Symmetry enriched U(1) quantum spin liquids on a pyrochlore lattice

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one is sufficien
transition.

Yao-Dong Li, **GC**, arXiv: **1607.02287,**
PRB Rapid Comm, 2017

Symmetry enriched topological order

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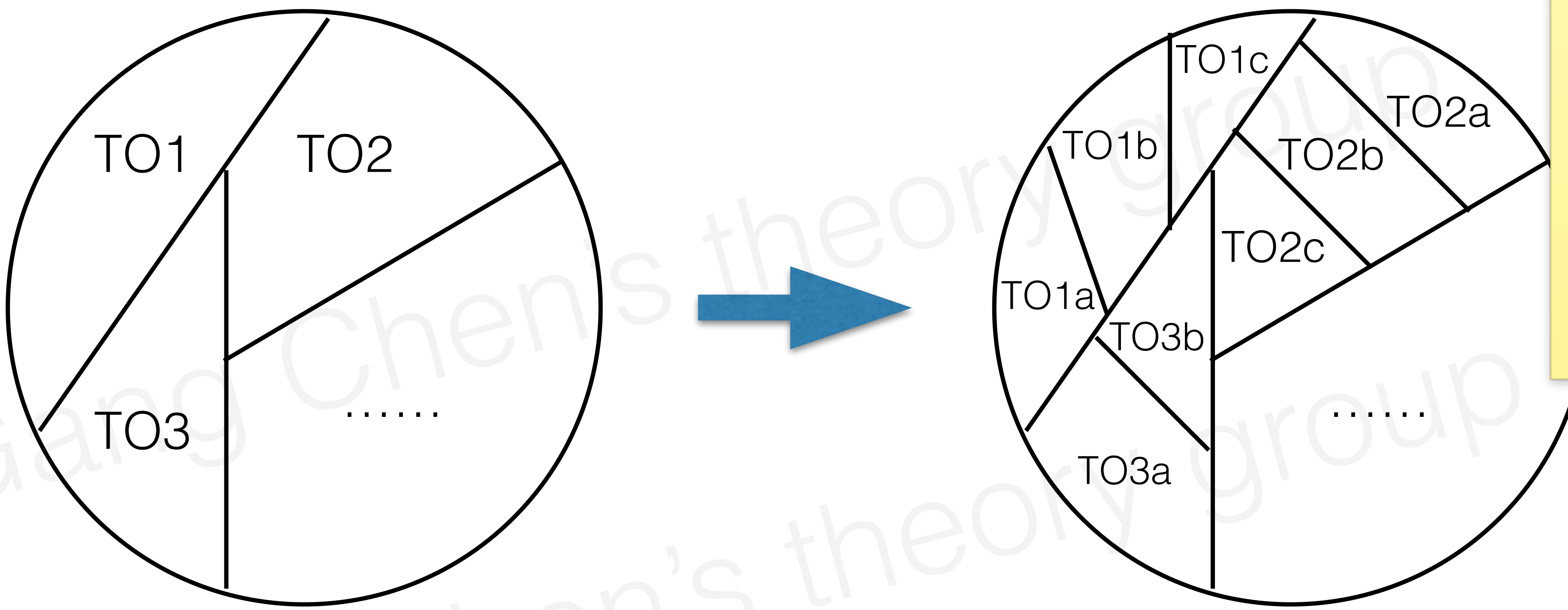
Ying Ran
Michael Hermele
Meng Cheng
Yuanming Lu
Chenjie Wang
Zhengcheng Gu
Michael Levin
A Kitaev
……



without symmetry

with symmetry:
the topological phases are richer,
even with the same topological order,
different SET phases cannot transform
into each other with finite-step local unitary
transformation w/o breaking symmetry.

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

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For intrinsic
topogolical

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Here I will g

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An important question

What are the *physical* degrees of freedom
and their interactions to realize these novel quantum phases?

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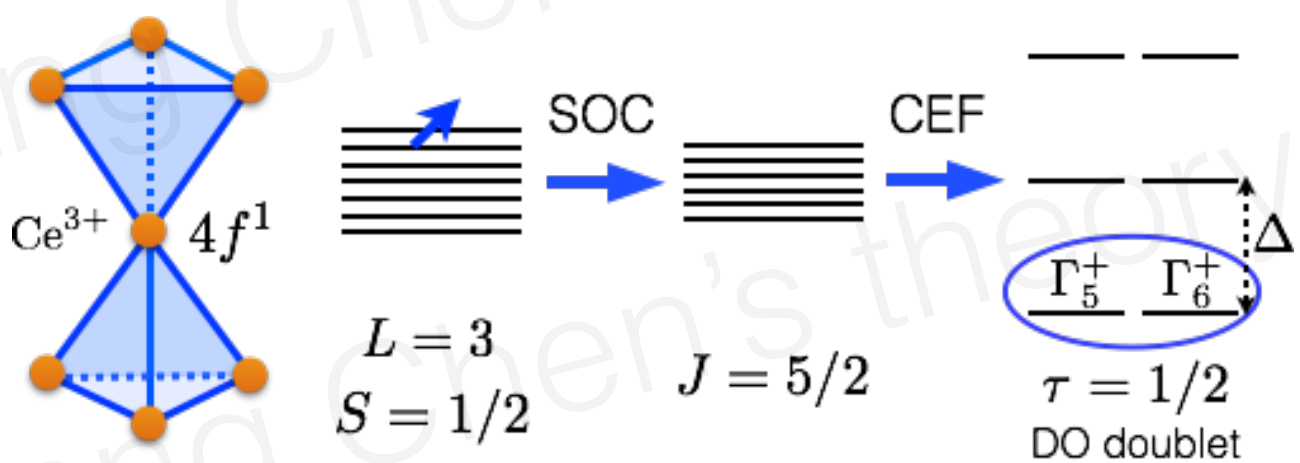
Candidate Quantum Spin Liquid in the Ce^{3+} Pyrochlore Stannate $Ce_2Sn_2O_7$

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 ±

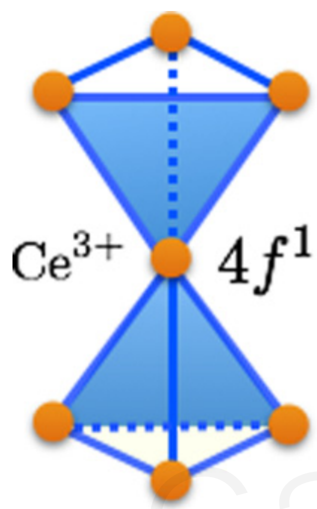
all the theor
sentence.

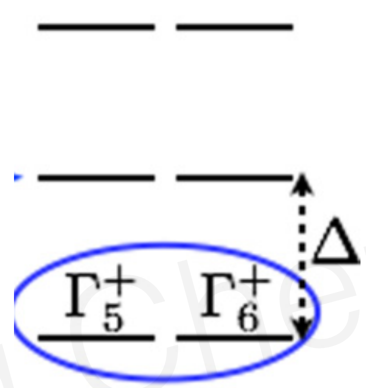


This doublet is **dipole-octupole doublet** !

Huang, **GC**, Hermele, PRL,112,167203 (2014), arXiv Nov 2013
Yao-Dong Li, **GC**, PRB Rapid Comm 2017
Yao-Dong Li, XQ Wang, **GC**, PRB Rapid Comm 2016

How does it work? Why so special?





$$|\Psi_+\rangle = a_1 |J^z = \frac{3}{2}\rangle + a_2 |J^z = -\frac{3}{2}\rangle$$

$$|\Psi_-\rangle = a_1^* |J^z = -\frac{3}{2}\rangle + a_2^* |J^z = \frac{3}{2}\rangle$$

$$e^{-i\frac{2\pi}{3}J^z}|\Psi_\pm\rangle = e^{-i\frac{2\pi}{3}\frac{3}{2}}|\Psi_\pm\rangle = -|\Psi_\pm\rangle$$

Huang, **GC**, Hermele, PRL,112,167203 (2014), arXiv Nov 2013
Yao-Dong Li, **GC**, PRB Rapid 2017
Yao-Dong Li, XQ Wang, **GC**, arXiv:1608.07008

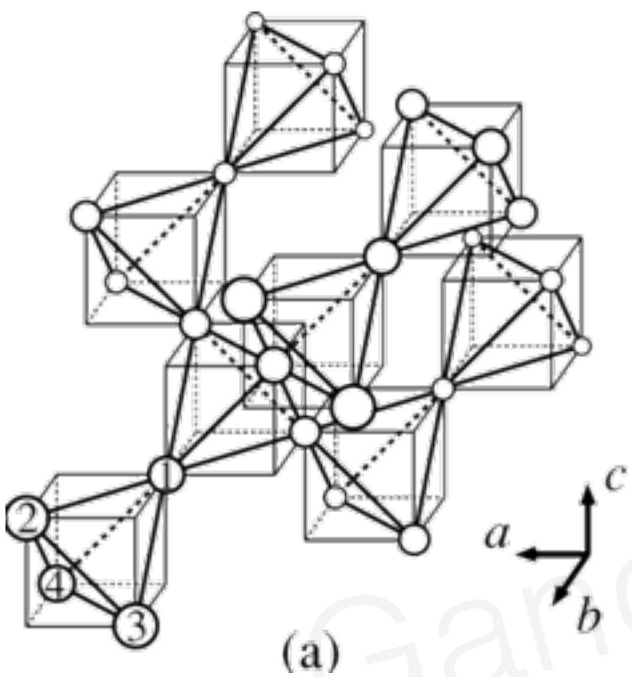
Symmetry Enriched U(1) topological order
and
Experimental signatures of Symmetry Enrichment

next i will introduce the realistic XYZ model that describe the interaction between these peculiar doublet, and discuss the remarkable physical properties.

this does not look like XYZ,

just because of the spatial uniformity, one can do a rotation in spin space without effecting real space,

Generic model: XYZ model



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

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

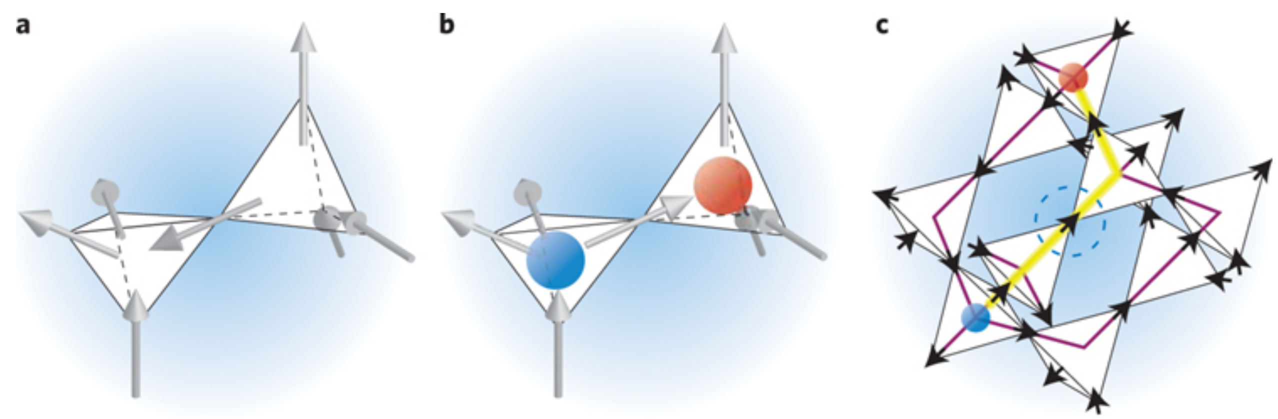
Rotation around the y axis in the effective spin space

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

XYZ model

Important: S^x and S^z transform identically (as a dipole), while 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

Hermele, Fisher, Balents
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 domi

as quant
there is r
a new ph
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the right
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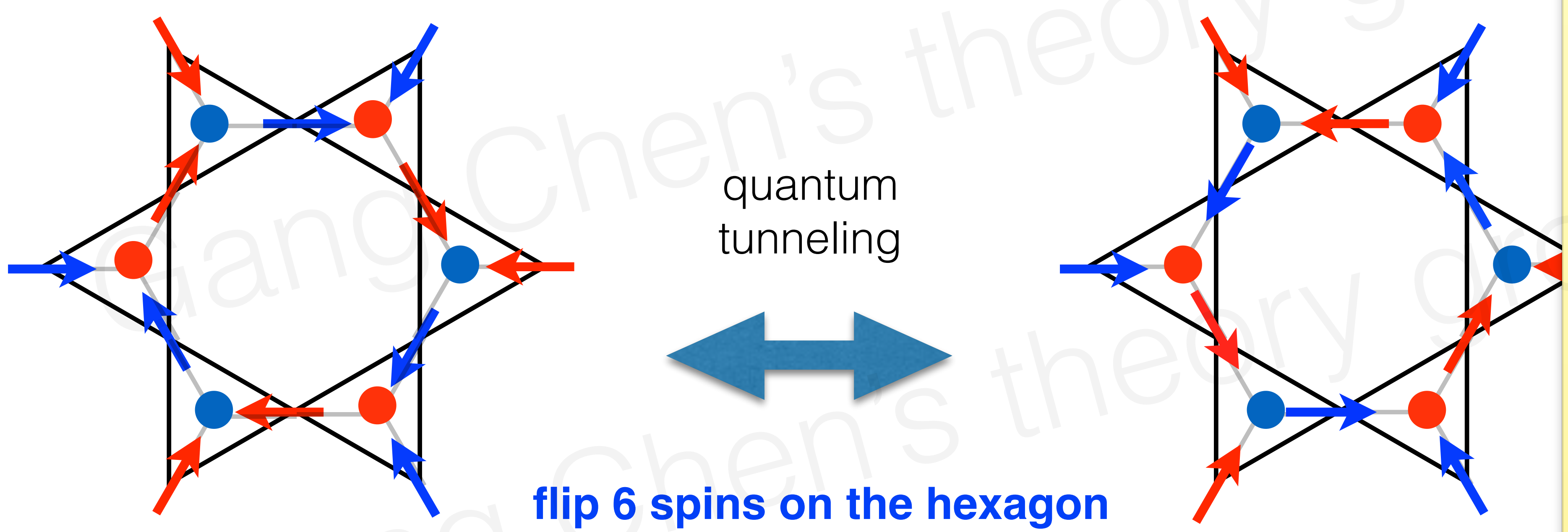
Emergent electric field $S^z \sim E$

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

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

1. But classical spin ice is purel
classical and is not a new phas
matter. It is smoothly connecte
high temperature paramagnetic

2. In contrast, quantum spin ice
new quantum phase of matter.

3. To obtain quantum spin ice, c
simply add quantum spin flip te
the ising hamiltonian.

4. the quantum term allows the
to tunnel from one spin ice stat
other.

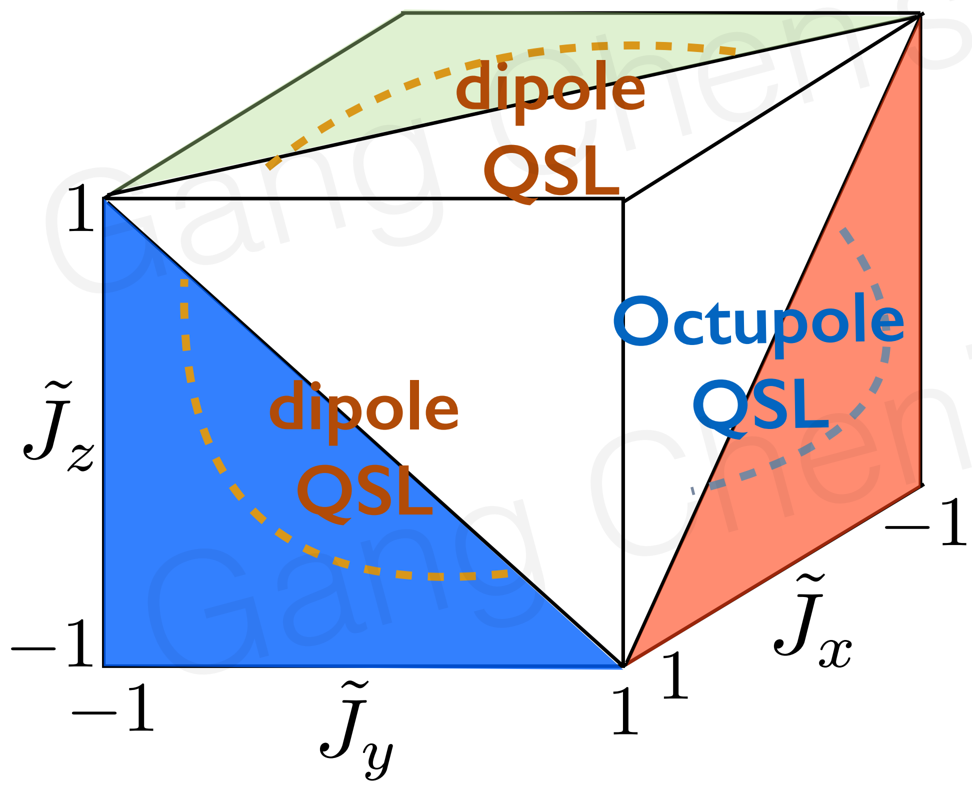
5. As long as the term is not too
the system is disordered, and th
ground sate is quantum spin ice

- Pretty much one can add any term to create **quantum** tunneling, as long as it is not t
induce magnetic order, the **ground state** is a quantum spin ice !

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

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

unlike XXZ model, XYZ model is r
richer



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

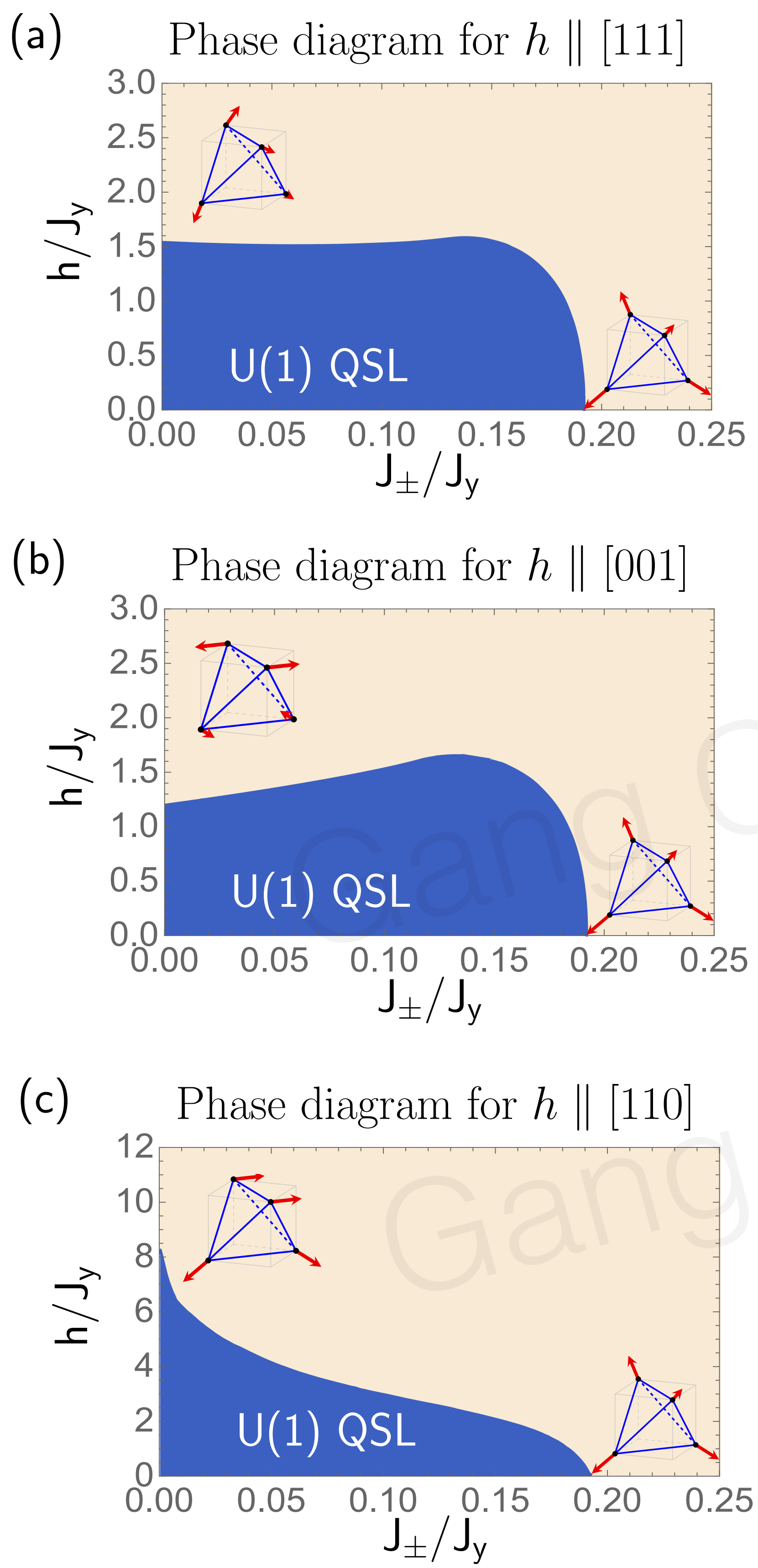
Infinite anisotropic g-factor

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

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].

physics is defined with observables.



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 expec
a field-driven Higgs transition to magnetic orderin
as the **field only couples to the matter field** (spi

without losing gen

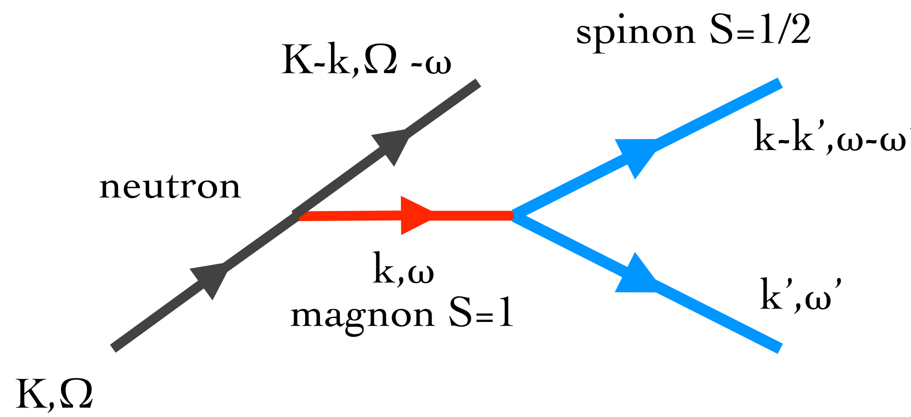
Higgs trnasiton is v
meisner effect in su

$$H = \sum_{\langle ij \rangle} J_y S_i^y S_j^y - J_{\pm}(S_i^+ S_j^- + S_i^- S_j^+)$$

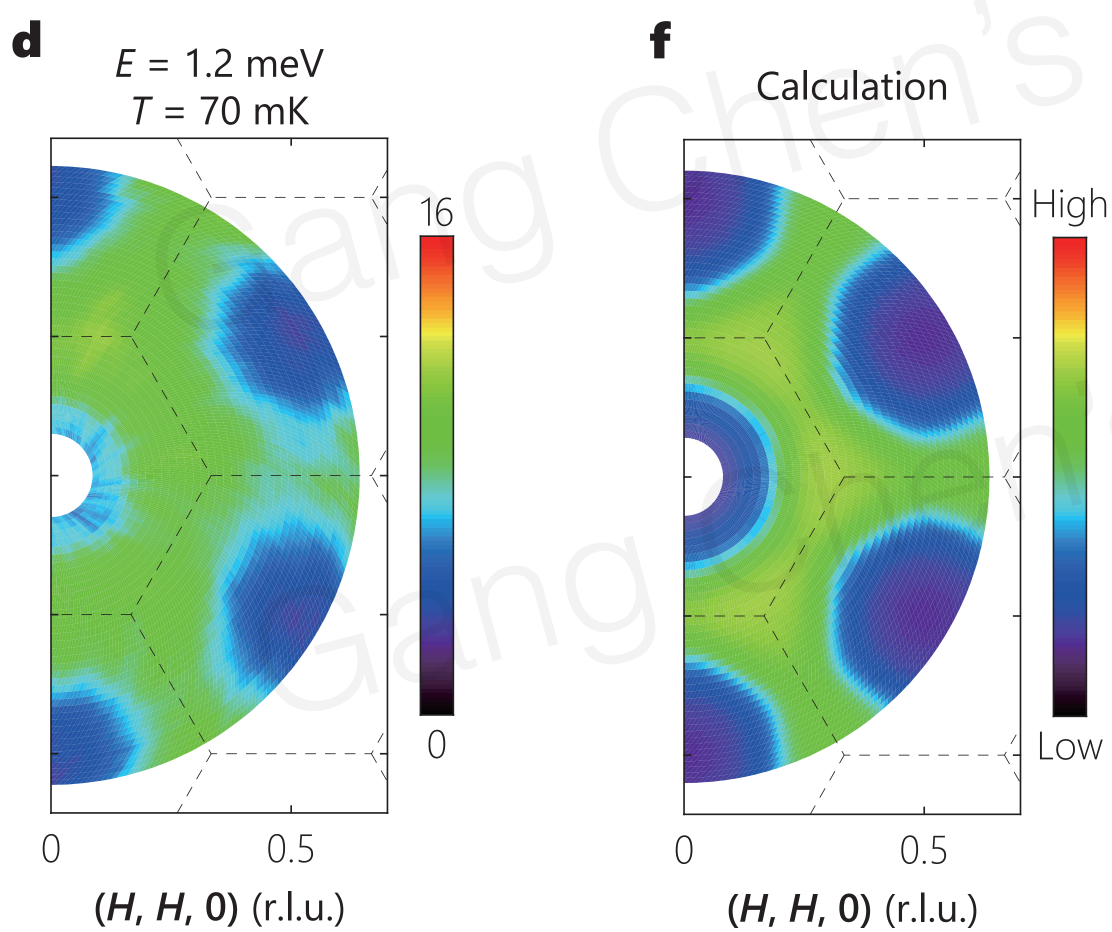
$$-h \sum_i (\hat{n} \cdot \hat{z}_i) S_i^z$$

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

Inelastic neutron scattering and spinon continuum



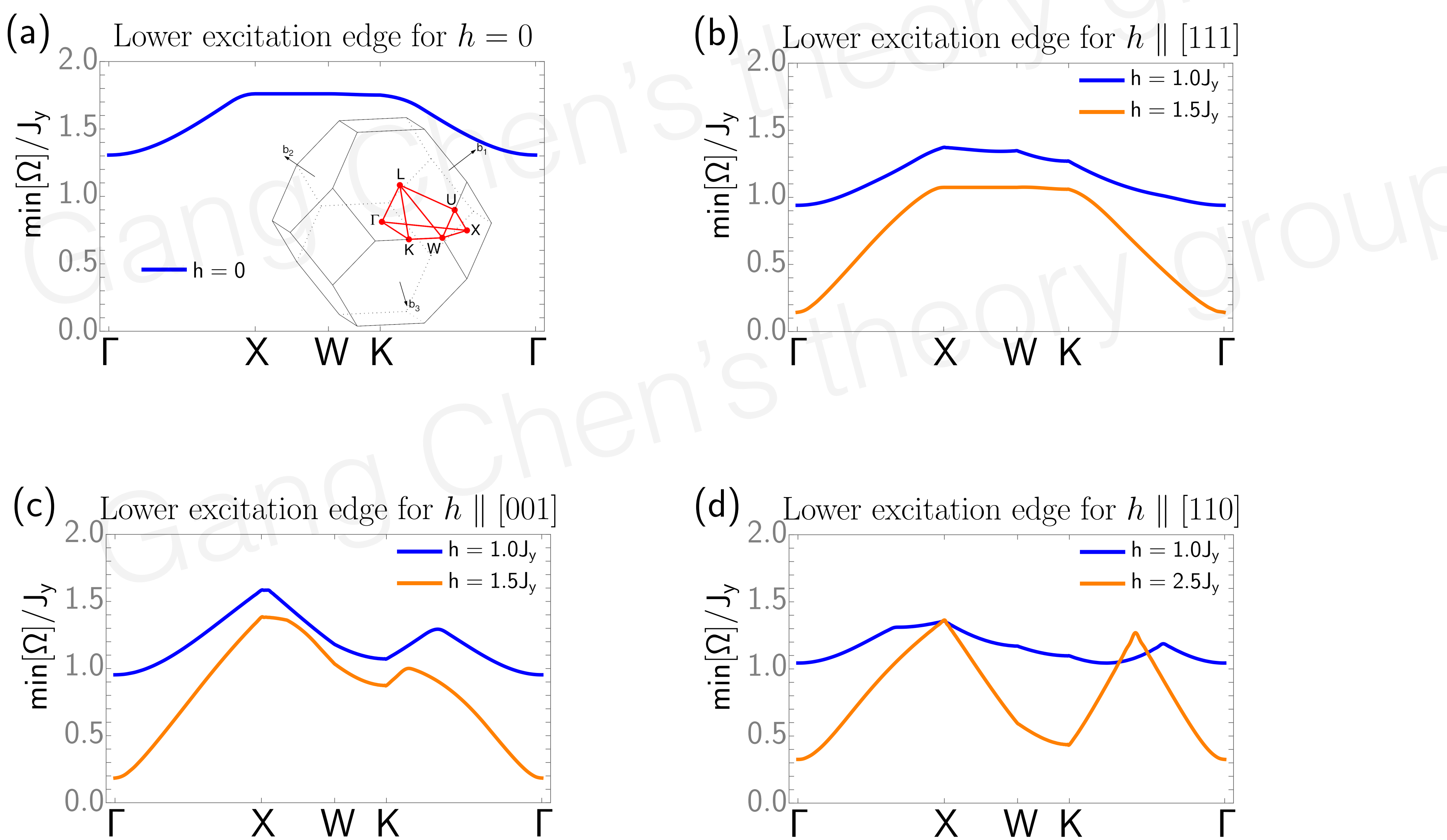
broad peak with
$\omega=\varepsilon(k')+\varepsilon(k-k')$



Spinon continuum of spinon Fermi surface
in **$YbMgGaO_4$**
Y Shen, Y-D Li,…., **GC***, Jun Zhao*
Nature 2016

Lower excitation edge

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



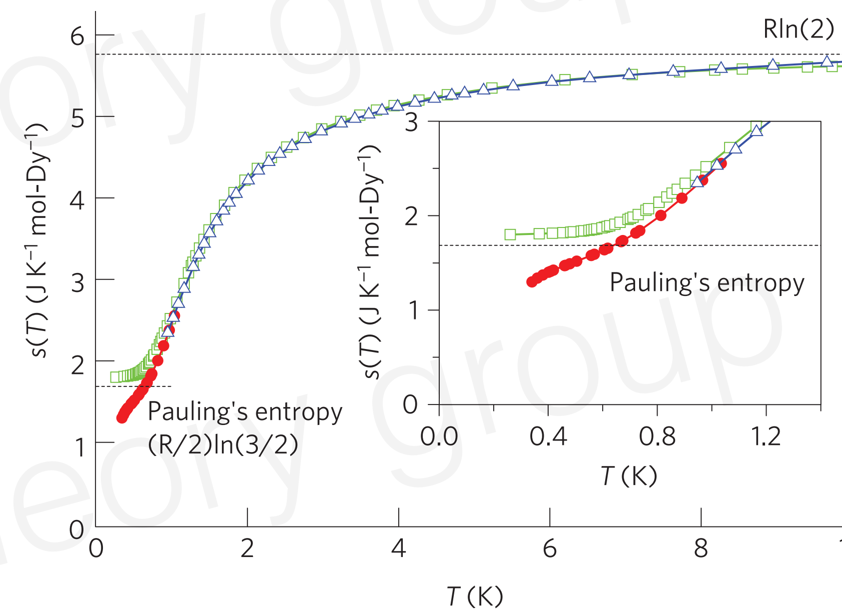
Material survey: other DO doublet systems

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.