Spinon magnetic resonance

Oleg Starykh, University of Utah

Topological phases of matter [TOPMAT]: from the quantum Hall effect to spin liquids

June 11, 2018

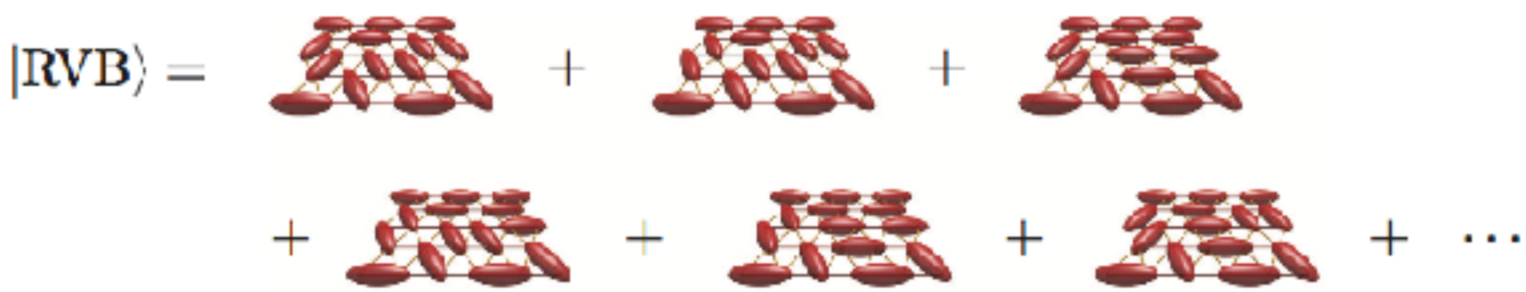
11 Jun-6 Jul 2018 Saclay (France)

My other projects I'd be glad to discuss at the workshop

- Topological phase of repulsively interacting quantum wire with SO coupling
- Weakly coupled critical SU(3) chains [bilinear-biquadratic spin S=1 chains]
- Chiral liquid in spin-1 XXZ model on triangular lattice/M=1/3 magnetization plateau

The big question(s)

What is quantum spin liquid?



No broken symmetries.
Quantum entangled state:
fractionalized excitations = spinons
emergent gauge fields

Figure 1. A 'resonating valence bond' (RVB) state. Ellipsoids indicate spin-zero singlet states of two $S = 1/2$ spins.

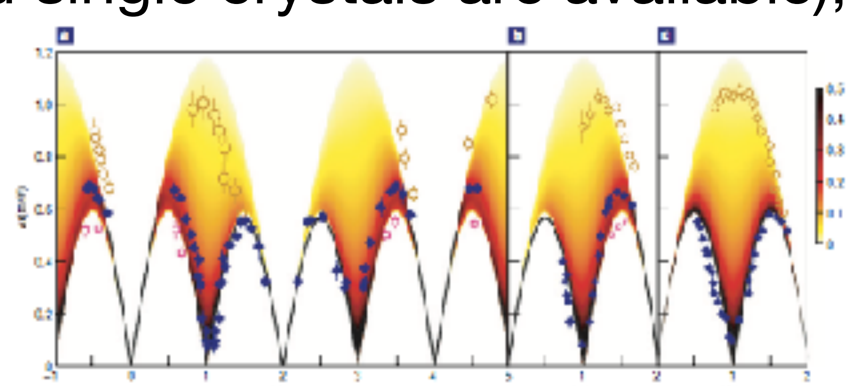
Savary, Balents 2017

Which materials realize it?

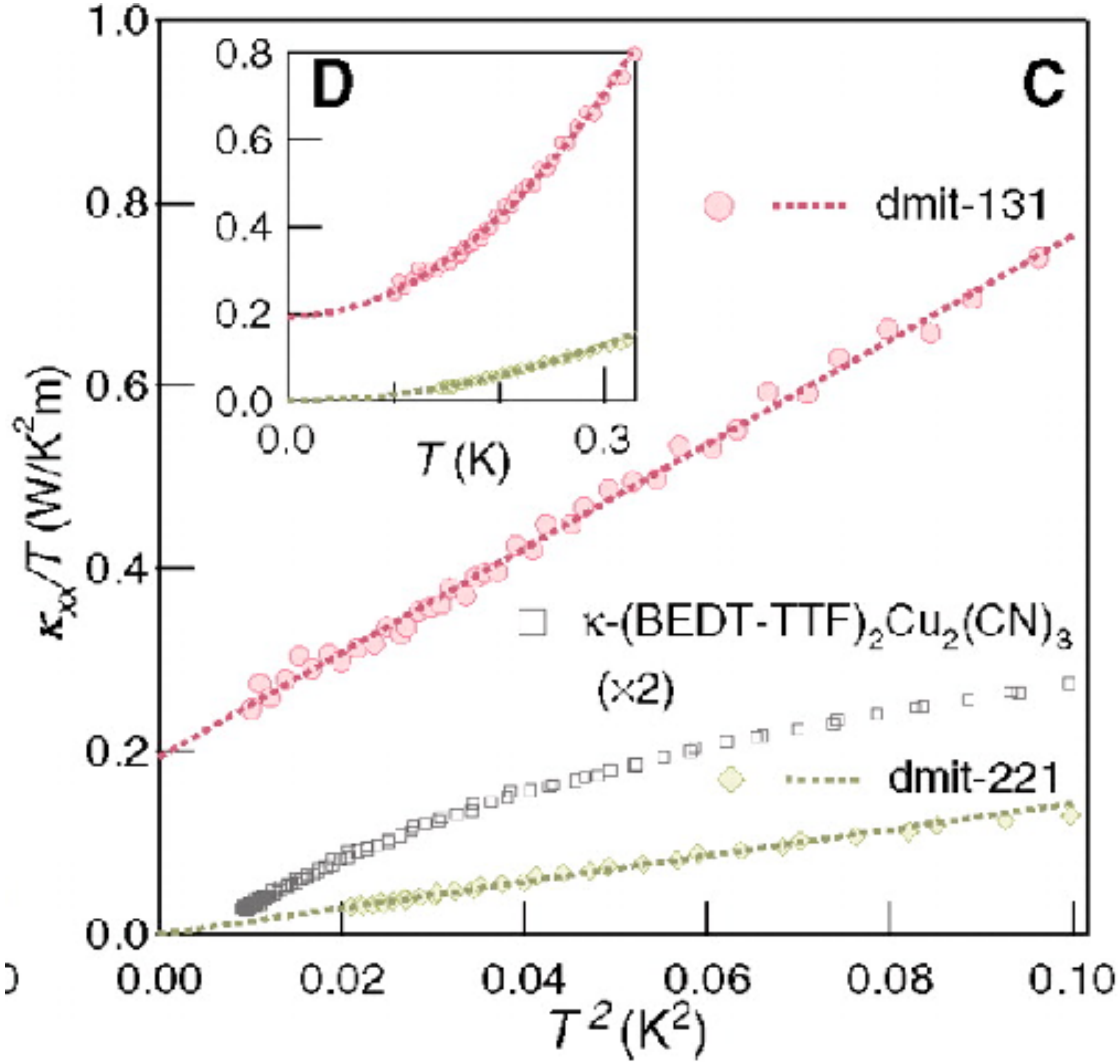
Past candidates: Cs2CuCl4, kagome volborthite…
Current candidates: kagome herbertsmithite, α-RuCl3, organic Mott insulators

How to detect/observe it?

Neutrons (if good single crystals are available), NMR, ESR



Organic Mott insulators: Spin liquid with spinon Fermi surface?



$EtMe_3Sb[Pd(dmit)_2]_2$ (dmit-131)

Spin liquid?

M. Yamashita et al, Science 2010

$Et_2Me_2Sb[Pd(dmit)_2]_2$ (dmit-221)

Non-magnetic charge-ordered

theory: O. Motrunich 2005, S.-S. Lee and P. A. Lee 2005

electrical insulator,
but metal-like thermal conductor

α-RuCl3: quantized thermal Hall

Majorana quantization and half-integer thermal quantum Hall effect in a Kitaev spin liquid

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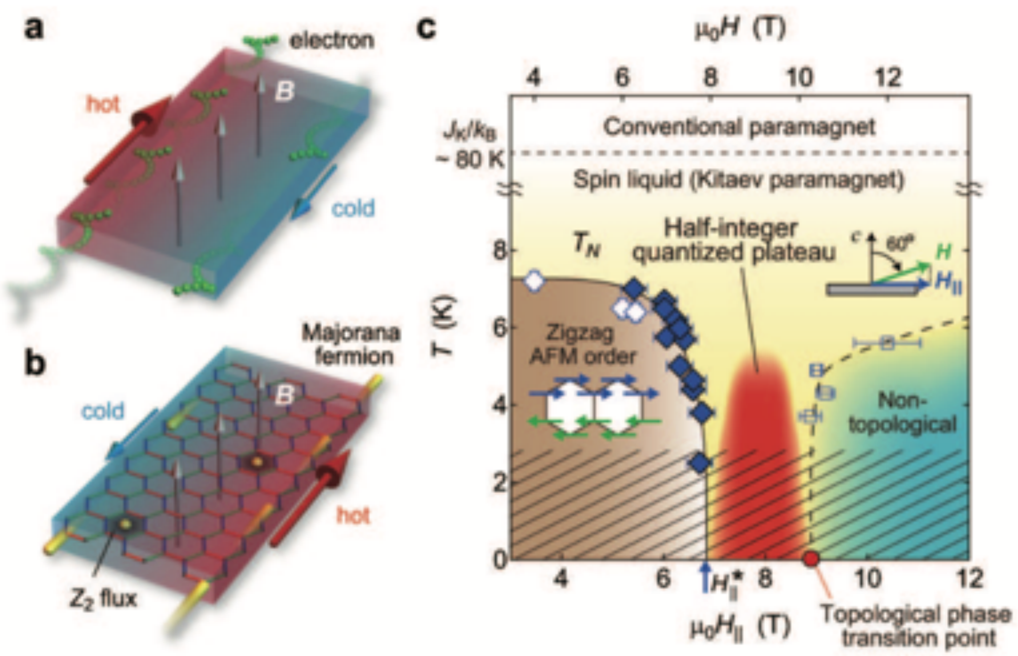
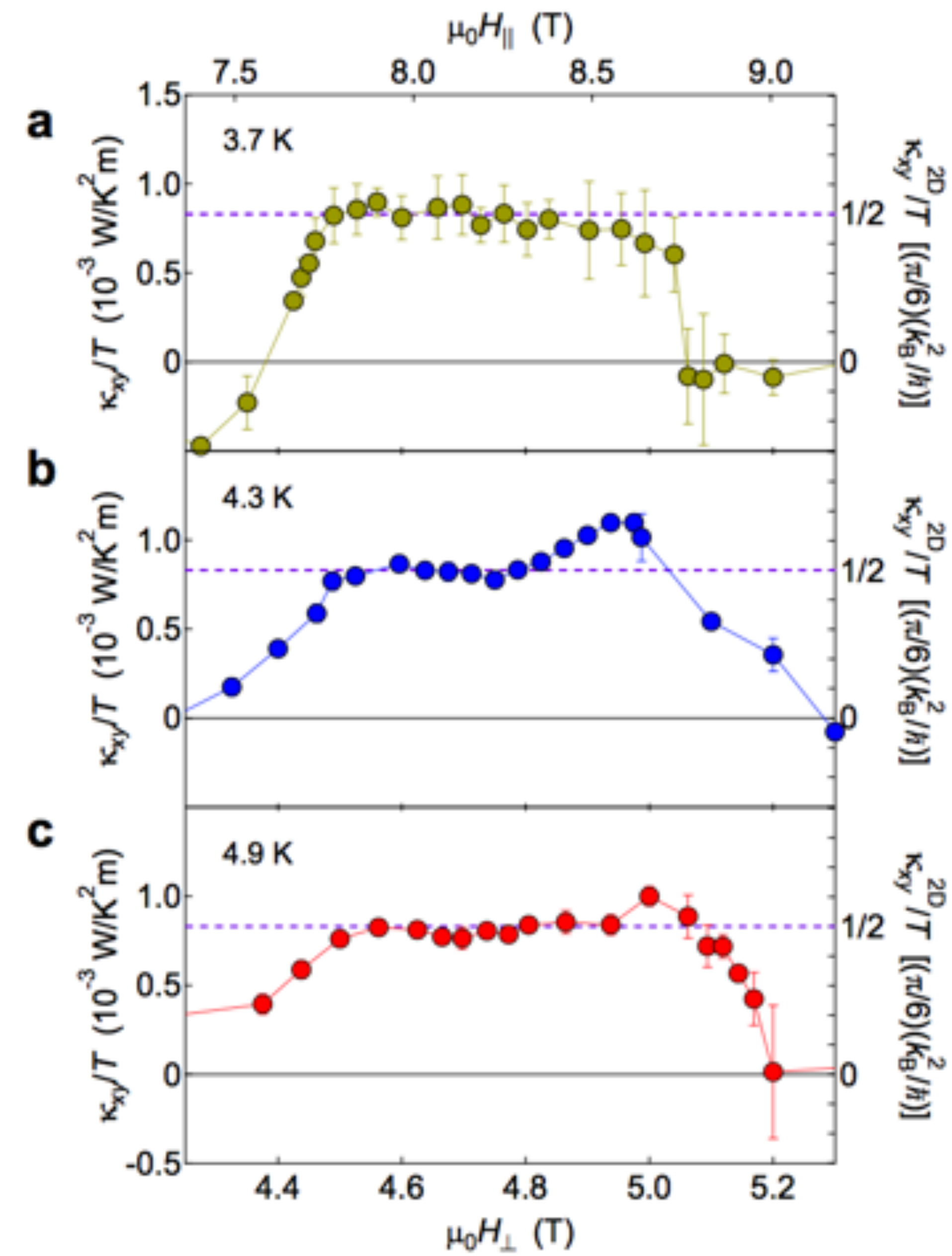


Edge Majorana spinons?



How to tell a spinon from a spin wave?

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

Bethe's solution: 1933
identification of spinons: 1981

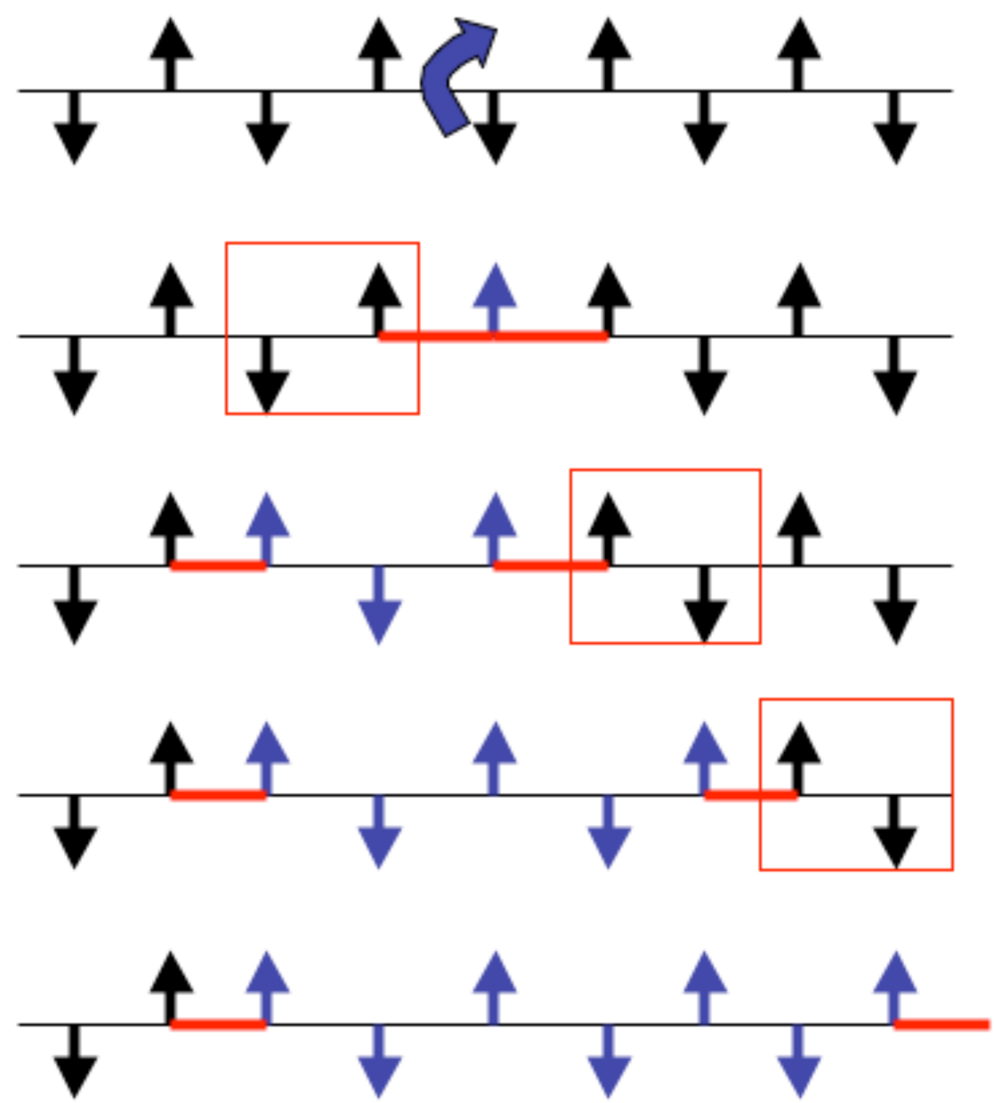
What is the spin of a spin wave?

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

Fully understood: d=1 chain

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

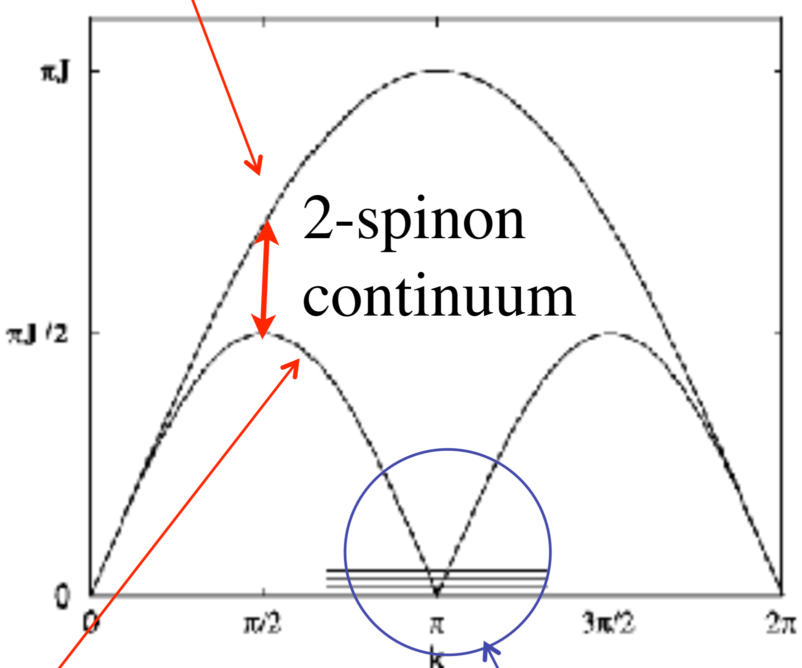
Upper boundary

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

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

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

Energy ε



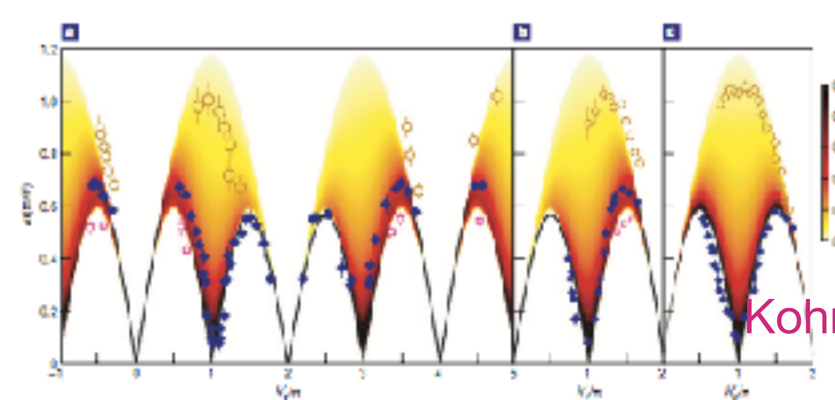
Q_x

Two particle Excitation

Lower boundary

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

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



Cs2CuCl4

Kohno, OS, Balents

Spinon

Magnetic

Resonance

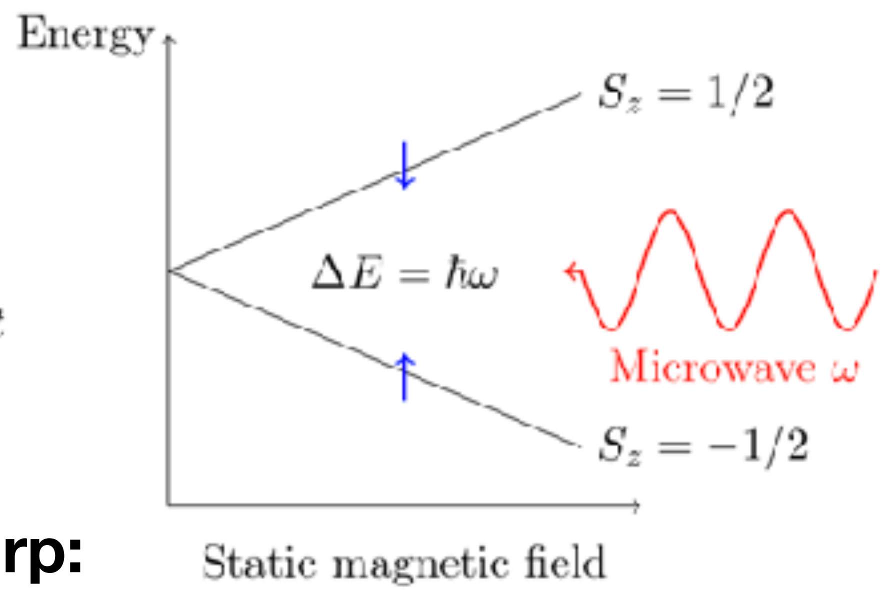
Electron Spin Resonance (ESR)

ESR measures absorption of electromagnetic radiation by a sample that is (typically) subjected to an external static magnetic field.

Linear response theory:

$$I(\vec{q}=0,\omega) = \frac{1}{2}|h|^2\omega \; \mathrm{Im}\chi_{\alpha\beta}(\vec{q}=0,\omega)$$

$$\chi_{\alpha\beta}(\vec{q}=0,\omega) = i\int_0^\infty dt \; \langle [S^\alpha(t), S^\beta(0)] \rangle e^{i\omega t}$$



For SU(2) invariant systems, completely sharp:

$$I(\omega) = \frac{1}{2}|h|^2\omega \; \delta(\omega - B)$$

No matter how exotic the ground state is!

M. Oshikawa and I. Affleck, Phys. Rev. B 65, 134410 (2002).

The key point

- Perturbations violating SU(2) symmetry do show up in ESR: line shift and line width!

- turn annoying material imperfection (spin-orbit, Dzyaloshinksii-Moriya) into a probe of exotic spin state and its excitations

- probe small-**q** excitations by ESR

absence of SU(2) is actually not a restriction!

Condensed matter physics in 21 century: the age of **spin-orbit**

- ✓ spintronics
- ✓ topological insulators, Majorana fermions
- ✓ Kitaev's non-abelian honeycomb spin liquid

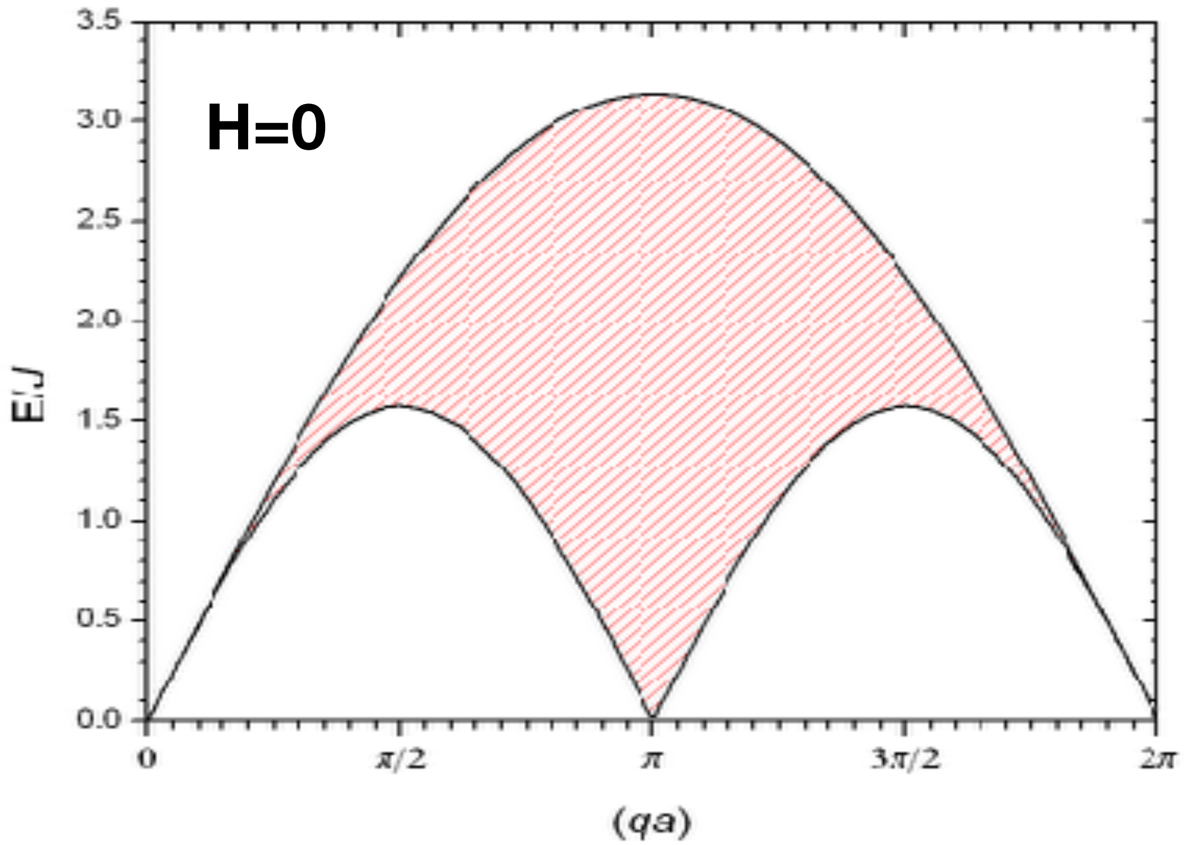
It is all about spin-orbit

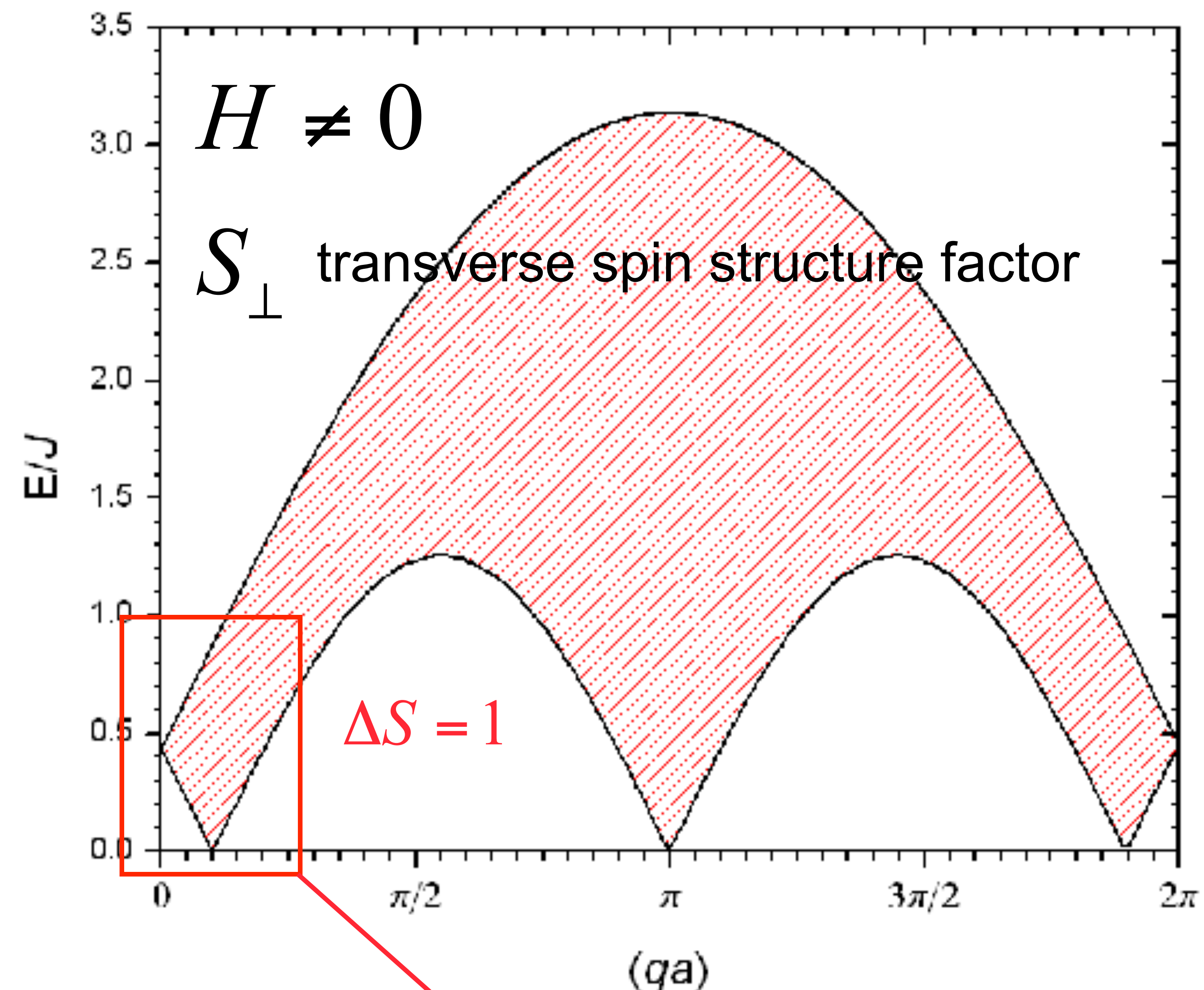
Outline

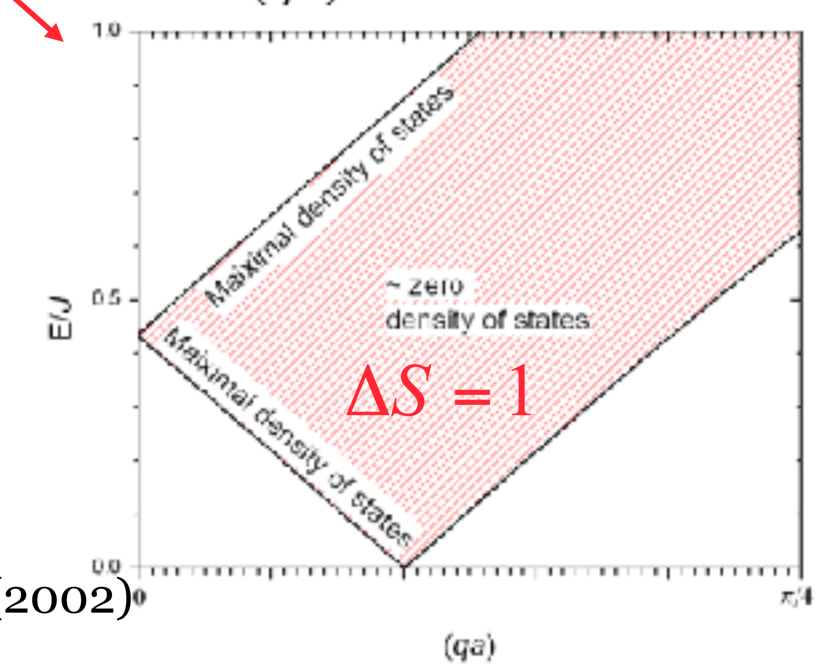
- *Main ingredients*
  - spin liquid
  - absence of spin-rotational symmetry (spin-orbit, DM, anisotropy…)

- *Line shape:* ESR of one-dimensional spinon continuum in Cs_2CuCl_4
- *Line shape:* ESR of two-dimensional spinon continuum *YbMgGaO4*
- *Line width: ESR of spinons coupled to gauge field*
- Conclusions

Probing spinon continuum in one dimension







$$I(\omega) \propto \delta(\omega - H)$$

Dender et al, PRL 1997

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

Uniform Dzyaloshinskii-Moriya interaction

$$H = \sum_{x,y,z} \boxed{J\mathbf{S}_{x,y,z}\cdot\mathbf{S}_{x+1,y,z}} - \boxed{\mathbf{D}_{y,z}\cdot\mathbf{S}_{x,y,z}\times\mathbf{S}_{x+1,y,z}} - g\mu_B \mathbf{H}\cdot\mathbf{S}_{x,y,z}$$

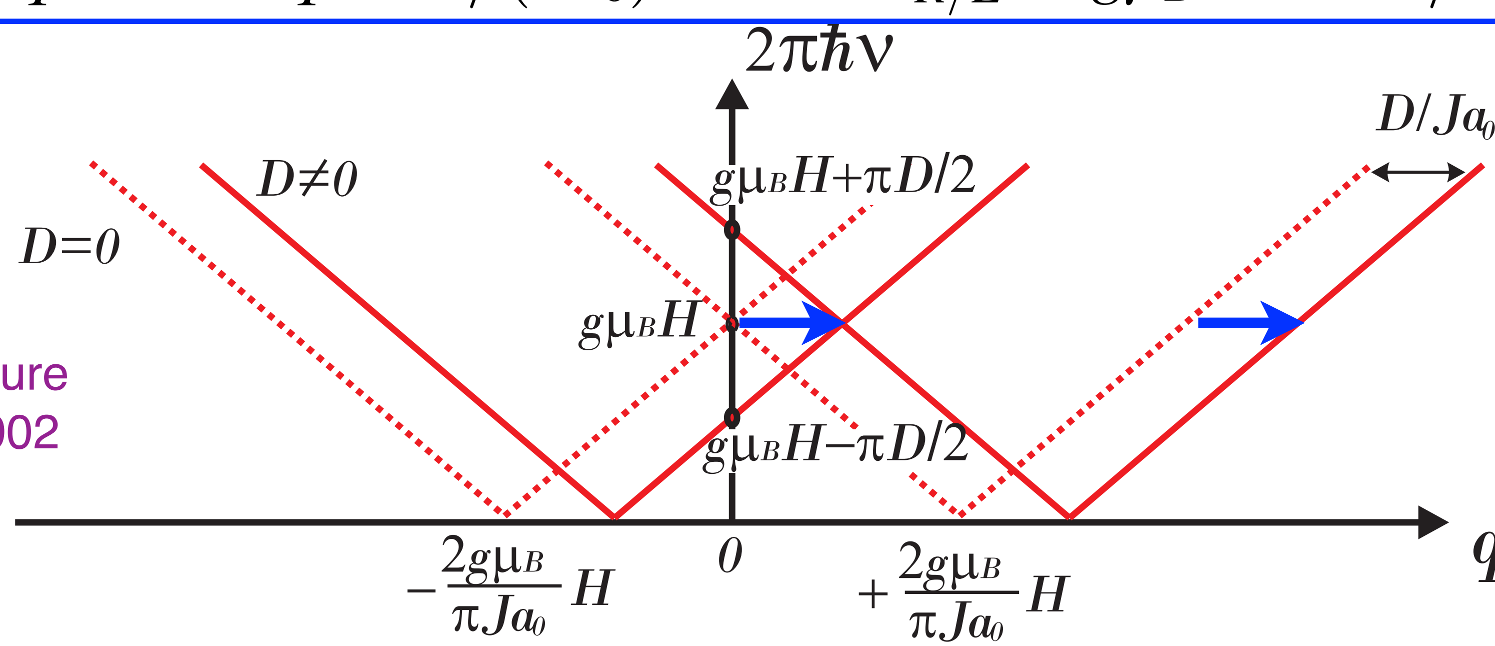
chain — uniform DM along the chain — magnetic field

!

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

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

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



dotted lines: D=0 picture
Oshikawa, Affleck 2002

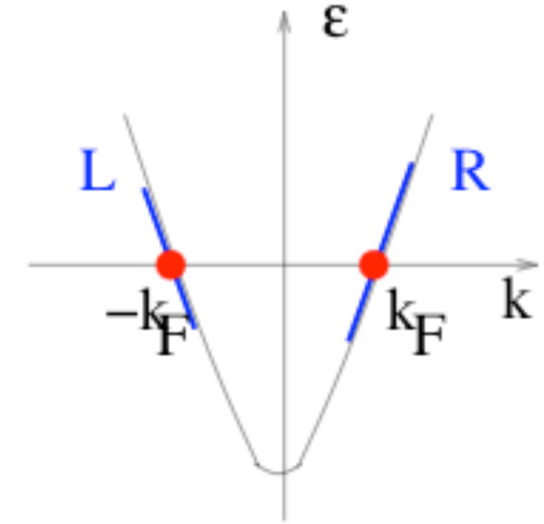
rotated basis: q=0
original basis: q=D/J

H || D

DM interaction allows to probe spinon continuum at finite "boost" momentum

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

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

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

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

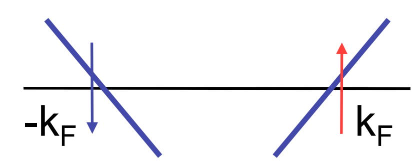
- *$2k_F$ (= π/a) fluctuations: charge density wave ε , spin density wave N*

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

Staggered Magnetization N

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

Spin flip ΔS=1



1/q

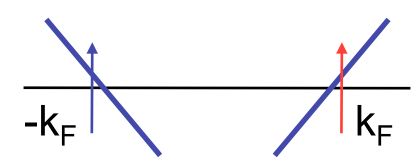
1/q

Staggered Dimerization

ε = $(-1)^x S_x S_{x+a}$

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

ΔS=0



1/q

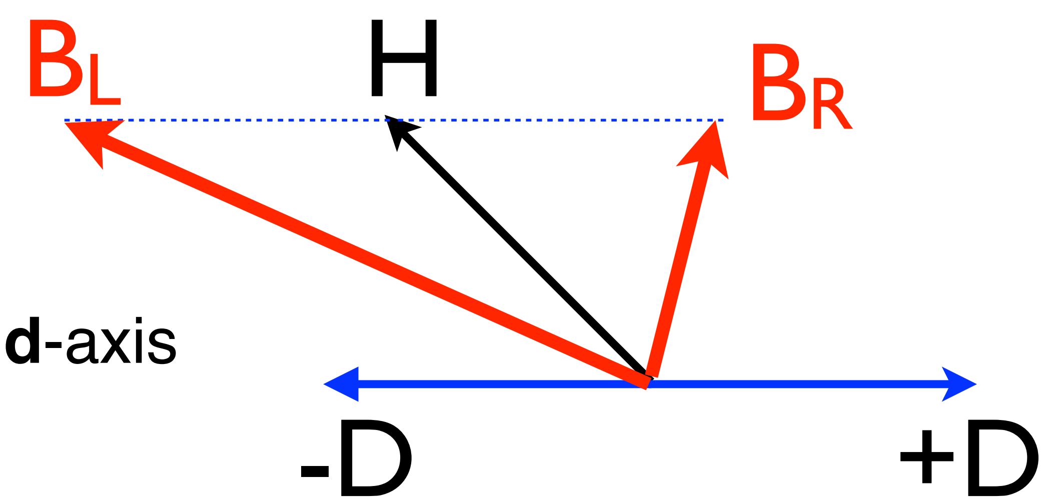
- Must be careful: **often** spin-charge separation must be enforced by hand

Arbitrary orientation of **H** and **D**

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

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. Hence **h_{mw} II b** is most effective.

Povarov et al, PRL 2011
Gangadharaiah, Sun, OS, PRB 2008

Cs_2CuCl_4 ESR data: T=1.3 K

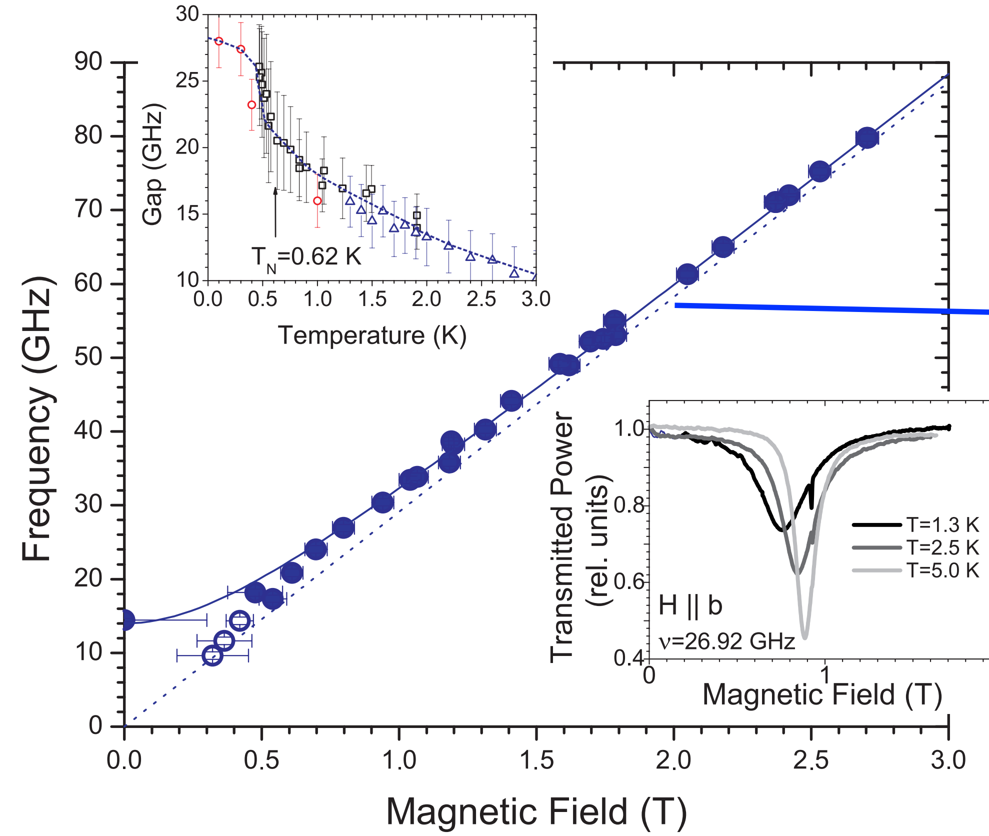
Povarov et al, 2011

- H along b-axis

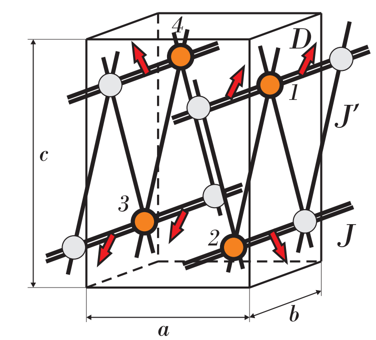
  ✓ **gap**-like behavior for ν > 17 GHz

$$2\pi\hbar\nu = \sqrt{(g_b\mu_B H)^2 + \Delta^2}$$

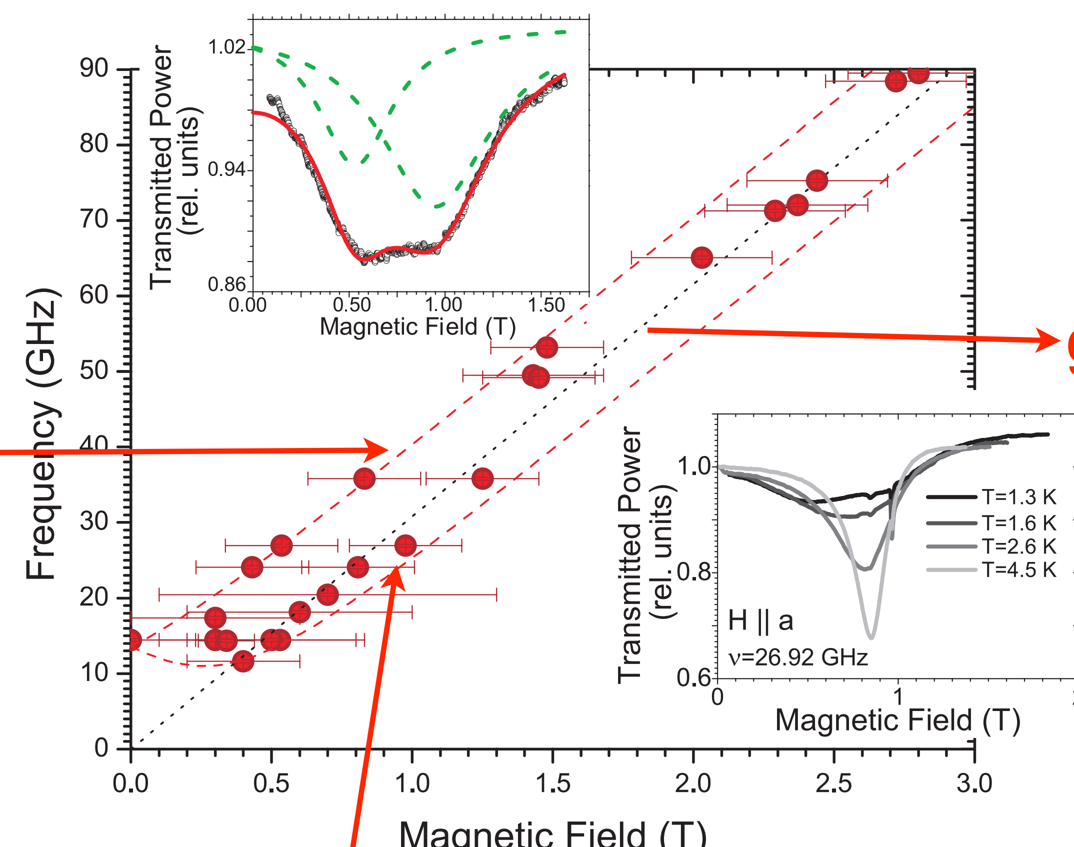
  ✓ loss of intensity for ν < 17 GHz



g_b = 2.08



- H along a-axis: splitting of the ESR line



g_a = 2.20

Cs2CuCl4 ESR data

PRL 107, 037204 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

Modes of Magnetic Resonance in the Spin-Liquid Phase of Cs_2CuCl_4

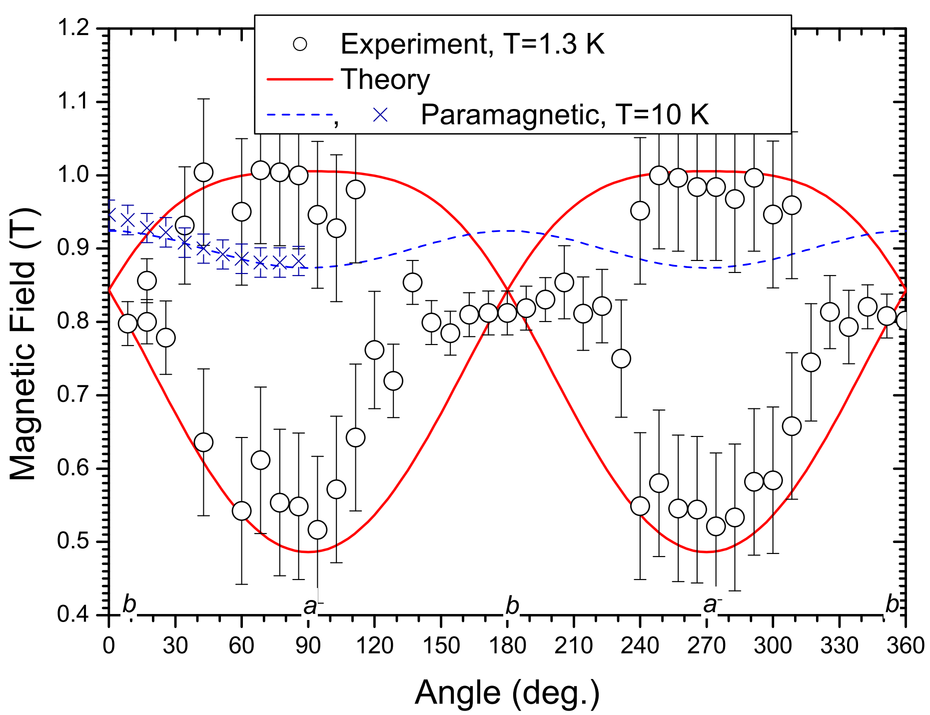
K. Yu. Povarov,[1,*] A. I. Smirnov,[1,2] O. A. Starykh,[3,4] S. V. Petrov,[1] and A. Ya. Shapiro[5]

- General orientation of **H** and **D**
- 4 sites/chains in unit cell

$$(2\pi\hbar\nu_R)^2 = (g_b\mu_B H_b)^2 + [g_a\mu_B H_a + (-1)^z\pi D_a/2]^2 + [g_c\mu_B H_c + (-1)^y\pi D_c/2]^2,$$

$$(2\pi\hbar\nu_L)^2 = (g_b\mu_B H_b)^2 + [g_a\mu_B H_a - (-1)^z\pi D_a/2]^2 + [g_c\mu_B H_c - (-1)^y\pi D_c/2]^2.$$

a-b plane

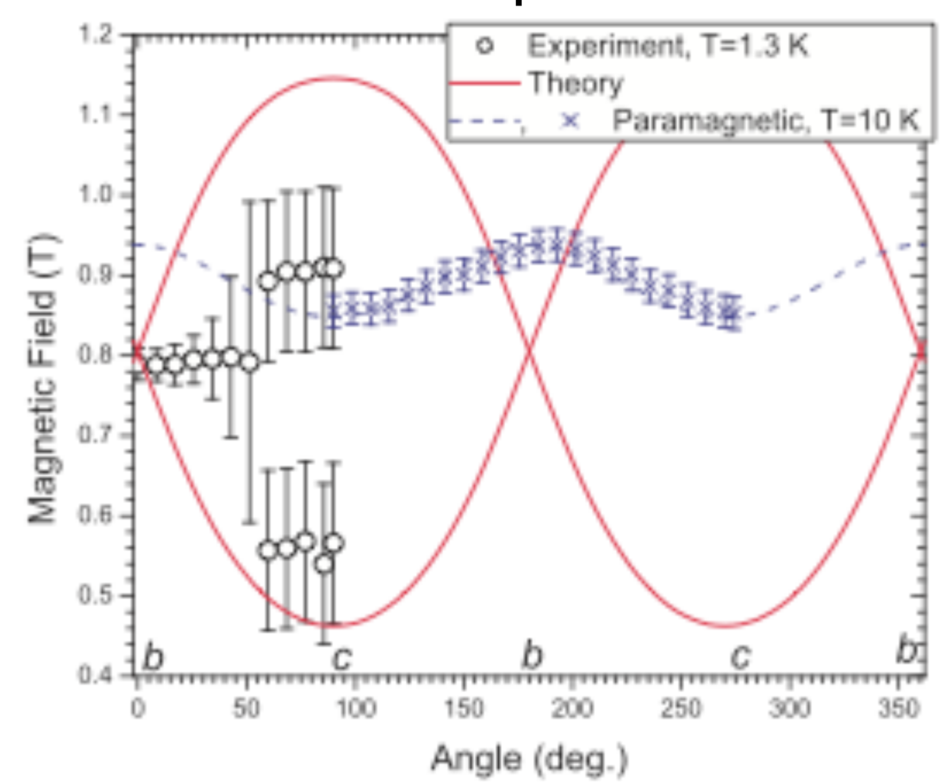


$$\boxed{\begin{aligned} D_a/(4\hbar) &= 8\ \text{GHz} \\ D_c/(4\hbar) &= 11\ \text{GHz} \end{aligned}}$$

0.3 Tesla
0.4 Tesla

D ~ J/10

b-c plane



- for **H** along b-axis only: the "gap" is determined by the DM interaction strength

$$\Delta = \frac{\pi}{2}\sqrt{D_a^2 + D_c^2} \rightarrow (2\pi\hbar)13.6\ \text{GHz}$$

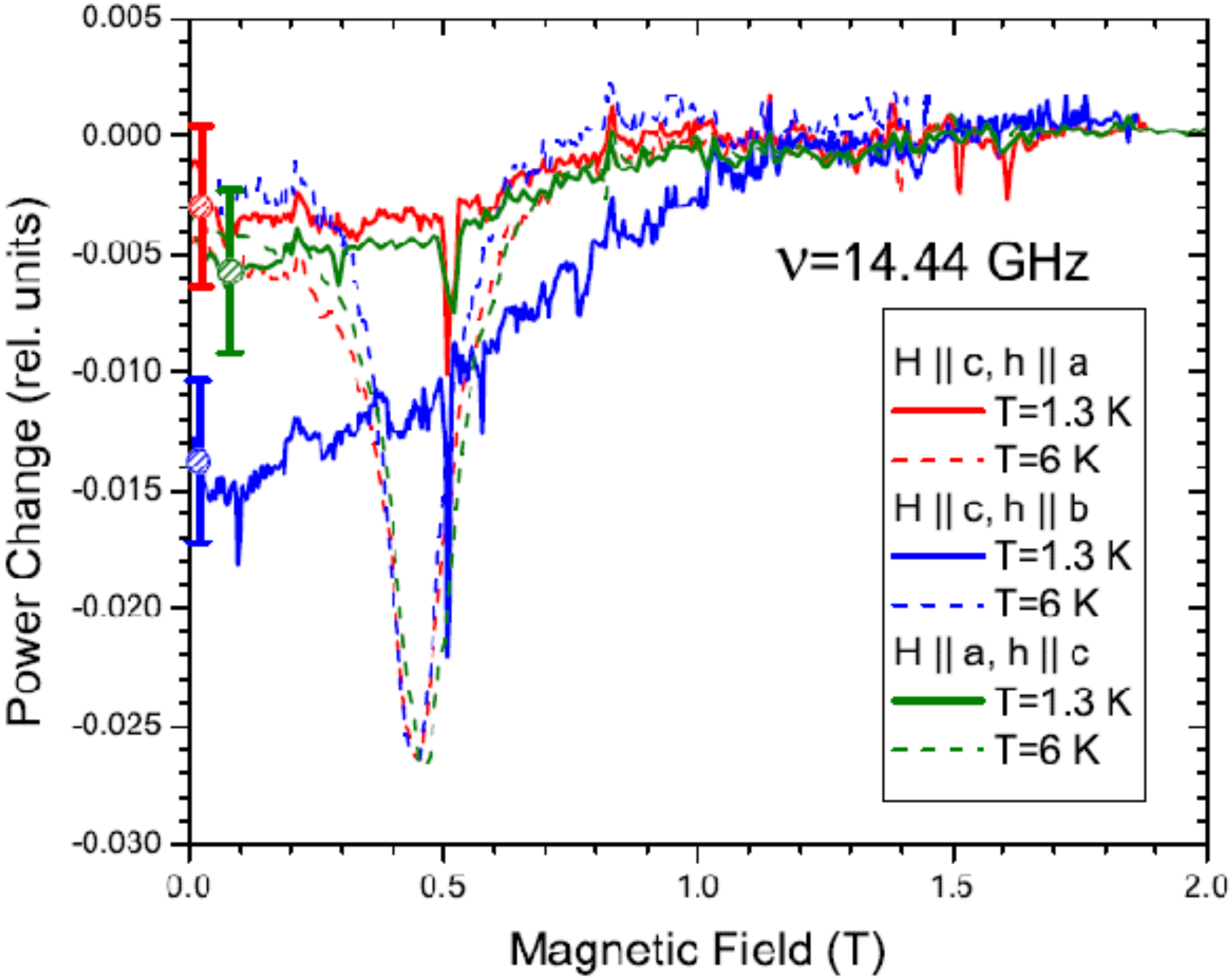
Linear in **T** line width

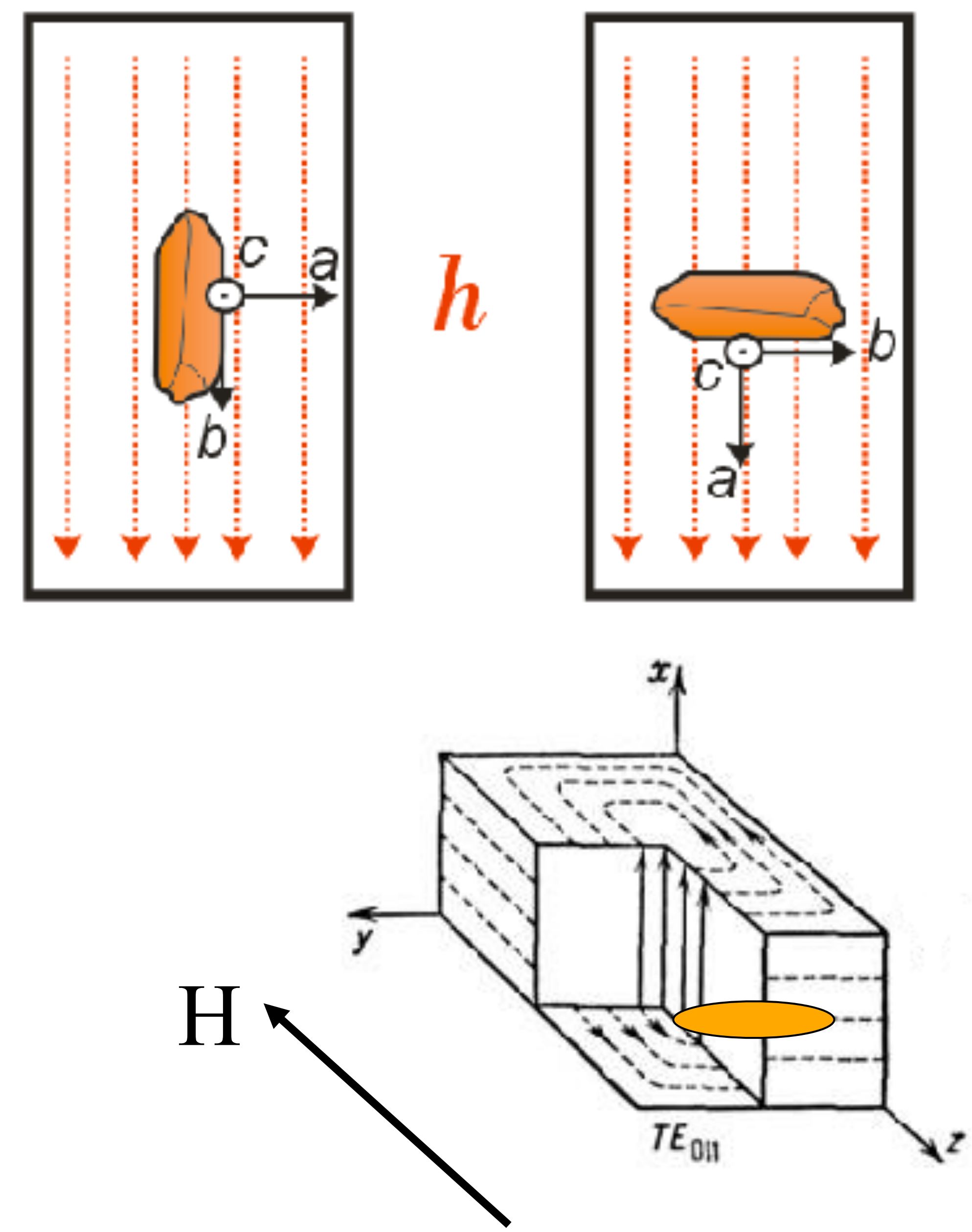
S. C. Furuya Phys. Rev. B 95, 014416 (2017)

Zero-field absorption:

1) ESR absorption in the absence of H $\nu \sim \sqrt{D_a^2 + D_c^2}$

2) strong polarization dependence in zero field





The largest absorption occurs when microwave field h(t) is lined along crystal b-axis, h || *b* [so that it is perpendicular to the **D** vector in *a*-*c* plane] Povarov et al, PRL 2011

PHYSICAL REVIEW B 92, 134417 (2015)

Electron spin resonance in a model $S = \frac{1}{2}$ chain antiferromagnet with a uniform Dzyaloshinskii-Moriya interaction

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[3]Neutron Scattering and Magnetism, Laboratory for Solid State Physics, ETH Zürich, Switzerland
(Received 27 July 2015; revised manuscript received 6 October 2015; published 22 October 2015)

The electron spin resonance spectrum of a quasi-1D $S = 1/2$ antiferromagnet $K_2CuSO_4Br_2$ was found to demonstrate an energy gap and a doublet of resonance lines in a wide temperature range between the Curie-Weiss and Neël temperatures. This type of magnetic resonance absorption corresponds well to the two-spinon continuum of excitations in $S = 1/2$ antiferromagnetic spin chain with a uniform Dzyaloshinskii-Moriya interaction between the magnetic ions. A resonance mode of paramagnetic defects demonstrating strongly anisotropic behavior due to interaction with spinon excitations in the main matrix is also observed.

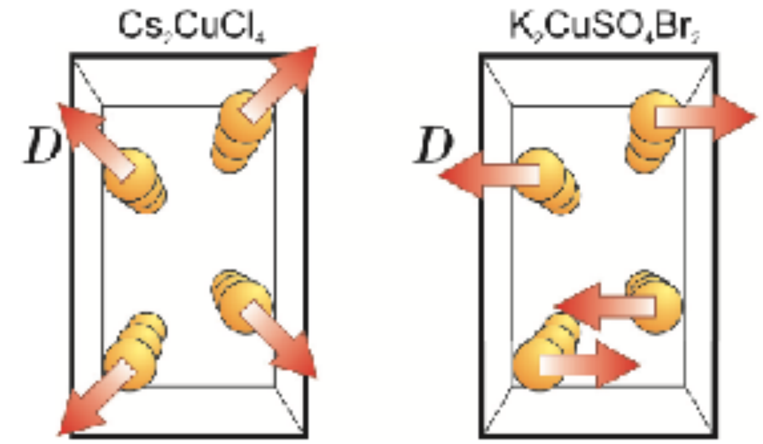


FIG. 2. (Color online) Comparison of the Dzyaloshinskii-Moriya vectors in Cs_2CuCl_4 and $K_2CuSO_4Br_2$. Perspective view along the spin chains.

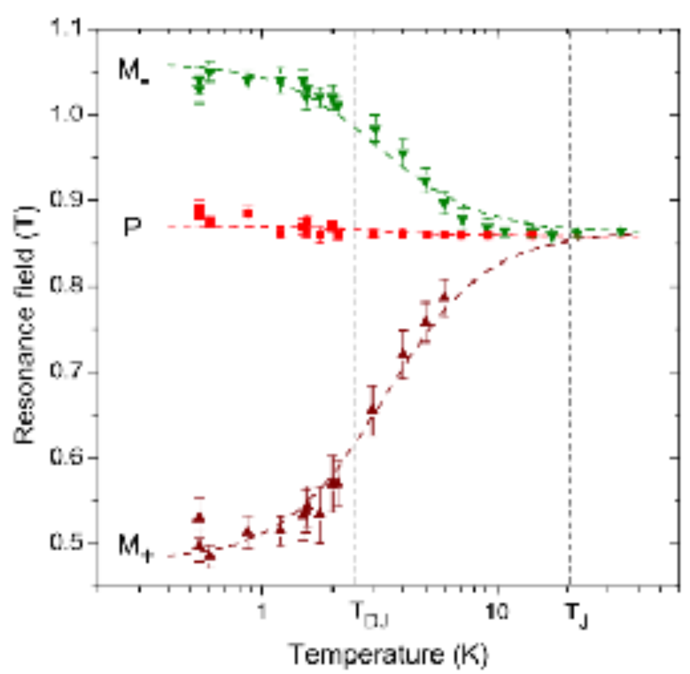


FIG. 4. (Color online) Temperature dependence of 27.83 GHz ESR fields at $\mathbf{H} \parallel b$ for the components of the doublet M_-, M_- and of the paramagnetic line P, associated with the defects. Characteristic temperatures marked on the horizontal axis are $T_{DJ} = \sqrt{DJ}/k_B$ and $T_J = J/k_B$. Dashed lines are guide to the eyes.

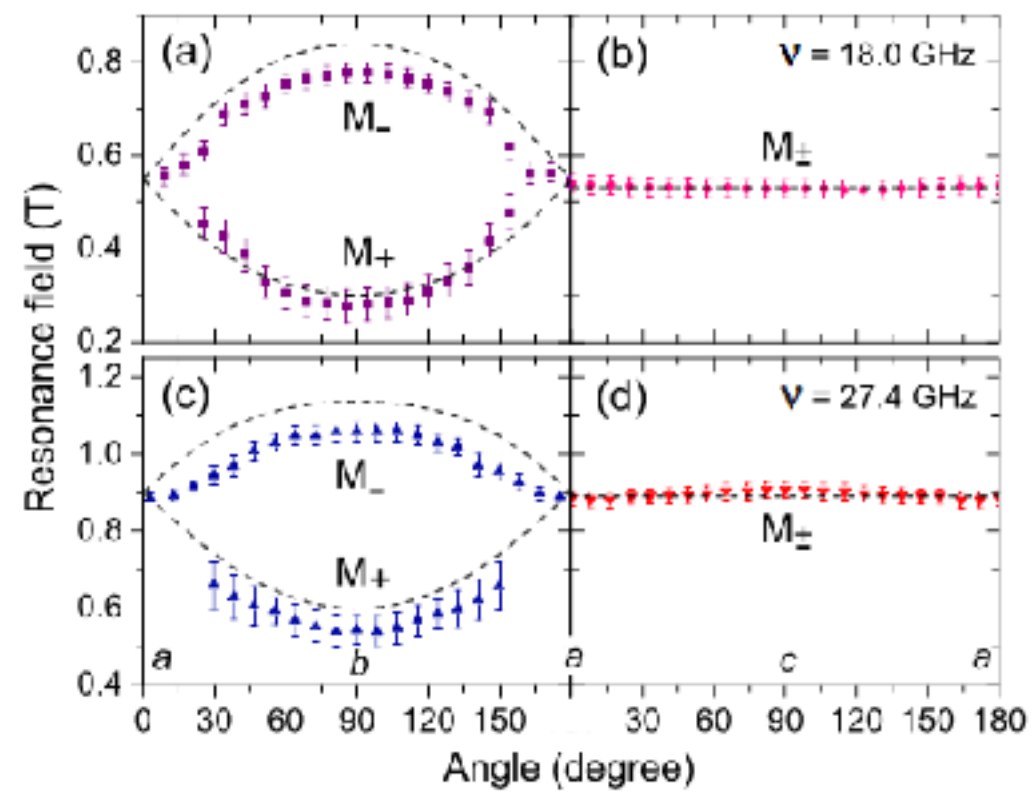
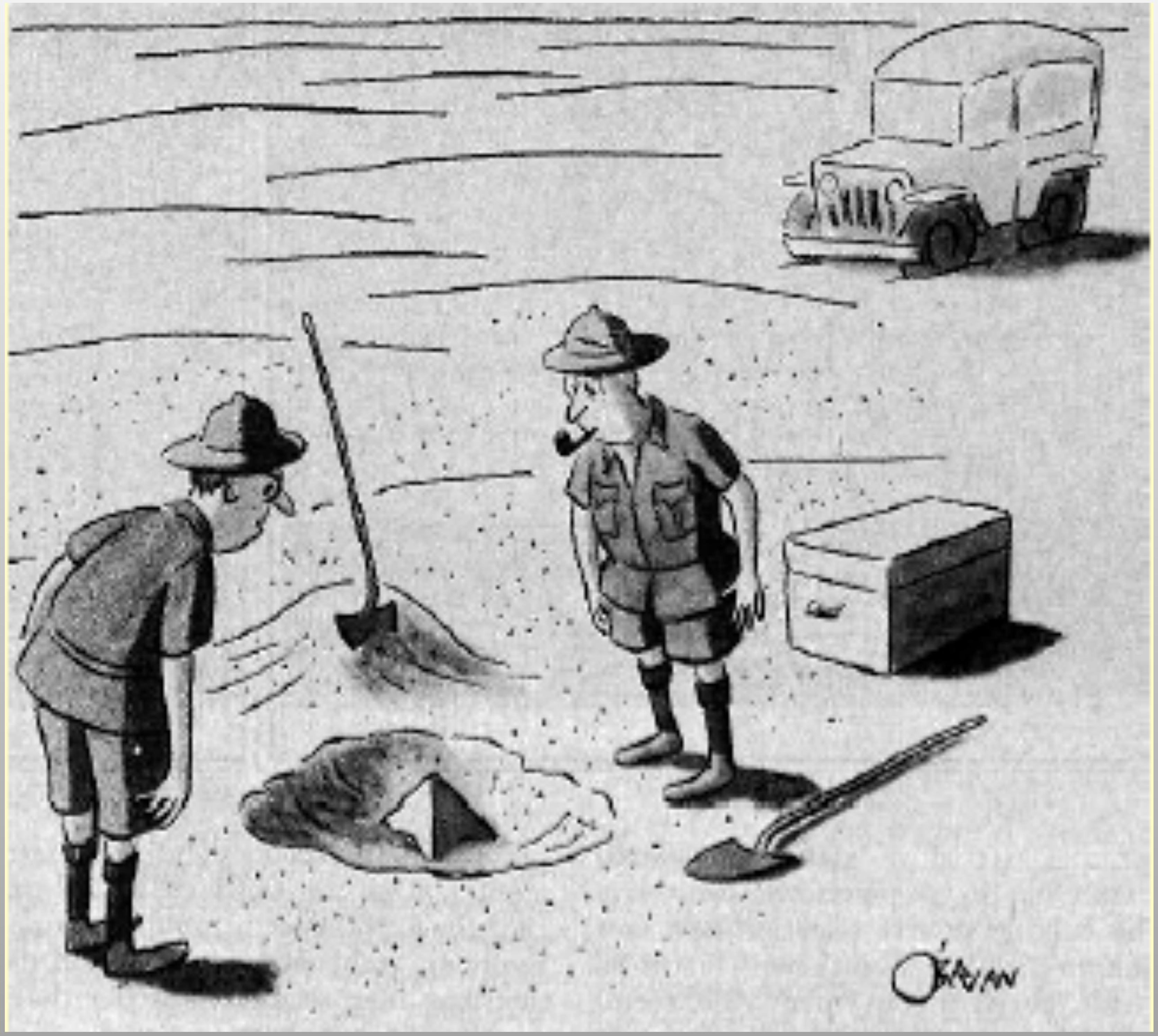


FIG. 8. (Color online) Angular dependencies of the resonant fields at two frequencies for $T = 1.3$ K. 18.0 GHz ESR fields for field in ab plane (upper left panel), and in ac plane (upper right panel). 27.4 GHz ESR fields for field in ab plane (lower left panel), and in ac plane (lower right panel). Dashed lines are theoretical dependencies according to (2).

J = 20 K, D = 0.27 K

Two-dimensional spin liquids with fractionalized excitations



"This could be the discovery of the century. Depending, of course, on how far down it goes"

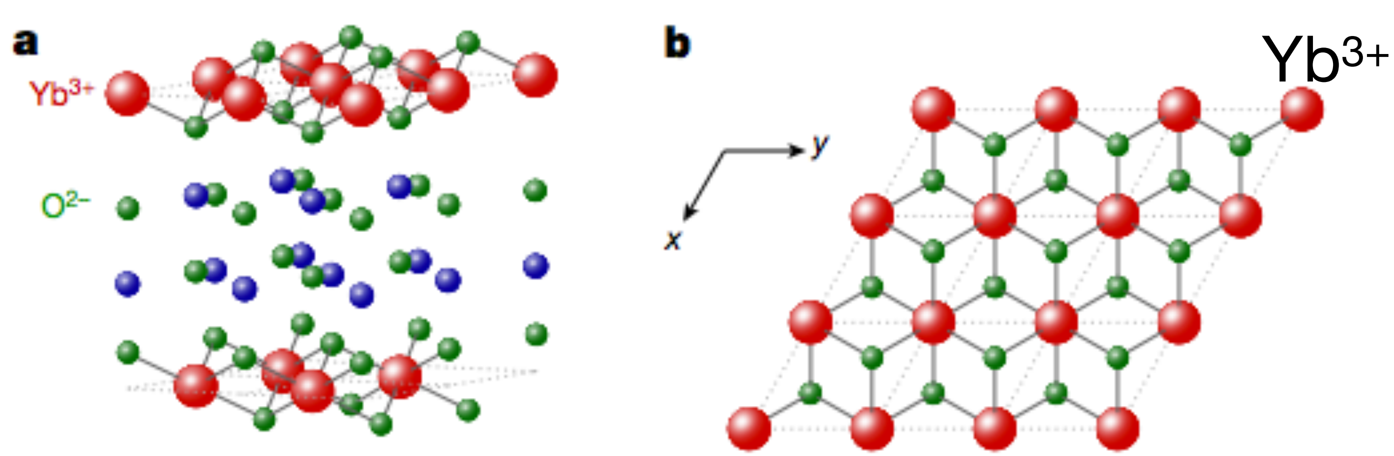
Two (and three) dimensional spin liquids

No magnetic order
Significant spin-orbit interaction
Fractionalized excitations

Kitaev materials
Pyrochlores
Iridates

YbMgGaO4
interesting
promising
simple lattice

Spinon Fermi surface state suggested by early neutron exps!



Higher dimensional extension (weak Mott insulators)

- origin of DM: spin-orbit tunneling in Hubbard model

$$\hat{H} = \sum_{i,j} \{c_{i,\alpha}^{+}(-t\delta_{\alpha\beta} + i\vec{\lambda}_{ij} \cdot \vec{\hat{s}}_{\alpha\beta})c_{j,\beta} + \mathrm{H.c.}\} + U\sum_{i} n_{i\uparrow}n_{i\downarrow}.$$

- 2D square lattice with ***uniform spin-orbit*** interaction ($YBa_2\ Cu_3\ O_{6+x}$)

$$\vec{\lambda}_{ij} = \lambda\hat{z} \times (\vec{r}_i - \vec{r}_j)$$

Coffey, Rice, Zhang 1991
Shekhtman, Entin-Wolhman, Aharony 1992
Bonesteel 1993

- (Lattice) spin-orbit interaction of Rashba type

$$\hat{H}_{\mathrm{SO}}(\mathbf{k}) = -2\lambda\sum_{k} c_{k,\alpha}^{\dagger}\{\hat{s}_x \sin[k_y] - \hat{s}_y \sin[k_x]\}c_{k,\beta}$$

- Transition to ***spinons*** via ***slave-rotor*** formulation $\qquad c_{r,\sigma} = f_{r,\sigma}e^{i\theta_r}$

Florens and Georges 2004
S.-S. Lee and P. A. Lee 2005

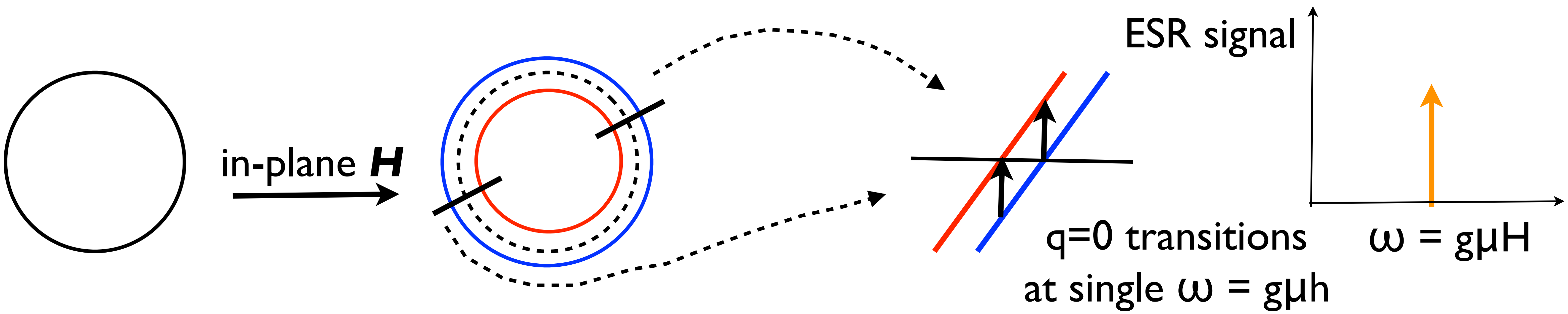
- (mean-field) Rashba Hamiltonian for free spinons ($f_{r,s}$)

$$\hat{H}_f = \sum_{i,j} f_{i,\alpha}^{+}(-t\delta_{\alpha\beta} + i\vec{\lambda}_{ij}^{\mathrm{eff}} \cdot \vec{s}_{\alpha\beta})f_{j,\beta} - \vec{H} \cdot f_{i,\alpha}^{+}\vec{s}_{\alpha\beta}f_{j,\beta}$$

Glenn, OS, Raikh, PRB 2012

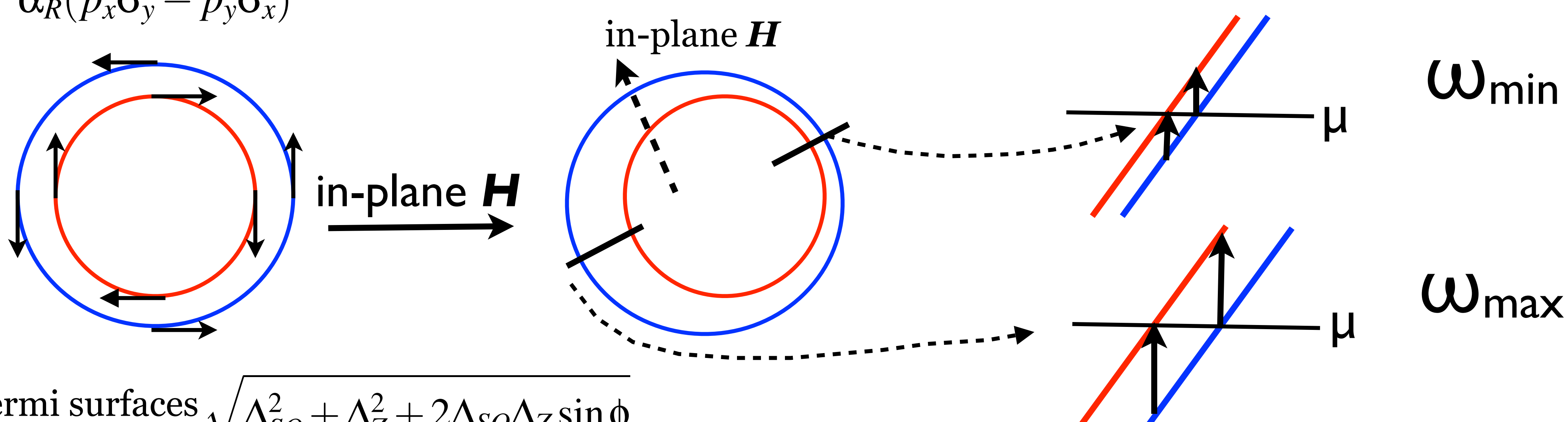
Estimates for 2d spinon gas using Rashba model as an example

no DM



DM

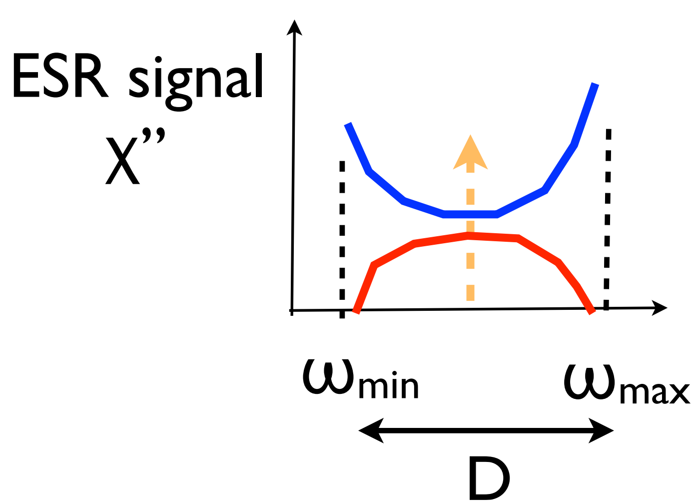
$\alpha_R(p_x\sigma_y - p_y\sigma_x)$



splitting of Fermi surfaces $\sqrt{\Delta_{SO}^2 + \Delta_Z^2 + 2\Delta_{SO}\Delta_Z \sin\phi}$

Glenn, OS, Raikh 2012

Energy absorption due to microwave h(t)



the width of the line ~ min(H, α_R k_F)

line shape is strongly polarization-dependent:

$[\omega - \omega_{min/max}]^{-1/2}$ for h(t) perpendicular to H

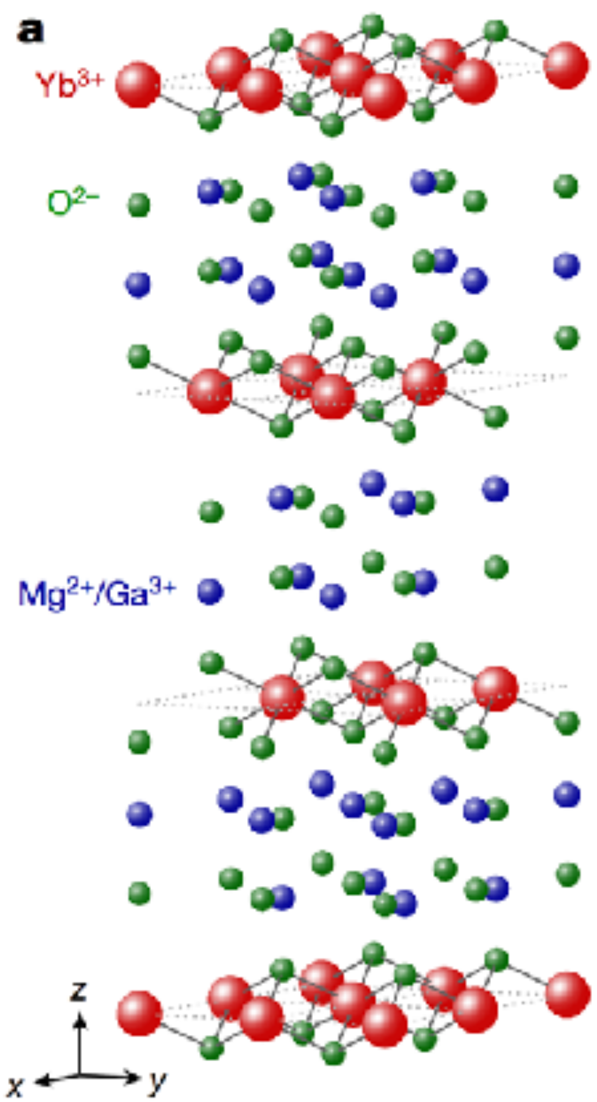
$[\omega - \omega_{min/max}]^{1/2}$ for h(t) parallel to H

2D spin liquid: YbMgGaO4

Sci Rep. 2015 Nov 10;5:16419. doi: 10.1038/srep16419.

Gapless quantum spin liquid ground state in the two-dimensional spin-1/2 triangular antiferromagnet YbMgGaO4.

Li Y[1], Liao H[2], Zhang Z[3], Li S[3], Jin F[1], Ling L[4], Zhang L[4], Zou Y[4], Pi L[4], Yang Z[5], Wang J[6], Wu Z[7], Zhang Q[1,8].



Rare-Earth Triangular Lattice Spin Liquid: A Single-Crystal Study of $YbMgGaO_4$

Yuesheng Li, Gang Chen, Wei Tong, Li Pi, Juanjuan Liu, Zhaorong Yang, Xiaoqun Wang, and Qingming Zhang
Phys. Rev. Lett. **115**, 167203 – Published 16 October 2015

Muon Spin Relaxation Evidence for the U(1) Quantum Spin-Liquid Ground State in the Triangular Antiferromagnet $YbMgGaO_4$

Yuesheng Li, Devashibhai Adroja, Pabitra K. Biswas, Peter J. Baker, Qian Zhang, Juanjuan Liu, Alexander A. Tsirlin, Philipp Gegenwart, and Qingming Zhang
Phys. Rev. Lett. **117**, 097201 – Published 23 August 2016

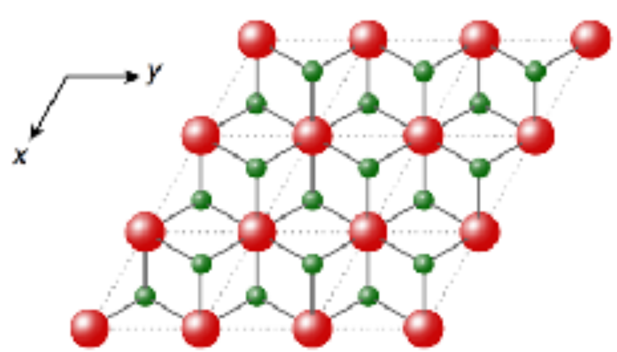


Figure from: Nature 540, pp 559–562 (2016).

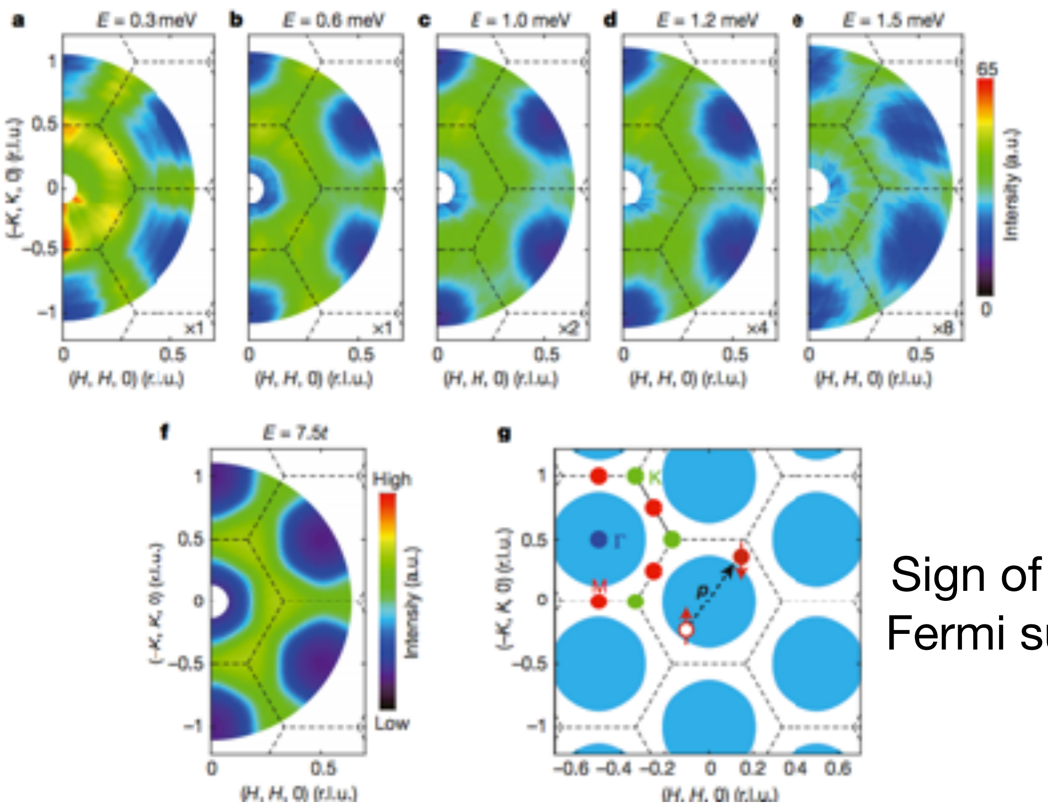
Strong spin-orbit coupling

$$
\begin{aligned}
\mathcal{H} = \sum_{<i,j>} & [J_1^{zz} S_i^z S_j^z + J_1^{\pm}(S_i^+ S_j^- + S_i^- S_j^+) \\
& + J_1^{\pm\pm}(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-) \\
& - \frac{iJ_1^{z\pm}}{2}(\gamma_{ij}^* S_i^+ S_j^z - \gamma_{ij} S_i^- S_j^z + \langle i \leftrightarrow j \rangle)] \\
+ \sum_{\langle\langle i,j \rangle\rangle} & [J_2^{zz} S_i^z S_j^z + J_2^{\pm}(S_i^+ S_j^- + S_i^- S_j^+)] \\
- \mu_0 \mu_B \sum_i & [g_\perp (H^x S_i^x + H^y S_i^y) + g_\parallel H^z S_i^z]
\end{aligned}
$$

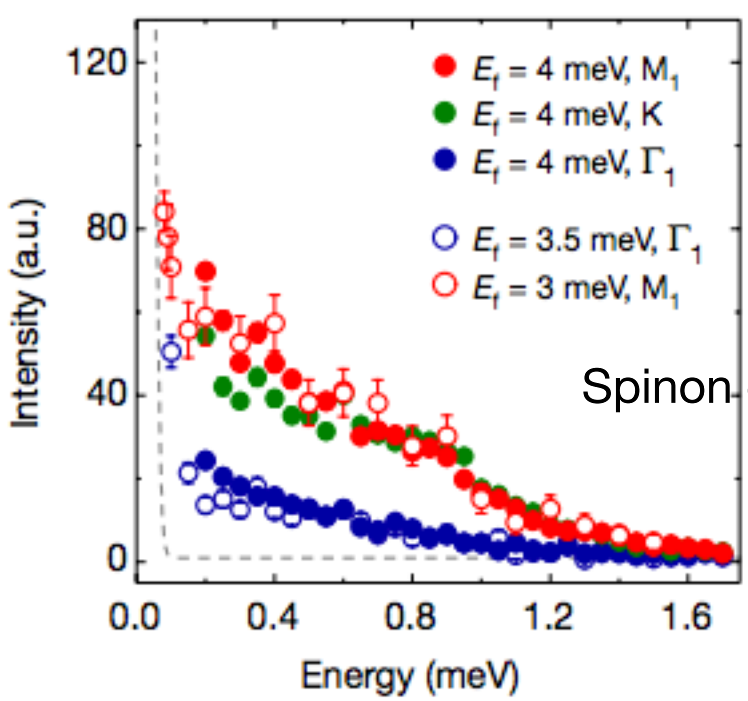
LETTER
doi:10.1038/nature20614

Evidence for a spinon Fermi surface in a triangular-lattice quantum-spin-liquid candidate

Yao Shen[1], Yao-Dong Li[1], Hongliang Wo[1], Yuesheng Li[2], Shoudong Shen[1], Bingying Pan[1], Qisi Wang[1], H. C. Walker[3], P. Steffens[4], M. Boehm[4], Yiqing Hao[1], D. L. Quintero-Castro[5], L. W. Harriger[6], M. D. Frontzek[7], Lijie Hao[8], Siqin Meng[8], Qingming Zhang[2,9,10,11], Gang Chen[1,11,12] & Jun Zhao[1,11]



Sign of spinon Fermi surface?

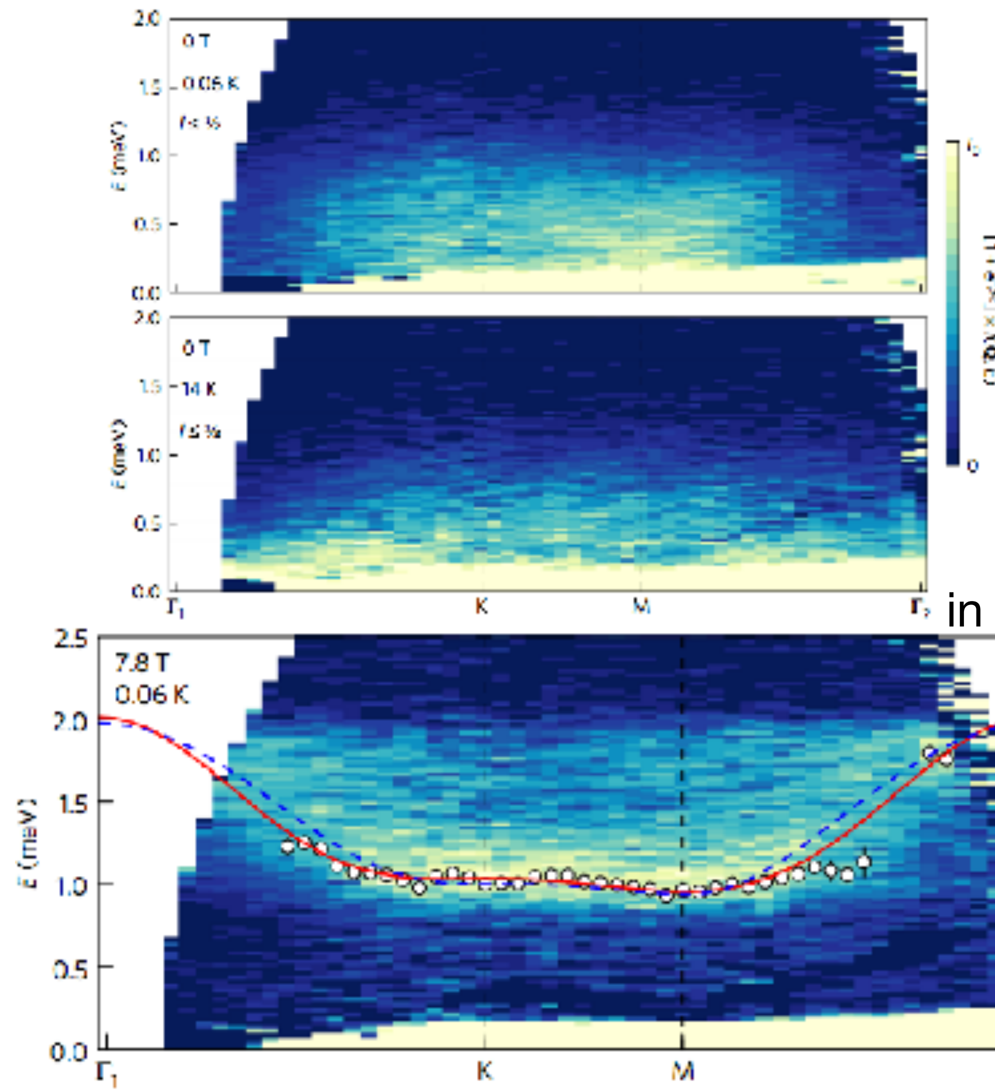


Spinon continuum?

nature physics LETTERS
PUBLISHED ONLINE: 5 DECEMBER 2016 | DOI: 10.1038/NPHYS3971

Continuous excitations of the triangular-lattice quantum spin liquid $YbMgGaO_4$

Joseph A. M. Paddison[1], Marcus Daum[1†], Zhiling Dun[2†], Georg Ehlers[3], Yaohua Liu[3], Matthew B. Stone[3], Haidong Zhou[2] and Martin Mourigal[1*]



Broad signal in polarized phase?

very disordered

$$\mathcal{H}=\sum_{\langle ij\rangle}\left[J_1^{zz}S_i^zS_j^z+J_1^{\pm}\left(S_i^+S_j^-+S_i^-S_j^+\right)+J_1^{\pm\pm}\left(\gamma_{ij}S_i^+S_j^++\gamma_{ij}^*S_i^-S_j^-\right)\right]$$

$$+\sum_{\langle\langle ij\rangle\rangle}\left[J_2^{zz}S_i^zS_j^z+J_2^{\pm}\left(S_i^+S_j^-+S_i^-S_j^+\right)\right]$$

$$-\mu_0\mu_B\sum_i\left[g_\perp\left(H^xS_i^x+H^yS_i^y\right)+g_\parallel H^zS_i^z\right] \qquad (1)$$

PHYSICAL REVIEW B 96, 054445 (2017)

Spinon Fermi surface $U(1)$ spin liquid in the spin-orbit-coupled triangular-lattice Mott insulator $YbMgGaO_4$

Yao-Dong Li,[1] Yuan-Ming Lu,[2] and Gang Chen[1,3,*]

Spinon hypothesis

PHYSICAL REVIEW LETTERS 120, 037204 (2018)

Spinon Magnetic Resonance of Quantum Spin Liquids

Zhu-Xi Luo,[1,*] Ethan Lake,[1] Jia-Wei Mei,[2] and Oleg A. Starykh[1,†]

Spinon mean-field Hamiltonian
derived with the help of
Projective Symmetry Group (PSG) analysis

$$S^a_{\mathbf{r}} = \frac{1}{2} f^\dagger_{\mathbf{r}\alpha} \sigma^a_{\alpha\beta} f_{\mathbf{r}\beta}$$

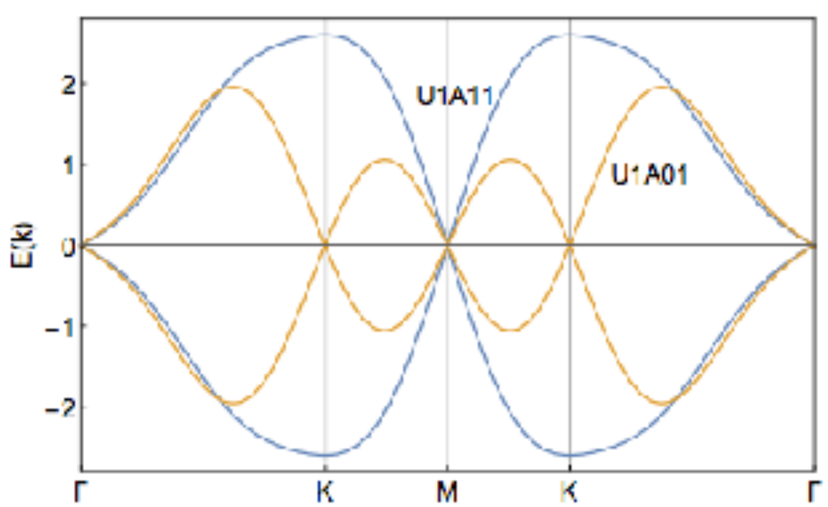


FIG. S-5. Spinon dispersions $E_{1,2}(\mathbf{k})$ along the line Γ-K-M-K-Γ for U1A11 and U1A01 states.

Basic idea: physical spin S is bilinear of spinons f, spinons have bigger symmetry group than spins, this leads to gauge freedom and different classes of possible mean-fields. These classes describe the same spin problem.

Dirac spectrum!

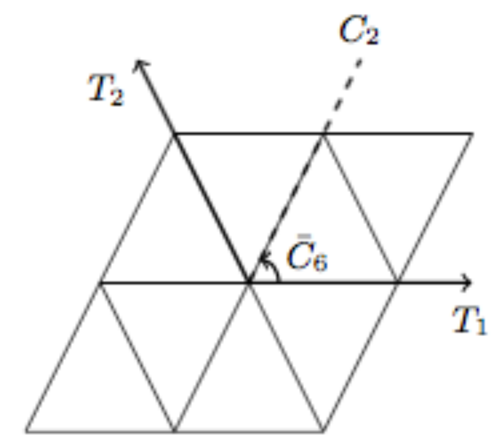
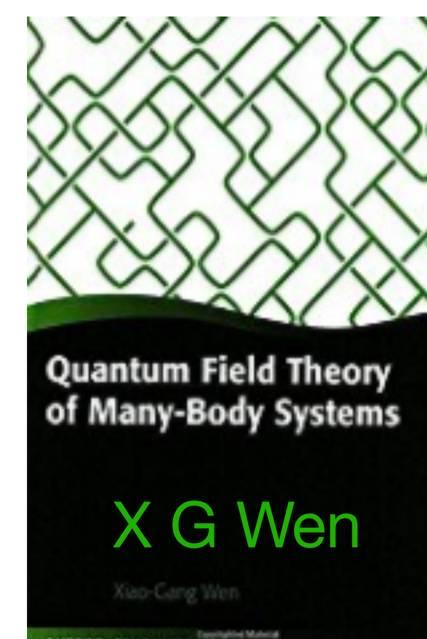


FIG. S-1. The symmetry operations.



Mean-field Hamiltonians

Symmetry	Transformation Rules
T_1	$\begin{cases} f_{(x,y)\uparrow} \to f_{(x+1,y)\uparrow} \\ f_{(x,y)\downarrow} \to f_{(x+1,y)\downarrow} \end{cases}$
T_2	$\begin{cases} f_{(x,y)\uparrow} \to f_{(x,y+1)\uparrow} \\ f_{(x,y)\downarrow} \to f_{(x,y+1)\downarrow} \end{cases}$
C_2	$\begin{cases} f_{(x,y)\uparrow} \to e^{i\pi/6} f^{\dagger}_{(y,x)\uparrow} \\ f_{(x,y)\downarrow} \to e^{-i\pi/6} f^{\dagger}_{(y,x)\downarrow} \end{cases}$
$\bar{C}_6$	$\begin{cases} f_{(x,y)\uparrow} \to e^{i\pi/3} f^{\dagger}_{(x-y,x)\downarrow} \\ f_{(x,y)\downarrow} \to -e^{-i\pi/3} f^{\dagger}_{(x-y,x)\uparrow} \end{cases}$
$\mathcal{T}$	$\begin{cases} f_{(x,y)\uparrow} \to f_{(x,y)\downarrow} \\ f_{(x,y)\downarrow} \to -f_{(x,y)\uparrow} \end{cases}$

TABLE I. U1A11 PSG analysis.

Symmetry	Transformation Rules
T_1	$\begin{cases} f_{(x,y)\uparrow} \to f_{(x+1,y)\uparrow} \\ f_{(x,y)\downarrow} \to f_{(x+1,y)\downarrow} \end{cases}$
T_2	$\begin{cases} f_{(x,y)\uparrow} \to f_{(x,y+1)\uparrow} \\ f_{(x,y)\downarrow} \to f_{(x,y+1)\downarrow} \end{cases}$
C_2	$\begin{cases} f_{(x,y)\uparrow} \to -e^{i\pi/6} f^{\dagger}_{(y,x)\downarrow} \\ f_{(x,y)\downarrow} \to e^{-i\pi/6} f^{\dagger}_{(y,x)\uparrow} \end{cases}$
$\bar{C}_6$	$\begin{cases} f_{(x,y)\uparrow} \to e^{i\pi/3} f^{\dagger}_{(x-y,x)\downarrow} \\ f_{(x,y)\downarrow} \to -e^{-i\pi/3} f^{\dagger}_{(x-y,x)\uparrow} \end{cases}$
$\mathcal{T}$	$\begin{cases} f_{(x,y)\uparrow} \to f_{(x,y)\downarrow} \\ f_{(x,y)\downarrow} \to -f_{(x,y)\uparrow} \end{cases}$

TABLE II. U1A01 PSG analysis.

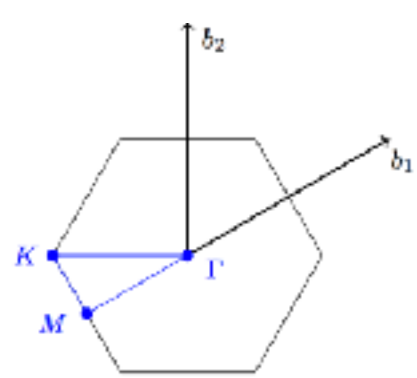
Eight types:

U1A00, U1A01, U1A10, U1A11; U1Bxx

SU(2) trivial Our focus π-flux

Accidental Symmetry
= ideal ESR

$$
\begin{aligned}
H = \sum_{x,y} \Big\{ & t_1 \left[i f^{\dagger}_{(x+1,y)\uparrow} f_{(x,y)\uparrow} + i f^{\dagger}_{(x,y+1)\uparrow} f_{(x,y)\uparrow} - i f^{\dagger}_{(x+1,y+1)\uparrow} f_{(x,y)\uparrow} \right. \\
& \left. - i f^{\dagger}_{(x+1,y)\downarrow} f_{(x,y)\downarrow} - i f^{\dagger}_{(x,y+1)\downarrow} f_{(x,y)\downarrow} + i f^{\dagger}_{(x+1,y+1)\downarrow} f_{(x,y)\downarrow} \right] \\
& + t_1' \left[e^{i\pi/3} f^{\dagger}_{(x+1,y)\uparrow} f_{(x,y)\downarrow} - f^{\dagger}_{(x,y+1)\uparrow} f_{(x,y)\downarrow} + e^{2i\pi/3} f^{\dagger}_{(x+1,y+1)\uparrow} f_{(x,y)\downarrow} \right. \\
& \left. + e^{2i\pi/3} f^{\dagger}_{(x+1,y)\downarrow} f_{(x,y)\uparrow} + f^{\dagger}_{(x,y+1)\downarrow} f_{(x,y)\uparrow} + e^{i\pi/3} f^{\dagger}_{(x+1,y+1)\downarrow} f_{(x,y)\uparrow} \right] \\
& + t_2' \left[e^{i\pi/6} f^{\dagger}_{(x+1,y-1)\uparrow} f_{(x,y)\downarrow} + e^{5i\pi/6} f^{\dagger}_{(x+1,y+2)\uparrow} f_{(x,y)\downarrow} - i f^{\dagger}_{(x-2,y-1)\uparrow} f_{(x,y)\downarrow} \right. \\
& \left. + e^{5i\pi/6} f^{\dagger}_{(x+1,y-1)\downarrow} f_{(x,y)\uparrow} - i f^{\dagger}_{(x-2,y-1)\downarrow} f_{(x,y)\uparrow} + e^{i\pi/6} f^{\dagger}_{(x+1,y+2)\downarrow} f_{(x,y)\uparrow} \right] + h.c. \Big\}
\end{aligned}
$$



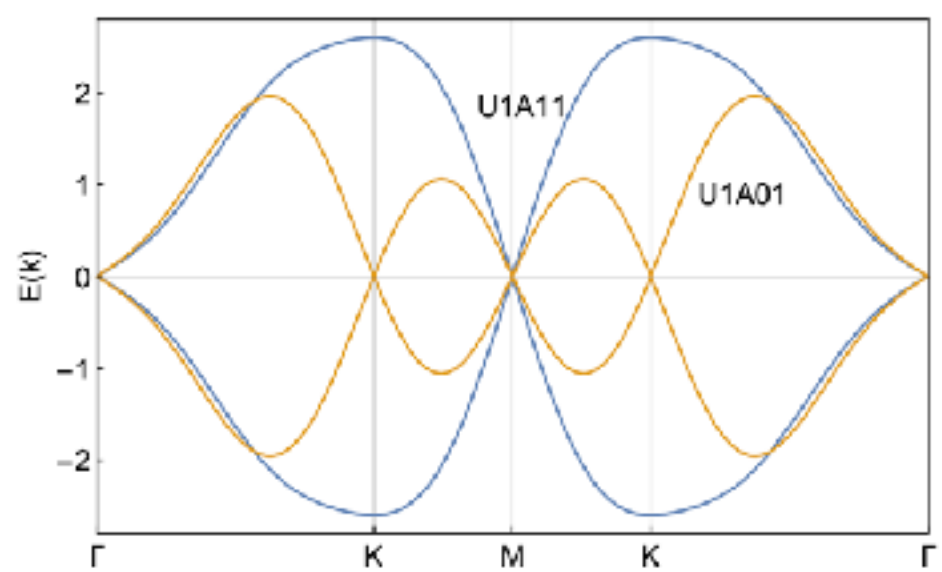
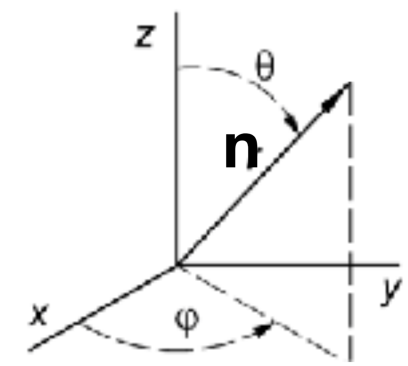


FIG. S-5. Spinon dispersions $E_{1,2}(\mathbf{k})$ along the line Γ-K-M-K-Γ for U1A11 and U1A01 states.

Spinon magnetic resonance

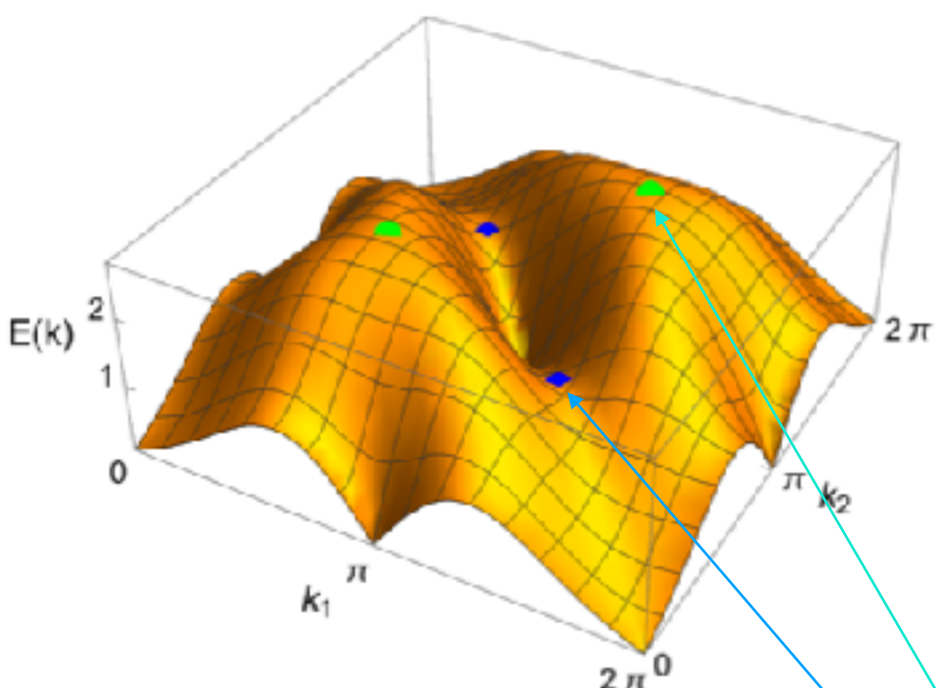
AC magnetic field couples to the total spin $S^a_{\mathbf{r}} = \frac{1}{2} f^\dagger_{\mathbf{r}\alpha}\sigma^a_{\alpha\beta} f_{\mathbf{r}\beta}$



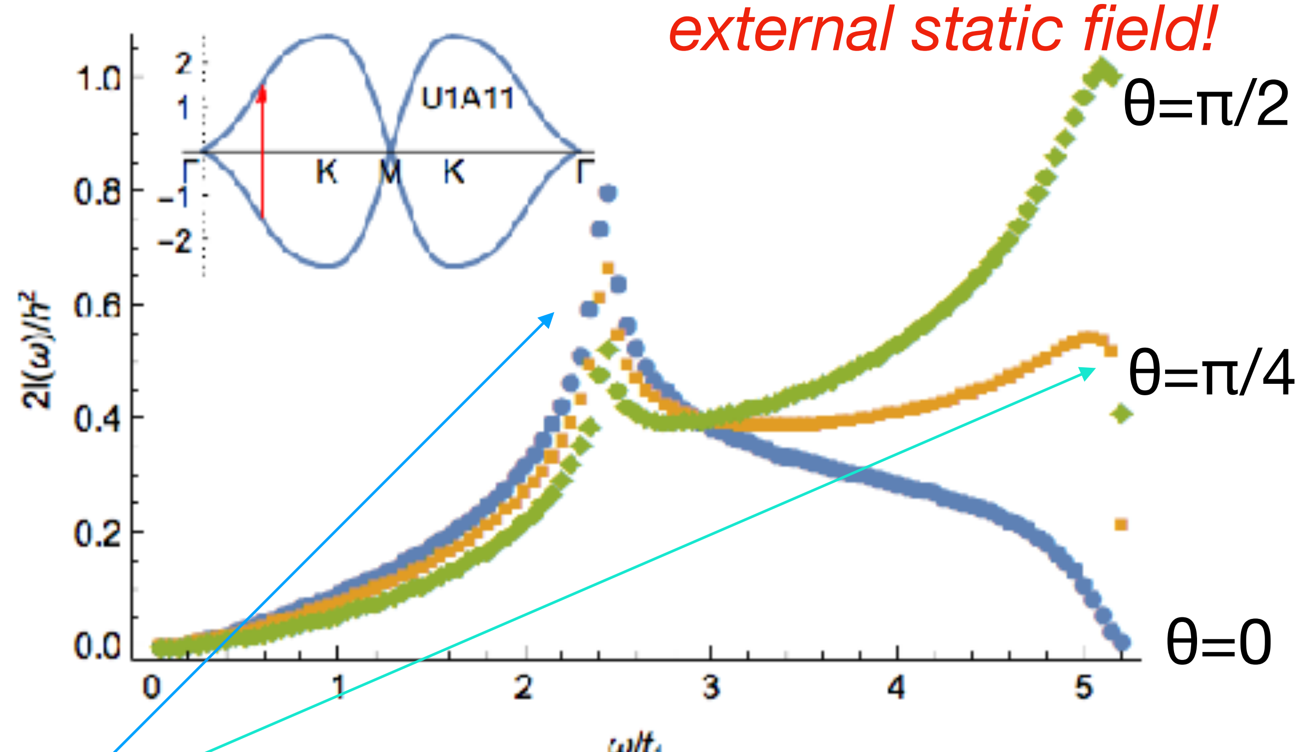
$$V(t) = he^{-i\omega t}\mathbf{n}\cdot\frac{1}{2}\sum_{\mathbf{r}}(f^\dagger_{\mathbf{r}\uparrow}, f^\dagger_{\mathbf{r}\downarrow})\boldsymbol{\sigma}\begin{pmatrix} f_{\mathbf{r}\uparrow} \\ f_{\mathbf{r}\downarrow}\end{pmatrix}$$

Rate of energy absorption $I(\omega) = -\omega\chi''_{\mathrm{nn}}(\omega)|h|^2/2$

Dynamic susceptibility at **q**=0 $$\chi_{\mathrm{nn}}(\omega) = \frac{1}{4N}\sum_{\mathbf{k}}\frac{n_{\mathbf{k}\alpha}-n_{\mathbf{k}\beta}}{\omega+E_\alpha(\mathbf{k})-E_\beta(\mathbf{k})+i0} \times(U^+_{\mathbf{k}}\sigma^a U_{\mathbf{k}})_{\alpha\beta}(U^+_{\mathbf{k}}\sigma^b U_{\mathbf{k}})_{\beta\alpha}\hat{n}^a\hat{n}^b$$

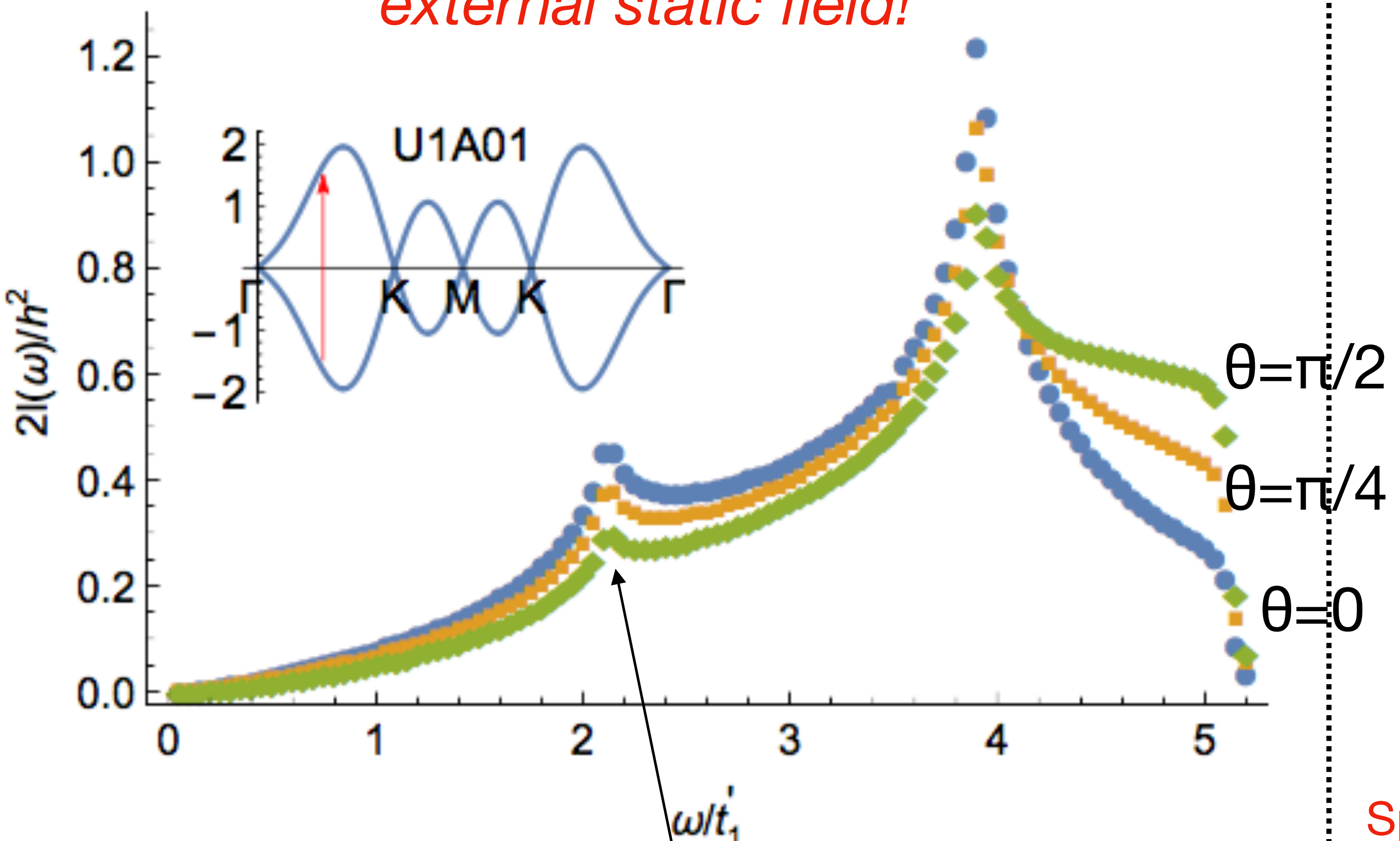


Absorption without external static field!

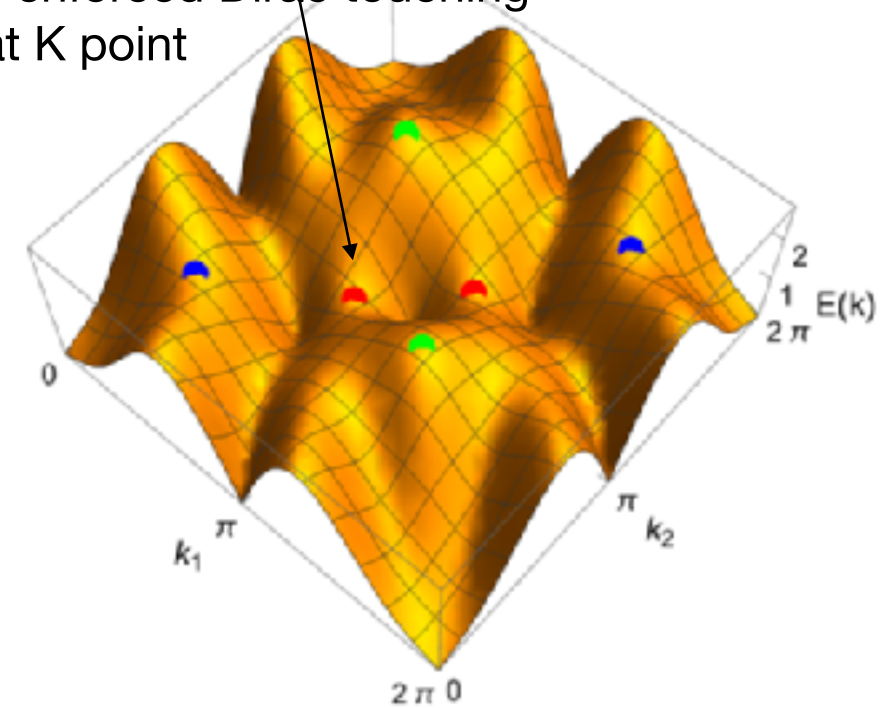


van Hove singularities

Absorption without external static field!

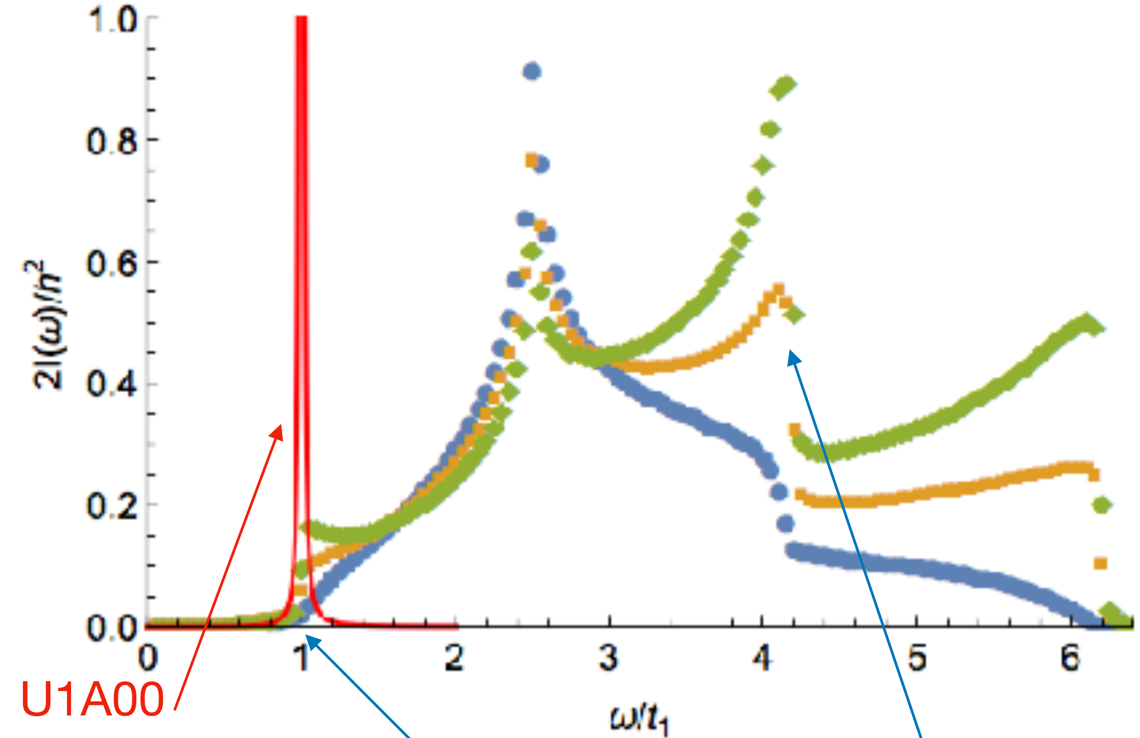


Additional extremum in the spinon spectrum due to symmetry-enforced Dirac touching at K point



With magnetic field along Z

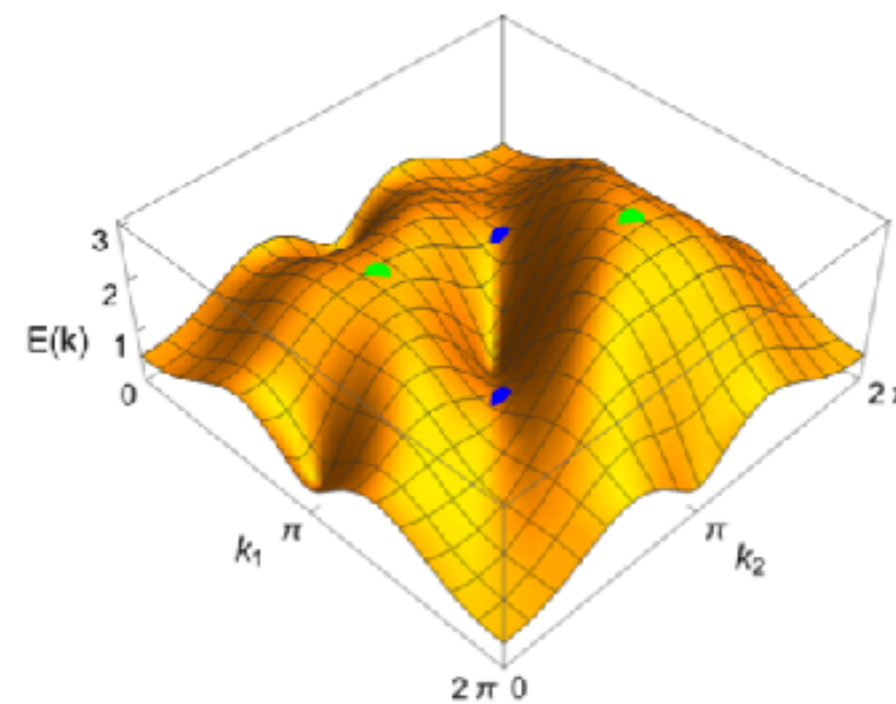
U1A11



U1A00
Spinon Fermi surface state,
accidental SU(2)
$\sin^2\theta\ \delta(\omega - B_z)$

threshold frequency is determined by B_z

additional singularity



Existing ESR in YbMgGaO4

Y. Li, G. Chen, W. Tong et al, Phys. Rev. Lett. 115, 167203 (2015).

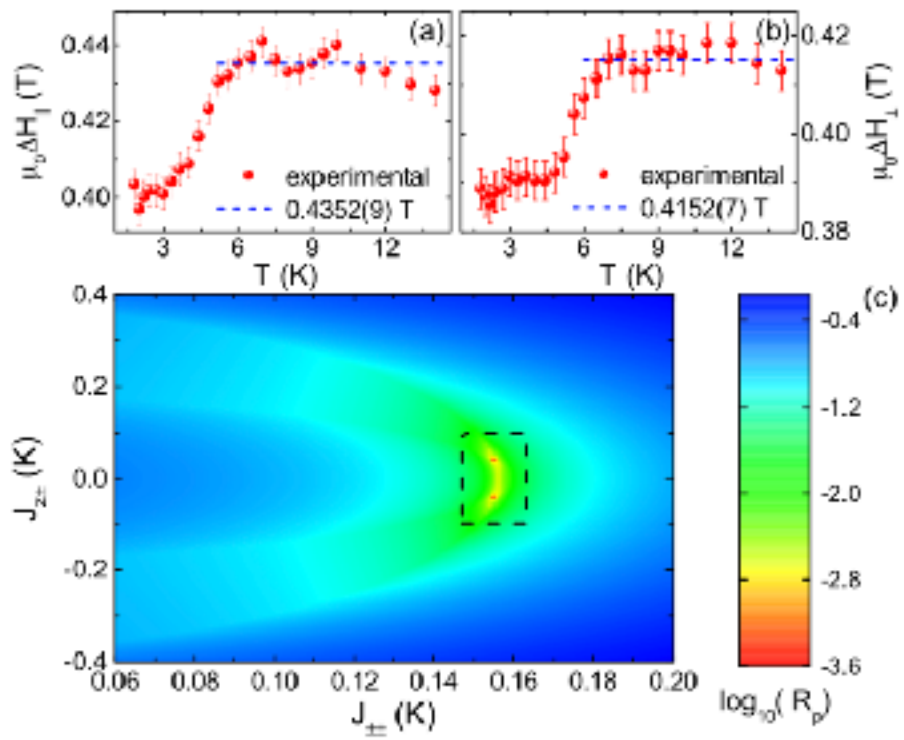


FIG. 3. (Color online.) The temperature dependence of ESR linewidths (a) parallel and (b) perpendicular to the c axis. The dashed lines are the corresponding constant fits to the ESR linewidth data at $T > 6$K. (c) The deviation, R_p, of the experimental ESR linewidthes from the theoretical ones for $YbMgGaO_4$. The dashed rectangle gives the optimal parameters $|J_{\pm\pm}| = 0.155(9)$K and $|J_{z\pm}| = 0.04(10)$K.

Minimum temperature: 1.8 K

X. Zhang, F. Mahmood, M. Daum et al, arXiv: 1708.07503.

Model	A	B	B*	C
J_1^{zz} (meV)	0.126	0.164	0.151(5)	0.149(5)
$J_1^{\pm}$ (meV)	0.109	0.108	0.088(3)	0.085(3)
$J_1^{\pm\pm}$ (meV)	0.013	0.056	0.13(2)	0.07(6)
$\lvert J_1^{z\pm}\rvert$ (meV)	0	0.098	0.1(1)	0.1(1)
J_2/J_1	0.22	0	0	0.18(7)
$g_\parallel$	3.72	3.72	3.81(4)	3.81(4)
$g_\perp$	3.06	3.06	3.53(5)	3.53(5)

TABLE I. Exchange parameters for different models derived from fitting the spin-wave dispersions. Models A and B are from [60] and [43], respectively. Model C is from our global fit to the TDTS and INS data. Model B* is from a global fit to the data by ignoring NNN interactions, *i.e.* $J_2 = 0$. Uncertainties in the values represent the 99.7% confidence interval (3 s.d.) in extracting the fitting parameters.

Lower the temperature to see the spinon effect!
T ~ 0.1 K

Linewidth *vs* line shape

- Spinon band structure determines *line shape* of absorption (discussed previously).
- Interactions determine h,T-dependent *line width* !

Ideal U(1) spin liquid

$$L_{u(1)} = \psi_\alpha^\dagger \Big(\partial_t - i A_0 + \epsilon(\nabla - i\vec{A}) \Big) \psi_\alpha$$

Rashba-like perturbation due to spin orbit interaction

$$\delta L_R = \alpha_R \psi_\alpha^\dagger \Big((p_x + A_x)\sigma^y - (p_y + A_y)\sigma^x \Big) \psi_\alpha$$

Mori-Kawasaki formalism

Retarded spin GF $$G^R_{S^+S^-}(\omega) \propto 1/(\omega - h - \Sigma(\omega))$$

Line width $$\eta(\omega = h) = \mathrm{Im}\Sigma(\omega = h) = -\frac{\mathrm{Im}\{G^R_{\mathcal{A}\mathcal{A}^\dagger}(\omega)\}}{2\langle S^z \rangle}$$

Perturbation is encoded in the **composite** operator
(depends on polarization of microwave radiation!)

$$\mathcal{A} = [\delta H_R, S^+] = -2i\alpha_R \sum_{p,q} \psi^\dagger_{p+q}\sigma^z\psi_p(A_{x,q} - iA_{y,q})$$

$$\eta(h) \sim \alpha_R^2 \int d\epsilon[1 + n_B(\epsilon) + n_B(h - \epsilon)]\mathrm{Im}G^R_{S^z_q S^z_{-q}}(\epsilon)\mathrm{Im}G^R_{A^-_q A^+_q}(h - \epsilon)$$

Gauge field propagator $$\mathrm{Im}G^R_{A^-_q A^+_q}(\nu) = \frac{\gamma q \nu}{\gamma^2\nu^2 + \chi^2 q^6}$$

\`Particle-hole' spinon continuum $$\mathrm{Im}G^R_{S^z_q S^z_{-q}}(\epsilon) = \frac{m}{2\pi}\frac{\epsilon}{\sqrt{v^2q^2 - \epsilon^2}}\Theta(vq - |\epsilon|)$$

Preliminary results for perturbed U(1) spin liquid

OS, Balents, in progress…

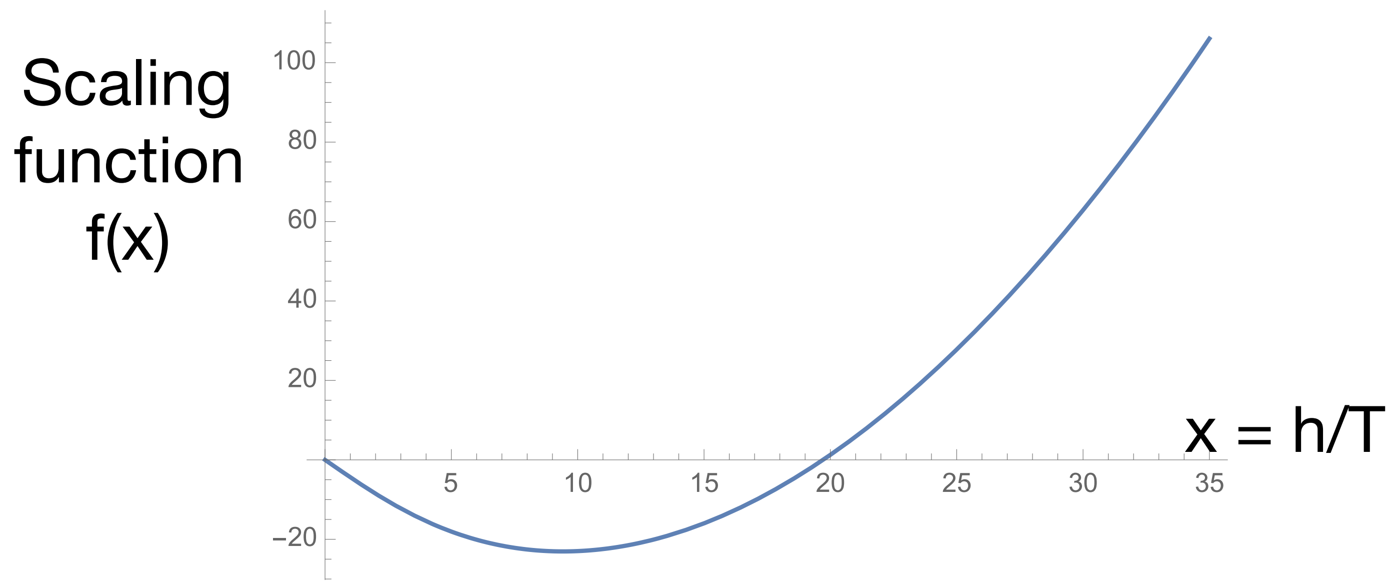
T = 0,
h>> T

$$\eta \sim \alpha_R^2 \omega^{5/3}/h \sim h^{2/3}, h > 0$$

$$\eta \sim \omega^{2/3}, h = 0$$

T > 0,
h<< T

$$\eta = \frac{1}{2\chi_{\mathrm{u}} h}\Big(\frac{mT}{8\pi\chi} + \tilde{c}_0 T^{5/3} f(\frac{h}{T})\Big) \sim \frac{T}{h} + T^{2/3}$$



$$f(x) \to -4.4x \text{ for } x \ll 1; f(x) \to 0.75x^{5/3} \text{ for } x \gg 1$$

Conclusion:

Spinon magnetic resonance is generic feature of spin liquids with significant spin-orbit interaction and fractionalized excitations

Main features:

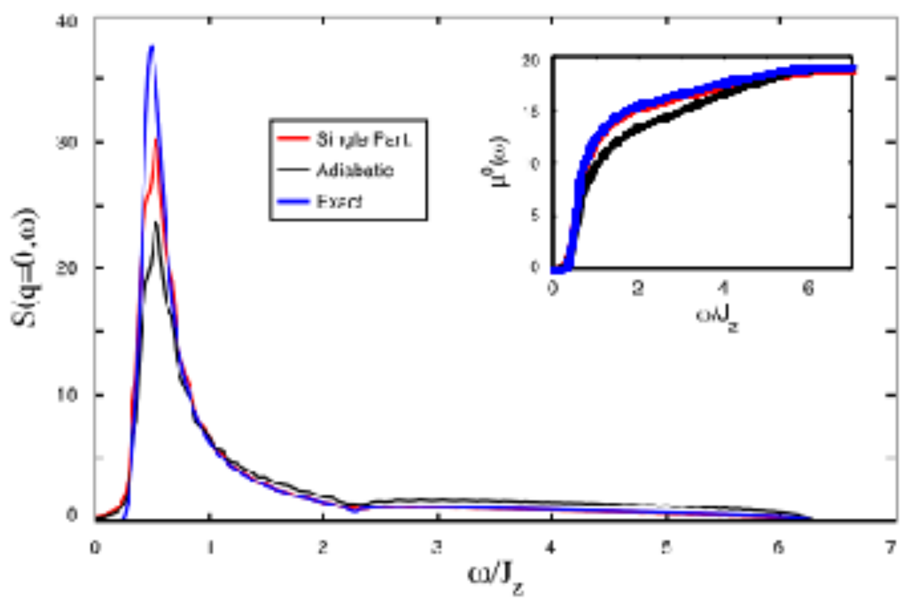
- **broad continuum response**
- **zero-field absorption** (polarized terahertz spectroscopy)
- **strong polarization dependence**
- **van Hove singularities of spinon spectrum**
- **interesting and varying h,T dependence of the *resonance line width***

Kitaev model and α-$RuCl_3$

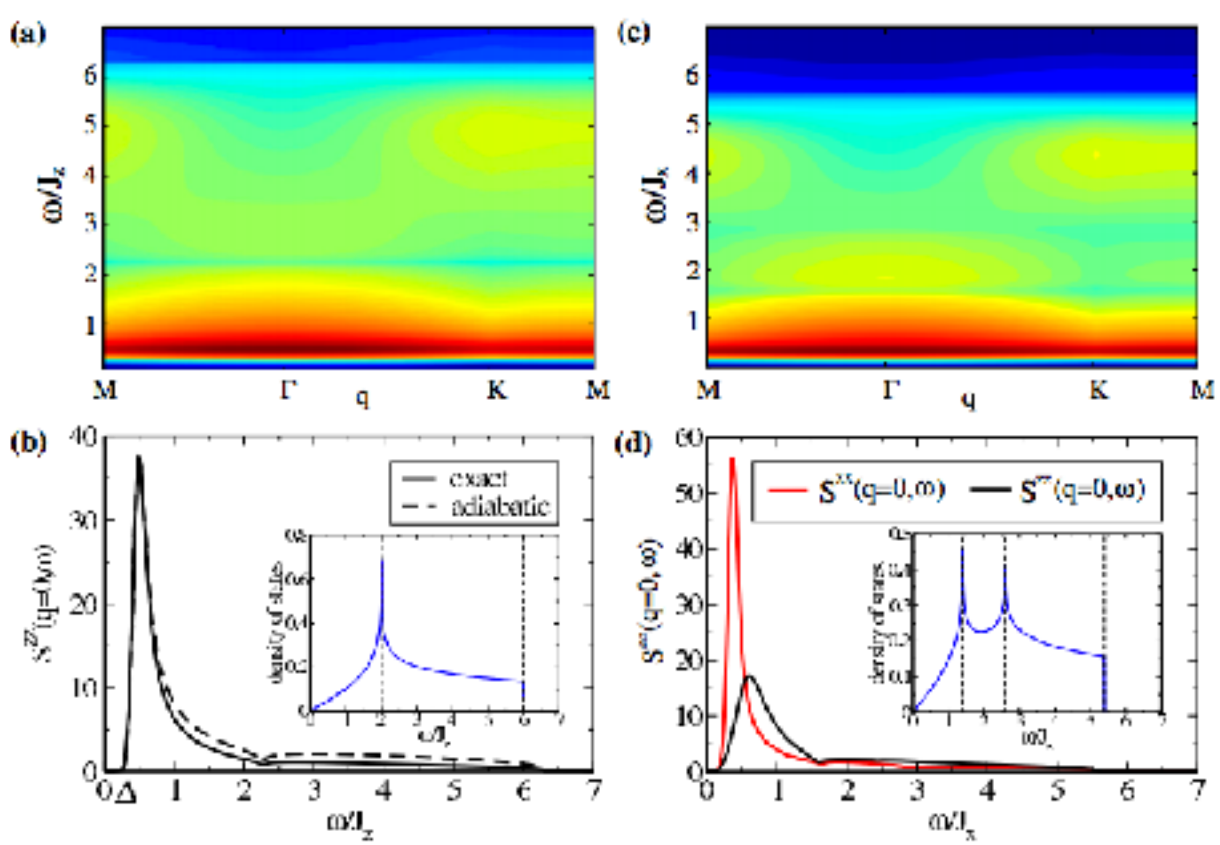
PHYSICAL REVIEW B **92**, 115127 (2015)

Dynamics of fractionalization in quantum spin liquids

J. Knolle,[1,2,*] D. L. Kovrizhin,[1,3] J. T. Chalker,[4] and R. Moessner[2]

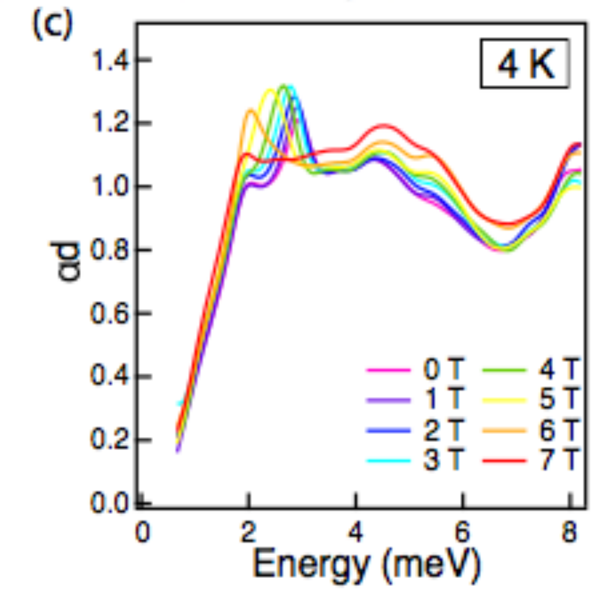


PRL **112**, 207203 (2014) PHYSICAL REVIEW LETT



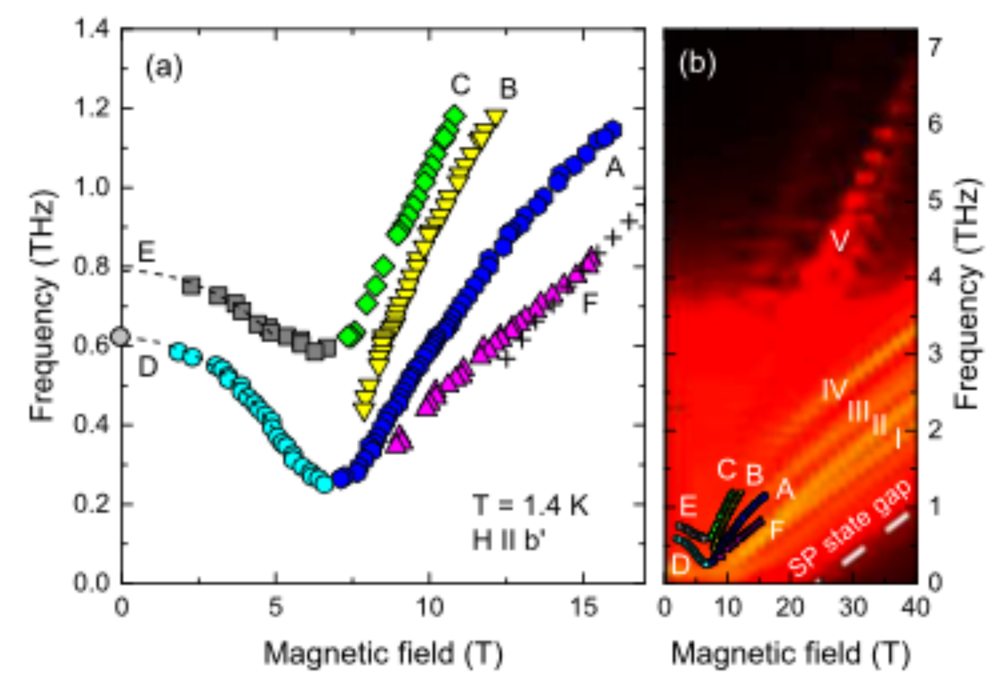
Antiferromagnetic resonance and terahertz continuum in α−$RuCl_3$

A. Little,[1,2] Liang Wu,[1,2,3,*] P. Lampen-Kelley,[4,5] A. Banerjee,[6] S. Patankar,[1,2] D. Rees,[1,2] C. A. Bridges,[7] J.-Q. Yan,[8] D. Mandrus,[4,5] S. E. Nagler,[6,9] and J. Orenstein[1,2]



Direct observation of the field-induced gap in the honeycomb-lattice material α-$RuCl_3$

A. N. Ponomaryov,[1] E. Schulze,[1,2] J. Wosnitza,[1,2] P. Lampen-Kelley,[3,4] A. Banerjee,[5] J. Q. Yan,[3] C. A. Bridges,[6] D. G. Mandrus,[3] S. E. Nagler,[5] A. K. Kolezhuk,[7,8] and S. A. Zvyagin[1]



Field evolution of magnons in α-RuCl$_3$ by high-resolution polarized terahertz spectroscopy

Liang Wu,[1,2,3,*] A. Little,[1,2] E. E. Aldape,[1] D. Rees,[1,2] E. Thewalt,[1,2] P. Lampen-Kelley,[4,5] A. Banerjee,[6] C. A. Bridges,[7] J.-Q. Yan,[8] D. Boone,[9,10] S. Patankar,[1,2] D. Goldhaber-Gordon,[11,10] D. Mandrus,[4,5] S. E. Nagler,[6] E. Altman,[1] and J. Orenstein[1,2,†]

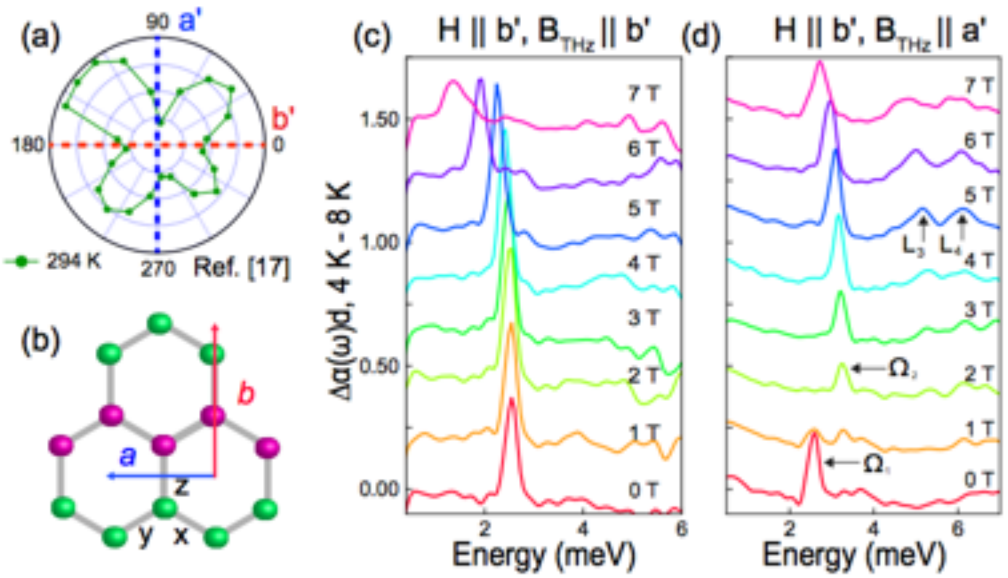


FIG. 1: (a) Transmitted THz electric field amplitude at T = 294 K as a function of sample angle. Blue and red lines represent the minimum transmission axes at $\mathbf{a}'$ and $\mathbf{b}'$ (b) Schematic of honeycomb structure showing **a** and **b** monoclinic axes relative to Ru-Ru bonds. Color of atoms illustrates zigzag order. Bond labels x, y, and z denote the component of the spin interacting along a given bond in the Kitaev model. (c) Magnon absorption as a function of frequency for $\mathbf{H} \parallel \mathbf{b}' \parallel \mathbf{B_{THz}}$ and $\mathbf{H} \parallel \mathbf{b}' \perp \mathbf{B_{THz}}$ respectively. The magnon contribution is extracted from the total THz absorption by subtracting a reference at T = 8 K, above T$_N$, from a T = 4 K spectrum at each field. Traces are offset for clarity.

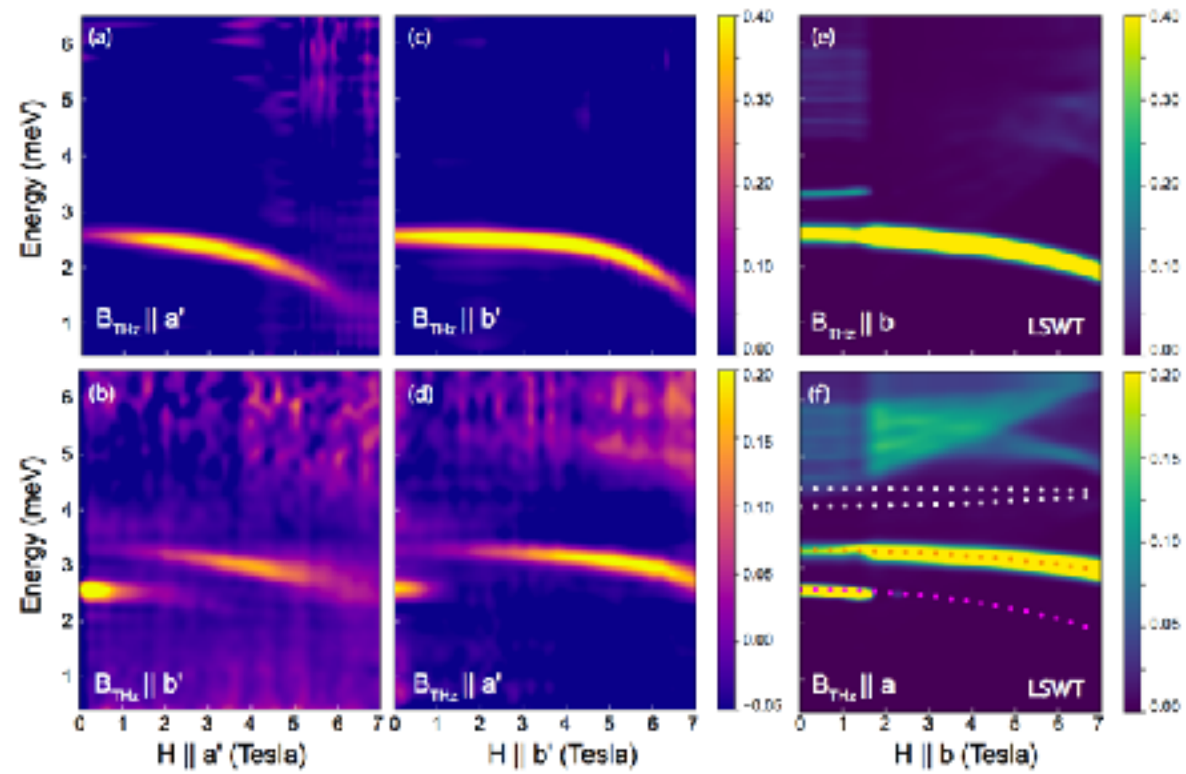


FIG. 2: Magnon energies and absorption strengths at $\mathbf{Q} = 0$ as a function of external in-plane magnetic field, **H**. Experimental

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Topical Review

Electrodynamics of quantum spin liquids

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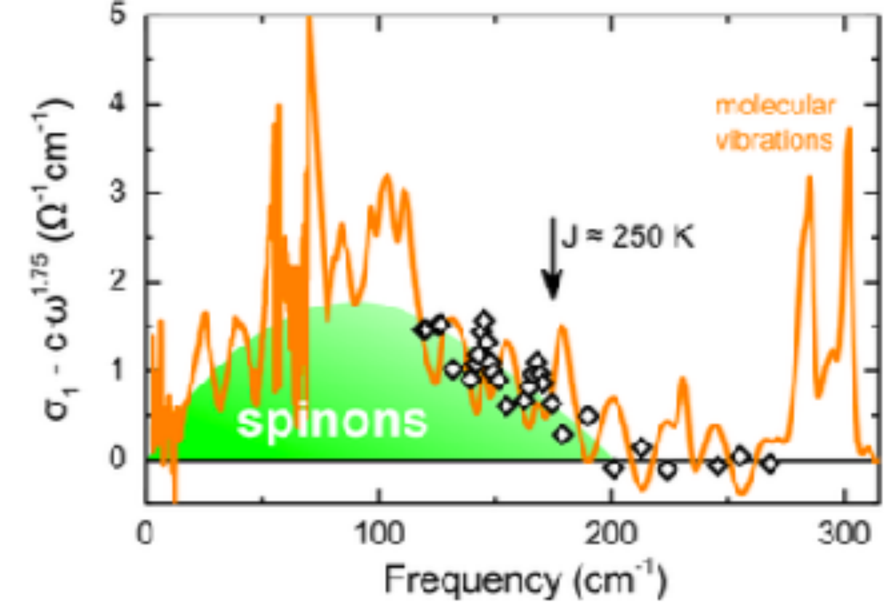

Figure 13. After subtracting the power-law background related with the Mott–Hubbard band, we obtain a broad low-energy feature below approximately 200 cm^{-1}, which is close to the antiferromagnetic exchange energy of β'-EtMe$_3$Sb[Pd(dmit)$_2$]$_2$. Hence, we associate it with the coherent spinon Fermi surface predicted previously [60, 62]. The dome-like shape of the spinon contribution arises due to the rapid decay towards $\omega \to 0$, consistent with a power ~~law such as the postulated ω^2~~ behavior [62]. This feature becomes visible when the background conductivity is sufficiently suppressed due to opening of the Mott gap. The strong, narrow modes at higher frequencies correspond to vibrational features.

Examples of current literature

200 cm^{-1} = 6 THz

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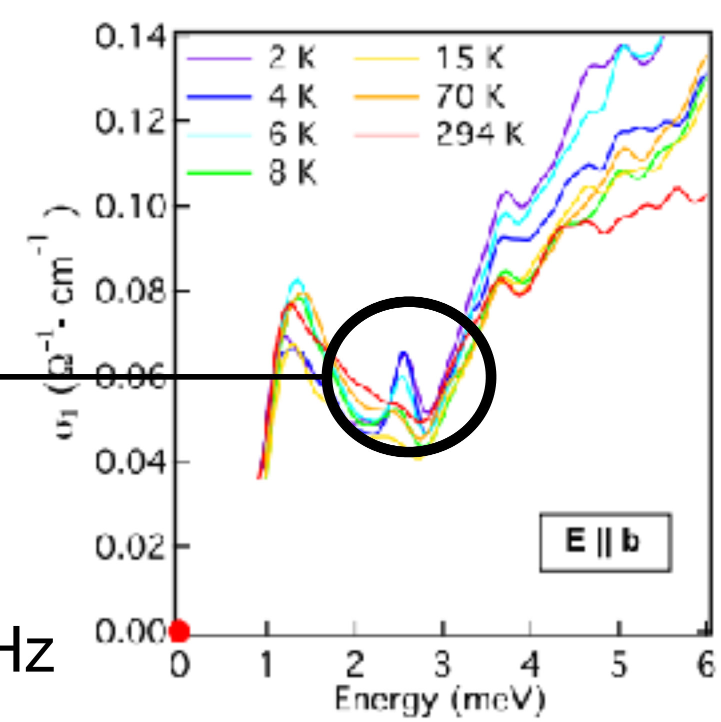
Antiferromagnetic Resonance and Terahertz Continuum in α-RuCl$_3$

A. Little,[1,2] Liang Wu,[1,2,3,*] P. Lampen-Kelley,[4,5] A. Banerjee,[5] S. Patankar,[1,2] D. Rees,[1,2] C. A. Bridges,[7] J.-Q. Yan,[8] D. Mandrus,[4,5] S. E. Nagler,[6,9] and J. Orenstein[1,2]

Spinons?



4 meV = 1 THz

FIG. 3. Absorption spectra interpreted as optical conductivity, with E parallel to b.