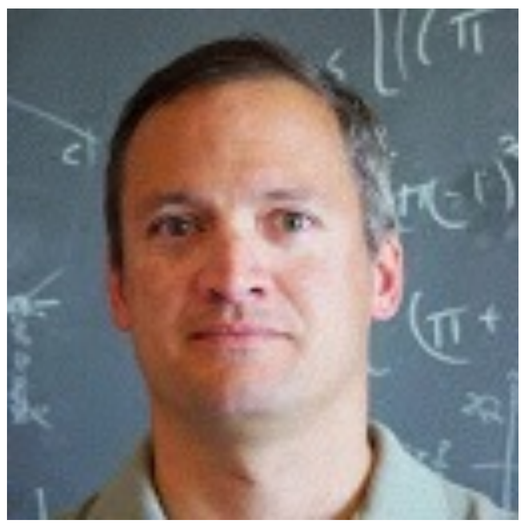
Frustration-driven multi magnon condensates and their excitations

Oleg Starykh, University of Utah, USA

Current trends in frustrated magnetism,
ICTP and Jawaharlal Nehru University, New Delhi, India, Feb 9-13, 2015

Collaborators



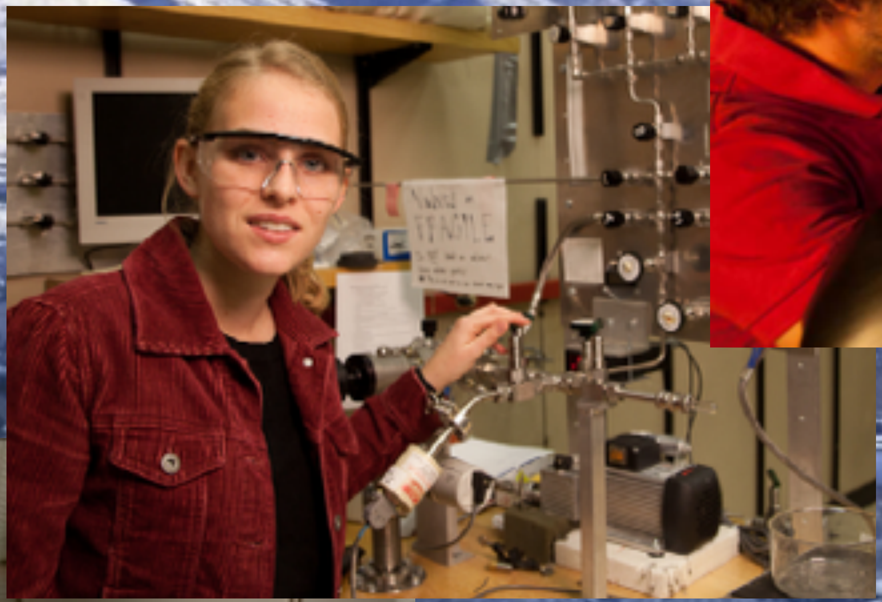
Leon Balents,
KITP, UCSB

Andrey Chubukov,
Univ of Minnesota

not today but
closely related findings:
spin-current state at the
tip of 1/3 magnetization plateau,
spontaneous generation of
orbiting spin currents
(ask me for details after the talk :))

Condensed Matter Physics at the University of Utah

Scanning Probe Microscopy
Nano-optics
Low Temperature Transport
Exotic Matter and High Pressure
Spin electronics
Organic Semiconductors
NMR and MRI



Strongly Correlated Electron Physics
Topological insulators
Frustrated magnetism
Superconductivity

Life at (and near) University of Utah

Outline

- Frustrated magnetism (brief intro)
- – emergence of composite orders from competing interactions
- Nematic *vs* SDW in $LiCuVO_4$
  - ✓ spin nematic: “magnon superconductor”
  - ✓ collinear SDW: “magnon charge density wave”
- Volborthite kagome antiferromagnet
- – experimental status - magnetization plateau
- – Nematic, SDW and ***more***
- – *Field theory of the Lifshitz point*
- Conclusions

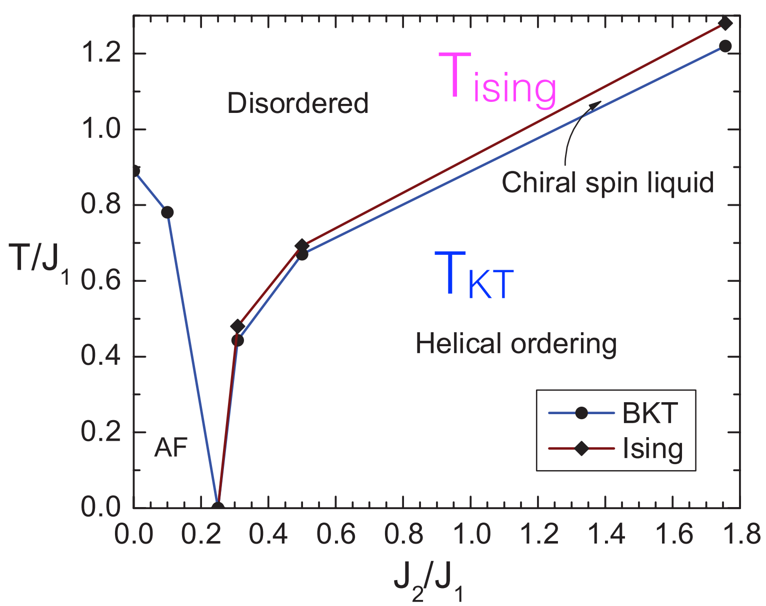
Emergent Ising order parameters

PHYSICAL REVIEW B **85**, 174404 (2012)

Chiral spin liquid in two-dimensional XY helimagnets

A. O. Sorokin[1,*] and A. V. Syromyatnikov[1,2,†]

$$H = \sum_{\mathbf{x}} (J_1 \cos(\varphi_{\mathbf{x}} - \varphi_{\mathbf{x+a}}) + J_2 \cos(\varphi_{\mathbf{x}} - \varphi_{\mathbf{x+2a}}) - J_b \cos(\varphi_{\mathbf{x}} - \varphi_{\mathbf{x+b}})),$$



Ising order: spin chirality

$$\chi = \sum_{\text{triangle}} \vec{S}_i \times \vec{S}_j$$

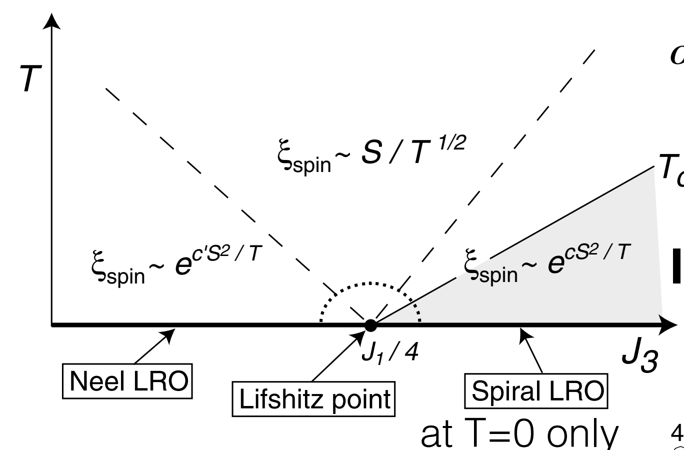
PRL **93**, 257206 (2004) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2004

Low-Temperature Broken-Symmetry Phases of Spiral Antiferromagnets

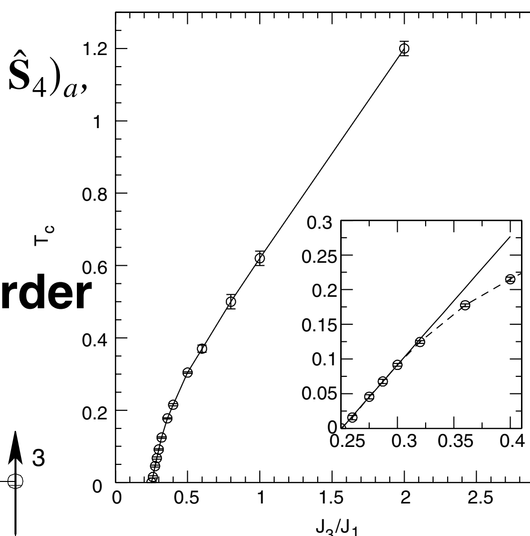
Luca Capriotti[1,2] and Subir Sachdev[2,3]

$$\hat{H} = J_1 \sum_{\langle i,j \rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j + J_3 \sum_{\langle\langle i,j \rangle\rangle} \hat{\mathbf{S}}_i \cdot \hat{\mathbf{S}}_j,$$

$$\sigma_a = (\hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_3 - \hat{\mathbf{S}}_2 \cdot \hat{\mathbf{S}}_4)_a,$$



Ising nematic order



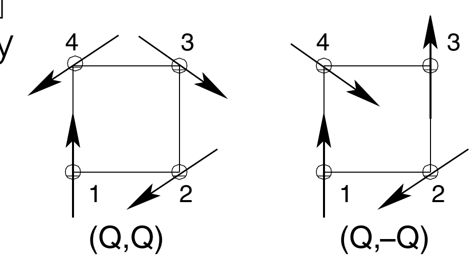


FIG. 2. The two different minimum energy configurations with magnetic wave vectors $\vec{Q} = (Q, Q)$ and $\vec{Q}^\star = (Q, -Q)$ with $Q = 2\pi/3$, corresponding to $J_3/J_1 = 0.5$.

Ising nematic in collinear spin system

VOLUME 64, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 1990

Ising Transition in Frustrated Heisenberg Models

P. Chandra
Corporate Research Science Laboratories, Exxon Research and Engineering Company, Annandale, New Jersey 08801
P. Coleman and A. I. Larkin[a]
Serin Physics Laboratory, Rutgers University, P.O. Box 849, Piscataway, New Jersey 08854

$$\sigma = \vec{N}_1 \cdot \vec{N}_2 = \pm 1$$

VOLUME 91, NUMBER 17 PHYSICAL REVIEW LETTERS week ending 24 OCTOBER 2003

Ising Transition Driven by Frustration in a 2D Classical Model with Continuous Symmetry

Cédric Weber,[1,2] Luca Capriotti,[3] Grégoire Misguich,[4] Federico Becca,[5] Maged Elhajal,[1] and Frédéric Mila[1]

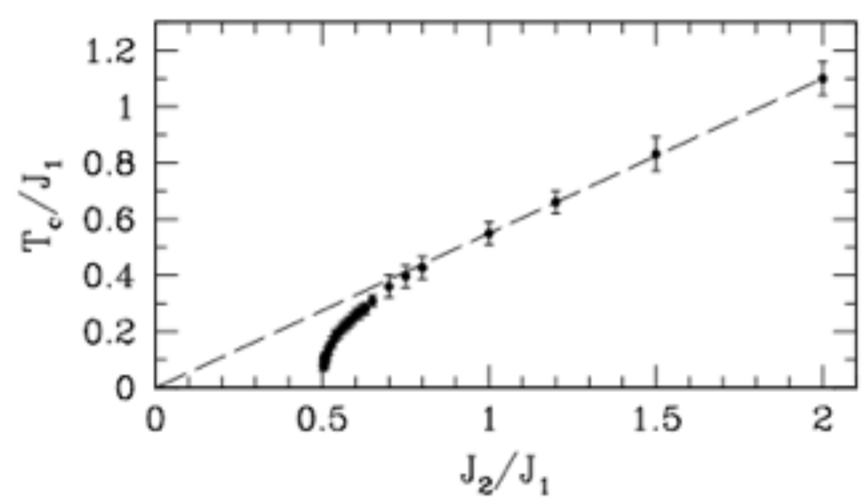


FIG. 4. Monte Carlo results for the critical temperature T_c as a function of the frustrating ratio J_2/J_1. The line is an extrapolation of the large J_2 data down to $J_2 = 0$ (see text).

Outline

- Frustrated magnetism (brief intro)

– emergence of composite orders from competing interactions

- Nematic *vs* SDW in $LiCuVO_4$

  ✓ spin nematic: "magnon superconductor"

  ✓ collinear SDW: "magnon charge density wave"

- Volborthite kagome antiferromagnet

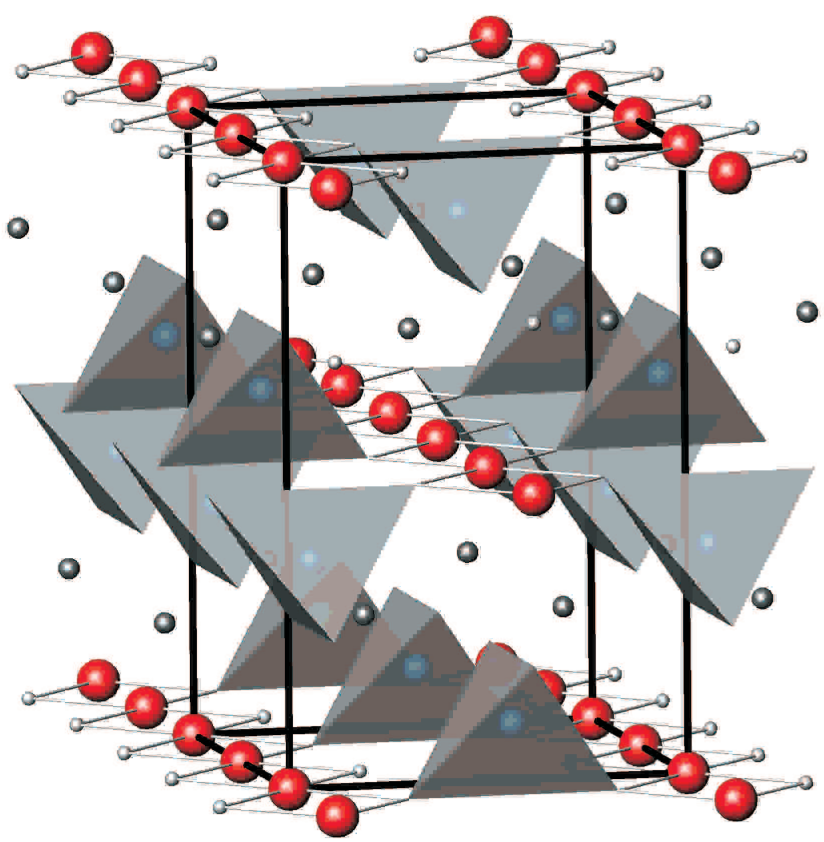
– experimental status - magnetization plateau

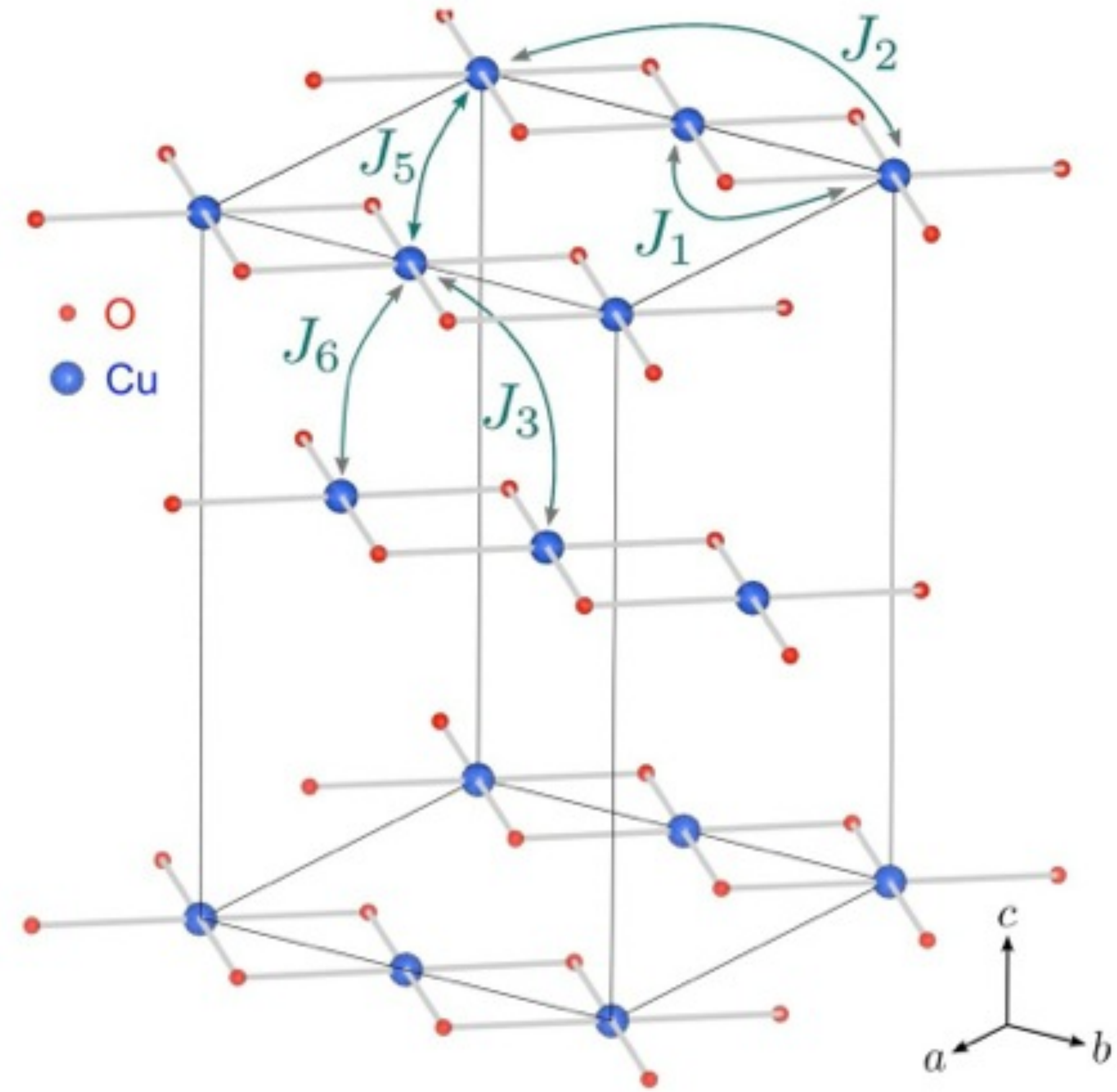
– Nematic, SDW and ***more***

– ***Field theory of the Lifshitz point***

- Conclusions

$LiCuVO_4$: magnon superconductor?





estimates:

J_1 = - 1.6 meV

J_2 = 3.9 meV (subject of **active** debates)

J_5 = -0.4 meV

High-field analysis: condensate of bound magnon pairs

$$\langle S^+ \rangle = 0 \qquad \langle S^+ S^+ \rangle \neq 0$$

Ferromagnetic $J_1 < 0$ produces attraction in real space

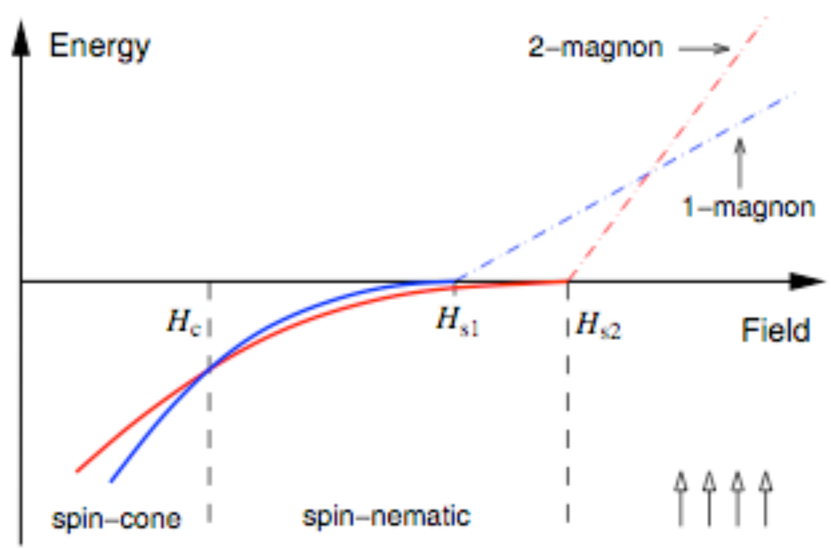


Fig. 1: (Color online) Energy-field diagram for a frustrated quantum magnet close to the saturation field. Dot-dashed lines show lowest one- and two-magnon states. Solid lines represent the ground-state energy for the one-magnon (spin-cone) and the two-magnon (spin-nematic) condensate.

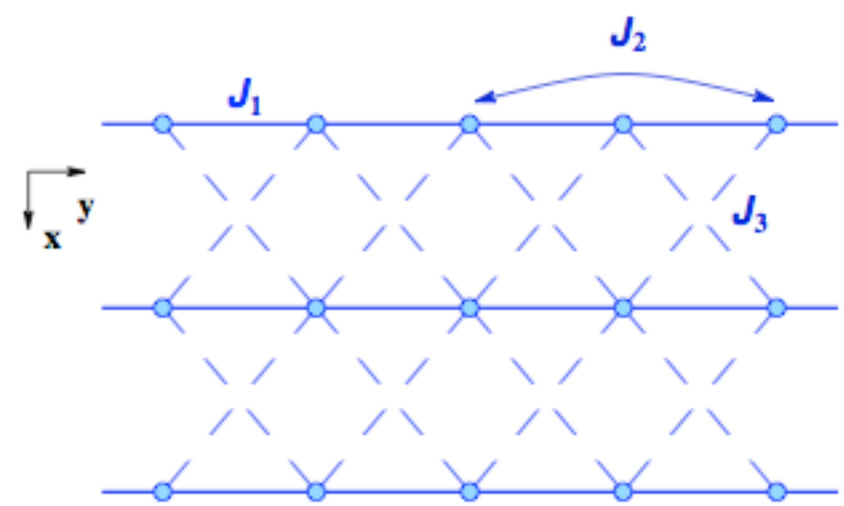


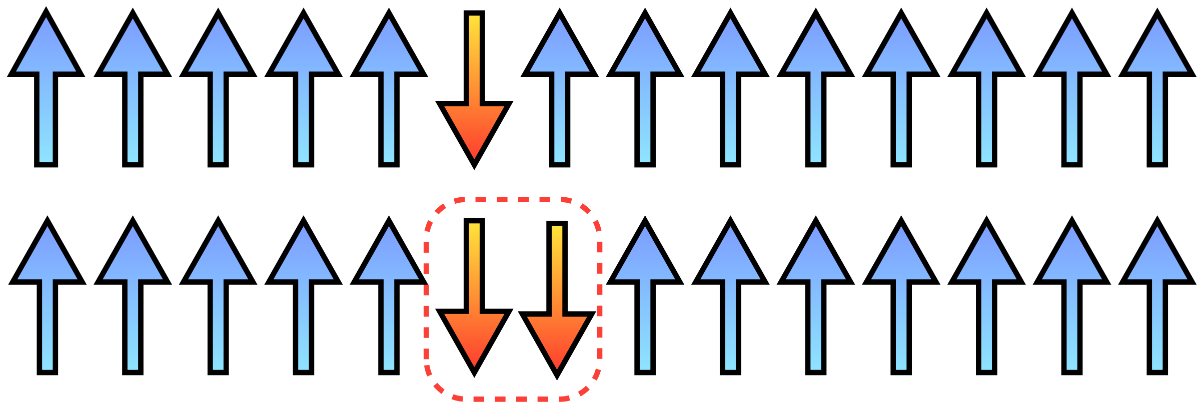
Fig. 2: (Color online) Two-dimensional array of copper ions in $LiCuVO_4$ with principal exchange couplings.

Chubukov 1991
Kecke et al 2007
Kuzian and Drechsler 2007
Hikihara et al 2008
Sudan et al 2009
Zhitomirsky and Tsunetsugu 2010

Magnon binding

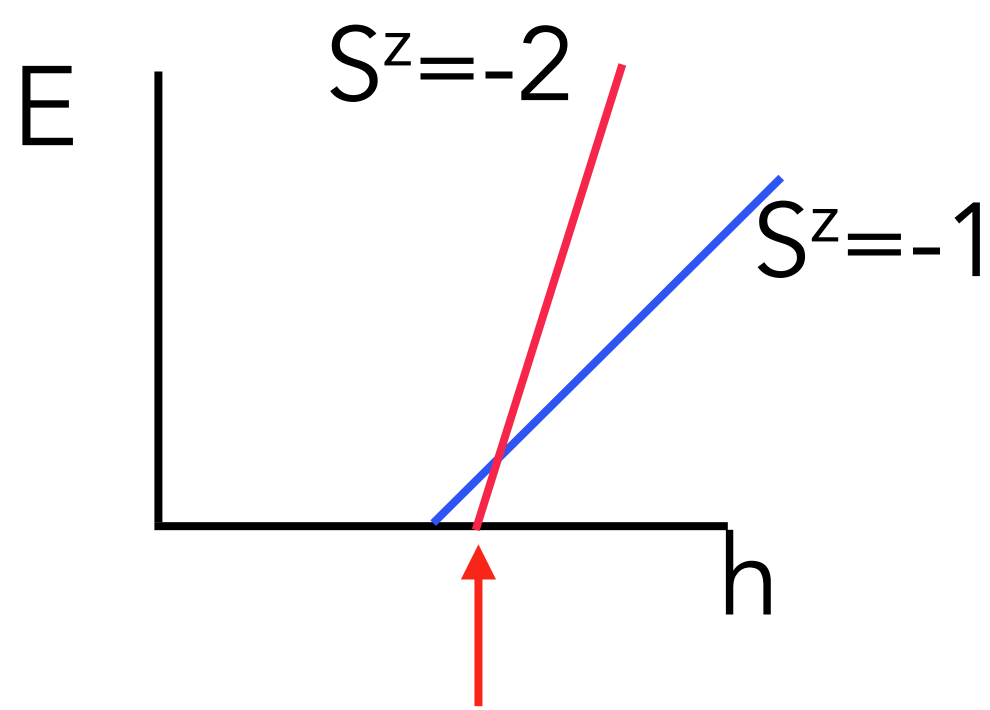
1-magnon

2-magnon bound state



$E-E_{FM} = \varepsilon_1 + h$

$E-E_{FM} = \varepsilon_2 + 2h$



$\varepsilon_2 < 2\,\varepsilon_1$: "molecular" bound state

Formation of molecular fluid

For d>1 at T=0 this is a molecular BEC
= true spin nematic

Hidden order

No dipolar order

$$\langle S_i^+ \rangle = 0$$

$$\langle S_i^+ S_j^- \rangle \sim e^{-|i-j|/\xi}$$ S^z=1 gap

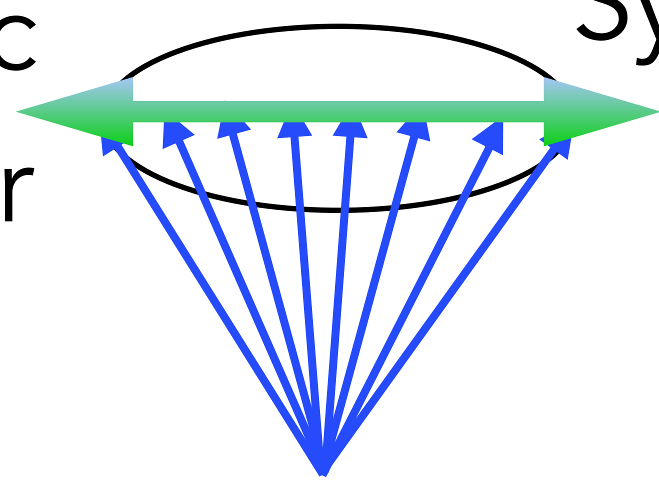
Nematic order

$$\langle S_i^+ S_{i+a}^+ \rangle \neq 0$$

Magnetic quadrupole moment

Symmetry breaking U(1) → Z_2

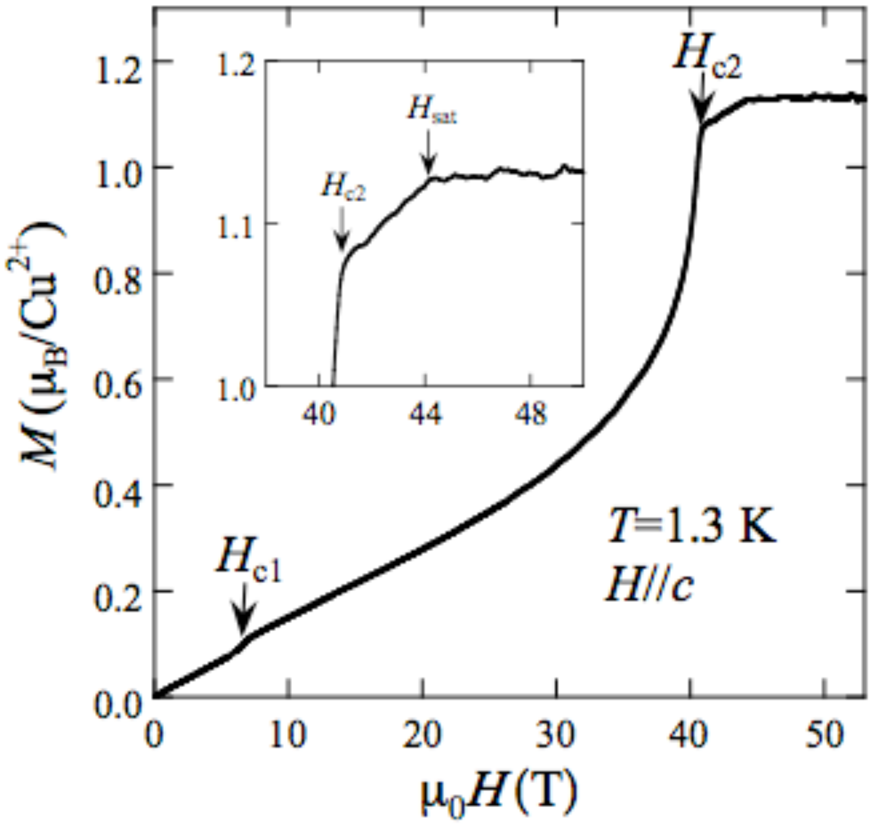
nematic director



can think of a fluctuating fan state

$LiCuVO_4$: NMR lineshape - collinear SDW along **B**

Hagiwara, Svistov et al, 2011



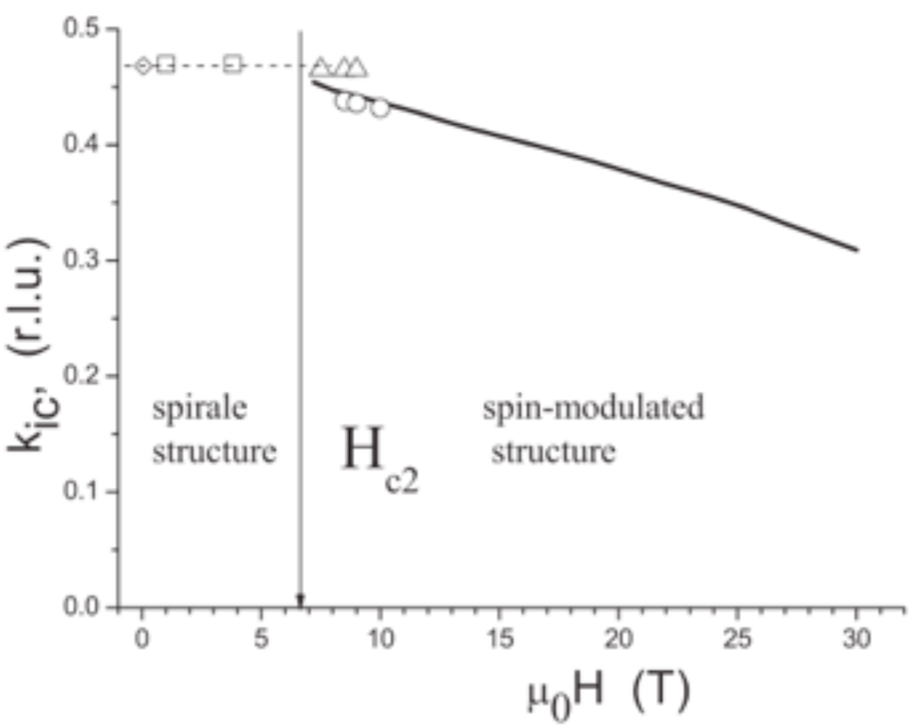
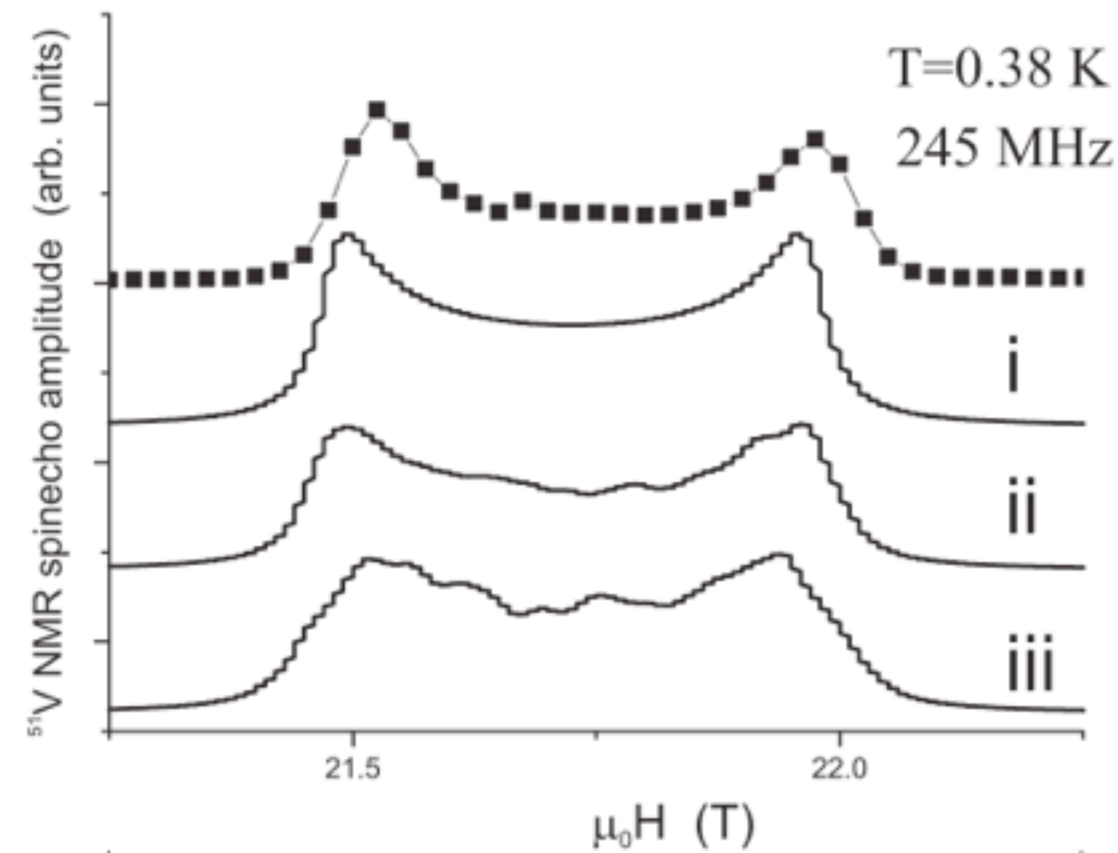
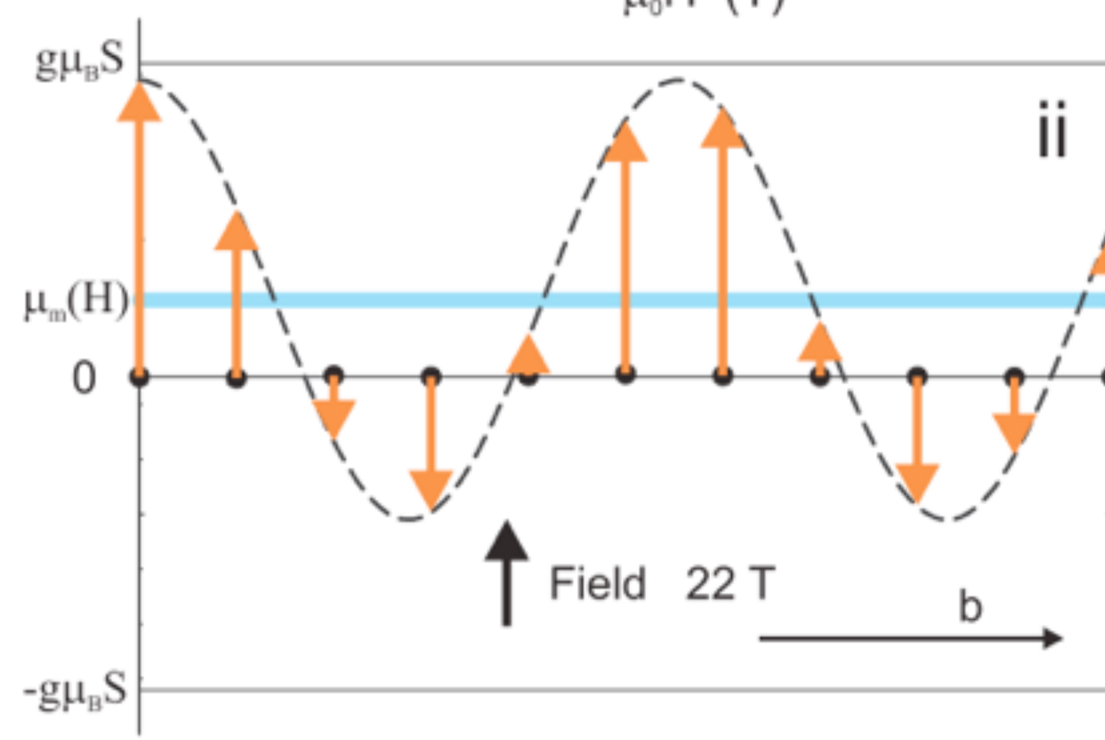


FIG. 2. Field dependence of the incommensurate wave vector k_{ic} for applied magnetic fields **H** ∥ **c** in $LiCuVO_4$. The open symbols

Buttgen et al 2012

PHYSICAL REVIEW B **85**, 214421 (2012)





Evidence of a Bond-Nematic Phase in $LiCuVO_4$

M. Mourigal,[1,2] M. Enderle,[1] B. Fåk,[3] R. K. Kremer,[4] J. M. Law,[4,*] A. Schneidewind,[5] A. Hiess,[1,†] and A. Prokofiev[6,7]

No spin-flip scattering above ~ 9 Tesla: **longitudinal SDW state**

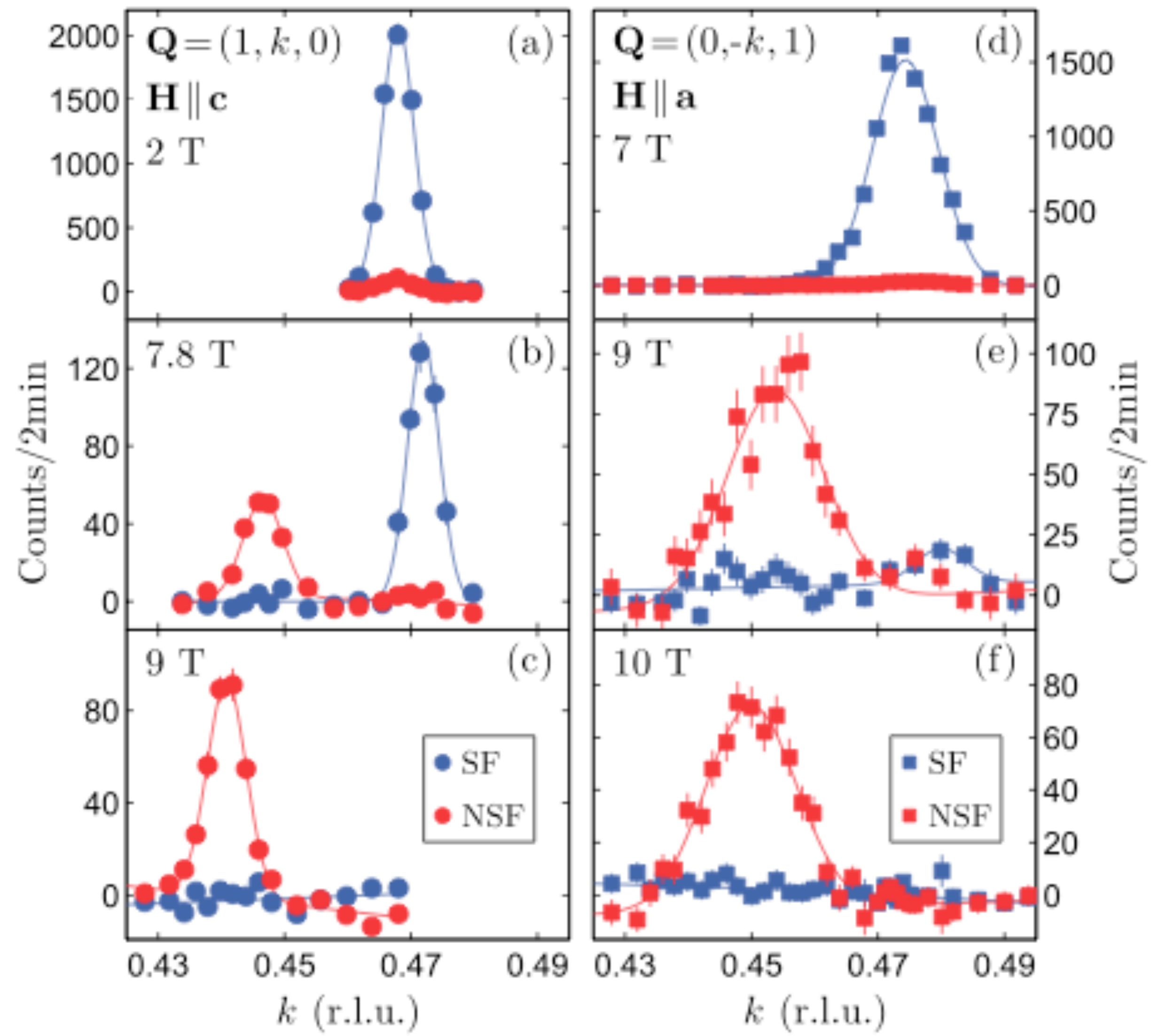
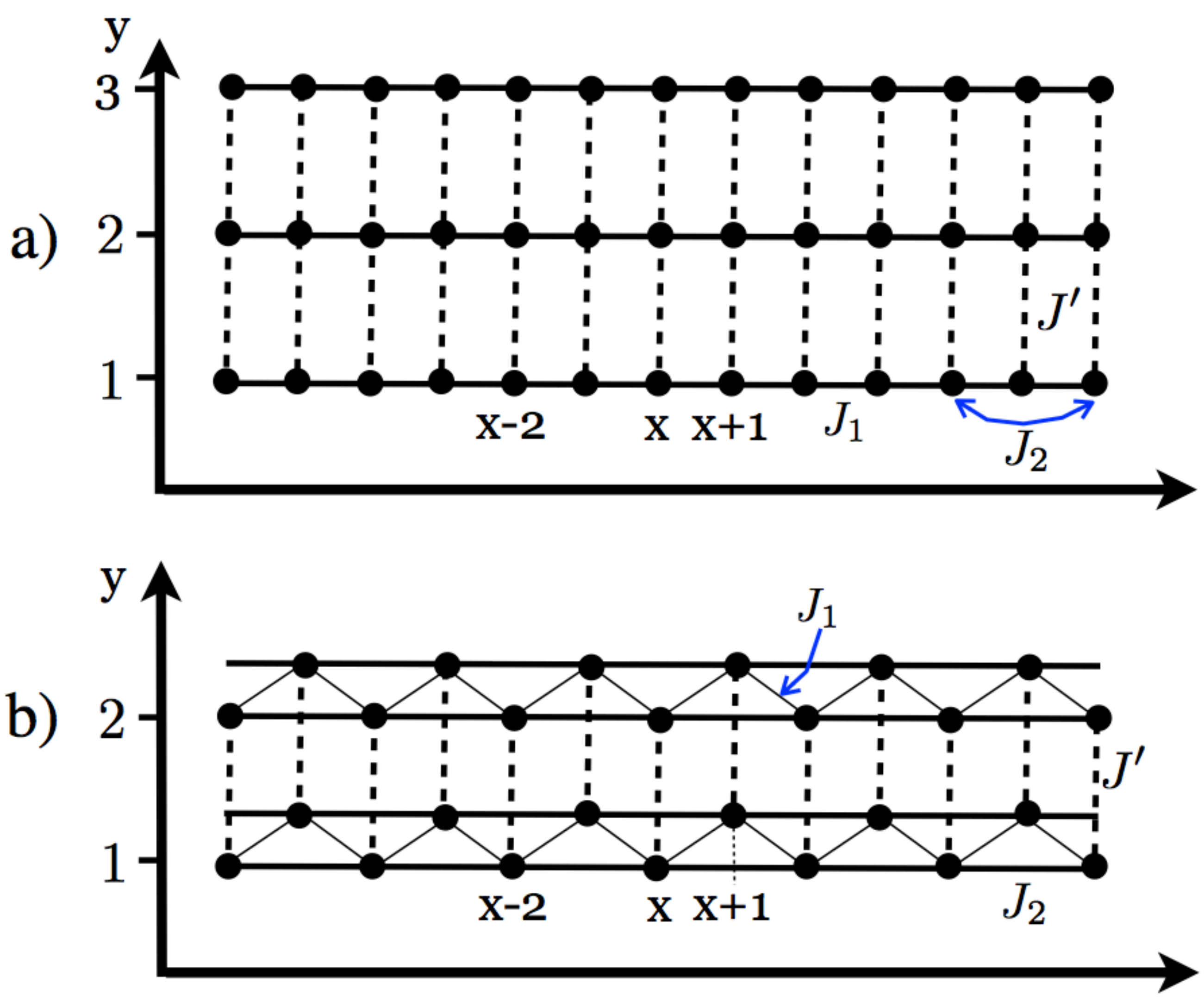


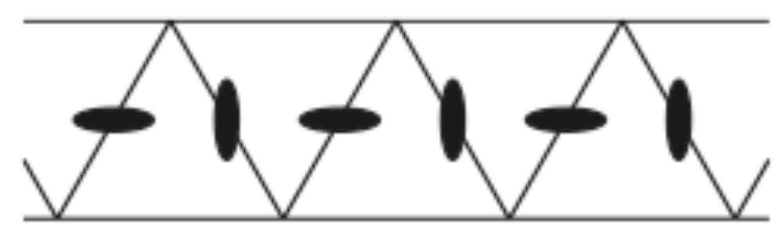
FIG. 3 (color online). Polarized cross sections measured at $T = 70$ mK for the magnetic reflections $\mathbf{Q} = (1, k_{IC}, 0)$ with $\mathbf{H}\|\mathbf{c}$ [left panels, (a)–(c)] and $\mathbf{Q} = (0, -k_{IC}, 1)$ with $\mathbf{H}\|\mathbf{a}$ [right panels, (d)–(f)].

SF = spin flip, ΔS = 1
NSF = no spin flip, ΔS = 0

Geometry (motivated by $LiCuVO_4$)



$J_1 < 0$ (ferro)
$J_2 > 0$, $J' > 0$ (afm)
in magnetic field



- No true condensation [U(1) breaking] in d=1.
- Inter-chain interaction is crucial for establishing symmetry breaking in d=2.
- Need to study weakly coupled “superconducting” chains

Sato et al 2013
Starykh and Balents 2014

Inter-chain interaction

$$H_{\text{inter-chain}} = \sum_y \int dx\ \vec{S}_y \cdot \vec{S}_{y+1} \sim \sum_y \int dx\ S_y^+ S_{y+1}^- + S_y^z S_{y+1}^z$$

Superconducting analogy: single-particle (magnon) tunneling between magnon superconductors is strongly suppressed at low energy (below the single-particle gap)

$$H_{\text{inter}}^{\perp} = \sum_y \int dx\ J' \langle S_y^+(x) S_{y+1}^-(x+1)\rangle_{\text{nematic ground state}} \to 0$$

Superconducting analogy: fluctuations generate two-magnon (***Josephson coupling***) tunneling between chains. They are generically weak, ~ $J_1(J'/J_1)^2 << J'$, but responsible for a true **two-dimensional nematic order**

$$H_{\text{nem}} \sim (J'^2/J_1) \sum_y \int dx\ [T_y^+(x) T_{y+1}^-(x) + \text{h.c.}]$$

$$T_y^+(x) \sim S_y^-(x) S_y^-(x+1)$$

At the same time, density-density inter-chain interaction does not experience any suppression. It drives the system toward a **two-dimensional collinear SDW order**.

$$S_y^z = M - 2n_{\text{pair}} = M - \tilde{A}_1 e^{i\frac{\sqrt{2}\pi}{\beta}\varphi_y^+(x)} e^{ik_{\text{sdw}}x}$$

$$H_{\text{inter-chain}}^z = H_{\text{sdw}} \sim J' \sum_y S_y^z S_{y+1}^z \sim J' \sum_y \int dx \cos[\frac{\sqrt{2}\pi}{\beta}(\varphi_y^+ - \varphi_{y+1}^+)]$$

Away from the saturation, **SDW** is more relevant [and stronger, via $J' >> (J')^2/J_1$] than the **nematic interaction**: **coupled 1d nematic chains order in a 2d SDW state.**

Simple scaling

$$H_{\text{nem}} \sim (J'^2/J_1) \sum_y \int dx \ [T_y^+(x) T_{y+1}^-(x) + \text{h.c.}]$$

- describes kinetic energy of magnon pairs, linear in magnon pair density n_{pair}

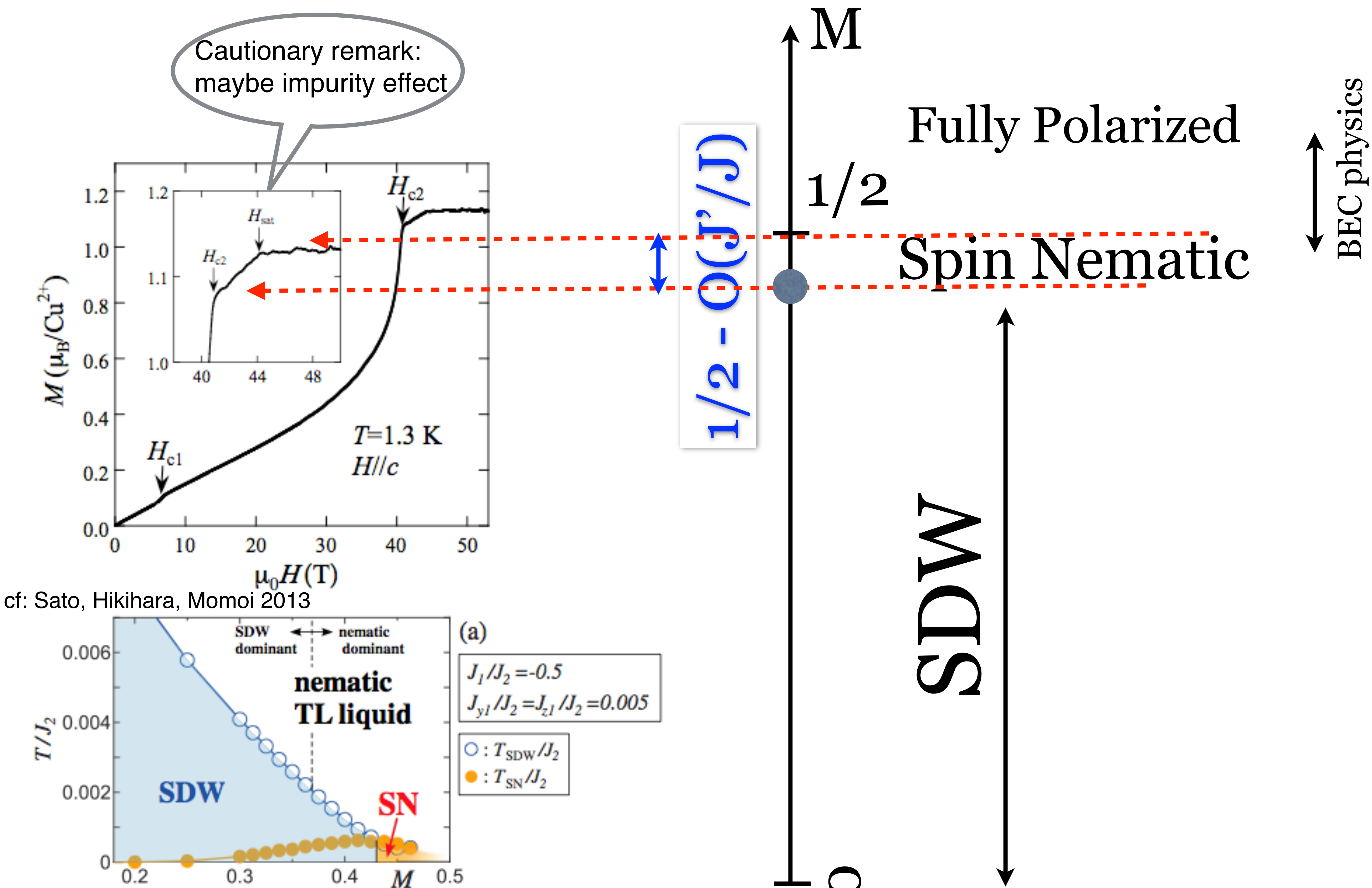
$$H^z_{\text{inter-chain}} = H_{\text{sdw}} \sim J' \sum_y S^z_y S^z_{y+1} \sim J' \sum_y \int dx \cos[\frac{\sqrt{2}\pi}{\beta}(\varphi^+_y - \varphi^+_{y+1})]$$

- describes potential energy of interaction between magnon pairs on neighboring chains, quadratic in magnon pair density n_{pair}

- Competition $\frac{(J')^2}{J_1} n_{\text{pair}} \sim J' n^2_{\text{pair}}$, hence $\boxed{n^*_{\text{pair}} \sim J'/J_1}$

- Hence:
- Spin Nematic *near saturation*, for $n_{\text{pair}} < n^*_{\text{pair}}$
- SDW for $n_{\text{pair}} > n^*_{\text{pair}}$

T=0 schematic phase diagram of weakly coupled **nematic** spin chains

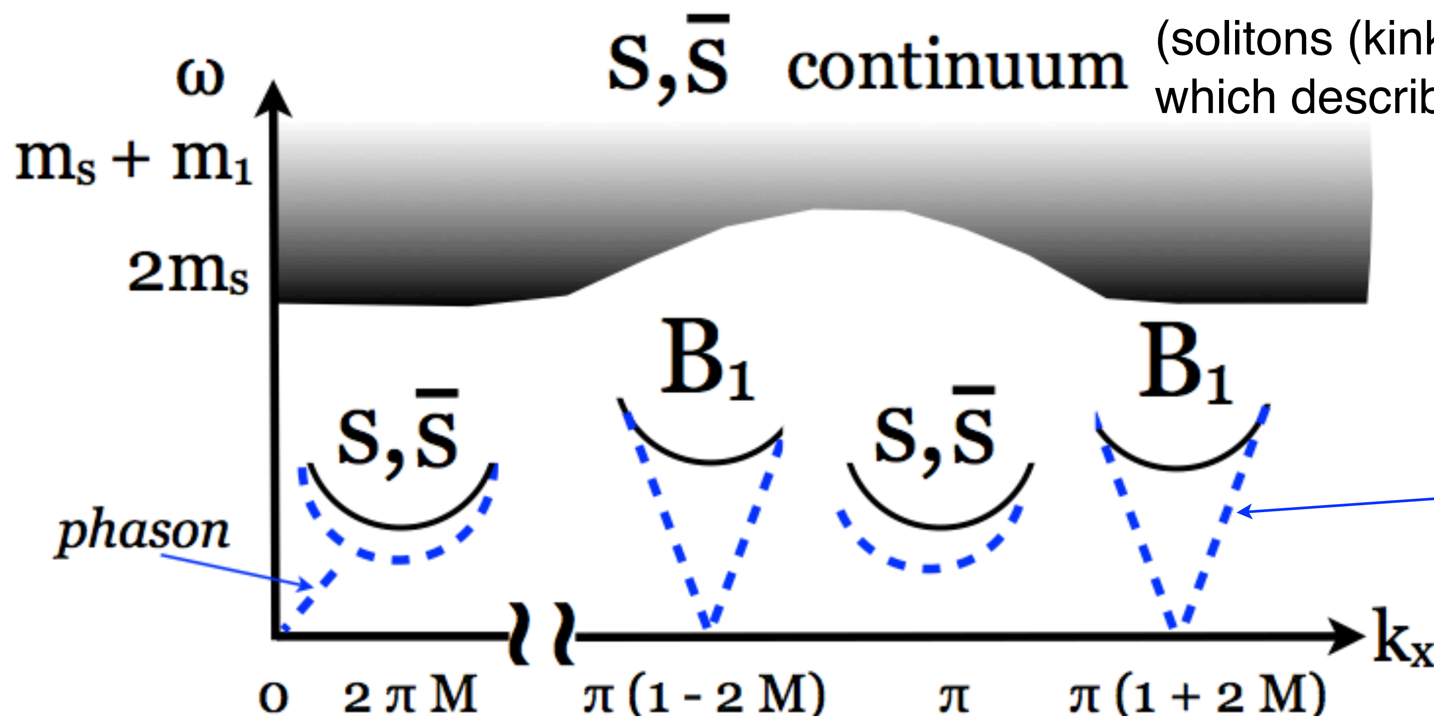


Excitations (via spin-spin correlation functions)

- 2d SDW $\langle S^z(\mathbf{r})\rangle = M + \mathrm{Re}\Big(\Phi e^{i\mathbf{k}_{\rm sdw}\cdot\mathbf{r}}\Big)$

- preserves U(1) [with respect to magnetic field] -> hence NO transverse spin waves

- breaks translational symmetry -> longitudinal phason mode at $k_{sdw} = \pi(1-2M)$ and k=0



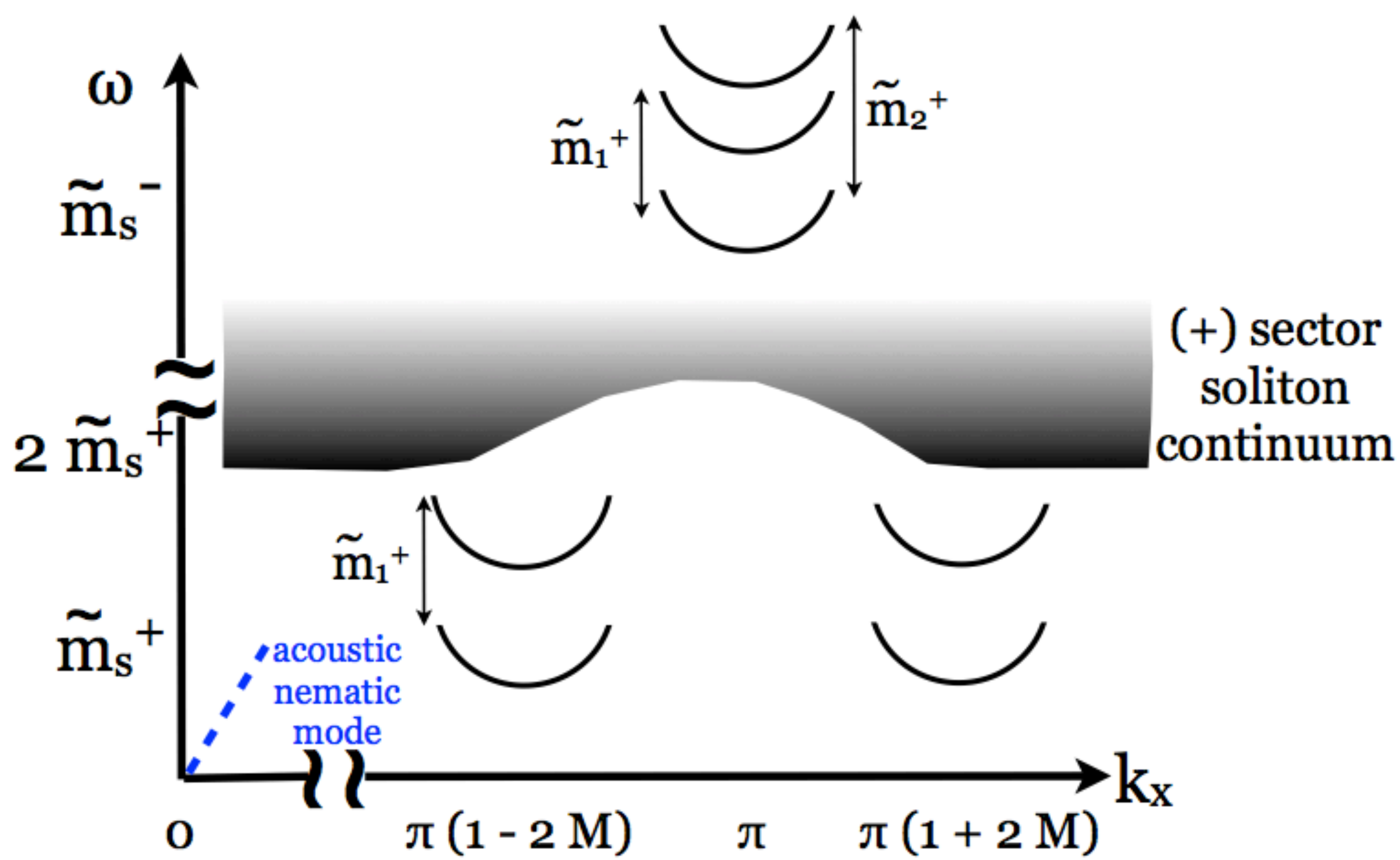
(solitons (kinks) of massive sine-Gordon model which describes 2d ***ordered*** state)

OS, Balents PRB 2014

Excitations (via spin-spin correlation functions)

- 2d Spin Nematic $\langle S^+(r) S^+(r') \rangle \sim \Psi \neq 0$
- breaks U(1) but ΔS=1 excitations are gapped (magnon superconductor) $\langle S^+(\mathbf{r}) \rangle = 0$
- gapless density fluctuations at k=0

(**-** sector: solitons of massive sine-Gordon model describing 1d ***zig-zag chain.***) Energy scale J_1



(**+** sector: solitons of massive sine-Gordon model which describes 2d ***ordered*** state.) Energy scale $(J')^2/J_1$

OS, Balents PRB 2014

Intermediate Summary

- Interesting magnetically ordered states: SDW and Spin Nematic
  - Gapped $\Delta S=1$ excitations (no usual spin waves!)
  - Linearly-dispersing ***phason*** mode with $\Delta S=0$ in **2d** SDW
  - SDW naturally sensitive to structural disorder
  - Linearly-dispersing ***magnon density*** waves in **2d** Spin Nematic
  - analogy with superconductor/charge density wave competition

Outline

- Frustrated magnetism (brief intro)

– emergence of composite orders from competing interactions

- Nematic *vs* SDW in $LiCuVO_4$

✓ spin nematic: “magnon superconductor”

✓ collinear SDW: “magnon charge density wave”

- Volborthite kagome antiferromagnet

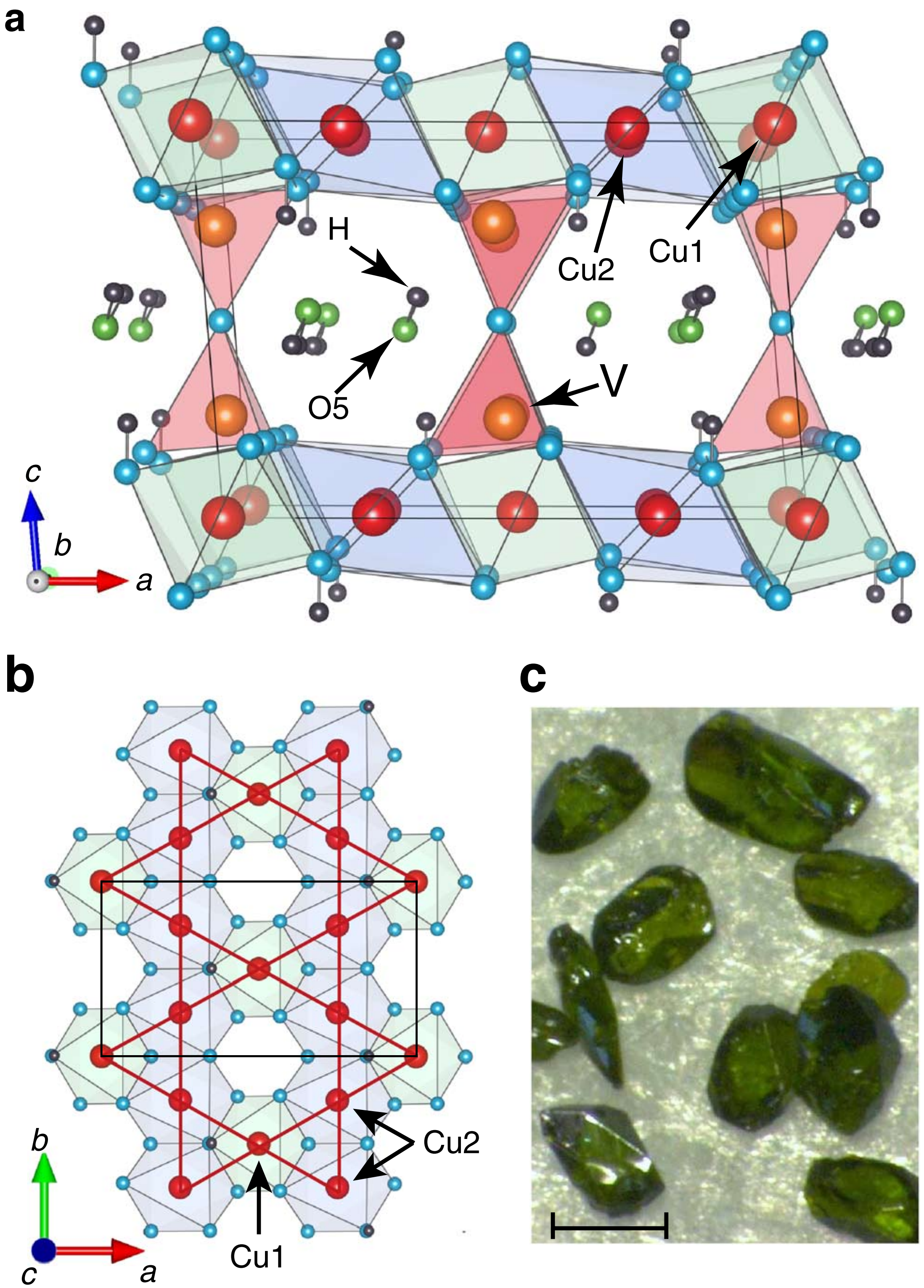
– experimental status - magnetization plateau

– Nematic, SDW and ***more***

– ***Field theory of the Lifshitz point***

- Conclusions

Volborthite



Volborthite's timeline

Formula: $Cu_3(V_2O_7)(OH)_2 \cdot 2H_2O$

System: Monoclinic **Colour:** Olive-green, ...

Hardness: 3½

Name: Named after Alexander von Volborth (1800-1876), Russian paleontologist, who first noted the mineral.

A secondary mineral found in the oxidized zones of vanadium-bearing hydrothermal deposits.

At least two different monoclinic space-group variants (C2/m, C2/c) seem to be stable at ambient temperature.

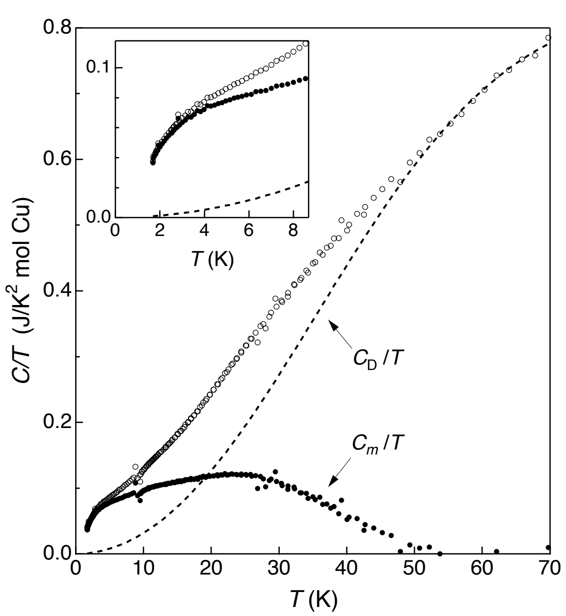
Visually similar to vésigniéite.

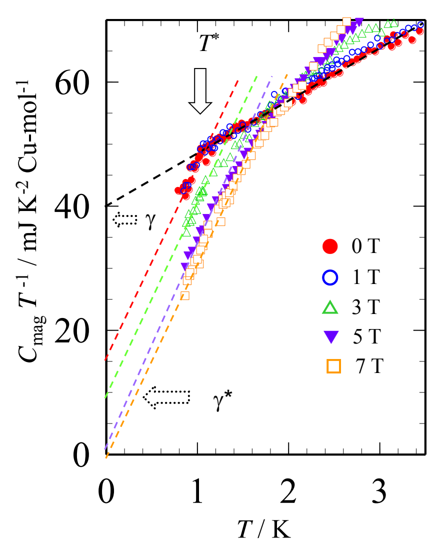
2001
quantum spin liquid?!

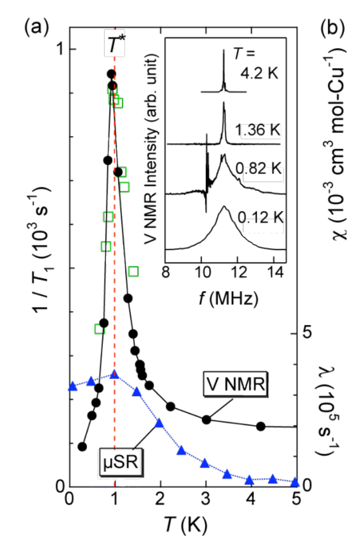
2009
impurity ordering at low T?
magnetization steps?

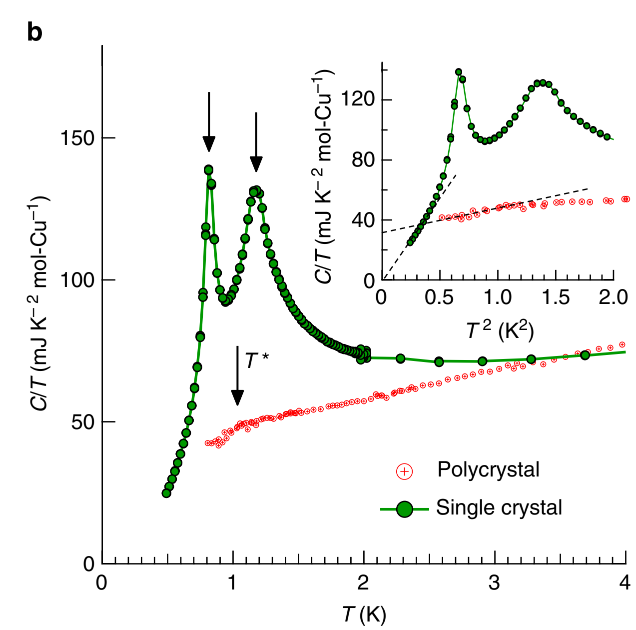
2012
magnetic order !

2014
magnetization plateau









time = material quality

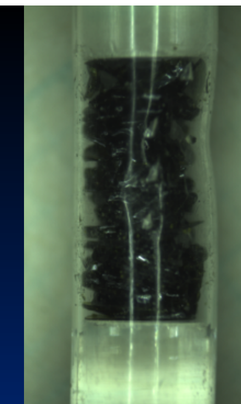
2014: huge plateau!

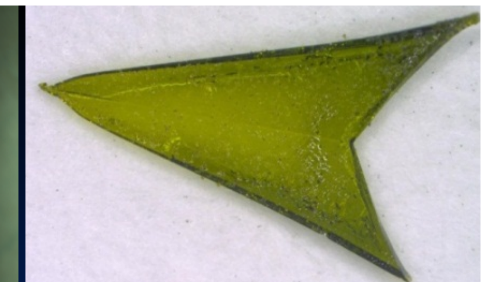
H. Ishikawa…M.Takigawa…Z.Hiroi, unpublished, 2014

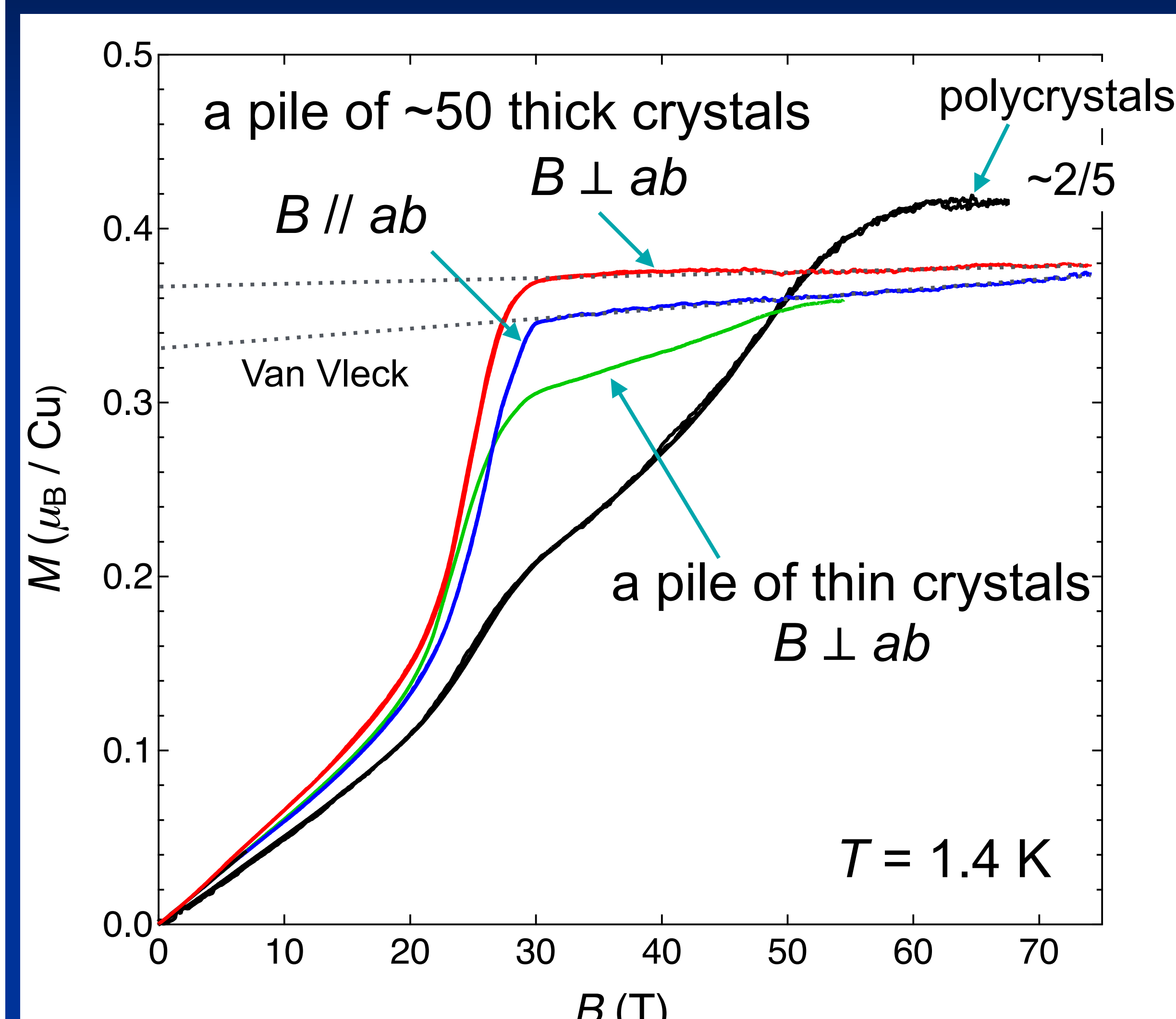
High-field magnetization

more different *MH* curves in a pile of 50 large “thick” arrowhead-shaped crystals

30 days growth







Huge 1/3 plateau!

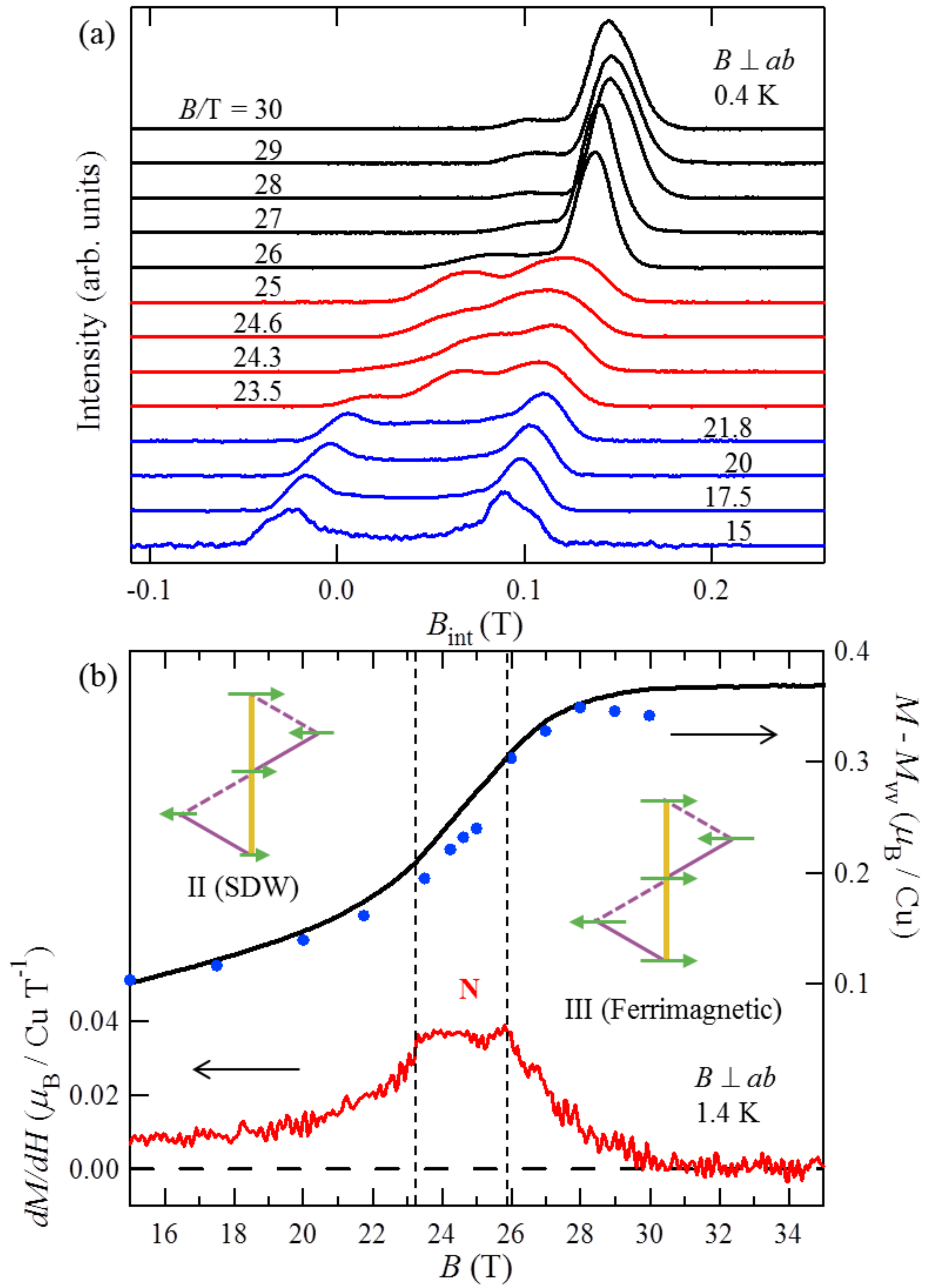
further optical meas.
@ Takeyama lab
It survives over 120 T!

Kagome plateau or ferrimagnetic state?

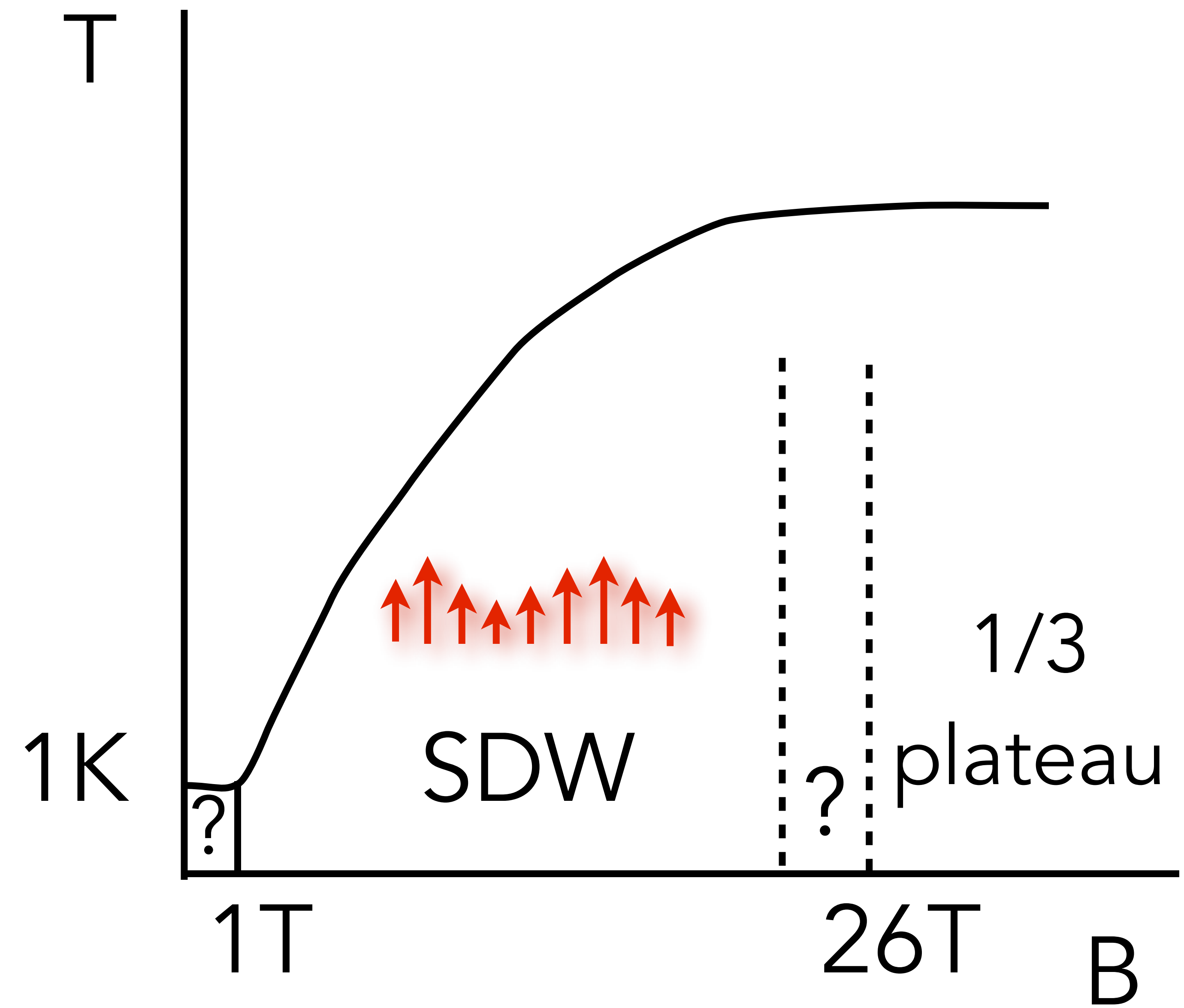
coupled to lattice, but already distorted

high-field mag. meas.
@ Tokunaga & Kindo labs

Phase diagram



H. Ishikawa *et al*, unpublished



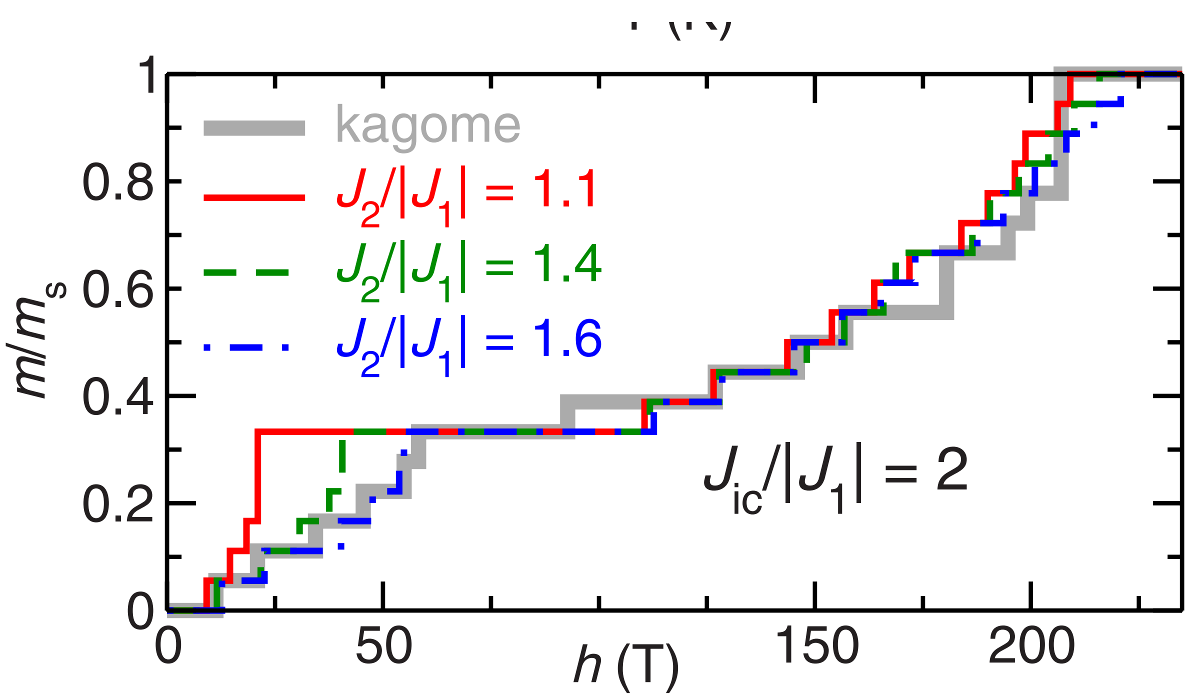
our interpretation

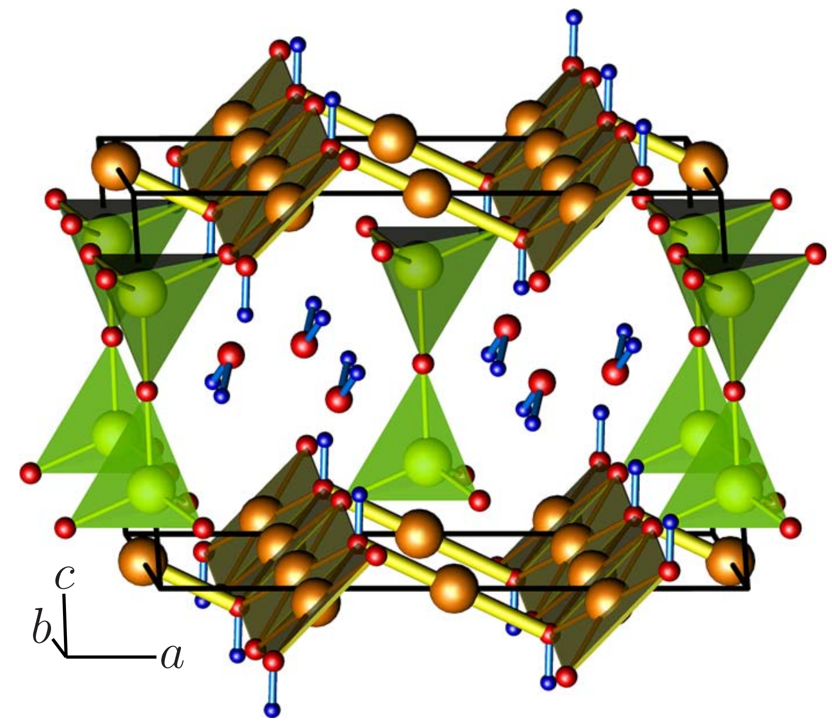
Frustrated ferromagnetism

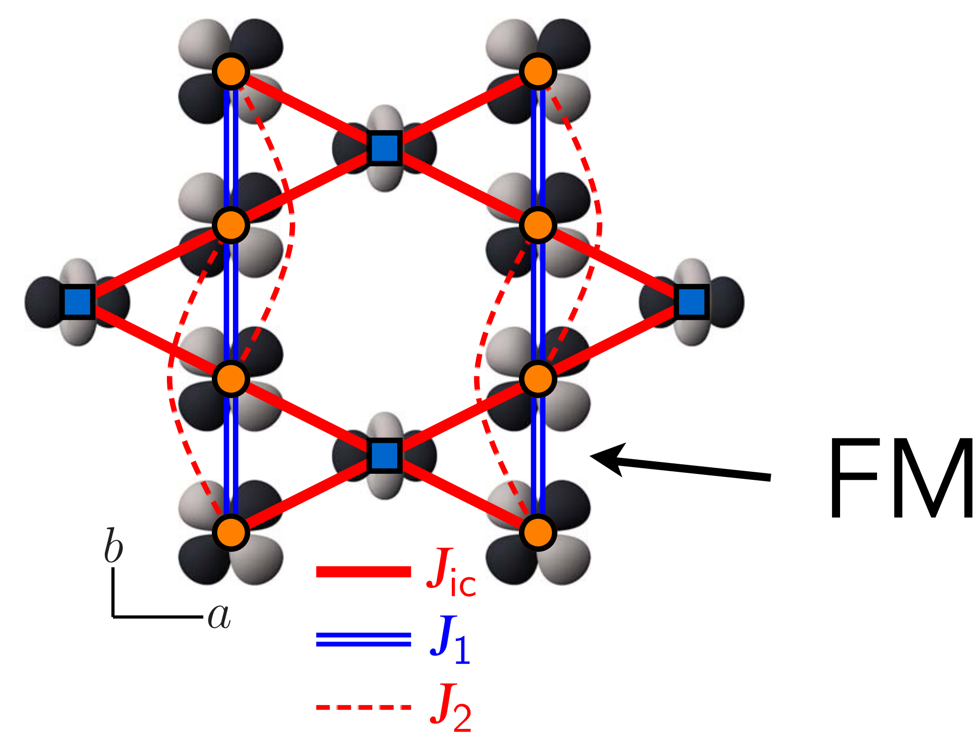
PHYSICAL REVIEW B **82**, 104434 (2010)

Coupled frustrated quantum spin-$\frac{1}{2}$ chains with orbital order in volborthite $Cu_3V_2O_7(OH)_2 \cdot 2H_2O$

O. Janson,[1,*] J. Richter,[2] P. Sindzingre,[3] and H. Rosner[1,†]
[1]*Max-Planck-Institut für Chemische Physik fester Stoffe, D-01187 Dresden, Germany*
[2]*Institut für Theoretische Physik, Universität Magdeburg, D-39016 Magdeburg, Germany*
[3]*Laboratoire de Physique Théorique de la Matière Condensée, Univ. P. & M. Curie, Paris, France*
(Received 9 August 2010; published 30 September 2010)







DFT gets it right!

$$J_1 < 0, J_2 > 0, J' > 0$$

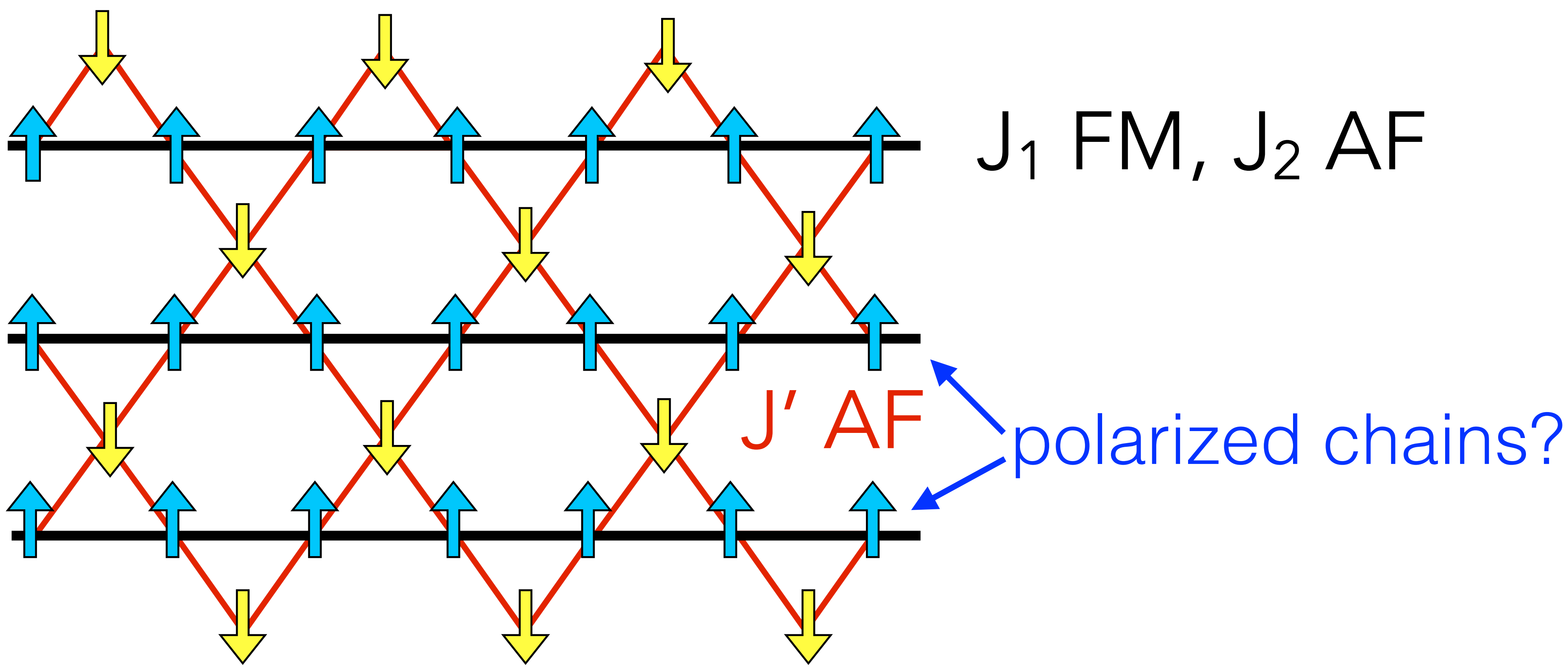
Ferrimagnetic state

PHYSICAL REVIEW B **82**, 104434 (2010)

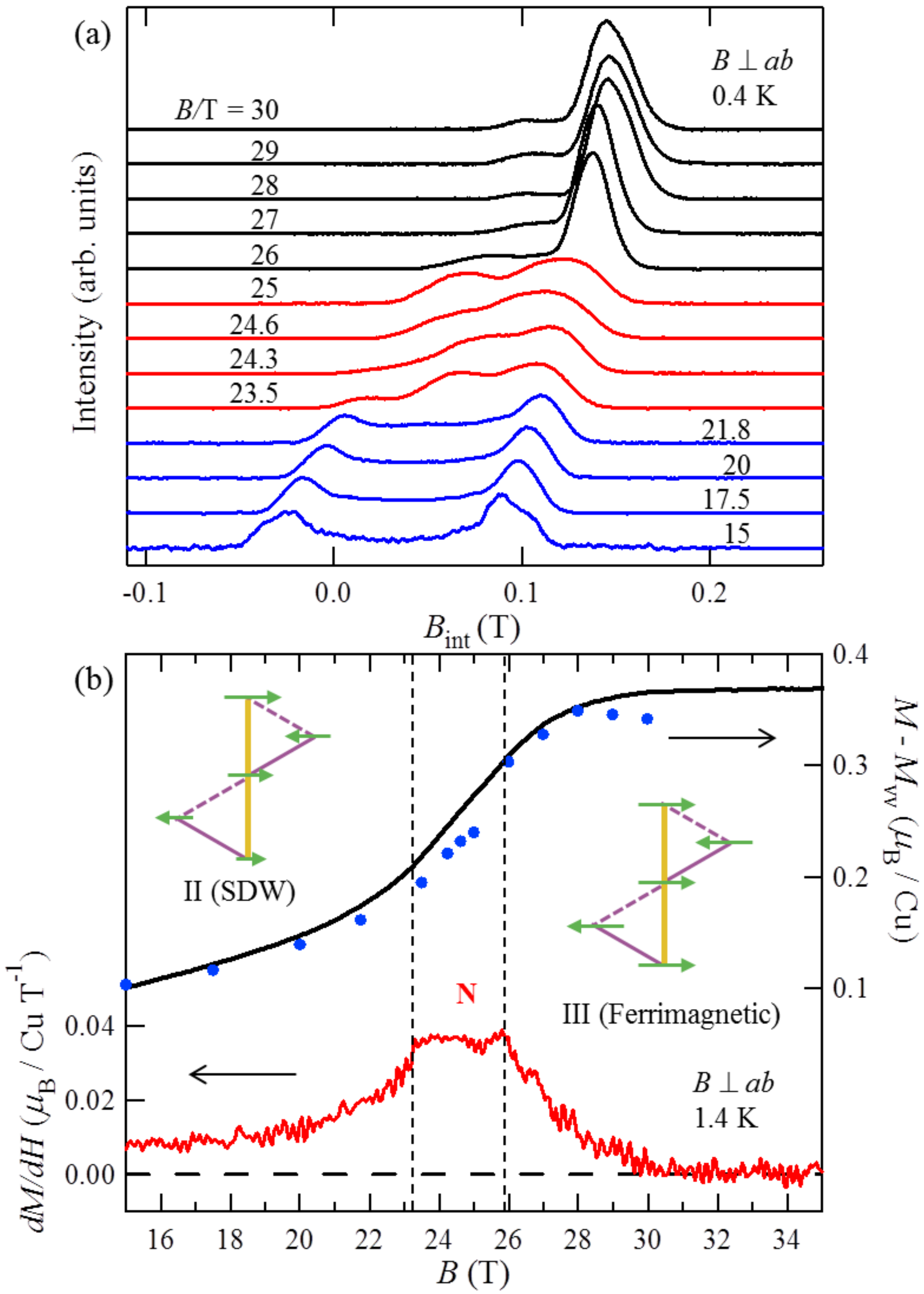
Coupled frustrated quantum spin-$\frac{1}{2}$ chains with orbital order in volborthite $Cu_3V_2O_7(OH)_2 \cdot 2H_2O$

O. Janson,[1,*] J. Richter,[2] P. Sindzingre,[3] and H. Rosner[1,†]
[1]*Max-Planck-Institut für Chemische Physik fester Stoffe, D-01187 Dresden, Germany*
[2]*Institut für Theoretische Physik, Universität Magdeburg, D-39016 Magdeburg, Germany*
[3]*Laboratoire de Physique Théorique de la Matière Condensée, Univ. P. & M. Curie, Paris, France*
(Received 9 August 2010; published 30 September 2010)

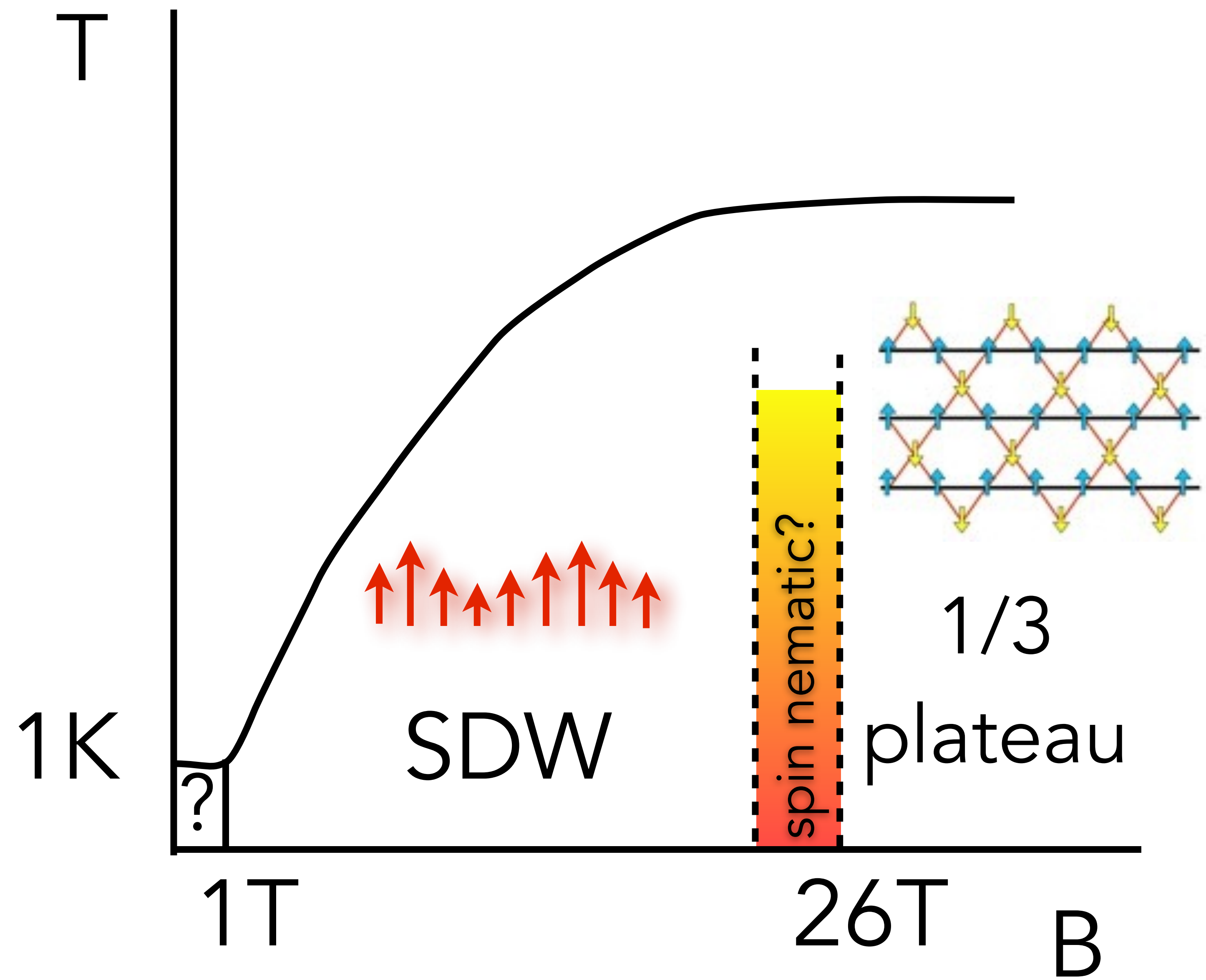
$$J_1 < 0, J_2 > 0, J' > 0$$



Phase diagram



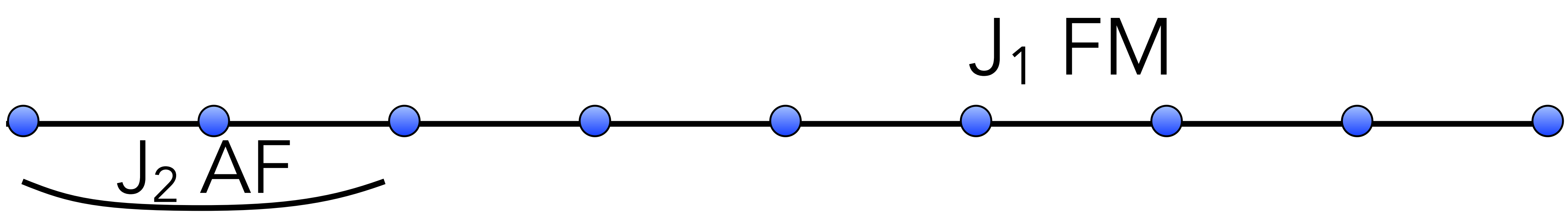
H. Ishikawa *et al*, unpublished



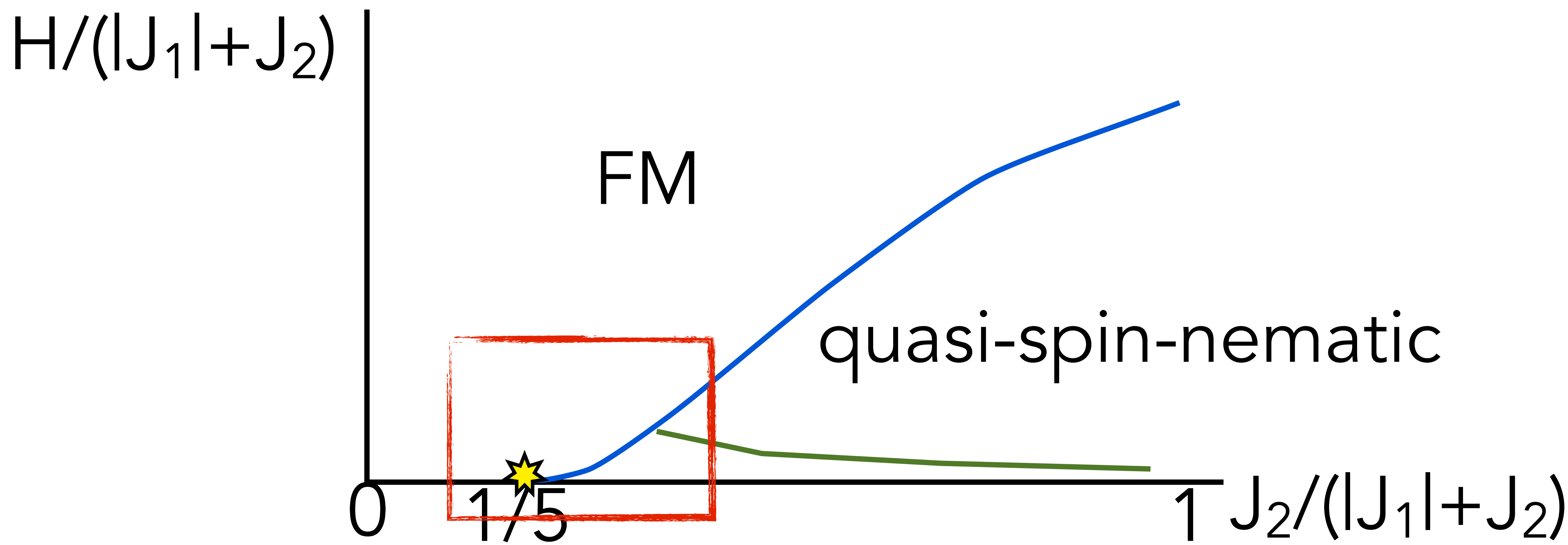
may be a spin nematic??

Spin chain redux

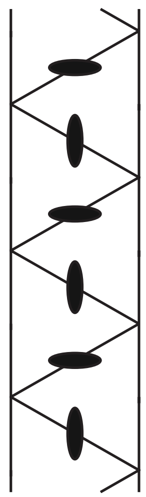
Frustrated ferromagnetic chain



$$H = J_1 \sum_i \mathbf{S}_i \cdot \mathbf{S}_{i+1} + J_2 \sum_i \mathbf{S}_i \cdot \mathbf{S}_{i+2} - h \sum_i S_i^z$$



Quasi-1d nematic



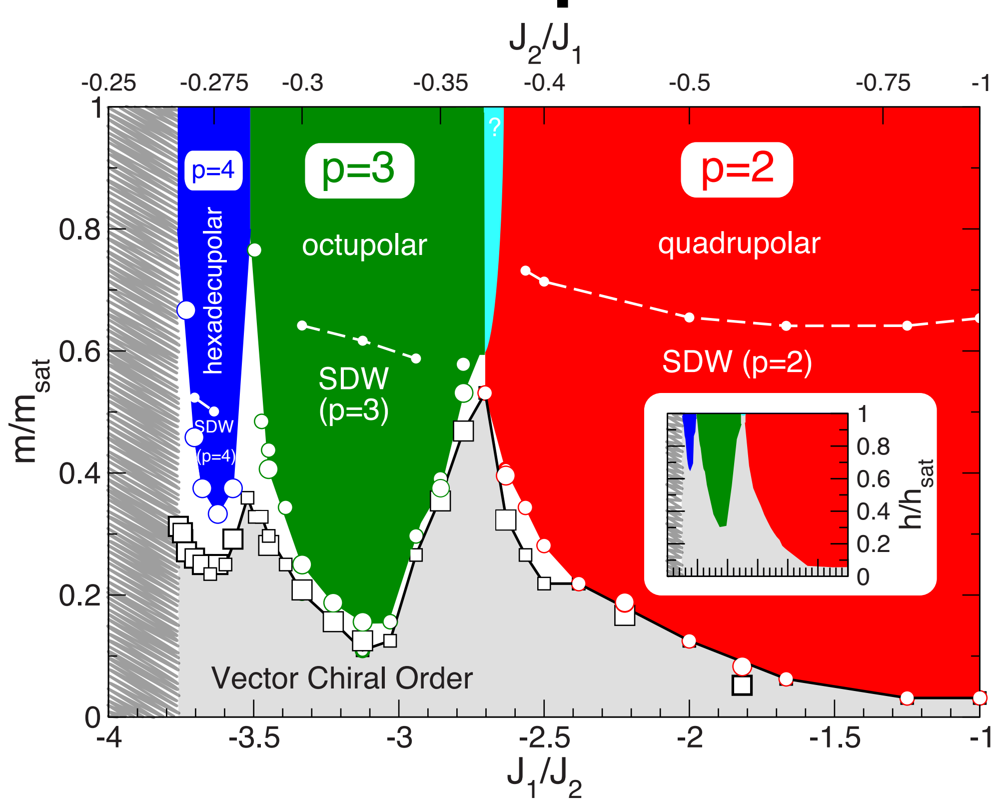
1d J_1-J_2 chain is only *quasi*-spin-nematic

power-law correlations

$\Psi \sim (S^+)^2$: spin-nematic

$\phi \sim S^z e^{i\, q\, x}$: SDW

Hikihara *et al*, 2008
Sudan *et al*, 2009

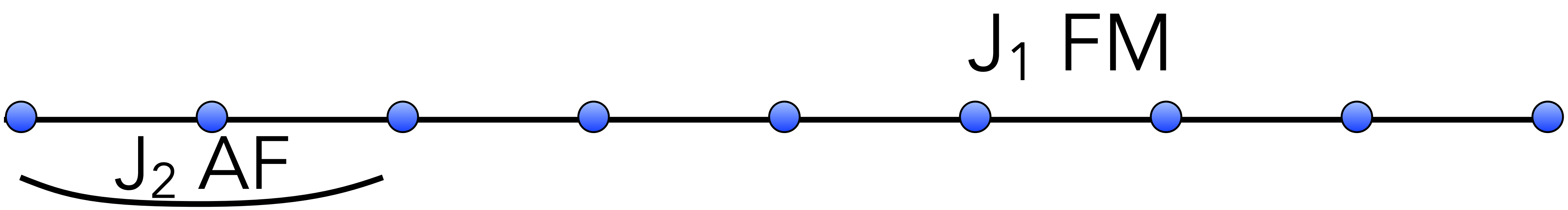


Ψ "dominant"

ϕ "dominant"

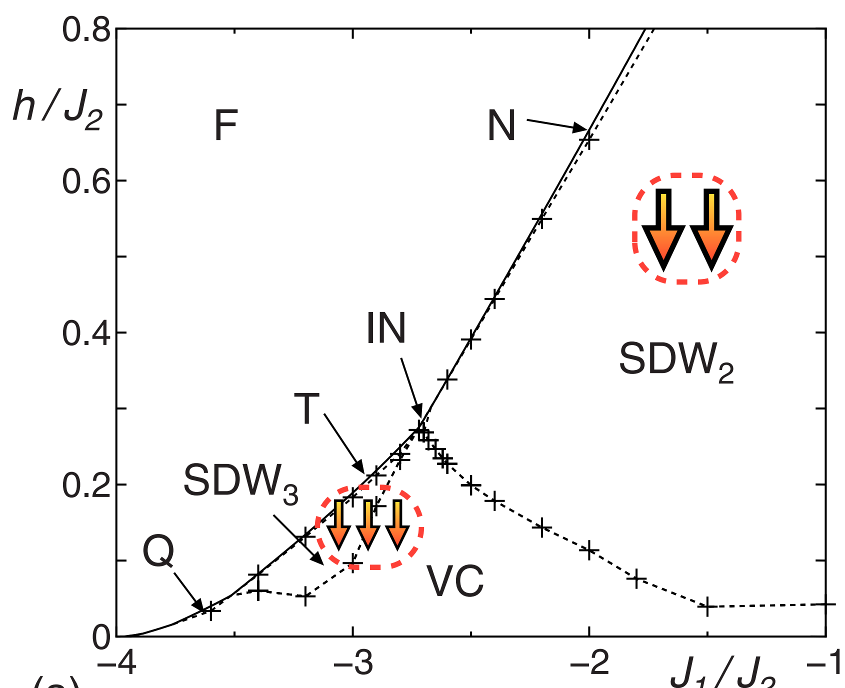
Multipolar phases

Frustrated ferromagnetic chain



$$H = J_1 \sum_i \mathbf{S}_i \cdot \mathbf{S}_{i+1} + J_2 \sum_i \mathbf{S}_i \cdot \mathbf{S}_{i+2} - h \sum_i S_i^z$$

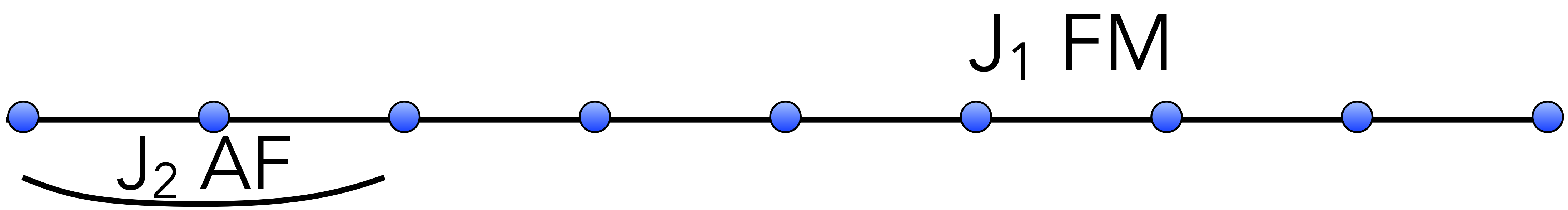
Hikihara *et al*, 2008



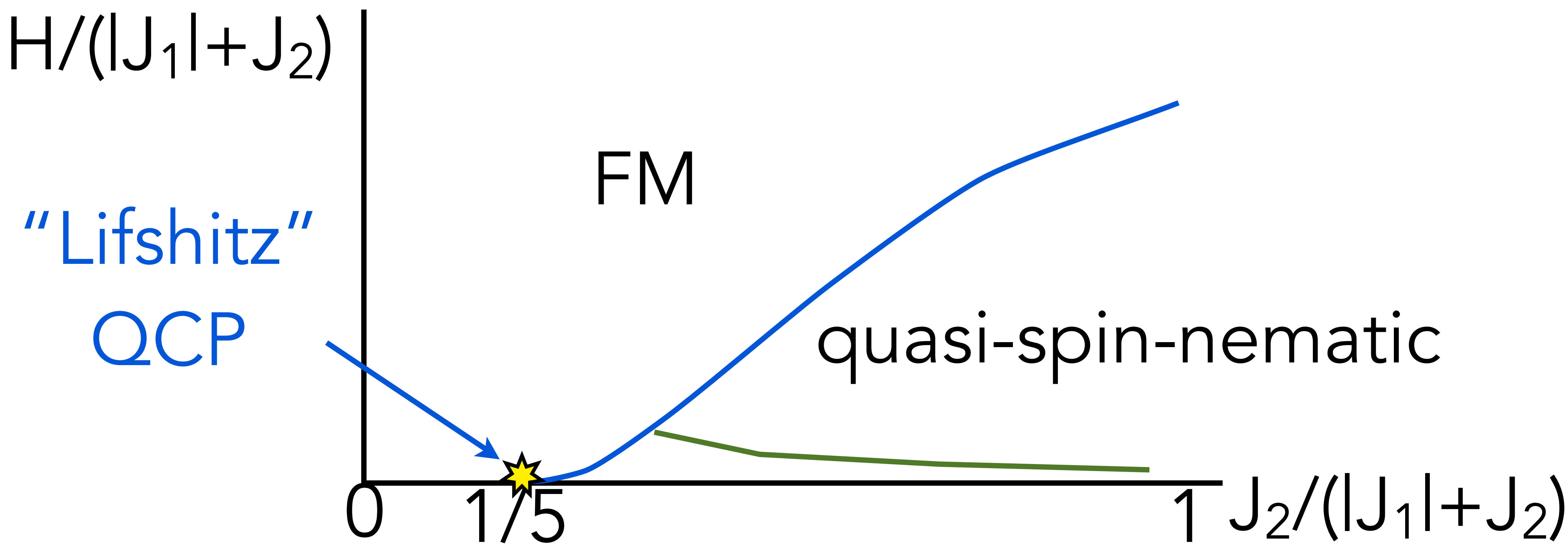
Is it an infinite progression?

A QCP parent?

Frustrated ferromagnetic chain



$$H = J_1 \sum_i \mathbf{S}_i \cdot \mathbf{S}_{i+1} + J_2 \sum_i \mathbf{S}_i \cdot \mathbf{S}_{i+2} - h \sum_i S_i^z$$



Lifshitz Point

- Unusual QCP: order-to-order transition
- Effective action - NLσM

$$S = \int dx d\tau \{ is\mathcal{A}_B[\hat{m}] + \delta|\partial_x \hat{m}|^2 + K|\partial_x^2 \hat{m}|^2 + u|\partial_x \hat{m}|^4 - h\hat{m}_z \}$$

$$\mathcal{A}_B = \frac{\hat{m}_1 \partial_\tau \hat{m}_2 - \hat{m}_2 \partial_\tau \hat{m}_1}{1 + \hat{m}_3}$$

Berry phase term

tunes QCP

two symmetry allowed interactions at O(q^4)

All properties near Lifshitz point obey "one parameter universality" dependent upon u/K ratio

Lifshitz Point

$$S = \int dx d\tau \{ is\mathcal{A}_B[\hat{m}] + \delta|\partial_x \hat{m}|^2 + K|\partial_x^2 \hat{m}|^2 + u|\partial_x \hat{m}|^4 - h\hat{m}_z \}$$

- Intuition: behavior near the Lifshitz point should be semi-classical, since "close" to FM state which is classical

$$x \to \sqrt{\frac{K}{|\delta|}} x \qquad \tau \to \frac{K}{\delta^2} \tau$$

$$S = \sqrt{\frac{K}{\delta}} \int dx d\tau \{ is\mathcal{A}_B[\hat{m}] + \mathrm{sgn}(\delta)|\partial_x \hat{m}|^2 + |\partial_x^2 \hat{m}|^2 + v|\partial_x \hat{m}|^4 - \overline{h}\hat{m}_z \}$$

Large parameter: saddle point!

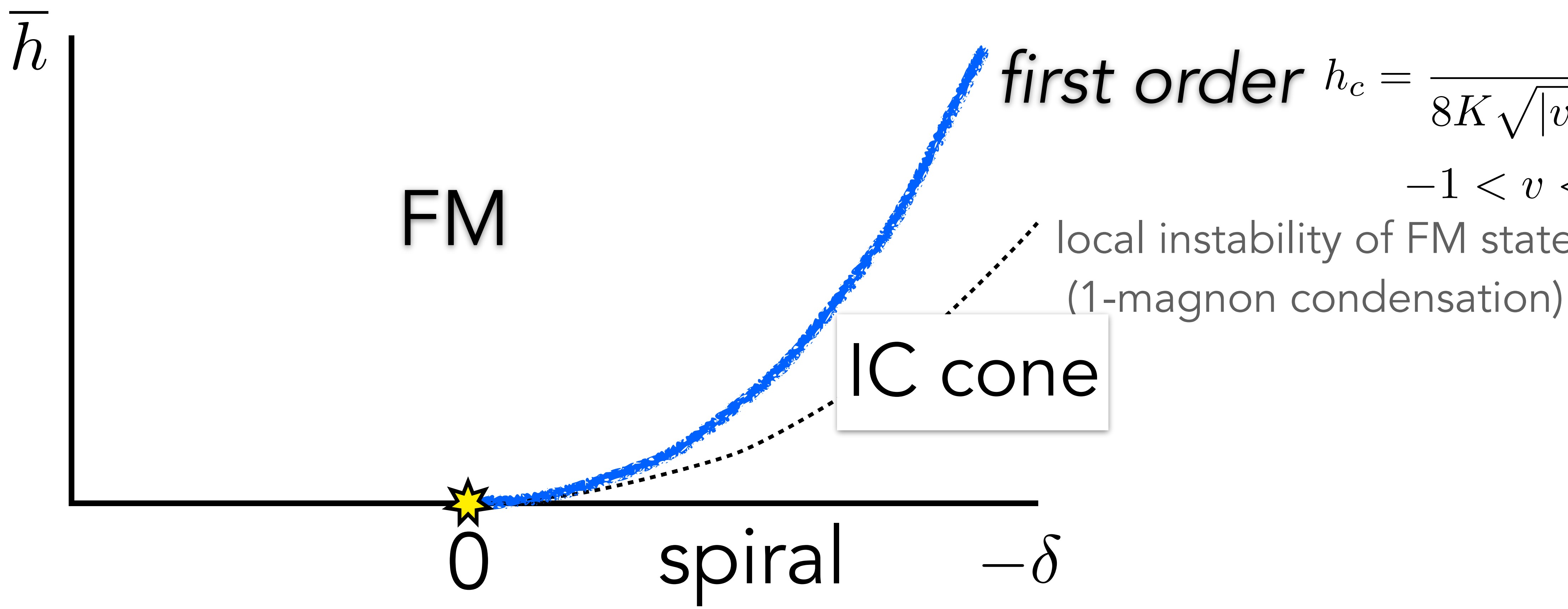
$$v = \frac{u}{K} \qquad \overline{h} = \frac{hK}{\delta^2}$$

Saddle point

$$S = \sqrt{\frac{K}{\delta}} \int dx d\tau \{ is\mathcal{A}_B[\hat{m}] + \text{sgn}(\delta)|\partial_x \hat{m}|^2 + |\partial_x^2 \hat{m}|^2 + v|\partial_x \hat{m}|^4 - \overline{h}\hat{m}_z \}$$

v derives from quantum fluctuations

By a spin wave analysis, one finds v ~ -3/(2S) < 0



$$h_c = \frac{\delta^2}{8K\sqrt{|v|}(1-\sqrt{|v|})}$$

$$-1 < v < -\frac{1}{4}$$

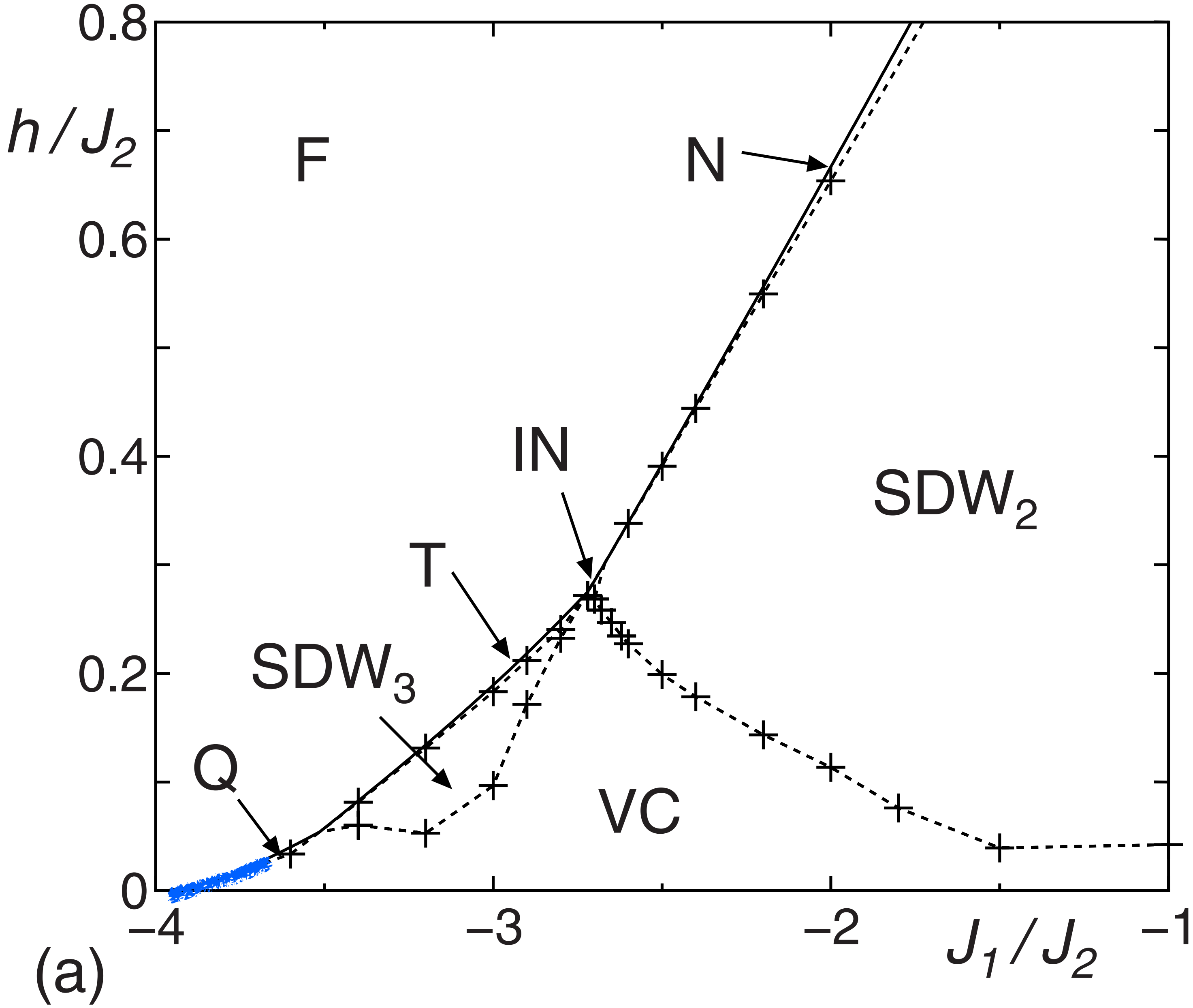
Phase diagram

Frustrated ferromagnetic chain

First order metamagnetic transition near Lifshitz point

Higher dimensions?

Hikihara et al, 2008



d>1

$$S = \int dx d^{d-1}y d\tau \{ is\mathcal{A}_B[\hat{m}] + \delta|\partial_x \hat{m}|^2 + c|\partial_y \hat{m}|^2 + K|\partial_x^2 \hat{m}|^2 + u|\partial_x \hat{m}|^4 - h\hat{m}_z \}$$

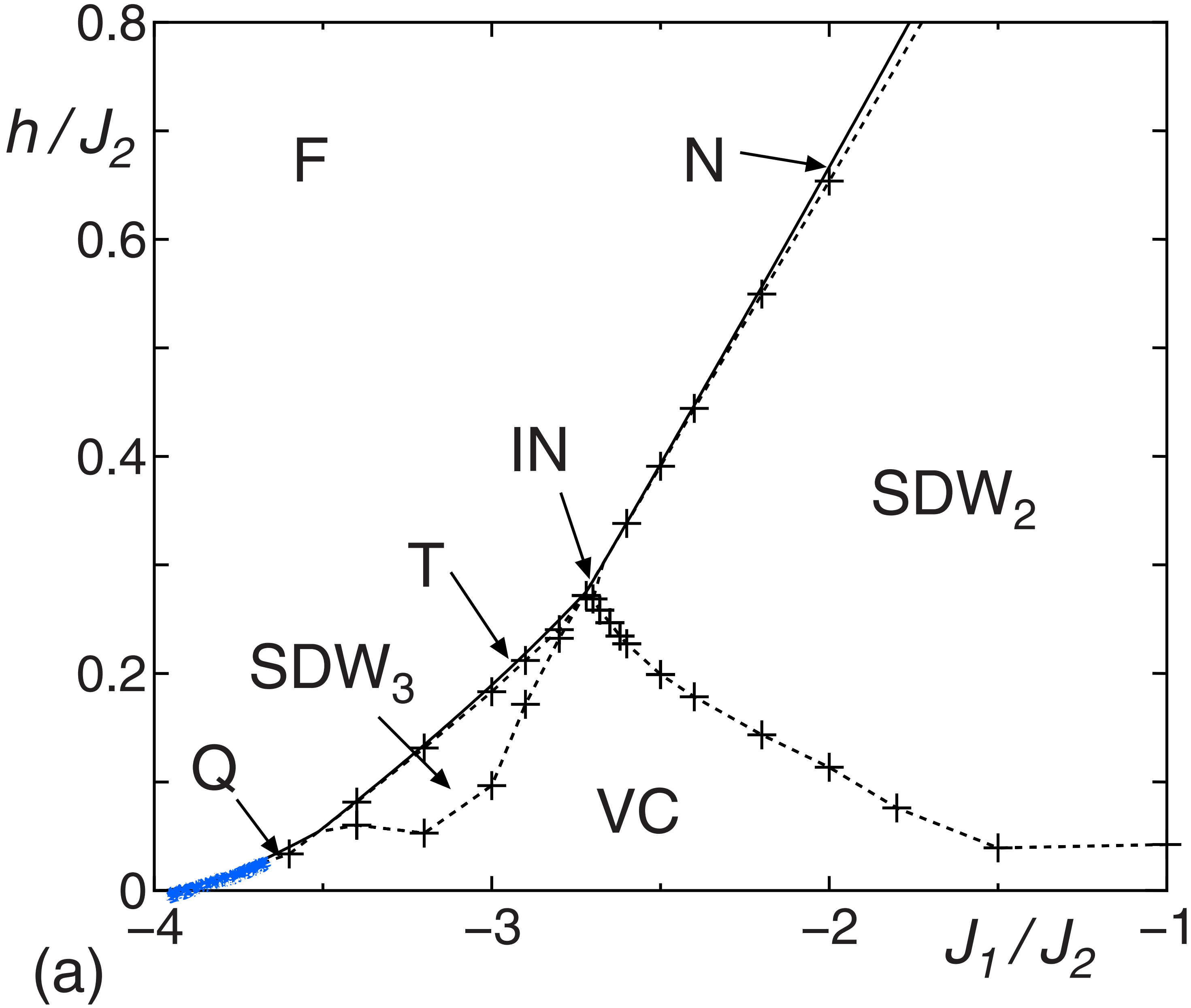
- Rescaling:

$$x \to \sqrt{\frac{K}{|\delta|}}x \qquad \tau \to \frac{K}{\delta^2}\tau \qquad y \to \frac{\sqrt{cK}}{\delta}y$$

$$S = \frac{\sqrt{K^d c^{d-1}}}{\delta^{d-1/2}} \int dx d^{d-1}y d\tau \{ is\mathcal{A}_B[\hat{m}] + \text{sgn}(\delta)|\partial_x \hat{m}|^2 + |\partial_x^2 \hat{m}|^2 + |\partial_y \hat{m}|^2 + v|\partial_x \hat{m}|^4 - \overline{h}\hat{m}_z \}$$

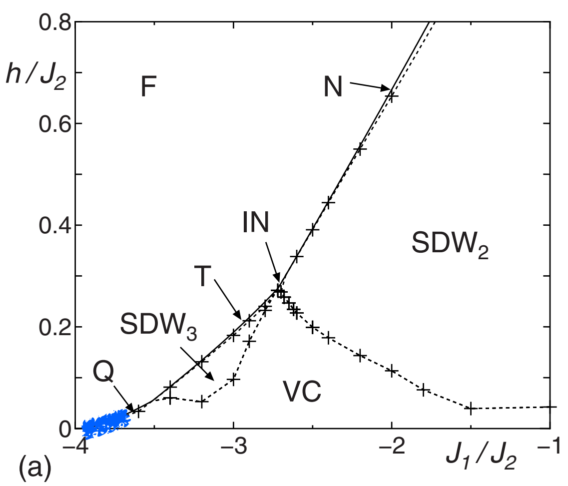
∴ Similar theory applies in d>1, and very similar conclusions apply

Phase diagram



multipolar phases from QCP?

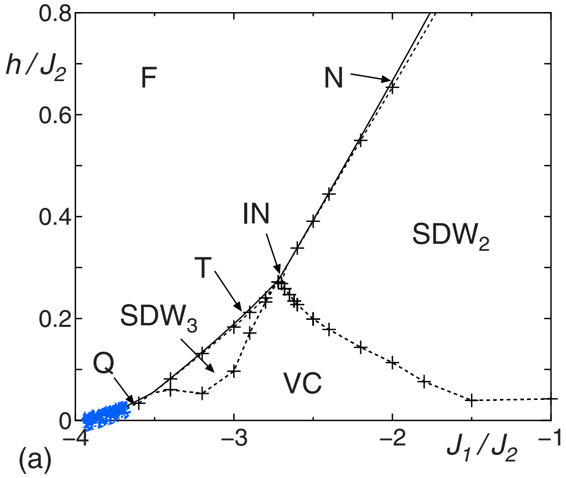
Origin of multipolar phases

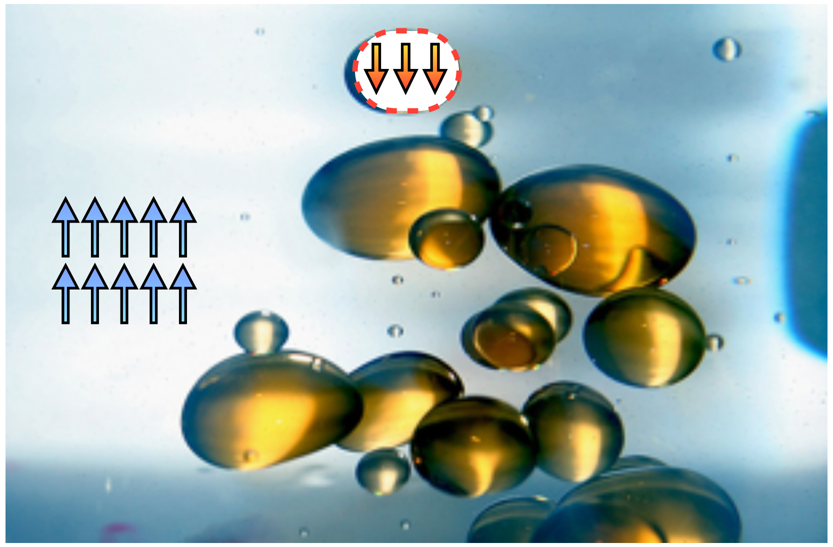


First order transition: partially polarized state *coexists* with plateau one

With enough quantum fluctuations, “bubbles” of partially polarized phase may become many-magnon bound states and form multipolar phases

Origin of multipolar phases





First order transition: partially polarized state *coexists* with plateau one

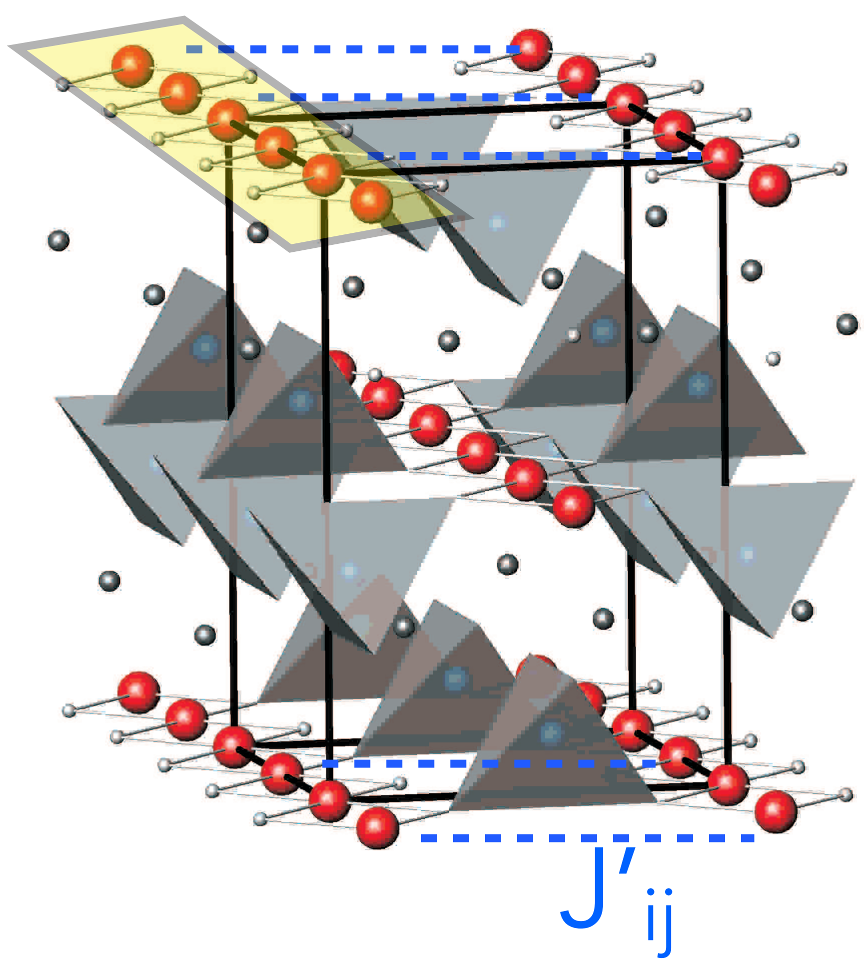
With enough quantum fluctuations, "bubbles" of partially polarized phase may become many-magnon bound states and form multipolar phases

Summary

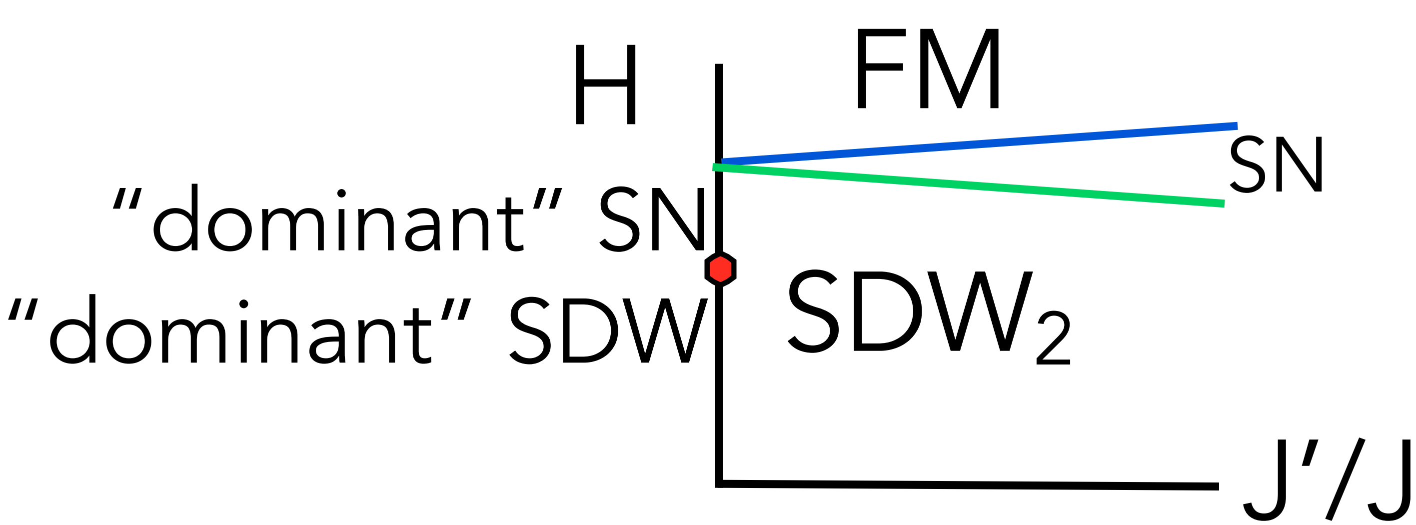
- Spin chains keep showing up in unexpected places
  - ✓ Nematic physics of frustrated ferromagnets
  - ✓ Explored Lifshitz point as a “parent” for multipolar states and metamagnetism

Quasi-1d nematic

1d J_1-J_2 chain



c.f. $J'/J \sim 0.1$ in $LiCuVO_4$

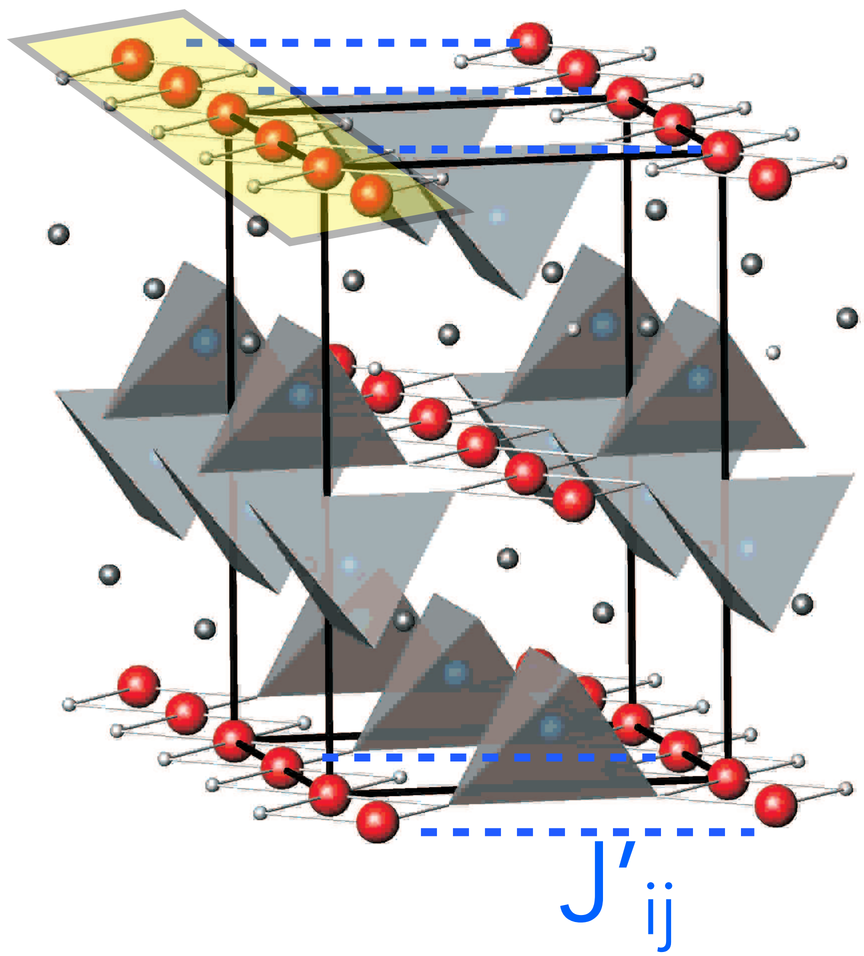


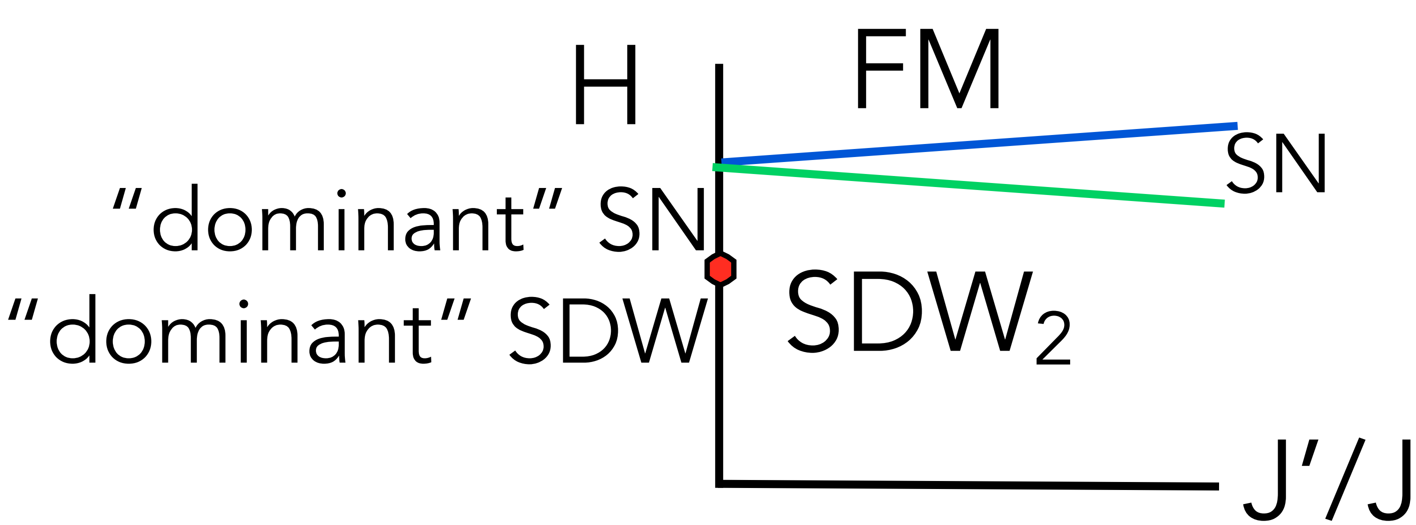
True nematic occurs in narrow range near FM state

O. Starykh + LB, 2013

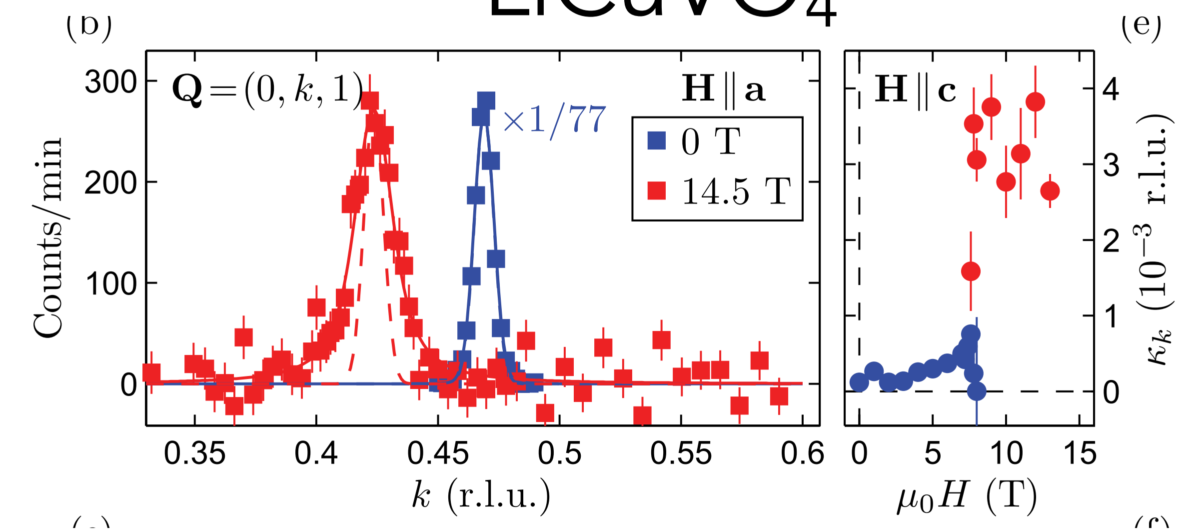
Quasi-1d nematic

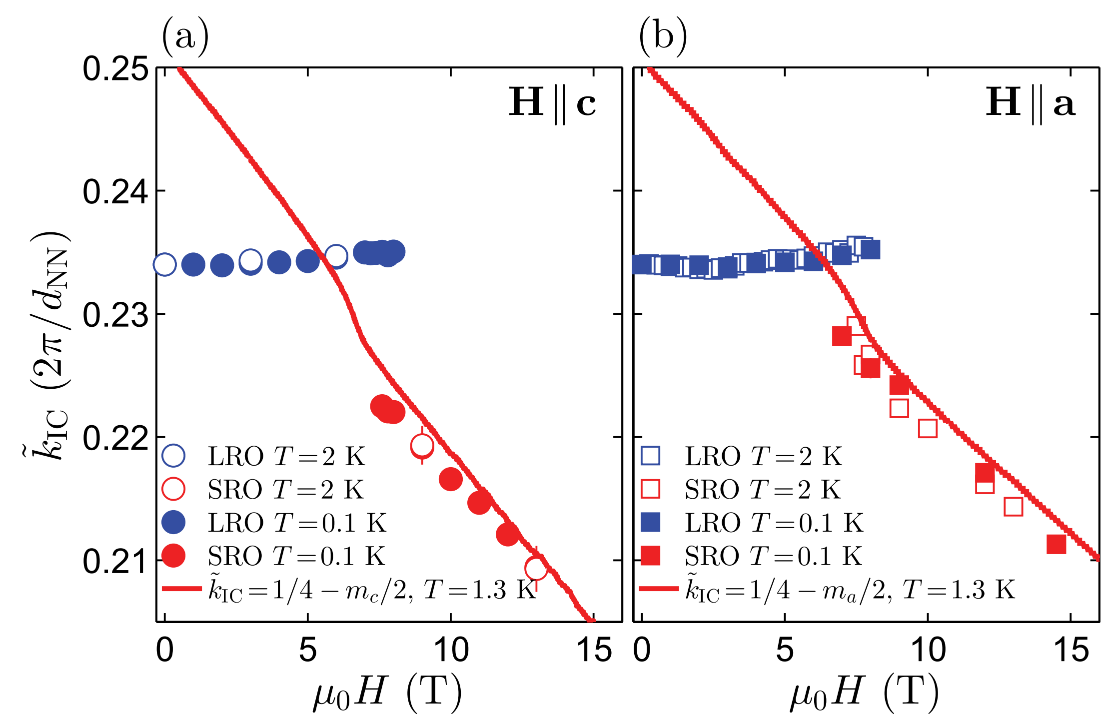
1d J_1-J_2 chain





$LiCuVO_4$

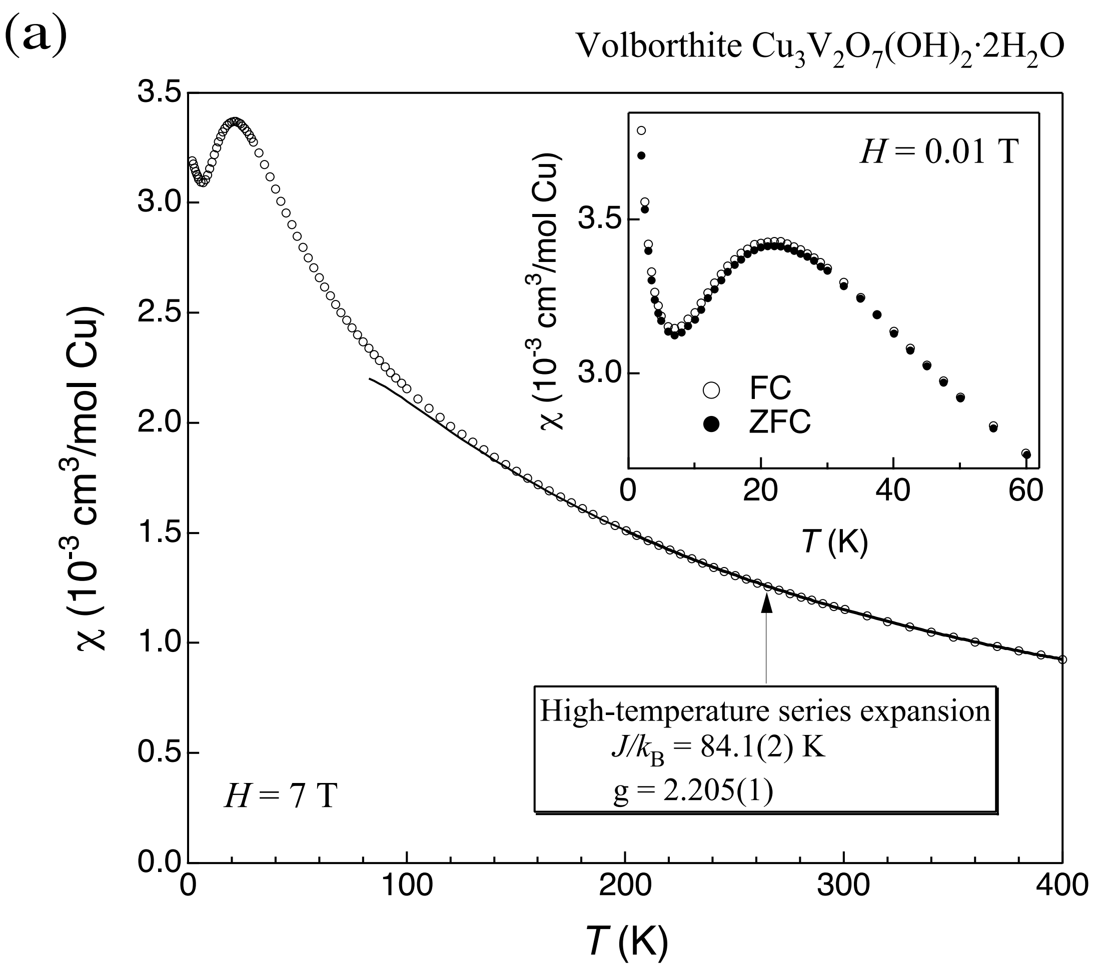


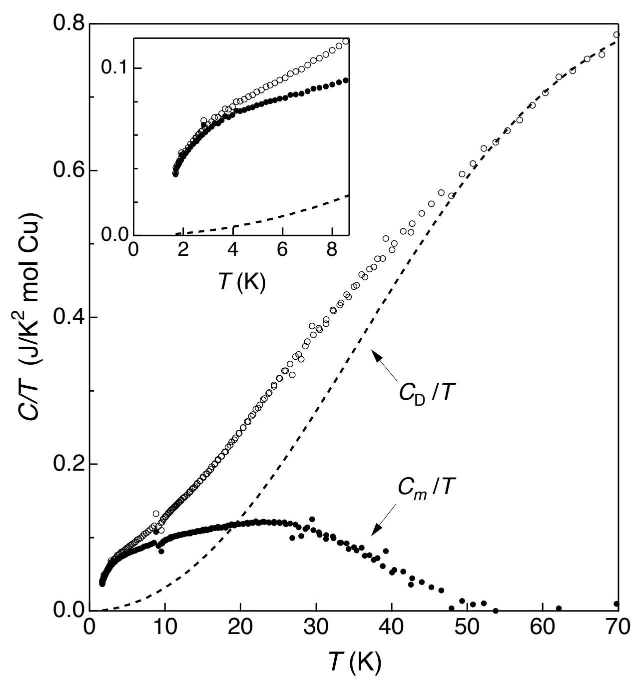


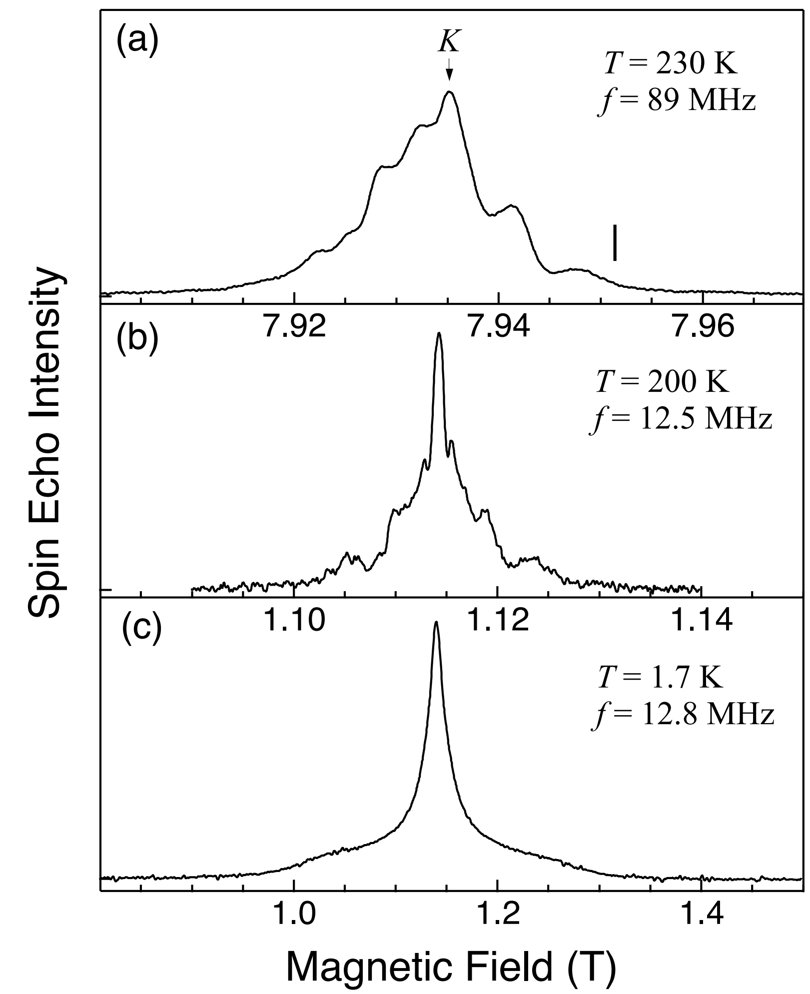
M. Mourigal *et al*, 2012

$q = 1/4 - M/2$

2001: a QSL?



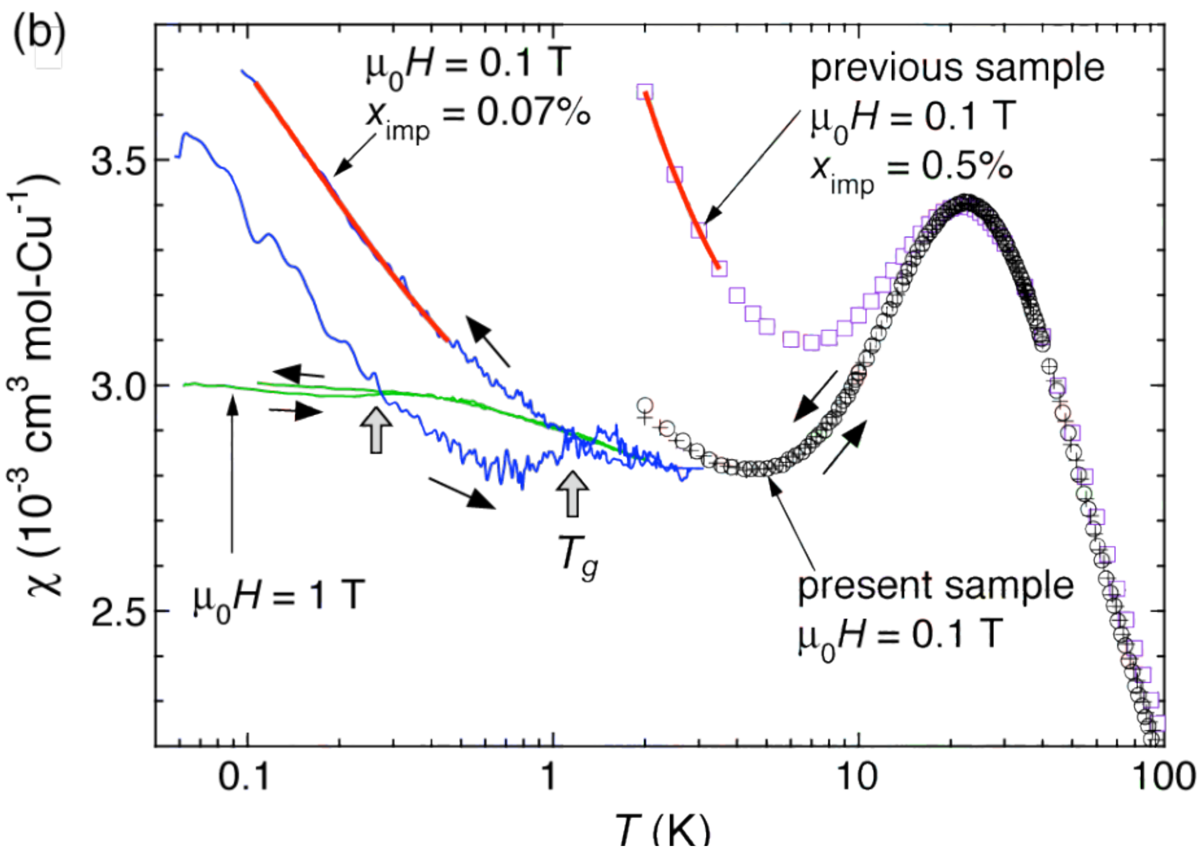


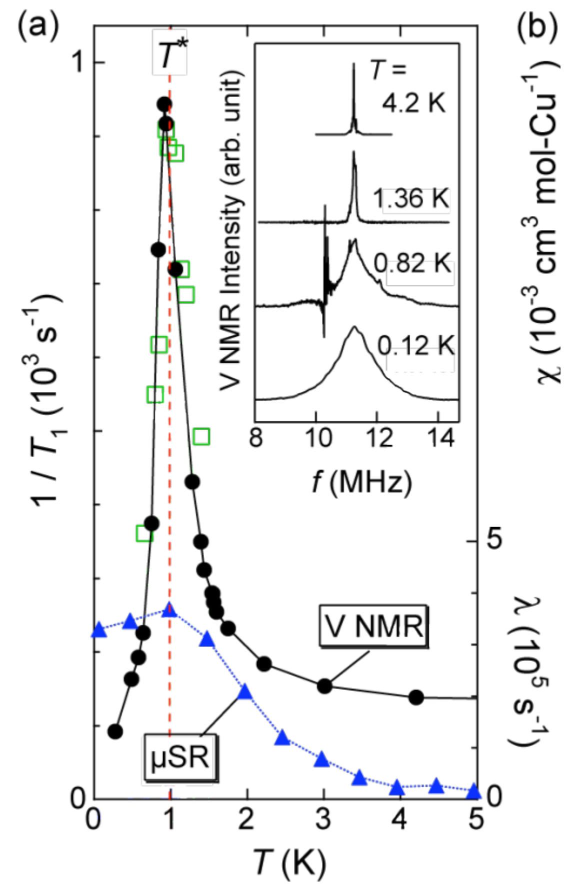


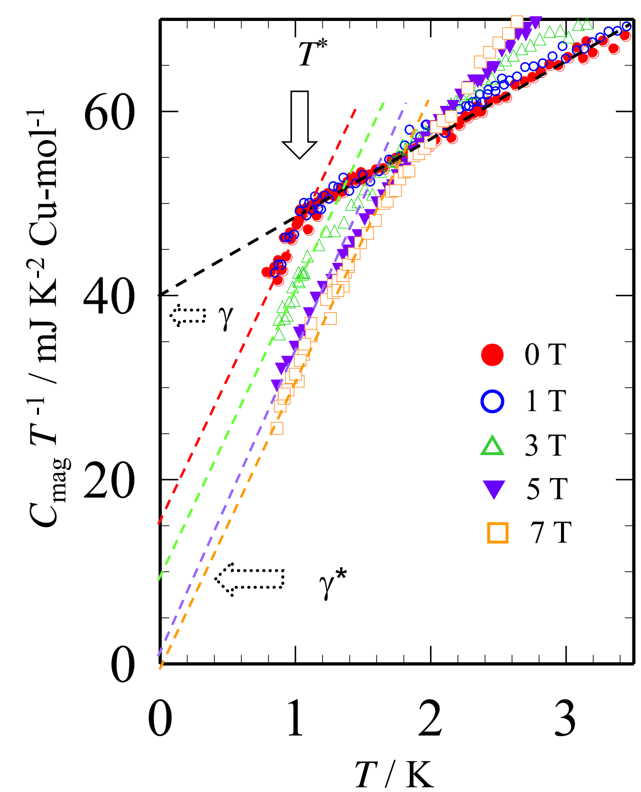
smooth thermodynamics

no spontaneous fields

2009: Impurity ordering at 1K? Fermionic QSL?





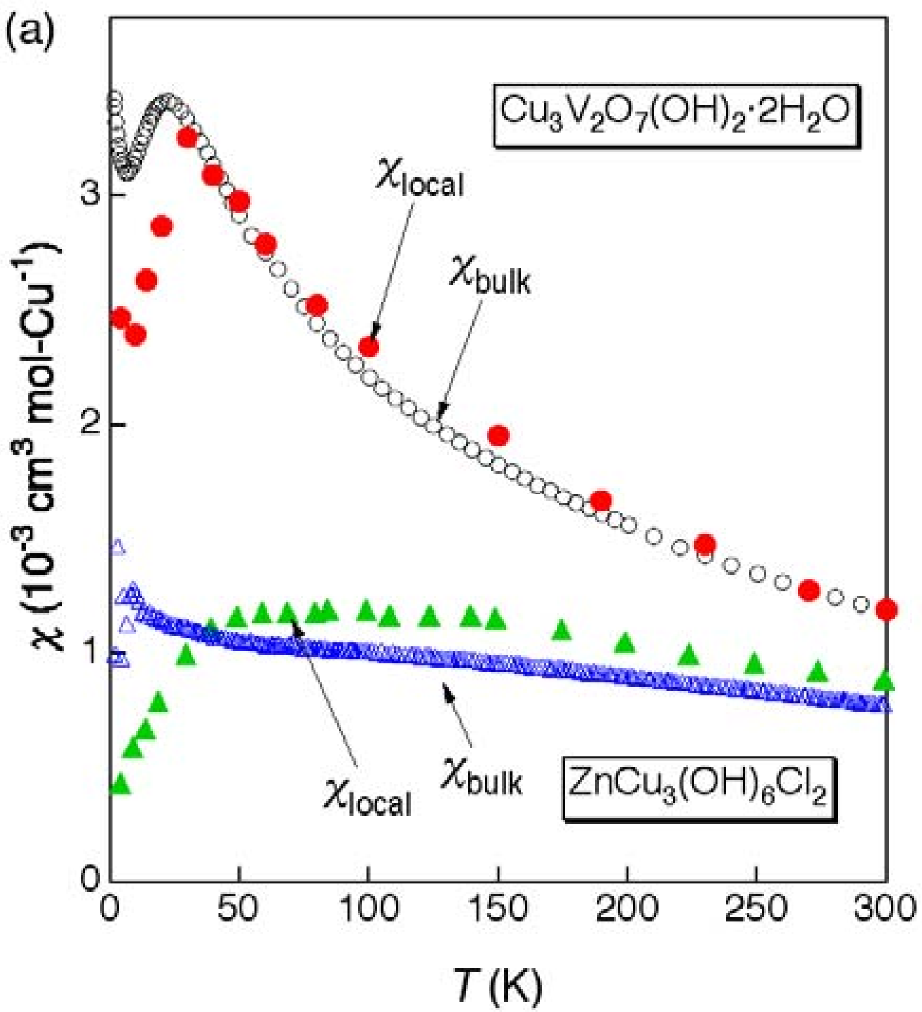


c.f. herbertsmithite:

x_{imp} ~ 5%

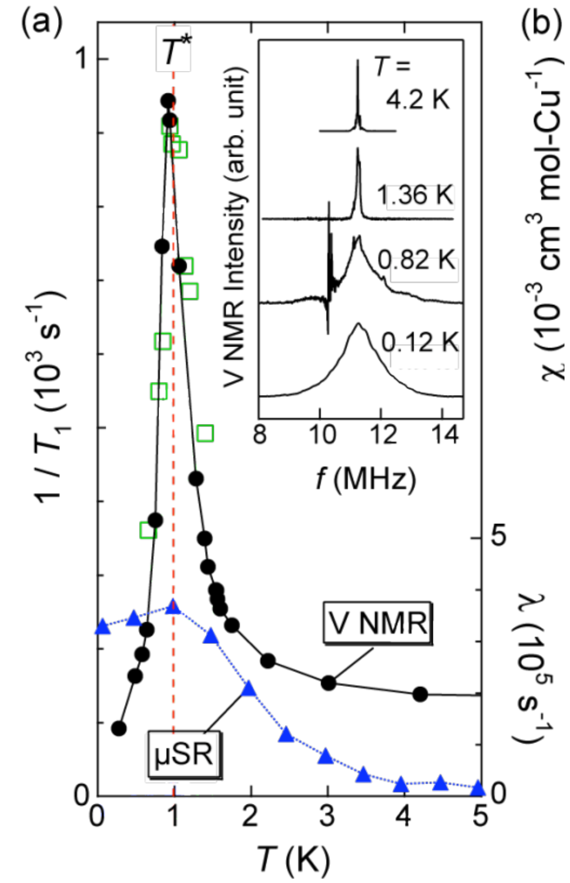
fermionic spinons?

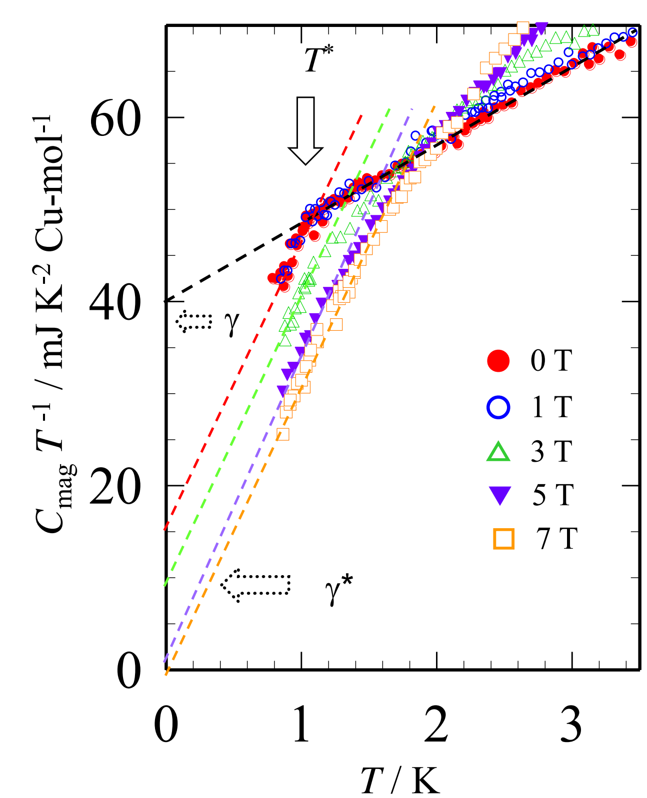
2009: Impurity ordering at 1K? Fermionic QSL?



c.f. herbertsmithite:

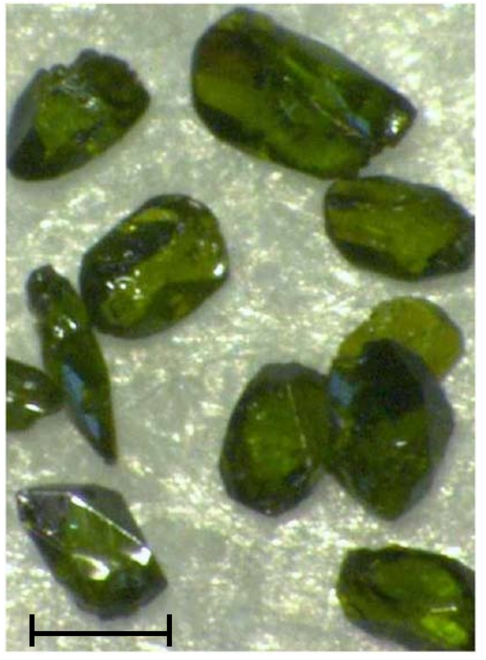
x_{imp} ~ 5%

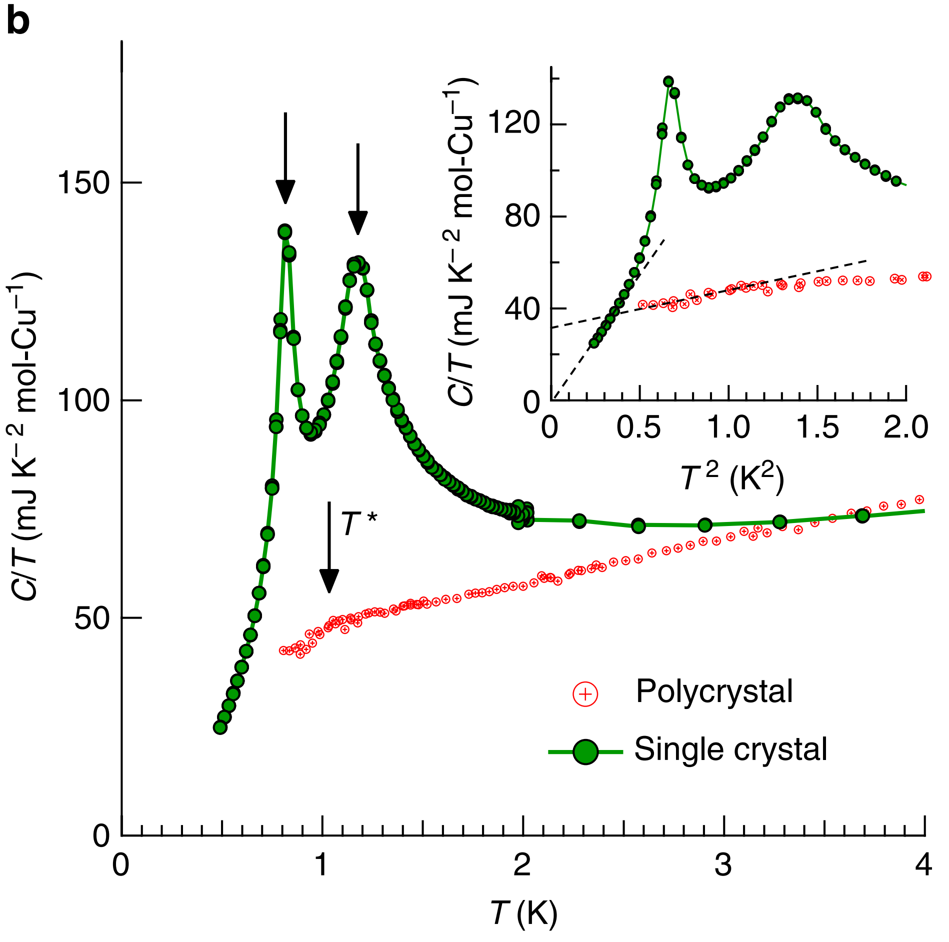




fermionic spinons?

2012: Ordering transitions!
Not a QSL





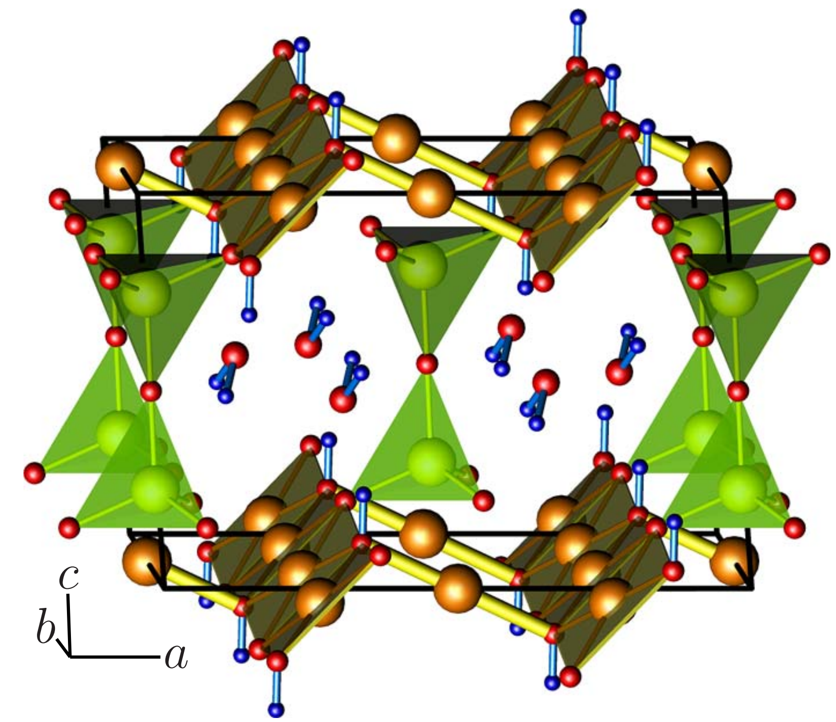
Amazing how much sample quality matters!

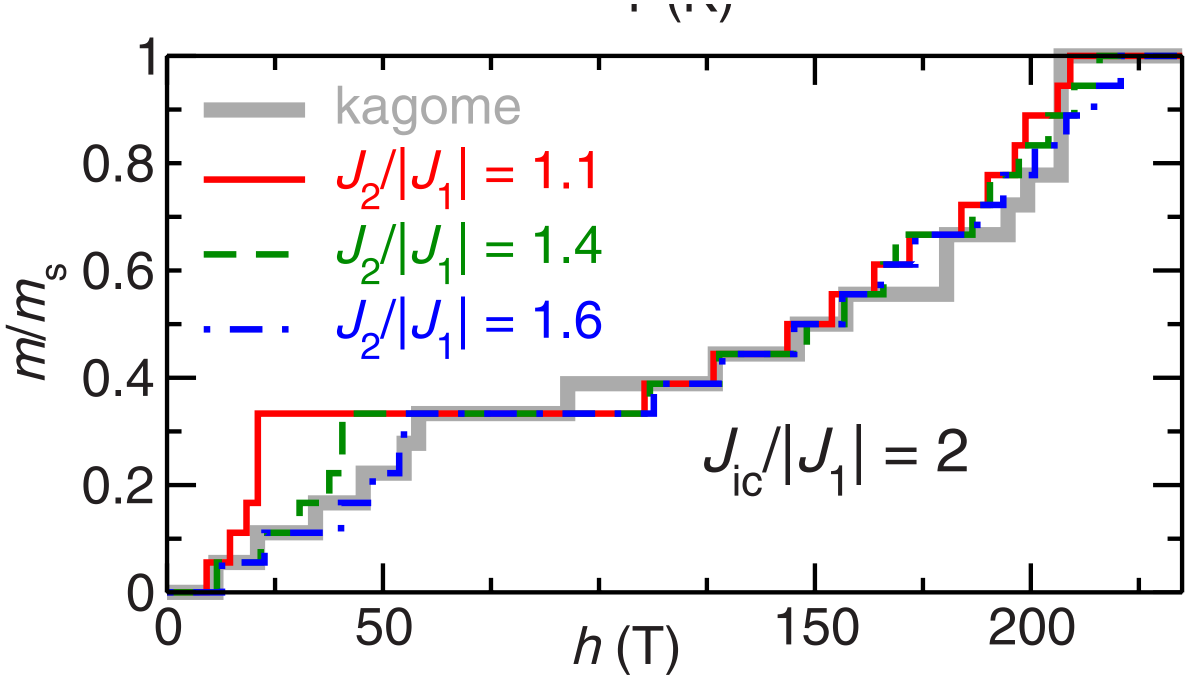
Frustrated ferromagnetism

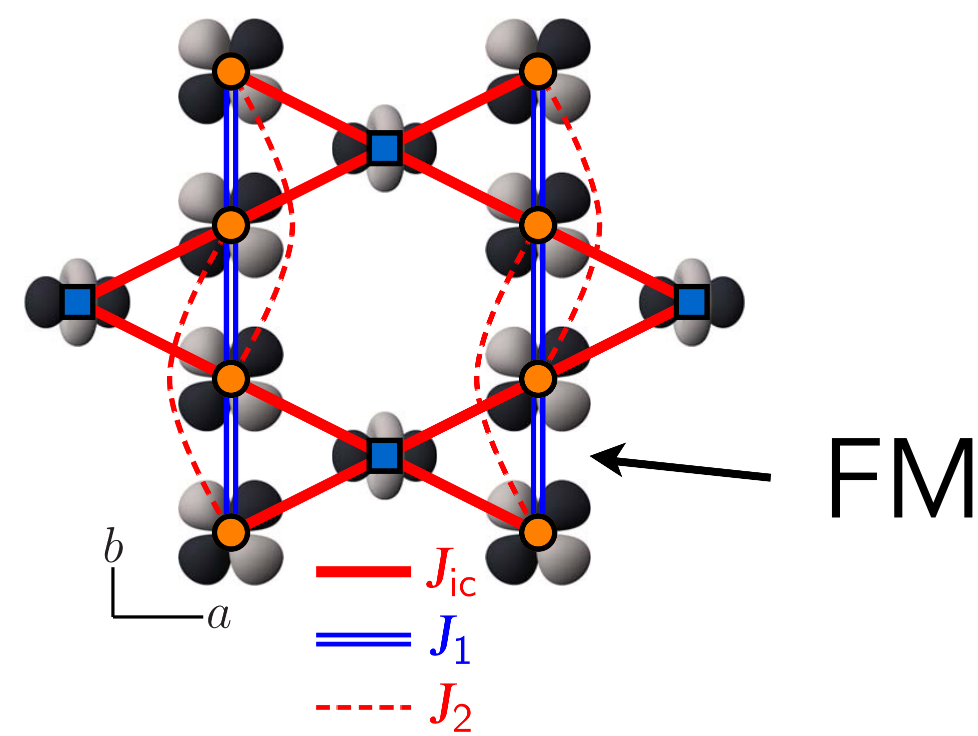
PHYSICAL REVIEW B **82**, 104434 (2010)

Coupled frustrated quantum spin-$\frac{1}{2}$ chains with orbital order in volborthite $Cu_3V_2O_7(OH)_2 \cdot 2H_2O$

O. Janson,[1,*] J. Richter,[2] P. Sindzingre,[3] and H. Rosner[1,†]
[1]*Max-Planck-Institut für Chemische Physik fester Stoffe, D-01187 Dresden, Germany*
[2]*Institut für Theoretische Physik, Universität Magdeburg, D-39016 Magdeburg, Germany*
[3]*Laboratoire de Physique Théorique de la Matière Condensée, Univ. P. & M. Curie, Paris, France*
(Received 9 August 2010; published 30 September 2010)

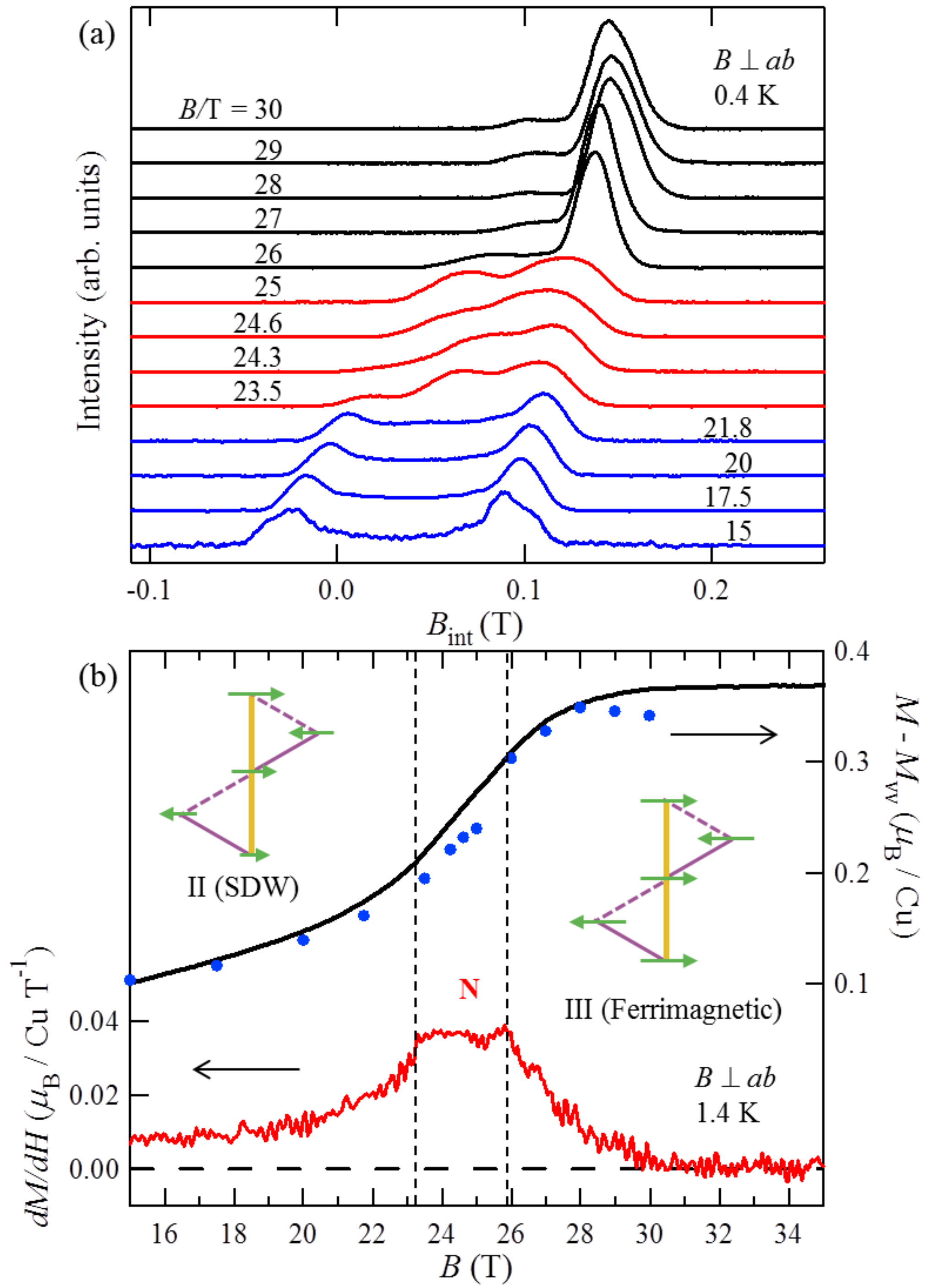




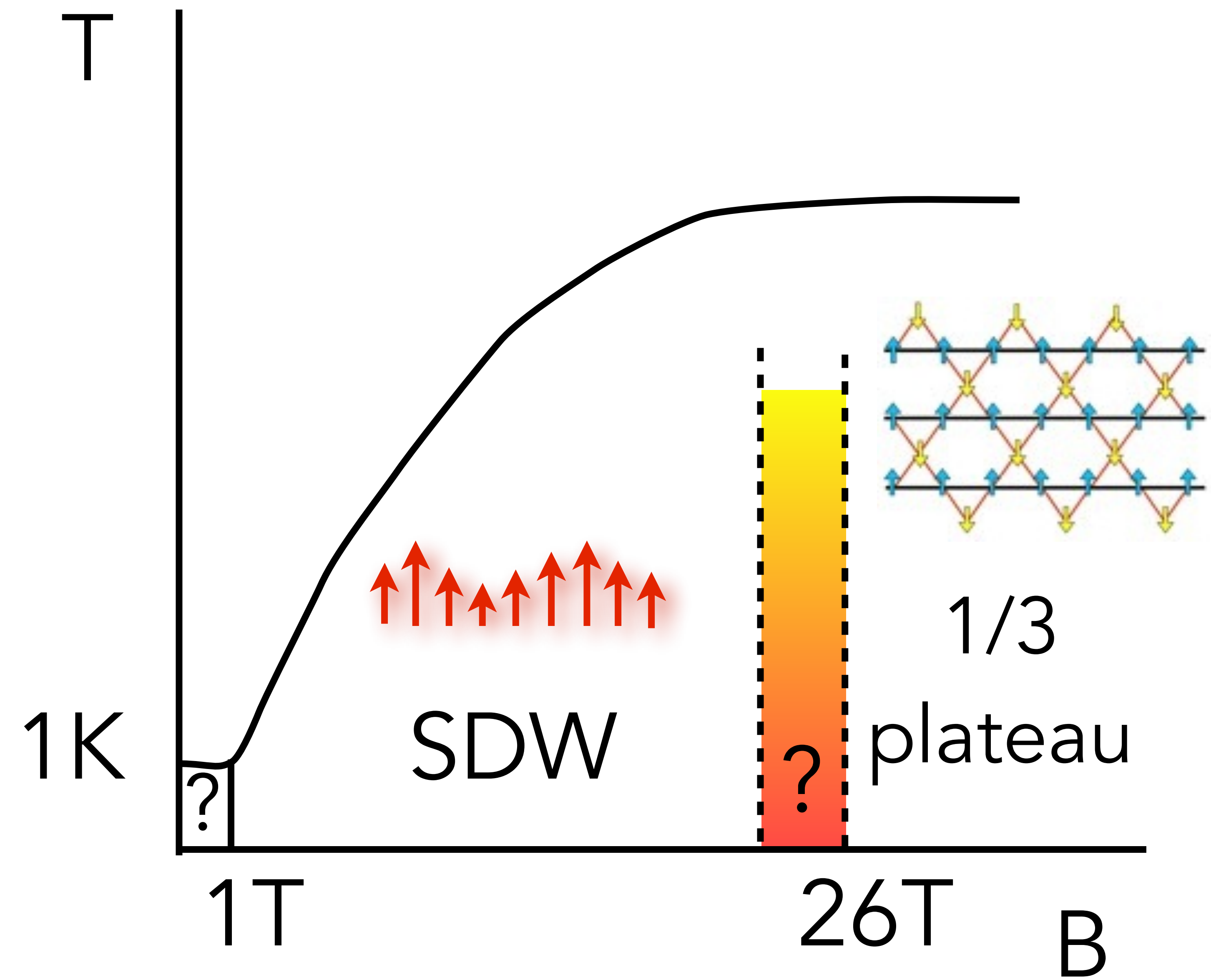


Prospects of observing novel quantum liquids

Phase diagram



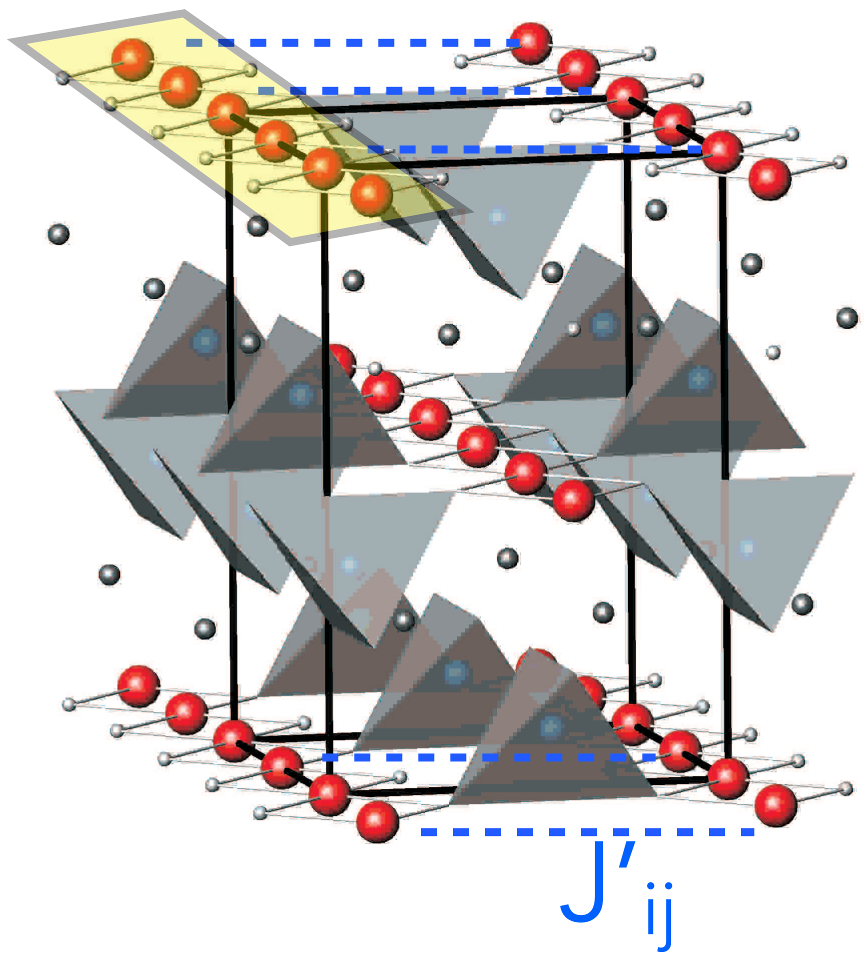
H. Ishikawa *et al*,
unpublished



our interpretation

Quasi-1d nematic

1d J_1-J_2 chain



Interchain coupling

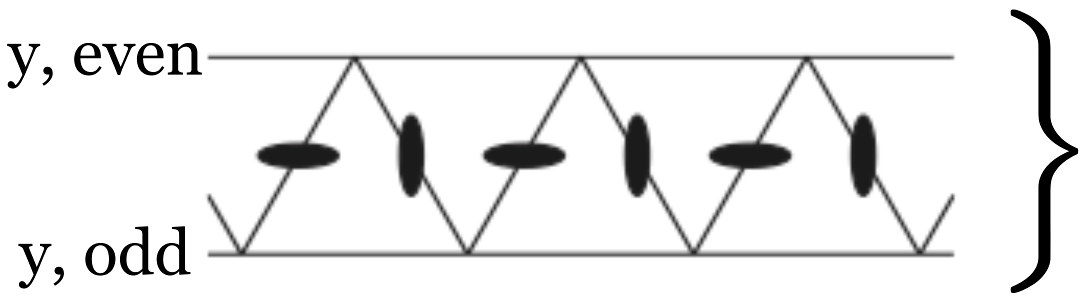
$$\sim J' \phi_y \phi_{y+1} + (J')^2/J\, \Psi_y \Psi_{y+1}$$

extra suppression of spin-nematic order in quasi-1d limit

Nematic chain

S^z-S^z (SDW) channel: in-chain $J_1 < 0$ gaps out relative mode $\varphi_y^- = (\varphi_{y,\mathrm{odd}} - \varphi_{y,\mathrm{even}})/\sqrt{2}$

$$H_{\mathrm{intra-chain}} = \sum_y \int dx J_1 \sin[\pi M] \cos[\frac{\sqrt{8}\pi}{\beta}\varphi_y^-]$$ local pair formation



J_1-J_2 chain

$$\langle S^+ \rangle = 0$$

quantum-disordered,
decays *exponentially:*
S^z = 1 excitations are gapped

$$S_y^+(x) \sim (-1)^x A_3 e^{i\frac{\beta}{\sqrt{2}}\theta_y^+(x)} e^{i(-1)^x \frac{\beta}{\sqrt{2}}\theta_y^-(x)}$$

Standard (in 1d) power-law decay:
critical nematic spin correlations,
but U(1) *is preserved*

$$T_y^+ = S_y^+(x) S_y^+(x+1) \sim e^{i\sqrt{2}\beta\theta_y^+(x)}$$

$$\langle T^+ \rangle = \langle S^+ S^+ \rangle \to 0$$

Physical picture: 1d magnon "superconductor"

Kolezhuk, Vekua (2005); Hikihara et al. (2008); Sato, Hikihara, Momoi (2013)

2d commensurate SDW
(such as 1/3 magnetization plateau)

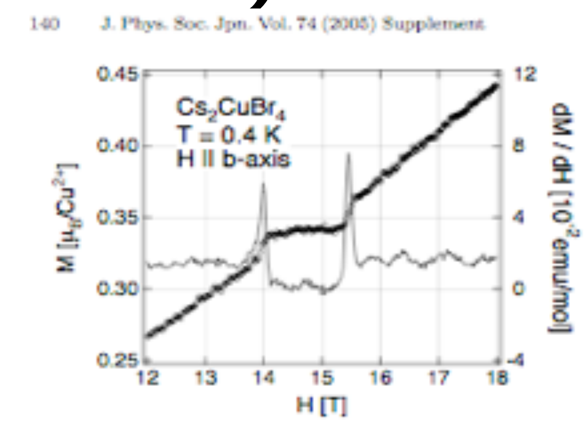
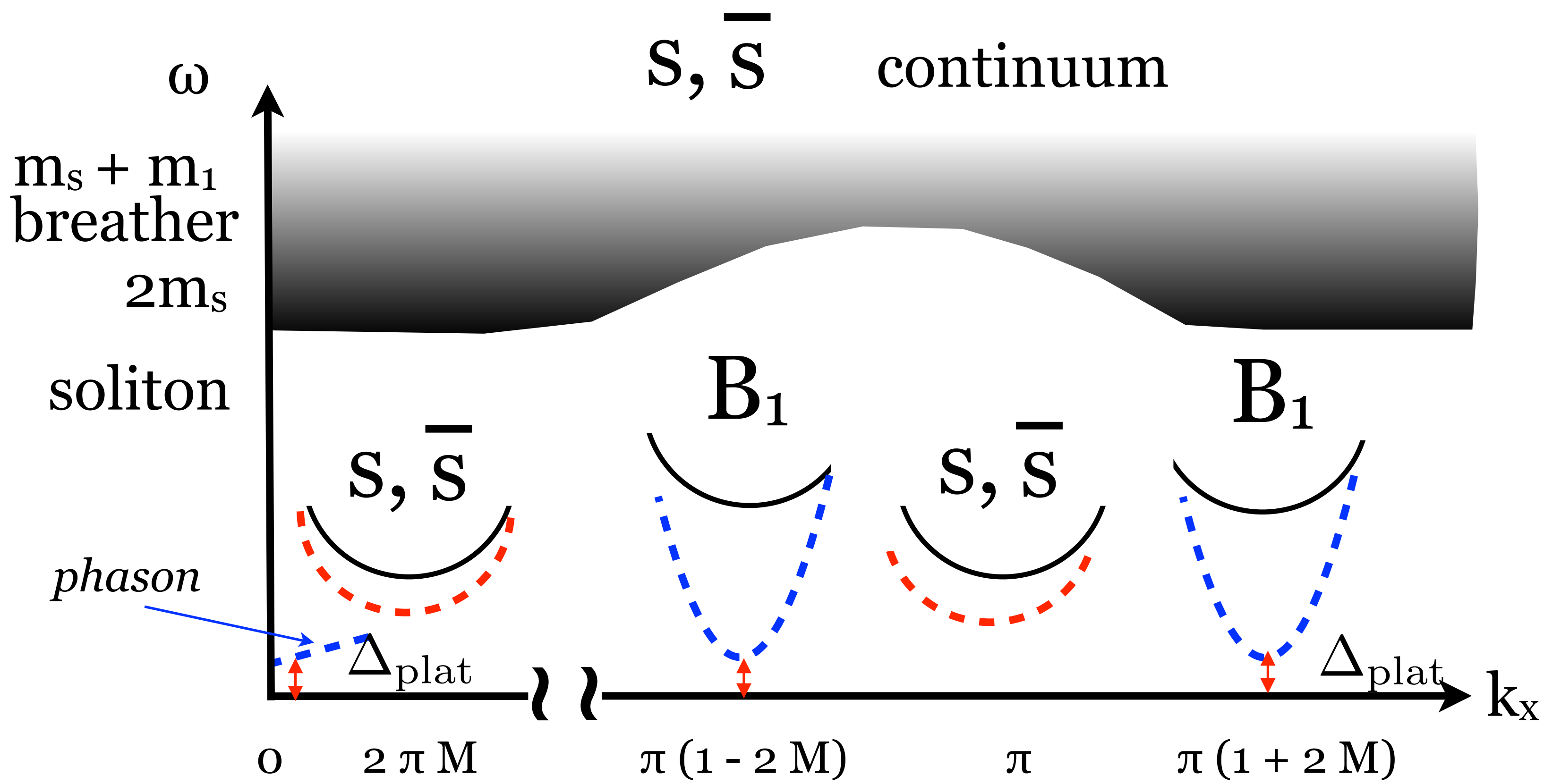


Fig. 8. The magnetization curve and dM/dH versus H for $H \parallel b$ measured at $T = 0.4$ K in magnetic fields up to 20 T.

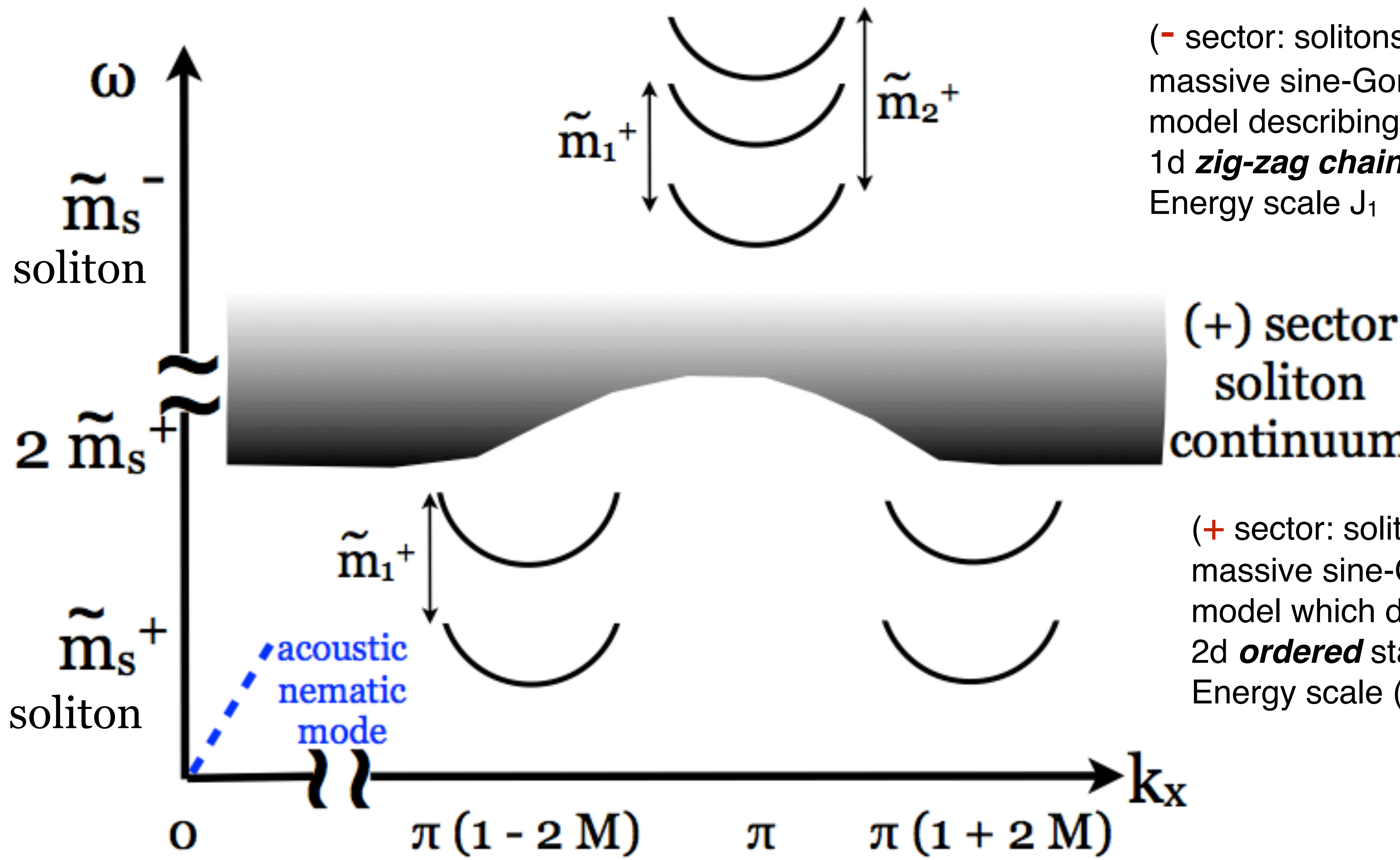


gapped transverse excitations

gapped phason

$$\chi^{zz}_{2d;plat}(q,\pi+q_y,\omega) \sim \frac{Z_{zz;2d}}{\Delta^2_{plat} + \left(v^2 q^2 + v_\perp^2 q_y^2\right) - \omega^2}.$$

2d Spin Nematic



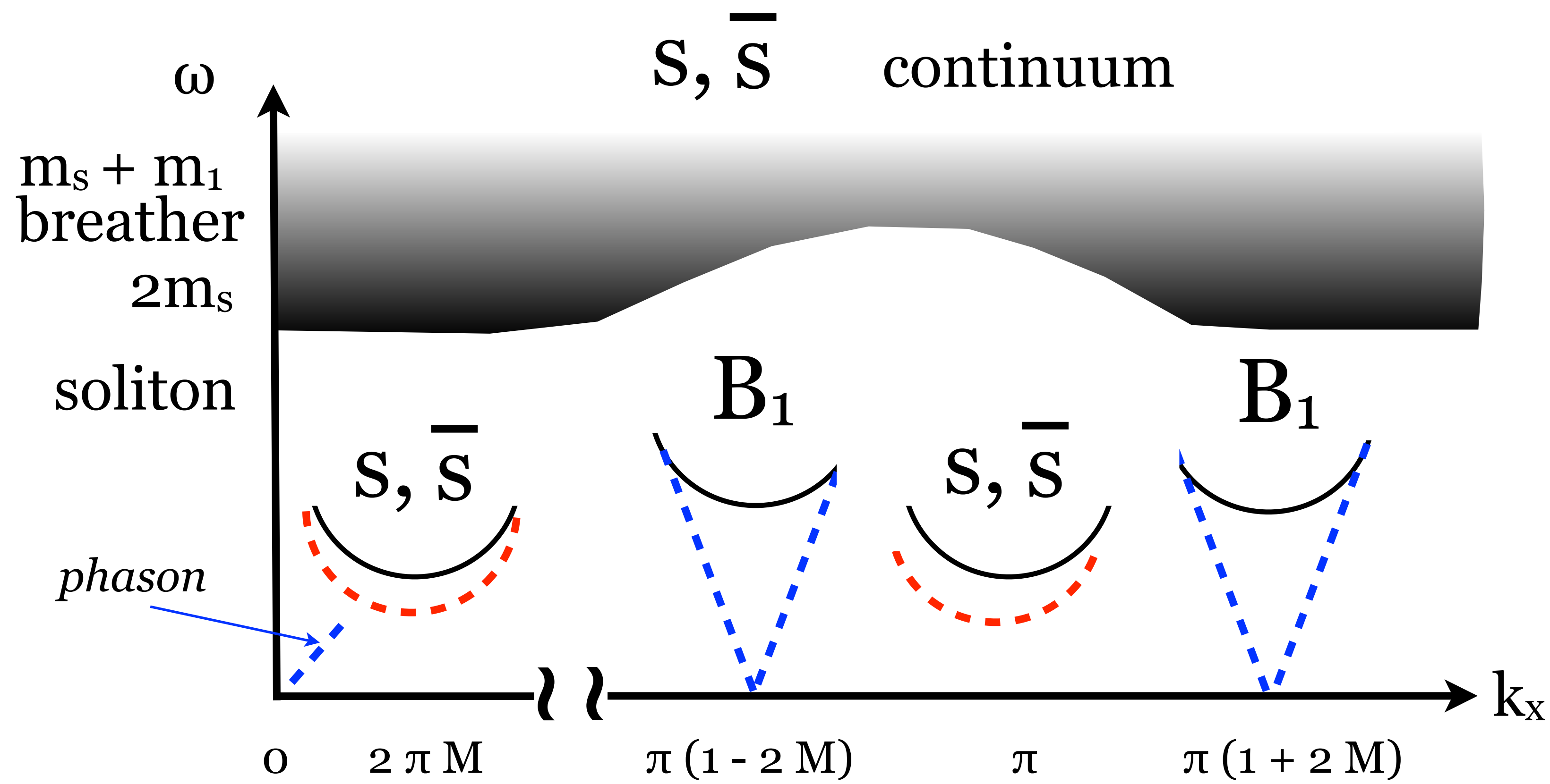
(- sector: solitons of massive sine-Gordon model describing 1d ***zig-zag chain.***) Energy scale J_1

(+ sector: solitons of massive sine-Gordon model which describes 2d ***ordered*** state.) Energy scale $(J')^2/J_1$

$$\mathrm{Im}\chi^{zz}_{2d}(k,\omega) \sim \frac{\rho_0 \epsilon_k}{\omega_B(k)} \delta[\omega - \omega_B(k)]$$

vanishing spectral weight as **k** -> 0 (isotropic) bosonization, sine-Gordon + inter-chain RPA/LG analysis

2d SDW



gapped transverse excitations

vanishing spectral weight as **k_x** -> 0 (anisotropic)

$$\chi^{zz}_{2d}(k_x, k_y, \omega) = \frac{v k_x^2 / \beta^2}{v^2 k_x^2 + v_\perp^2 k_y^2 - \omega^2},$$

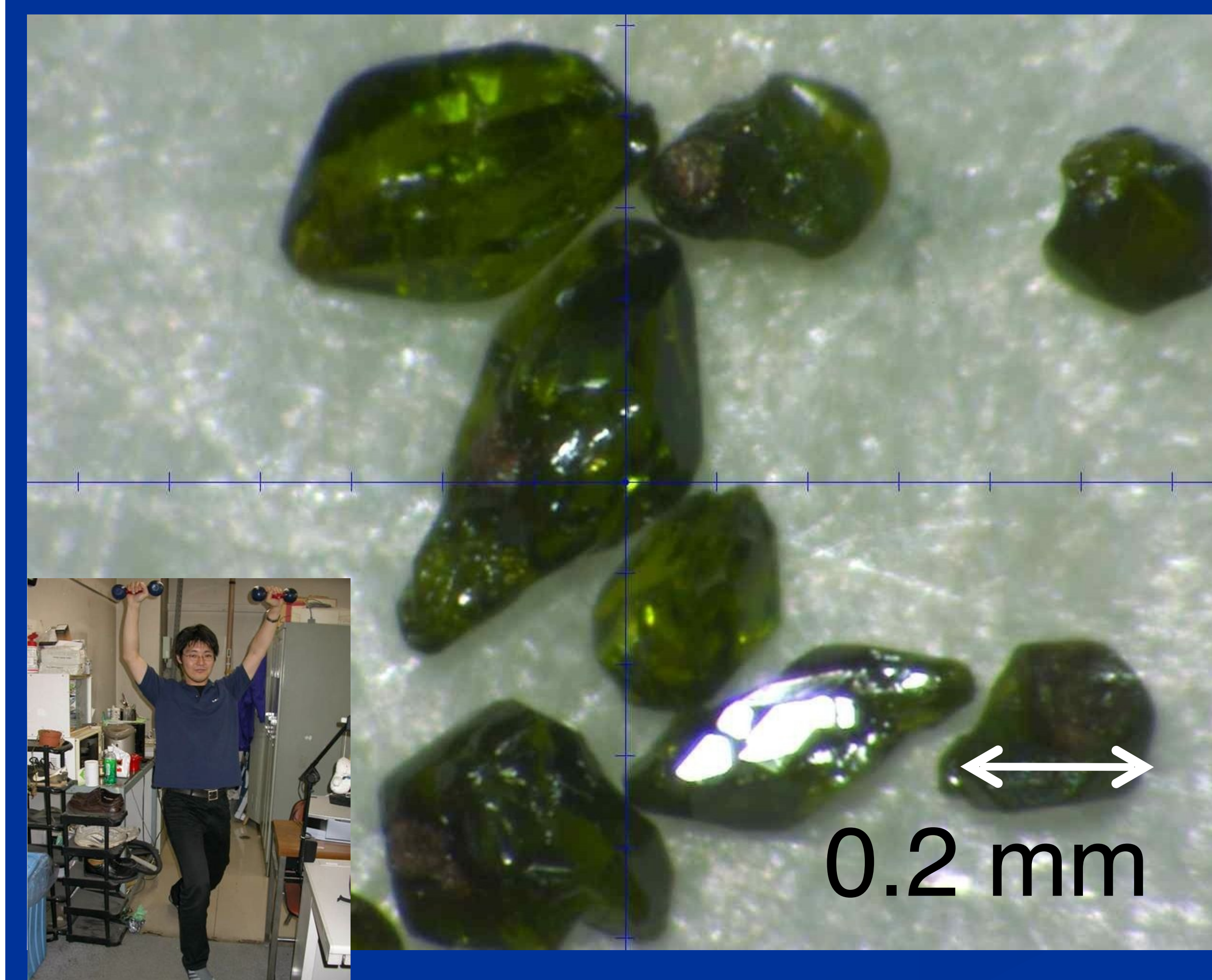
phason (longitudinal)

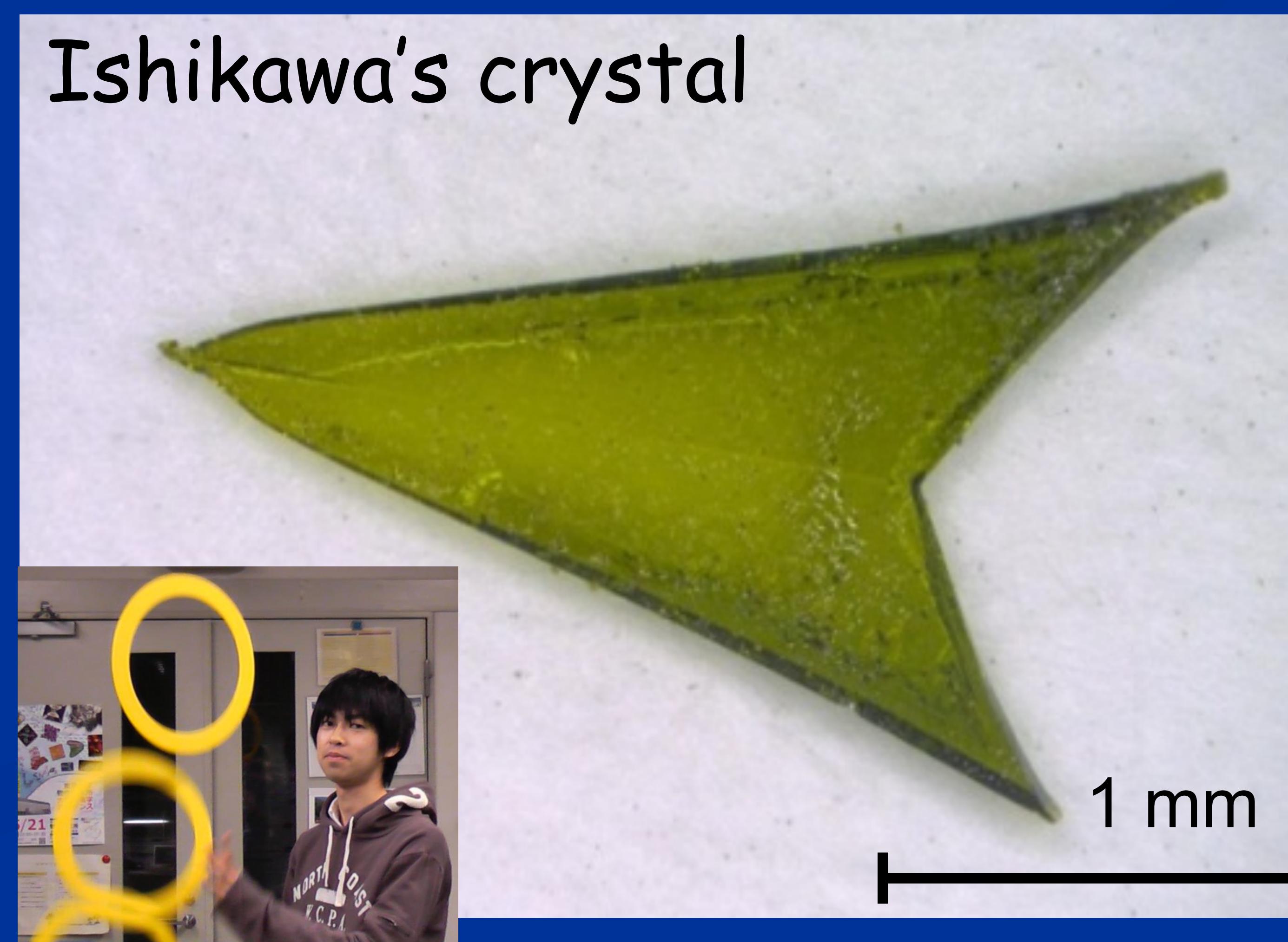
$$\chi^{zz}_{2d}(q, \pi + q_y, \omega) \sim \frac{Z_{zz;2d}}{(v^2 q^2 + v_\perp^2 q_y^2) - \omega^2}$$

Single crystals of volborthite

1. natural leaf crystals, long time ago
2. low-quality polycrystalline samples by precipitation, 2001
3. high-quality polycrystalline samples by hydrothermal annealing, 2009
4. small single crystals, 2012
5. large arrowhead-shaped crystals, 2013

H. Yoshida's crystal

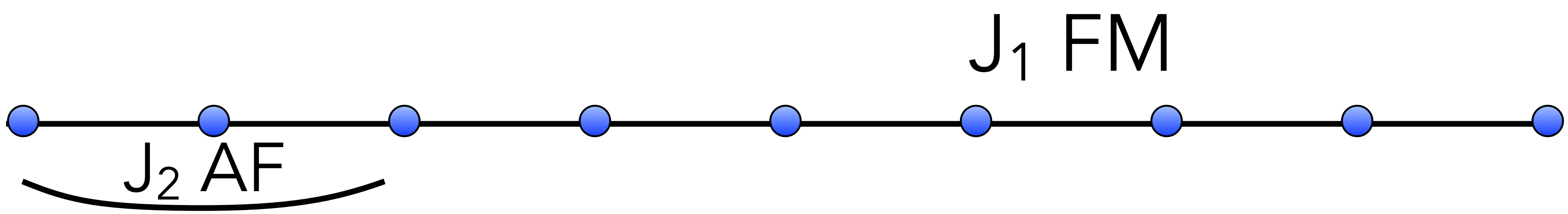




Ishikawa's crystal

Spin nematic redux

Frustrated ferromagnetic chain



$$H = J_1 \sum_i \mathbf{S}_i \cdot \mathbf{S}_{i+1} + J_2 \sum_i \mathbf{S}_i \cdot \mathbf{S}_{i+2} - h \sum_i S_i^z$$