Spectroscopic signatures of **spinon Fermi surface** in a rare-earth triangular lattice spin liquid

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A rare-earth triangular lattice quantum spin liquid: $YbMgGaO_4$

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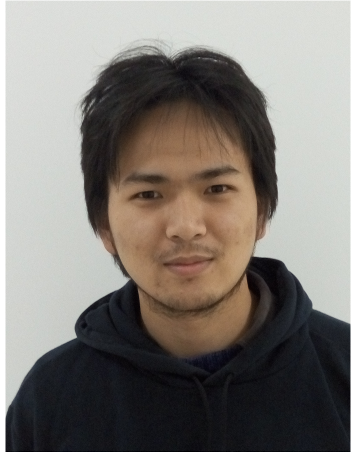

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more recently,
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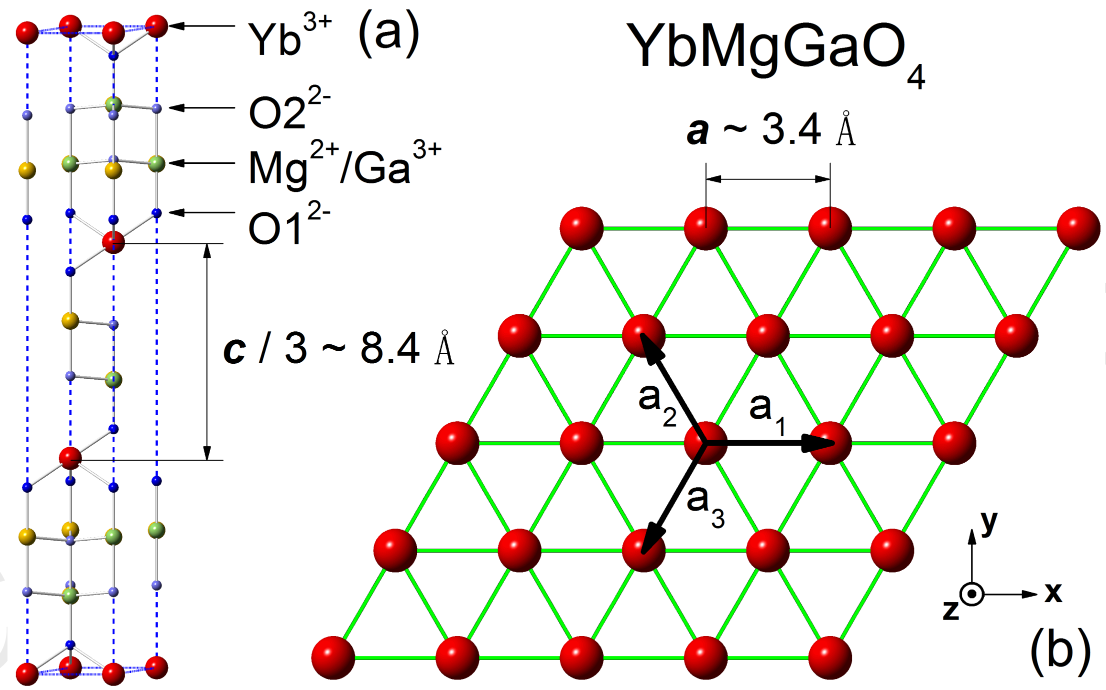
A rare-earth triangular lattice quantum spin liquid: $YbMgGaO_4$



- Hastings-Oshikawa-Lieb-Shultz-Mattis theorem.
- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2015).
- This is the **first** strong spin-orbit coupled QSL with odd number of electrons and effective spin-1/2.
- It is the **first** clear observation of $T^{2/3}$ heat capacity. I think it is spinon Fermi surface U(1) QSL.
- Inelastic neutron scattering is consistent with spinon Fermi surface results.
- We understand the microscopic Hamiltonian and the physical mechanism.

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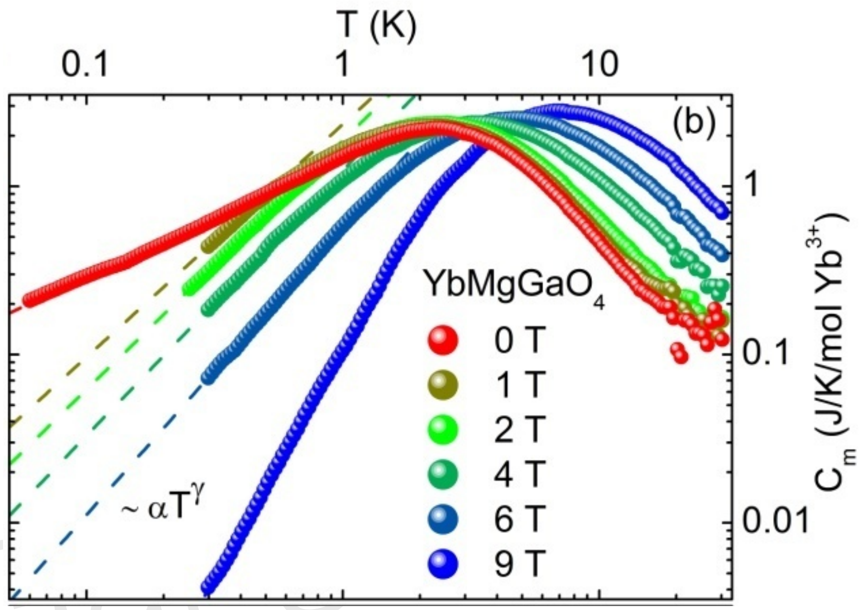
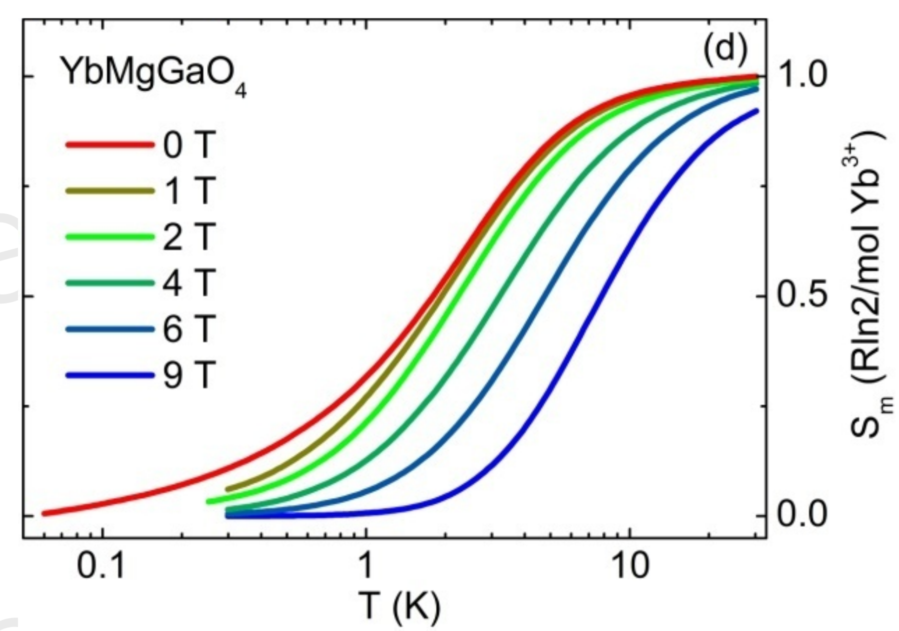
$YbMgGaO_4$



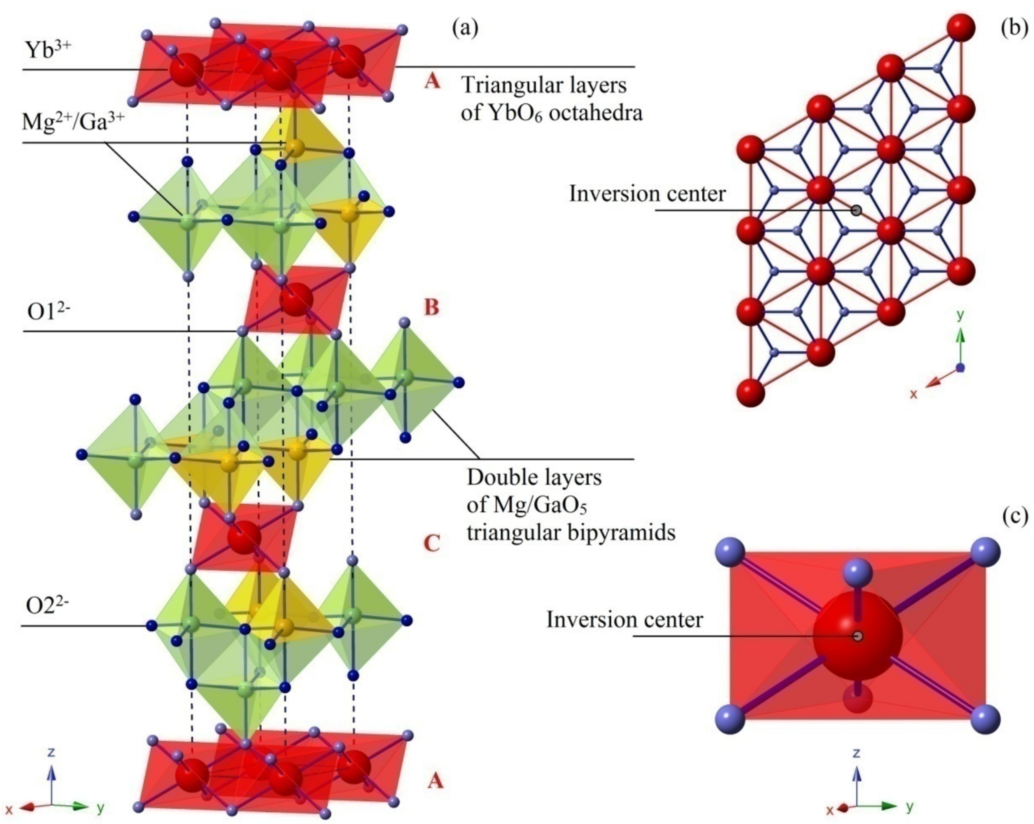


- observation of $T^{2/3}$ heat capacity
- Entropy: effective spin-1/2 local moments

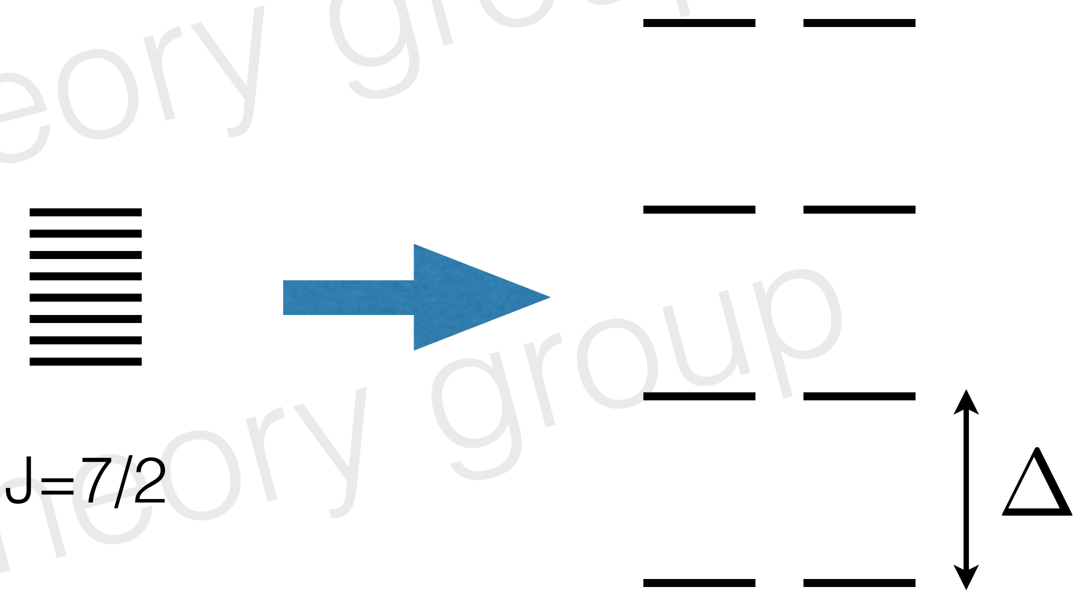
No breaking of time reversal symmetry at finite temperature.

Our proposal for ground state: spinon Fermi surface U(1) QSL.

Microscopics



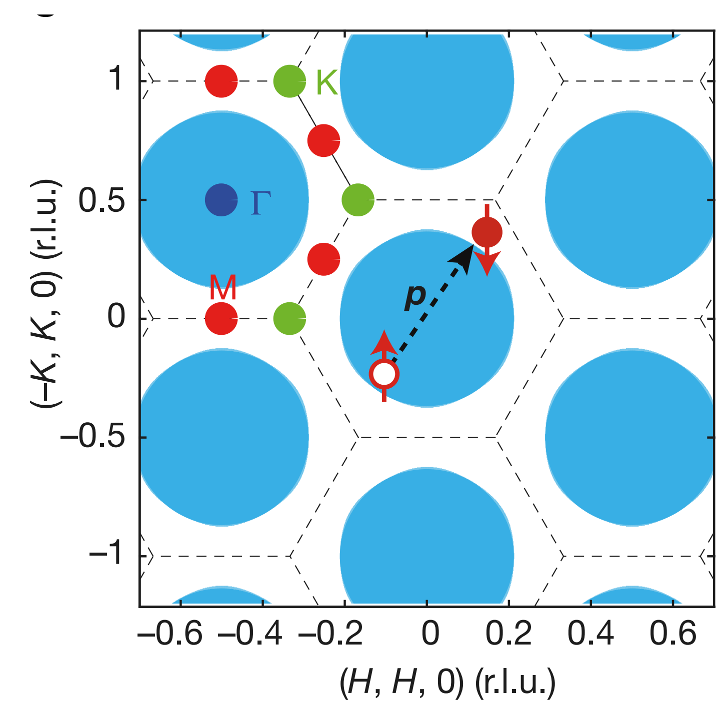
Yb^{3+} ion: 4f^{13} has J=7/2 due to SOC.

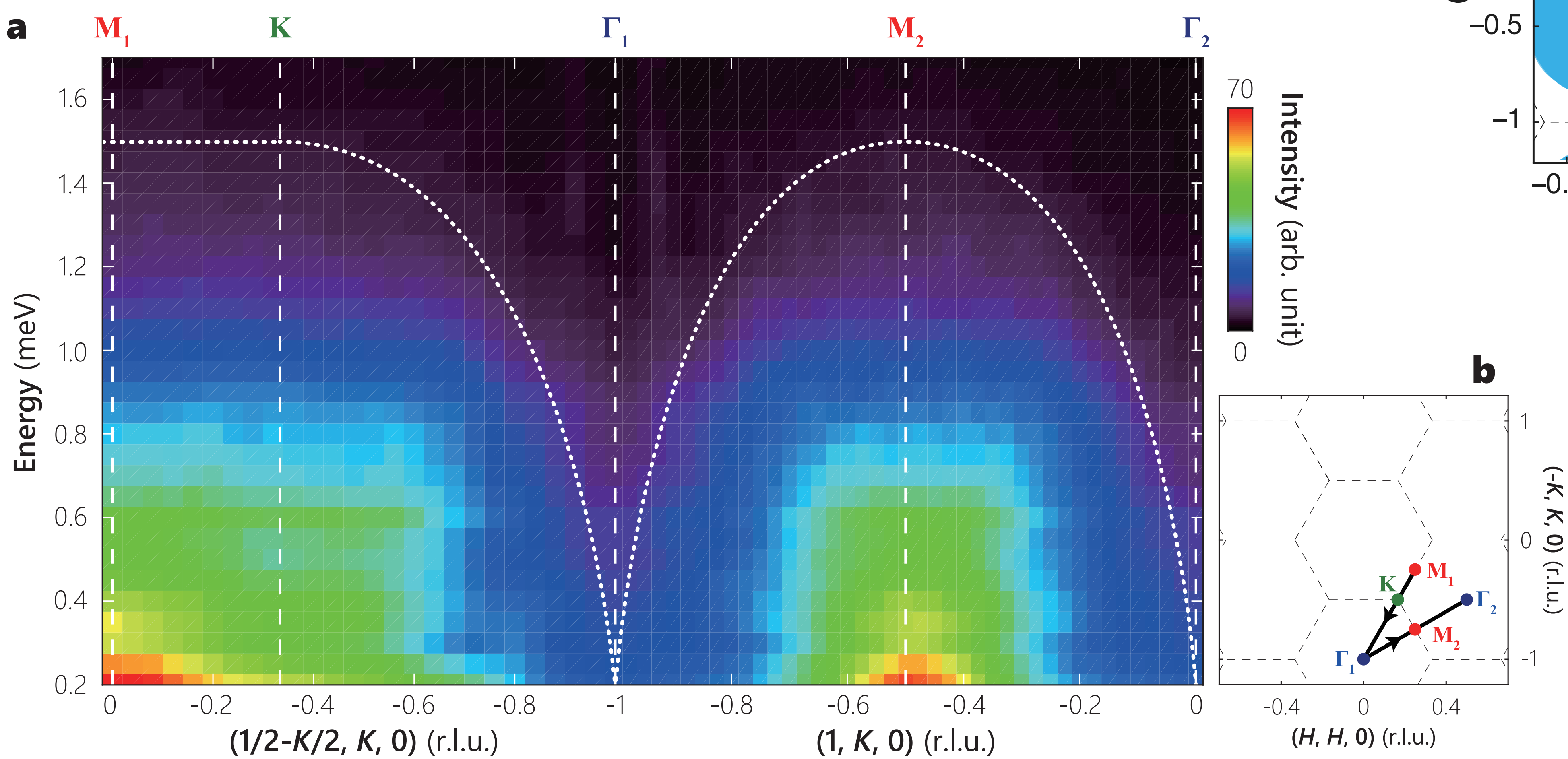


also in Mastuda's talk?

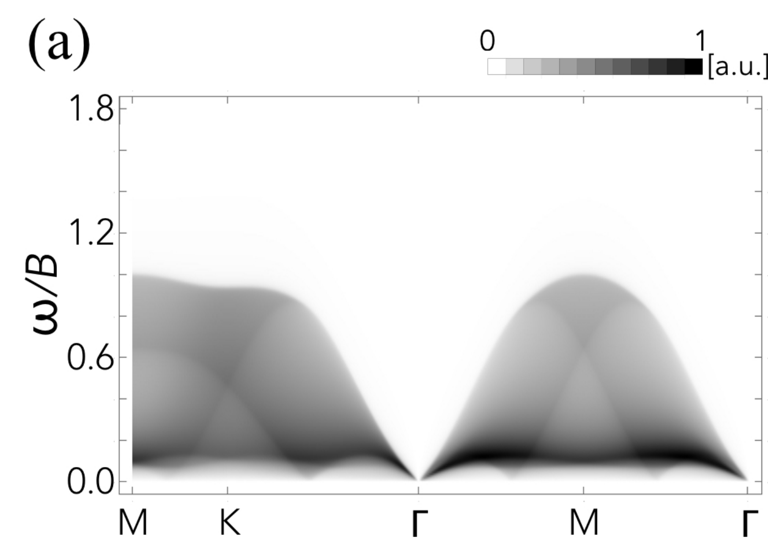
At $T \ll \Delta$, the only active DOF is the ground state doublet that gives rise to an effective spin-1/2.

Advantage for neutron scattering





Continuum excitation



Yao Shen, …Gang Chen*, Jun Zhao* Nature

Yao-Dong Li, Yuanming Lu, Gang Chen, arXiv 1612

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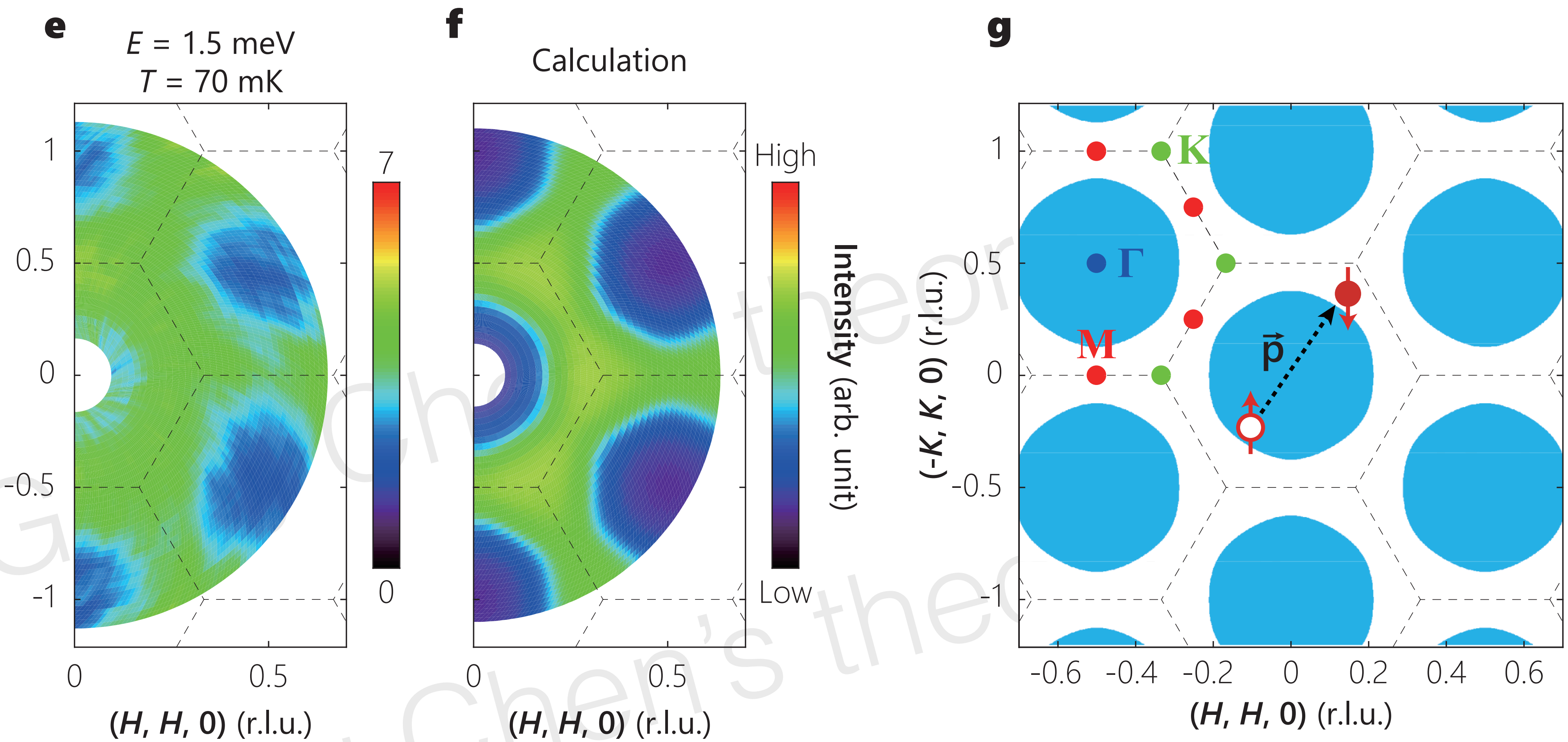
Spinon continuum

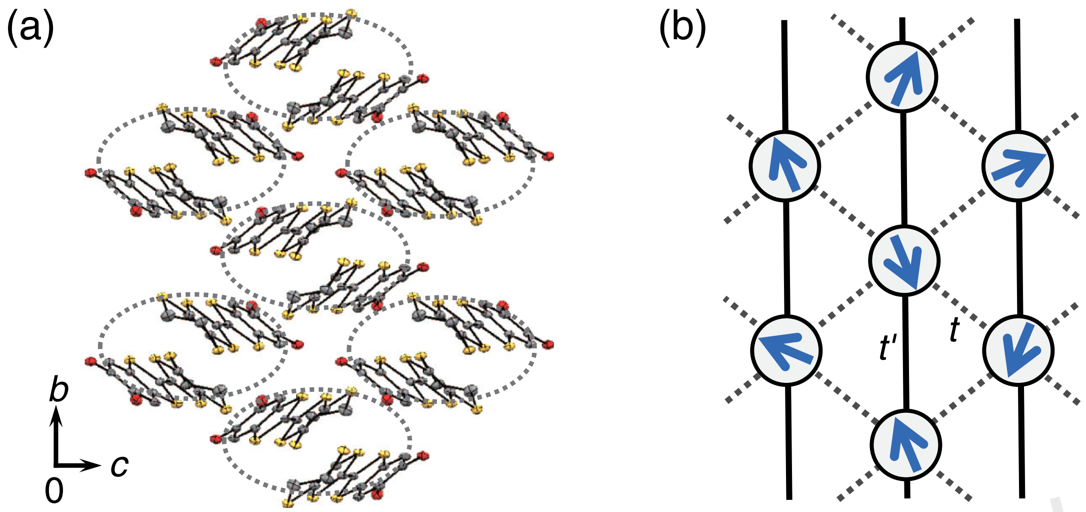


Yao Shen, …Gang Chen*, Jun Zhao* Nature

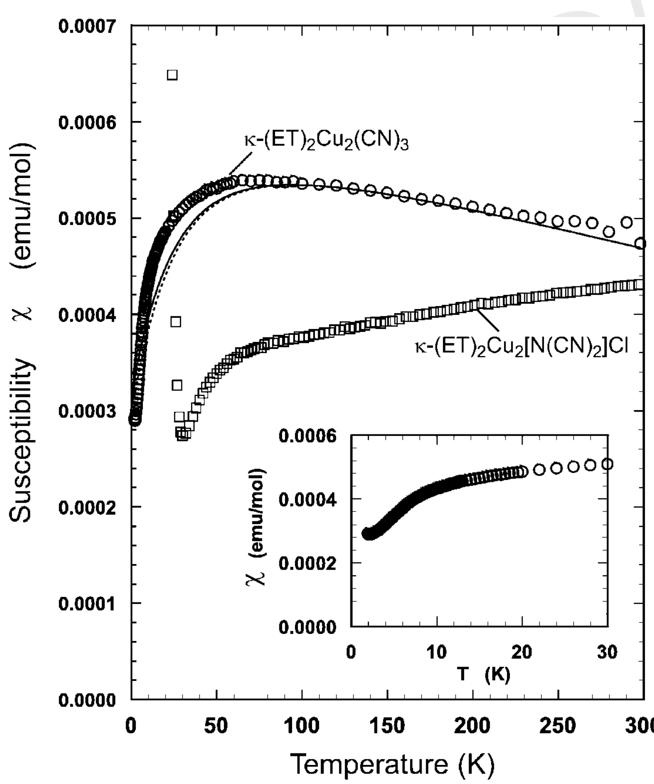
Spinon Fermi surface from a pure spin system!

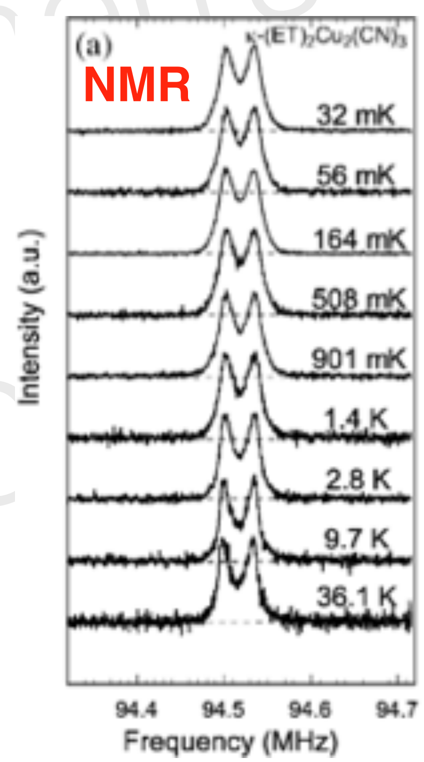
very different from organic spin liquids

Kanoda



kappa-(BEDT-TTF)2Cu2(CN)3,
EtMe3Sb[Pd(dmit)2]2,
kappa–H3(Cat-EDT-TTF)2 **a new one!**





Other experiments: transport, heat capacity, optical absorption, etc,
Unfortunately, **no neutron scattering** so far.

Weak Mott insulating
Strong charge fluctuation -> Ring exchange -> disorder

* No magnetic order down to 32mK
* Constant spin susceptibility at zero temperature

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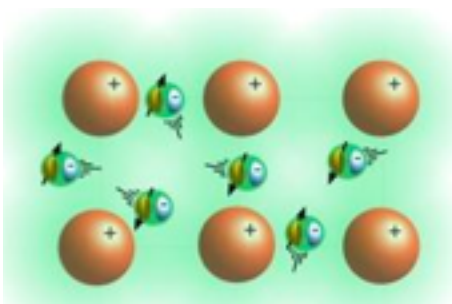
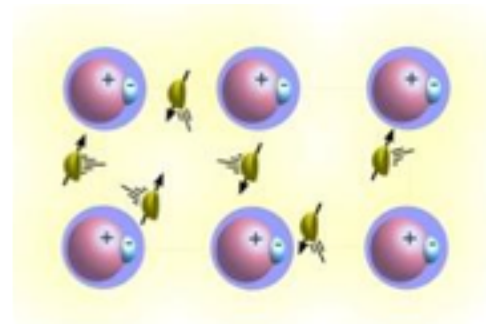
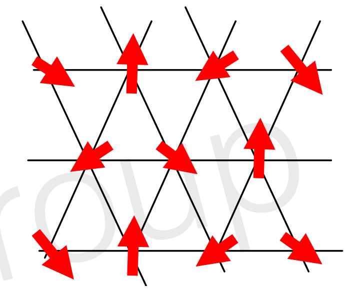
$$H = -t \sum_{\langle ij\rangle,\sigma} c^\dagger_{i\sigma} c_{j\sigma} + h.c. + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Sung-Sik Lee T Senthil P Lee

Senthil's cartoon





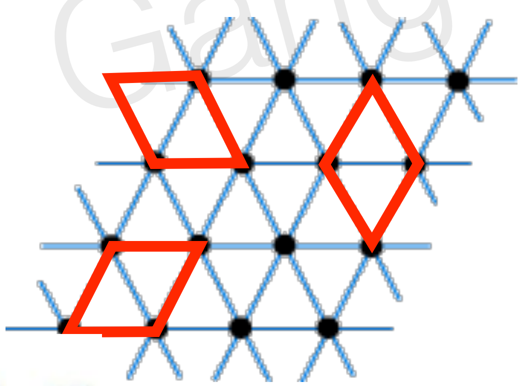


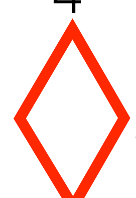
Mott transition

Fermi liquid — metal | **weak** Mott regime — U(1) QSL with spinon Fermi surface supported by various different numerics | **strong** Mott regime — 120-degree order → U/t

- **Physical mechanism** for weak Mott insulator spin liquids: perturbation in t/U

$$H_{\rm pert} = \sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + K \sum_{1234} (P_{1234} + P^{-1}_{1234}) + \cdots$$





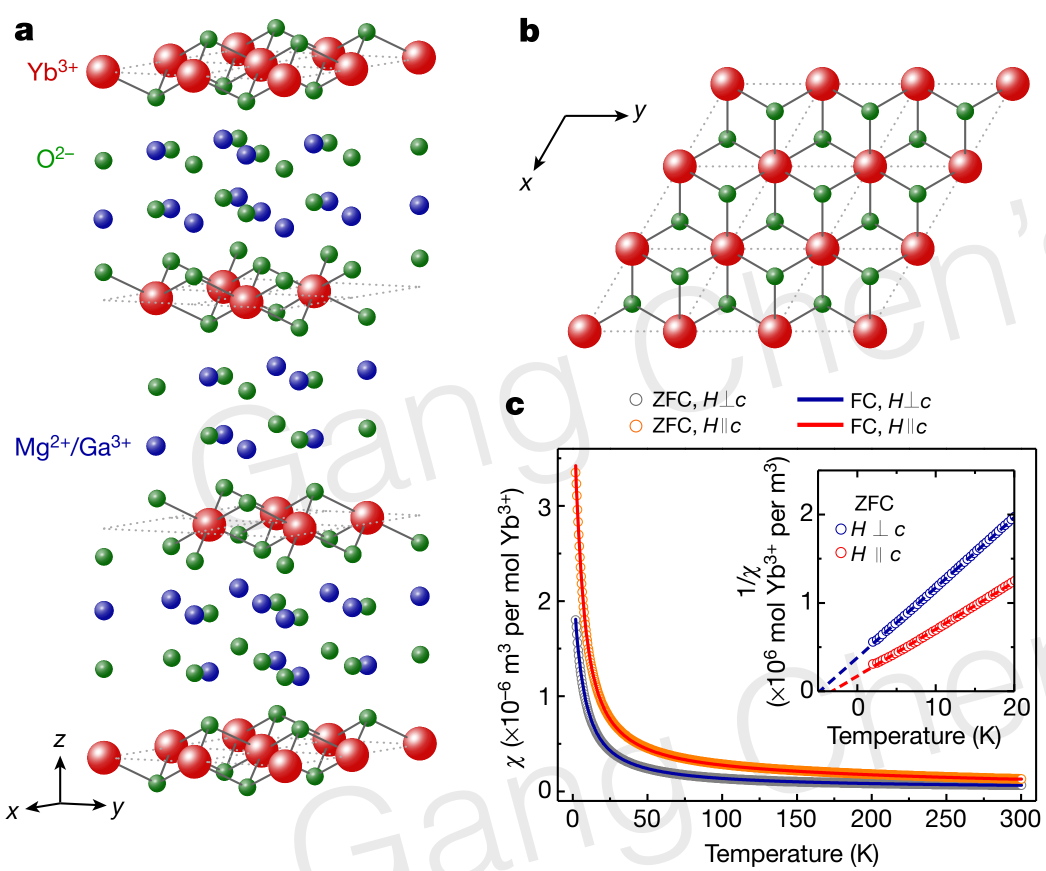
4-site ring exchange

$$\begin{aligned} &(\mathbf{S}_1 \cdot \mathbf{S}_2)(\mathbf{S}_3 \cdot \mathbf{S}_4) \\ +&(\mathbf{S}_1 \cdot \mathbf{S}_4)(\mathbf{S}_2 \cdot \mathbf{S}_3) \\ -&(\mathbf{S}_1 \cdot \mathbf{S}_3)(\mathbf{S}_2 \cdot \mathbf{S}_4) \end{aligned}$$

Motrunich

Spin-orbit entanglement in strong Mott regime

4f electron is very localized, and dipolar interactions weak, very different from organics



$$\mathcal{H} = \sum_{\langle ij \rangle} [J_{zz} S_i^z S_j^z + J_{\pm}(S_i^+ S_j^- + S_i^- S_j^+) + J_{\pm\pm}(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-) - \frac{i J_{z\pm}}{2}(\gamma_{ij}^* S_i^+ S_j^z - \gamma_{ij} S_i^- S_j^z + \langle i \leftrightarrow j \rangle)], \quad (1)$$

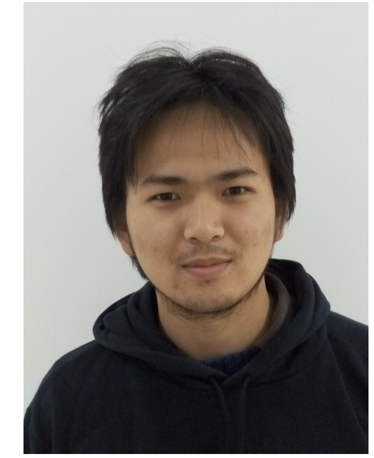
where $S_i^{\pm} = S_i^x \pm i S_i^y$, and the phase factor $\gamma_{ij} = 1, e^{i2\pi/3}, e^{-i2\pi/3}$ for the bond ij along the $\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3$ direction (see Fig. 1), respectively. This generic Hamil-

The spin-1/2 XXZ model supports conventional order.

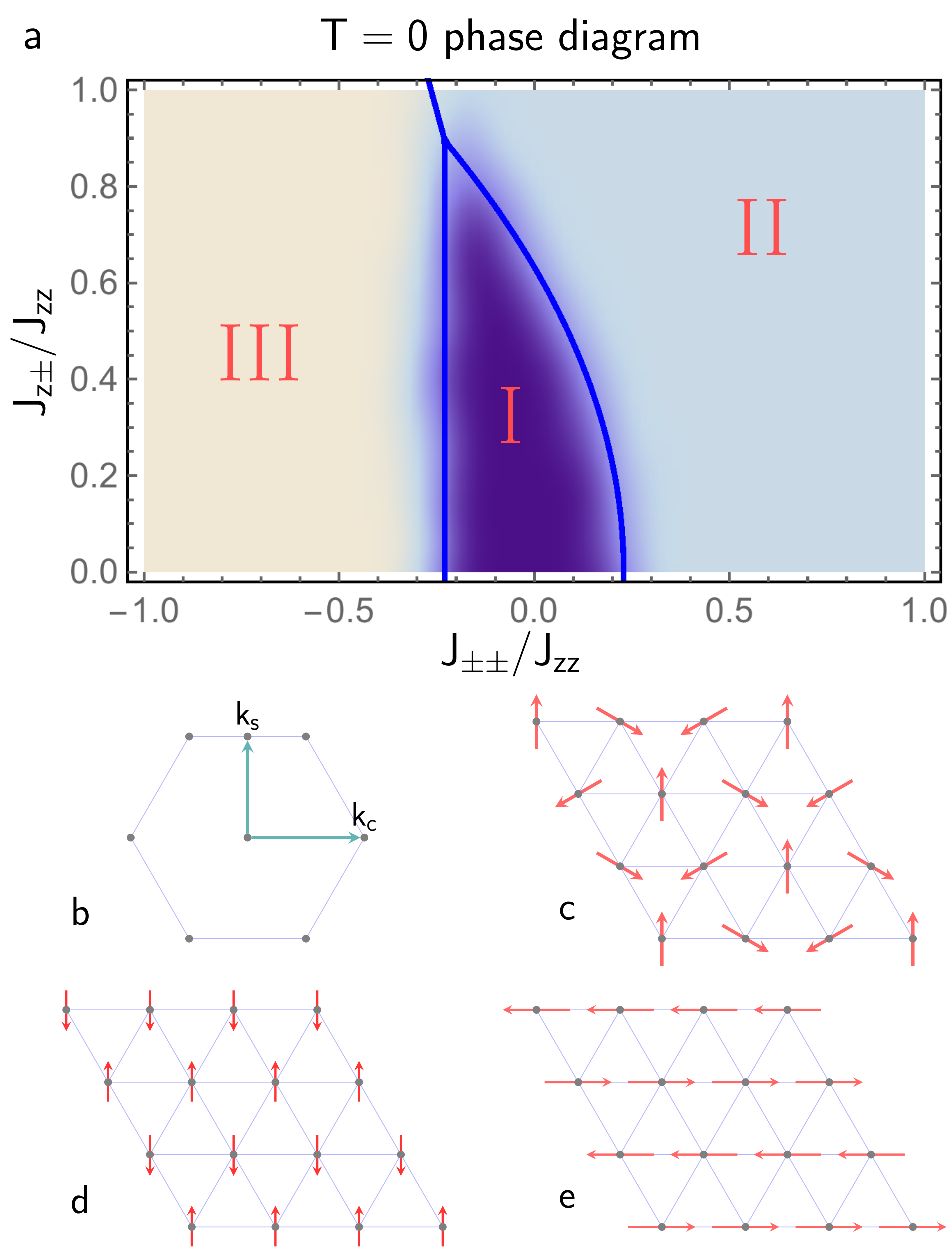
(Yamamoto, etc, PRL 2014)

Ga/Mg disorder may do something too. But not very clear at this stage.

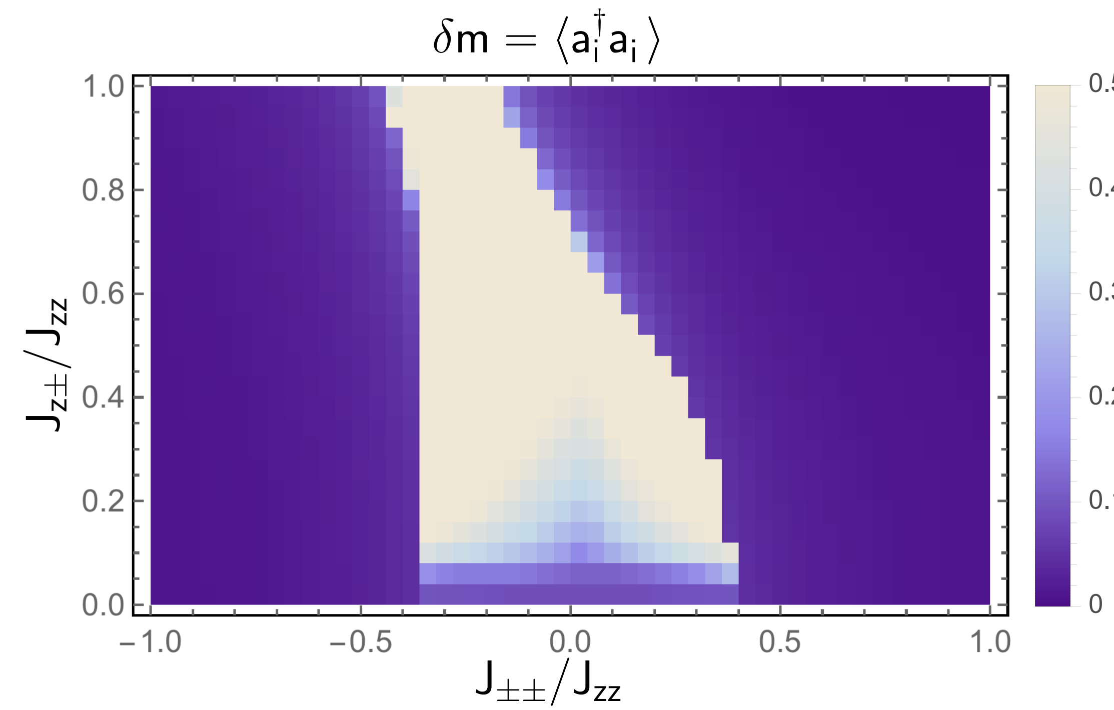
Conservative treatment



Yao-Dong Li



mean-field phases



with quantum fluctuation

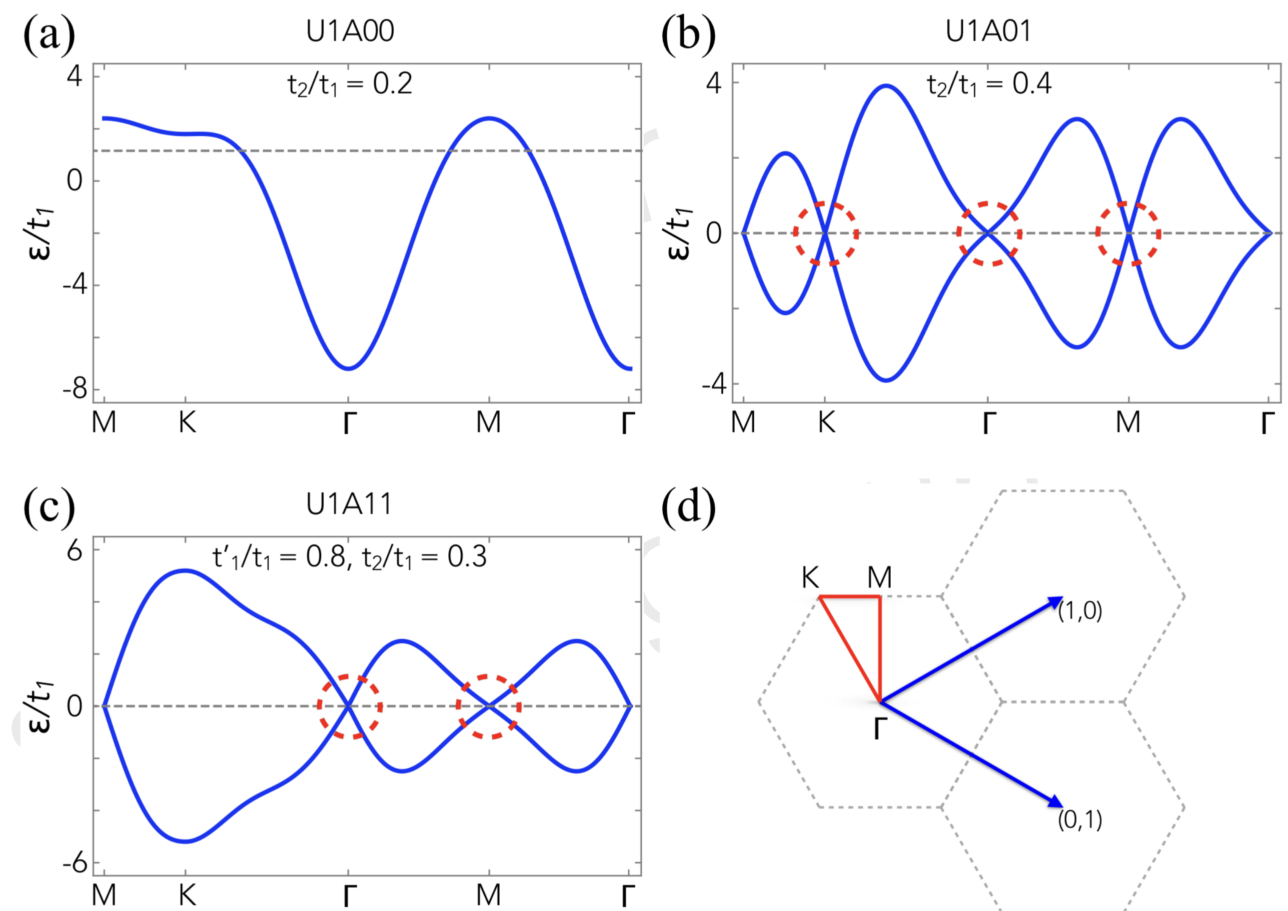
YD Li, XQ Wang, GC, PRB 94, 035107, 2016

Parton construction and PSG classification

$$\boldsymbol{S}_i = \sum_{\alpha\beta} \frac{1}{2} f_{i\alpha}^{\dagger} \boldsymbol{\sigma}_{\alpha\beta} f_{i\beta}$$

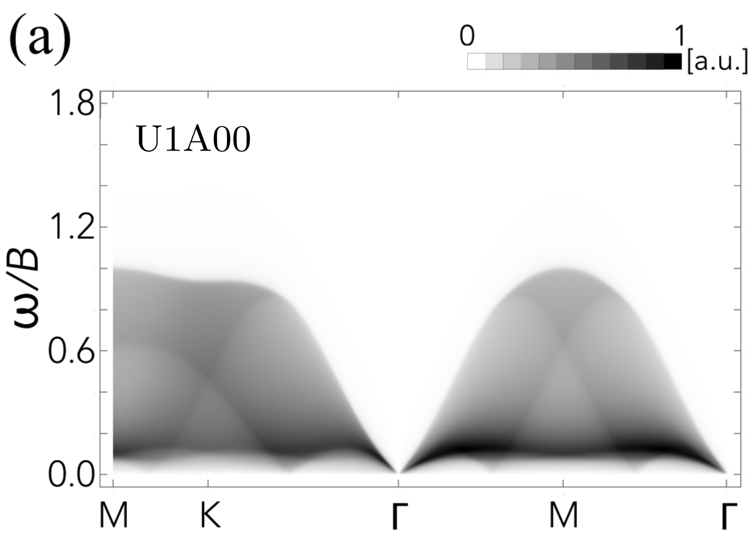
$$H_{\text{MF}} = -\sum_{(\boldsymbol{r}\boldsymbol{r}')} \sum_{\alpha\beta} \left[t_{\boldsymbol{r}\boldsymbol{r}',\alpha\beta} f^{\dagger}_{\boldsymbol{r}\alpha} f_{\boldsymbol{r}'\beta} + h.c. \right],$$

U(1) QSL	$W_{\boldsymbol{r}}^{T_1}$	$W_{\boldsymbol{r}}^{T_2}$	$W_{\boldsymbol{r}}^{C_2}$	$W_{\boldsymbol{r}}^{C_6}$
U1A00	$I_{2\times 2}$	$I_{2\times 2}$	$I_{2\times 2}$	$I_{2\times 2}$
U1A10	$I_{2\times 2}$	$I_{2\times 2}$	$i\sigma^y$	$I_{2\times 2}$
U1A01	$I_{2\times 2}$	$I_{2\times 2}$	$I_{2\times 2}$	$i\sigma^y$
U1A11	$I_{2\times 2}$	$I_{2\times 2}$	$i\sigma^y$	$i\sigma^y$

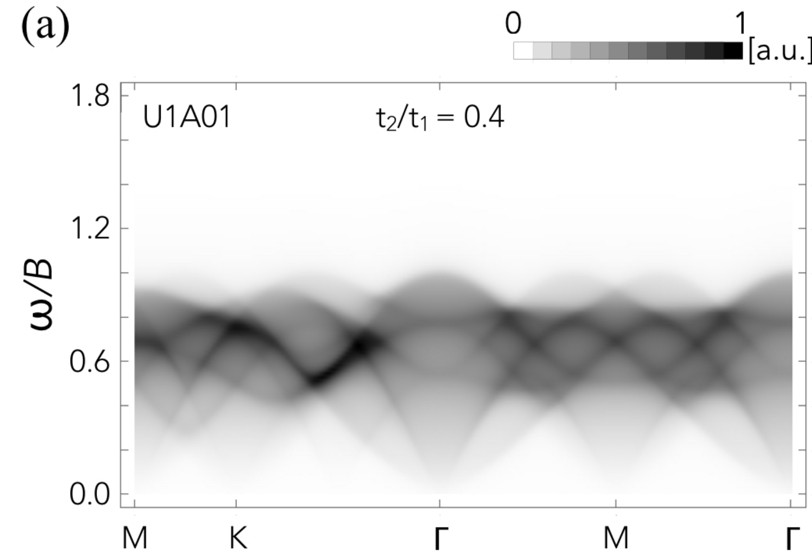


The U1A00 state is the spinon Fermi surface state that we proposed in Shen, et al, Nature.

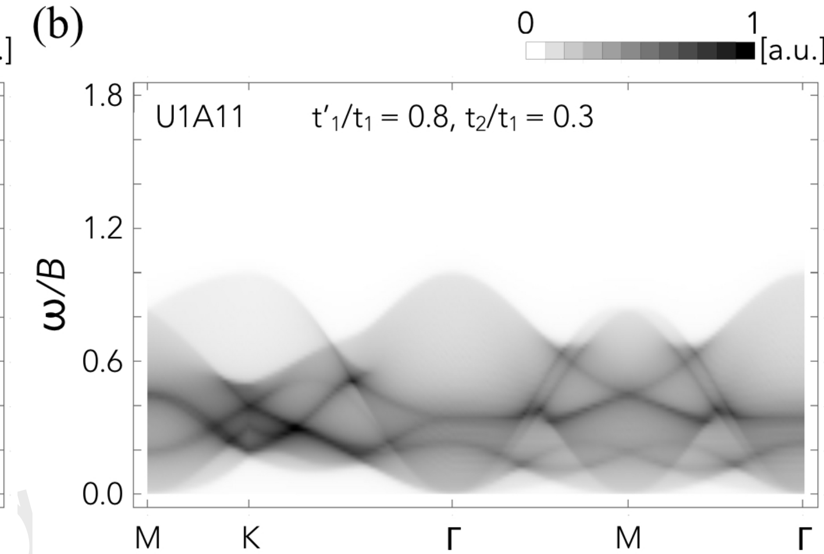
Classification scheme is different from X-G Wen's original work.



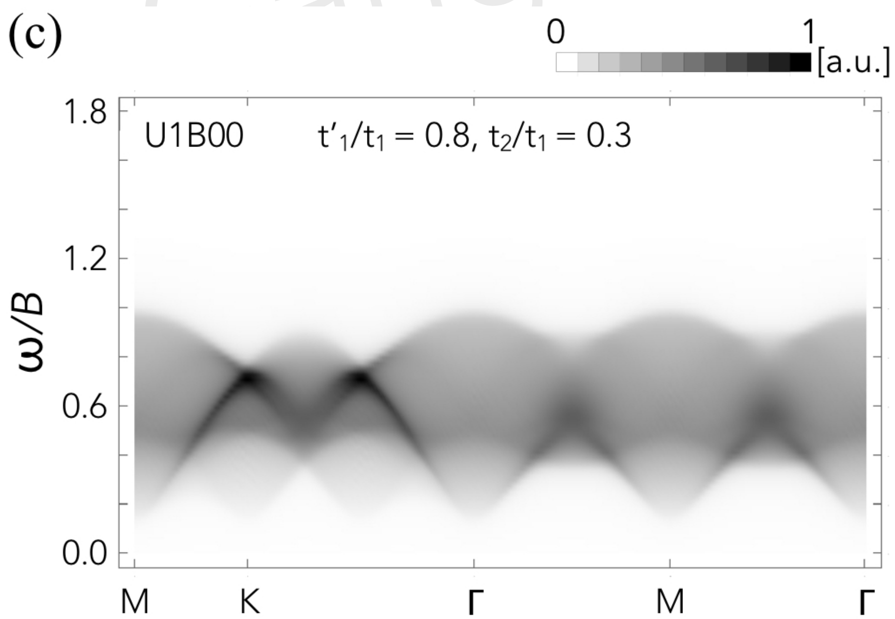
U1A00



U1A01



U1A11



U1B state

Summary

1. We propose YbMgGaO4 realizes a U(1) QSL with spinon Fermi surface.

2. Current experiments are reasonably consistent with the theoretical prediction from this proposal.

Ref: YS Li, GC, … QM Zhang, PRL, 2015
Y Shen, YD Li,…, GC, J Zhao, Nature, Dec 2016
YD Li, XQ Wang, GC, PRB 94, 035107, 2016
YD Li, YM Lu, GC, arXiv 1612.03447
YD Li, Y Shen, YS Li, J Zhao, GC, arXiv 1608.06445

Gang Chen's theory group