Connect Emergence to Reality:

“Magnetic Monopole” Condensation out of U(1) Topological Order

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OUTLINE

1. 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, PRB in press

2. Rare-earth triangular lattice quantum spin liquid: **$YbMgGaO_4$**

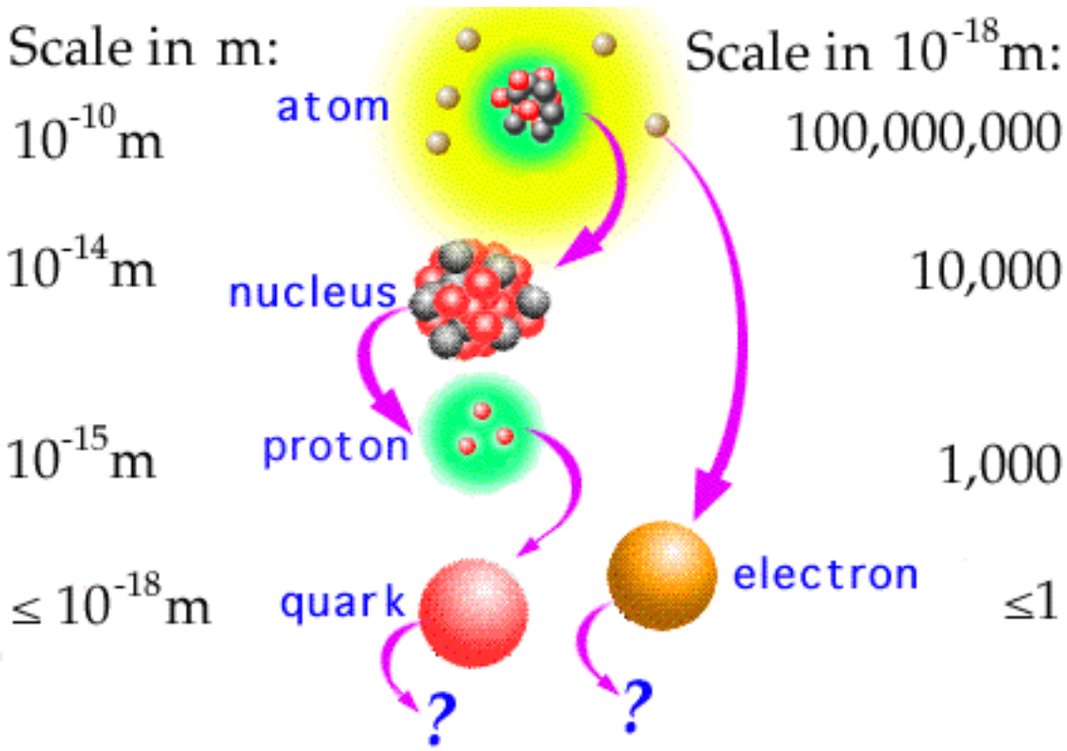
- To my best knowledge, this is the **first strong spin-orbit coupled** quantum spin liquid candidate with odd number of electrons per unit cell and effective spin-1/2 moment.

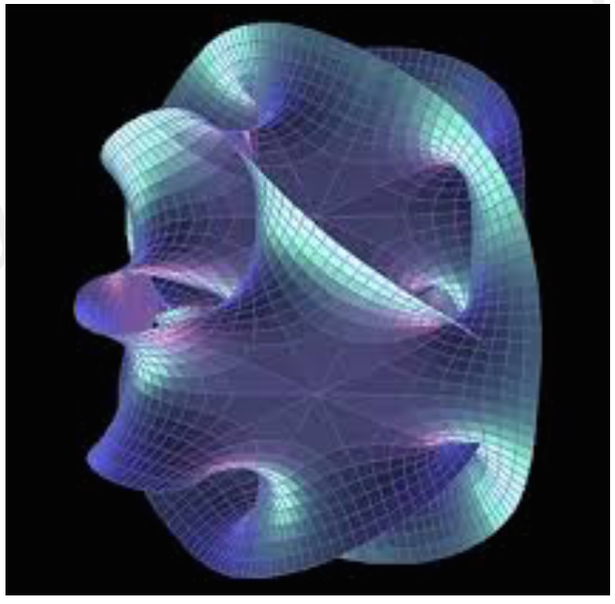
Yuesheng Li, Gang Chen*, …, Qingming Zhang*, PRL,115,167203 (2015)
Yaodong Li, Xiaoqun Wang, Gang Chen*, PRB, 94,035107 (2016)
Yao Shen, …., Gang Chen*, Jun Zhao*, arXiv 1607.02615
Yaodong Li, …., Gang Chen*, arXiv 1608.06445

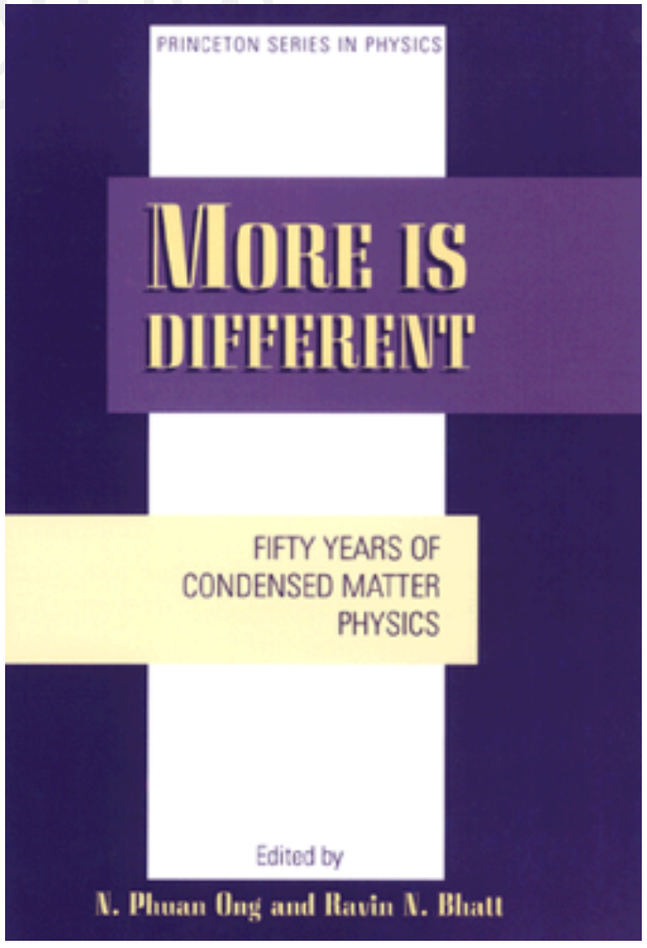
More works are coming up…..

復旦大學 FUDAN UNIVERSITY

Reduction vs Emergence





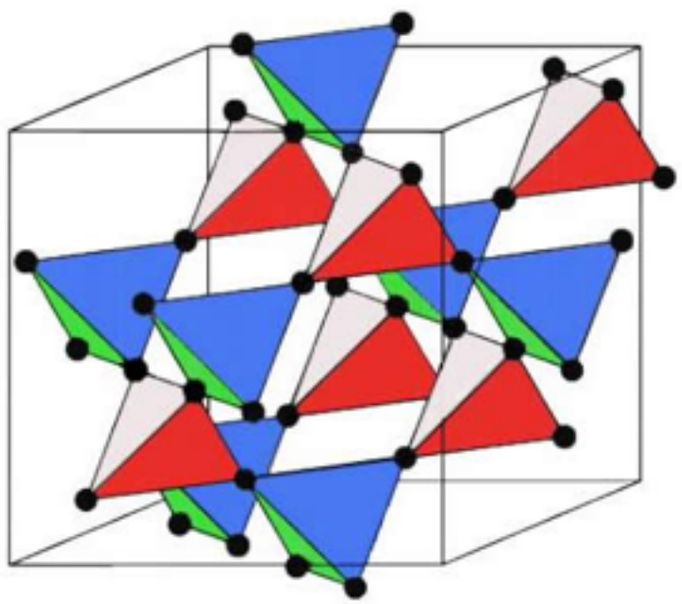


Condensed matter is full of emergence

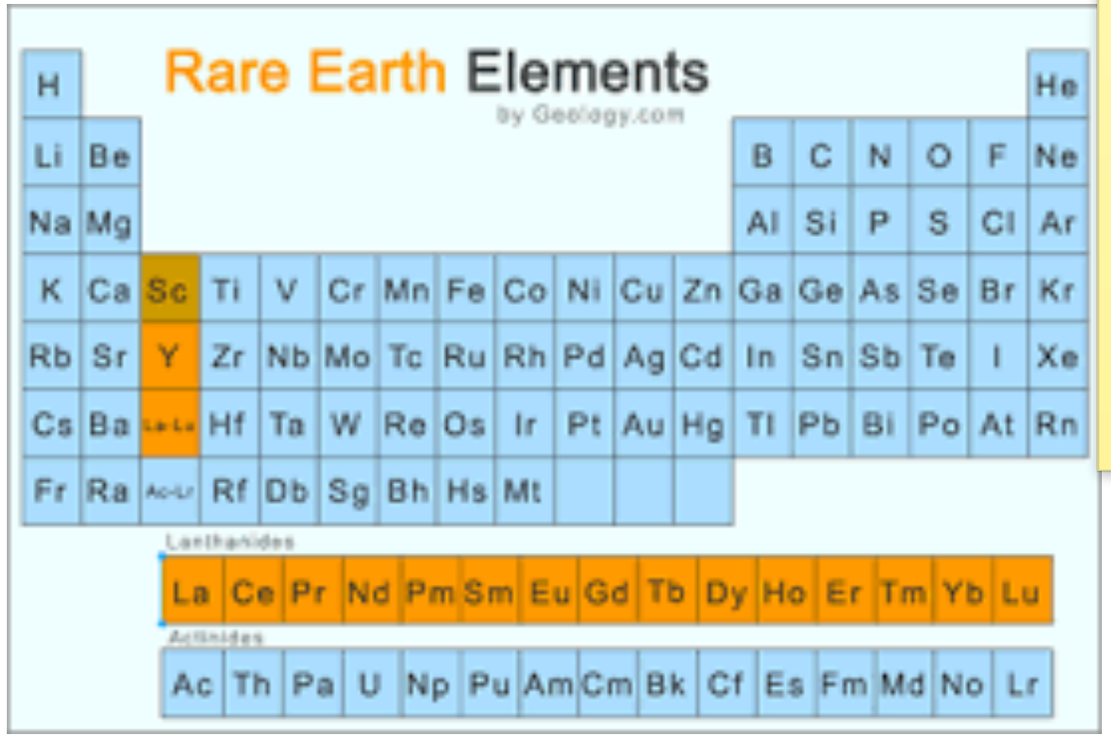
1. Monopole condensation out of U(1) topological order

- 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
spin ice system.

spin ice is realized
pyrochlore system
earth ions
form pyrochlore la
host the Ising spin
crystal field effect
points either into
the tetrahedron

The interaction be
AFM, it favor 2 sp
tetrahedra. This is
ice rule.

Beucase of the ar
position in water i
near it, 2 are close

Spin ice in rare-earth pyrochlo

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

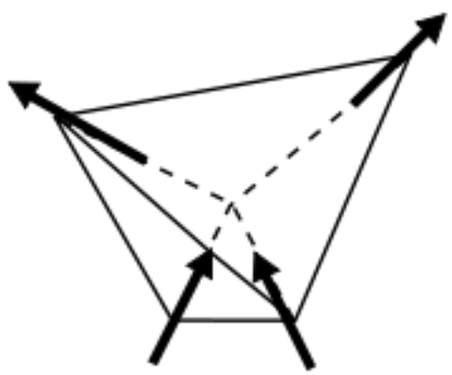
Castelnovo, Gingras, Moessner, Sondhi, Schiff
Penc, …….

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

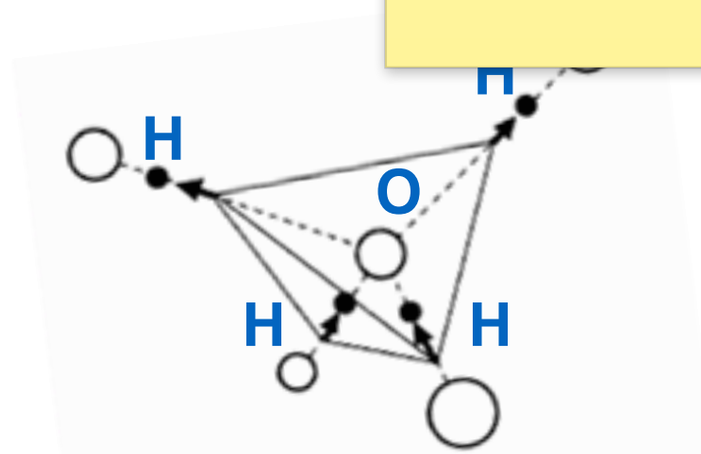
spin ice is realized in rare earth pyrochlore systems, where the rare earth ions
form pyrochlore lattice and
host the Ising spin. because of the crystal field effect, the ising spin points either into or out of the center of the tetrahedron

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.



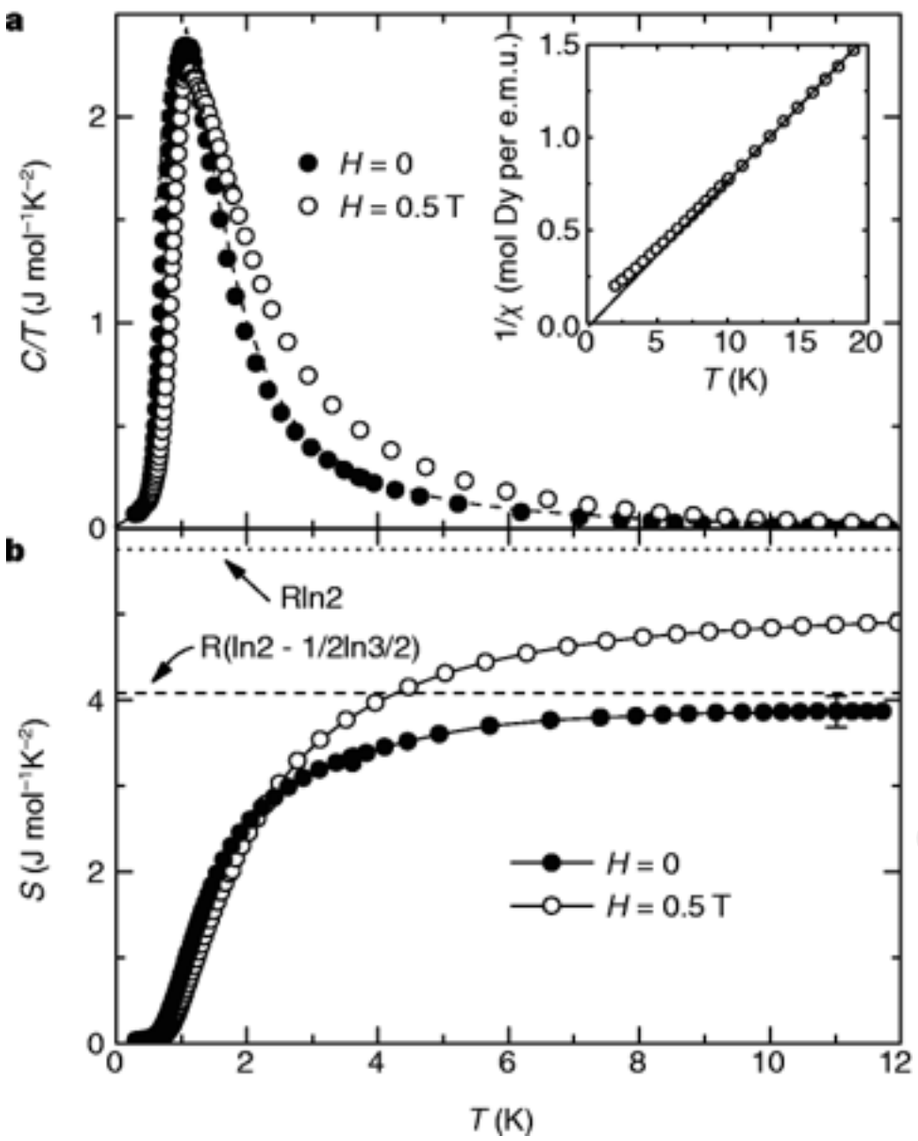
2-in 2-out
spin ice rule

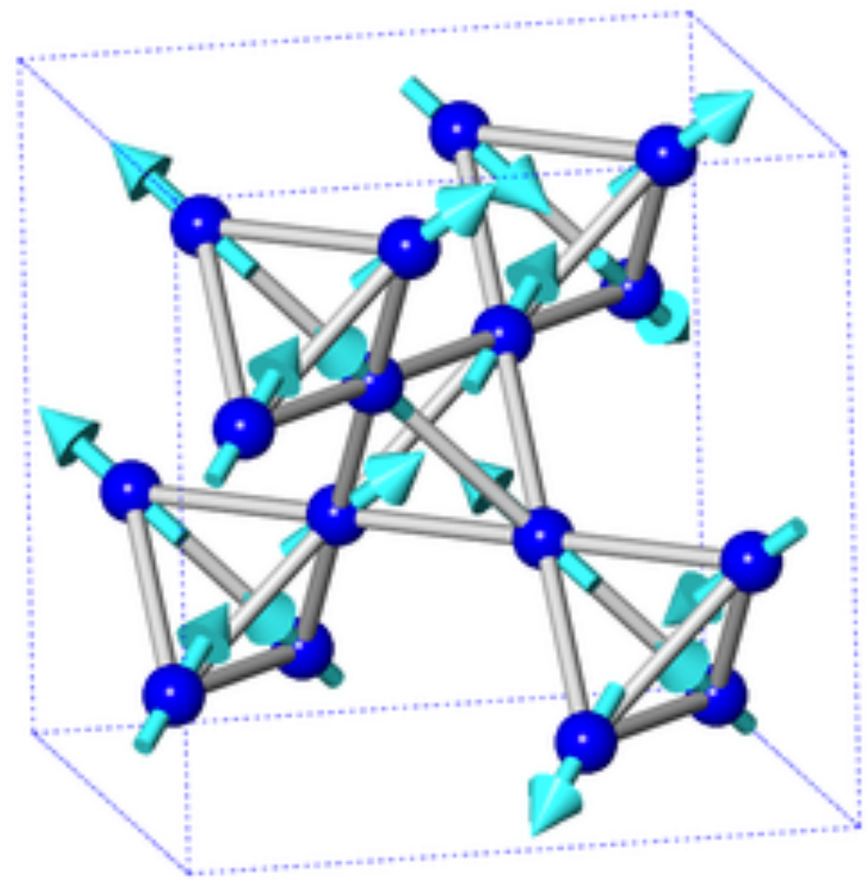


2-in 2-out
water ice rule

from wiki

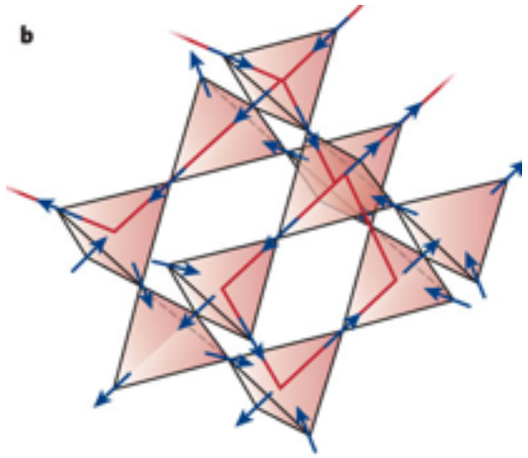
Classical spin ice



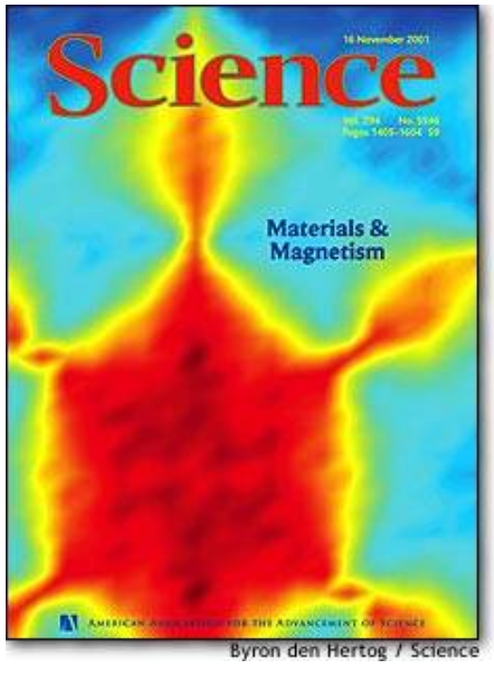


Pauling entropy in spin ice,
Ramirez, etc, Science 1999

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.



Byron den Hertog / Science

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

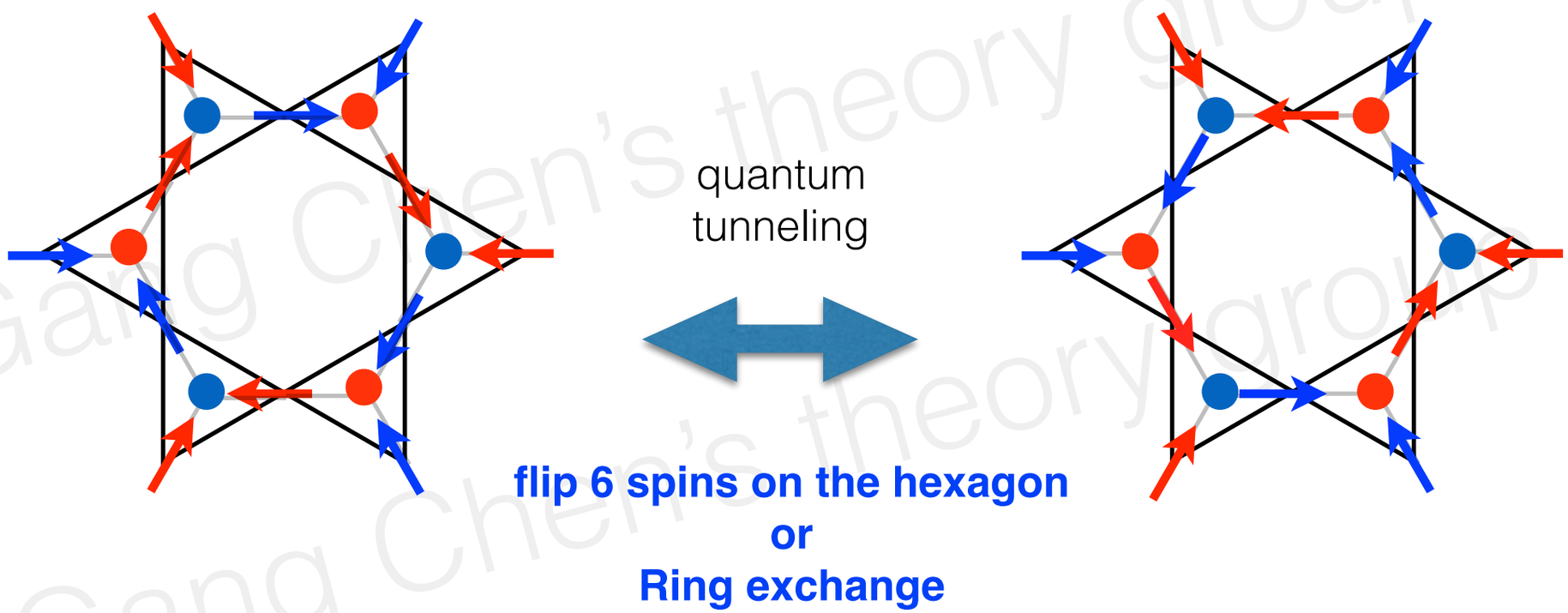
2. at T << Jzz, the system is th
fluctuating within the ice manif
classical spin ice and interestin
consequences. Many of them v
in nature and science.

Pinch points in spin correlation

Quantum fluctuation can leads 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….

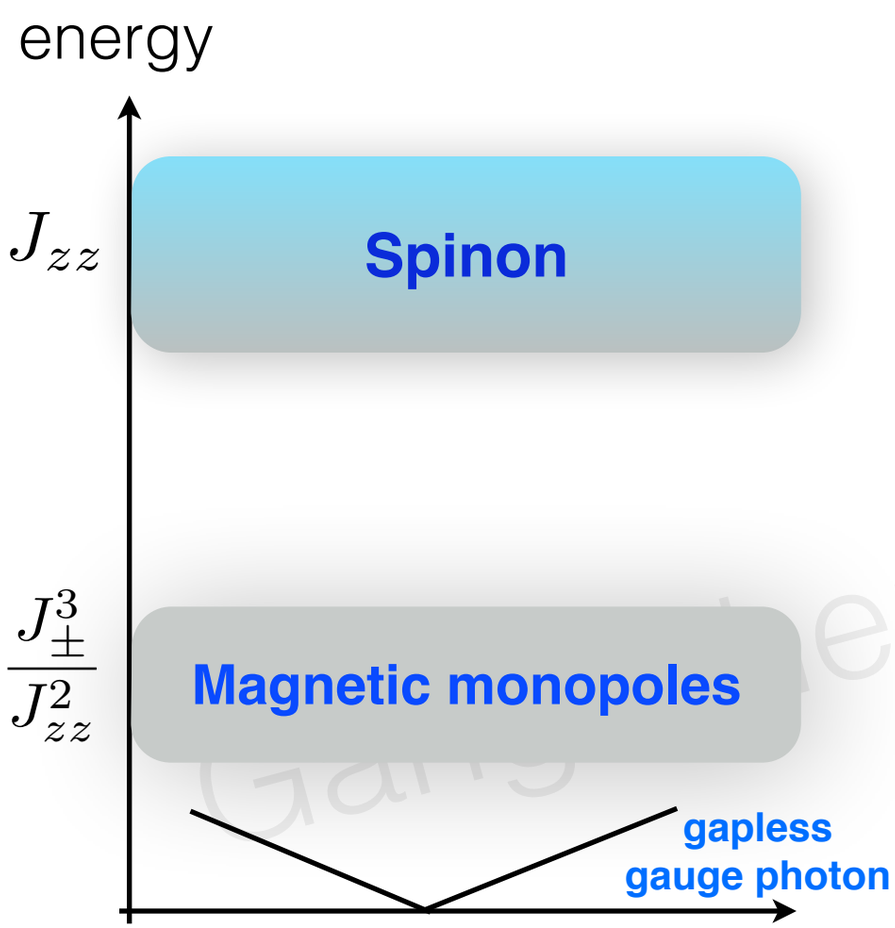


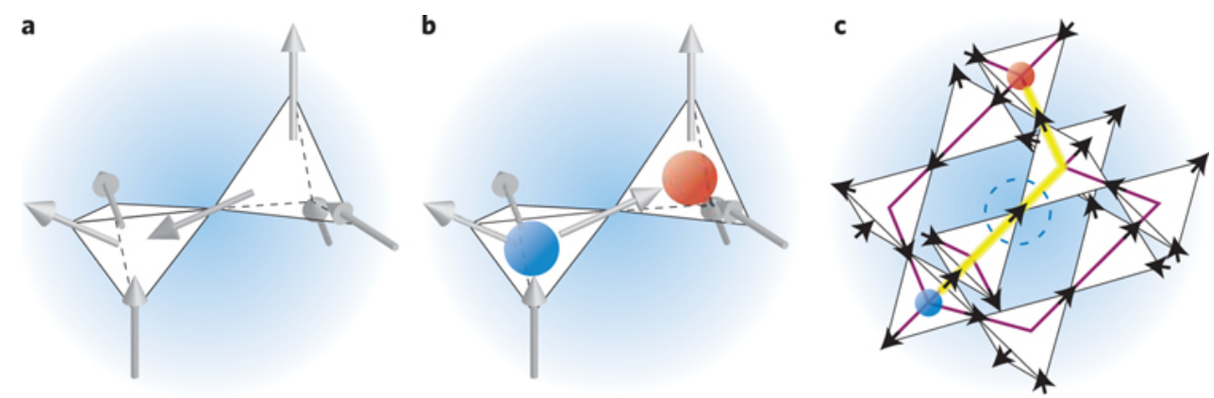
- Pretty much one can add any term to create **quantum** tunneling, as long as it is not too large to induce magnetic order, the **ground state** is a quantum spin ice !

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.

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 breakin

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

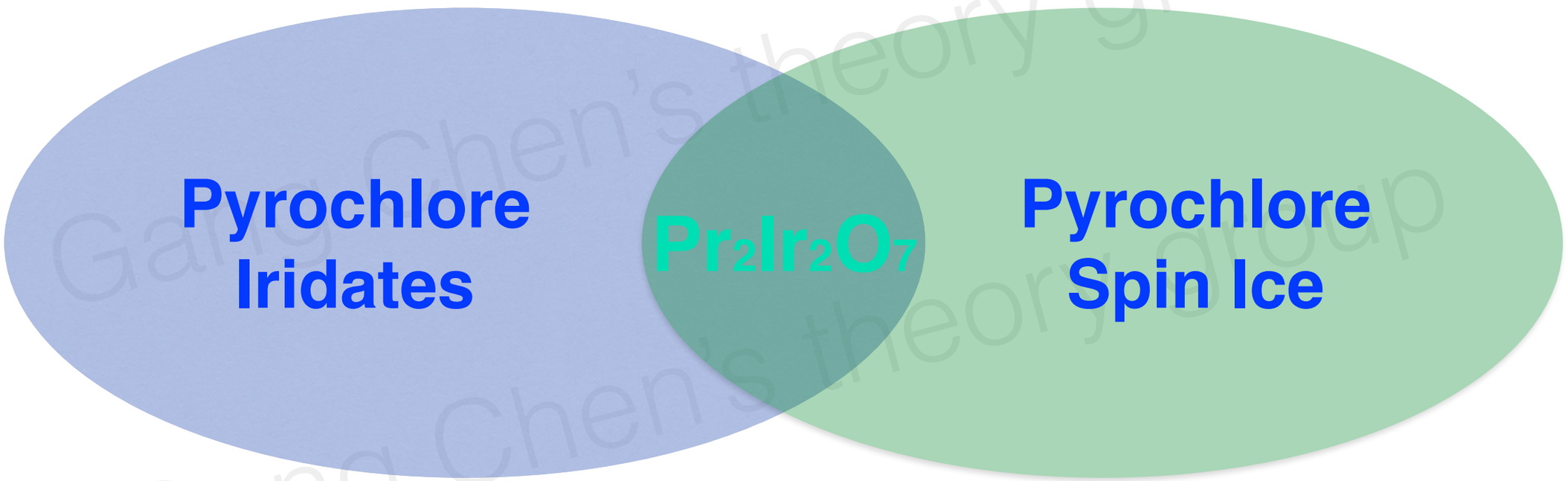
Yaodong Li, **Gang Chen,** Arxiv 1607

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

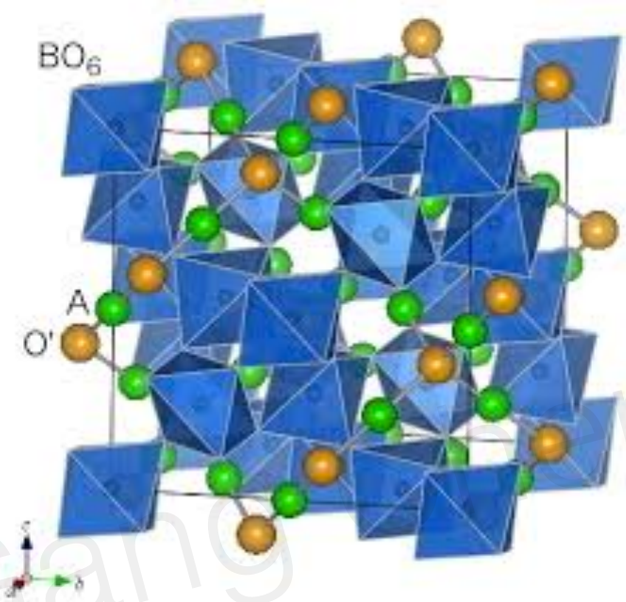


Over the years, there are a lot of effort in pyro
in this family of materials, almost all of them e
insulator xtion with some magnetic order, exc

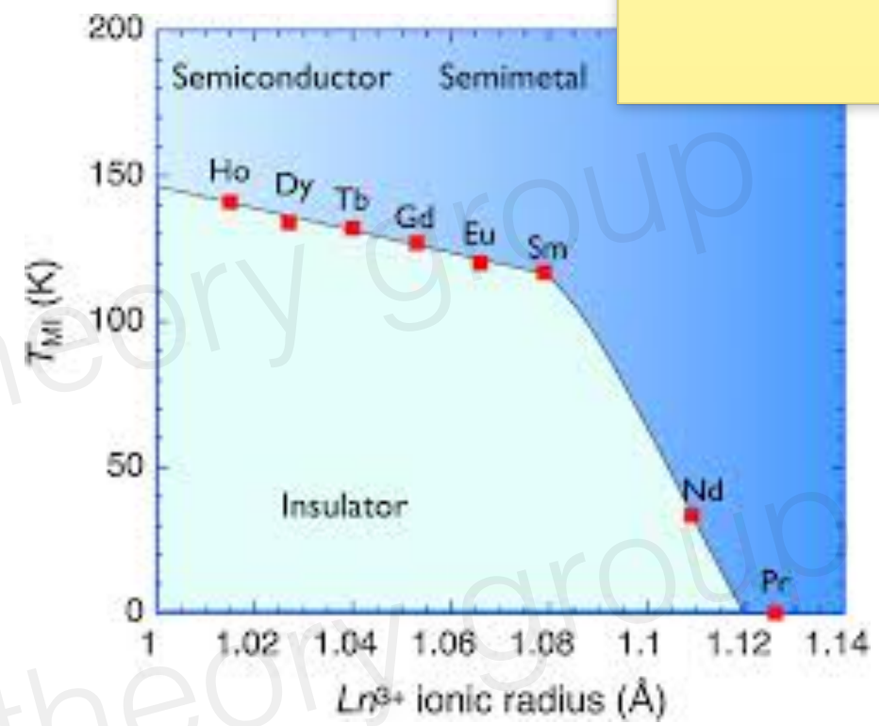
Pr2Ir2O7 is unique, it remains metallic, and so

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

Pyrochlore iridates: $Pr_2Ir_2O_7$



$R_2Ir_2O_7$



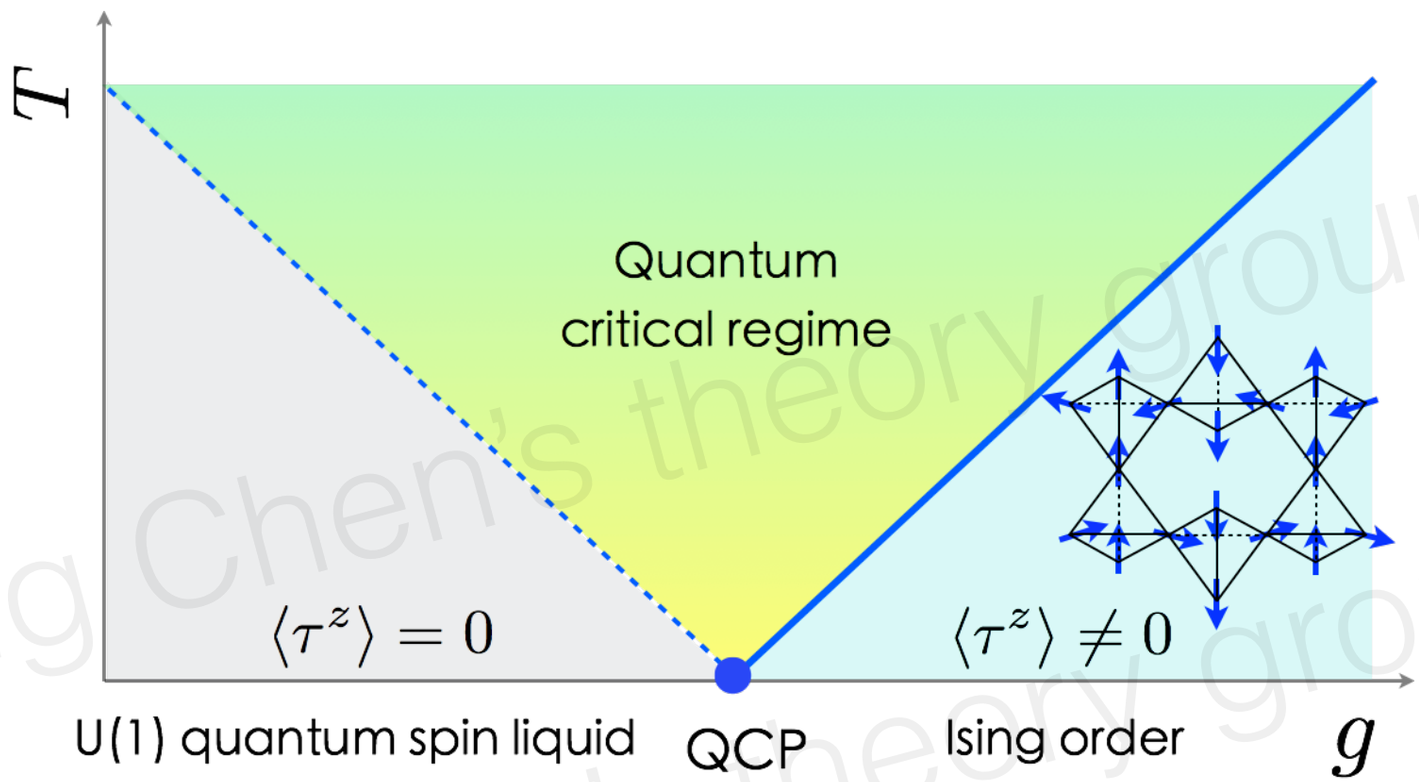
K Matsuhira, M Wakeshima, Y Hinatsu, S. Takagi
JPSJ, 2011

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

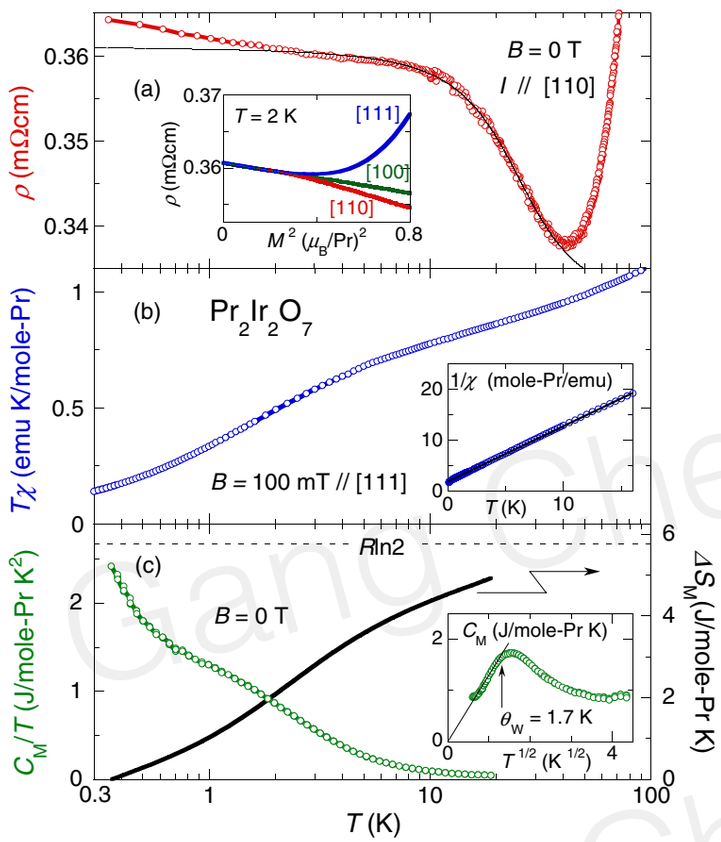
this is the take home message.



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.

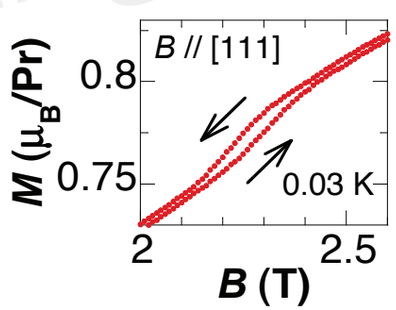
The Ir conduction electrons may drive the transition, but do not influence the nature of the phase transition.

$Pr_2Ir_2O_7$ a featureless disordered state near an ordered state



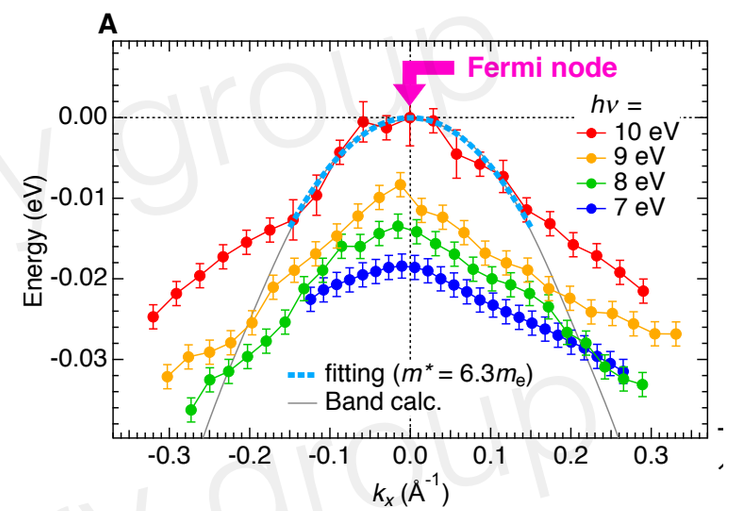
Nakatsuji, etc

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**,

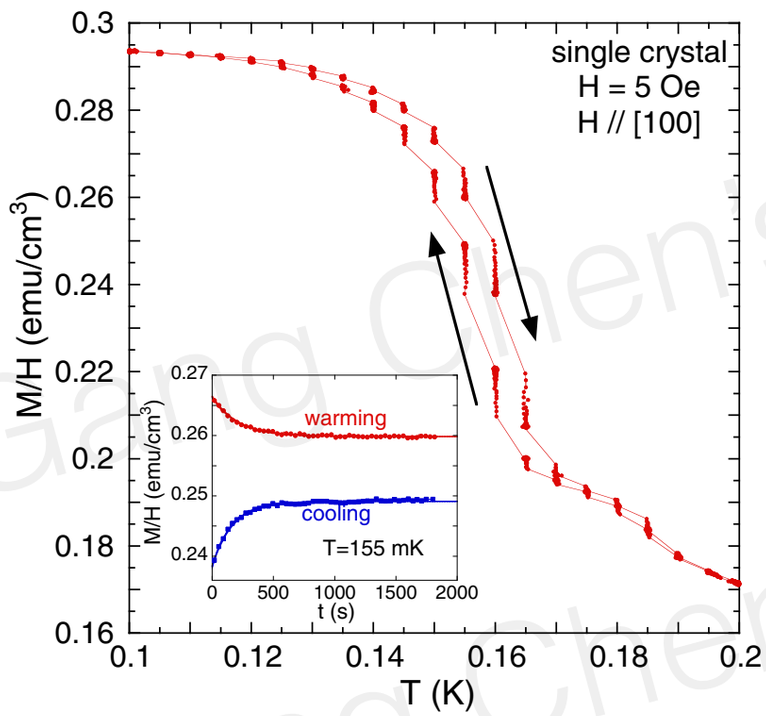
Recently, some samples are found AFM ordered.

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]



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

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,*]

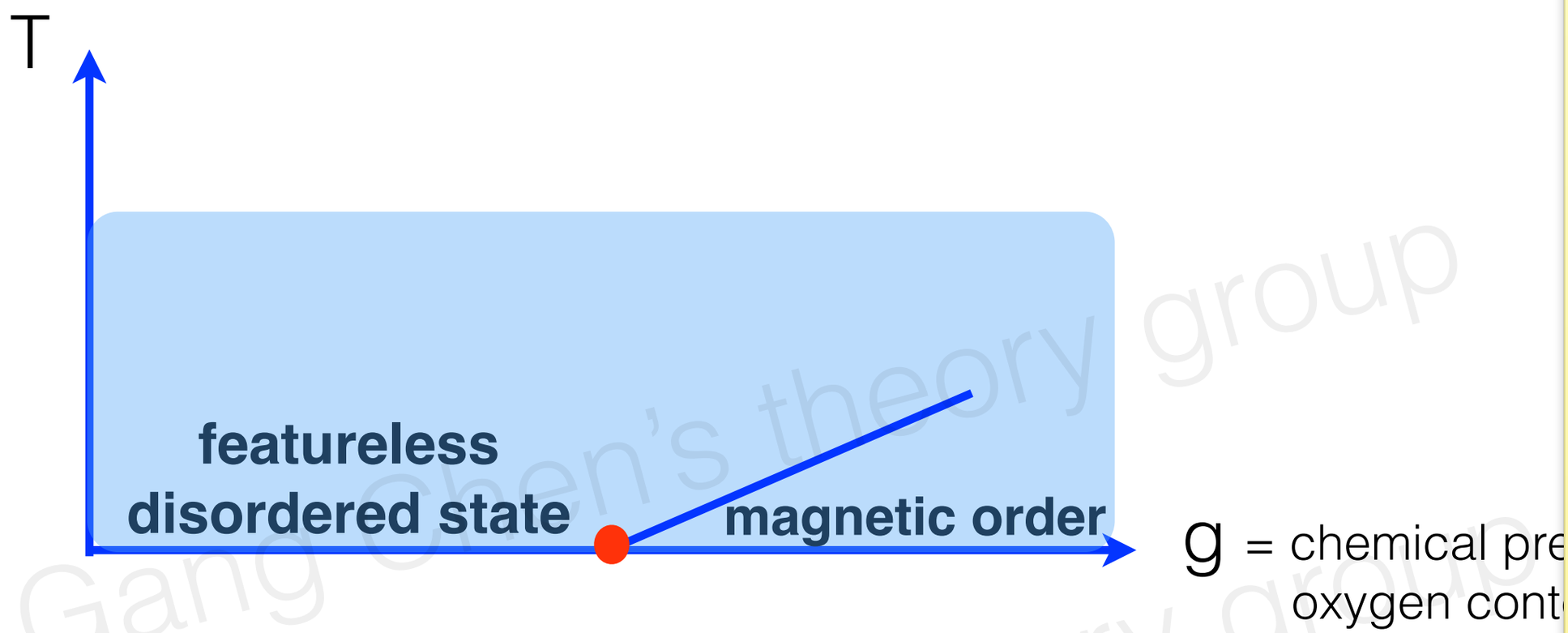
waves [14]. Although one neutron study [15] supported ferromagnetic order in $Yb_2Ti_2O_7$, intriguingly, the majority of neutron scattering measurements have reported a lack of magnetic ordering and the absence of spin waves at low fields in this material [16–18]. In a recent study,

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



- 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**?

this is a summary of the m

the system is probably nea
between a featureless disc
magnetic ordered state.

and the tuning parameter
cheical pressure, oxyten c

improtant questions are

what is
phase is more importatnt

disordred state is hard to

phase tarnsition is more v

magnetic order is easy to

One can use proximate ph
transiton

Insight from high-Tc superconductors

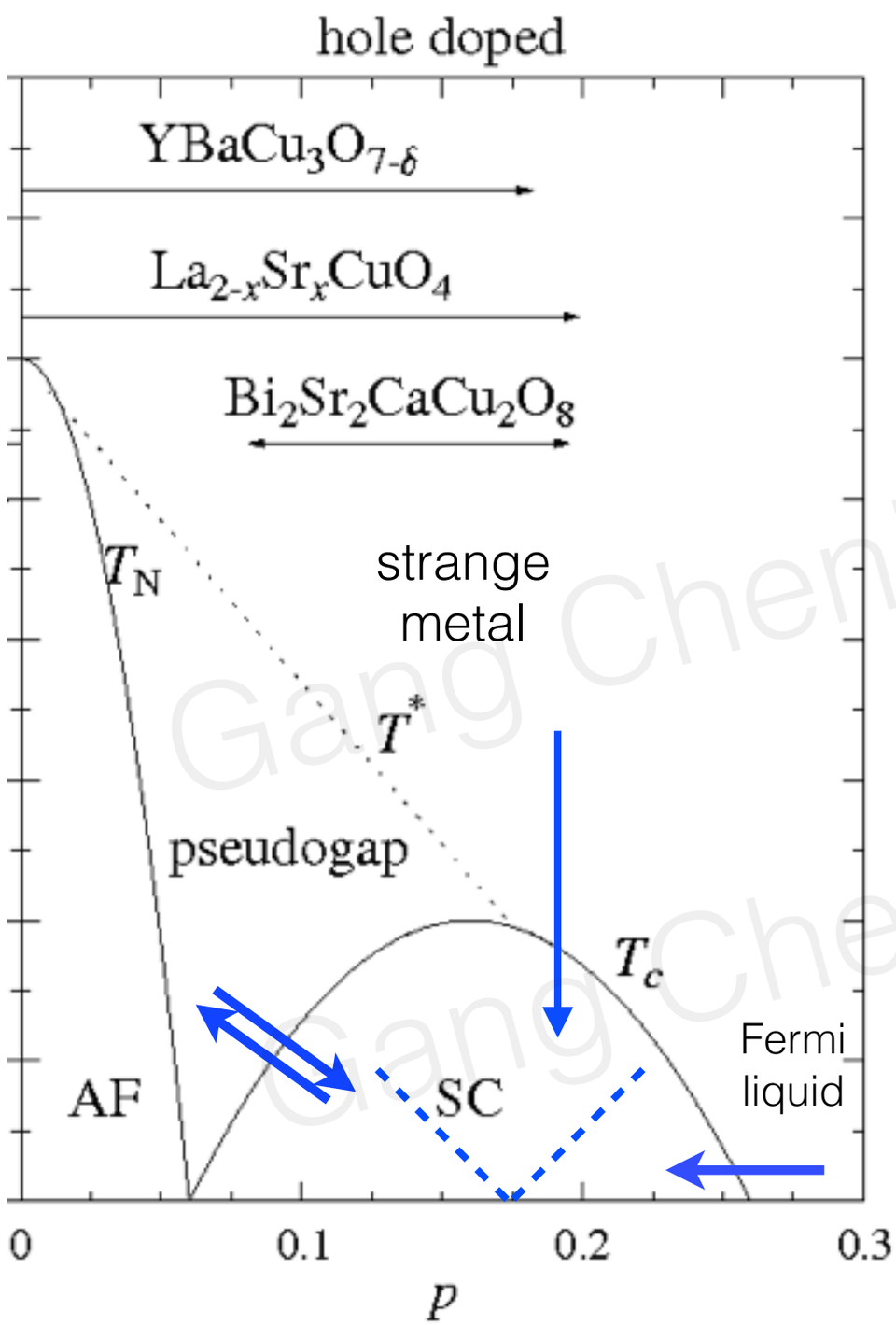


Figure from wiki

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?

To proceed, one
supercond.
i am not an exp
learned someth
fuchunzhang's t

this is the high t

one important q
between differe

there are a coup

one can for inst
obtain SC from
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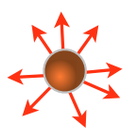
some people m

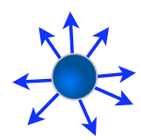
Confinement transition out of U(1) quantum spin liquid

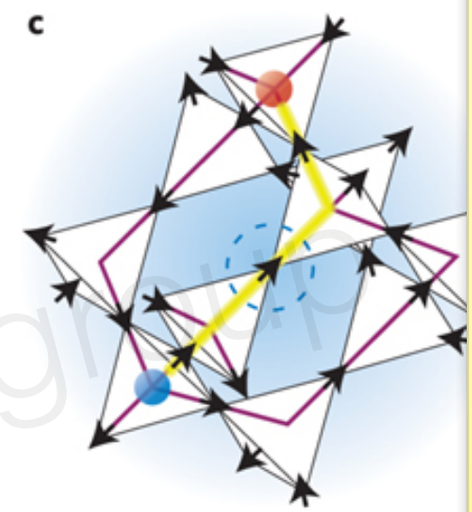
spinon



gauge photon

spinon





I want to porpose that the di
quantum spin liquid. and the
to ordered side is a confinem

in quntum spin ice, spinon a

in ordered pahse when tau_z
separate two spinous, isince
necessary effect the tau_z al
end it has a energy cost tha
separtin.

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

featureless disordered state
= quantum spin ice spin liquid

Spinons are deconfined.

Ising order

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.

Lattice gauge theory formalism: technical pa

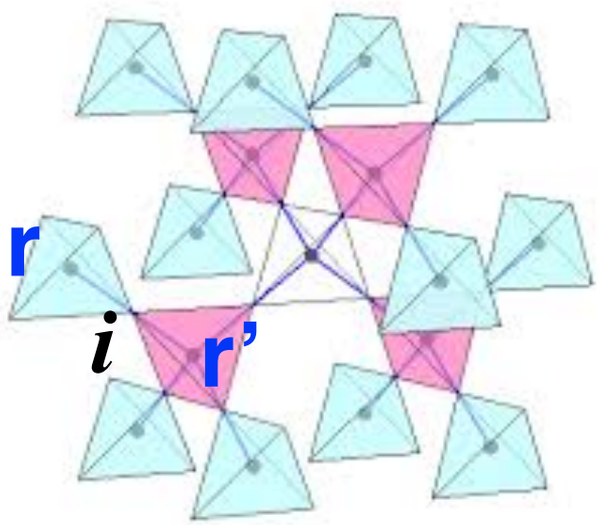
in the lattice gauge theory forr
the sz component is mapped
lattice electric field, while S+ ,
mapped to vector gauge potn

the system is described by a l
gauge theory on the diamond
formed by the center of the py

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

IN the gauge langue, in a orde
E is static, is storng fluting, th
magnetic mono is concedes, v
confined the electric charge.

the background monopole co
disrupts the free motion of the
the spinons are confined.



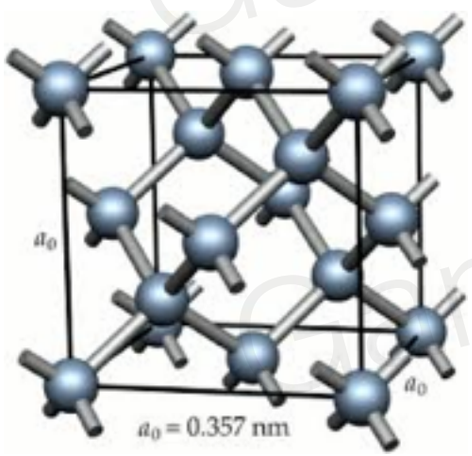
$$E_{\mathbf{rr}'} \sim \tau_i^z, e^{iA_{\mathbf{rr}'}} \sim \tau_i^+$$

Hermele, Fisher, Ba

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

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

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).

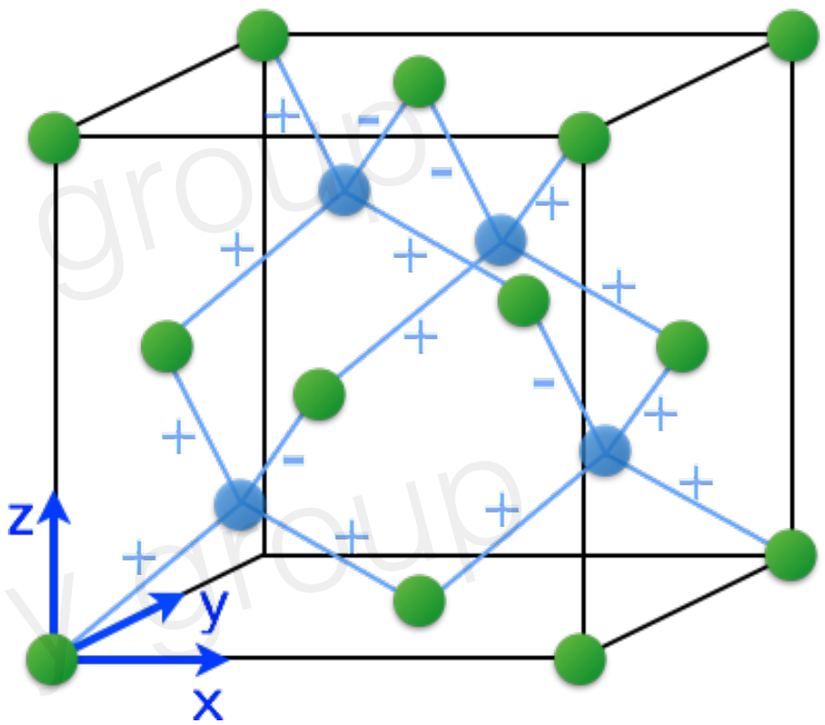
nt and the
on.

s-vortex duality.

Electromagnetic duality

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

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



monopole hopping on
dual lattice

Motrunich, Senthil 2005,
Bergman, Fiete, Balents 2006

Proximate magnetic order generically
breaks translation symmetry

this is a bit technical.

I will explain by analogy

Implication for experiments

it turns out the magnet
Pr22y is a prxoiamte p
the state is q=2pi AFM

while YTO magnetic st
not proximate to QSI.
the tasniont is 1st orde
thati is what the obser

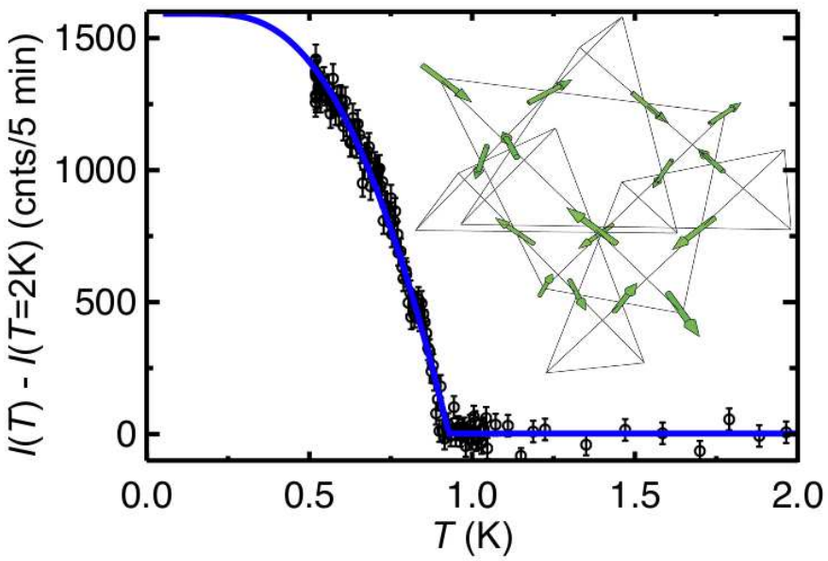
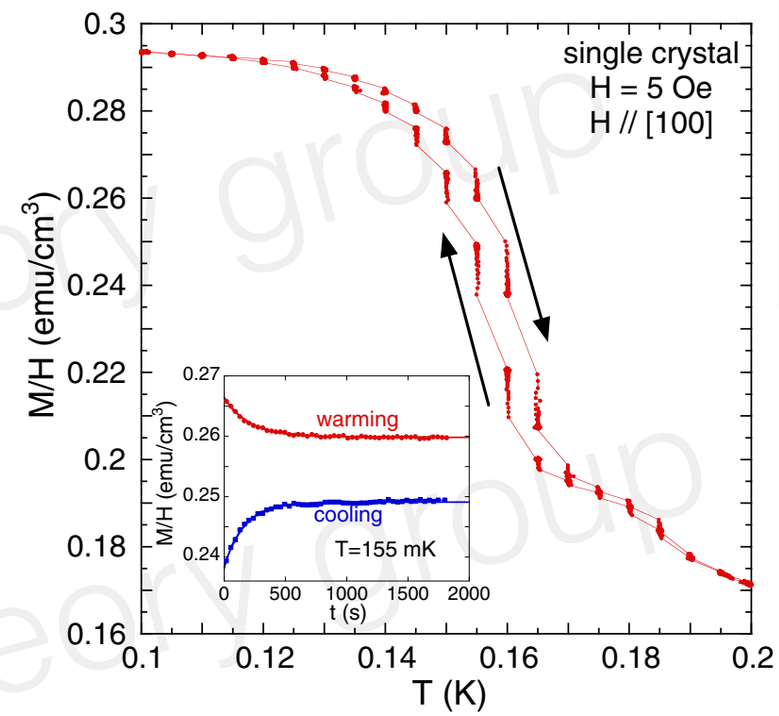


FIG. 2. (color online) Temperature dependence of elastic neutron scattering intensity of $Pr_{2+x}Ir_{2-x}O_{7-\delta}$ at the position of the $\mathbf{q}_m = (100)$ reflection. The intensity measured at $T = 2$ K was subtracted as a background. Curve: Ising mean-field theory fit to the data, which yields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

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]



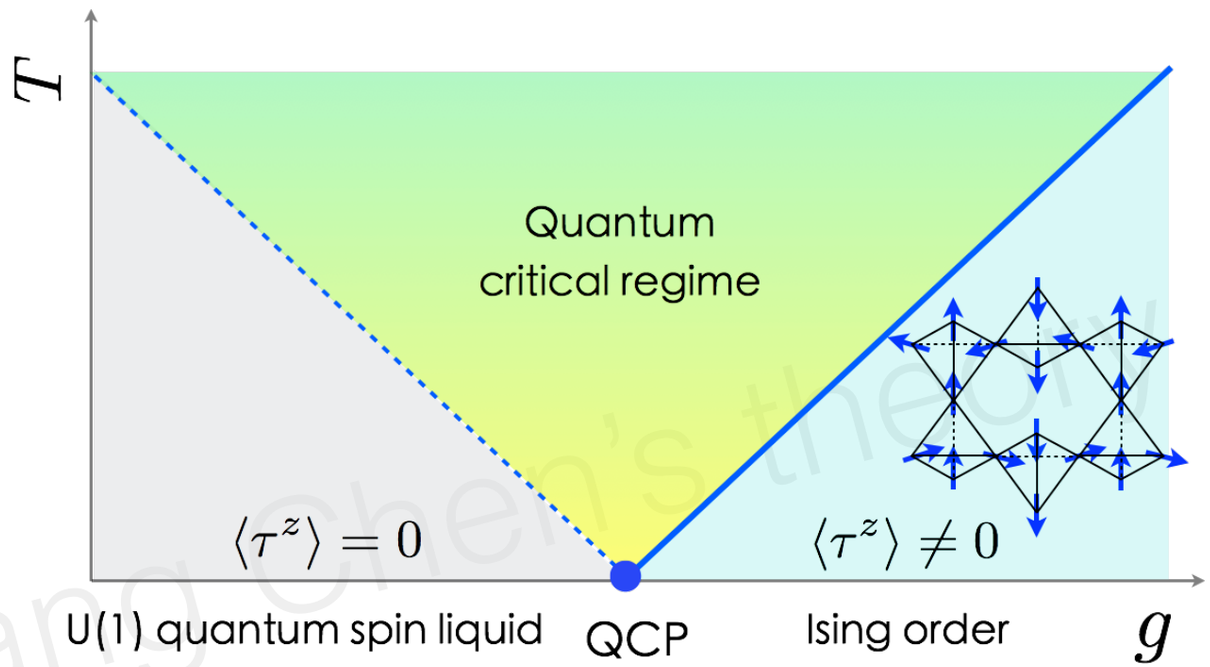
Magnetic order is discovered in some samples. (MacLaughlin, etc, 2015)

$Yb_2Ti_2O_7$

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



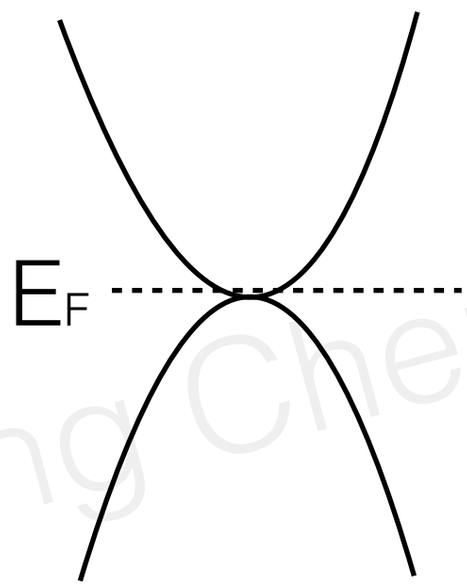
g is the mass of the monopole

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

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



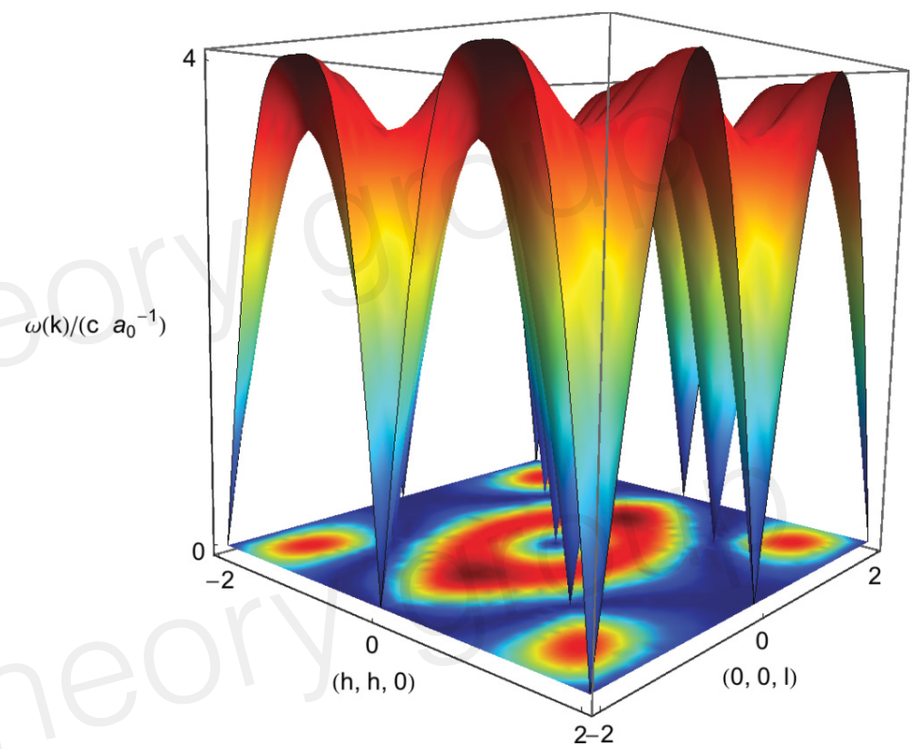


Fig from Benton, etc, PRB 2012

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.

2. Rare-earth triangular lattice quantum spin liquid: **$YbMgGaO_4$**

Yuesheng Li, Gang Chen*, …, Qingming Zhang*, PRL,115,167203 (2015)
Yaodong Li, Xiaoqun Wang, Gang Chen*, PRB, 94,035107 (2016)
Yao Shen, …., Gang Chen*, Jun Zhao*, arXiv 1607.02615
Yaodong Li, …., Gang Chen*, arXiv 1608.06445

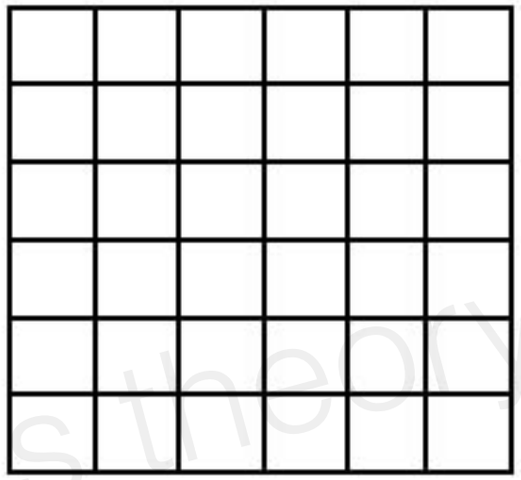
More works are coming up…..

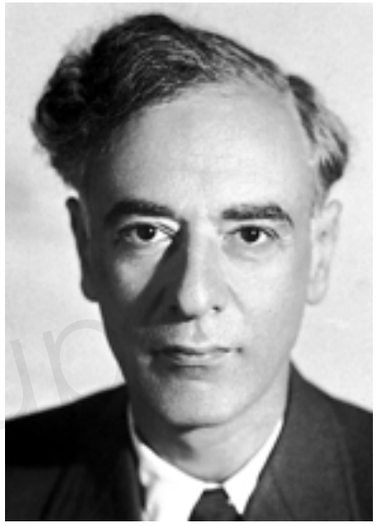
Outline

- A general introduction to quantum spin liquids
- Spinon Fermi surface U(1) quantum spin liquid
- Rare earth triangular lattice quantum spin liquid and experiment prediction
- Control spinons in a quantum spin ice U(1) quantum spin liquid

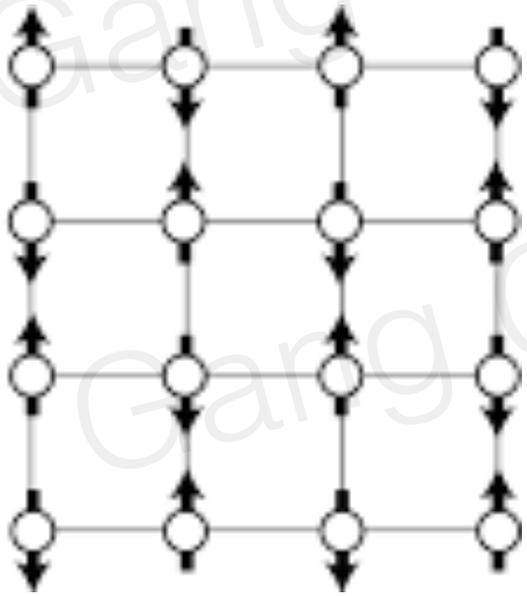
Neel vs Landau (1930-40s)

Neel

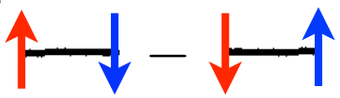




Landau



$$H = J \sum_{\langle ij \rangle} \mathbf{S}_i \cdot \mathbf{S}_j$$

Spin singlet $= \frac{1}{\sqrt{2}}\Big[$  $\Big]$

P. W. Anderson

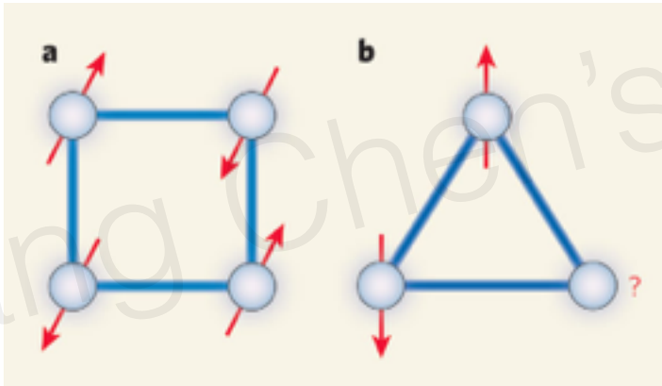
The idea of quantum spin liquid (1973)

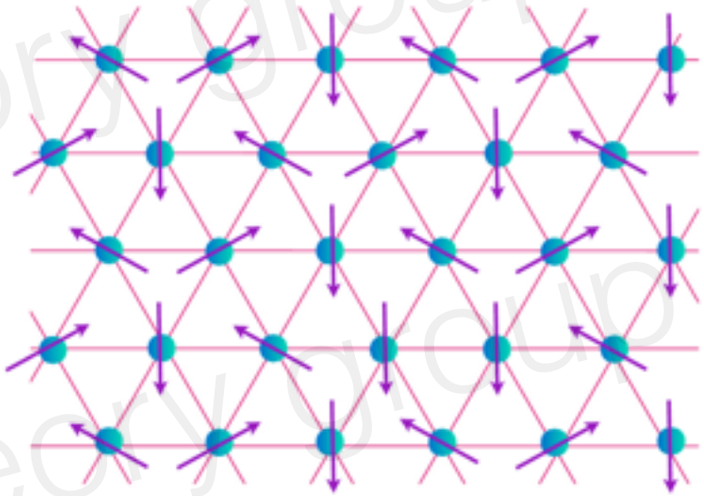
it is very il
motivation

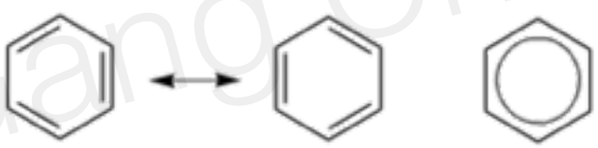
RESONATING VALENCE BONDS: A NEW KIND OF INSULATOR?*

P. W. Anderson

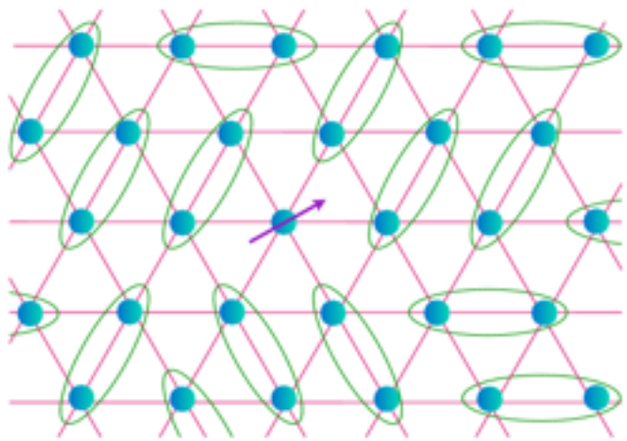
type would be insulating; it would represent an alternative state to the Néel antiferromagnetic state for S = 1/2. An estimate of

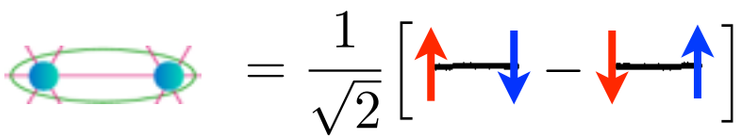




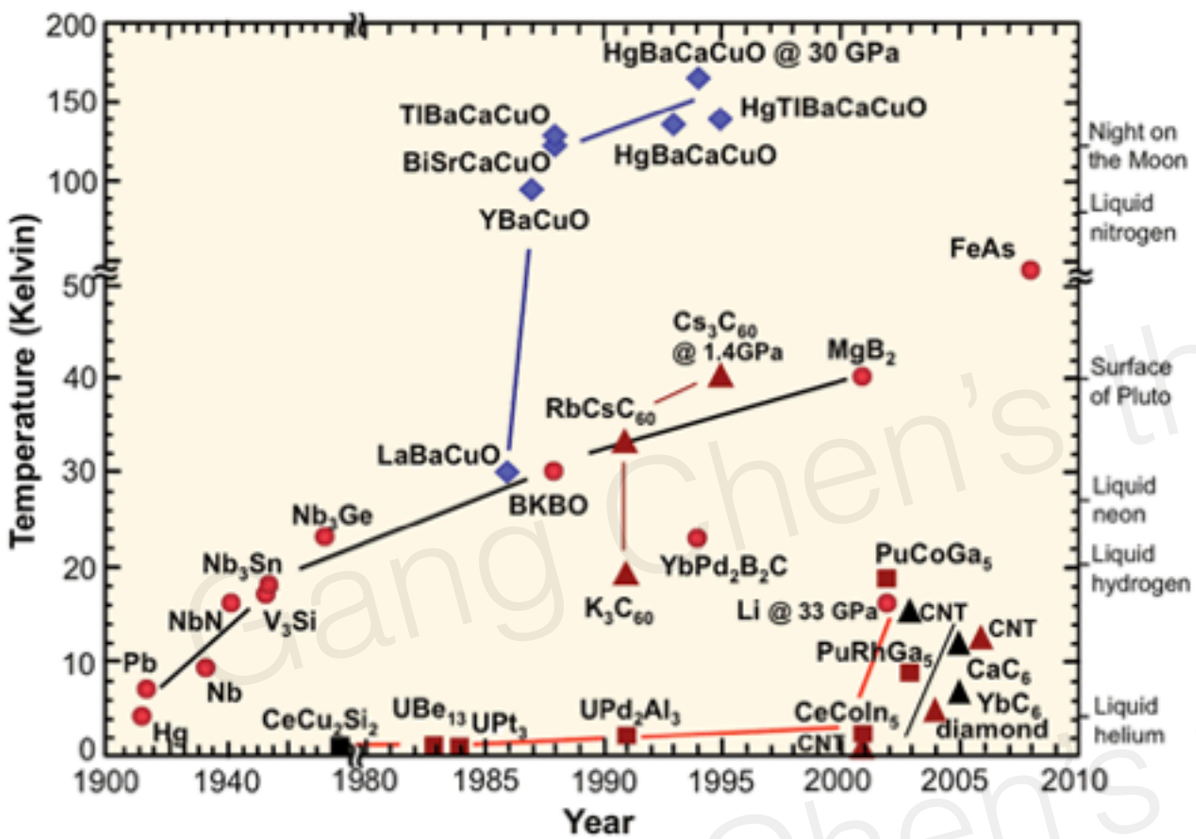


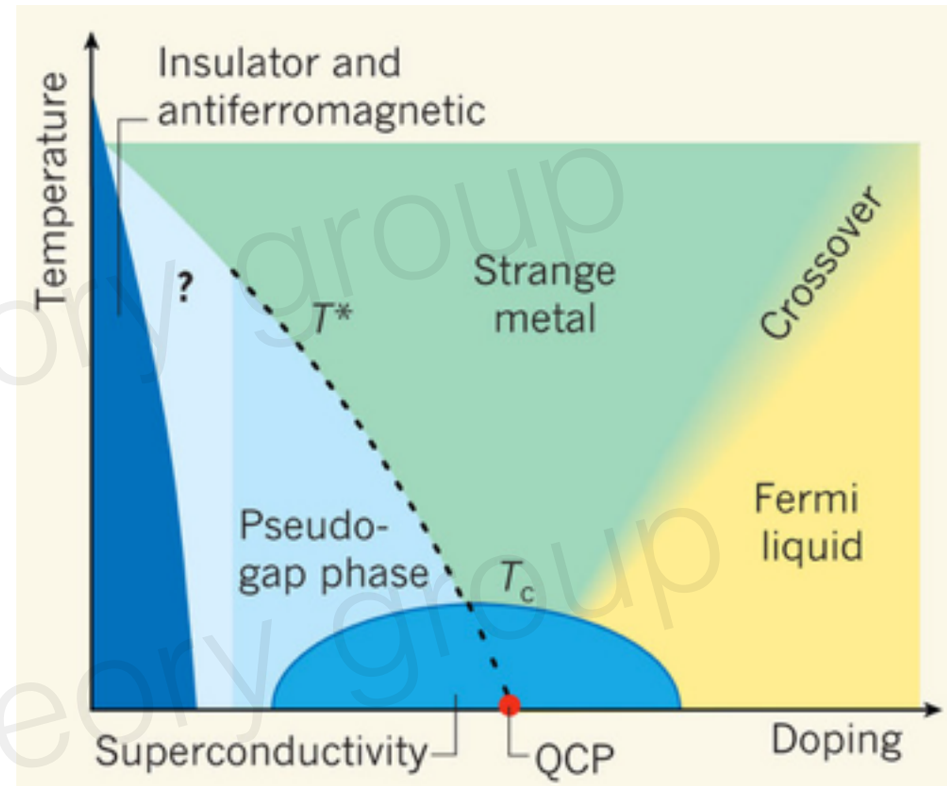
Pauling's RVB wavefunction
for Benzene molecule



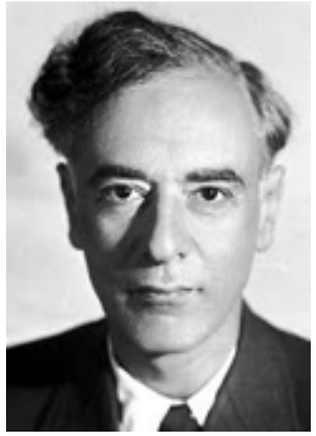


High temperature superconductivity (1986)



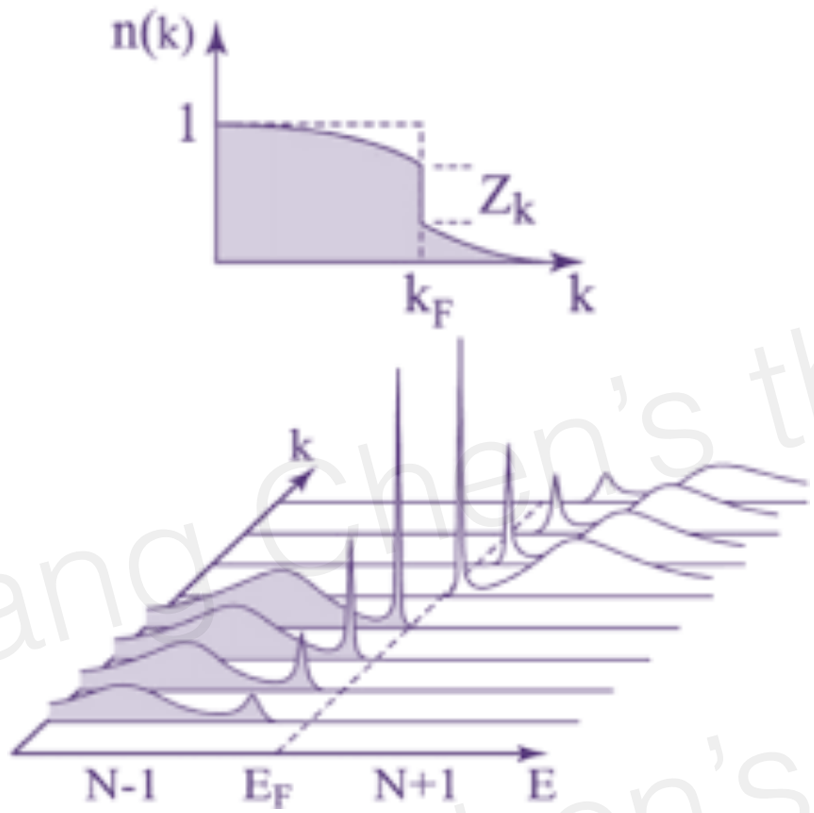


The idea is to view Mott insulator (QSL) as the parent state of high-temperature superconductor. In the QSL, there are preformed Cooper pairs. Doping it allows to Cooper pairs to condense and lead to superconductivity.

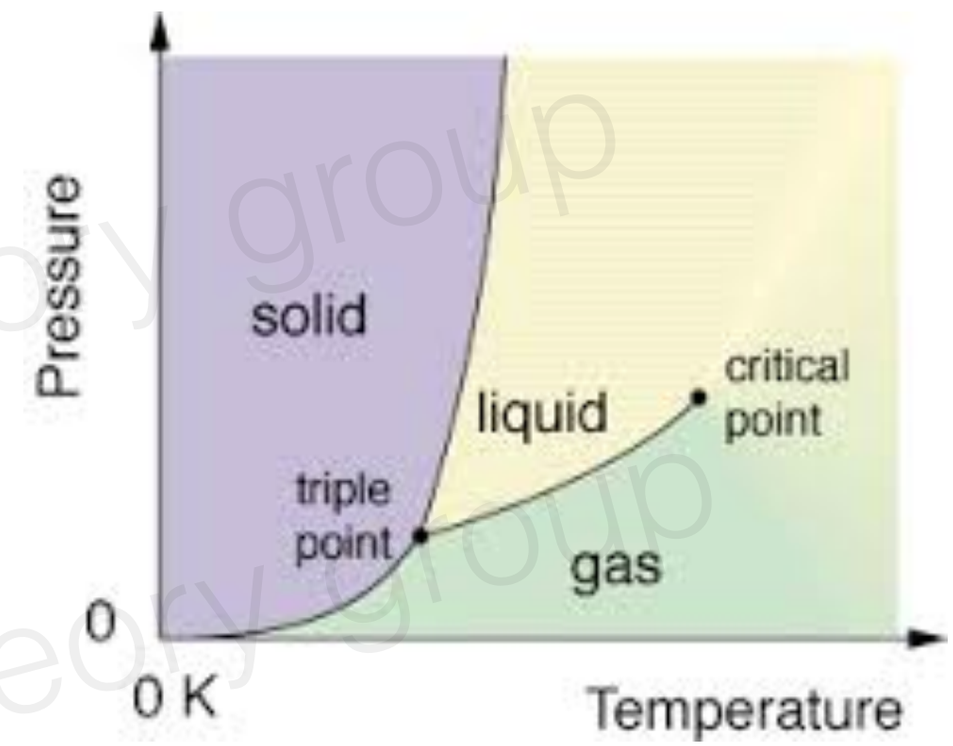


Landau

Two milestones of 20th century condensed matter physics



Landau Fermi liquid theory



Landau symmetry breaking theory

These two paradigms break down after the discovery of fractional quantum Hall effect in 1980s.

Quantum spin liquid

- Quantum spin liquid is a new quantum phase of matter, and cannot be characterized by Landau symmetry breaking, instead by emergent gauge structure and deconfined fractionalized excitations.

- QSL, its existence, is very clear, at least at the level of theory.

  - Exactly solvable model with QSL ground state: e.g. Kitaev model and extension.
  - Classification of QSLs: many distinct symmetry enriched QSLs (XG Wen etc).
  - Numerical solutions: DMRG, QMC, exact diagonalization, etc.

QSL is **robust** against any local perturbation. So it should exist in Nature **!**

QSL: existing experiments

- 2D triangular and Kagome lattice

  organics: kappa-$(BEDT\text{-}TTF)_2Cu_2(CN)_3$, $EtMe_3Sb[Pd(dmit)_2]_2$, κappa–$H_3(Cat\text{-}EDT\text{-}TTF)_2$
  herbertsmithite ($ZnCu_3(OH)_6Cl_2$), $Ba_3NiSb_2O_9$, $Ba_3CuSb_2O_9$, $LiZn_2Mo_3O_8$, $ZnCu_3(OH)_6Cl_2$
  volborthite ($Cu_3V_2O_7(OH)_2$), $BaCu_3V_2O_3(OH)_2$, $[NH_4]_2[C_7H_{14}N][V_7O_6F_{18}]$, Na_2IrO_3, $CsCu_2Cl_4$, $CsCu_2Br_4$, $NiGa_2S_4$, He-3 layers on graphite, etc

- 3D pyrochlore, hyperkagome, FCC lattice, diamond lattice, etc

  $Na_4Ir_3O_8$, IrO_2, Ba_2YMoO_6, $Yb_2Ti_2O_7$, $Pr_2Zr_2O_7$, $Pr_2Sn_2O_7$, $Tb_2Ti_2O_7$, $Nd_2Zr_2O_7$, $FeSc_2S_4$, etc

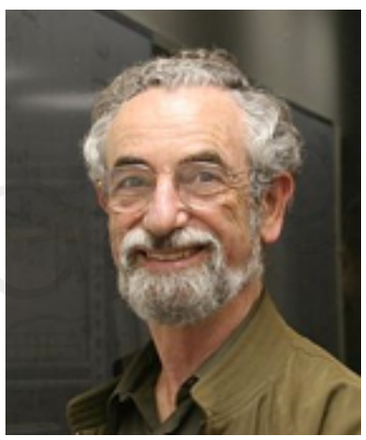
- Ultracold atom and molecules on optical lattices: temperature is too high now.

Some candidate materials have already been ruled out.
Not being a QSL does not necessarily mean the physics is not interesting !

- Spinon Fermi surface U(1) quantum spin liquid

Any guiding rule to find QSL? Not really.

Frustrated lattice? Honeycomb Kitaev model.
Frustrated interaction? We do not really know unless we identify the interaction.
Low dimensionality? 3D lattice also has QSL.
Odd electrons per cell? Many QSLs have even electrons per cell.



Lieb

Oshikawa

Hastings

Vishwanath

- Hastings-Oshikawa-Lieb-Shultz-Mattis theorem.
- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2016).

2. A rare-earth triangular lattice quantum spin liquid: **$YbMgGaO_4$**

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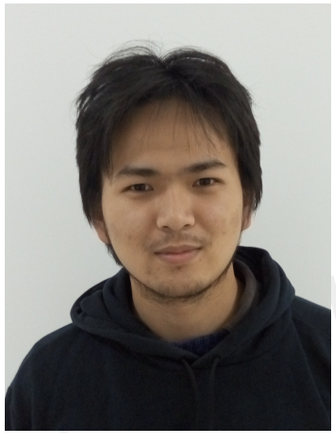

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Hongliang Wo, Shoudong Shen, Bingying Pan, Qisi Wang, Yiqing Hao, Lijie Hao (Fudan),
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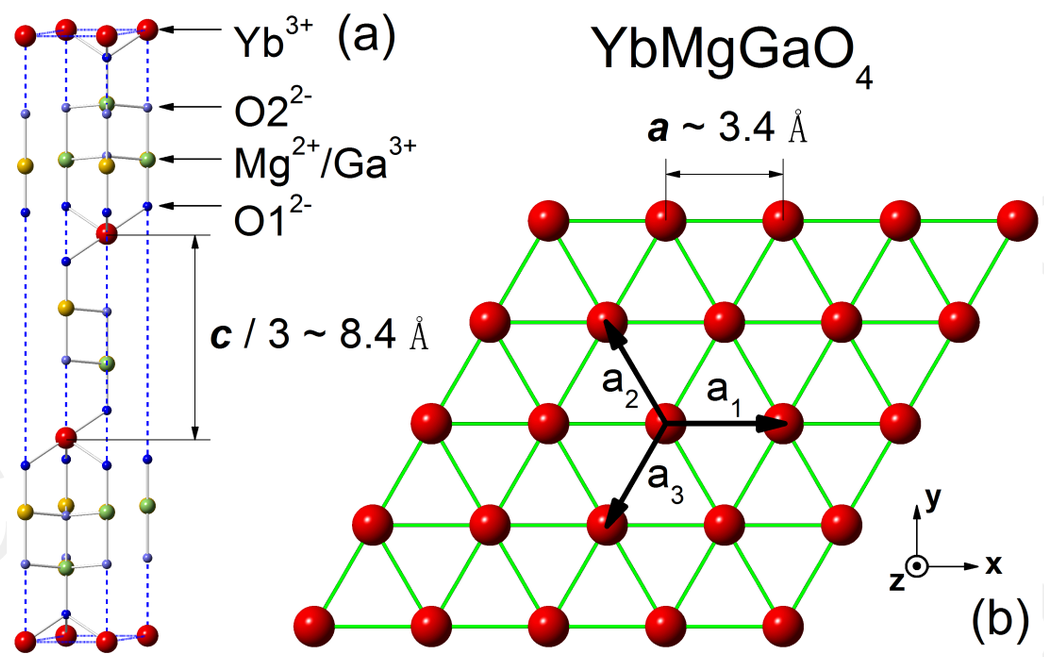
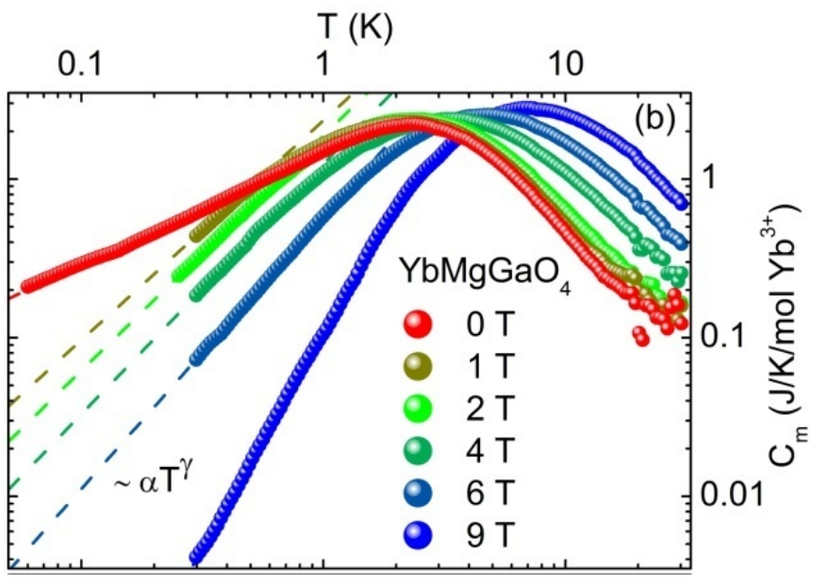
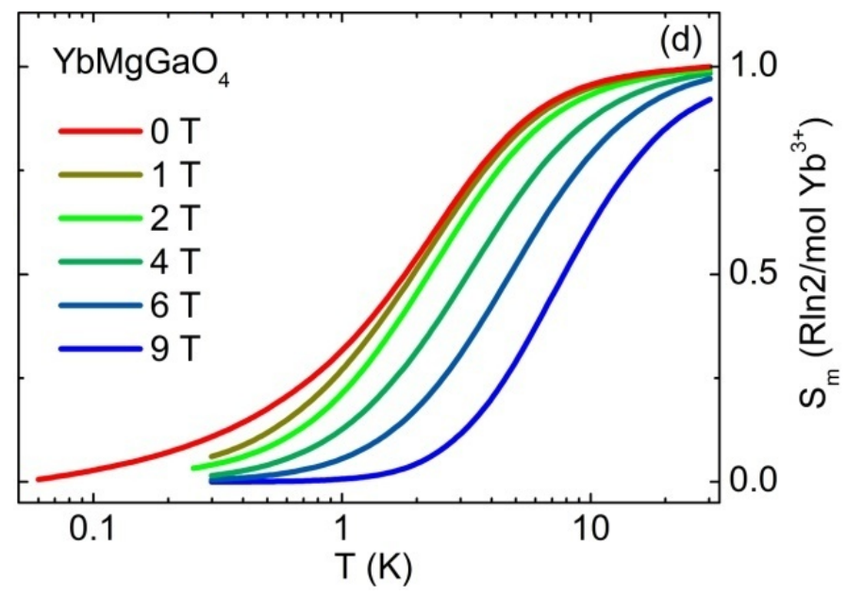
A rare-earth triangular lattice quantum spin liquid: **$YbMgGaO_4$**



- Hastings-Oshikawa-Lieb-Shultz-Mattis theorem.
- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2015).
- This is the **first** strong spin-orbit coupled QSL with odd number of electrons and effective spin-1/2.
- It is the **first** clear observation of $T^{2/3}$ heat capacity. I think it is spinon Fermi surface U(1) QSL.
- Inelastic neutron scattering is consistent with spinon Fermi surface results.
- We understand the microscopic Hamiltonian and the physical mechanism.

$YbMgGaO_4$

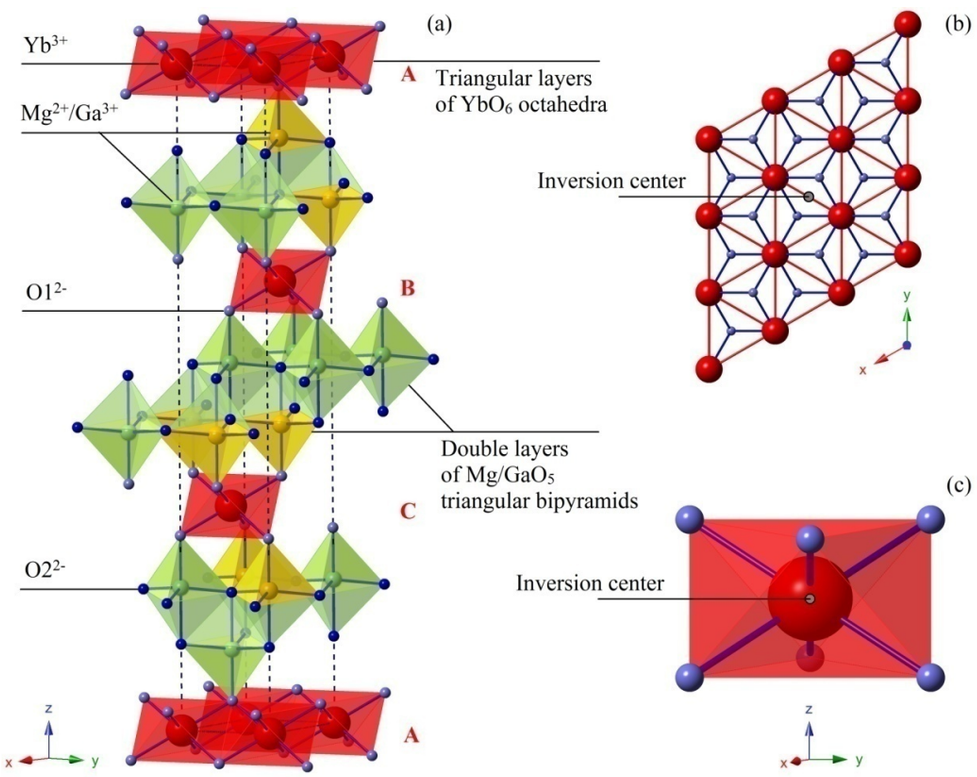




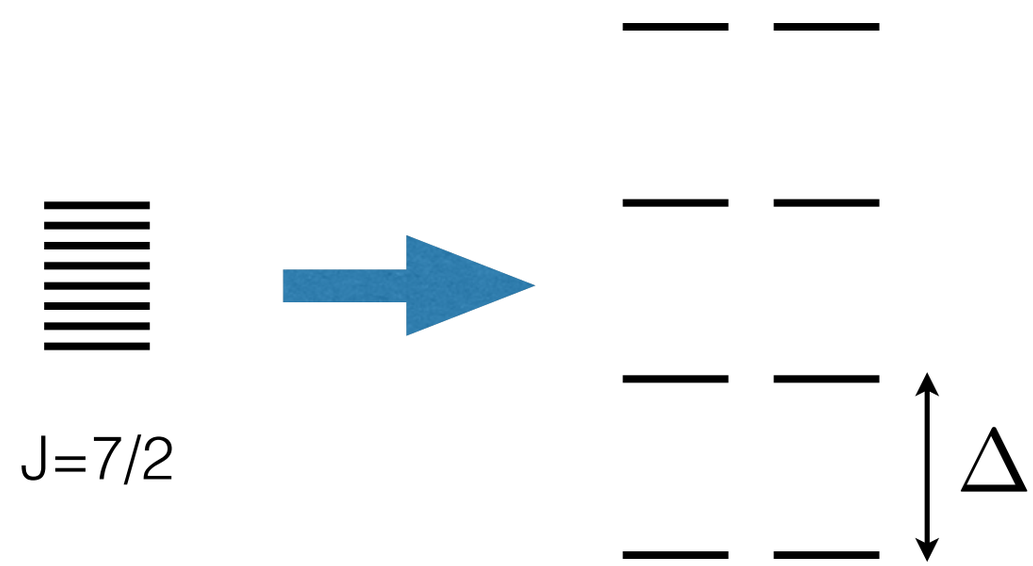
- observation of $T^{2/3}$ heat capacity
- Entropy: effective spin-1/2 local moments

Our proposal for ground state: spinon Fermi surface U(1) QSL.

Microscopics



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



At $T \ll \Delta$, the only active DOF is the ground state doublet that gives rise to an effective spin-1/2.

Can this kind of system support a QSL ground state? Yes.

Filling constraints for spin-orbit coupled insulators in symmorphic and non-symmorphic crystals

Haruki Watanabe,[1] Hoi Chun Po,[1] Ashvin Vishwanath,[1,2] and Michael P. Zaletel[3]

May 2015

and a crystalline lattice or a magnetic field. Mott insulators are a particularly interesting class, with an odd number of electrons in each unit cell. Their low energy physics is captured by a spin model with an odd number of $S = 1/2$ moments in the unit cell. A powerful result due to Lieb, Schultz, and Mattis in 1D[1], later extended to higher dimensions by Hastings and Oshikawa[2,3], holds that if all symmetries remain unbroken, the ground state must be 'exotic' - such as a Luttinger liquid in 1D, or a quantum spin liquid in higher dimensions, with fractional 'spinon' excitations. These exotic states cannot be represented as simple product states, as a consequence of long ranged quantum entanglement. This general re-

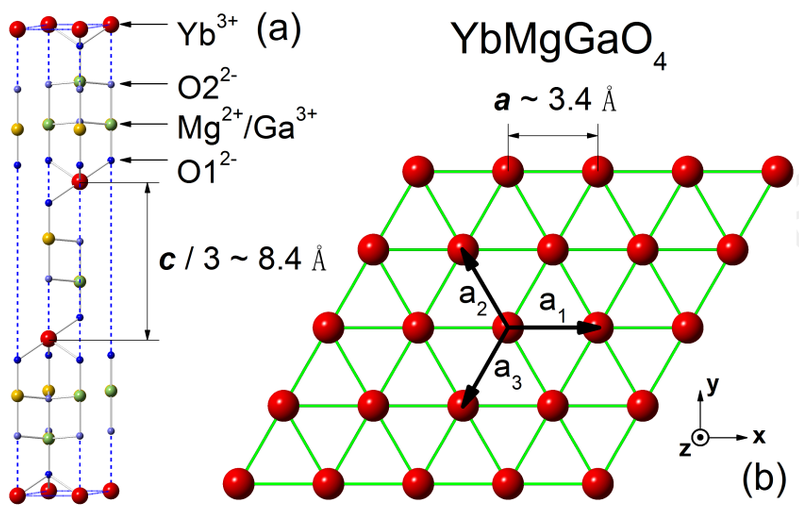
tirely different theoretical approaches are needed. We argue that if a spin-orbit coupled insulator at odd filling is time-reversal symmetric, its ground state must, in a precise sense, be exotic. We introduce two theoreti-

"this kind of system" means effective spin-1/2, spin-orbi
coupling, odd number of electron per cell.

as you may know, there are many theoretical works tryin
constrain the possible states from being exisitg .

What is the physical origin of the QSL?

4f electron is very localized, and dipolar interactions weak.



PhysRevLett, 2015

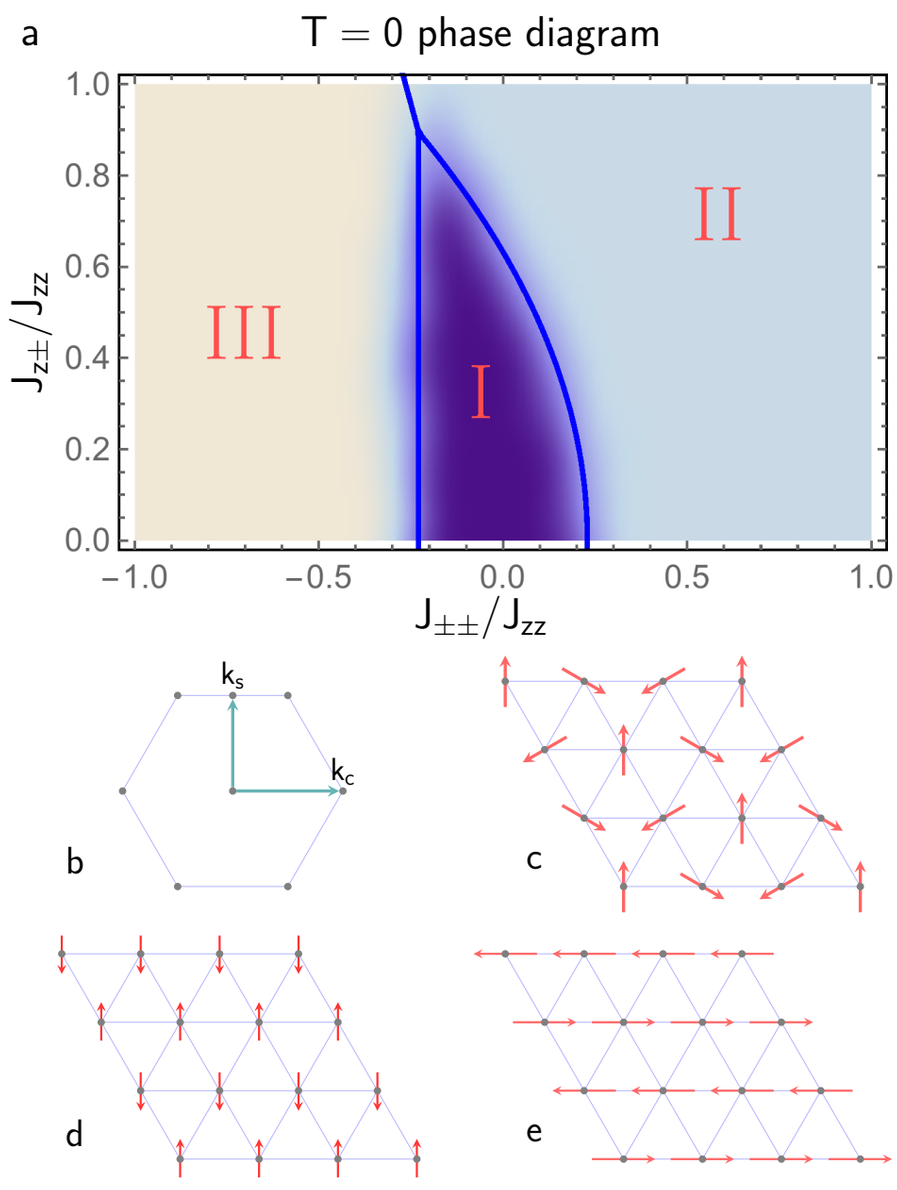
$$\mathcal{H} = \sum_{\langle ij \rangle} \Big[J_{zz} S_i^z S_j^z + J_{\pm}(S_i^+ S_j^- + S_i^- S_j^+) + J_{\pm\pm}(\gamma_{ij} S_i^+ S_j^+ + \gamma_{ij}^* S_i^- S_j^-) - \frac{i J_{z\pm}}{2}(\gamma_{ij}^* S_i^+ S_j^z - \gamma_{ij} S_i^- S_j^z + \langle i \leftrightarrow j \rangle) \Big], \quad (1)$$

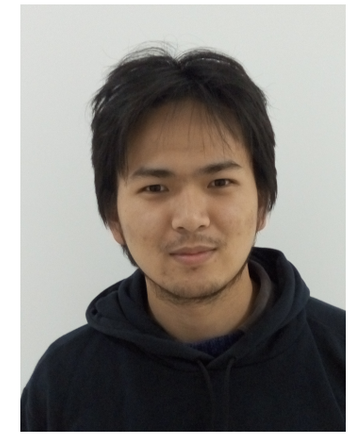
where $S_i^{\pm} = S_i^x \pm i S_i^y$, and the phase factor $\gamma_{ij} = 1, e^{i2\pi/3}, e^{-i2\pi/3}$ for the bond ij along the $\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3$ direction (see Fig. 1), respectively. This generic Hamil-

The spin-1/2 XXZ model supports conventional order.

(Yamamoto, etc, PRL 2014)

Anisotropic spin interaction could potentially stabilize QSL.





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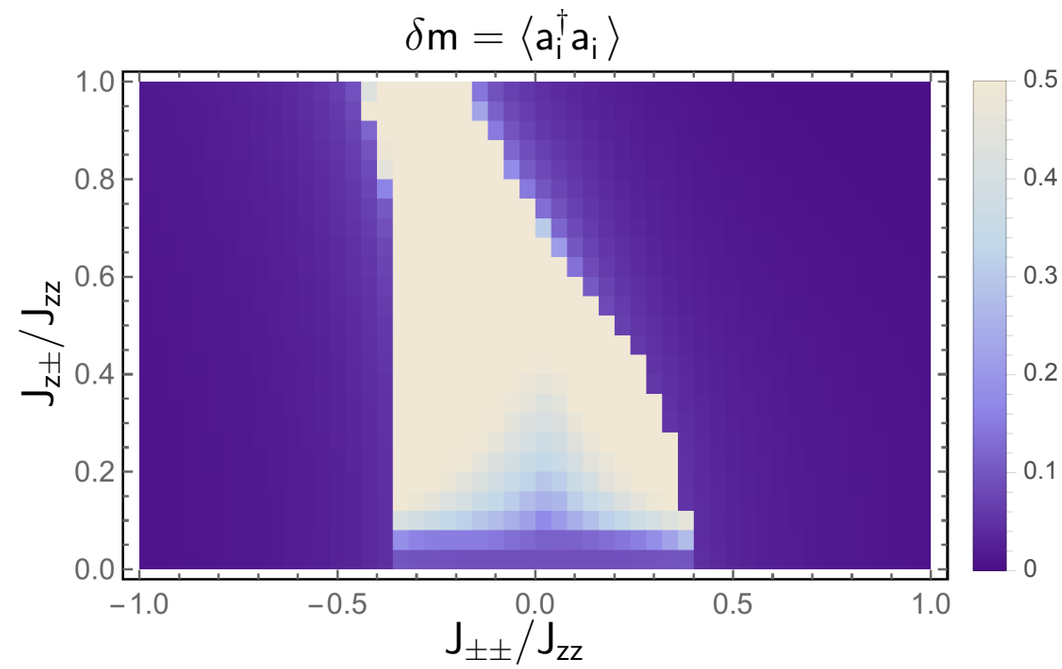
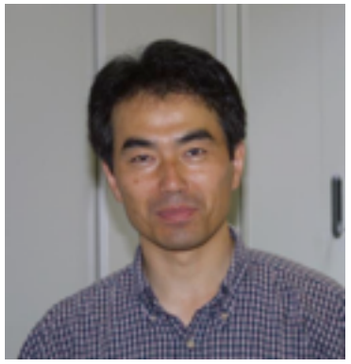
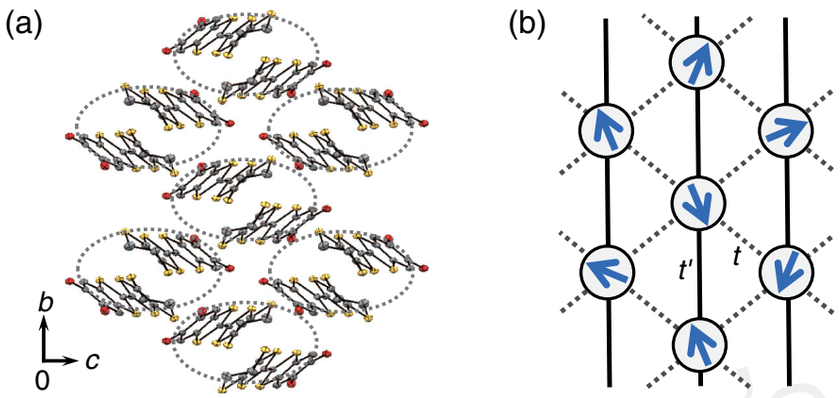


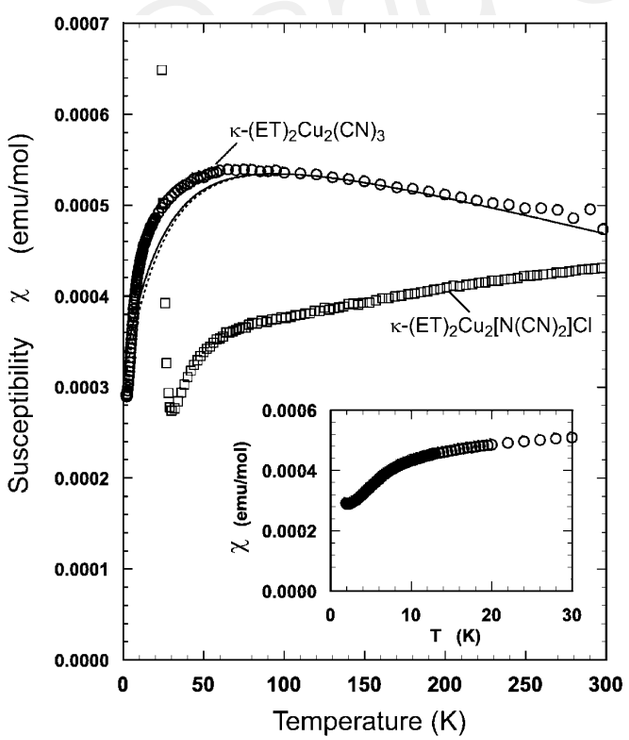
Spinon Fermi surface U(1) QSL in organic magnets?

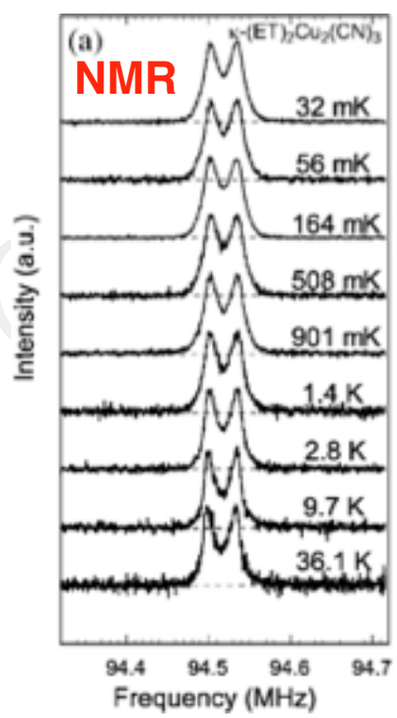


Kanoda



kappa-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$,
EtMe$_3$Sb[Pd(dmit)$_2$]$_2$,
kappa–H$_3$(Cat-EDT-TTF)$_2$ **a new one!**





* No magnetic order down to 32mK
* Constant spin susceptibility at zero temperature

Other experiments: transport, heat capacity, optical absorption, etc, Unfortunately, **no neutron scattering** so far.

- Theoretical understanding: expected phase diagram

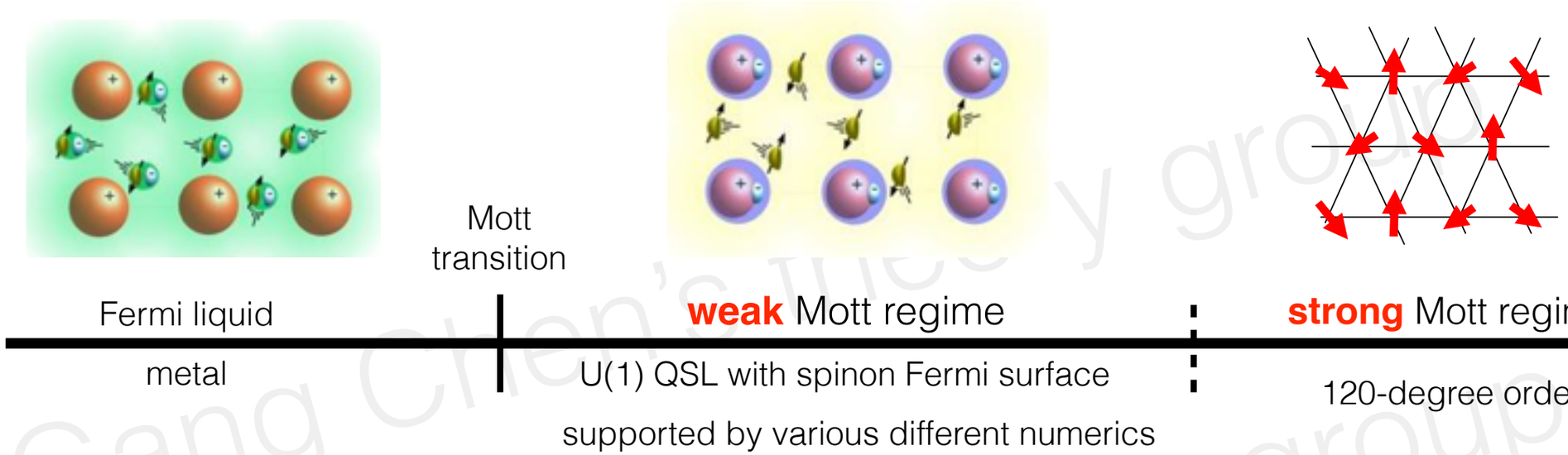
$$H = -t \sum_{\langle ij \rangle, \sigma} c^\dagger_{i\sigma} c_{j\sigma} + h.c. + U \sum_i n_{i\uparrow} n_{i\downarrow}$$


Sung-Sik Lee


T Senthil

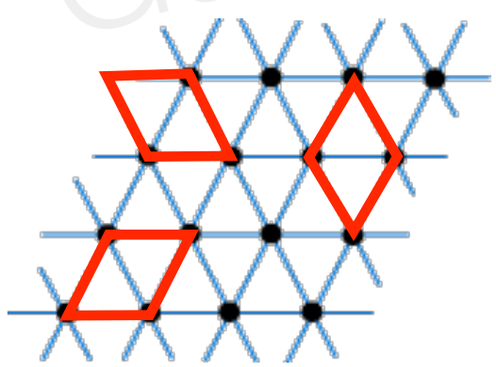

Patrick Lee

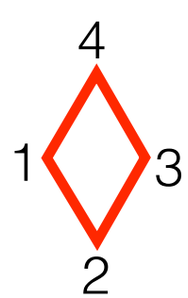
Senthil's cartoon



- **Physical mechanism** for weak Mott insulator spin liquids: perturbation in t/U

$$H_{\text{pert}} = \sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + K \sum_{1234} (P_{1234} + P_{1234}^{-1}) + \cdots$$



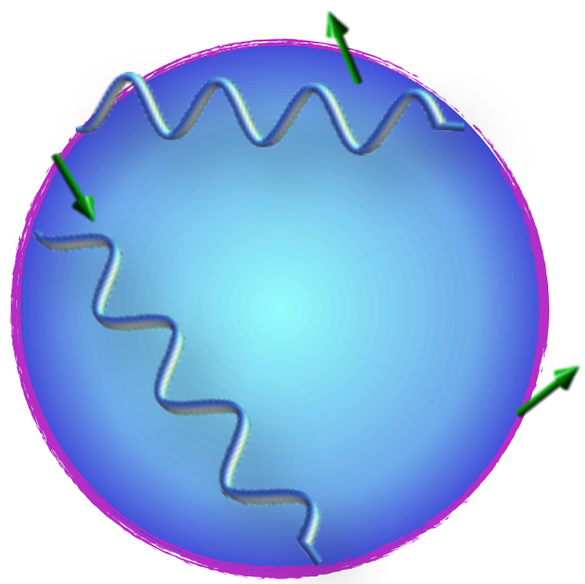


4-site ring exchange

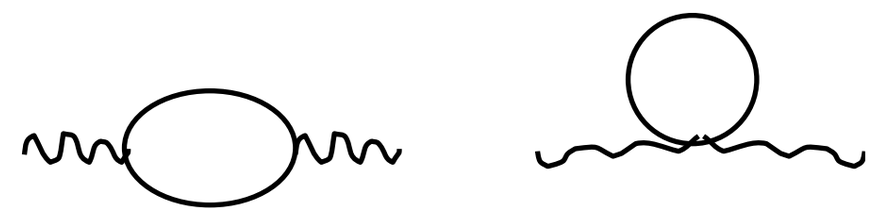
$$(\mathbf{S}_1 \cdot \mathbf{S}_2)(\mathbf{S}_3 \cdot \mathbf{S}_4)$$
$$+(\mathbf{S}_1 \cdot \mathbf{S}_4)(\mathbf{S}_2 \cdot \mathbf{S}_3)$$
$$-(\mathbf{S}_1 \cdot \mathbf{S}_3)(\mathbf{S}_2 \cdot \mathbf{S}_4)$$


Motrunich

Low energy property of spinon Fermi surface U(1) QSL: spinon non-Fermi liquid



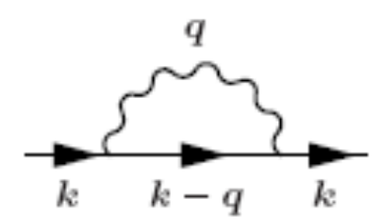
$$S = \int d^3x \left[\Psi_j^*(\partial_0 - ia_0 - \mu_F)\Psi_j + \frac{1}{2m}\Psi_j^*(-i\nabla - \mathbf{a})^2\Psi_j + \frac{1}{4g^2} f_{\mu\nu} f_{\mu\nu} \right].$$



gauge photon is overly Landau-damped.

Spinon Fermi surface coupled with dynamical U(1) gauge field: instanton event is suppressed.

dual to extremal/charged black hole?

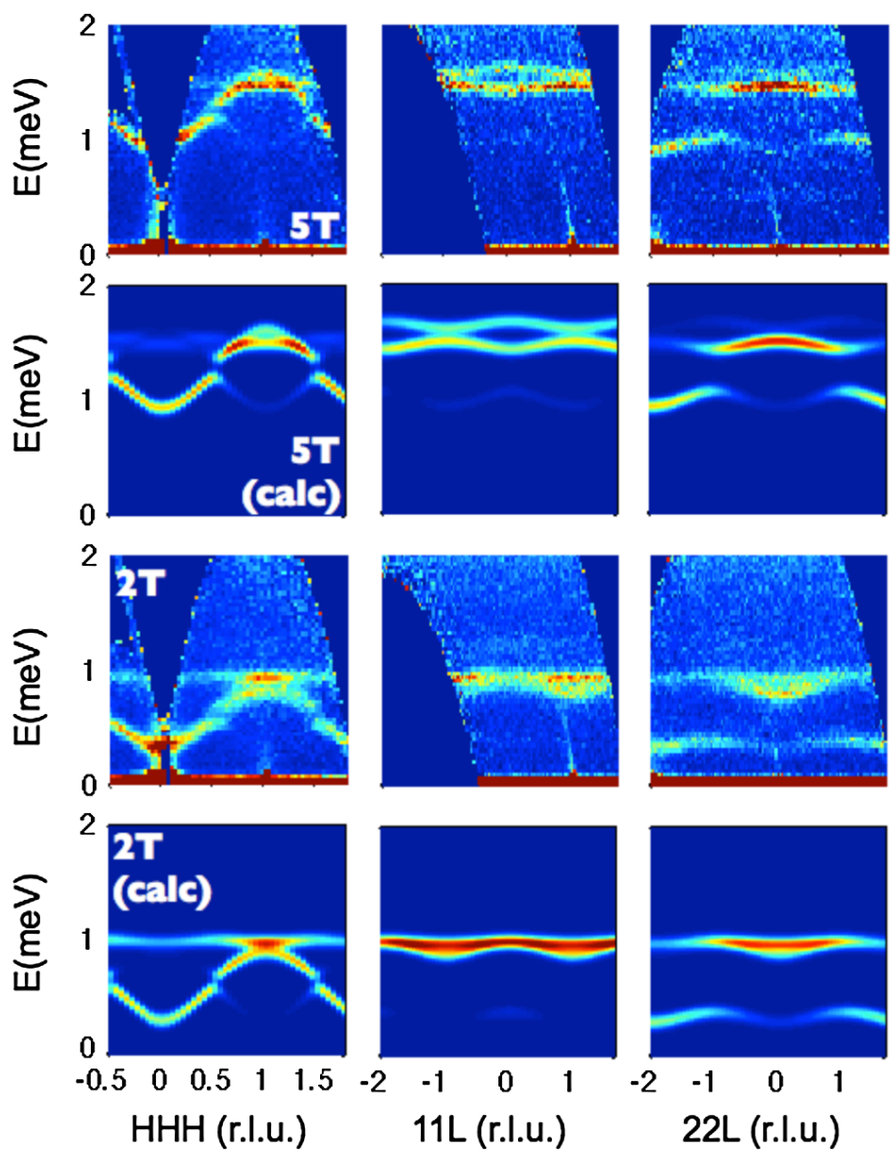


$$Re\Sigma \sim Im\Sigma \sim \omega^{2/3}$$

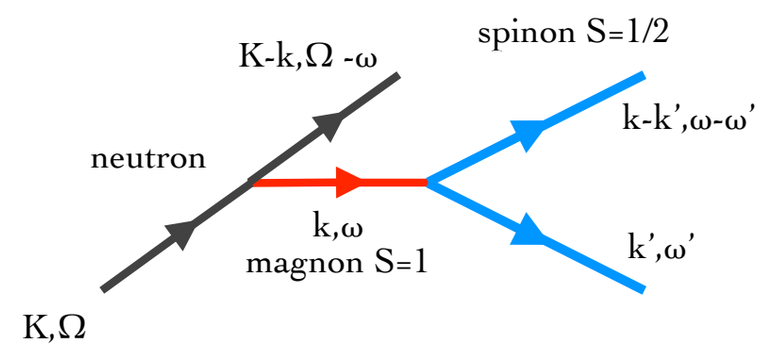
Hermele et al., PRB 70, 214437 (04)

Sung-Sik Lee, PRB 78, 085129(08).

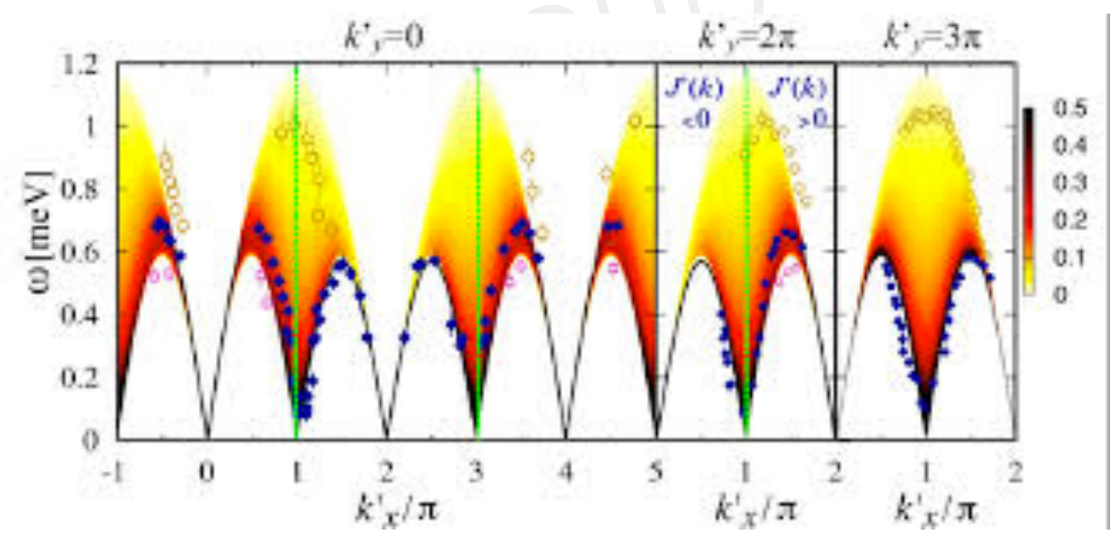
Spin wave vs (fractionalized) spinon continuum



spin wave in Yb2Ti2O7
L Savary, et al, PRX 2011

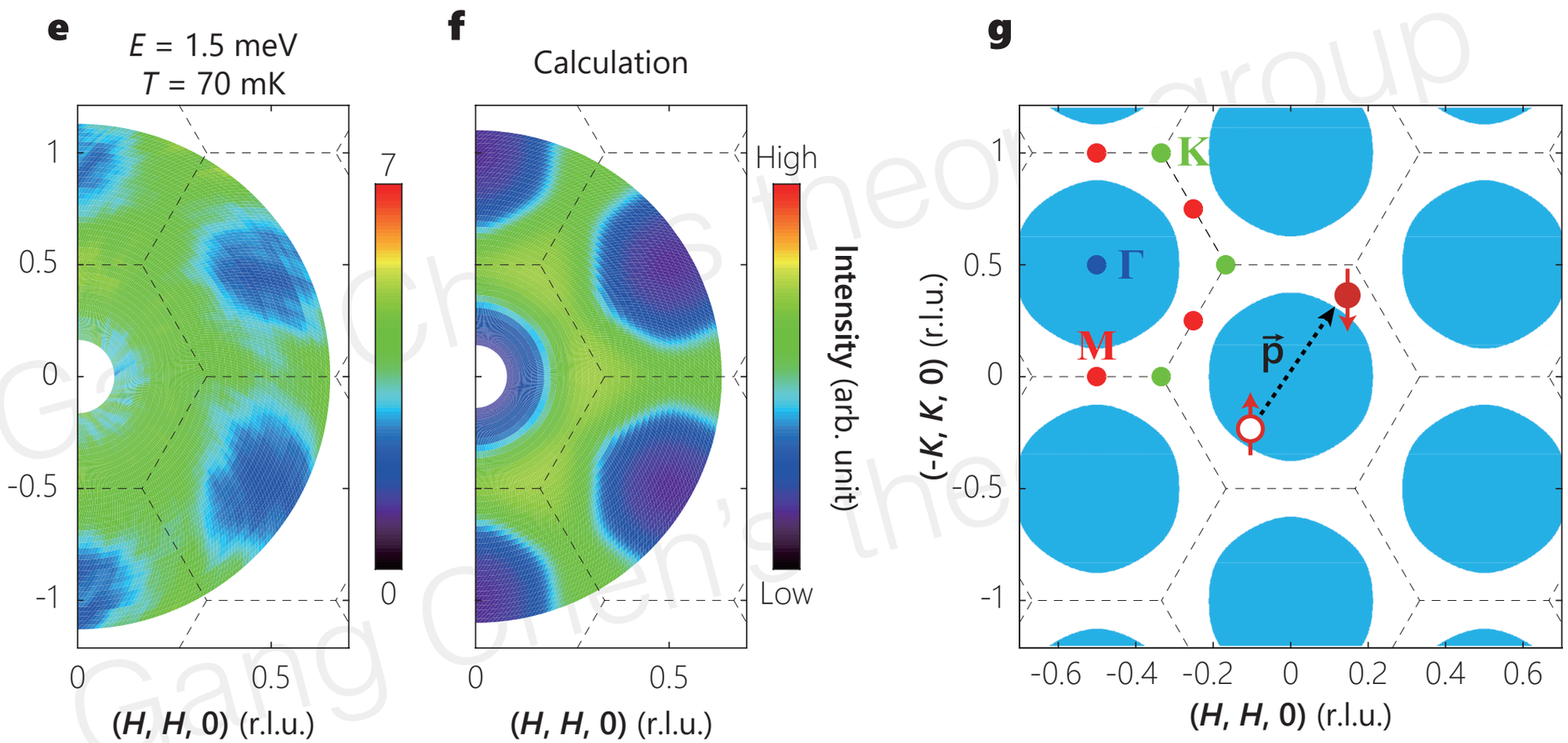


broad peak with
$\omega=\varepsilon(k')+\varepsilon(k-k')$



spinon continuum in Cs2CuCl4
Masanori, etc NatPhys 2009
but these are **1d spinons** !

Huge spinon continuum at all energies



Yao Shen, …Gang Chen*, Jun Zhao* arxiv 2016