“Magnetic” monopole condensation transition out of quantum spin ice: **quantum spin ice** in **pyrochlore iridates**

Gang Chen

Fudan University, Shanghai

Gang Chen, arXiv:1602.02230.

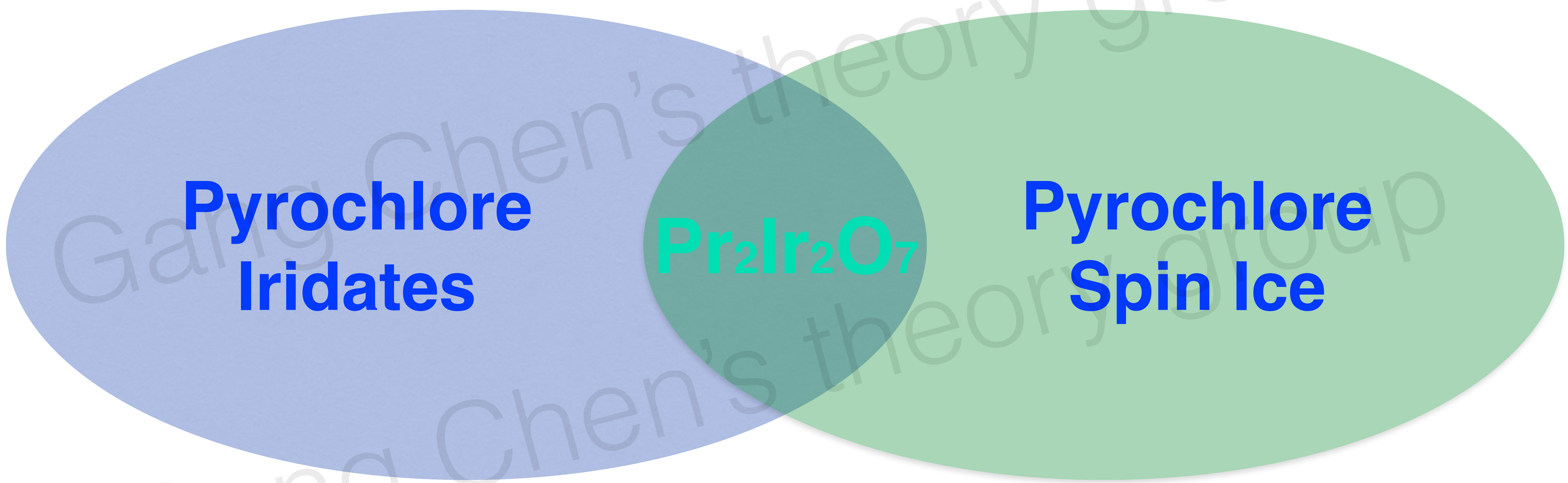
Longer talk can be found at KITP website last Sep.

Job opportunities

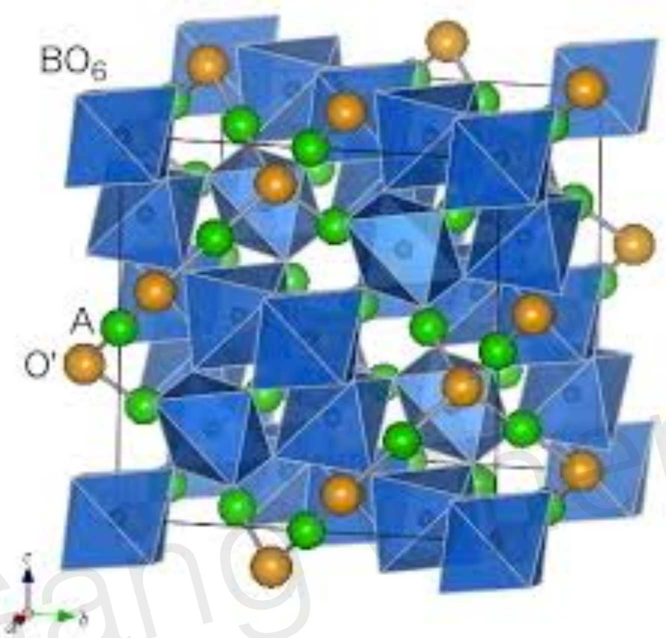
- **Postdocs** are generously funded and will have tremendous freedom.

Shanghai, China

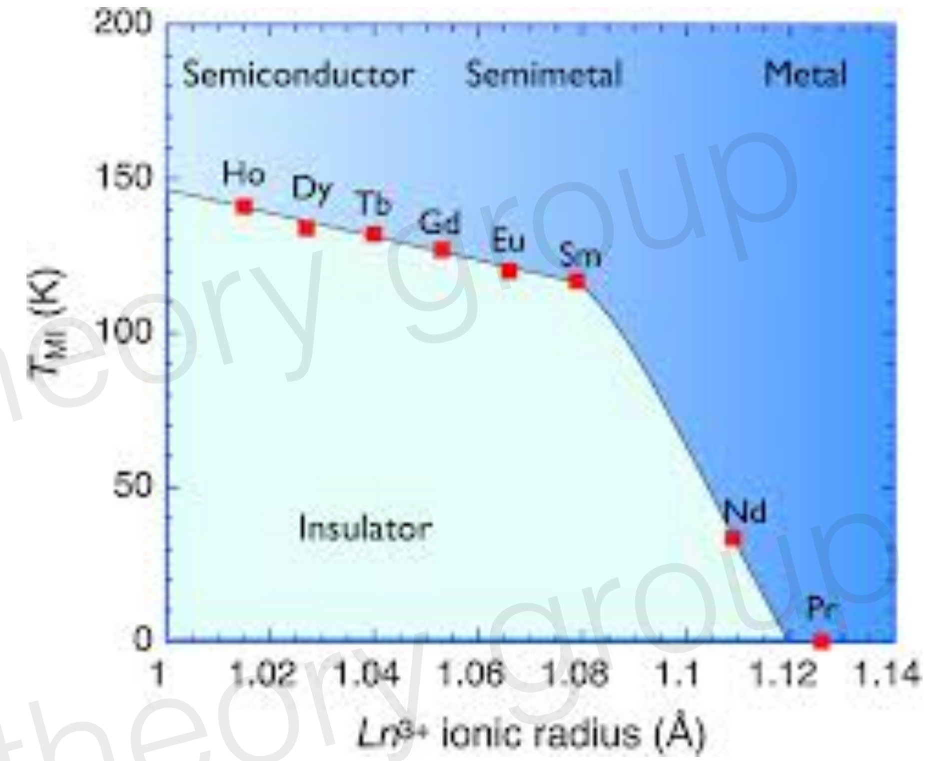
Pyrochlore Iridate and Pyrochlore Spin Ice



Pyrochlore iridates: $Pr_2Ir_2O_7$



$R_2Ir_2O_7$

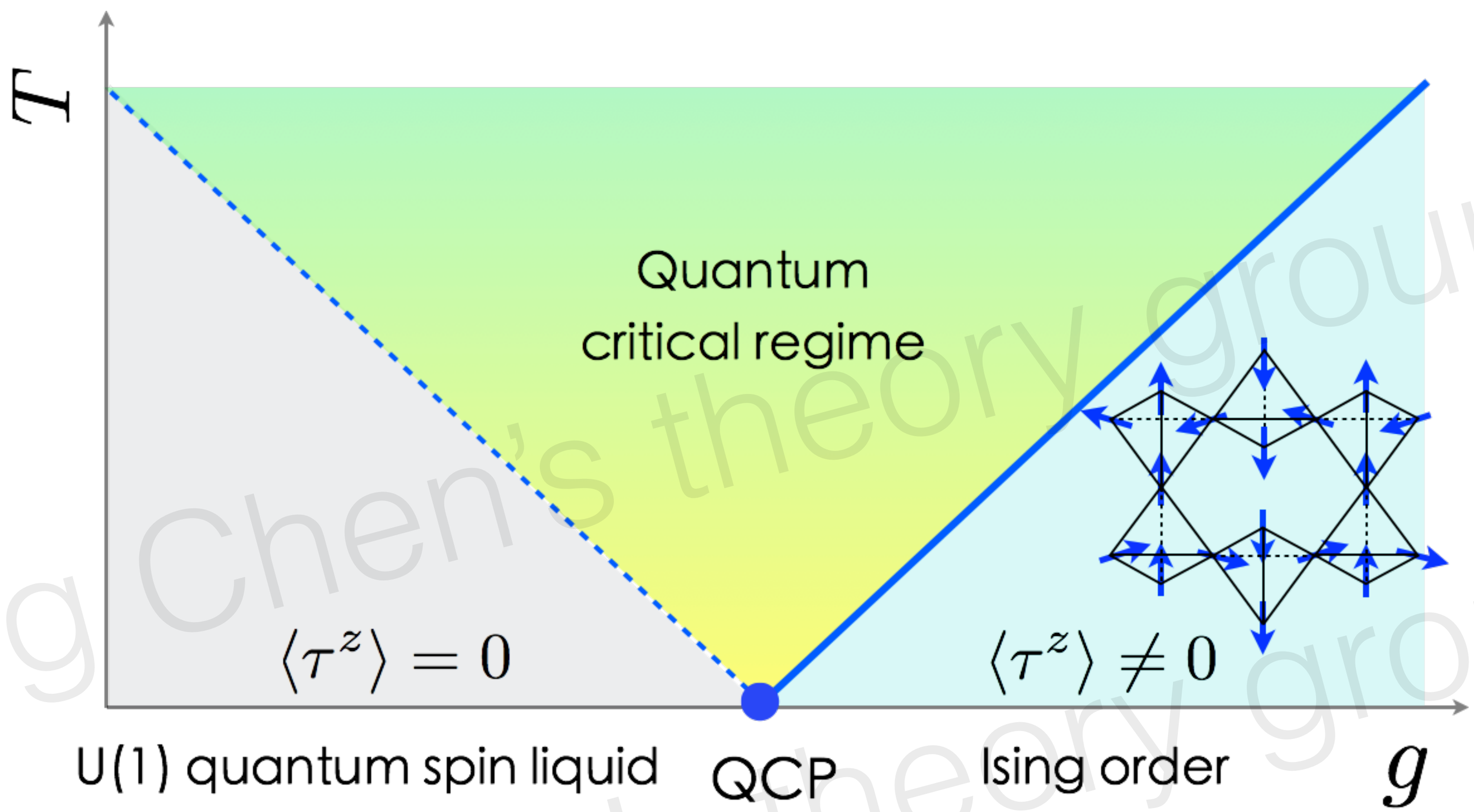


K Matsuhira, M Wakeshima, Y Hinatsu, S. Takagi
JPSJ, 2011

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

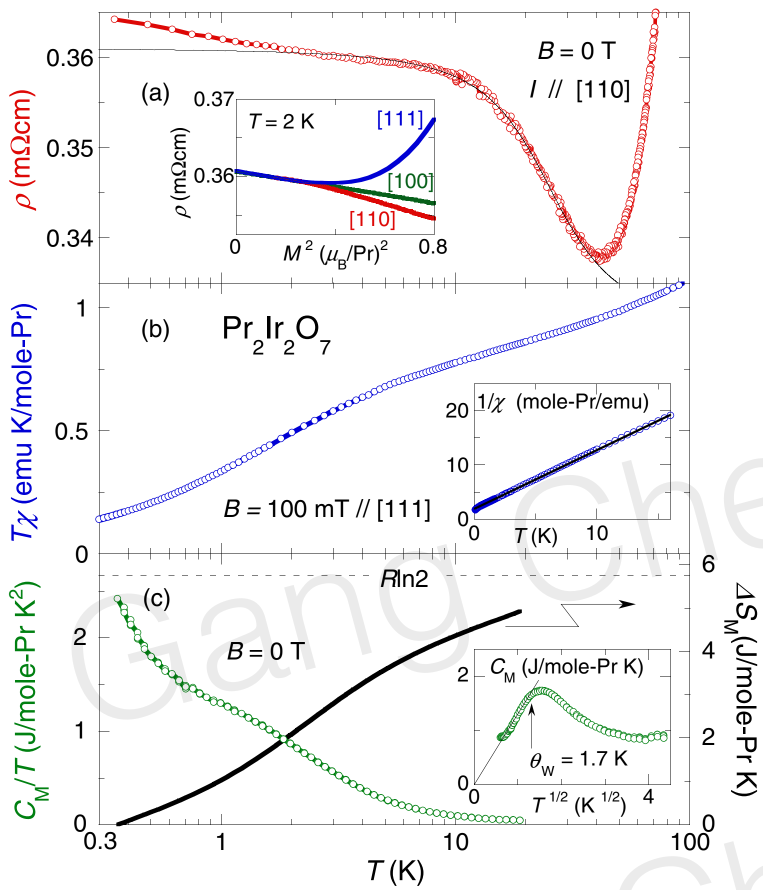
My proposal for $Pr_2Ir_2O_{7\text{-delta}}$



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.

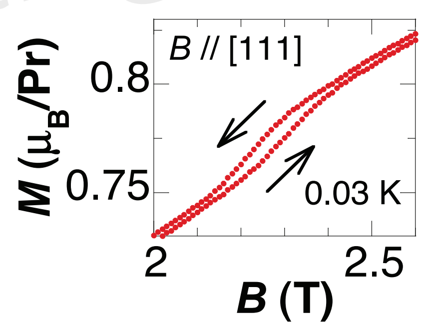
The Ir conduction electrons may drive the transition, but do not influence the nature of the phase transition.

$Pr_2Ir_2O_7$ a featureless disordered state near an ordered state



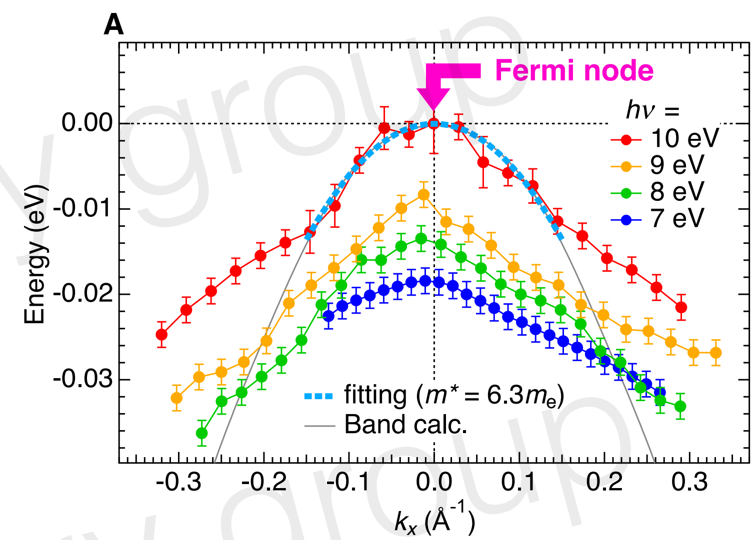
Nakatsuji, etc

PRL **96,** 087204 (2006)



metamagnetic transition

ARPES: quadratic band touching of Ir 5d electrons



Valence band approaches the Fermi energy at few meV resolution

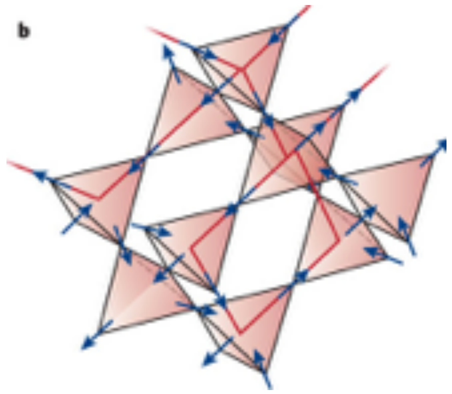
T Kondo, S Shin, etc 2014

B J Yang, Yong Baek Kim 2011

E G Moon, CK Xu, Y B Kim, L Balents, 2013

Expts are **sample dependent**,

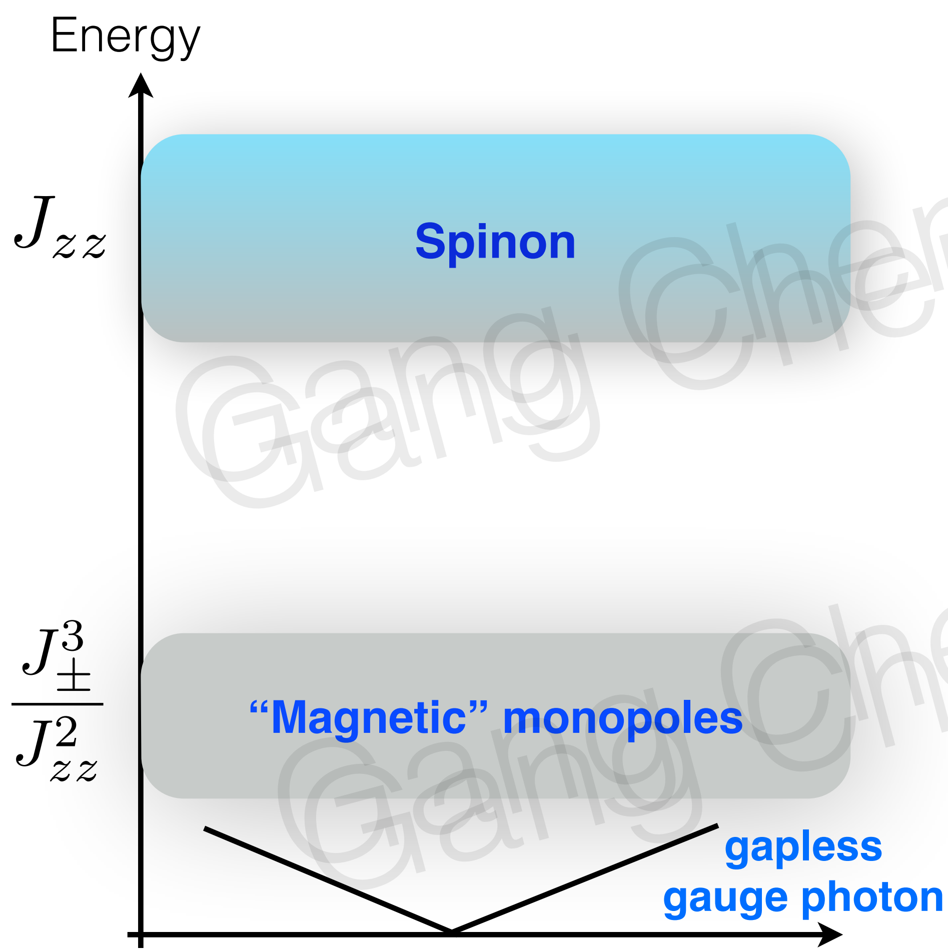
Recently, some samples are found AFM ordered.

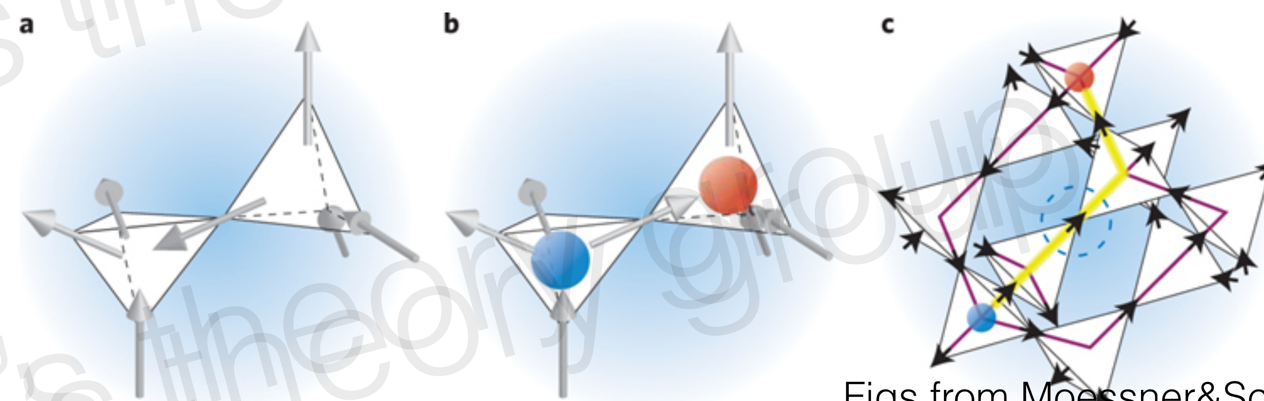


Quantum spin ice U(1) spin liquid

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

Senthil Motrunich, 2002
Hermele, Fisher, Balents, 2003
Moessner, Huse, Isakov, YB Kim…





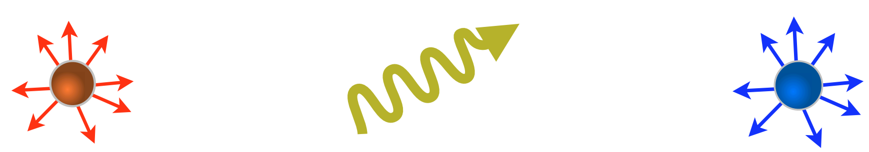
Figs from Moessner&Schiffer,2009

Spinon deconfinement

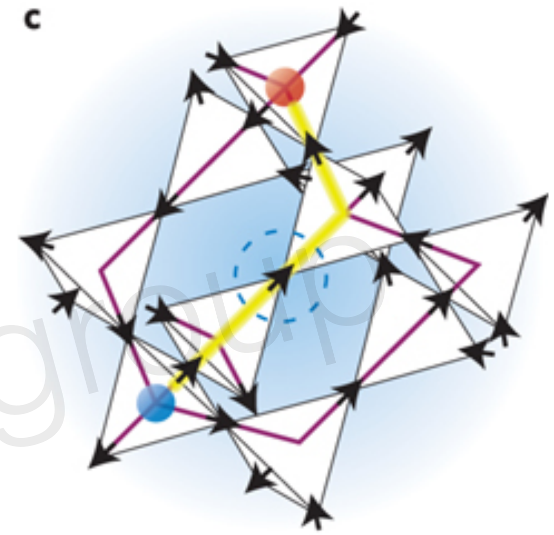
QSI (U(1) QSL) is an example of Xiao-Gang Wen’s string net condensed state.
The physics of QSI is described by **compact quantum electrodynamics**.

Confinement transition out of U(1) quantum spin liquid

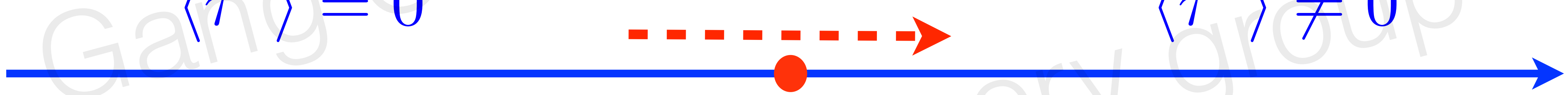
spinon | gauge photon | spinon



c



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



featureless disordered state
= quantum spin ice spin liquid

Ising 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.

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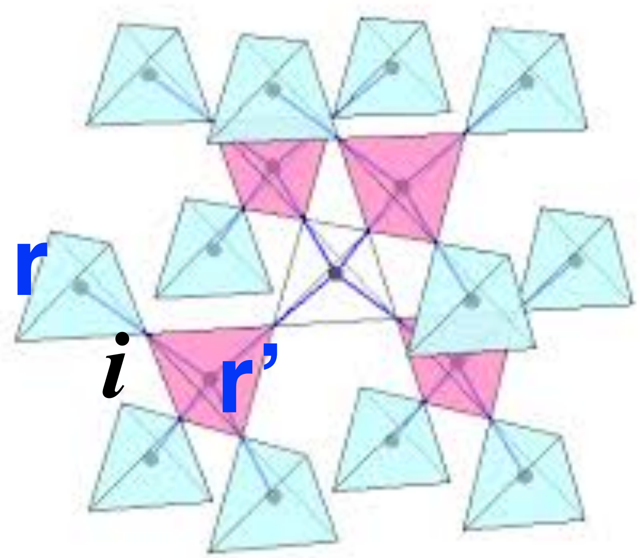
Lattice gauge theory formalism: technical part



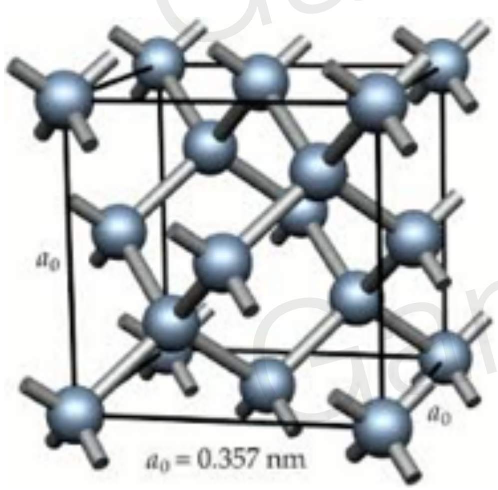
$$E_{\mathbf{rr'}} \sim \tau_i^z, e^{iA_{\mathbf{rr'}}} \sim \tau_i^+$$

Hermele, Fisher, Balents, 2004

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

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

$H_{\rm LGT}$ 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).

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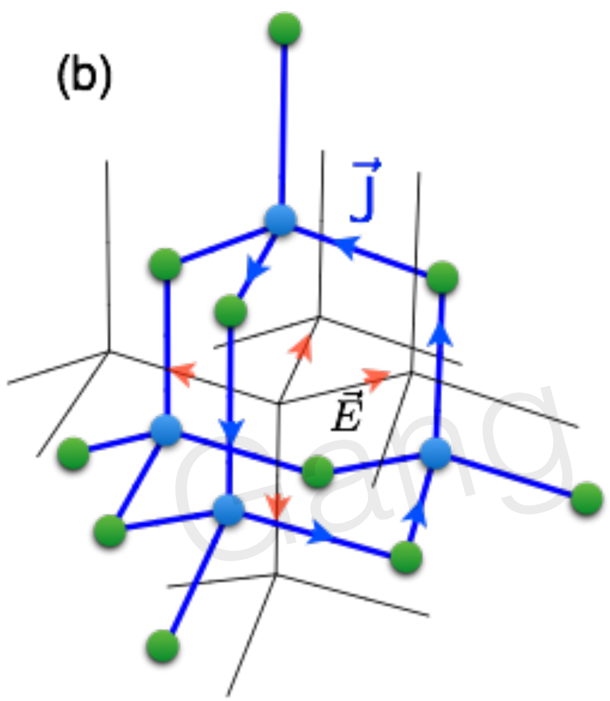
Electromagnetic duality

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



Motrunich, Senthil 2005,
Bergman, Fiete, Balents 2006

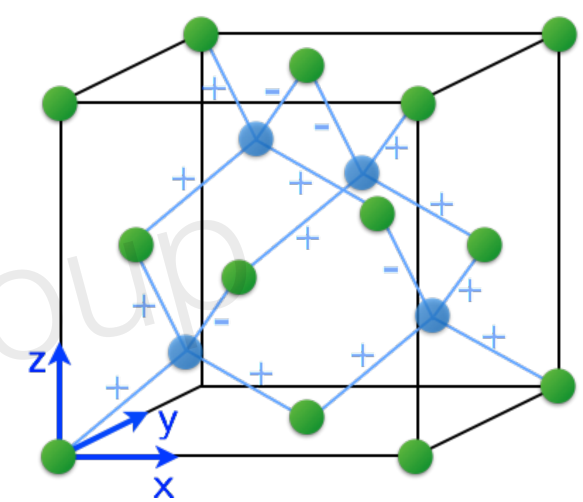
Insert monopole variables

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

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.



monopole hopping on dual lattice

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

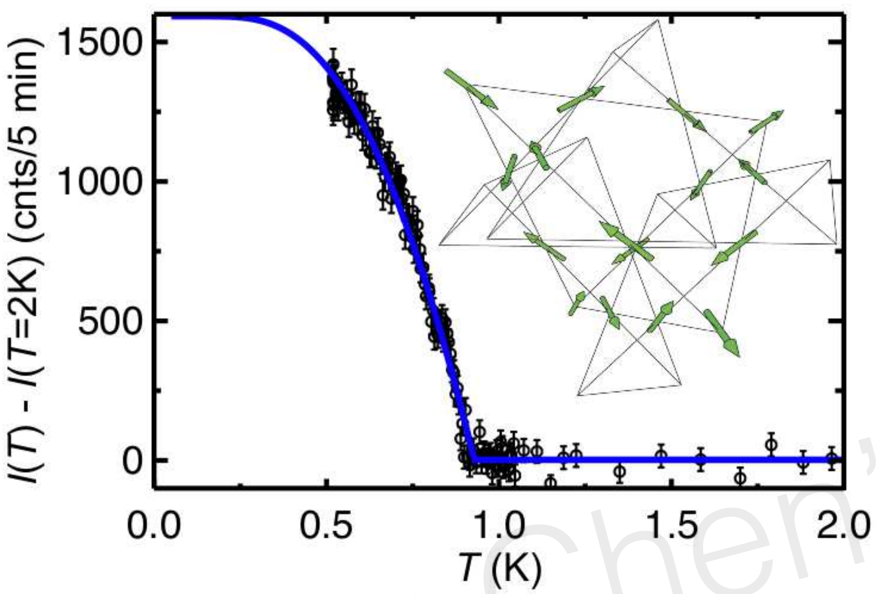
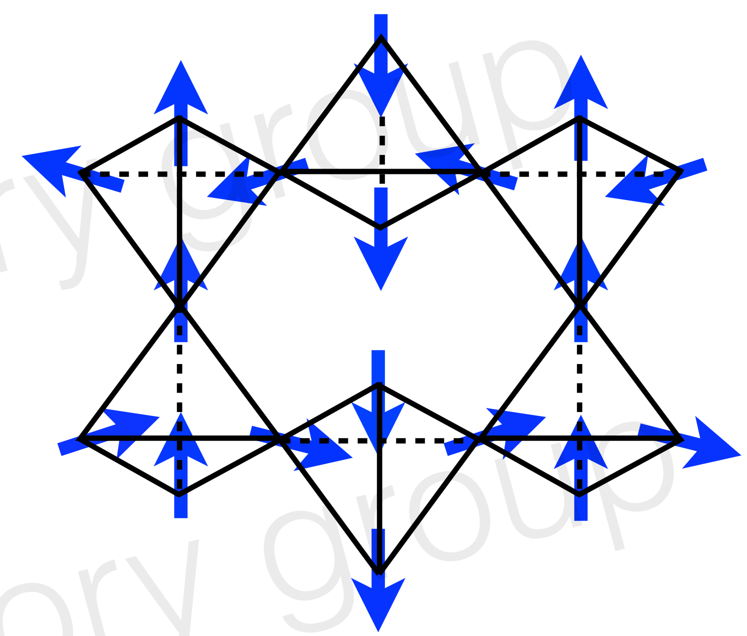


FIG. 2. (color online) Temperature dependence of elastic neutron scattering intensity of $Pr_{2+x}Ir_{2-x}O_{7-\delta}$ at the position of the $\mathbf{q}_m = (100)$ reflection. The intensity measured at $T = 2$ K was subtracted as a background. Curve: Ising mean-field theory fit to the data, which yields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

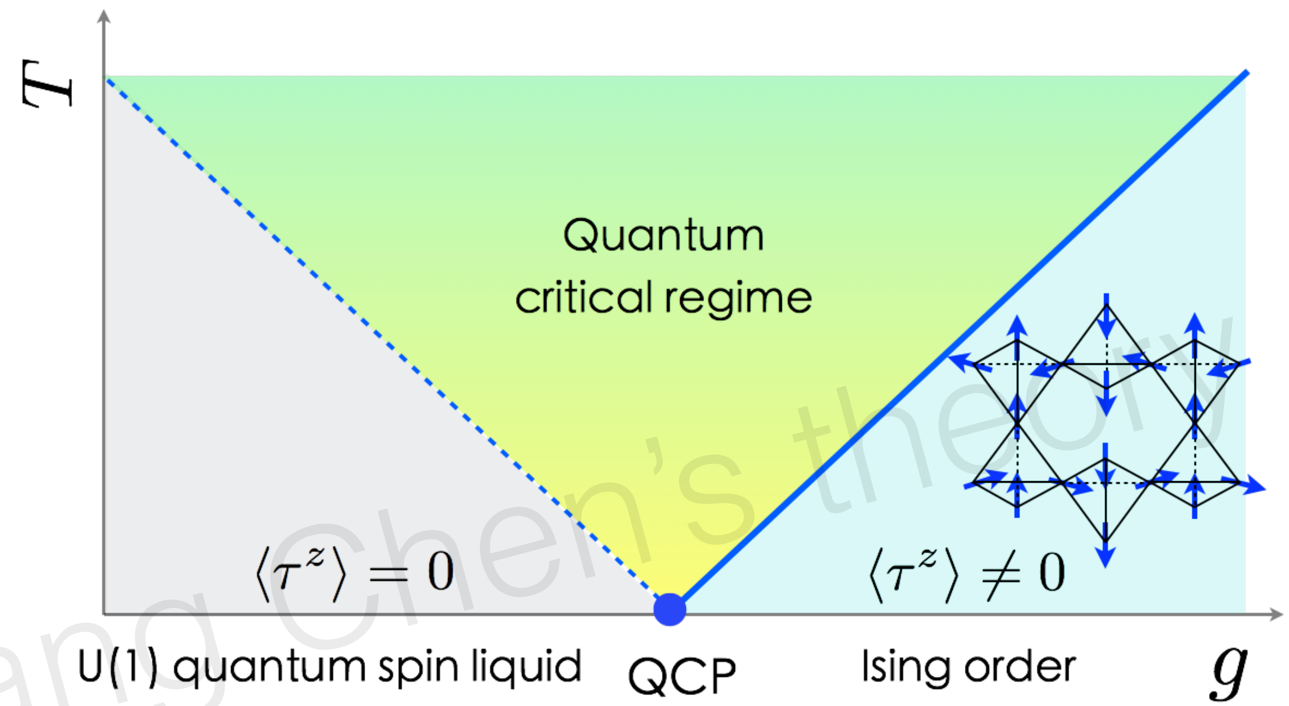
Ising order is discovered in
some samples. (MacLaughlin, etc, 2015)



Ising order,
Q= 2Pi(001)

break translation symmetry

Subsidiary order and weak divergence



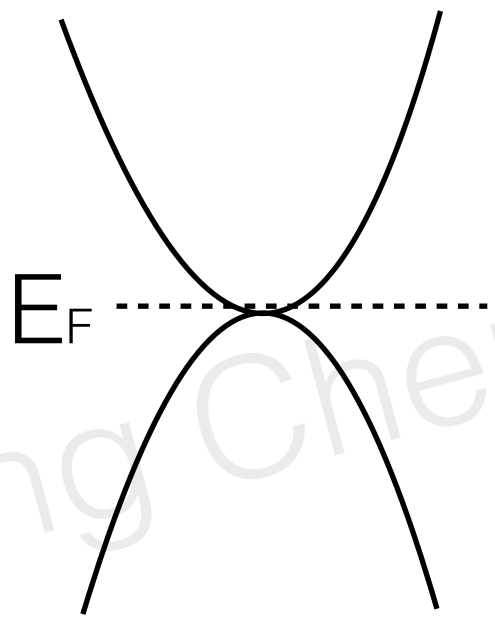
g is the mass of the monopole

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

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



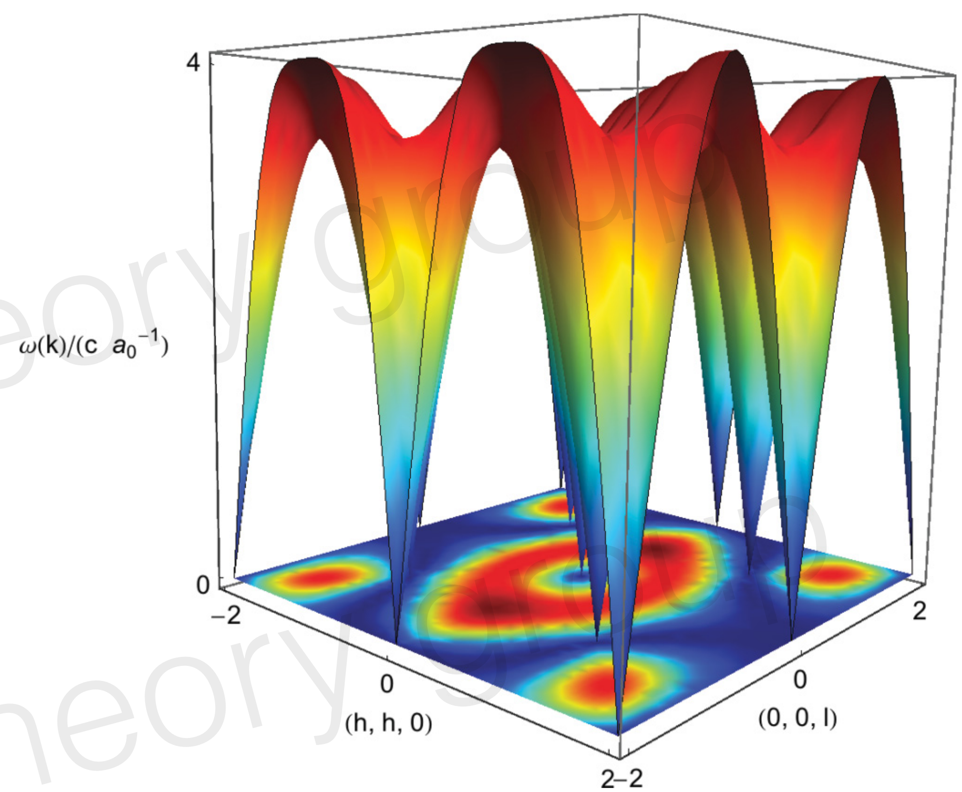


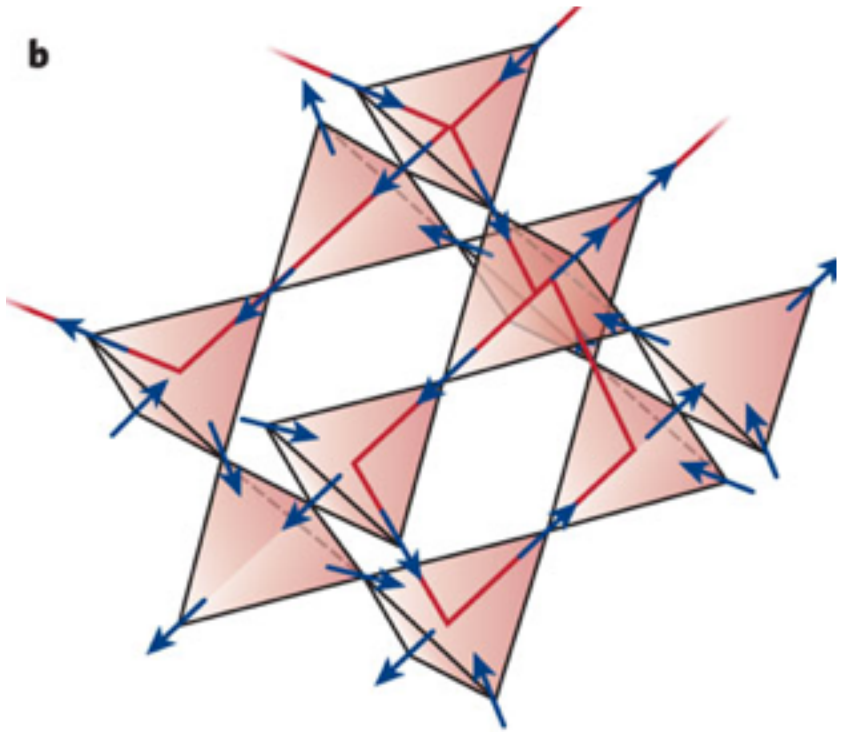
Fig from Benton, etc, PRB 2012

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

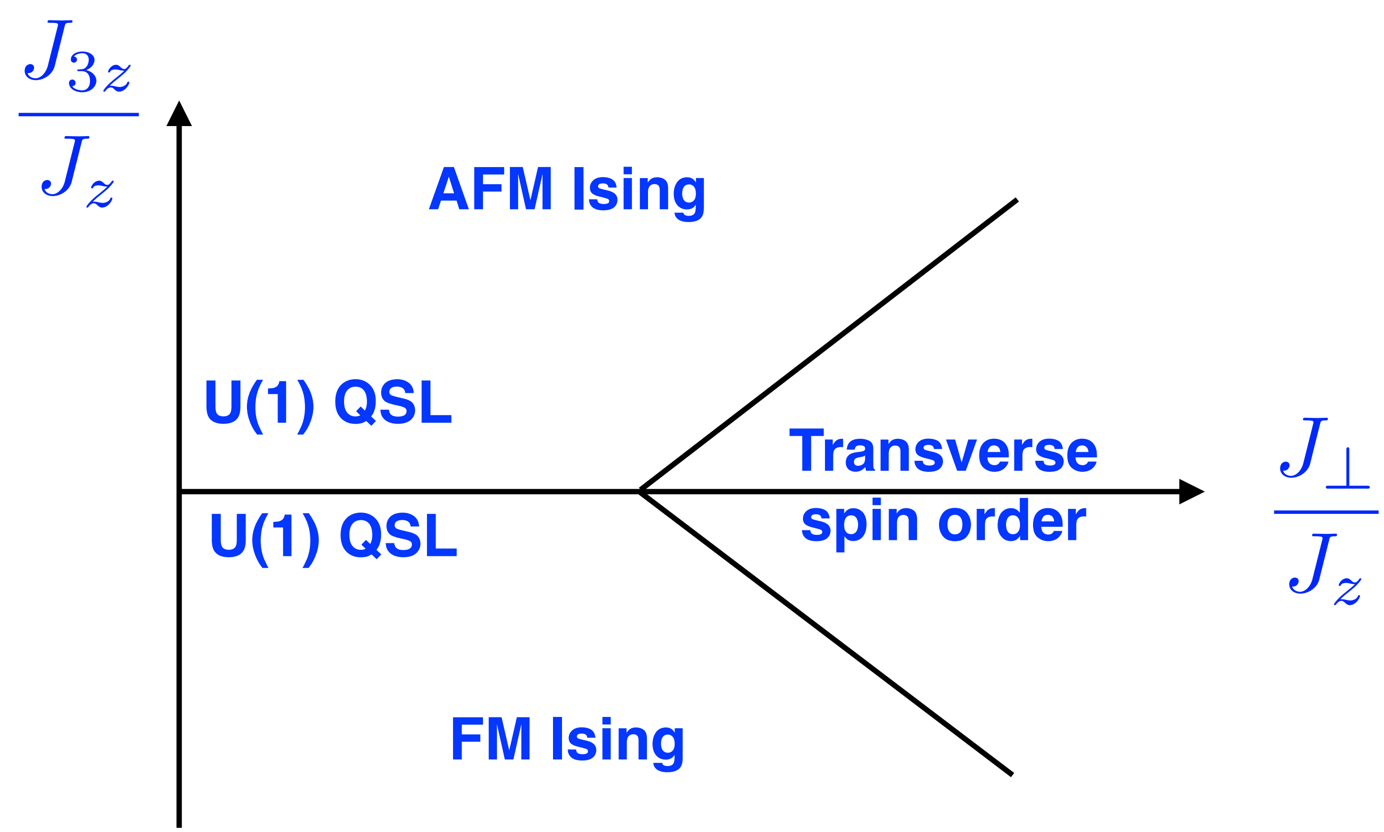
Emergent gauge photons are near the **suppressed pinch points**

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

Sign problem free model for quantum Monte Carlo



$$H_1 = \sum_{\langle ij \rangle} J_z \tau_i^z \tau_j^z - J_\perp (\tau_i^+ \tau_j^- + h.c.) + \sum_{\langle\langle\langle ij \rangle\rangle\rangle} J_{3z} \tau_i^z \tau_j^z,$$



schematic phase diagram

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.

Thank you !

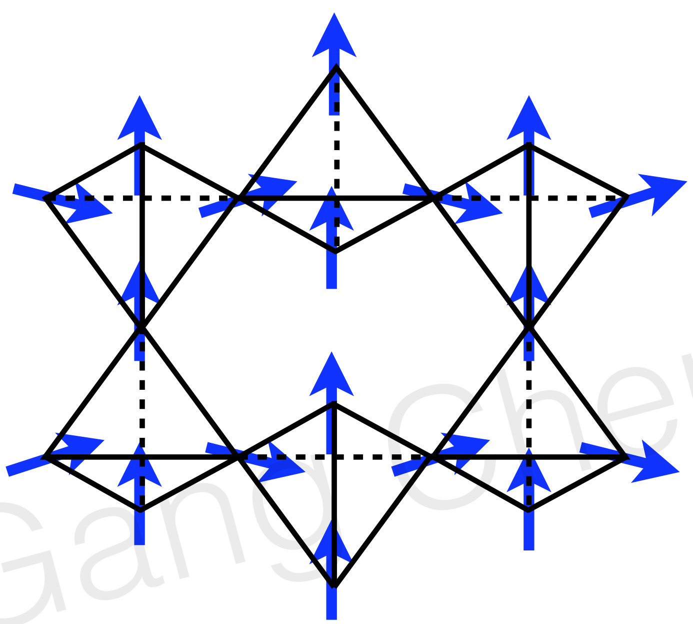
Email: gchen_physics@fudan.edu.cn

Implication for $Yb_2Ti_2O_7$

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

First-order magnetic transition in $Yb_2Ti_2O_7$

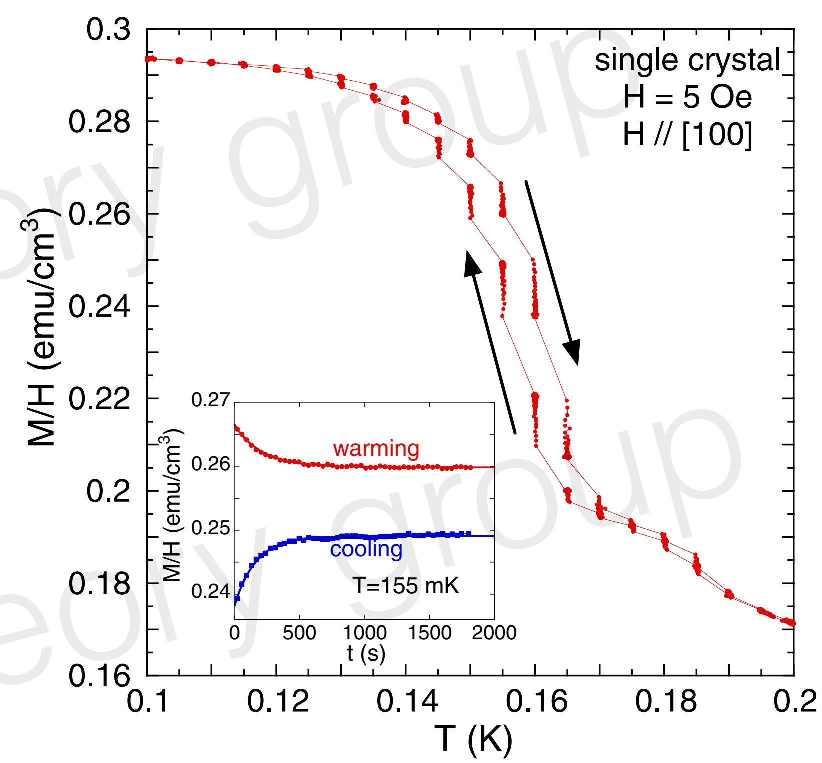
E. Lhotel,[1,*] S. R. Giblin,[2] M. R. Lees,[3] G. Balakrishnan,[3] L. J. Chang,[4] and Y. Yasui[5]



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

but with some spin reorientation

Savary, Balents, PRL, PRB 2012
Coldea, etc 2015, Gingras et al 2015



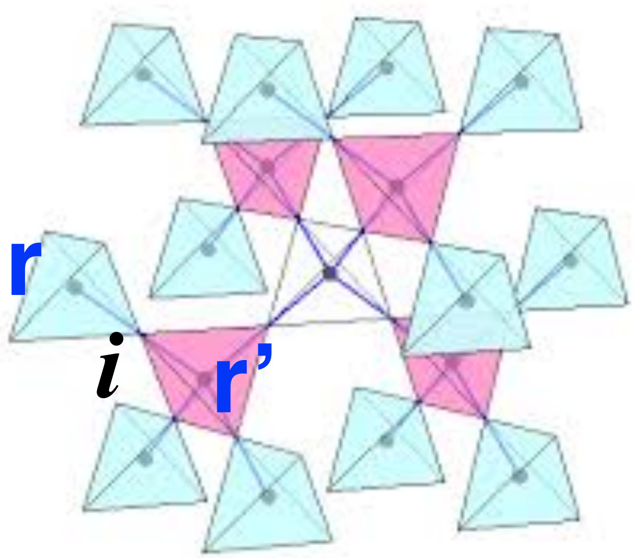
$Yb_2Ti_2O_7$

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

Theoretical framework: compact QED and electromagnetic duality

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

Lattice gauge theory formalism: technical part



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Hermele, Fisher, Balents, 2004

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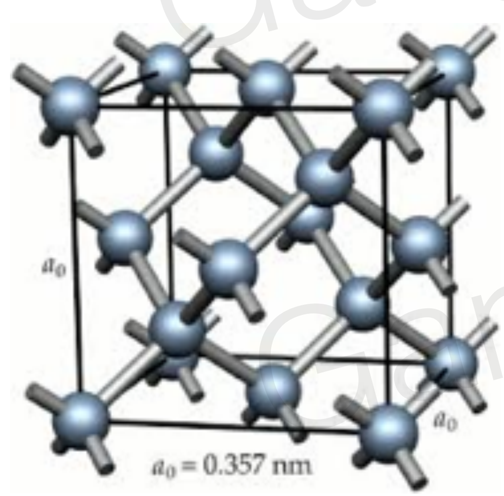
H_{LGT} captures the **universal properties** of QSI.



diamond lattice

- In an ordered state, <tau_z>!=0, <tau^+> is strongly fluctuating.
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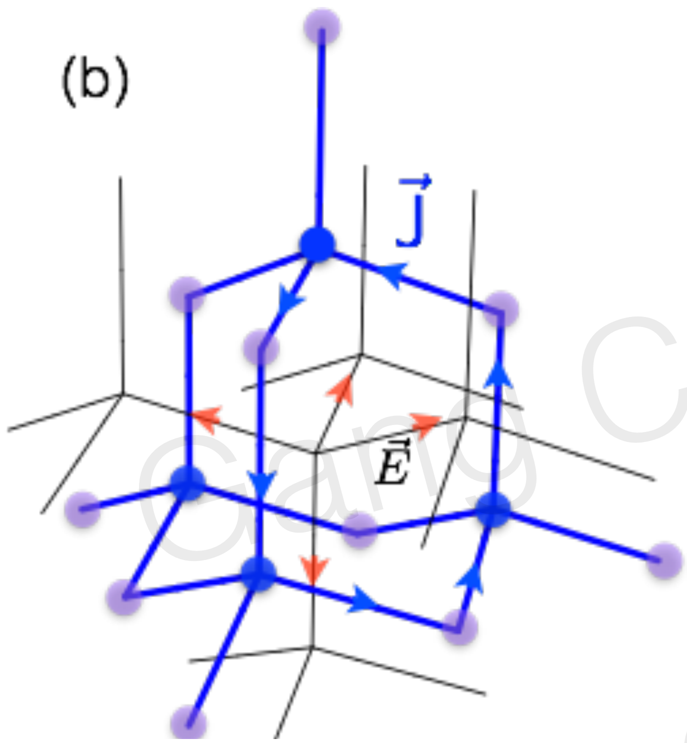
Electromagnetic duality

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

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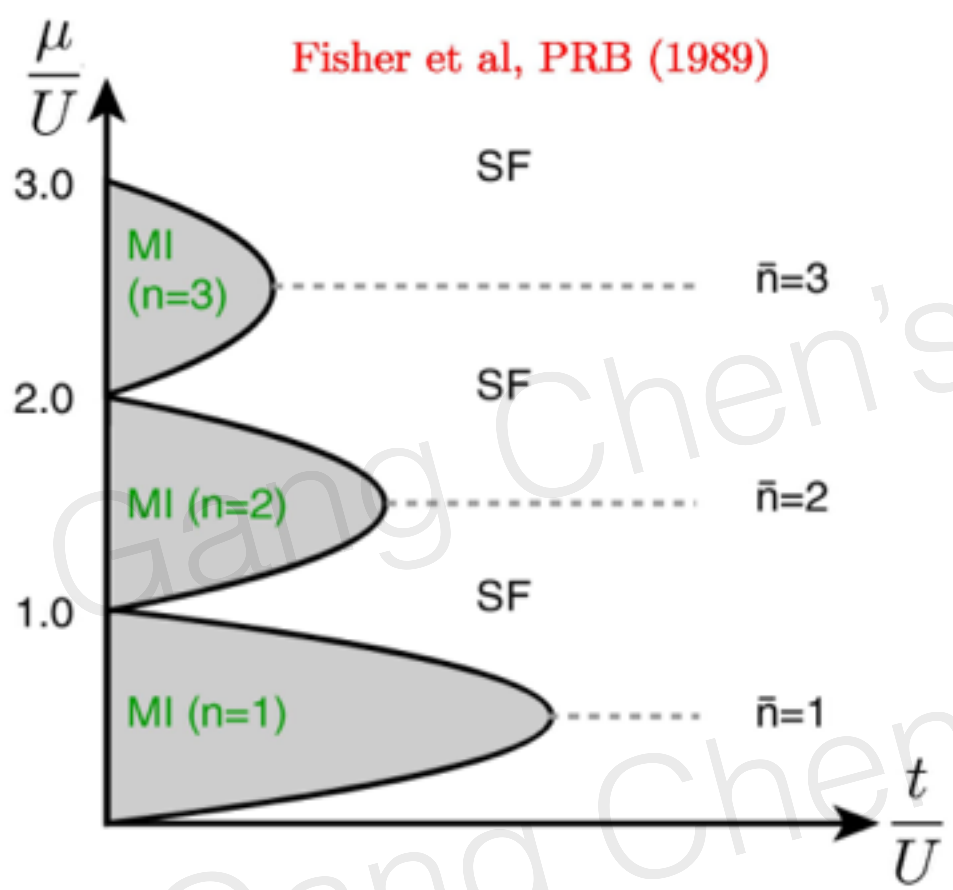
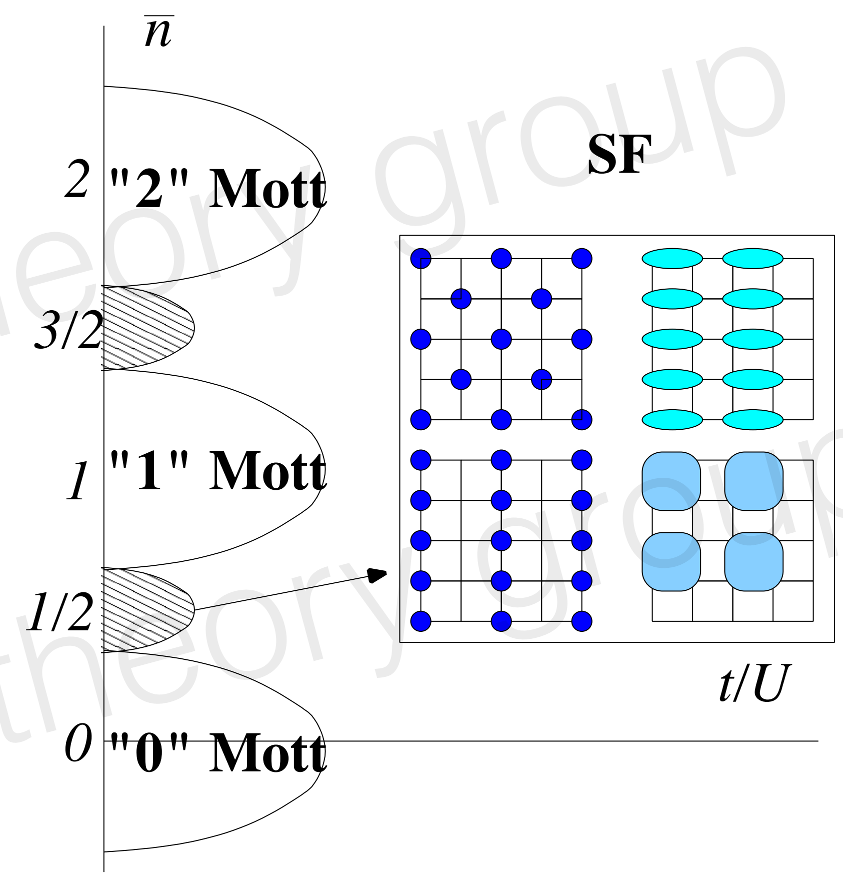
- **B magnetic field** is strongly fluctuating, the fluctuation of dual U(1) gauge field is weak.

Analogy with Boson-vortex duality



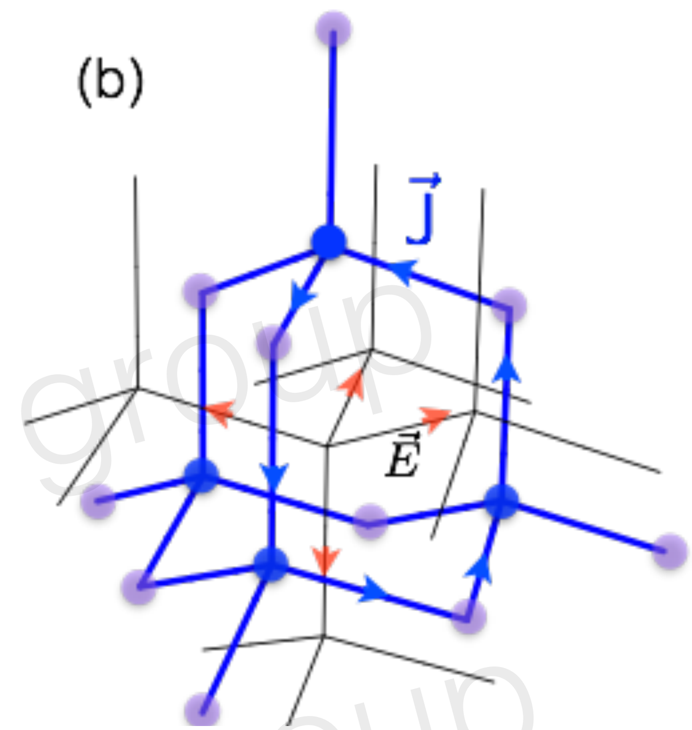


Balents, et al, 2005

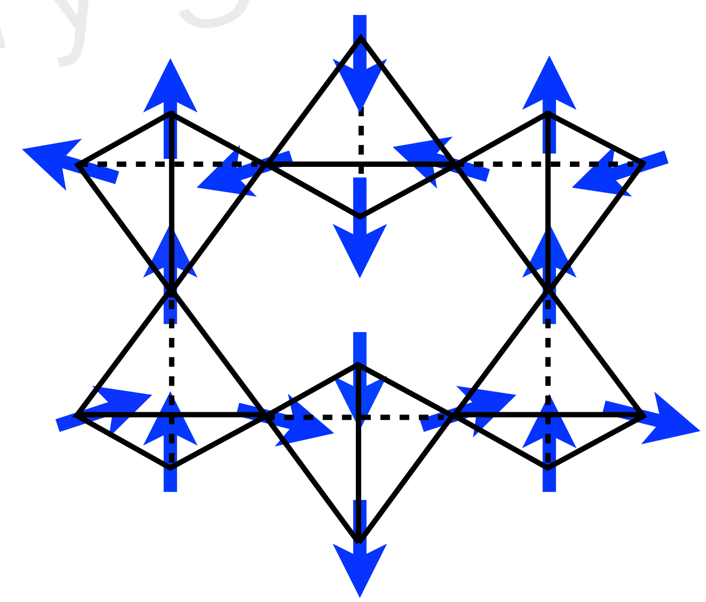
Physical observables are gauge invariant

- Monopole loop current defines the magnetic order

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

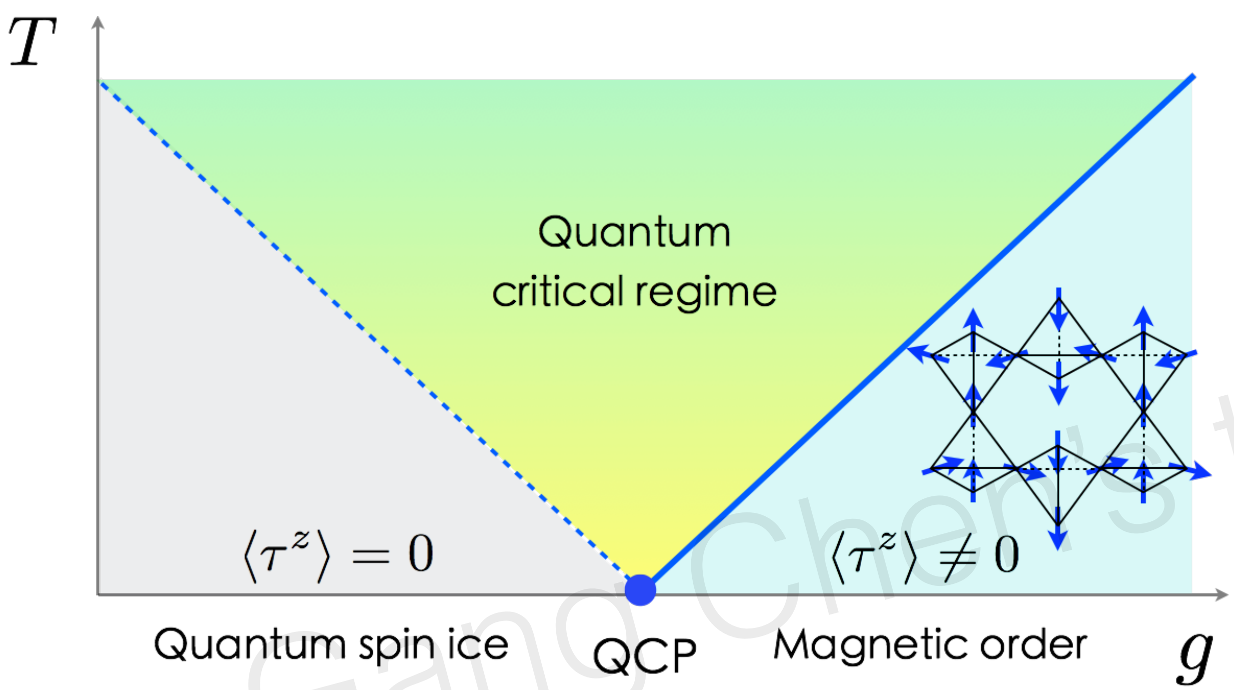


Proximate magnetic order generically breaks translation symmetry.



Q= 2Pi(001)

Critical theory for proximate ordering transition



g is the mass of the monopole

Determined by **projective symmetry group**

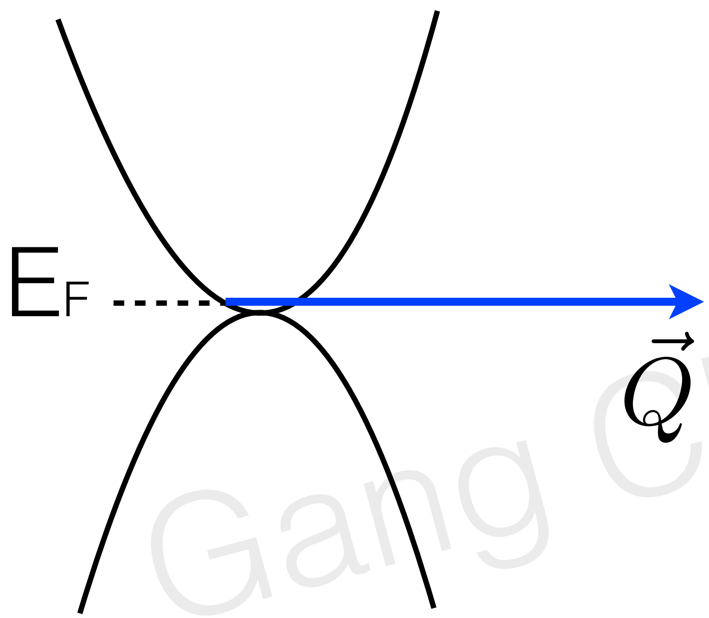
$$L = \sum_a \left[|(\partial_\mu - i\tilde{a}_\mu)\phi_a|^2 + m^2|\phi_a|^2 \right] + \frac{{F_{\mu\nu}}^2}{2}$$
$$+ u_0 (\sum_a |\phi_a|^2)^2 + \cdots,$$

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

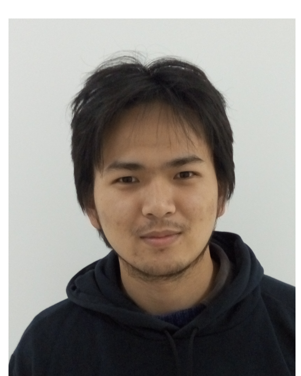
Ir conduction electron Fermi surface does not modify the critical property.



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