Survey of spin liquid physics and/or materials

Gang Chen
HKU

This topic is hard to be systematic.

Theoretical classification

1. Topological spin liquid: intrinsic topological order, fully gapped.

2. Critical spin liquid: usually refers to QSLs with strongly coupled gapless gauge and gapless matter, e.g. 2d U(1) Dirac QSL, 2d U(1) spinon fermi surface QSL

3. Somewhat in between:
   3d U(1) QSL, 2d Z2 QSL with gapless fermionic matter may fit better to topological spin liquid.

With symmetries, more and finer QSLs can emerge.

Experimental diagnosis

1. Thermodynamics:
   Cv, chi, NMR knight shift, muSR, neutron, etc

2. Spectroscopic measurements:
   NMR-T1, inelastic neutron, etc

3. Charge physics, phonon sector (acoustic attenuation), thermal transports, etc

Remark:

1. 需要把各种实验提供的信息综合起来，并不能孤立地看单一的实验。
2. 普适性和具体性重叠：当我们谈论特定phase时，关注的更多的是phase的普适性质。然而具体到某个系统时，就要考虑有些具体的实现，而具体实现又能带来一些新的特殊性。
3. 现象学和微观学结合：
   a) 从某些现象归纳，来期望另外的现象
   b) 从微观上推导模型解决，这个难度大，但相对solid

Smoking guns measurements?

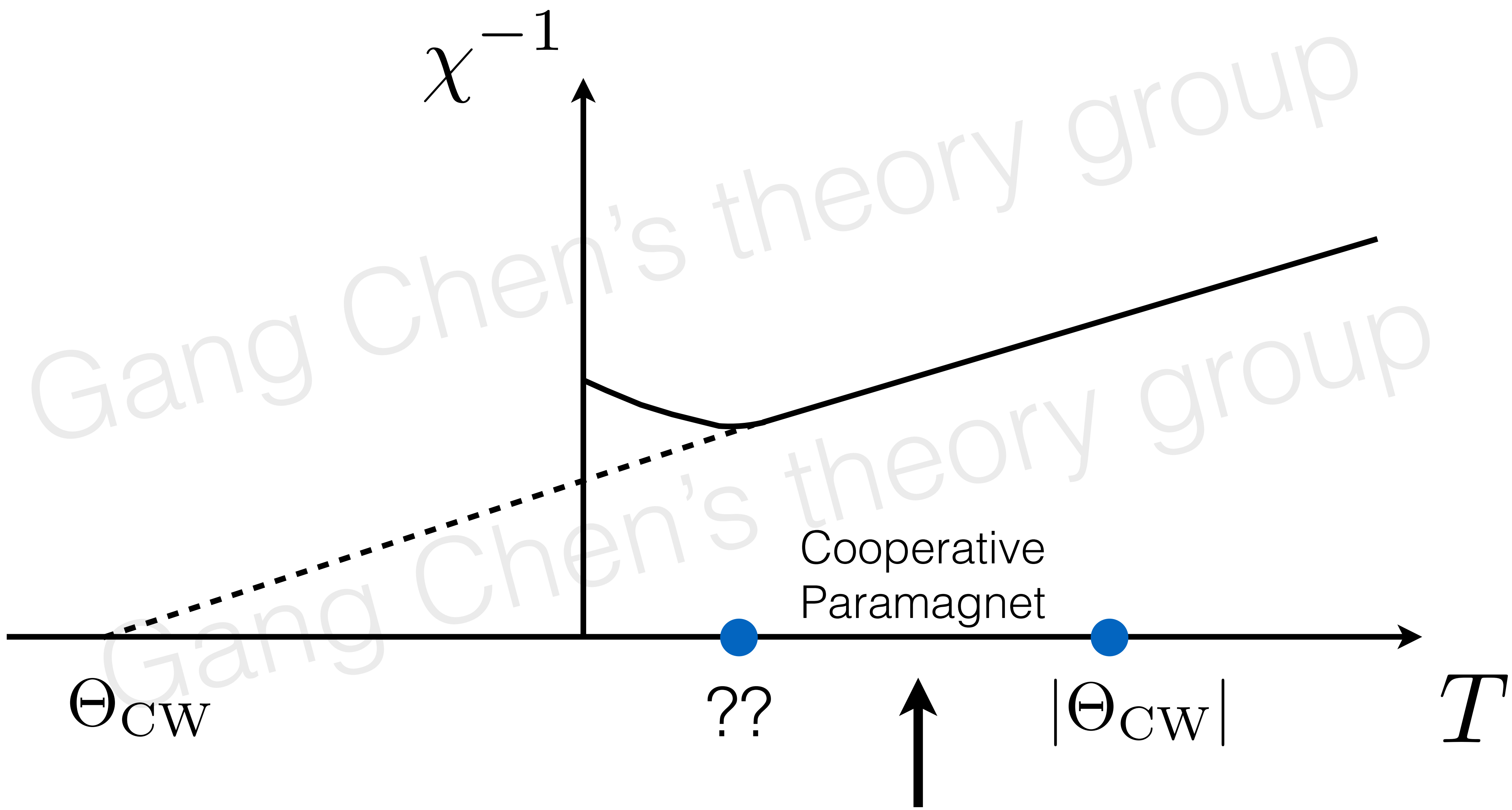
Smoking gun experiments are system specific, phase specific, degrees of freedom specific….

Some striking examples:

Pyrochlore spin ice U(1) QSL: Cv ~ T^3, prefactor is 1000 large of phonon's.

Gapped Kitaev spin liquid: kxy/T=half quantization

澄清: spin liquid vs cooperative paramagnet



Classical spin liquid refers to this regime
where the spin correlation is important.

if you have any ques
material, we can cha

Some candidate spin liquid materials

- 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, YbMgGaO4, NaYbS2, 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

- Kitaev honeycomb materials: RuCl3, 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 !

Some physical mechanisms (not uniquely defined)

或许可以提供寻找spin liquid一些线索吧

The more you work in this field, the more you feel that there is no (simple) general rule of thumb.

1. Weak Mott insulators: a couple organics, $Na_4Ir_3O_8$, etc

2. Cluster localization/Mott: 1T-TaS_2, $Li_2ZnMo_3O_8$

3. Strong frustration: geometric frustration (not necessarily), small spin (not necessarily either), many many examples

4. Spin-orbital entanglement, orbital presence, SU(N) systems, etc

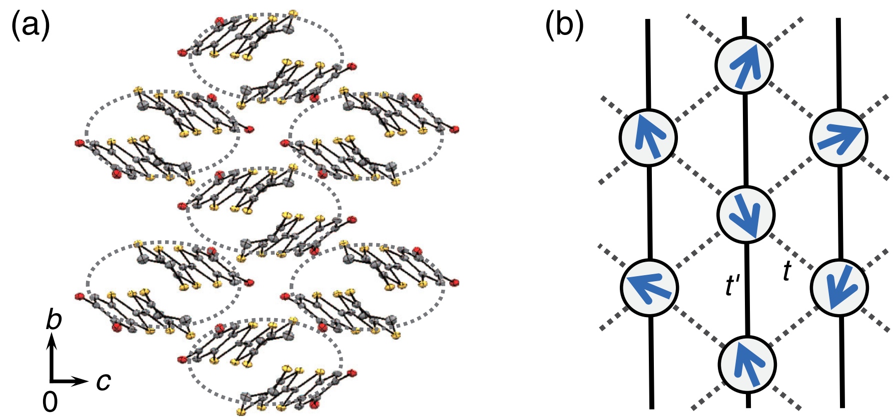
A characteristic (not always): Mott insulators with odd filling even with SOC.
Counter examples: Kitaev QSL, Pyrochlore U(1) QSL

下边的报告内容按照quantum spin liquid
的物理机制来组织，并部分address下边的问题

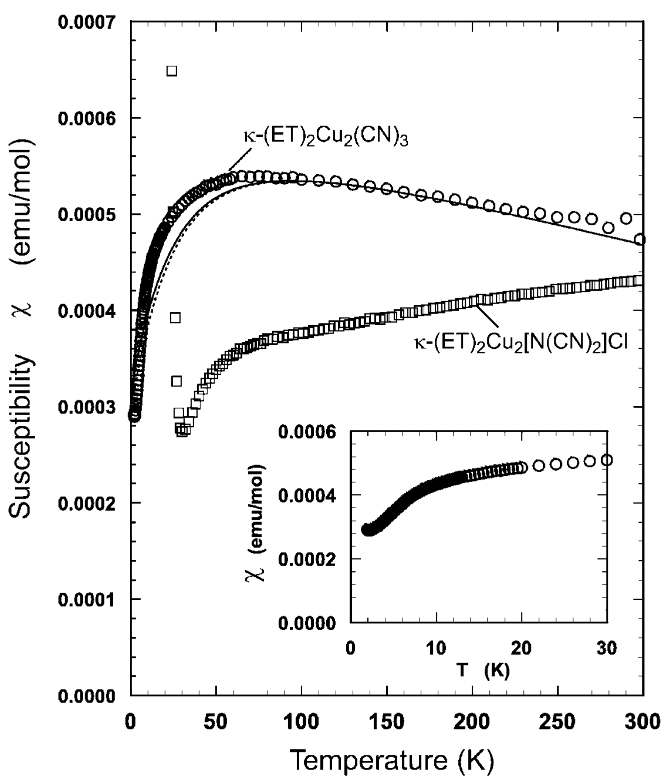
1. 自由度是什么 (degrees of freedom)？
2. 自由度之间可能的相互作用 (interaction)
3. 相关的现象(relevant phenomena)
4. 什么的机制、解释、期望 (mechanism, explanation)。

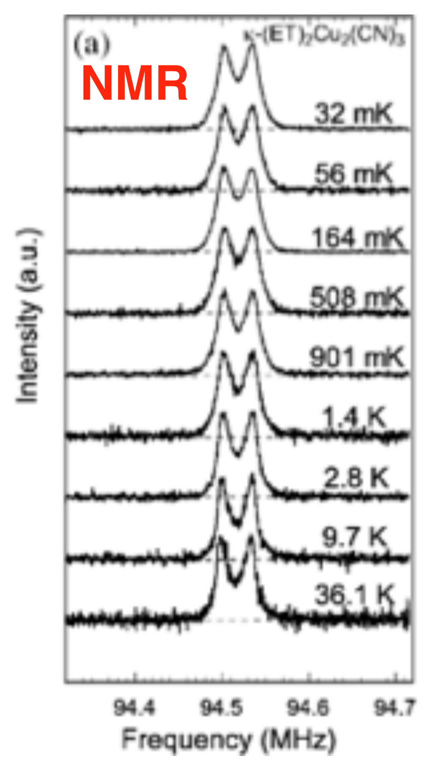
Weak Mott insulator: organics

Kanoda



kappa-(BEDT-TTF)2Cu2(CN)3,
EtMe3Sb[Pd(dmit)2]2,
kappa−H3(Cat-EDT-TTF)2 **a new one!**

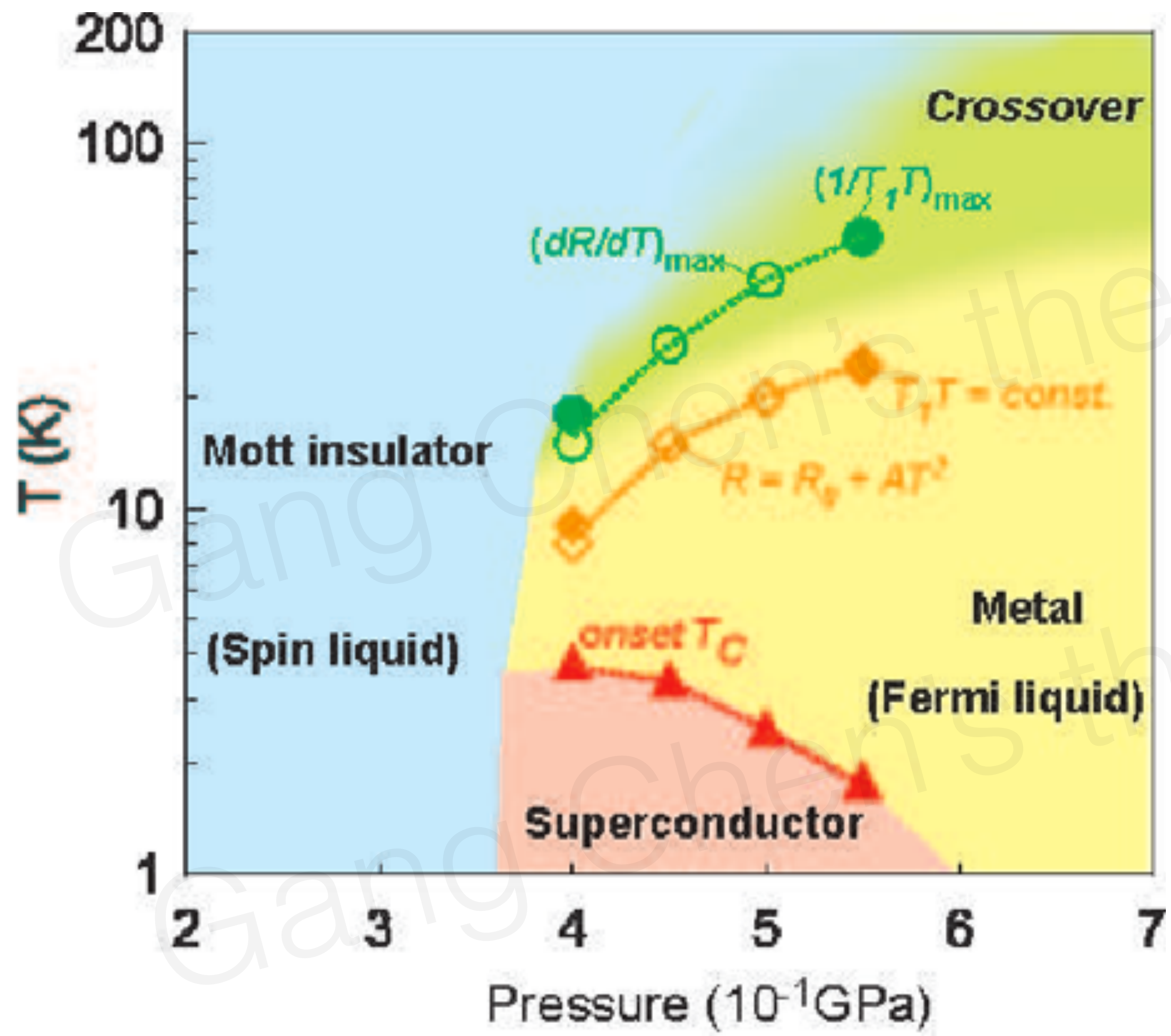


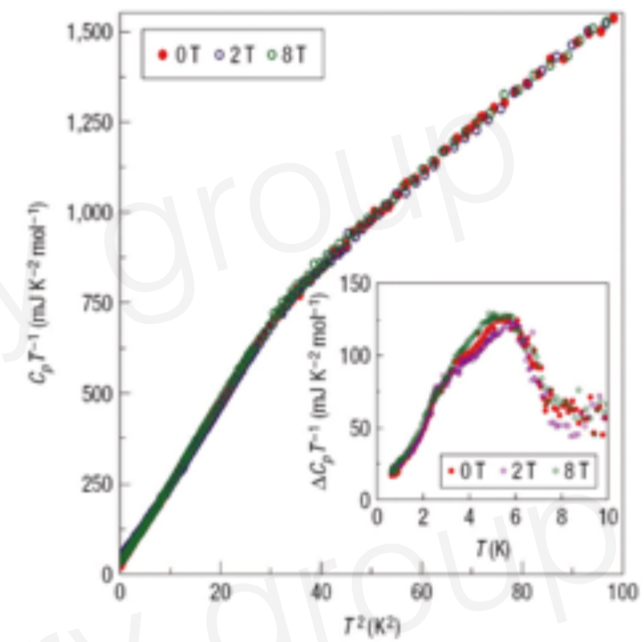


* No magnetic order down to 32mK
* Constant spin susceptibility at zero temperature

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

Proximity to Mott transition





anomaly at ~6K

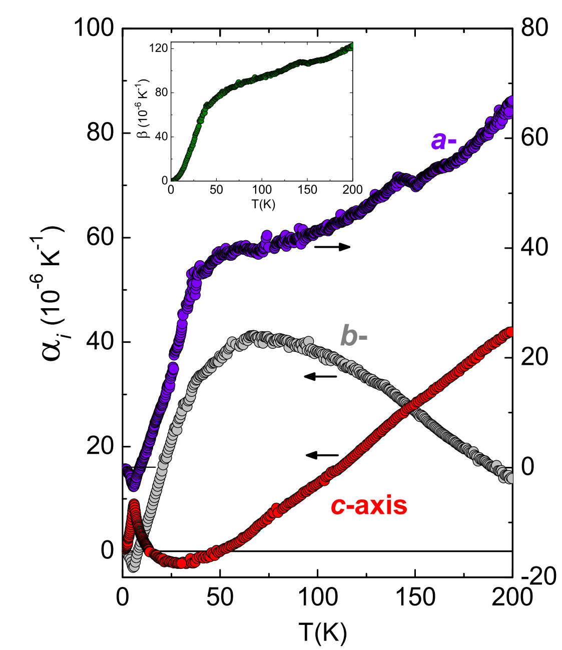
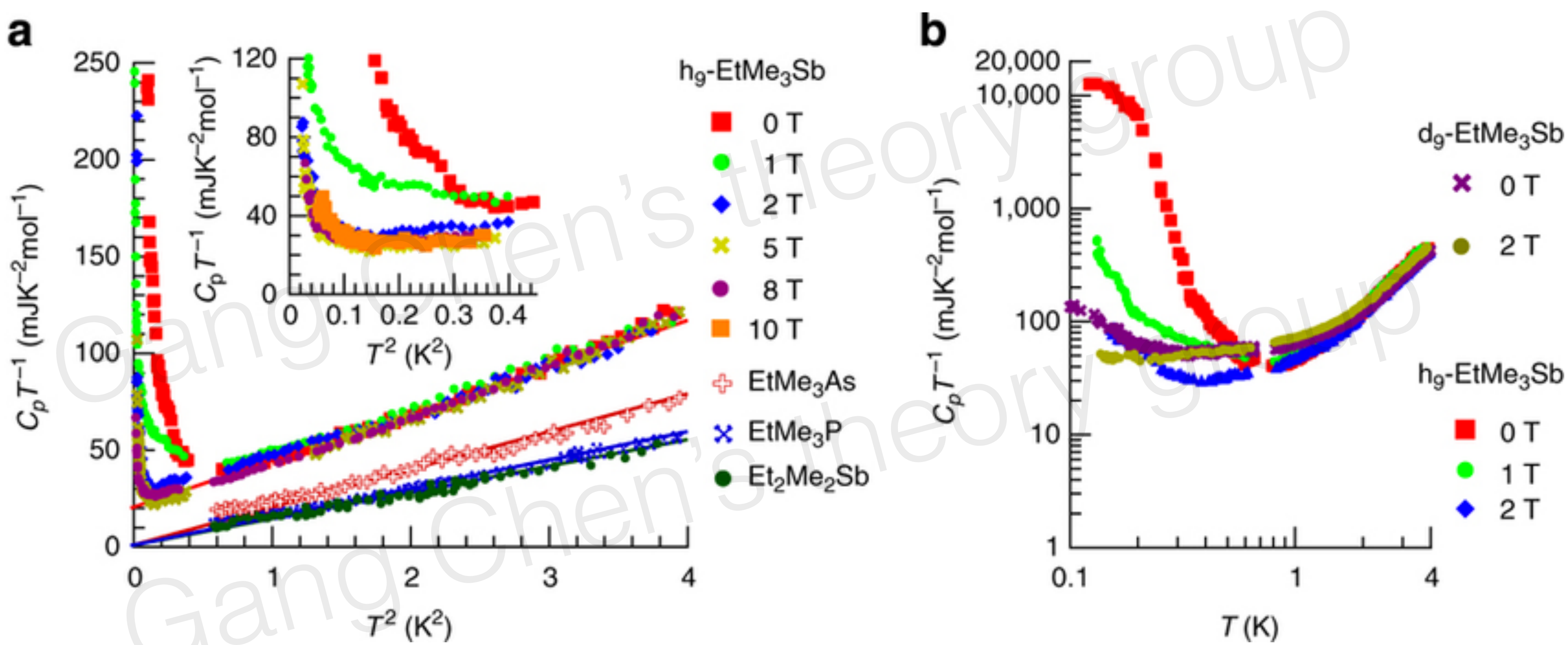


FIG. 1: (Color online) Uniaxial expansivities α_i of κ-(BEDT-TTF)$_2$Cu$_2$(CN)$_3$ along the in-plane $i = b$ and c axes (left scale) and along the out-of-plane $i = a$ axis (right scale). Inset shows the volume expansion coefficient β.

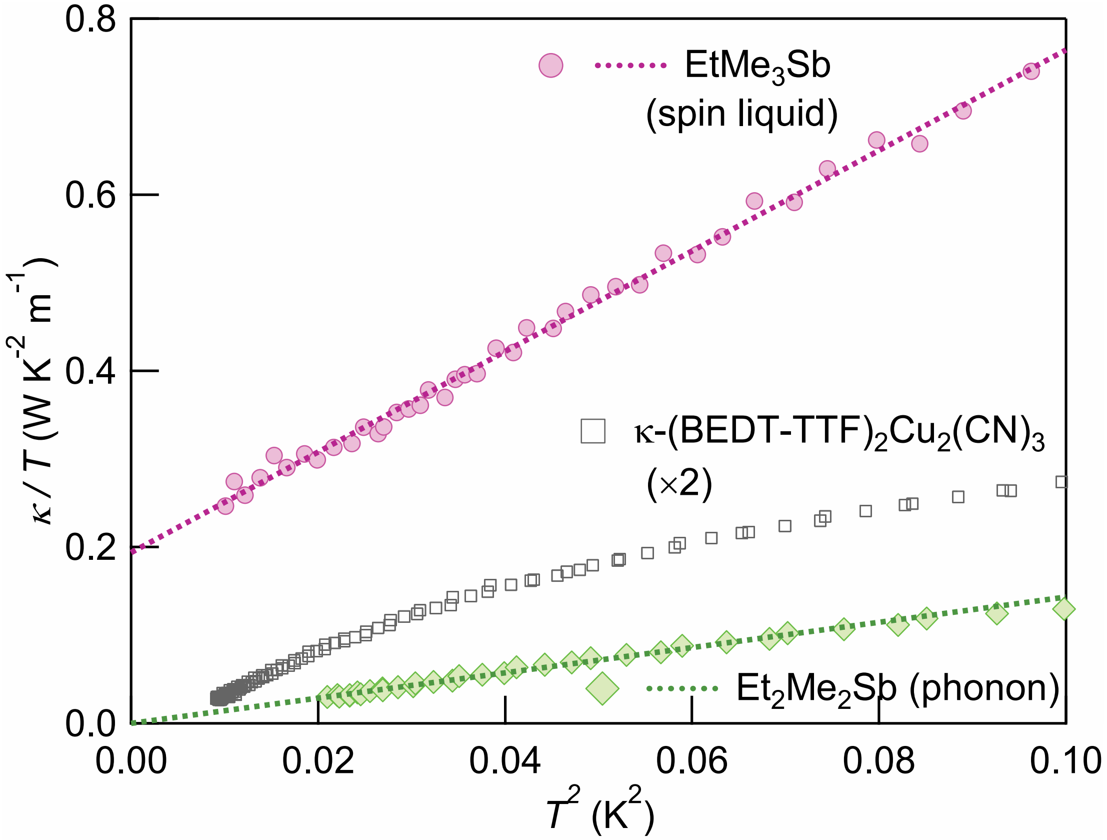
dmit organics



Thermal transport kxx ??

Thermal-transport studies of Two-dimensional Quantum Spin Liquids

Minoru Yamashita, Takasada Shibauchi, and Yuji Matsuda



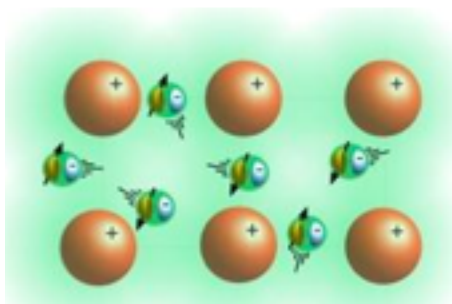
Shiyan will talk about this in a couple days.

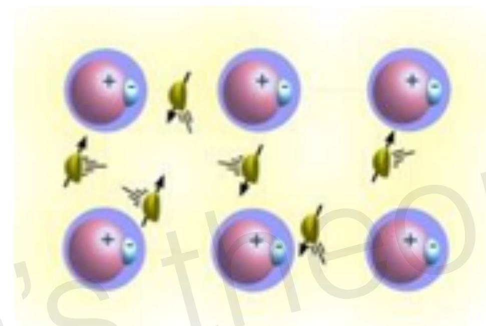
- Theoretical understanding: expected phase diagram

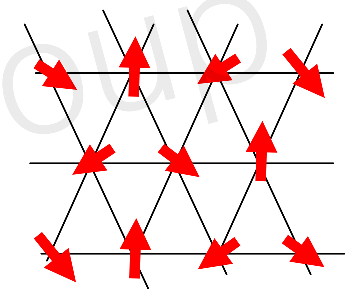
$$H = -t \sum_{\langle ij \rangle, \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + h.c. + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Sung-Sik Lee T Senthil P Lee

Senthil's cartoon







Mott transition

Fermi liquid metal

weak Mott regime

U(1) QSL with spinon Fermi surface

supported by various different numerics

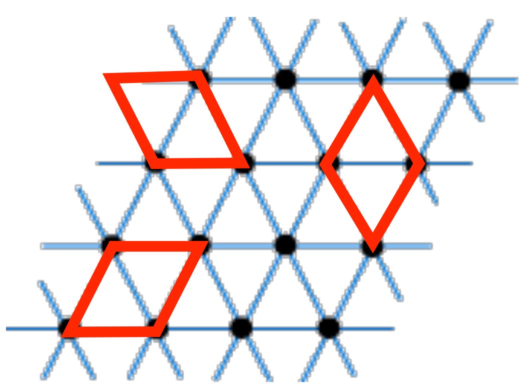
strong Mott regime

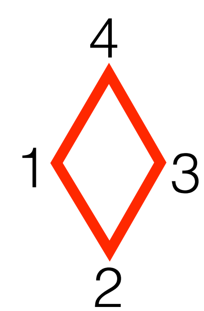
120-degree order

U/t

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

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





4-site ring exchange

$$\begin{aligned} &(\mathbf{S}_1 \cdot \mathbf{S}_2)(\mathbf{S}_3 \cdot \mathbf{S}_4) \\ +&(\mathbf{S}_1 \cdot \mathbf{S}_4)(\mathbf{S}_2 \cdot \mathbf{S}_3) \\ -&(\mathbf{S}_1 \cdot \mathbf{S}_3)(\mathbf{S}_2 \cdot \mathbf{S}_4) \end{aligned}$$

Motrunich

On top of this state

1. Amperean pairing: U1->Z2 crossover (PA Lee, SS Lee)
2. Spin-lattice coupling: 2kF Kohn anomaly (Senthil, Mross)
3. Quantum oscillation (Motrunich)
4. Thermal Hall transport kxy (Nagaosa, PA Lee, Katsura)
5. Whether this state can exist in theory? How to describe it? (SS Lee, Max, Mross, Senthil, Hong Liu, etc)

   "strong-coupled gapless system with infinite critical fermion modes"

About triangular lattice Hubbard model

A recent numerics (DMRG) from Berkeley claims
a chiral spin liquid.

Prof Donna Sheng may be a good person to consult.

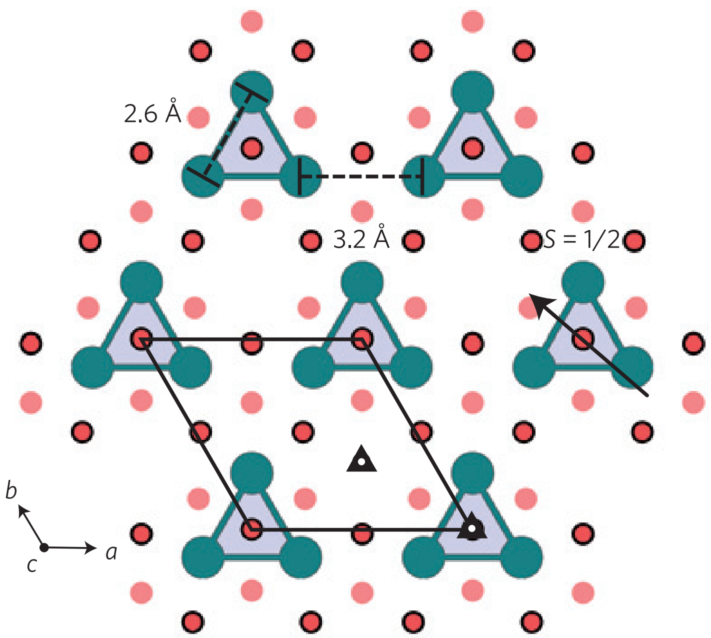
Observation of a chiral spin liquid phase of the Hubbard model on the triangular lattice: a density matrix renormalization group study

Aaron Szasz,[1,2,*] Johannes Motruk,[1,2] Michael P. Zaletel,[3,1] and Joel E. Moore[1,2]

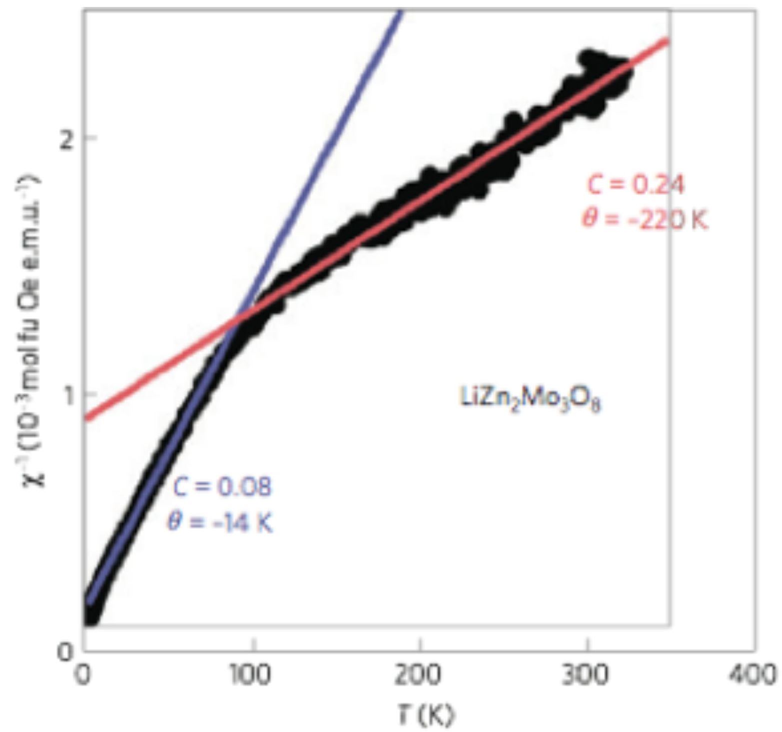
[1] *Department of Physics, University of California, Berkeley, California 94720, USA*
[2] *Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[3] *Department of Physics, Princeton University, Princeton, New Jersey 08540, USA*

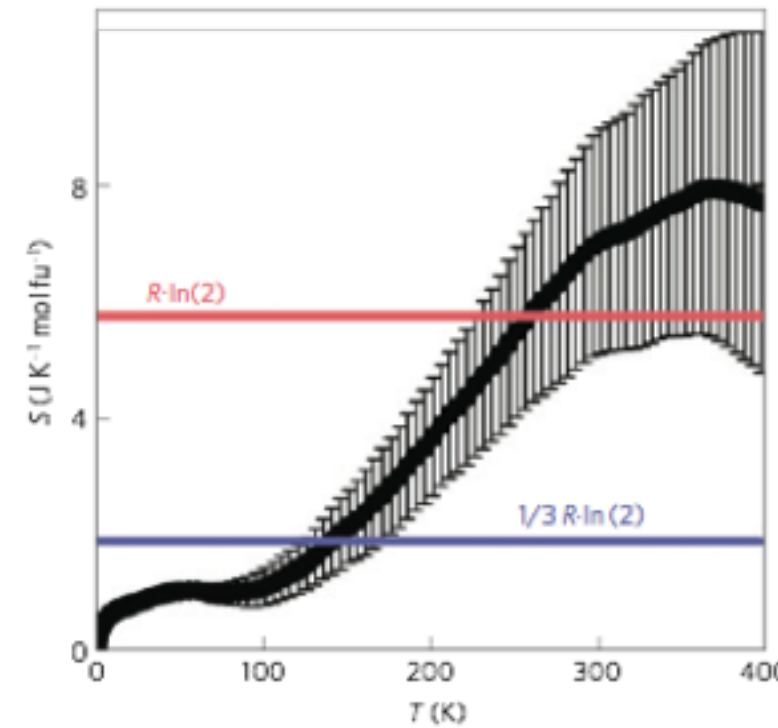
Cluster localization in $LiZn_2Mo_3O_8$

T. McQueen



Nature Material 2012





- Why striking and difficult? Neither model works.
  1. Triangular lattice Heisenberg model
  2. Triangular lattice Hubbard model at 1/2 filling

- Further low-temperature experiments: NMR, muSR, neutron scattering, proposed as a spin liquid candidate.

Emergent honeycomb lattice in $LiZn_2Mo_3O_8$

Rebecca Flint and Patrick A. Lee
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, U.S.A.

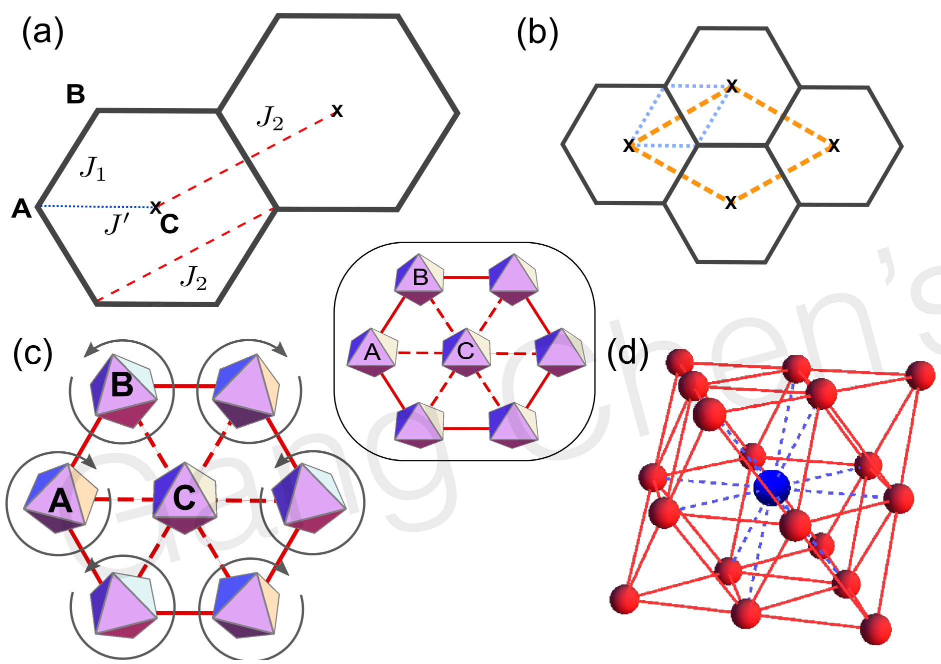
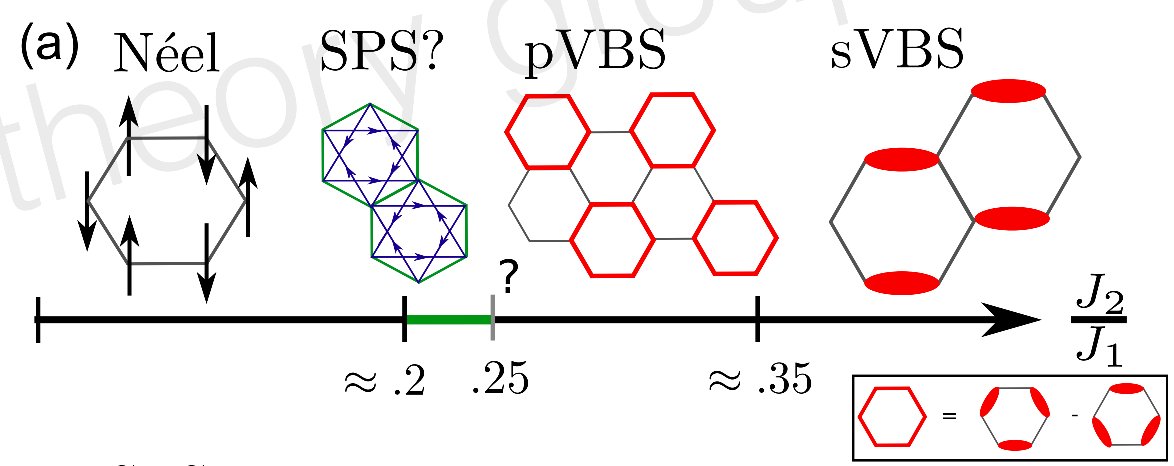
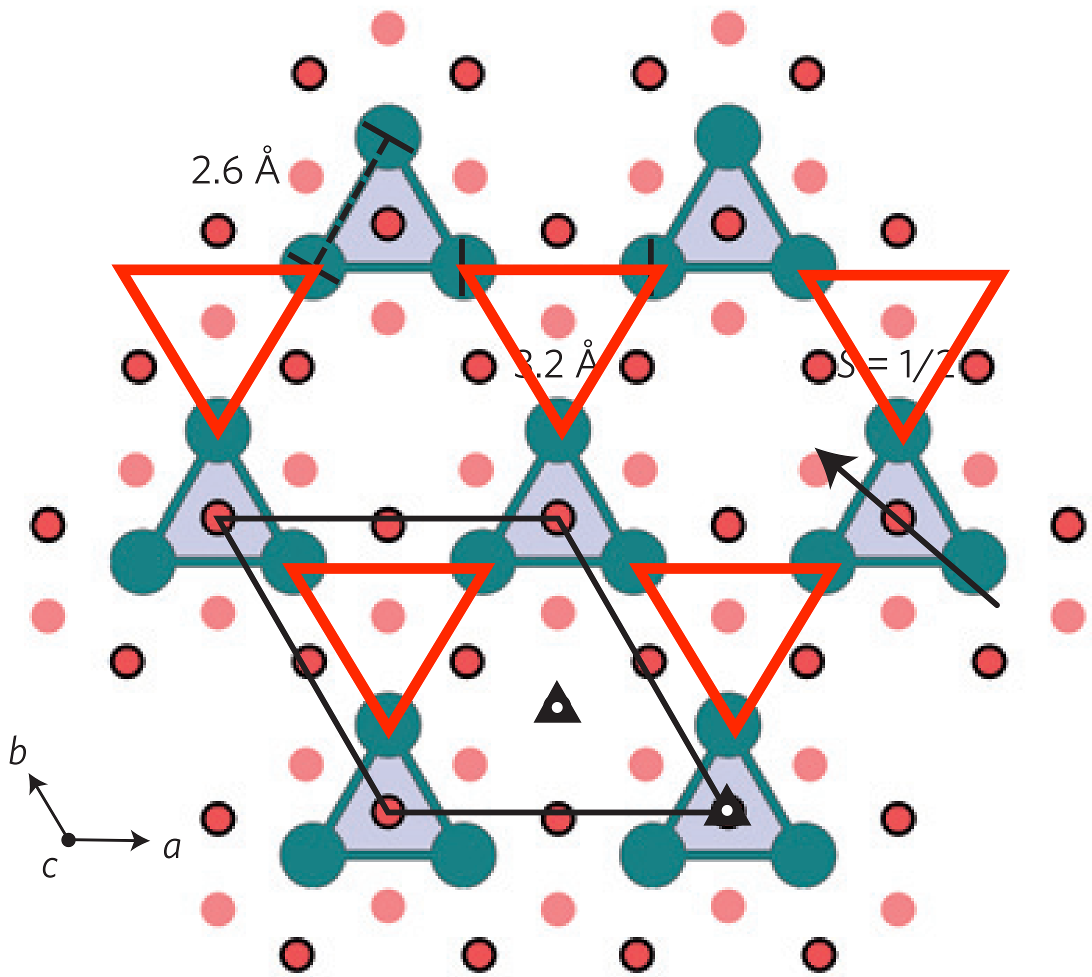


FIG. 1. (a) $J_1 - J_2 - J'$ lattice, where $J' = J_1$ describes the triangular lattice and $J' = 0$ describes decoupled honeycomb ($J_1 - J_2$) and triangular (J_2) lattices. The A and B sublattices of the honeycomb lattice and the C sublattice of central spins are labeled. (b) Unit cells: blue dotted lines show the small initial unit cell, while orange dashed lines show the larger final unit cell. Both have trigonal symmetry - only the lattice vector changes. (c) These rotations convert the triangular lattice into the $J_1 - J_2 - J'$ lattice: the A and B clusters rotate in opposite directions, while the C clusters do not rotate. Inset shows original configuration. (d) The basic unit of the depleted fcc lattice: strong bonds are shown as red (solid) lines, weak bonds as blue (dashed) lines. The central layer forms the emergent honeycomb lattice.

$$H = J_1 \sum_{\langle ij \rangle_{A,B}} \vec{S}_i \cdot \vec{S}_j + J_2 \sum_{\langle\langle ij \rangle\rangle_{A,B}} \vec{S}_i \cdot \vec{S}_j + J' \sum_{\langle ij \rangle_{\{(A,B),C\}}} \vec{S}_i \cdot \vec{S}_j .$$



A Claim: a single-band extended Hubbard model on an anisotropic Kagome lattice with **1/6 electron filling.**



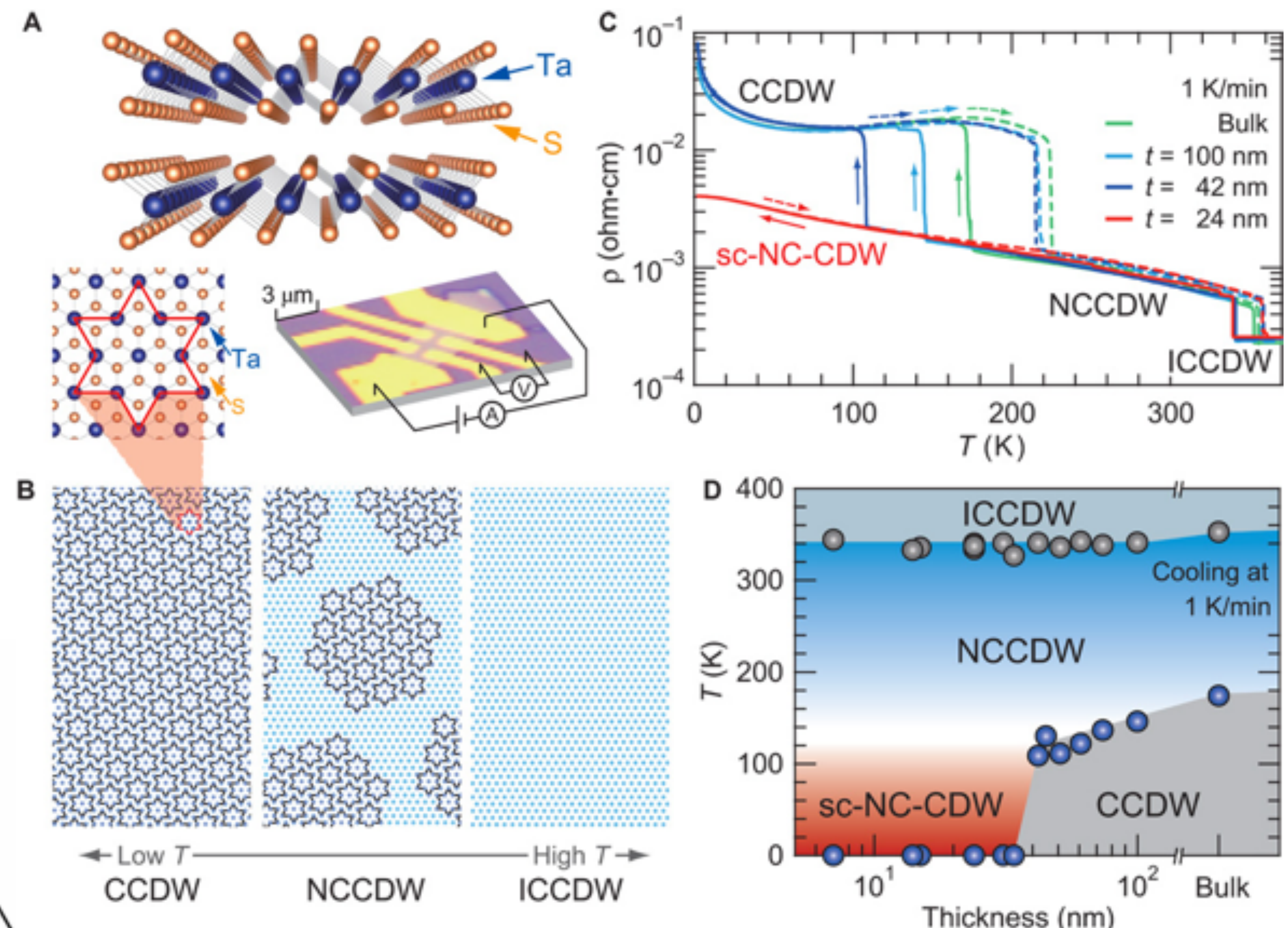
$$H = \sum_{\langle ij\rangle \in \mathrm{u}} [-t_1(c^\dagger_{i\sigma} c_{j\sigma} + h.c.) + V_1 n_i n_j] + \sum_{\langle ij\rangle \in \mathrm{d}} [-t_2(c^\dagger_{i\sigma} c_{j\sigma} + h.c.) + V_2 n_i n_j] + \sum_i \frac{U}{2}(n_i - \frac{1}{2})^2,$$

3 spins behave as an effective spin-1/2 moments

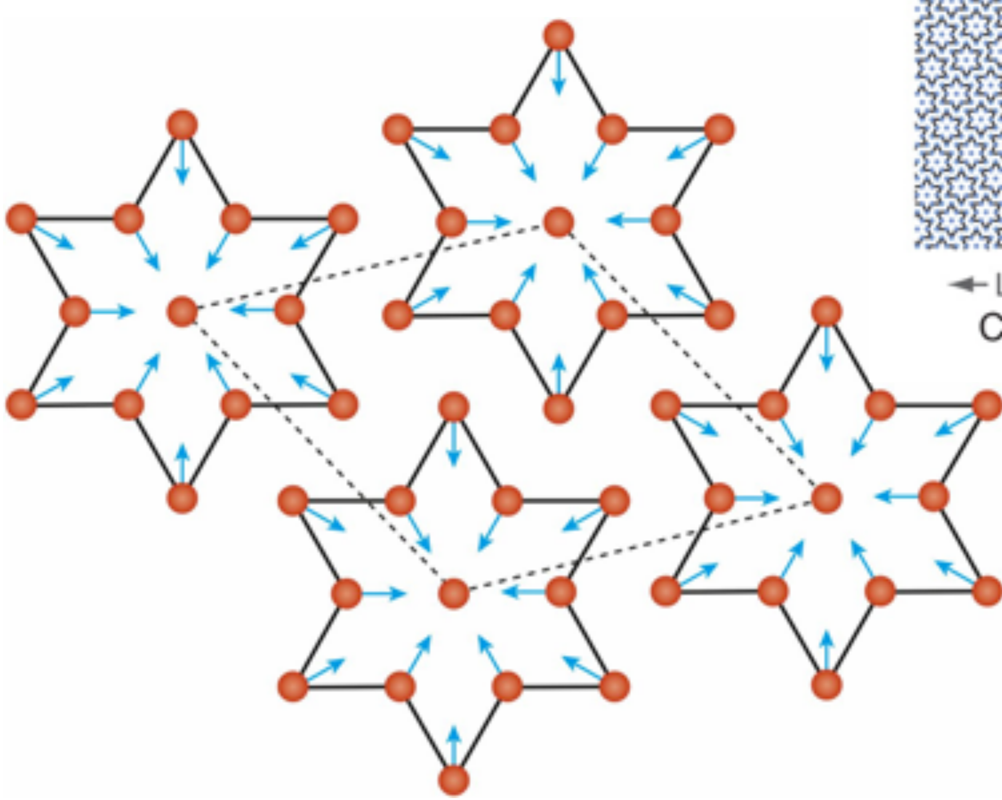
G Chen, HY Kee, YB Kim, 2015
G Chen, PA Lee, 2018

Cluster localization

1T-TaS2



PA Lee, KT Law



supertriangular lattice of David stars

Spinon Fermi surface ?

Spinon Fermi surface in a cluster Mott insulator model on a triangular lattice and possible application to 1T-TaS$_2$

Wen-Yu He,[1] Xiao Yan Xu,[1,*] Gang Chen,[2,3] K. T. Law,[1] and Patrick A. Lee[4,†]

$$
\begin{aligned}
\tilde{\mathcal{H}}_{\text{eff}} = J \sum_{\langle i,j \rangle} \left(S_i^x S_j^x + S_i^y S_j^y + (1+\gamma) S_i^z S_j^z \right) + K \sum_{\langle i,j,k,l \rangle} \Big[\left(S_i^x S_j^x + S_i^y S_j^y + (1+\gamma) S_i^z S_j^z \right) \left(S_k^x S_l^x + S_k^y S_l^y + (1+\gamma) S_k^z S_l^z \right) \\
+ \left(S_j^x S_k^x + S_j^y S_k^y + (1+\gamma) S_j^z S_k^z \right) \left(S_i^x S_l^x + S_i^y S_l^y + (1+\gamma) S_i^z S_l^z \right) - (\boldsymbol{S}_i \cdot \boldsymbol{S}_k)(\boldsymbol{S}_j \cdot \boldsymbol{S}_l) \Big] .
\end{aligned}
$$

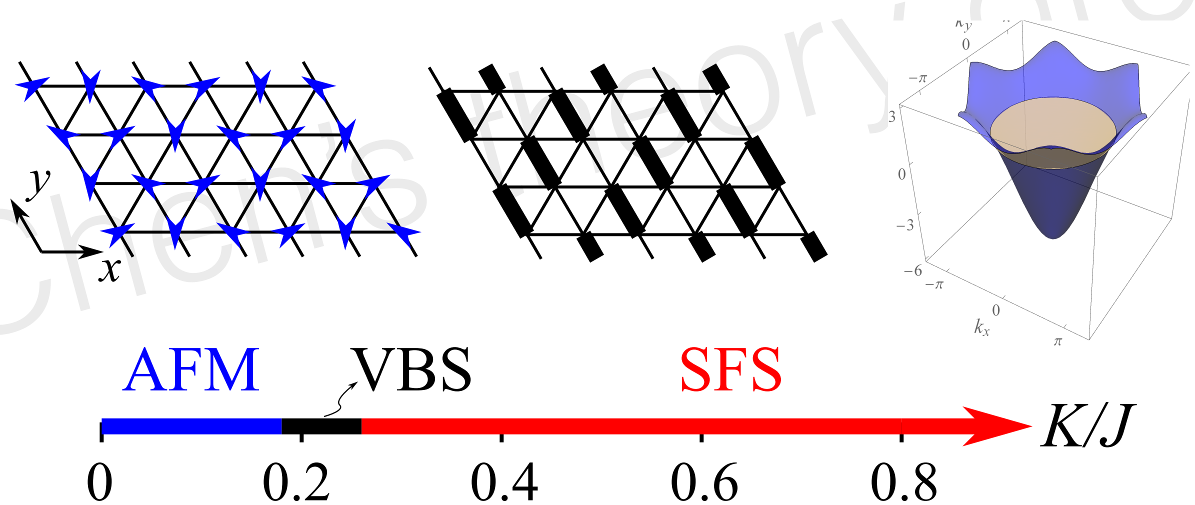
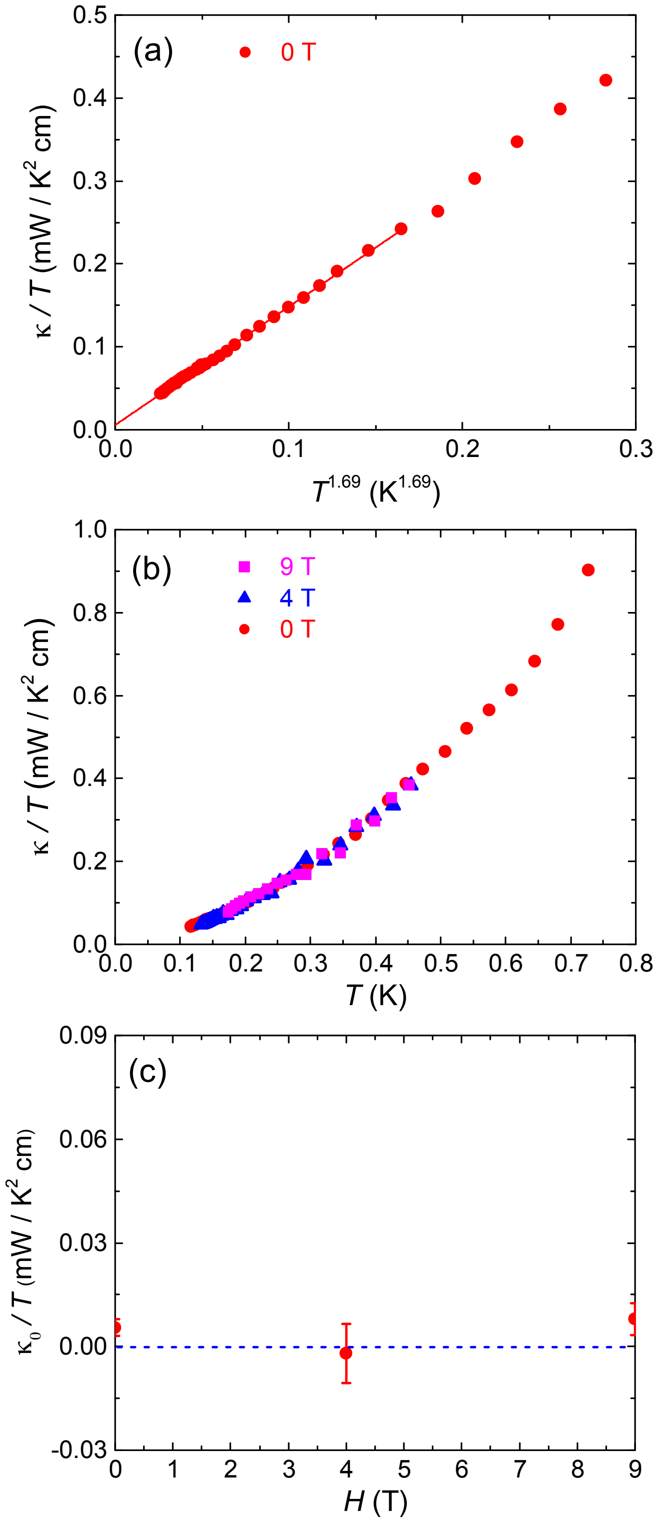


FIG. 1. Phase diagram for isotropic case ($\gamma = 0$), while for small anisotropy case related to real materials 1T-TaS$_2$ the phase diagram is similar. It is mainly obtained from six wide systems and confirmed in eight wide systems. Here AFM denotes 120°-spin order; VBS denotes valence bond solid state (or call dimerized phase); SFS denotes a quantum spin liquid with a spinon Fermi surface.

Gang Chen's theory group



Shiyan's data

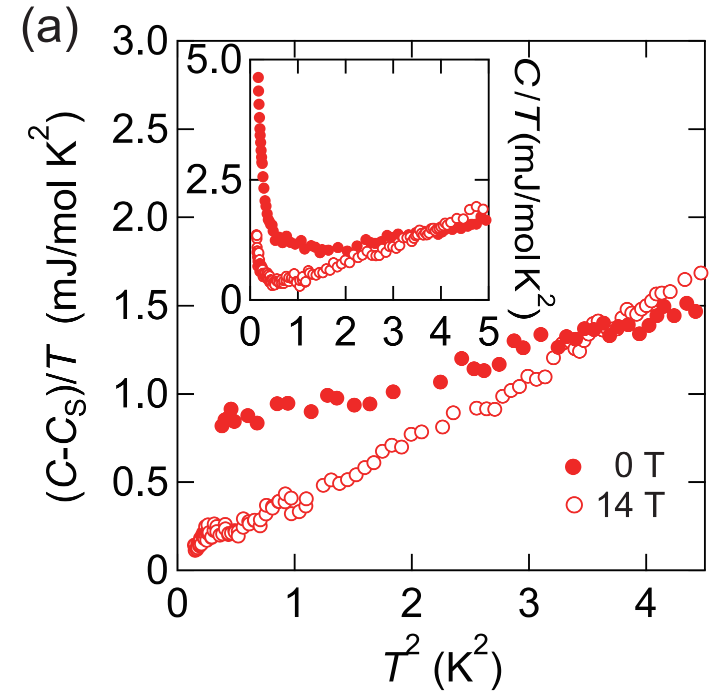
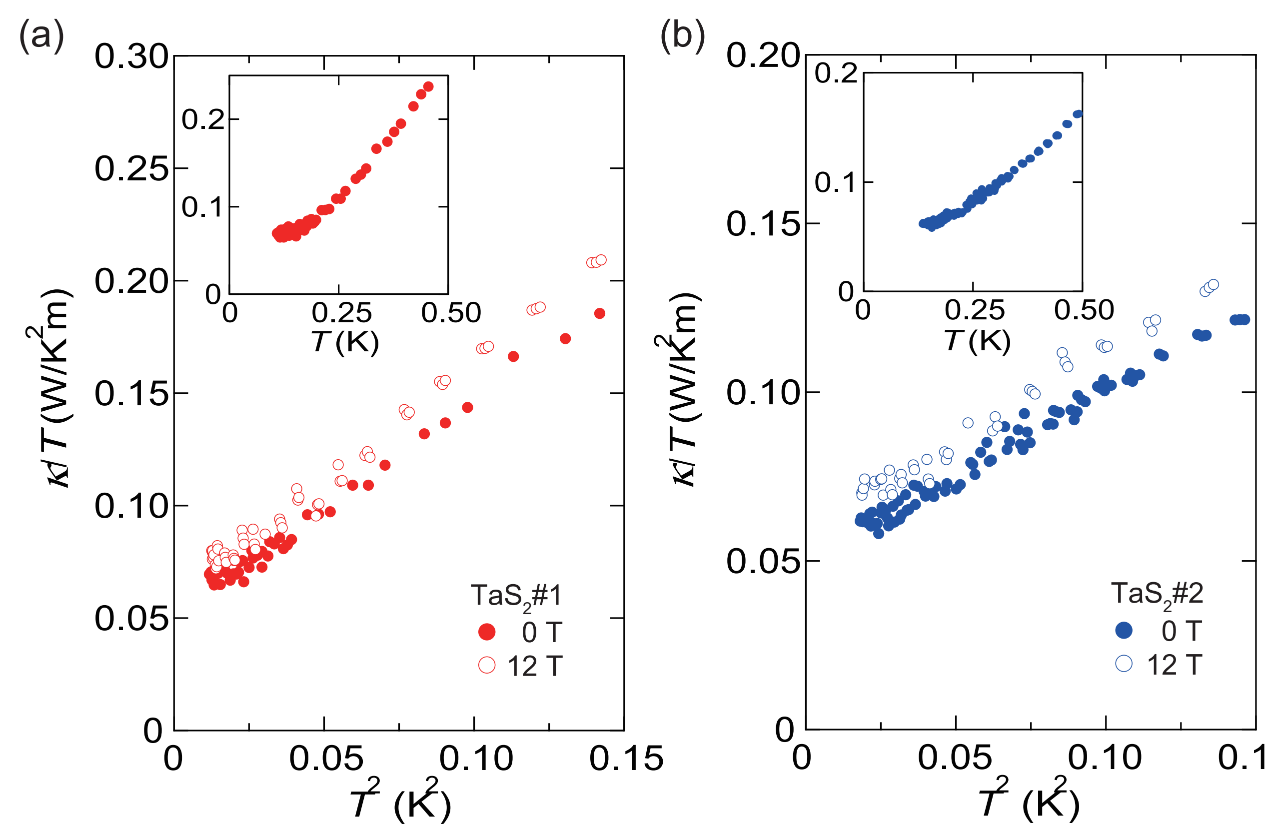


FIG. 2. (a) The inset shows C/T in zero field (filled red circles) and in magnetic field of $\mu_0 H$=14 T for $\boldsymbol{H} \perp ab$ plane (open red circles) plotted as a function of T^2. The main panel shows the specific heat obtained after subtracting the Schottky contribution, $(C - C_S)/T$, plotted as a function of T^2 in zero field (filled red circles) and at $\mu_0 H$=14 T (open



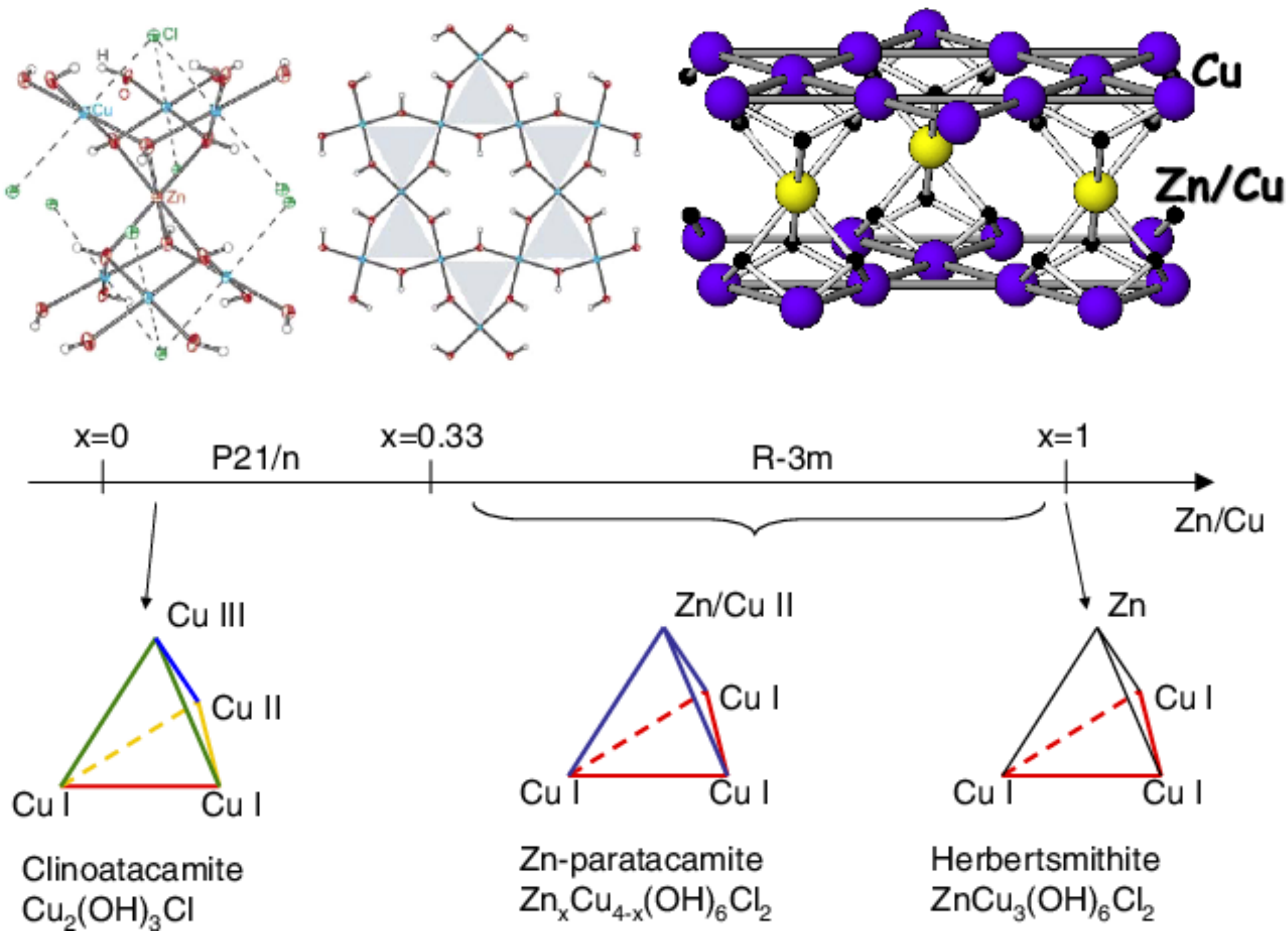
Matsuda

Recent measurements

Unpublished STM data from Christopher Butler and Hanaguri, Japan on 1T-TaS_2

Unpublished data on 1T-$TaSe_2$, STM
observe some extra supermodulation on top of the supercell structure

Frustrated magnets: kagome



I assume Jiawei will talk about it

Issues

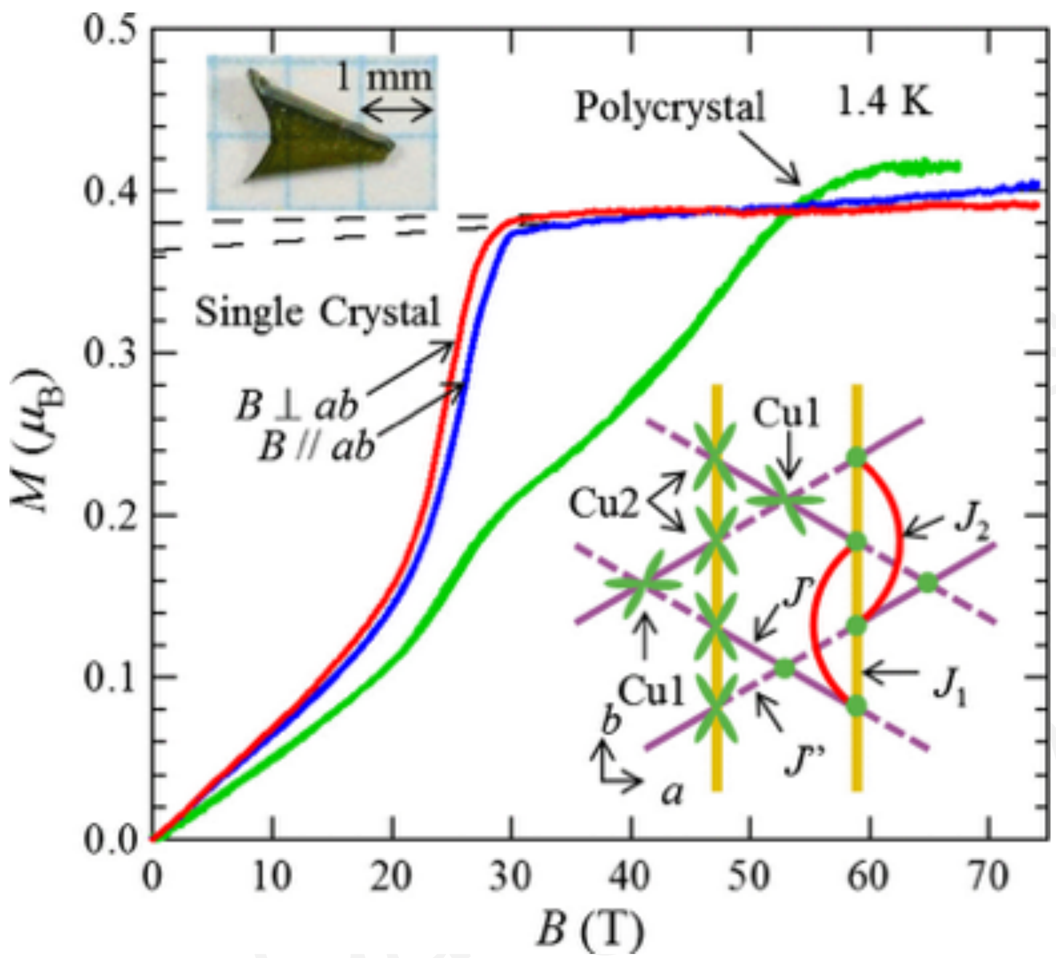
1. "theory/numerics" on heisenberg model fluctuates between Z2 QSL
   and U(1) Dirac.

2. Expts by Young Lee points to Z2, but some recent NMR may like fermi surface
   or Dirac.

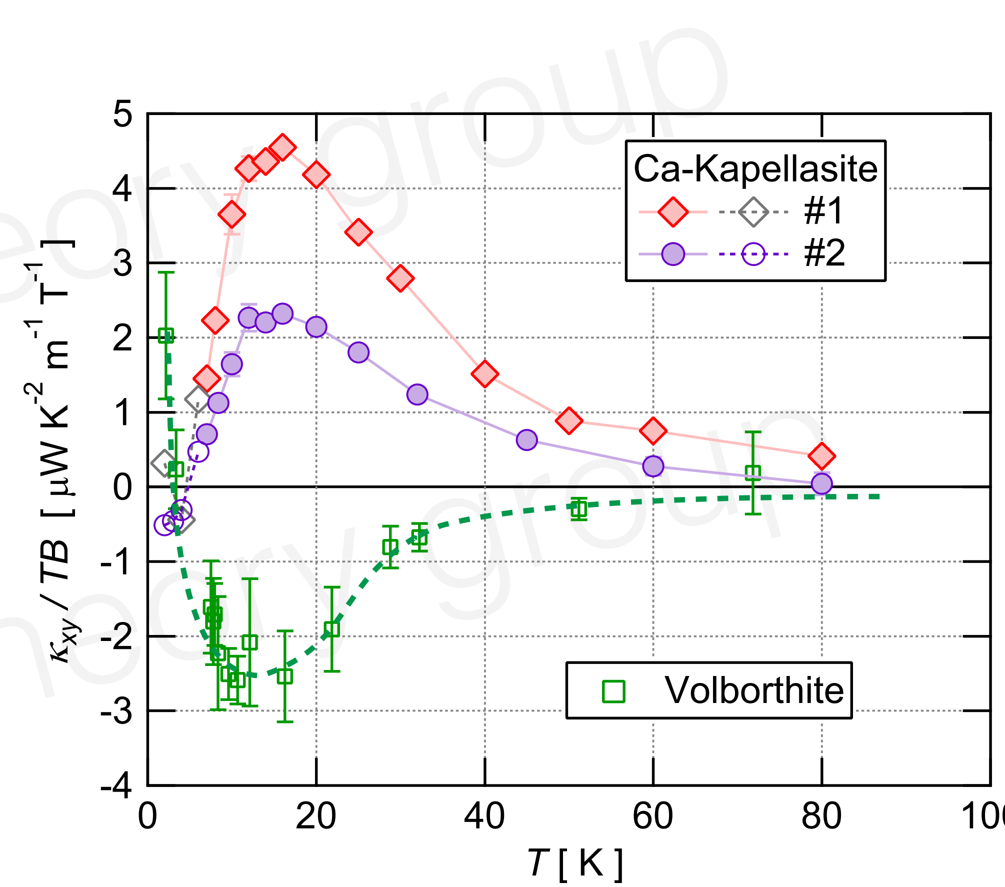
3. Materials are not really Heisenberg, addition interactions comparable or
   larger than Z2 gaps (spinless gap). [Jiawei Mei, G Chen]

Volborthite and Kapellasite

Large thermal Hall effect in spin-1/2 Kagome magnets



Z Hiroi's group



Minoru Yamashita's group

1. Why it is finite? All neutral excitations.
2. Non-monotonic.
3. Opposite signs in two materials.

evolution in magnetic fields

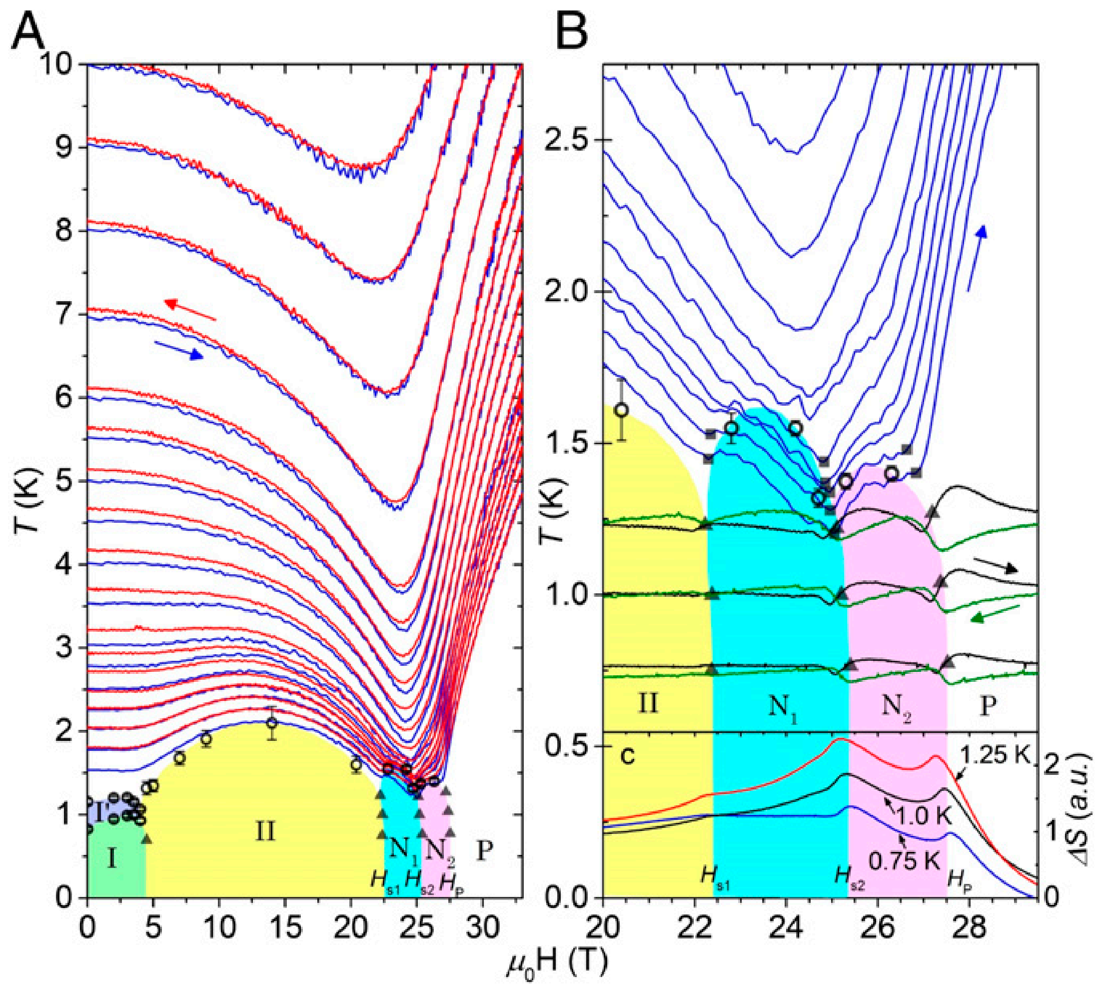
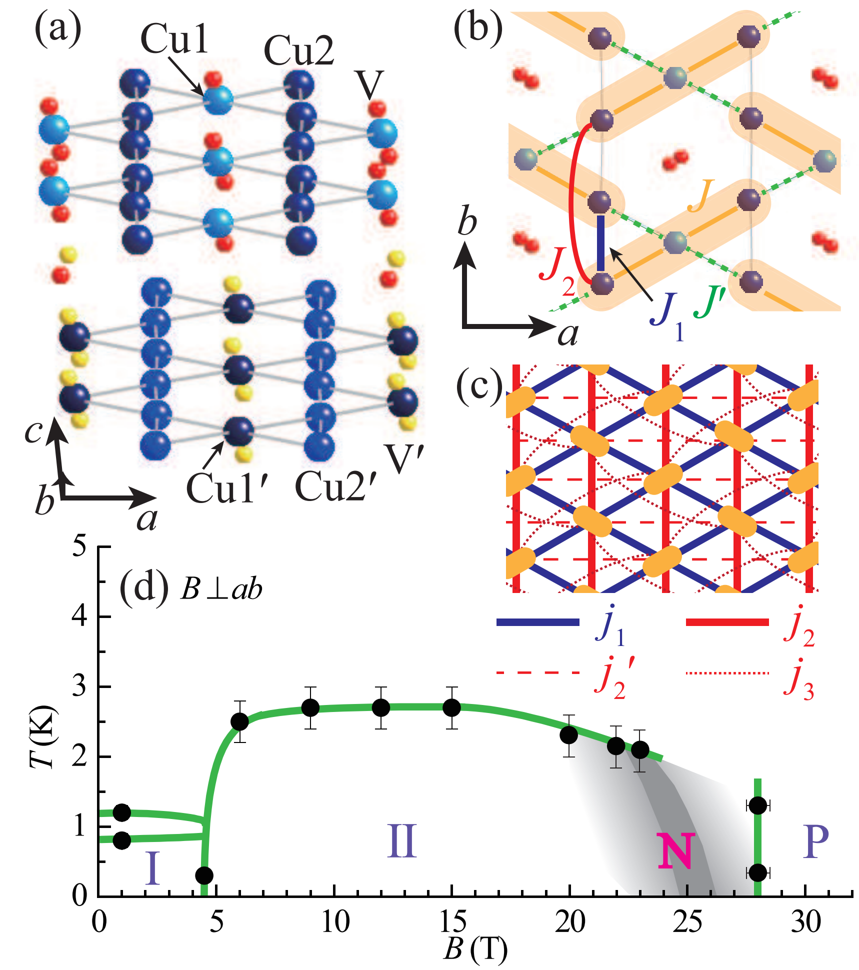


Fig. 3. Magnetocaloric effect and magnetic phase diagram of volborthite. (*A*) Experimental measurements of the MCE in volborthite, showing the evolution of temperature with changing magnetic field under (quasi-)adiabatic conditions (A-MCE). Results are shown for both rising (blue curves) and falling (red curves) magnetic field and reflect contours of constant entropy. The onset of the hidden-order phases, N_1 and N_2, is associated with tight bunching curves and a dip in the entropy contour, corresponding to a change in sign of the MCE. Black triangles show phase boundaries at low temperature, extracted from complimentary measurements of MCE under isothermal conditions (I-MCE). The phase boundaries extracted from measurements of heat capacity, $C(T)$, are shown with open circles. (*B*) Detail of phases N_1 and N_2, showing results for A-MCE measured in rising field (blue curves), I-MCE in rising field (black curves), and I-MCE in falling field (green curves). The black squares show the evolution of a corresponding feature in the A-MCE. Two distinct domes can be resolved at finite temperature, bounded by the critical fields $H_{s1} = 22.5$ T, $H_{s2} = 25.5$ T, and $H_P = 27.5$ T. (*C*) Changes of entropy extracted from measurements of I-MCE at low temperature (*Methods*). The field boundaries of the SN phase, N_2, and presumed supersolid phase, N_1, are sharply distinguished by local anomalies in entropy.

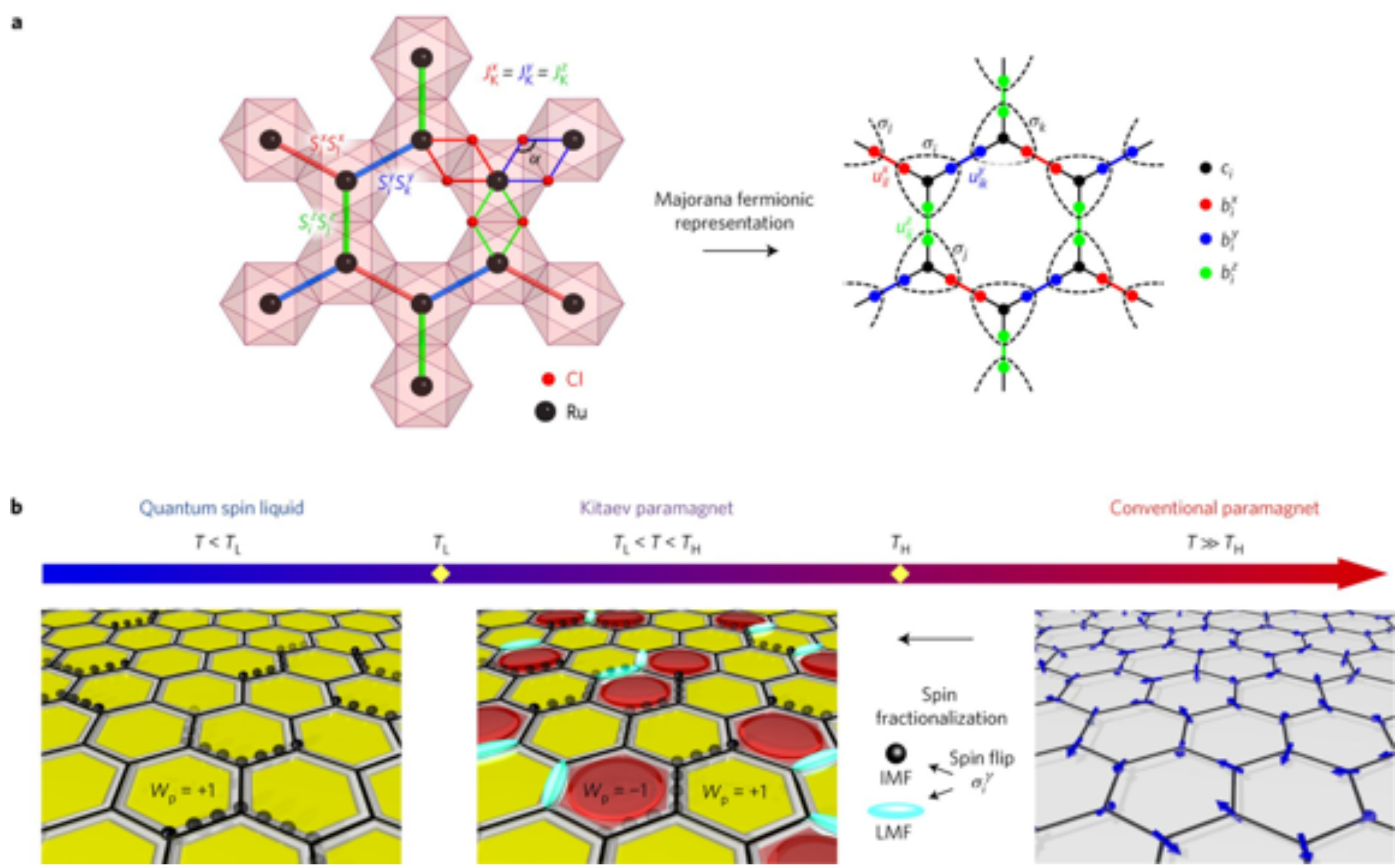


The interaction is anisotropic here, due to the distinct orbital content of the Cu ions.

Frustrated magnets: honeycomb Kitaev materials (non heisenberg)

Na2IrO3, Li2IrO3, alpha-RuCl3, etc

New examples: OsCl3, Co-honeycomb, YbCl3



Let me talk about this on Wednesday

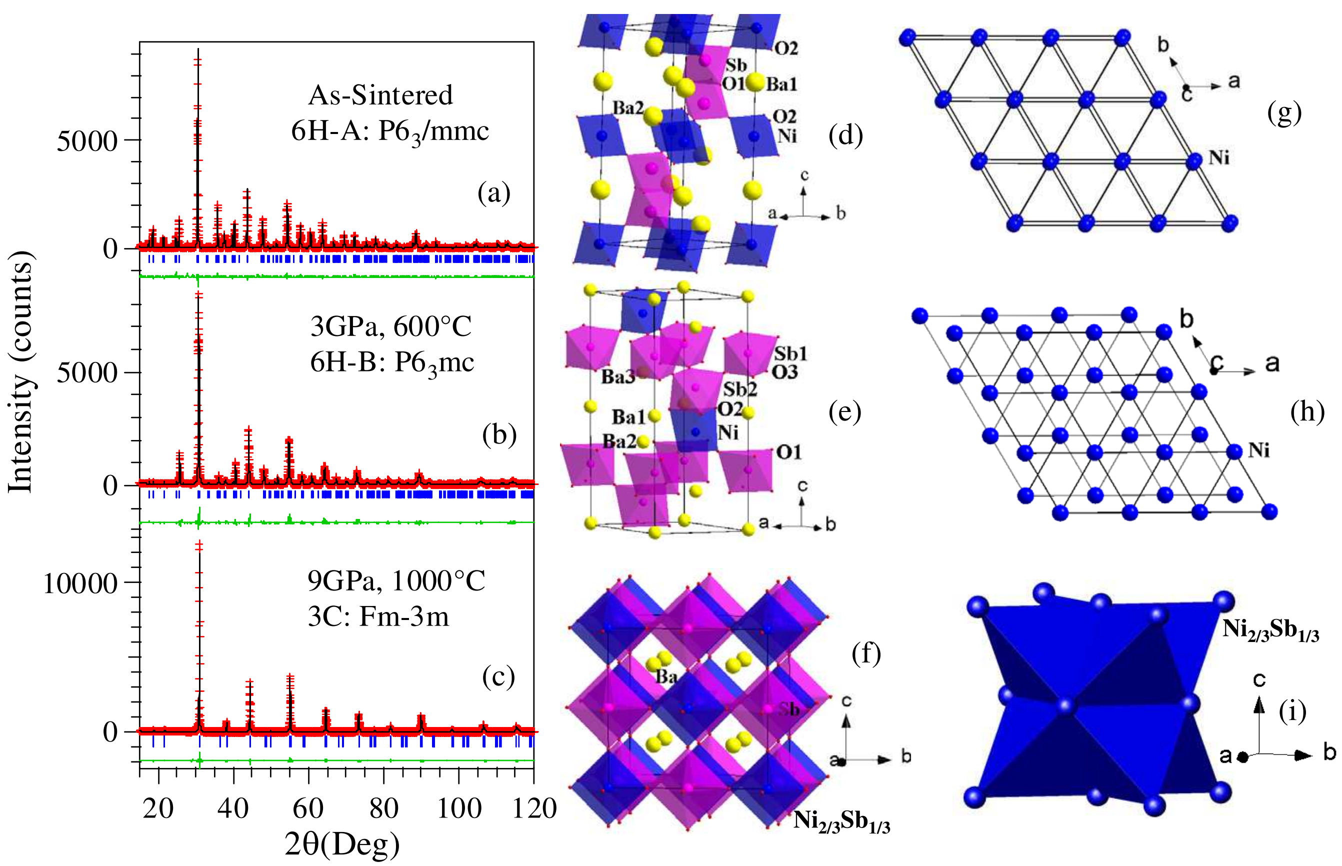
Frustrated magnets: spin-1 magnets [可作为某个专题]

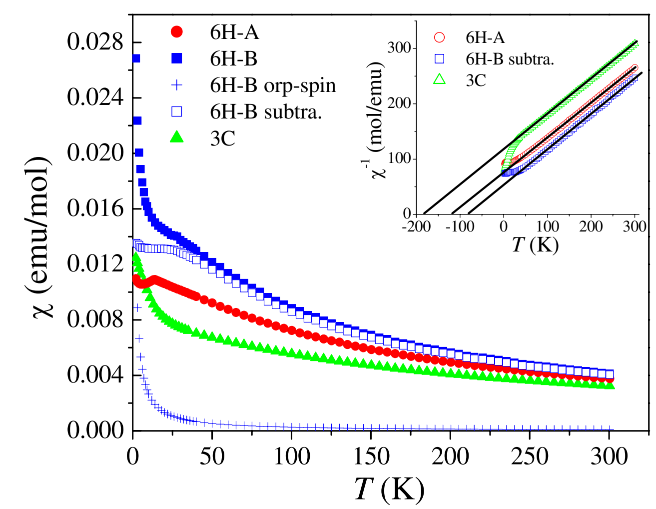
自旋-1仍很quantum,仍可以stabilize量子态。

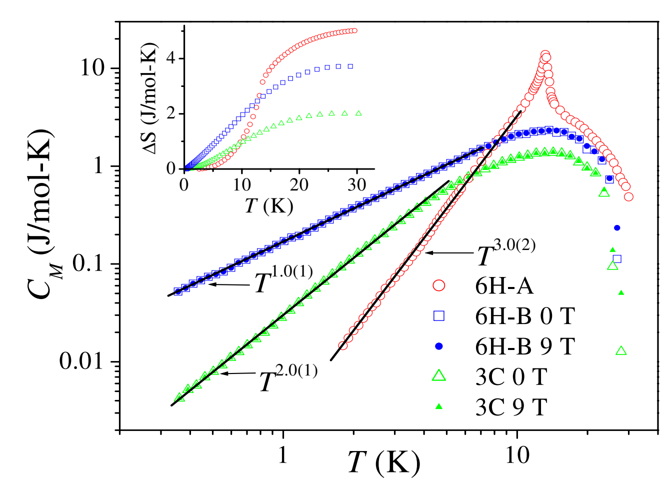
Ni-triangular magnets

High pressure sequence of $Ba_3NiSb_2O_9$ structural phases: new $S = 1$ quantum spin-liquids based on Ni^{2+}

J. G. Cheng,[1] G. Li,[2] L. Balicas,[2] J. S. Zhou,[1] J. B. Goodenough,[1] Cenke Xu,[3] and H. D. Zhou[2,*]







三个理论

Spin Liquid Phases for Spin-1 systems on the Triangular lattice

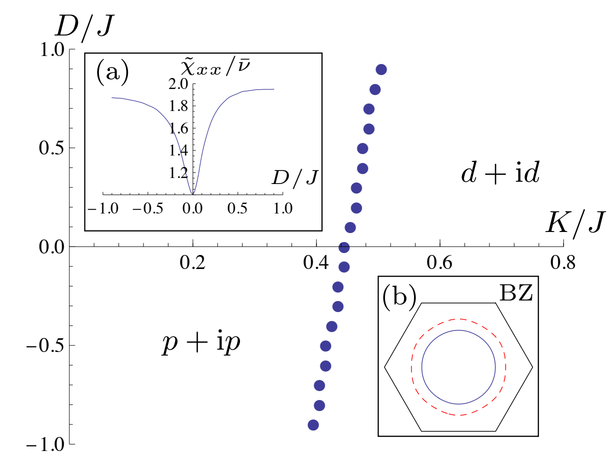
Cenke Xu,[1] Fa Wang,[2] Yang Qi,[3] Leon Balents,[1,4] and Matthew P. A. Fisher[1]

construct a spin liquid state with quadratic band touching,
not a model study

Exotic $S = 1$ spin liquid state with fermionic excitations on triangular lattice

Maksym Serbyn, T. Senthil, and Patrick A. Lee
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Dated: September 28, 2018)

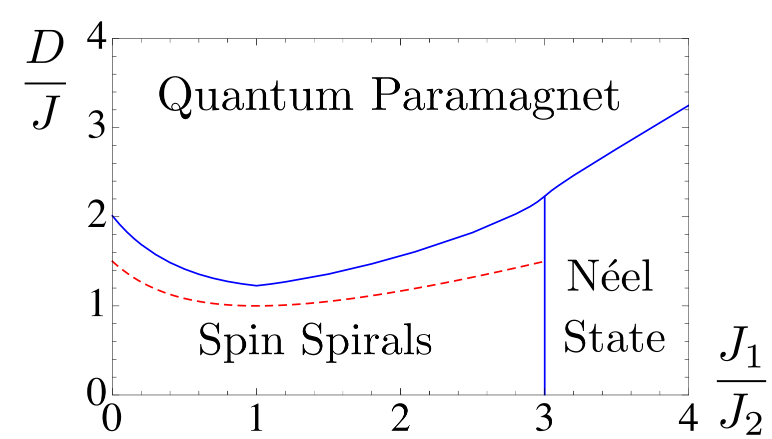
$$H = \sum_{\langle \boldsymbol{ij} \rangle} [J \vec{S}_{\boldsymbol{i}} \cdot \vec{S}_{\boldsymbol{j}} + K(\vec{S}_{\boldsymbol{i}} \cdot \vec{S}_{\boldsymbol{j}})^2] + D \sum_{\boldsymbol{i}} (S^z_{\boldsymbol{i}})^2,$$



Frustrated quantum critical theory of putative spin-liquid phenomenology in 6H-B-$Ba_3NiSb_2O_9$

G. Chen, M. Hermele, and L. Radzihovsky

$$\mathcal{H}_{\text{ex}} = J_1 \sum_{\langle ij \rangle \in \text{AB}} \mathbf{S}_i \cdot \mathbf{S}_j + J_2 \sum_{\langle ij \rangle \in \text{AA and BB}} \mathbf{S}_i \cdot \mathbf{S}_j .$$



Ni-diamond lattice: $NiRh_2O_4$

maybe SPT,
maybe QSL

T. McQueen

APS March Meeting 2017

Monday–Friday, March 13–17, 2017; New Orleans, Louisiana

Session B48: Frustrated Magnetism: Spinels, Pyrochlores, and Frustrated 3D Magnets I

11:15 AM–2:15 PM, Monday, March 13, 2017
Room: 395

Sponsoring Units: GMAG DMP
Chair: Martin Mourigal, Georgia Tech

Abstract: B48.00006 : S = 1 on a Diamond Lattice in NiRh2O4

12:15 PM–12:27 PM

Preview Abstract

MathJax ***On*** | *Off* *Abstract*

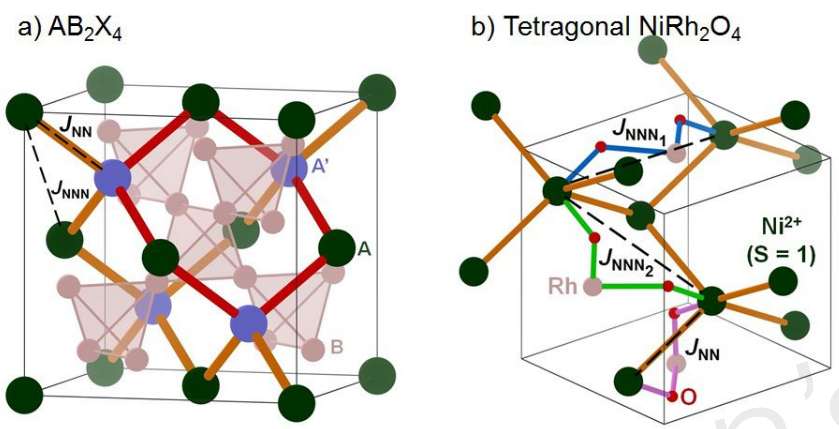
Authors:

Juan Chamorro
(Johns Hopkins University)

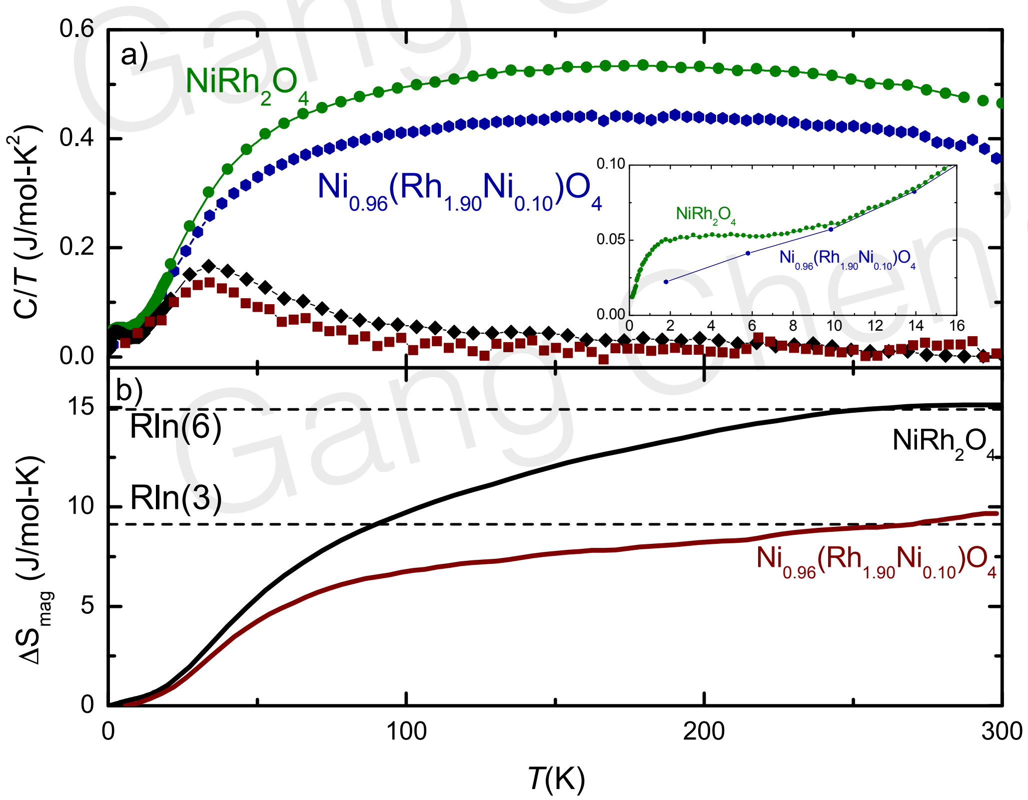
Tyrel McQueen
(Johns Hopkins University)

An S = 1 system has the potential of rich physics, and has been the subject of intense theoretical work. Extensive work has been done on one-dimensional and two-dimensional S = 1 systems, yet three dimensional systems remain elusive. Experimental realizations of three-dimensional S = 1, however, are limited, and no system to date has been found to genuinely harbor this. Recent theoretical work suggests that S = 1 on a diamond lattice would enable a novel topological paramagnet state, generated by fluctuating Haldane chains within the structure, with topologically protected end states. Here we present data on NiRh2O4, a tetragonal spinel that has a structural phase transition from cubic to tetragonal at T = 380 K. High resolution XRD shows it to have a tetragonally distorted spinel structure, with Ni2+ (d8, S = 1) on the tetrahedral, diamond sublattice site. Magnetic susceptibility and specific heat measurements show that it does not order magnetically down to T = 0.1 K. Nearest neighbor interactions remain the same despite the cubic to tetragonal phase transition. Comparison to theoretical models indicate that this system might fulfill the requirements necessary to have both highly entangled and topological behaviors.

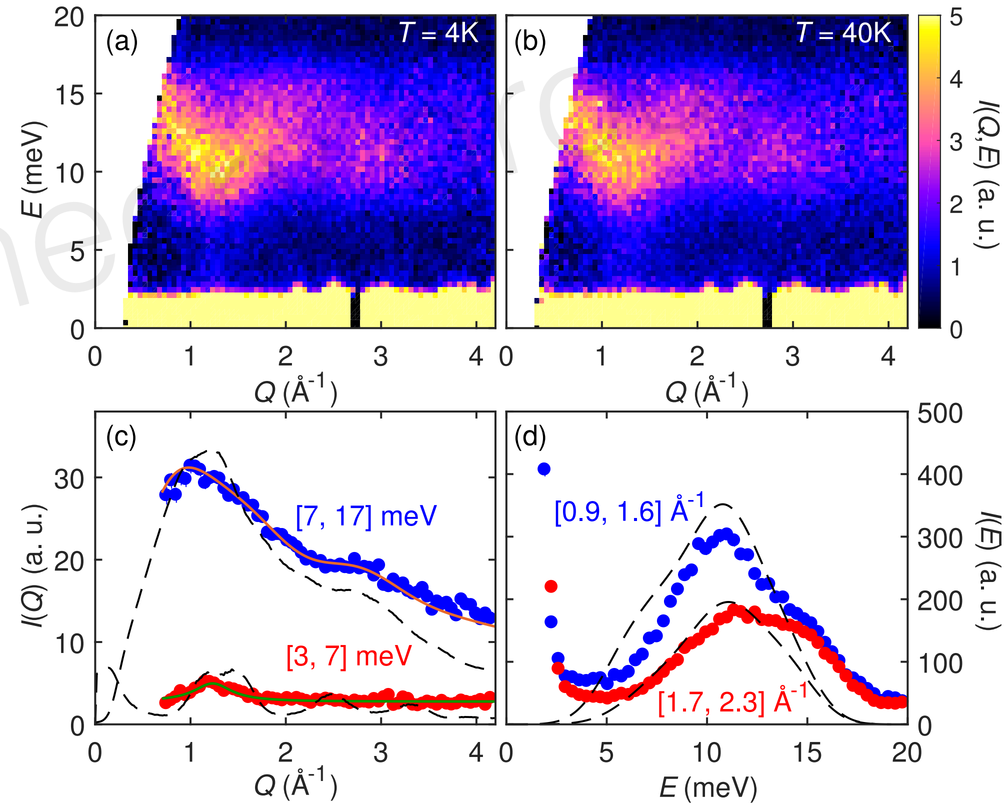
Ni-diamond lattice: NiRh2O4



T. McQueen



orbital active

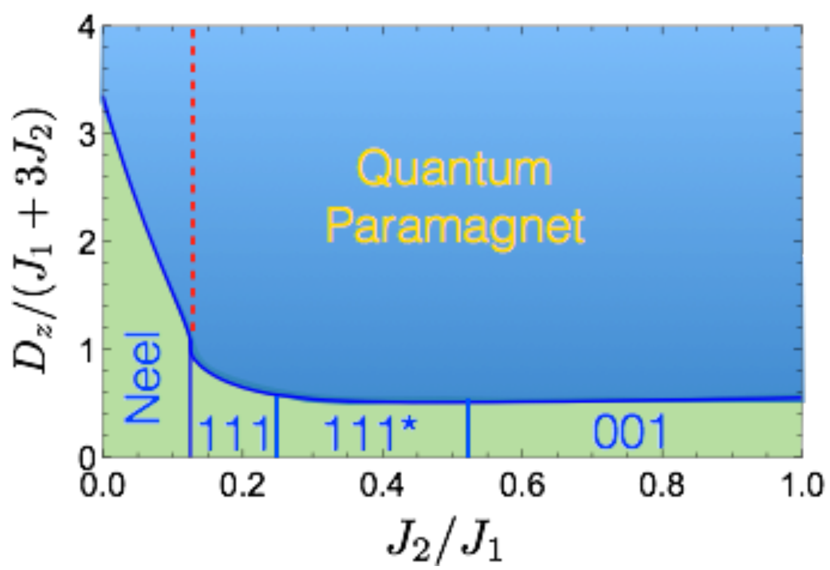


inelastic neutron

Quantum Paramagnet and Frustrated Quantum Criticality in a Spin-One Diamond Lattice Antiferromagnet

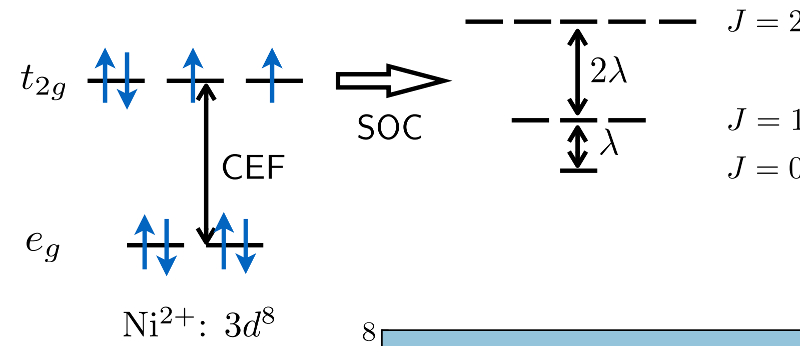
Gang Chen[1,2*]
[1] State Key Laboratory of Surface Physics, Department of Physics,

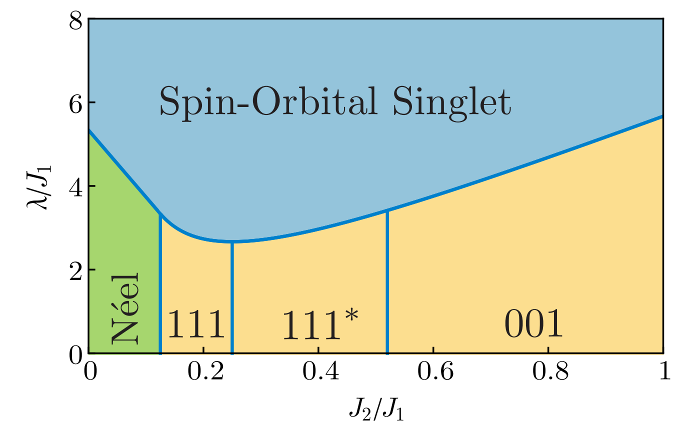
$$H = J_1 \sum_{\langle \boldsymbol{r}\boldsymbol{r}'\rangle} \boldsymbol{S}_{\boldsymbol{r}}\cdot\boldsymbol{S}_{\boldsymbol{r}'} + J_2 \sum_{\langle\langle \boldsymbol{r}\boldsymbol{r}'\rangle\rangle} \boldsymbol{S}_{\boldsymbol{r}}\cdot\boldsymbol{S}_{\boldsymbol{r}'} + D_z \sum_{\boldsymbol{r}} (S_{\boldsymbol{r}}^z)^2, \quad (1)$$



Spin-orbital entanglement in d^8 Mott insulators: Possible excitonic magnetism in diamond lattice antiferromagnets

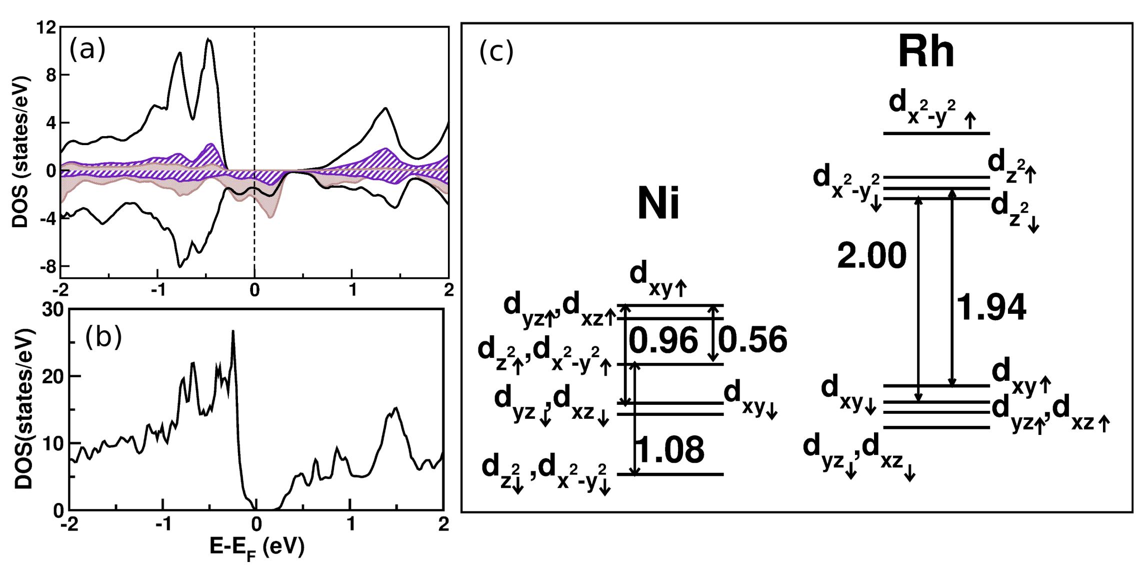
Fei-Ye Li and Gang Chen*





The Curious Case of $NiRh_2O_4$: A Spin-Orbit Entangled Diamond Lattice Paramagnet

Shreya Das,[1] Dhani Nafday,[2] Tanusri Saha-Dasgupta,[1,2] and Arun Paramekanti[3,*]

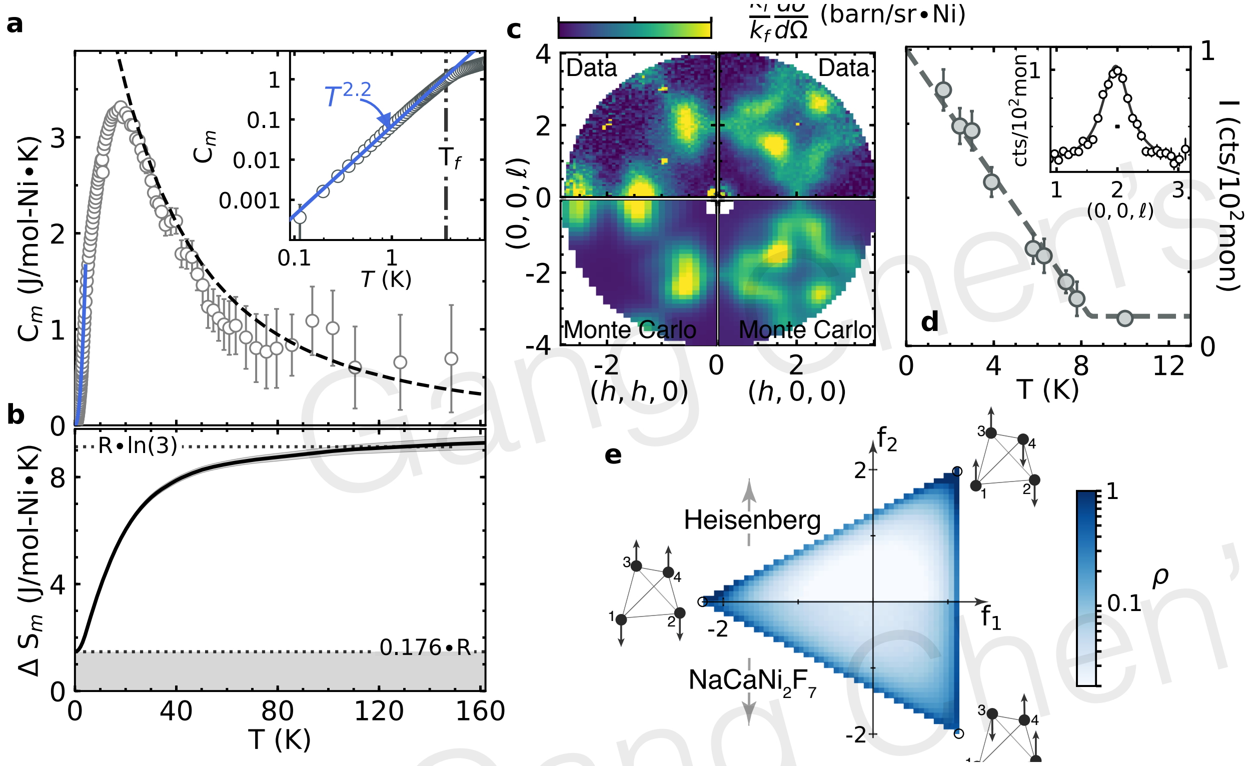


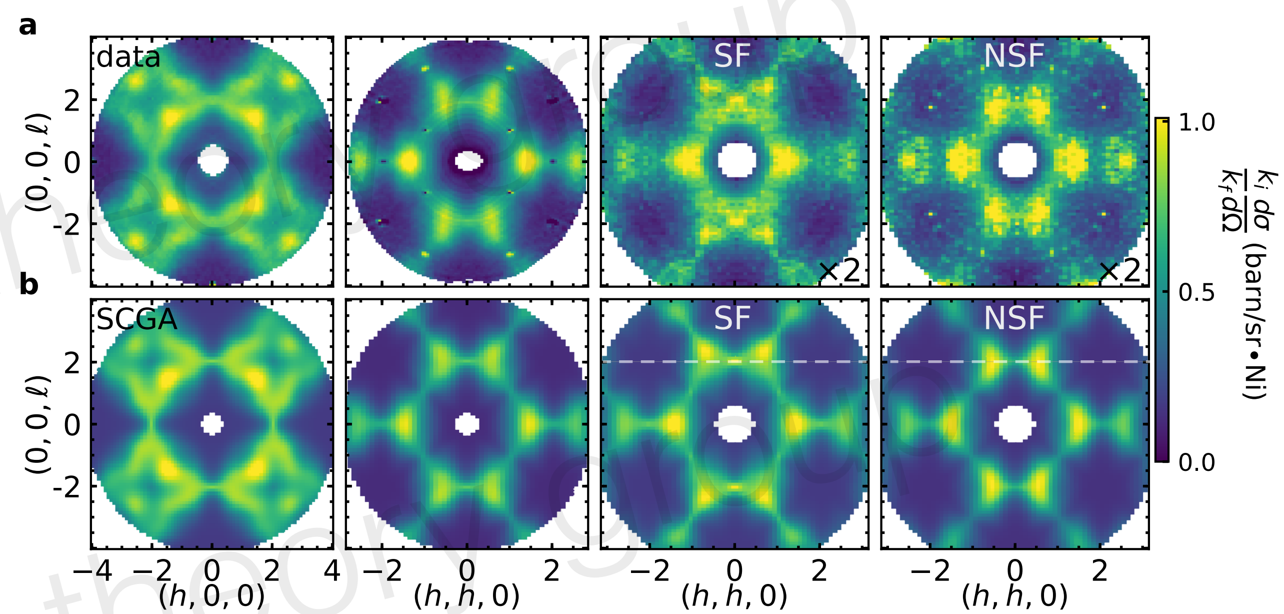
Ni-pyrochlore magnet

NaCaNi2F7

Continuum of quantum fluctuations in a three-dimensional $S=1$ Heisenberg magnet

K. W. Plumb,[1] Hitesh J. Changlani,[1] A. Scheie,[1] Shu Zhang,[1] J. W. Krizan,[2] J. A. Rodriguez-Rivera,[3,4] Yiming Qiu,[3] B. Winn,[5] R. J. Cava,[2] and C. L. Broholm[1,3,6]





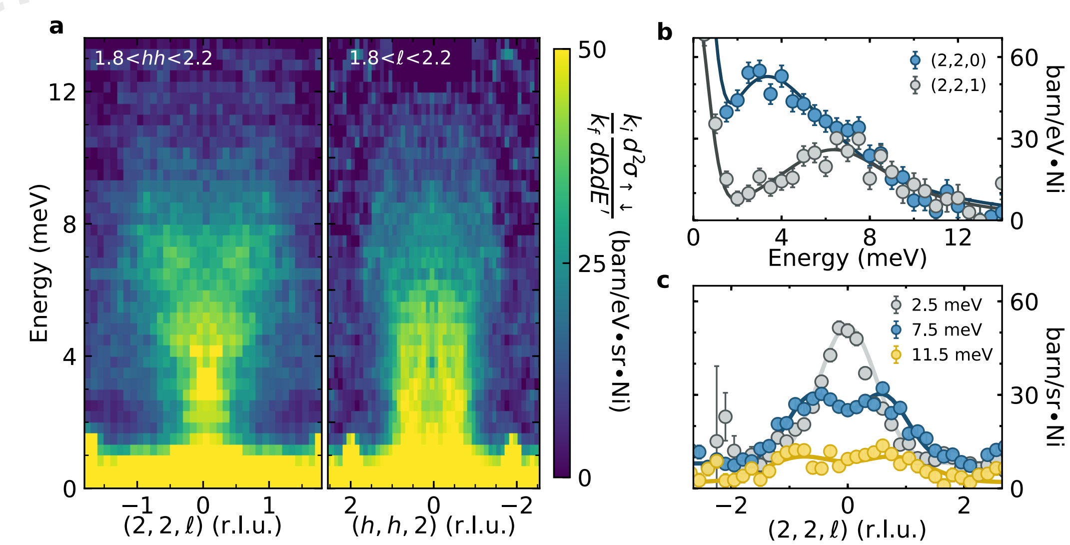


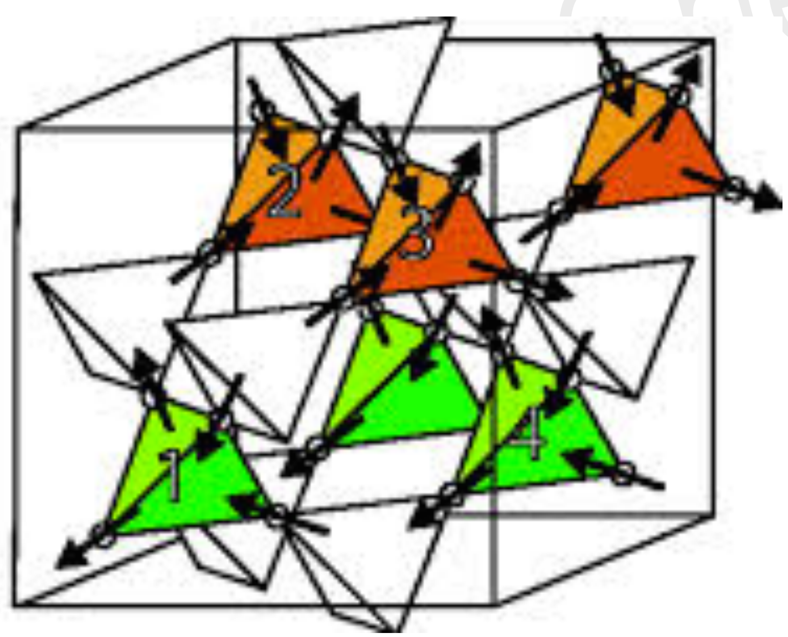
Figure 4: Magnetic excitations in $NaCaNi_2F_7$. a, Energy-momentum cuts through the

One of the hardest problems in quantum magnetism

Frustrated magnets: pyrochlore spin ice

1. rare-earth pyrochlores: $Ho_2Ti_2O_7$, $Dy_2Ti_2O_7$, $Ho_2Sn_2O_7$, $Dy_2Sn_2O_7$, Er_2Ti_2O7, $Yb_2Ti_2O_7$, $Tb_2Ti_2O_7$, $Er_2Sn_2O_7$, $Tb_2Sn_2O_7$, $Pr_2Sn_2O_7$, $Nd_2Sn_2O_7$, $Gd_2Sn_2O_7$, …….

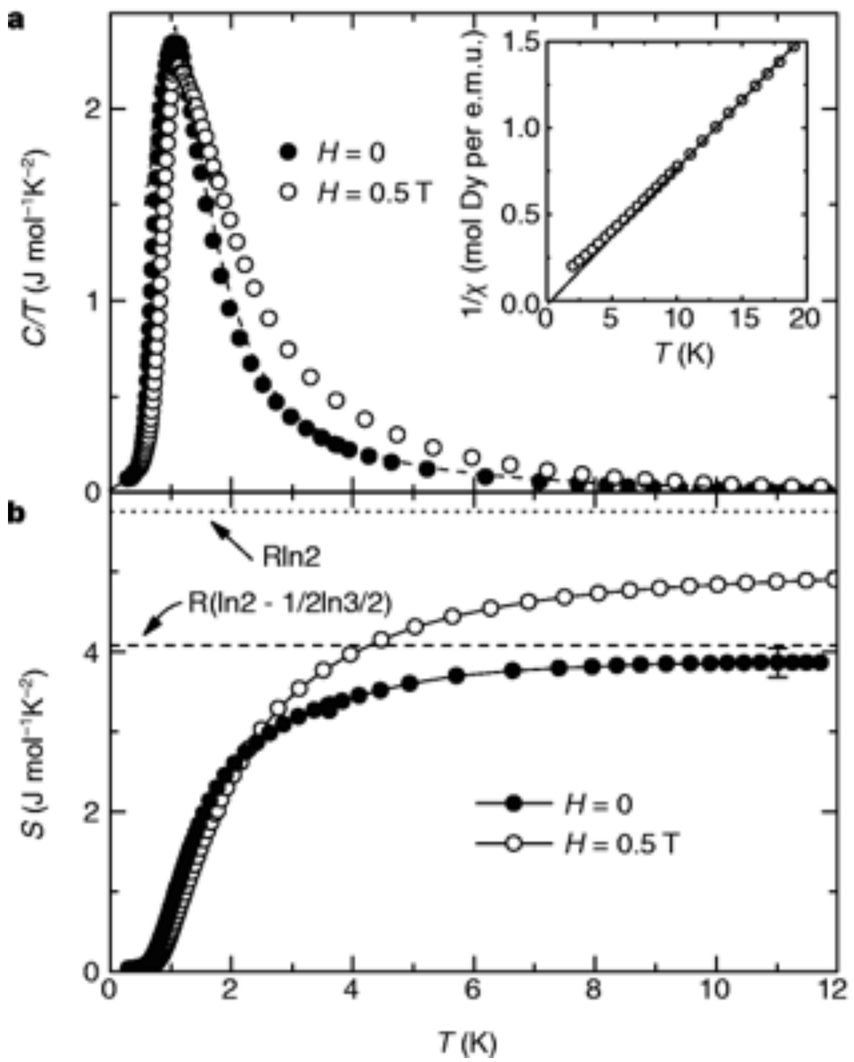
2. rare-earth B-site spinel: $CdEr_2S_4$,$CdEr_2Se_4$, $CdYb_2S_4$, $CdYb_2Se_4$, $MgYb_2S_4$, $MgYb_2S_4$, $MnYb_2S_4$, $MnYb_2Se_4$, $FeYb_2S_4$, $CdTm_2S_4$ $CdHo_2S_4$, $FeLu_2S_4$, $MnLu_2S_4$, $MnLu_2Se_4$, ….



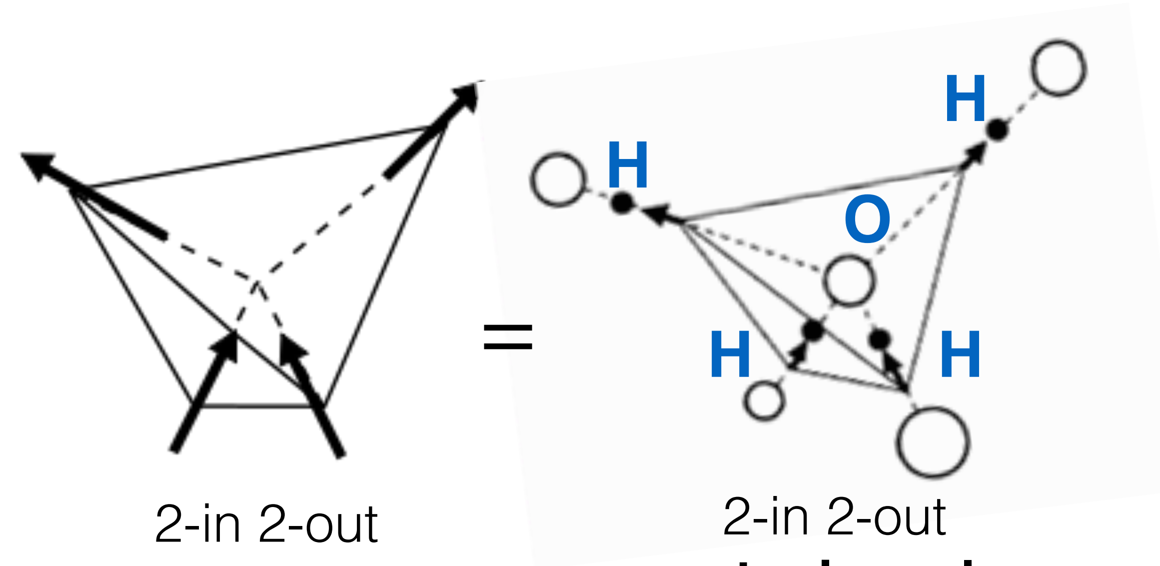
crystal field doublet -> effective spin-1/2

Spin ice

$Dy_2Ti_2O_7$

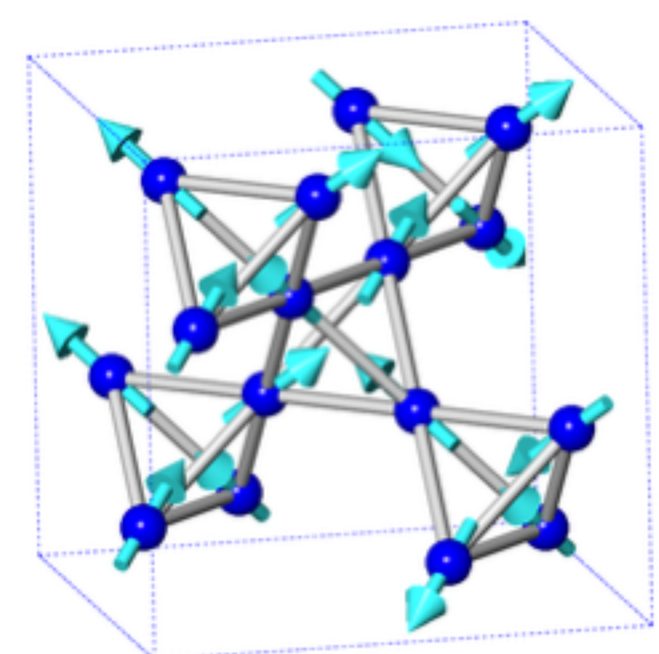


Pauling entropy in spin ice,
Ramirez, etc, Science 1999



2-in 2-out
spin ice rule

2-in 2-out
water ice rule



Lattice gauge theory for U(1) spin liquid

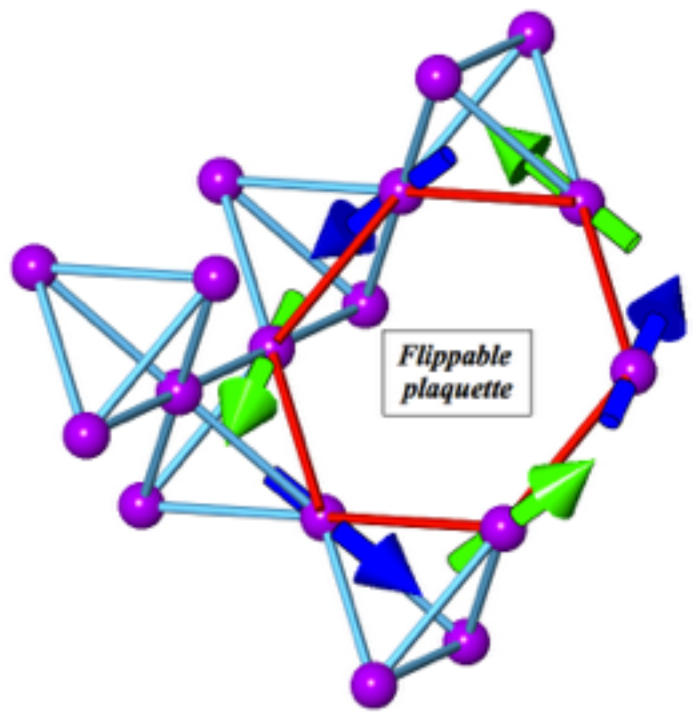


Figure from Michel Gingras

$$\mathcal{H}_{\mathrm{XXZ}} = \sum_{\langle ij \rangle} J_{zz} S_i^z S_j^z - J_\perp (S_i^+ S_j^- + S_i^- S_j^+),$$

3rd order degenerate perturbation
(Hermele, Fisher, Balents 2004)

$$\mathcal{H}_{\mathrm{eff}} = -\frac{12 J_\perp^3}{J_{zz}^2} \sum_{⬡_{\mathrm{p}}} (S_i^+ S_j^- S_k^+ S_l^- S_m^+ S_n^- + h.c.),$$

$$E_{\boldsymbol{r}\boldsymbol{r}'} \simeq S^z_{\boldsymbol{r}\boldsymbol{r}'}$$
$$e^{iA_{\boldsymbol{r}\boldsymbol{r}'}} \simeq S^\pm_{\boldsymbol{r}\boldsymbol{r}'}$$

$$K = 24 J_\perp^3 / J_{zz}^2$$

Lattice gauge theory
on the diamond lattice

$$\mathcal{H}_{\mathrm{LGT}} = -K \sum_{⬡_{\mathrm{d}}} \cos(\mathrm{curl}\, A) + U \sum_{\boldsymbol{r}\boldsymbol{r}'} (E_{\boldsymbol{r}\boldsymbol{r}'} - \frac{\eta_{\boldsymbol{r}}}{2})^2$$

inserting spinon matter (Savary Balents 2012)

$$H = \sum_{\mathbf{r} \in \mathrm{I,II}} \frac{J_{zz}}{2} Q_{\mathbf{r}}^2 - J_\pm \left\{ \sum_{\mathbf{r}\in \mathrm{I}} \sum_{\mu,\nu\neq\mu} \Phi^\dagger_{\mathbf{r}+\mathbf{e}_\mu} \Phi_{\mathbf{r}+\mathbf{e}_\nu} \mathsf{s}^-_{\mathbf{r},\mathbf{r}+\mathbf{e}_\mu} \mathsf{s}^+_{\mathbf{r},\mathbf{r}+\mathbf{e}_\nu} + \sum_{\mathbf{r}\in \mathrm{II}} \sum_{\mu,\nu\neq\mu} \Phi^\dagger_{\mathbf{r}-\mathbf{e}_\mu} \Phi_{\mathbf{r}-\mathbf{e}_\nu} \mathsf{s}^+_{\mathbf{r},\mathbf{r}-\mathbf{e}_\mu} \mathsf{s}^-_{\mathbf{r},\mathbf{r}-\mathbf{e}_\nu} \right\}$$

One could think more realistically, …

- 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

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

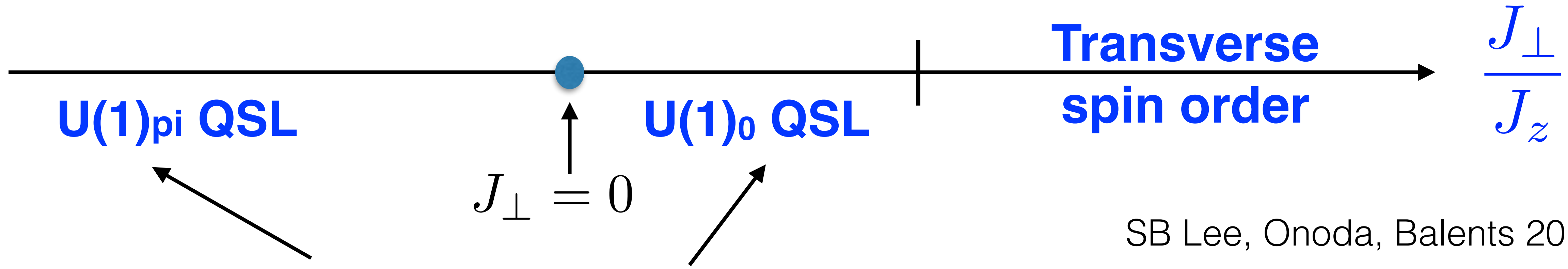
Y-P Huang, **GC**, M Hermele, PRL 2014
Y-D LI, **GC**, PRB 2017

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

no sign problem for QMC on any lattice.

It supports nontrivial phases

one may wonder if qsi exist in some physica

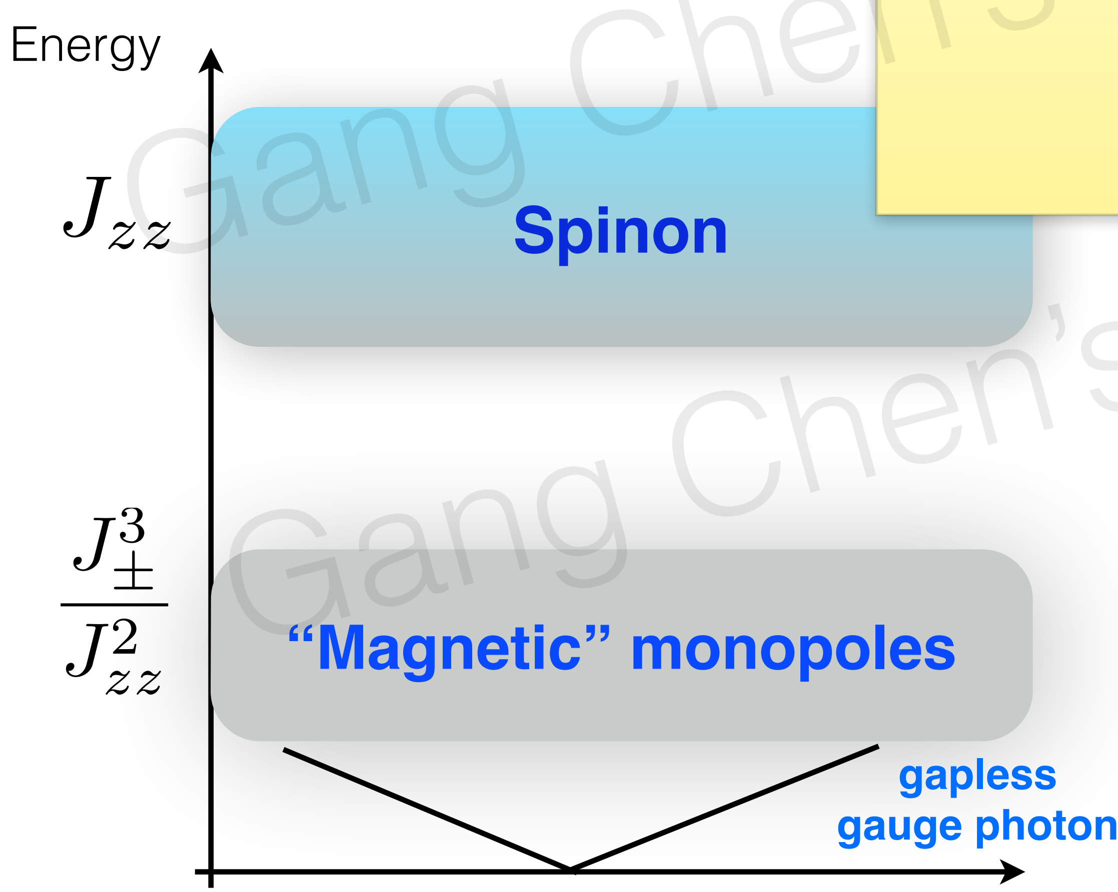


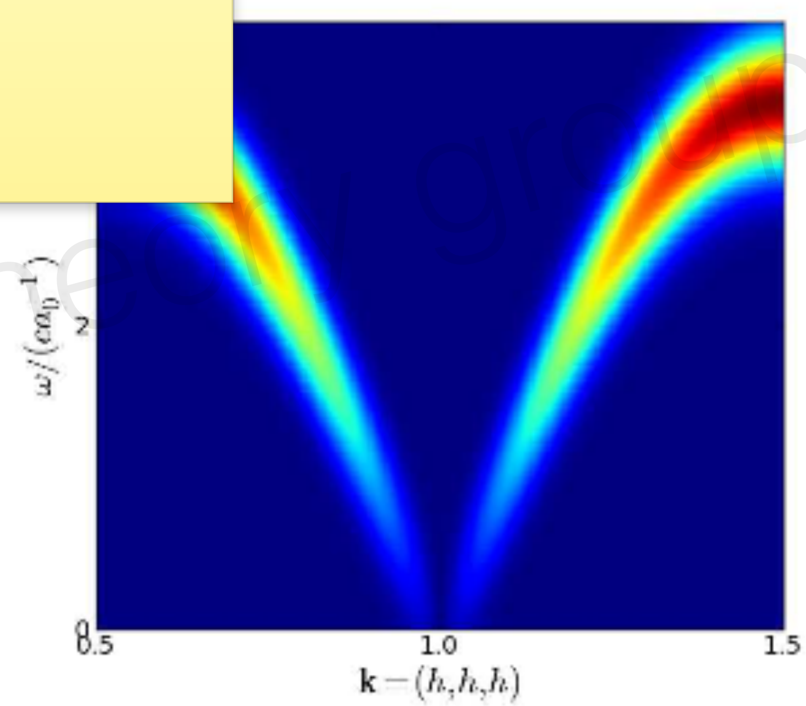
SB Lee, Onoda, Balents 2012

Related by unitary transformation (Hermele, Fisher, Balents 2004)

Besides the quantitative differences, are there sharp distinctions between the $U(1)_{pi}$ QSL on the left and the $U(1)_0$ QSL on the right?

with modern understanding of topological phase,



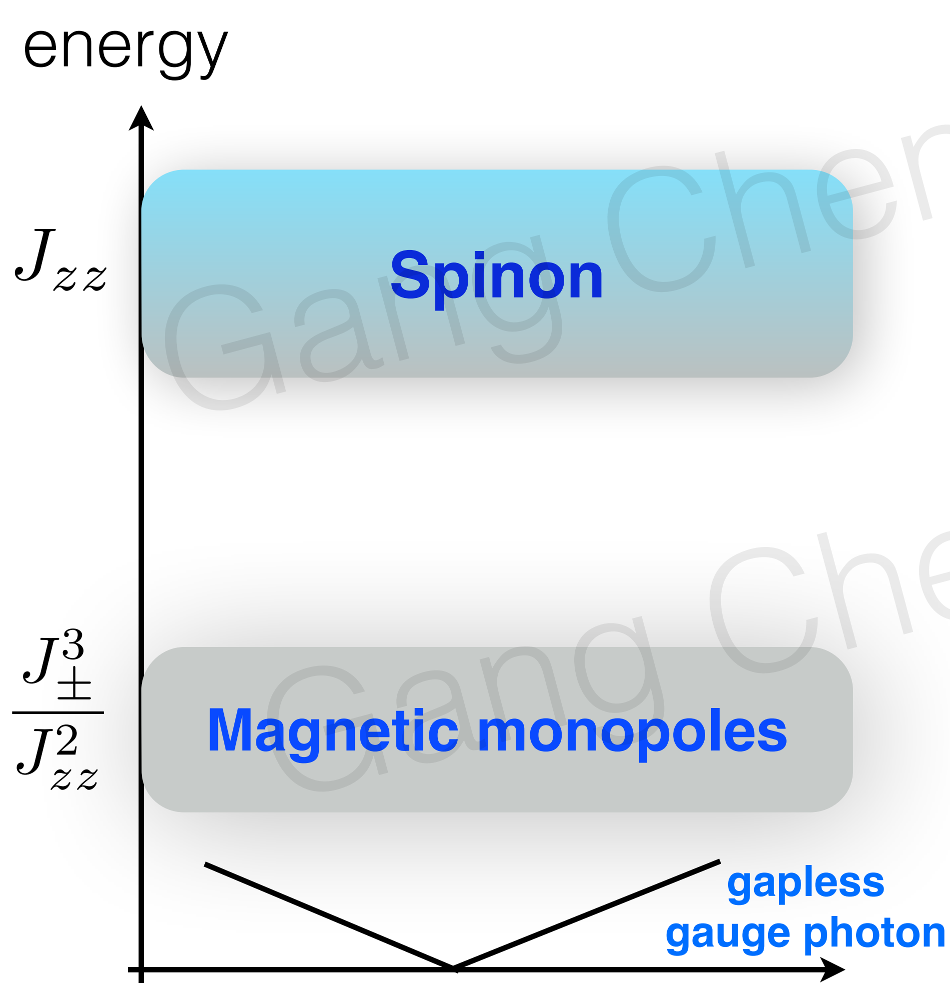


$I(\omega) \sim \omega$

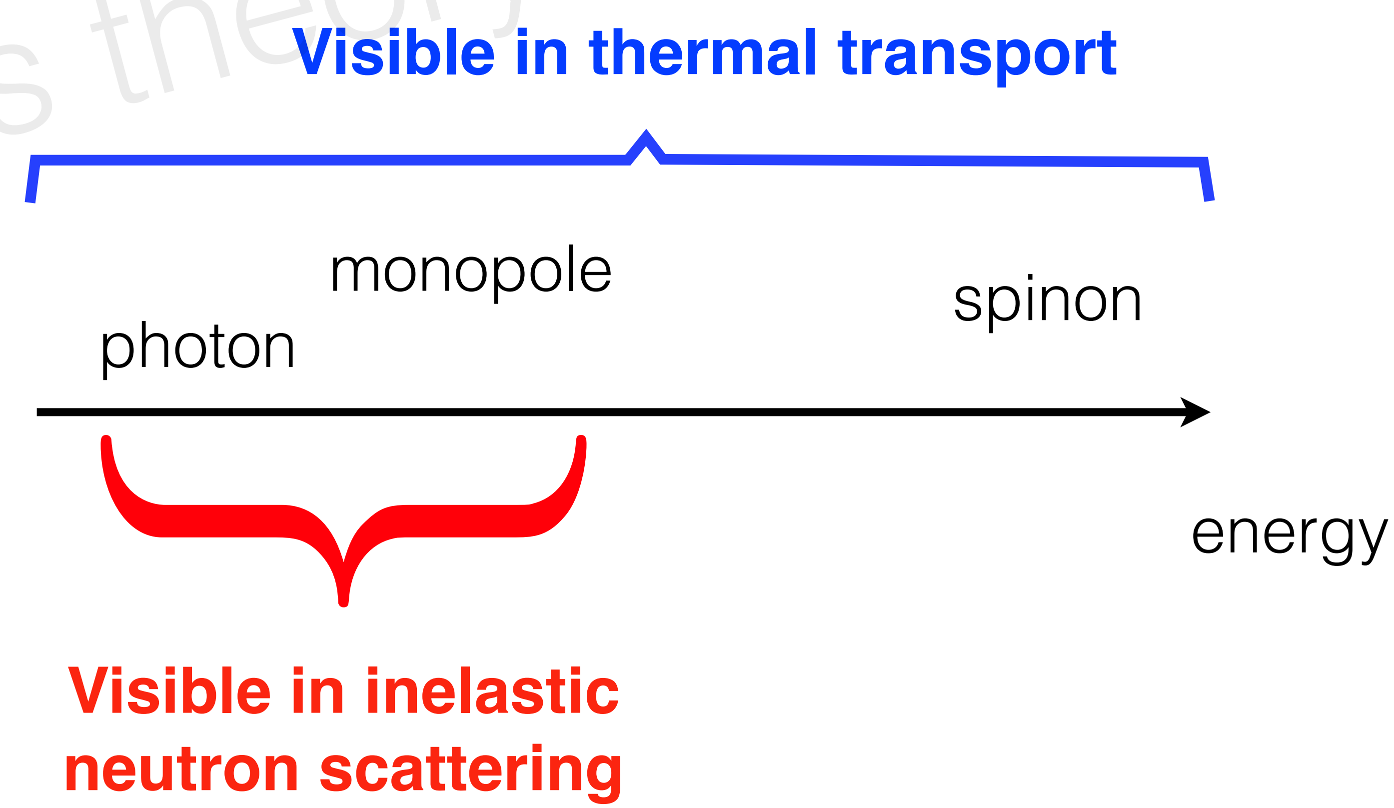
Nic Shannon, etc 2012, Savary, Balents, 2012

low energy scale suppressed intensity

Suggestion 1: combine thermal transport with inelastic neutron



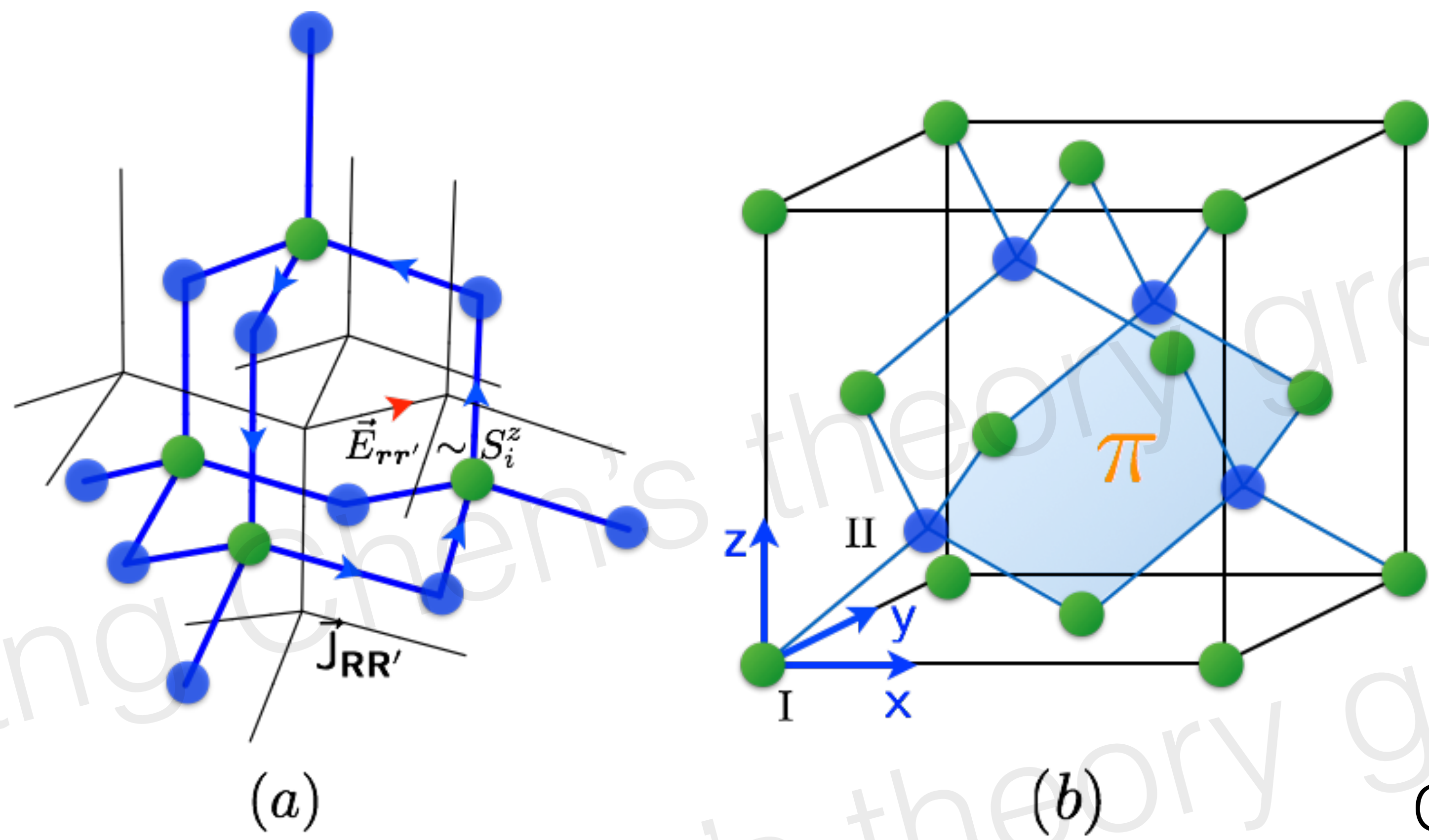
For **non-Kramers doublets** such as Pr ion in $Pr_2Zr_2O_7$ and Tb ion in $Tb_2Ti_2O_7$



G Chen, PRB 2017

Gang Chen's theory group

Suggestion 2: effect of the external magnetic field



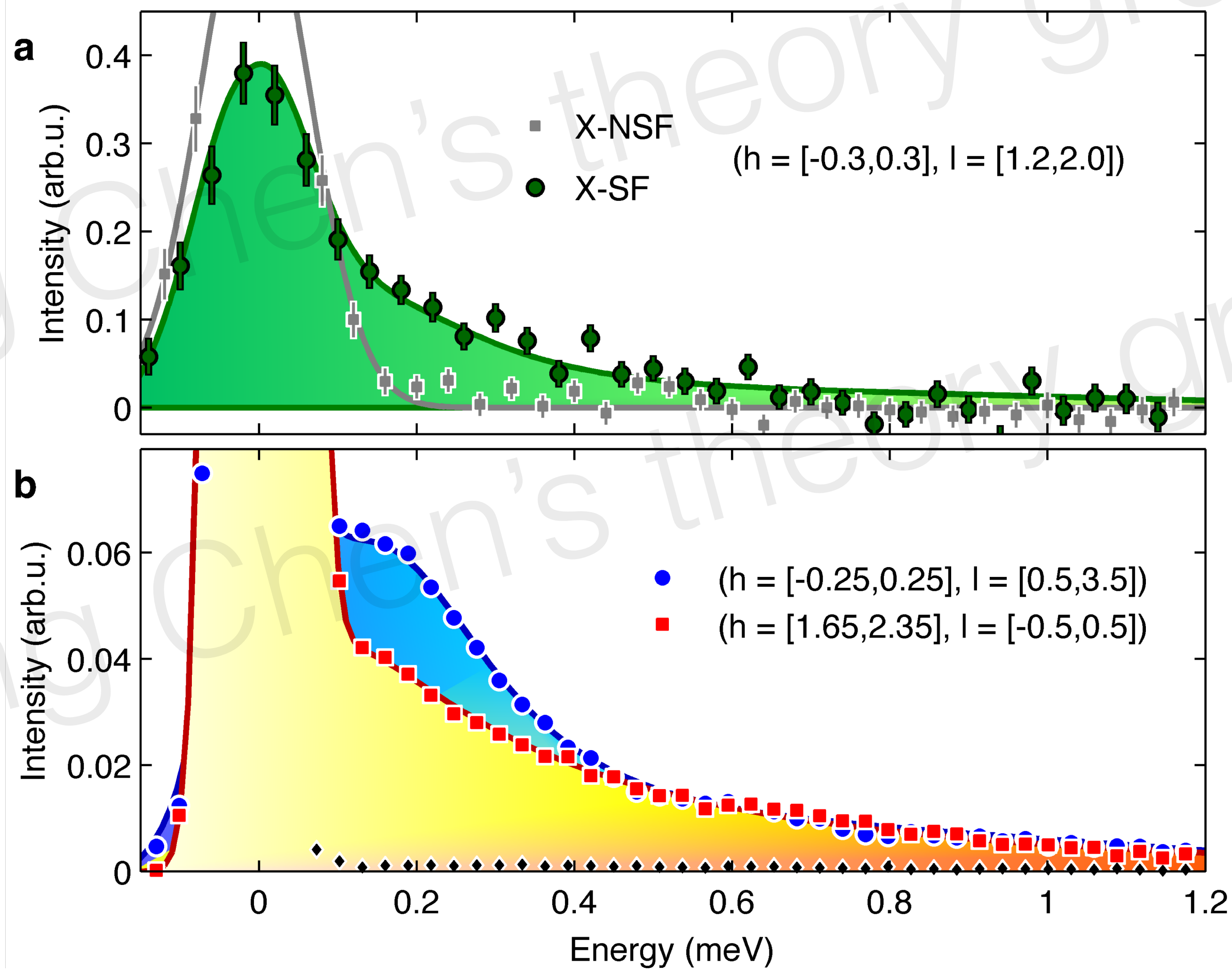
G Chen, PRB 2017

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

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

Thermal Hall effect: theory by XT Zhang, G Chen, etc,
expts by P Ong, Science 2013

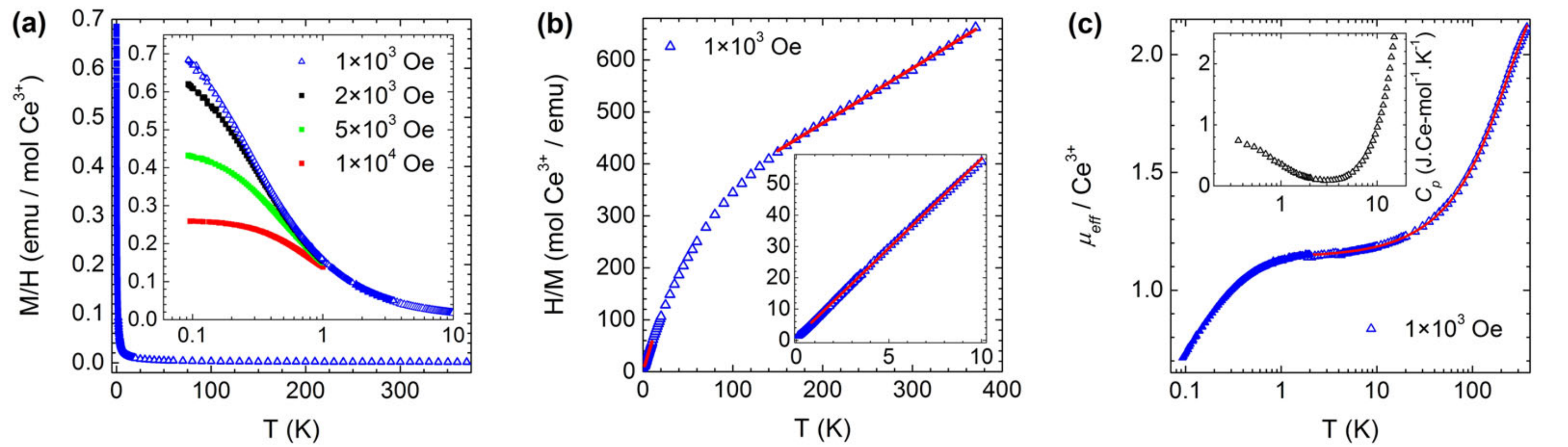
In fact, continuum has been observed in $Pr_2Hf_2O_7$
(R. Sibille, et al, arXiv 1706.03604). Nature Physics

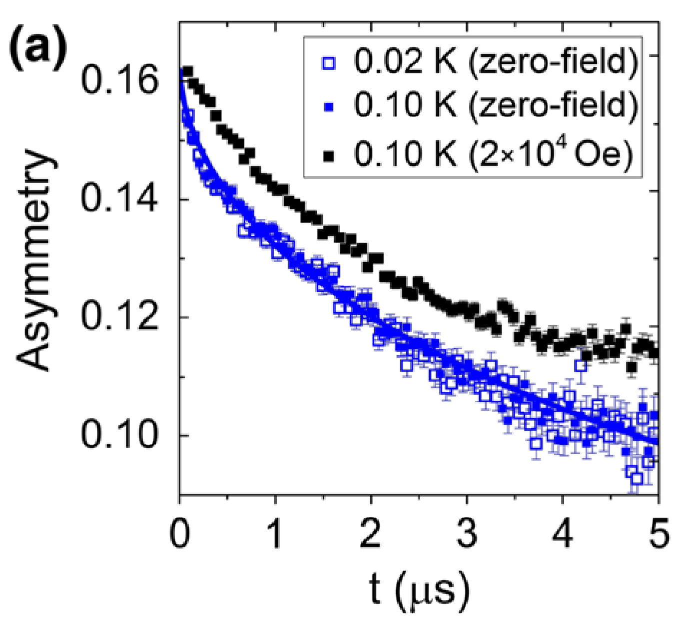


This is a non-Kramers doublet version of pyrochlore U(1) spin liquid candidate.

Candidate Quantum Spin Liquid in the Ce^{3+} Pyrochlore Stannate $Ce_2Sn_2O_7$

Romain Sibille,[1,*] Elsa Lhotel,[2] Vladimir Pomjakushin,[3] Chris Baines,[4] Tom Fennell,[3,†] and Michel Kenzelmann[1]
[1]*Laboratory for Scientific Developments and Novel Materials, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*
[2]*Institut Néel, CNRS, and Université Joseph Fourier, BP 166, 38042 Grenoble Cedex 9, France*
[3]*Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*
[4]*Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*





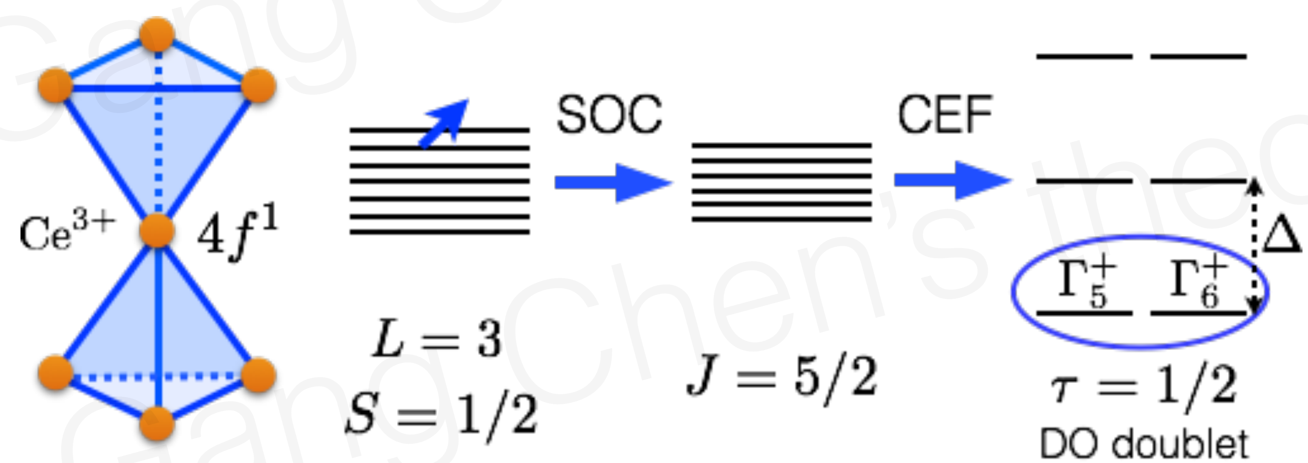
No order down to 0.02K !

Candidate Quantum Spin Liquid in the Ce^{3+} Pyrochlore Stannate $Ce_2Sn_2O_7$

Romain Sibille,[1,*] Elsa Lhotel,[2] Vladimir Pomjakushin,[3] Chris Baines,[4] Tom Fennell,[3,†] and Michel Kenzelmann[1]

$4f^1$ ion in D_{3d} local symmetry to the susceptibility was realized between $T = 1.8$ and 370 K, and the resulting calculation of the single ion magnetic moment is shown in Fig. 2(c). The wave functions of the ground state Kramers doublet correspond to a linear combination of $m_J = \pm 3/2$ states. The fitted coefficients result in energy levels at 50 ±

all the theor
sentence.



Yao-Dong Li, **GC**,
arXiv2016, PRB 2017

This doublet is **dipole-octupole doublet**

Huang, **GC**, Hermele, PRL,112,167203 (2014), arXiv Nov 2013
Yao-Dong Li, **GC**, PRB Rapid Comm 2017
Yao-Dong Li, XQ Wang, **GC**, PRB Rapid Comm 2016

Ce2Zr2O7: a non-spin-ice pyrochlore U(1) spin liquid

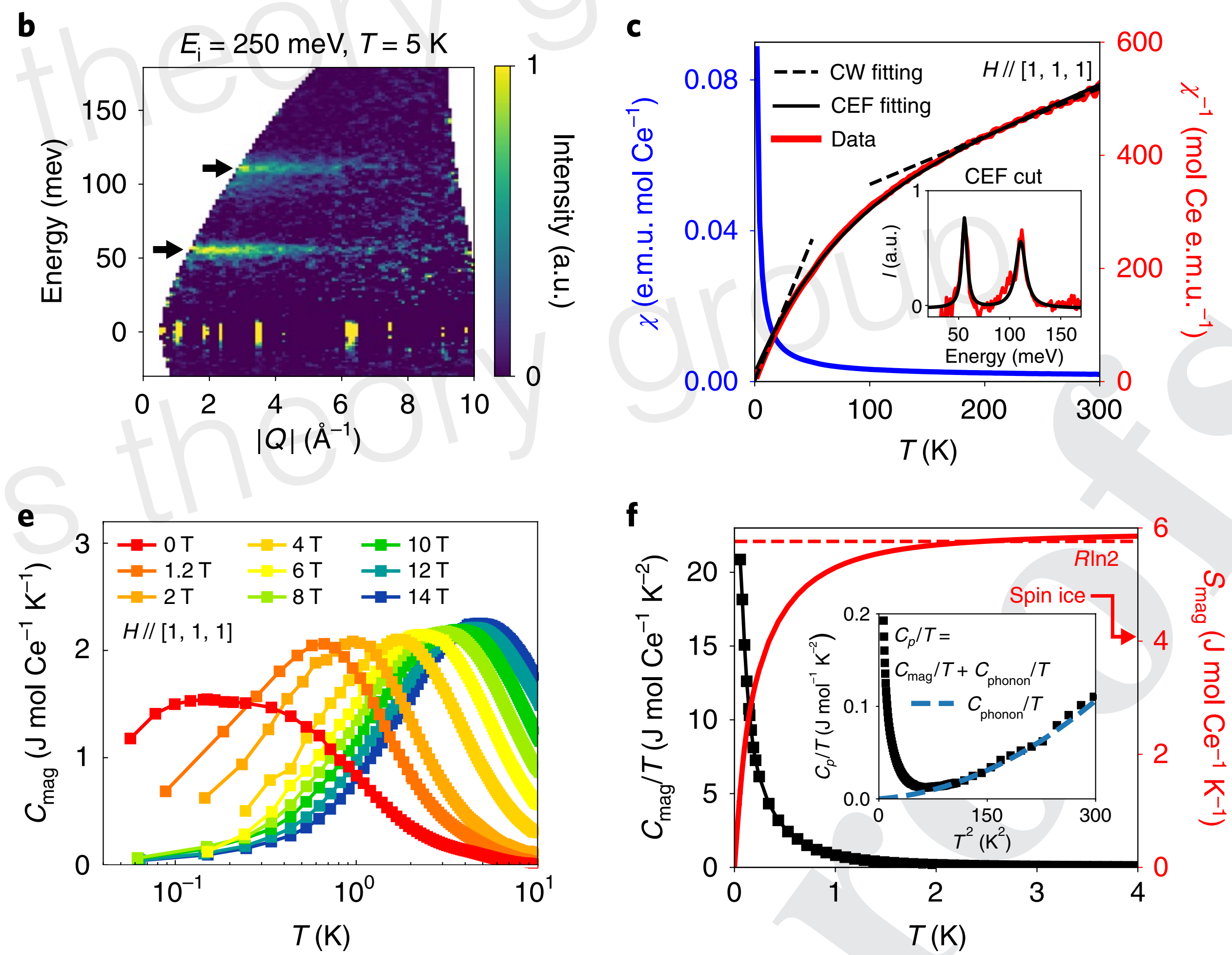
Experimental signatures of a three-dimensional quantum spin liquid in effective spin-1/2 $Ce_2Zr_2O_7$ pyrochlore

Bin Gao[1,11], Tong Chen[1,11], David W. Tam[1], Chien-Lung Huang[1], Kalyan Sasmal[2], Devashibhai T. Adroja[3], Feng Ye[4], Huibo Cao[4], Gabriele Sala[4], Matthew B. Stone[4], Christopher Baines[5], Joel A. T. Barker[5], Haoyu Hu[1], Jae-Ho Chung[1,6], Xianghan Xu[7], Sang-Wook Cheong[7], Manivannan Nallaiyan[8], Stefano Spagna[8], M. Brian Maple[2], Andriy H. Nevidomskyy[1], Emilia Morosan[1], Gang Chen[9,10] and Pengcheng Dai[1]*

Nature Physics, 2019

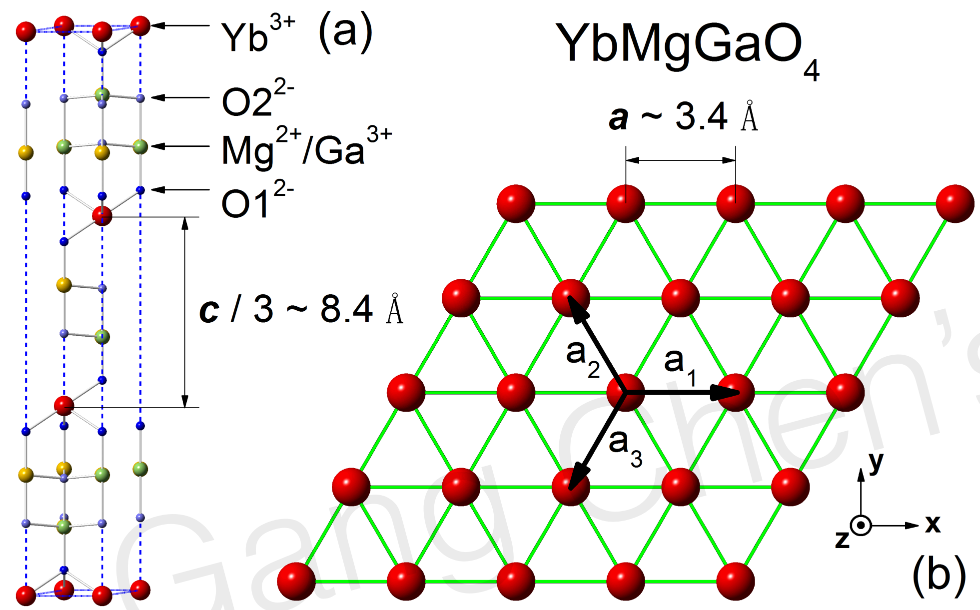
also Gaulin's group, PRL 2019

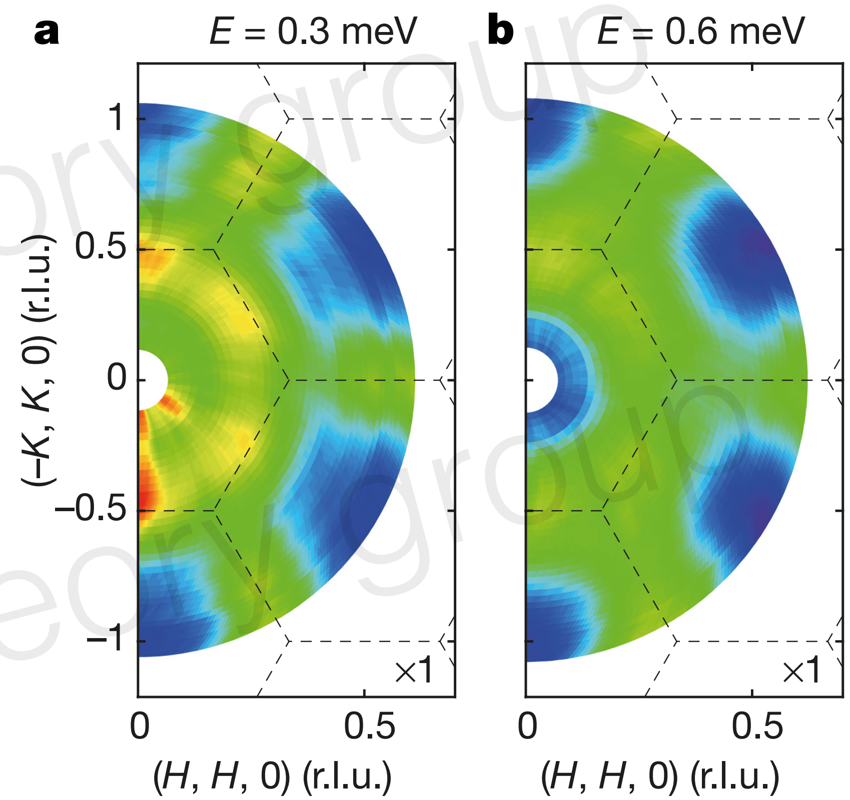
nature of fermion sign problem

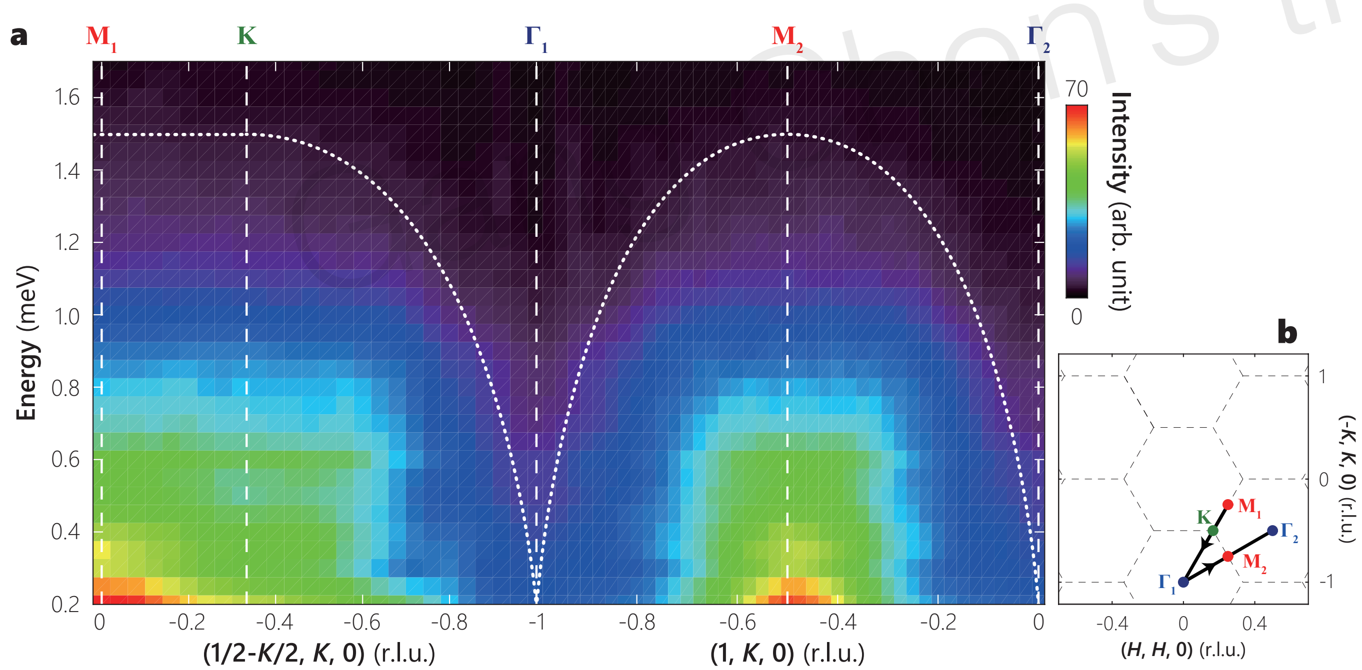


Our suggestion [**YD Li & GC, 1902.07075**]: this material is in U1B phase?

Rare-earth triangular lattice magnets: spin liquid



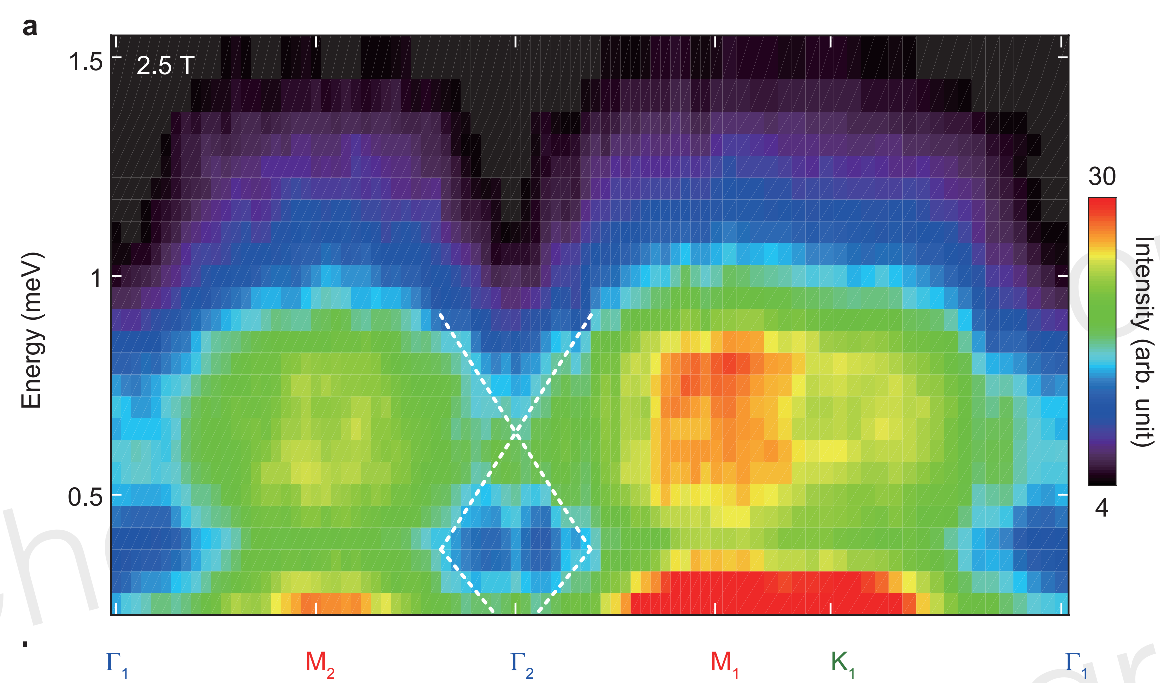


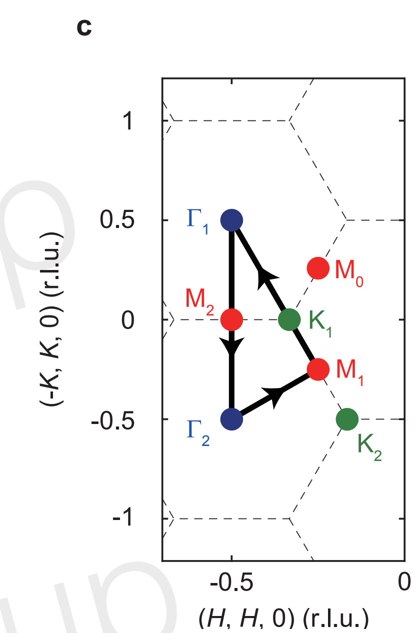


Yuesheng Li, Qingming Zhang,
Jun Zhao, Yao Shen, Yaodong Li, G Chen

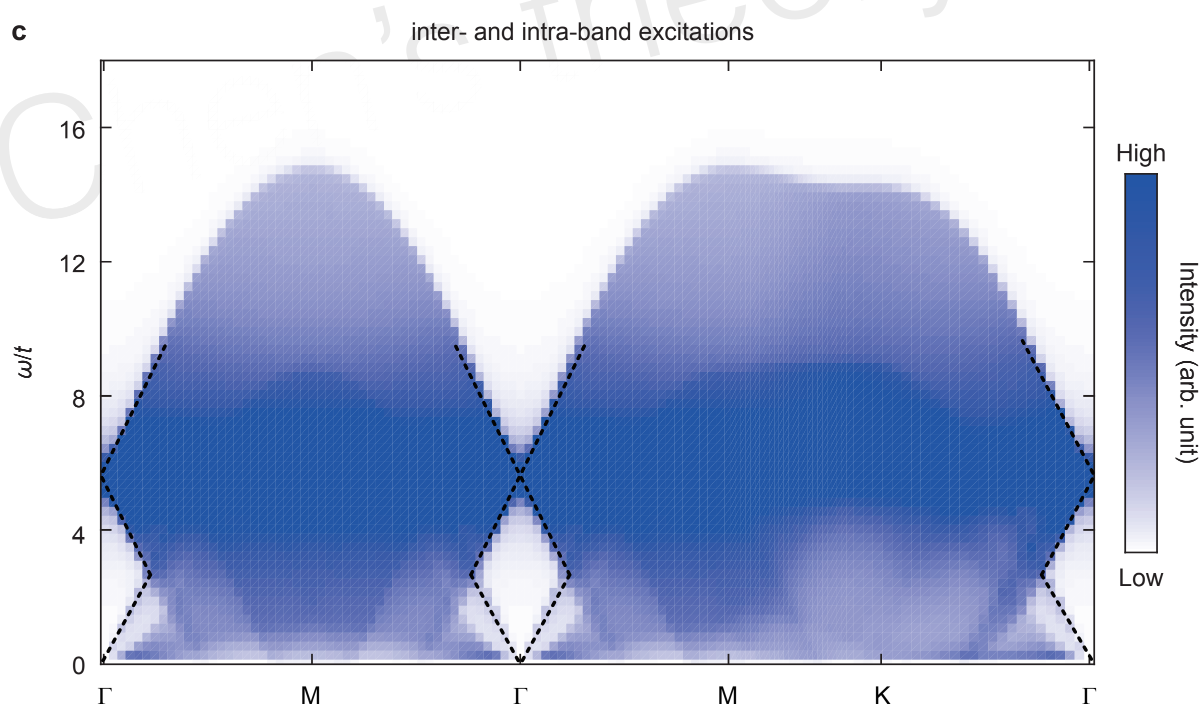
Excitation continuum in weakly magnetized YbMgGaO4

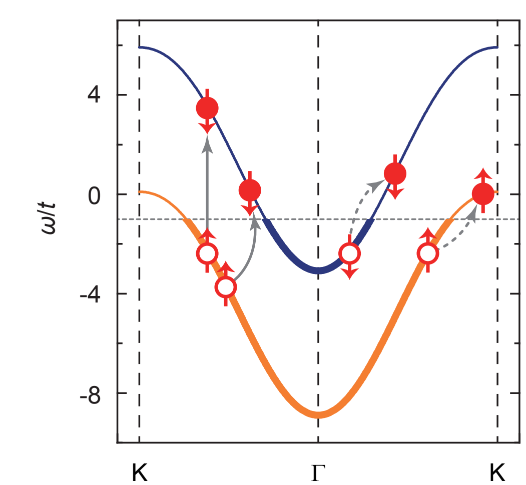
Experiment:
Y Shen, YD Li, …, GC*, J Zhao*
arXiv: 1708.06655
Nat Comm





Theoretical results for
the experimental parameter





YD Li, **GC***, PRB 96, 075105 (2017)

Use new materials to support materials

Compound	Magnetic ion	Space group	Local moment	Θ_{CW} (K)	Magnetic transition	Frustration para. f	Refs.
$YbMgGaO_4$	$Yb^{3+}(4f^{13})$	$R\bar{3}m$	Kramers doublet	-4	PM down to 60 mK	$f > 66$	[4]
$CeCd_3P_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-60	PM down to 0.48 K	$f > 200$	[5]
$CeZn_3P_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-6.6	AFM order at 0.8 K	$f = 8.2$	[7]
$CeZn_3As_3$	$Ce^{3+}(4f^{1})$	$P6_3/mmc$	Kramers doublet	-62	Unknown	Unknown	[8]
$PrZn_3As_3$	$Pr^{3+}(4f^{2})$	$P6_3/mmc$	Non-Kramers doublet	-18	Unknown	Unknown	[8]
$NdZn_3As_3$	$Nd^{3+}(4f^{3})$	$P6_3/mmc$	Kramers doublet	-11	Unknown	Unknown	[8]

YD Li, XQ Wang, GC*, PRB 94, 035107 (2016)

Magnetism in the $KBaRE(BO_3)_2$ (RE=Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu) series: materials with a triangular rare earth lattice

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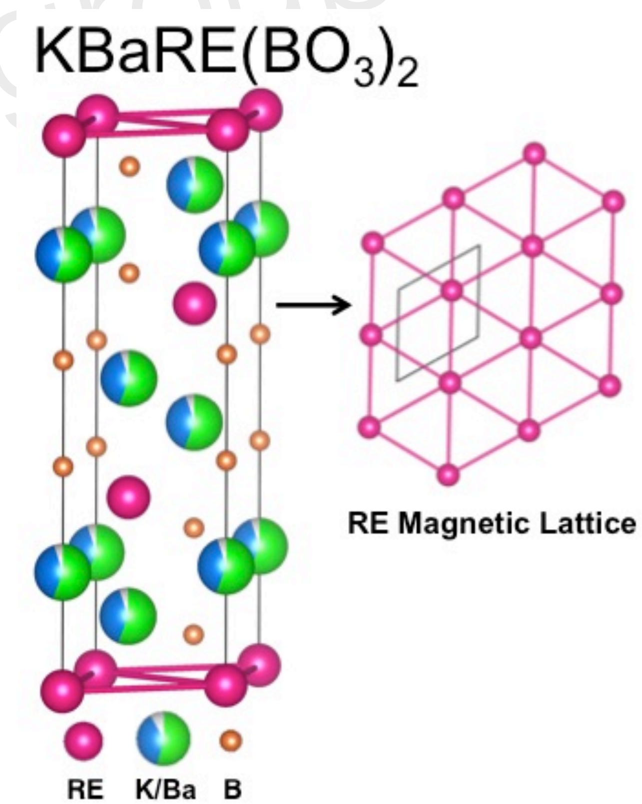

many ternary chalcogenides $NaRES_2$, $NaRESe_2$, $KRES_2$, $KRESe_2$, $KRETe_2$, $RbRES_2$, $RbRESe_2$, $RbRETe_2$, $CsRES_2$, $CsRESe_2$, etc.)

A recent fashion !

Spin-orbit entanglement: e.g. Ba2YMoO6

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Valence Bond Glass on an fcc Lattice in the Double Perovskite Ba_2YMoO_6

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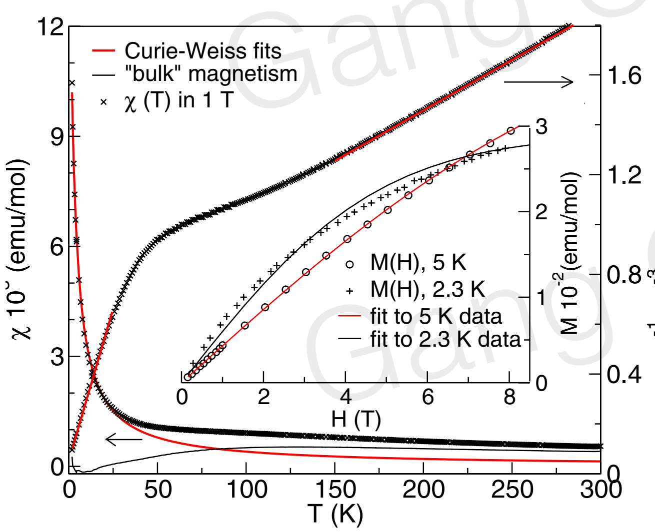
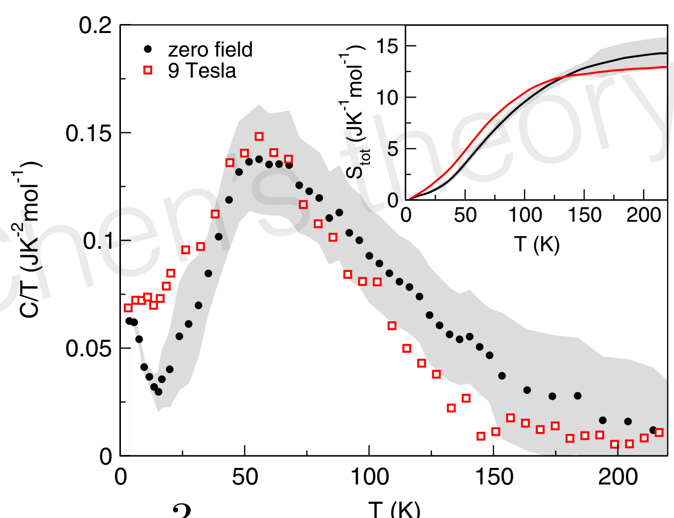
We report on the unconventional magnetism in the cubic *B*-site ordered double perovskite Ba_2YMoO_6, using ac and dc magnetic susceptibility, heat capacity and muon spin rotation. No magnetic order is observed down to 2 K while the Weiss temperature is ~ -160 K. This is ascribed to the geometric frustration in the lattice of edge-sharing tetrahedra with orbitally degenerate Mo^{5+} $s = 1/2$ spins. Our experimental results point to a gradual freezing of the spins into a disordered pattern of spin singlets, quenching the orbital degeneracy while leaving the global cubic symmetry unaffected, and providing a rare example of a valence bond glass.

$S_{\mathrm{tot}} = 12 \pm 2\ \mathrm{J\,K^{-1}\,mol^{-1}}$





$$j = \frac{3}{2} \longleftrightarrow S_{\mathrm{tot}} = R \ln 4 = 11.5$$

Linear T specific heat

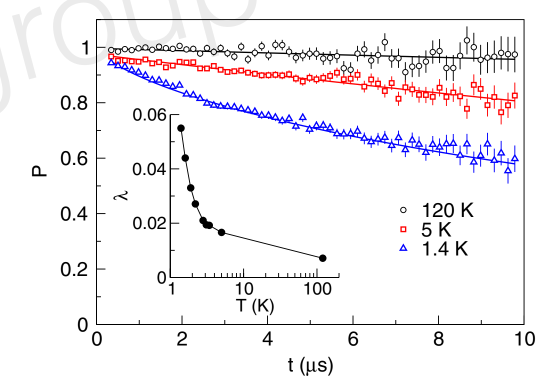


FIG. 5 (color online). The muon spin relaxation at 120, 5 and 1.4 K. The relaxation follows an exponential decay ($P(t) = \exp[-t/\lambda]^{\beta}$, solid lines) with $\beta = 1$ for all but the 1.4 K data, where $\beta = 0.7$. The temperature dependence of the relaxation rate λ is shown in the inset.

Triplet and in-gap magnetic states in the ground state of the quantum frustrated fcc antiferromagnet Ba_2YMoO_6

J. P. Carlo,[1,2,*] J. P. Clancy,[1] T. Aharen,[3] Z. Yamani,[2] J. P. C. Ruff,[1] J. J. Wagman,[1] G. J. Van Gastel,[1] H. M. L. Noad,[1] G. E. Granroth,[4] J. E. Greedan,[3,5] H. A. Dabkowska,[5] and B. D. Gaulin[1,5,6]

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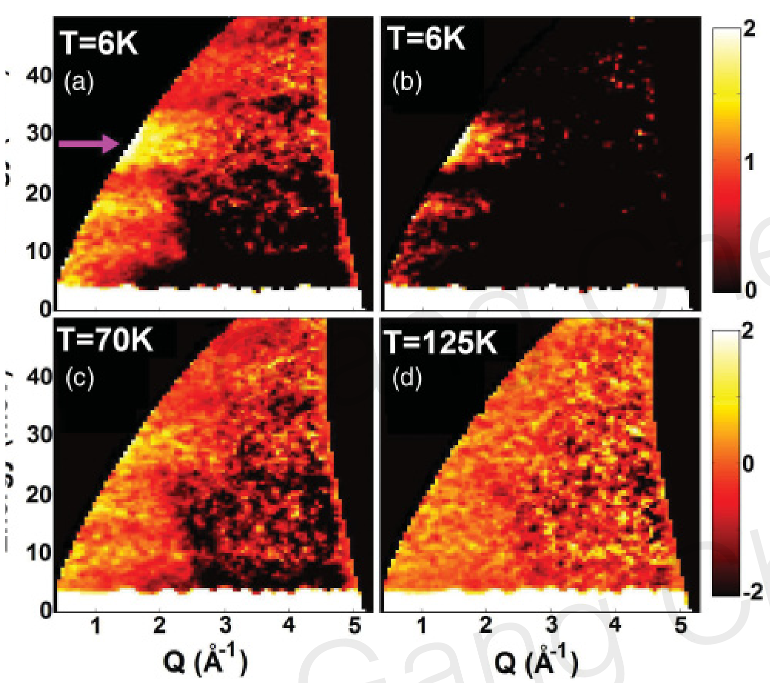


FIG. 2. (Color online) (a), (c), (d) Dynamic susceptibility $\chi''(Q,\hbar\omega)$ at $T = 6$, 70, and 125 K, where $\chi''(Q,\hbar\omega)$ at $T = 175$ K s been subtracted from each to isolate the magnetic scattering, described in the text. (b) shows $\Delta\chi''(Q,\hbar\omega)$ at $T = 6$ K with $= 175$ K subtracted, but with the plotted intensity scale range stricted to >0 only, thus highlighting where $\chi''(Q,\hbar\omega)$ at 6 K ceeds that at 175 K. The lower intensity scale refers to (a), (c), d (d), and the upper refers to (b).

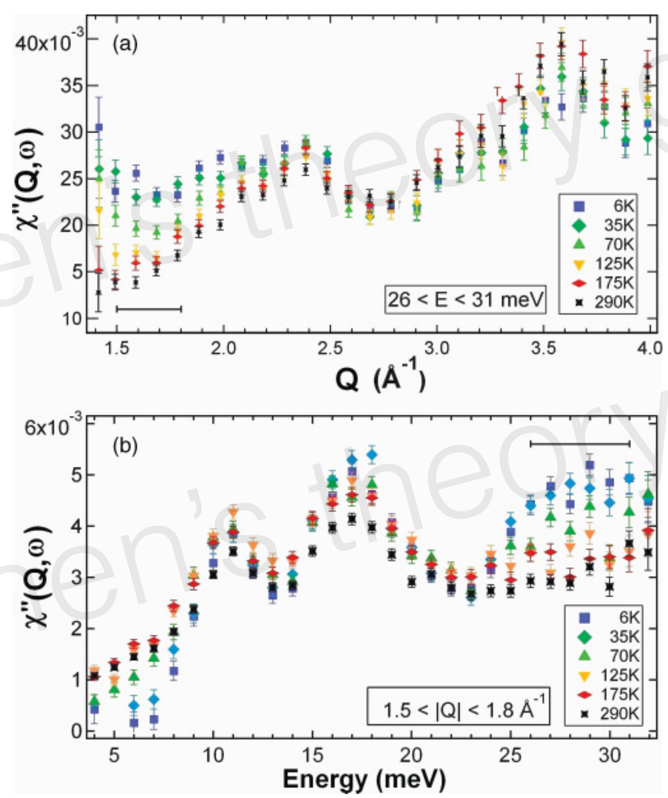


FIG. 3. (Color online) (a) $\chi''(Q,\hbar\omega)$ plotted versus Q for six temperatures, integrated in energy between 26 and 31 meV. (b) $\chi''(Q,\hbar\omega)$ plotted versus energy for six temperatures, integrated in Q over the range 1.5 Å^{-1} $< Q <$ 1.8 Å^{-1}. The scattering centered on ~28 meV exists only at low $Q <$ 2.5 Å^{-1} and at low $T <$ 125 K, and is therefore magnetic in origin and consistent with a weakly dispersive spin-triplet excitation.

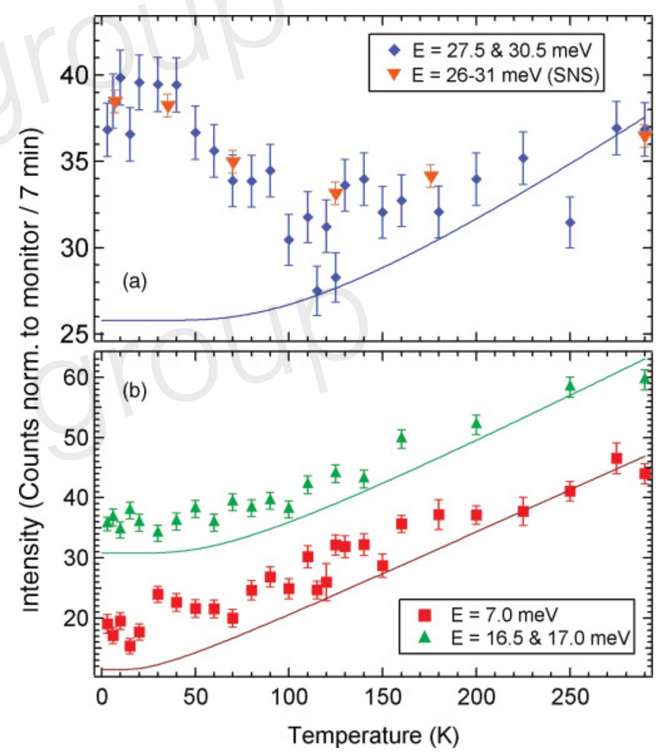
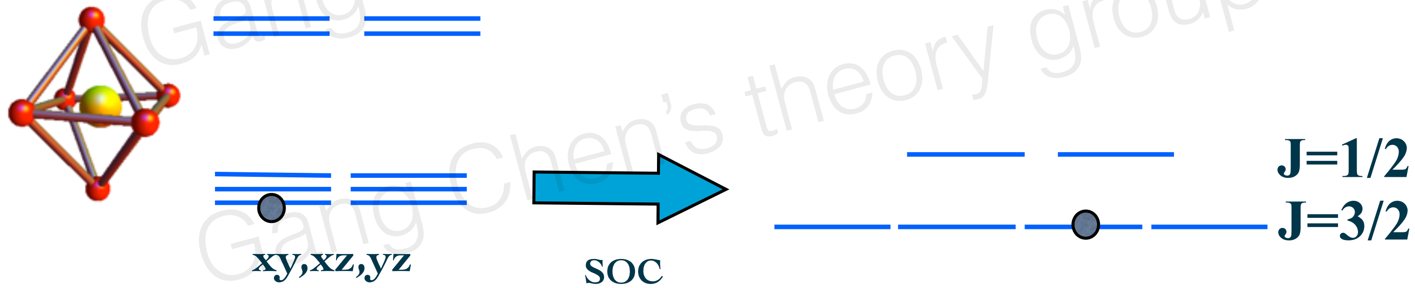


FIG. 4. (Color online) (a) Temperature dependence of the background-subtracted scattering intensity at $Q = 1.7$ Å^{-1} at the average of 27.5 and 30.5 meV, collected with the C5 triple-axis spectrometer, showing a characteristic fall-off of the triplet intensity toward zero at ~125 K; normalized SEQUOIA (SNS) data at 26–31 meV is included for reference. (b) Temperature dependence of the background-subtracted intensity at 7 meV and a 16.5–17 meV energy transfer. The solid lines represent fits of the $T > 200$ K data to the thermal occupancy factor. Excess low-temperature scattering is attributed to either (a) the triplet excitation, or (b) magnetic states within the gap.

$Re^{6+}, Os^{7+}, Mo^{5+}$



$M = \mathcal{P}_{\frac{3}{2}}[2\boldsymbol{S} + (-\boldsymbol{l})]\mathcal{P}_{\frac{3}{2}} = 0!!$

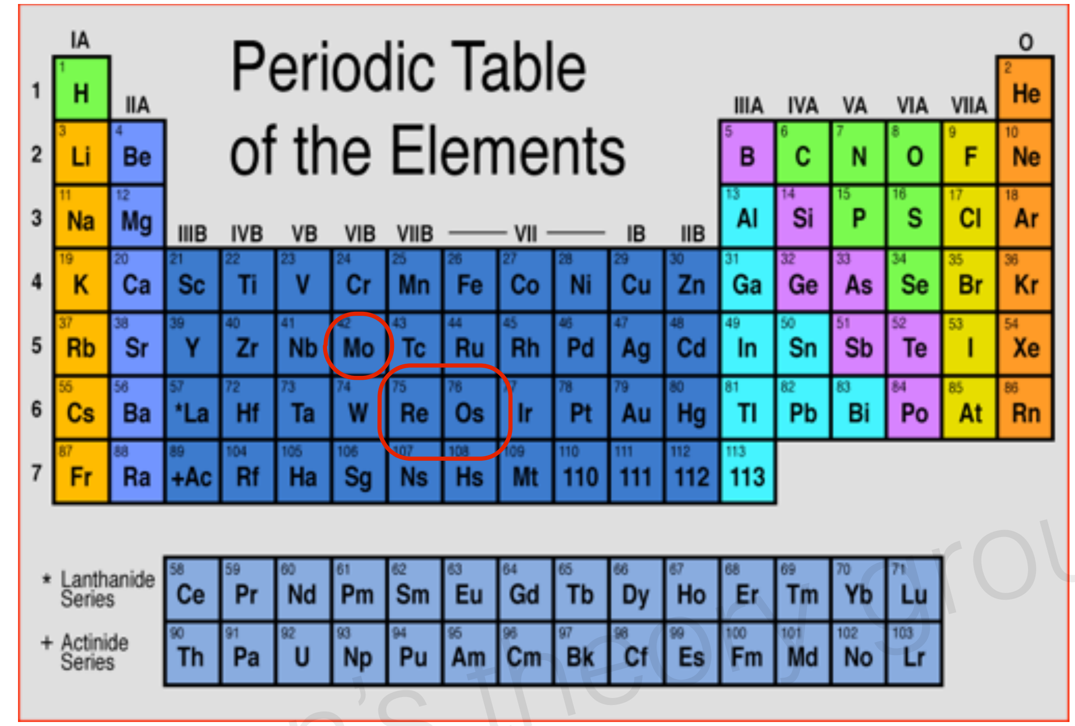
$\lambda \sim 1481K$ in Mo^{5+}

$M \sim 1.3 - 1.4\mu_B$

for Ba_2YMoO_6

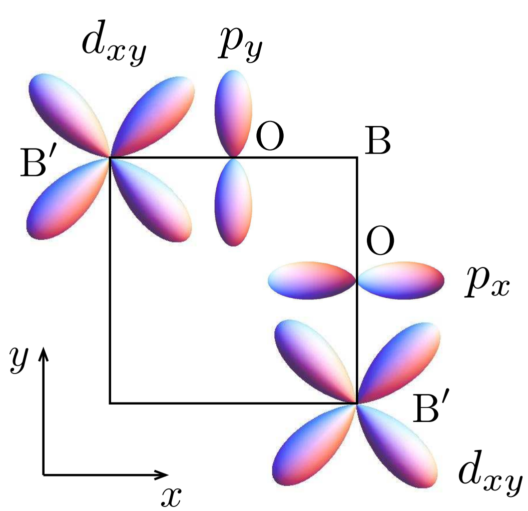
$M \sim 0.6 - 0.7\mu_B$

for Ba_2CaReO_6, Ba_2LiOsO_6, Ba_2CaOsO_6



Chen, Balents, Rodrigo, PRB 2010

Exchange interaction and singlets



$$H_{\rm XY} = J\Big(\mathbf{S}_{i,xy} \cdot \mathbf{S}_{j,xy} - \gamma\, n_{i,xy} n_{j,xy}\Big) \\ -\lambda\, \mathbf{l}_i \cdot \mathbf{S}_i - \lambda\, \mathbf{l}_j \cdot \mathbf{S}_j$$

$$\mathbf{S}_{i,xy} \equiv \mathbf{S}_i\, n_{i,xy}$$

Singlets

$J \gg \lambda$ $$\frac{1}{\sqrt{2}}\big(|S_i^z = \frac{1}{2}, xy\rangle|S_j^z = -\frac{1}{2}, xy\rangle - |S_i^z = -\frac{1}{2}, xy\rangle|S_j^z = \frac{1}{2}, xy\rangle\big)$$

$J \ll \lambda$ $$\frac{1}{\sqrt{2}}\big(|j^z = \frac{1}{2}\rangle_i|j^z = -\frac{1}{2}\rangle_j - |j^z = -\frac{1}{2}\rangle_i|j^z = \frac{1}{2}\rangle_j\big)$$

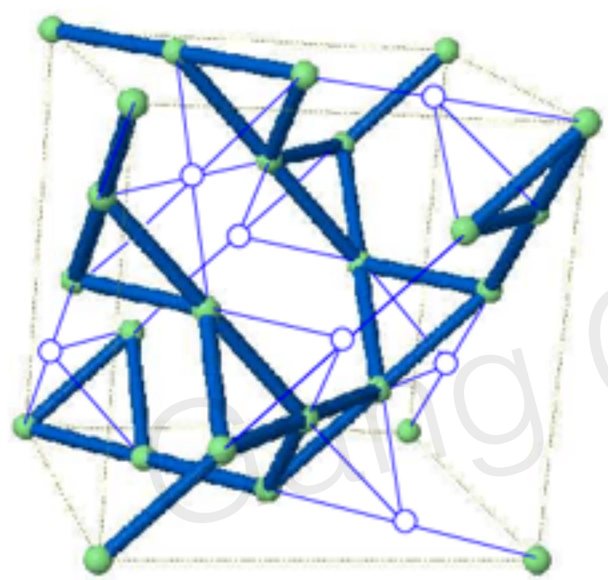
Na4Ir3O8 hyperkagome AFMagnet

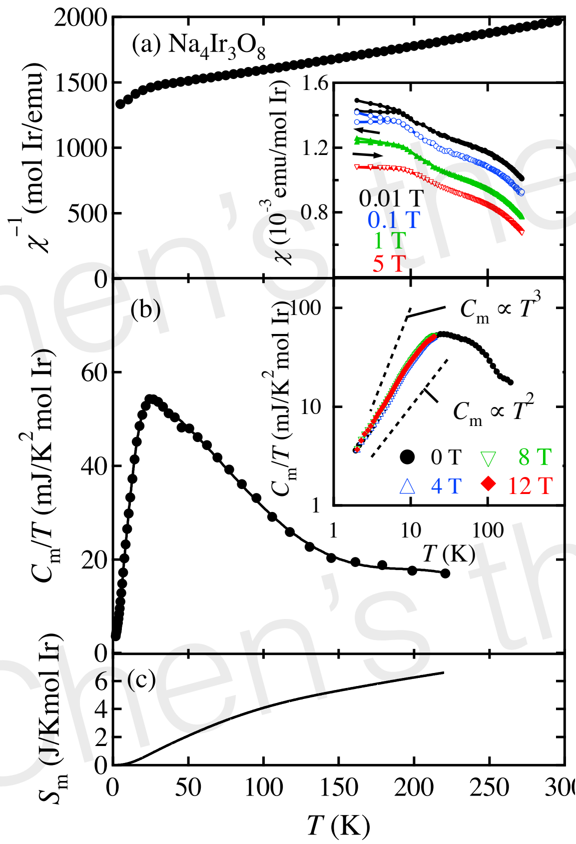
Frozen state and spin liquid physics in $Na_4Ir_3O_8$: an NMR study

A.C. Shockley,[1,*] F. Bert,[1] J-C. Orain,[1] Y. Okamoto,[2] and P. Mendels[1]

Spin-Liquid State in the $S = 1/2$ Hyperkagome Antiferromagnet $Na_4Ir_3O_8$

Yoshihiko Okamoto[1,*], Minoru Nohara[2], Hiroko Aruga-Katori[1], and Hidenori Takagi[1,2]





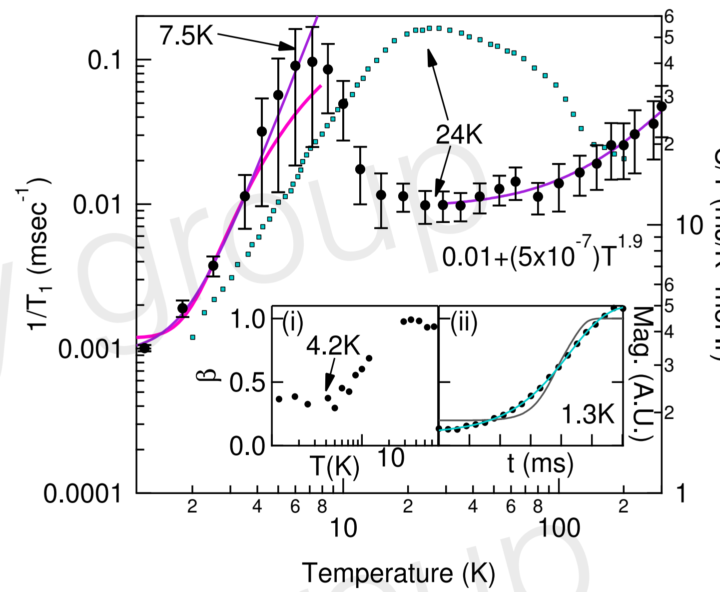
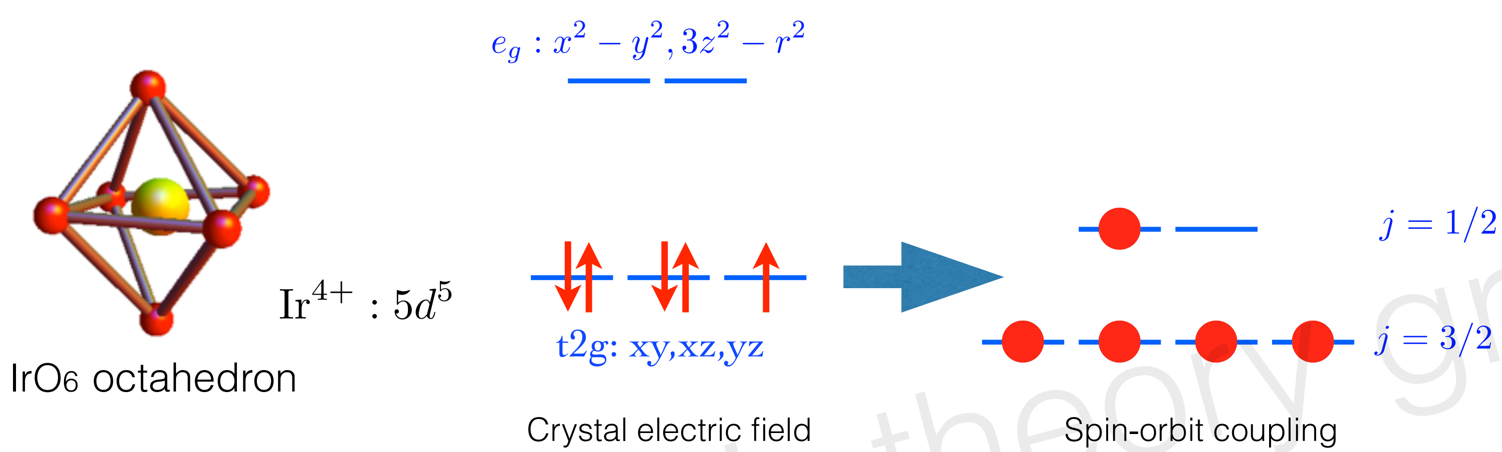


FIG. 4. ${}^{23}T_1^{-1}$ (left axis, black circles) and C/T from [14] (right axis, blue squares) as a function of temperature. The purple lines are fits. Inset: (i) The stretch exponent, β, as described in the text as a function of temperature. (ii) The relaxation curve (solid circles) at 1.3 K fit with a stretched exponent (blue line, $\beta = 0.4$) and exponential fit (grey line, $\beta = 1$).

very large Wilson Ratio !

(i) A fermionic approach naturally leading to a spinon Fermi surface. The maximum of C/T, far too high for a spin glass freezing [43], could be the landmark of a crossover from a $U(1)$ spin liquid to a $\mathbb{Z}_2$ one with a paired spinon state and line nodes in the gap below 20 K [18]. The mixing with triplet states induced by SOC or Dzyaloshinkii-Moriya interactions could explain why the susceptibility keeps its Pauli-like behavior. Yet, our $1/T_1$ data, if intrinsic, contradicts the existence of a gap as it does not decrease, below the maximum of the specific heat. Furthermore, for a Dirac U(1) spin liquid, one expects $1/T_1 \sim T^\eta$ where η is related to the shape of the correlation function and remains unknown [44]. This is not what is observed here since T_1 is dominated by a constant term for $T > 20$ K.

theories



$$\langle \{t_{2g}\} | \mathbf{L} | \{t_{2g}\} \rangle = -\mathbf{l}, \quad H_{soc} = -\lambda \mathbf{l} \cdot \mathbf{S}, \quad \mathbf{j} = \mathbf{l} + \mathbf{S}$$

It is interesting to look at how the magnetic moment M = L+2S = -l+2S varies.

Yi Zhou, Fuchun Zhang, PA Lee

perature independent at temperatures below $\sim T_c$. The transition at 20 K is then interpreted as a transition between a $U(1)$ spin liquid to a Z_2 spin liquid where spinons are paired at low temperature. This theory also predicts the appearance of superconductivity if the $Na_4Ir_3O_8$ system can be doped.

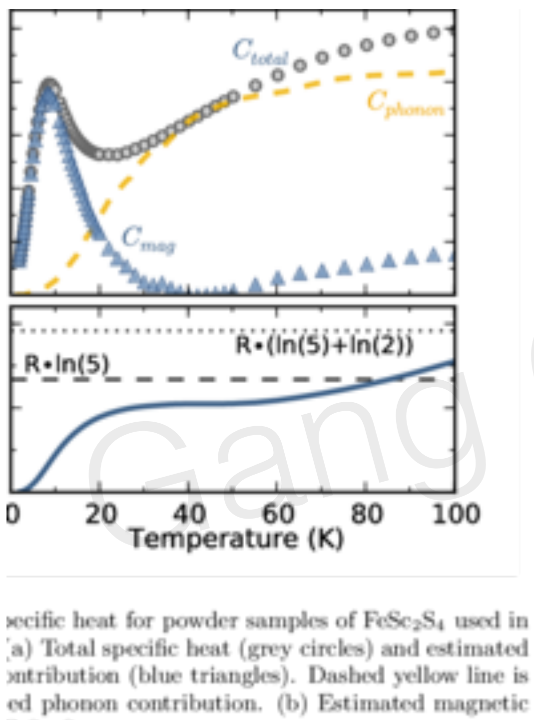
G Chen, Balents

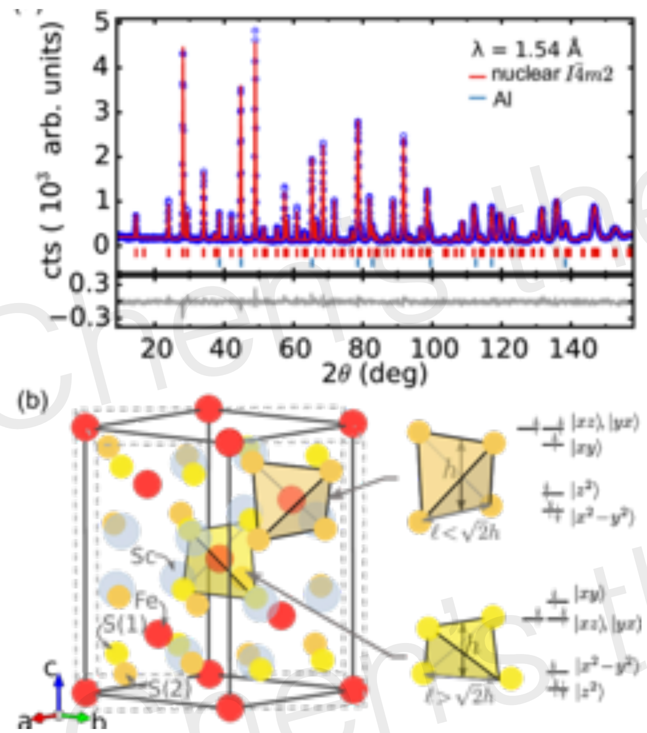
spin-orbit coupling of Ir,
anisotropic superexchange
J=1/2

G Chen, YB Kim

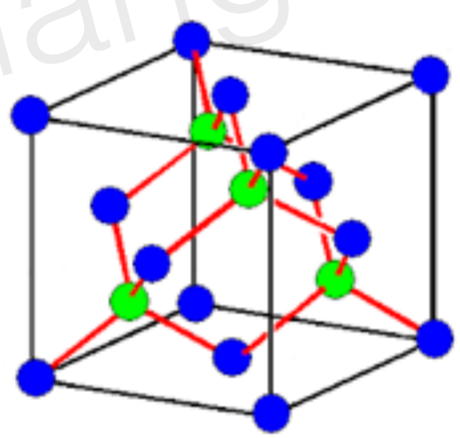
proximate to Mott transition
spinon-Fermi surface U(1) QSL

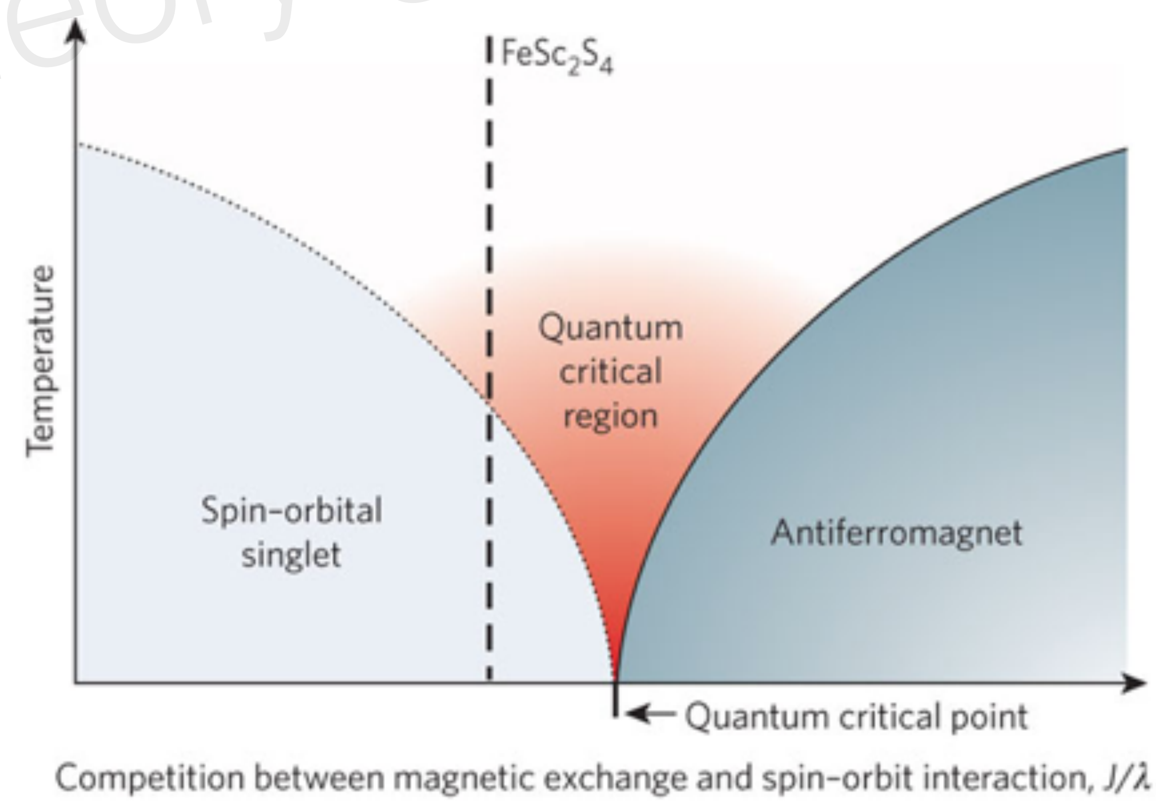
Orbital degree of freedom:
e.g. Fe-based diamond magnet, LaTiO3, LiNiO2, NaNiO2





G Chen, Balents, Schnyer,

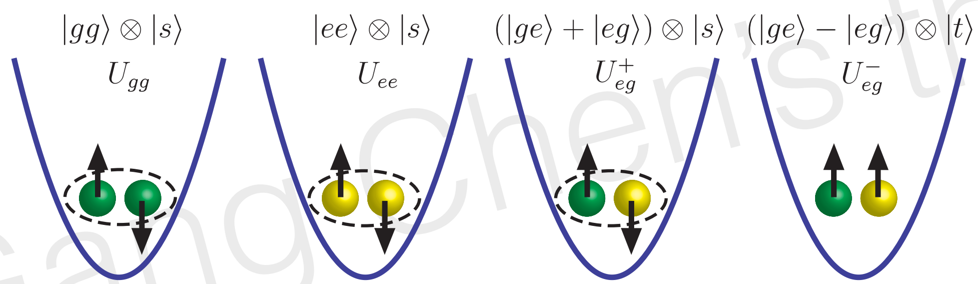




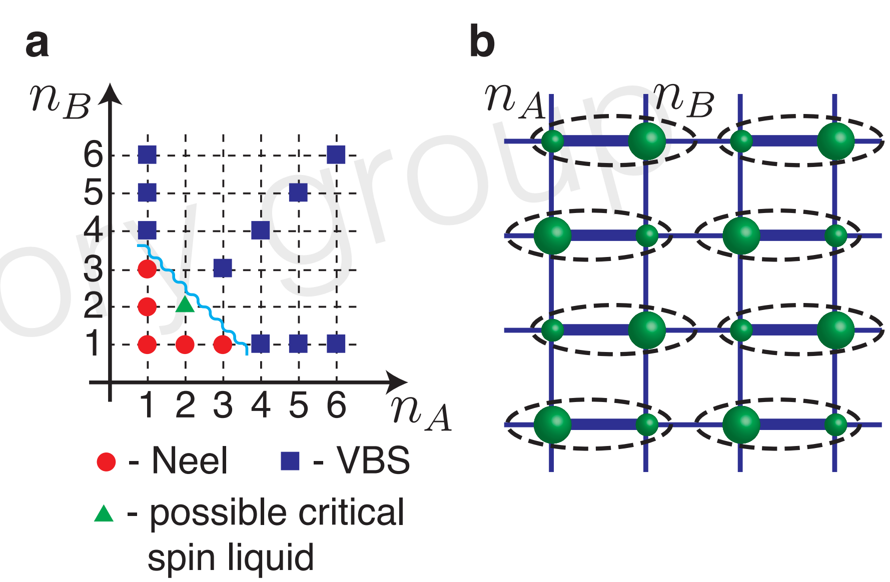
SU(N) “magnets”: more generally, large-symmetry-group magnets

Two-orbital SU(N) magnetism with ultracold alkaline-earth atoms

A. V. Gorshkov[1*], M. Hermele[2], V. Gurarie[2], C. Xu[1], P. S. Julienne[3], J. Ye[4], P. Zoller[5], E. Demler[1,6], M. D. Lukin[1,6], and A. M. Rey[4]



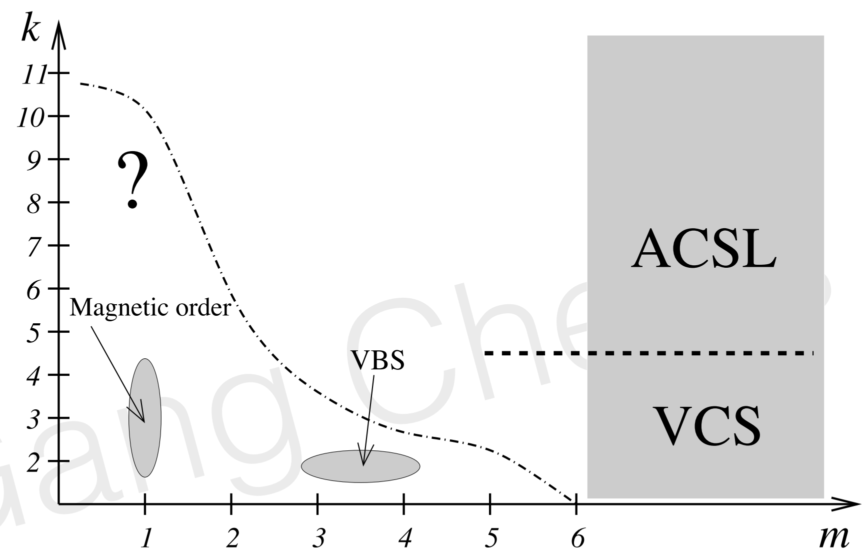
$$
\begin{aligned}
H = & \sum_{\alpha m} \int d^3\mathbf{r}\,\Psi^{\dagger}_{\alpha m}(\mathbf{r})\left(-\frac{\hbar^2}{2M}\nabla^2 + V_\alpha(\mathbf{r})\right)\Psi_{\alpha m}(\mathbf{r}) \qquad (1) \\
& + \hbar\omega_0 \int d^3\mathbf{r}\,(\rho_e(\mathbf{r}) - \rho_g(\mathbf{r})) + \frac{g^{+}_{eg} + g^{-}_{eg}}{2} \int d^3\mathbf{r}\,\rho_e(\mathbf{r})\rho_g(\mathbf{r}) \\
& + \sum_{\alpha, m<m'} g_{\alpha\alpha} \int d^3\mathbf{r}\,\rho_{\alpha m}(\mathbf{r})\rho_{\alpha m'}(\mathbf{r}) \\
& + \frac{g^{+}_{eg} - g^{-}_{eg}}{2} \sum_{mm'} \int d^3\mathbf{r}\,\Psi^{\dagger}_{gm}(\mathbf{r})\Psi^{\dagger}_{em'}(\mathbf{r})\Psi_{gm'}(\mathbf{r})\Psi_{em}(\mathbf{r}).
\end{aligned}
$$



Gang Chen's theory group

Mott Insulators of Ultracold Fermionic Alkaline Earth Atoms: Underconstrained Magnetism and Chiral Spin Liquid

Michael Hermele,[1] Victor Gurarie,[1] and Ana Maria Rey[1,2]
[1] *Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[2] *JILA, University of Colorado and NIST, Boulder, Colorado, 80309, USA*
(Dated: October 7, 2018)



$$\mathcal{H} = J \sum_{\langle \boldsymbol{r}\boldsymbol{r}'\rangle} S_{\alpha\beta}(\boldsymbol{r}) S_{\beta\alpha}(\boldsymbol{r}'),\ S_{\alpha\beta}(\boldsymbol{r}) = f^{\dagger}_{\boldsymbol{r}\alpha} f_{\boldsymbol{r}\beta},$$

more delocalized in local Hilbert space
even with a large local Hilbert space

Dimer description of the SU(4) antiferromagnet on the triangular lattice

Anna Keselman[1*,2], Lucile Savary[3,1], Leon Balents[1,4]

Emergent Fermi surface in a triangular-lattice SU(4) quantum antiferromagnet

Anna Keselman,[1] Bela Bauer,[2] Cenke Xu,[3] and Chao-Ming Jian[2]

May be relevant to twisted bilayer graphene

Summary

This field is quite rich.

There is no general guiding principle.