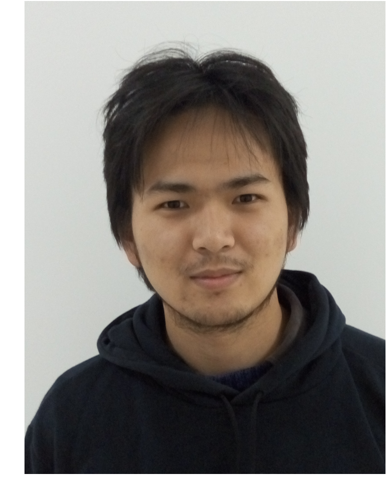
Symmetry Enriched U(1) Topological Orders on a Pyrochlore Lattice
and
Prediction for Spinon Fermi Surface Spin Liquid

Gang Chen (陈 钢)
Fudan University, Shanghai

Outline of Part 1



Yao-Dong Li
(Fudan -> US)

- Symmetry Enriched Topological order
- Dipole-Octupole Doublet in a Spin Liquid **$Ce_2Sn_2O_7$**
- Experimental consequence of Symmetry Enriched U(1) spin liquids

Yao-Dong Li, **GC**, PhysRev B, Rapid Communication, Jan 2017

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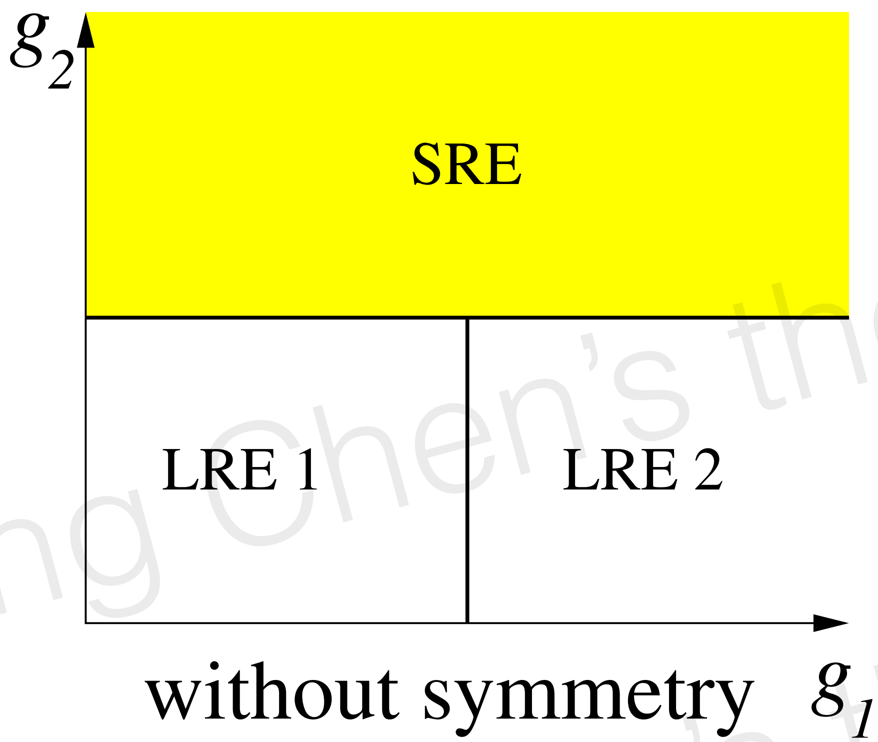
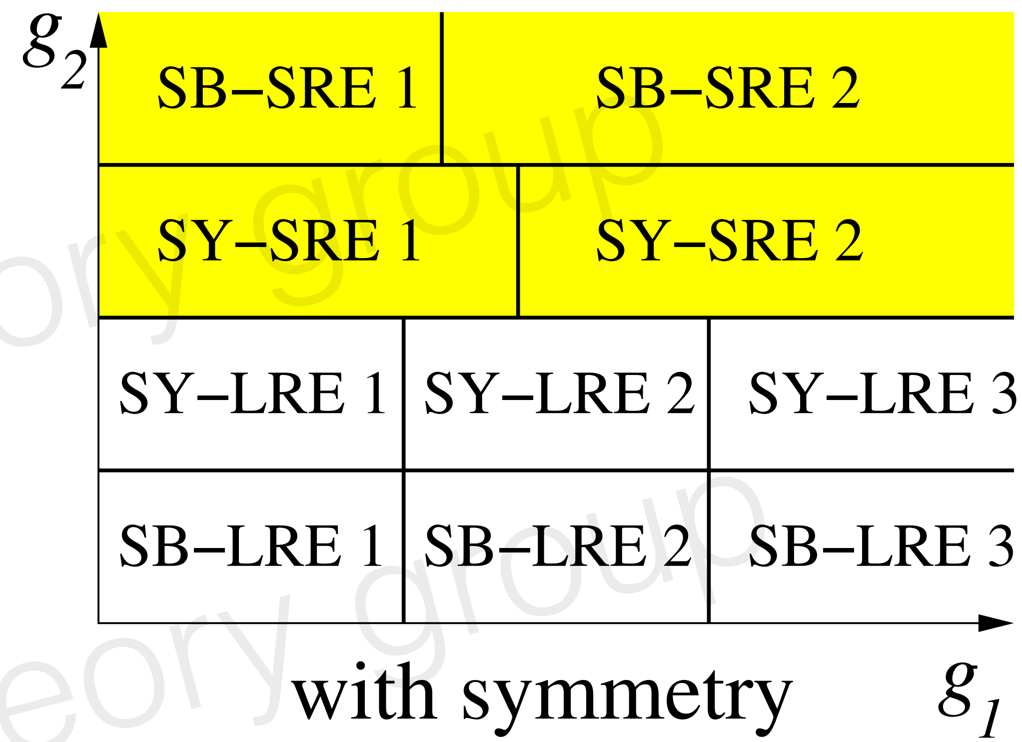
Symmetry enriched topological order

Xiao-Gang Wen
(文小剛)

Wen's universal phase diagram





LRE=long-range entanglement
SRE=short-range entanglement

Intrinsic topological order has long range entanglement (LRE).

Here, I am using a more general notion of "topological order" here.
I include the exotic phases whose gauge sector is gapless.

PRL **115,** 097202 (2015) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2015

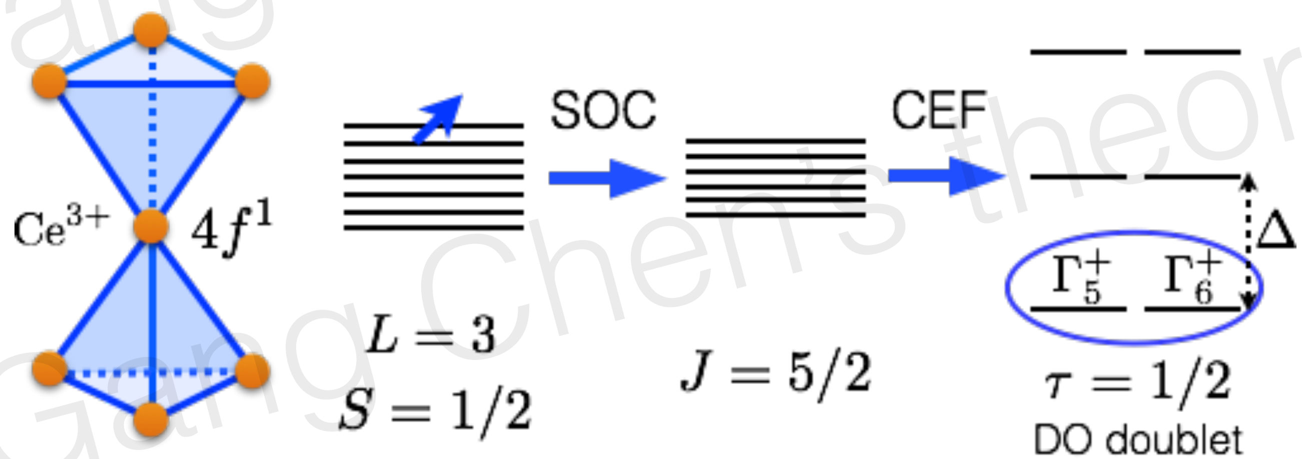
Candidate Quantum Spin Liquid in the Ce^{3+} Pyrochlore Stannate $Ce_2Sn_2O_7$

Romain Sibille,[1,*] Elsa Lhotel,[2] Vladimir Pomjakushin,[3] Chris Baines,[4] Tom Fennell,[3,†] and Michel Kenzelmann[1]

$4f^1$ ion in D_{3d} local symmetry to the susceptibility was realized between $T = 1.8$ and 370 K, and the resulting calculation of the single ion magnetic moment is shown in Fig. 2(c). The wave functions of the ground state Kramers doublet correspond to a linear combination of $m_J = \pm 3/2$ states. The fitted coefficients result in energy levels at 50 ±

Ce^{3+} $(4f^1, {}^2F_{5/2})$.

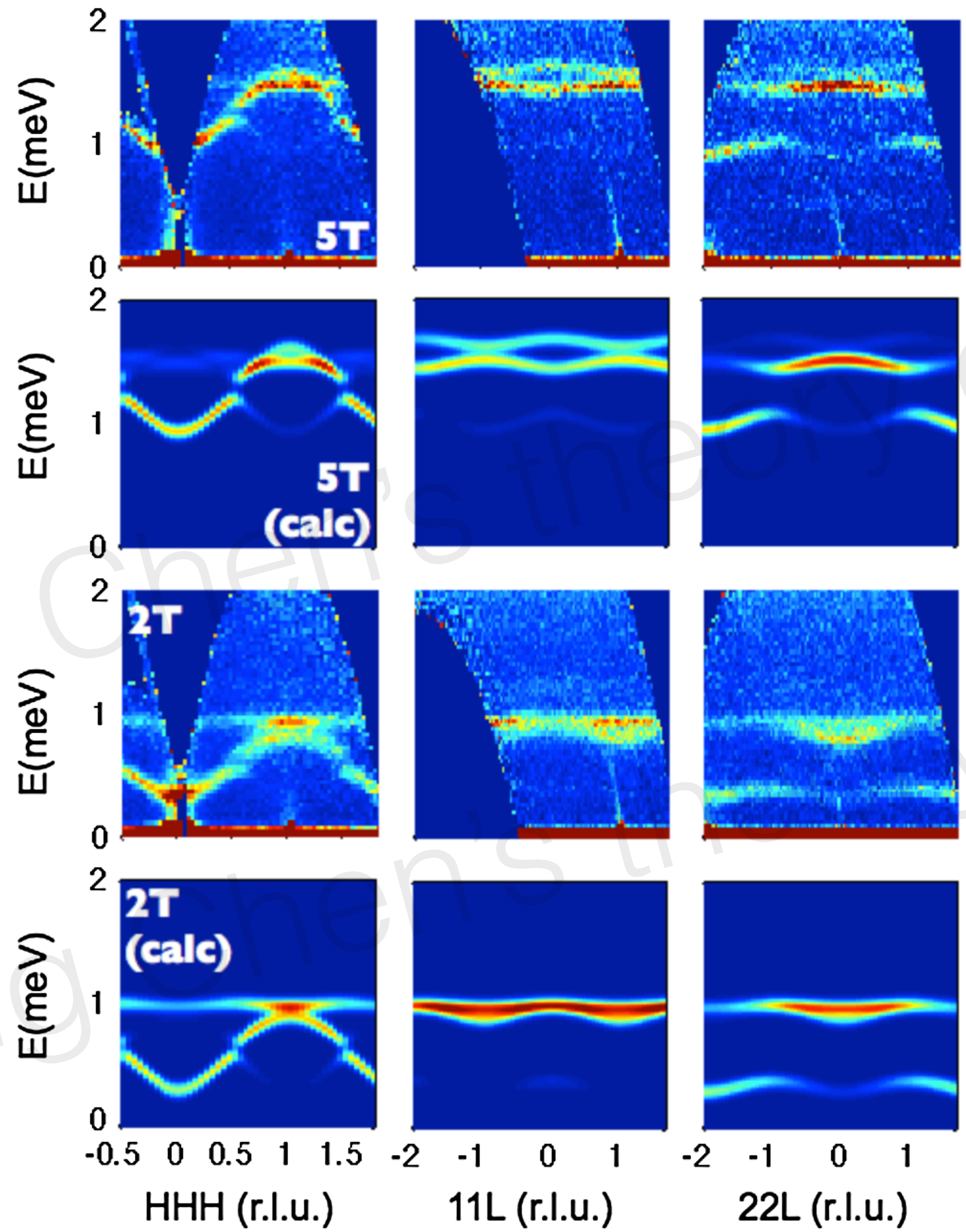
$$J = \frac{5}{2}$$



This doublet is **dipole-octupole doublet !**

Huang, **GC**, Hermele, PRL,112,167203 (2014),
Yao-Dong Li, **GC**, PhysRev B, Rapid Comm
Yao-Dong Li, XQ Wang, **GC**, PhysRev B, Rapid Comm

Connection to pyrochlore ice spin liquid?



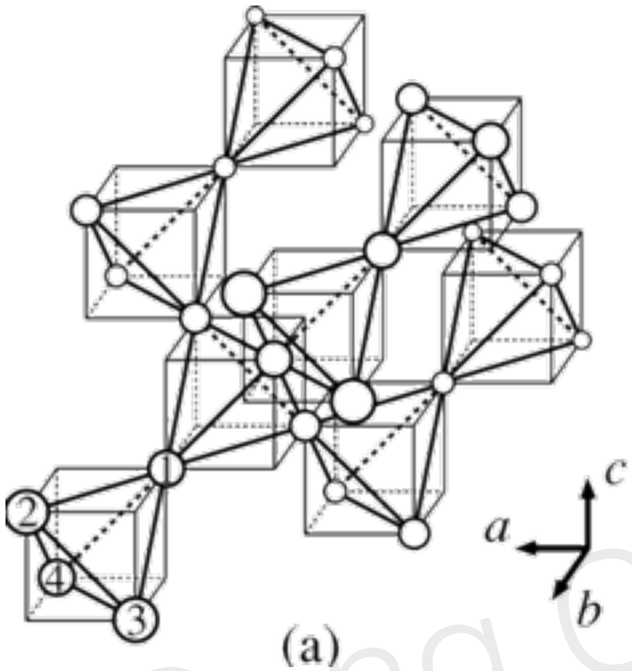
Kate Ross, L Savary, Balents, etc

Symmetry Enriched U(1) topological order

and

Experimental signatures of Symmetry Enrichment

Generic model: XYZ model



(a)

$$T_d \times \mathcal{I} \times translations$$

$$H = \sum_{\langle ij \rangle} J_z S_i^z S_j^z + J_x S_i^x S_j^x + J_y S_i^y S_j^y + J_{xz}(S_i^x S_j^z + S_i^z S_j^x)$$

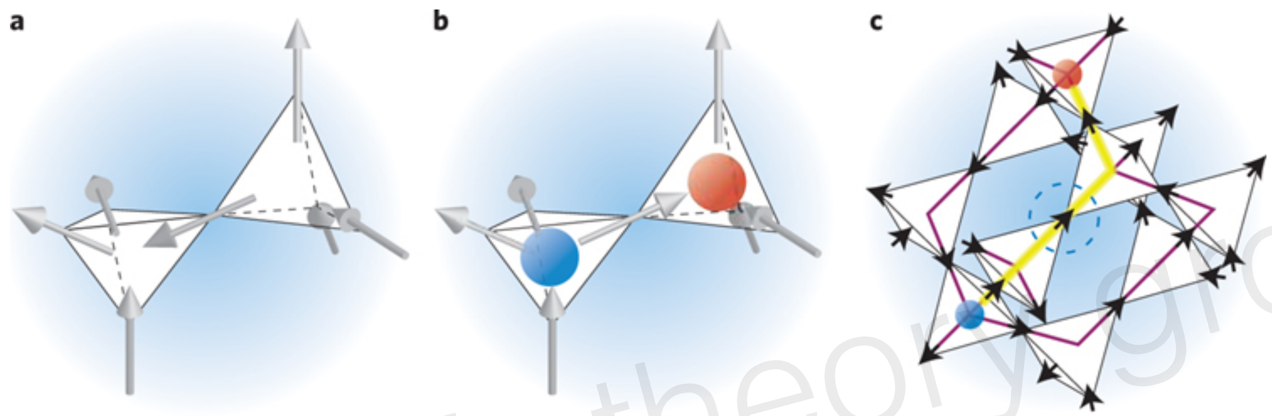
Rotation around the y axis
in the effective spin space

$$H_{\rm XYZ} = \sum_{\langle ij \rangle} \tilde{J}_z \tilde{S}_i^z \tilde{S}_j^z + \tilde{J}_x \tilde{S}_i^x \tilde{S}_j^x + \tilde{J}_y \tilde{S}_i^y \tilde{S}_j^y$$

XYZ model

Important: $\boldsymbol{S}^x$ and $\boldsymbol{S}^z$ transform identically (as a dipole), while $\boldsymbol{S}^y$ transforms as an octupole moment under *mirror.*

XXZ limit: U(1) QSL of spin ice regime



Figs from Moessner&Schiffer,2009

Spinon deconfinement

Leon, Hermele, Fisher, Moessner, Huse, Sondhi

$$H = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z - J_{\pm} \sum_{\langle i,j \rangle} \left(S_i^+ S_j^- + S_i^- S_j^+ \right) + \cdots\cdots$$

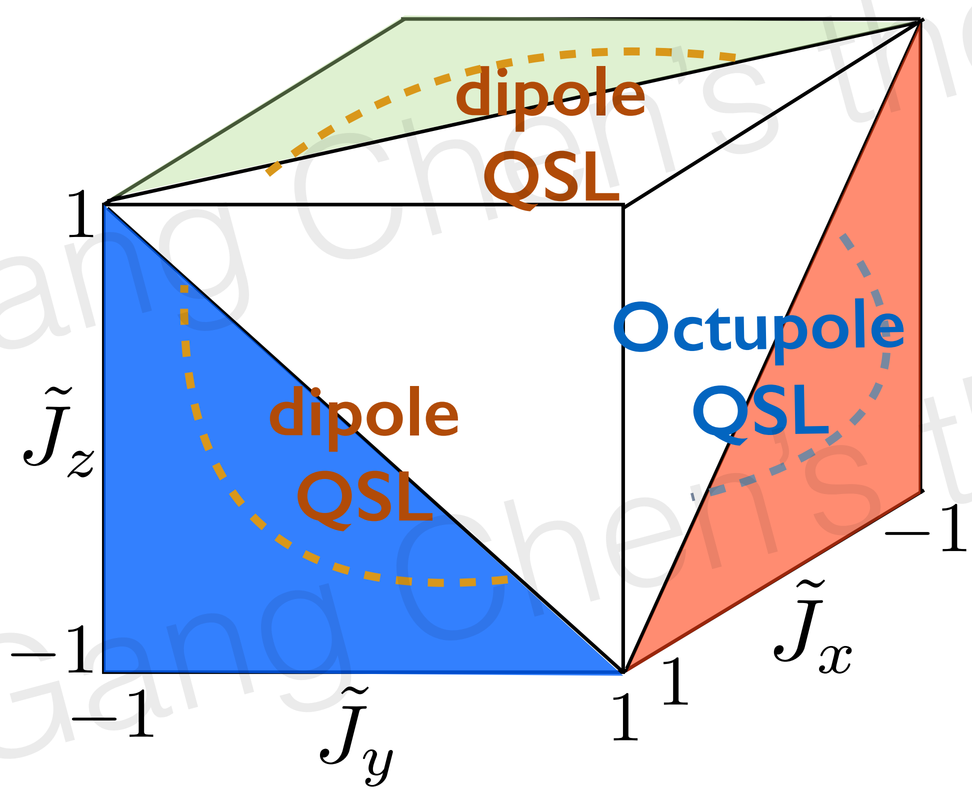
XXZ model can lead to U(1) QSL when Jzz is dominant

Emergent electric field $S^z \sim E$

Emergent vector potential $S^{\pm} \sim e^{\pm i A}$

XYZ model is the generic model that describes the interaction between DO doublets.

$$H_{\mathrm{XYZ}} = \sum_{\langle ij \rangle} \tilde{J}_z \tilde{S}_i^z \tilde{S}_j^z + \tilde{J}_x \tilde{S}_i^x \tilde{S}_j^x + \tilde{J}_y \tilde{S}_i^y \tilde{S}_j^y$$



Study phase on a cube: $-1 \leq \tilde{J}_{x,y,z} \leq 1$.

3D phase diagram

Each component (not just Sz) can be emergent electric field, depending on the parameters !

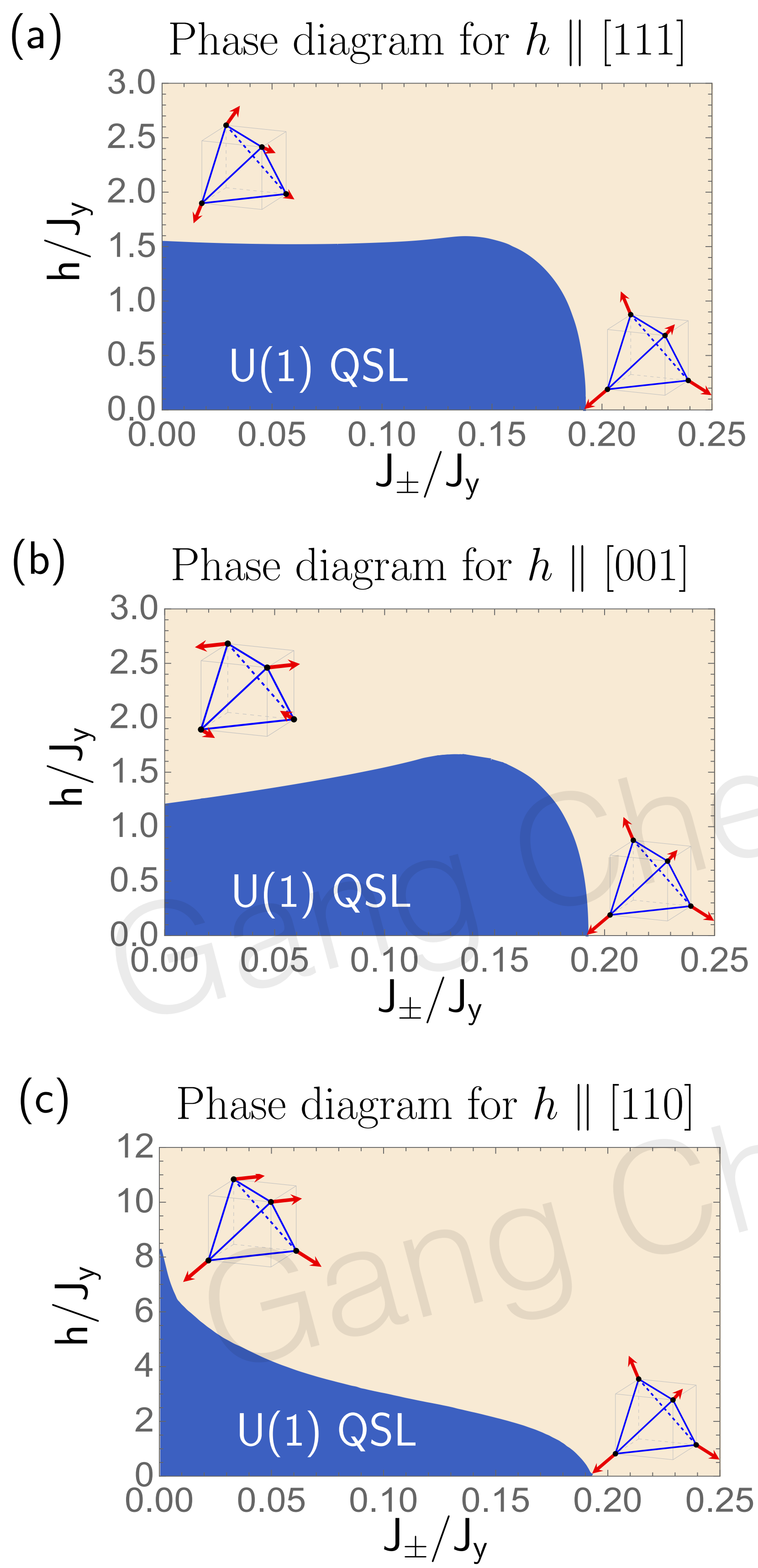
The shady part does not sign problem for quantum Monte Carlo

Infinite anisotropic g-factor

$$H = \sum_{\langle ij \rangle} J_z S_i^z S_j^z + J_x S_i^x S_j^x + J_y S_i^y S_j^y + J_{xz}(S_i^x S_j^z + S_i^z S_j^x) - h \sum_i (\hat{n} \cdot \hat{z}_i) S_i^z$$

Different U(1) QSLs	Heat capacity	Inelastic neutron scattering measurement
Octupolar U(1) QSL for DO doublets	$C_v \sim T^3$	Gapped spinon continuum
Dipolar U(1) QSL for DO doublets	$C_v \sim T^3$	Both gapless gauge photon and gapped spinon continuum
Dipolar U(1) QSL for non-Kramers' doublets [23]	$C_v \sim T^3$	Gapless gauge photon
Dipolar U(1) QSL for usual Kramers' doublets [22]	$C_v \sim T^3$	Both gapless gauge photon and gapped spinon continuum

TABLE I. List of the physical properties of different U(1) QSLs on the pyrochlore lattice. "Usual Kramers doublet" refers to the Kramers doublet that is not a DO doublet. They transform as a two-dimensional irreducible representation under the D_{3d} point group. Although the dipolar U(1) QSL for DO doublets behaves the same as the one for usual Kramers' doublets, their physical origins are rather different [31].



Field-driven Higgs transition for octupolar U(1) QSL

How to tell if **$Ce_2Sn_2O_7$** is an octupolar U(1) QSL or not ?

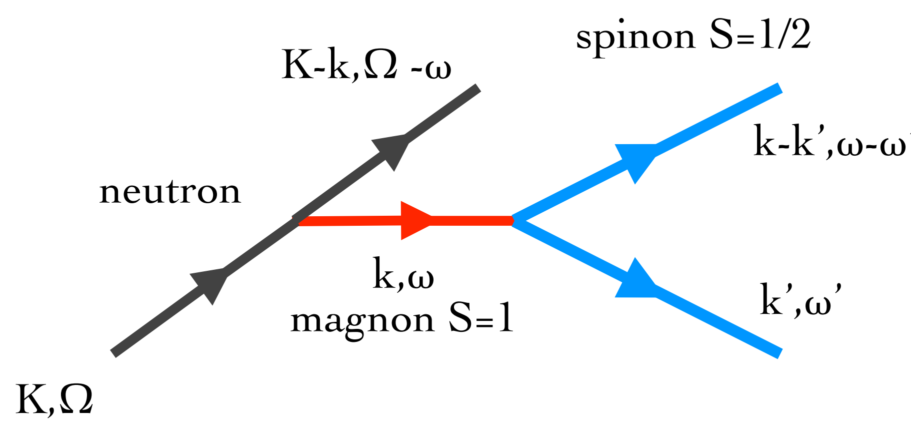
The idea to use a little knob that could simply lead to some clear experimental consequence, very much like the isotope effect of BCS superconductors.

Here we apply external magnetic field, and expect a field-driven Higgs transition to magnetic ordering as the **field only couples to the matter field** (spinons).

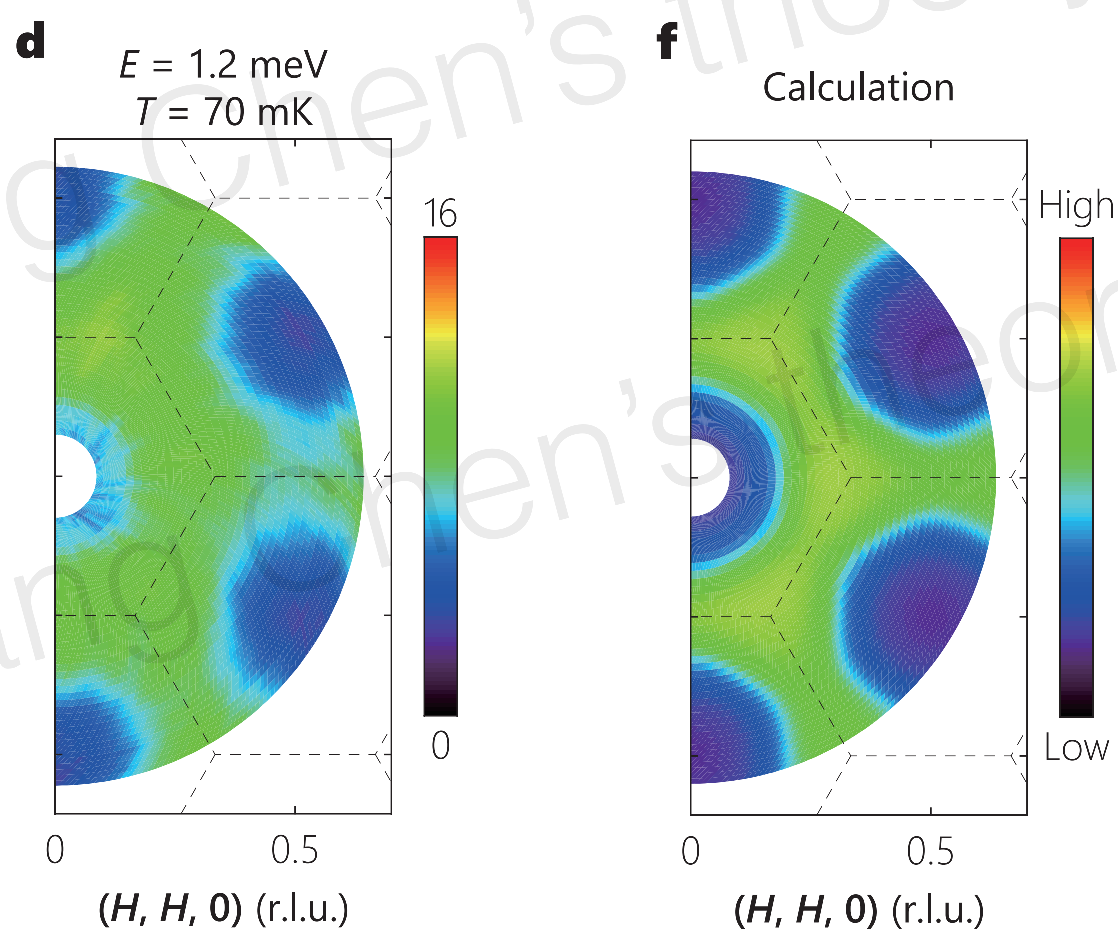
$$H = \sum_{\langle ij \rangle} J_y S_i^y S_j^y - J_{\pm}(S_i^+ S_j^- + S_i^- S_j^+) - h \sum_i (\hat{n} \cdot \hat{z}_i) S_i^z$$

$$S_i^{\pm} \equiv S_i^z \pm i S_i^x$$

Inelastic neutron scattering and spinon continuum



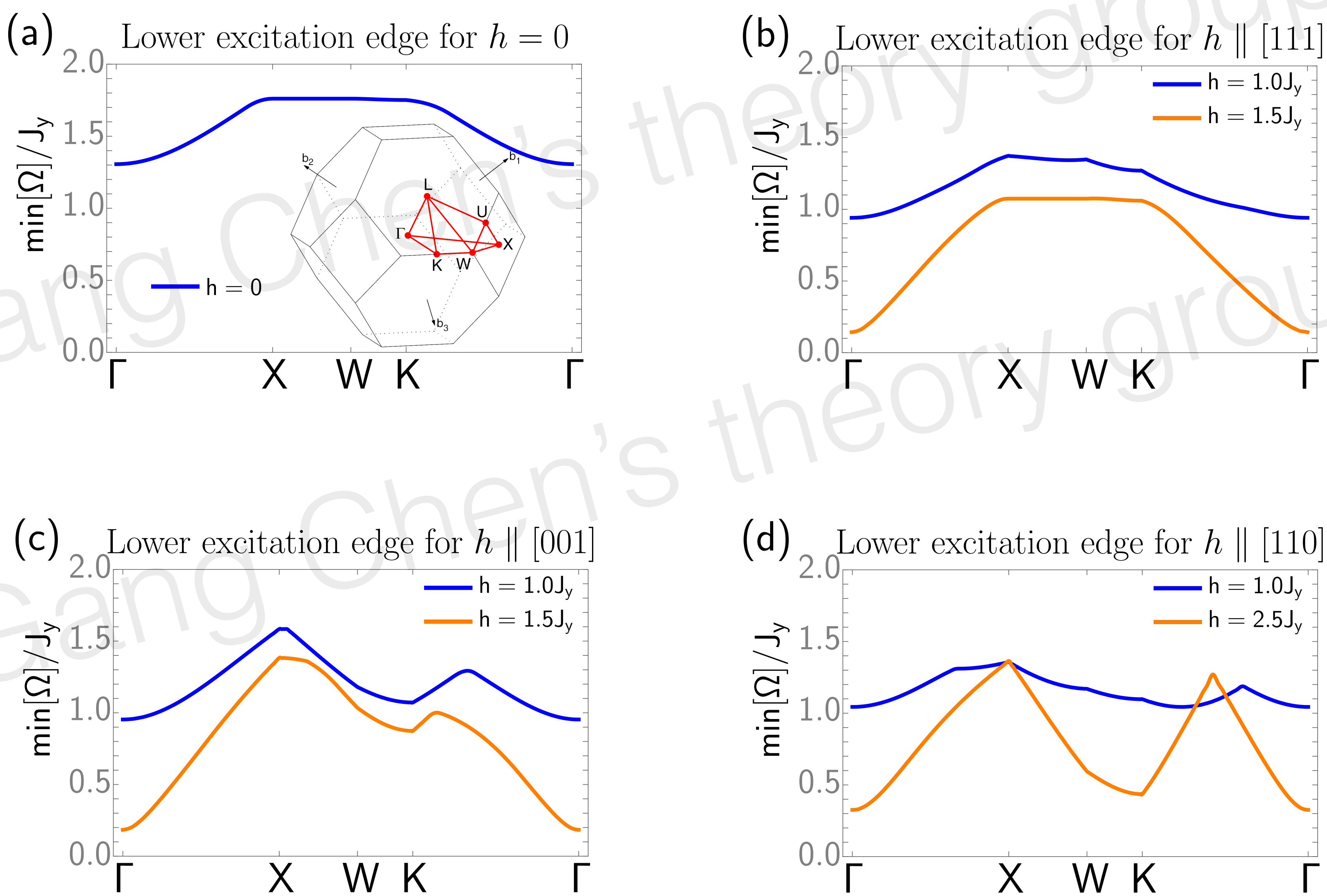
broad peak with
ω=ε(k’)+ε(k-k’)



Spinon continuum
in **YbMgGaO4**
Y Shen, Y-D Li,…., **GC**, Jun Zhao
arXiv July 2016

Lower excitation edge

$$\mathbf{q} = \mathbf{k}_1 + \mathbf{k}_2,$$
$$\Omega(\mathbf{q}) = \omega_i(\mathbf{k}_1) + \omega_j(\mathbf{k}_2),$$



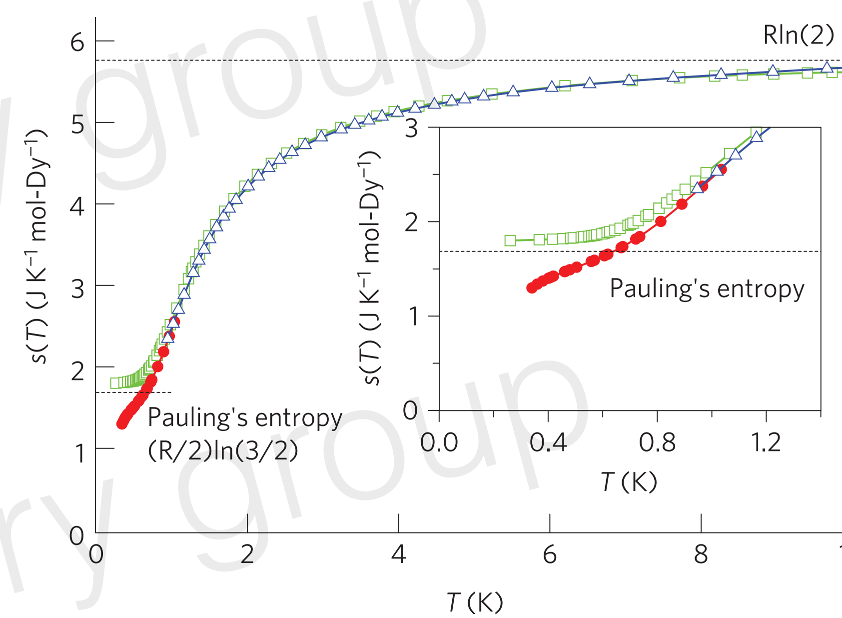
Material survey: other DO doublet systems

Our doublet can potentially be realized for any Kramers spin moment with J>1/2.

Two well-known systems:

- Pyrochlores $A_2B_2O_7$,

  e.g. ,
  $Nd_2Ir_2O_7$, $Nd_2Sn_2O_7$, **$Nd_2Zr_2O_7$**, etc
  $Dy_2Ti_2O_7$,
  $Cd_2Os_2O_7$, etc
  $Ce_2Sn_2O_7$,



Prof Gaulin's group, Dy2Ti2O7, Nat Phys, 2013

- Spinels AB_2X_4, B=lanthanide?

  e.g. $CdEr_2Se_4$

  $CdYb_2S_4$

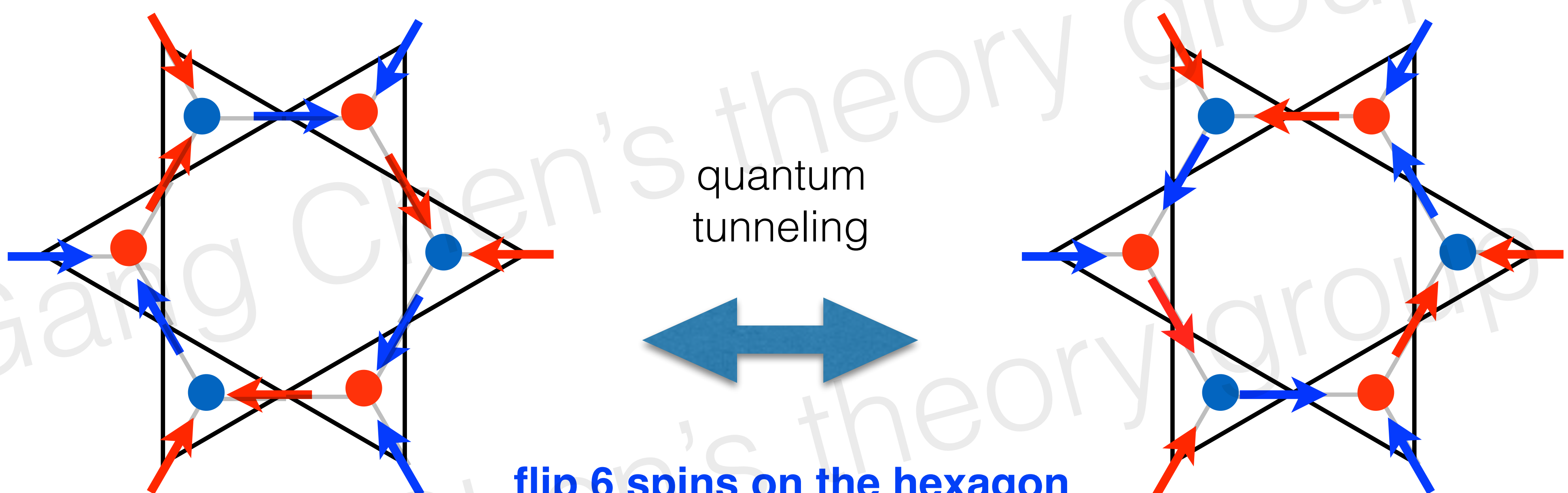
Conclusion

- We point out a new doublet dubbed "dipole-octupole" doublet that is realized in the spin liquid material $Ce_2Sn_2O_7$.
- This doublet supports distinct symmetry enriched U(1) spin liquids.
- We predict the experimental signatures of distinct symmetry enrichments.

Quantum fluctuation can lead to U(1) QSL

$$H = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z - J_{\pm} \sum_{\langle i,j \rangle} \left(S_i^+ S_j^- + S_i^- S_j^+ \right) + \cdots\cdots$$

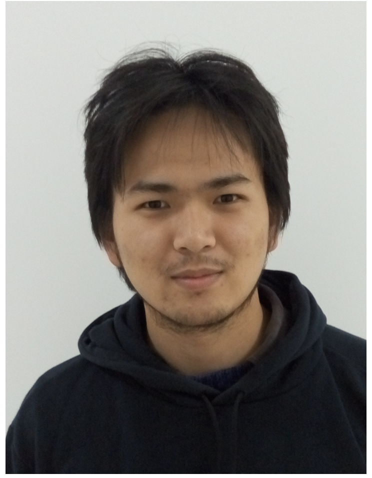
Hermele, Fisher, Balents,
Moessner, Isakov, YB Kim….



flip 6 spins on the hexagon
or
Ring exchange

- Pretty much one can add any term to create **quantum** tunneling, as long as it is not too large to induce magnetic order, the **ground state** is a quantum spin ice U(1) quantum spin liquid !

Outline of Part 2



Yao-Dong Li
(Fudan->US)

- Some background of the triangular spin liquid candidate YbMgGaO4
- Roadmap and our small little idea
- Our Prediction for experiments

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

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

Experimental collaborators

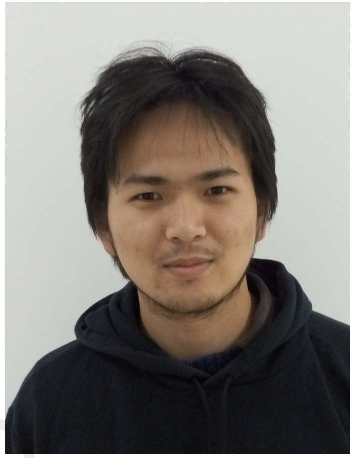
Yuesheng Li (Renmin)
Qingming Zhang (Renmin)

Yao Shen (Fudan)
Jun Zhao (Fudan)

Theoretical collaborators

Yaodong Li (Fudan)

more recently,
Yuan-Ming Lu (OSU)



Yao-Dong Li
(Fudan->US)

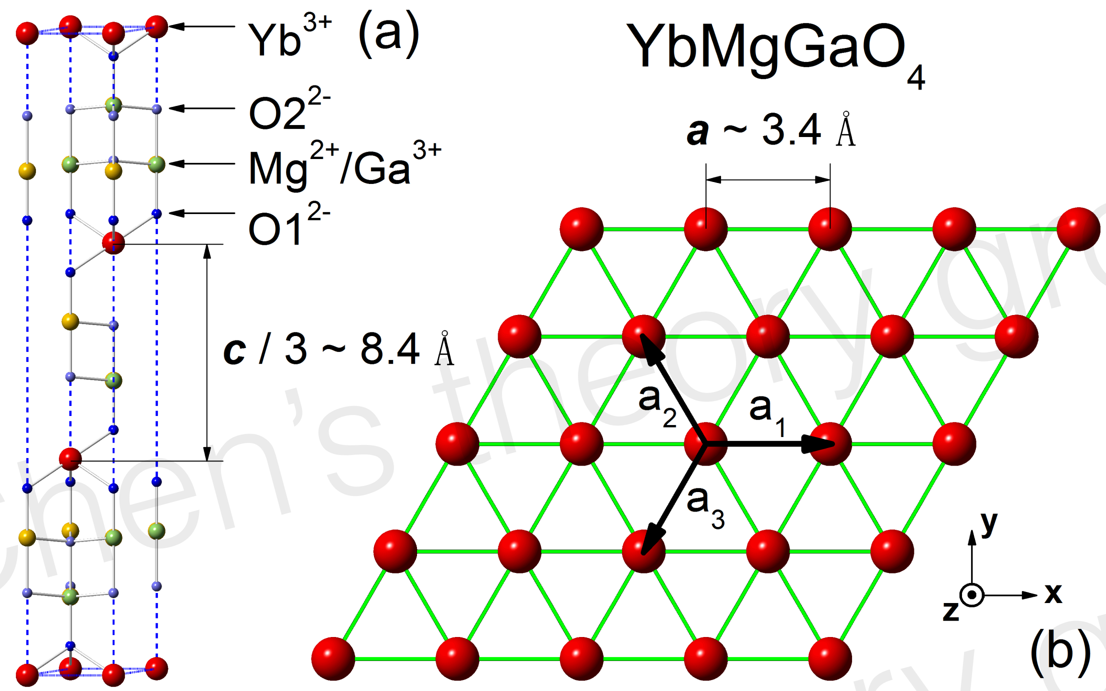
Other contributors:

Wei Tong (High Magnetic field Lab, Hefei)
Pi Li (High Magnetic field Lab, Hefei)
Juanjuan Liu (Renmin Univ, Beijing)
Zhaorong Yang (Institute of Solid-State Physics, Hefei)

Xiaoqun Wang (Renmin, Shanghai Jiaotong)

Hongliang Wo, Shoudong Shen, Bingying Pan, Qisi Wang, Yiqing Hao, Lijie Hao (Fudan),
Siqin Meng (Neutron Scattering Laboratory, China Institute of Atomic Energy, Beijing)

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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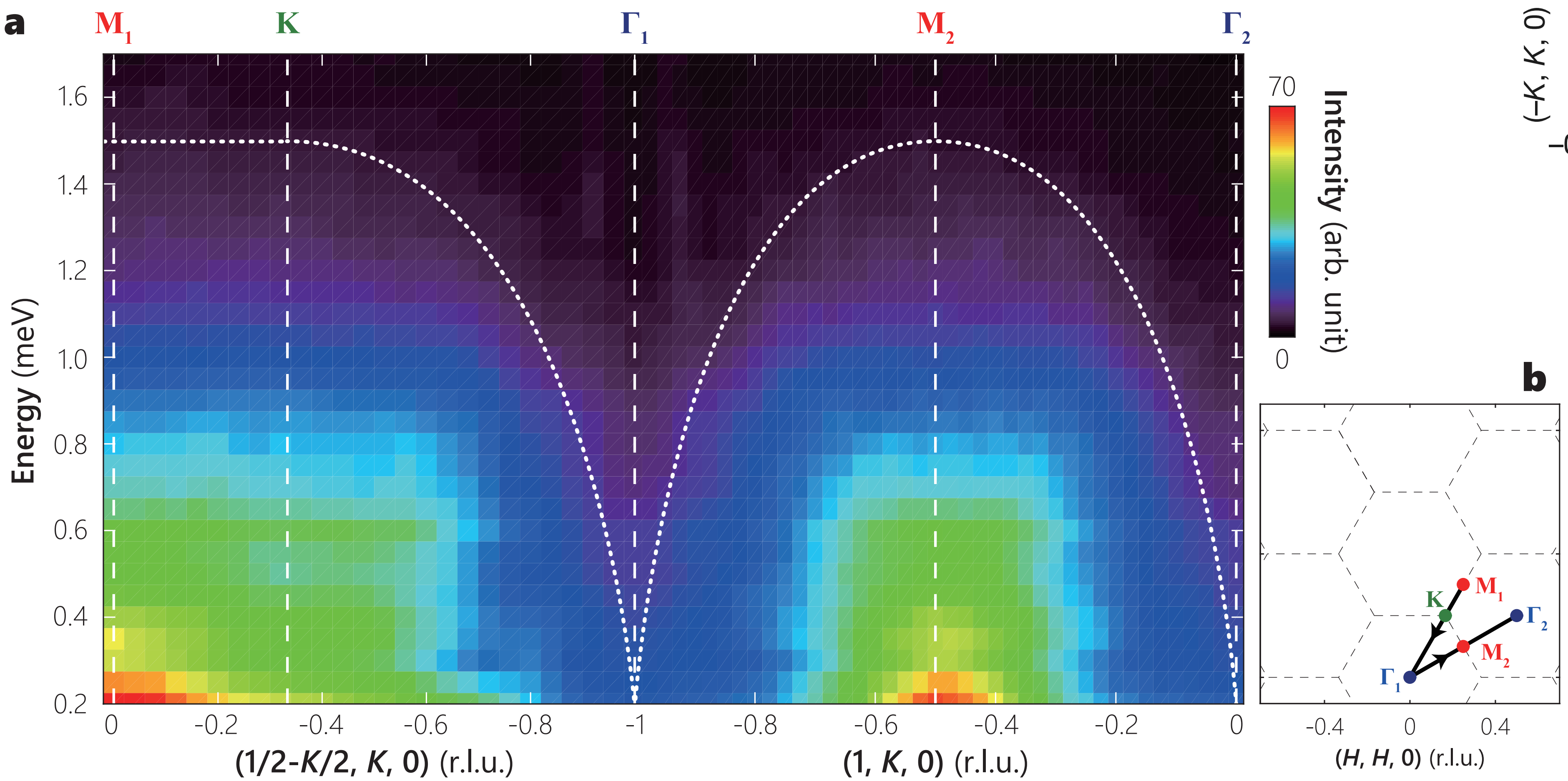
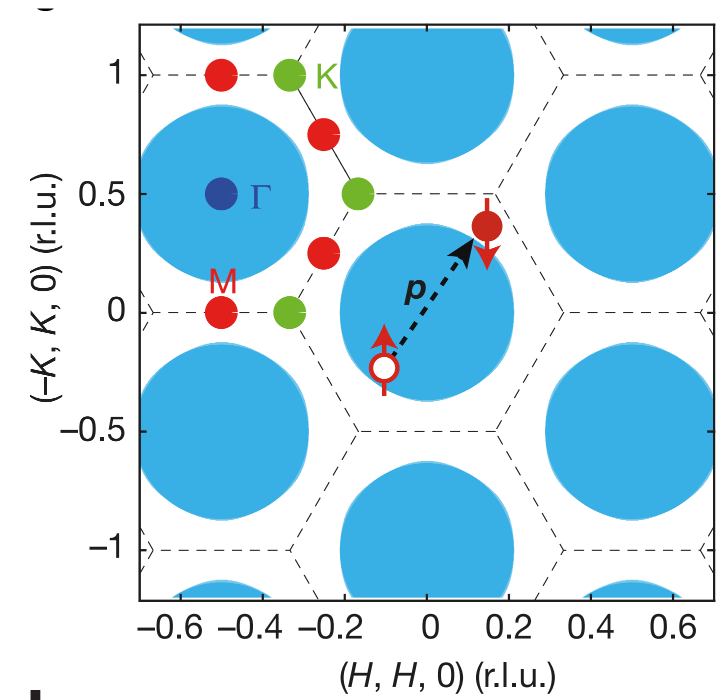
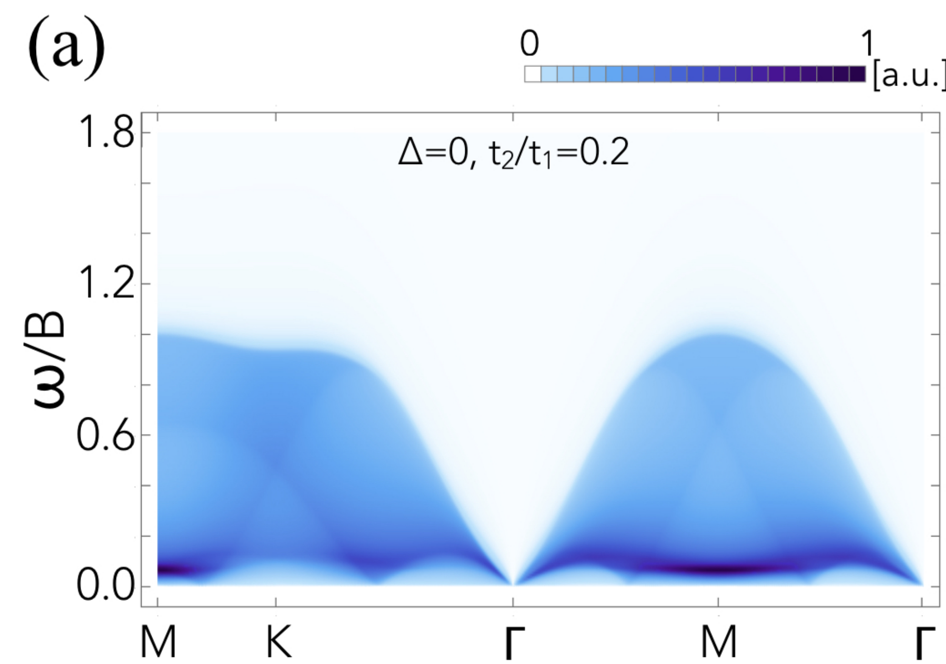
Advantage for neutron scattering





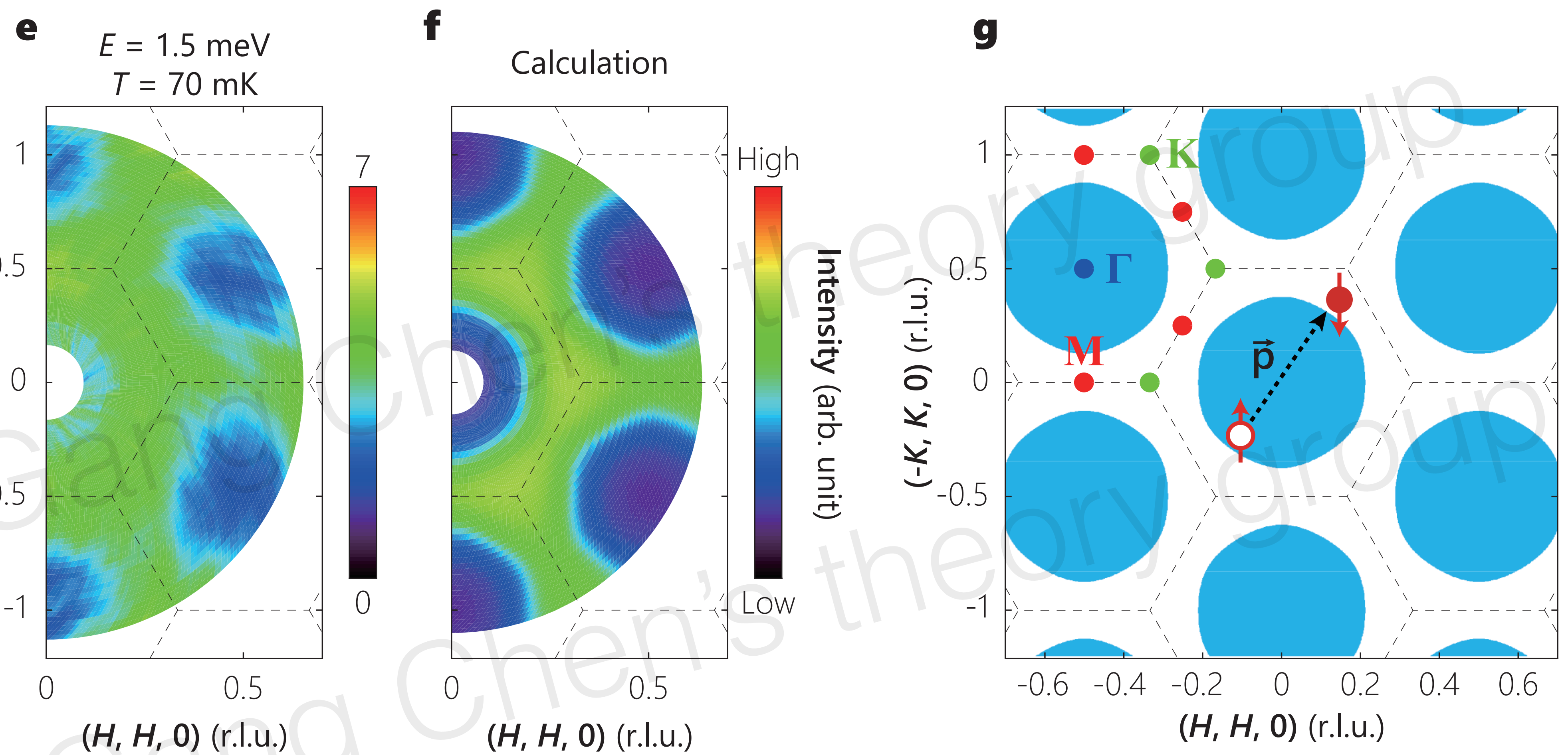
Continuum excitation

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



Yao Shen, …Gang Chen*, Jun Zhao*   Nature
Consistent results from Martin Mourgal's group

Spinon continuum



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

Two major questions

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

   (discussed in our new work arXiv:1703.01876)

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

A 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 idea: 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.

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

Weak field regime vs strong field regime

1. Very strong field simply polarizes the spin and kills QSL

2. Weak field acts a perturbation to the QSL: the factionalized spinons remain to be a valid description of the magnetic excitation.

So what will happen?

Strong Mott regime: only Zeeman coupling

We start with the fermionic parton construction for the spin operator with $\boldsymbol{S}_i = \frac{1}{2} f^\dagger_{i\alpha} \boldsymbol{\sigma}_{\alpha\beta} f_{i\beta}$, where $f^\dagger_{i\alpha}$ ($f_{i\alpha}$) creates (annihilates) one spinon with spin $\alpha (=\uparrow, \downarrow)$ at the site i and $\boldsymbol{\sigma} = (\sigma^x, \sigma^y, \sigma^z)$ is a vector of Pauli matrices. This construction is further supplemented by a Hilbert space constraint $\sum_\alpha f^\dagger_{i\alpha} f_{i\alpha} = 1$.

$$H_{\rm MF} = -t_1 \sum_{\langle ij \rangle, \alpha} f^\dagger_{i\alpha} f_{j\alpha} - t_2 \sum_{\langle\langle ij \rangle\rangle, \alpha} f^\dagger_{i\alpha} f_{j\alpha} - \mu \sum_{i,\alpha} f^\dagger_{i\alpha} f_{i\alpha}$$

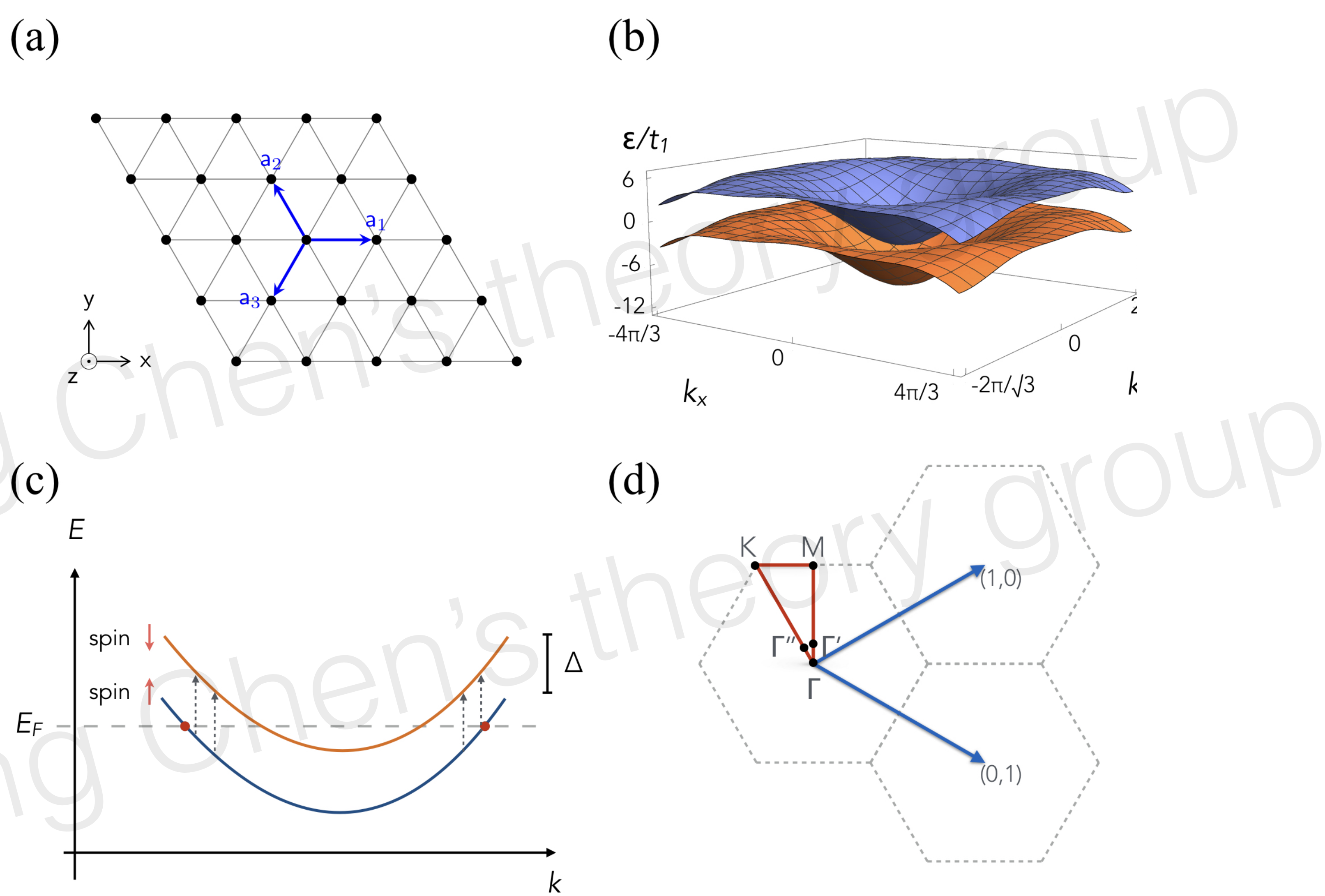
$\longrightarrow$

$$H_{\rm MF_h} = -t_1 \sum_{\langle ij \rangle, \alpha} f^\dagger_{i\alpha} f_{j\alpha} - t_2 \sum_{\langle\langle ij \rangle\rangle, \alpha} f^\dagger_{i\alpha} f_{j\alpha} - \sum_{i,\alpha\beta} g_z \mu_{\rm B} h_z f^\dagger_{i\alpha} \frac{\sigma^z_{\alpha\beta}}{2} f_{i\beta} - \mu \sum_{i,\alpha} f^\dagger_{i\alpha} f_{i\alpha},$$

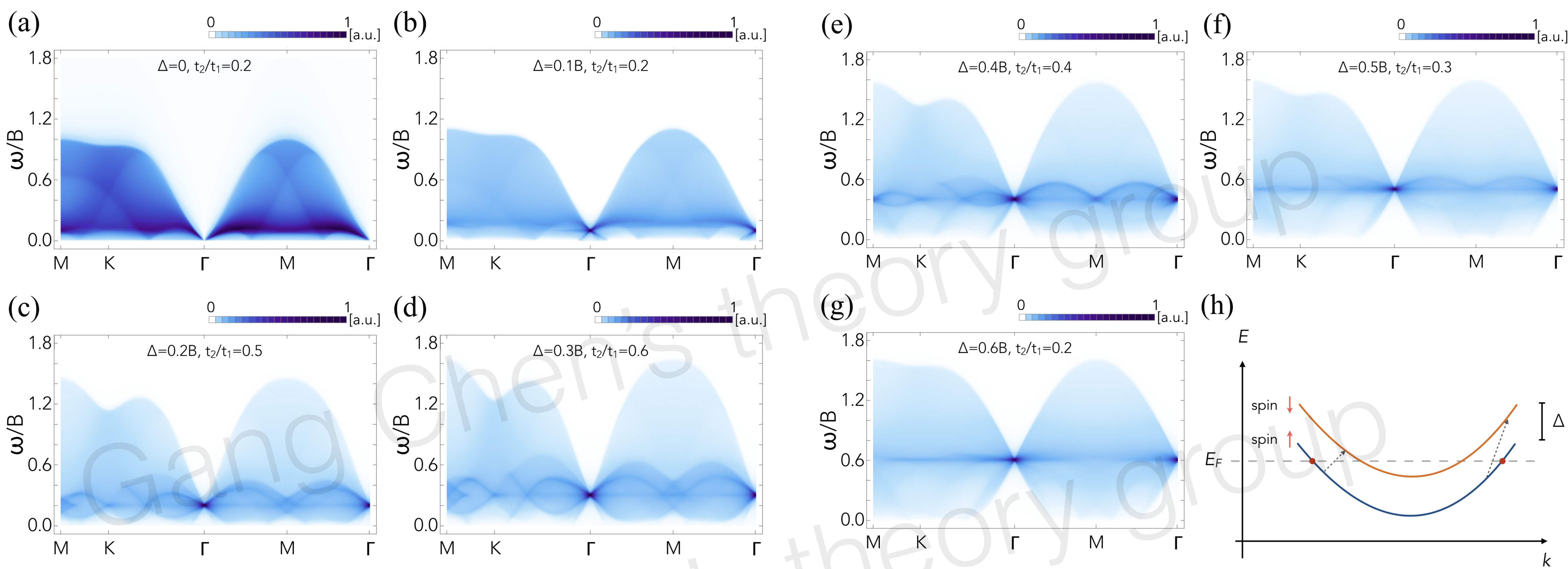
No magnetic field

With magnetic field

Field splits the spin-up and down spinon bands



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. Testable predictions have been made.