Connect Emergence to Reality:

"Magnetic Monopole" Condensation out of U(1) Topological Order

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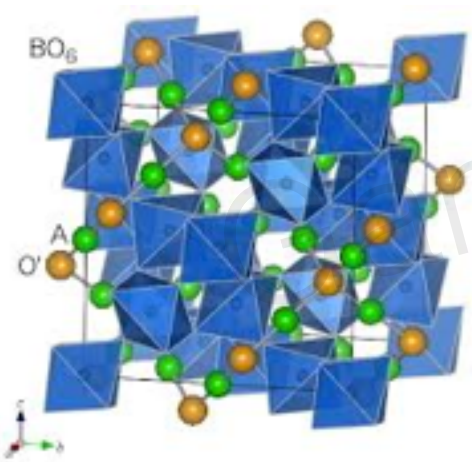
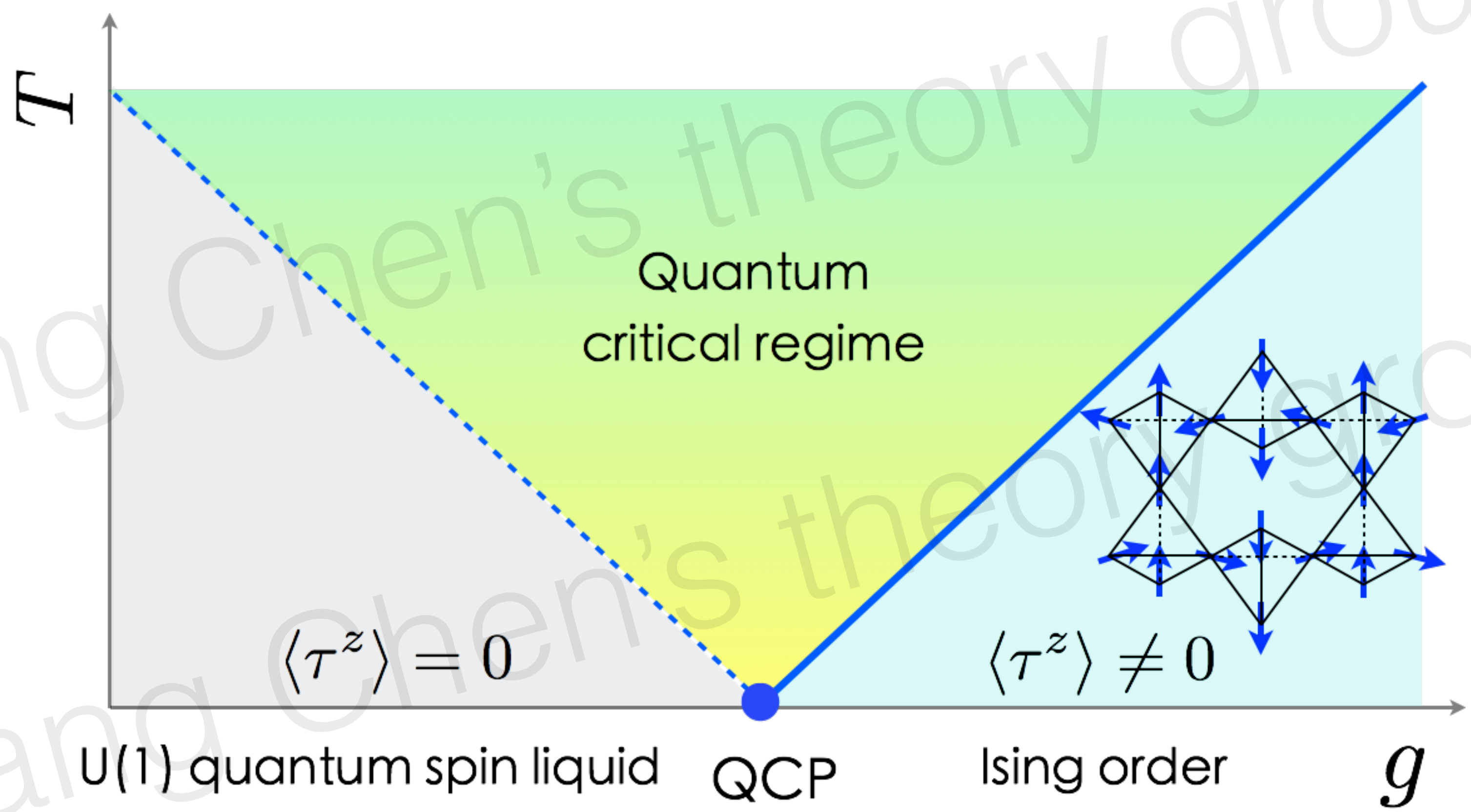
OUTLINE

Monopole condensation transition out of U(1) topological order.

- I propose $Pr_2Ir_2O_7$ sample is close to quantum phase transition between a 3D U(1) topological ordered state and Ising order.

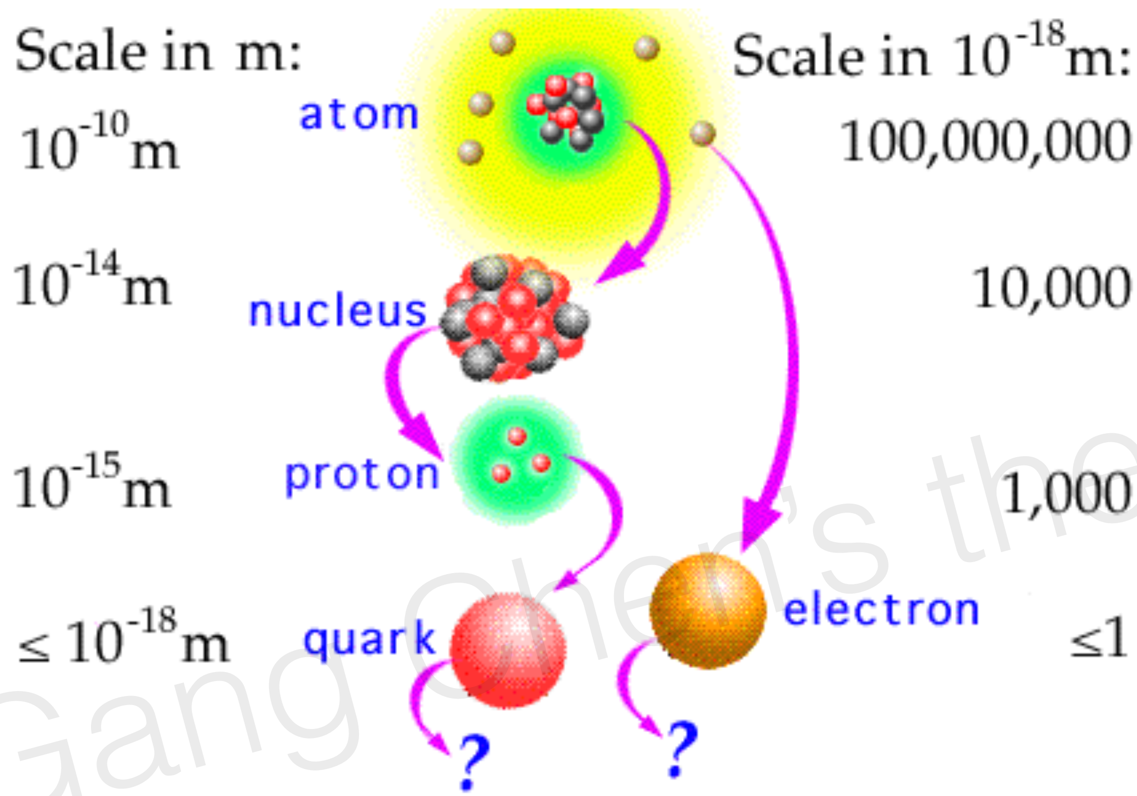


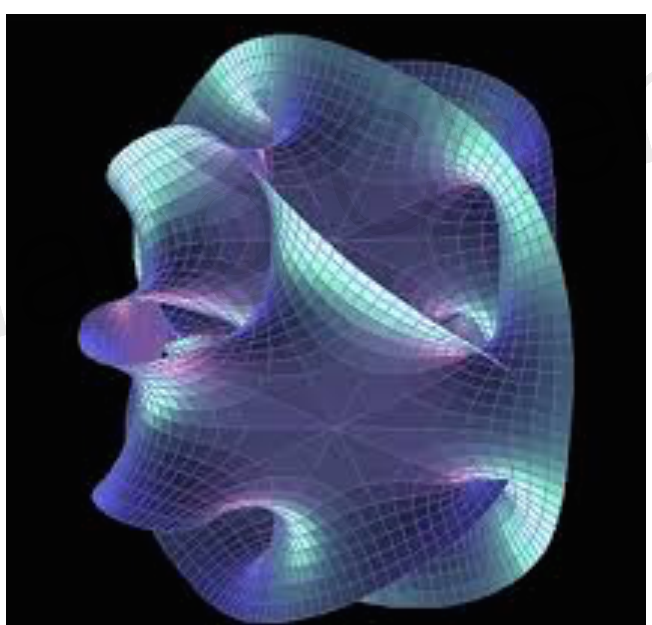


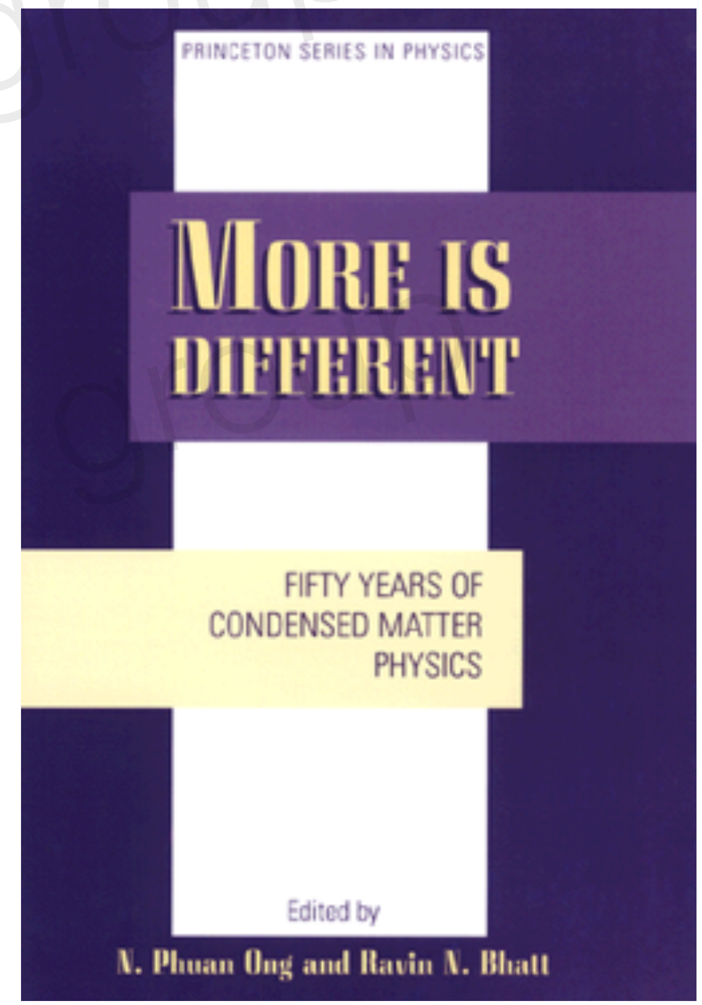
Gang Chen, arXiv 1602.02230**,** Phys. Rev. B. **94**, **205107** (2016)

Yao-Dong Li, Gang Chen, in preparation, 2017
for conduction electrons.

Reduction vs Emergence





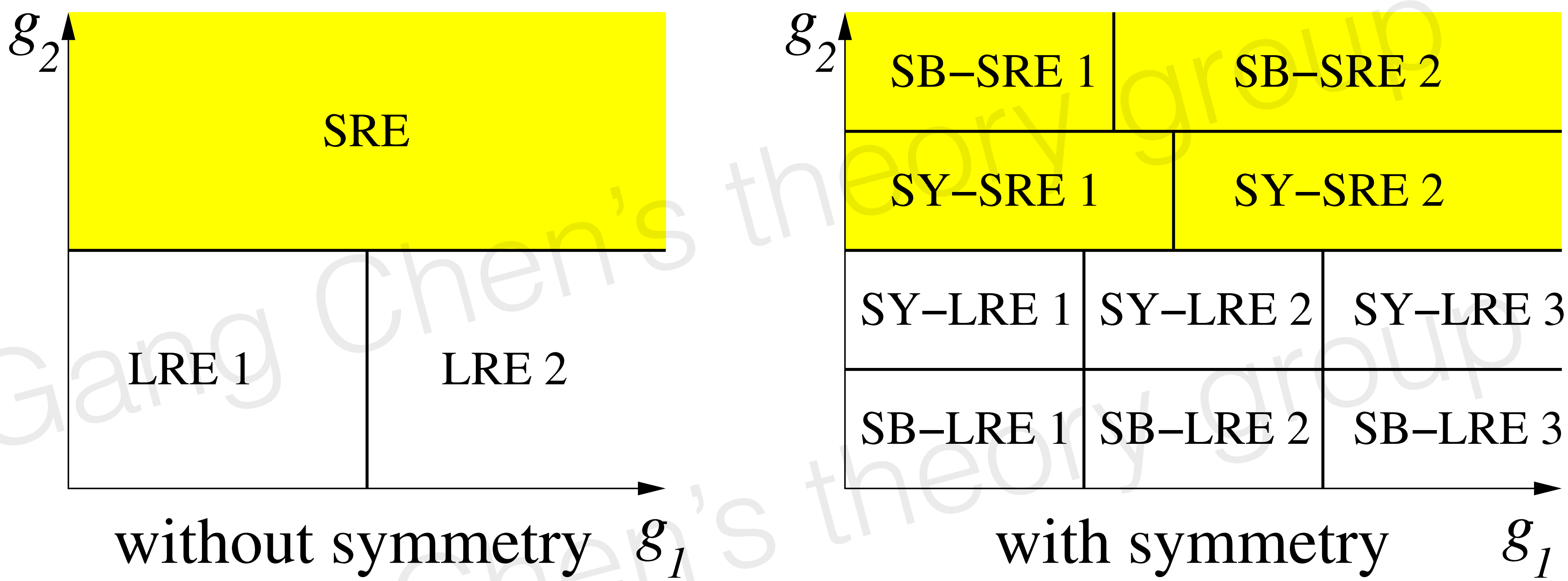


Condensed matter is full of emergence

Gang Chen's theory group

Xiao-Gang Wen

Wen’s universal phase diagram for symmetry and topology



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

Intrinsic topological order has long range entanglement (LRE).

the interplay betwe
great discovery of
symmetry breaking
entanglement.

For intrinsic topolo
topogolical order, t

symmetry and intri

finite step local uni

The classification c
the degree of freed
understanding how

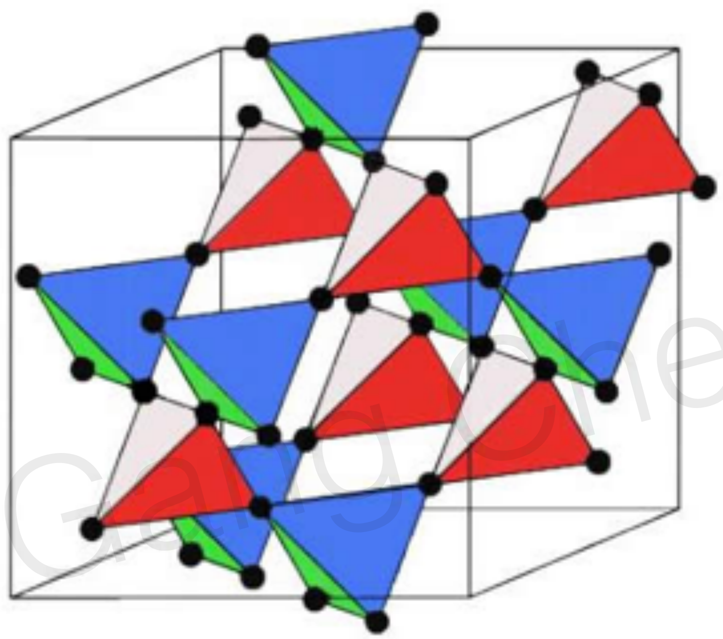
Here I will give a re

finite step local uni

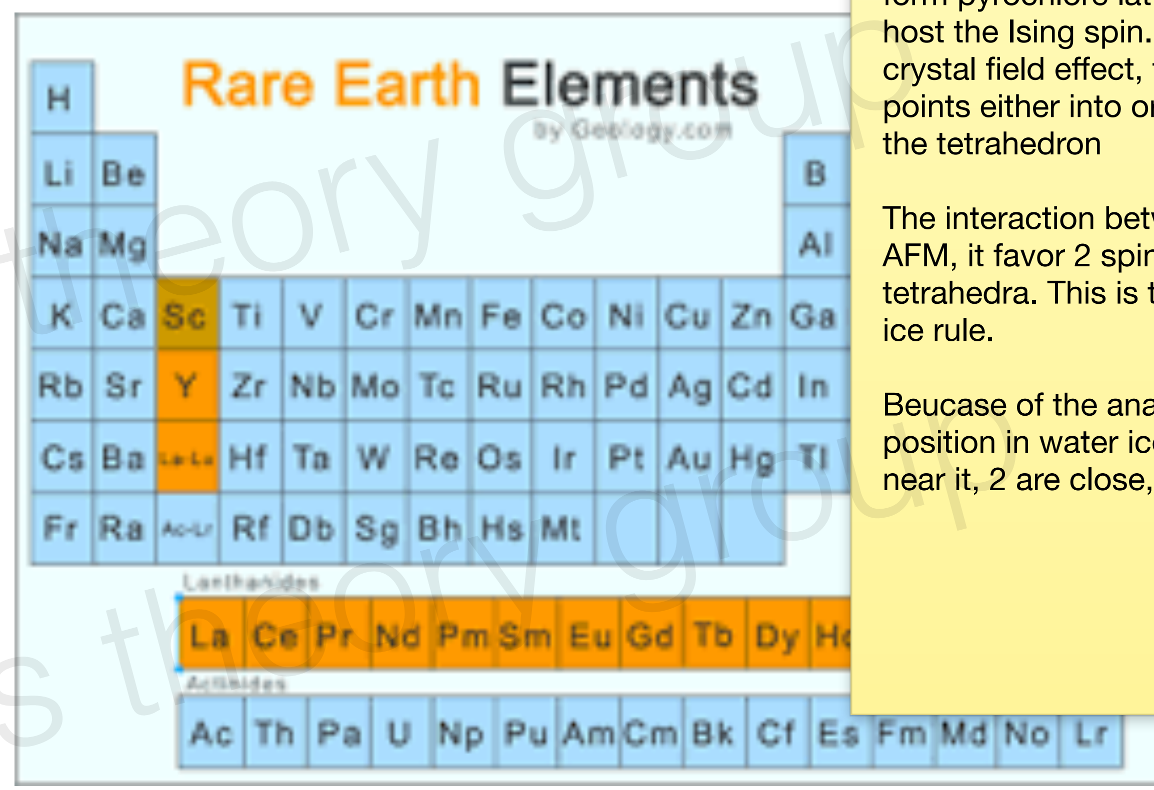
Monopole condensation out of U(1) topological order

- Introduction to spin ice, classical and quantum.
- Magnetic transition of quantum spin ice U(1) quantum spin liquid is the confinement transition of compact U(1) lattice gauge theory (or compact quantum electrodynamics)
- Monopole condensation and proximate phases

Spin ice in rare-earth pyrochlores



$RE_2M_2O_7$



OVer years, there are a lot of activity in spin ice system.

spin ice is realized in rare earth pyrochlore systems, where the rare earth ions
form pyrochlore lattice and
host the Ising spin. because of the crystal field effect, the ising spin points either into or out of the center of the tetrahedron

The interaction between the ising is AFM, it favor 2 spin in 2 spin out of the tetrahedra. This is the 2-in 2-out spin ice rule.

Beucase of the analog relation with H position in water ice, each O has 4 H near it, 2 are close, 2 are further.

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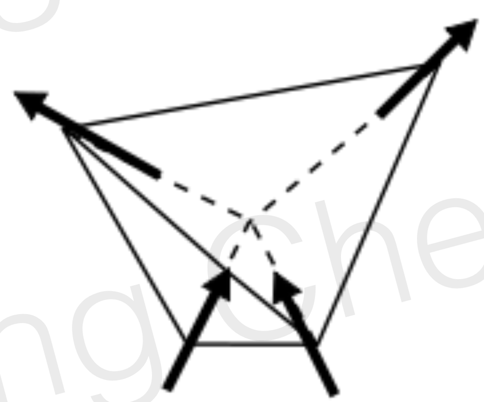
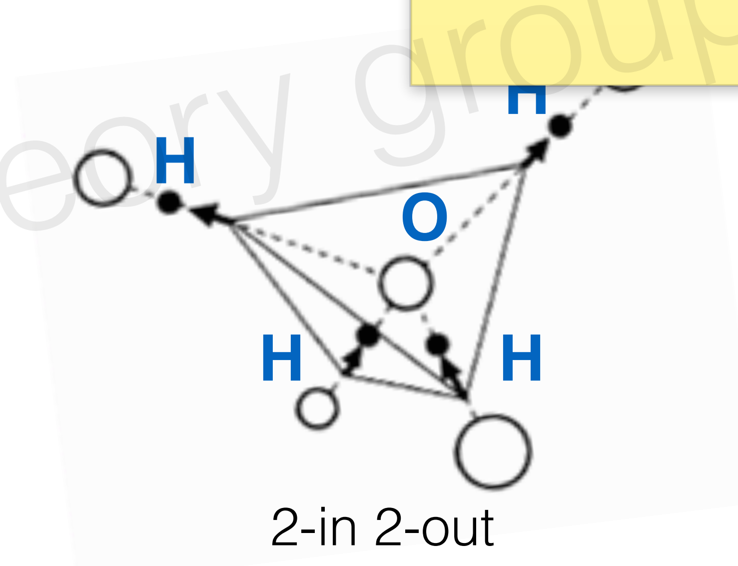
$$H = J_{zz} \sum_{\langle i,j \rangle} S_i^z S_j^z + \text{dipolar}$$

Castelnovo, Gingras, Moessner, Sondhi, Schiff
Penc, …….



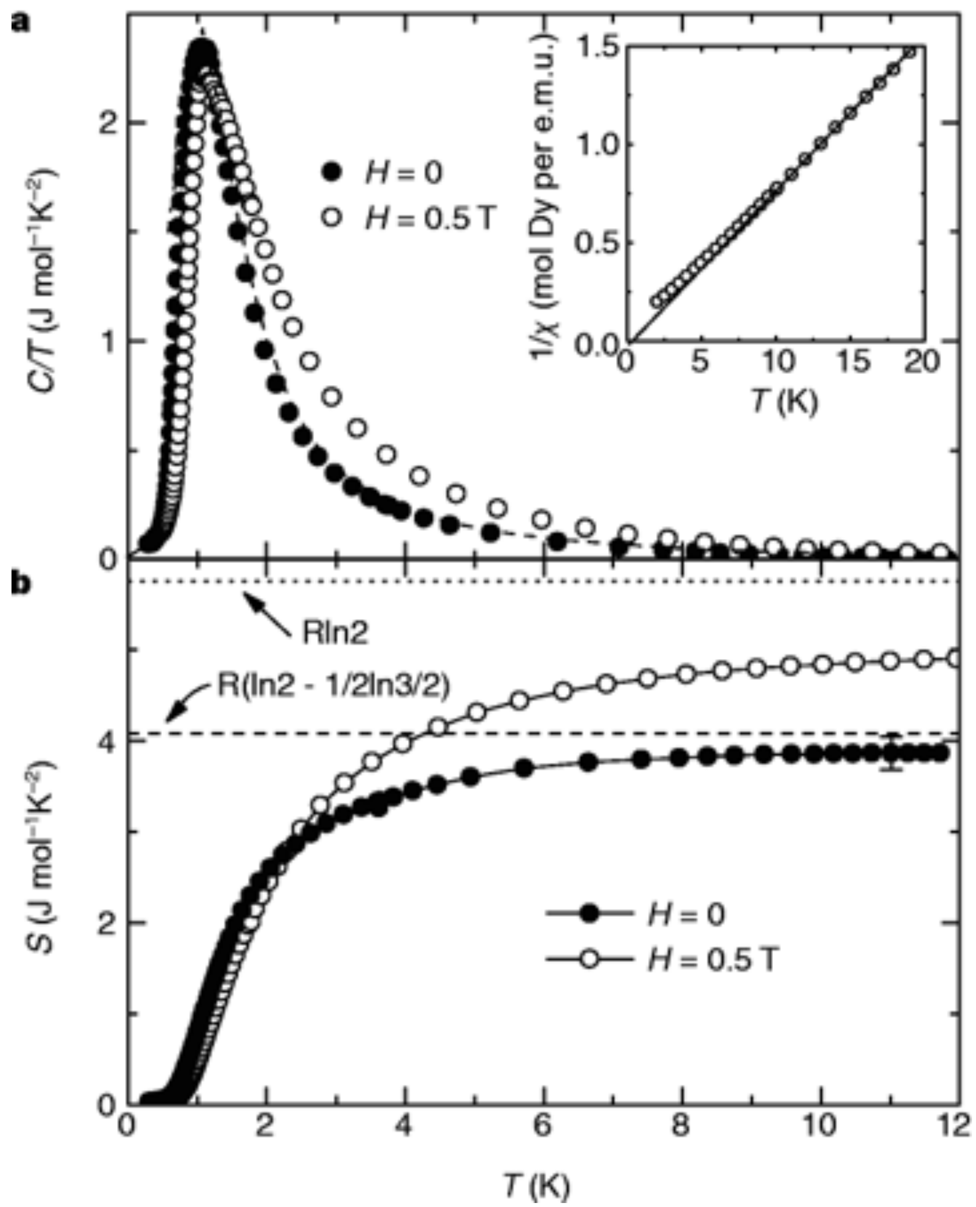
2-in 2-out
spin ice rule

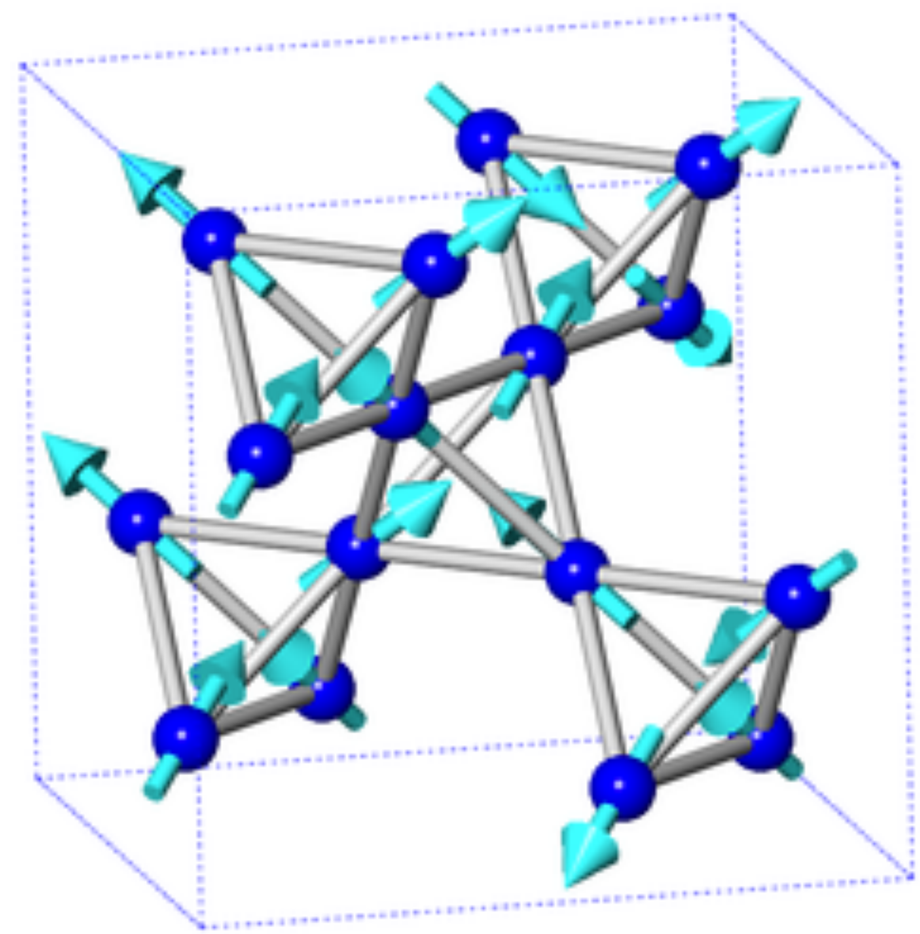


2-in 2-out
water ice rule

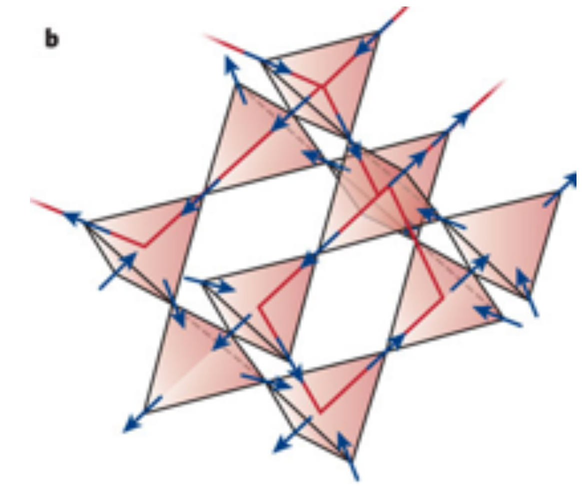
from wiki

Classical spin ice



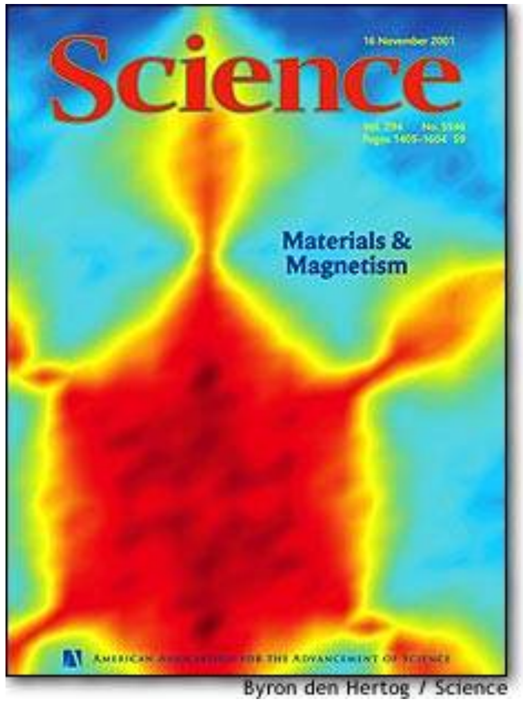


Pauling entropy in spin ice,
Ramirez, etc, Science 1999



Classical spin ice

- The "2-in 2-out" states are extensively degenerate.
- At T < Jzz, the system **thermally** fluctuates within the ice manifold, leading to classical spin ice and interesting experimental discoveries.



Pinch points in spin correlation

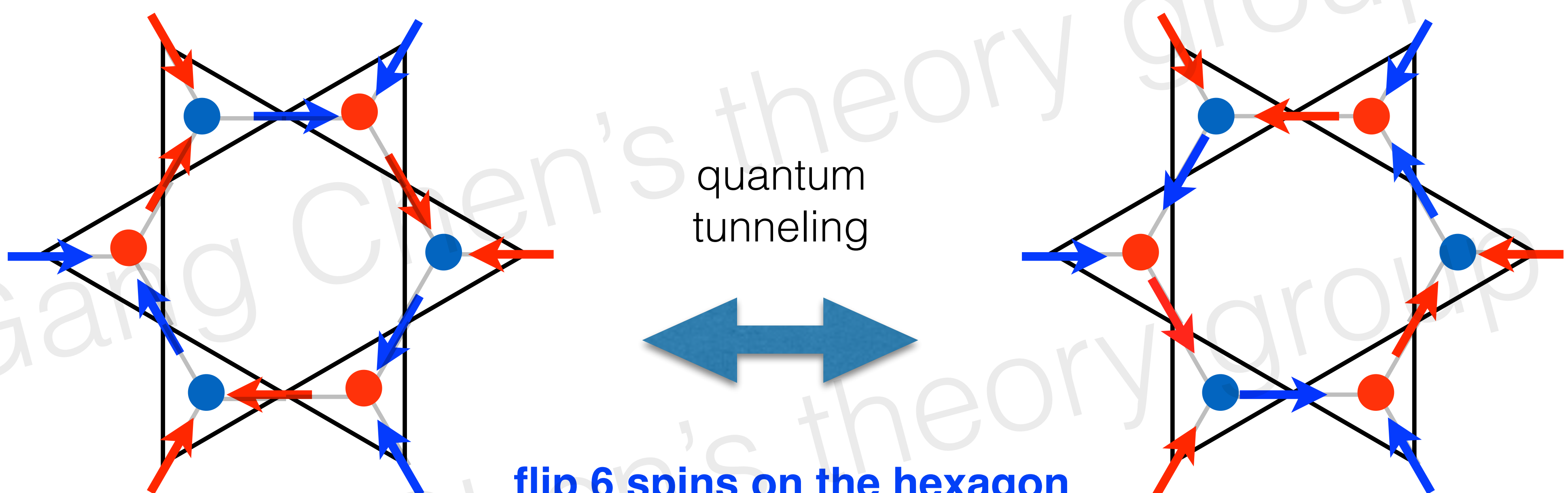
1. the 2-in 2-out spin ice is act
extensively degenerate. On
tetrahedron, one can choos
the other 2-out.

2. at T << Jzz, the system is th
fluctuating within the ice manif
classical spin ice and interestin
consequences. Many of them w
in nature and science.

Quantum fluctuation can leads to U(1) QSL

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

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



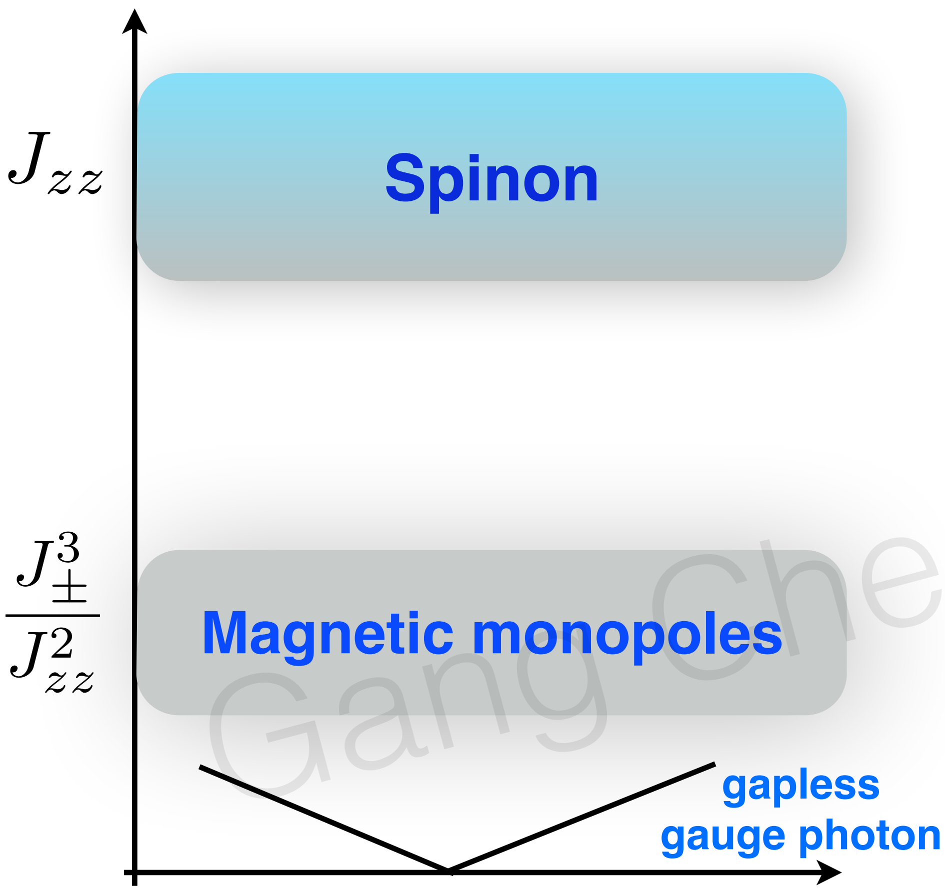
flip 6 spins on the hexagon
or
Ring exchange

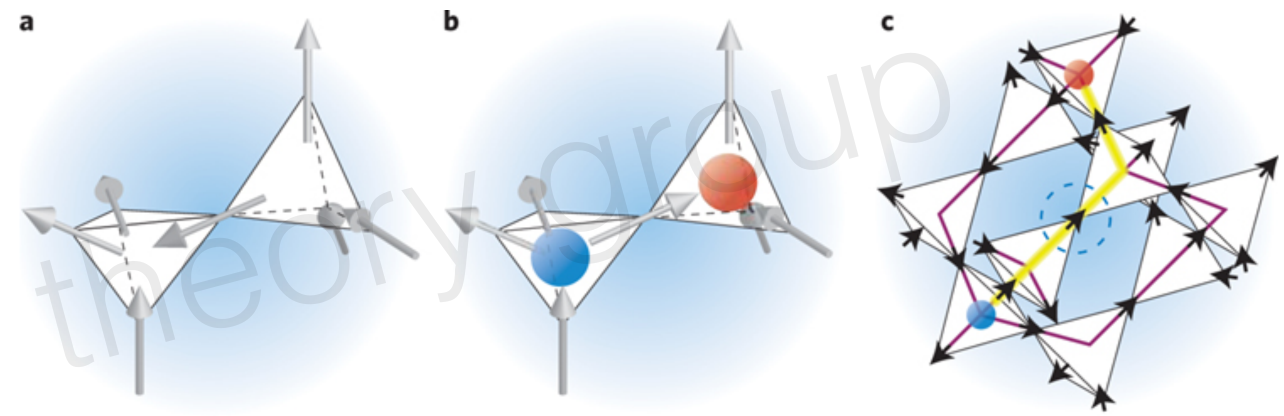
- Pretty much one can add any term to create **quantum** tunneling, as long as it is not too large to induce magnetic order, the **ground state** is a quantum spin ice !

1. But classical spin ice is purely classical and is not a new phase o matter. It is smoothly connected to high temperature paramagnetic ph

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

U(1) QSL is NOT a Landau symmetry breaking phase





Figs from Moessner&Schiffer,2009

Spinon deconfinement

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

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as quantum spin ice is a disordered state,
there is no long range order, no symmeetry b
a new phase of matter and cannot be unders
in the landau's paradigm of symmetry breakir

Important question: Has 3D U(1) QSL been realized in experiments,

or realized in the context of spin ice?

What would be the experimental evidence?

one may wonder if qsi exist in some physical system.

The answer is probably.

one can write a realistic hamiltonain and show, (even prove) the ground state should be quantum spin ice.

the real difficulty is to confirm it experimentally.

because it does not have LRO, unlike trivial order phase, it is very difficult to confirm it.

TO cofnirm it ,one should observe either deconfined spinons or emergent gpless

Realistic models

- Kramers' doublet

$$H = \sum_{\langle ij\rangle}\{J_{zz}\mathsf{S}_i^z\mathsf{S}_j^z - J_{\pm}(\mathsf{S}_i^+\mathsf{S}_j^- + \mathsf{S}_i^-\mathsf{S}_j^+) + J_{\pm\pm}(\gamma_{ij}\mathsf{S}_i^+\mathsf{S}_j^+ + \gamma_{ij}^*\mathsf{S}_i^-\mathsf{S}_j^-) + J_{z\pm}[\mathsf{S}_i^z(\zeta_{ij}\mathsf{S}_j^+ + \zeta_{ij}^*\mathsf{S}_j^-) + i \leftrightarrow j]\},$$

S. H. Curnoe, PRB (2008).

Savary, Balents, PRL 2012

- Non-Kramers' doublet

$$H = \sum_{\langle ij\rangle}\{J_{zz}\mathsf{S}_i^z\mathsf{S}_j^z - J_{\pm}(\mathsf{S}_i^+\mathsf{S}_j^- + \mathsf{S}_i^-\mathsf{S}_j^+) + J_{\pm\pm}(\gamma_{ij}\mathsf{S}_i^+\mathsf{S}_j^+ + \gamma_{ij}^*\mathsf{S}_i^-\mathsf{S}_j^-)$$

S. Onoda, etc, 2009

SB Lee, Onoda, Balents, 2012

- Dipole-octupole doublet

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

Y-P Huang, **Gang Chen**, M Hermele, PRL 2014

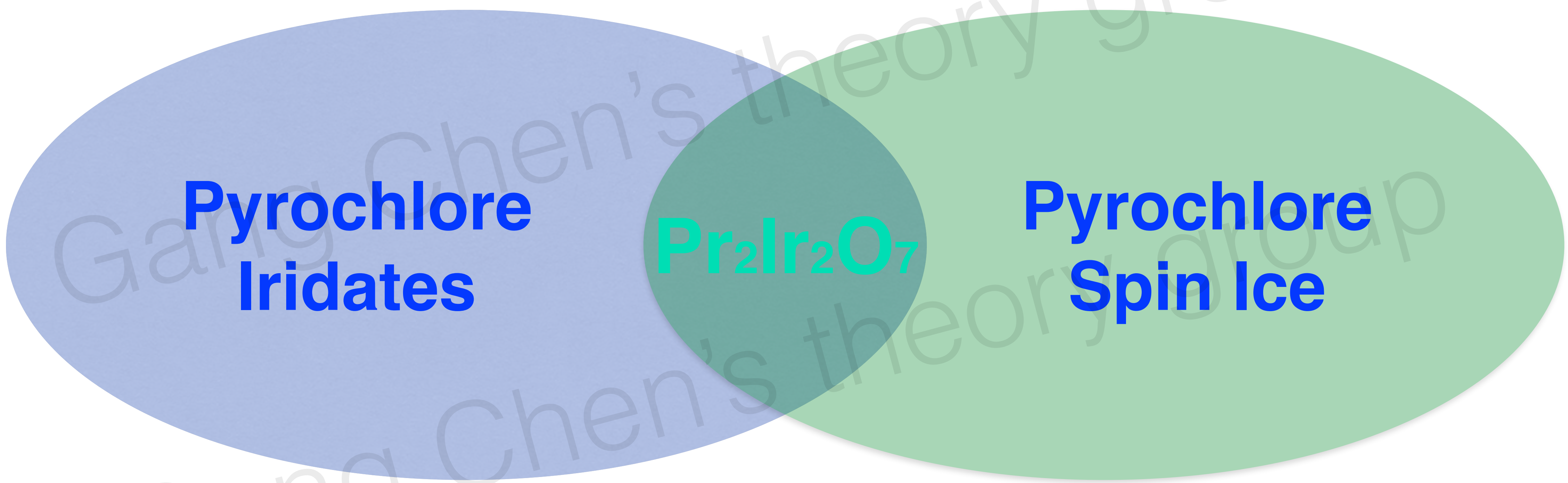
Yaodong Li, **Gang Chen,** Arxiv 1607

$Nd_2Ir_2O_7$, $Nd_2Sn_2O_7$, $Nd_2Zr_2O_7$, $Ce_2Sn_2O_7$, etc

no sign problem for QMC on any lattice.

It supports nontrivial phase like quantum spin ice U(1) quantum spin liquid.

Pyrochlore Iridate and Pyrochlore Spin Ice

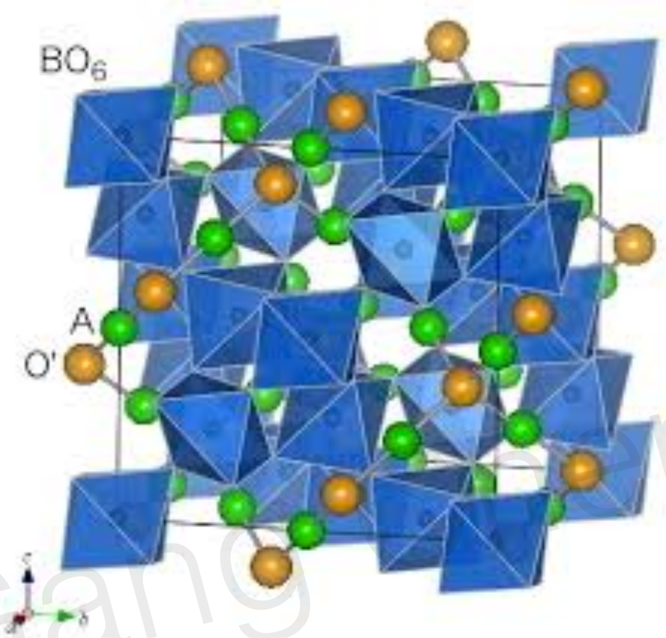


Pyrochlore iridates: $Pr_2Ir_2O_7$

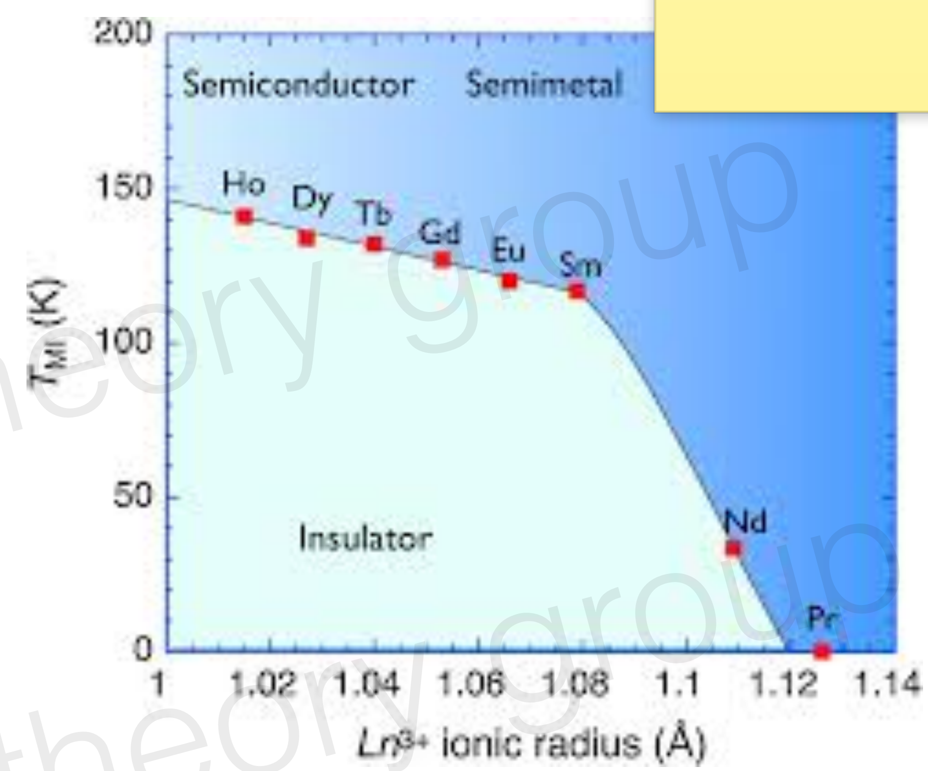
Over the years, there are a lot of effort in pyro
in this family of materials, almost all of them e
insulator xtion with some magnetic order, exc

Pr2Ir2O7 is unique, it remains metallic, and so

most of the work in the field focus on the iridiu
discuss local moment physics.



$R_2Ir_2O_7$

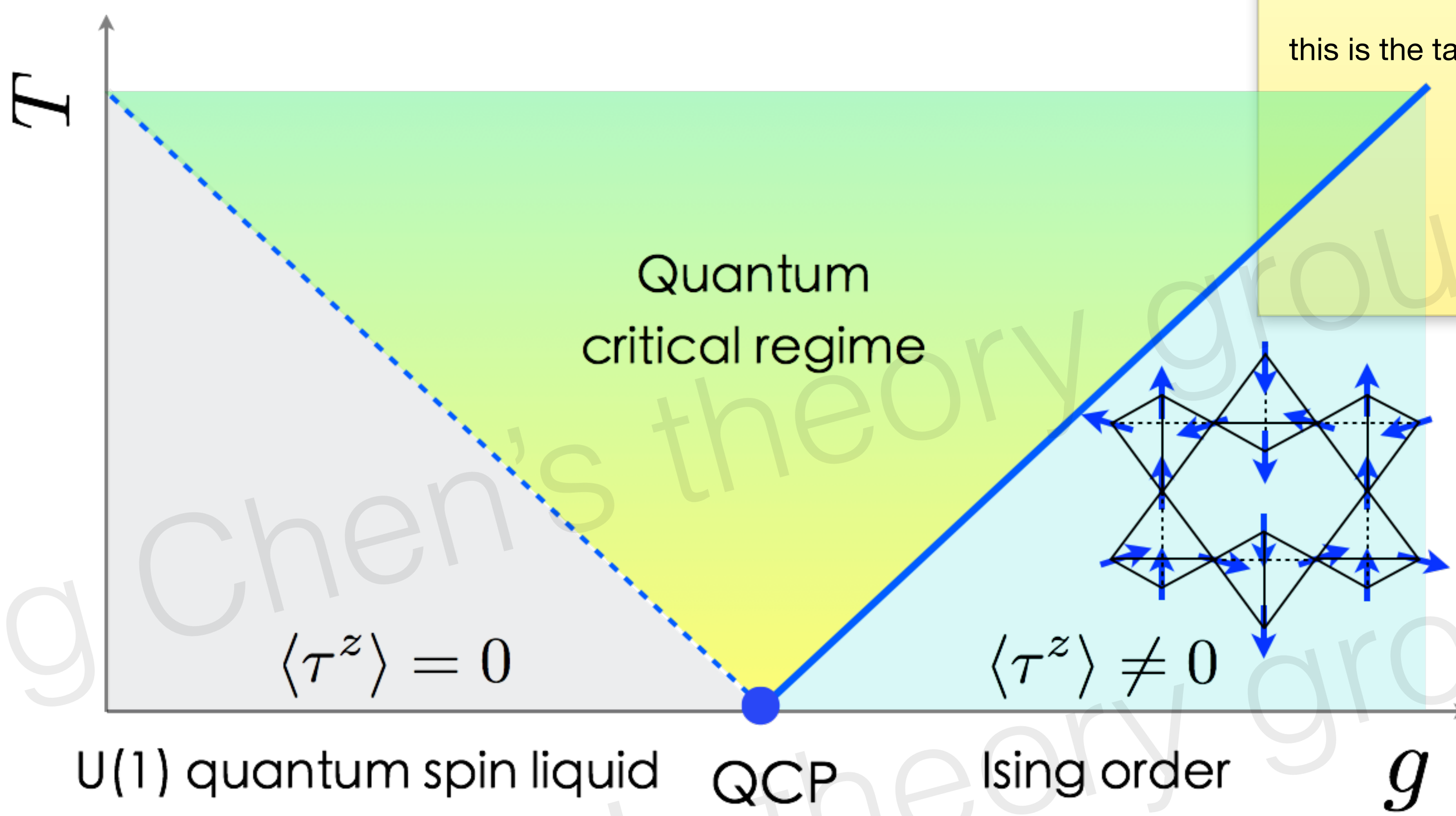


K Matsuhira, M Wakeshima, Y Hinatsu, S. Takagi
JPSJ, 2011

Many nice experimental works by S Nakatsuji, P Gegenwart, L Balicas, etc

Ref: D Pesin, L Balents, 2009, Xian-Gang Wan, etc 2010, Witczak-Krempa, Yong Baek Kim, SungBin Lee; Michael Hermele, Gang Chen, etc

My proposal for $Pr_2Ir_2O_{7\text{-delta}}$

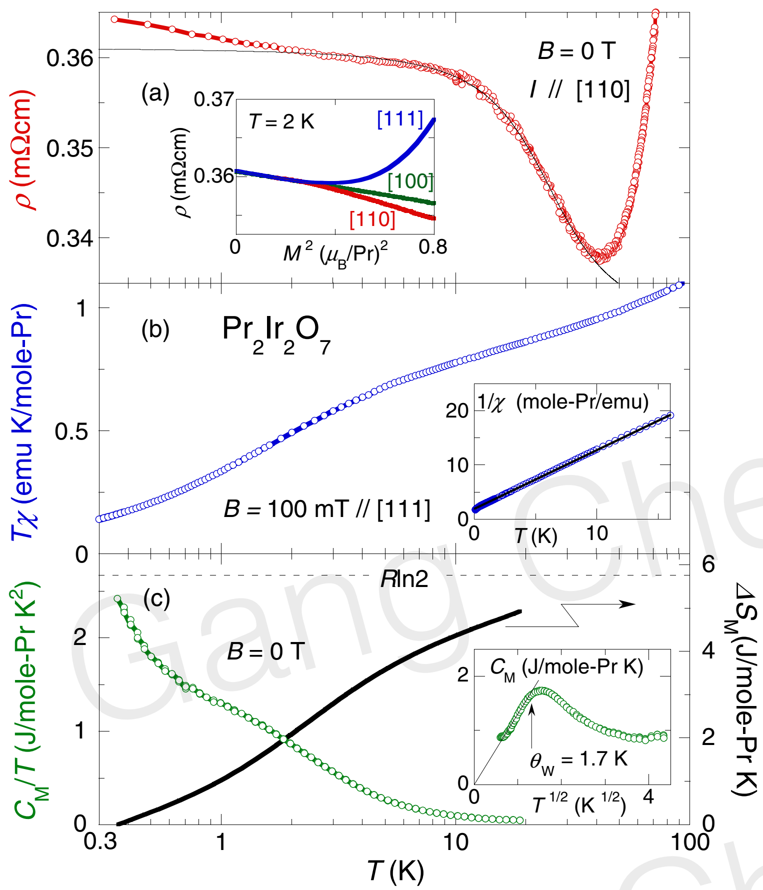


this is the take home message.

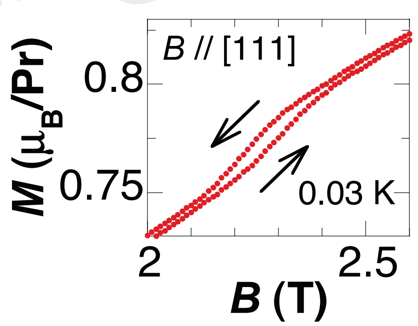
Pr local moments are close to a "magnetic" monopole condensation transition from quantum spin ice quantum spin liquid to an AFM long-range ordered state.

The Ir conduction electrons may drive the transition, but do not influence the nature of the phase transition.

$Pr_2Ir_2O_7$ a featureless disordered state near an ordered state

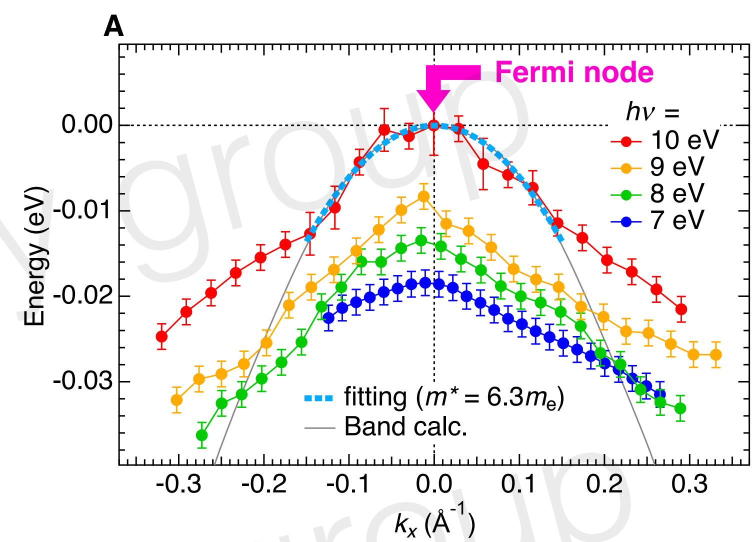


Nakatsuji, etc
PRL **96,** 087204 (2006)



metamagnetic transition

ARPES: quadratic band touching of Ir 5d electrons



Valence band approaches the Fermi energy at few meV resolution

T Kondo, S Shin, etc 2014
B J Yang, Yong Baek Kim 2011
E G Moon, CK Xu, Y B Kim, L Balents, 2013

Expts are **sample dependent**,
Recently, some samples are found AFM ordered.

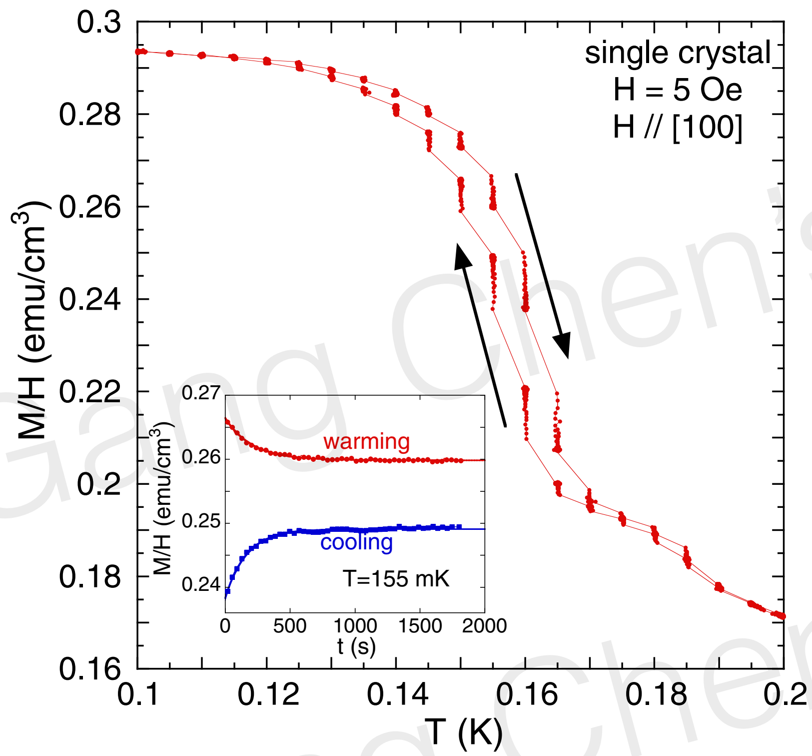
Yaodong Li, Gang Chen
in **preparation 2017**

Experiments: a featureless state near an ordered state

PHYSICAL REVIEW B **89**, 224419 (2014)

First-order magnetic transition in $Yb_2Ti_2O_7$

E. Lhotel,[1,*] S. R. Giblin,[2] M. R. Lees,[3] G. Balakrishnan,[3] L. J. Chang,[4] and Y. Yasui[5]



PHYSICAL REVIEW X 1, 021002 (2011)

Quantum Excitations in Quantum Spin Ice

Kate A. Ross,[1] Lucile Savary,[2] Bruce D. Gaulin,[1,3,4] and Leon Balents[5,*]

waves [14]. Although one neutron study [15] supported ferromagnetic order in $Yb_2Ti_2O_7$, intriguingly, the majority of neutron scattering measurements have reported a lack of magnetic ordering and the absence of spin waves at low fields in this material [16–18]. In a recent study,

Some samples have FM LRO with 1st transition. Some samples do not have order.

this slide should be quick.

antoher system is purely local m
also some sample order
soem sample do not order

but order ferromagneically .

Summary of experimental results

this is a summary of the messy experiments.

the system is probably near some transition between a featureless disordered state and magnetic ordered state.

and the tuning parameter can be cheical pressure, oxyten content.

improtant questions are

what is
phase is more importatnt tha nphase transiton.

disordred state is hard to characterize.

phase tarnsition is more visible in epeirmtnes,

magnetic order is easy to dtect in experimetns.

One can use proximate phase and phase transiton

emical pressure,
gen content ……

- What is the structure of the m
- What is the relationship betwe   red state and various magnetic st
- What is the nature of the featu   Is it **QSI**?

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Insight from high-Tc superconductors

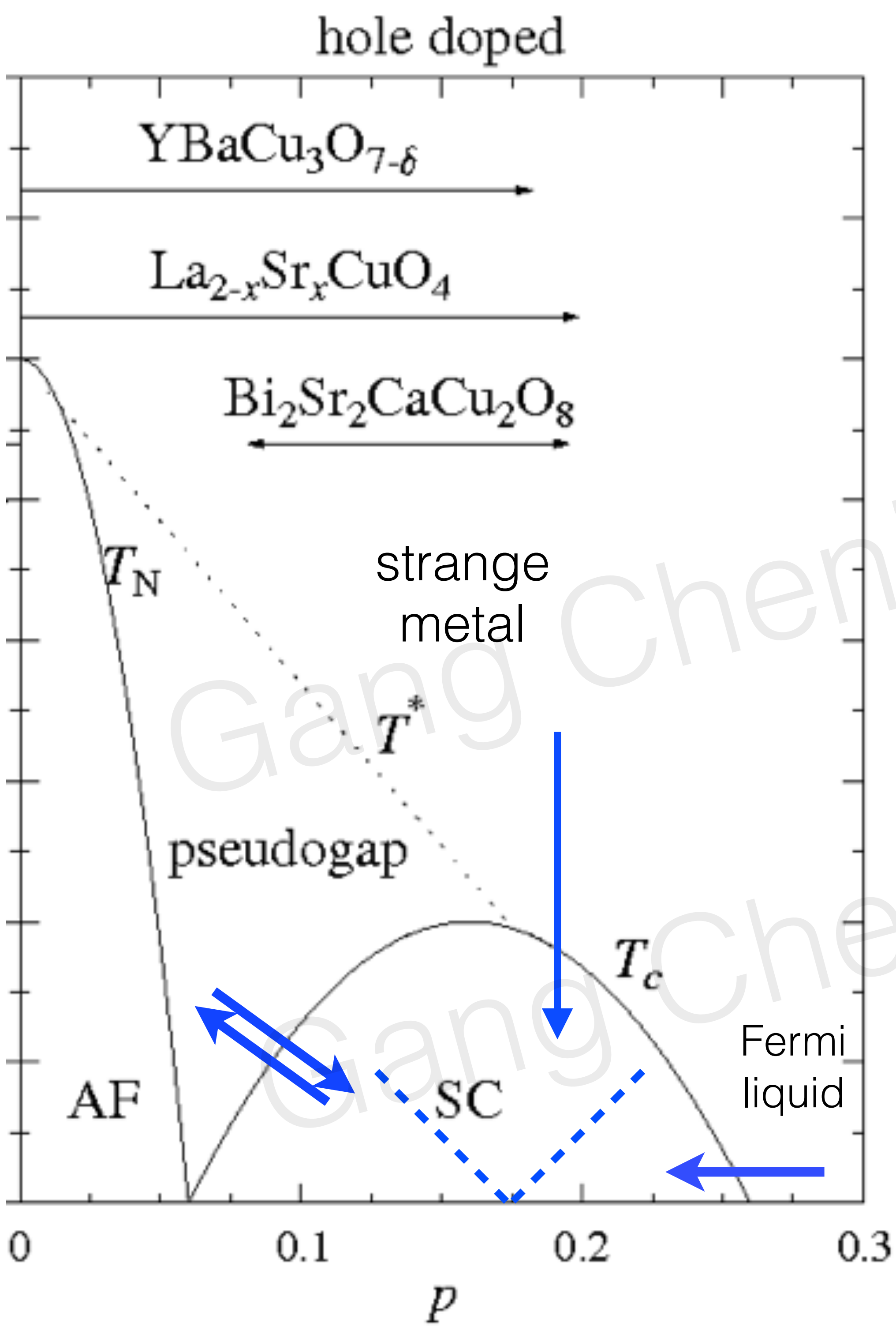
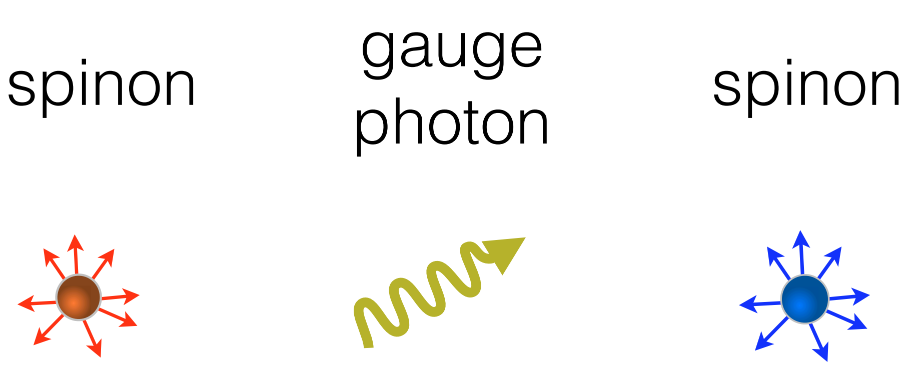


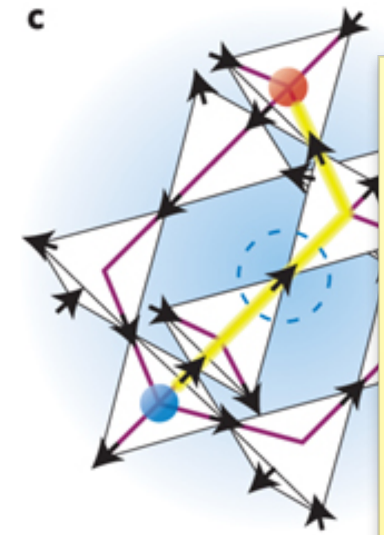
Figure from wiki

One important question is to understand the relationship between different phases (and/or orders)

1. Perturbative treatment (not interesting): instability of Fermi liquid;
2. Attack from top: instability of non-Fermi liquid;
3. Attack from Left, attack from Right: what is PG (Z2 topological order?) ? (Senthil, Balents, Nayak, Fisher 2000-2002);
4. Attack from bottom: some quantum criticality under the SC dome?

Confinement transition out of U(1) quantum spin liquid





I want to porpose that the disordere
quantum spin liquid. and the manget
to ordered side is a confinemnent tra

in quntum spin ice, spinon are decon

in ordered pahse when tau_z is non
separate two spinous, isince tau is s
necessary effect the tau_z along the
end it has a energy cost that grow l
separtin.

$\langle \tau^z \rangle = 0$

$\langle \tau^z \rangle \neq 0$

featureless disordered state
= quantum spin ice spin liquid

Ising ord

Spinons are deconfined.

Spinons are confined !

More generally, for **non-Kramers' doublet**, the magnetic transition out of U(1) QSL **MUST** be a confinement transition, this may apply to Tb2Ti2O7.

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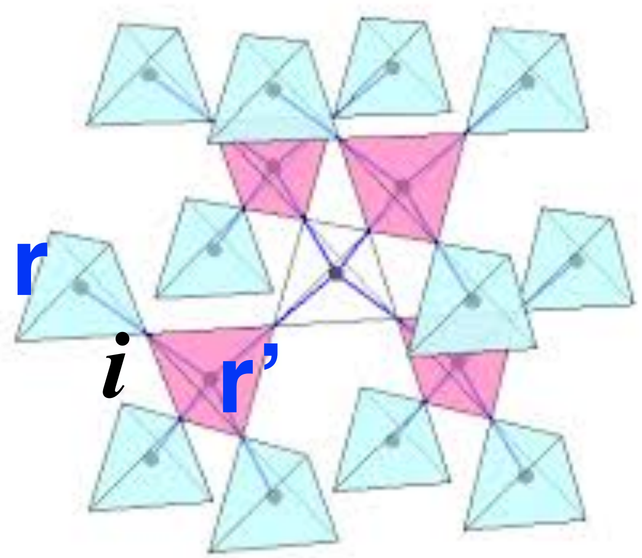
Lattice gauge theory formalism: technic



$$E_{\mathbf{rr'}} \sim \tau_i^z, e^{iA_{\mathbf{rr'}}} \sim \tau_i^+$$

Hermele, F

$$H_{\text{ring}} = -\sum_{\hexagon_p} \frac{K}{2}(\tau_1^+\tau_2^-\tau_3^+\tau_4^-\tau_5^+\tau_6^- + h.c.),$$

$$H_{\text{LGT}} = \sum_{\langle \mathbf{rr'} \rangle} \frac{U}{2}(E_{\mathbf{rr'}} - \frac{\epsilon_{\mathbf{r}}}{2})^2 - \sum_{\hexagon_d} K \cos(curl\ A),$$

H_{LGT} captures the **universal properties** of (

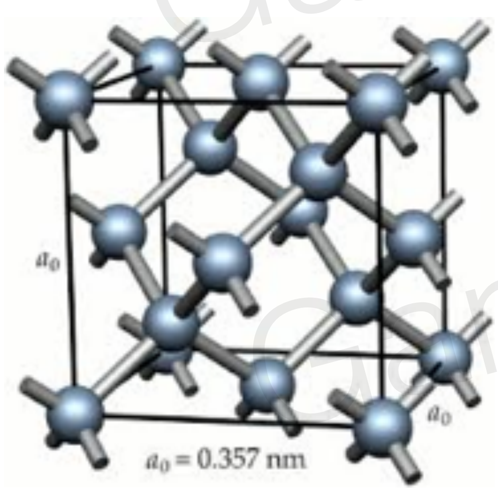
in the lattice gauge theory formulation, the sz component is mapped to he lattice electric field, while S+ ,S- is mapped to vector gauge potnential.

the system is described by a lattice gauge theory on the diamond lattice formed by the center of the pyrochlore

in a ordereed staet, Sz !=0 from heisnbeg relation, S+ is strong fluting

IN the gauge langue, in a ordered state, E is static, is storng fluting, the magnetic mono is concedes, which confined the electric charge.

the background monopole condensate disrupts the free motion of the spinons, the spinons are confined.



diamond lattice

- In an ordered state, <tau_z>!=0, <tau^+> is strongly fluctuating.
- In the gauge language, "**E field**" is static, "**B magnetic field**" is strongly fluctuating, the magnetic monopole (carrying magnetic charge) is condensed, which confines the electric charge carriers (spinons).

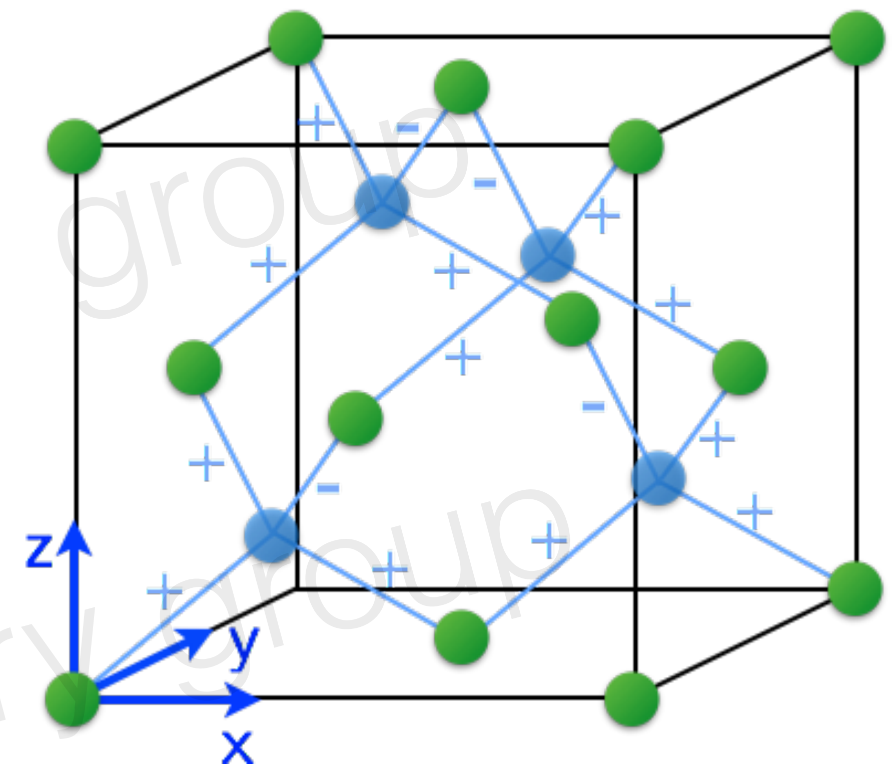
nt and the
on.

s-vortex duality.

Electromagnetic duality

Monopole lives on dual diamond lattice, carry magnetic charge or dual U(1) gauge charge.

$$H_{\text{dual}} = \sum_{\hexagon_d^*} \frac{U}{2}(curl\, a - \bar{E})^2 - \sum_{\mathbf{r},\mathbf{r}'} K \cos B_{\mathbf{r}\mathbf{r}'} - \sum_{\mathbf{r},\mathbf{r}'} t \cos(\theta_{\mathbf{r}} - \theta_{\mathbf{r}'} + 2\pi a_{\mathbf{r}\mathbf{r}'}).$$



Motrunich, Senthil 2005,
Bergman, Fiete, Balents 2006

monopole hopping on
dual lattice

Proximate magnetic order generically
breaks translation symmetry

this is a bit technical.

I will explain by analogy

Implication for experiments

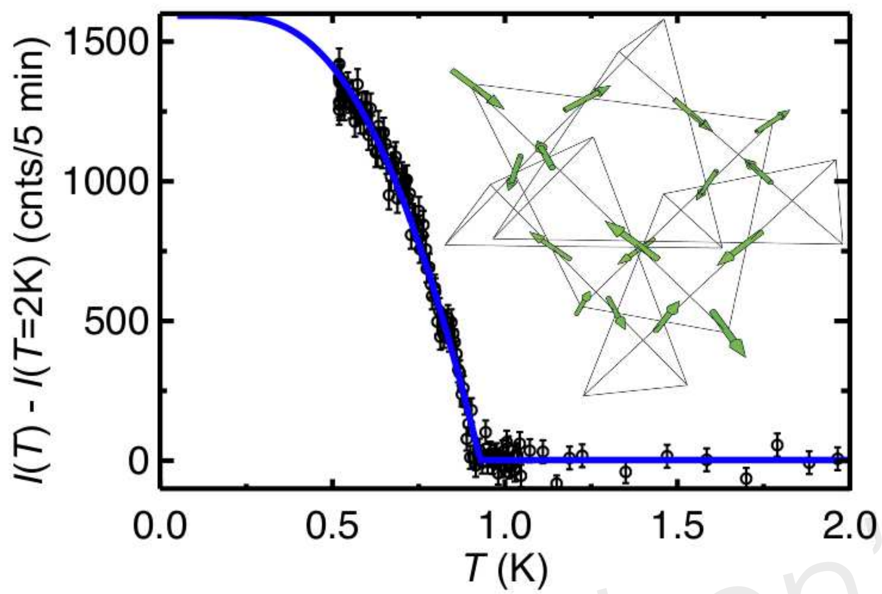


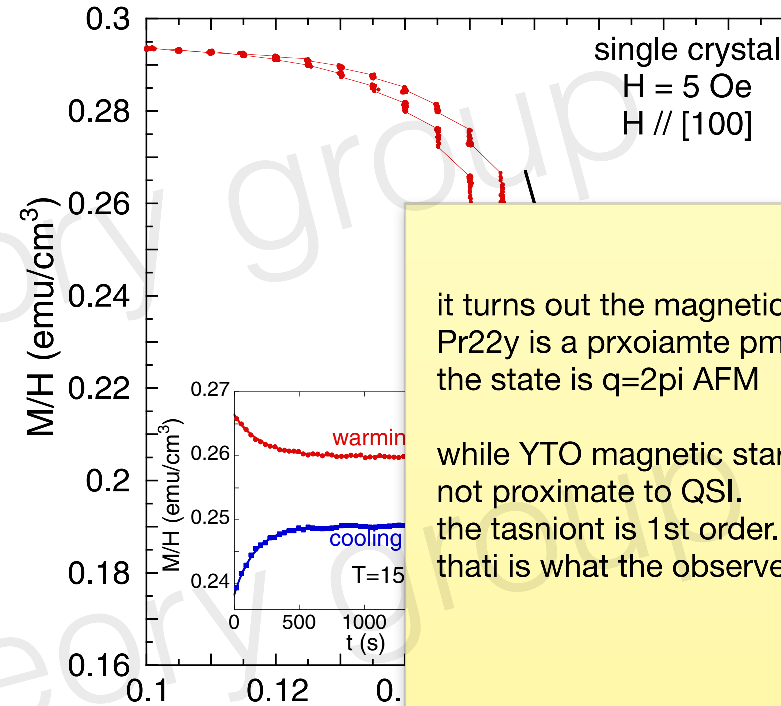
FIG. 2. (color online) Temperature dependence of elastic neutron scattering intensity of $Pr_{2+x}Ir_{2-x}O_{7-\delta}$ at the position of the $\mathbf{q}_m = (100)$ reflection. The intensity measured at $T = 2$ K was subtracted as a background. Curve: Ising mean-field theory fit to the data, which yields a transition temperature of $T_M = 0.93(1)$ K. Inset: sketch of the 2-in/2-out magnetic structure.

Magnetic order is discovered in some samples. (MacLaughlin, etc, 2015)

PHYSICAL REVIEW B **89**, 224419 (2014)

First-order magnetic transition in $Yb_2Ti_2O_7$

E. Lhotel,[1,*] S. R. Giblin,[2] M. R. Lees,[3] G. Balakrishnan,[3] L. J. Chang,[4] and Y. Yasui[5]



it turns out the magnetic phase is Pr22y is a prxoiamte pmagnetic order, the state is q=2pi AFM

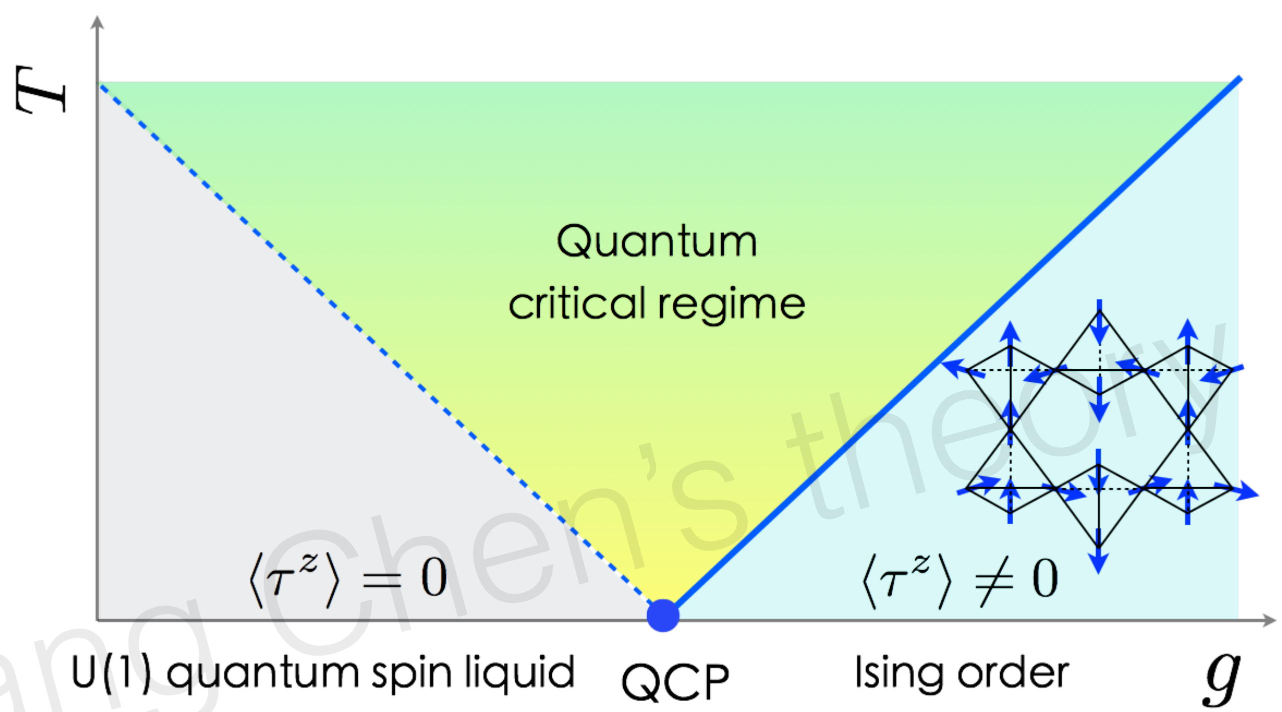
while YTO magnetic start is Q=FM is not proximate to QSI.
the tasniont is 1st order.
thati is what the observe in experiments

Yb2

PIO: different samples have different Fermi energy -> RKKY-> **magnetic order, Q= 2Pi(001)**

YTO: First order transition to **Q=0 FM state**.

Subsidiary order and weak divergence



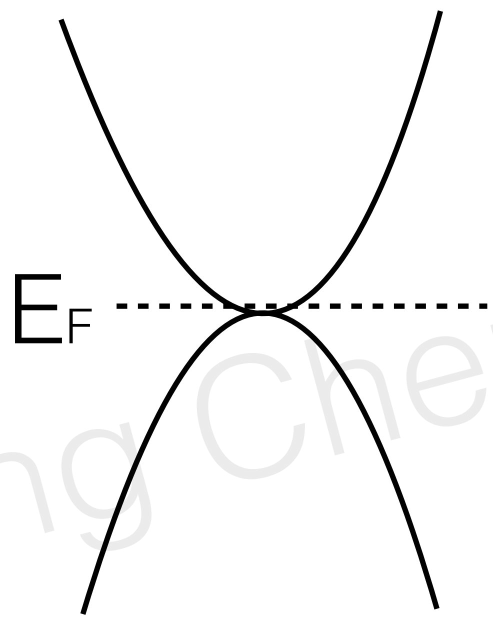
g is the mass of the monopole

$$L = \sum_a \left[|(\partial_\mu - i\tilde{a}_\mu)\phi_a|^2 + m^2 |\phi_a|^2 \right] + \frac{{F_{\mu\nu}}^2}{2} + u_0 (\sum_a |\phi_a|^2)^2 + u_1 \sum_{a \neq b} |\phi_a|^2 |\phi_b|^2 + \cdots ,$$

The critical theory is described by gapless monopoles coupled with a fluctuating U(1) gauge field in 3+1D.

a unusual weak divergence $\chi(Q) \sim -\ln T$ “subsidiary order” (Kivelson) !

More experimental prediction for $Pr_2Ir_2O_{7\text{-delta}}$



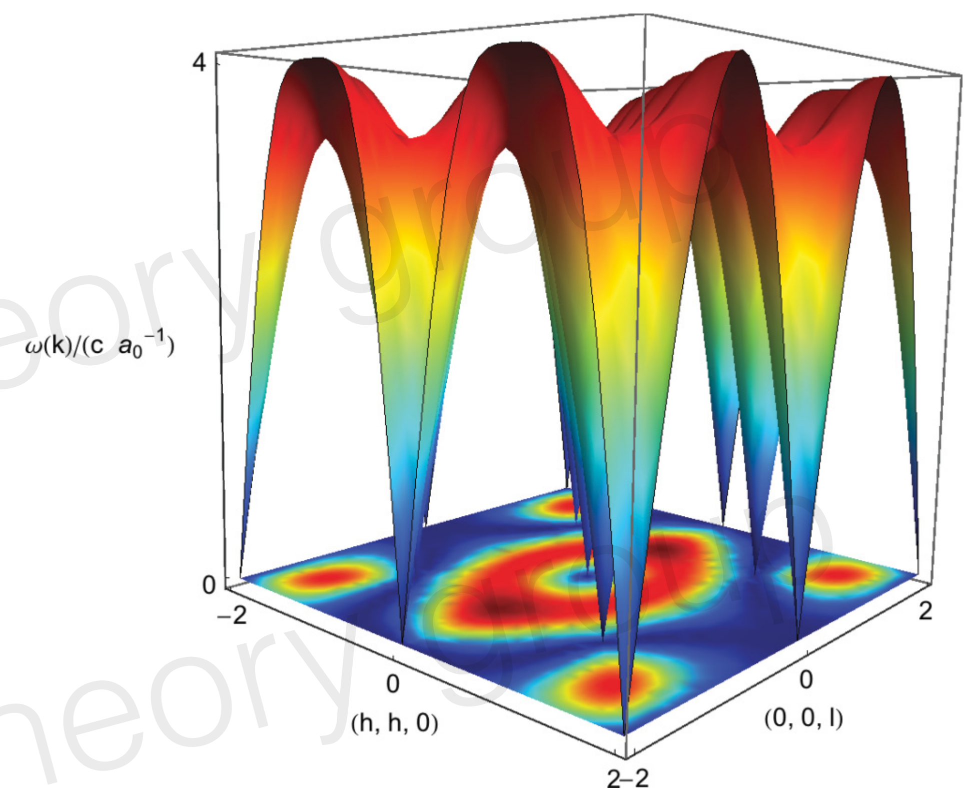


Fig from Benton, etc, PRB 2012

Particle-hole excitations are centered at **Gamma** point

Emergent gauge photons are near the **suppressed pinch points**

The energy scales are different, maybe inelastic neutron scattering can work.

Summary

- I have studied the phase diagram near quantum spin ice quantum spin liquid.

- Using field theoretic technique, I have obtained the structure of the magnetic states and the nature of the magnetic transition.

- I use the theoretical results to explain the puzzling experiments in $Pr_2Ir_2O_7$ and $Yb_2Ti_2O_7$. It implies the disordered phase is a quantum spin ice U(1) quantum spin liquid.

Ref: Gang Chen, arXiv:1602.02230, longer talk can be found at KITP website last Sep.

Work in progress: sign problem free model that demonstrates both proximate and unproximate magnetic transition out of QSI QSL.
In preparation: Yao-Dong Li and Gang Chen, conduction electrons.