Unusual phases of antiferromagnetic spin chains with uniform Dzyaloshinskii-Moriya interaction

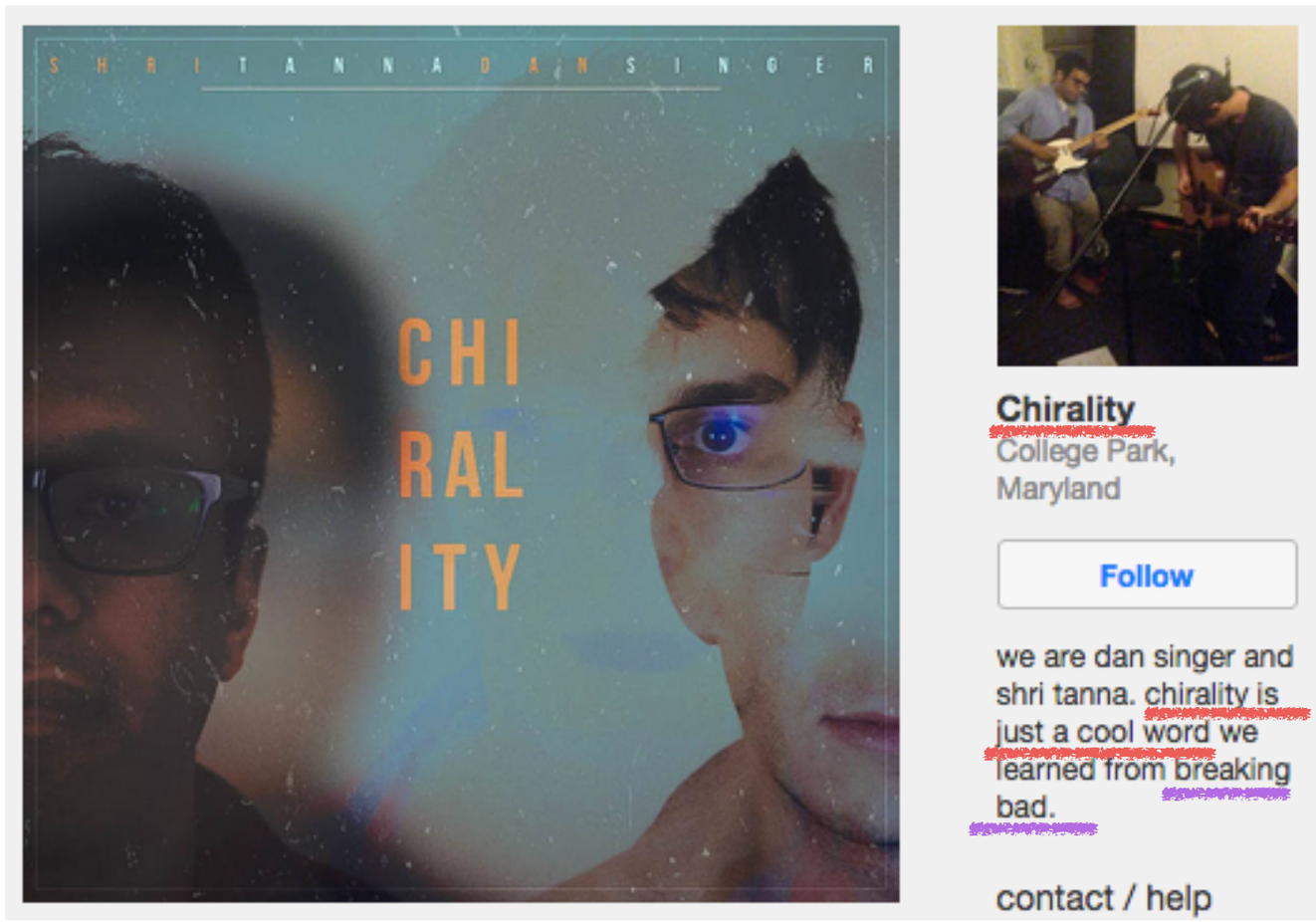
Oleg Starykh, University of Utah



Magnetic Adatoms as Building Blocks for Quantum Magnetism
17th -20th August 2015, SPICE, Mainz

Unusual phases of antiferromagnetic spin chains with uniform Dzyaloshinskii-Moriya interaction

Oleg Starykh, University of Utah



Magnetic Adatoms as Building Blocks for Quantum Magnetism
17th -20th August 2015, SPICE, Mainz

Outline

- Chains with strong Dzyaloshinskii-Moriya interaction (DM)
- J’ (interchain) << D (DM) << J (chain exchange)
- Interesting interplay of DM and magnetic field
- Unusual 2d collinear SDW state
- **Main idea**: *turn annoying material imperfection (DM) into a probe of exotic spin state and its excitations*

Dzyaloshinskii-Moriya (DM) interaction

J. Phys. Chem. Solids Pergamon Press 1958. Vol. 4. pp. 241–255.

A THERMODYNAMIC THEORY OF "WEAK" FERROMAGNETISM OF ANTIFERROMAGNETICS

D

I. DZYALOSHINSKY

Institute for Physical Problems, Academy of Sciences of the U.S.S.R., Moscow

(*Received* 19 *February* 1957)

PHYSICAL REVIEW VOLUME 120, NUMBER 1 OCTOBER 1, 1960

Anisotropic Superexchange Interaction and Weak Ferromagnetism

M

TÔRU MORIYA*

Bell Telephone Laboratories, Murray Hill, New Jersey

(Received May 25, 1960)

$$\mathbf{D}_{ij} \cdot \mathbf{S}_i \times \mathbf{S}_j$$

- often the leading effect of Spin-Orbit (SO) interaction
- reduces symmetry to U(1) [rotations about D axis] at a given bond
- Easy plane anisotropy (perp. to D)
- Promotes magnetic order and (typically) stabilizes incommensurate non-collinear (spiral) states

DM in atomic chains on surfaces

Information Transfer by Vector Spin Chirality in Finite Magnetic Chains

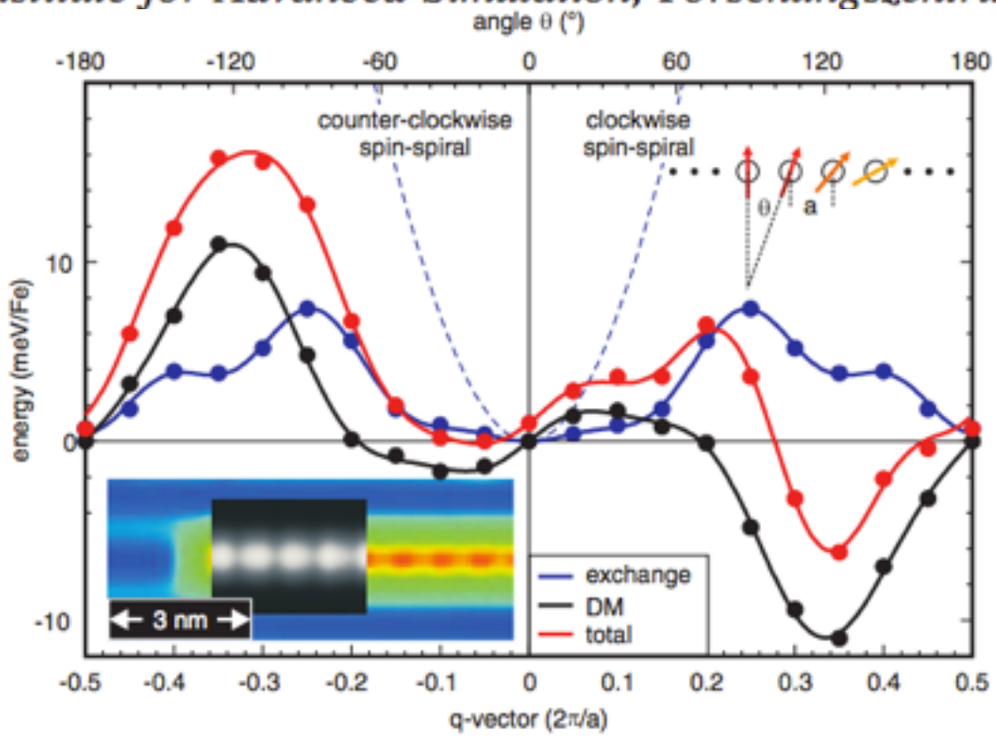
Matthias Menzel,[1] Yuriy Mokrousov,[2] Robert Wieser,[1] Jessica E. Bickel,[1] Elena Vedmedenko,[1] Stefan Blügel,[2]
Stefan Heinze,[3] Kirsten von Bergmann,[1] André Kubetzka,[1] and Roland Wiesendanger[1]

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[2]*Peter Grünberg Institut and Institute for Advanced Simulation, Forschungszentrum Jülich, D-52425 Jülich, Germany*

[3]*Institut für Theoretische Physik* *l, Leibnizstr. 15, 24098 Kiel, Germany*

12)



DM selects vector chirality

FIG. 3 (color). DFT calculations and comparison to experimental findings. Spin-spiral dispersion from first-principles calculations: contributions from Heisenberg exchange (blue dots) and Dzyaloshinskii-Moriya interaction (black dots) and their sum (red dots). The lines represent fits to the calculations with an extended Heisenberg model and the dashed blue line is the Heisenberg exchange dispersion of a freestanding bi-atomic Fe chain. Inset: comparison of a simulated SPSTM image of a 120° spin spiral (gray scale inset; 5 Å above the surface, 50% spin polarization of the tip) with experimental data (color; constant current image, measurement parameters: $U = +300$ mV, $I = 5$ nA, $T = 8$ K).

$K_2CuSO_4Br_4$

s=1/2, highly one-dimensional
chain exchange J = 20 K, inter-chain J’ = 0.03 K
uniform DM interaction D =0.27 K

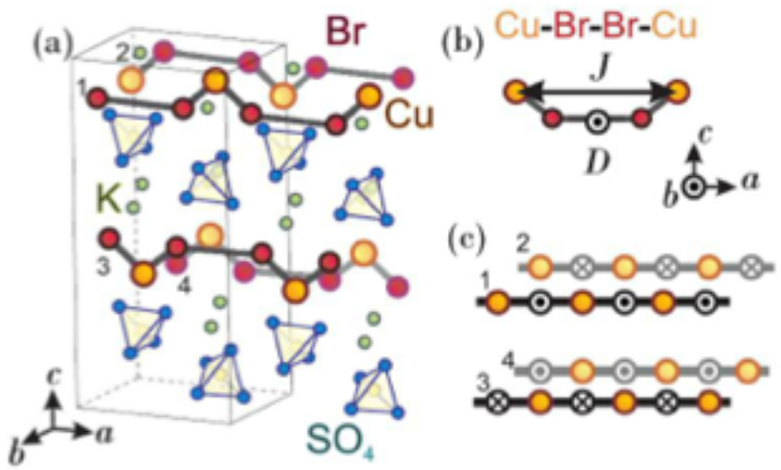


FIG. 1. (Color online) (a) Schematic representation of $K_2CuSO_4Br_2$ crystal structure. (b) Magnetic interactions between the Cu^{2+} ions as given in Hamiltonian (1). Vector **D** presents the symmetry allowed parameter of Dzyaloshinskii–Moriya interaction. (c) Two sets of nonequivalent spin chains with the opposite direction of DM vector.

DM interaction:

– uniform along the chain

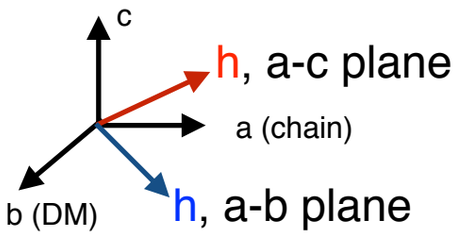
– staggered between chains

- J’ (interchain) << D (DM) << J (chain exchange)

Electron spin resonance in a model $S = 1/2$ chain antiferromagnet with a uniform Dzyaloshinskii–Moriya interaction

A. I. Smirnov,[1] T. A. Soldatov,[1,2] K. Yu. Povarov,[3,*] M. Hälg,[3] W. E. A. Lorenz,[3] and A. Zheludev[3]
[1]*P. L. Kapitza Institute for Physical Problems, RAS, 119334 Moscow, Russia*[†]
[2]*Moscow Institute for Physics and Technology, 141700 Dolgoprudny, Russia*
[3]*Neutron Scattering and Magnetism, Laboratory for Solid State Physics, ETH Zürich, Switzerland*[‡]
(Dated: July 28, 2015)

Data



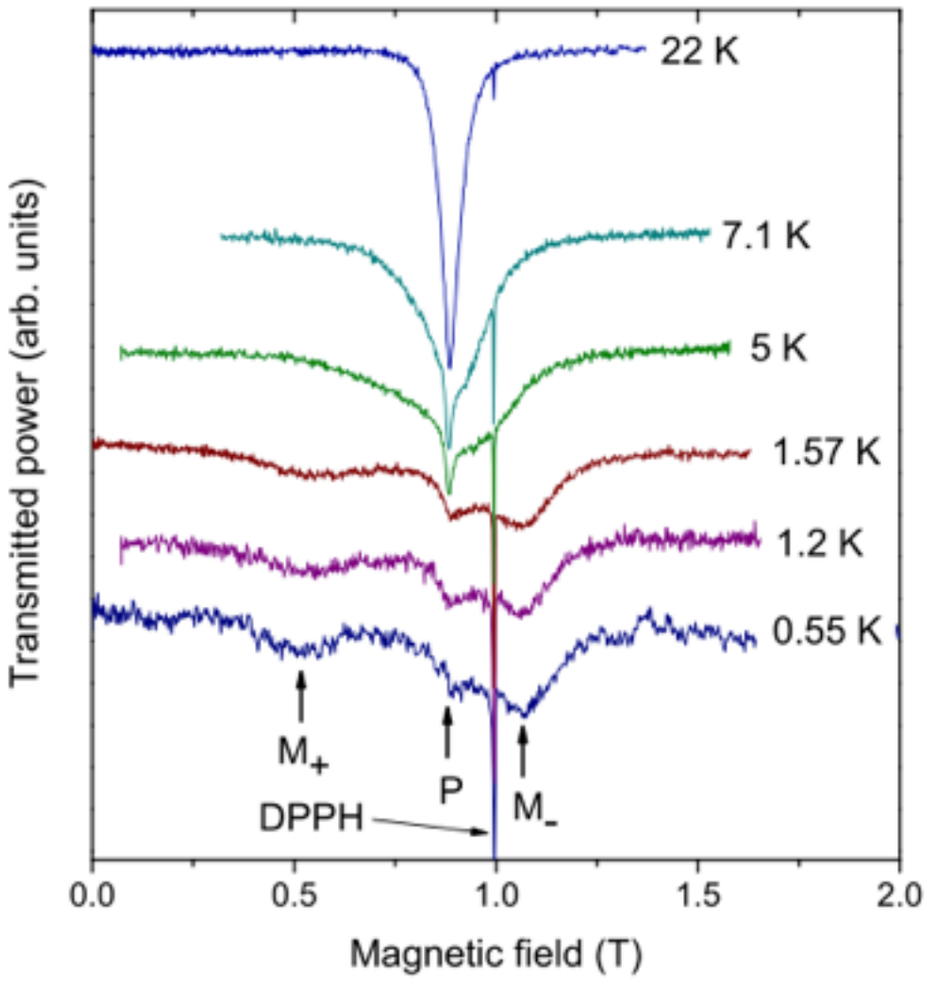


FIG. 2. (Color online) Temperature evolution of the 27.83 GHz ESR line of sample A at $\mathbf{H} \parallel b$. M_+ and M_- label the components of the doublet, P is a paramagnetic line associated with residual defects. A narrow line at 0.994 T is the DPPH label.

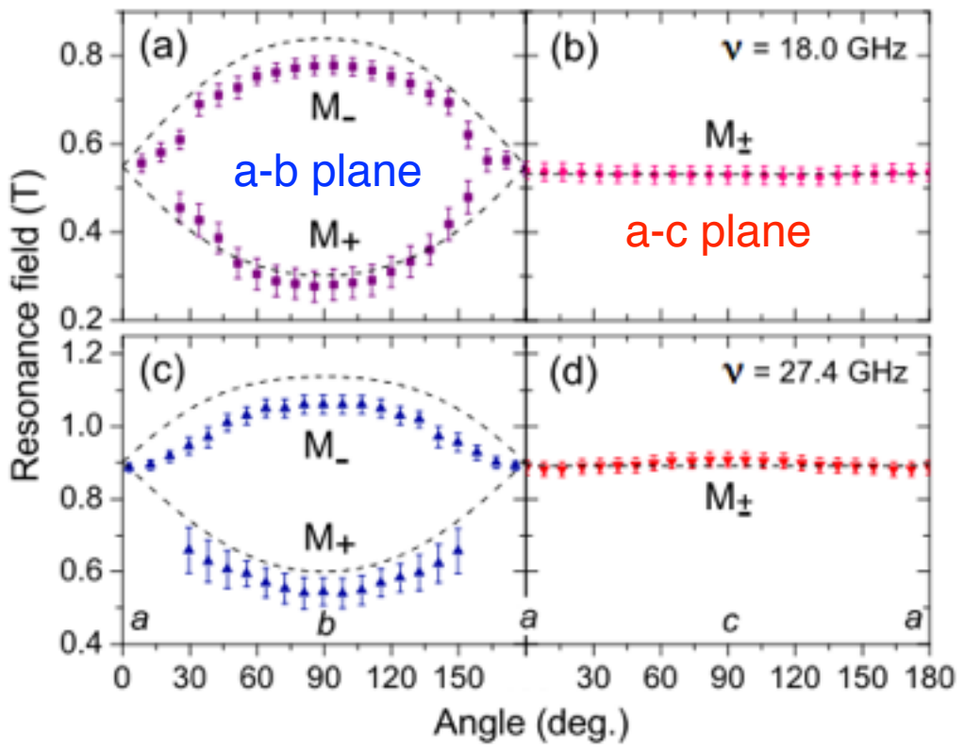


FIG. 7. (Color online) Angular dependencies of the resonant fields at two frequencies for $T = 1.3$ K. 18.0 GHz ESR fields for field in ab plane (upper left panel), and in ac plane (upper right panel). 27.4 GHz ESR fields for field in ab plane (lower left panel), and in ac plane (lower right panel) Dashed lines are theoretical dependencies according (2).

ESR - electron spin resonance

- Simple (in principle) and sensitive probe of magnetic *anisotropies* (and, also, **q=0** probe: $S = \Sigma_r S_r$)

$$I(h,\omega) = \frac{\omega}{4L}\int dt e^{i\omega t}\langle [S^+(t), S^-]\rangle$$

Zeeman **H** along **z**, microwave radiation **h** polarized perpendicular to it.

- Probes excitations at small q
- For the ideal SU(2)-invariant chain in paramagnetic phase $I(H,\omega) \sim \delta(\omega - H)\, m(H)$ [analogue of Kohn's Th] Oshikawa, Affleck PRB 2002

doi:10.1016/0375-9601(81)90335-2 | How to Cite or Link Using DOI
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Spinons in d=1

Bethe's solution: 1933
identification of spinons: 1981

What is the spin of a spin wave?

L. D. Faddeev and L. A. Takhtajan

Leningrad Branch of the Steklov Mathematical Institute, Leningrad, USSR

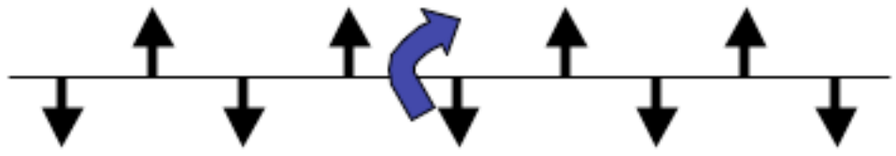
Received 15 July 1981. Available online 16 September 2002.

Abstract

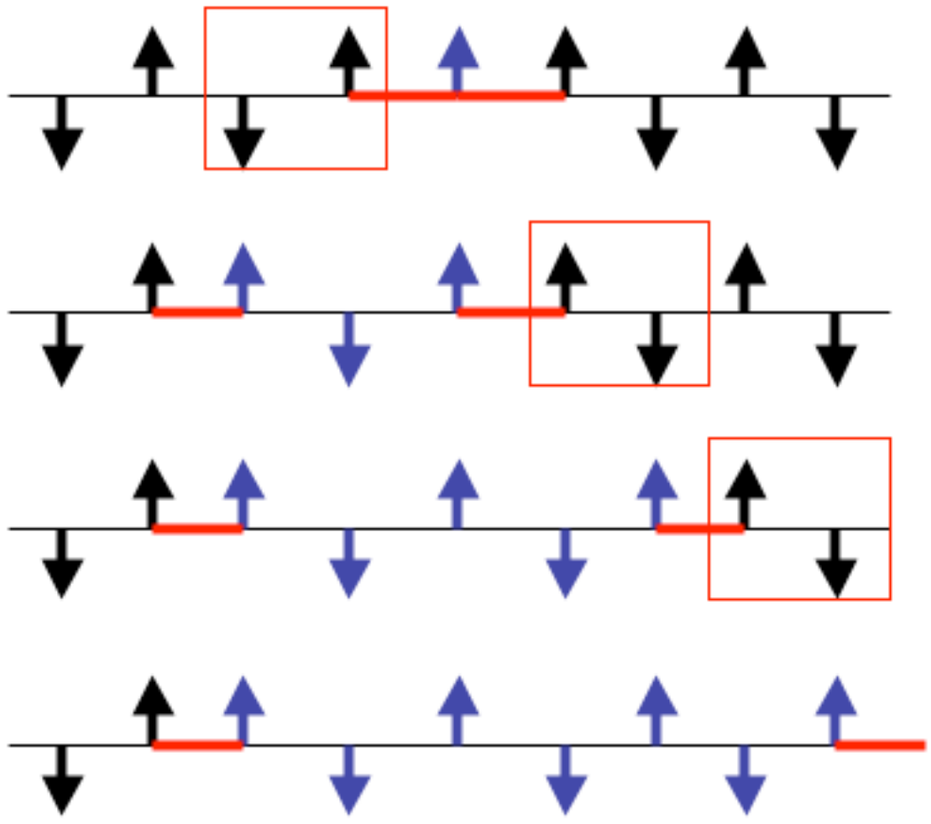
We argue that the spin of a spin wave in the Heisenberg antiferromagnetic chain of spins $\frac{1}{2}$ is equal to $\frac{1}{2}$ rather than 1 as is generally considered to be true.

Article Outline

• References

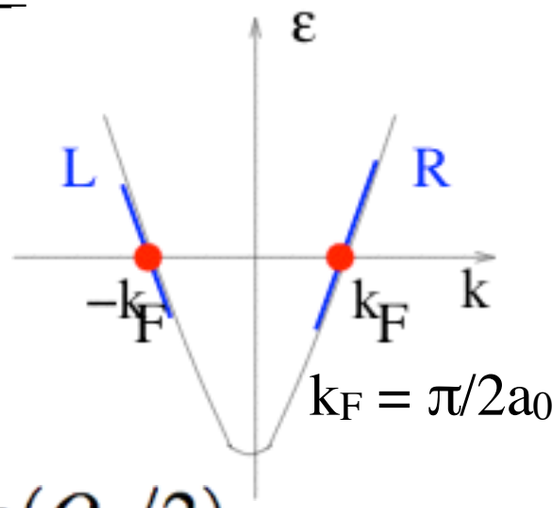


S=1 spin wave breaks into two domain walls / spinons: hence each is carrying S=1/2



Two-spinon continuum of spin-1/2 chain

Spinon energy $\omega(k_x) = \frac{\pi J}{2}|\sin(k_x)|$ de Cloizeaux-Peason dispersion, 1962



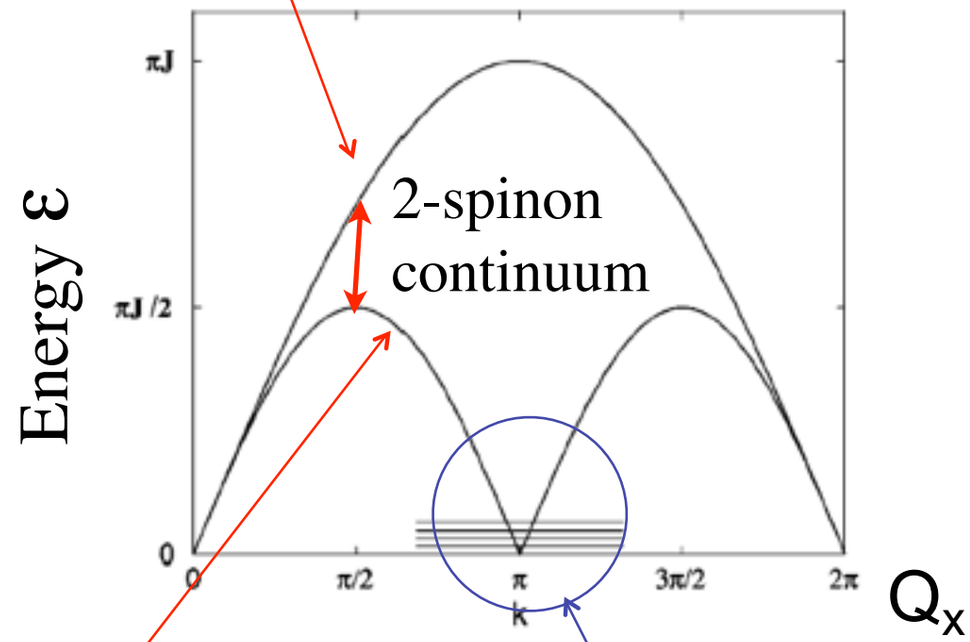
S=1 excitation $\begin{cases} \varepsilon = \omega(k_{x1}) + \omega(k_{x2}) \\ Q_x = k_{x1} + k_{x2} \end{cases}$

$$\varepsilon = \pi J \sin(\frac{Q_x}{2}) \cos(\frac{k_{x1} - k_{x2}}{2})$$

Variables:
k_{x1} and k_{x2}
or
ε and Q_x

$\omega_{2,\text{upper}} = \pi J \sin(Q_x/2)$
$k_{x1} = k_{x2} = Q_x/2$

Upper boundary



Lower boundary

Low-energy sector $Q_{AFM}=\pi$

$$\omega_{2,\text{lower}} = \frac{\pi J}{2}\sin(Q_x)$$
$$k_{x1} = 0, k_{x2} = Q_x$$

Inelastic neutron scattering

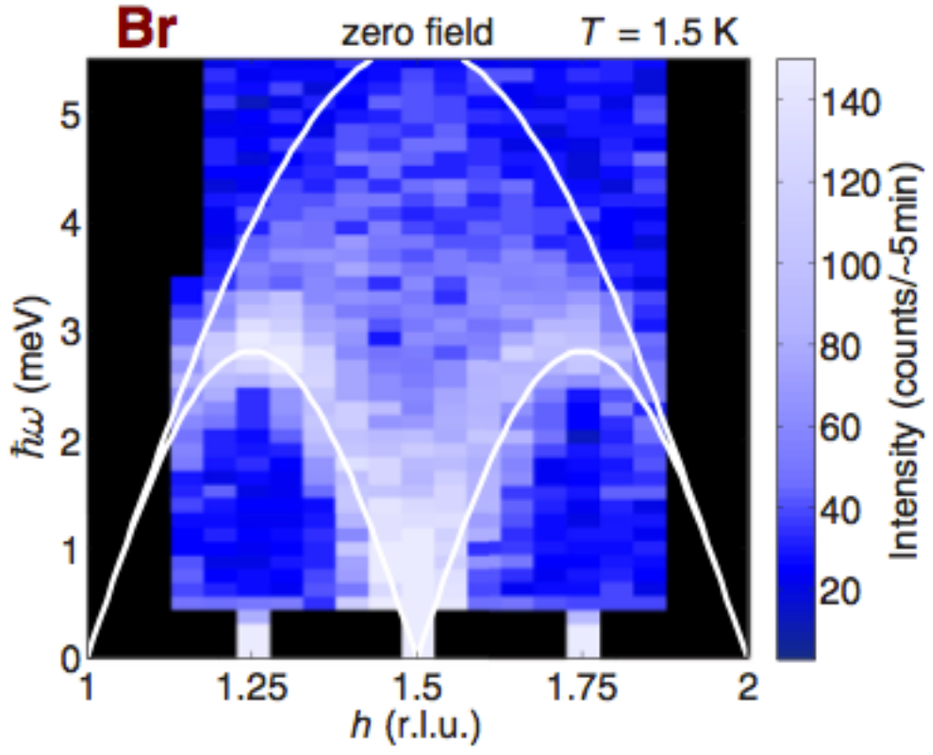


FIG. 7. (Color online) Neutron scattering intensity map of the two-spinon continuum along the a^* axis $[\mathbf{q} = (h,0,0)]$ for $K_2CuSO_4Br_2$ in zero magnetic field. Raw data are shown in Fig. 8. The white line indicates the lower and upper boundary of the continuum following Eqs. (4) and (5) with $J_{\mathrm{Br},a} = 20.7$ K.

PHYSICAL REVIEW B **90**, 174413 (2014)

Quantum spin chains with frustration due to Dzyaloshinskii-Moriya interactions

M. Hälg,[1,*] W. E. A. Lorenz,[1] K. Yu. Povarov,[1,2] M. Månsson,[1,3] Y. Skourski,[4] and A. Zheludev[1]

[1]*Neutron Scattering and Magnetism, Laboratory for Solid State Physics, ETH Zürich, CH-8093 Zürich, Switzerland*

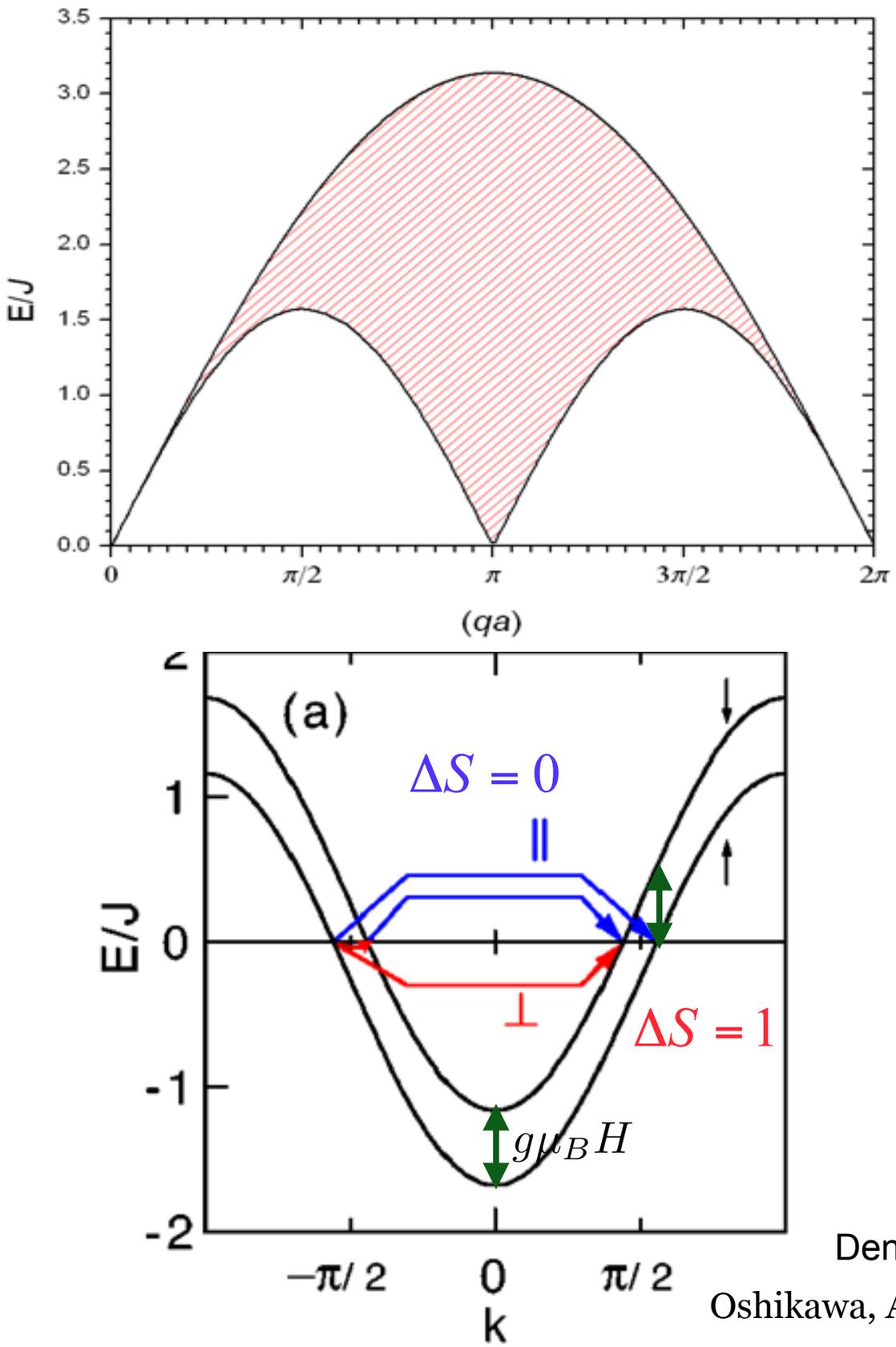
[2]*P. L. Kapitza Institute for Physical Problems, RAS, 119334 Moscow, Russia*

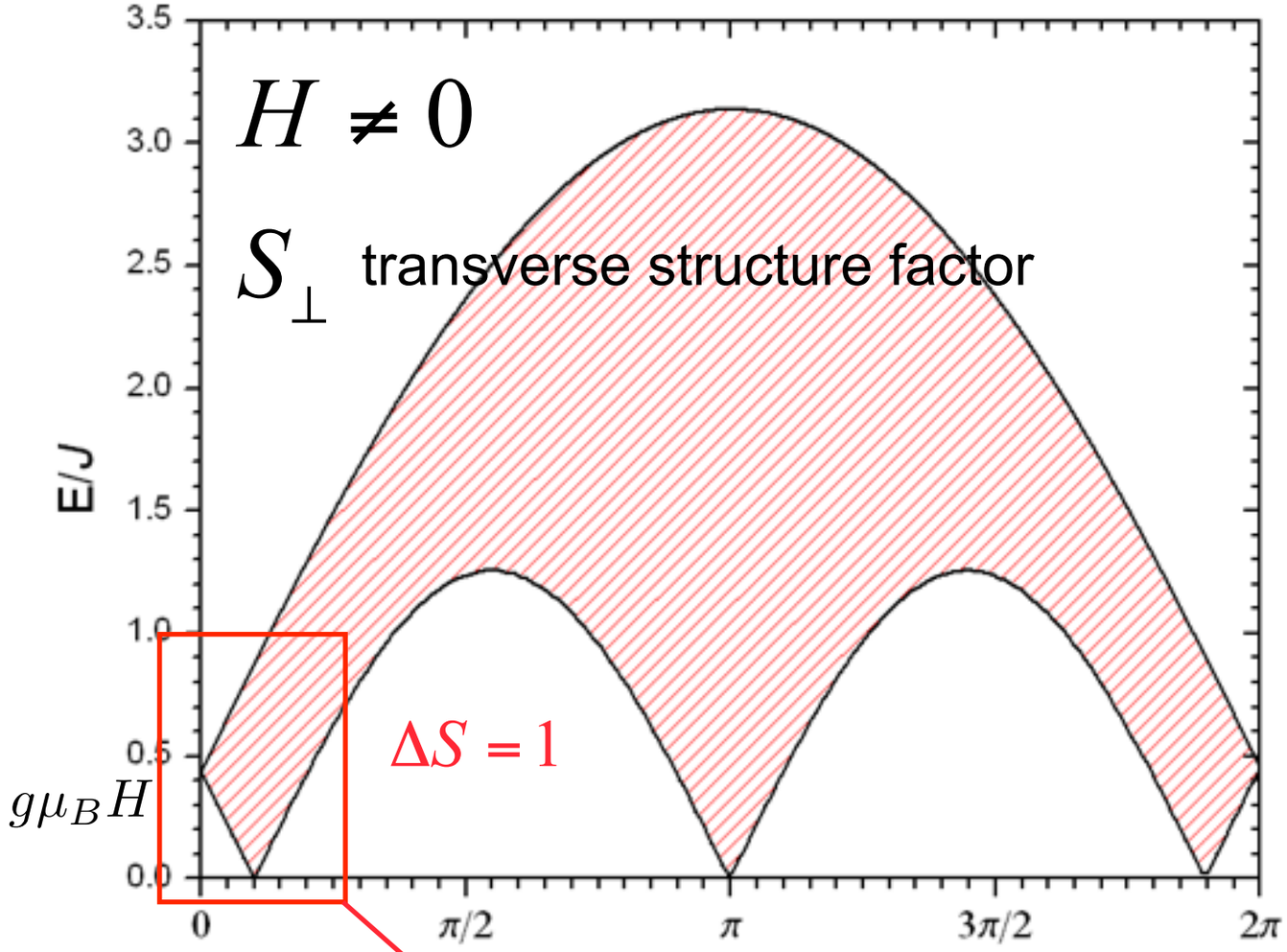
[3]*Laboratory for Neutron Scattering and Imaging, Paul Scherrer Insitut, CH-5232 Villigen, Switzerland*

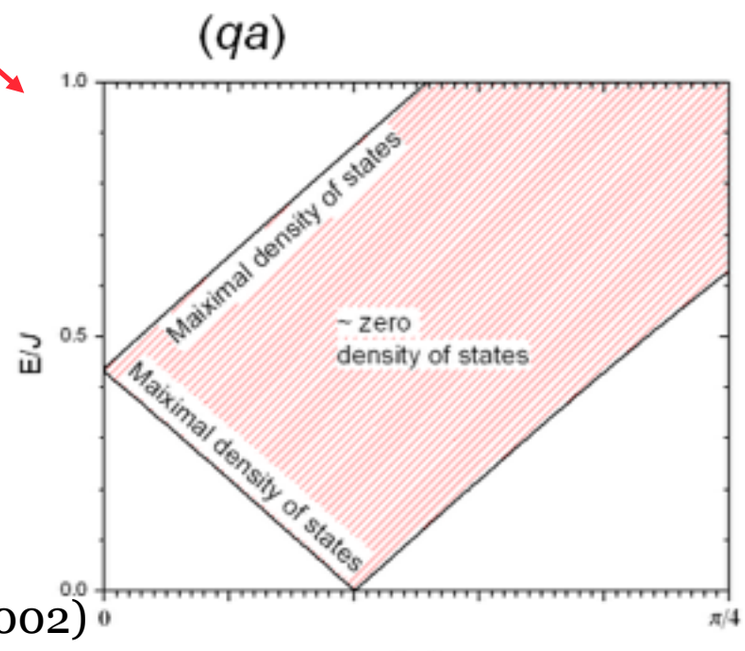
[4]*Hochfeld-Magnetlabor Dresden, Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden, Germany*

(Received 25 August 2014; revised manuscript received 22 October 2014; published 12 November 2014)

Spinon continuum in magnetic field







Dender et al, PRL 1997

Oshikawa, Affleck, PRB **65** 134410 (2002)

Explanation I: H along DM axis

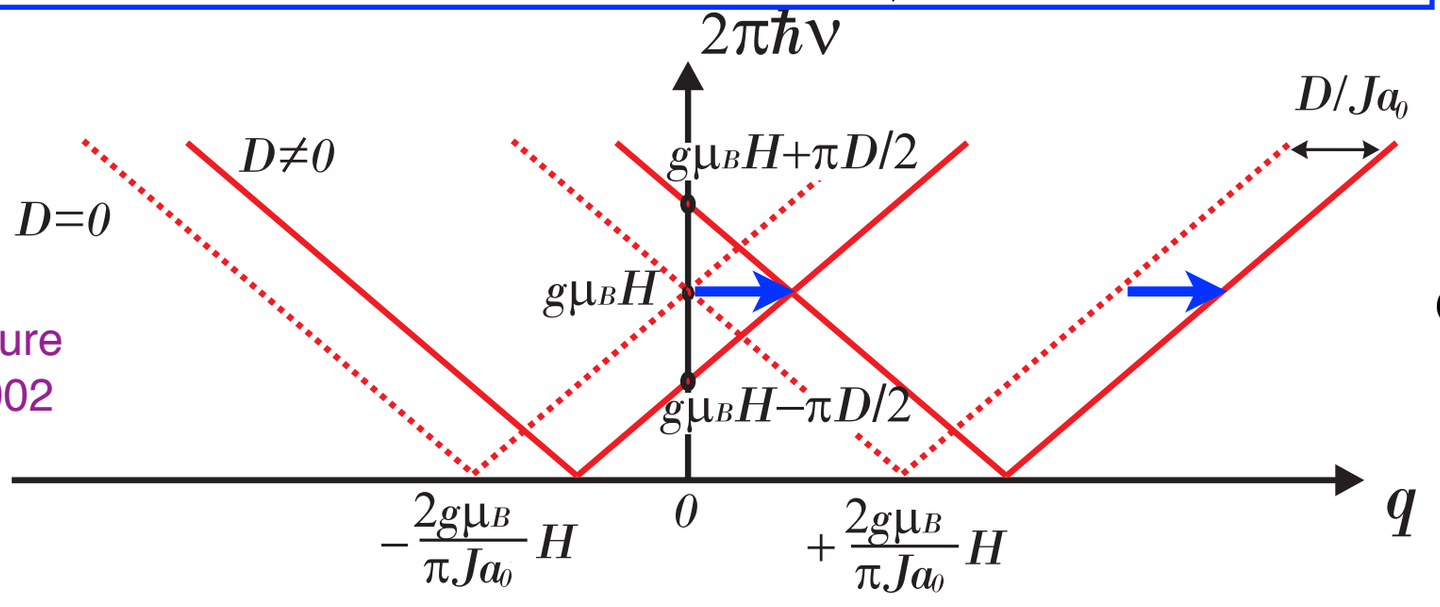
$$H = \sum_{x,y,z} \boxed{JS_{x,y,z} \cdot S_{x+1,y,z}} - \boxed{D_{y,z} \cdot S_{x,y,z} \times S_{x+1,y,z}} - g\mu_B H \cdot S_{x,y,z}$$

chain — uniform DM along the chain — magnetic field

Unitary rotation about **z**-axis $S^+(x) \rightarrow S^+(x)e^{i(D/J)x}, S^z(x) \rightarrow S^z(x)$

- removes DM term from the Hamiltonian (to D^2 accuracy)
- ***boosts*** momentum to $D/(J\,a_0)$

$$q = 0 \rightarrow q = D/(Ja_0) \Rightarrow 2\pi\hbar\nu_{R/L} = g\mu_B H \pm \pi D/2$$



dotted lines: D=0 picture
Oshikawa, Affleck 2002

rotated basis: q=0
original basis: q=D/J

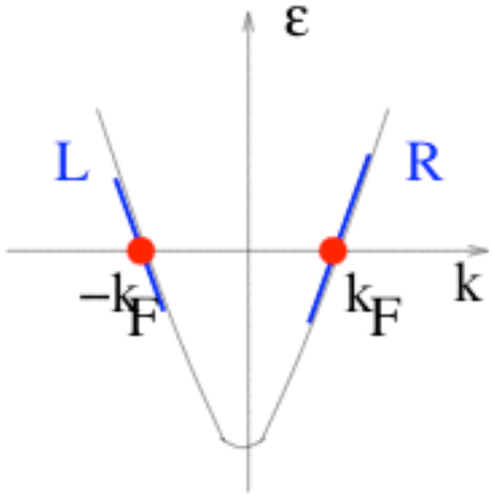
Chiral probe: **ESR probes *right*- and *left*-moving modes (spinons) independently**

Explanation II: arbitrary orientation

Relevant spin degrees of freedom

- Spin-1/2 AFM chain = half-filled (1 electron per site, $k_F=\pi/2a$) fermion chain

$$H_{\text{dirac}} = iv \int dx \sum_{s=\uparrow,\downarrow} (\Psi^+_{L,s}\partial_x\Psi_{L,s} - \Psi^+_{R,s}\partial_x\Psi_{R,s})$$



- *q=0 fluctuations: right (R) and left (L) spin currents*

$$\vec{M}_{R/L} = \Psi^\dagger_{R/L,s} \frac{\vec{\sigma}_{ss'}}{2} \Psi_{R/L,s'}$$

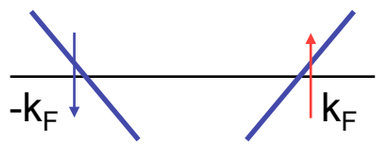
- *$2k_F$ (= π/a) fluctuations: charge density wave ε , spin density wave N*

Susceptibility

Staggered Magnetization N

$$\begin{cases} N^+ \sim \Psi^+_{R\uparrow}\Psi_{L\downarrow} + \text{h.c.} \\ N^z \sim \Psi^+_{R\uparrow}\Psi_{L\uparrow} - \Psi^+_{R\downarrow}\Psi_{L\downarrow} + \text{h.c.} \end{cases}$$

Spin flip ΔS=1



1/q

1/q

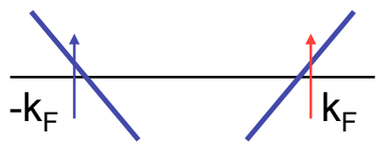
$$\chi_{1d}(q)$$

Staggered Dimerization

$\mathcal{E} = (-1)^x S_x S_{x+a}$

$$\varepsilon \sim i\left(\Psi^\dagger_{R\uparrow}\Psi_{L\uparrow} + \Psi^\dagger_{R\downarrow}\Psi_{L\downarrow} - \text{h.c.}\right)$$

ΔS=0



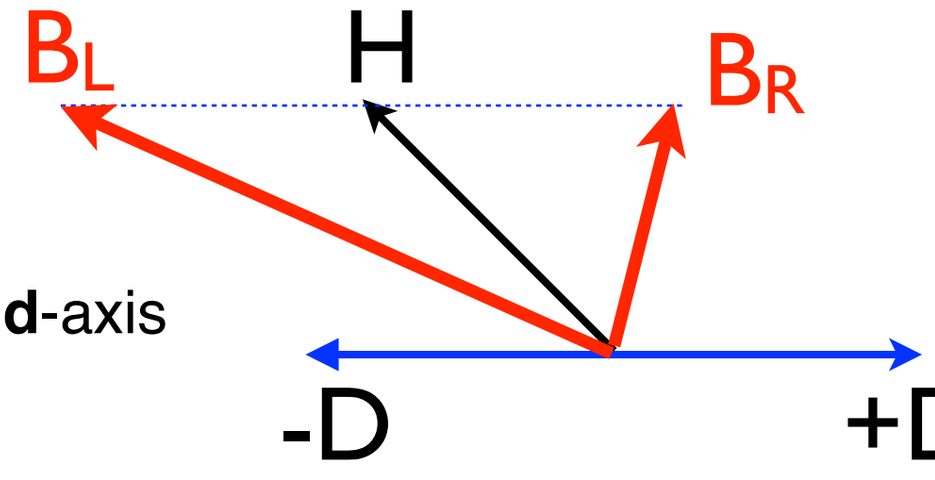
1/q

- Must be careful: **often** spin-charge separation must be enforced by hand

Explanation II: arbitrary orientation

$$H = \boxed{\frac{2\pi v}{3}[(\vec{M}_R)^2 + (\vec{M}_L)^2]} \quad \boxed{-\frac{vD}{J}[M_R^d - M_L^d]} \quad -g\mu_B H[M_R^z + M_L^z]$$

unperturbed chain — uniform DM along the chain — magnetic field

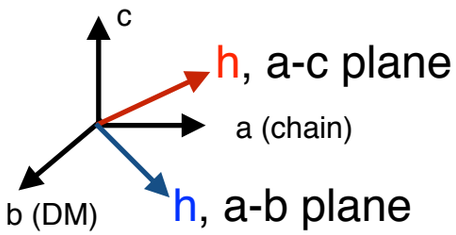


Uniform DM produces internal
momentum-dependent magnetic field along **d**-axis

- Total field acting on right/left movers $g\mu_B\vec{H} \pm \hbar v\vec{D}/J$
- Hence ESR signals at $2\pi\hbar\nu_{R/L} = |g\mu_B\vec{H} \pm \hbar v\vec{D}/J|$
- Polarization: for H=0 maximal absorption when microwave field h_{mw} is perpendicular to the internal (DM) one.

Gangadharaiah, Sun, OS, PRB 2008
Povarov et al, PRL 2011
Karimi, Affleck 2011
Smirnov et al 2015

Data



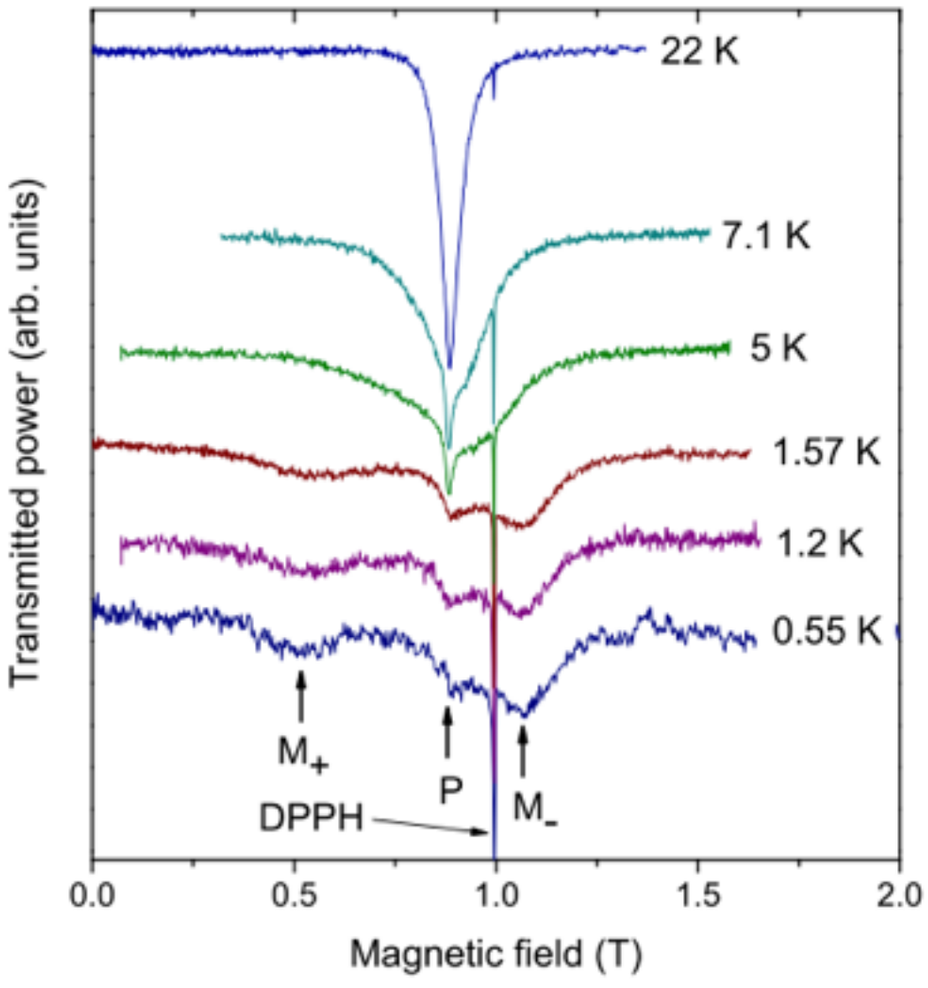


FIG. 2. (Color online) Temperature evolution of the 27.83 GHz ESR line of sample A at $\mathbf{H} \parallel b$. M_+ and M_- label the components of the doublet, P is a paramagnetic line associated with residual defects. A narrow line at 0.994 T is the DPPH label.

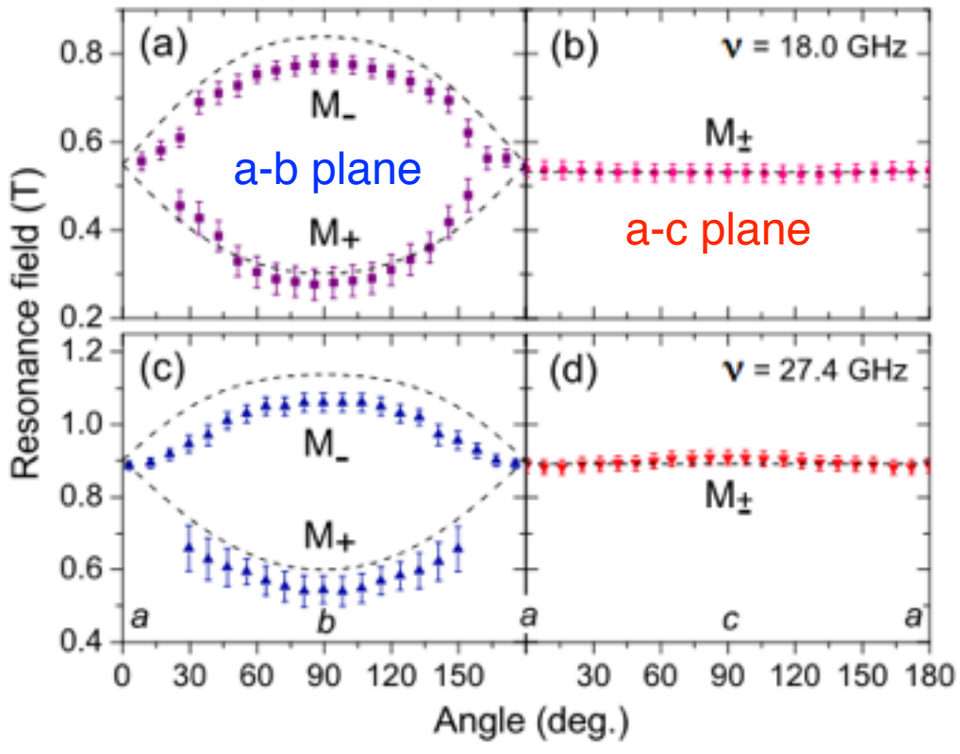


FIG. 7. (Color online) Angular dependencies of the resonant fields at two frequencies for $T = 1.3$ K. 18.0 GHz ESR fields for field in ab plane (upper left panel), and in ac plane (upper right panel). 27.4 GHz ESR fields for field in ab plane (lower left panel), and in ac plane (lower right panel) Dashed lines are theoretical dependencies according (2).

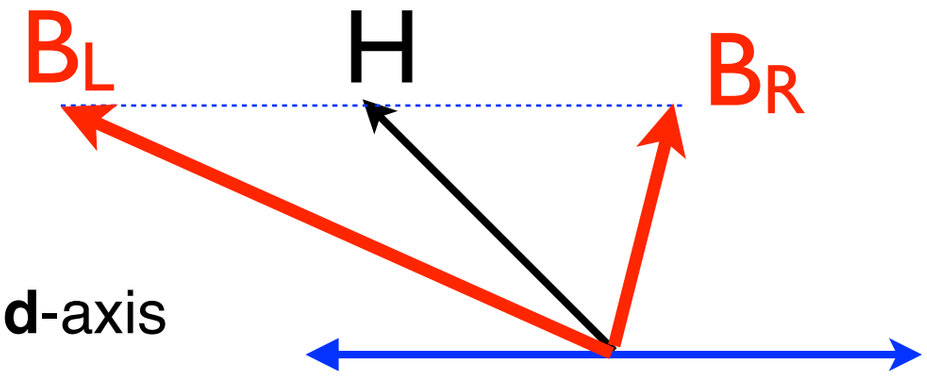
Allows for direct determination of D=0.27 K.

Similar to previous study of Cs2CuCl4 (Povarov et al 2010) but without any additional assumptions.

Lineshape?

$$H_0 = \boxed{\frac{2\pi v}{3}[(\vec{M}_R)^2 + (\vec{M}_L)^2]} \quad \boxed{-\frac{vD}{J}[M_R^d - M_L^d]} \quad -g\mu_B H[M_R^z + M_L^z]$$

unperturbed chain | uniform DM along the chain | magnetic field



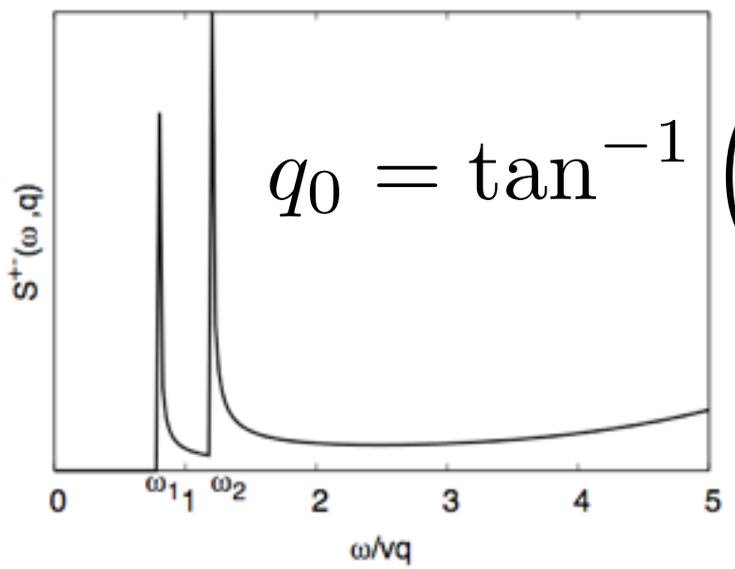
- Uniform DM produces internal momentum-dependent magnetic field along **d**-axis

- Interaction between spinons

$$H_{\rm int} = -g_{\rm bs}\{M_R^x M_L^x + M_R^y M_L^y + (1+\lambda_{\rm DM}) M_R^z M_L^z\}$$

easy-plane anisotropy $\lambda_{\rm DM} \sim (D/J)^2$

$$q_0 = \tan^{-1}\left(\frac{D}{J}\right)$$



Garate, Affleck 2010
Karimi, Affleck 2011
Imambekov, Glazman 2008

Hard problem !
wide range of behaviors is possible

Interchain interactions

$$J' \ll D \ll J$$

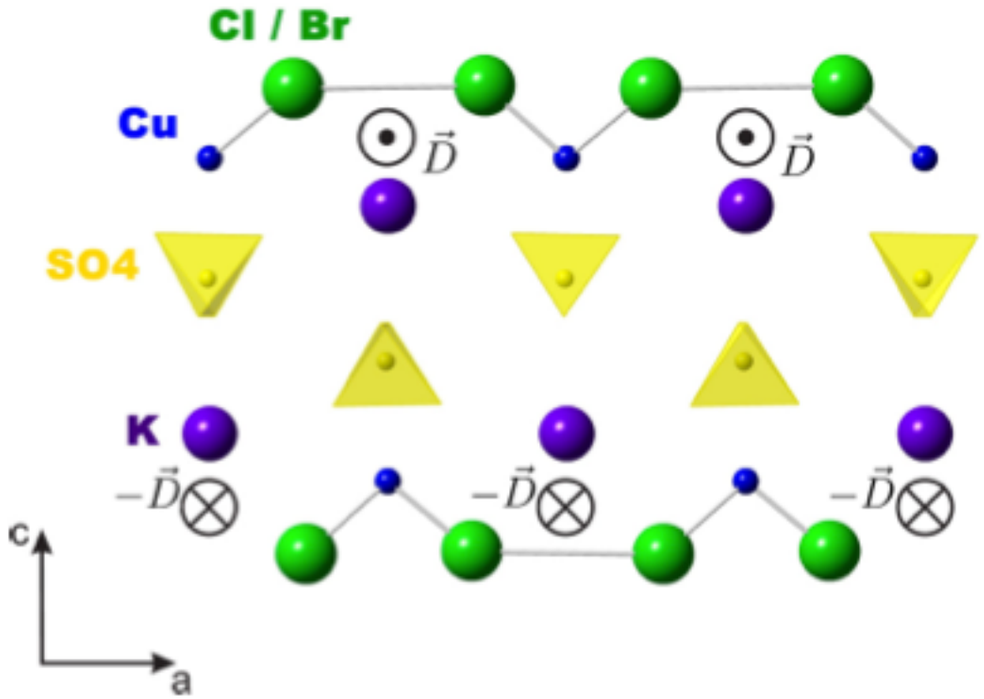


FIG. 9. (Color online) The antisymmetric contribution **D** to J_a points along the *b* axis, is uniform along the chain, and antiparallel in adjacent chains.

DM interaction:

– uniform along given chain

– staggered between chains

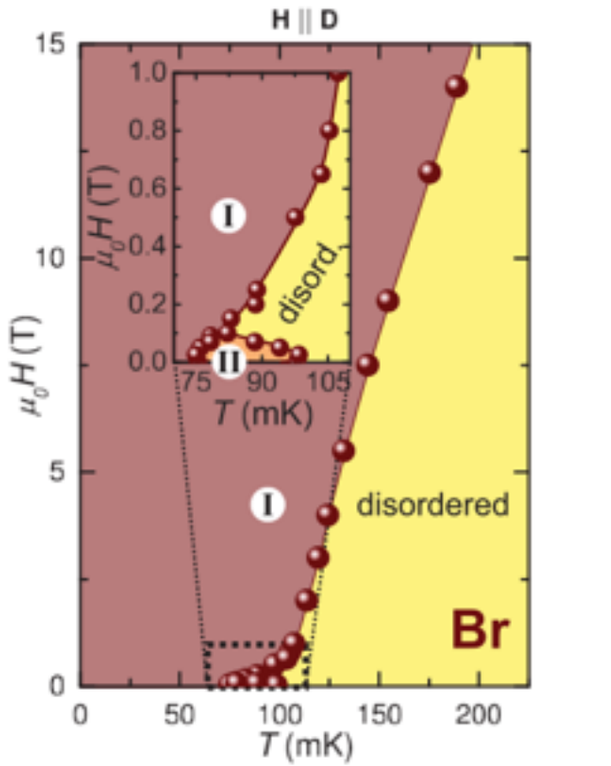


FIG. 12. (Color online) Magnetic phase diagram of $K_2CuSO_4Br_2$ for a magnetic field applied along the *b* axis, parallel to the DM vector. The highlighted regions are guides to the eye, denoting different phases. The inset shows the low-field phase (phase II) observed in $K_2CuSO_4Br_2$ only. Phases I and II are interpreted as two distinct magnetically ordered phases.

Interchain interactions

$$H_0 = \frac{2\pi v}{3}\{\vec{M}_R \cdot \vec{M}_R + \vec{M}_L \cdot \vec{M}_L\} - \vec{h} \cdot (\vec{M}_R + \vec{M}_L) + \vec{D} \cdot (\vec{M}_R - \vec{M}_L)$$

$$H_{\rm int} = -g_{\rm bs}\{M_R^x M_L^x + M_R^y M_L^y + (1+\lambda_{\rm DM}) M_R^z M_L^z\}$$

$$H'_{\rm interchain} = J' \sum_y \vec{N}_y \cdot \vec{N}_{y+1}$$

$(-1)^y$

Chiral rotation of $\boldsymbol{M_{R/L}}$*, followed by rotation of* $\boldsymbol{N}$*, abelian bosonization, RG of all couplings…*

Garate, Affleck 2010
Wen Jin, Starykh 2015

Intuitive picture:

DM is **staggered between chains**, forces spins in adjacent chains to **rotate in opposite directions** (but in the same spin (xy) plane). Hence interchain interaction is strongly **frustrated for the x/y spin** components, but remains **intact for the z** components. Hence expect **2d collinear SDW state** ordered along the field (and, DM) axis.

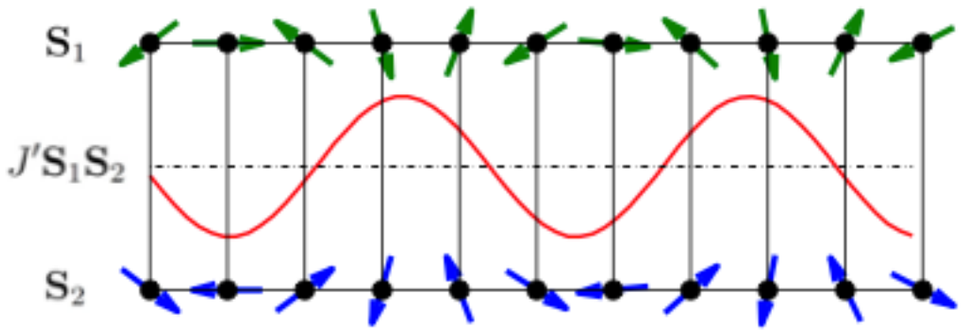
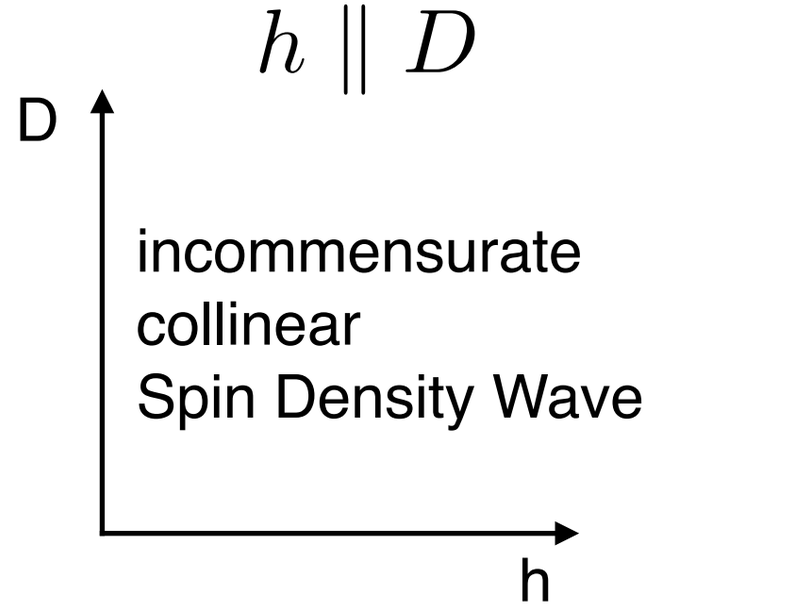
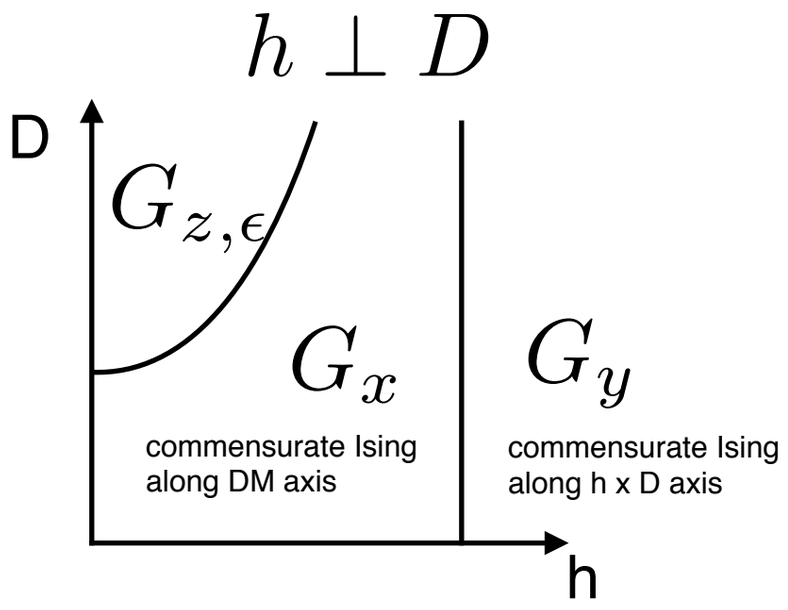


Illustration of frustration caused by DM interactions along the chain with interchain interactions J' for spin components perpendicular to $\mathbf{D}$. As $\mathbf{D}$ is antiparallel in nearest-neighbor chains, these exhibit helical correlations with opposing helicity. The effective interchain coupling $J' \sum_i \mathbf{S}_{1,i} \cdot \mathbf{S}_{2,i}$ vanishes for transverse spin components.

Interchain interactions

RG supports this intuition.

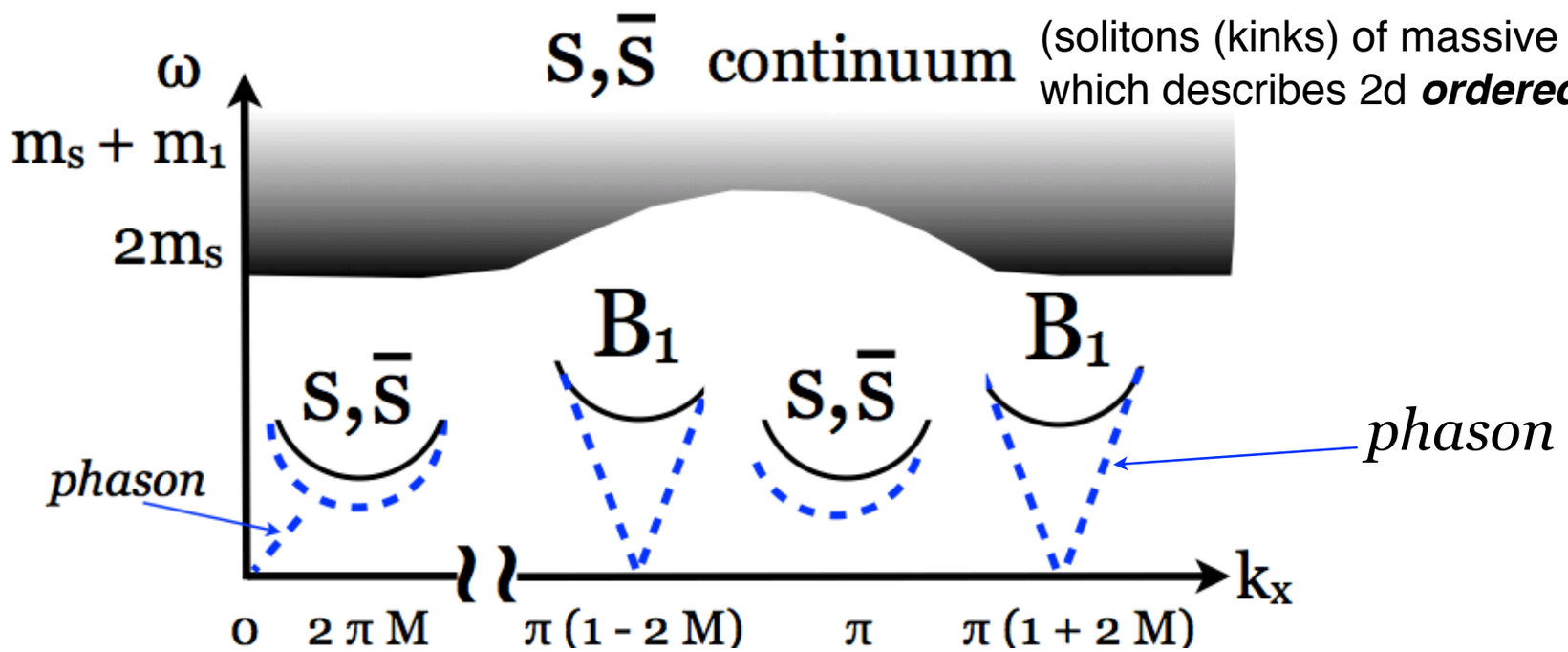




Incommensurate Collinear SDW

(more typical for metals, not insulators)

- 2d SDW $\langle S^z(\mathbf{r})\rangle = M + \mathrm{Re}\left(\Phi e^{i\mathbf{k}_{\mathrm{sdw}}\cdot\mathbf{r}}\right)$
- preserves U(1) [with respect to magnetic field and DM] -> hence NO transverse spin waves
- breaks translational symmetry -> longitudinal phason mode at $k_{sdw} = \pi(1\text{-}2M)$ and k=0



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

OS, Balents PRB 2014

Conclusions

- DM leads to interesting novel physics
- ESR is a chiral probe of critical spinons (neutral fermions)
  - measurements at small momentum ~ D/J
  - allows to extract parameters of DM (spin-orbit) interaction
- Higher-dimensional extension: alternating (between chains) DM opens way to collinear SDW phase [ordered, but *without* spin waves]