Dirty frustrated magnets: order from disorder and disorder by disorder

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spsms

Outline

collaborators:

- Order from disorder — V. Maryasin (UJF & CEA)
  - vacancies in triangular AF: lifting degeneracy in magnetic field
  - unified theory of thermal/quantum and quenched fluctuations
- Disorder by disorder — H. Tsunetsugu (ISSP)
  - frustrated ferro/antiferromagnetic chain: field-induced spin glass

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Introduction

- Magnetic frustration:
  - competing interactions
  - classical degeneracy
- Disorder: fluctuations in regular spin models
  - thermal effects tuned by T
  - quantum effects turned by $\hbar$ or S
- <u>Disorder: structural disorder</u>
  - bond disorder (magnetoelastic, chemical, …)
  - site disorder (vacancies, nonmagnetic impurities,…)

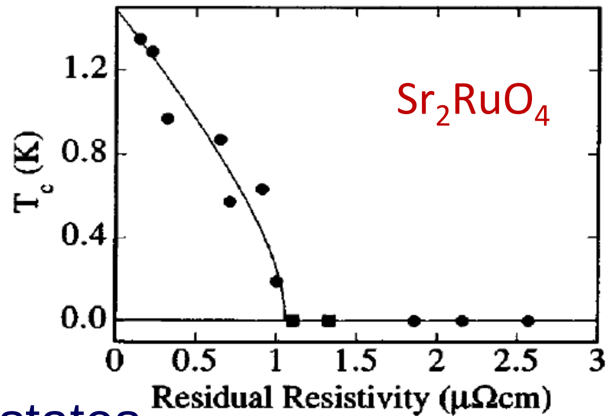
Impurities in magnetic solids: nuisance or useful experimental tool?

- ultimate probe for unconventional SC
- local spin polarization probed by NMR,

  Zn-Cu substitution in high-T_c cuprates

- impurity-induced textures in spin liquids, QC states

  Sachdev *et al*; Sen *et al*; Vojta *et al.*



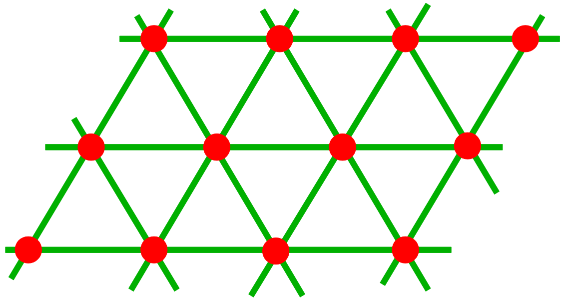
➢ example of new states in frustrated magnets

Part I

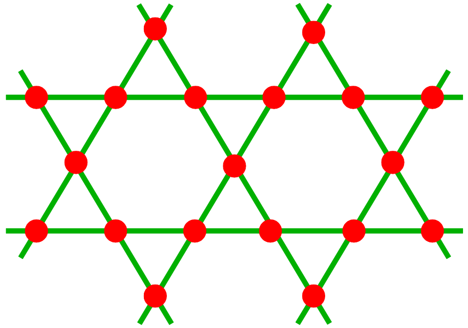
ORDER FROM STRUCTURAL DISORDER

Frustrated lattices

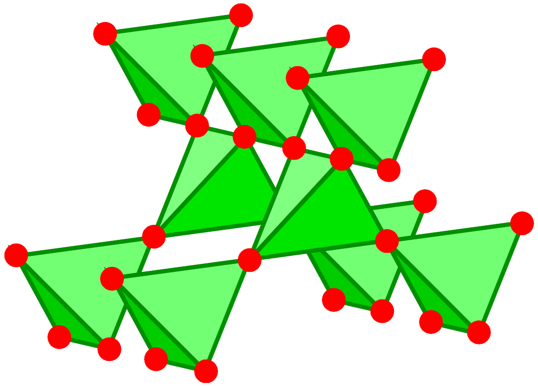
- triangular (2D)



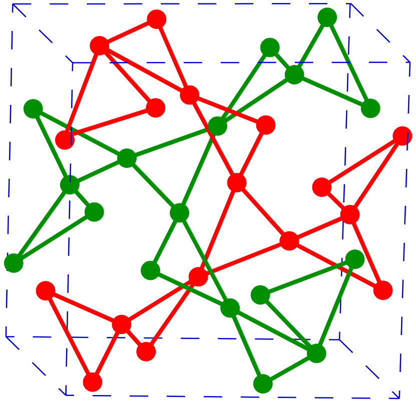
- kagomé (2D)



- pyrochlore (3D)



- garnet or hyper-kagomé (3D)



and many more…

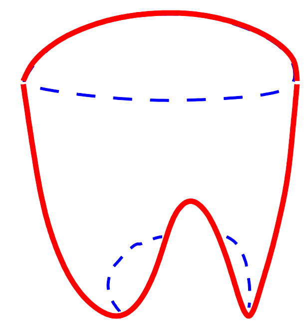
Order from disorder in a nutshell

Villain *et al* (1980), Shender (1982)

- spontaneous symmetry breaking
  (Mexican hat potential)

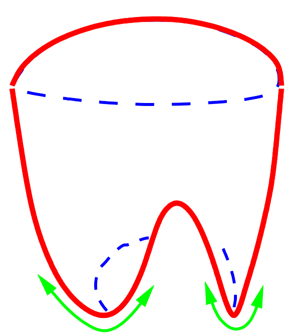
by A. Tsvelik

- accidental degeneracy:



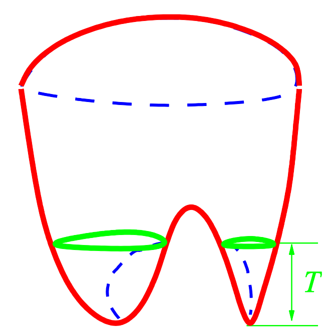
- quantum fluctuations:

$$\delta E = \frac{1}{2}\sum_{\mathbf{k}} \hbar\omega_{\mathbf{k}}$$

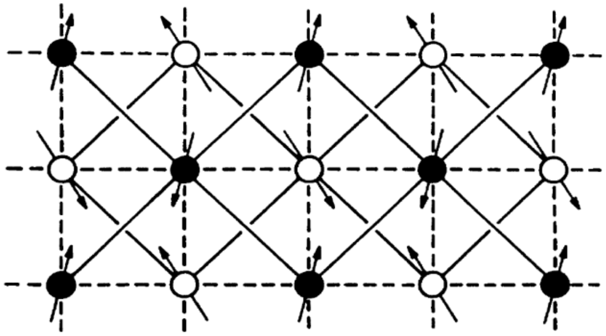


- thermal fluctuations:

$$\delta F = T\sum_{\mathbf{k}} \ln \omega_{\mathbf{k}}$$



Impurity in J_1-J_2 SAFM



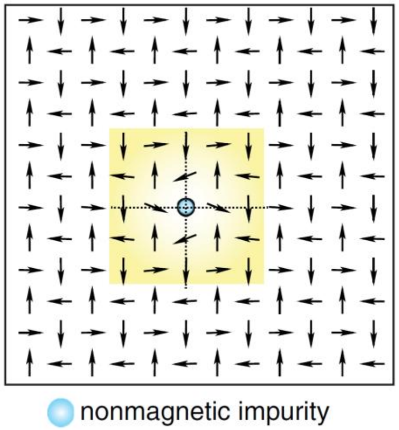
ground states for $J_2 > \frac{1}{2} J_1$:

degeneracy between $(\pi, 0)$ and $(0, \pi)$ states

- vacancy in one sublattice creates uncompensated moment and a local field on the other sublattice

⇨ orthogonal or anticollinear sublattice orientation

Henley (1989),
Weber & Mila (2012)



- "local-field approach" is not universal
- Z_2 symmetry is preserved

Effective Hamiltonian: thermal and quantum disorder

- transformation to the rotating local frame

$$\hat{H}=\sum J_{ij}\mathbf{S}_i\cdot\mathbf{S}_j\rightarrow\sum J_{ij}\left[\underline{S_i^yS_j^y+\cos\theta_{ij}(S_i^xS_j^x}+S_i^zS_j^z)+\underline{\sin\theta_{ij}(S_i^zS_j^x-S_i^xS_j^z)}\right]$$

- real-space perturbation theory (linked-cluster expansion)

$$\hat{H}_0=-h_{loc}\sum S_i^z \qquad \hat{V}=\sum J_{ij}\left[S_i^yS_j^y+\cos\theta_{ij}S_i^xS_j^x\right]$$

- thermal fluctuations

$$\Delta F^{(2)}=-\frac{T}{2h_{loc}}\sum(1+\cos^2\theta_{ij})$$

- quantum fluctuations

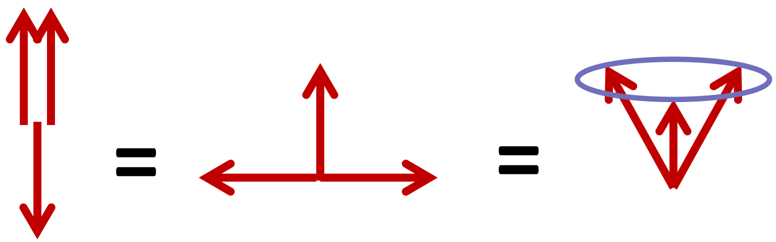
$$\Delta E^{(2)}=-\frac{J^2S^2}{8h_{loc}}\sum(1-\cos\theta_{ij})^2$$

$$\boxed{H_{eff}\sim-\sum(\mathbf{S}_i\cdot\mathbf{S}_j)^2}$$

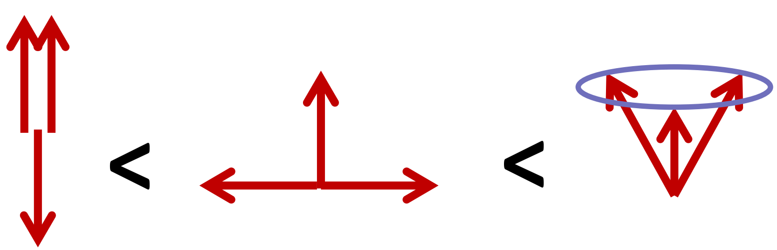
➢ negative biquadratic exchange → **most** collinear states

Heisenberg triangular AF in external field

- classical degeneracy, $H = 3JS = \frac{1}{3} H_s$

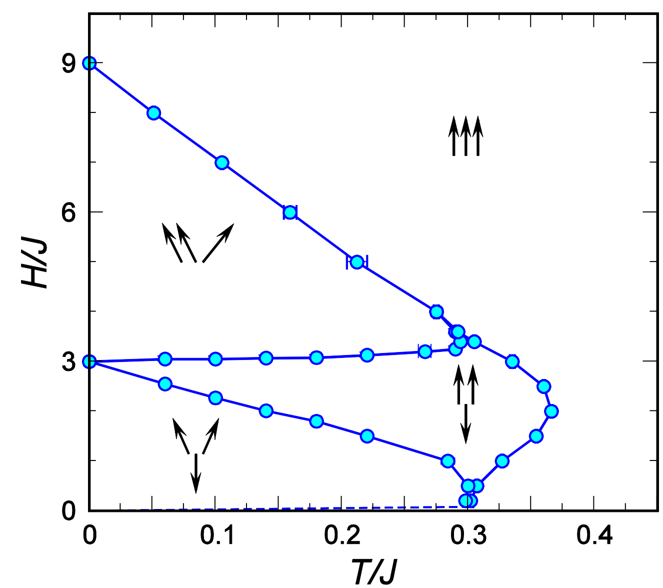


- effect of thermal fluctuations:



Kawamura & Miyashita (1985), Gvozdikova *et al* (2011)

- Monte Carlo phase diagram:



Effective Hamiltonian: structural disorder

- transformation to the rotating local frame

$$\hat{H} = \sum J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j \rightarrow \sum J_{ij} \left[\underline{S_i^y S_j^y + \cos\theta_{ij} (S_i^x S_j^x} + S_i^z S_j^z) + \underline{\sin\theta_{ij} (S_i^z S_j^x - S_i^x S_j^z)} \right]$$

- bond disorder: $J_{ij} = J + \delta J_{ij}$

$$\Delta E = -\frac{\delta J^2}{2h_{loc}} \sum \sin^2 \theta_{ij}$$

- site disorder: $\mathbf{S}_i \rightarrow \mathbf{S}_i (1 - \varepsilon p_i)$

  with $p_i = 0 \text{ or } 1; \ \langle p_i \rangle = \langle p_i^2 \rangle = n_{imp}$

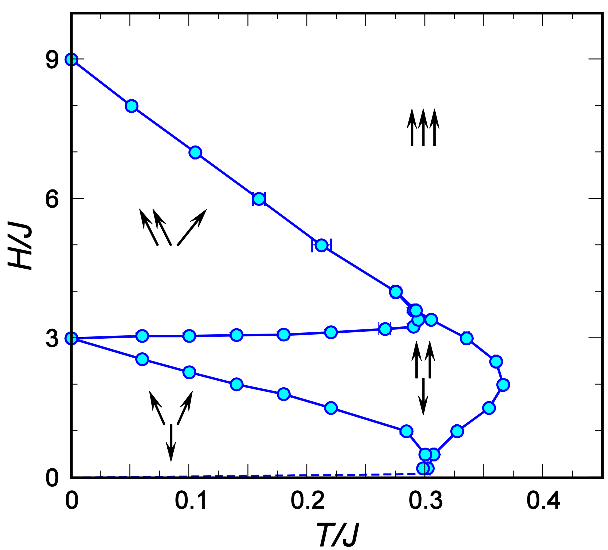
  then $\delta J_{ij} \approx \varepsilon (p_i + p_j)$

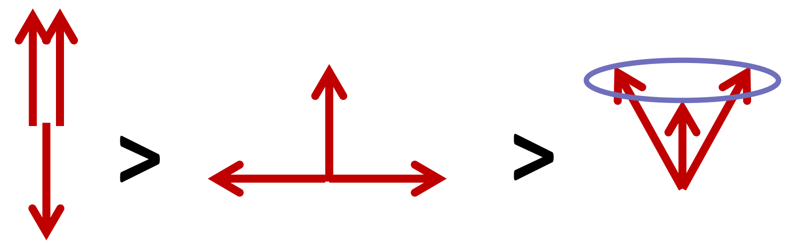
$$\boxed{H_{eff} \sim + \sum (\mathbf{S}_i \cdot \mathbf{S}_j)^2}$$

- positive biquadratic exchange $\rightarrow$ **least** collinear states

Diluted triangular AF in external field

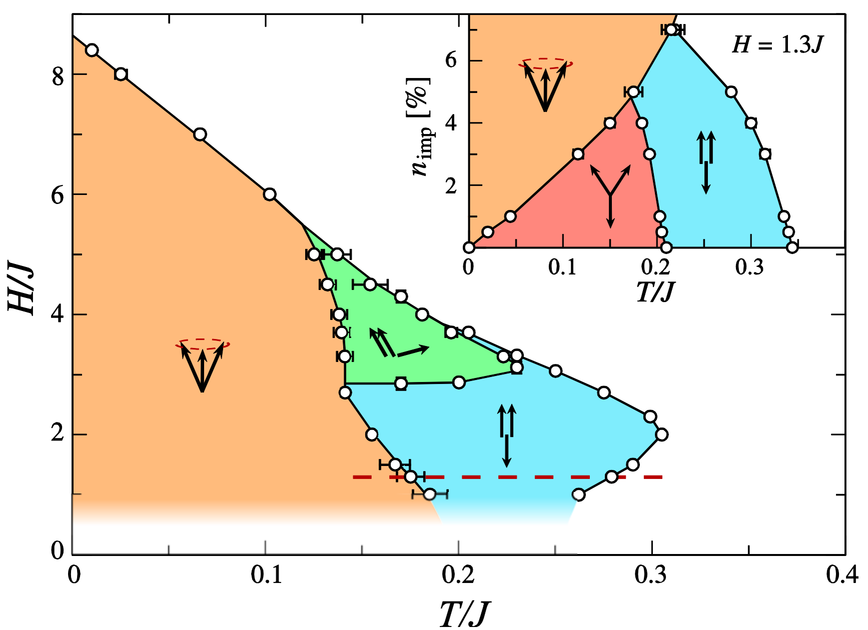
- Monte Carlo phase diagram:





vs

- 5% of vacancies



Maryasin & MZ (2013)

Order versus disorder

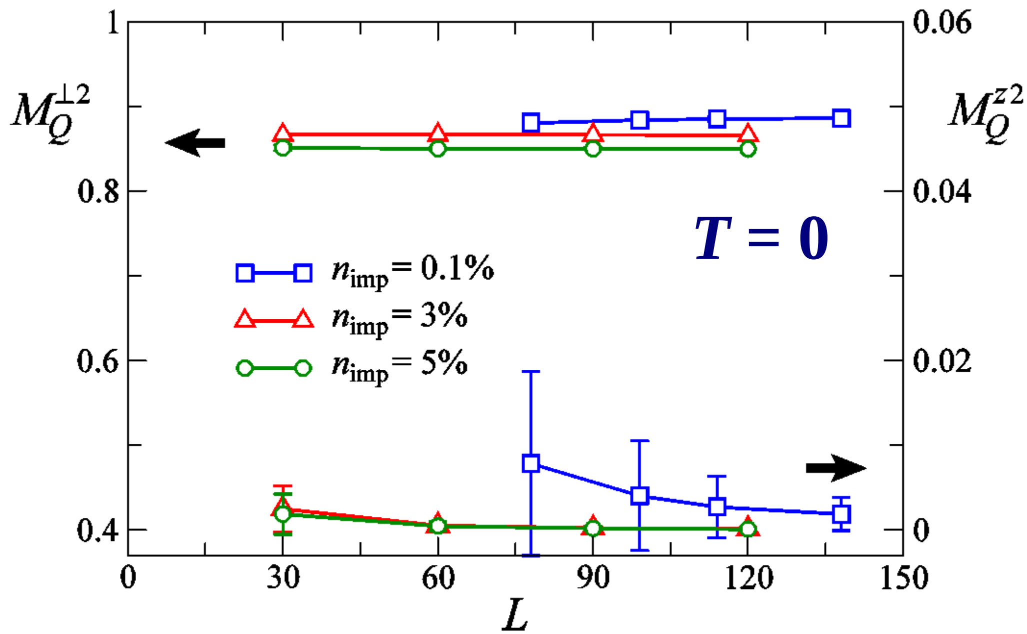
- antiferromagnetic OP

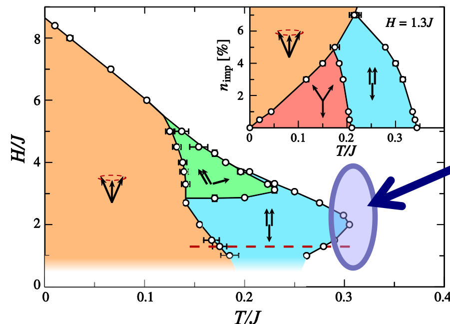
$$\mathbf{M}_{\mathbf{Q}} = \sum_i \langle\langle \mathbf{S}_i \rangle\rangle_c e^{i\mathbf{Q}\cdot\mathbf{r}_i}$$

conical $M_Q^{\perp}$; coplanar M_Q^{z}

- versus spin-glass OP

$$q_{\mathrm{EA}} = \left\langle \sum_i \langle \mathbf{S}_i \rangle^2 \right\rangle_c$$



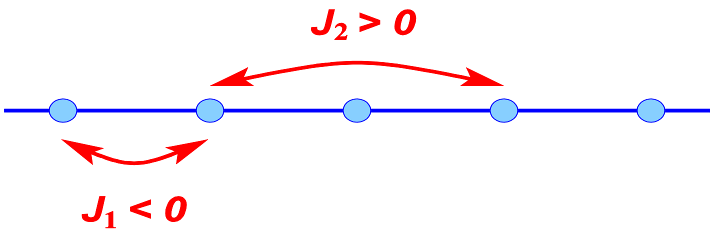


spin-glass?

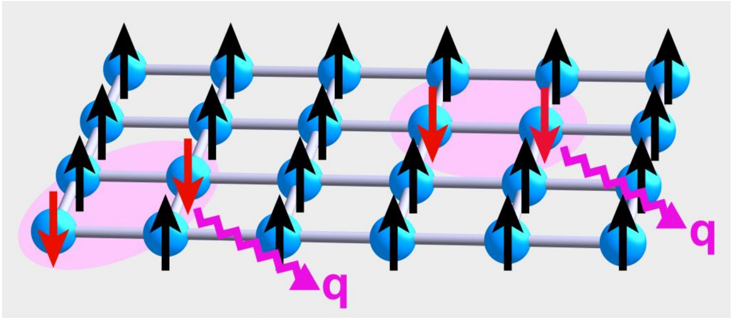
Part II

Disorder in frustrated spin chain

High-field nematic state in frustrated spin chain

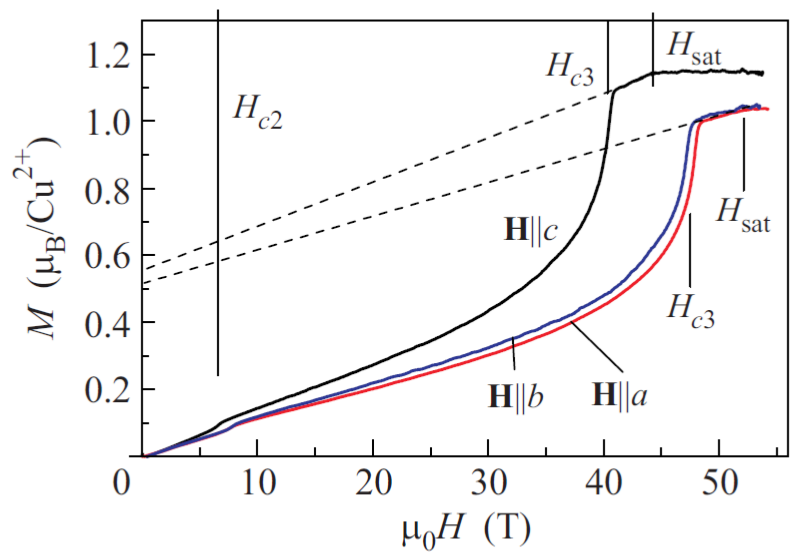


- bound magnon pairs out of competing ferro/antiferromagnetic exchanges



$$|\psi_2\rangle = \sum f_{ij} S_i^- S_j^- |\uparrow\uparrow\uparrow\rangle$$

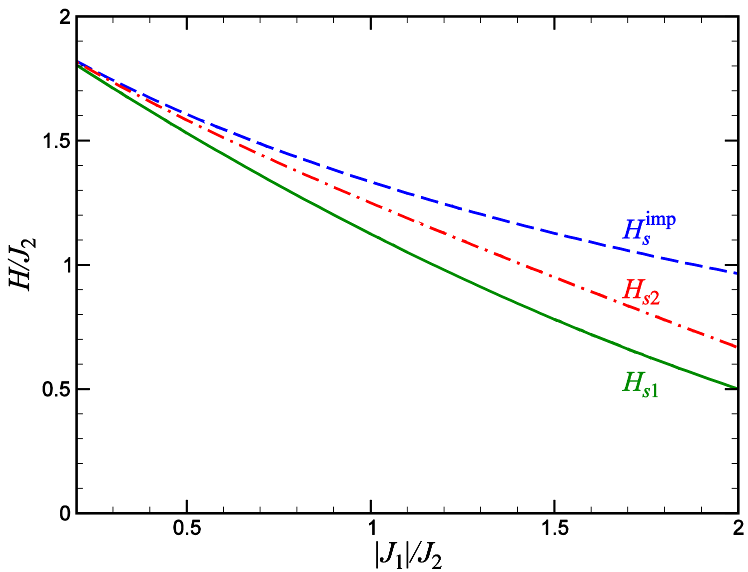
- spin-nematic phase in $LiCuVO_4$?



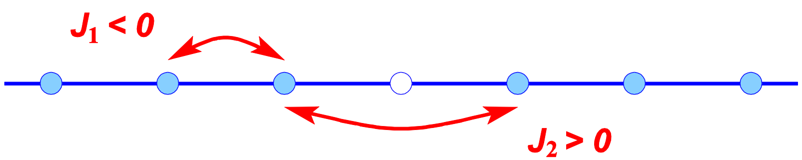
Chubukov (1991), …
Tsunetsugu & MZ (2010)

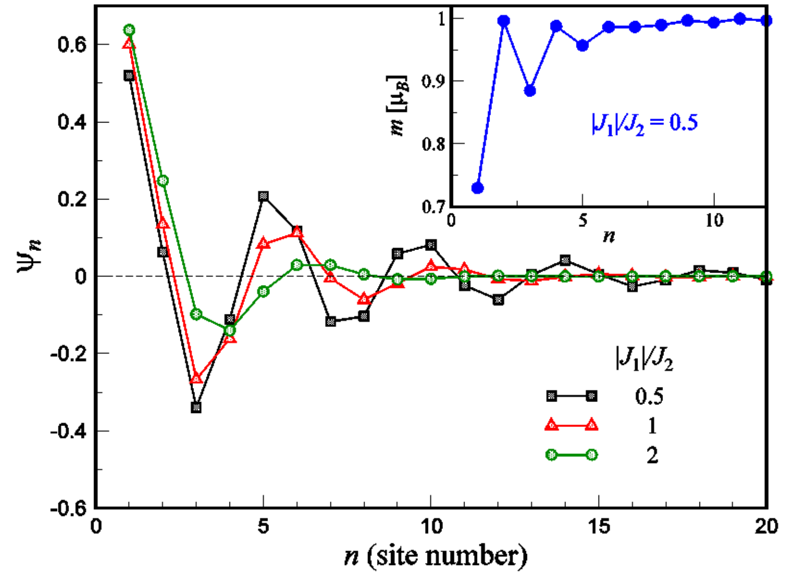
Svistov *et al* (2011)

Bound magnon state on a vacancy: 1D



Tsunetsugu & MZ, unpublished





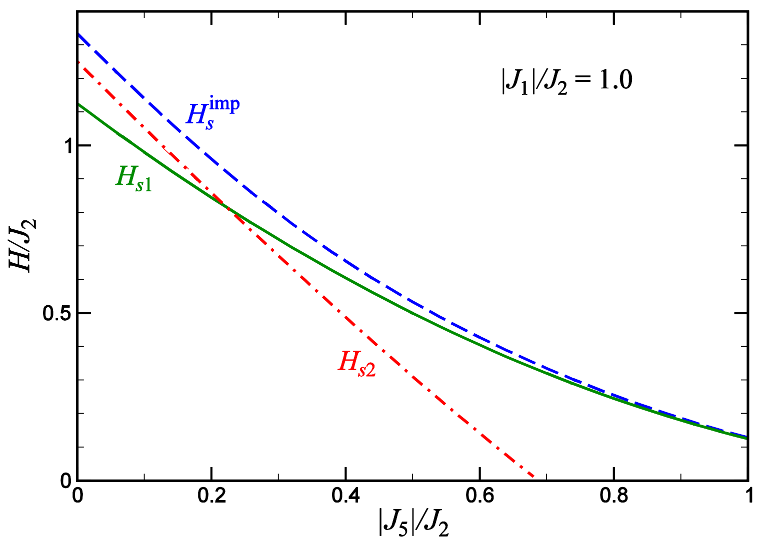
- 1-magnon Schroedinger equation

$$(\varepsilon - \varepsilon_{\mathbf{q}})\psi(\mathbf{q}) = \frac{1}{2N}\sum_{\mathbf{p}}(J_{\mathbf{q}-\mathbf{p}} - J_{\mathbf{q}})\psi(\mathbf{p})$$

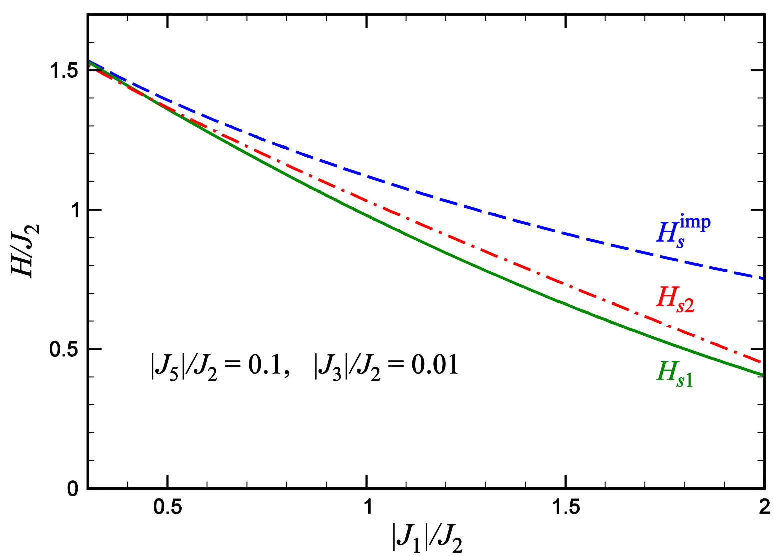
$$H_s^{\mathrm{imp}} = H_{s1} + E_B$$

Bound magnon state on a vacancy: $D > 1$

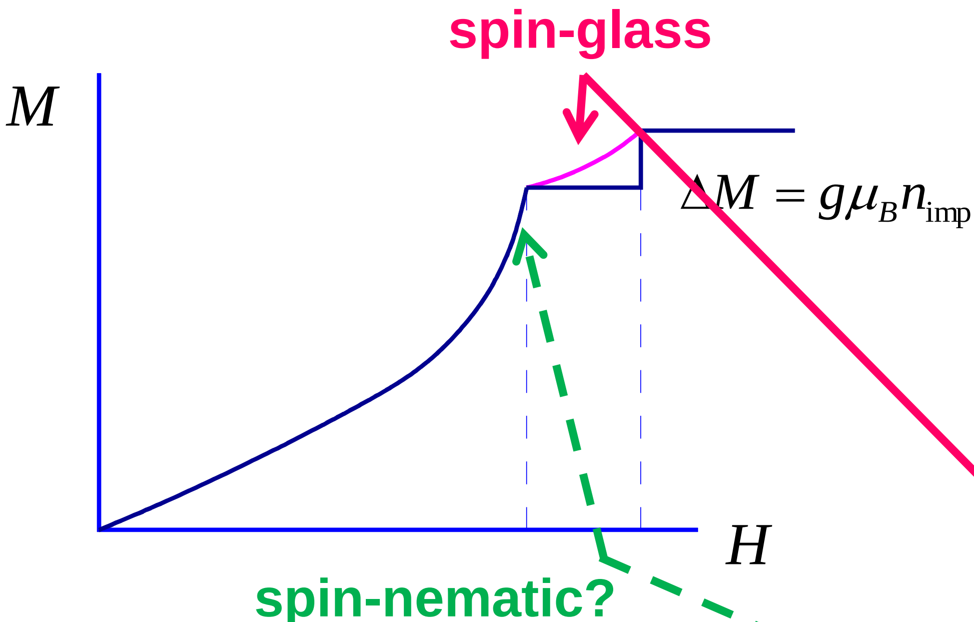
- 2D array of J_1-J_2 chains



- 3D model for $LiCuVO_4$

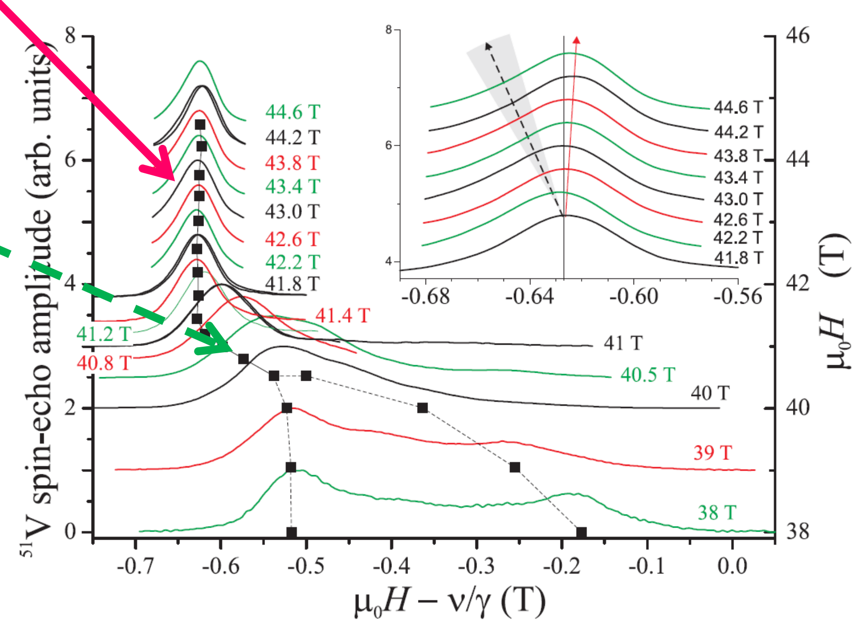


Localized magnons and ***M(H)***



- step for isolated vacancies, shoulder for impurity band

Buettgen *et al*, unpublished



Outlook

- structural disorder in frustrated magnets induces an opposite OBDO compared to thermal/quantum fluctuations.

- intersting phase diagrams, controled impurity doping for switching chirality, …

- beyond 2nd order: pyrochlore $Er_2Ti_2O_7$ (no magnetic field is needed)

- field-induced spin glass state in ferro/antiferromagnetic chain, other models?

- but, spin-nematic in $LiCuVO_4$ still got a chance