  Phys Rev. Lett. 98, 117205, 2007

- Algebraic Vortex liquid ?

  Ryu, Motrunich, Alicea, M.PA. Fisher
  Phys Rev. B. 184406 2007

Conclusions and open questions?

- Spin ½ Heisenberg on the kagomé lattice may be gapless:

  Gap = 0 +/- .01, J χ (T=.01K) = .09 +/- .015
- Continuum of very dense low lying excitations:

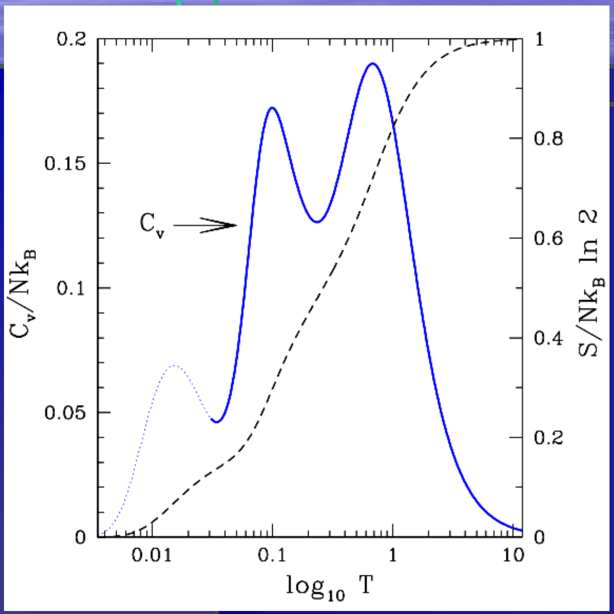
  a very good explanation of the ultra-low temperature dynamics of $ZnCu_3(OH)_6Cl_2$
- Is it a VBC?

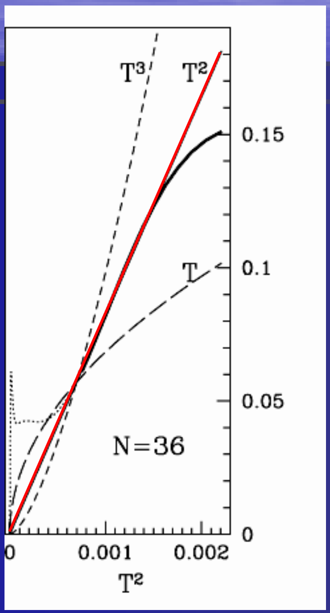
  VBC not fully convincing

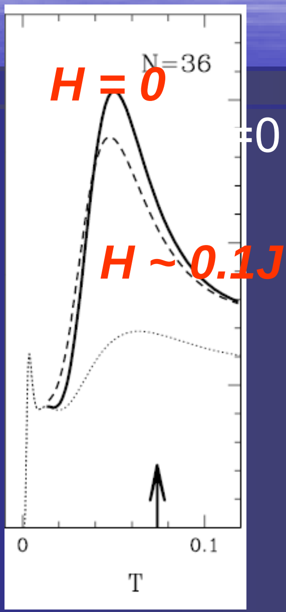
  Our conclusions would be different for a pyrochlore, or integer spins on a kagome lattice
- A « Critical » Spin or Vortex Liquid?

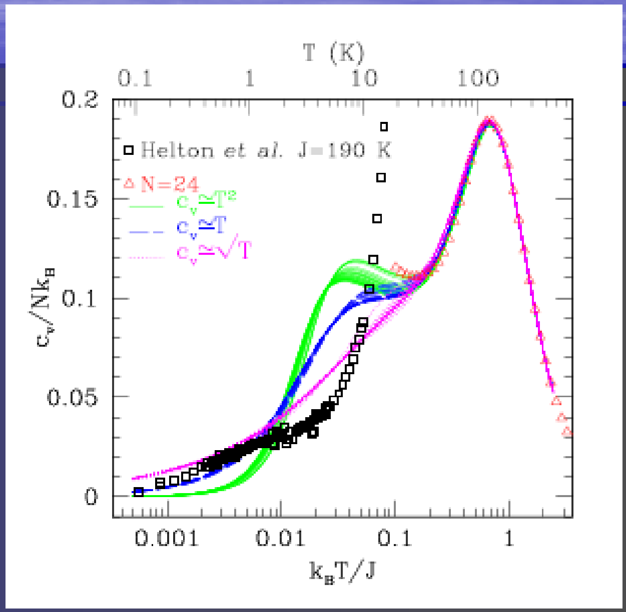
  May be plausible.. Many features still to be explored

KHAF specific heat









P. Sindzingre et al.. PRL 00
Exact diagonalizations

G. Misguich & .Sindzingre 07 H.T. series

Is it generic for quantum cooperative paramagnets?
A. Ramirez et al.. PRL 00 (SCGO),
S. Nakatsuji et al. Science 2005 ($NiGa_2S_4$)

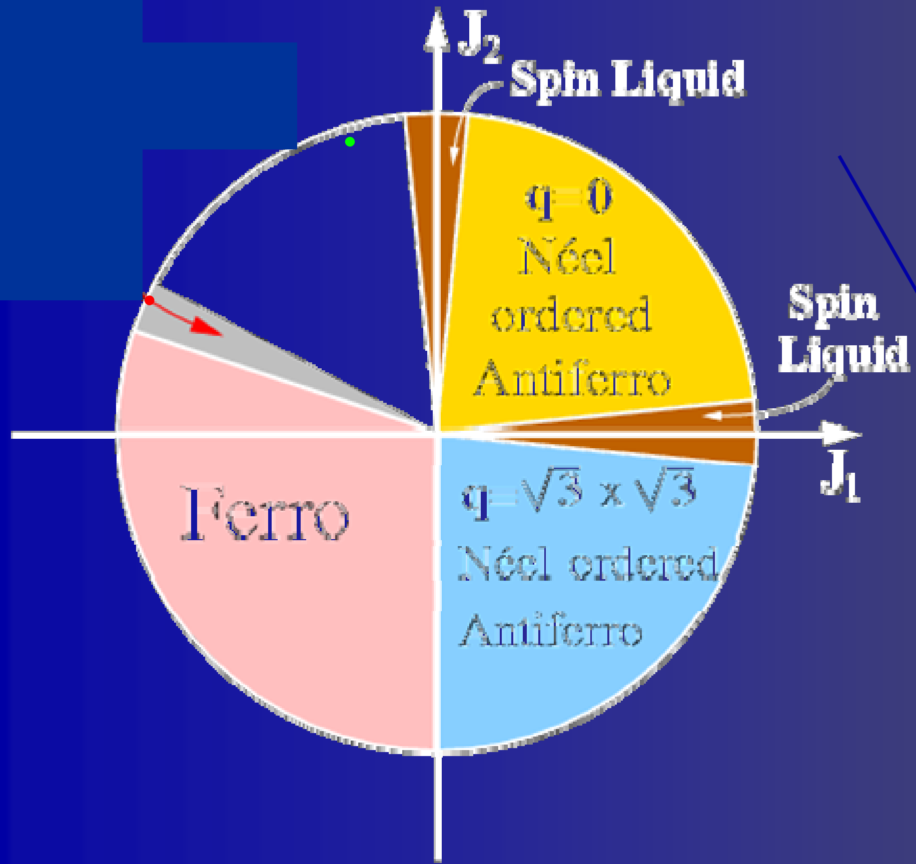
The J_1-J_2 model on the kagomé lat.

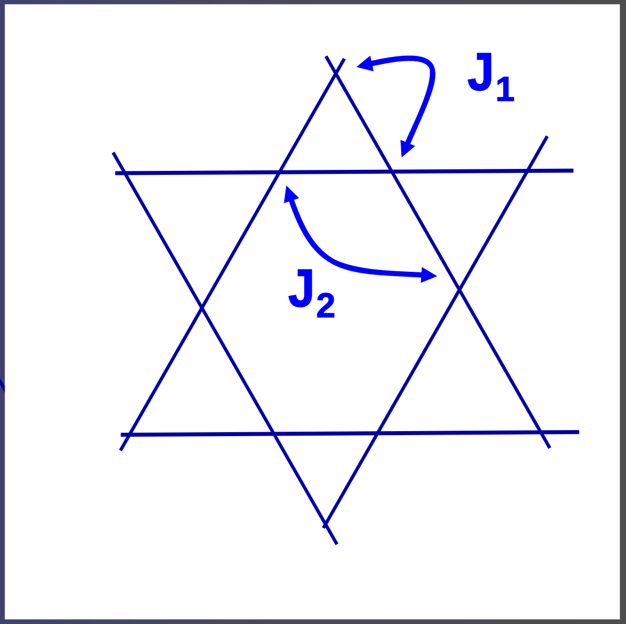
a new chiral low temperature phase

role of thermally activated Z_2 vortices

J.-C. Dommenge (Rutgers),
L. Messio & P. Viot (Paris)

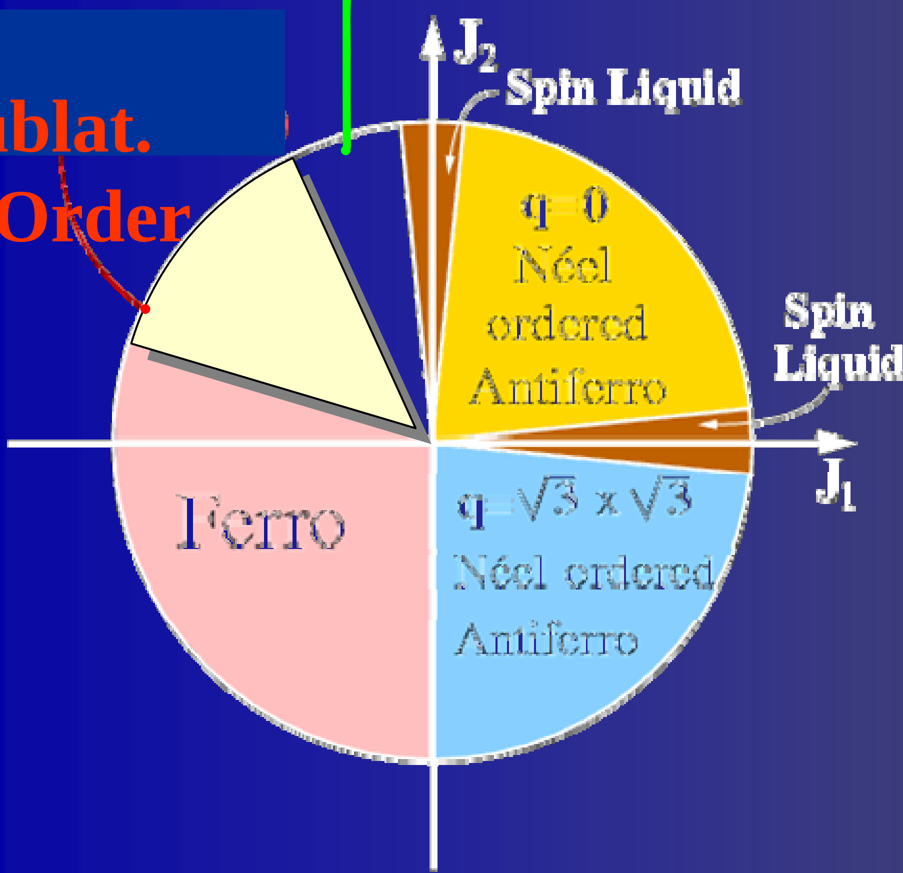
Quantum phase diagram of the J_1-J_2 model on the kagomé latt.





Spin-1/2 phase diagram of the J_1-J_2 model on the kagomé latt.

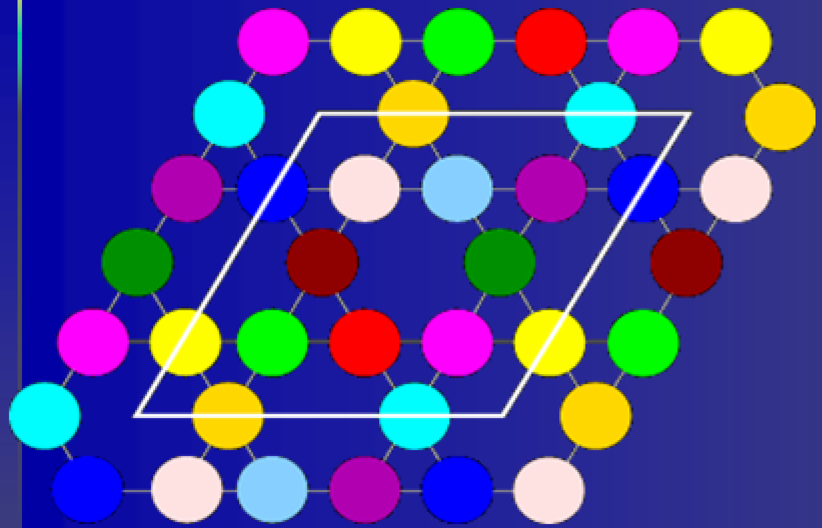
12 Sublat. Néel Order



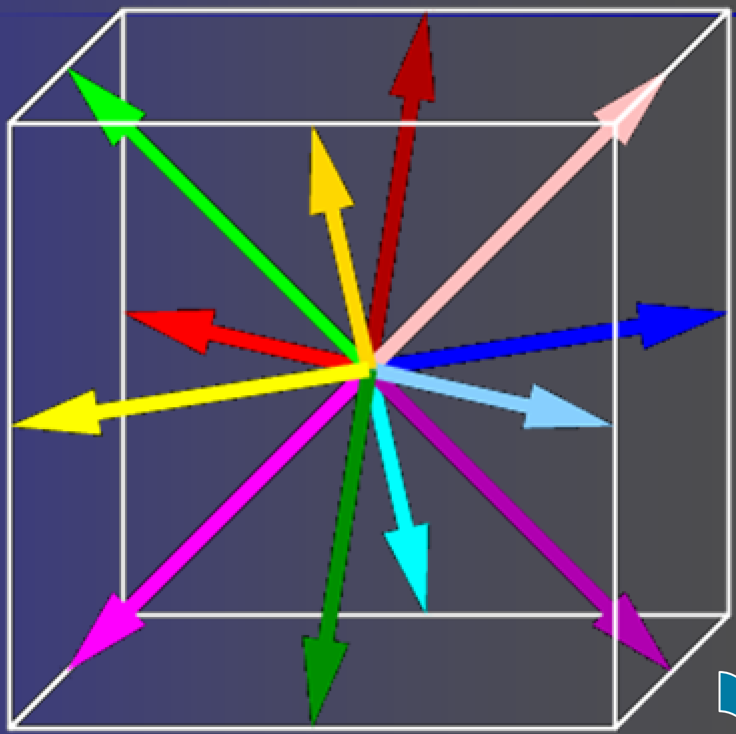
A new fully gapped quant. ph.

J2/|J1| < 3

T=0 semi classical Néel order



12 sub-lattice Néel order

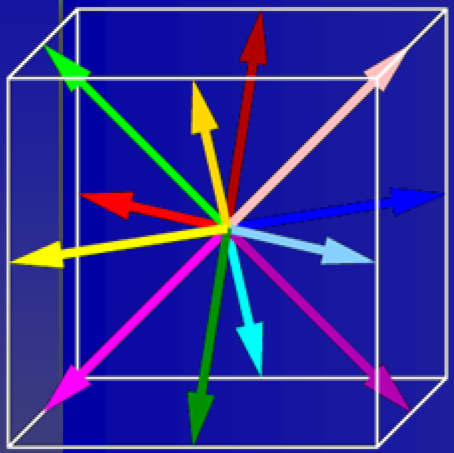


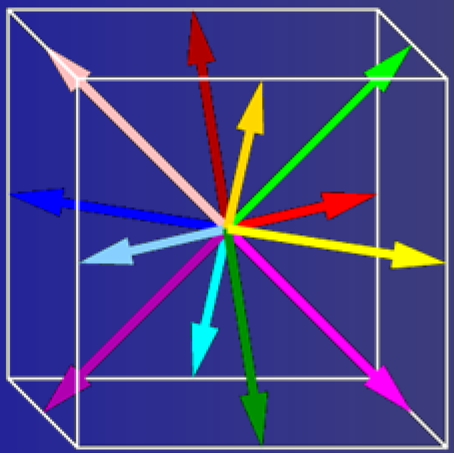
cuboctahedron symmetry of the order parameter

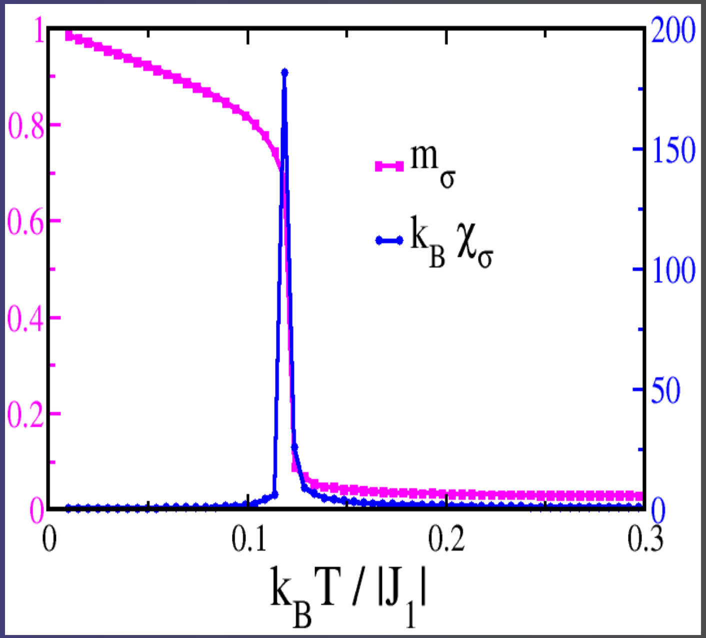
NO LRO in spin-spin correlations at T ≠0

Chiral symmetry breaking
(M.C. study - classical spins)

N=768, $J_2/|J_1|=0.38$



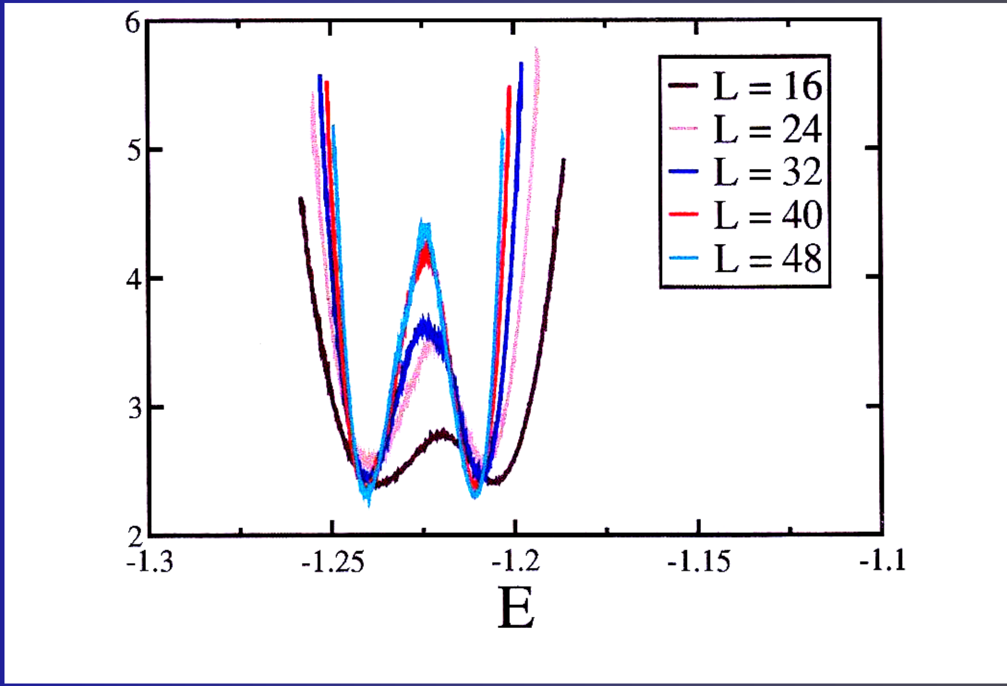




Scalar chirality $\sigma=+1$ $\sigma=-1$

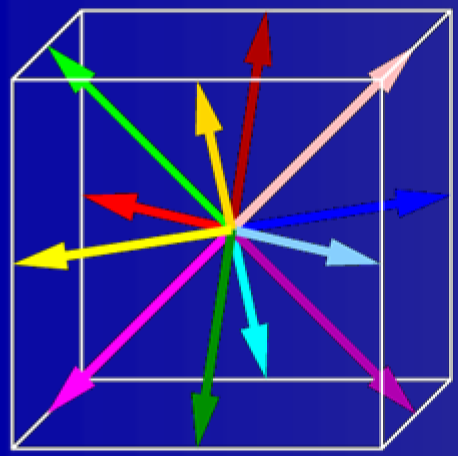
Weak universality (Suzuki 1984) ?

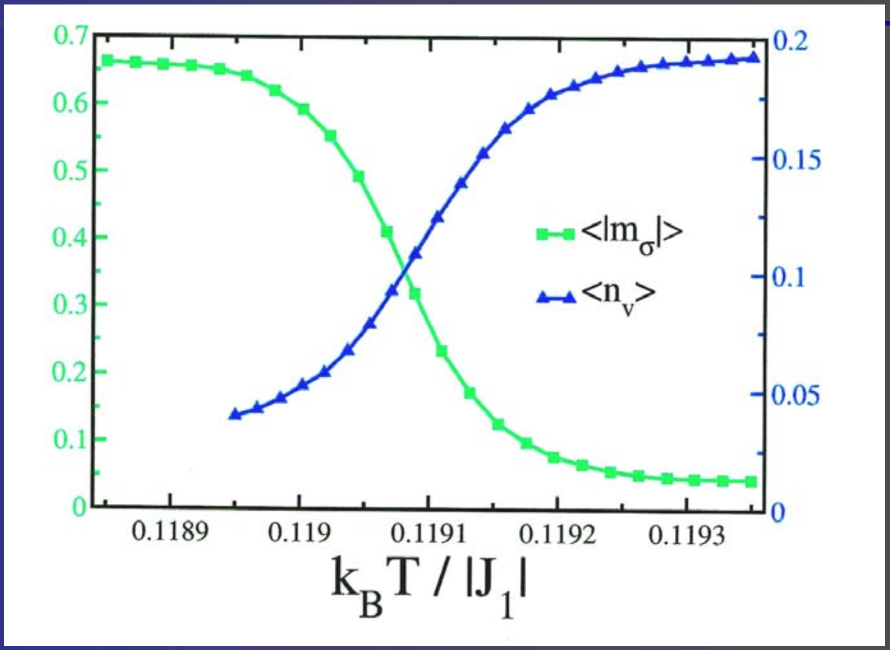
Free energy histogram
J2 / |J1| = 0.38



A very weak first order phase transition !

First order chiral phase transition mechanism?



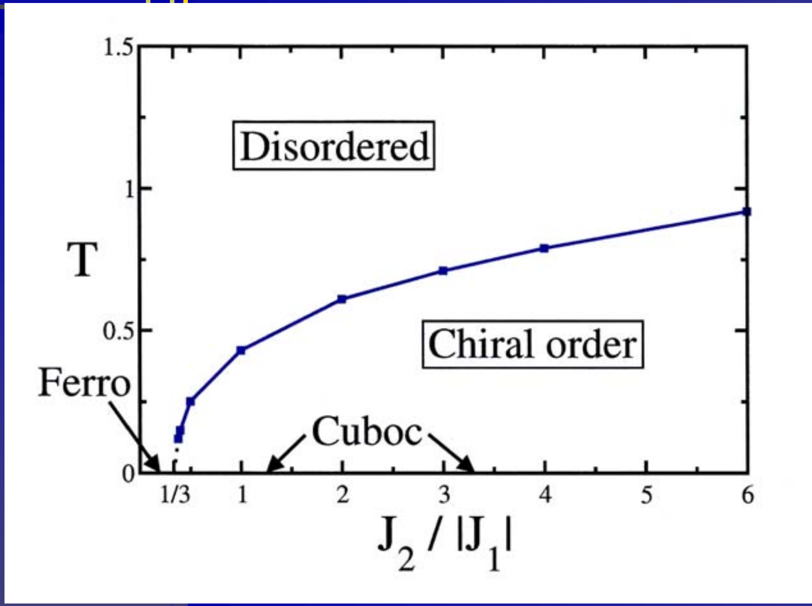


O_3 is completely broken
Z_2 vortices can be present

$J_2/|J_1| = 0.38$

At $T \neq 0$ chirality disappears and Z_2 vortices proliferate

T≠0 Phase diagram of the F-AF model



The chiral phase transition:

- ✓ weakly first order at small $J_2/|J_1|$
- ✓ due to Z_2 vortices
- ✓ going towards criticality when $J_2/|J_1|$ increases
- ✓ cross over from 1st to 2nd order depends on chem. pot. of vortices

May be not so rare in frustrated magnets *(Momoi et al PRL 97)*

Conclusion of this 2nd part

- 2 new phases in the J1<0 - J2 >0 model on the kagomé lattice
  - A semi-classical chiral phase with no LRO in spins, but with chiral order at T ≠ 0 and a weekly first order phase transition driven by Z_2 defects
  - A quantum gapped phase

J.C. Domenge, P. Sindzingre, C. L. & L. Pierre: PRB '05.

L. Messio, P. Viot, C.L & L. Pierre (in prep.)