Spin Nematic Order in Triangular Antiferromagnet

関連する発表
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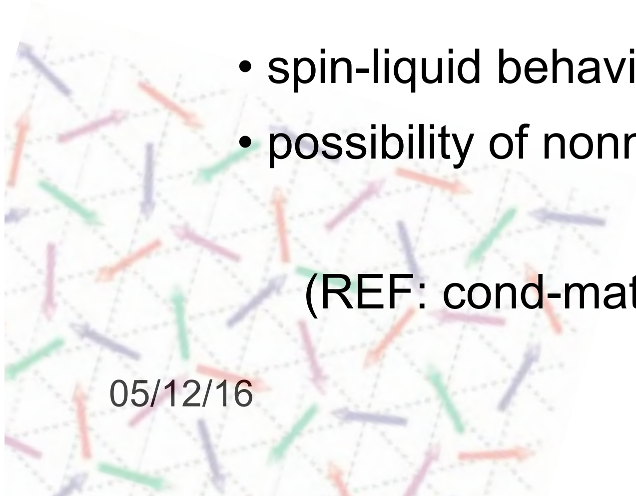
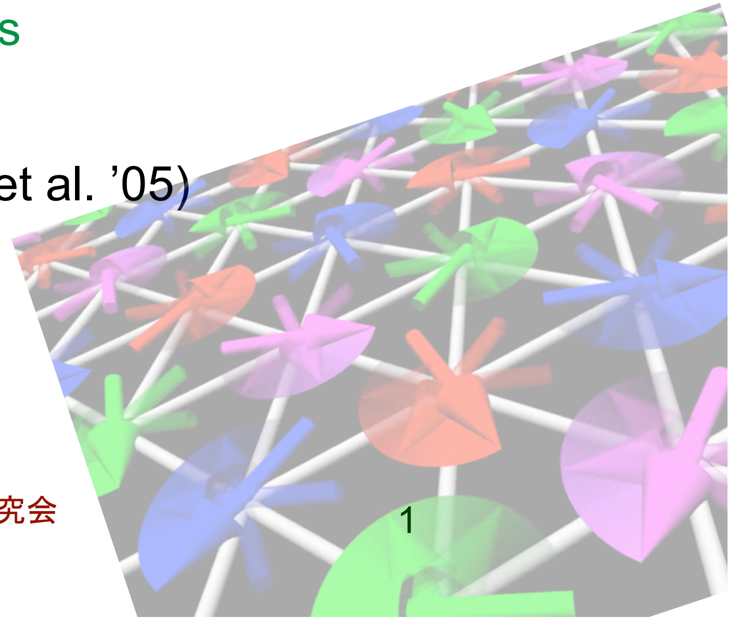
Search for exotic quantum states
-- competing/complex orders -> super-clean systems
-- effects of non-Heisenberg interaction
(many-body ring exchanges etc)
-- novel quantum criticality/universality class
-- new phenomena (hopefully, observable)



- spin-liquid behavior in $NiGa_2S_4$ (Nakatsuji et al. '05)
- possibility of nonmagnetic order scenario

(REF: cond-mat/0512209)

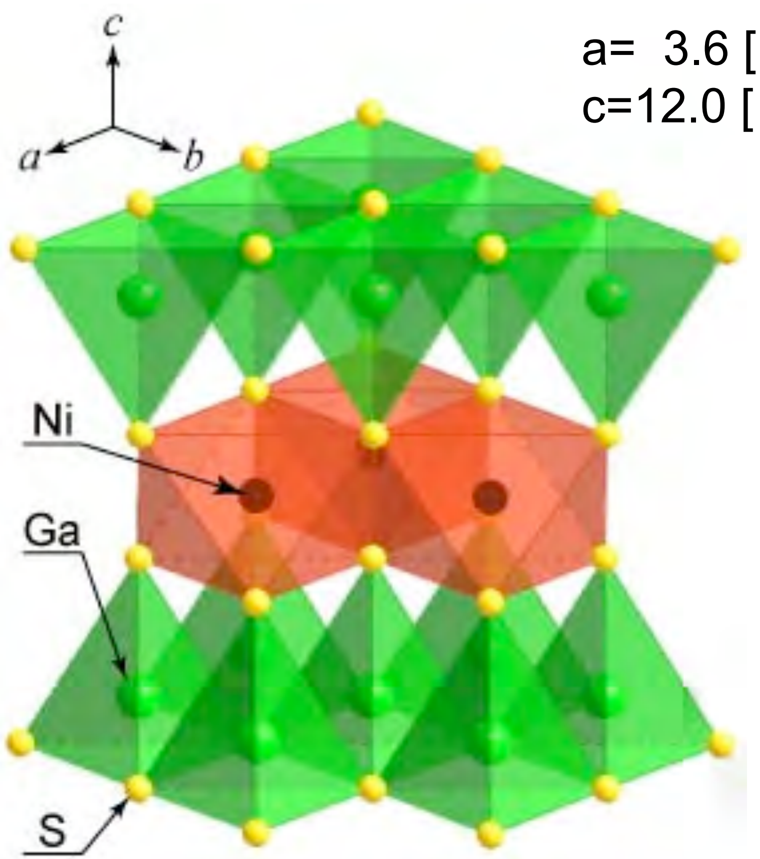


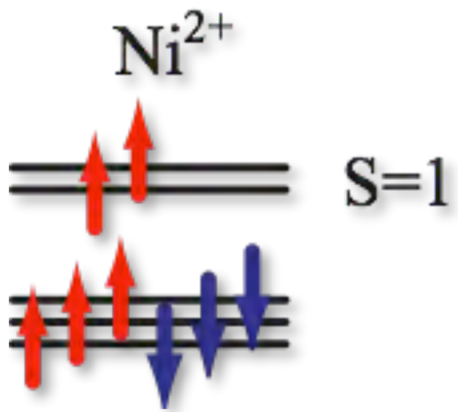
$NiGa_2S_4$: (1) S=1 triangular antiferromagnet

- S=1 spin system (Ni^{2+})
- Quasi-2D triangular structure

Nakatsuji et al., *Science* **309**, 1697 ('05)

a= 3.6 [Å]
c=12.0 [Å]

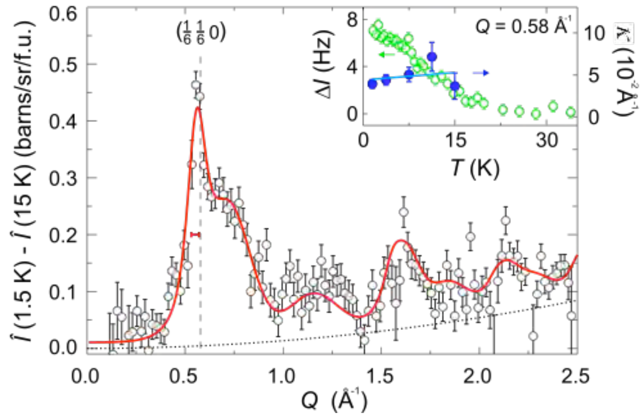


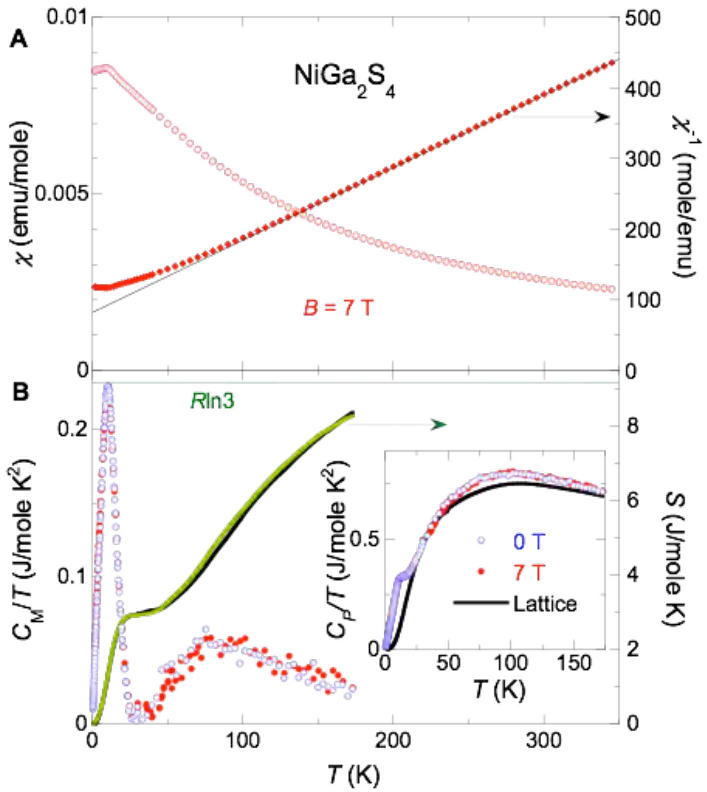


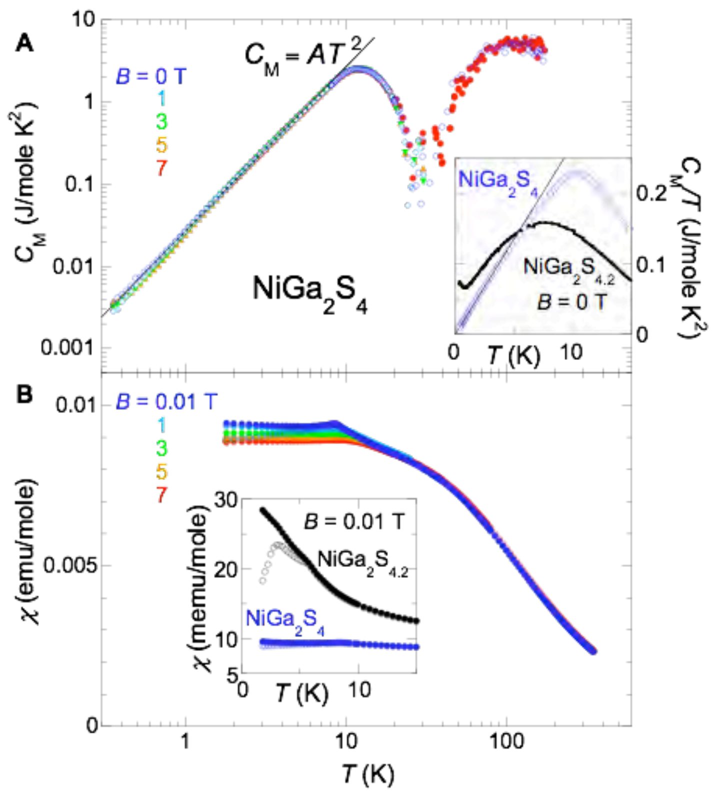
$NiGa_2S_4$: (2) New “Spin-Liquid” material

Nakatsuji et al., *Science* **309**, 1697 (‘05)

- No phase transition down to 0.35[K]
- gapless excitations $C(T)\propto T^2$
- Finite $\chi\approx 8\times10^{-3}$[emu/mole] at T≈0
- Finite $\xi\approx 25$[Å] at T≈0
- Spatial modulation in spin correlations Q≈(1/6,1/6,0)







Spin Liquid / Non-magnetic Order

- Absence of magnetic LRO at T=0
- Periodic structure, no glassy behavior

⇒ "spin liquid"
in this sense

- RVB state or non-magnetic order?
- possibility of spin "nematic" order (= quadrupolar order)

Non-magnetic order: $\langle \mathbf{S} \rangle = \mathbf{0}$

Order parameter: $Q_{\mu\nu} = \frac{1}{2} \langle S_\mu S_\nu + S_\nu S_\mu \rangle$

S≧1

Quadrupolar Moment

More precisely,
anisotropic spin fluctuations

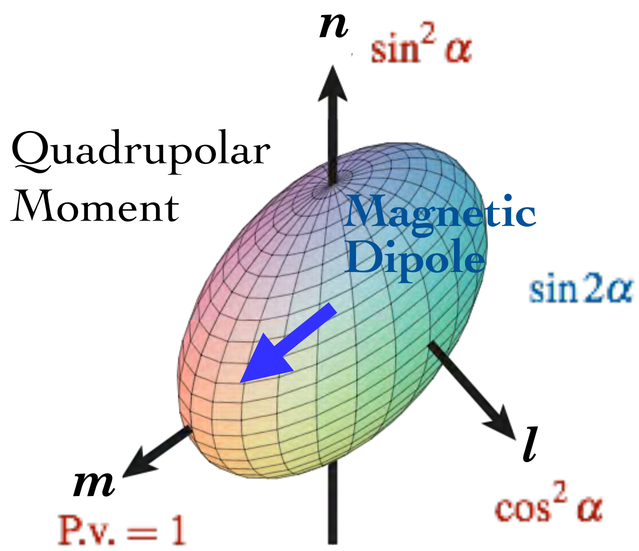
$$D_1 = \langle 2S_z^2 - S_x^2 - S_y^2 \rangle, \; D_2 = \langle S_x^2 - S_y^2 \rangle$$ etc

Local Degrees of Freedom

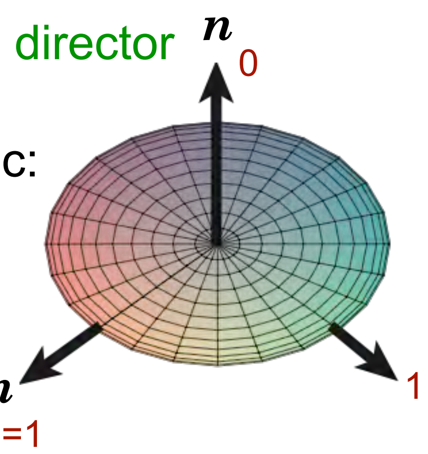
- S=1 ⇒ 3-component wavefn.

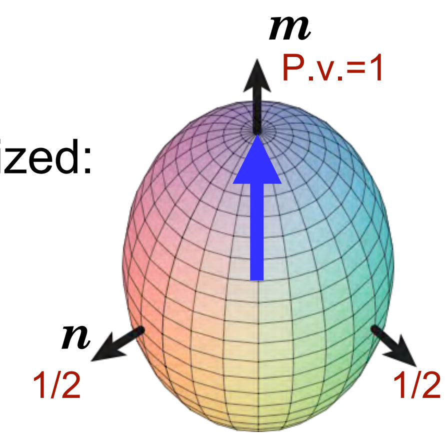
  $$|\psi\rangle = [\psi(+1), \psi(0), \psi(-1)]$$

  ⇒ 4 real parameters
  (θ,ϕ,χ): direction of Quad. moment
  α: principle value parameter



- (Non-magnetic state)
  = completely oblate (disk shape)
  Quad. moment (P.v.=0,1,1)





Phenomenological Model

$$H = J\sum_{\langle i,j\rangle} \mathbf{S}_i \cdot \mathbf{S}_j + K\sum_{\langle i,j\rangle} (\mathbf{S}_i \cdot \mathbf{S}_j)^2$$

Bilinear-Biquadratic model

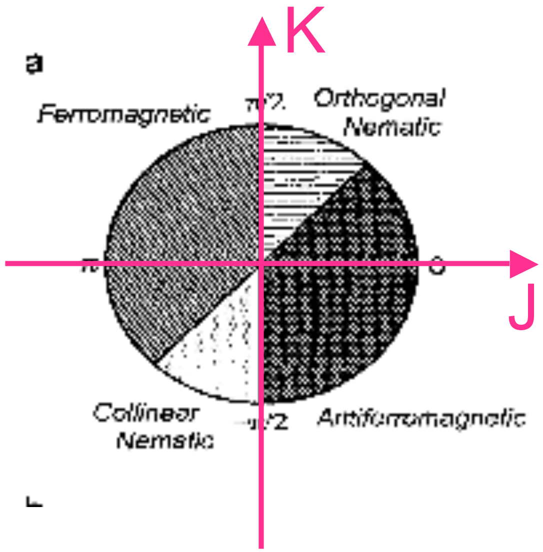
J=20[K], K=150[K]

(cf Ring exchanges)

- Mean Field Approx.

$$\mathbf{S}_i \cdot \mathbf{S}_j \Longrightarrow \mathbf{M}_i \cdot \mathbf{M}_j$$

$$(\mathbf{S}_i \cdot \mathbf{S}_j)^2 \Longrightarrow \mathrm{Tr}\,[\mathbf{Q}_i \mathbf{Q}_j] - \tfrac{1}{2}\mathbf{M}_i \cdot \mathbf{M}_j$$



Antiferro biquad. coupling (K>0)

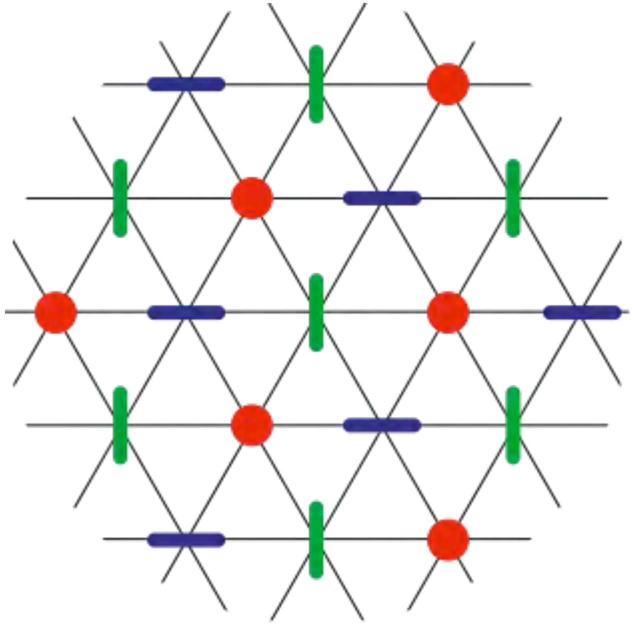
⇒ $\mathbf{n}_i \perp \mathbf{n}_j$

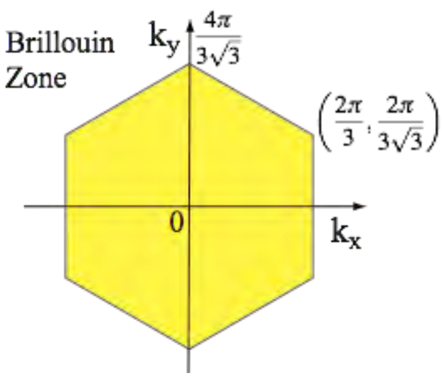
orthogonal arrangement
“disklike” Quad. moments

AF Nematic Phase on Triangular Lattice

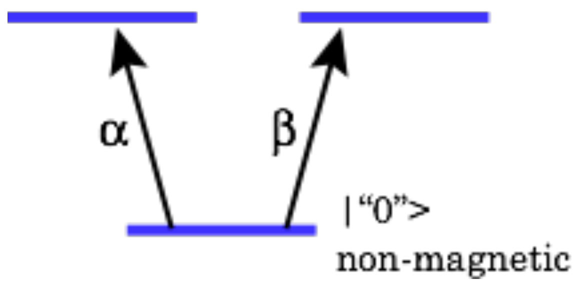
- 3-sublattice structure
  disk-like Quad. moments

- K>0
  0<J<K





Quantum Fluctuations and Boson Excitations (1)



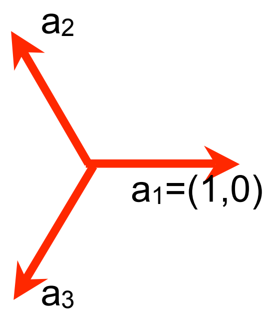
- 2 types of bosons
  for describing local excited states
- quantum fluctuations of nematic AF order
- Bogoliubov transformation

3 sublattices x 2 types = 6 modes of Boson excitations

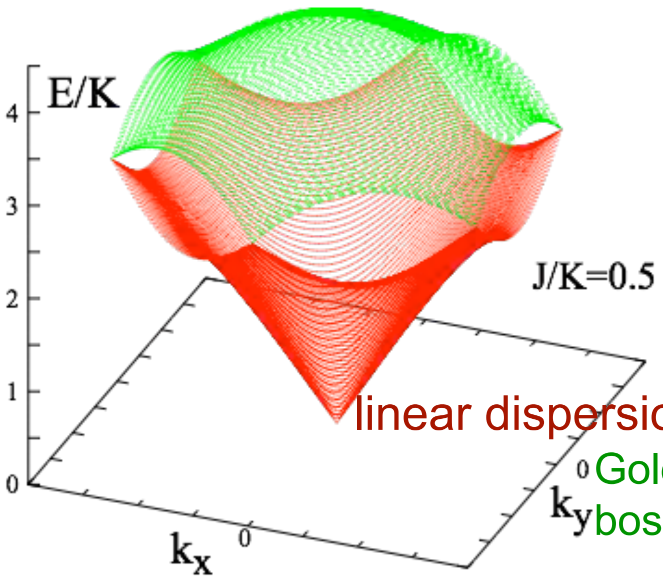
⇒ 3 degenerate sets of gapless & gapful modes

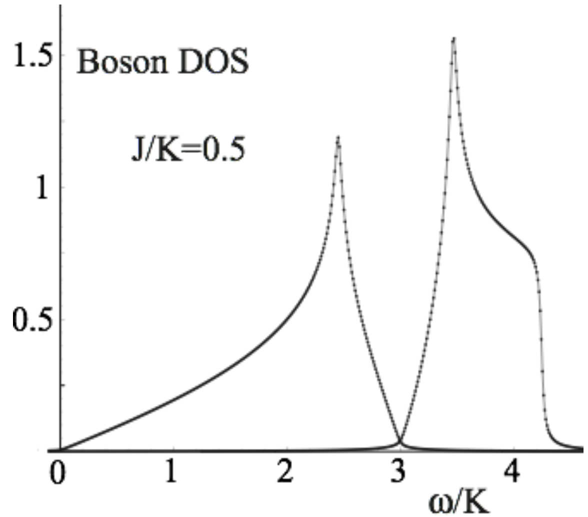
$$E_{\pm}(\mathbf{k}) = 3K\sqrt{(1 \pm \Gamma_{\mathbf{k}})(1 \pm \Delta\Gamma_{\mathbf{k}})}$$

$$\Delta = 1 - \frac{2J}{K} \qquad \Gamma_{\mathbf{k}} = \frac{1}{3}\left|\sum_{j=1}^{3} e^{i\mathbf{k}\cdot\mathbf{a}_j}\right|$$



Quantum Fluctuations and Boson Excitations (2)





linear dispersion

Goldstone boson

specific heat $C \propto T^2$

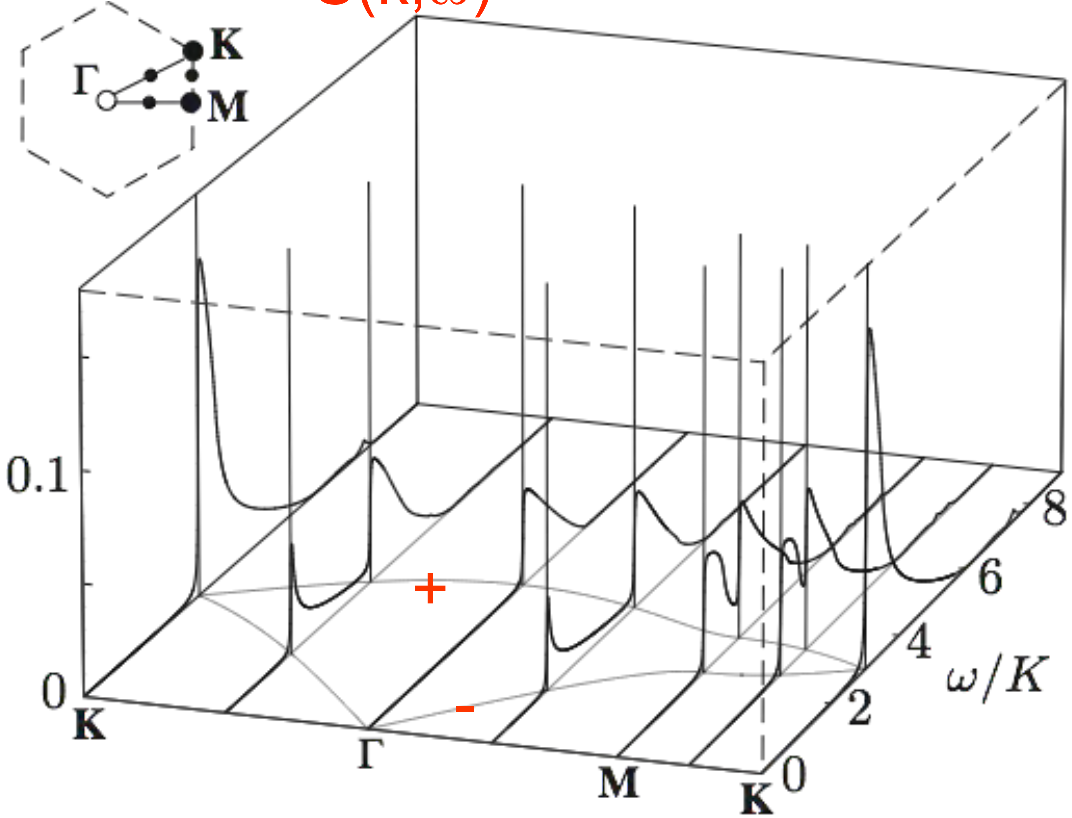
contribute to $S_{spin}(k,\omega)$

>75% stays in the original “nematic” state

⇒ justify the Gaussian approx.

Spin Dynamics

S(k,ω)



delta-function peaks
at $\omega = E_{\pm}(\mathbf{k})$

bosons: contribute to magnetic dipolar fluctuations -> *magnons*

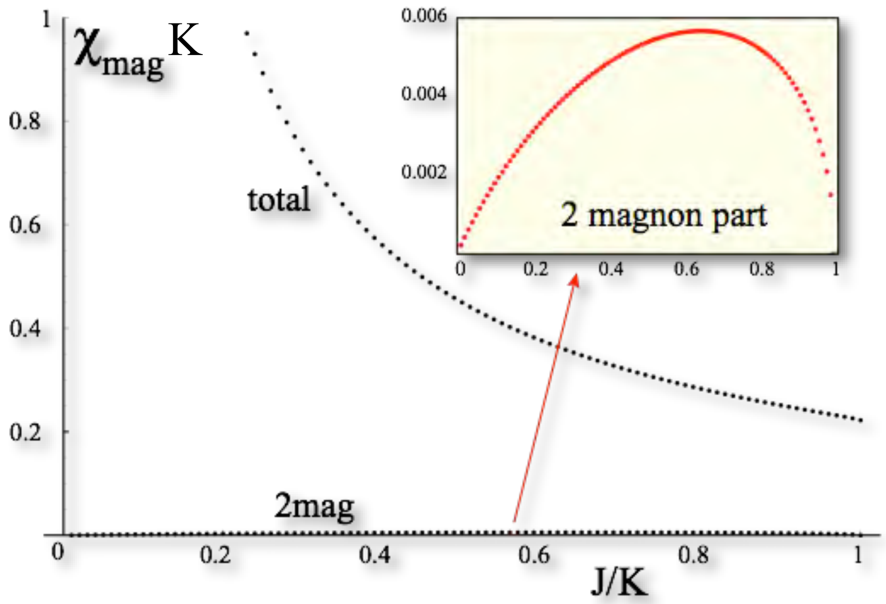
2-magnon continuum

Magnetic Susceptibility

$$\chi_{mag} = \chi(1\text{ boson}) + \chi(2\text{ boson})$$

$$\chi(1\text{ boson}) = \frac{2}{9J}$$

classical value

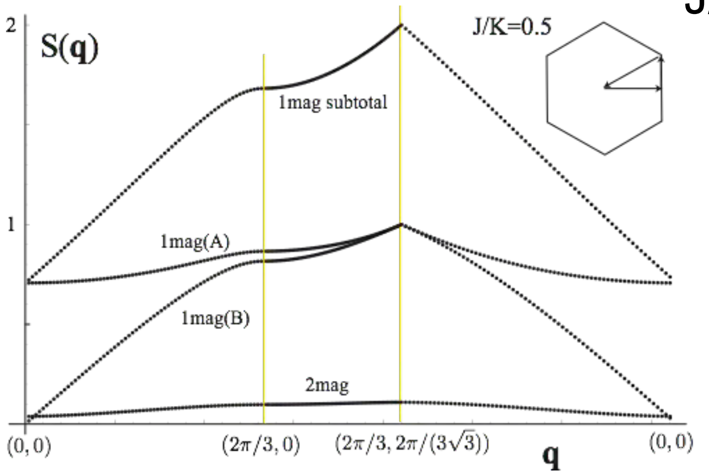


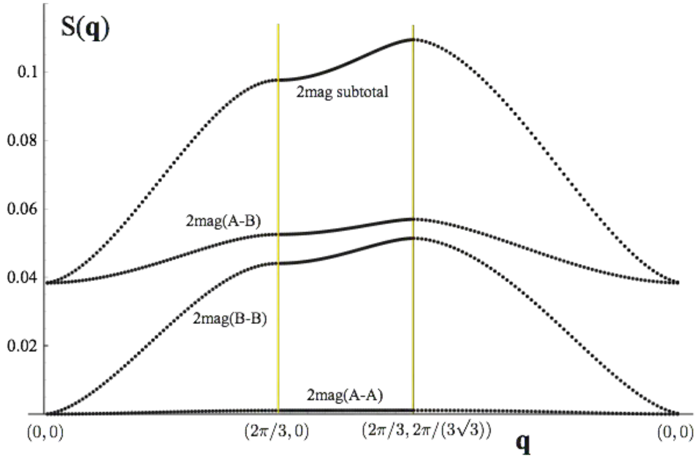
$$\chi^{\mu\mu}_{mag} = \frac{2}{3}\lim_{\mathbf{k}\to\mathbf{0}} \sum_{a,b=A,B,C} \int_0^\infty d\omega \frac{S^{\mu\mu}_{ab}(\mathbf{k},\omega)}{\omega}$$

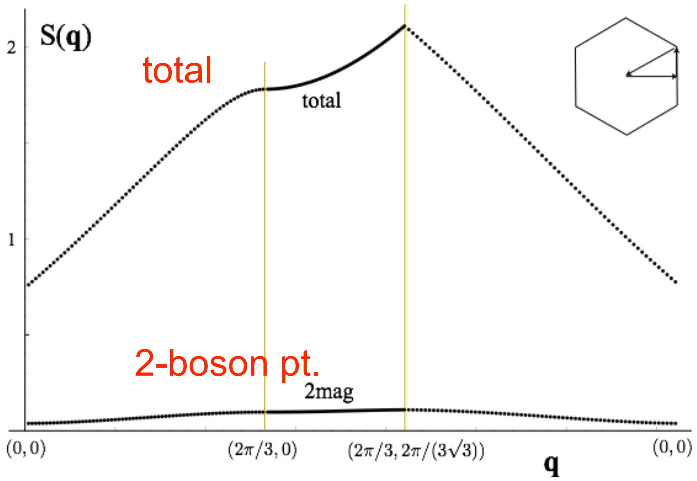
- 2-boson part is very small
- classical value does not depend on K

Spatial Spin Correlation

J/K=0.5







- NO divergence
- only cone singularity
  const.-a|$\boldsymbol{k}$-$\boldsymbol{Q}_0$|
- algebraic decay
  <S(r)S(0)>～1/r^3
- (cf.) " ξ < ∞" neutron exp.

Summary

- spin-liquid behavior in S=1 triangular magnet $NiGa_2S_4$
- propose spin-quadrupole (=spin nematic) order at T=0
  low-T properties are determined by T=0 order
- study bilinear-biquadratic model as a phenomelogical effective Hamiltonian to investigate quantum effects
- gapless & gapful “magnon” excitations
- explain most basic properties of $NiGa_2S_4$

Future Project

- Search for nematic and other nontrivial states (flux/chirality, multipoles etc.)
- Effects of ring exchange processes
- Construct realistic microscopic model for NiGa2S4
- More details of spin dynamics