Spinon magnetic resonance of two-dimensional U(1) spin liquids with Fermi surface

Oleg Starykh, University of Utah

July 14, 2018

Outline

- *Main ingredients*
  - spin liquid
  - absence of spin-rotational symmetry: spin-orbit, DM, anisotropy…
- *Line shape:* ESR of two-dimensional spinon continuum *YbMgGaO4*
- *Line width: ESR of spinons coupled to gauge field*
- Conclusions

The big question(s)

What is quantum spin liquid?

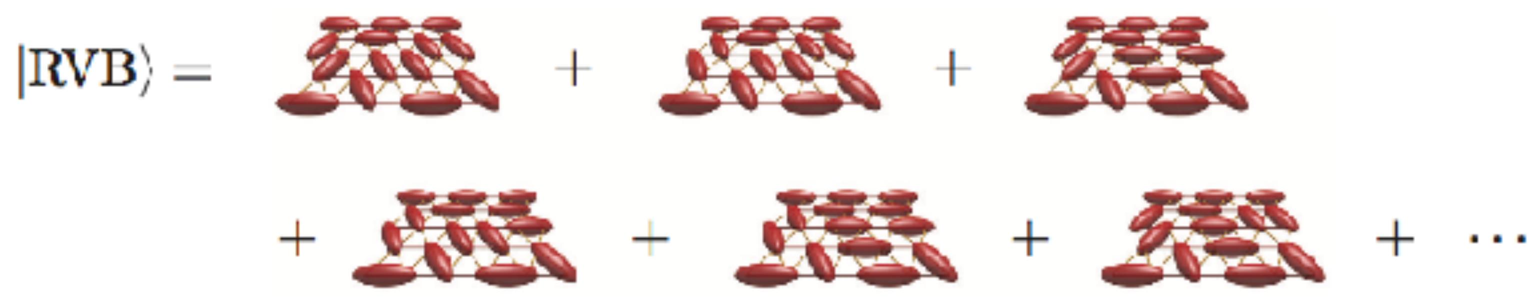


Figure 1. A 'resonating valence bond' (RVB) state. Ellipsoids indicate spin-zero singlet states of two $S = 1/2$ spins.

Savary, Balents 2017

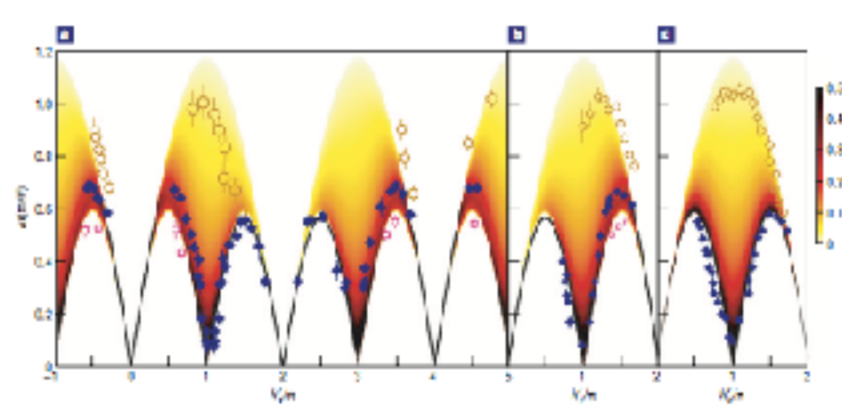
No broken symmetries.
Quantum entangled state:
fractionalized excitations = spinons
emergent gauge fields

Which materials realize it?

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

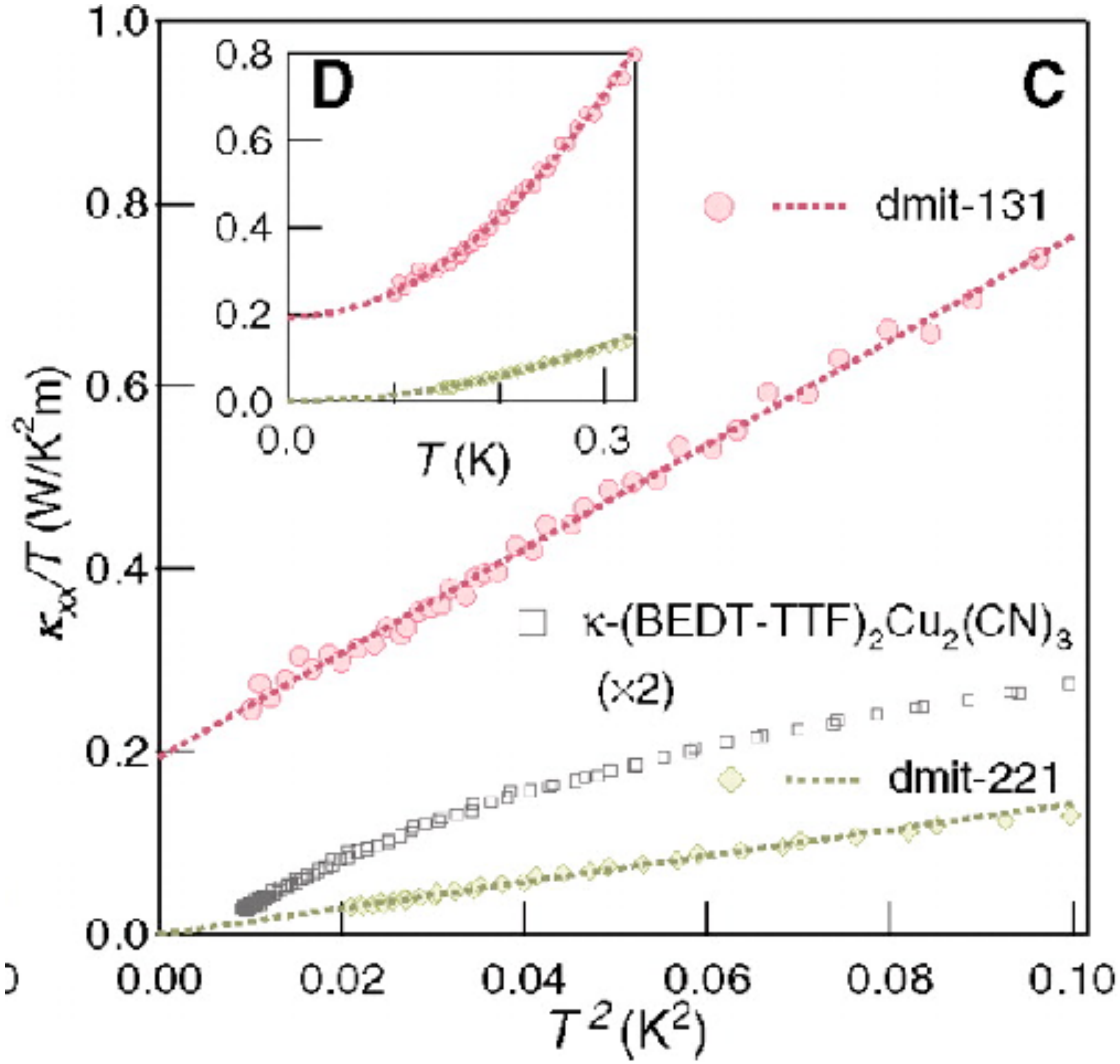
How to detect/observe it?

Neutrons (if good single crystals are available), RIXS, NMR, thermal transport, terahertz optics, ESR



Organic Mott insulators: Spin liquid with spinon Fermi surface?

THERMAL TRANSPORT



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

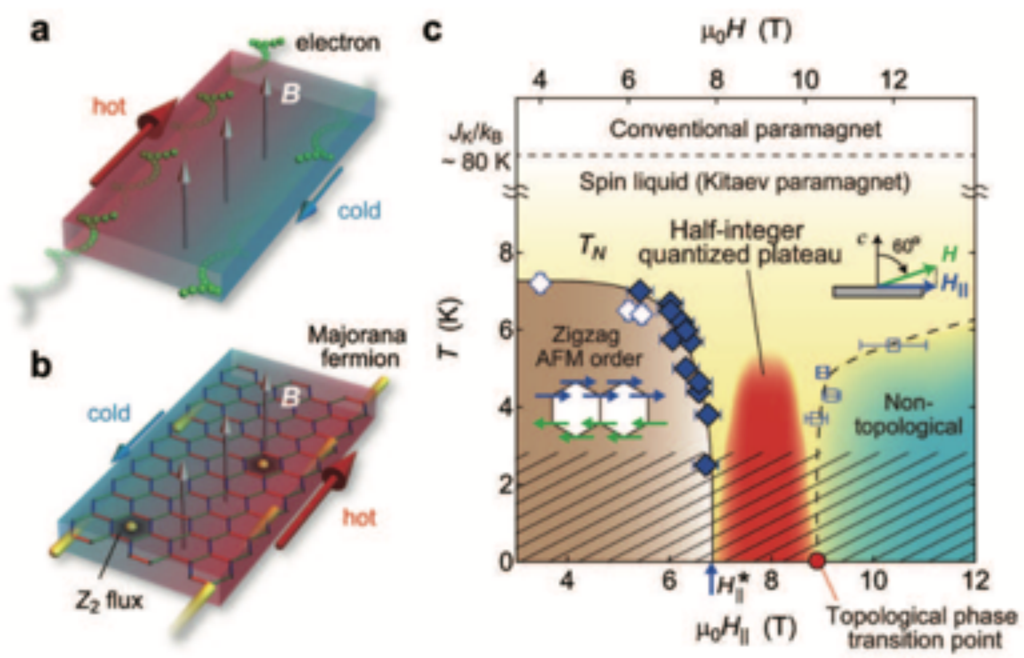
electrical insulator,
but metal-like thermal conductor

α-RuCl3: quantized thermal Hall

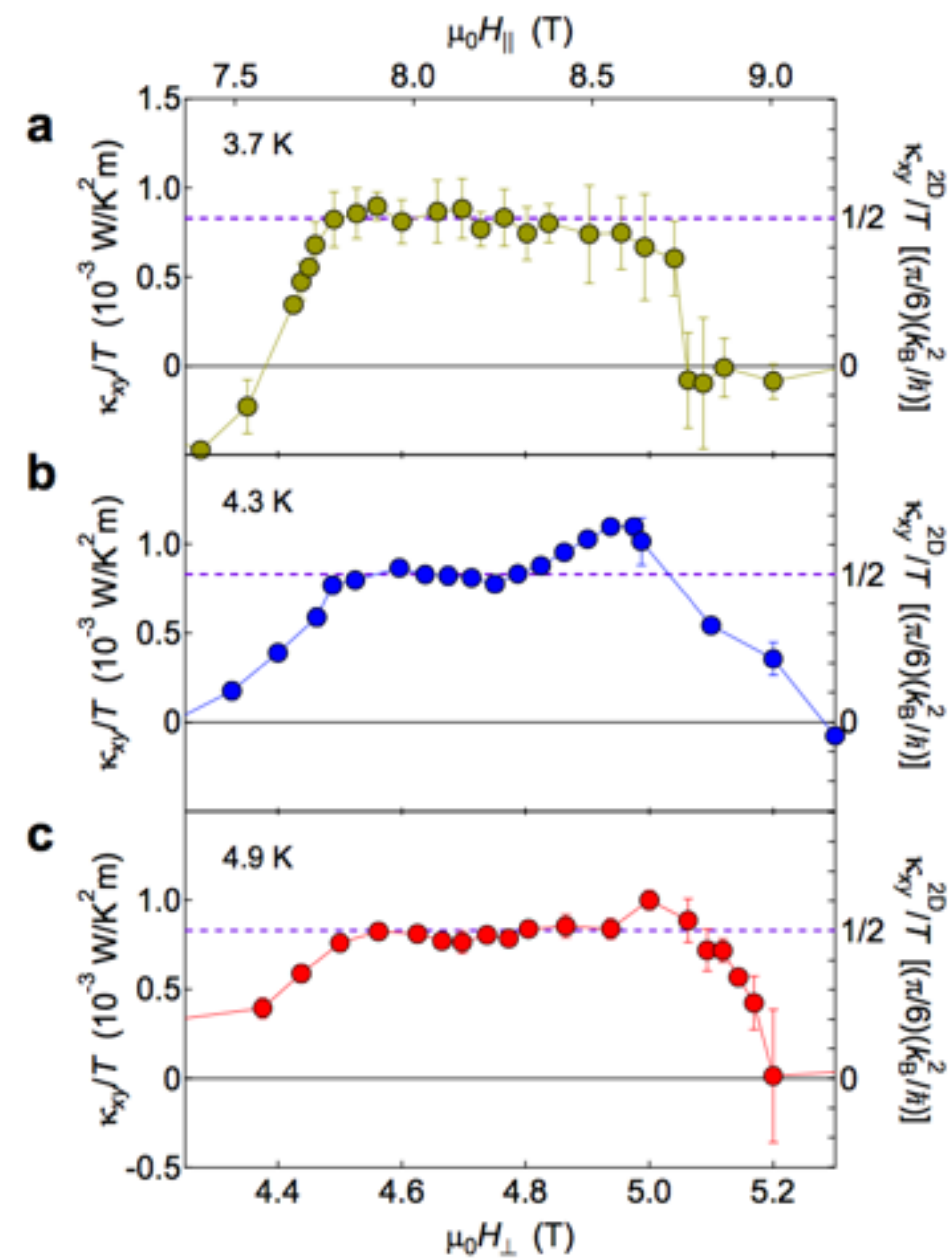
THERMAL TRANSPORT

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

Y. Kasahara[1], T. Ohnishi[1], N. Kurita[2], H. Tanaka[2], J. Nasu[2], Y. Motome[3], T. Shibauchi[4], and Y. Matsuda[1]
[1]*Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[2]*Department of Physics, Tokyo Institute of Technology, Meguro, Tokyo 152-8551, Japan*
[3]*Department of Applied Physics, University of Tokyo, Bunkyo, Tokyo 113-8656, Japan and*
[4]*Department of Advanced Materials Science, University of Tokyo, Chiba 277-8561, Japan*



Edge Majorana spinons?!



Materials

Mott Physics in Organic Conductors with Triangular Lattices

Annual Review of Condensed Matter Physics
Vol. 2:167-188 (Volume publication date March 2011)
First published online as a Review in Advance on January 12, 2011
https://doi.org/10.1146/annurev-conmatphys-062910-140521

Kazushi Kanoda
Reizo Kato

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

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*]

10.30 am - 11.00 am: Bella Lake
Exploration of the quantum spin liquid state in $Ca_{10}Cr_7O_{28}$.

2.00 pm - 2.30 pm: Philippe Mendels
Low-T ^{17}O NMR study of herbertsmithite crystals.

9.30 am -10.00 am: Liang Wu
Antiferromagnetic resonance and terahertz continuum in α-$RuCl_3$

10.30 am - 11.00 am: Arnab Banerjee (invited)
Magnetic disorder, order and models of α-$RuCl_3$

6.00 pm -6.30 pm: Yasuhiro Shimizu
Quantum criticality of Kitaev spin liquid

9.00 am - 9.30 am: Yuji Matsuda (invited)
Thermal Hall effect in a Kitaev spin liquid: A possible signature of Majorana chiral edge current

Kitaev materials


Spinon
Magnetic
Resonance
CRO 2 1 ENG
FIFA

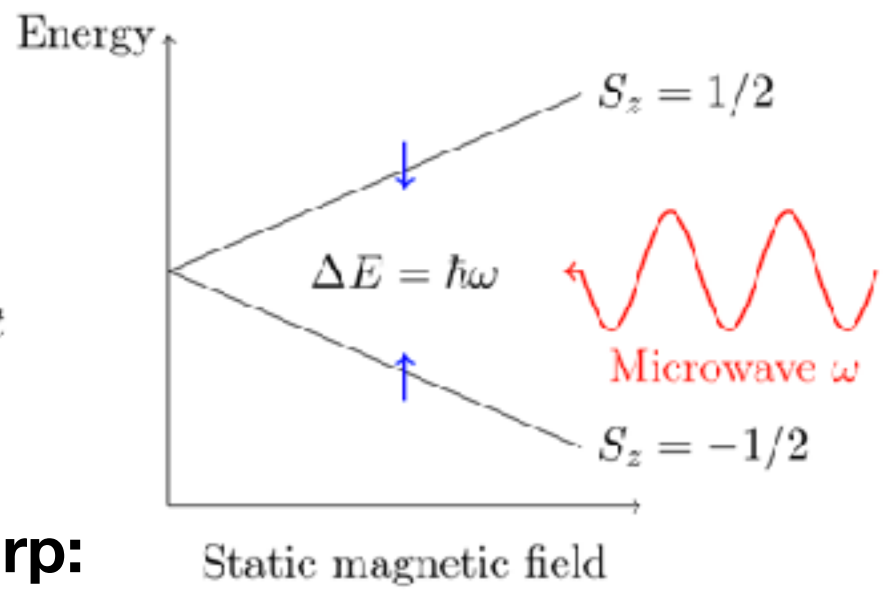
Electron Spin Resonance (ESR)

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 “imperfections” (spin-orbit, Dzyaloshinksii-Moriya) into a probe of exotic spin state and its excitations

Condensed matter physics in 21 century:

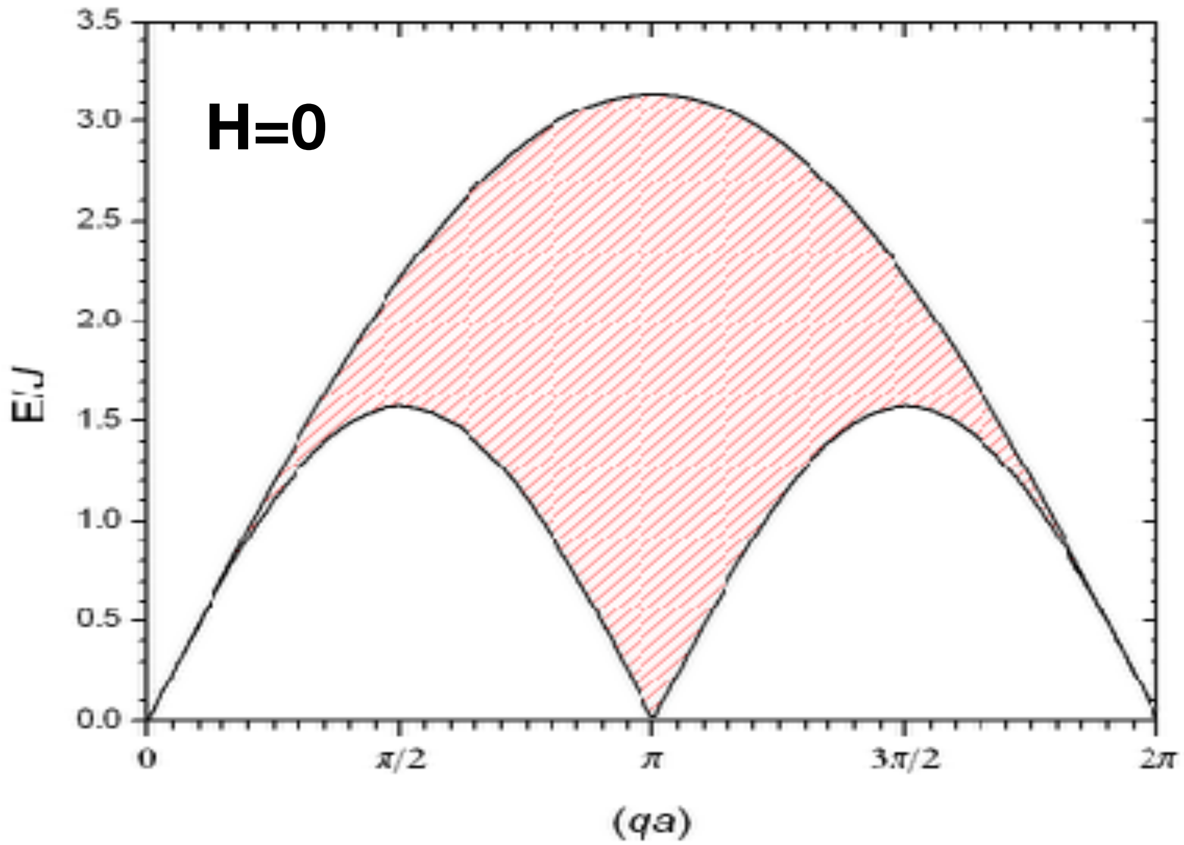
the age of **spin-orbit**

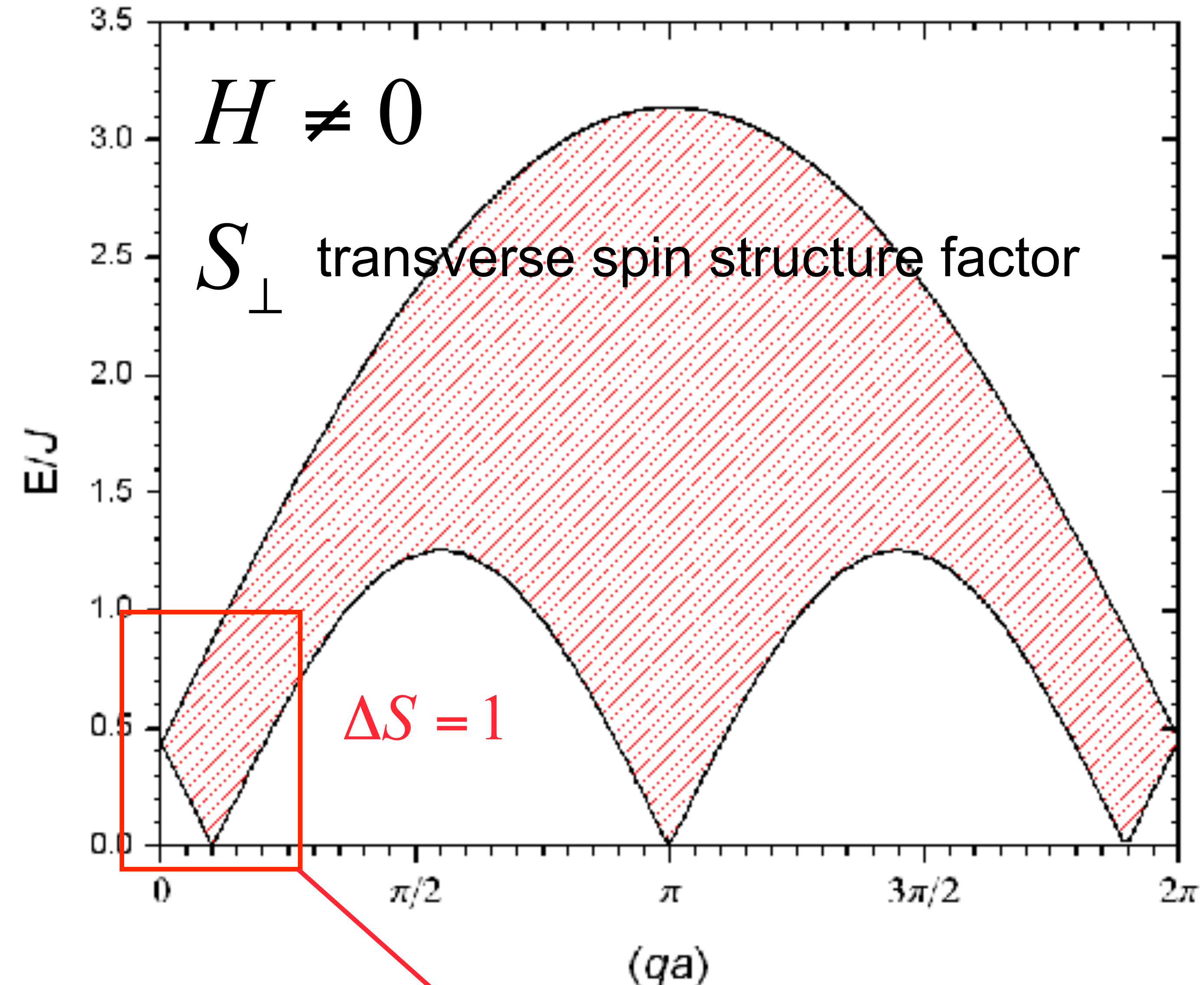
✓ spintronics

✓ topological insulators, Majorana fermions

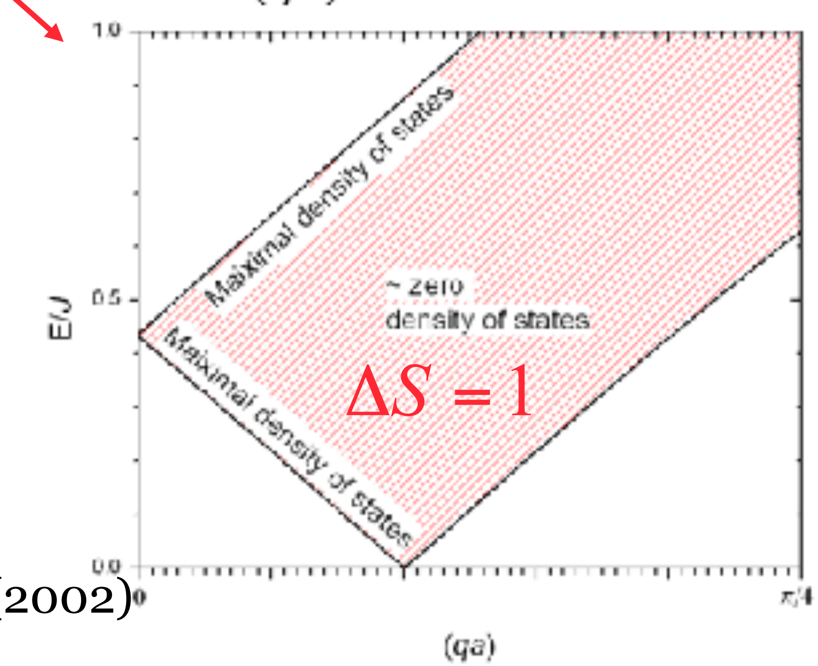
✓ Kitaev’s non-abelian honeycomb spin liquid

Probing spinon continuum in one dimension





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



Dender et al, PRL 1997

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

Uniform Dzyaloshinskii-Moriya interaction

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

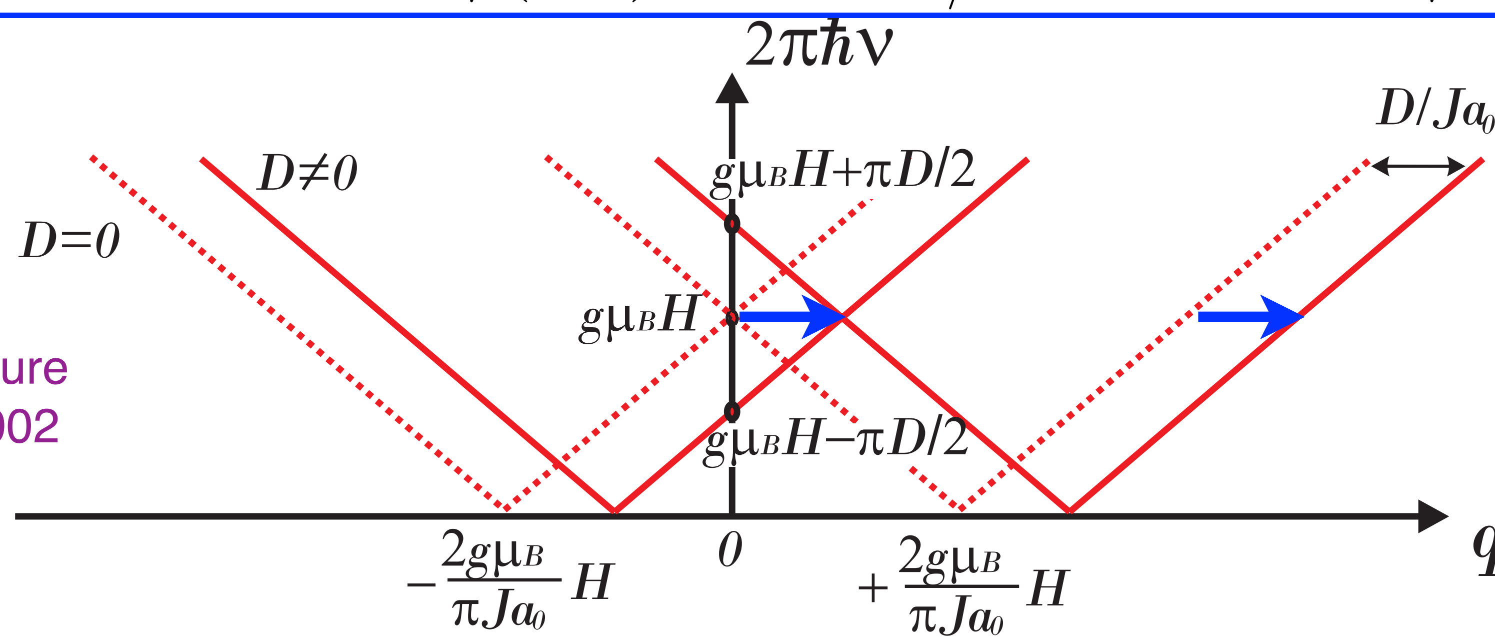
chain — uniform DM along the chain — magnetic field

!

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

- 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

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

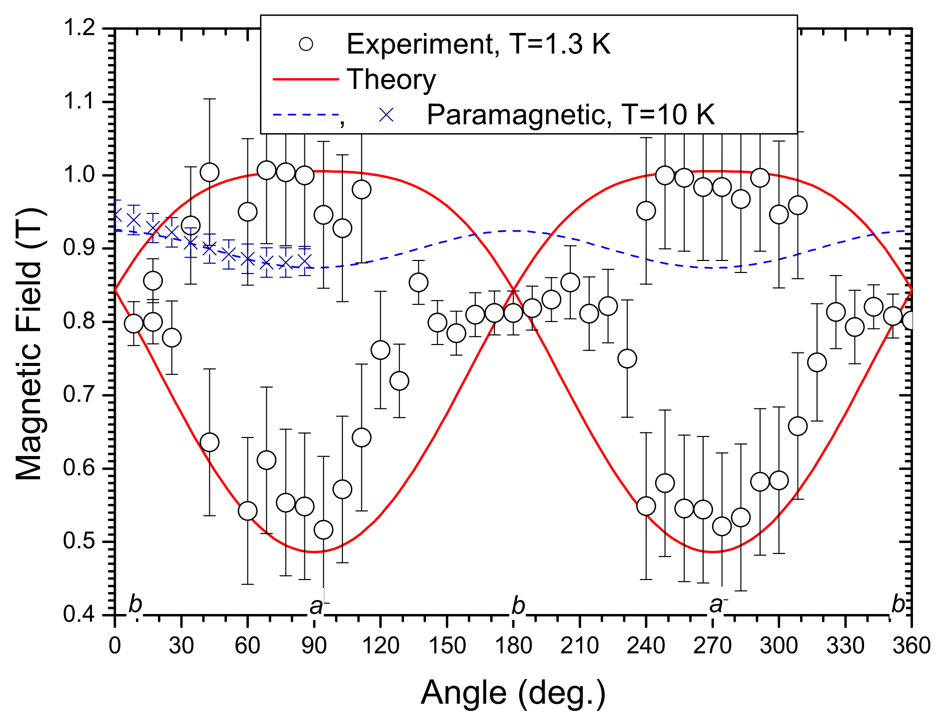
K. Yu. Povarov,[1,*] A. I. Smirnov,[1,2] O. A. Starykh,[3,4] S. V. Petrov,[1] and A. Ya. Shapiro[5]

- 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

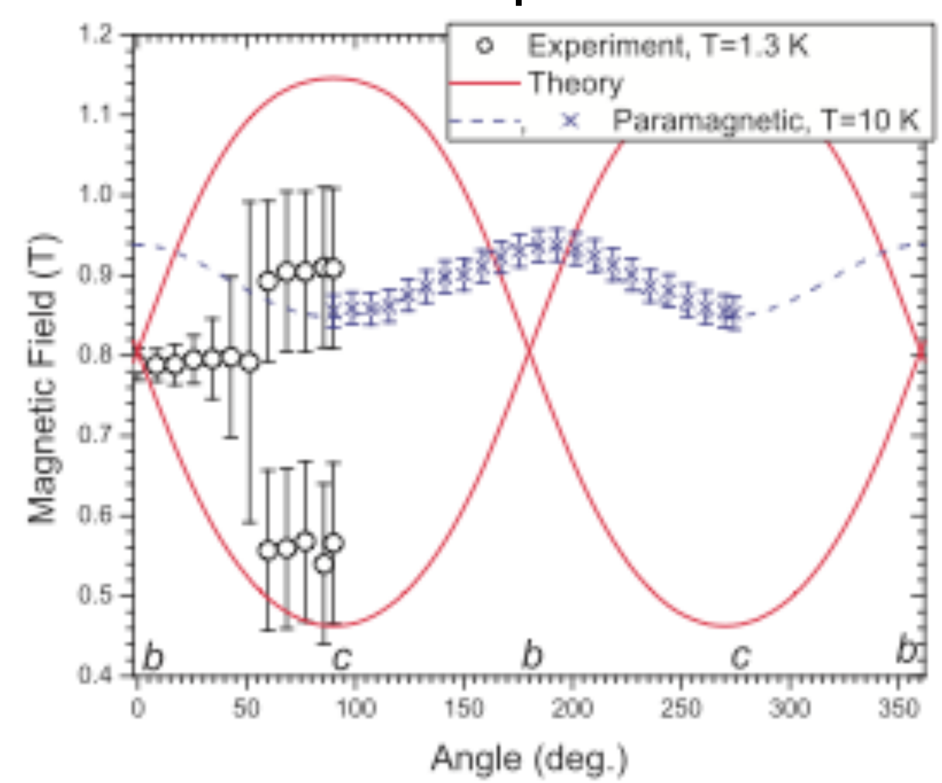


$$D_a/(4\hbar) = 8 \text{ GHz}$$
$$D_c/(4\hbar) = 11 \text{ GHz}$$

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

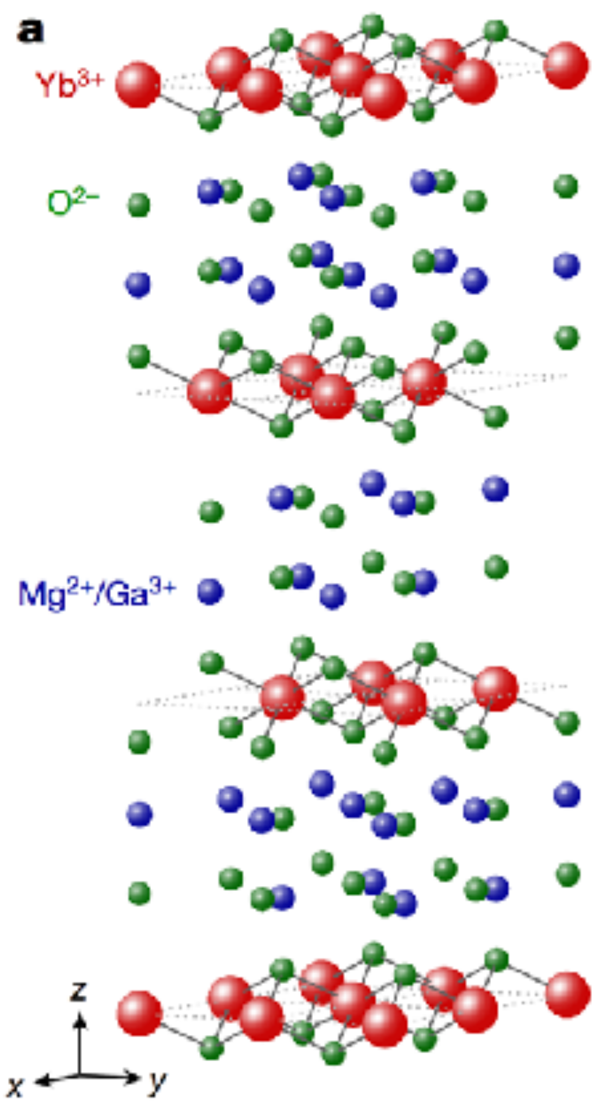
S. C. Furuya Phys. Rev. B 95, 014416 (2017)

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

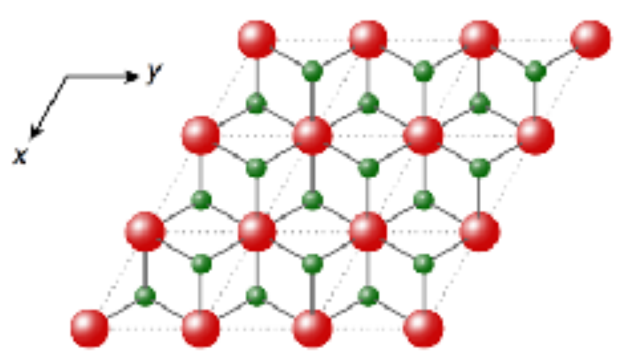


Figure from: Nature 540, pp 559–562 (2016).

Strong spin-orbit coupling

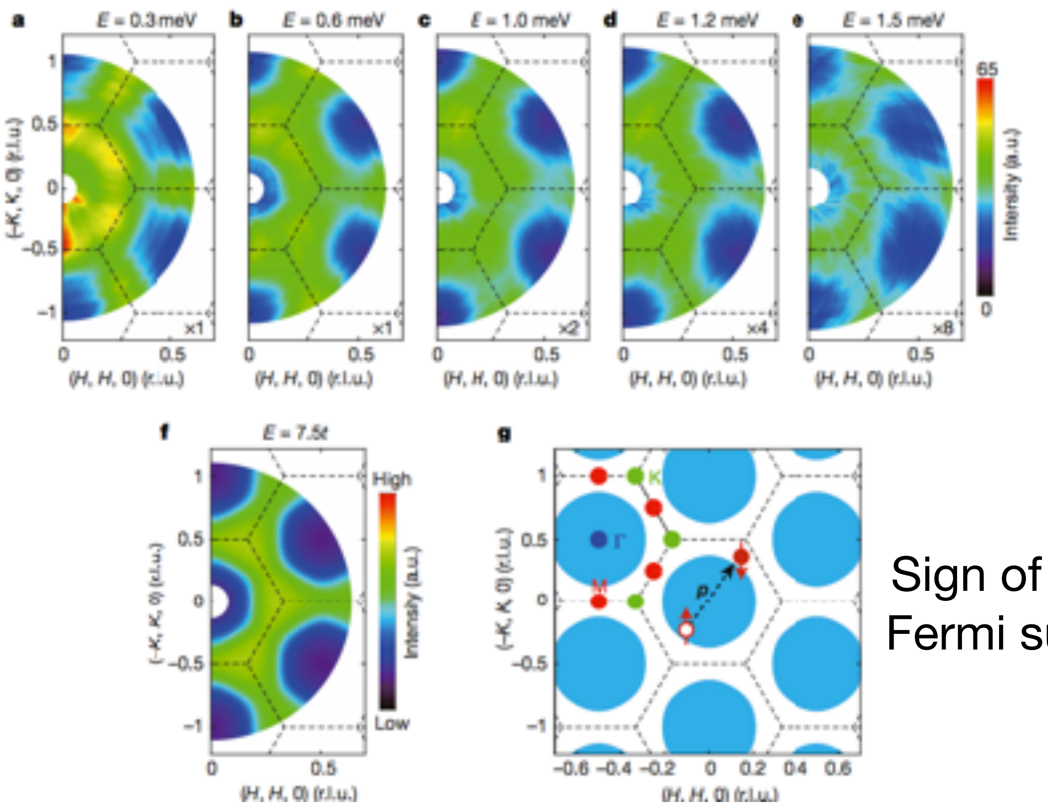
$$
\begin{aligned}
\mathcal{H} = \sum_{<i,j>} & [J_1^{zz} S_i^z S_j^z + J_1^{\pm}(S_i^+ S_j^- + S_i^- S_j^+) \\
& + J_1^{\pm\pm}(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-) \\
& - \frac{iJ_1^{z\pm}}{2}(\gamma_{ij}^* S_i^+ S_j^z - \gamma_{ij} S_i^- S_j^z + \langle i \leftrightarrow j \rangle)]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

LETTER

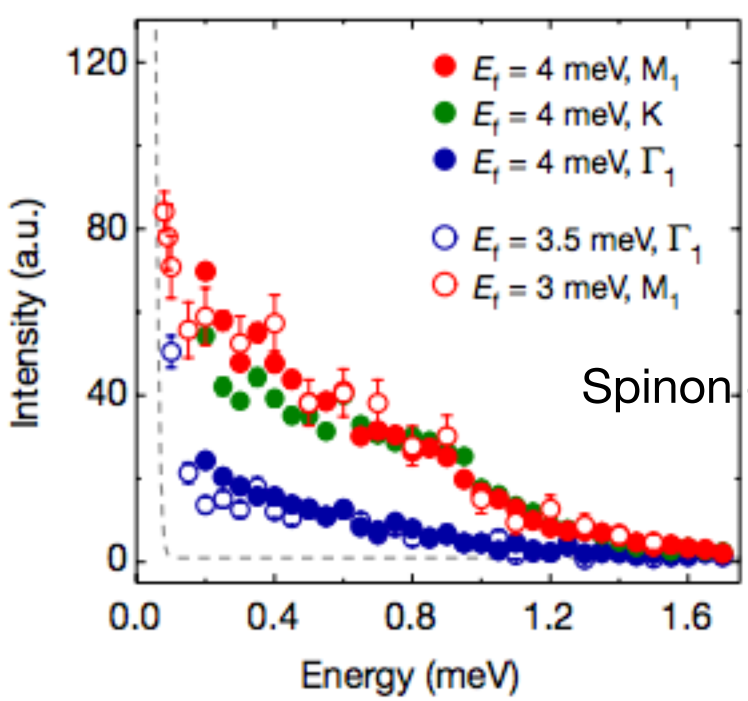
doi:10.1038/nature20614

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



Sign of spinon Fermi surface?

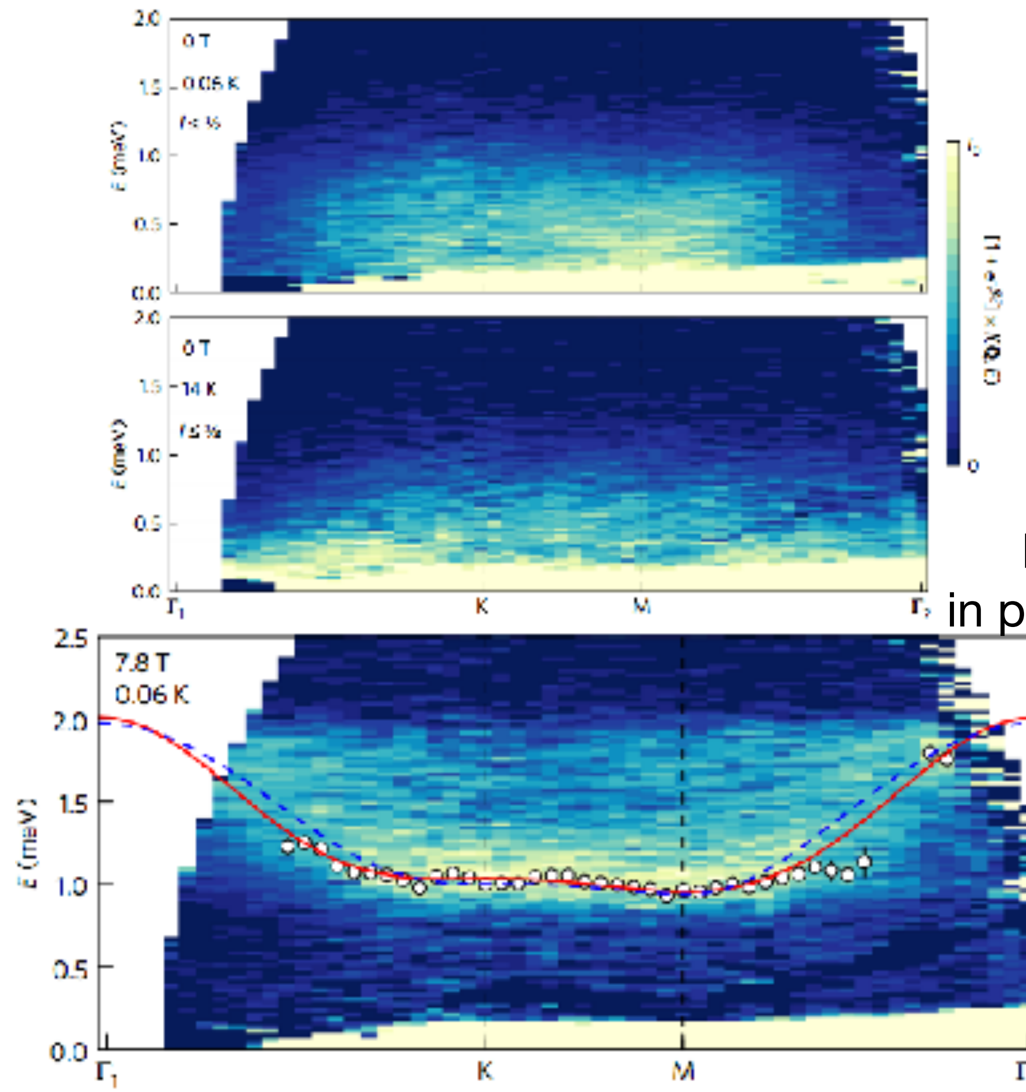


Spinon continuum?

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

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

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

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

Spinon hypothesis

PHYSICAL REVIEW LETTERS 120, 037204 (2018)

PHYSICAL REVIEW B 96, 054445 (2017)

Spinon Fermi surface $U(1)$ spin liquid in the Mott insulator Yb

Yao-Dong Li,[1] Yuan-Ming Lu,

ance of Quantum Spin Liquids

Jia-Wei Mei,[2] and Oleg A. Starykh[1,†]

NEO-ROMANTICISM

S an

Projecti analysis

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

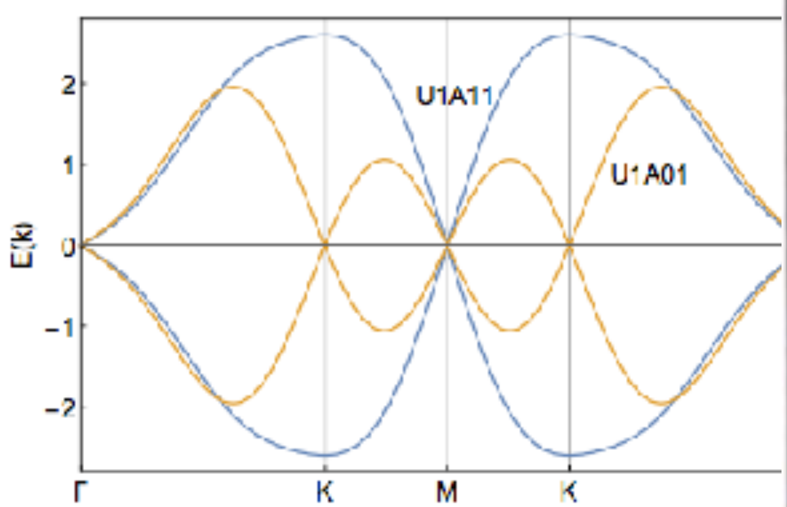
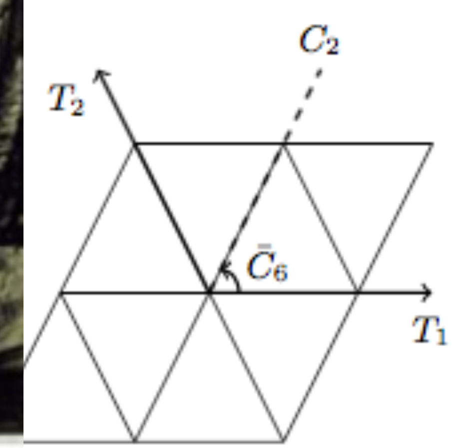


FIG. S-5. Spinon dispersions $E_{1,2}(\mathbf{k})$ along the line Γ-K-M-K-Γ for U1

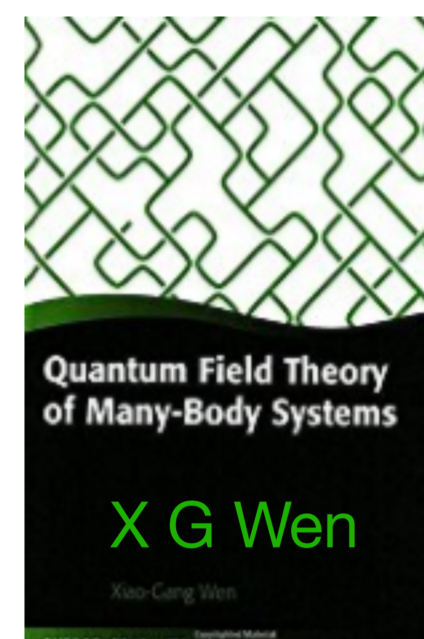
Dirac spectrum!

John Craxton
Dreamer in Landscape 1942
Tate

cal spin S is bilinear of spinons f,
ger symmetry group than spins,
to gauge freedom and
es of possible mean-fields.
escribe the same spin problem.



S-1. The symmetry operations.



Spinon hypothesis

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,*]

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

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

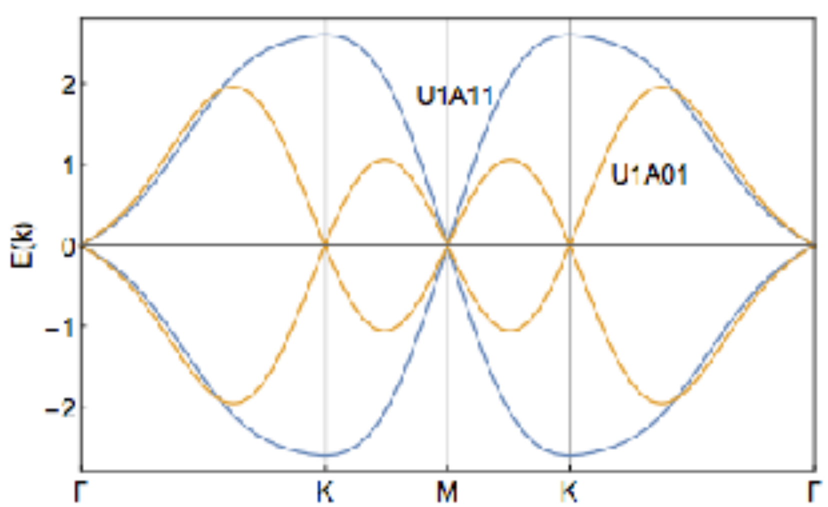


FIG. S-5. Spinon dispersions $E_{1,2}(\mathbf{k})$ along the line Γ-K-M-K-Γ for U1A11 and U1A01 states.

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!

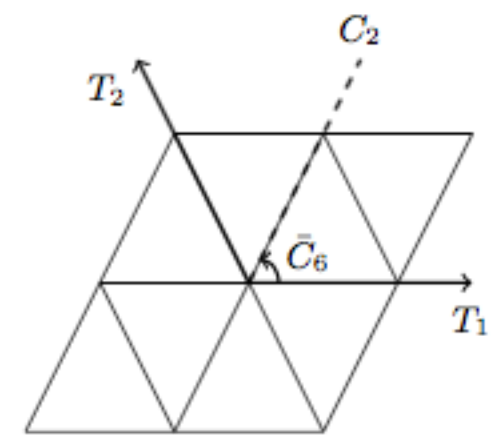
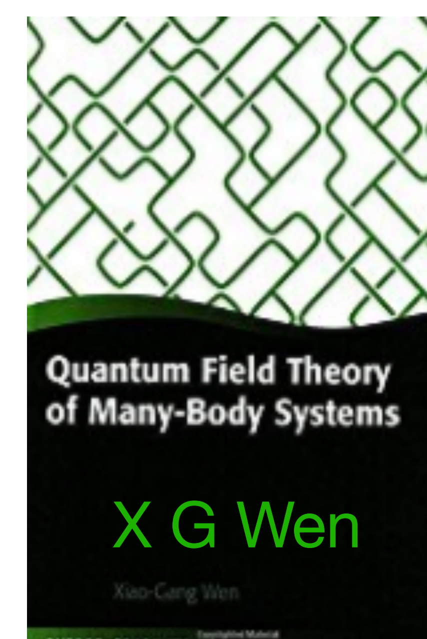


FIG. S-1. The symmetry operations.



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.

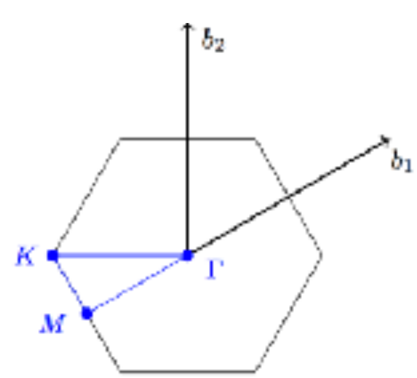
Eight types:

U1A00, **U1A01**, **U1A10, U1A11**; **U1Bxx**

SU(2) trivial Our focus π-flux

Accidental Symmetry
= ideal ESR

$$H = \sum_{x,y} \Big\{ t_1 \big[\, i f^\dagger_{(x+1,y)\uparrow} f_{(x,y)\uparrow} + i f^\dagger_{(x,y+1)\uparrow} f_{(x,y)\uparrow} - i f^\dagger_{(x+1,y+1)\uparrow} f_{(x,y)\uparrow}$$
$$- i f^\dagger_{(x+1,y)\downarrow} f_{(x,y)\downarrow} - i f^\dagger_{(x,y+1)\downarrow} f_{(x,y)\downarrow} + i f^\dagger_{(x+1,y+1)\downarrow} f_{(x,y)\downarrow} \big]$$
$$+ t_1' \big[\, e^{i\pi/3} f^\dagger_{(x+1,y)\uparrow} f_{(x,y)\downarrow} - f^\dagger_{(x,y+1)\uparrow} f_{(x,y)\downarrow} + e^{2i\pi/3} f^\dagger_{(x+1,y+1)\uparrow} f_{(x,y)\downarrow}$$
$$+ e^{2i\pi/3} f^\dagger_{(x+1,y)\downarrow} f_{(x,y)\uparrow} + f^\dagger_{(x,y+1)\downarrow} f_{(x,y)\uparrow} + e^{i\pi/3} f^\dagger_{(x+1,y+1)\downarrow} f_{(x,y)\uparrow} \big]$$
$$+ t_2' \big[\, e^{i\pi/6} f^\dagger_{(x+1,y-1)\uparrow} f_{(x,y)\downarrow} + e^{5i\pi/6} f^\dagger_{(x+1,y+2)\uparrow} f_{(x,y)\downarrow} - i f^\dagger_{(x-2,y-1)\uparrow} f_{(x,y)\downarrow}$$
$$+ e^{5i\pi/6} f^\dagger_{(x+1,y-1)\downarrow} f_{(x,y)\uparrow} - i f^\dagger_{(x-2,y-1)\downarrow} f_{(x,y)\uparrow} + e^{i\pi/6} f^\dagger_{(x+1,y+2)\downarrow} f_{(x,y)\uparrow} \big] + h.c. \Big\}$$



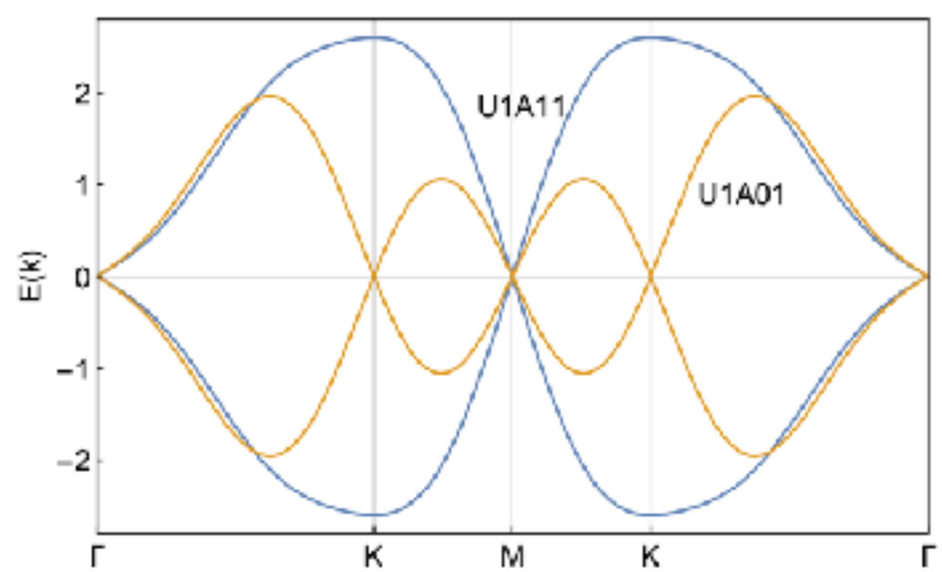
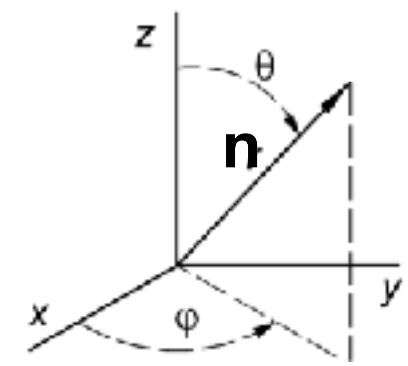


FIG. S-5. Spinon dispersions $E_{1,2}(\mathbf{k})$ along the line Γ-K-M-K-Γ for U1A11 and U1A01 states.

Calculation of parameters - Iaconis et al, 2018

Spinon magnetic resonance (low T)

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

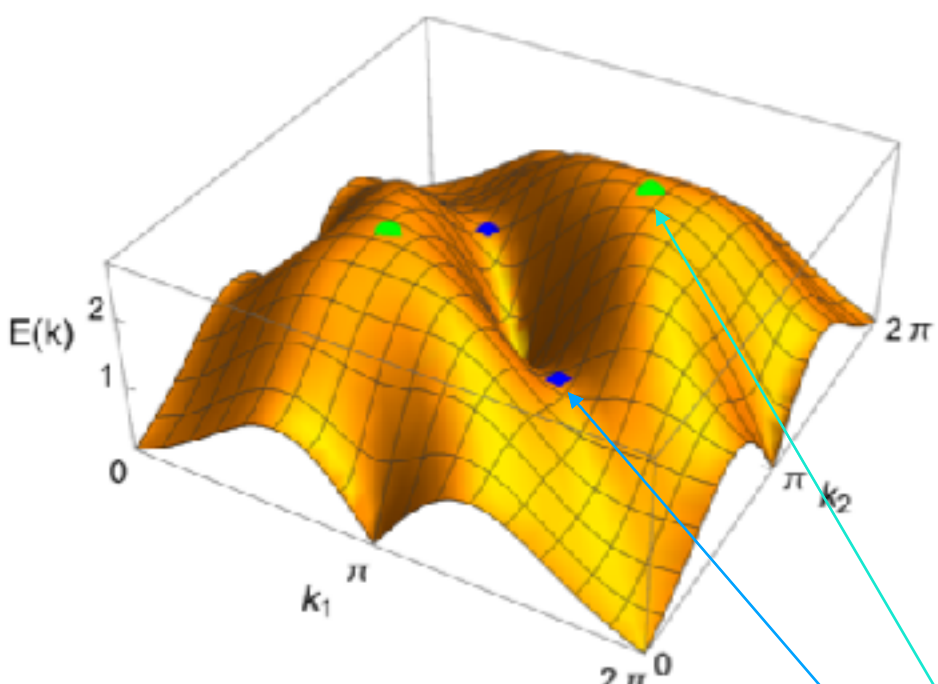


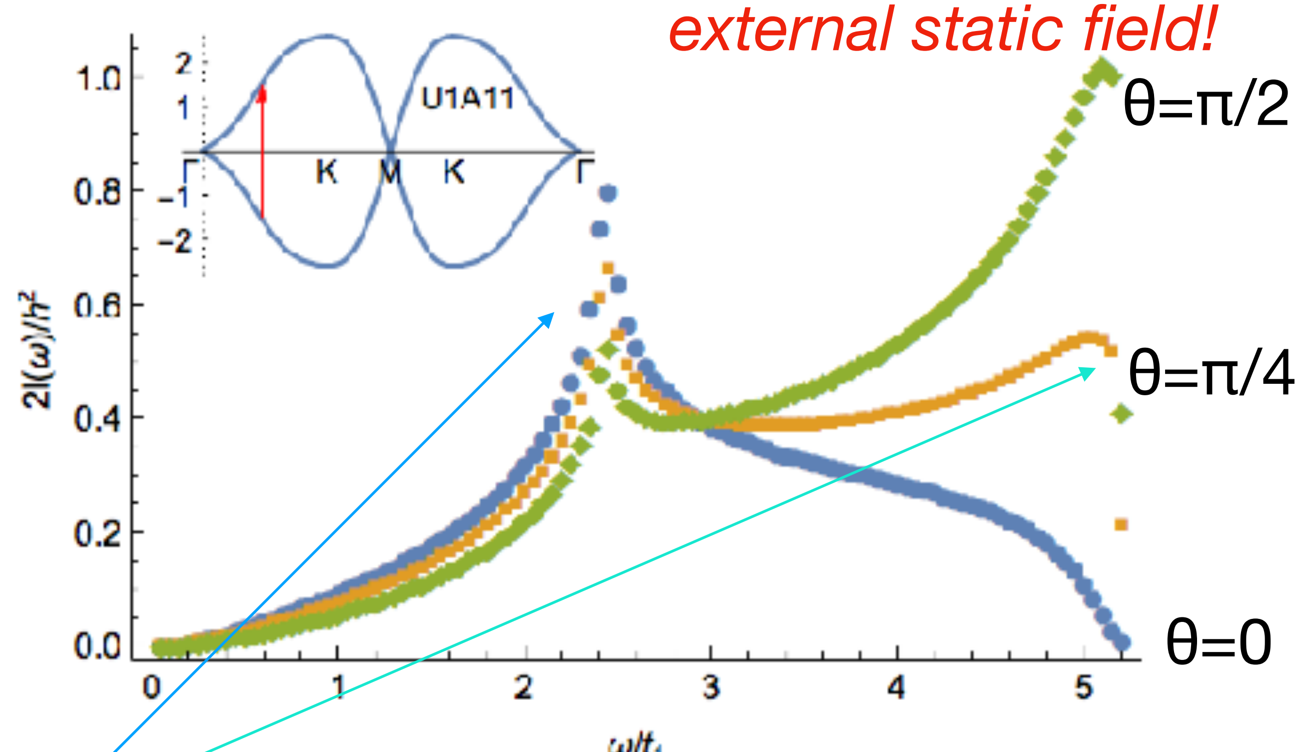
$$V(t) = h e^{-i\omega t} \mathbf{n} \cdot \frac{1}{2} \sum_{\mathbf{r}} (f^\dagger_{\mathbf{r}\uparrow}, f^\dagger_{\mathbf{r}\downarrow}) \boldsymbol{\sigma} \begin{pmatrix} f_{\mathbf{r}\uparrow} \\ f_{\mathbf{r}\downarrow} \end{pmatrix}$$

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

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

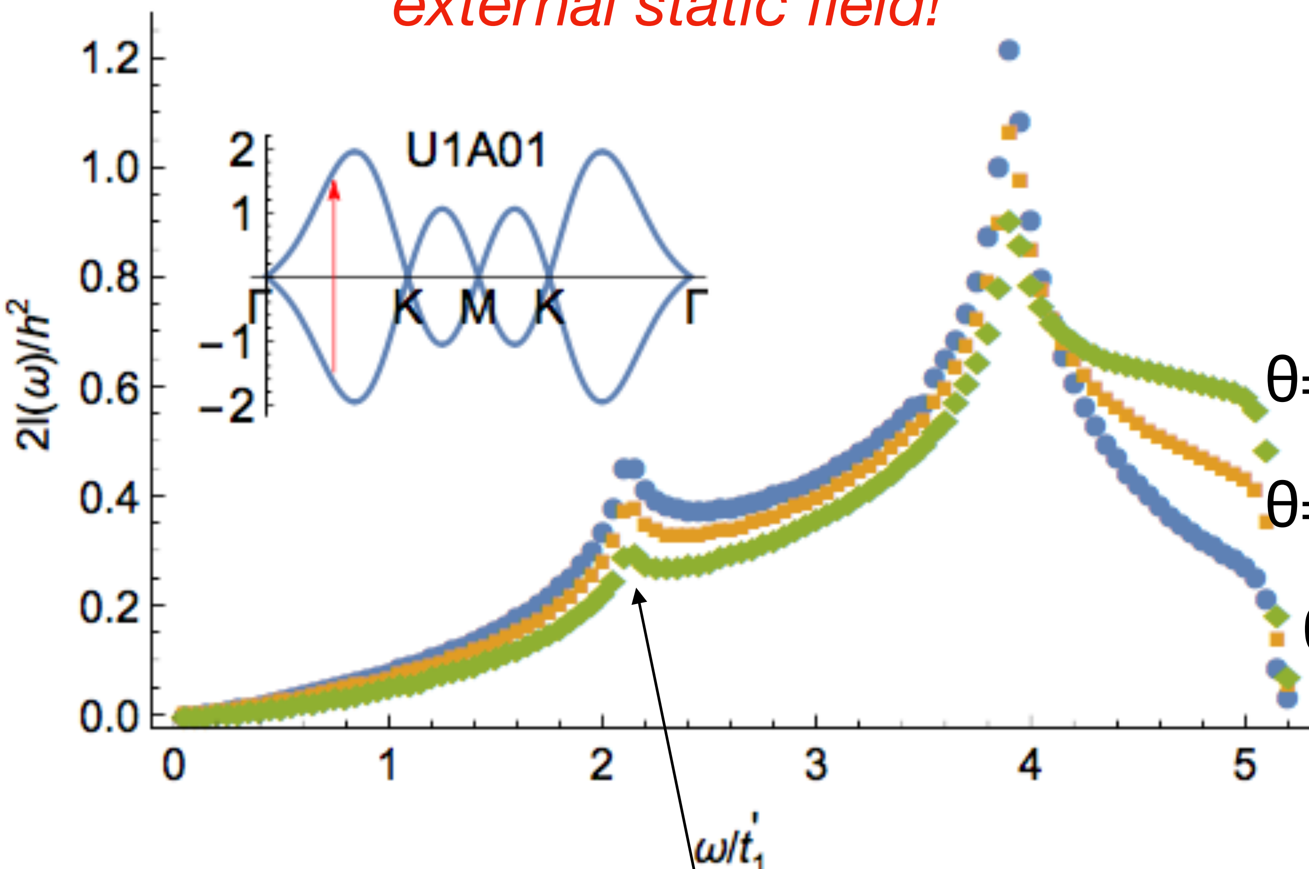
Absorption without external static field!



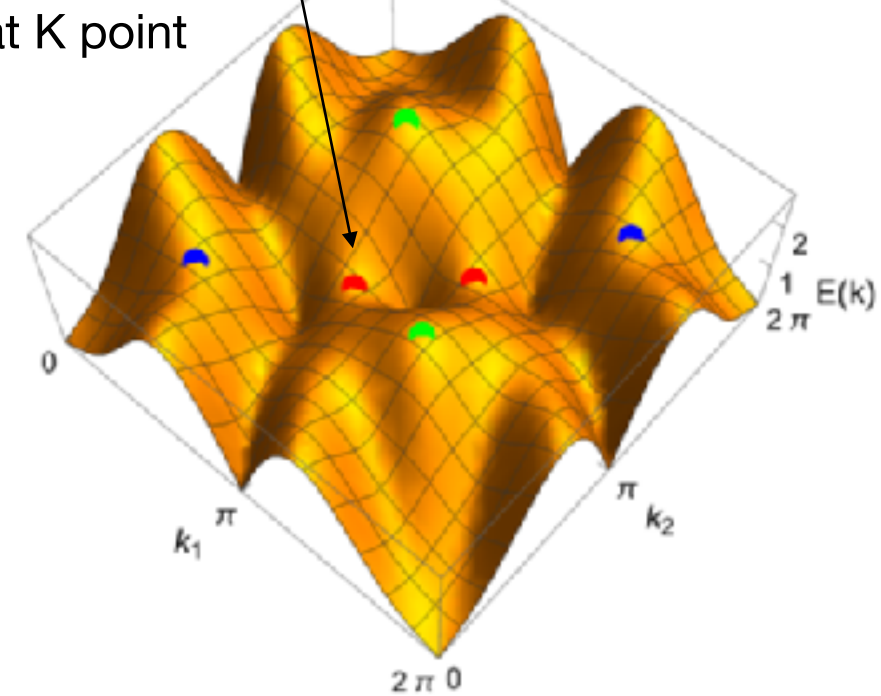


van Hove singularities

Absorption without external static field!

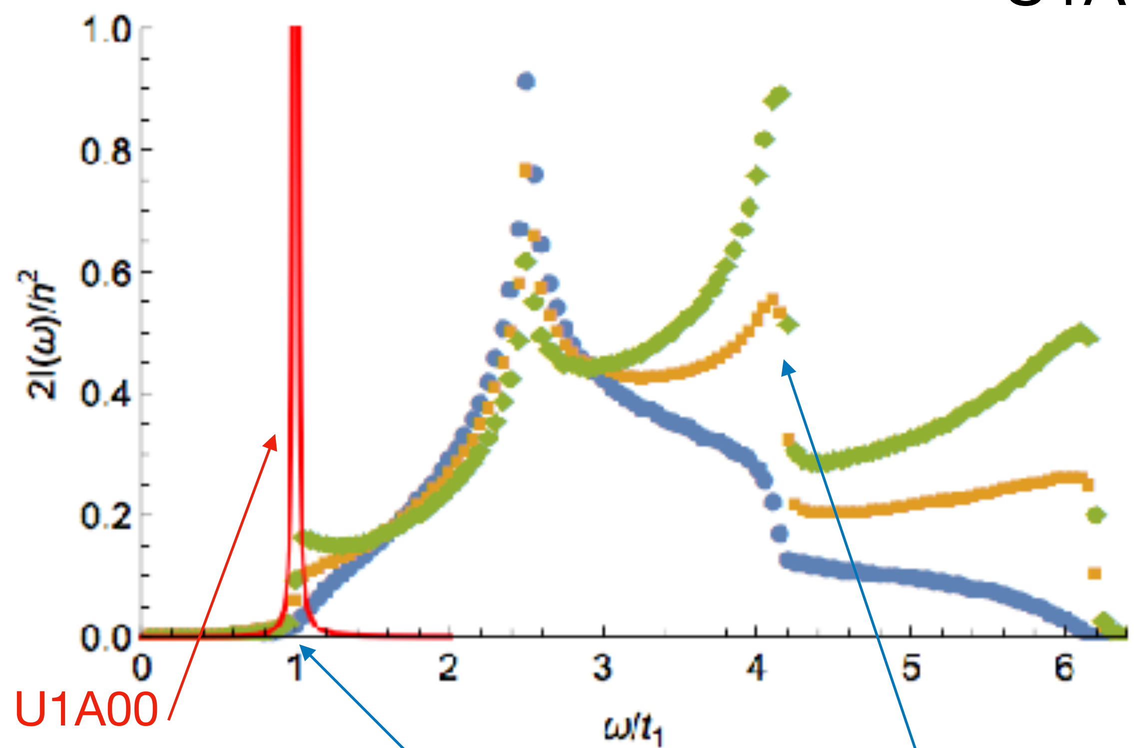


Additional extremum in the spinon spectrum due to symmetry-enforced Dirac touching at K point



With magnetic field along Z

U1A11

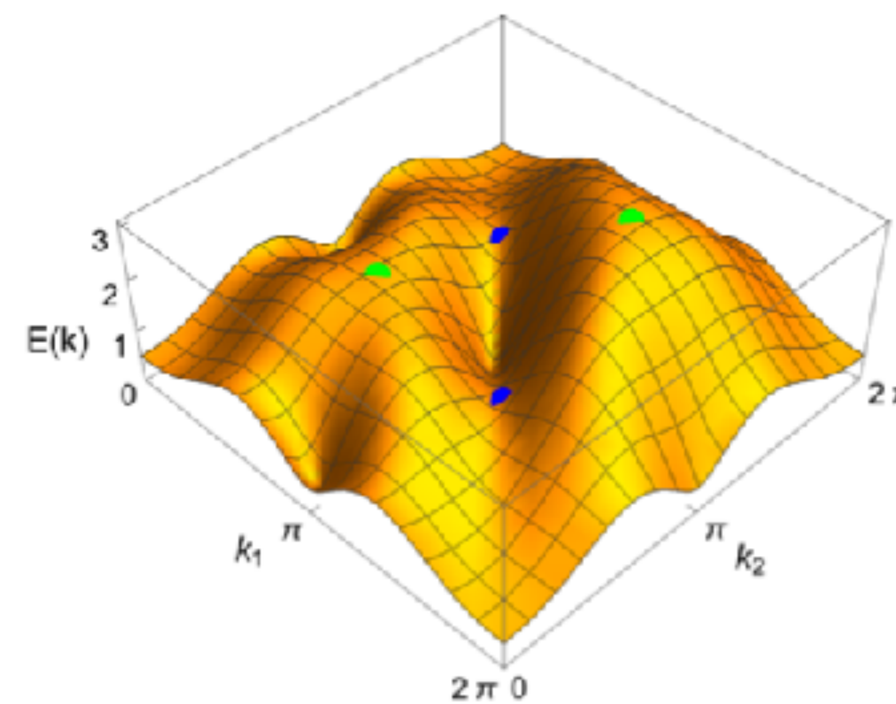


U1A00 Spinon Fermi surface state, **accidental SU(2)**

$\sin^2\theta\ \delta(\omega - B_z)$

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).

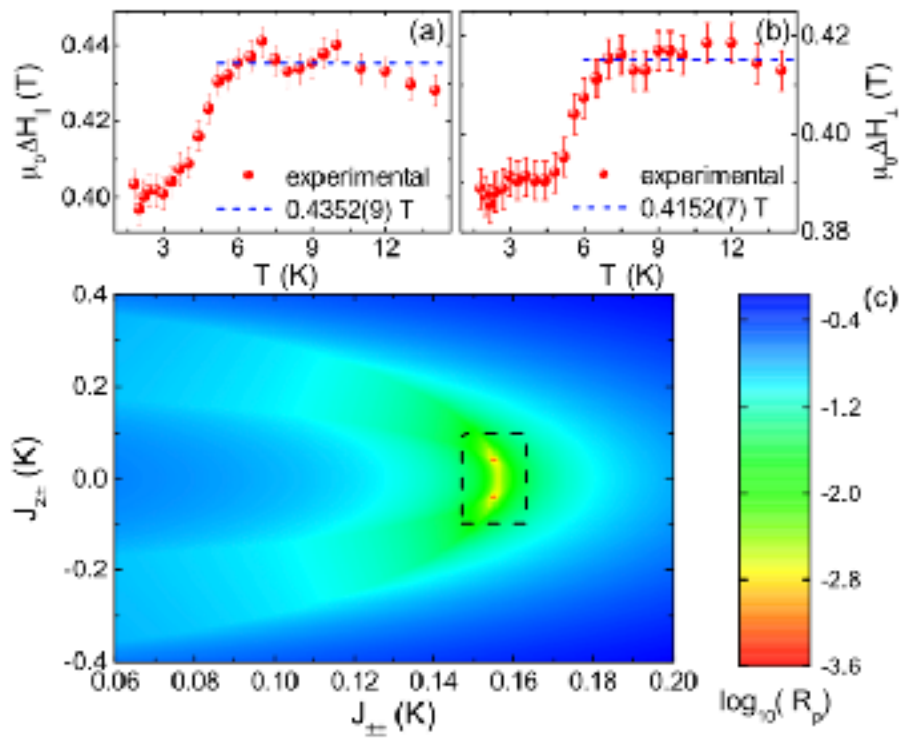


FIG. 3. (Color online.) The temperature dependence of ESR linewidths (a) parallel and (b) perpendicular to the c axis. The dashed lines are the corresponding constant fits to the ESR linewidth data at $T > 6$K. (c) The deviation, R_p, of the experimental ESR linewidthes from the theoretical ones for $YbMgGaO_4$. 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

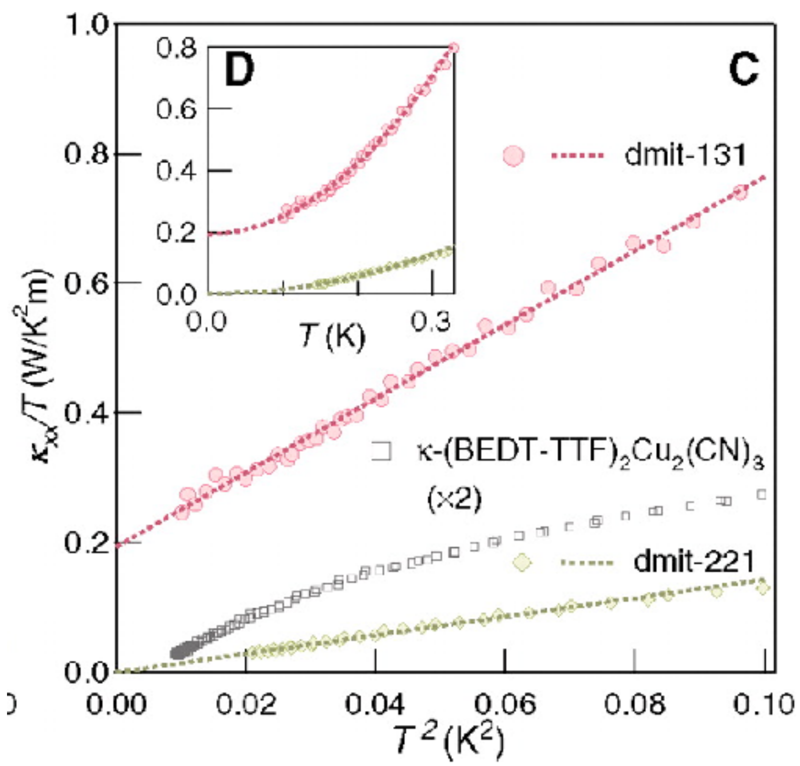
X. Zhang, F. Mahmood, M. Daum et al,
arXiv: 1708.07503.

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

Organic Mott insulators: Spin liquid with spinon Fermi surface?



EtMe$_3$Sb[Pd(dmit)$_2$]$_2$ (dmit-131)

Spin liquid?

M. Yamashita et al, Science 2010

Et$_2$Me$_2$Sb[Pd(dmit)$_2$]$_2$ (dmit-221)

Non-magnetic
charge-ordered

Spin-orbit interaction is present in closely related materials

PHYSICAL REVIEW B **68**, 024512 (2003)

Dzialoshinskii-Moriya interaction in the organic superconductor κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Cl

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(Received 11 February 2003; published 23 July 2003)

The authors report ^{13}C NMR and magnetization measurements on the magnetic state of oriented single crystals of the organic superconductor κ-(BEDT-TTF)$_2$Cu[N(CN)$_2$]Cl. To understand these data a spin Hamiltonian based on the *Pnma* symmetry of the crystal is developed. When interpreted in the context of this Hamiltonian, the measurements provide a detailed picture of the spin ordering. It is found that the Dzialoshinskii-Moriya (DM) interaction is largely responsible for the details of the ordering above the spin-flop field. Of particular note, the interplane correlations are determined by the intraplane DM interactions and the direction of the applied field.

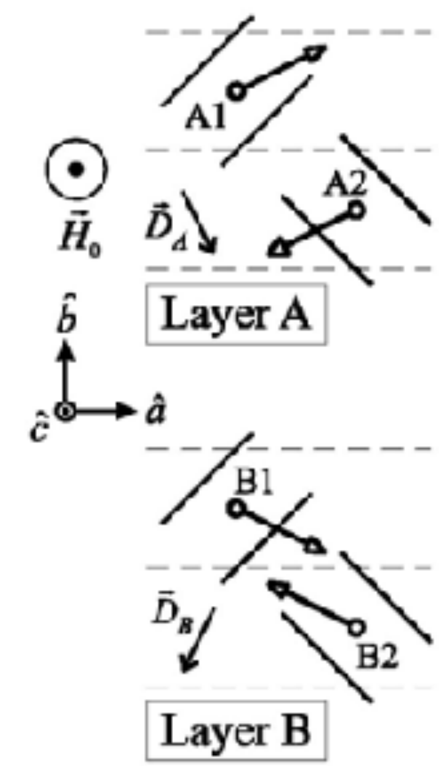
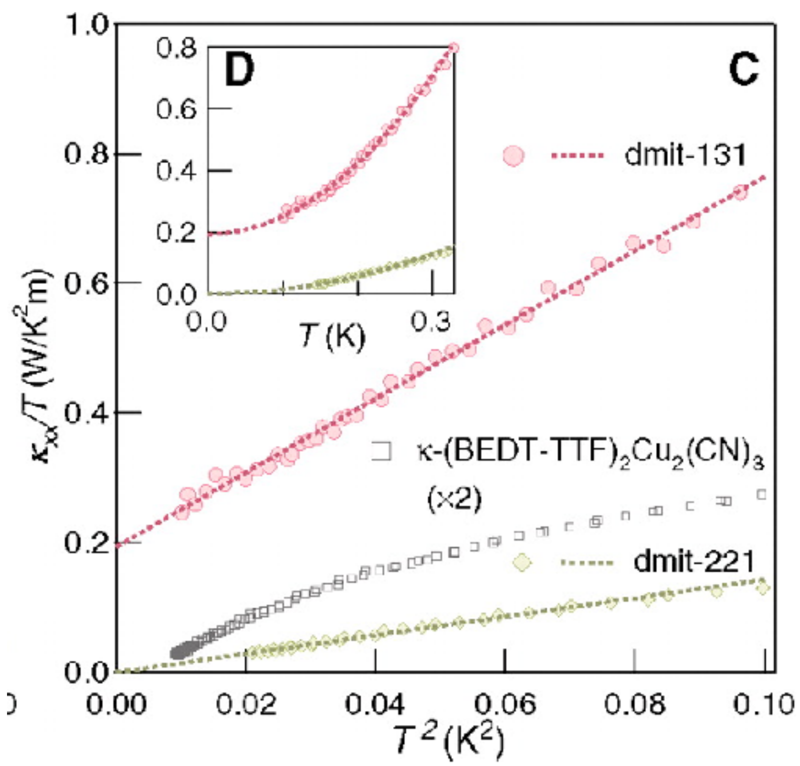


FIG. 6. Depiction of DM vectors and electron spin ordering

Organic Mott insulators: Spin liquid with spinon Fermi surface?



EtMe$_3$Sb[Pd(dmit)$_2$]$_2$ (dmit-131)

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M. Yamashita et al, Science 2010

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Non-magnetic charge-ordered

Spin-orbit interaction is present in closely related materials

PHYSICAL REVIEW B 95, 060404(R) (2017)

Importance of spin-orbit coupling in layered organic salts

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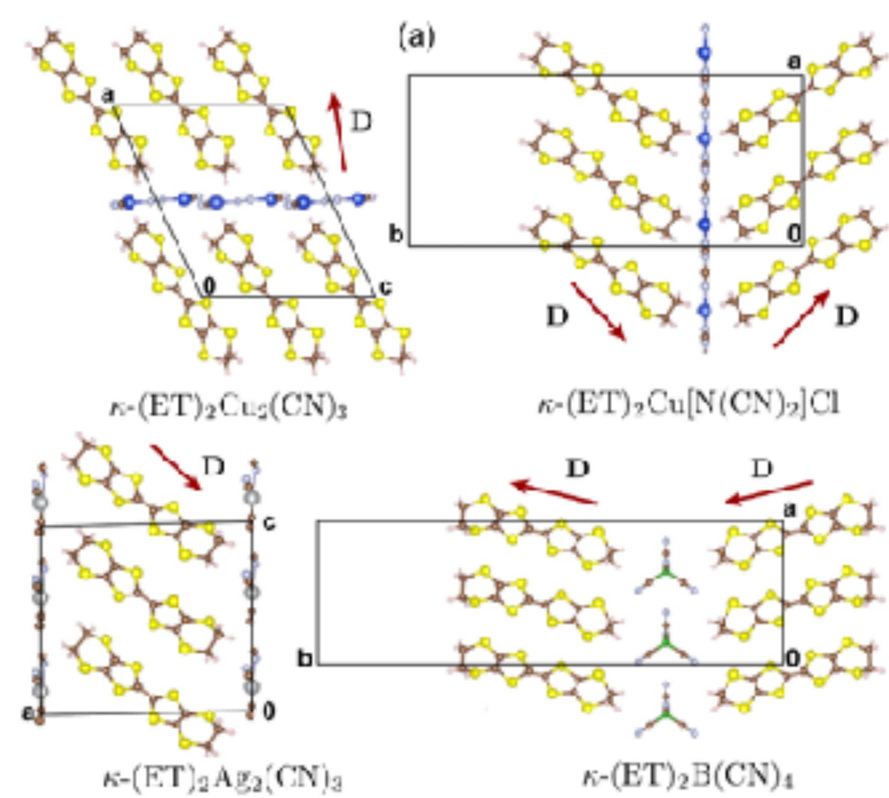
(Received 2 November 2016; revised manuscript received 4 January 2017; published 7 February 2017)

We investigate the spin-orbit coupling (SOC) effects in α- and κ-phase BEDT-TTF and BEDT-TSF organic salts. Contrary to the assumption that SOC in organics is negligible due to light C, S, and H atoms, we show the relevance of such an interaction in a few representative cases. In the weakly correlated regime, SOC manifests primarily in the opening of energy gaps at degenerate band touching points. This effect becomes especially important for Dirac semimetals such as α-(ET)$_2$I$_3$. Furthermore, in the magnetic insulating phase, SOC results in additional anisotropic exchange interactions, which provide a compelling explanation for the puzzling field-induced behavior of the quantum spin-liquid candidate κ-(ET)$_2$Cu$_2$(CN)$_3$. We conclude by discussing the importance of SOC for the description of low-energy properties in organics.



Linewidth *at (relatively) high* T

- Spinon band structure determines *line shape* of absorption (discussed previously).

- Interactions determine h,T-dependent *line width* !

Ideal U(1) spin liquid

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

Rashba-like perturbation due to spin orbit interaction

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

Gauge-invariant response functions of fermions coupled to a gauge field

Yong Baek Kim, Akira Furusaki, Xiao-Gang Wen, and Patrick A. Lee
Phys. Rev. B **50**, 17917 – Published 15 December 1994

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

Landau damping,
$\nu \sim q^3$

`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

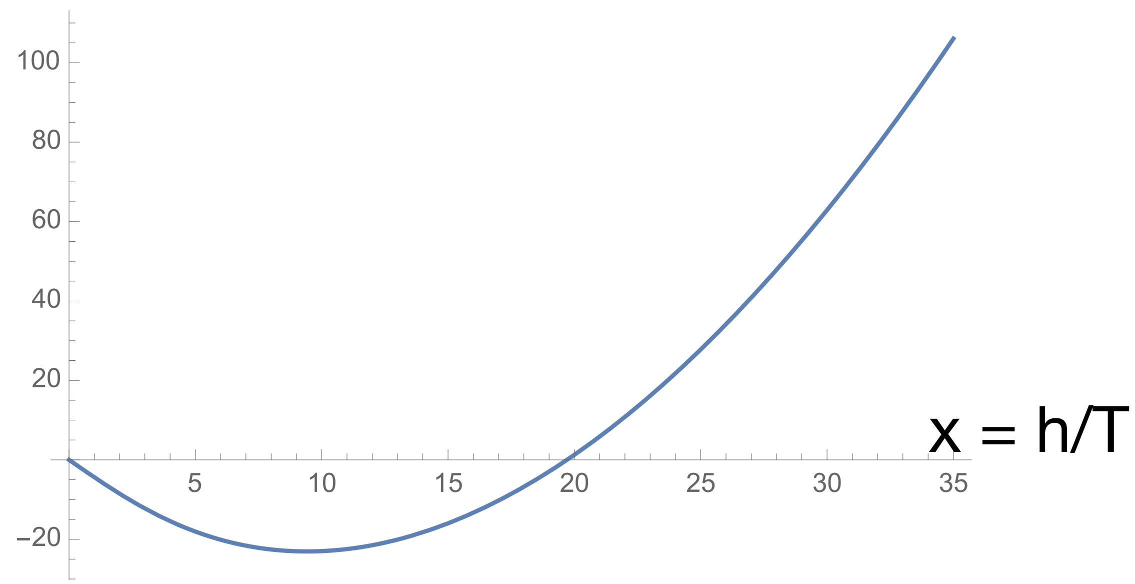
$$\eta \sim \alpha_R^2 \omega^{5/3}/h \sim h^{2/3}, h > 0$$

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

T > 0,
h<< T

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

Scaling function f(x)



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

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***

Already checked in one dimension!

Spinon magnetic resonance has been observed and studied experimentally in quasi-1d materials Cs_2CuCl_4 and $K_2CuSO_4Br_2$ with uniform DM interaction: K. Povarov, A. Smirnov, OS *et al*, Phys. Rev. Lett. **107**, 037204 (2011).