Quantum excitations of “hidden orders”

and

Thermal transport of “hidden particles”

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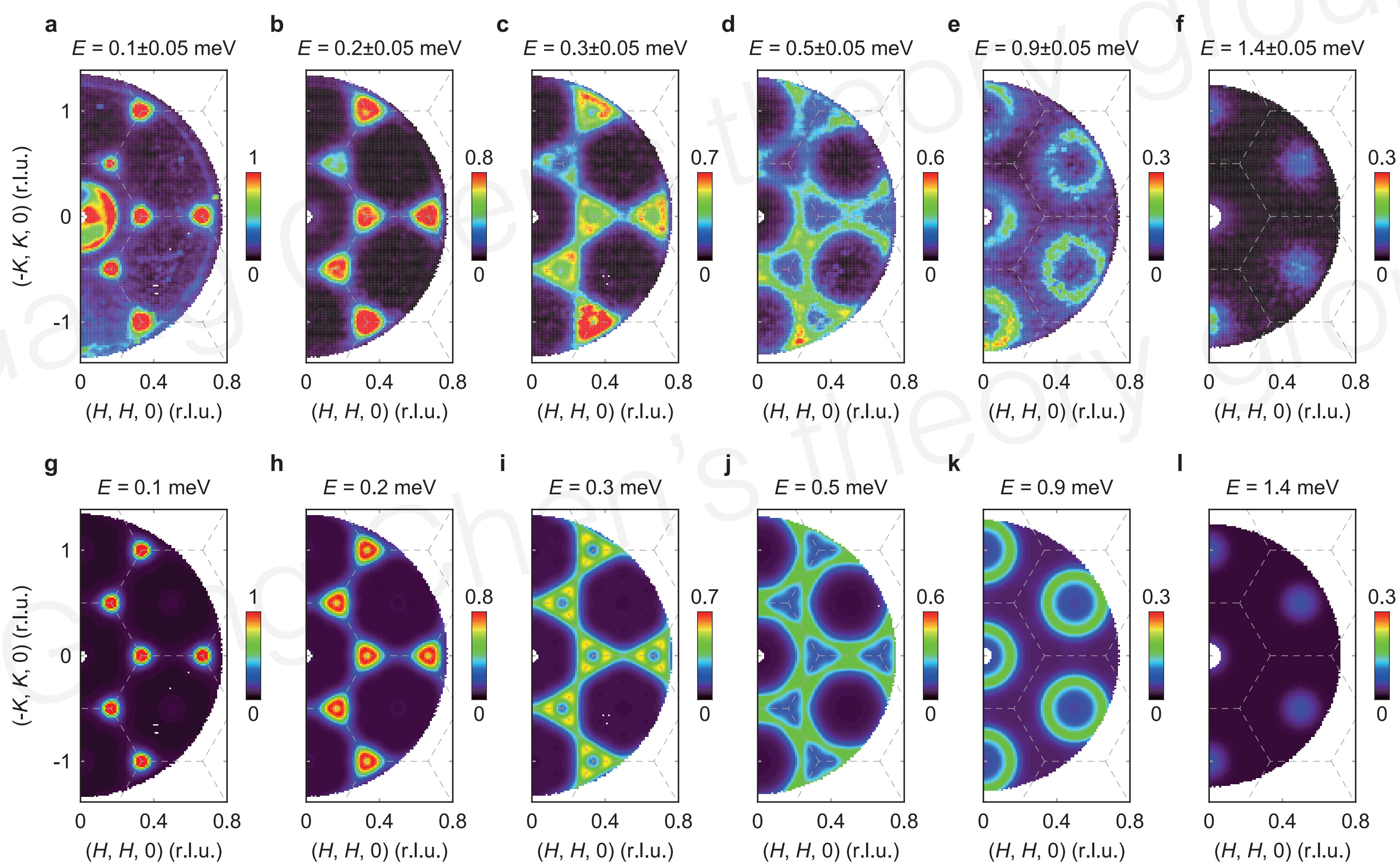
Organizing committee: Leon Balents, Gang Chen, Michel Gingras, Sungbin Lee, Jie Ma, Rajiv Singh, Yuan Wan, Xiaoqun Wang

Outline

- Intertwined multipolar orders and quantum excitations of a triangular lattice magnet TmMgGaO4

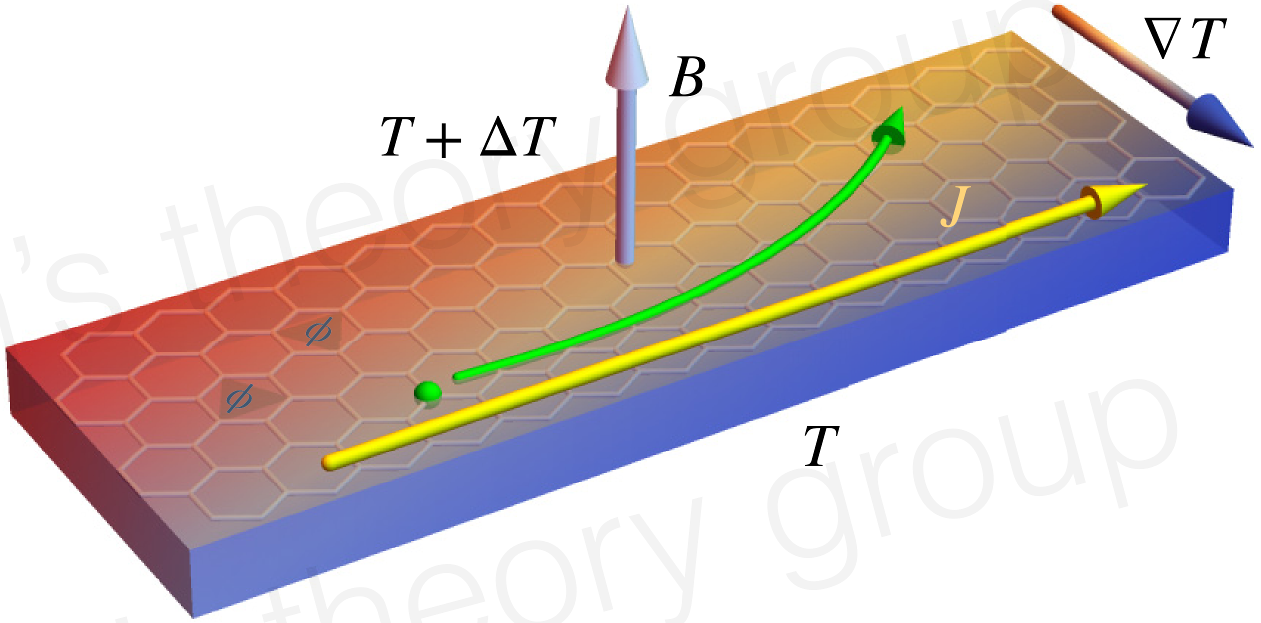


Expt

Theory

- Thermal Hall effect in quantum spin liquids

Yong Hao Gao
Fudan University



Refs:
Yong Hao Gao, GC, arXiv 1901.01522
Yong Hao Gao, C Hickey, T Xiang, S Trebst, GC, PR Research, 1, 013014 (2019)
Xiao-Tian Zhang, Yong Hao Gao, Chunxiao Liu, GC, arXiv 1904.08865 [Pyrochlore U(1) QSL]

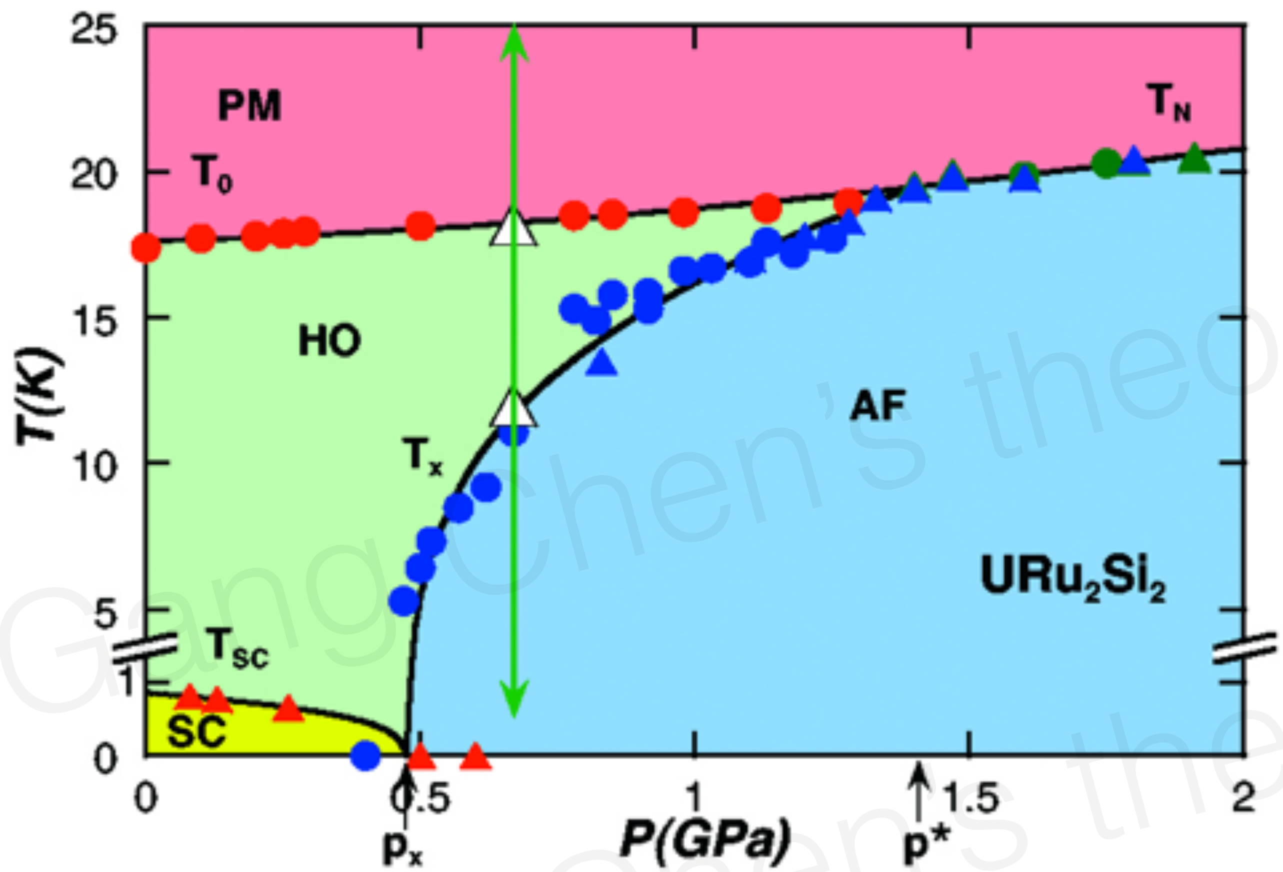
** To be released ✓Taken ⇐Transferred ◇ In Progress ☆Planned or In Cart

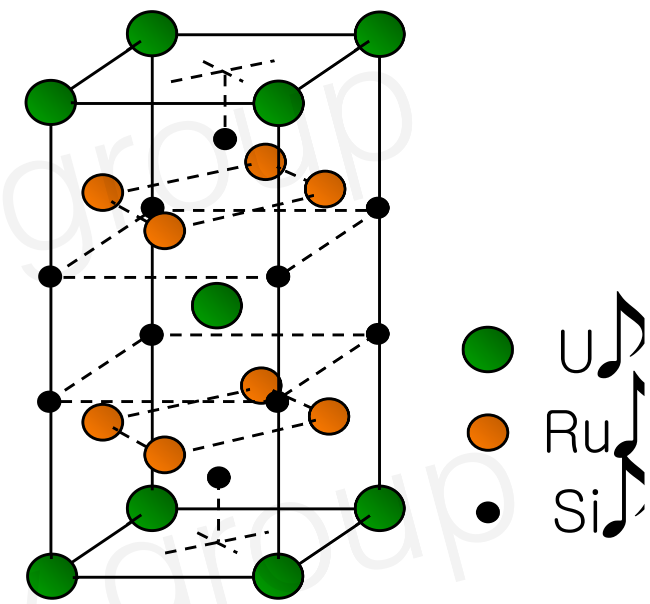
Course	Description	Term	Grade	Units	Status
CAES 1000	(4) Core University English	2019-20 Sem 2		6.00	◇
CCCH 9003	Modernity and Traditional Chin	2019-20 Sem 1		6.00	◇
CCHU 9070	Making Movies: Creative Expres	2019-20 Sem 2		6.00	◇
CCST 9017	Hidden Order in Daily Life: A	2019-20 Sem 1		6.00	◇
CUND 9003	(4) Cantonese for Non-Cantones	2019-20 Sem 1		6.00	◇
MATH 1013	(4) University mathematics II	2019-20 Sem 1		6.00	◇
PHYS 1150	(4) Problem solving in physics	2019-20 Sem 2		6.00	◇
PHYS 1250	(4) Fundamental physics	2019-20 Sem 1		6.00	◇

"The hidden order in art" by Anton Ehrenzweig
"The hidden order in corruption" by Kraina Ksiazek

……

Hidden order in condensed matter





- Hidden order: “dark matter” in CMT
- URu_2Si_2
  - Second order transition at ~17K, $\Delta S \sim 0.42$ Rln2
  - Order parameters unknown after decades

Hidden Order Behaviour in URu_2Si_2
(A Critical Review of the Status of Hidden Order in 2014)

J. A. Mydosh[a*] and P. M. Oppeneer[b]

Table 1. Summary of ongoing contemporary experiments to characterise the heavy fermion precursor, the HO transition and the HO and superconducting states of URu_2Si_2.

Angular resolved photoemission (ARPES) [7–11]
Quantum oscillations (QO) [12–14]
Elastic and inelastic neutron scattering [15–19]
Nuclear magnetic and quadrupolar resonance (NMR, NQR) [20–22]
Scanning tunneling microscopy (STM) and spectroscopy (STS) [23, 24]
Ultrafast time-resolved ARPES and reflection spectroscopy [25, 26]
Phononic Raman [27] and electronic Raman spectroscopy [28]
Optical spectroscopy [29–31]
Polar Kerr effect [32]
Magnetic torque measurements [5, 33]
Cyclotron resonance [34]
X-ray diffraction [35, 36]
X-ray resonant scattering (XRS) [37, 38]
Point contact spectroscopy (PCS) [39–41]
Resonance ultrasonics [42]
Core-level spectroscopy (XAS, EELS) [43]
Elasto-resistivity [44]

Every quantum material is a universe, and our telescopes are the experimental probes.
telescopes can be applied if there are more kinds of degrees of freedom.

Table 2. Summary of analytic theories and models proposed to explain the HO, with an emphasise on the recent contributions. For proposals of specific multipolar magnetic order on the U ions, see Table 3.

Barzykin & Gorkov (1995)	three-spin correlations [45]
Kasuya (1997)	uranium dimerisation [46]
Ikeda & Ohashi (1998)	d-spin density wave [47]
Okuno & Miyake (1998)	CEF & quantum fluctuations [48]
Chandra et al. (2002)	orbital currents [49]
Viroszek et al. (2002)	unconv. spin density wave [50]
Mineev & Zhitomirsky (2005)	staggered spin density wave [51]
Varma & Zhu (2006)	helicity (Pomeranchuk) order [52]
Elgazzar et al. (2009)	dynamical symmetry breaking [53]
Kotetes et al. (2010)	chiral d-density wave [54]
Dubi & Balatsky (2011)	hybridization wave [55]
Pepin et al. (2011)	modulated spin liquid [56]
Fujimoto (2011)	spin nematic order [57]
Riseborough et al. (2012)	unconv. spin-orbital density wave [58]
Das (2012)	spin-orbital density wave [59]
Chandra et al. (2013)	hastatic order [60]
Hsu & Chakravarty (2013)	singlet-triplet d-density wave [61]

Various theoretical proposals, still unresolved

Table 3. Summary of proposals for a specific multipolar magnetic ordering on the uranium ion to explain the HO, with an emphasise on the recent contributions. Note that different symmetries are possible for high-rank multipoles, therefore some kind of multipoles appear more than once.

Nieuwenhuys (1987)	dipole (2^1) order [62]
Santini & Amoretti (1994)	quadrupolar (2^2) order [63]
Kiss & Fazekas (2005)	octupolar (2^3) order [64]
Hanzawa & Watanabe (2005)	octupolar order [65]
Hanzawa (2007)	incommensurate octupole [66]
Haule and Kotliar (2009)	hexadecapolar (2^4) order [67]
Cricchio et al. (2009)	dotriacontapolar (2^5) order [68]
Harima et al. (2010)	antiferro quadrupolar order [69]
Thalmeier & Takimoto (2011)	$E(1,1)$-type quadrupole [70]
Kusunose & Harima (2011)	antiferro hexadecapole[71]
Ikeda et al. (2012)	E^--type dotriacontapole [72]
Rau & Kee (2012)	E-type dotriacontapole [73]
Ressouche et al. (2012)	dotriacontapolar order [16]

How to identify the nature of the "hidden orders"?

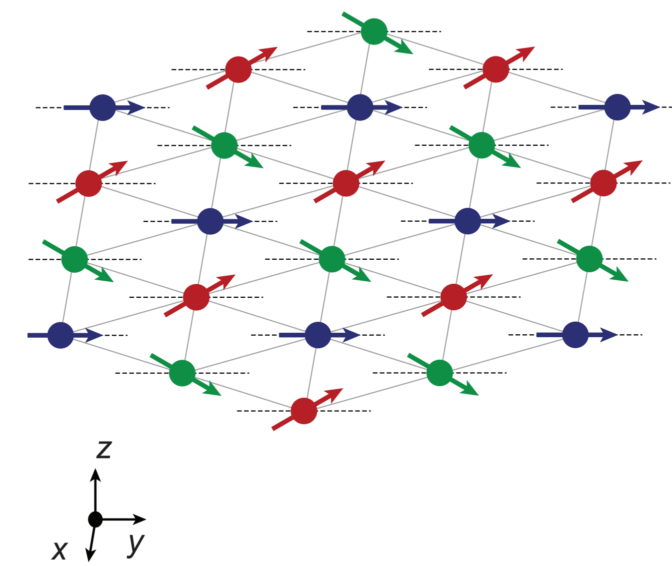
Our simple proposal : Orthogonal operator approach

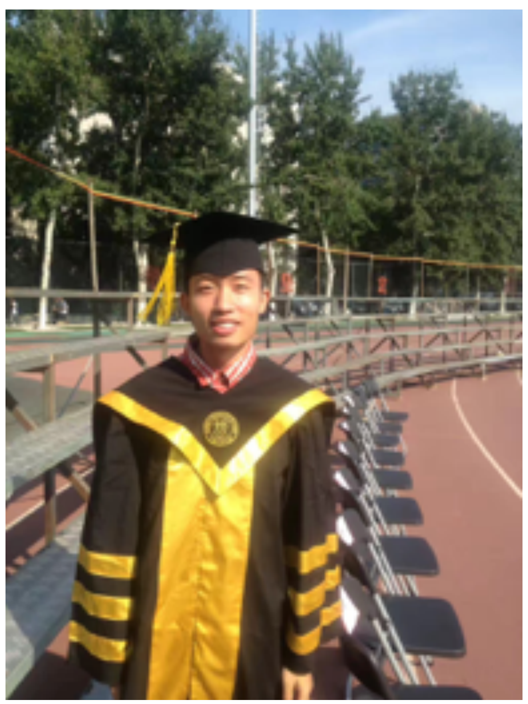
Find physical observables whose operators do not commute with the "proposed" hidden order operators, and these observables are easier to detect experimentally. The dynamic correlations or spectra reveals the structure and the nature of the hidden orders.

Yaodong Li, Xiaoqun Wang, GC, PRB (R) 94, 201114 (2016): **hidden octupolar order**
Changle Liu, Yaodong Li, GC, PRB 98, 045119 (2018): **hidden quadrupolar order**

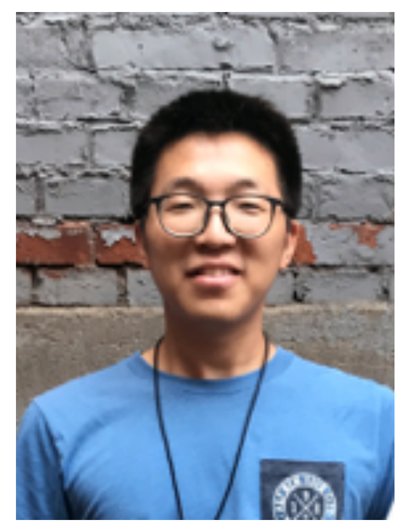
Intertwined multipolar structure in TmMgGaO4

arXiv 1810.05054
[To appear in Nature Communications]

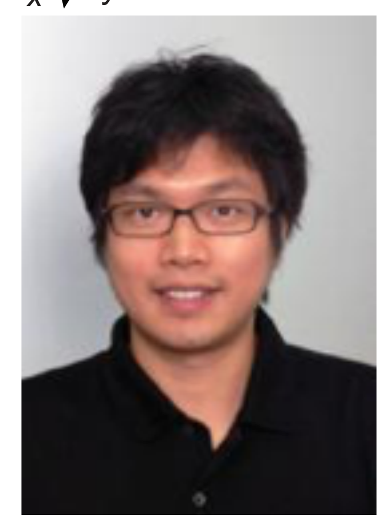




Changle Liu
(Fudan)



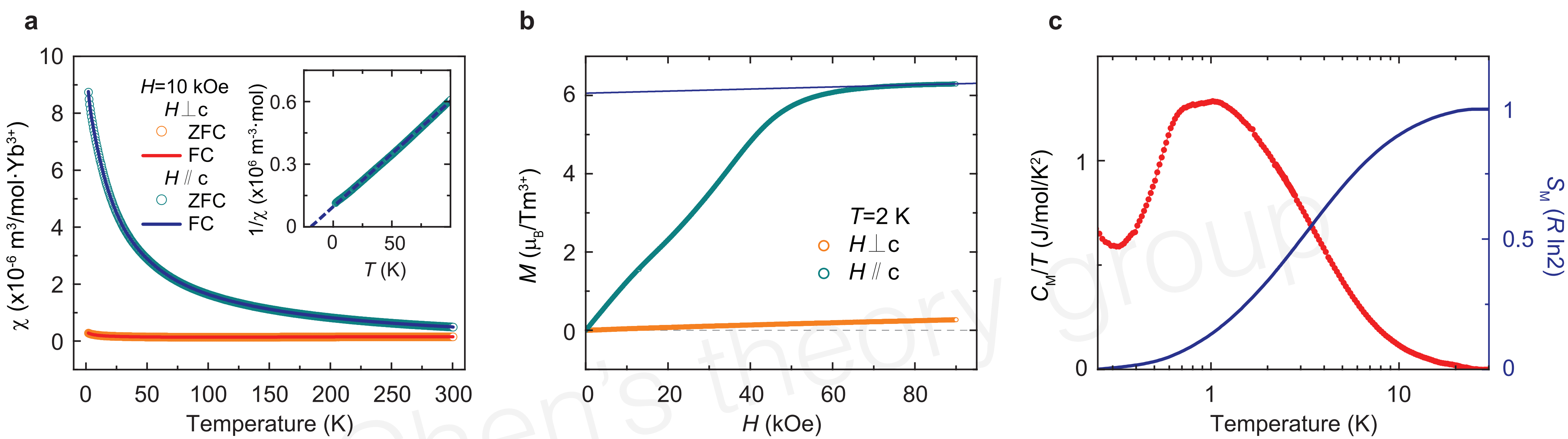
Yao Shen
(Fudan)



Jun Zhao
(Fudan)

This material is not our motivation, but our application.

Tm in TmMgGaO4 looks like non-Kramers doublets



Y Shen, Changle Liu, …, GC, Jun Zhao, arXiv 1810.05054
[To appear in Nature Communications]

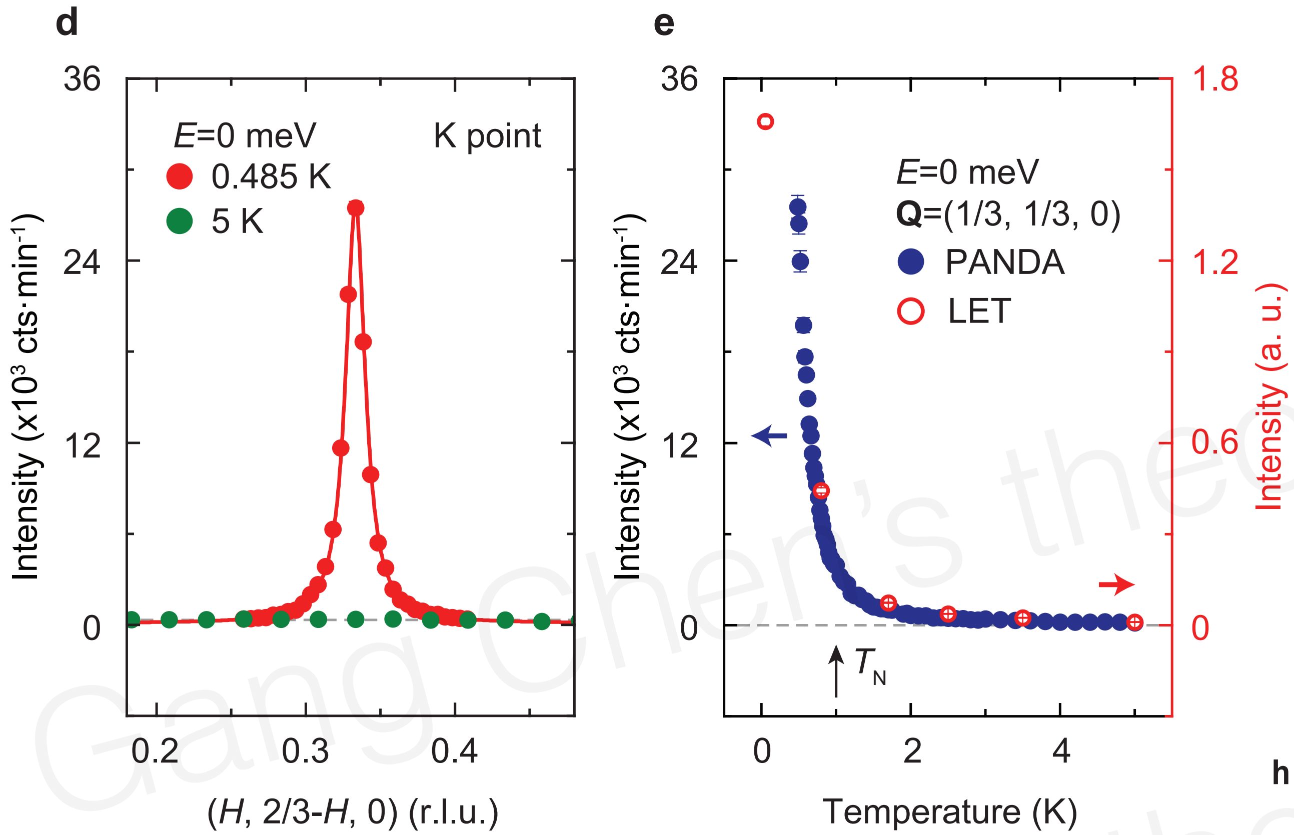
Transverse components are hidden, only the z component is visible in magnetic fields.

Actually, it is thought to be Ising.

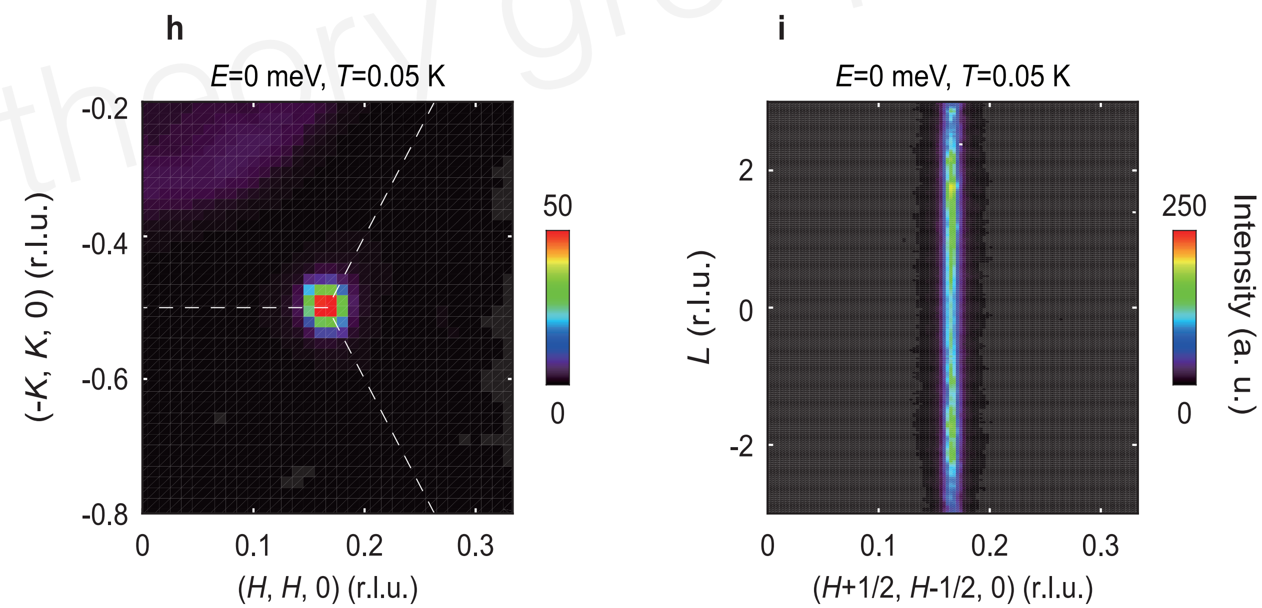
Li, Y., Bachus, S., Tokiwa, Y., Tsirlin, A. A. & Gegenwart, P. Absence of zero-point entropy in a triangular Ising antiferromagnet.

at https://arxiv.org/abs/1804.00696 (2018).

The system orders antiferromagnetically

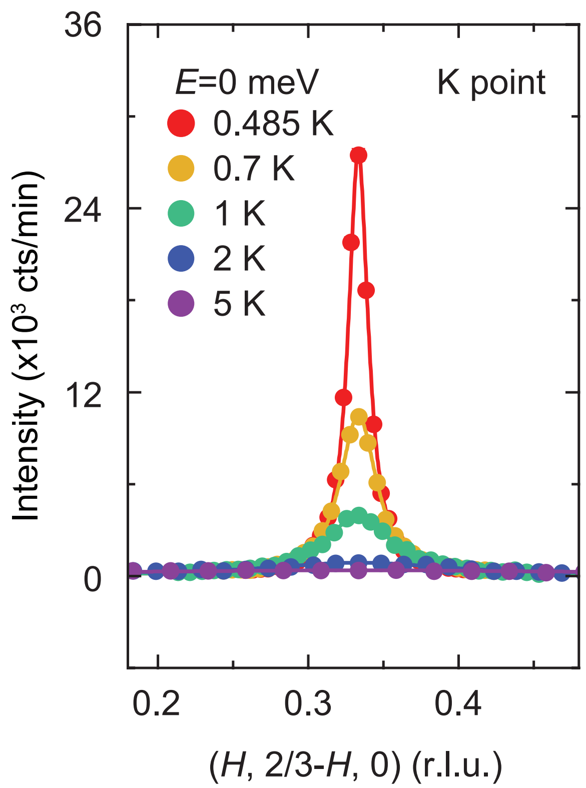


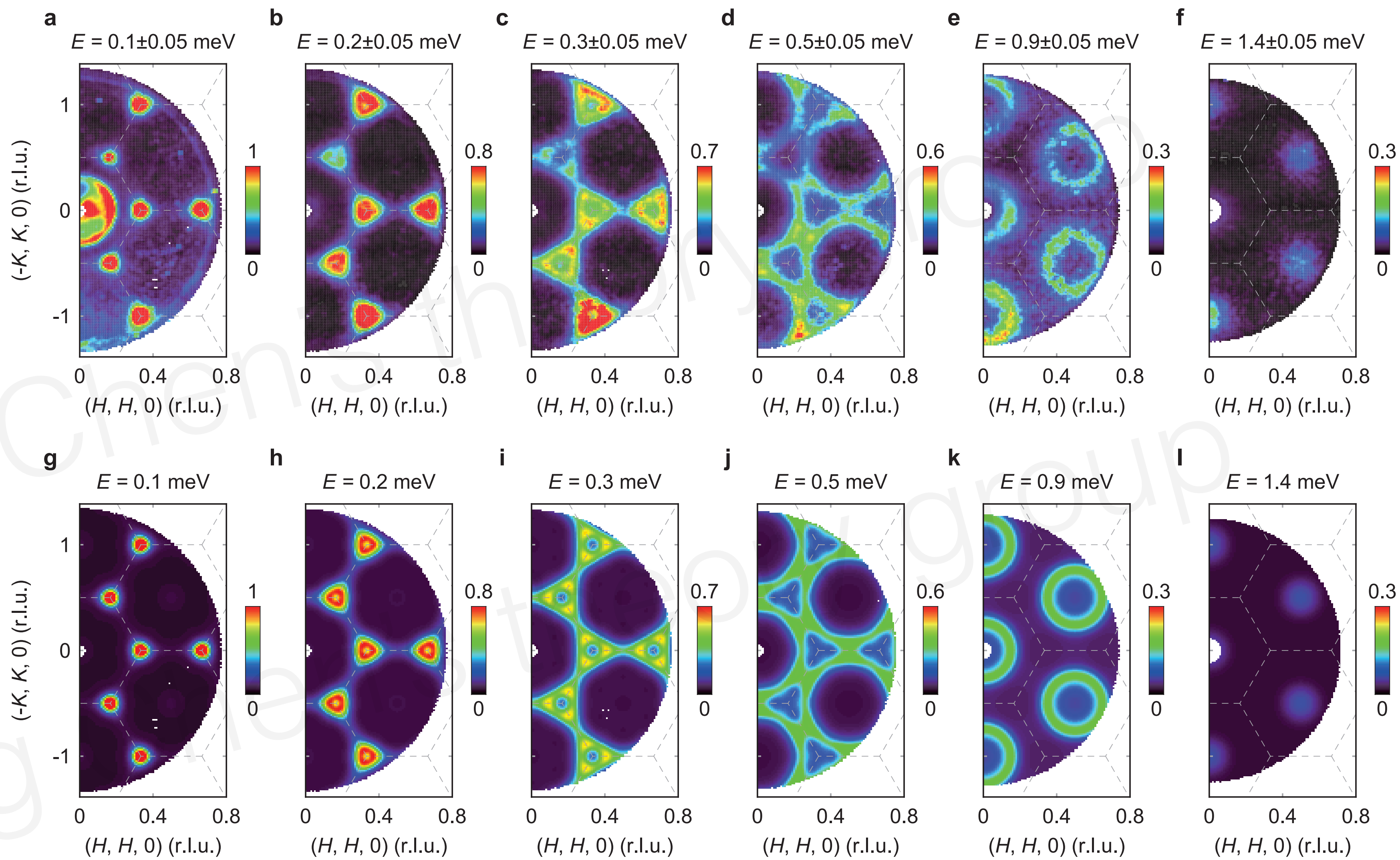
Y Shen, Changle Liu, …, GC, Jun Zhao,
arXiv 1810.05054
[To appear in Nature Communications]



along c direction,
truly 2D

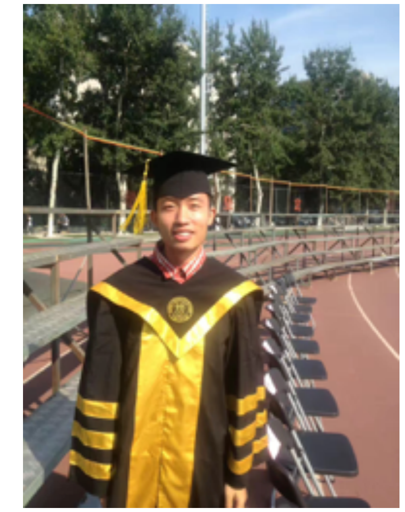
Well-defined spin wave



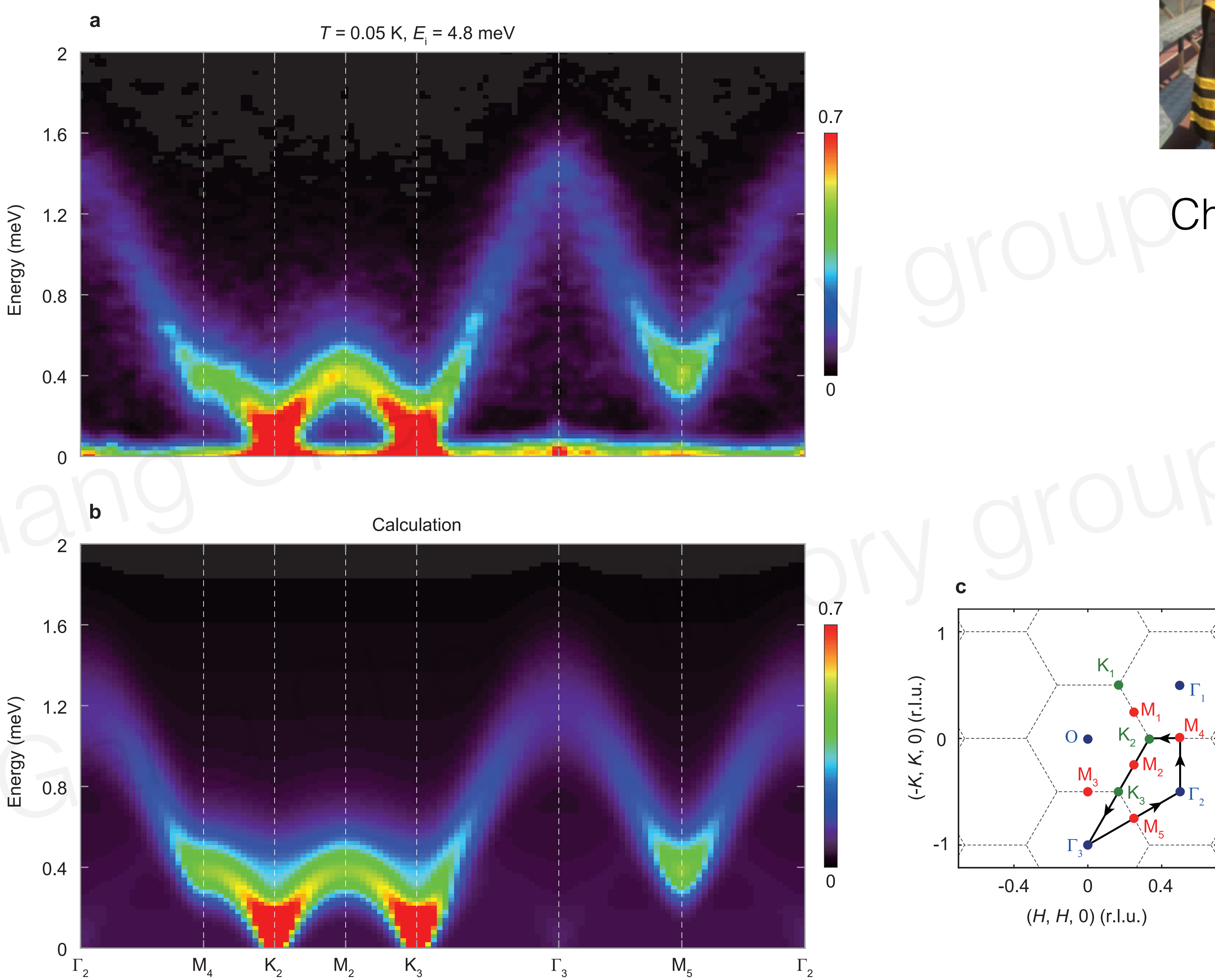


The presence of well-defined spin wave indicates the presence of the "hidden order" ?

Dispersions: w-k relation

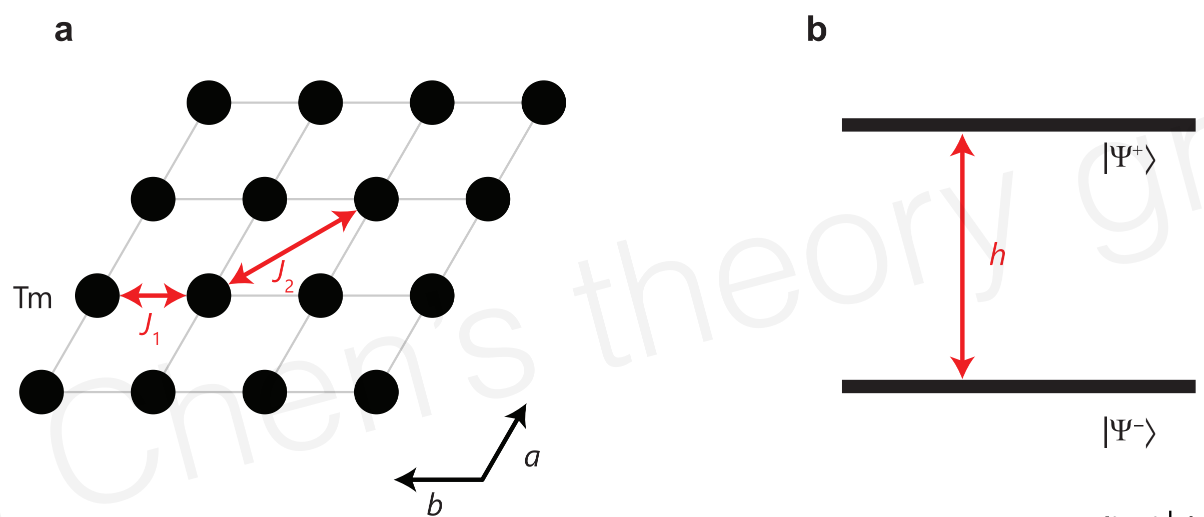


Changle Liu



Actually, they are not non-Kramers doublets

lattice[1]. In $TmMgGaO_4$, the Tm^{3+} ion possess an electron configuration $4f^{12}$, in which the orbital and spin angular momentum ($L = 5$, $S = 1$) are entangled into the total angular momentum $J = 6$ due to



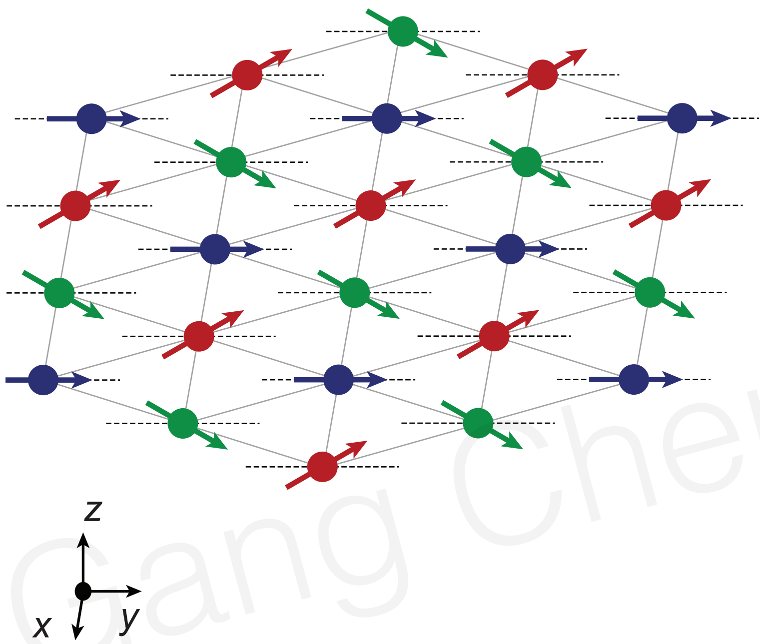
$$|\Psi^+\rangle \sim |J^z = 6\rangle + |J^z = -6\rangle + ...,$$
$$|\Psi^-\rangle \sim |J^z = 6\rangle - |J^z = -6\rangle + ...$$

$$S_i^x = \frac{i}{2}(|\Psi_i^-\rangle\langle\Psi_i^+| - |\Psi_i^+\rangle\langle\Psi_i^-|),$$
$$S_i^y = \frac{1}{2}(|\Psi_i^+\rangle\langle\Psi_i^+| - |\Psi_i^-\rangle\langle\Psi_i^-|),$$
$$S_i^z = \frac{1}{2}(|\Psi_i^+\rangle\langle\Psi_i^-| + |\Psi_i^-\rangle\langle\Psi_i^+|)$$

Here, these two singlets, $|\Psi_i^+\rangle$ and $|\Psi_i^-\rangle$, carry A_{1g} and A_{2g} representation of the D_{3d} group, respectively.

Intrinsic quantum Ising model

"Intrinsic" means the transverse field has an intrinsic origin.



$$\mathcal{H} = \sum_{\langle ij \rangle} J_1^{zz} S_i^z S_j^z + \sum_{\langle\langle ij \rangle\rangle} J_2^{zz} S_i^z S_j^z - h \sum_i S_i^y.$$

J_1^{zz}=0.54(2) meV, J_2^{zz}=0.026(6) meV, h=0.62(2) meV.

For the case of quasi-1d magnets $CoNb_2O_6$, $BaCo_2V_2O_8$ and $SrCo_2V_2O_8$, because of the local Co^{2+} environment and the special lattice geometry, the system realizes the Ising interactions between the local moments. The transverse field is then introduced externally by applying a magnetic field normal to the Ising spin direction. This

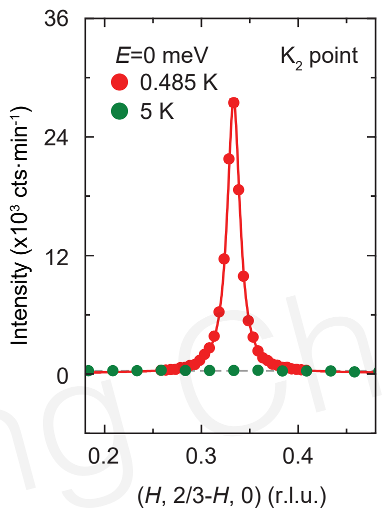
from GC, submitted but unpublished 2019

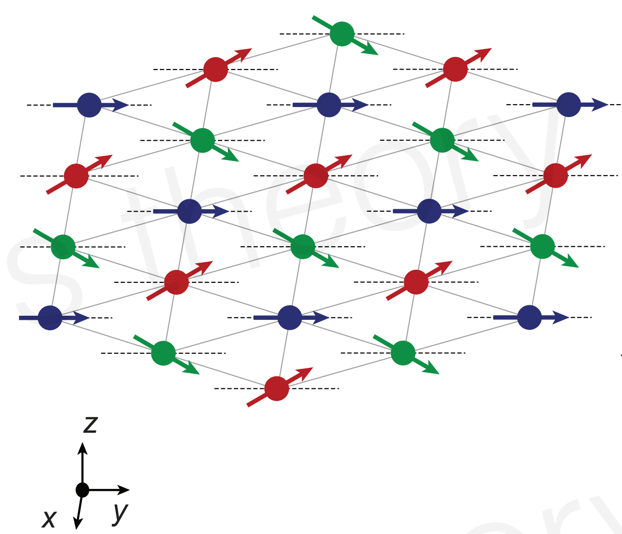
Extrinsic quantum Ising model
R Coldea, Sungbin Lee, Balents,…
Bella Lake, Congjun Wu, Alois Loidl
Jianda Wu…..

Orthogonal operator: Sz

Transverse components are hidden.

The 3-sublattice Sz order [at K] is a quantum effect, arising from the geometrical frustration and quantum order by disorder. [known from weak field limit, Sondhi, Moessner]





Y Shen, Changle Liu, …, GC, Jun Zhao, arXiv 1810.05054
[To appear in Nature Communications]

Dynamic measurement: only Sz is visible by neutron spin.

$$\mathcal{S}^{zz}(\mathbf{q},\omega > 0) = \frac{1}{2\pi N}\sum_{ij}\int_{-\infty}^{+\infty} dt\, e^{i\mathbf{q}\cdot(\mathbf{r}_i-\mathbf{r}_j)-i\omega t}\langle S_i^z(0)S_j^z(t)\rangle.$$

as if it is polarized neutron scattering.

Changle Liu, Yaodong Li, GC, PRB 98, 045119 (2018)

Summary-1

1. The interplay between geometrical frustration and multipolar local moments leads to rich phases and excitations.

2. The manifestation of the hidden multipolar orders is rather non-trivial, both in the static and dynamic measurements.

3. The orthogonal operator approach can be used to reveal the dynamics of hidden orders. This is general and can be adapted to many other hidden order systems.

4. Finally, the non-trivial Berry phase effect has not yet been discussed. This thought has been hinted in Kivelson's recent work (PNAS 2018).

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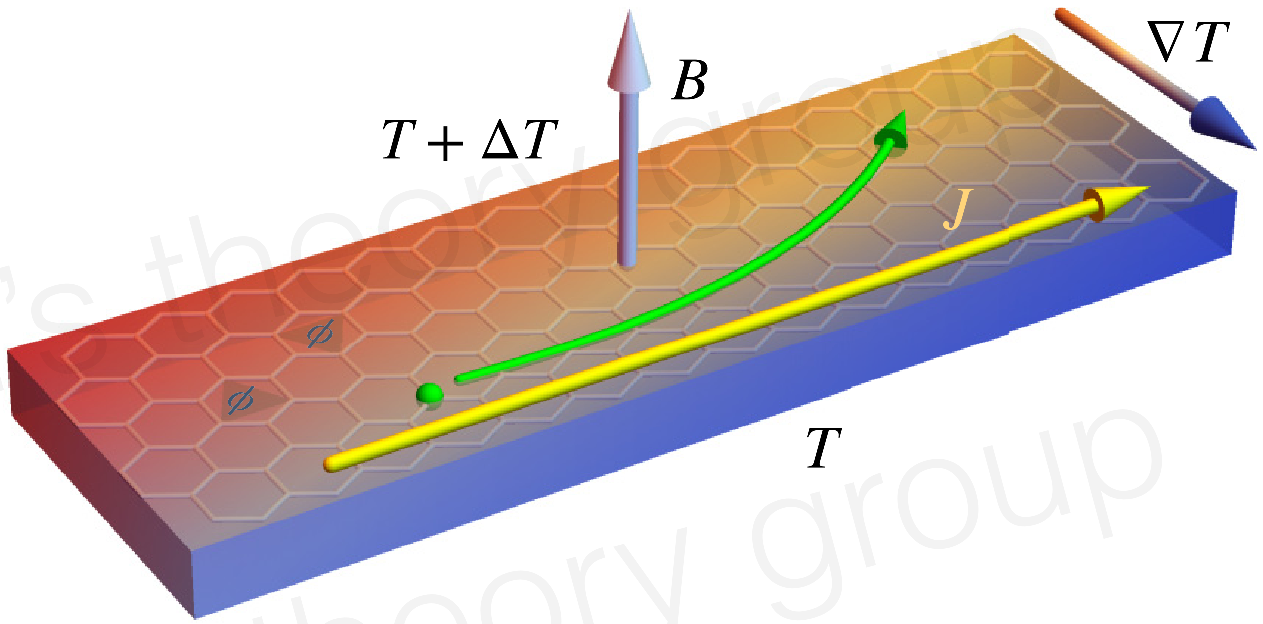
• Thermal Hall effect in quantum spin liquids

Yong Hao Gao
Fudan University



Refs:
Yong Hao Gao, GC, arXiv 1901.01522
Yong Hao Gao, C Hickey, T Xiang, S Trebst, GC, PR Research, 1, 013014 (2019)
Xiao-Tian Zhang, Yong Hao Gao, Chunxiao Liu, GC, arXiv 1904.08865 [Pyrochlore U(1) QSL]

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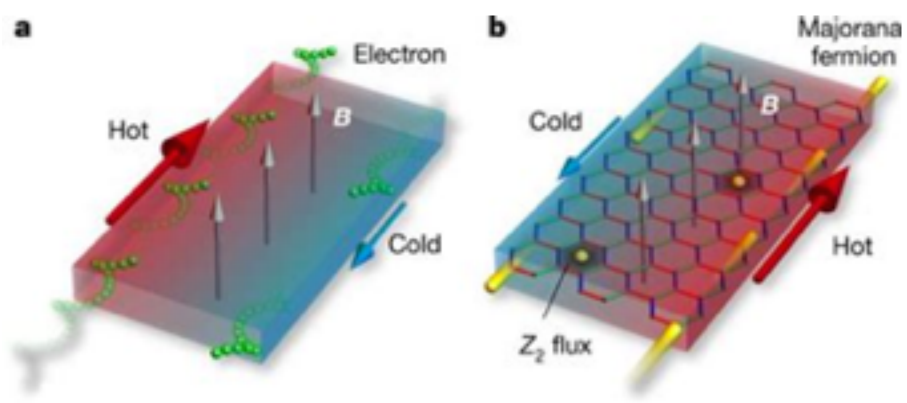
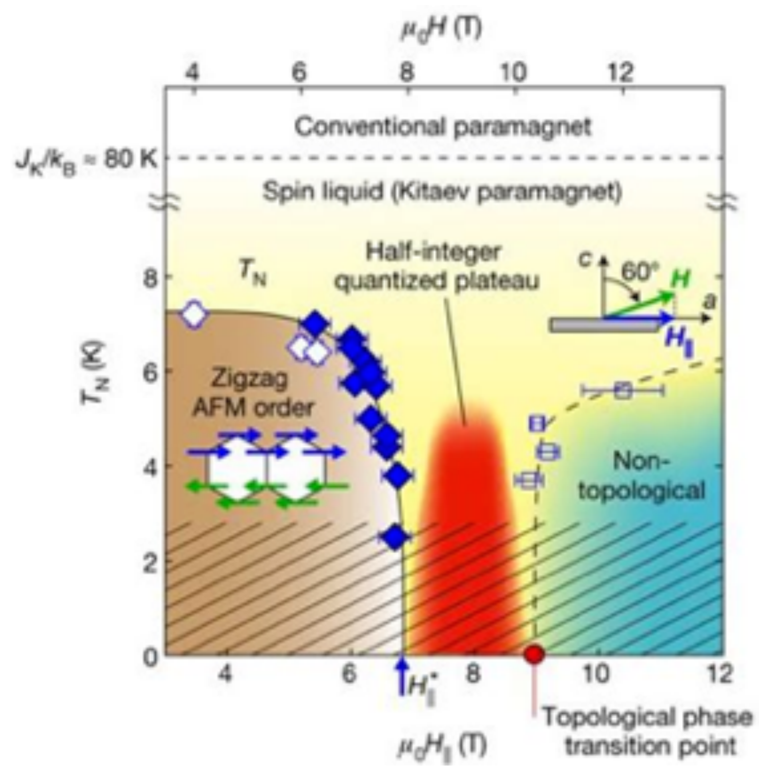
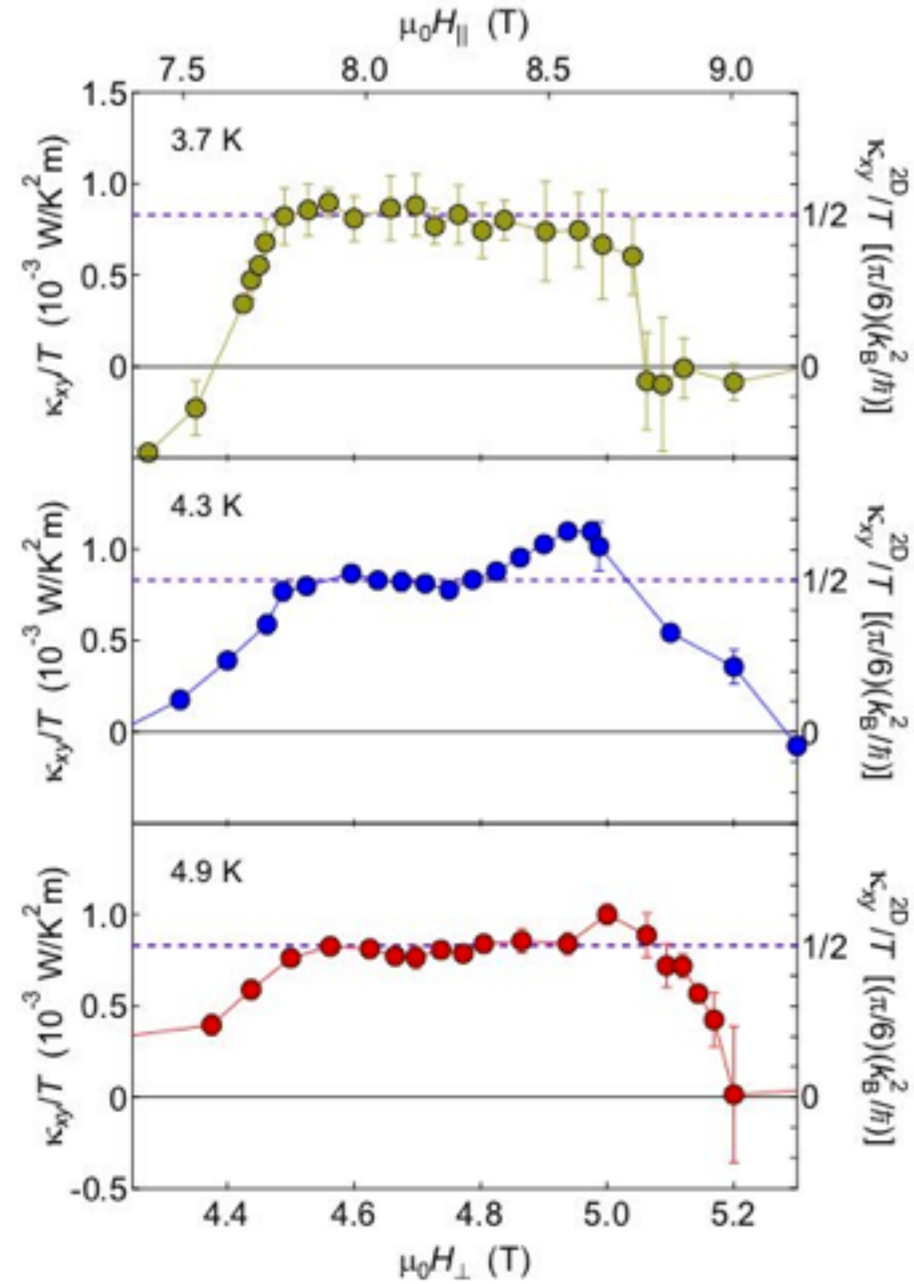
Quantized thermal Hall effect in $RuCl_3$?







Yuji Matsuda's group

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Thermal transport in Mott insulator

Low-T regime: proximate to ground state

various q-particle description

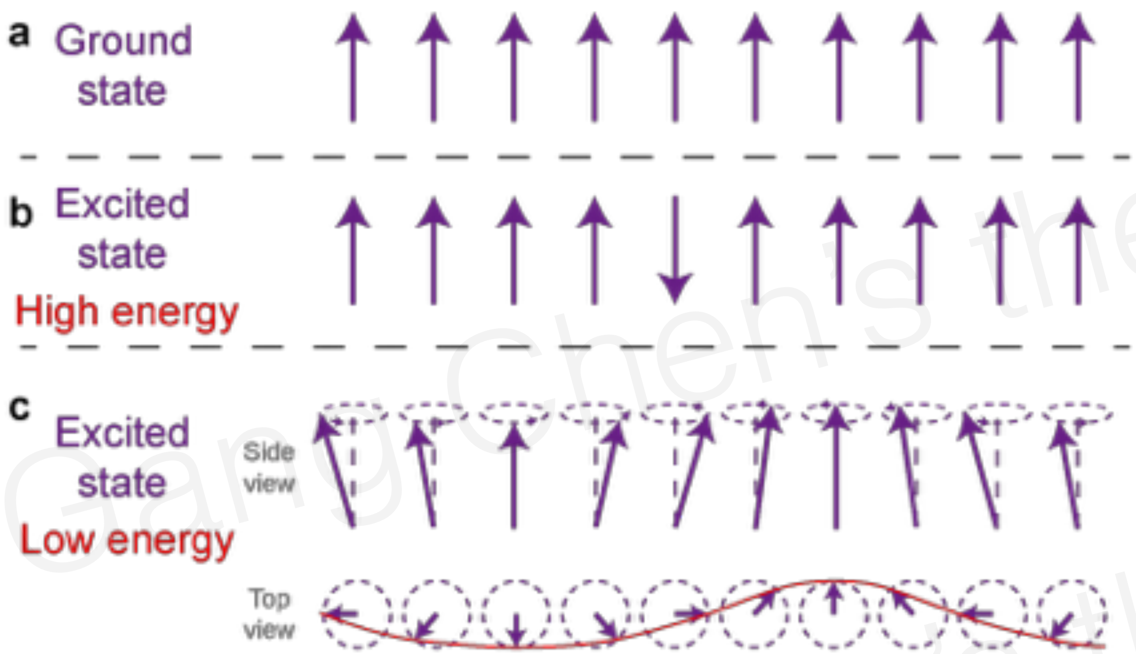
Intermediate-T: correlated/cooperative paramagnet

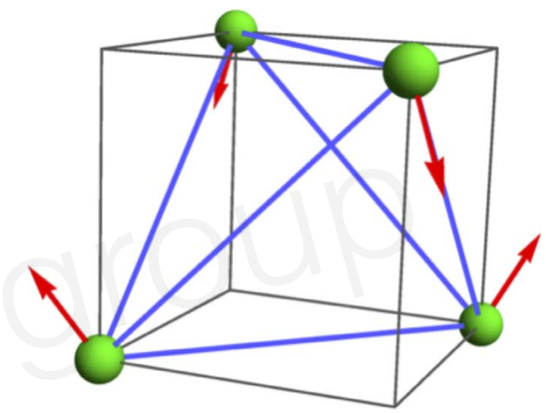
High-T regime: trivial paramagnet

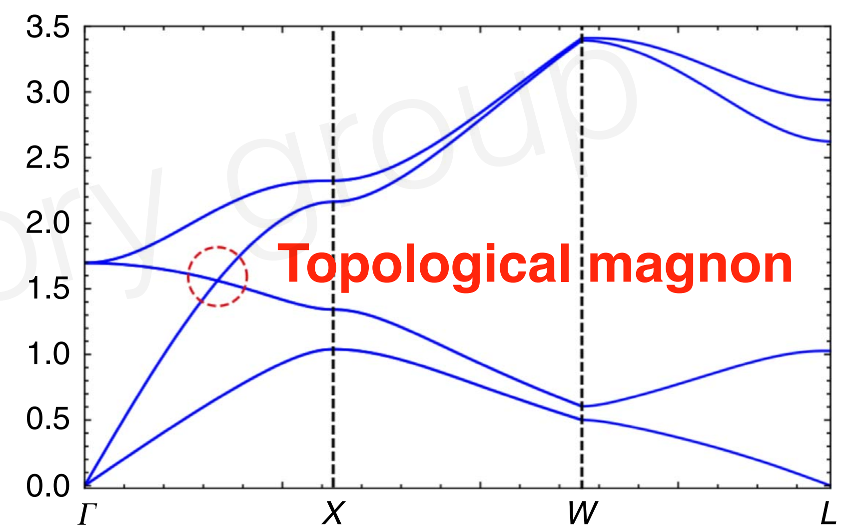
T=0 → T

Transport of "un-particle"
No good understanding
Ads-CMT?

Low-temperature regime 1: simple magnons



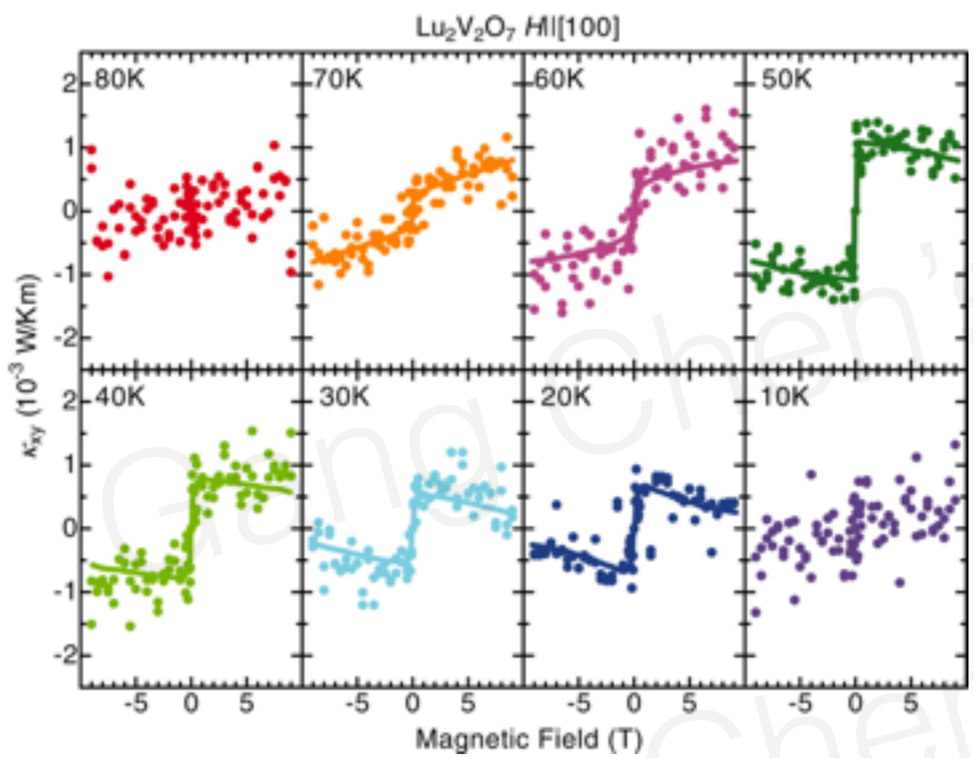




F-Y Li, YD Li, YB Kim, Balents, Yu, **GC**, Ncomms 2016

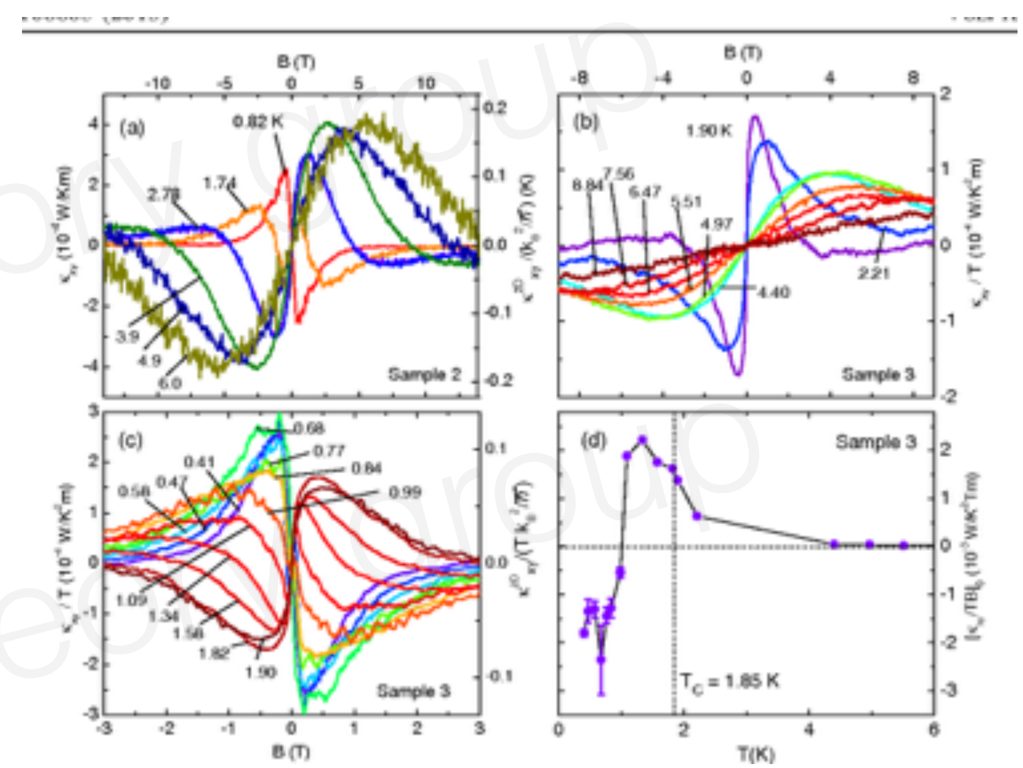
Magnetic orders and magnons

Magnon thermal Hall effect



$Lu_2V_2O_7$: pyrochlore ferromagnet

Nagaosa, Takura, et al

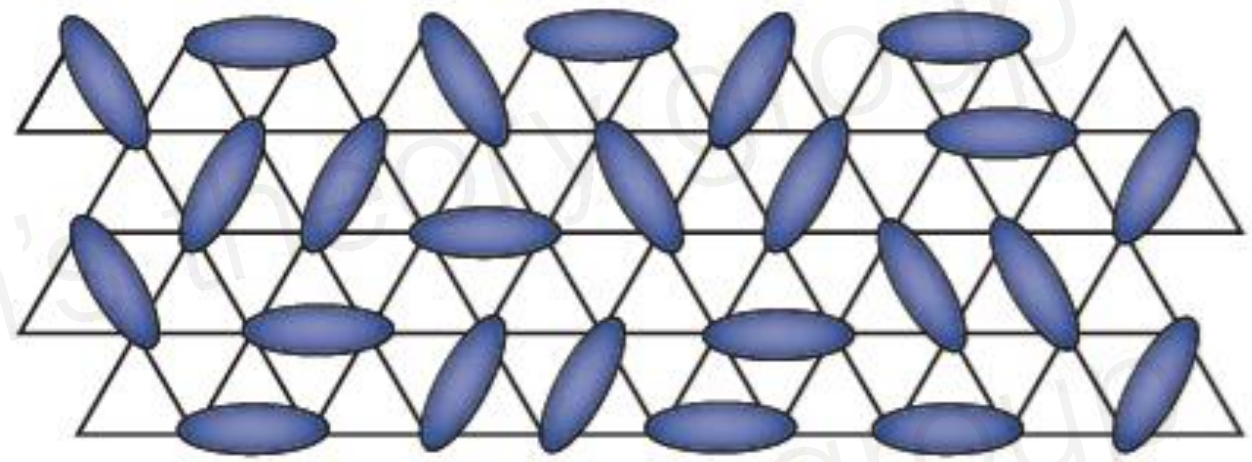


Cu(1-3, bdc): kagome ferromagnet

Young Lee, P Ong, et al

Low-temperature regime 2: quantum spin liquid

PW Anderson



RVB state for QSL

1970-1980s, lattice gauge theory was developing.
We now know that we need lattice gauge theory to **describe** QSLs.
Different branches of theoretical physics merge.

Gauge structure: deconfinement and fractionalization

Emergent gauge structure by fluctuating mean-field states

PW Anderson, Baskaran, Affleck, Xiao-Gang Wen, …..

"Cutting spin into halves, and glue them back by gauge fields." - Xiao-Gang Wen

We will concentrate on the spin liquid states of a pure spin-1/2 model on a 2D square lattice

$$H_{spin} = \sum_{<\boldsymbol{ij}>} J_{\boldsymbol{ij}} \boldsymbol{S_i} \cdot \boldsymbol{S_j} + ... \qquad (1)$$

$$\boldsymbol{S_i} = \frac{1}{2} f^{\dagger}_{\boldsymbol{i}\alpha} \boldsymbol{\sigma}_{\alpha\beta} f_{\boldsymbol{i}\beta} \qquad (2)$$

In terms of the fermion operators the Hamiltonian Eq. (1) can be rewritten as

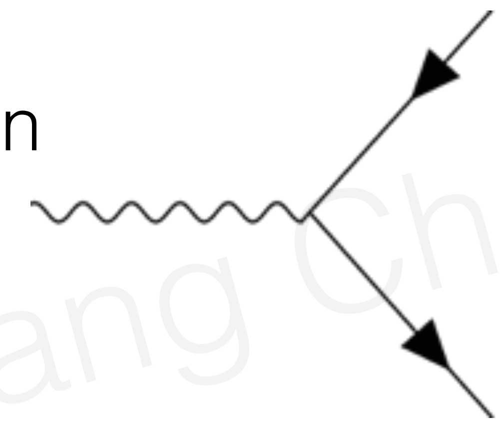
$$H = \sum_{\langle \boldsymbol{ij} \rangle} -\frac{1}{2} J_{\boldsymbol{ij}} \left(f^{\dagger}_{\boldsymbol{i}\alpha} f_{\boldsymbol{j}\alpha} f^{\dagger}_{\boldsymbol{j}\beta} f_{\boldsymbol{i}\beta} + \frac{1}{2} f^{\dagger}_{\boldsymbol{i}\alpha} f_{\boldsymbol{i}\alpha} f^{\dagger}_{\boldsymbol{j}\beta} f_{\boldsymbol{j}\beta} \right) \qquad (3)$$

$$\begin{aligned} H_{mean} &= \sum_{\langle \boldsymbol{ij} \rangle} -\frac{3}{8} J_{\boldsymbol{ij}} \Big[(\chi_{\boldsymbol{ji}} f^{\dagger}_{\boldsymbol{i}\alpha} f_{\boldsymbol{j}\alpha} + \eta_{\boldsymbol{ij}} f^{\dagger}_{\boldsymbol{i}\alpha} f^{\dagger}_{\boldsymbol{j}\beta}\, \epsilon_{\alpha\beta} + h.c) \\ &\quad - |\chi_{\boldsymbol{ij}}|^2 - |\eta_{\boldsymbol{ij}}|^2 \Big] \qquad (7) \\ &\quad + \sum_{\boldsymbol{i}} \Big[a_0^3 (f^{\dagger}_{\boldsymbol{i}\alpha} f_{\boldsymbol{i}\alpha} - 1) + [(a_0^1 + i a_0^2) f_{\boldsymbol{i}\alpha} f_{\boldsymbol{i}\beta} \epsilon_{\alpha\beta} + h.c.] \Big] \end{aligned}$$

Consequence: spin fractionalization and continuum

spinon
(half-integer spin excitation**)**

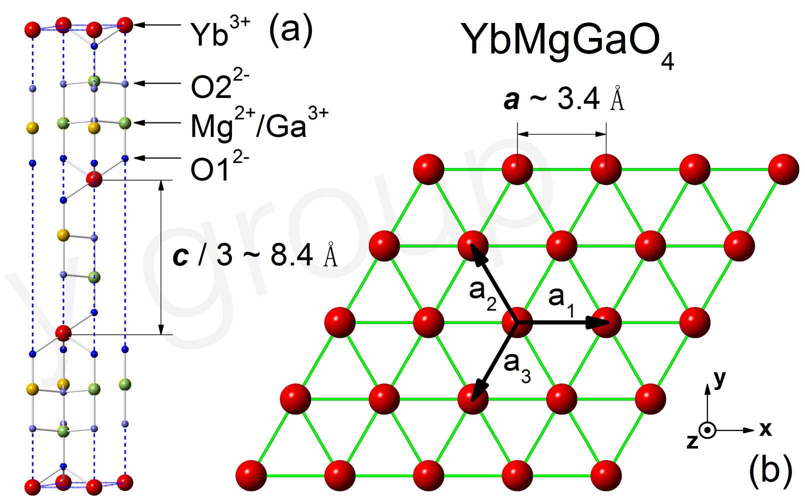
neutron

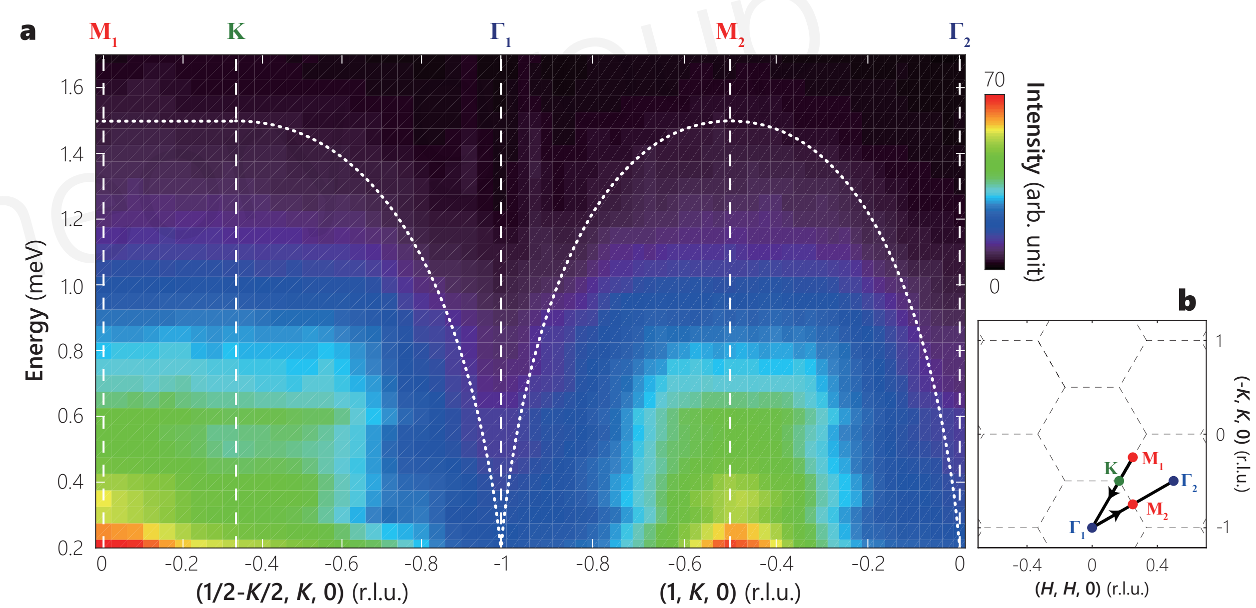


spinon

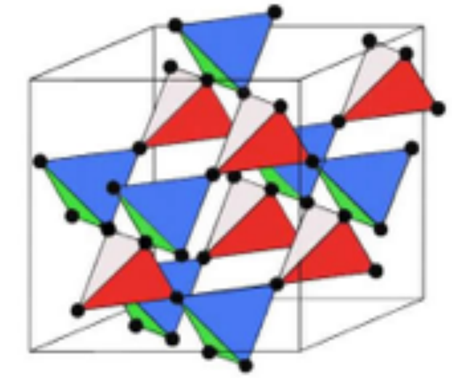
$$P = q_1 + q_2$$

$$E = \omega(q_1) + \omega(q_2)$$



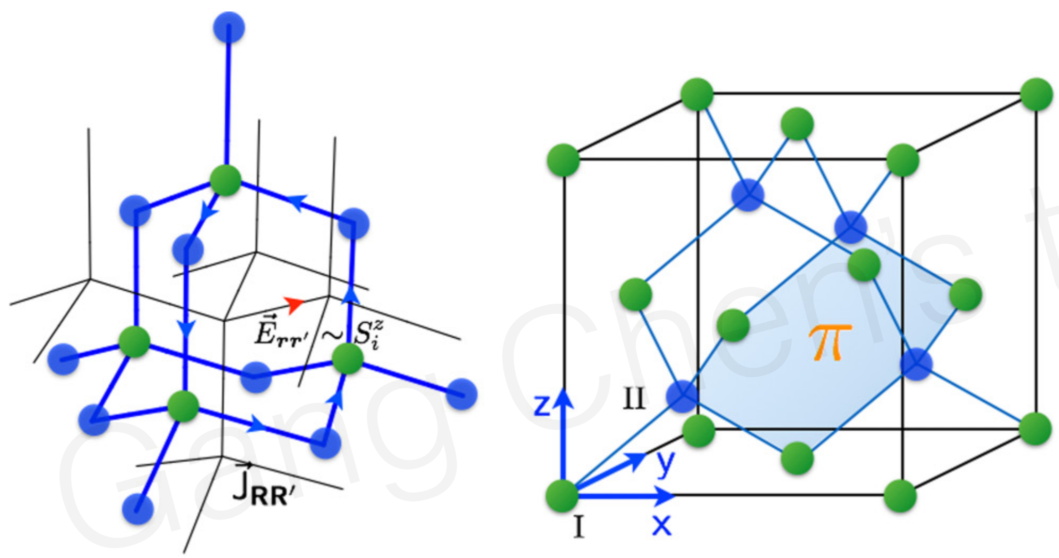


With Qingming Zhang, Jun Zhao
2015-2018



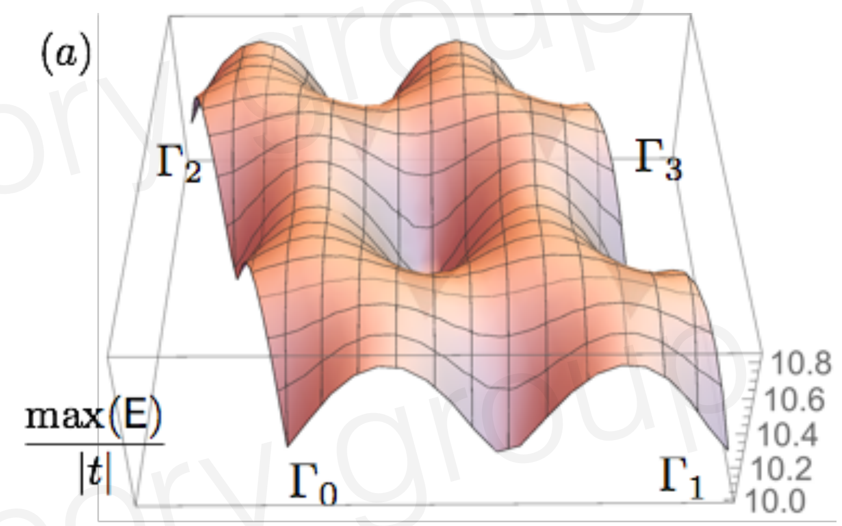
Consequence: symmetry fractionalization

XG Wen PRB, 2002
Essin, Hermele, 2012



translation symmetry is realized projectively

$$T_\mu^m T_\nu^m (T_\mu^m)^{-1} (T_\nu^m)^{-1} = e^{i\pi} = -1.$$



Enhanced spectral periodicity in monopole continuum for 3D U(1) QSL

GC, PRB, 96,195127 (2017)

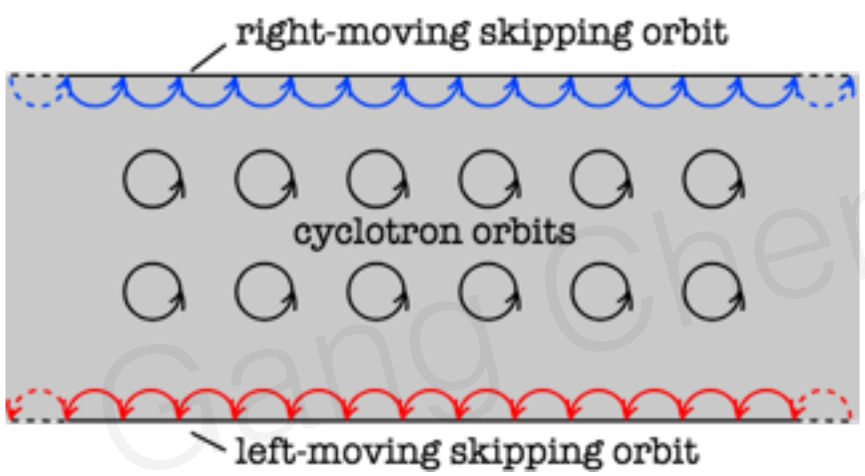
Matter-gauge coupling?

Deconfinement and fractionalization are consequences of the matter-gauge coupling in the deconfined phase.

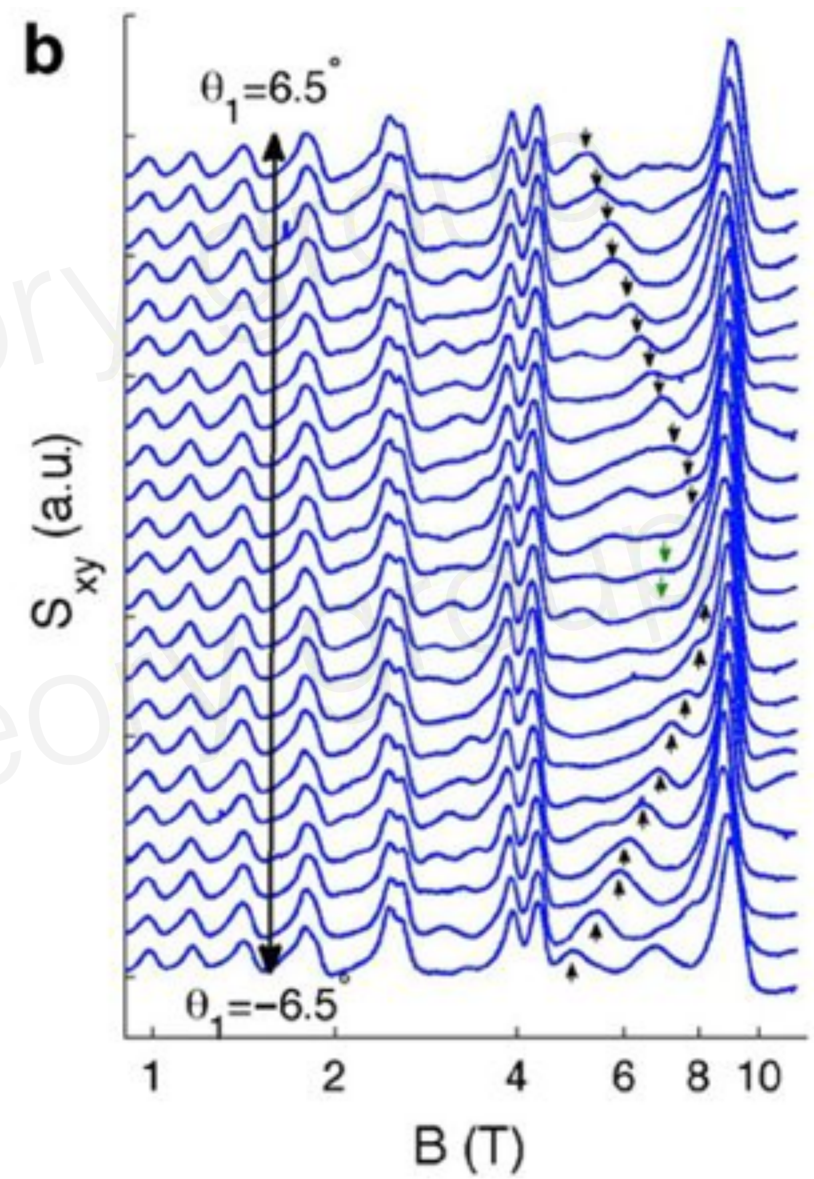
What is the direct evidence of the matter-gauge coupling?

$$H_{\text{dual}} = \boxed{-t \sum_{\langle \mathbf{R}\mathbf{R}' \rangle} e^{-i2\pi \alpha_{\mathbf{R}\mathbf{R}'}} \Phi^{\dagger}_{\mathbf{R}} \Phi_{\mathbf{R}'}} - \mu \sum_{\mathbf{R}} \Phi^{\dagger}_{\mathbf{R}} \Phi_{\mathbf{R}} + \frac{U}{2} \sum_{\hexagon^*} \left(curl\alpha - \frac{\eta_r}{2} \right)^2 - K \sum_{\langle \mathbf{R}\mathbf{R}' \rangle} \cos B_{\mathbf{R}\mathbf{R}'} + \cdots ,$$

Electrons in fields: signature of matter-gauge coupling?



Cyclotron motion of electrons:
from Lorentz force



Quantum oscillation in bismuth

Consequence of matter-gauge coupling in QSL ?

Orbital magnetic field effects in spin liquid with spinon Fermi sea: Possible application to κ-$(ET)_2Cu_2(CN)_3$

Olexei I. Motrunich
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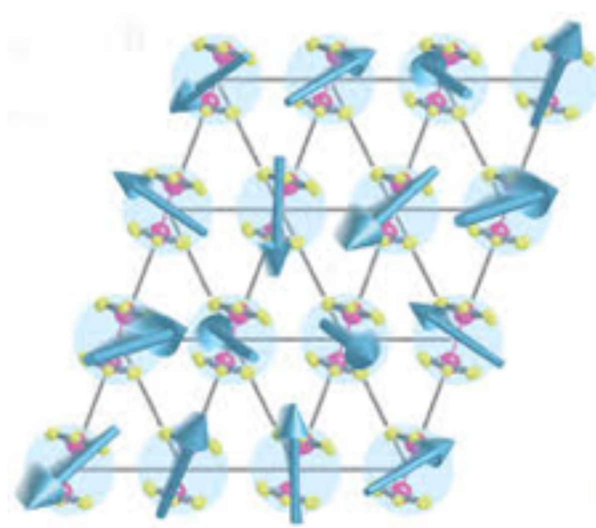
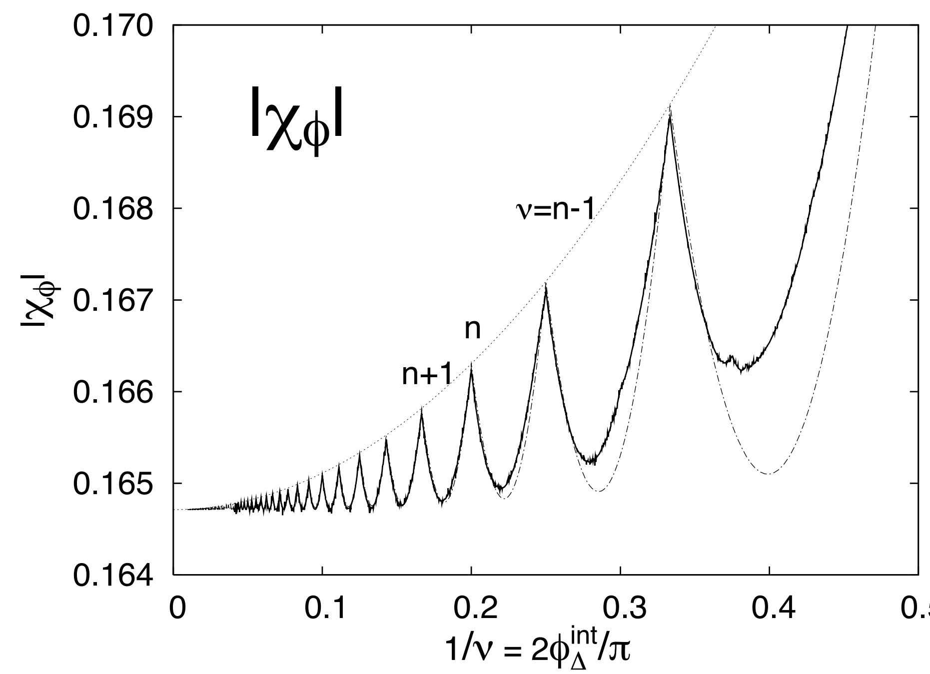


$$\hat{H}_{\rm ring} = J_2 \sum P_{12} + J_4 \sum \left(P_{1234} + P_{1234}^{\dagger}\right)$$



Quantum oscillation of spinon Fermi surface

Weak Mott insulators: spinons are not far from electrons.

Thermal Hall effect in weak Mott insulator QSL

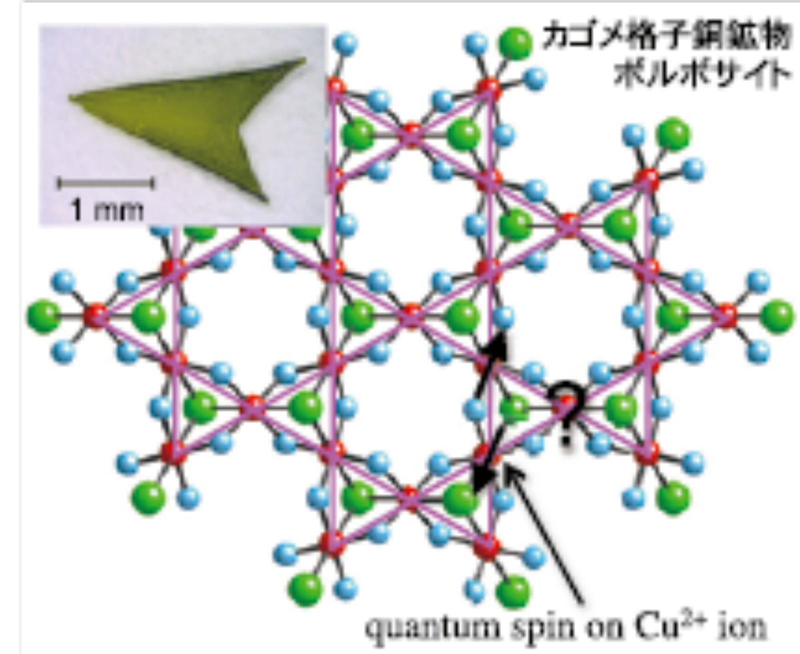
Theory of the Thermal Hall Effect in Quantum Magnets

Hosho Katsura[1], Naoto Nagaosa[1,2], Patrick A Lee[3]

$$
\begin{aligned}
\mathcal{L} &= \sum_{j,\sigma} f_{j\sigma}^{\dagger}(\partial_\tau - i a_j^0 - \mu) f_{j\sigma} \\
&- \sum_{j,k} t_f e^{i a_{jk}} f_{j\sigma}^{\dagger} f_{k\sigma} + \mathcal{L}_g,
\end{aligned} \tag{7}
$$

Following the previous works [14, 25], we take the spinon metal with a Fermi surface as a candidate for the 2D quantum spin liquid realized in κ-$(ET)_2Cu_2(CN)_3$[12]. In a magnetic field $F_{xy} = B_z$, the average of the gauge flux $\langle \mathcal{F}_{xy} \rangle = cF_{xy}$ is induced with c a constant of the order of unity because of the coupling between $\mathcal{F}_{xy}$ and F_{xy} in $\mathcal{L}_g$ [14, 24]. Therefore, the spinons are subject to the *effective magnetic field* $\langle \mathcal{F}_{xy} \rangle$ and to the Lorentz force.

Why there is thermal Hall effect
in strong Mott insulator QSL?



The D.O.F. are spins, not electrons.

The excitations are neutral spinons, do not carry external U(1) gauge charge.

There is only Zeeman coupling to the field.

How can magnetic field twist the spinon motion
and create Hall effect?

My purpose is to understand the physical properties of QSLs,
not trying to uniquely confirming QSLs.
Eventually, we will be able to use the understanding to control / design expts/phenomena.

Different cases of thermal Hall effects in QSLs

1. Chiral spin liquids: quantized w/o field
2. Gapless Z2 QSL: magnetic field changes the spinon band topology and creates chiral edge states: e.g. Kitaev spin liquid, (not much different from case 1), apply to QSL w/ gapped gauge.
3. Gapped Z2 QSL: magnetic field rigidly split the spinon bands.
4. U(1) QSL: external field comes to modify the internal continuous gauge field and thereby indirectly twists the motion of matter fields, and generate thermal Hall effects.

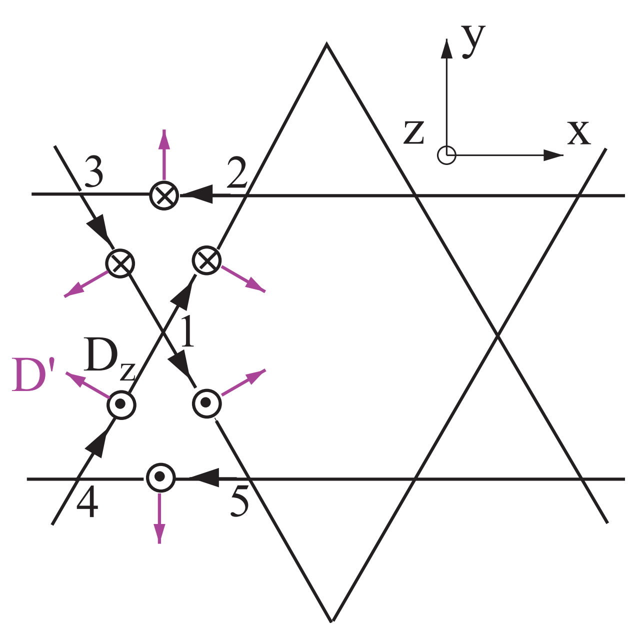
A distant observation by Patrick Lee and Nagaosa

PHYSICAL REVIEW B **87**, 064423 (2013)

Proposal to use neutron scattering to access scalar spin chirality fluctuations in kagome lattices

Patrick A. Lee*
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Naoto Nagaosa



$$\langle f_\chi | S_z(\boldsymbol{r}_1) | i \rangle = -\sum_{jk} \frac{2D_{jk}}{\Delta_t} \langle \alpha_\chi | S_z(\boldsymbol{r}_1) \hat{z} \cdot \boldsymbol{S}(\boldsymbol{r}_j) \times \boldsymbol{S}(\boldsymbol{r}_k) | 0 \rangle.$$

Pairwise spin correlation contains
a piece of gauge field correlation.

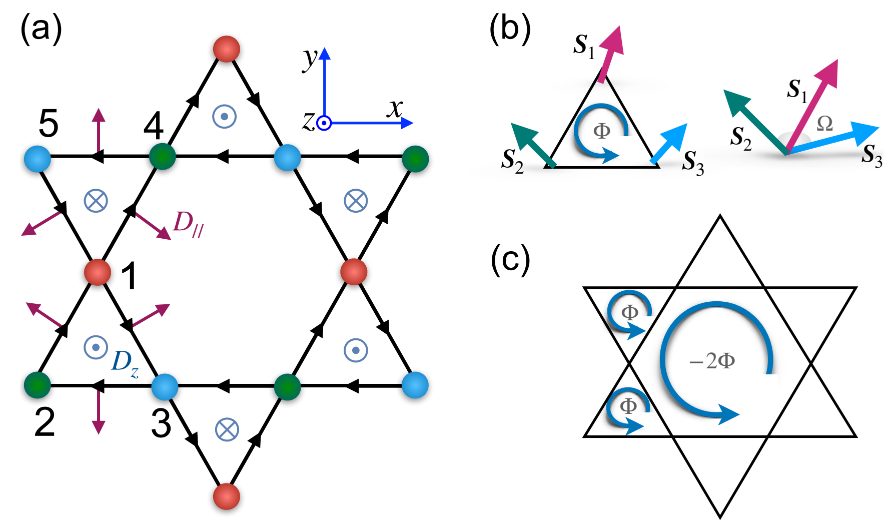
$$\sin\Phi = \tfrac{1}{2}\mathbf{S_1} \cdot (\boldsymbol{S_2} \times \boldsymbol{S_3})$$

$$\mathcal{H}_{\rm DM} = \sum_{\langle ij \rangle} \boldsymbol{D}_{ij} \cdot \boldsymbol{S}_i \times \boldsymbol{S}_j$$

XG Wen, F Wilczek, A Zee, PRB, 1989

Observation: induced internal gauge flux and emergent Lorentz force

Yong Hao Gao



$$H = \sum_{i,j} J_{ij} \boldsymbol{S_i} \cdot \boldsymbol{S_j} + \sum_{i,j} \boldsymbol{D}_{ij} \cdot \boldsymbol{S_i} \times \boldsymbol{S_j} - \sum_i B S_i^z,$$

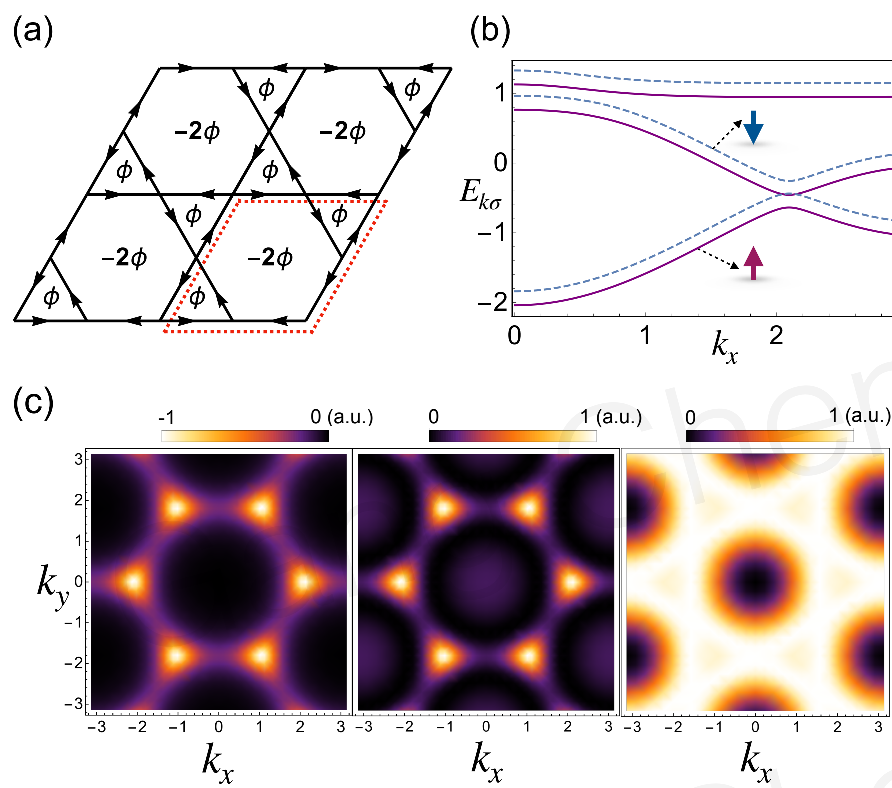
$$\langle \boldsymbol{S}_i \times \boldsymbol{S}_j \cdot \boldsymbol{S}_k \rangle \sim \langle \boldsymbol{S}_i \times \boldsymbol{S}_j \rangle \cdot \langle \boldsymbol{S}_k \rangle \neq 0$$

The combination of Zeeman coupling and DMI generates an internal U(1) gauge flux distribution.

This provides a way to **control** emergent D.O.F. with external probes.

复旦大學 FUDAN UNIVERSITY

Spinon thermal Hall effect



Spinon bands and
Berry curvatures

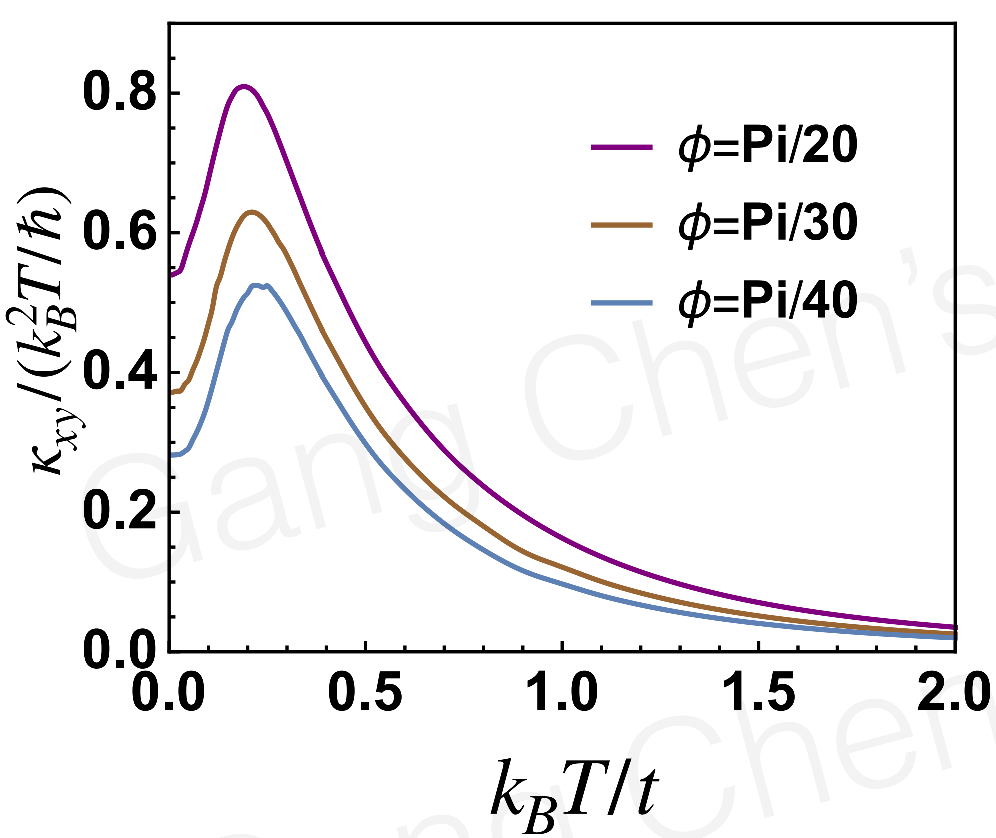
$$H_{\rm MF}[\phi] = -t\sum_{\langle ij\rangle}[e^{-i\phi/3} f^\dagger_{i\sigma} f_{j\sigma} + h.c.] - \mu \sum_i f^\dagger_{i\sigma} f_{i\sigma}$$

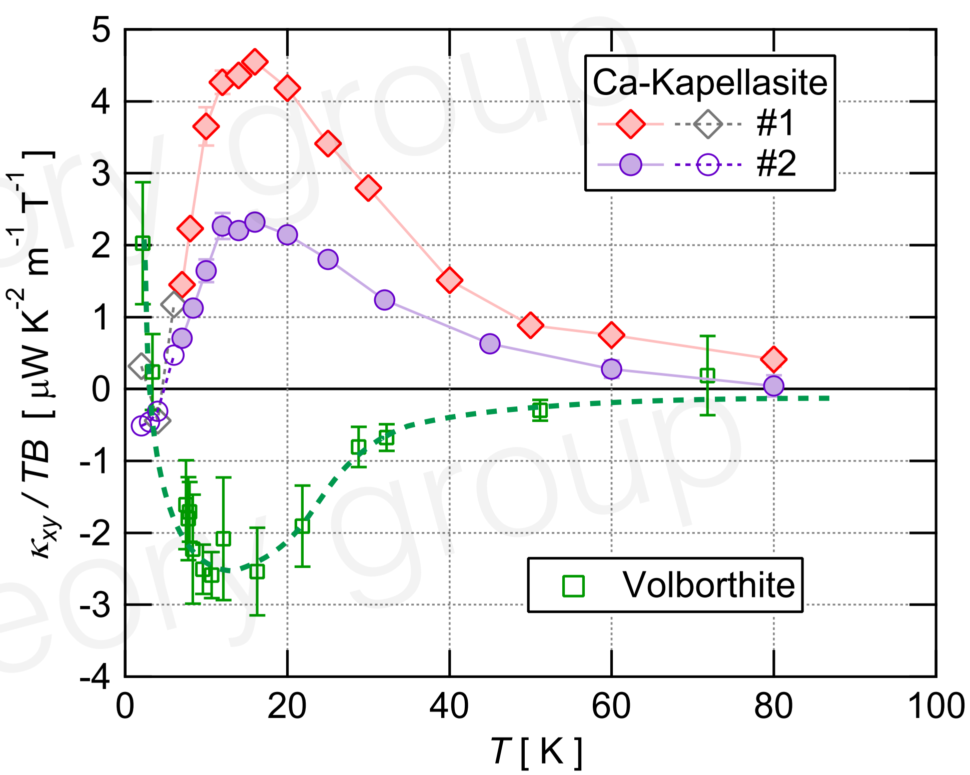
$$-B\sum_{i,\alpha\beta} f^\dagger_{i\alpha} \frac{\sigma^z_{\alpha\beta}}{2} f_{i\beta},$$

$$\kappa_{xy} = -\frac{1}{T}\int d\epsilon (\epsilon-\mu)^2 \frac{\partial f(\epsilon,\mu,T)}{\partial \epsilon}\sigma_{xy}(\epsilon).$$

$$\sigma_{xy}(\epsilon) = -\sum\nolimits_{\boldsymbol{k},\sigma,\xi_{n,\boldsymbol{k}}<\epsilon} \Omega_{n,\boldsymbol{k},\sigma}$$

Spinon thermal Hall effect



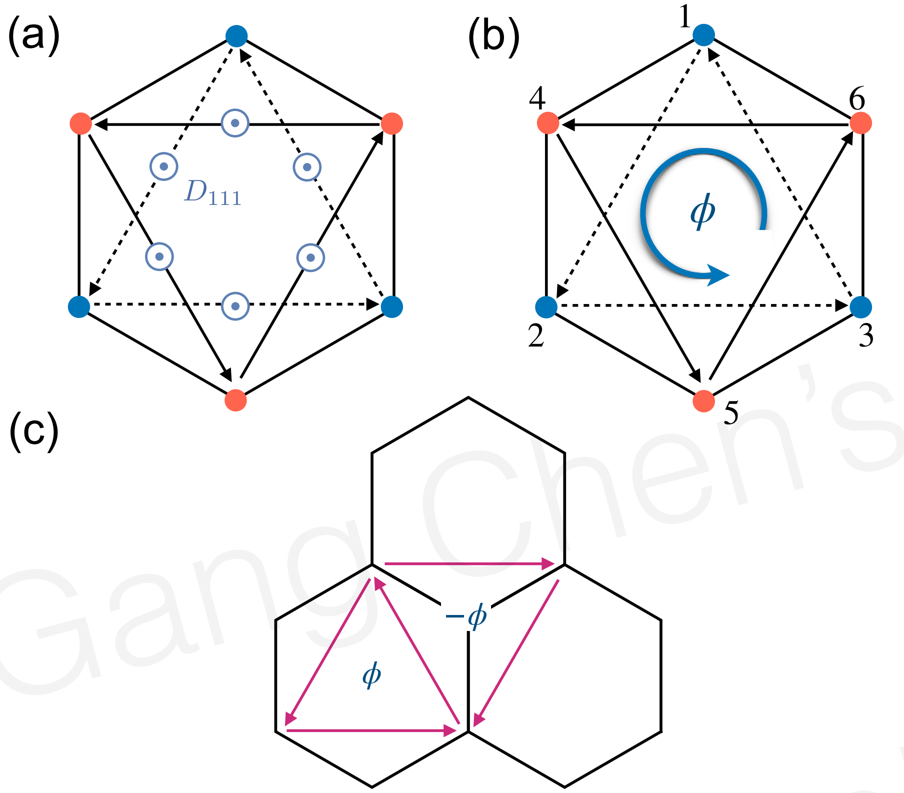


Minoru Yamashita's group

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

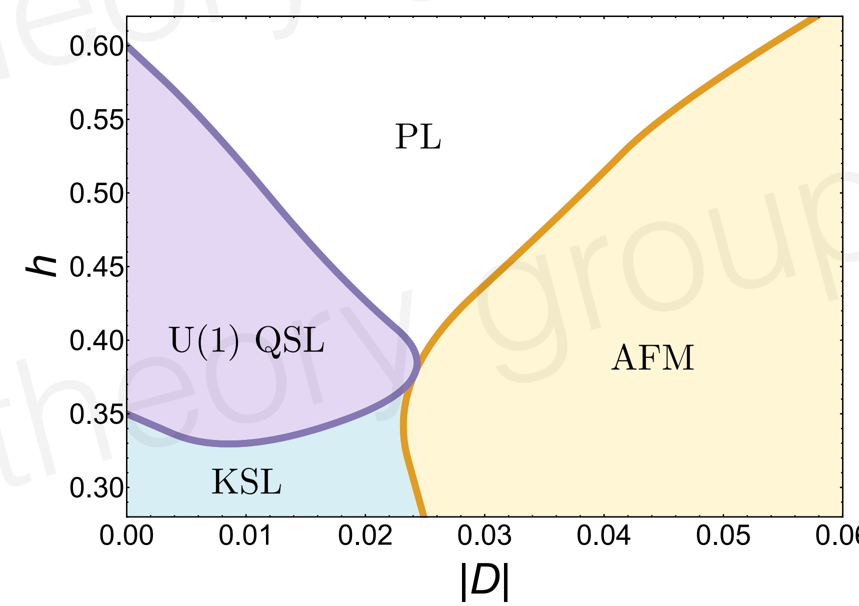
Thermal Hall signatures of non-Kitaev spin liquids in honeycomb Kitaev materials

Yong Hao Gao[1], Ciarán Hickey[2], Tao Xiang[3,4], Simon Trebst[2], and Gang Chen[5] PR research 2019



$$H = \sum_{\langle ij\rangle\in\gamma} K S_i^\gamma S_j^\gamma + \sum_{\langle\langle i,j\rangle\rangle} \boldsymbol{D}_{ij}\cdot\boldsymbol{S_i}\times\boldsymbol{S_j} - \sum_i \boldsymbol{h}_i\cdot\boldsymbol{S}_i. \quad (18)$$

In Fig. 6 we show the resulting phase diagram, with the U(1) spin liquid region stable up to a maximal Dzyaloshinskii-Moriya interaction of about $|\boldsymbol{D}| \sim 0.025K$. We should



C. Hickey and S. Trebst, Emergence of a field-driven U(1) spin liquid in the Kitaev honeycomb model, Nat. Commun. **10**, 530 (2019).
H.-C. Jiang, C.-Y. Wang, B. Huang, and Y.-M. Lu, Field induced quantum spin liquid with spinon Fermi surfaces in the Kitaev model, arXiv:1809.08247.
L. Zou and Y.-C. He, Field-induced neutral Fermi surface and QCD_3-Chern-Simons quantum criticalities in Kitaev materials, arXiv:1809.09091.

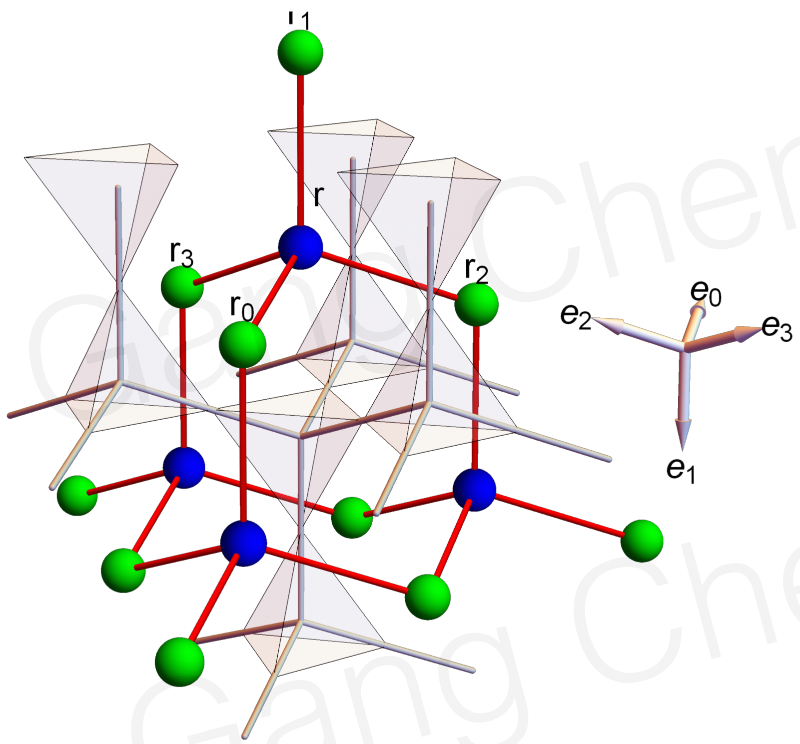
F Pollmann's group, Trivedi's group

With more generic interactions in RuCl3, can this state be realized in finite field ?

Xiao-Tian Zhang

Topological thermal Hall effect of "magnetic monopoles" in pyrochlore U(1) spin liquid

Xiao-Tian Zhang[1,4], Yong Hao Gao[2,4], Chunxiao Liu[3], and Gang Chen[4*]
International Center for Quantum Materials, Peking University, Beijing, 100871, China



arXiv 1904.08865

netic monopoles" and creates a TTHE in the system. The dual Hamiltonian for the "magnetic monopoles", that captures this effect, is given as

$$\mathcal{H}_{\text{dual}} = -t \sum_{\mathsf{rr}'} \Phi_{\mathsf{r}}^{\dagger} \Phi_{\mathsf{r}'} e^{-i2\pi a_{\mathsf{rr}'}} - \mu \sum_{\mathsf{r}} \Phi_{\mathsf{r}}^{\dagger} \Phi_{\mathsf{r}} + \sum_{rr'} \frac{U}{2} (\text{curl } a - \bar{E}_{rr'})^2 - K \sum_{\mathsf{rr}'} \cos B_{\mathsf{rr}'} \quad (1)$$

$$\mathcal{H}_{\text{Zeeman}} = - g\mu_B H_0 \sum_i (\hat{n} \cdot \hat{z}_i) \tau_i^z \simeq - g\mu_B H_0 \sum_i (\hat{n} \cdot \hat{z}_i) (\text{curl } a_{rr'} - \bar{E}_{rr'}),$$

Experiments by P Ong's group.
Science

Other recent works

arXiv:1812.08792

Thermal Hall effect in square-lattice spin liquids: a Schwinger boson mean-field study

Rhine Samajdar,[1] Shubhayu Chatterjee,[1,2] Subir Sachdev,[1,3] and Mathias S. Scheurer[1]

PHYSICAL REVIEW LETTERS **121,** 097203 (2018)

Spin Thermal Hall Conductivity of a Kagome Antiferromagnet

Hayato Doki,[1] Masatoshi Akazawa,[1] Hyun-Yong Lee,[1] Jung Hoon Han,[2] Kaori Sugii,[1] Masaaki Shimozawa,[1] Naoki Kawashima,[1] Migaku Oda,[3] Hiroyuki Yoshida,[3] and Minoru Yamashita[1,*]
[1]*The Institute for Solid State Physics, The University of Tokyo, Kashiwa, 277-8581, Japan*
[2]*Department of Physics, Sungkyunkwan University, Suwon 16419, Korea*
[3]*Department of Physics, Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan*

quantum antiferromagnets [2,3,7,8,49–53]. In the SBMFT framework, spin is expressed by a pair of bosons $(b_{i\uparrow}, b_{i\downarrow})$ as $\mathbf{S}_i = \frac{1}{2}\sum_{\alpha,\beta=\uparrow,\downarrow} b^\dagger_{i\alpha}\boldsymbol{\sigma}_{\alpha\beta}b_{i\beta}$, where $\boldsymbol{\sigma}$ is the Pauli matrices. We decouple the Hamiltonian by taking a mean-field value of the bond operator $\chi_{ij} = \langle b^\dagger_{i\sigma}b_{j\sigma}\rangle$ and diagonalize it to

They use Schwinger bosons, then do mean-field decoupling, obtain mean-field spinon Hamiltonian, and calculate the spinon thermal Hall contribution.

Summary 2

1. We point out the physical origin of emergent Lorentz force on spinons and obtain the resulting topological thermal Hall effects.

2. We establish the connection between microscopic interactions and emergent D.O.F. and thus provide a scheme to control the emergent D.O.F.

3. Our results can be extended to other non-centrosymmetric QSLs with with Dzyaloshinskii-Moriya interaction.

4. **Thermal transports in Mott insulators are not well understood.**