Magnetic monopole condensation transition out of quantum spin ice: search for **quantum spin ice** in **pyrochlore iridates**

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currently on a visit at Perimeter Institute, Waterloo, Canada

Job opening

- **Postdocs** are generously funded and will have tremendous freedom.

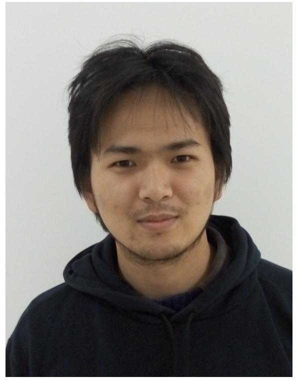
Shanghai, China

Outline

- Introduction: pyrochlore iridates and quantum spin ice
- Magnetic transition out of certain type quantum spin ice **must** be a confinement transition of compact QED
- Magnetic monopole condensation and proximate phases

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

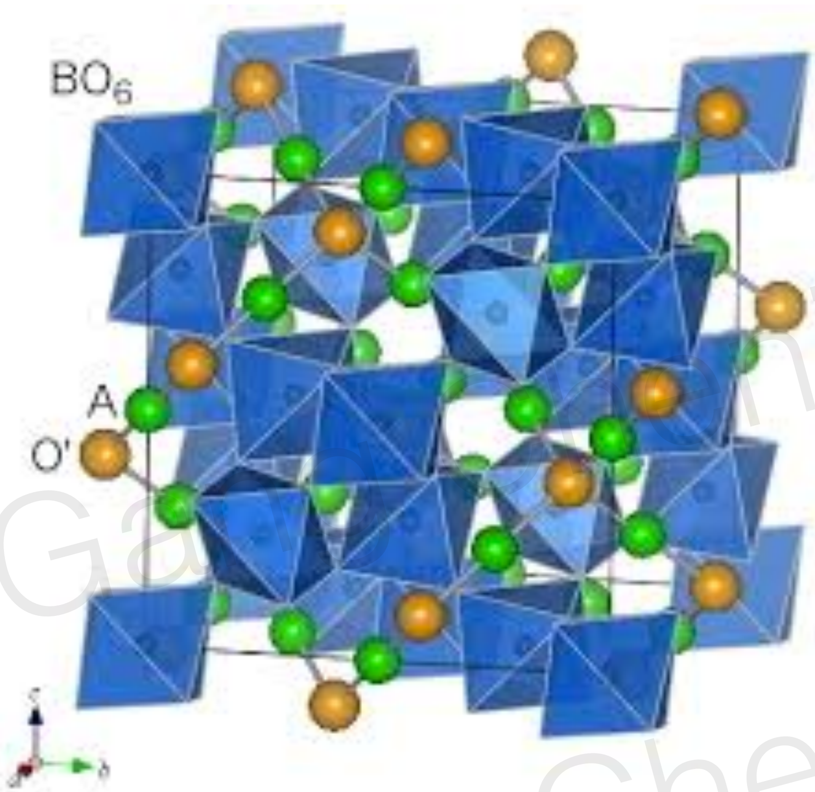
My Poster: The first odd-electron-per-cell quantum spin liquid beyond **Oshikawa-Hastings-Lieb-Shultz-Mattis** theorem.

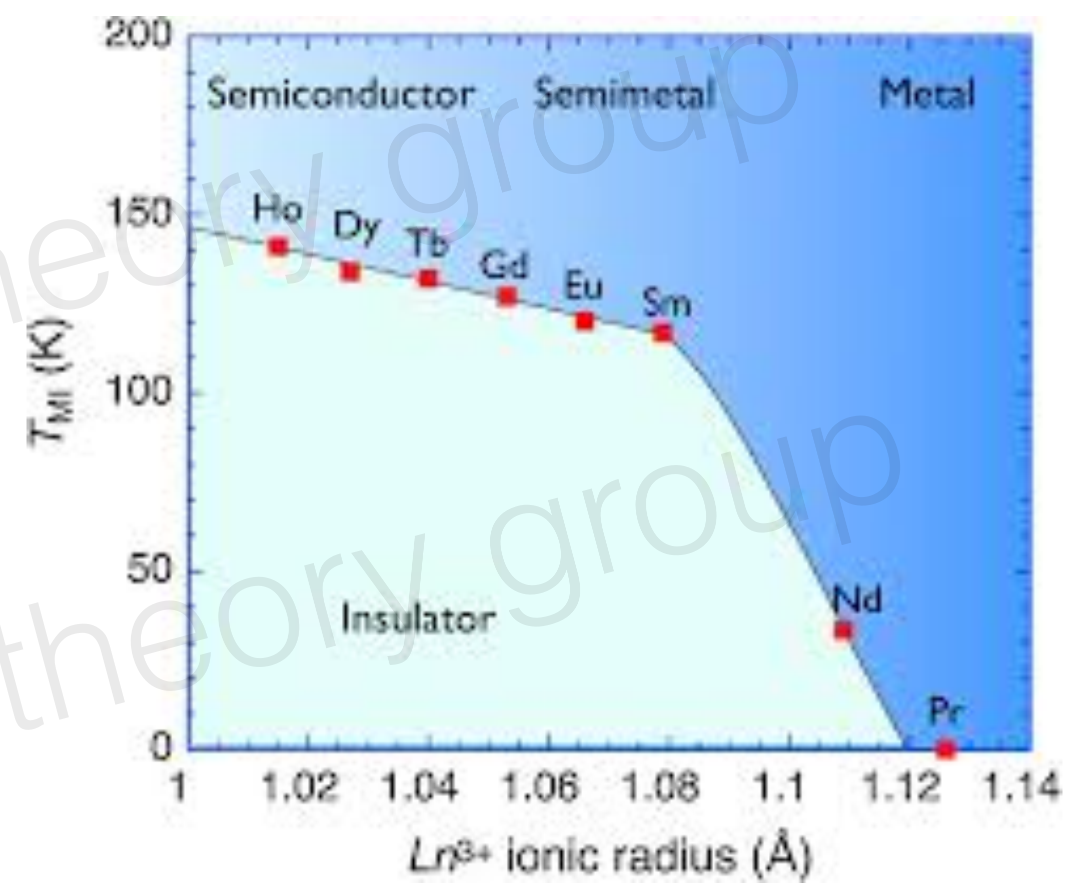


Yao-Dong Li

Gang Chen's theory group

Pyrochlore iridates



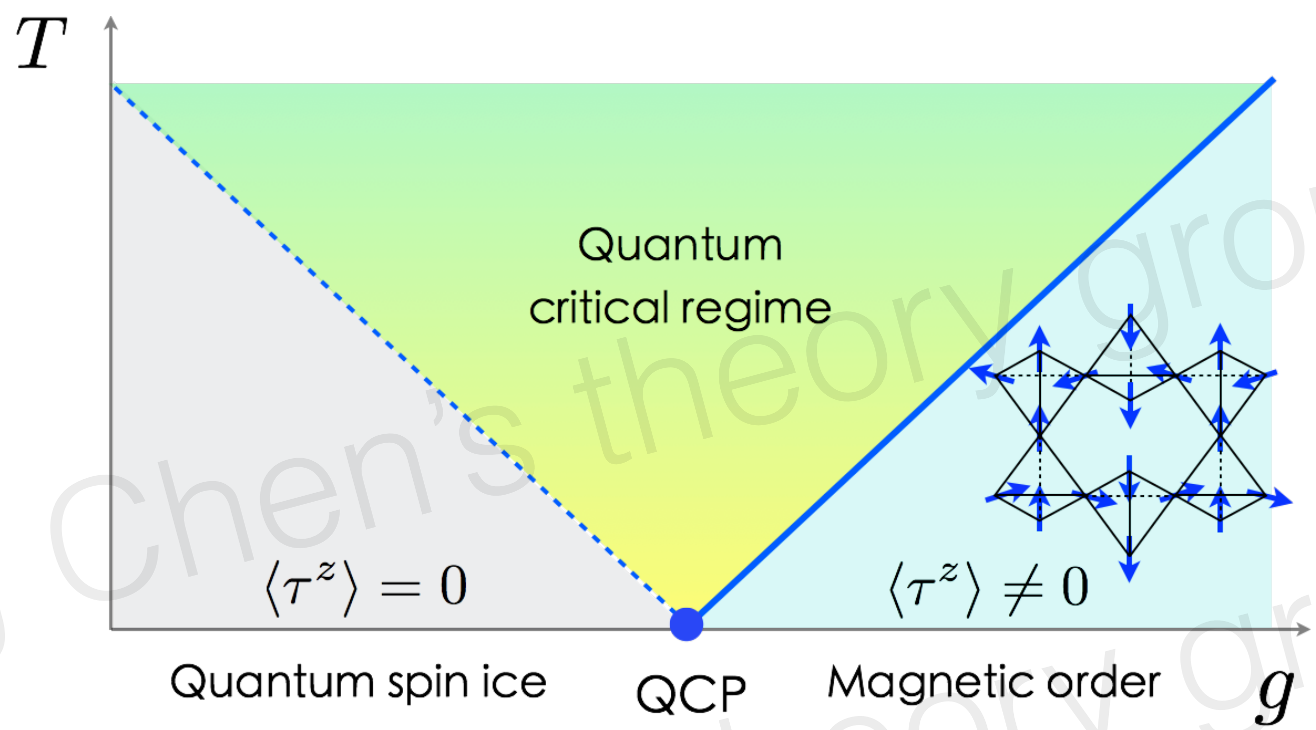


$R_2Ir_2O_7$

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

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

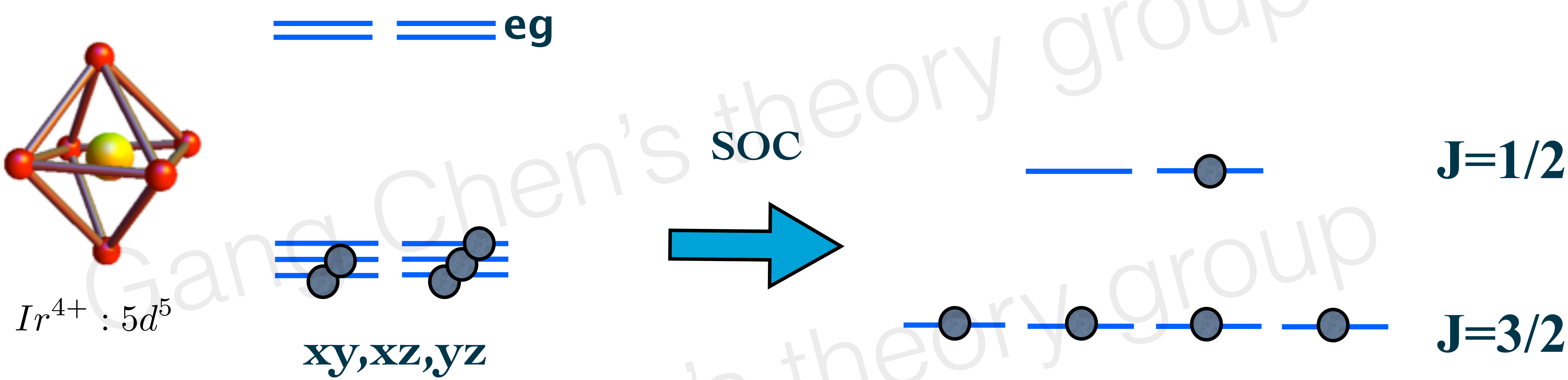
My proposal for $Pr_2Ir_2O_{7\text{-delta}}$



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

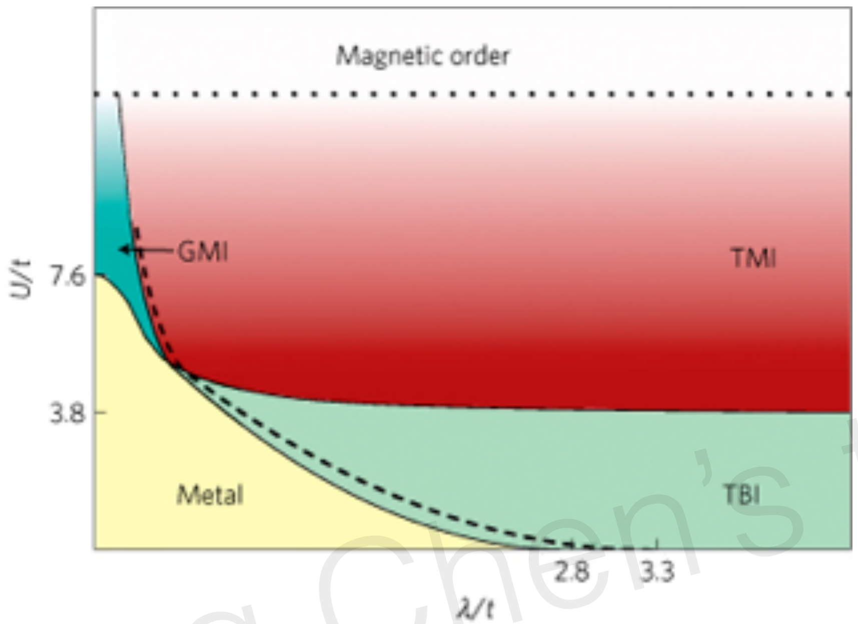
The Ir conduction electrons may drive the transition, but do not influence the nature of the phase transition.

The interplay of spin-orbit coupling and correlation in 4d/5d transition metal systems (not just iridates)

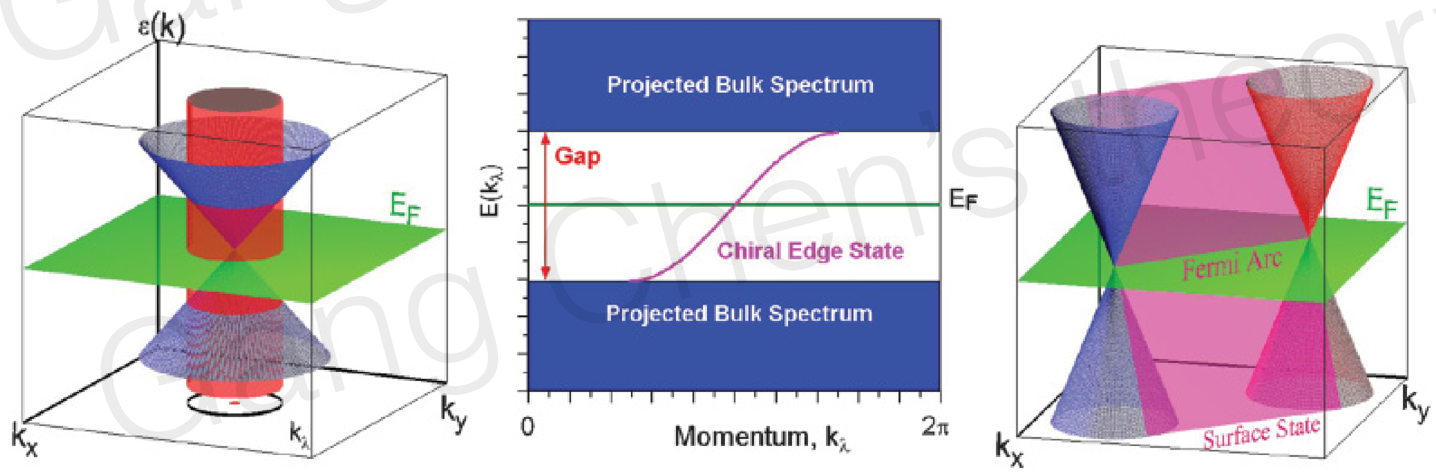


B.J. Kim, et al, 2008 **GC**, L. Balents, 2008 G Jackeli, G Khaliullin, 2009

The interplay of spin-orbit coupling and correlation



D Pesin, L Balents, July 2009



Magnetic order
induces Weyl nodes

Xiangang Wan
Nanjing University,
Nanjing, China

Xiangang Wan, A Turner,
A Vishwanath, S Savrasov,
June 2010

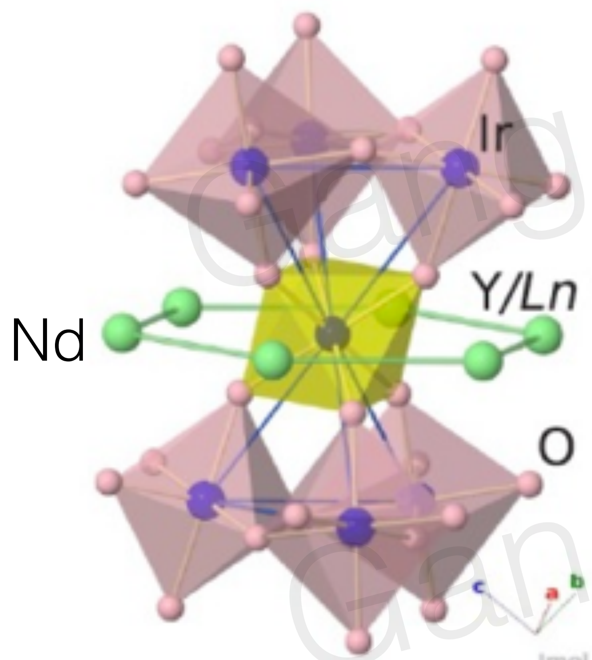
(see Prof Hasan's talk)

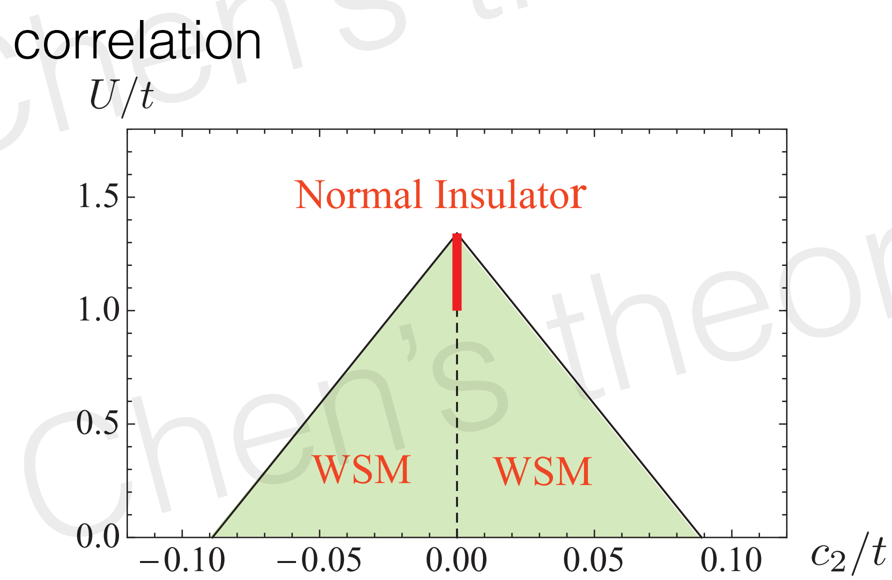
W Witczak-Krempa, YB Kim 2011
W Witczak-Krempa, **GC**, YB Kim, L Balents, Ann **Review** of CMP 2013

Rare earth local moment physics: e.g. $Nd_2Ir_2O_7$

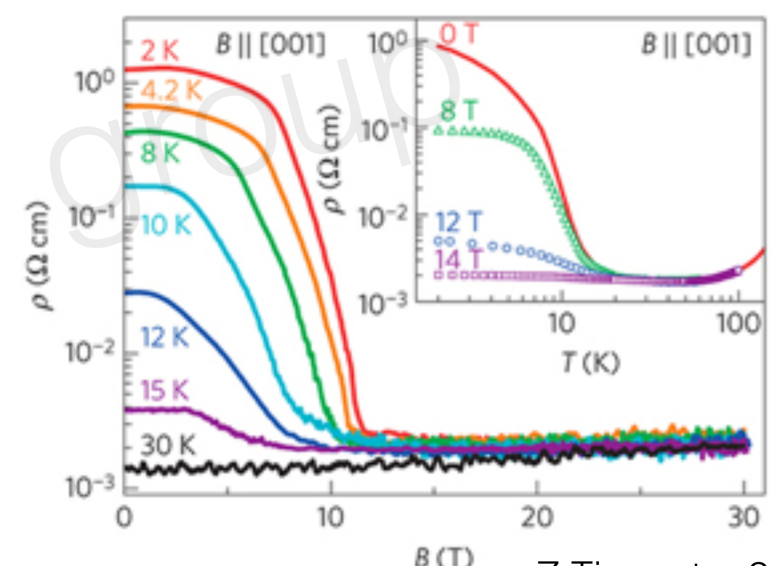
f-d exchange could help magnetic order and Weyl semimetal: all-in all-out order in Nd2Ir2O7.

External field can modify the Ir band structure indirectly via f-d exchange (remarkable experiments by S. Nakastuji's group.)





= "f-d exchange"

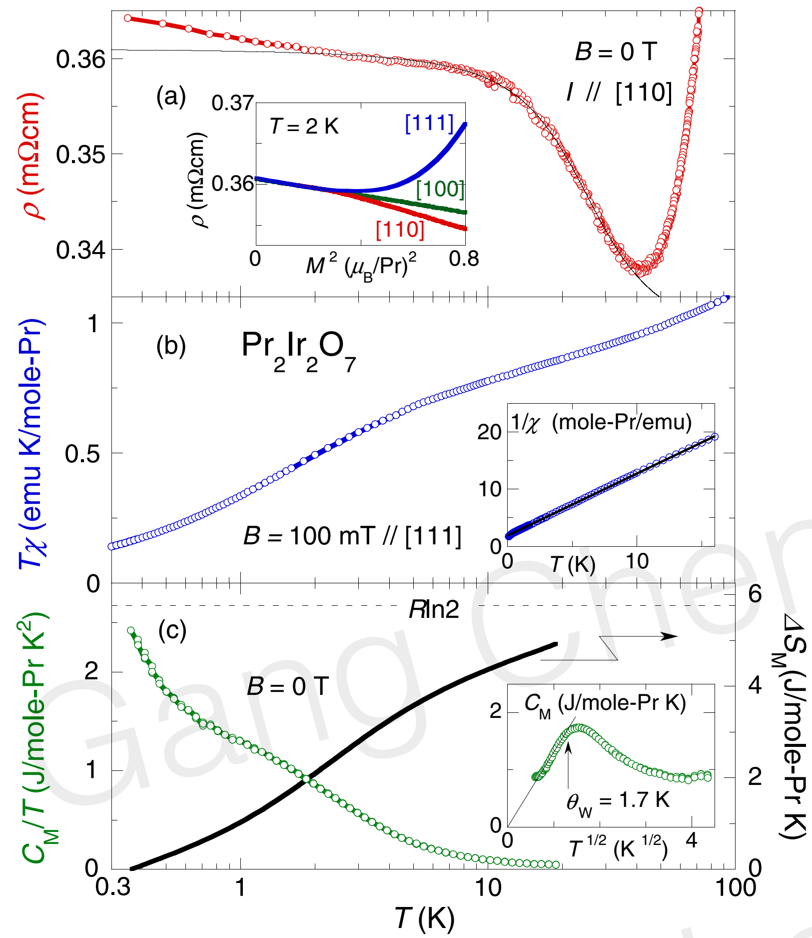


Z Tian, etc, 2015

GC, Hermele, PRB, 2012
YP Huang, **GC**, Hermele, PRL, 2013
Z. Tian,…., Balents, Nakastuji, Nature Physics, 2015
R Flint, T Senthil, 2013,
SB Lee, A Paramekanti, YB Kim, 2013

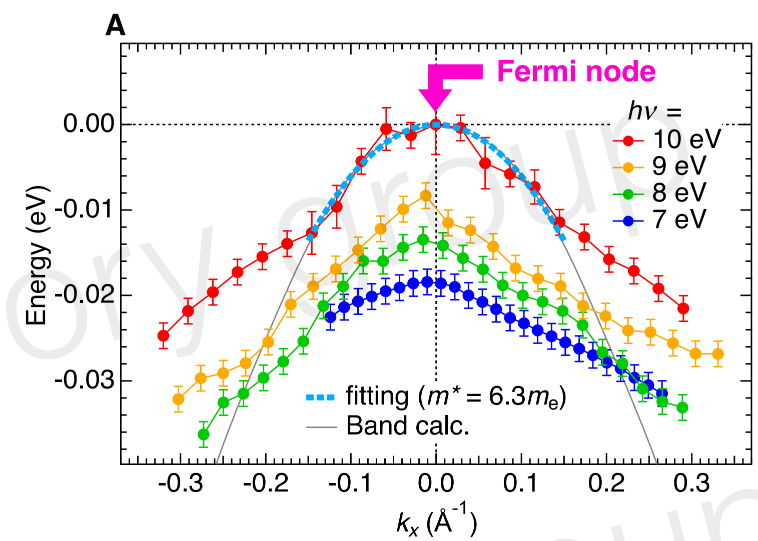
復旦大學 FUDAN UNIVERSITY

$Pr_2Ir_2O_7$ a featureless disordered state near an ordered state



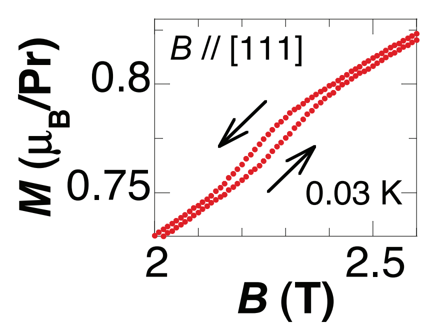
Nakatsuji, etc PRL **96,** 087204 (2006)

ARPES: quadratic band touching of Ir 5d electrons



Valence band approaches the Fermi energy at few meV resolution

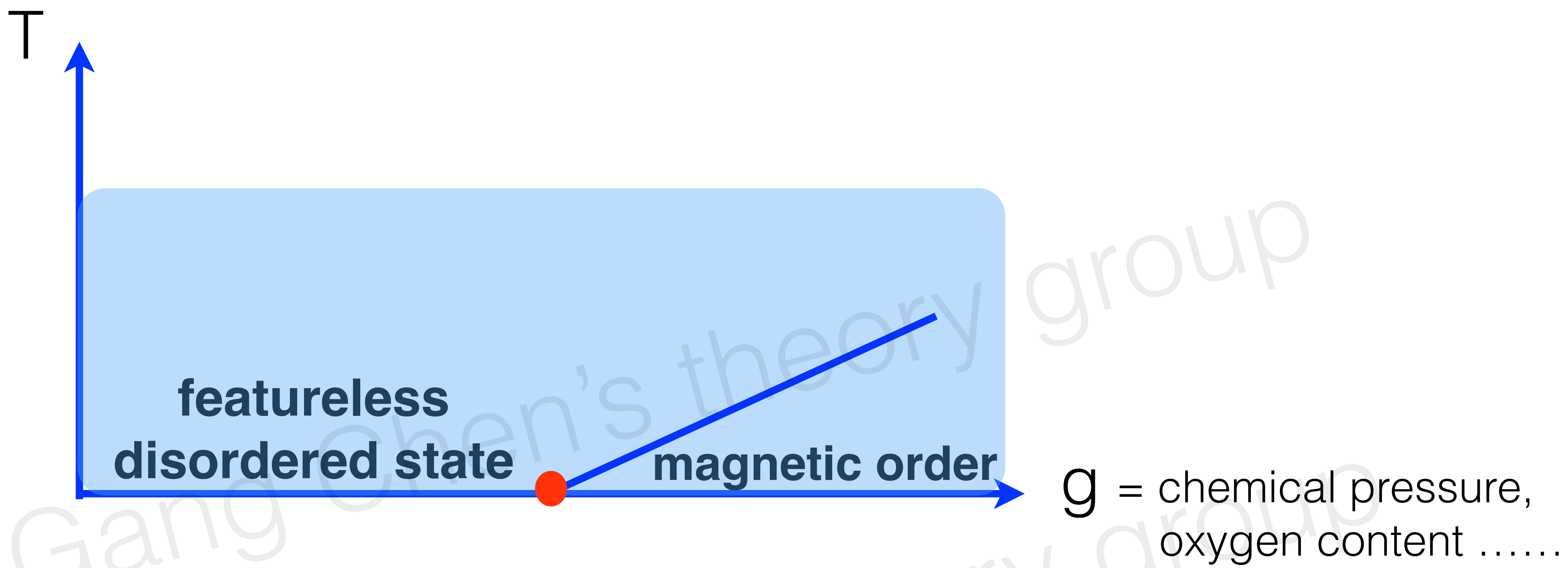
T Kondo, S Shin, etc 2014
B J Yang, Y B Kim 2011
E G Moon, CK Xu, Y B Kim, L Balents, 2013



metamagnetic transition

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

Summary of experimental results



- What is the structure of the magnetic order?
- What is the relationship between the featureless disordered state and various magnetic states?
- What is the nature of the featureless disordered states? Is it **QSI**?

Insights from high-Tc superconductors

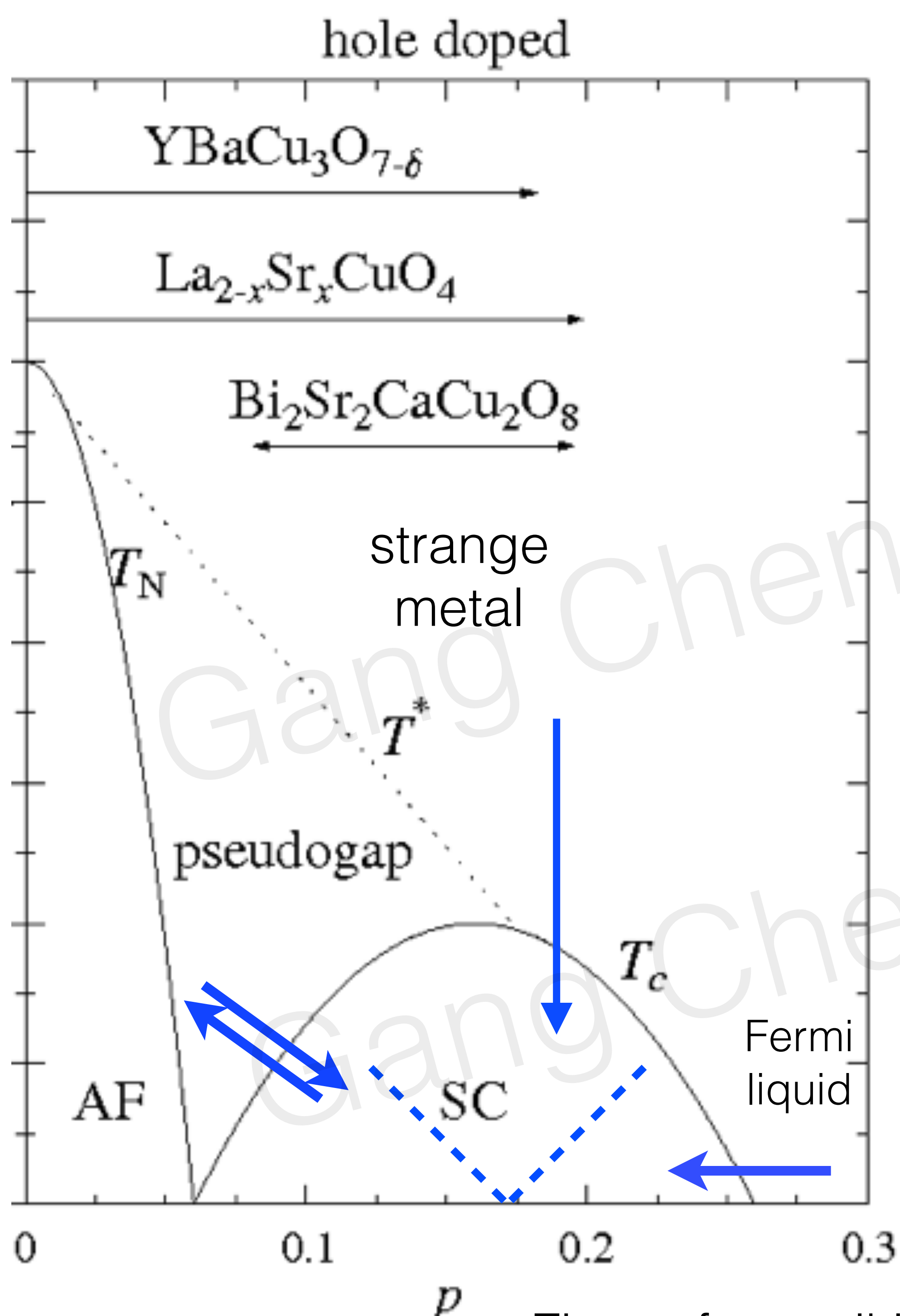


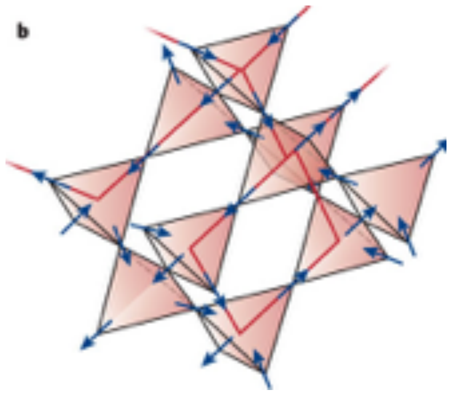
Figure from wiki

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?

What is quantum spin ice ?

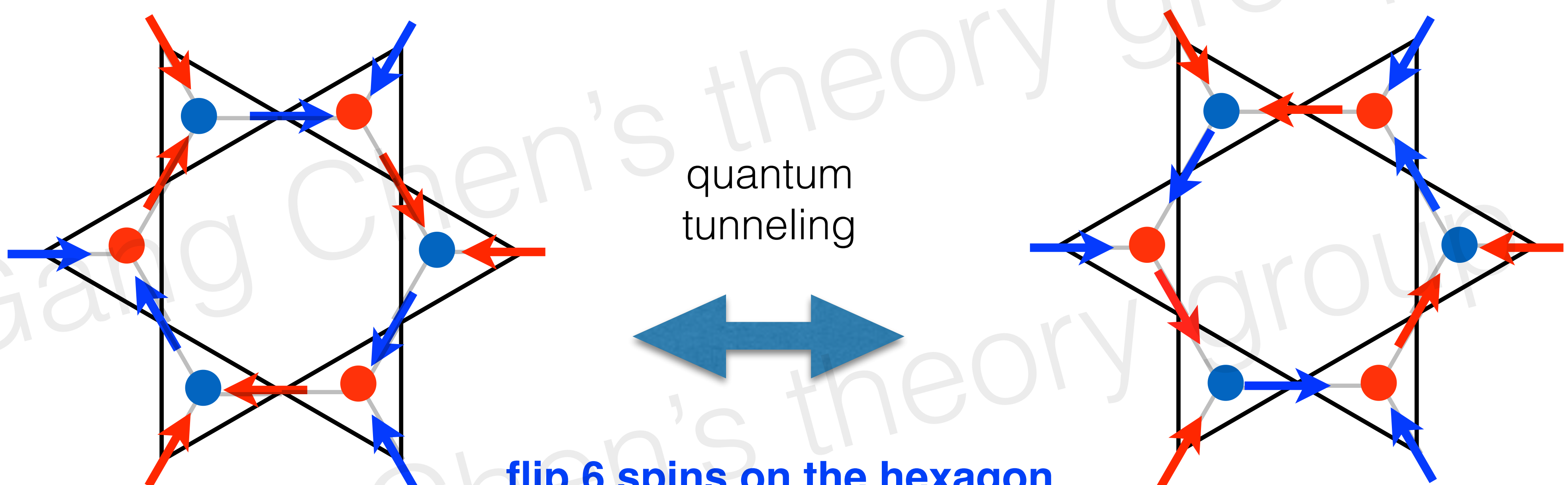
Reference: M Hermele, MPA Fisher, L Balents, L Savary, R Moessner, K Ross, B. Gaulin, C. Broholm, S Nakatsuji, etc



Quantum spin ice

$$H = J_{zz} \sum_{\langle ij \rangle} \tau_i^z \tau_j^z - J_{\pm} \sum_{\langle ij \rangle} (\tau_i^+ \tau_j^- + \tau_i^- \tau_j^+) + \cdots$$

Hermele, Fisher, Balents, 2003



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 !

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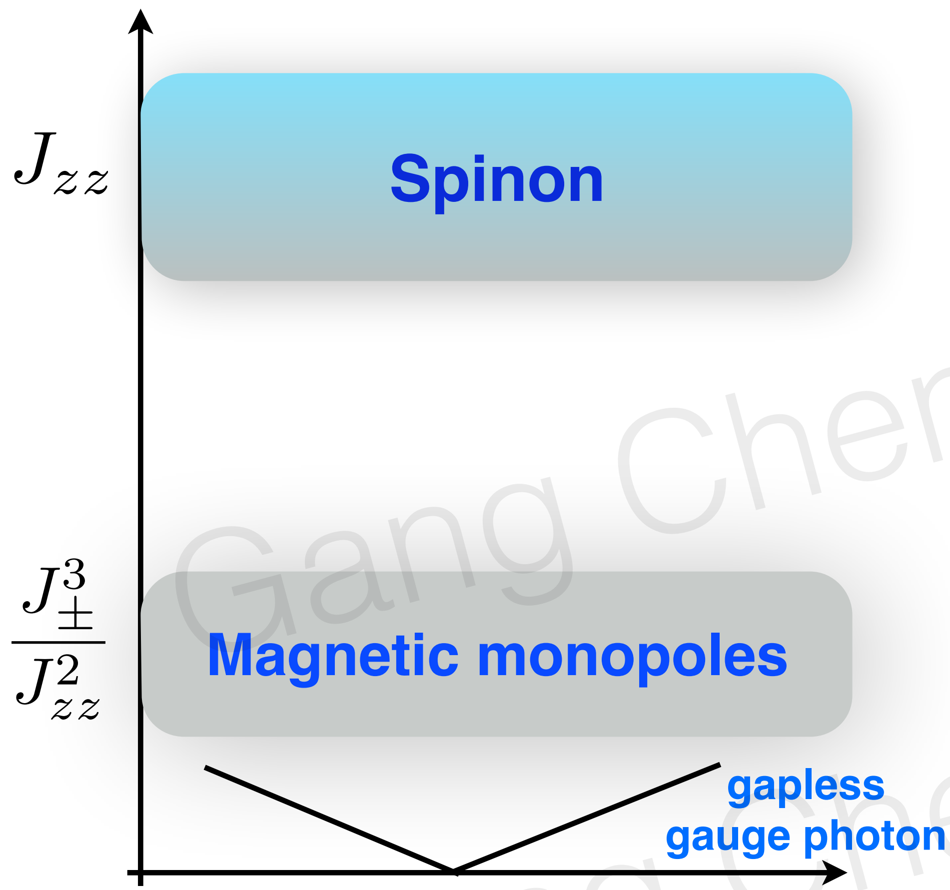
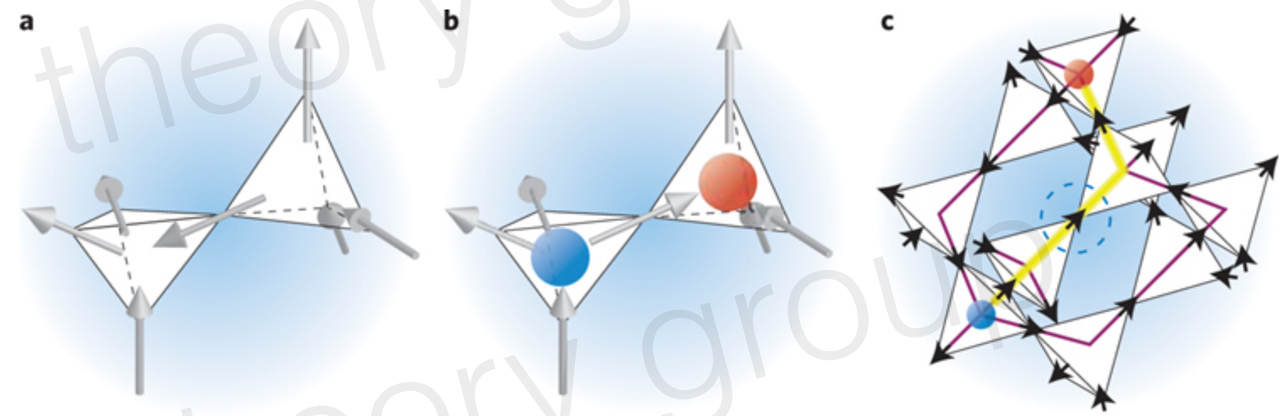
Compact QED: spinon vs monopole





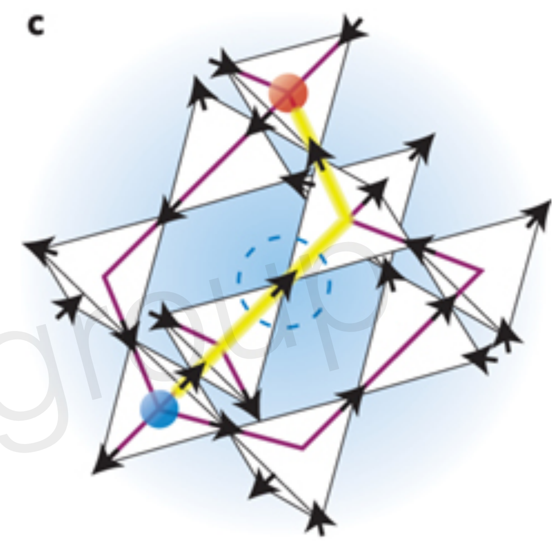
Figs from Moessner&Schiffer,2009

Spinon deconfinement

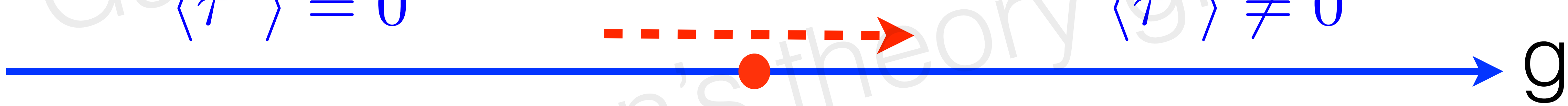
QSI is an example of Xiao-Gang Wen's string net condensed state.
The physics of QSI is described by **compact quantum electrodynamics**.

Attack from left (quantum spin ice)

spinon | gauge photon | spinon



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



featureless disordered state
=quantum spin ice??

magnetic order

Spinons are deconfined.

Spinons are confined !

More generally, for non-Kramers' doublet, the magnetic transition out of QSI **must** be a confinement transition, this may apply to Tb2Ti2O7.

Theoretical framework: compact QED and electromagnetic duality

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

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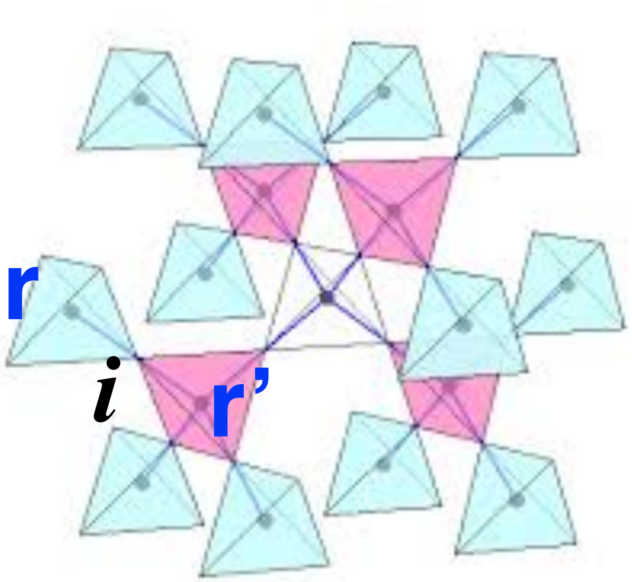
Lattice gauge theory formalism: technical part



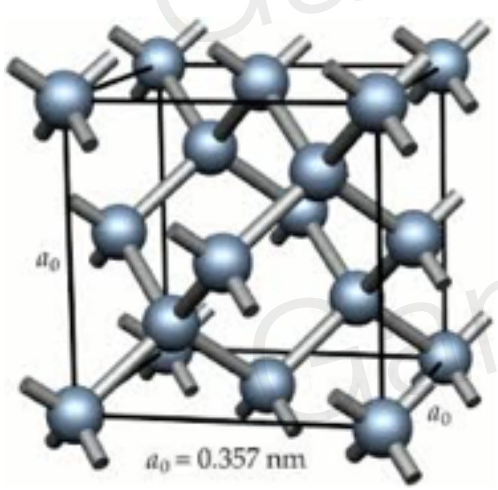
$$E_{\mathbf{rr'}} \sim \tau_i^z, e^{iA_{\mathbf{rr'}}} \sim \tau_i^+$$

Hermele, Fisher, Balents, 2004

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

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

H_{LGT} captures the **universal properties** of QSI.



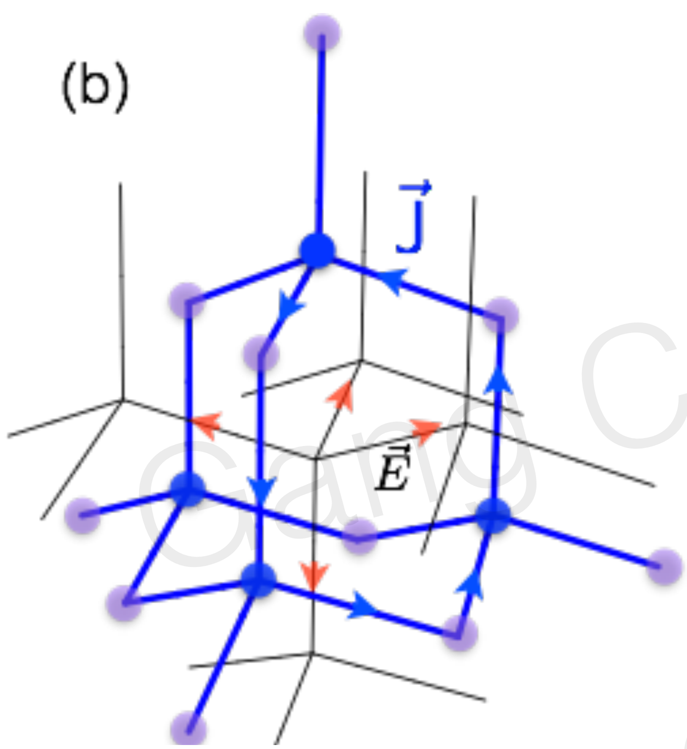
diamond lattice

- 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).

Electromagnetic duality

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

To study monopole physics, we need to use a technique called "duality" to make it explicit.



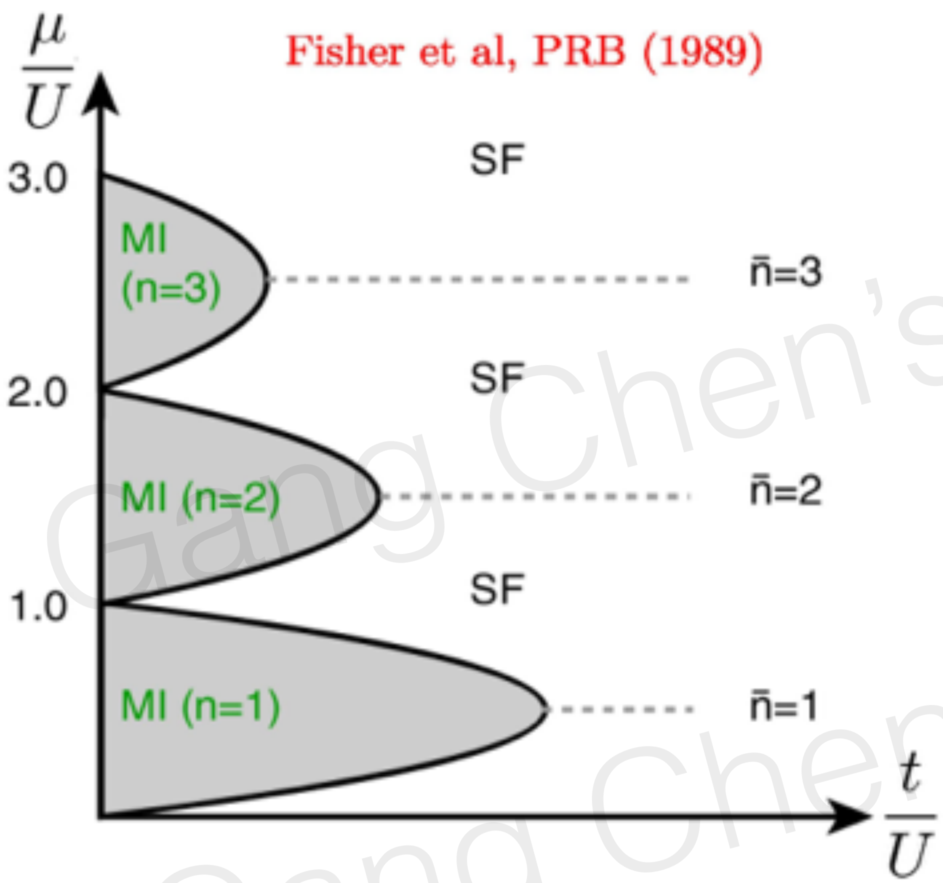
Motrunich, Senthil 2005,
Bergman, Fiete, Balents 2006

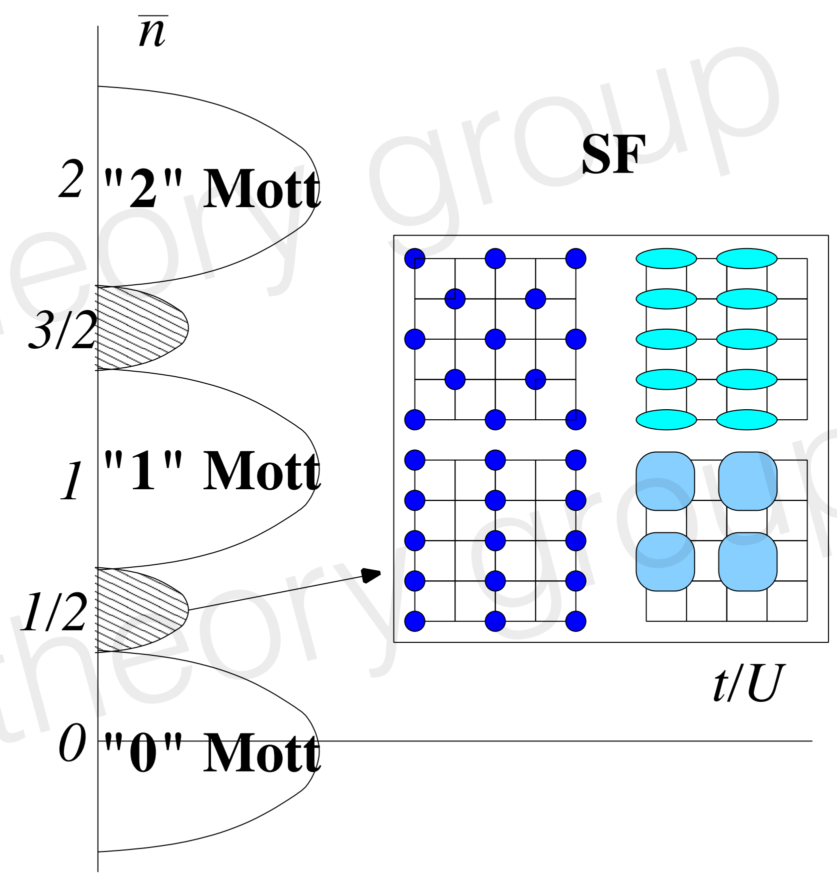
insert monopole variables

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

- **B magnetic field** is strongly fluctuating, the fluctuation of dual U(1) gauge field is weak.

Analogy with Boson-vortex duality





Balents, et al, 2005

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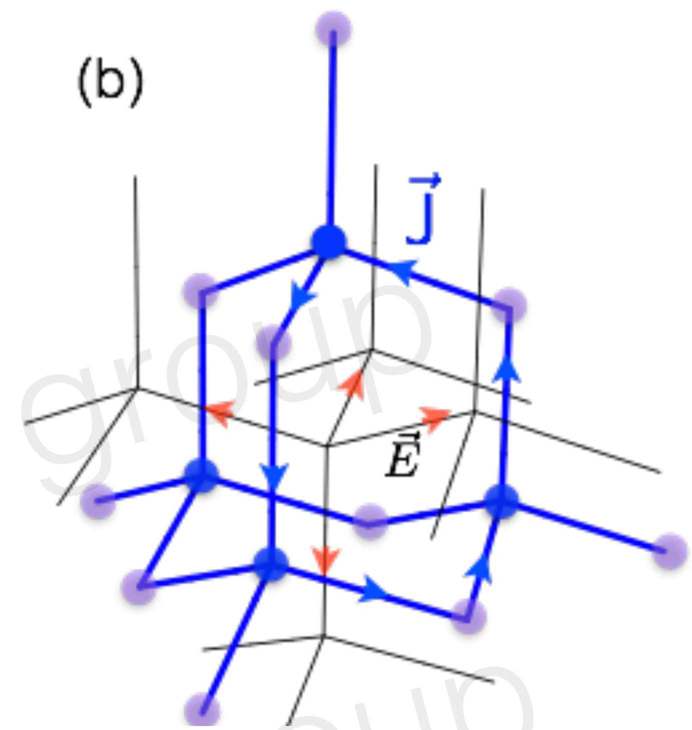
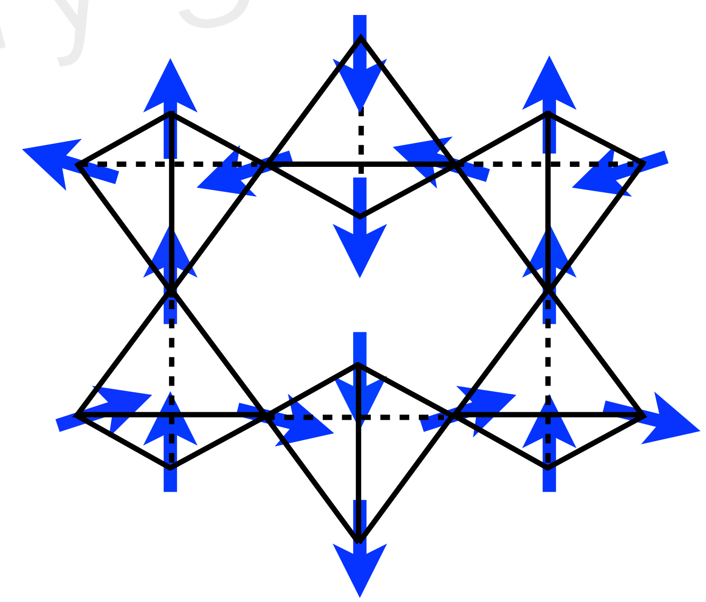
Physical observables are gauge invariant

- Monopole loop current defines the magnetic order



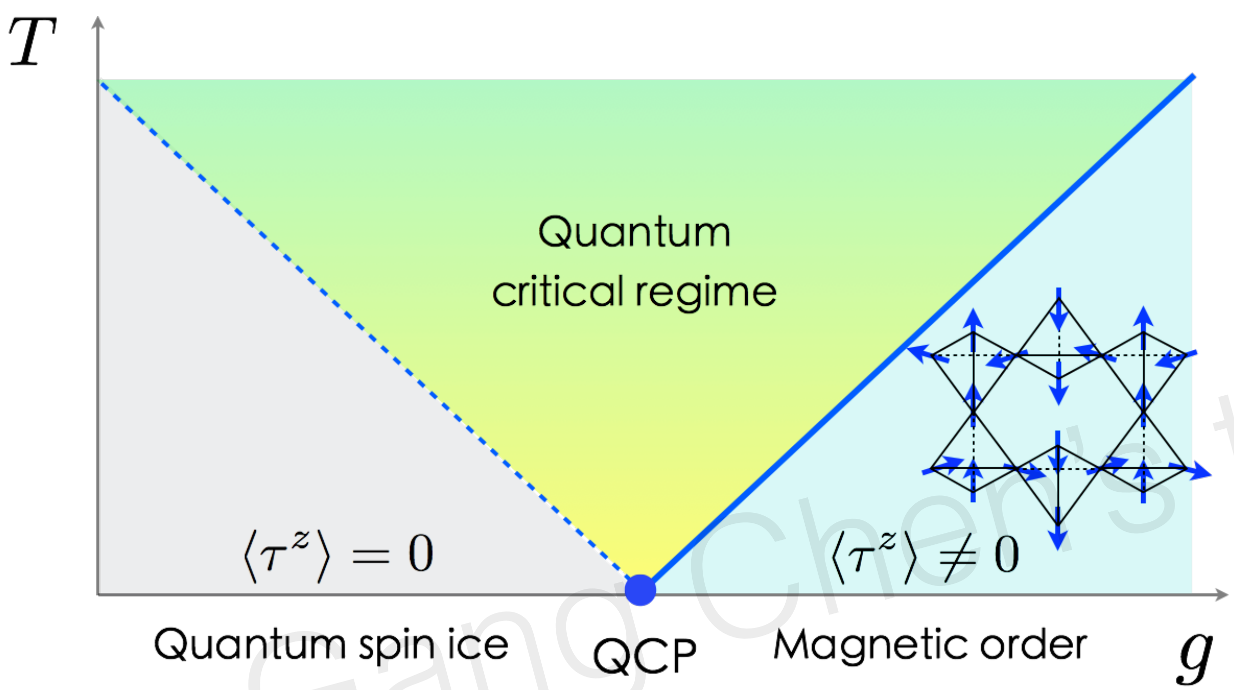
$$\tau_i^z \sim E_{\mathbf{rr}'} \sim \sum_{\mathbf{rr}' \in \hexagon_d^*} \mathsf{J}_{\mathbf{rr}'},$$

Proximate magnetic order generically breaks translation symmetry.



Q= 2Pi(001)

Critical theory for proximate ordering transition



g is the mass of the monopole

Determined by **projective symmetry group**

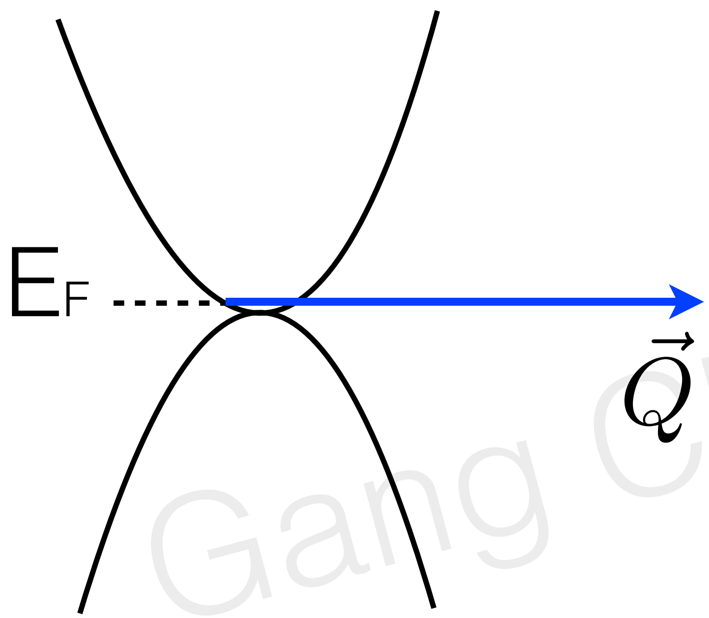
$$L = \sum_a \big[|(\partial_\mu - i\tilde{a}_\mu)\phi_a|^2 + m^2 |\phi_a|^2 \big] + \frac{{F_{\mu\nu}}^2}{2} + u_0 \Big(\sum_a |\phi_a|^2\Big)^2 + \cdots ,$$

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

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

Ir conduction electrons

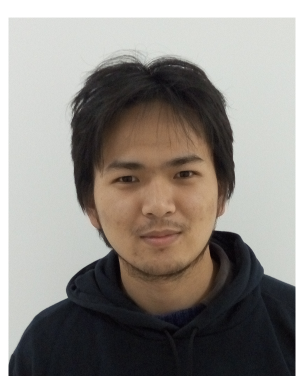
Ir conduction electron Fermi surface does not modify the critical property.



Ordering wavevector $|Q| >> K_F$, Yukawa coupling and Landau damping is suppressed.

Lohneysen, A Rosch, Vojta, Wolfle, **RMP** 2007

But deep in the ordered regime, magnetic order influences the conduction electron bands.



Yao-Dong Li, **GC**, in preparation, 2016

Implication for $Pr_2Ir_2O_{7\text{-delta}}$

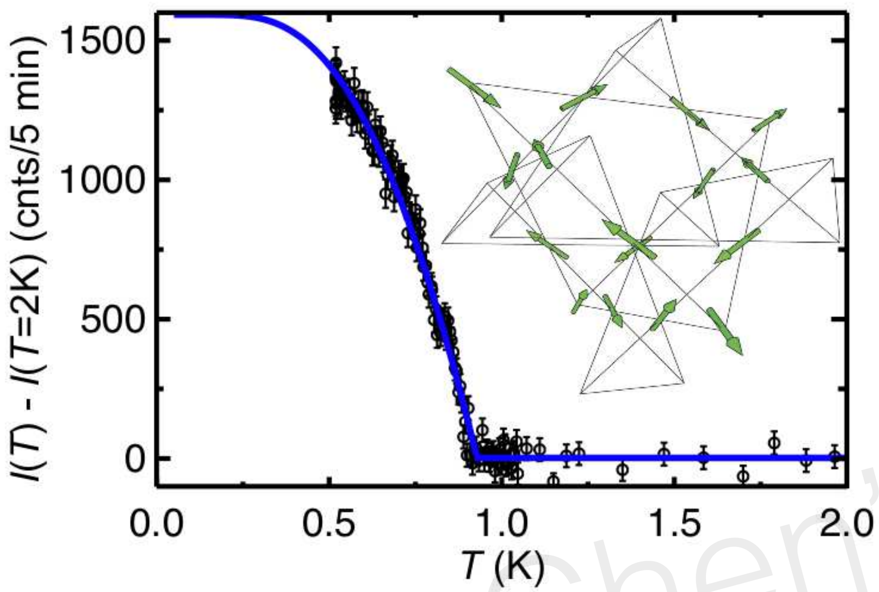
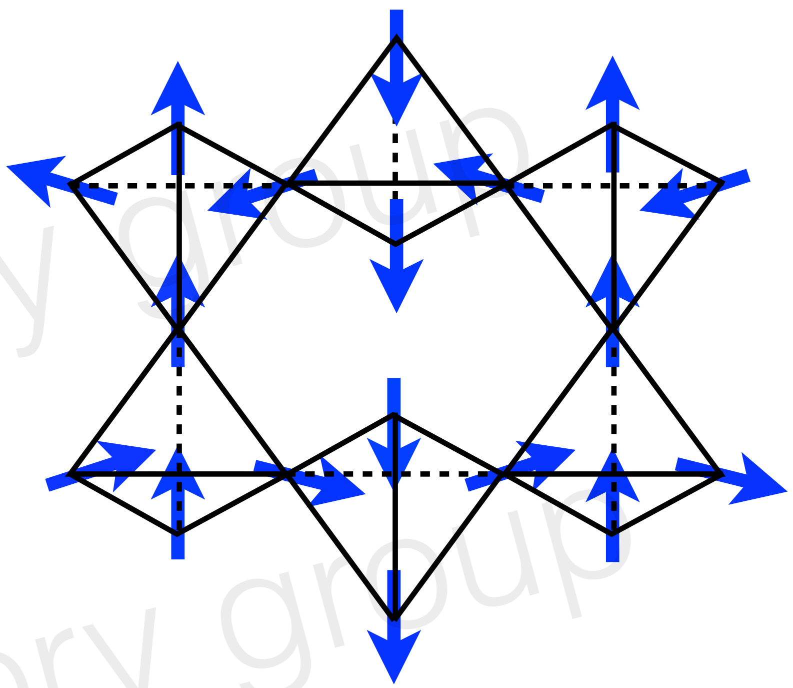


FIG. 2. (color online) Temperature dependence of elastic neutron scattering intensity of $Pr_{2+x}Ir_{2-x}O_{7-\delta}$ at the position of the $\mathbf{q}_m = (100)$ reflection. The intensity measured at $T = 2$ K was subtracted as a background. Curve: Ising mean-field theory fit to the data, which yields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



Q= 2Pi(001)

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

Pr2Ir2O7: different samples have different Fermi energy -> RKKY-> **magnetic order, Q= 2Pi(001)**

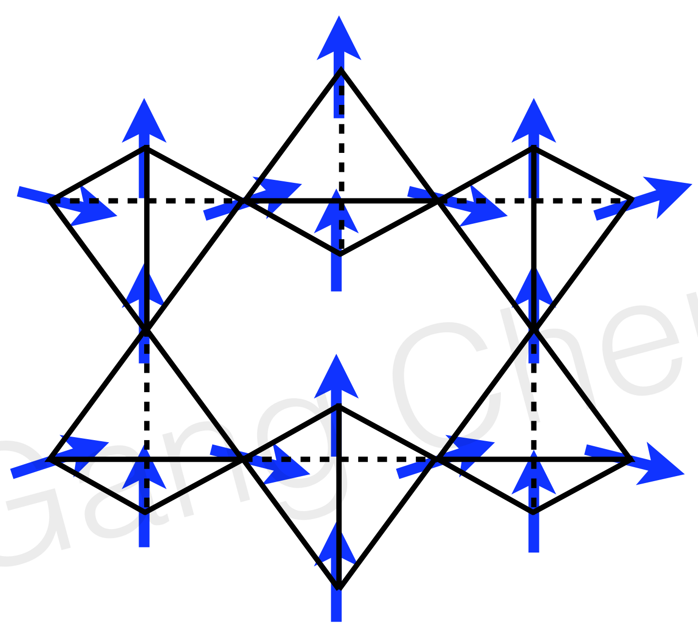
Gang Chen's theory group

Implication for $Yb_2Ti_2O_7$

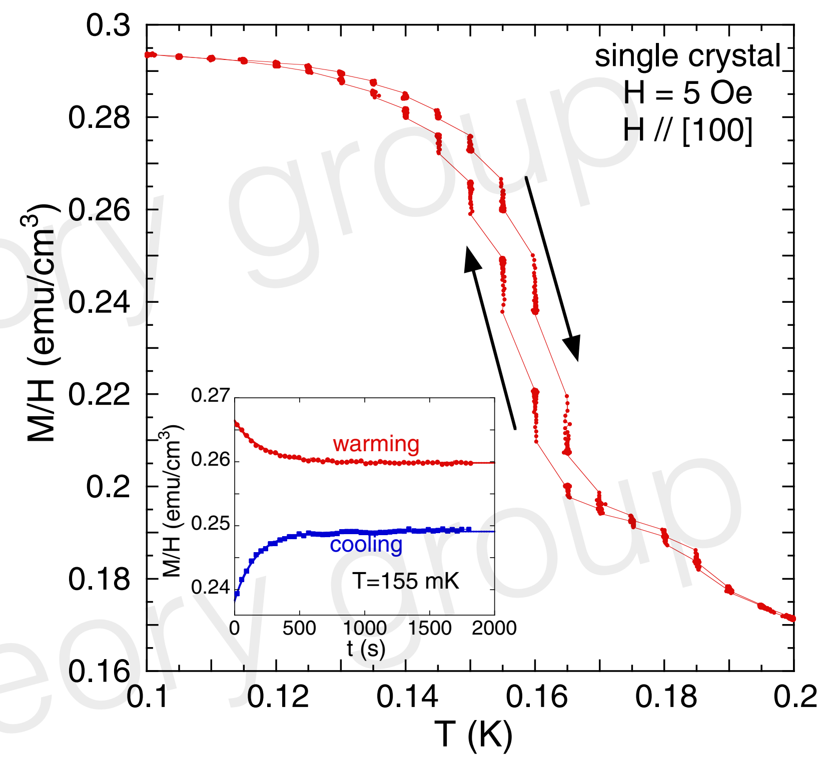
PHYSICAL REVIEW B **89**, 224419 (2014)

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]



$\mathbf{Q} = (000)$ state



$Yb_2Ti_2O_7$

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

Or see **Kate Ross**' talk

Summary

- I have studied the phase diagram near quantum spin ice.
- 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 likely to be a QSI.

Work in progress: sign problem free model that demonstrates both proximate and unproximate magnetic transition out of QSI.