one is sufficient to
transition.

Detecting spin fractionalization in spinon Fermi surface spin liquid:

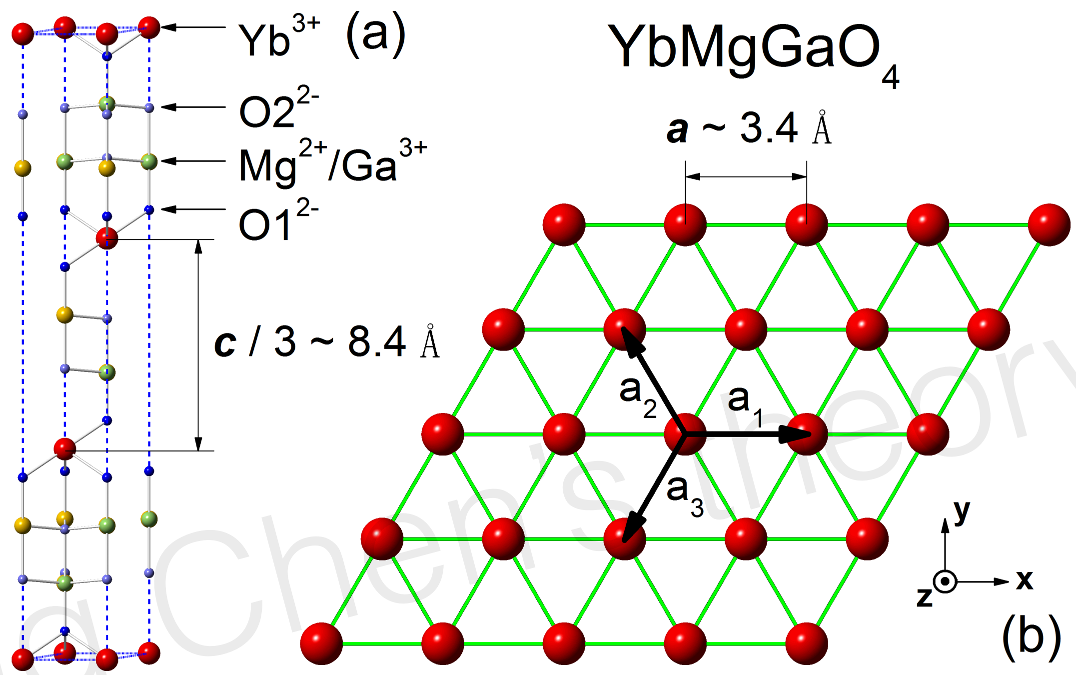
Prediction and Application to YbMgGaO4

Gang Chen (陈 钢)

Fudan University, Shanghai

People’s Republic of China

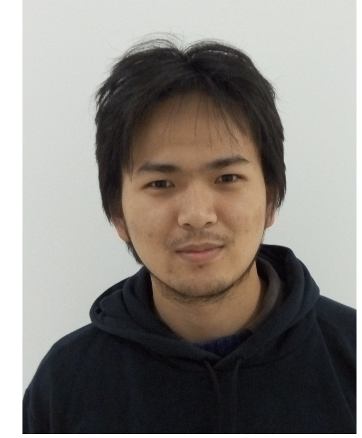
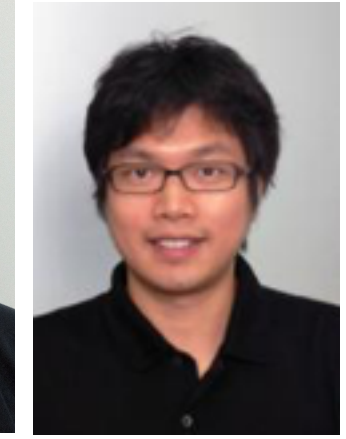
A rare-earth triangular lattice quantum spin liquid: $YbMgGaO_4$



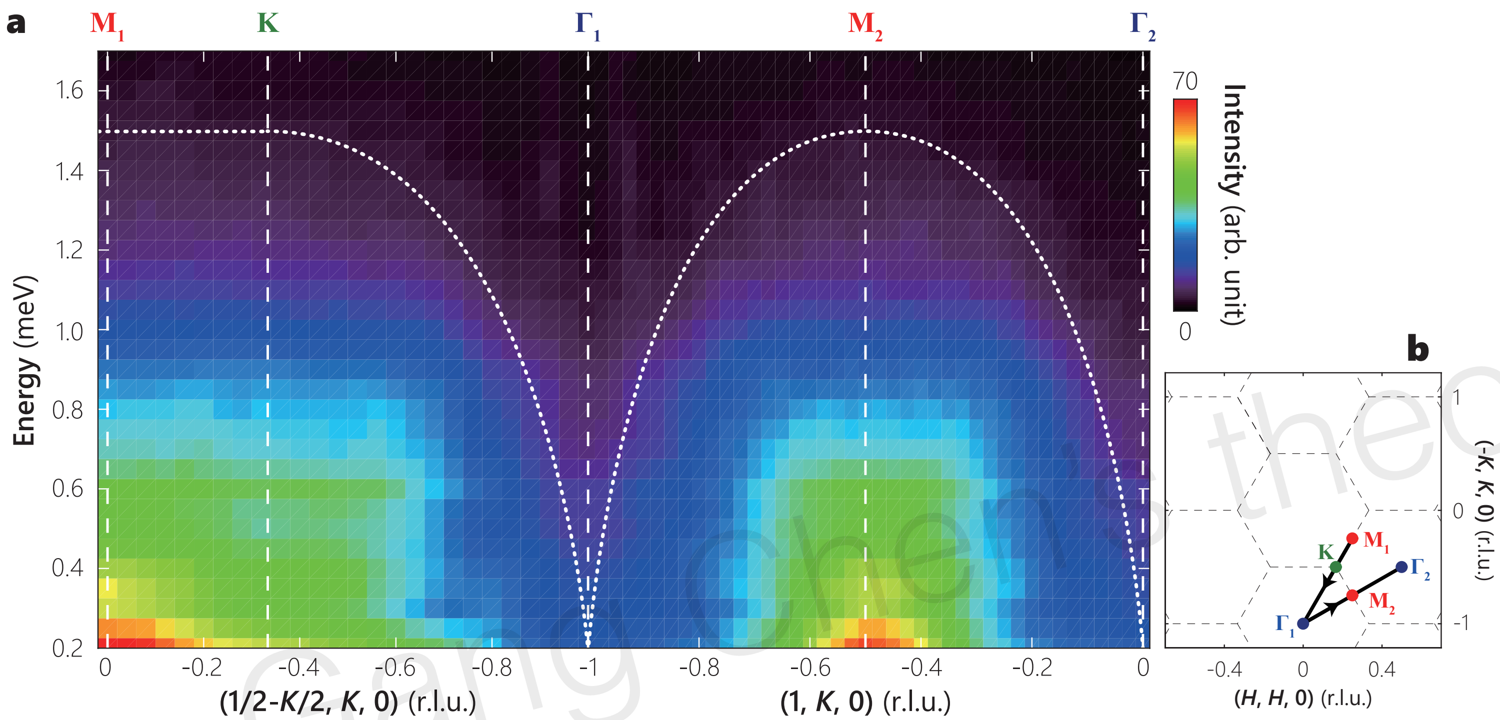
Experimental collaborators
Yuesheng Li, Qingming Zhang

- 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 electron filling** 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.

Advantage for neutron scattering

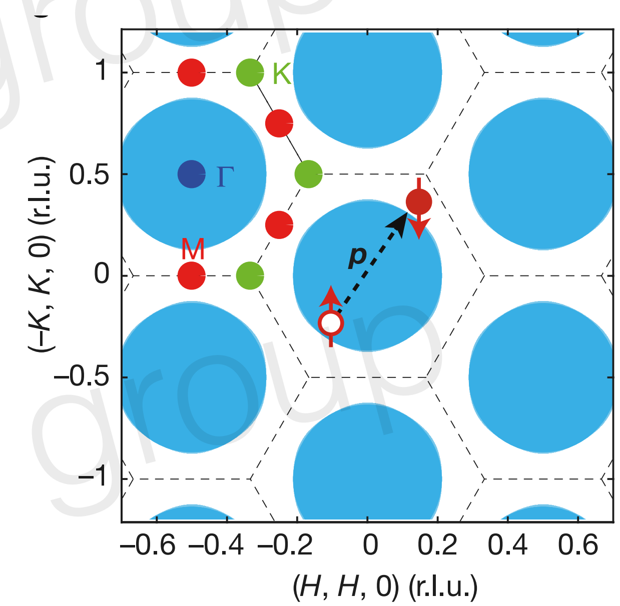




Yao Shen (Fudan) **Yao-Dong Li (Fudan)** **Jun Zhao (Fudan)**



Continuum excitation

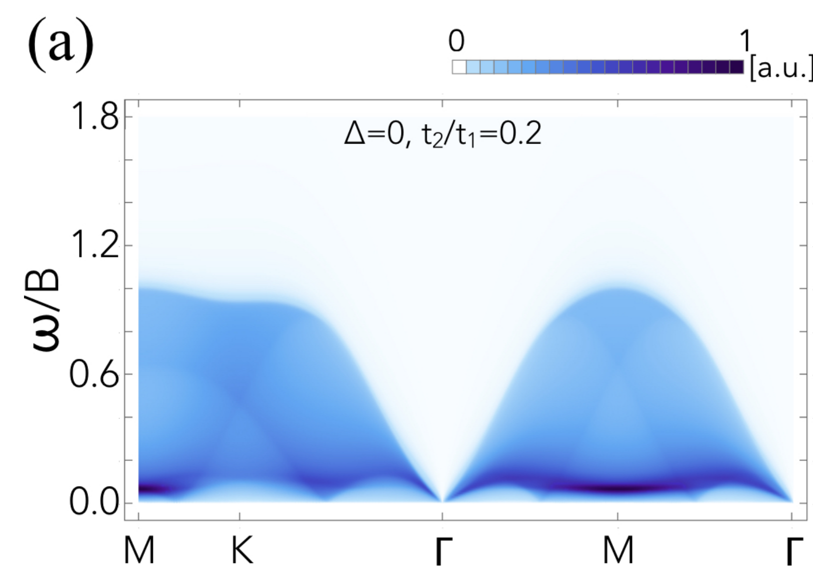
Near T = 0, low but not-Very-low energy excitation



spinon particle-hole excitation

Yao Shen, Yaodong Li …GC*, Jun Zhao* **Nature** 2016

Consistent results from Paddison et al, Nature Physics 2016



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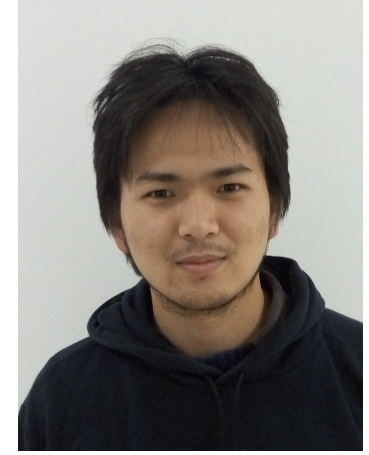
Parton construction and PSG classification



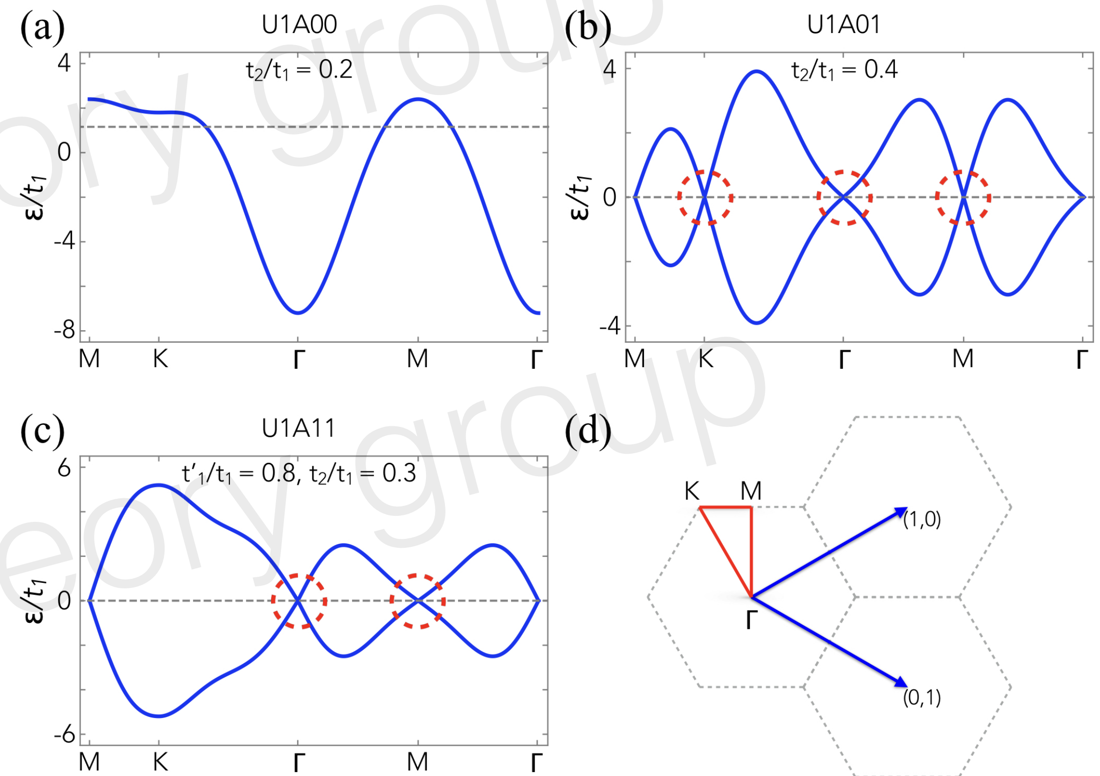
Yao-Dong Li
(Fudan)

Yuan-Ming Lu
(OSU)

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

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

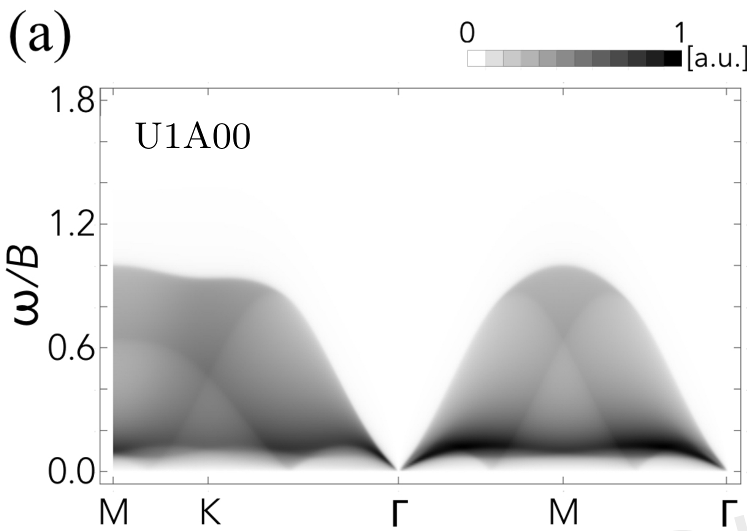
U(1) QSL	$W_{\boldsymbol{r}}^{T_1}$	$W_{\boldsymbol{r}}^{T_2}$	$W_{\boldsymbol{r}}^{C_2}$	$W_{\boldsymbol{r}}^{C_6}$
U1A00	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$
U1A10	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$	$I_{2\times2}$
U1A01	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$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



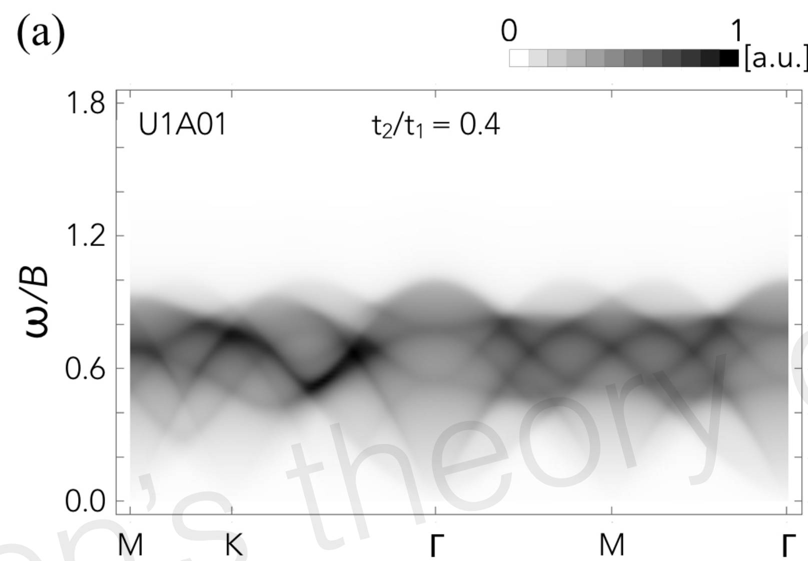
The U1A00 state is the spinon Fermi surface state that we proposed in Shen, et al, Nature.

Yao-Dong Li, Yuan-Ming Lu, Gang Chen, arXiv **1612.03447**

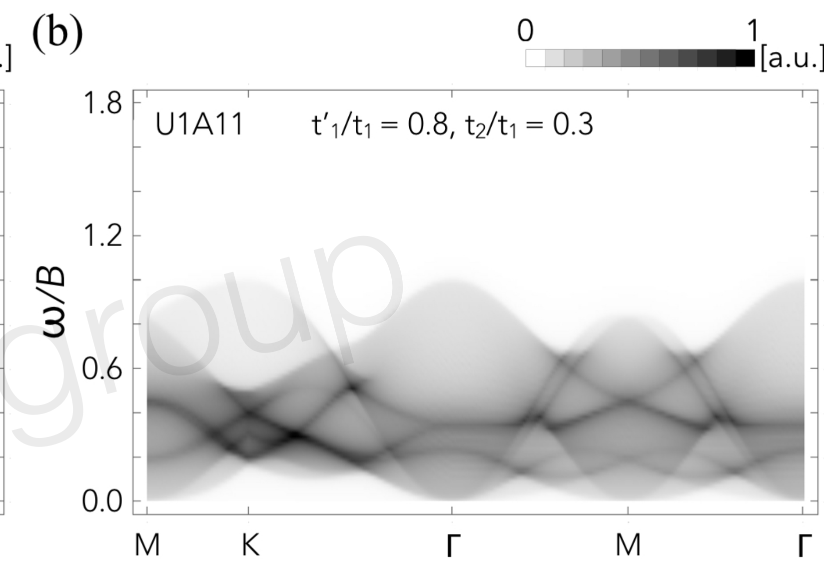
Dynamic spin structure factor



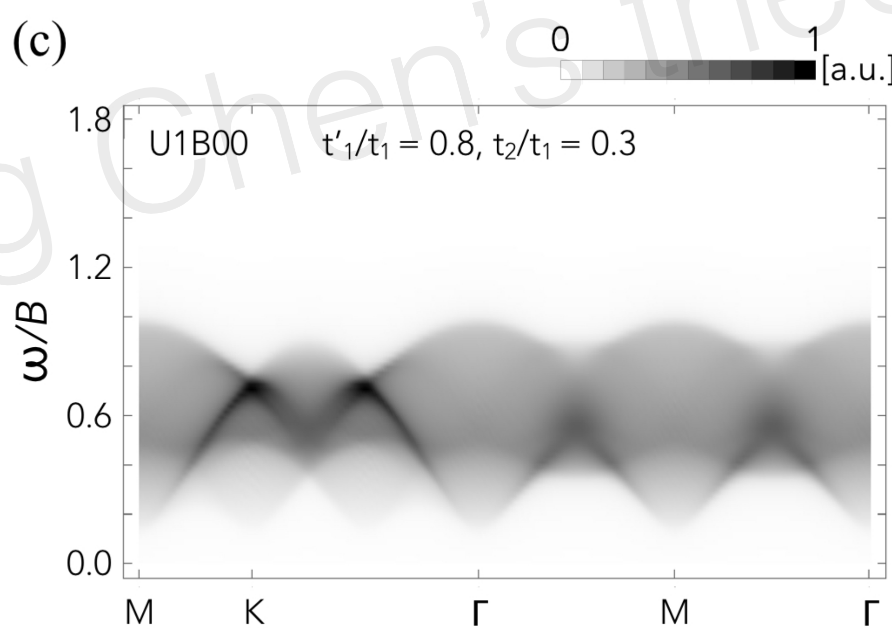
U1A00



U1A01

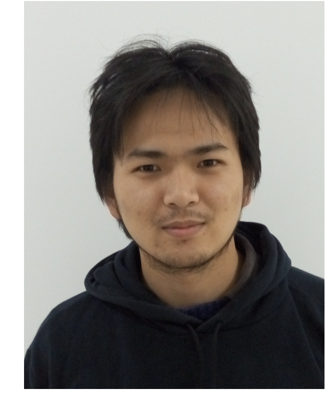


U1A11



U1B state

Two major questions



Yao-Dong Li
(Fudan)

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

   discussed in our new work

   Yao-Dong Li, Gang Chen, arXiv:1703.01876

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

Gang Chen's theory group

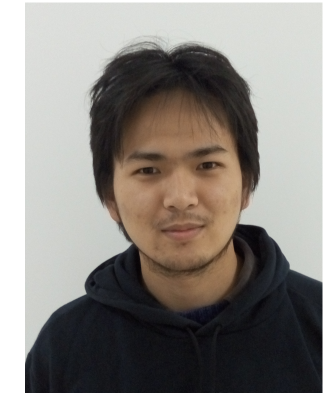
Our Roadmap

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) ?

Our new idea: explore the weak field regime



Yao-Dong Li
(Fudan)

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.

Yao-Dong Li, **GC**, arXiv: **1703.01876**

isotope effect in BCS superconductor

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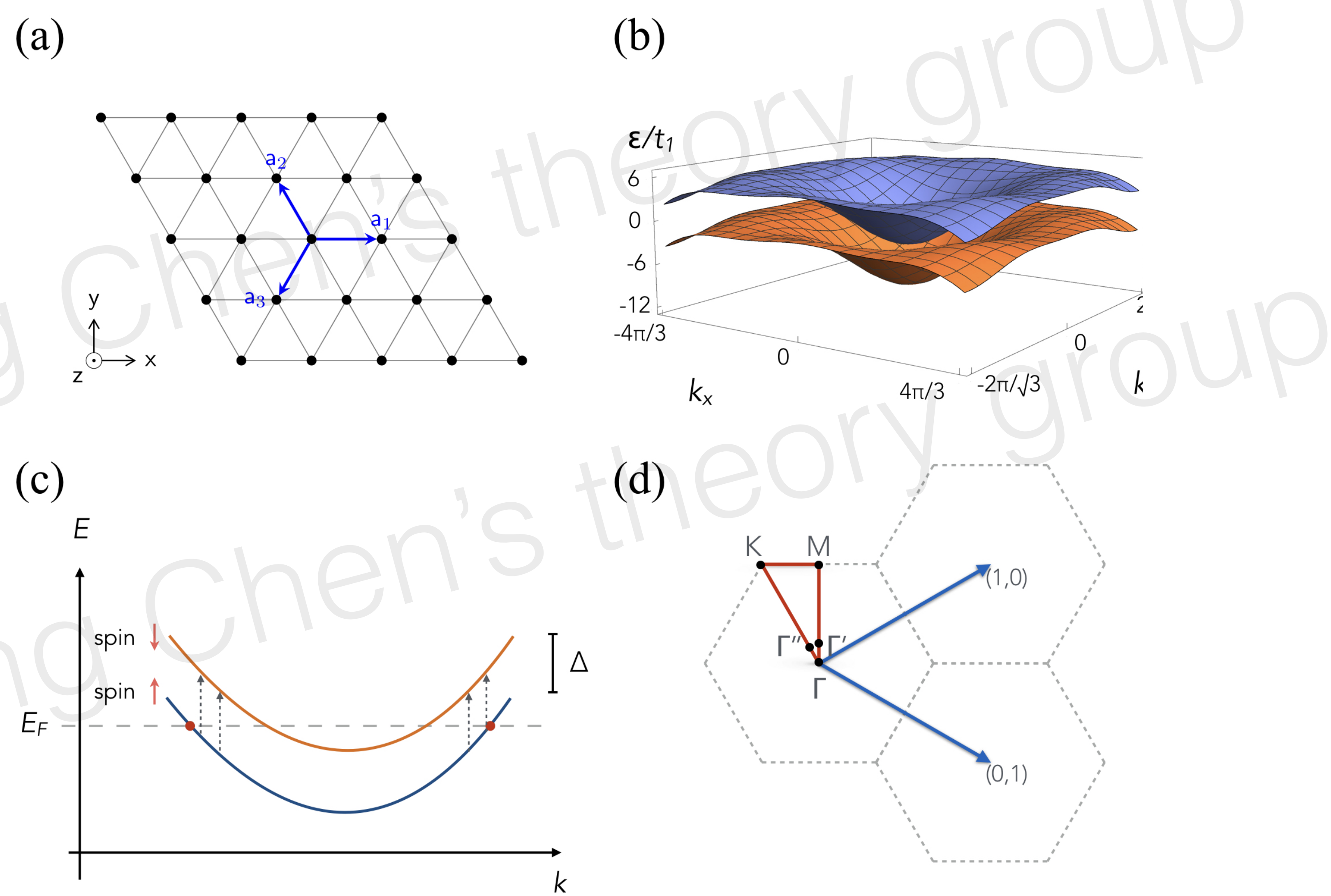
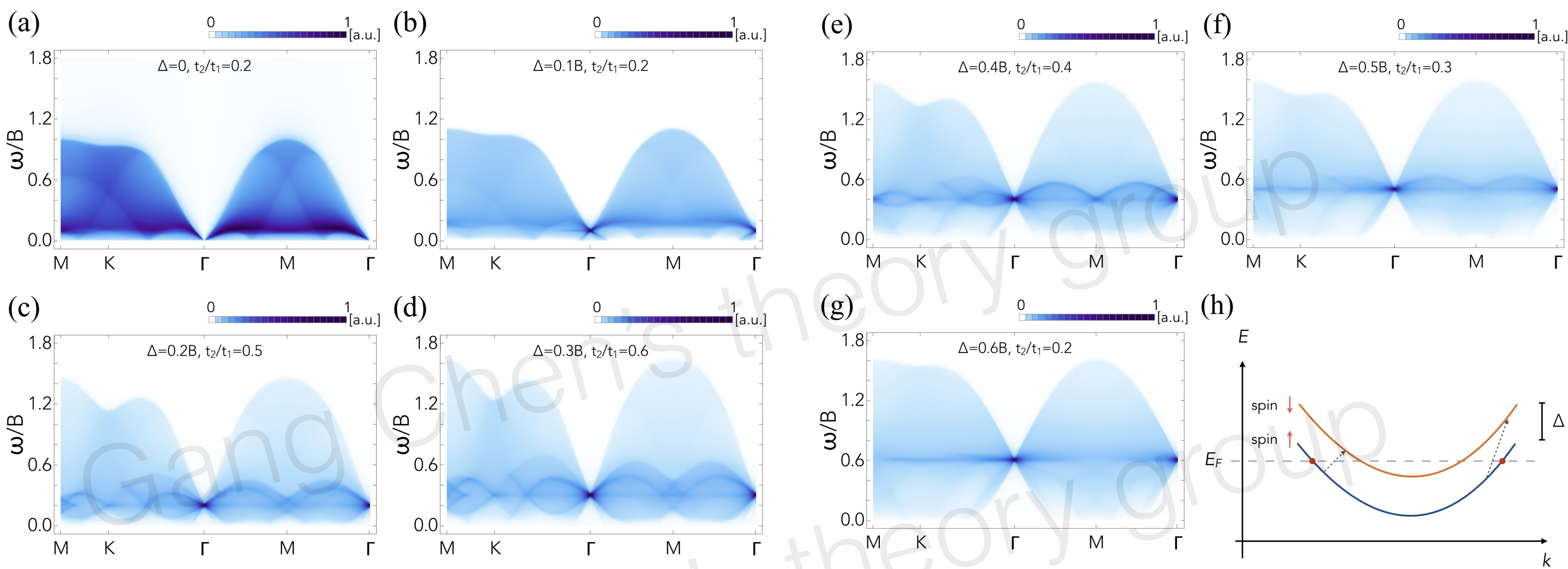
Strong Mott regime: only Zeeman coupling to field

Magnetic field splits the spin-up and down spinon bands



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 !!

Summary

1. We propose the weak field regime to detect the behavior of fractionalization.

2. Such a regime is quite feasible in current laboratory settings.

3. Predictions have been made. **It can be immediately tested by inelastic neutron.**

4. It is a small effect, but if it is observed, it gives a very strong support of the QSL ground state in this system. The idea can be well extended to other strong-Mott-insulating QSL systems.

Gang Chen's theory group

Lots of isostructure rare-earth materials, lots of opportunity !

Yao-Dong Li, XQ Wang, **GC**, PRB 2016

Yao-Dong Li, YM Lu, **GC**, arXiv **1612.03447**

Yao-Dong Li, **GC**, arXiv: **1703.01876**