Recent progress on the spin-orbit-coupled spin liquid candidate $YbMgGaO_4$

Gang Chen
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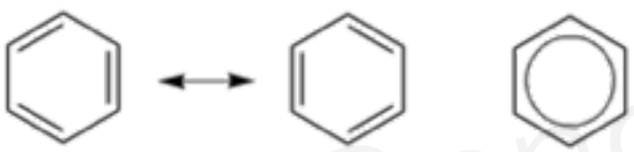
The idea of **resonant valence bonds** of spins

P. W. Anderson

RESONATING VALENCE BONDS: A NEW KIND OF INSULATOR?*

P. W. Anderson

type would be insulating; it would represent an alternative state to the Néel antiferromagnetic state for S = 1/2. An estimate of



benzene molecule

Pauling's RVB state of benzene molecule

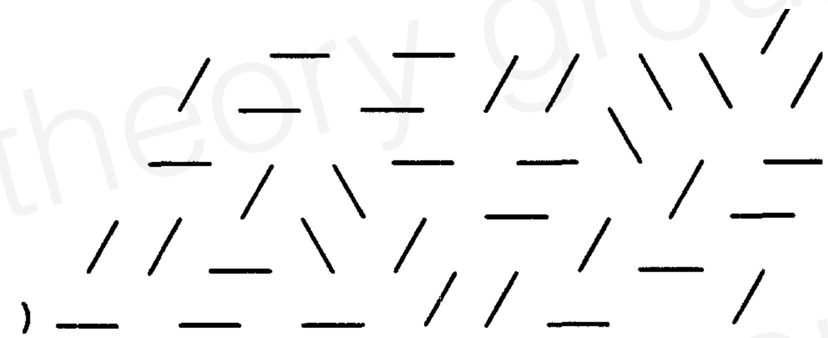
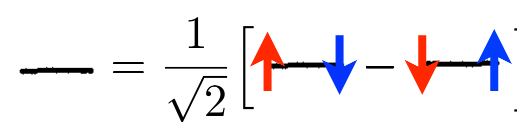


FIG. 3

Random arrangements of pair bonds on a triangle lattice. (a) Shows a regular ar-



Anderson's spin singlet RVB states, then possible application to high-Tc superconductor in 1987.

It is NOT a Landau symmetry breaking state. This brings up an **old and fundamental question**, how do we characterize phase of matter? Does spin liquid even exist?

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One-slide introduction to quantum spin liquids

The existence of spin liquid (in **theory**) is well established and is supported by

- Exactly solvable models: e.g. Kitaev model and its variants
- Classification: many many spin liquids (X.-G. Wen, etc)
- Numerical studies: DMRG, quantum Monte Carlo, exact diagonalization, etc

QSL is a **new phase of matter**, and is not characterized by symmetry, but characterized by an emergent gauge structure and deconfined excitations that carry fractional (spin) quantum numbers.

What's needed? Experiments, and the connection from theory to experiments!

Candidate spin liquid materials

- 2D triangular and Kagome lattice

  organics: kappa-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$, $EtMe_3Sb[Pd(dmit)_2]_2$, κappa–$H_3(Cat\text{-}EDT\text{-}TTF)_2$
  herbertsmithite ($ZnCu_3(OH)_6Cl_2$), $Ba_3NiSb_2O_9$, $Ba_3CuSb_2O_9$, $LiZn_2Mo_3O_8$, $ZnCu_3(OH)_6Cl_2$
  volborthite ($Cu_3V_2O_7(OH)_2$), $BaCu_3V_2O_3(OH)_2$, $[NH_4]_2[C_7H_{14}N][V_7O_6F_{18}]$, Na_2IrO_3, $CsCu_2Cl_4$, $CsCu_2Br_4$, $NiGa_2S_4$, He-3 layers on graphite, etc

- 3D pyrochlore, hyperkagome, FCC lattice, diamond lattice, etc

  $Na_4Ir_3O_8$, IrO_2, Ba_2YMoO_6, $Yb_2Ti_2O_7$, $Pr_2Zr_2O_7$, $Pr_2Sn_2O_7$, $Tb_2Ti_2O_7$, $Nd_2Zr_2O_7$, $FeSc_2S_4$, etc

- Ultracold atom and molecules on optical lattices: temperature is too high now.

Some candidate materials have already been ruled out.
Not being a QSL does not necessarily mean the physics is not interesting !

Outline

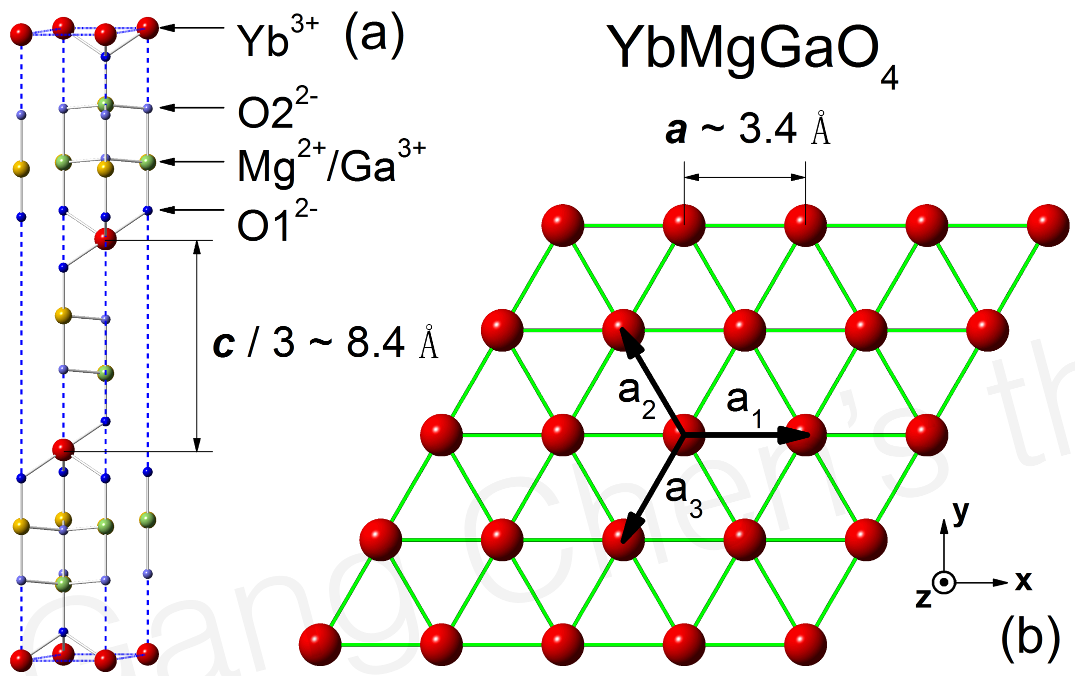
a. Early thermodynamics and microscopic modeling

b. Phenomenological approaches and neutron scattering

c. Prediction of the weak-field behavior and our roadmap

a. Early thermodynamics and microscopic modeling

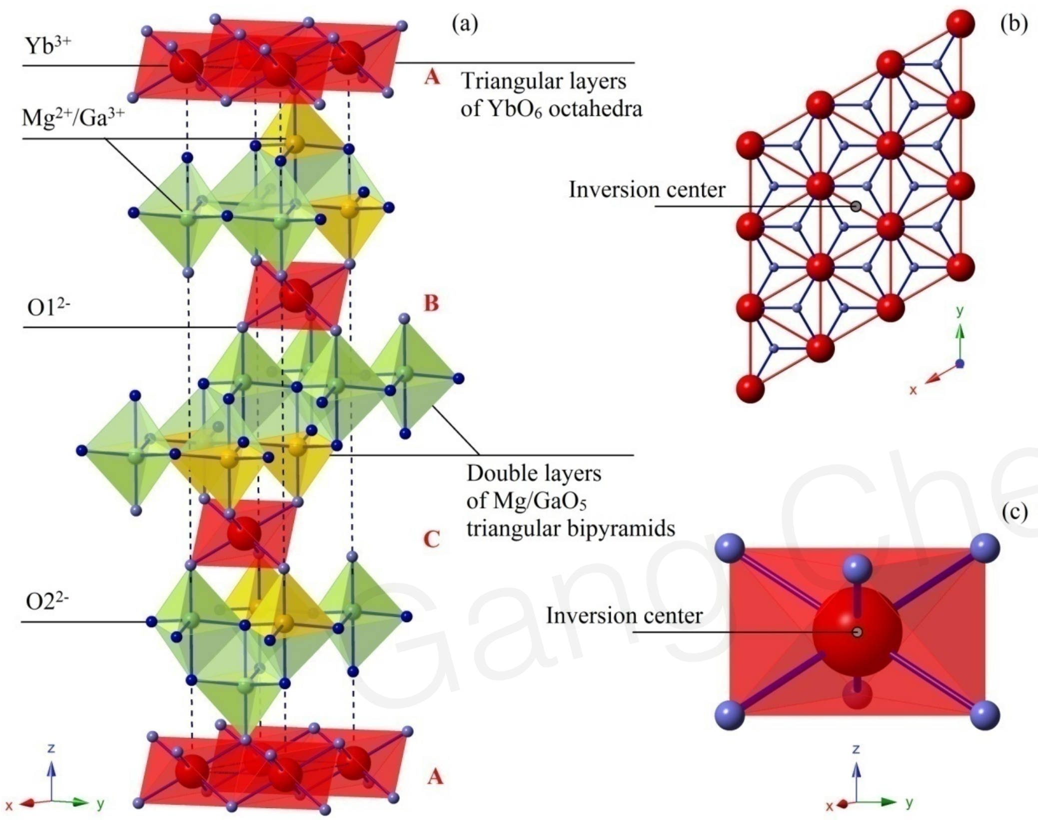
A rare-earth triangular lattice quantum spin liquid: **$YbMgGaO_4$**



Qingming Zhang

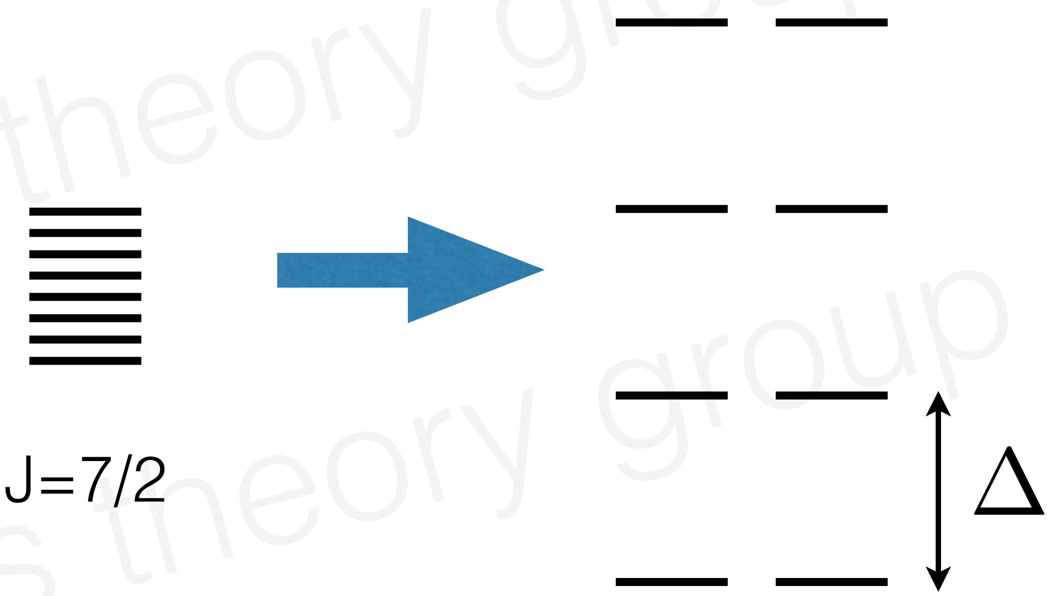
- Hastings-Oshikawa-Lieb-Shultz-Mattis theorem.
- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2015).
- This is likely the **first strong spin-orbit coupled QSL with odd electron filling** and effective spin-1/2.
- It is the first clear observation of $T^{2/3}$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

The microscopics



YS Li, …QM Zhang, Srep 2015

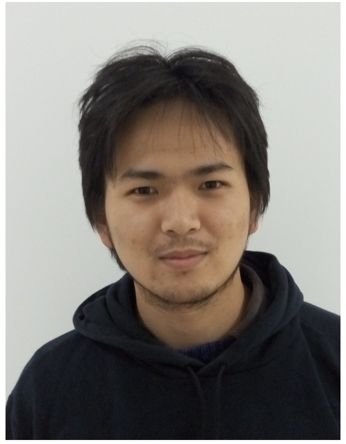
Yb^{3+} ion: $4f^{13}$ has J=7/2 due to SOC.



YS Li, **GC**, …, QM Zhang, PRL 2015
YD Li, XQ Wang, **GC**, arxiv1512, PRB 2016

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

Modeling

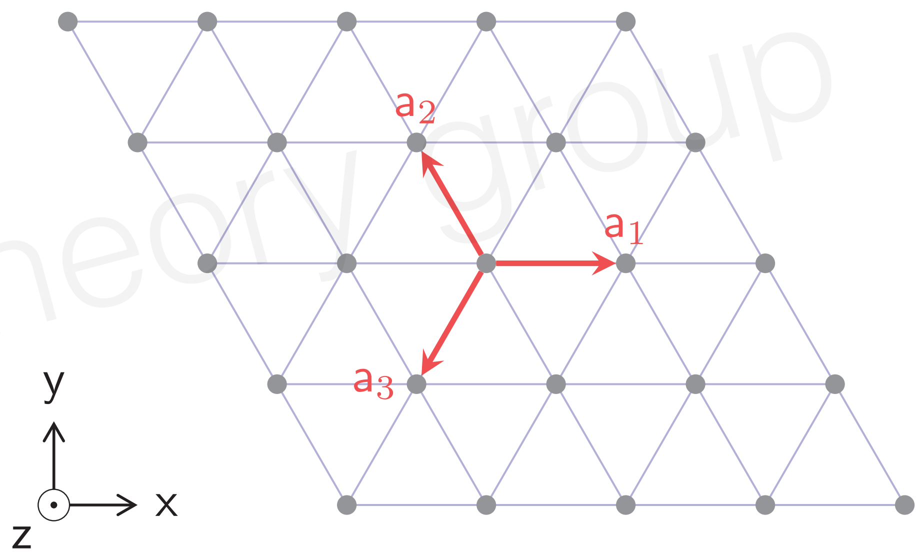


Yao-Dong Li
(Fudan -> UCSB)

4f electron is very localized, and dipolar interactions weak.

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

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-



anisotropic both in spin space and in real space !

YD Li, XQ Wang, GC, arXiv1512, PRB 2016

Polarized neutron scattering

arXiv 1705.05699

Strong exchange anisotropy in $YbMgGaO_4$ from polarized neutron diffraction

Sándor Tóth,[1,*] Katharina Rolfs,[2] Andrew R. Wildes,[3] and Christian Rüegg[1,4]

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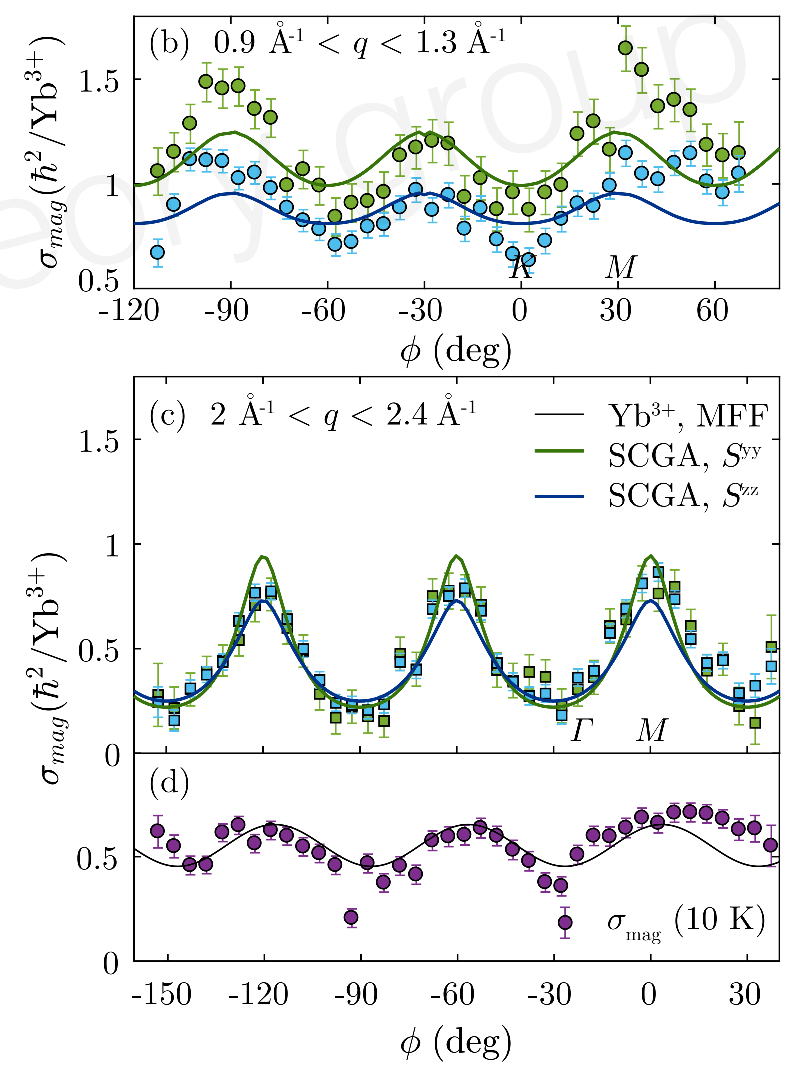
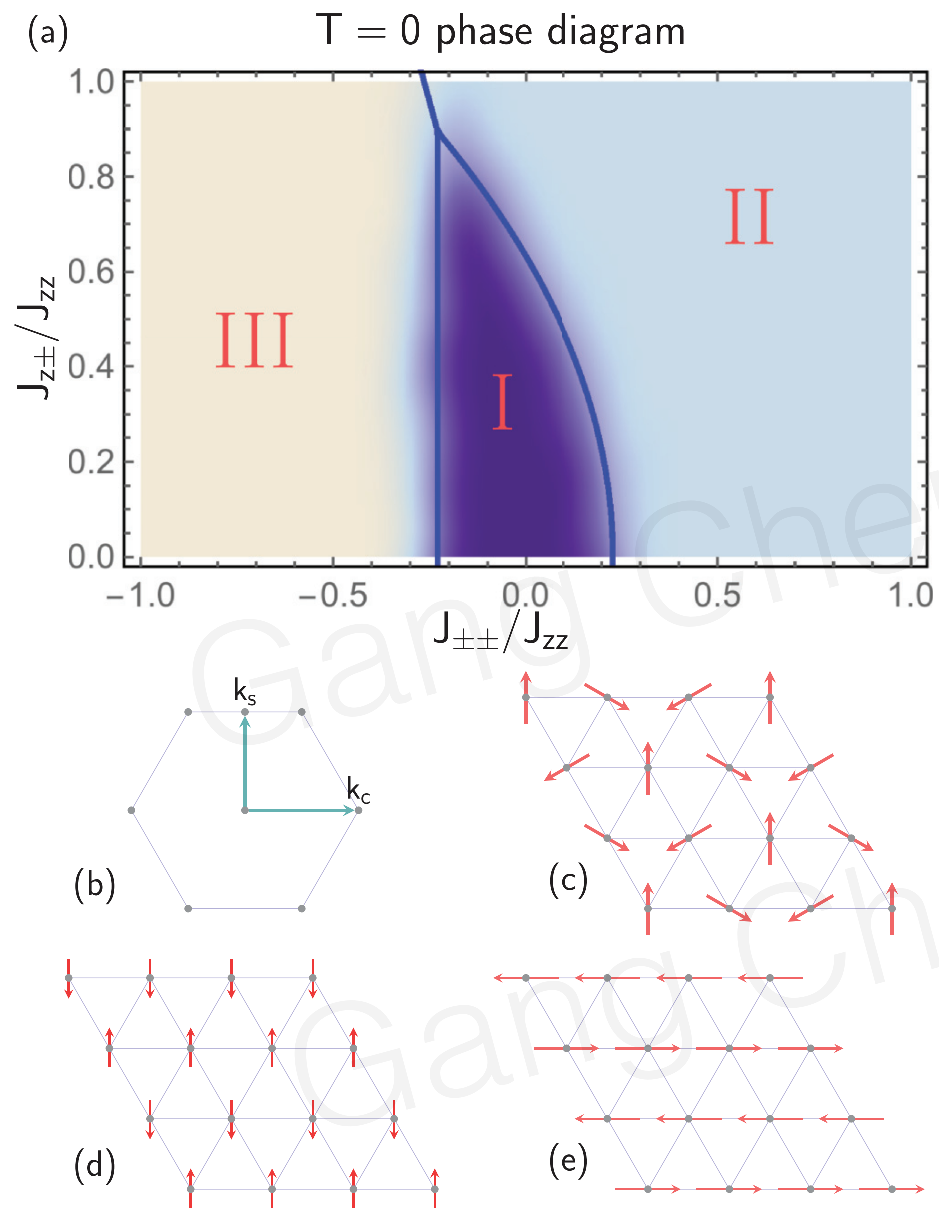
[2] *Laboratory for Scientific Developments and Novel Materials, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland*
[3] *Institut Max von Laue-Paul Langevin, 38042 Grenoble 9, France*
[4] *Department of Quantum Matter Physics, University of Geneva, 1211 Genève, Switzerland*

(Dated: May 17, 2017)

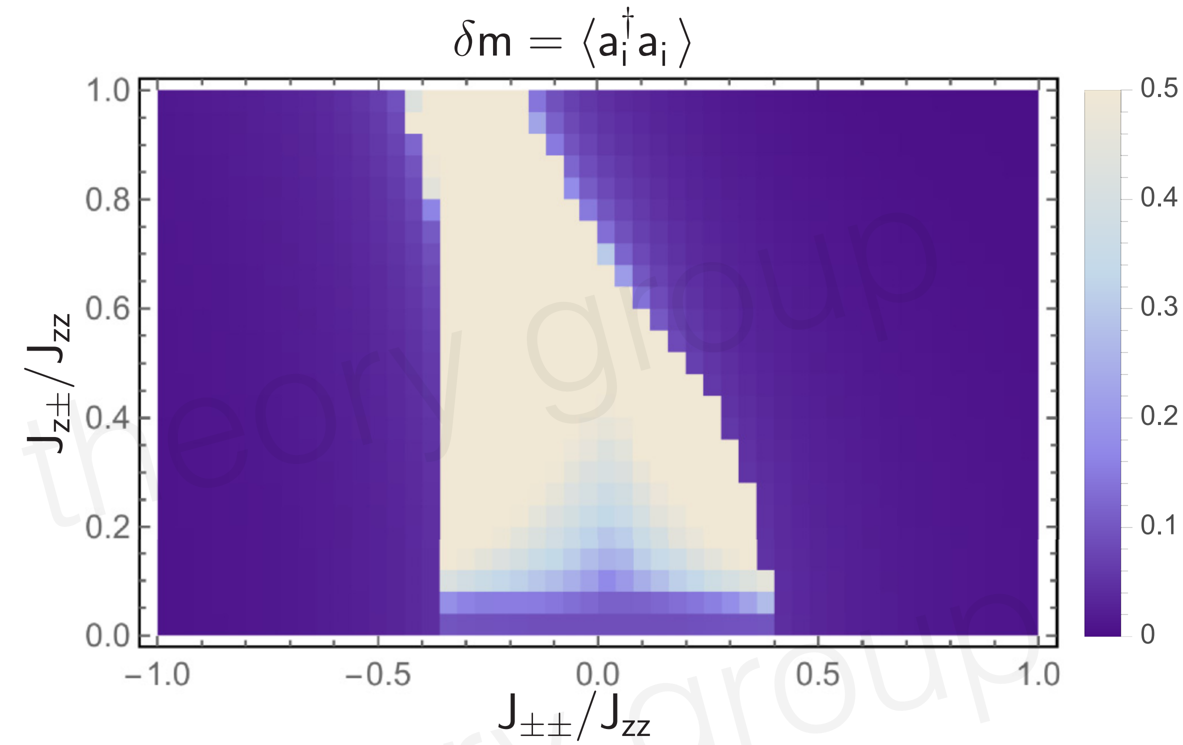
We measured the magnetic correlations in the triangular lattice spin-liquid candidate material $YbMgGaO_4$ via polarized neutron diffraction. The extracted in-plane and out-of-plane components of the magnetic structure factor show clear anisotropy. We found that short-range correlations persist at the lowest measured temperature of 52 mK and neutron scattering intensity is centered at the M middle-point of the hexagonal Brillouin-zone edge. Moreover, we found pronounced spin anisotropy, with different correlation lengths for the in-plane and out-of-plane spin components. When comparing to a self-consistent Gaussian appoximation, our data clearly support a model with only first-neighbor coupling and strongly anisotropic exchanges.



Phase diagram: a conservative approach



mean-field phase diagram



quantum fluctuations

Quantum fluctuation becomes very strong in certain parameter regimes

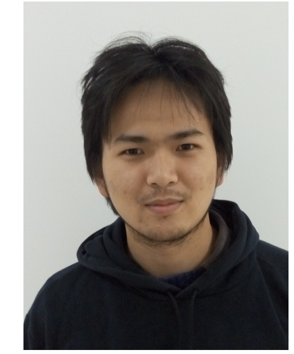
More prediction includes the strong field behaviors.

YD Li, XQ Wang, GC, arXiv1512, PRB 2016
YD Li, Y Shen,…., GC, arXiv1608, PRB 2018

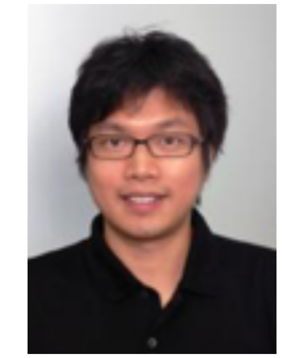
b. Phenomenological approaches and neutron scattering

Inelastic neutron scattering

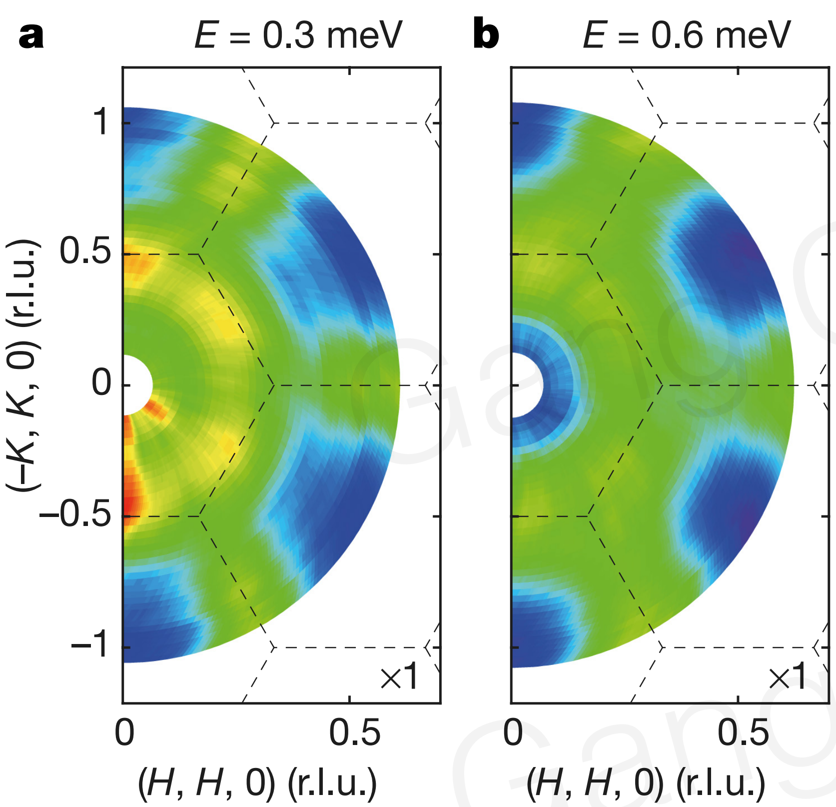
Yao Shen
(Fudan)

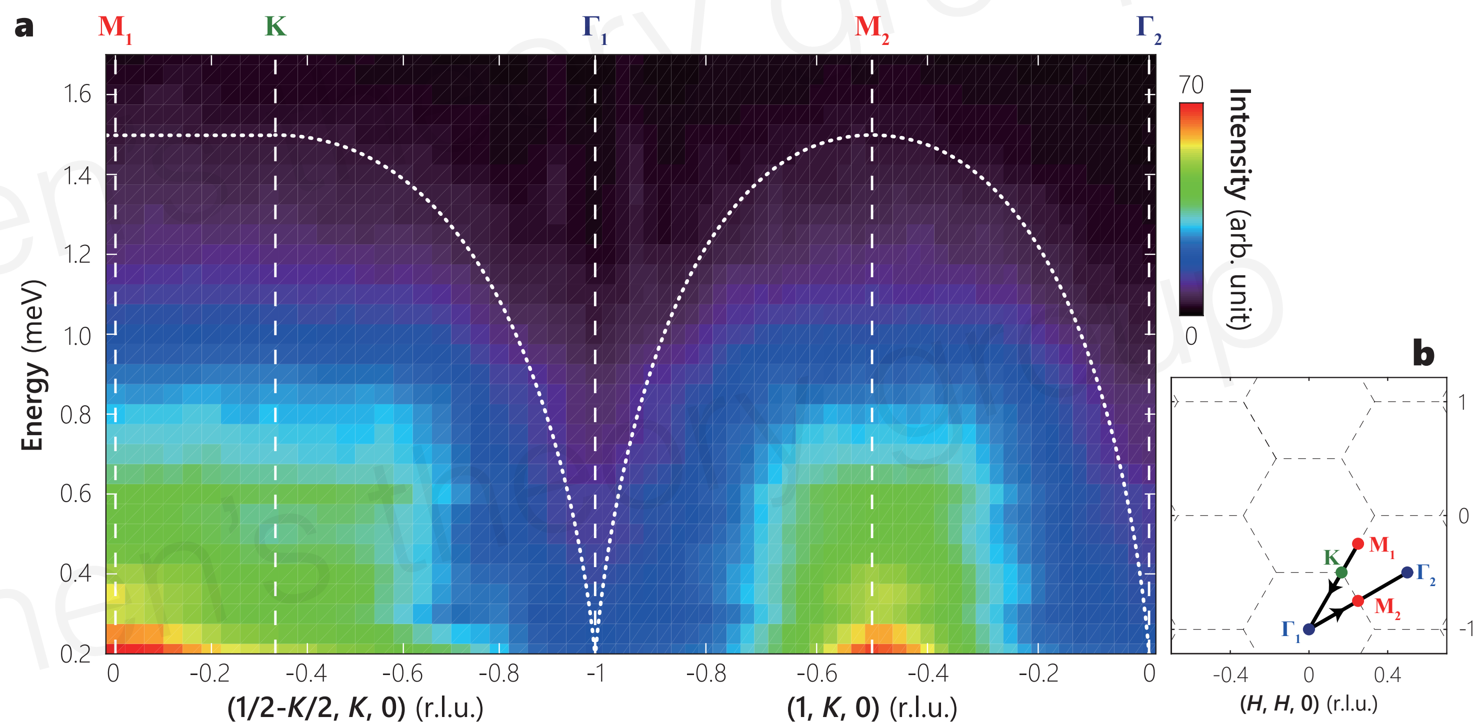


Yao-Dong Li
(Fudan->UCSB)



Jun Zhao
(Fudan)





Y Shen, YD Li …GC*, J Zhao* **Nature** 2016

consistent neutron results from Martin Mourigal's group, Nature Physics

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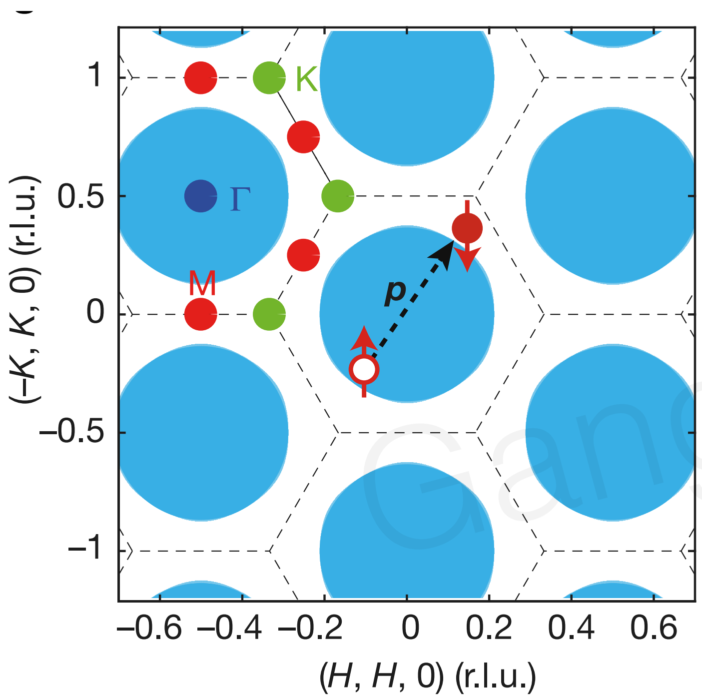
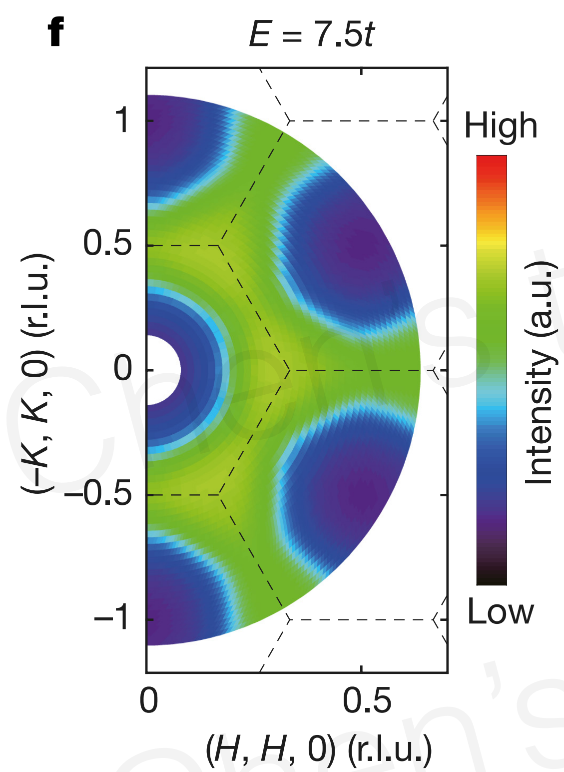
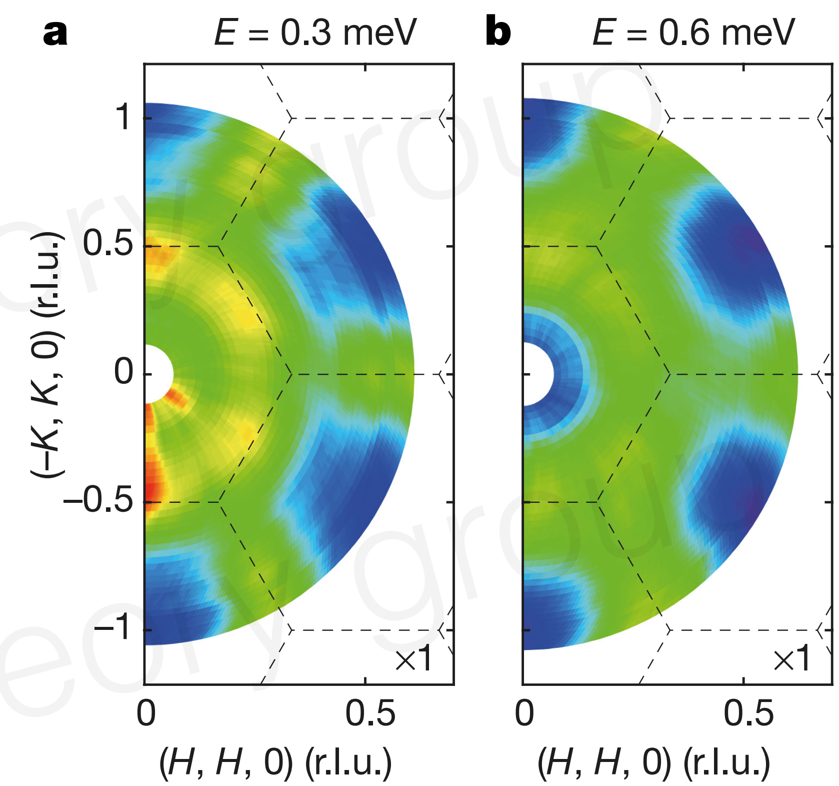
Spinon Fermi surface state







$$\boldsymbol{S}_{\boldsymbol{r}} = \frac{1}{2}\sum_{\alpha,\beta} f^{\dagger}_{\boldsymbol{r}\alpha}\boldsymbol{\sigma}_{\alpha\beta} f_{\boldsymbol{r}\beta}, \qquad H_{\mathrm{MFT}} = -t\sum_{\langle ij\rangle}(f^{\dagger}_{i\alpha} f_{j\alpha} + \mathrm{h.c.}) - \mu\sum_{i} f^{\dagger}_{i\alpha} f_{i\alpha}$$

Prediction from the 0 flux uniform spinon hopping

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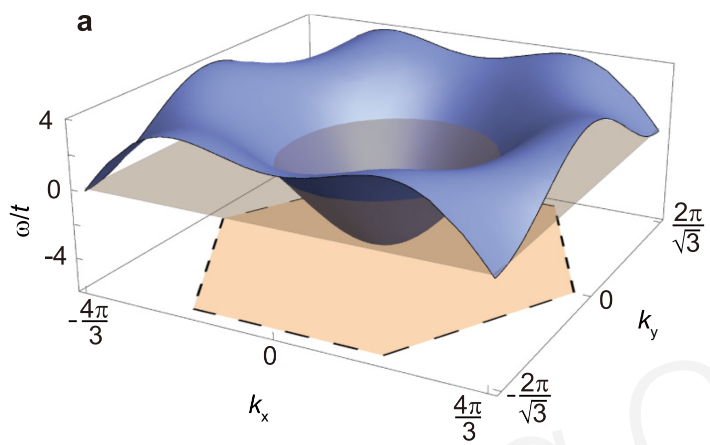
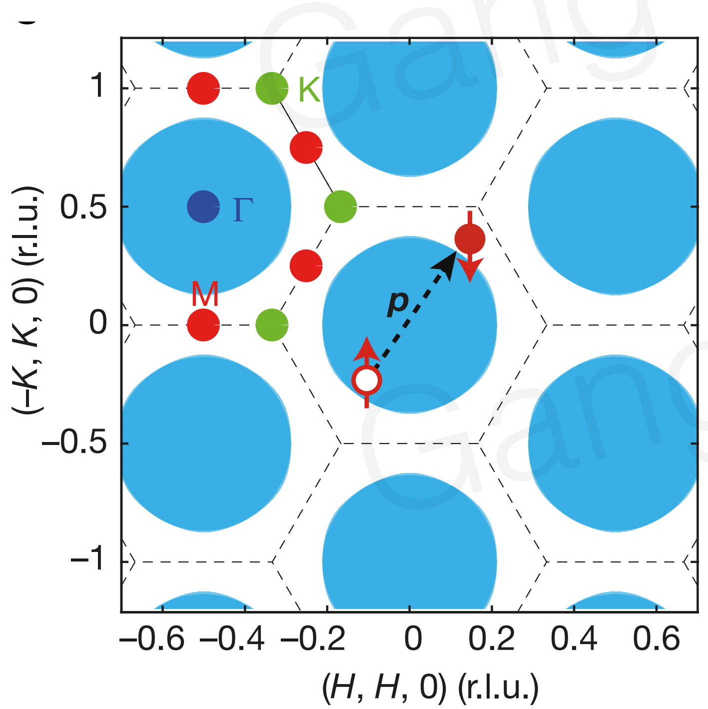
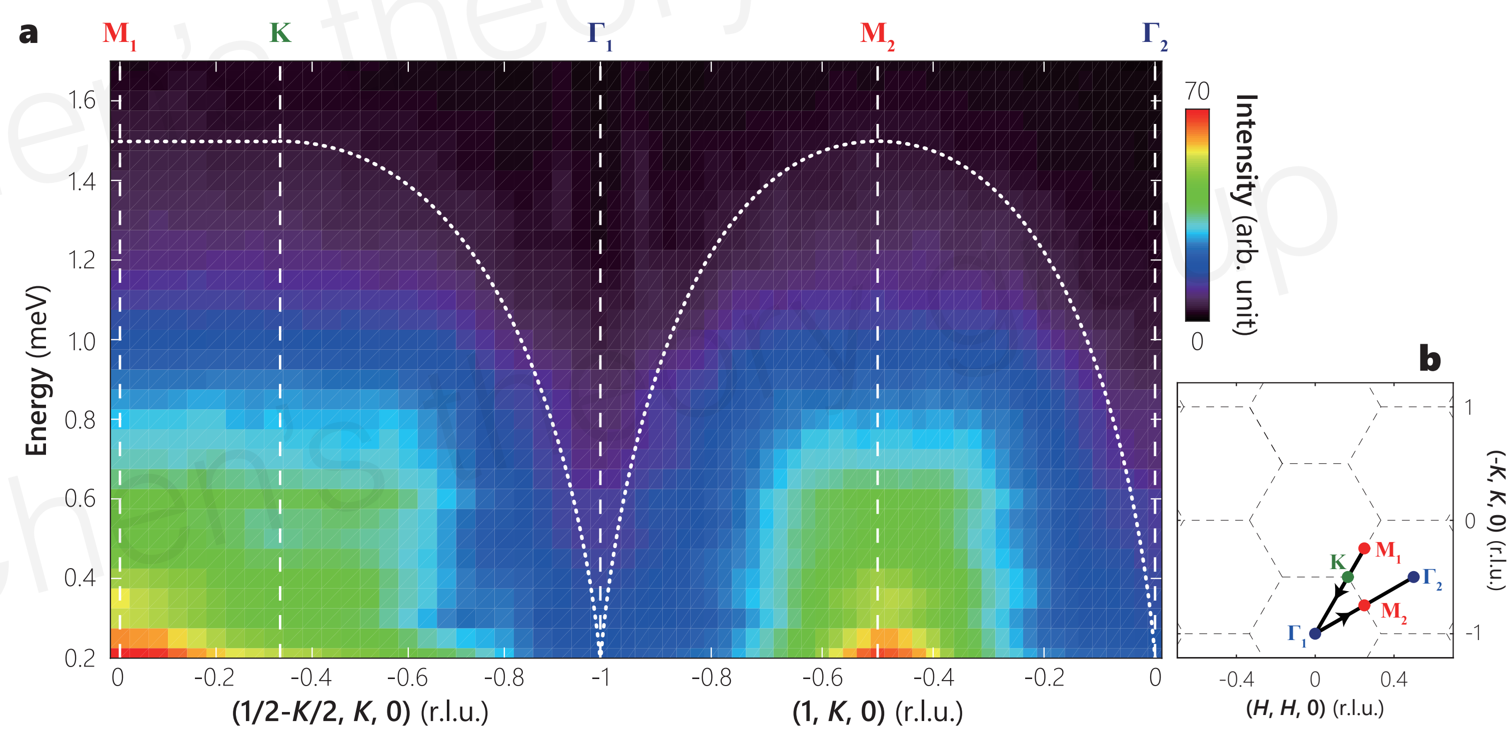
Y Shen, YD Li …GC*, J Zhao* **Nature** 2016

Particle-hole continuum of the spinon Fermi surface

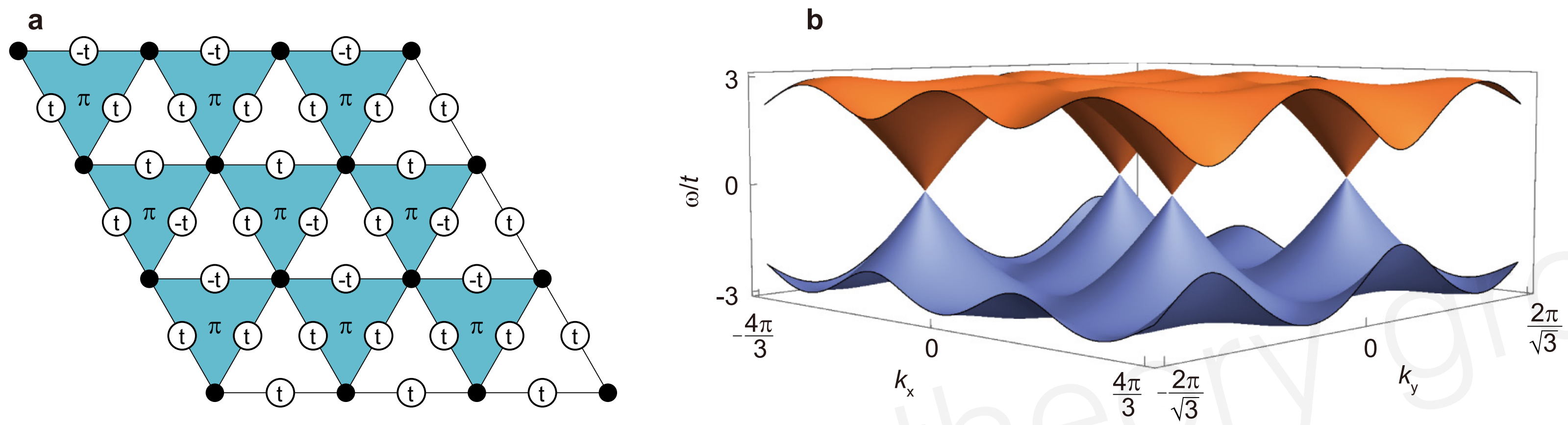






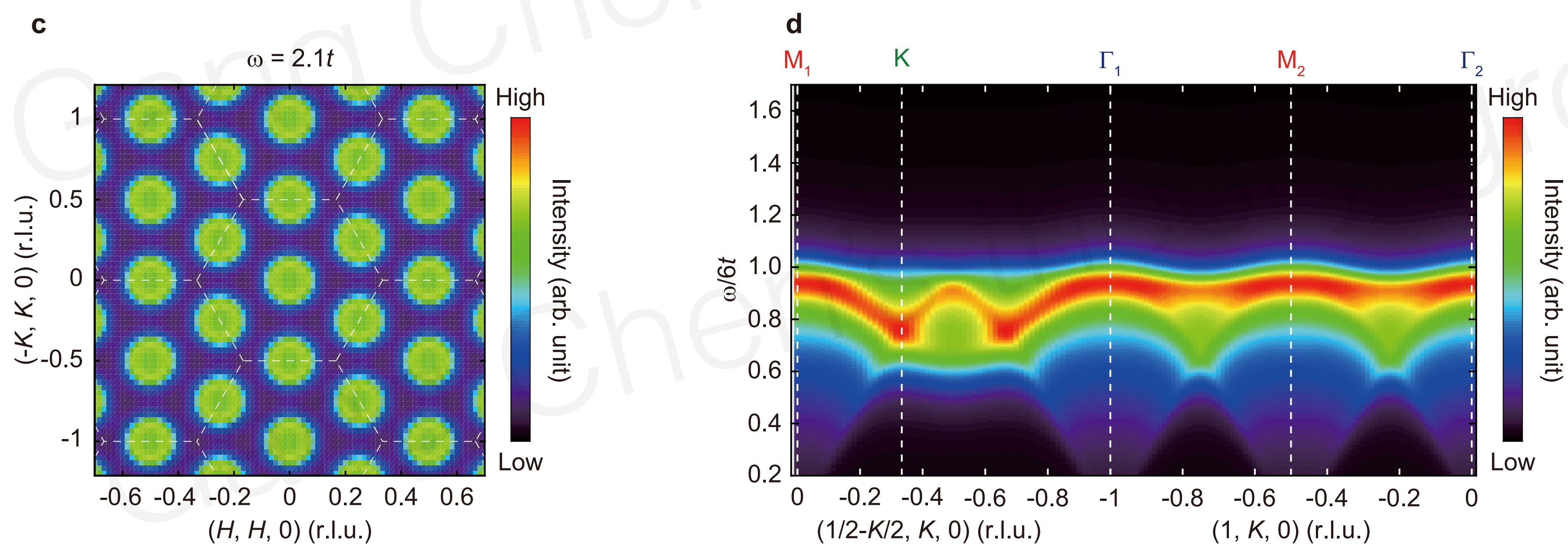
Y Shen, YD Li **…GC*, J Zhao*** **Nature** 2016

How about Dirac spin liquid?



Pi flux

Dirac spectrum

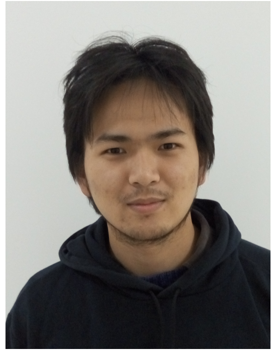


fixed energy

along high symmetry momentum

also inconsistent with thermodynamics, likewise, Z2 QSL does not work either.

Y Shen, YD Li **...GC***, J Zhao* **Nature** 2016



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More assurance from projective symmetry group analysis

Yao-Dong Li, YM Lu, GC*, arXiv **1612.03447**, PhysRevB 96, 054445

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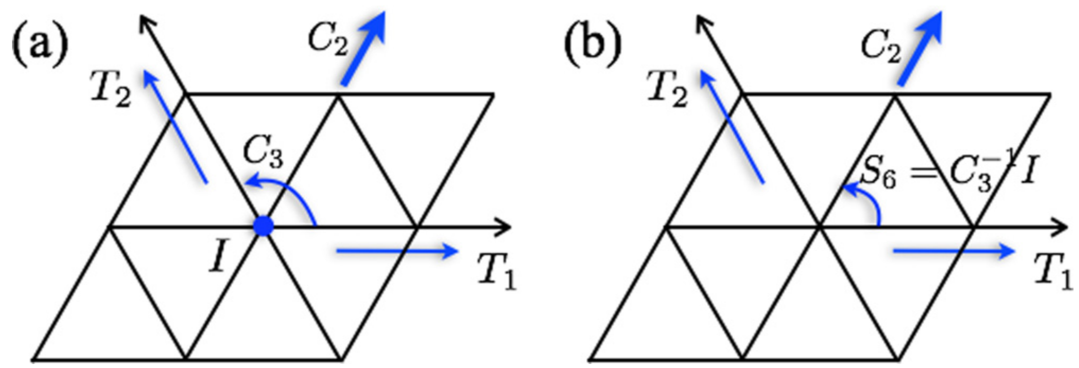
Spin transformation and gauge transformation



$$T_1^{-1} T_2 T_1 T_2^{-1} = T_1^{-1} T_2^{-1} T_1 T_2 = 1,$$

$$C_2^{-1} T_1 C_2 T_2^{-1} = C_2^{-1} T_2 C_2 T_1^{-1} = 1,$$

$$S_6^{-1} T_1 S_6 T_2 = S_6^{-1} T_2 S_6 T_2^{-1} T_1^{-1} = 1,$$

$$(C_2)^2 = (S_6)^6 = (S_6 C_2)^2 = 1.$$

YD Li, XQ Wang, **GC**, arXiv1512, PRB 2016

YD Li, YM Lu, GC, arXiv **1612.03447**, PRB

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

$$\Psi_{\boldsymbol{r}} = (f_{\boldsymbol{r}\uparrow}, f_{\boldsymbol{r}\downarrow}^{\dagger}, f_{\boldsymbol{r}\downarrow}, -f_{\boldsymbol{r}\uparrow}^{\dagger})^T$$

$$\boldsymbol{S}_{\boldsymbol{r}} = \frac{1}{4} \Psi_{\boldsymbol{r}}^{\dagger} (\boldsymbol{\sigma} \otimes I_{2\times 2}) \Psi_{\boldsymbol{r}},$$

$$\boldsymbol{G}_{\boldsymbol{r}} = \frac{1}{4} \Psi_{\boldsymbol{r}}^{\dagger} (I_{2\times 2} \otimes \boldsymbol{\sigma}) \Psi_{\boldsymbol{r}},$$

$$[S_{\boldsymbol{r}}^{\mu}, G_{\boldsymbol{r}}^{\nu}] = 0.$$

The spin transformation and gauge transformation commute with each other.

XG Wen PRB 2002

Reduction and simplification: classification mean field states

Mean-field model

$$H_{\rm MF} = -\frac{1}{2}\sum_{(\boldsymbol{r},\boldsymbol{r}')}\big[\Psi^\dagger_{\boldsymbol{r}} u_{\boldsymbol{r}\boldsymbol{r}'}\Psi_{\boldsymbol{r}'} + h.c.\big],$$

$$\Psi_{\boldsymbol{r}} = (f_{\boldsymbol{r}\uparrow}, f^\dagger_{\boldsymbol{r}\downarrow}, f_{\boldsymbol{r}\downarrow}, -f^\dagger_{\boldsymbol{r}\uparrow})^T$$

symmetry transformation $\mathcal{O}$

$$u_{\boldsymbol{r}\boldsymbol{r}'} = \mathcal{G}^{\mathcal{O}\dagger}_{\mathcal{O}(\boldsymbol{r})}\mathcal{U}^\dagger_{\mathcal{O}} u_{\mathcal{O}(\boldsymbol{r})\mathcal{O}(\boldsymbol{r}')}\mathcal{U}_{\mathcal{O}}\mathcal{G}^{\mathcal{O}}_{\mathcal{O}(\boldsymbol{r}')}.$$

spin rotation ($\mathcal{U}_{\mathcal{O}}$) — gauge rotation ($\mathcal{G}^{\mathcal{O}}_{\mathcal{O}(\boldsymbol{r}')}$)

group relation $\mathcal{O}_1\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4 = 1$

$$\begin{aligned}
&\mathcal{U}_{\mathcal{O}_1}\mathcal{G}^{\mathcal{O}_1}_{\boldsymbol{r}}\mathcal{U}_{\mathcal{O}_2}\mathcal{G}^{\mathcal{O}_2}_{\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}\mathcal{U}_{\mathcal{O}_3}\mathcal{G}^{\mathcal{O}_3}_{\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}\mathcal{U}_{\mathcal{O}_4}\mathcal{G}^{\mathcal{O}_4}_{\mathcal{O}_4(\boldsymbol{r})}\\
=&\,\mathcal{U}_{\mathcal{O}_1}\mathcal{U}_{\mathcal{O}_2}\mathcal{U}_{\mathcal{O}_3}\mathcal{U}_{\mathcal{O}_4}\mathcal{G}^{\mathcal{O}_1}_{\boldsymbol{r}}\mathcal{G}^{\mathcal{O}_2}_{\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}\mathcal{G}^{\mathcal{O}_3}_{\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}\mathcal{G}^{\mathcal{O}_4}_{\mathcal{O}_4(\boldsymbol{r})}\\
\in&\,\mathrm{IGG},
\end{aligned}$$

$$\mathcal{U}_{\mathcal{O}_1}\mathcal{U}_{\mathcal{O}_2}\mathcal{U}_{\mathcal{O}_3}\mathcal{U}_{\mathcal{O}_4} = \pm I_{4\times4}, \qquad \{\pm I_{4\times4}\}\subset \mathrm{IGG}$$

$$\mathcal{G}^{\mathcal{O}_1}_{\boldsymbol{r}}\mathcal{G}^{\mathcal{O}_2}_{\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}\mathcal{G}^{\mathcal{O}_3}_{\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}\mathcal{G}^{\mathcal{O}_4}_{\mathcal{O}_4(\boldsymbol{r})} \in \mathrm{IGG}$$

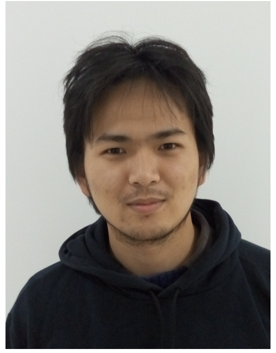
Projective symmetry group classification

U(1) QSL	$W_{\boldsymbol{r}}^{T_1}$	$W_{\boldsymbol{r}}^{T_2}$	$W_{\boldsymbol{r}}^{C_2}$	$W_{\boldsymbol{r}}^{C_6}$
U1A00	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$
U1A10	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$	$I_{2\times2}$
U1A01	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$
U1A11	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$	$i\sigma^y$
U1B00	$I_{2\times2}$	$(-1)^x I_{2\times2}$	$(-1)^{xy} I_{2\times2}$	$(-1)^{xy-\frac{y(y-1)}{2}} I_{2\times2}$
U1B10	$I_{2\times2}$	$(-1)^x I_{2\times2}$	$i\sigma^y(-1)^{xy}$	$(-1)^{xy-\frac{y(y-1)}{2}} I_{2\times2}$
U1B01	$I_{2\times2}$	$(-1)^x I_{2\times2}$	$(-1)^{xy} I_{2\times2}$	$i\sigma^y(-1)^{xy-\frac{y(y-1)}{2}}$
U1B11	$I_{2\times2}$	$(-1)^x I_{2\times2}$	$i\sigma^y(-1)^{xy}$	$i\sigma^y(-1)^{xy-\frac{y(y-1)}{2}}$

TABLE III. The transformation for the spinons under four U1A PSGs that are labeled by U1A$n_{C_2}n_{S_6}$.

U(1) PSGs	T_1	T_2	C_2	S_6
U1A00	$f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow}$	$f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f_{(y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{i\frac{5\pi}{6}} f_{(y,x),\uparrow}$	$f_{(x,y),\uparrow} \to e^{-i\frac{\pi}{3}} f_{(x-y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f_{(x-y,x),\downarrow}$
U1A10	$f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow}$	$f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f^{\dagger}_{(y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{-i\frac{\pi}{6}} f^{\dagger}_{(y,x),\downarrow}$	$f_{(x,y),\uparrow} \to e^{-i\frac{\pi}{3}} f_{(x-y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f_{(x-y,x),\downarrow}$
U1A01	$f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow}$	$f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f_{(y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{i\frac{5\pi}{6}} f_{(y,x),\uparrow}$	$f_{(x,y),\uparrow} \to -e^{-i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\uparrow}$
U1A11	$f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow}$	$f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f^{\downarrow\dagger}_{(y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{-i\frac{\pi}{6}} f^{\downarrow\dagger}_{(y,x),\downarrow}$	$f_{(x,y),\uparrow} \to -e^{-i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\uparrow}$

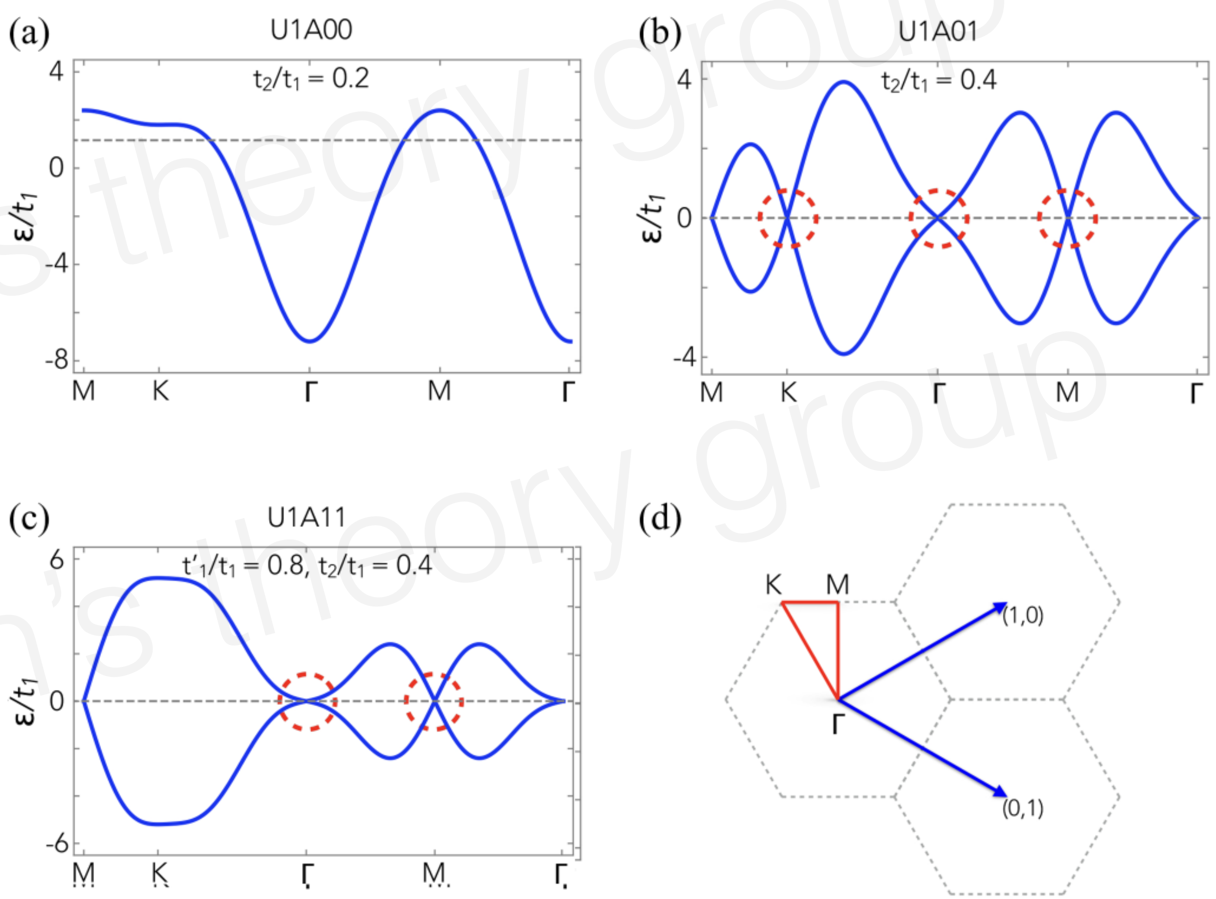
Spectroscopic constraints



We use PSG to predict the corresponding spectrum.

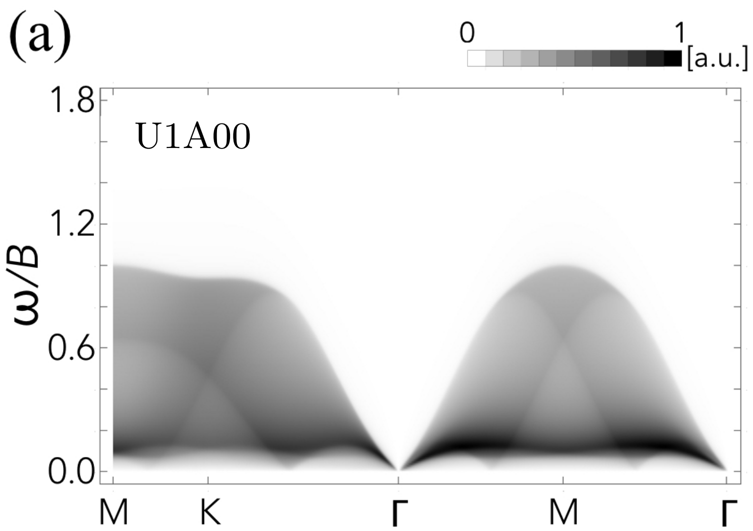
$$H_{\rm MF} = -\sum_{(\boldsymbol{rr'})}\sum_{\alpha\beta}\big[\,t_{\boldsymbol{rr'},\alpha\beta} f^\dagger_{\boldsymbol{r}\alpha} f_{\boldsymbol{r'}\beta} + h.c.\,\big],$$

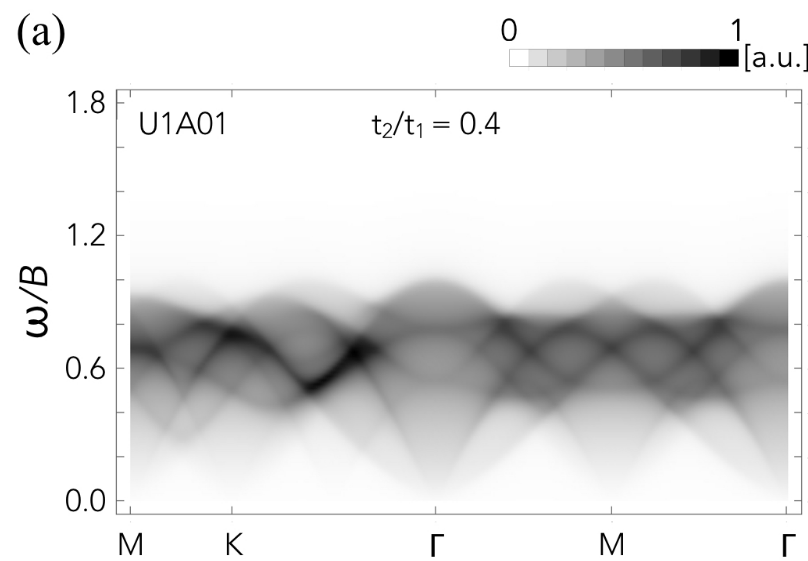
U(1) QSL	$W_{\boldsymbol{r}}^{T_1}$	$W_{\boldsymbol{r}}^{T_2}$	$W_{\boldsymbol{r}}^{C_2}$	$W_{\boldsymbol{r}}^{C_6}$
U1A00	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$
U1A10	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$	$I_{2\times2}$
U1A01	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$
U1A11	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$	$i\sigma^y$

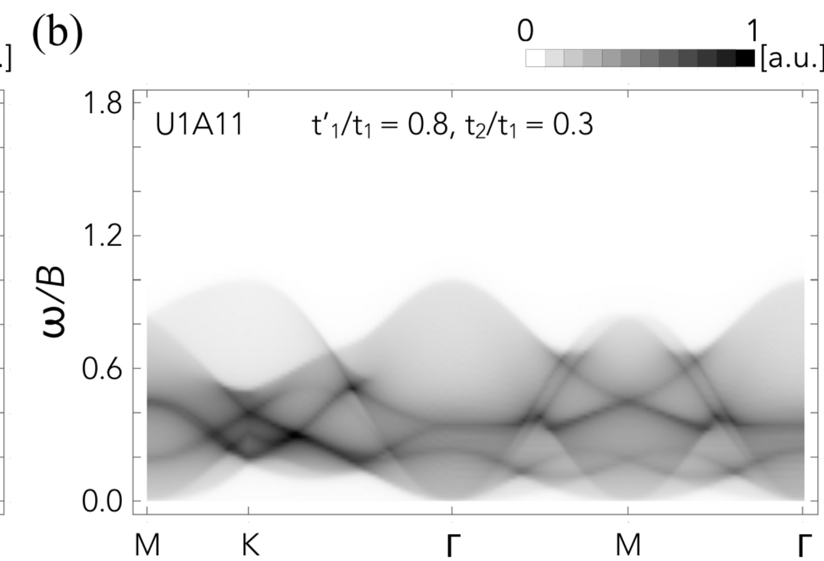


The U1A00 state is the spinon Fermi surface state that we proposed in Shen, et al, Nature.

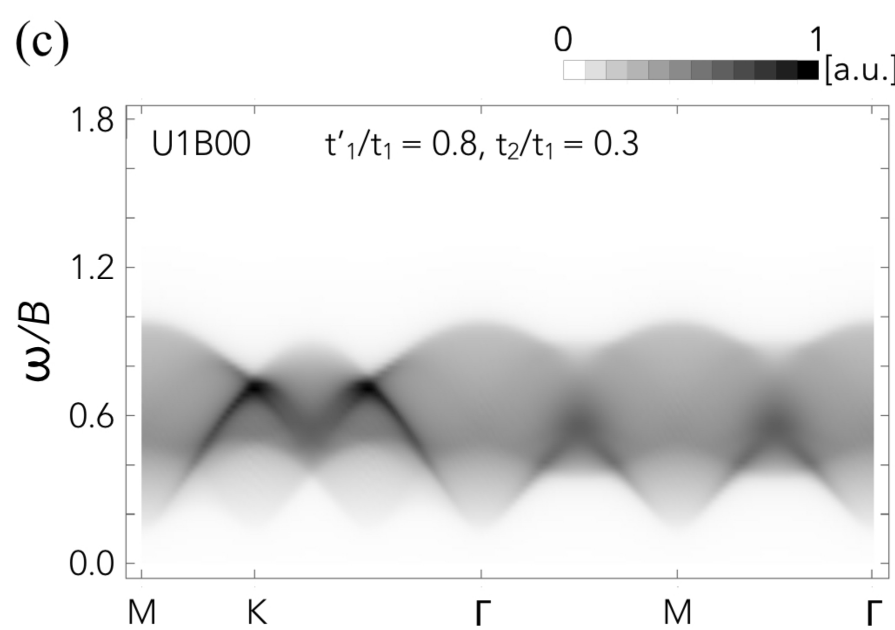
Dynamic spin structure factor







U1A00 U1A01 U1A11

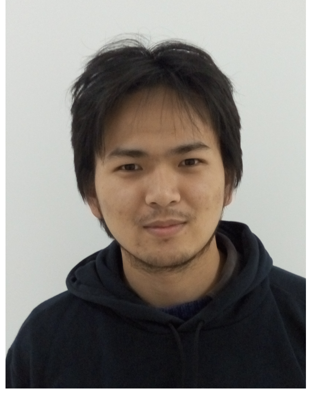


U1B state

c. **Prediction** of the weak-field behavior and our roadmap

Like isotope effect in BCS superconductors

Two major questions so far



Yao-Dong Li

1. Whether the continuum represents the fractionalized spinon excitation? Probably most important !

   discussed in
   Y-D Li, GC, arXiv:1703.01876
   PhysRevB, 96, 075105

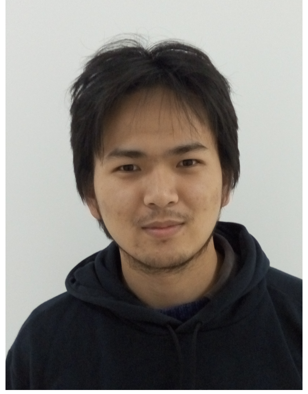
2. What is the physical origin of the QSL physics ?

Our Roadmap

1. **Detect fractionalized excitations, i.e. spinons**
   a) detect the fractionalization.
   b) detect the emergent fermion statistics.

2. Detect the emergent U(1) gauge field ?

3. Detect the spinon-gauge coupling (i.e. Lorentz coupling) ?



Yao-Dong Li
(Fudan)

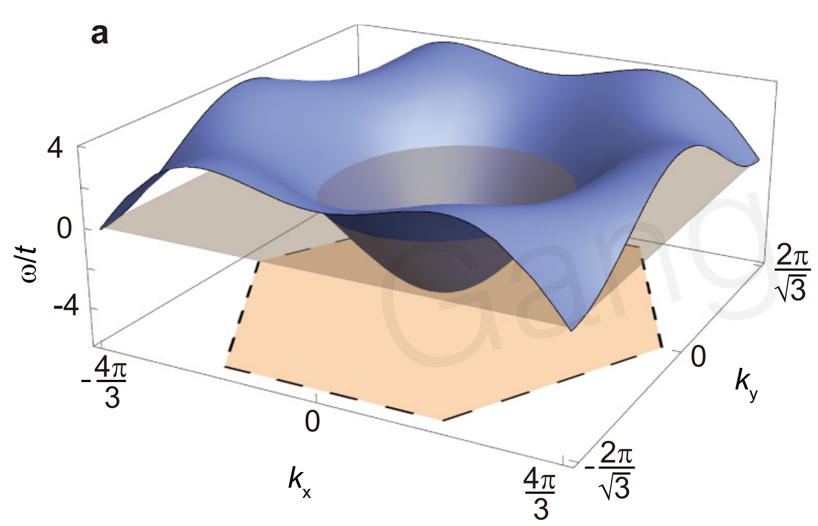
Explore the weak field regime

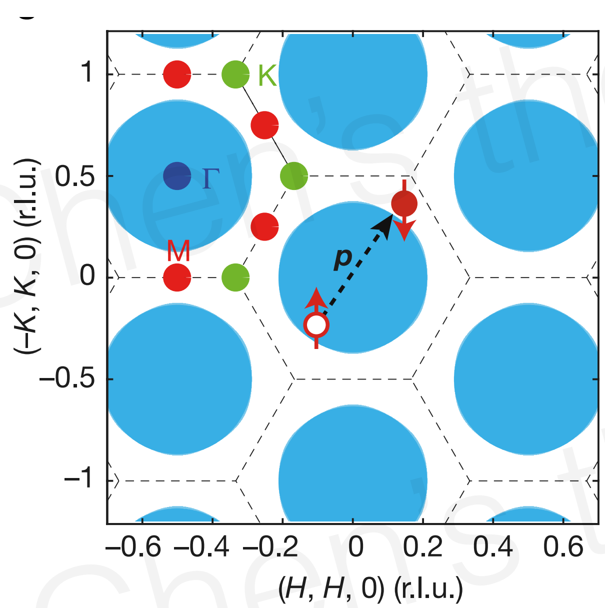
Continuing the recent proposal of the spinon Fermi surface U(1) spin liquid state for $YbMgGaO_4$ in Yao-Dong Li, *et al*, arXiv:1612.03447 and Yao Shen, *et al*, Nature 2016, we explore the experimental consequences of the external magnetic fields on this exotic state. Specifically, we focus on the *weak field regime* where the spin liquid state is preserved and the fractionalized spinon excitations remain to be a good description of the magnetic excitations. From the spin-1/2 nature of the spinon excitation, we predict the unique features of spinon continuum when the magnetic field is applied to the system. Due to the small energy scale of the rare-earth magnets, our proposal for the spectral weight shifts in the magnetic fields can be immediately tested by inelastic neutron scattering experiments. Several other experimental aspects about the spinon Fermi surface and spinon excitations are discussed and proposed. Our work provides a new way to examine the fractionalized spinon excitation and the candidate spin liquid states in the rare-earth magnets like $YbMgGaO_4$.

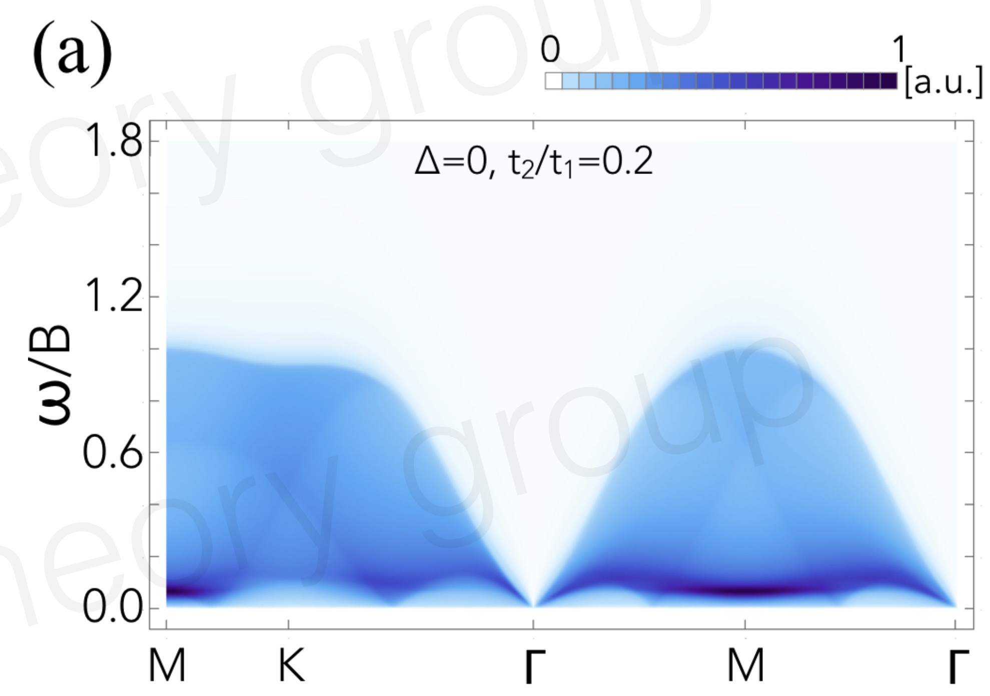
Reasonable, Feasible, and Predictable.

YD Li, **GC**, arXiv: **1703.01876**
PhysRevB, 96, 075105

Zero-field particle-hole continuum

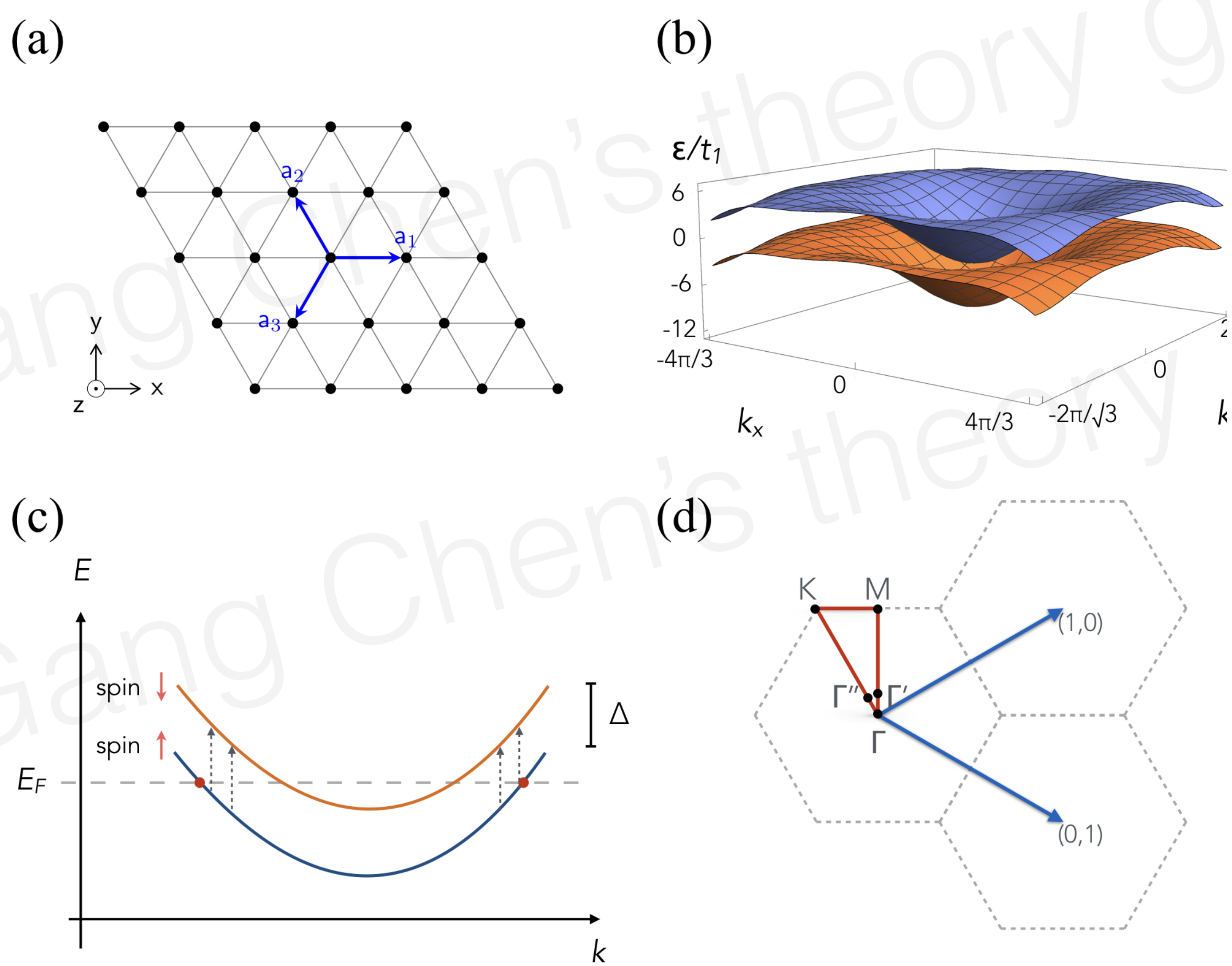






Strong Mott regime: only Zeeman coupling to field

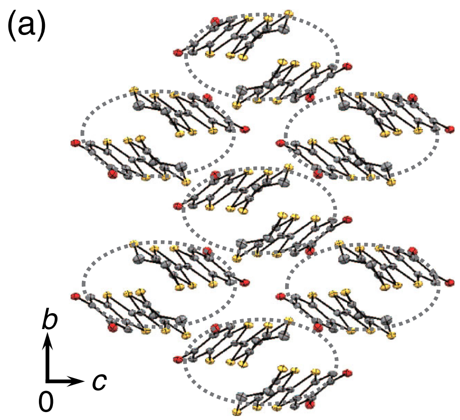
Magnetic field splits the spin-up and down spinon bands, **different from the organics**

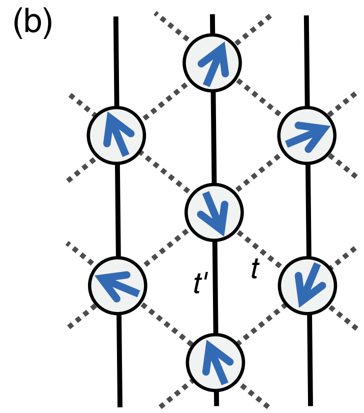


FUDAN UNIVERSITY 复旦大学

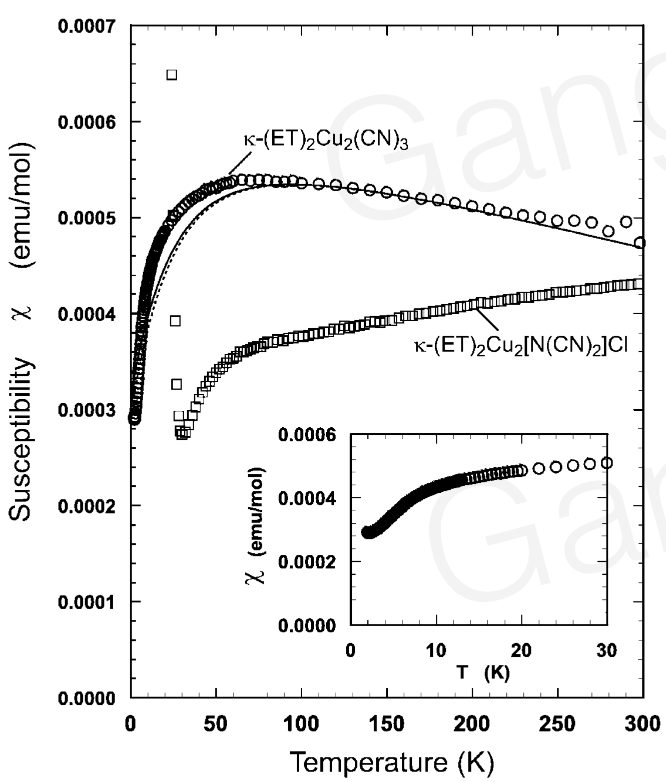
Organic spin liquids?

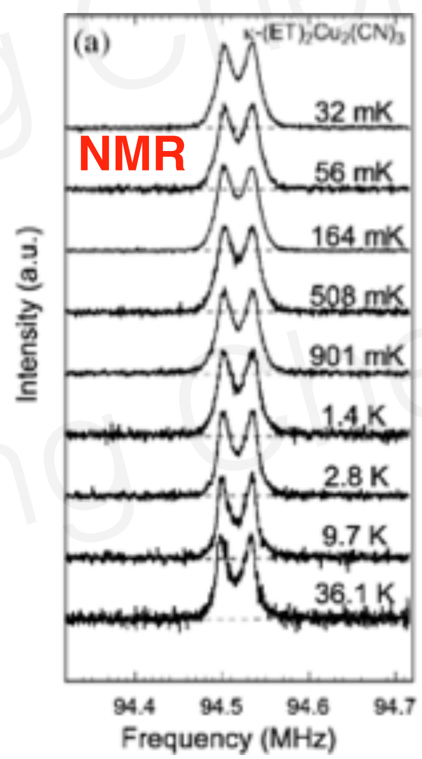

Kanoda

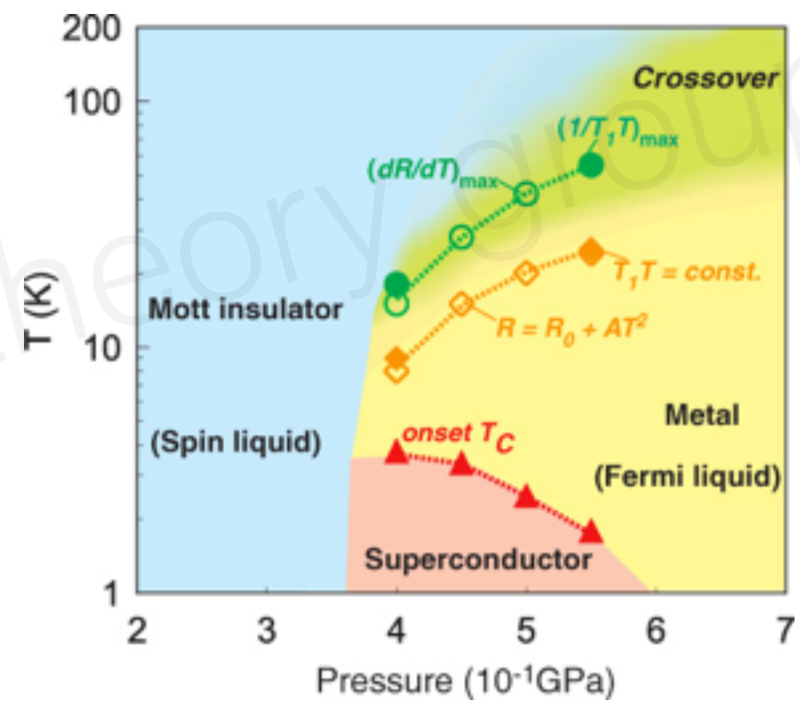




kappa-(BEDT-TTF)2Cu2(CN)3,
EtMe3Sb[Pd(dmit)2]2,
kappa–H3(Cat-EDT-TTF)2 **a new one!**



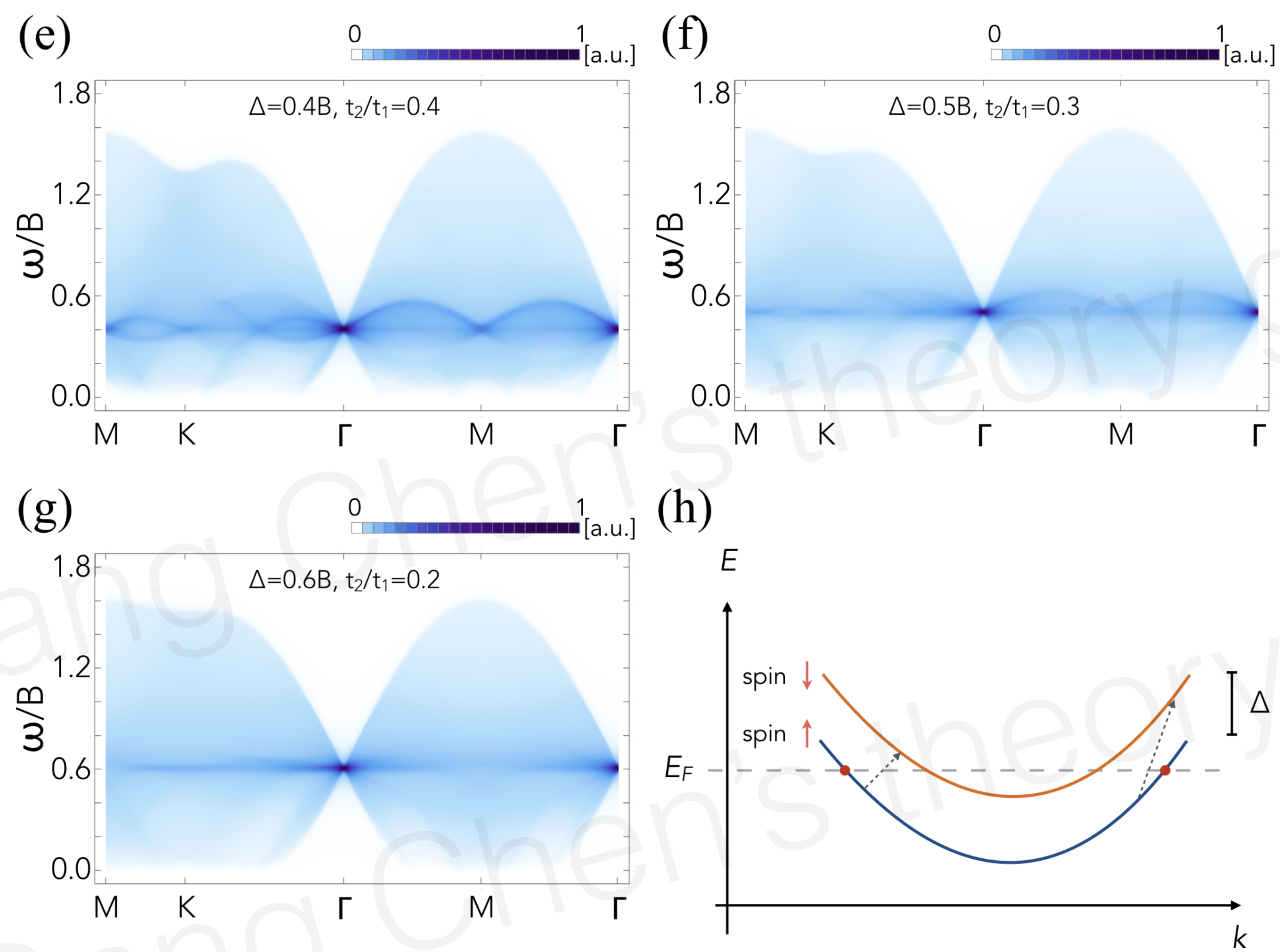




* No magnetic order down to 32mK
* Constant spin susceptibility at zero temperature

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

Prediction for dynamic spin structure factor



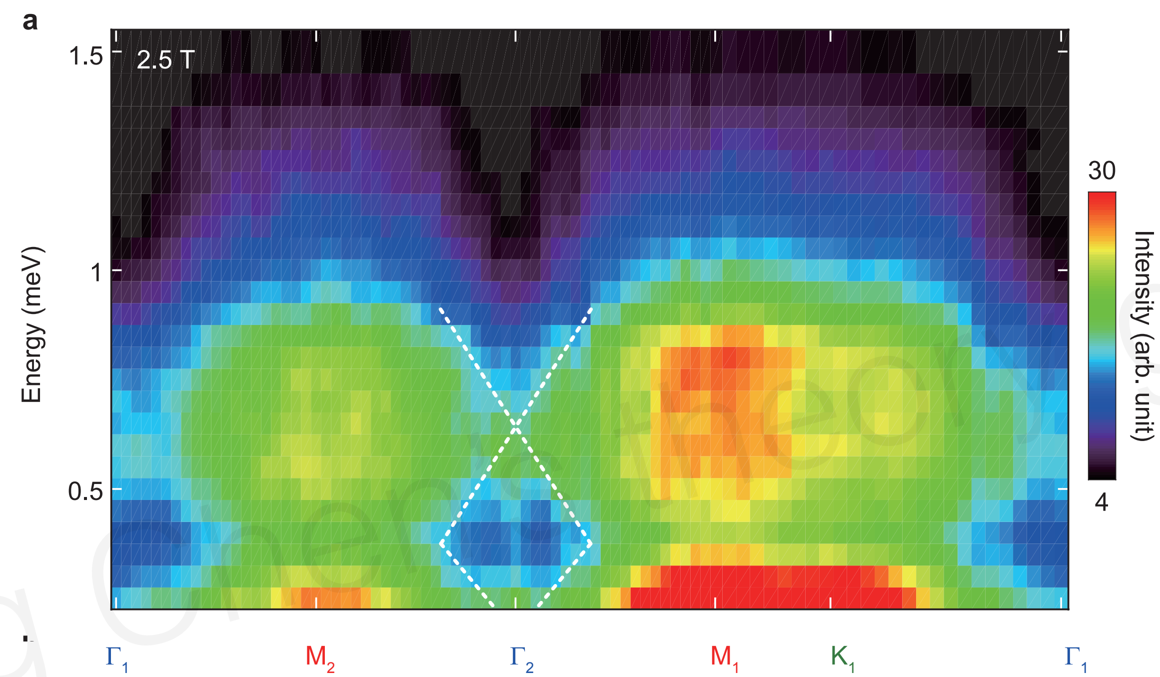
We predict:

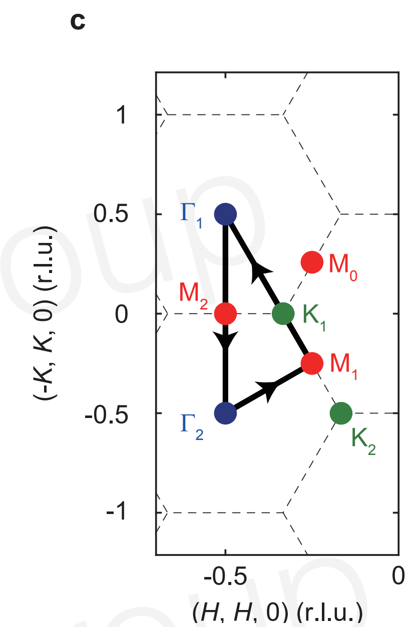
1. The system remains gapless and spinon continuum persists
2. spectral weight shifts
3. the spectral crossing at Gamma point
4. the presence of lower and upper excitation edges

Very different from magnon in the field !!

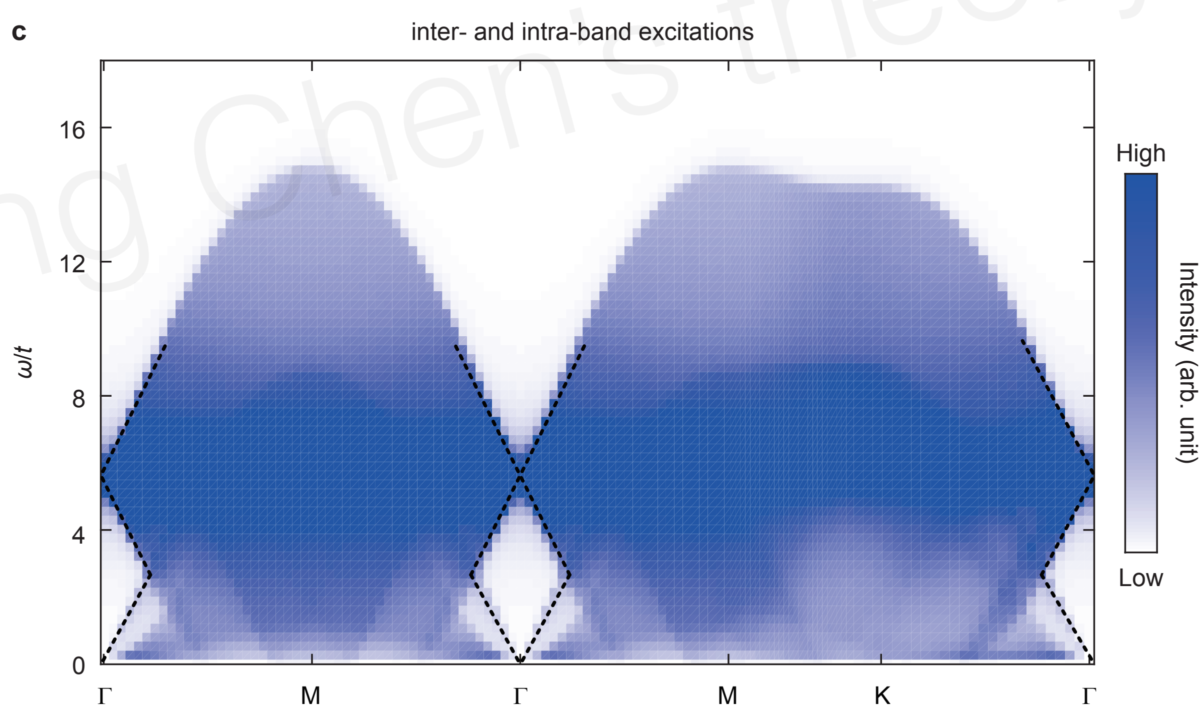
Excitation continuum in weakly magnetized YbMgGaO4

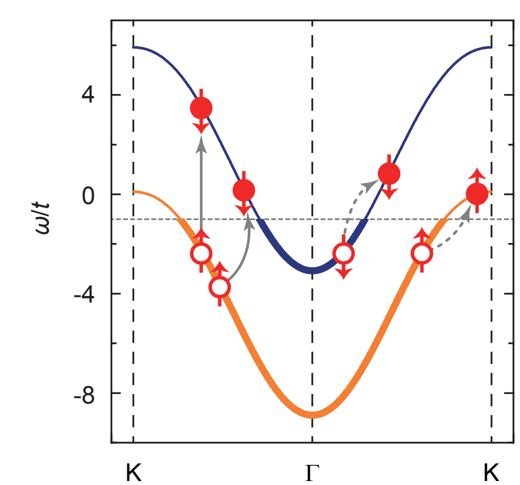
Experiment:
Y Shen, YD Li, …, GC*, J Zhao*
arXiv: 1708.06655
Nature Comms





Theoretical results for
the experimental parameter





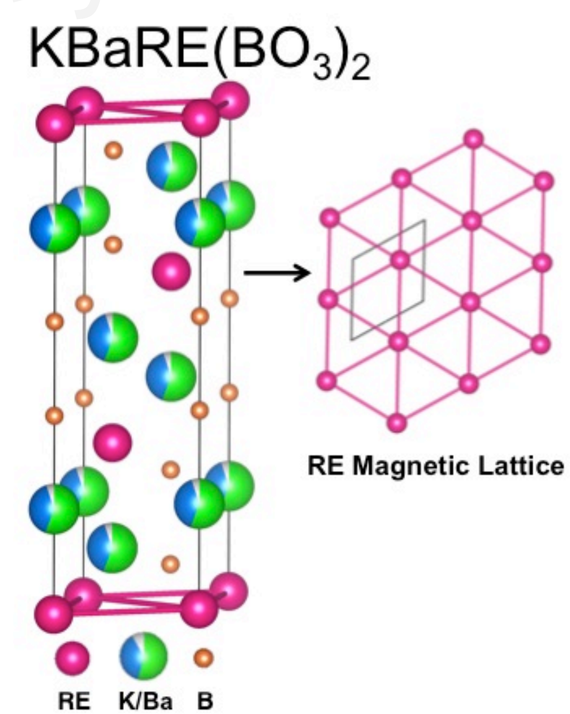
Finally, lots of isostructural materials

Compound	Magnetic ion	Space group	Local moment	Θ_{CW} (K)	Magnetic transition	Frustration para. f	Refs.
$YbMgGaO_4$	$Yb^{3+}(4f^{13})$	$R\bar{3}m$	Kramers doublet	-4	PM down to 60 mK	$f > 66$	[4]
$CeCd_3P_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-60	PM down to 0.48 K	$f > 200$	[5]
$CeZn_3P_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-6.6	AFM order at 0.8 K	$f = 8.2$	[7]
$CeZn_3As_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-62	Unknown	Unknown	[8]
$PrZn_3As_3$	$Pr^{3+}(4f^{2})$	$P6_3/mmc$	Non-Kramers doublet	-18	Unknown	Unknown	[8]
$NdZn_3As_3$	$Nd^{3+}(4f^{3})$	$P6_3/mmc$	Kramers doublet	-11	Unknown	Unknown	[8]

YD Li, XQ Wang, GC*, PRB 94, 035107 (2016)

Magnetism in the $KBaRE(BO_3)_2$ (RE=Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) series: materials with a triangular rare earth lattice

M. B. Sanders, F. A. Cevallos, R. J. Cava
Department of Chemistry, Princeton University, Princeton, New Jersey 08544



Summary

1. We propose YbMgGaO4 to be a spin-orbit-coupled spin liquid.

2. The signature of spin fractionalization has been discovered and interpreted as spinons.

3. Predictions have been made for the weakly magnetized regime. It can be immediately tested by inelastic neutron. It has been **confirmed** in Jun Zhao's recent experiment.

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Y Shen, YD Li, .., GC*, J Zhao*, arXiv 1708.06655, Nature Comms 2018

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