What does inelastic neutron scattering measure in quantum spin ice?

1st Asia Pacific Workshop on Quantum Magnetism

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Our recent works on quantum spin ice

Ce2Sn2O7, symmetry enriched U(1) QSL and field-driven Anderson-Higgs transition
Y-D Li, **GC**, PRB Rapid Comm, 95, 041106, (2017)

Quantum spin ice with dipole-octupole doublet
Y-P Huang, **GC**, M Hermele, PRL 112, 167203, (2014)

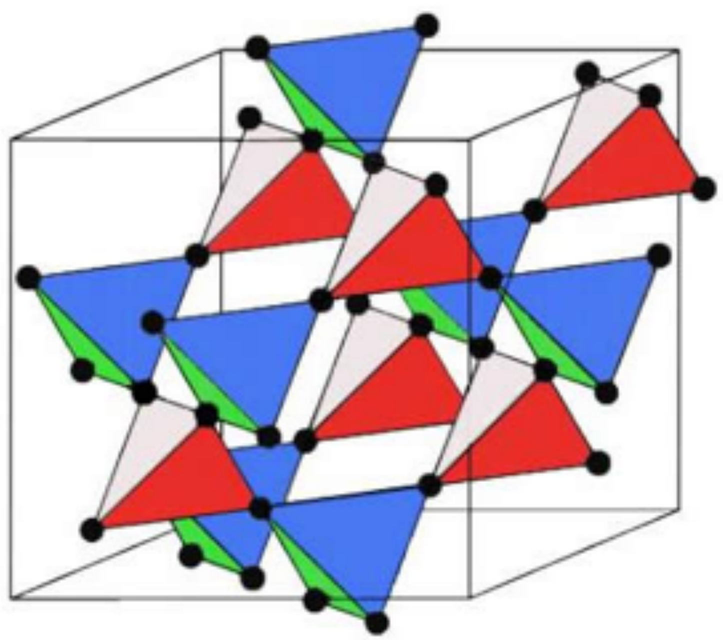
Quantum spin ice on the breathing pyrochlore lattice.
L Savary, XQ Wang, HY Kee, YB Kim, Y Yu, **GC**, PRB 94, 205107, (2016)

“Magnetic Monopole” condensation transition out of spin ice U(1) QSL: Pr2Ir2O7
GC, PRB 94, 205107, (2016)

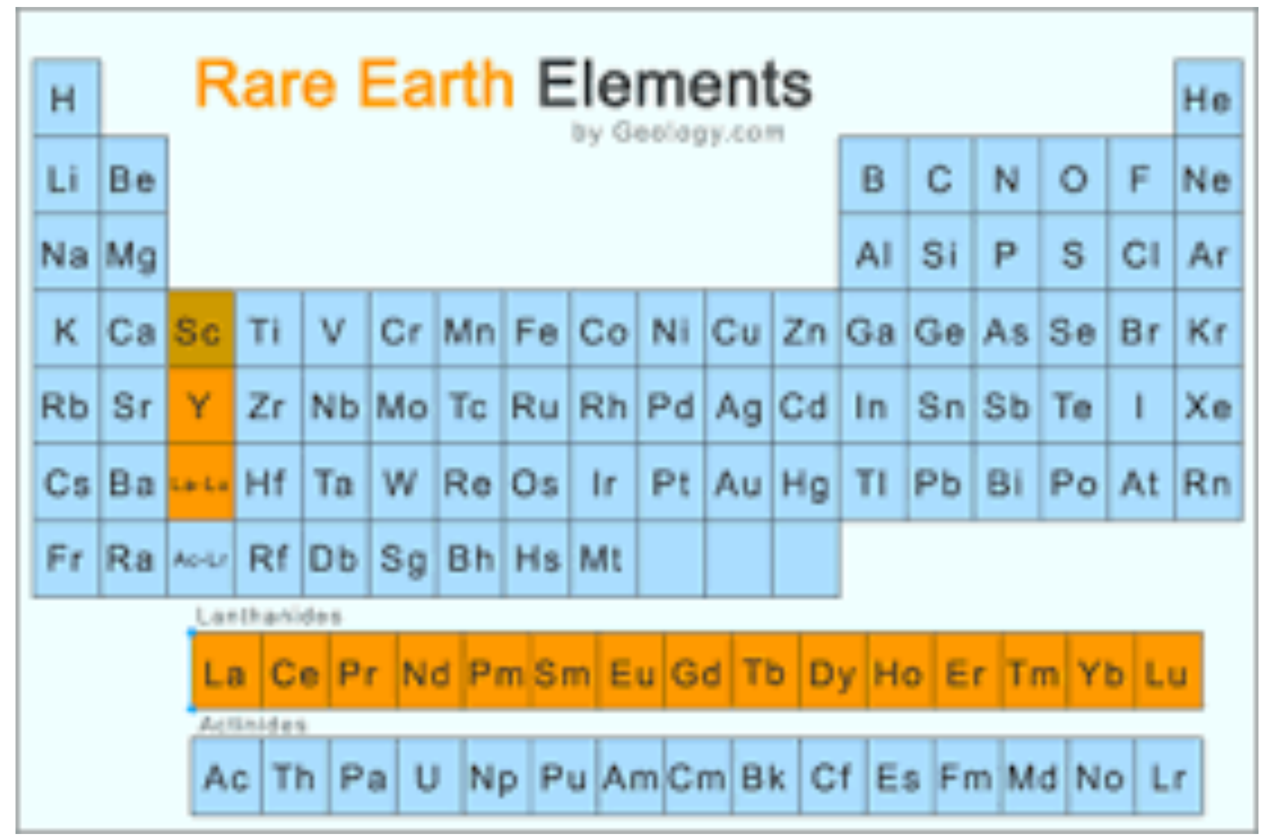
Spectral periodicity of spinon continuum in quantum spin ice
Gang Chen, PhysRevB, 96, 085136, (August 2017)

What does inelastic neutron scattering measure in quantum spin ice?
Gang Chen, arXiv:1706.04333

Pyrochlore spin ice



$RE_2M_2O_7$

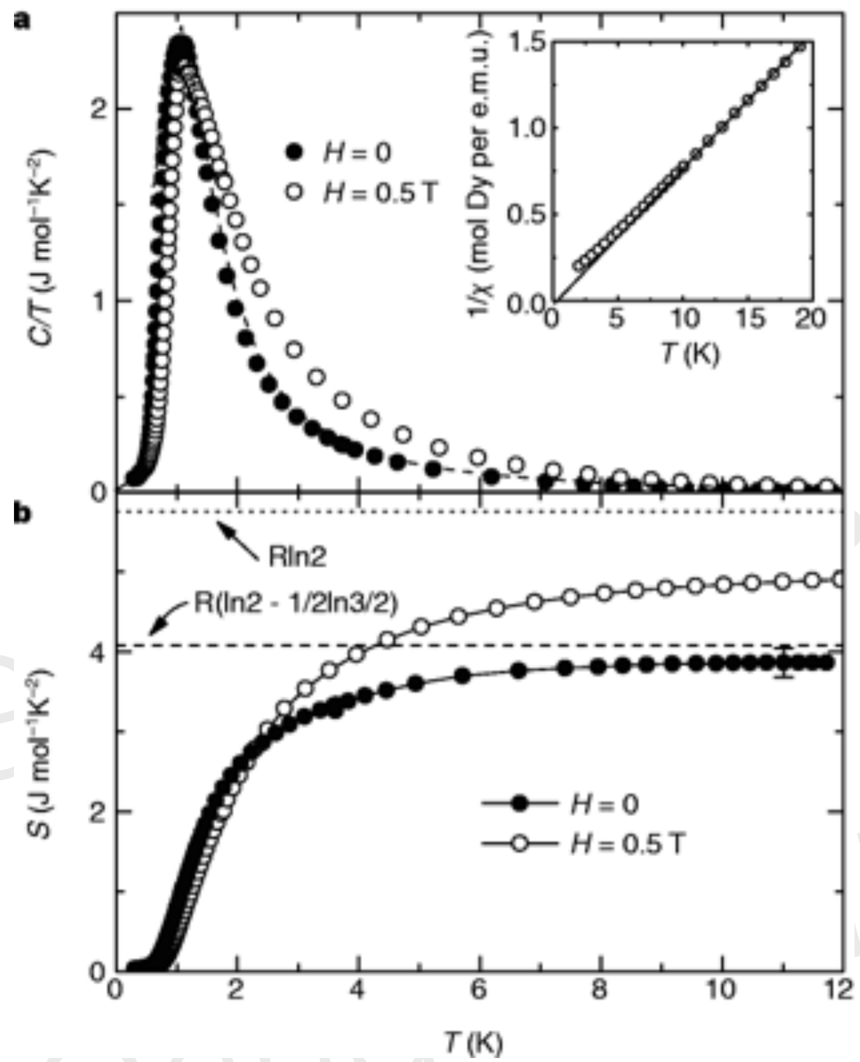


$$H = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z + \text{dipolar}$$

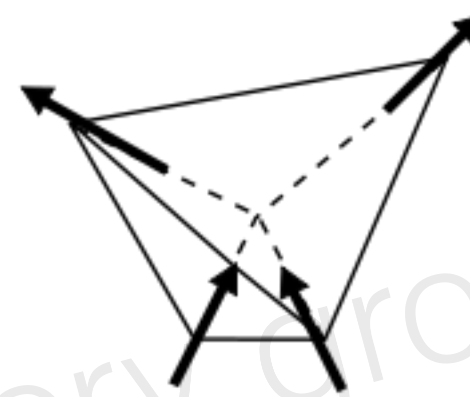
Castelnovo, Gingras, Moessner, Sondhi, Schiffer,
Shannon, Moon, Kim, Savary, Balents, …….

Classical spin ice

$Dy_2Ti_2O_7$

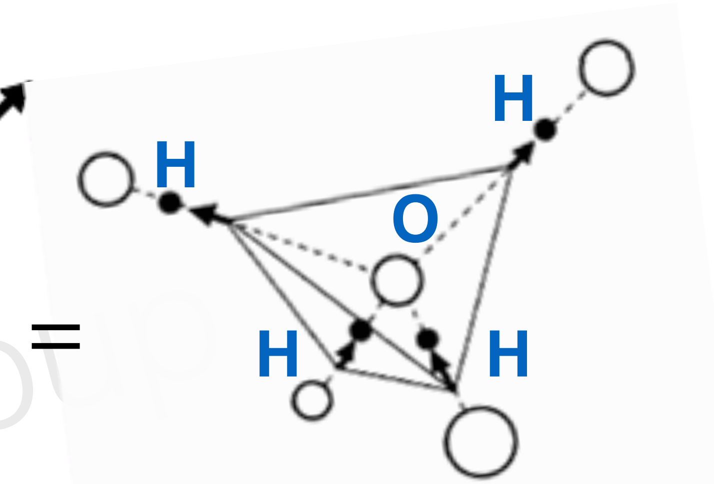


Pauling entropy in spin ice,
Ramirez, etc, Science 1999

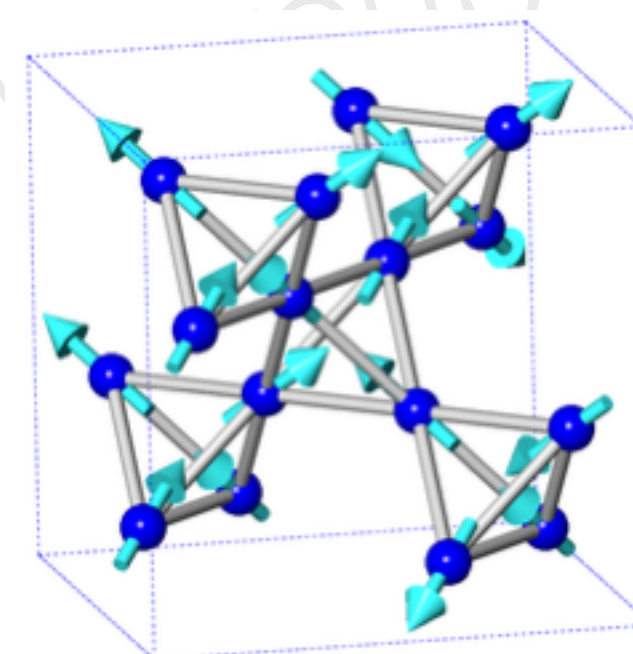


2-in 2-out
spin ice rule

=



2-in 2-out
water ice rule



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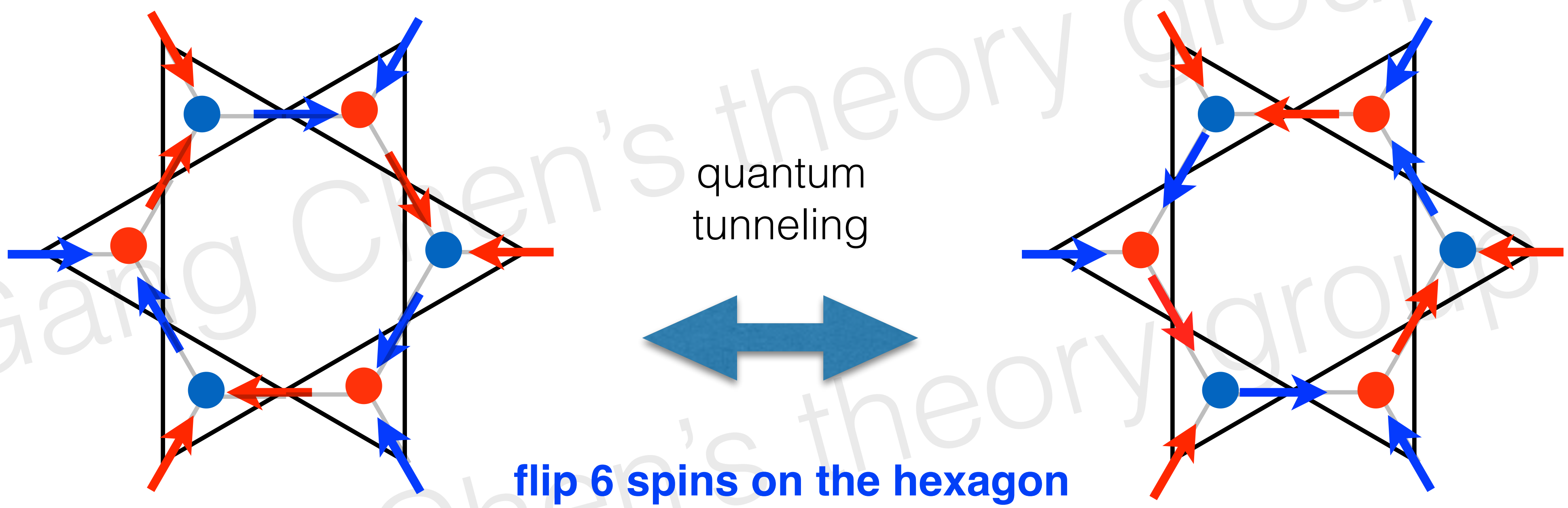
U(1) quantum spin liquid

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

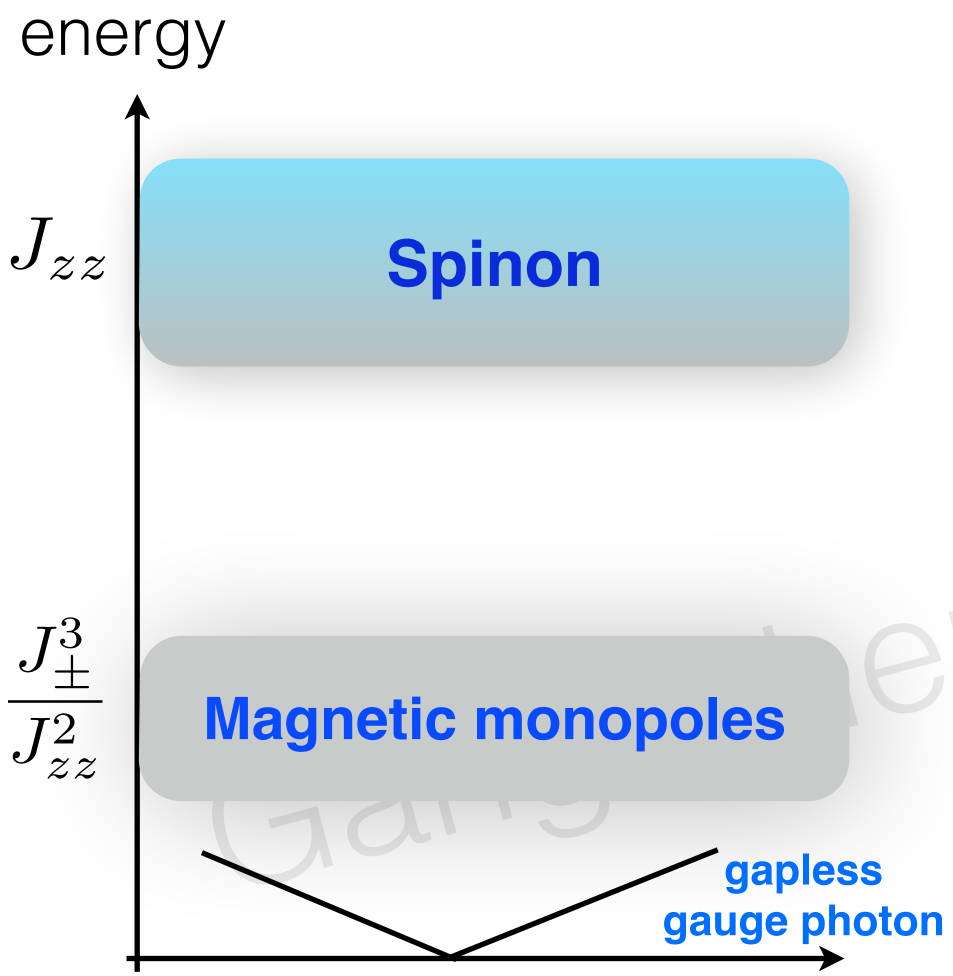
Hermele, Fisher, Balents, Moessner, Isakov, YB Kim….

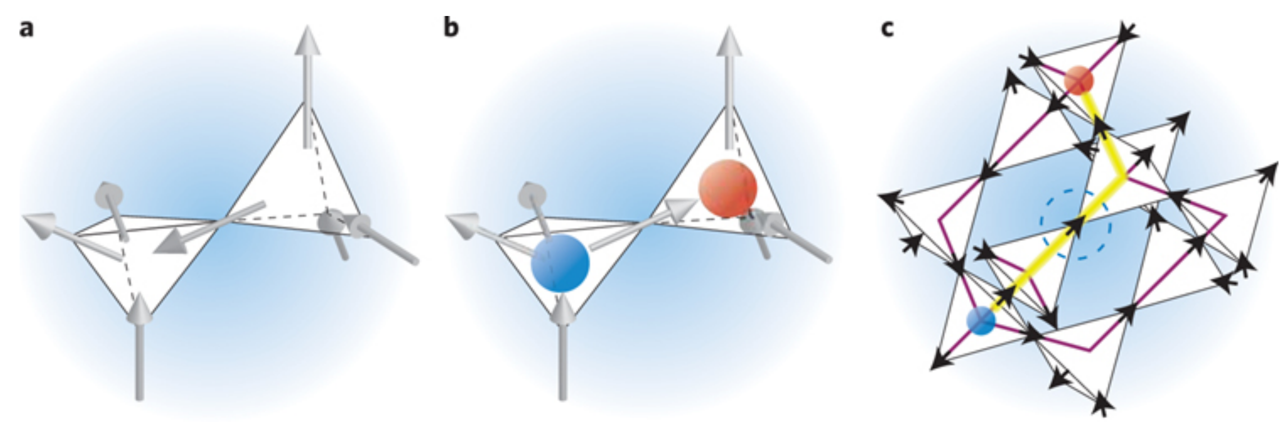


flip 6 spins on the hexagon
or
Ring exchange

- 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 U(1) quantum spin liquid !

Excitations in the U(1) QSL



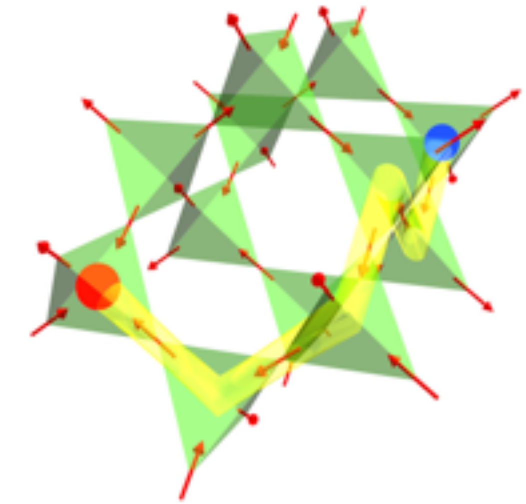


Figs from Moessner&Schiffer,2009

Spinon deconfinement

- No LRO, no symmetry breaking, **cannot** be understood in Landau's paradigm!
- The right description is in terms of fractionalization and emergent gauge structure.

Equivalence of "notations"



Excitations (notation 1)	Excitations (notation 2)
Spinon	Magnetic monopole
"Magnetic monopole"	Electric monopole
Gauge photon	Gauge photon

Spinon / Magnetic monopole → **has classical analogue**

"Magnetic monopole" / Electric monopole and Gauge photon → **purely quantum, no classical analogue**

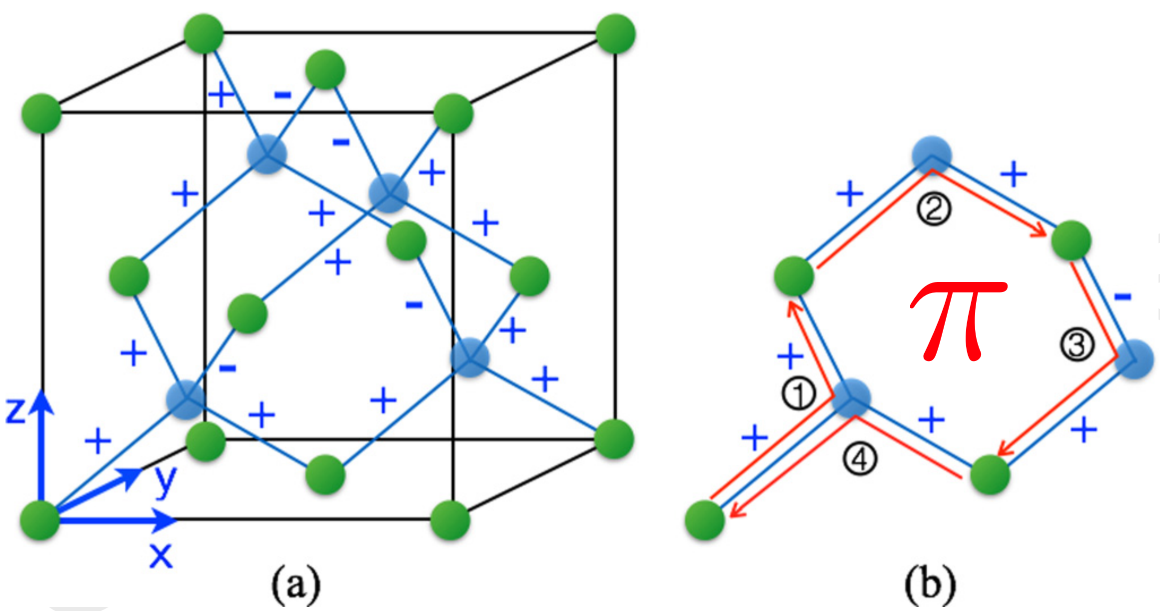
Notation 1 ↑ This talk

Notation 2 ↑ Eun-Gook Moon's talk

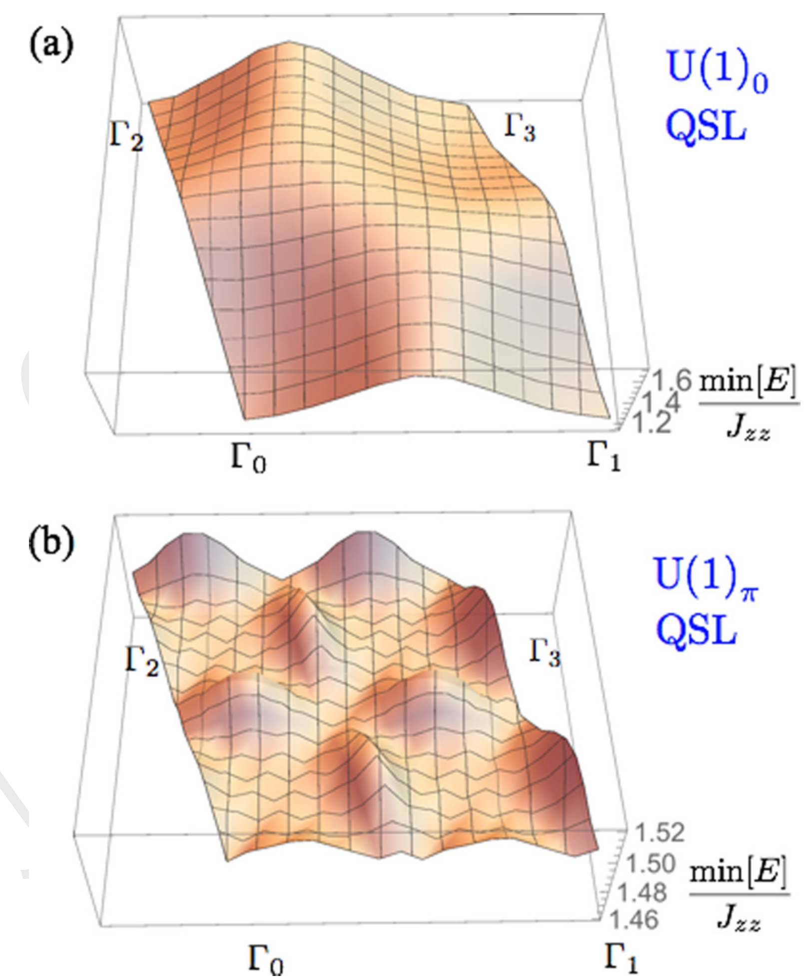
"Magnetic monopole" is probably closer in spirit to **Dirac's monopole (1931).**
One has to confirm that "magnetic monopole" is emergent excitation, rather than a fictitious particle.

What piece of experimental info indicates these exotic and emergent particles?

Spinon continuum: background flux and folded Brillouin zone



diamond lattice of
pyrochlore centers



Occasionally, the spinon experiences a **PI** background
flux as it moves on the diamond hexagons.

Spectral periodicity of spinon
lower excitation edges:
Pi flux -> folded Brillouin zone

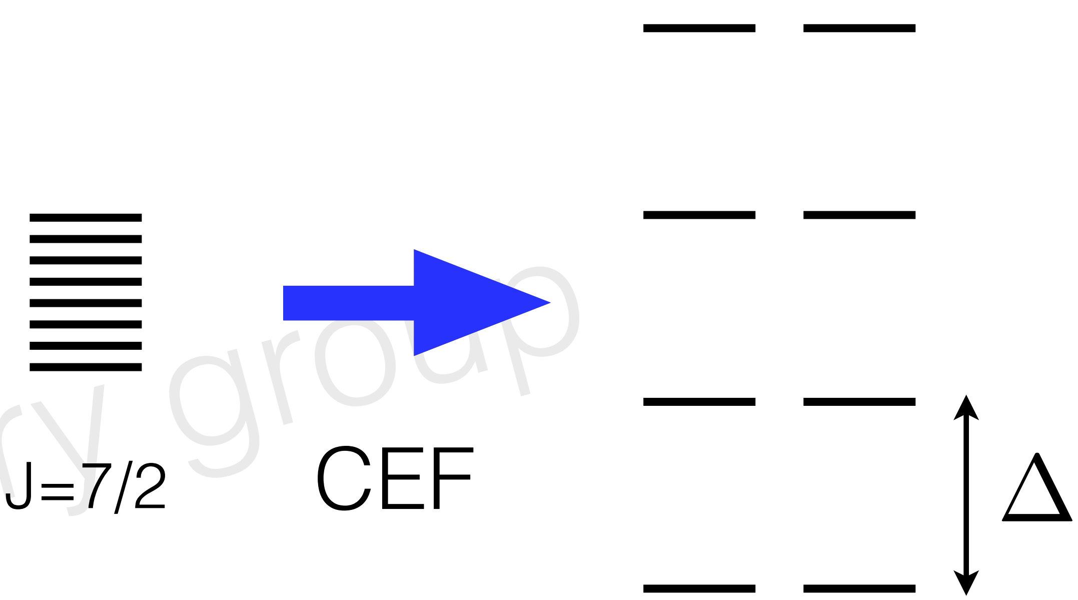
Sungbin Lee, S Onoda, Balents, PRB 2012
Gang Chen, PRB, 96, 085136, 2017

Kramers vs Non-Kramers doublet

Kramers doublet: e.g. Yb ion in $Yb_2Ti_2O_7$

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

$$\mathcal{T}: S^x \rightarrow -S^x, S^y \rightarrow -S^y, S^z \rightarrow -S^z$$

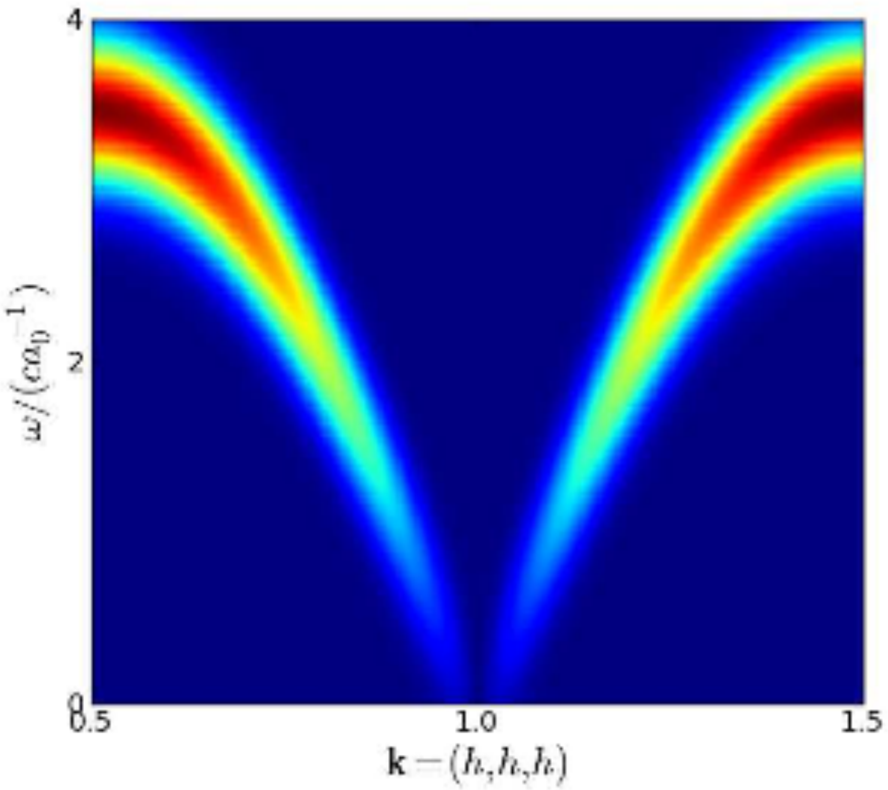


(unusual example is dipole-octupole doublet in $Ce_2Sn_2O_7$ and $Nd_2Zr_2O_7$),
YP Huang, GC, Hermele, PRL 2014; YD Li, GC, PRB2016, YD Li, GC, PRB 2017

In contrast, the Tb ion in $Tb_2Ti_2O_7$, Pr ion in $Pr_2Ir_2O_7$, $Pr_2Sn_2O_7$, $Pr_2Zr_2O_7$, etc, are **non-Kramers doublets**

$$\mathcal{T}: \quad S^{x,y} \rightarrow S^{x,y}, \quad S^z \rightarrow -S^z.$$

Emergent light: U(1) photon



$$I(\omega) \sim \omega$$

emergent U(1) photon in U(1) QSL

Hermele etc 2004
N Shannon etc 2012,
L Savary etc 2012

$$S_z \sim E \text{ (emergent electric field)}$$

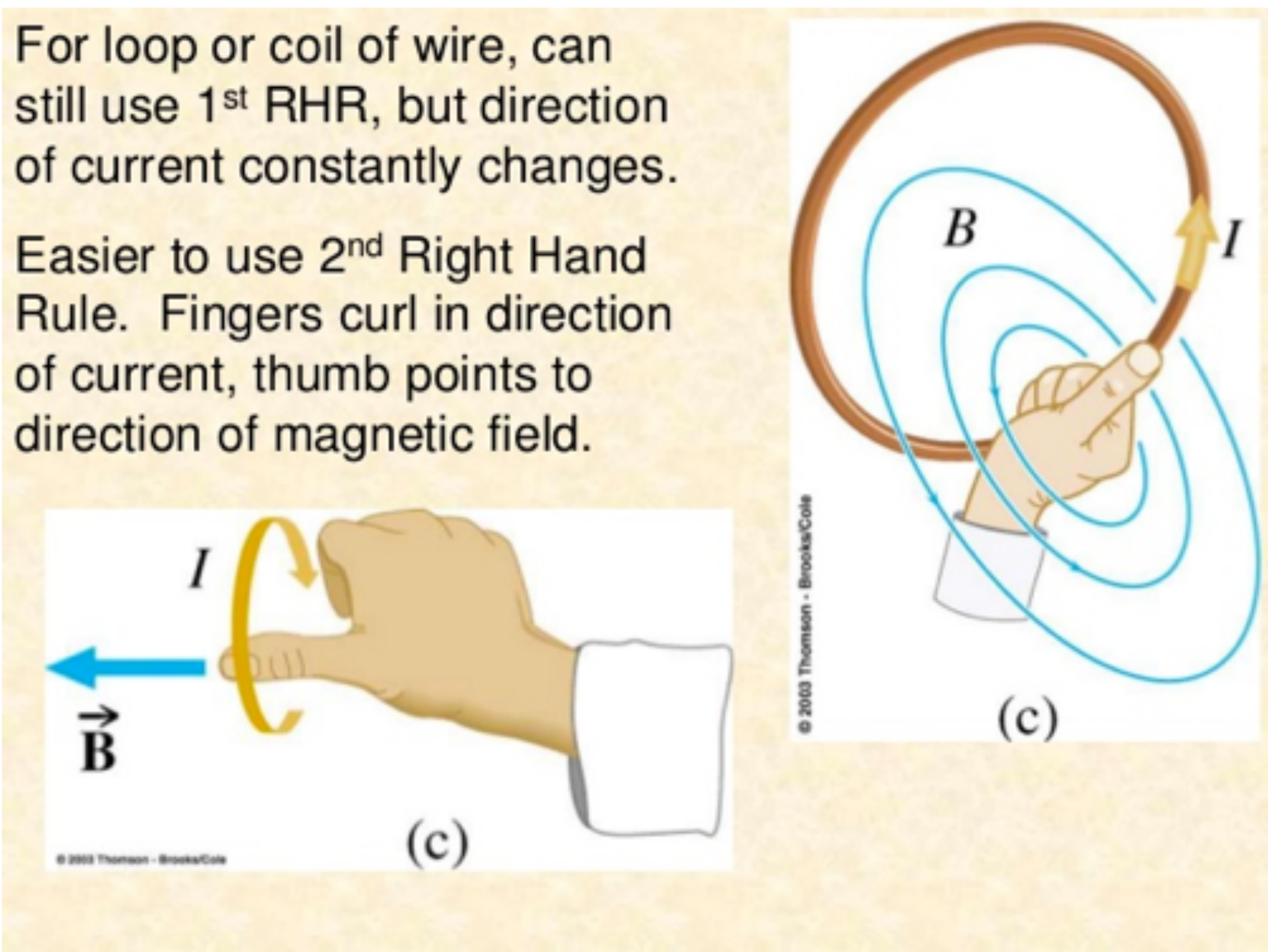
Low energy theory

$$\mathrm{Im}[E^{\alpha}_{-\mathbf{k},-\omega} E^{\beta}_{\mathbf{k},\omega}] \propto [\delta_{\alpha\beta} - \frac{k_\alpha k_\beta}{\mathbf{k}^2}]\, \omega\, \delta(\omega - v|\mathbf{k}|),$$

The well-known result of the photon modes in the INS measurement was obtained by considering the low-energy field theory that describes the long-distance quantum fluctuation within the spin ice manifold. The actual spin dynamics, that is captured by the S^z correlation in the INS measurement, operates in a broad energy scale up to the exchange energy and certainly contains more information than just the photon mode from the low-energy Maxwell field theory. What is the other informa-

Gang Chen, arXiv:1706.04333

Electromagnetic duality

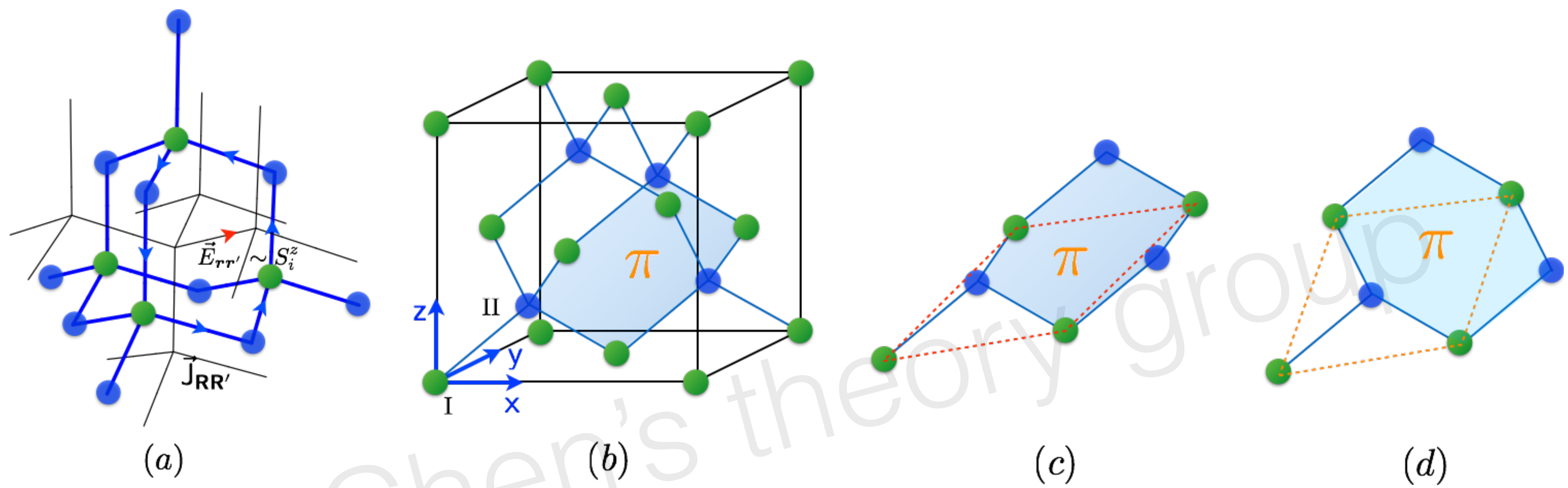


Duality

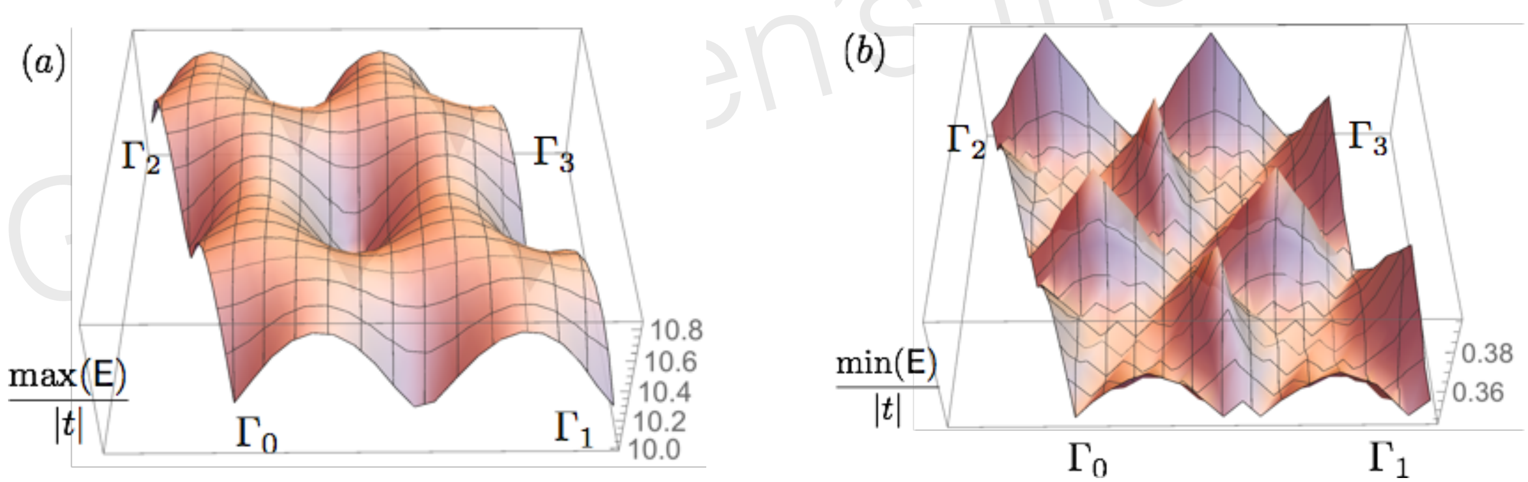
Electric loop current -> Magnetic field
Magnetic loop current -> Electric field

$$S_z \sim E \text{ (emergent electric field)}$$

Sz correlation = monopole loop current correlation



$$H_{\rm dual} = -t \sum_{\langle \mathbf{RR}' \rangle} e^{-i2\pi\alpha_{\mathbf{RR}'}} \Phi^\dagger_{\mathbf{R}} \Phi_{\mathbf{R}'} - \mu \sum_{\mathbf{R}} \Phi^\dagger_{\mathbf{R}} \Phi_{\mathbf{R}} + \frac{U}{2} \sum_{\hexagon^*} (curl\alpha - \frac{\eta_{\boldsymbol{r}}}{2})^2 - K \sum_{\langle \mathbf{RR}' \rangle} \cos B_{\mathbf{RR}'} + \cdots$$

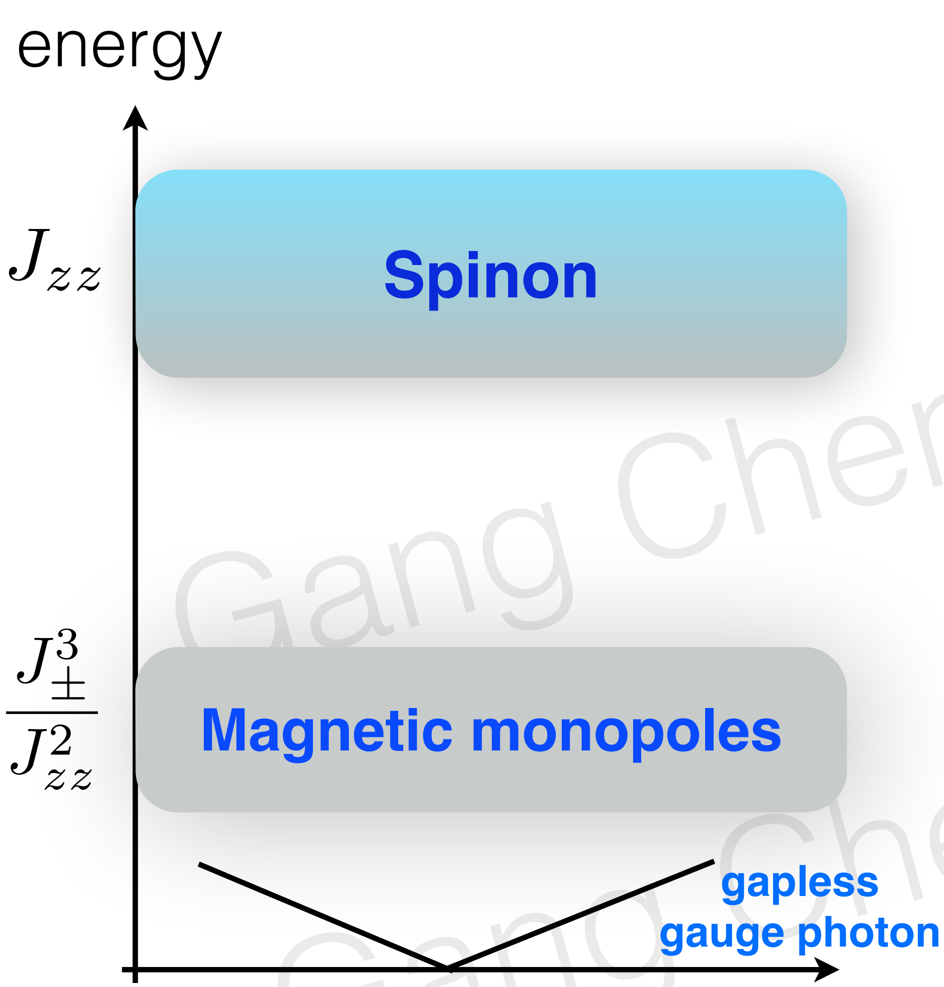


the upper edge

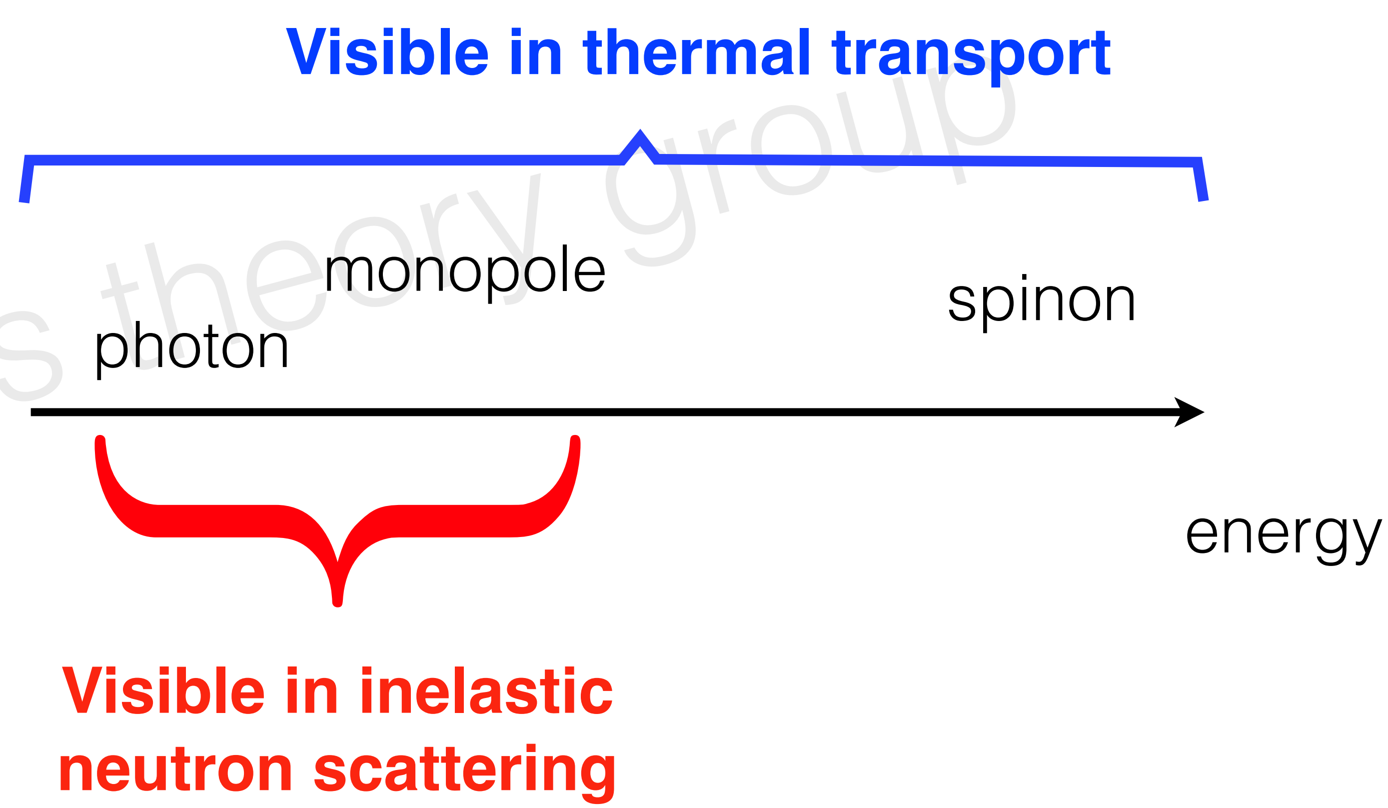
the lower edge

Monopole always experiences Pi flux

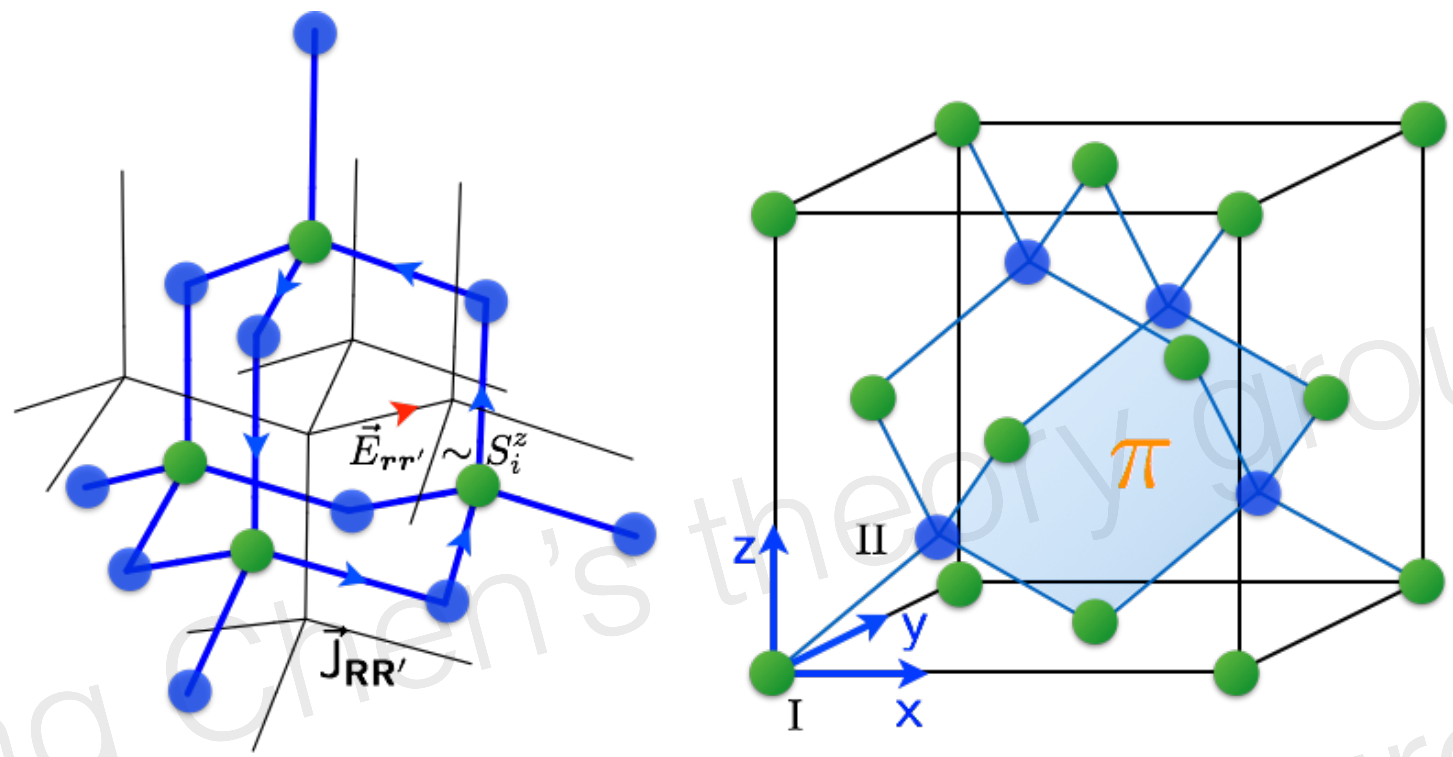
Suggestion 1: combine thermal transport with inelastic neutron



For **non-Kramers doublets** such as Pr ion in $Pr_2Zr_2O_7$ and Tb ion in $Tb_2Ti_2O_7$



Suggestion 2: effect of the external magnetic field



(a) (b)

$$H_{Zeeman} = \vec{B} \cdot \sum_i S_i^z \hat{z}_i$$

The weak magnetic field polarizes Sz slightly, and thus modifies the background electric field distribution. This further modulates monopole band structure, creating "**Hofstadter**" monopole band, which may be detectable in inelastic neutron.

Summary

1. We point out the existence of “magnetic monopole continuum” in the U(1) quantum spin liquid, and monopole is purely **quantum origin**.

2. We further point out that the “magnetic monopole” always experiences a Pi flux, and thus supports enhanced spectral periodicity with **folded Brillouin zone**.

In fact, continuum has been observed in $Pr_2Hf_2O_7$ (R. Sibille, et al, arXiv 1706.03604).