Fractionalization and its experimental consequences in spin liquids

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Outline

1. Signatures of fractionalization in U(1) spin liquid?

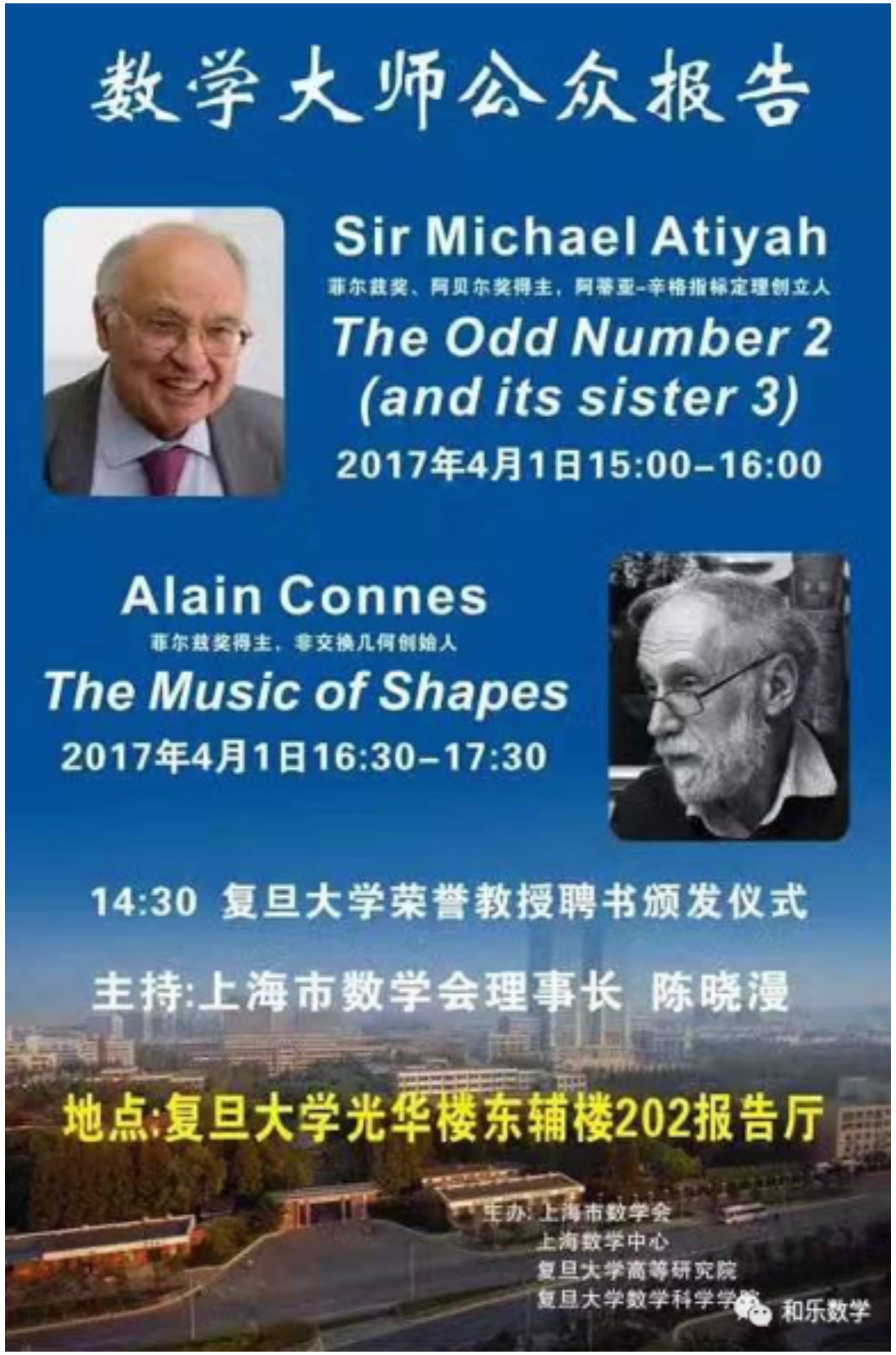
GC PRB 94,205107 (2016)
GC PRB 96,085136 (2017)
GC arxiv1706.04333(2017)

2. Spin quantum number fractionalization in YbMgGaO4?
Is it spinon Fermi surface spin liquid?

YD Li, XQ Wang, **GC***,	PRB 94, 035107 (2016)
YD Li, XQ Wang, **GC***,	PRB 94, 201114 (2016)
YD Li, Y Shen, YS Li, J Zhao, **GC***,	arXiv 1608.06445
YD Li, YM Lu, **GC***,	PRB 96, 054445 (2017)
YD Li, **GC***,	PRB 96, 075105 (2017)

YS Li, **GC***, .., QM Zhang*,	PRL 115, 167203 (2015)
Y Shen, YD Li, .., **GC***, J Zhao*,	Nature, 540, 559 (2016)
Y Shen, YD Li, .., **GC***, J Zhao*,	arXiv 1708.06655

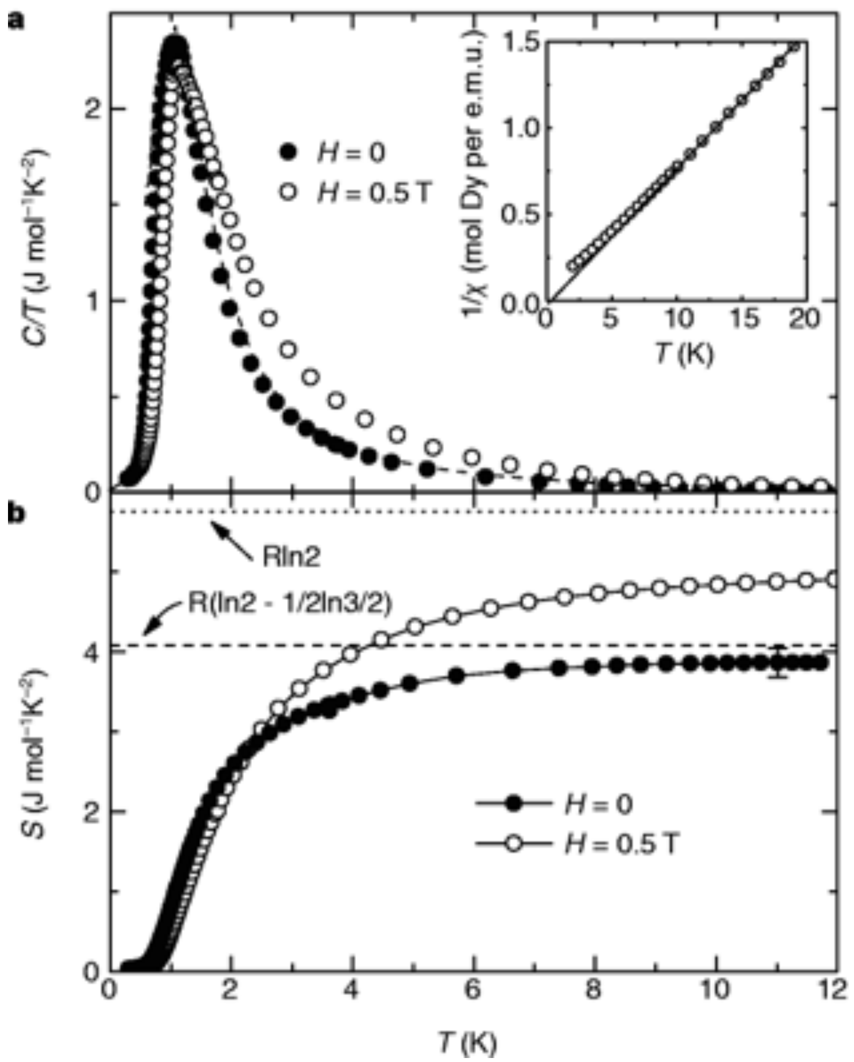
The odd number “2”



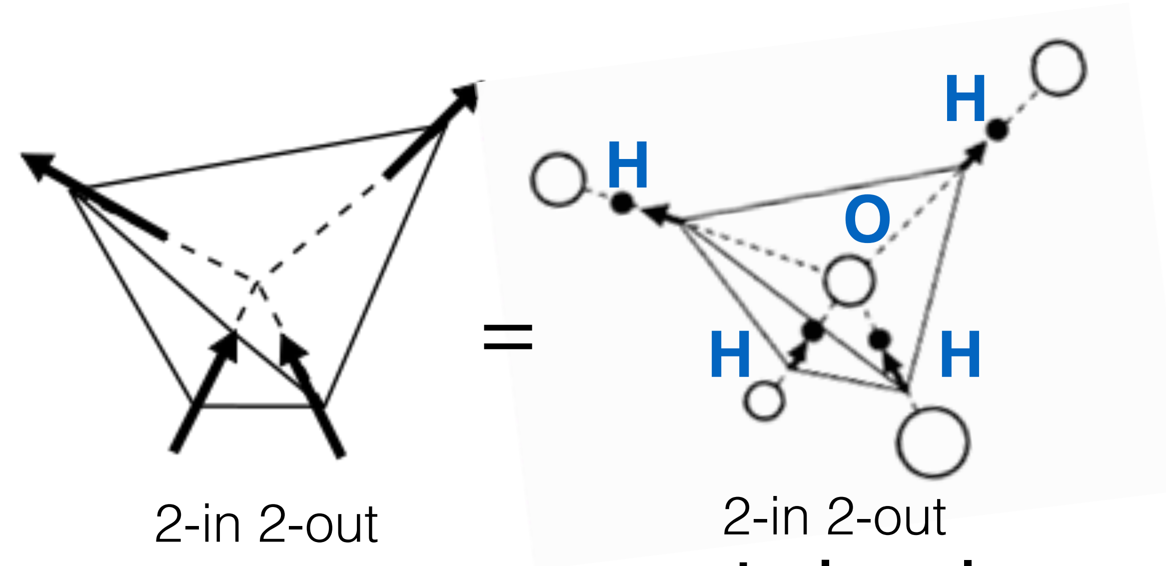
Chenjie Wang
(PI, Canada -> City University of Hong Kong, China)

Spin ice

$Dy_2Ti_2O_7$

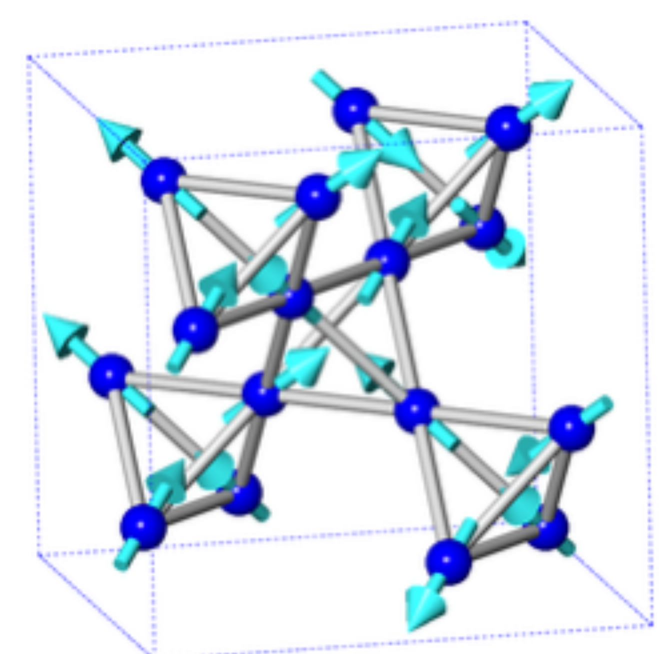


Pauling entropy in spin ice,
Ramirez, etc, Science 1999



2-in 2-out
spin ice rule

2-in 2-out
water ice rule



Lattice gauge theory for U(1) spin liquid

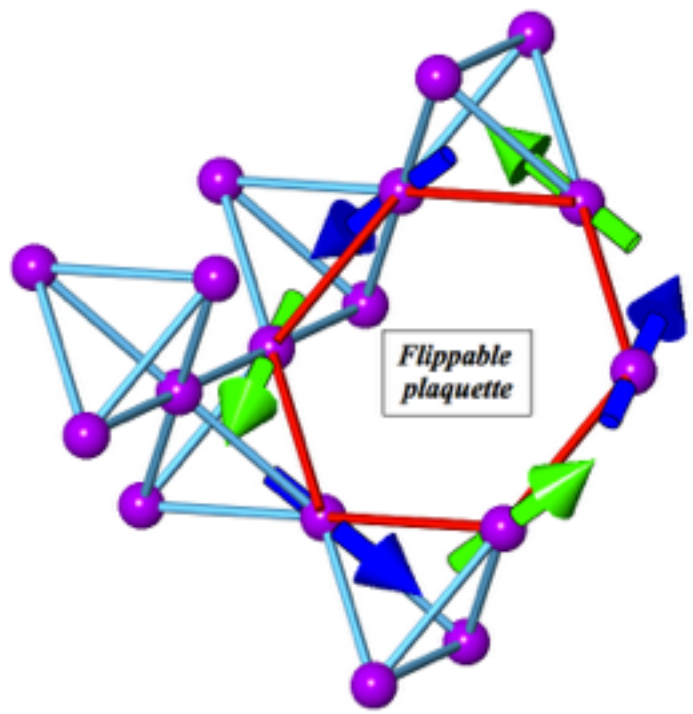


Figure from Michel Gingras

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

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

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

$$E_{\boldsymbol{rr'}} \simeq S^z_{\boldsymbol{rr'}}$$
$$e^{iA_{\boldsymbol{rr'}}} \simeq S^{\pm}_{\boldsymbol{rr'}}$$

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

Lattice gauge theory
on the diamond lattice

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

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

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

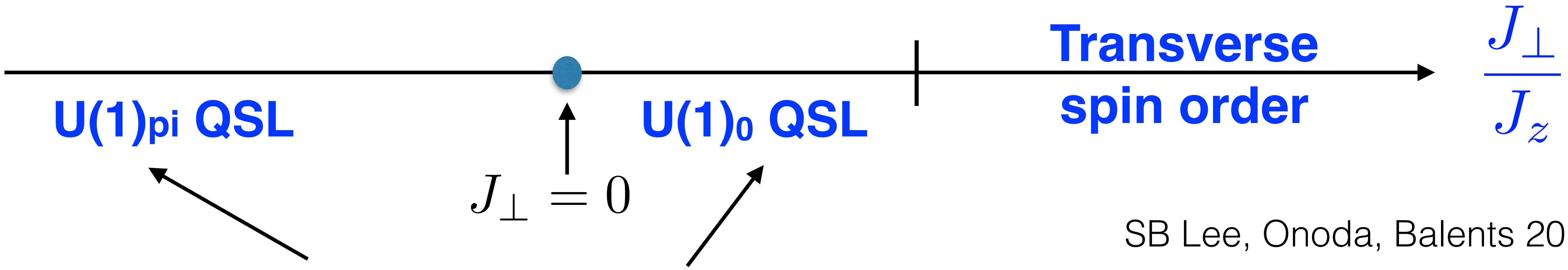
Y-P Huang, **GC**, M Hermele, PRL 2014
Y-D LI, **GC**, PRB 2017

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

no sign problem for QMC on any lattice.

It supports nontrivial phases

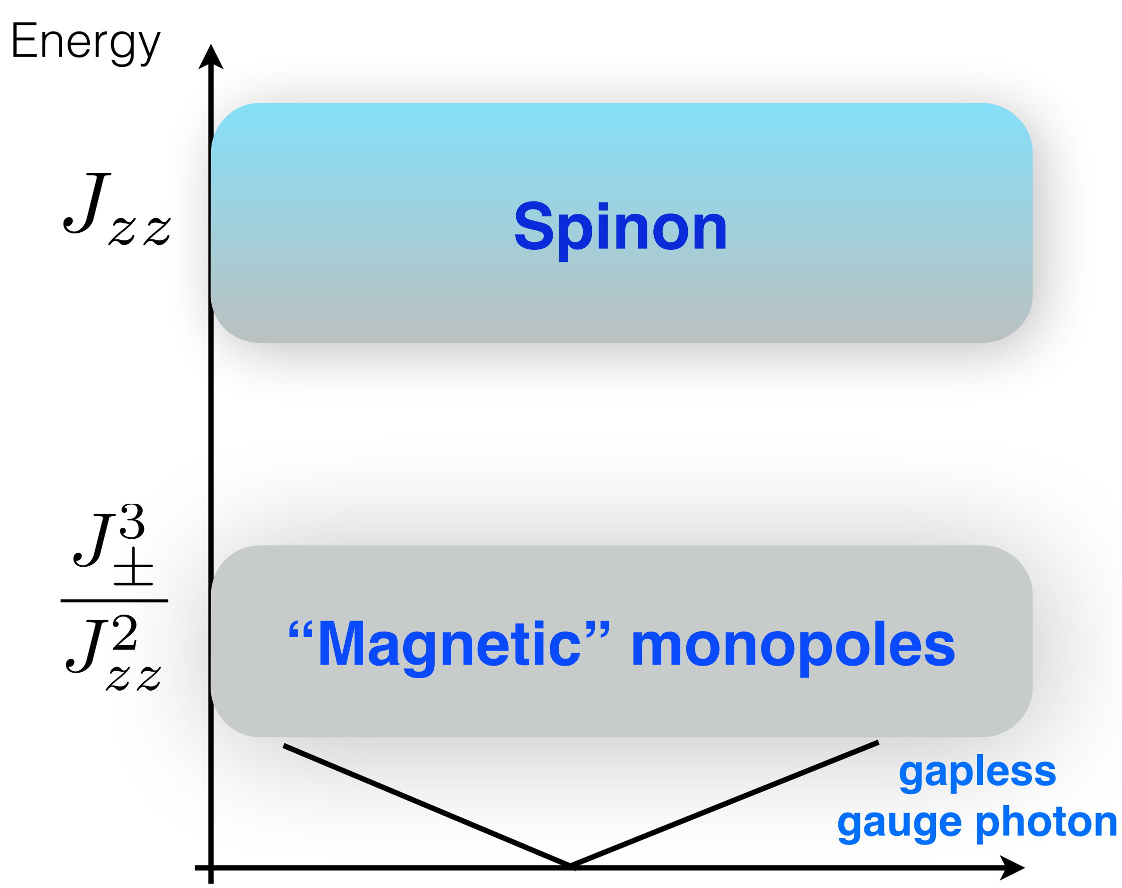
one may wonder if qsi exist in some physica

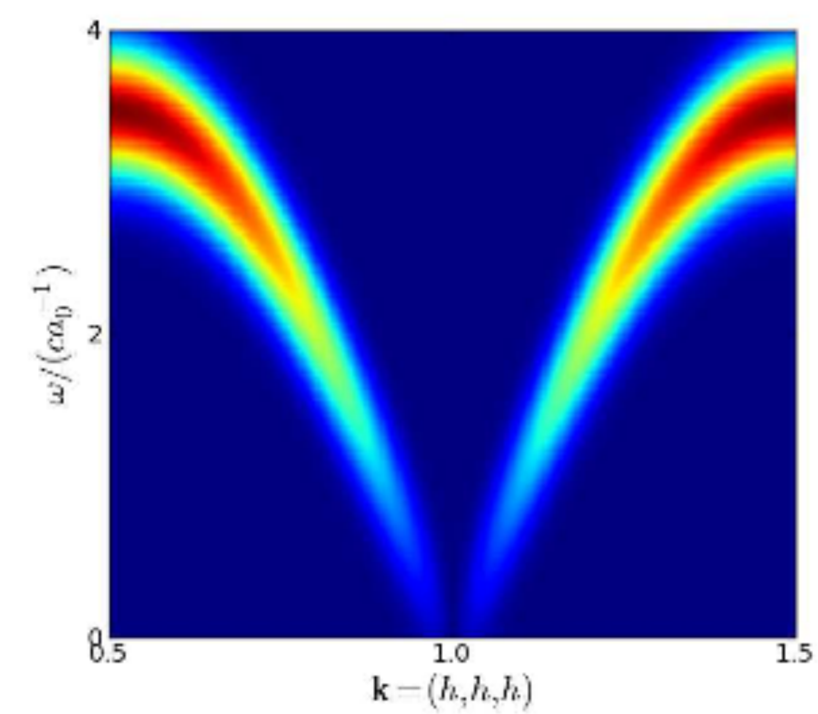


SB Lee, Onoda, Balents 2012

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?

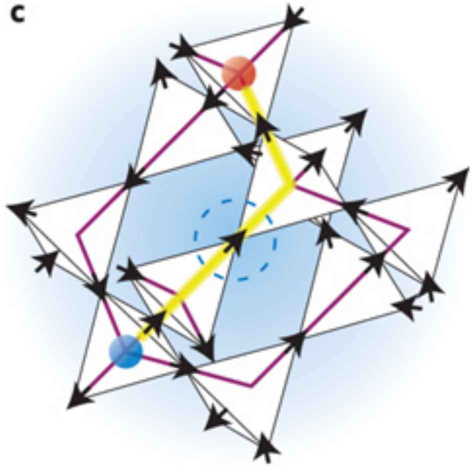




$I(\omega) \sim \omega$

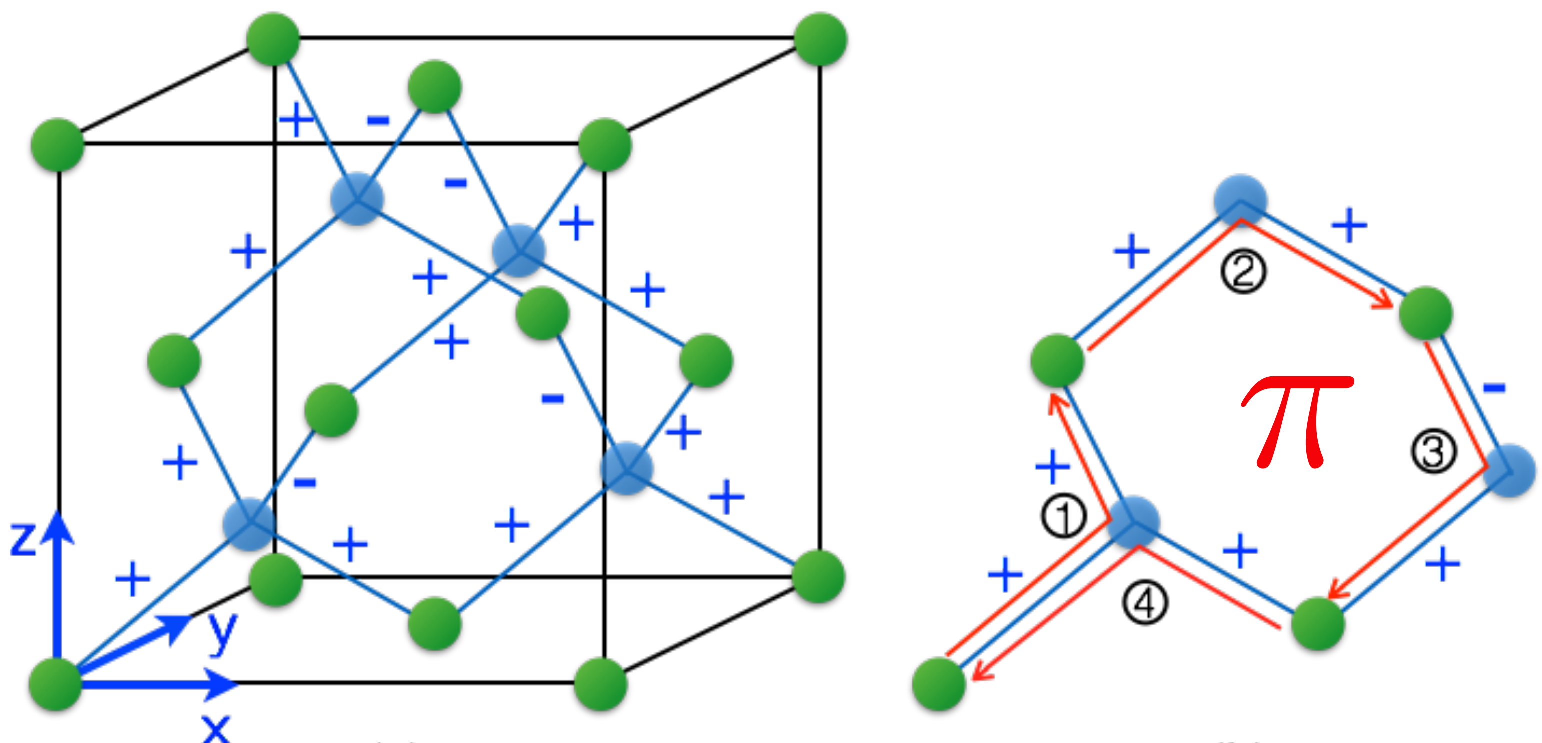
Nic Shannon, etc 2012, Savary, Balents, 2012

low energy scale suppressed intensity



Pi flux and the spinon translation

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



(a) (b)

If $K < 0, \ curl A = \pi$

If $K > 0, \ curl A = 0$

$$T^s_\mu T^s_\nu (T^s_\mu)^{-1} (T^s_\nu)^{-1} = \pm 1$$

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

Savary, Balents, 2012

Aharonov-Bohm flux experienced by spinon via the 4 translation
is identical to the flux in the hexagon.

Pi flux means crystal symmetry fractionalization

with definitive momentum
quantum number

It is like symmetry breaki

$$T^s_\mu T^s_\nu = -T^s_\nu T^s_\mu$$

2-spinon scattering state in an inelastic neutron scattering measurement

$$|a\rangle \equiv |\boldsymbol{q}_a; z_a\rangle,$$

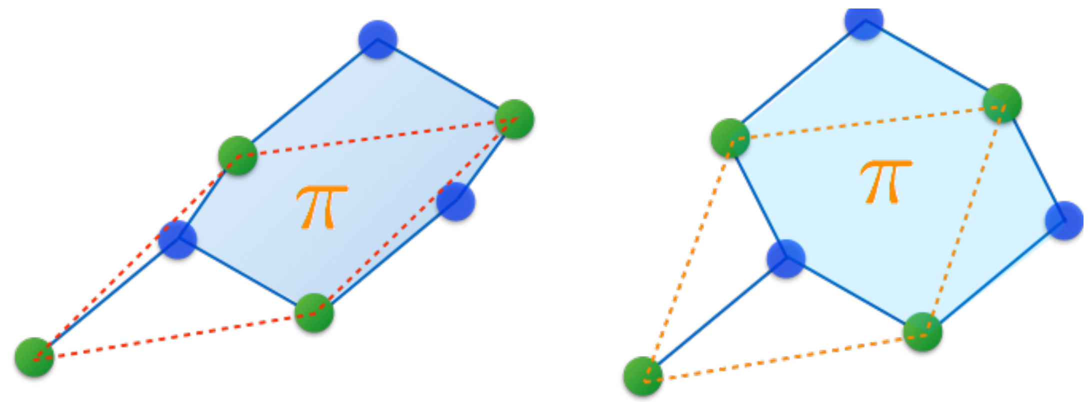
construct another 3 equal-energy states by translating one spinon by 3 lattice vector

$$|b\rangle = T^s_1(1)|a\rangle, \quad |c\rangle = T^s_2(1)|a\rangle, \quad |d\rangle = T^s_3(1)|a\rangle$$

$$\begin{aligned} T_1|b\rangle &= T^s_1(1)T^s_1(2)T^s_1(1)|a\rangle = +T^s_1(1)[T_1|a\rangle], \\ T_2|b\rangle &= T^s_2(1)T^s_2(2)T^s_1(1)|a\rangle = -T^s_1(1)[T_2|a\rangle], \\ T_3|b\rangle &= T^s_3(1)T^s_3(2)T^s_1(1)|a\rangle = -T^s_1(1)[T_3|a\rangle], \end{aligned} \Longrightarrow \mathbf{q}_b - \mathbf{q}_a = 2\pi(100)$$

Xiao-Gang Wen, 2001, 2002, Essin, Hermele, 2014
Gang Chen, 1704.02734

Spectral periodicity of the spinon continuum



Lower edge of 2-spinon continuum $$\mathcal{L}(\boldsymbol{q}) = \mathcal{L}(\boldsymbol{q} + 2\pi(100)) = \mathcal{L}(\boldsymbol{q} + 2\pi(010)) = \mathcal{L}(\boldsymbol{q} + 2\pi(001)),$$

Upper edge of 2-spinon continuum $$\mathcal{U}(\boldsymbol{q}) = \mathcal{U}(\boldsymbol{q} + 2\pi(100)) = \mathcal{U}(\boldsymbol{q} + 2\pi(010)) = \mathcal{U}(\boldsymbol{q} + 2\pi(001)).$$

But elastic neutron scattering will NOT see extra Bragg peak.

Xiao-Gang Wen, 2001, 2002, Essin, Hermele, 2014
Gang Chen, 1704.02734

Calculation to demonstrate the above prediction

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

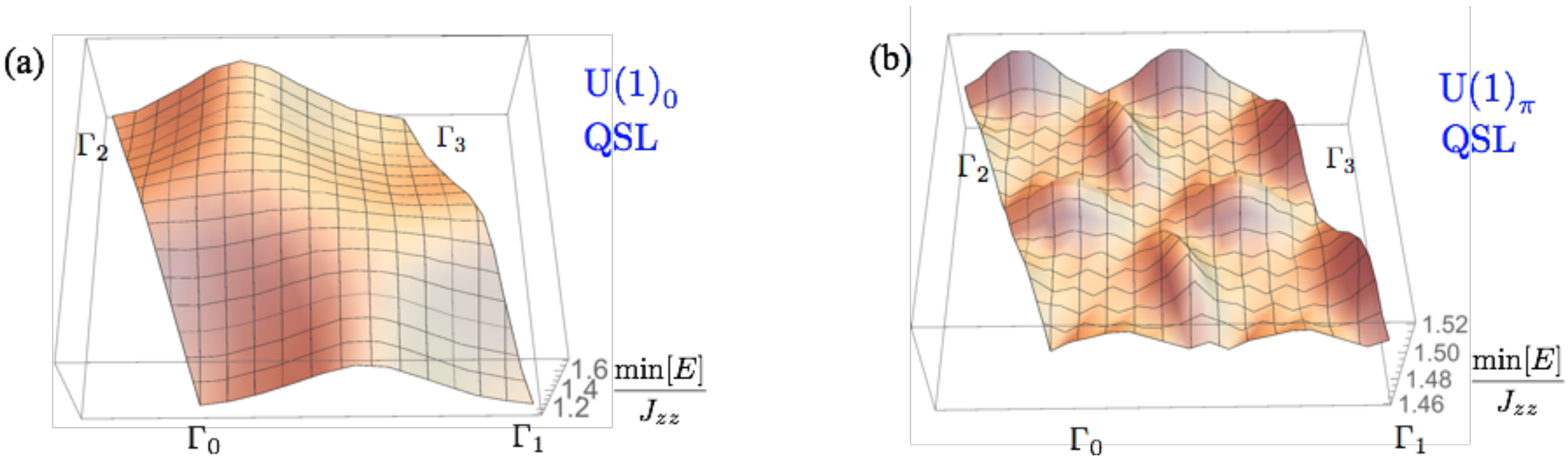
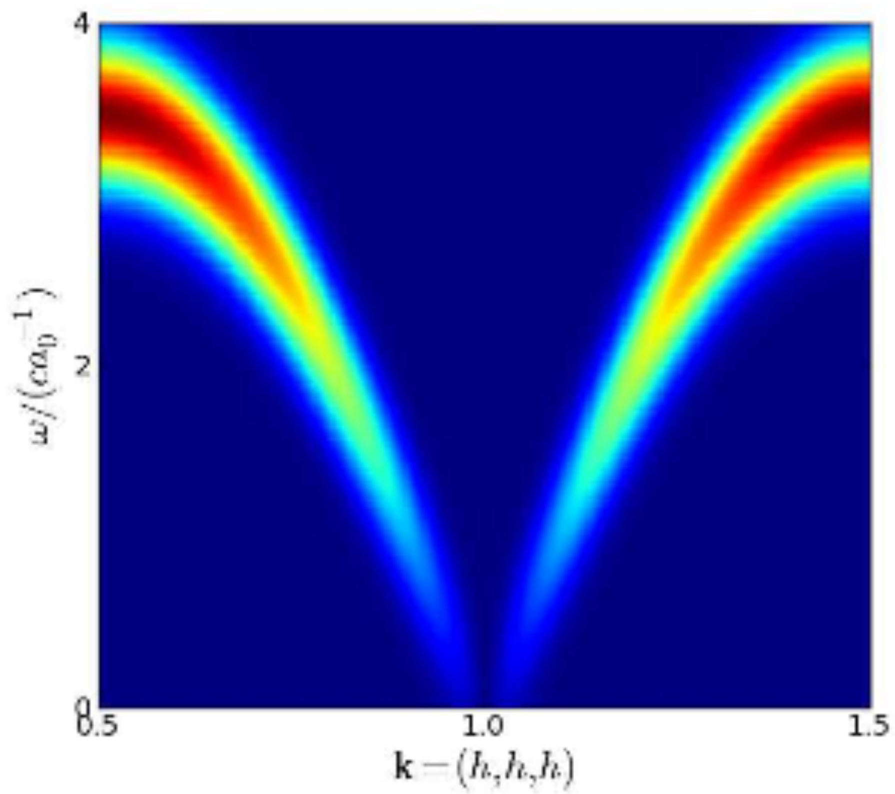
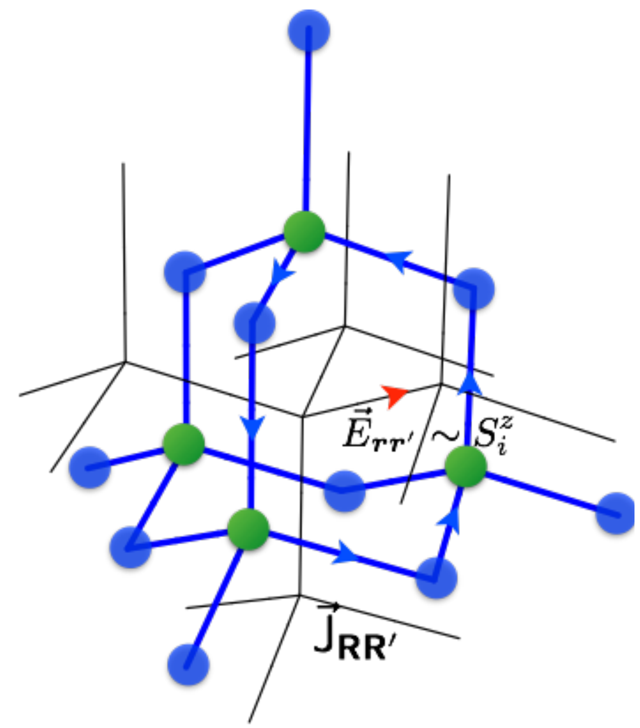


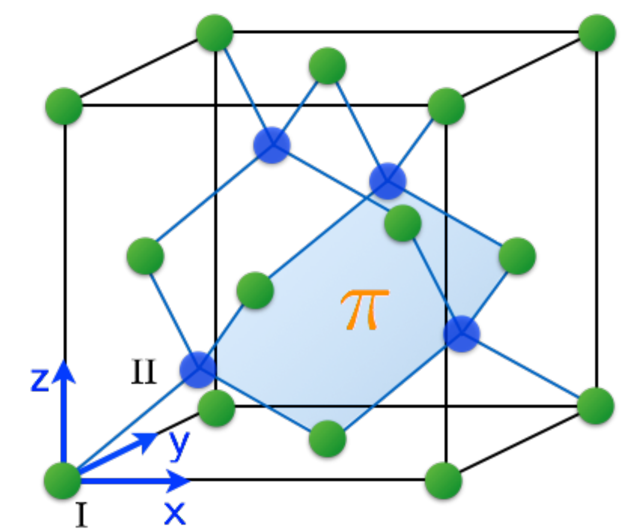
FIG. 3. (Color online.) The lower excitation edge of the spinon continuum in U(1)$_0$ and U(1)$_\pi$ QSLs. Here, $\Gamma_0\Gamma_1 = 2\pi(\bar{1}11), \Gamma_0\Gamma_2 = 2\pi(1\bar{1}1)$. We set $J_\perp = 0.12 J_{zz}$ for U(1)$_0$ QSL in (a) and $J_\perp = -J_{zz}/3$ for U(1)$_\pi$ QSL in (b).

Lower excitation edge of spinon continuum within the gauge MFT calculation

How to observe the “magnetic monopole”?







$S_z \sim E$ (emergent electric field)

$$\mathrm{Im}[E^{\alpha}_{-\mathbf{k},-\omega} E^{\beta}_{\mathbf{k},\omega}] \propto [\delta_{\alpha\beta} - \frac{k_\alpha k_\beta}{\mathbf{k}^2}]\,\omega\,\delta(\omega - v|\mathbf{k}|),$$

Low energy theory

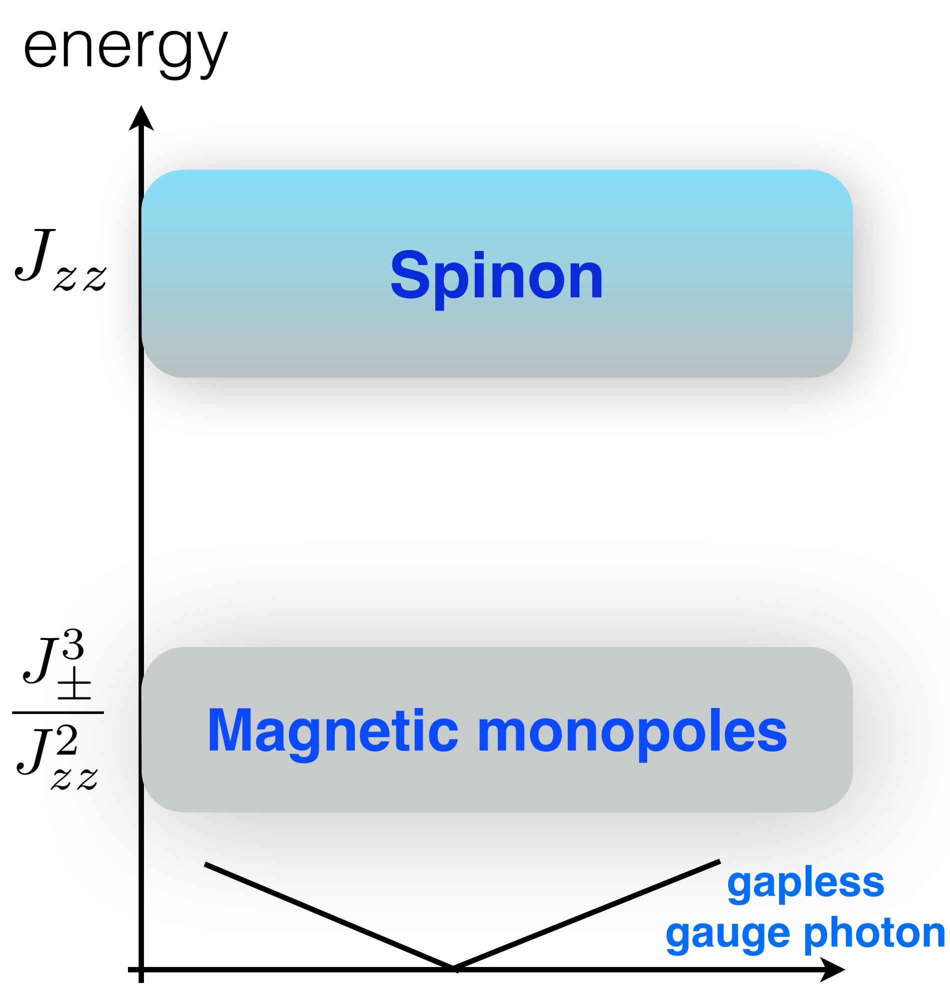
Electromagnetic duality

Electric loop current -> Magnetic field
Magnetic loop current -> Electric field

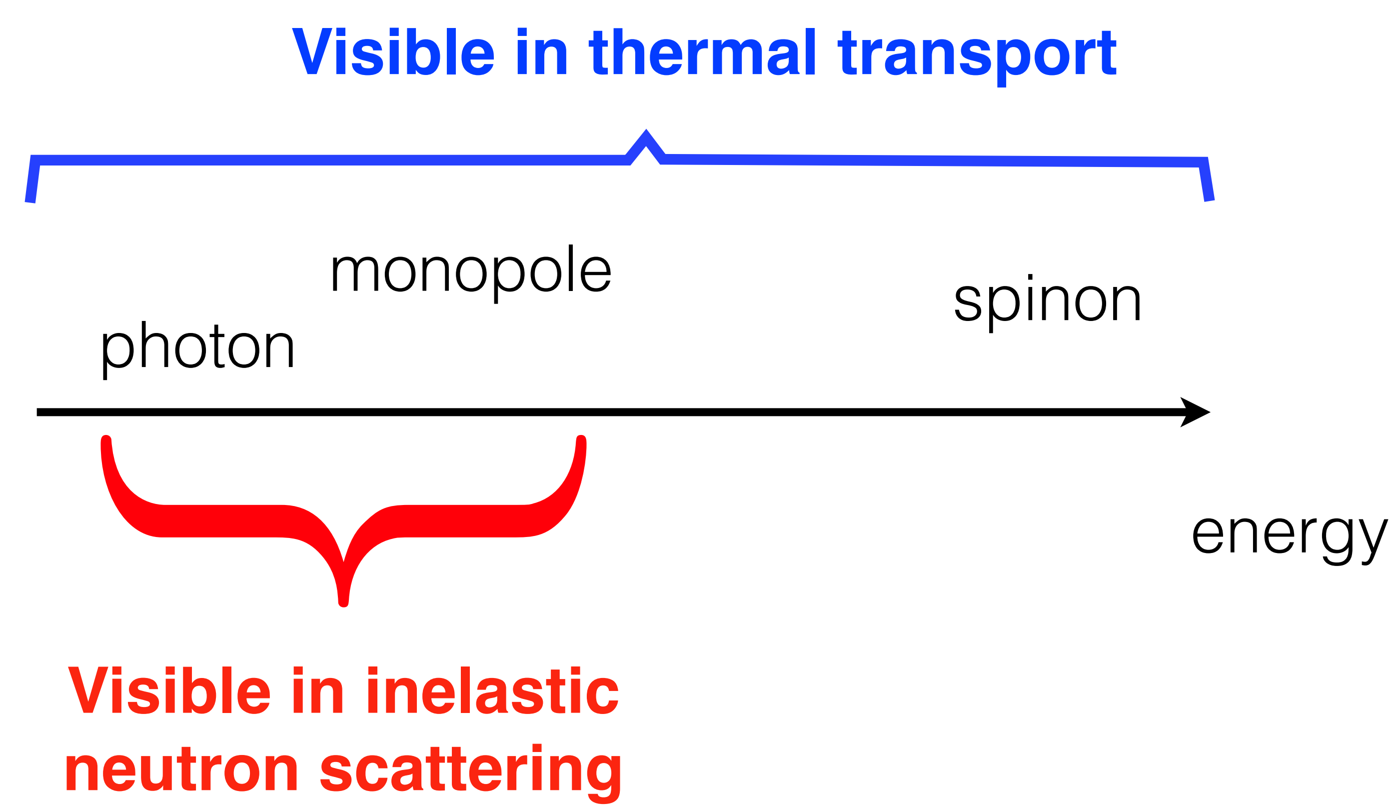
at higher energy, detect monopole continuum

Gang Chen, arXiv 1706.04333 (2017)

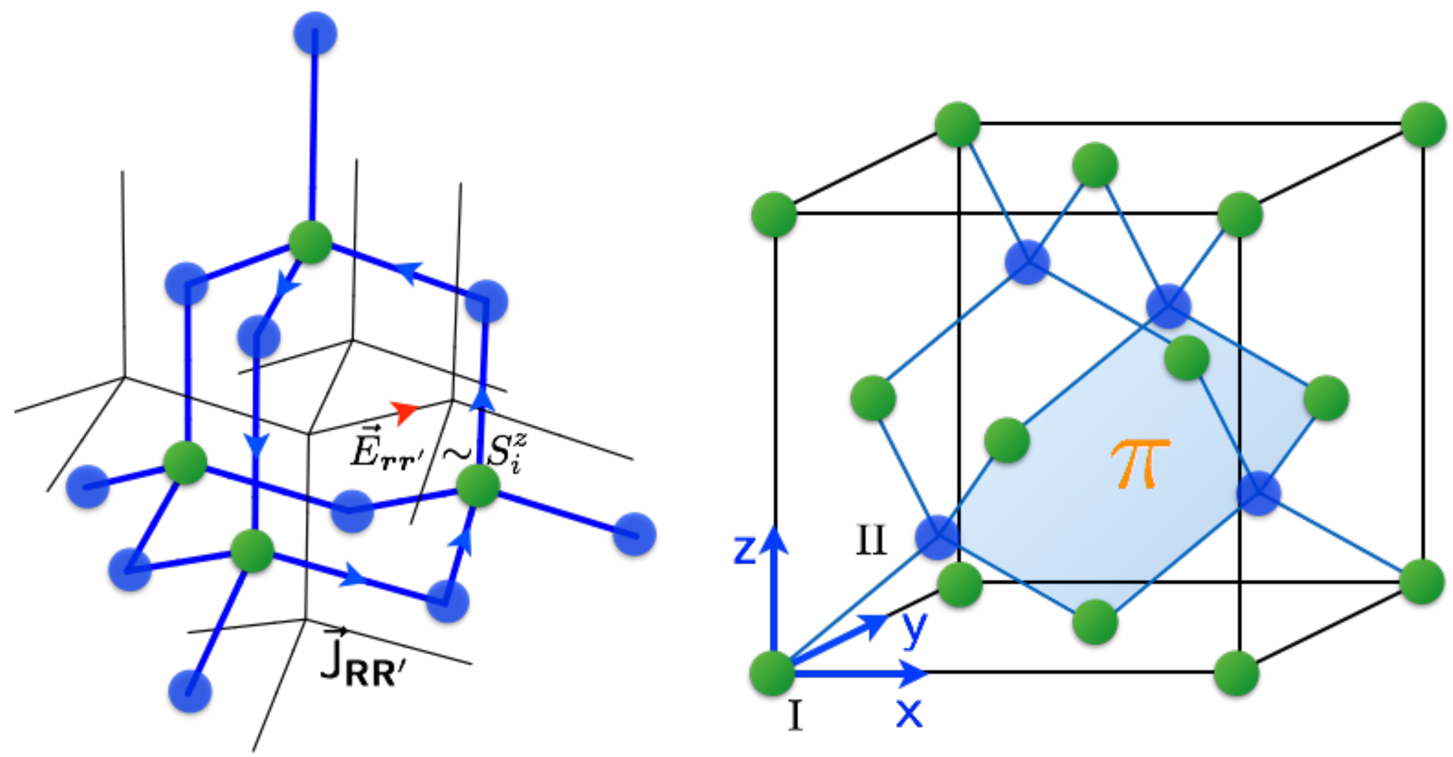
Suggestion 1: combine thermal transport with inelastic neutron



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



Suggestion 2: effect of the external magnetic field



(a) (b)

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

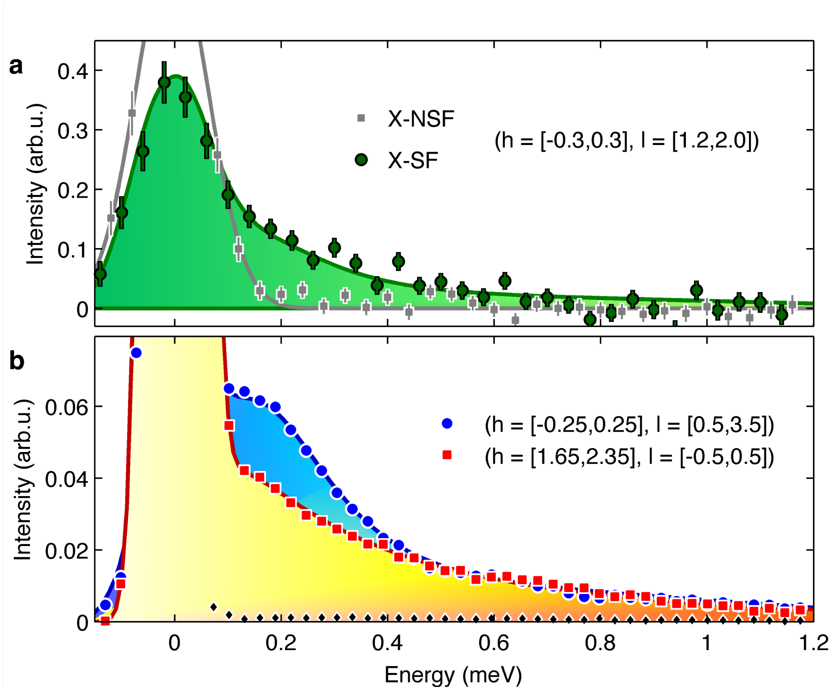
The weak magnetic field polarizes Sz slightly, and thus modifies the background electric field distribution. This further modulates monopole band structure, creating "**Hofstadter**" monopole band, which may be detectable in inelastic neutron.

Summary 1

1. We point out the existence of “magnetic monopole continuum” in the U(1) quantum spin liquid, and monopole is purely **quantum origin**.

2. We point out that the “magnetic monopole” always experiences a Pi flux, and thus supports enhanced spectral periodicity with **folded Brillouin zone, while** spinons most of the time experience Pi flux**.**

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



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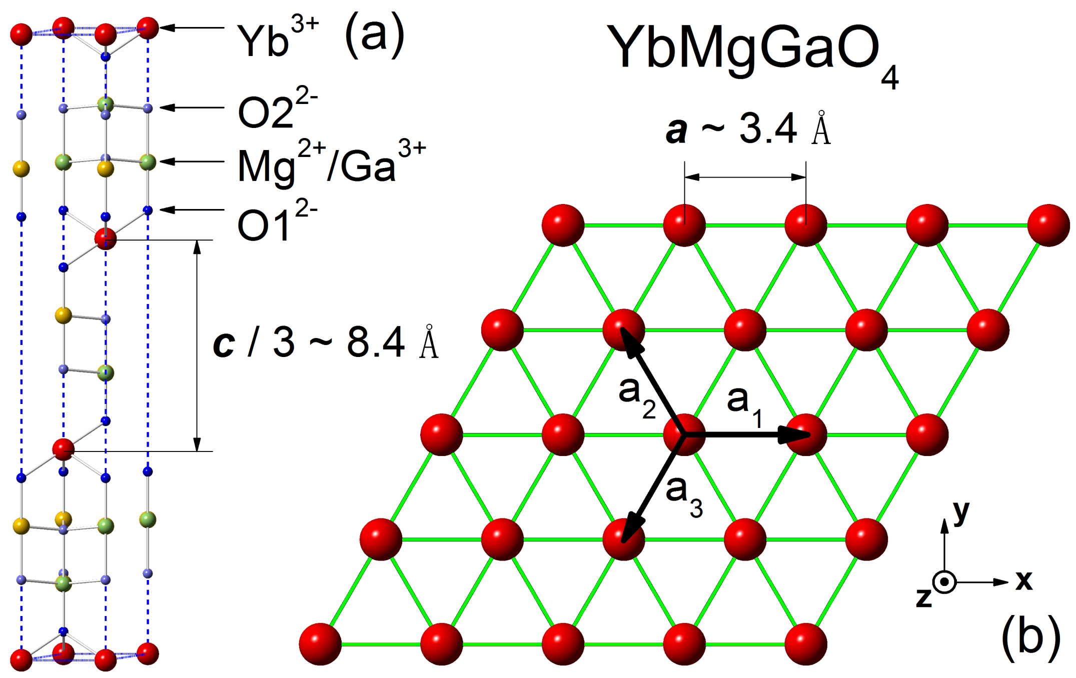
Y Shen, YD Li, .., **GC***, J Zhao*,	arXiv 1708.06655

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

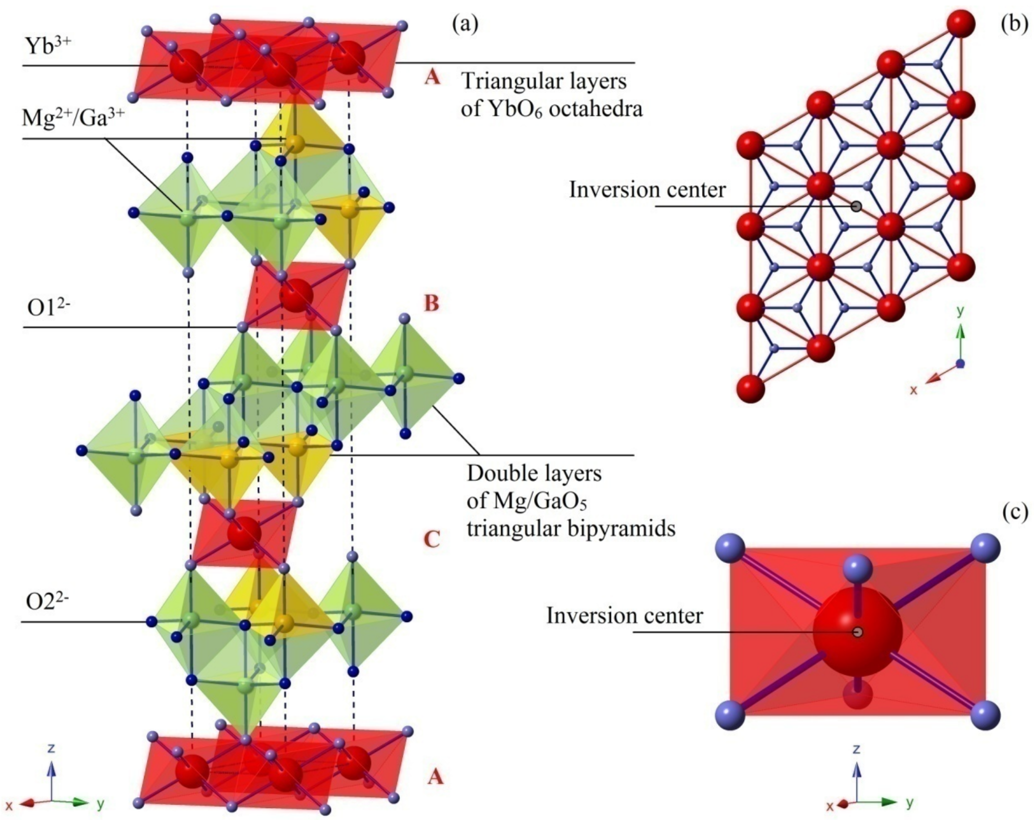


Qingming Zhang (Renmin)

Yuesheng Li (Renmin)

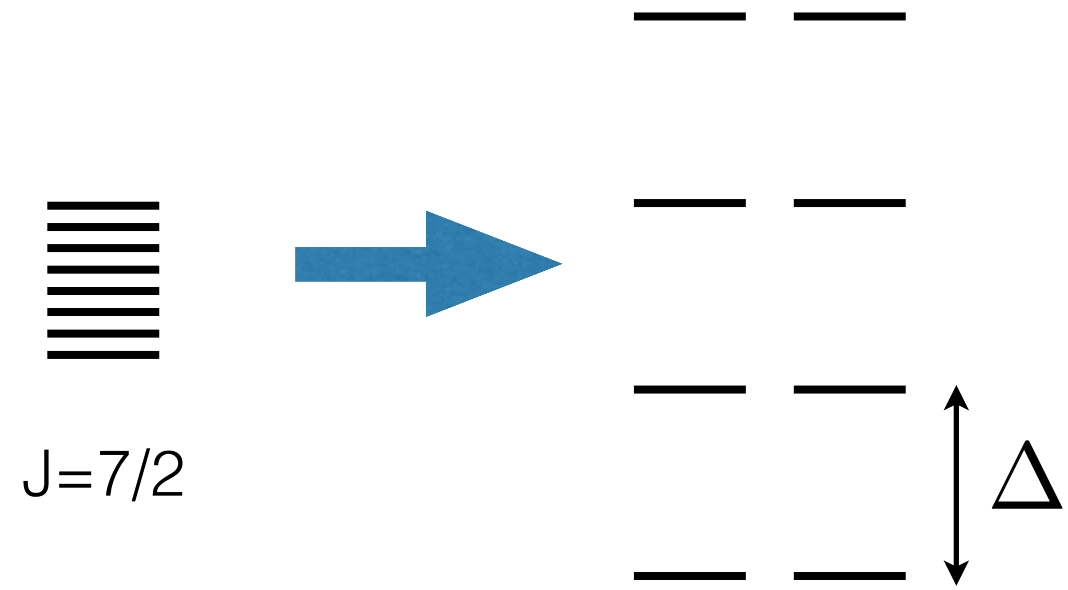
- Hastings-Oshikawa-Lieb-Shultz-Mattis theorem.
- Recent extension to spin-orbit coupled insulators (Watanabe, Po, Vishwanath, Zaletel, PNAS 2015).
- This is likely the **first strong spin-orbit coupled QSL with odd electron filling** and effective spin-1/2.
- It is the first clear observation of $T^{2/3}$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

The microscopics



YS Li, …QM Zhang, Srep 2015

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

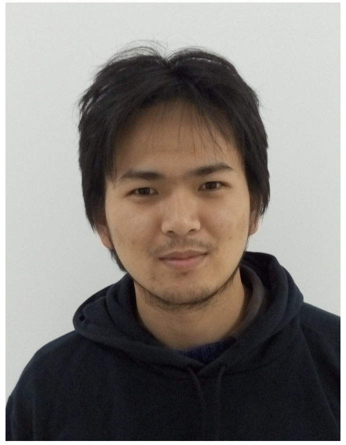


YS Li, **GC**, …, QM Zhang, PRL 2015
YD Li, XQ Wang, **GC**, arXiv1512, PRB 2016

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

Modeling

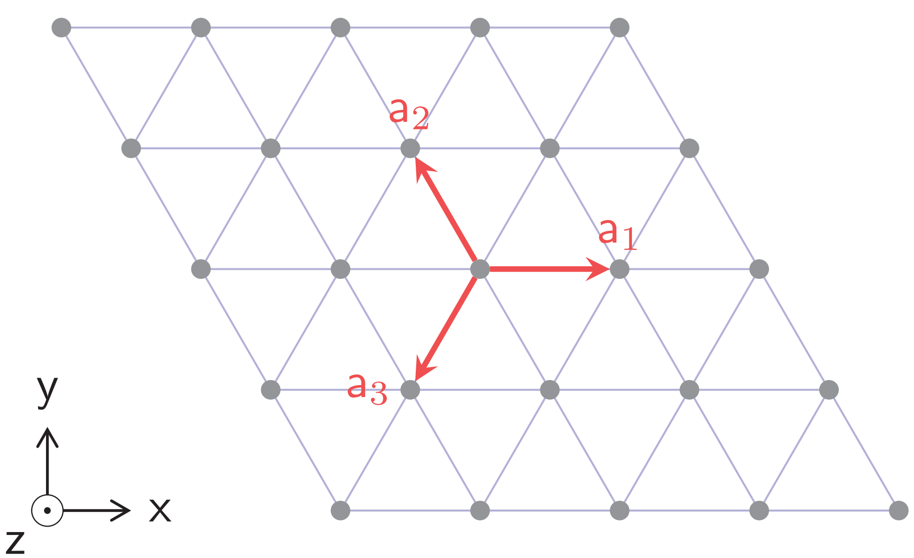
4f electron is very localized, and
dipolar interactions weak.



Yao-Dong Li
(Fudan -> here)

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

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-



anisotropic both in spin space and in real space !

YD Li, XQ Wang, GC, arXiv1512, PRB 2016
YD Li, Y Shen, YS Li, J Zhao, GC*, arXiv 1608.06445

DMRG: Chernyshev, White, 2017
Jize Zhao, XQ Wang, 2017

Polarized neutron scattering

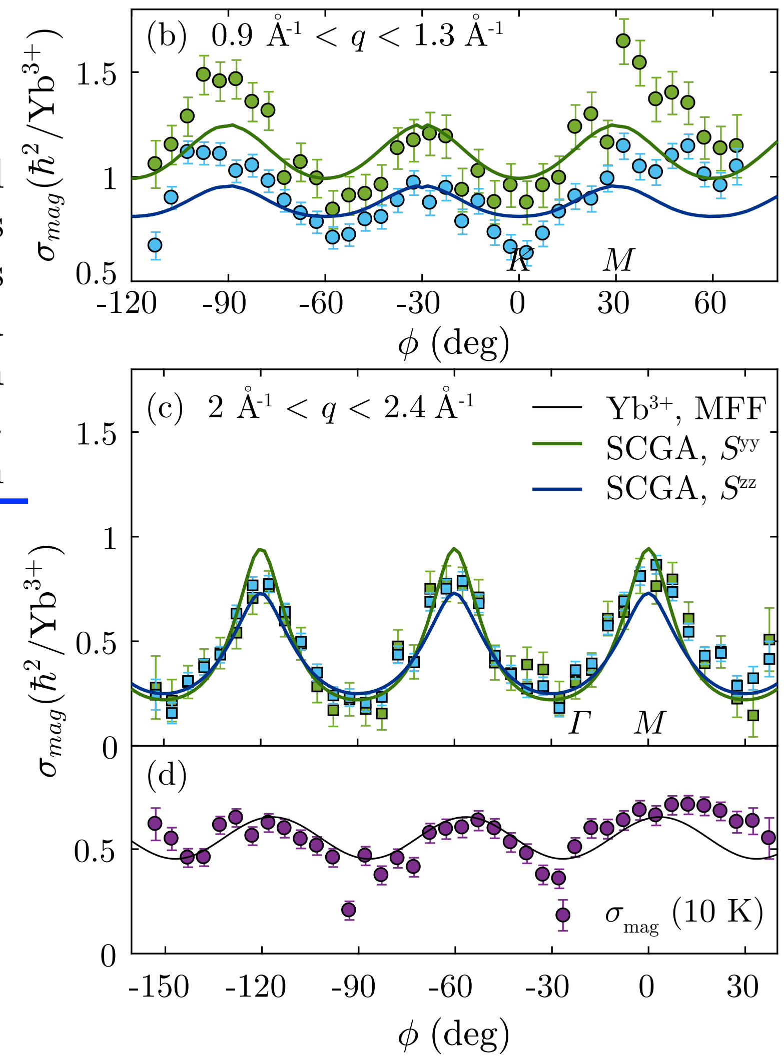
Strong exchange anisotropy in $YbMgGaO_4$ from polarized neutron diffraction

Sándor Tóth,[1,*] Katharina Rolfs,[2] Andrew R. Wildes,[3] and Christian Rüegg[1,4]

[1] *Laboratory for Neutron Scattering and Imaging, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland*
[2] *Laboratory for Scientific Developments and Novel Materials, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland*
[3] *Institut Max von Laue-Paul Langevin, 38042 Grenoble 9, France*
[4] *Department of Quantum Matter Physics, University of Geneva, 1211 Genève, Switzerland*

(Dated: May 17, 2017)

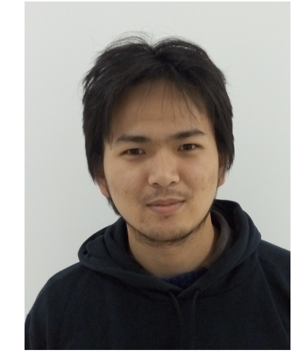
We measured the magnetic correlations in the triangular lattice spin-liquid candidate material $YbMgGaO_4$ via polarized neutron diffraction. The extracted in-plane and out-of-plane components of the magnetic structure factor show clear anisotropy. We found that short-range correlations persist at the lowest measured temperature of 52 mK and neutron scattering intensity is centered at the M middle-point of the hexagonal Brillouin-zone edge. Moreover, we found pronounced spin anisotropy, with different correlation lengths for the in-plane and out-of-plane spin components. When comparing to a self-consistent Gaussian appoximation, our data clearly support a model with only first-neighbor coupling and strongly anisotropic exchanges.



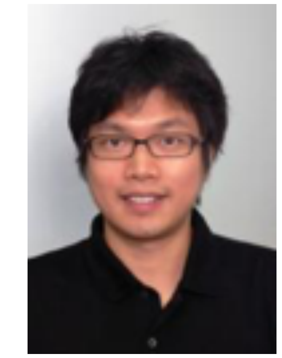
arXiv 1705.05699

Inelastic neutron scattering

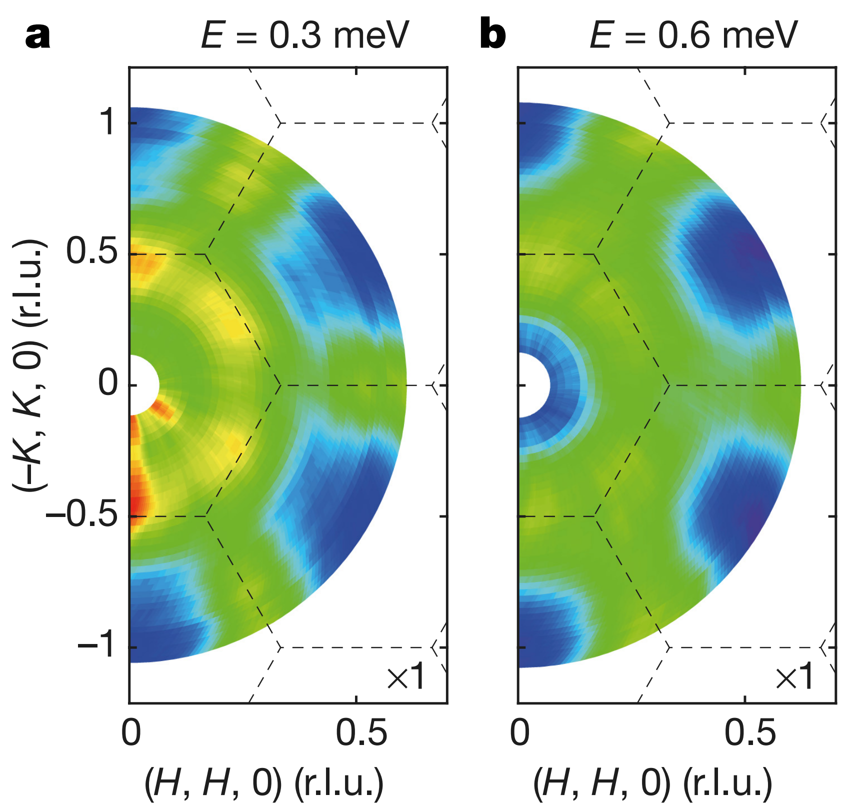
Yao Shen
(Fudan)

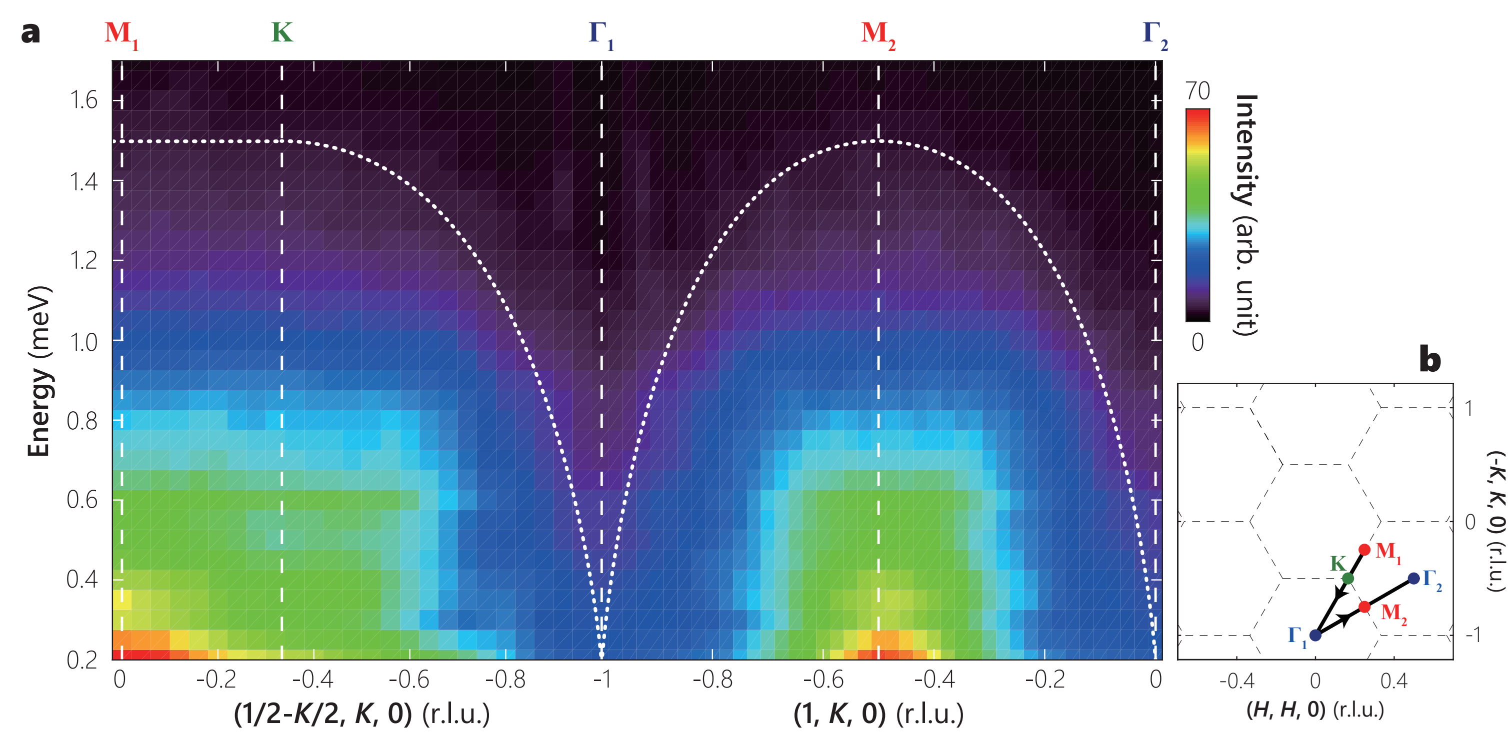


Yao-Dong Li
(Fudan->here)



Jun Zhao
(Fudan)

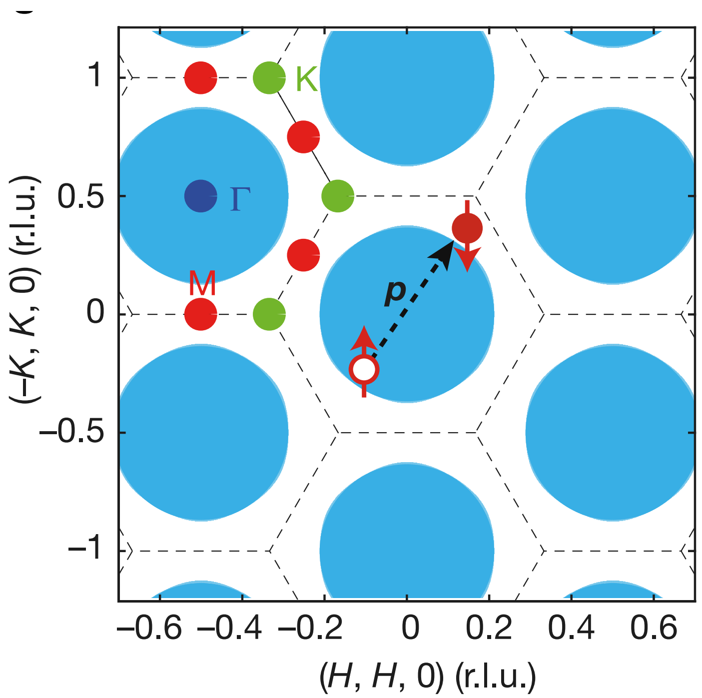


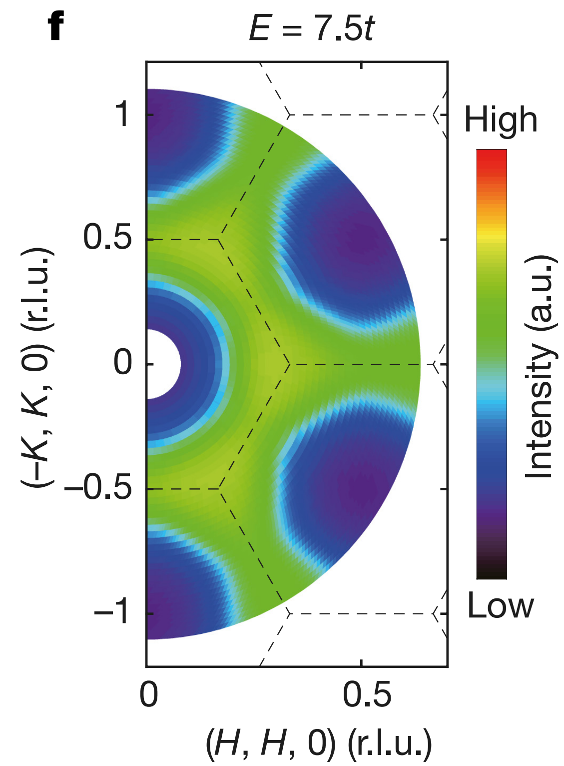


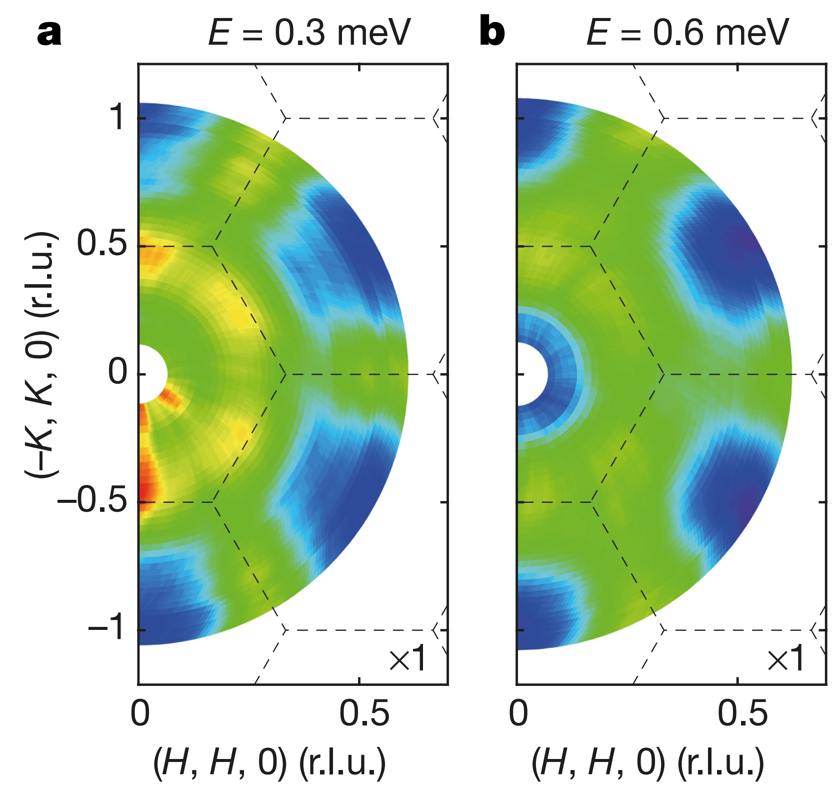
Y Shen, YD Li …GC*, J Zhao* **Nature** 2016

consistent neutron results from Martin Mourigal's group, Nature Physics

Spinon Fermi surface state





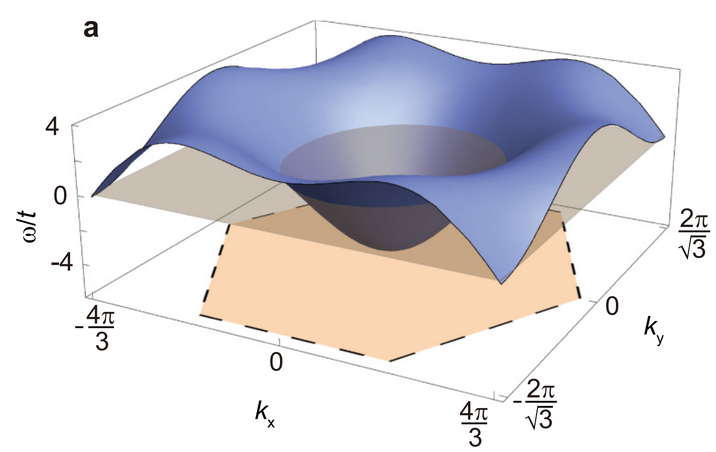


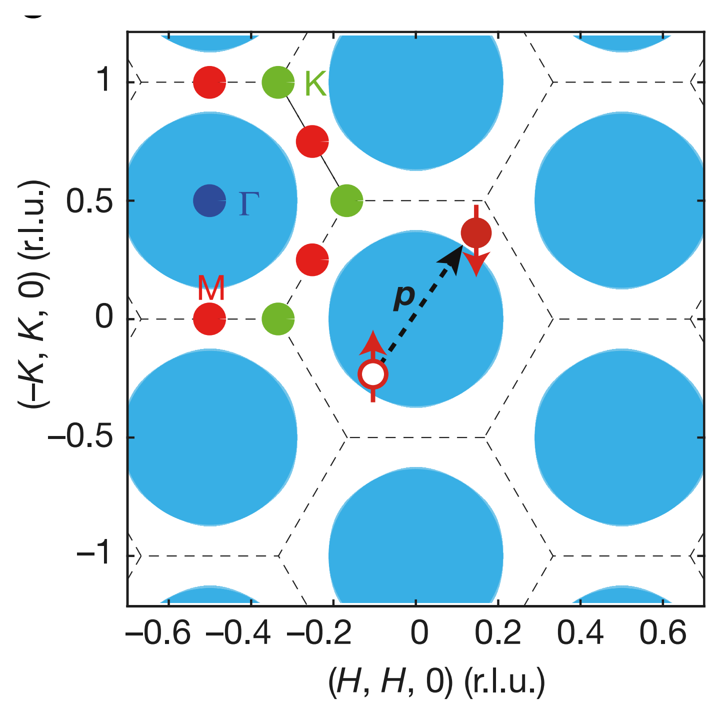
$$\boldsymbol{S}_{\boldsymbol{r}} = \frac{1}{2}\sum_{\alpha,\beta} f^{\dagger}_{\boldsymbol{r}\alpha}\boldsymbol{\sigma}_{\alpha\beta} f_{\boldsymbol{r}\beta}, \qquad H_{\mathrm{MFT}} = -\,t\sum_{\langle ij\rangle}(f^{\dagger}_{i\alpha} f_{j\alpha} + \mathrm{h.c.}) - \mu\sum_{i} f^{\dagger}_{i\alpha} f_{i\alpha}$$

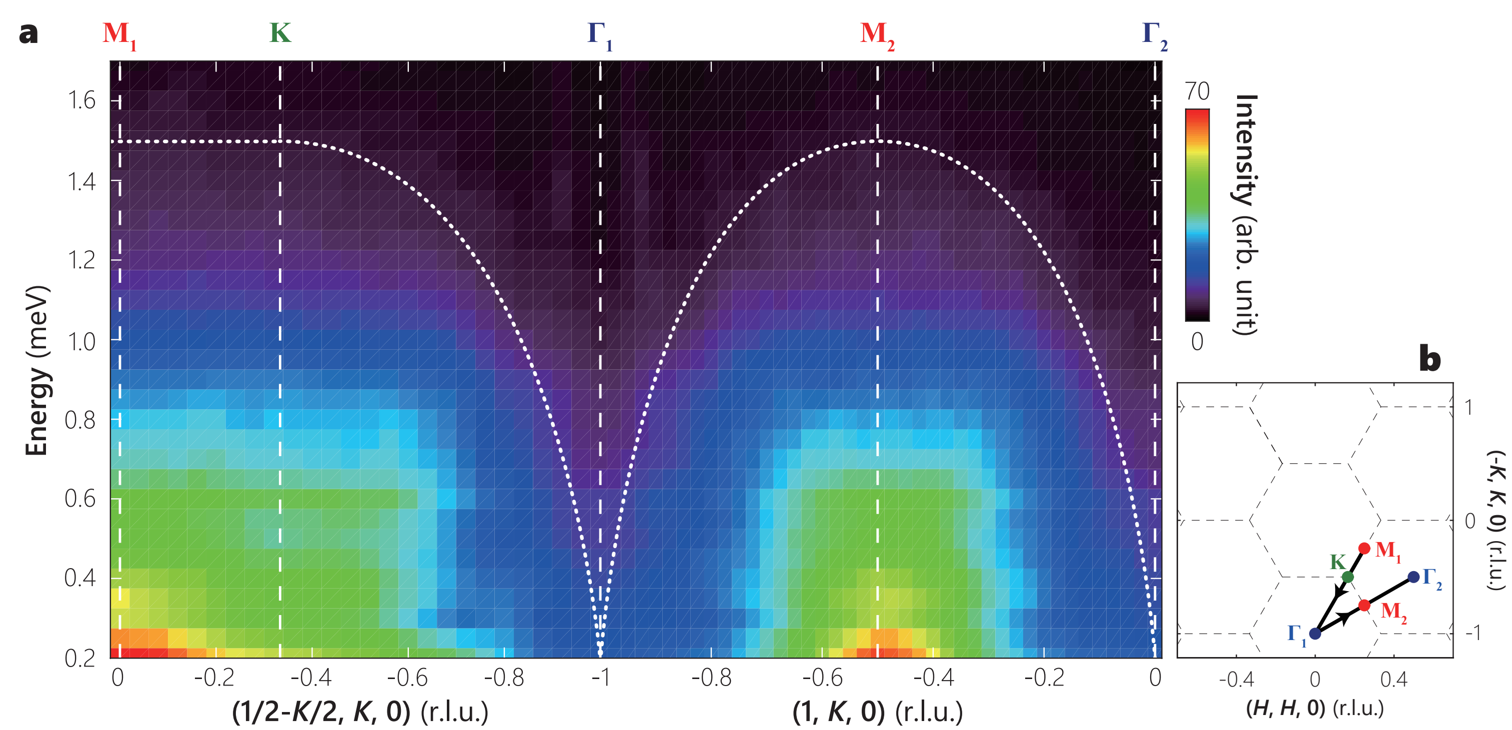
Prediction from the 0 flux uniform spinon hopping

Y Shen, YD Li …GC*, J Zhao* **Nature** 2016

Particle-hole continuum of the spinon Fermi surface

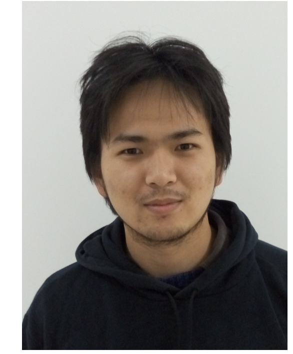






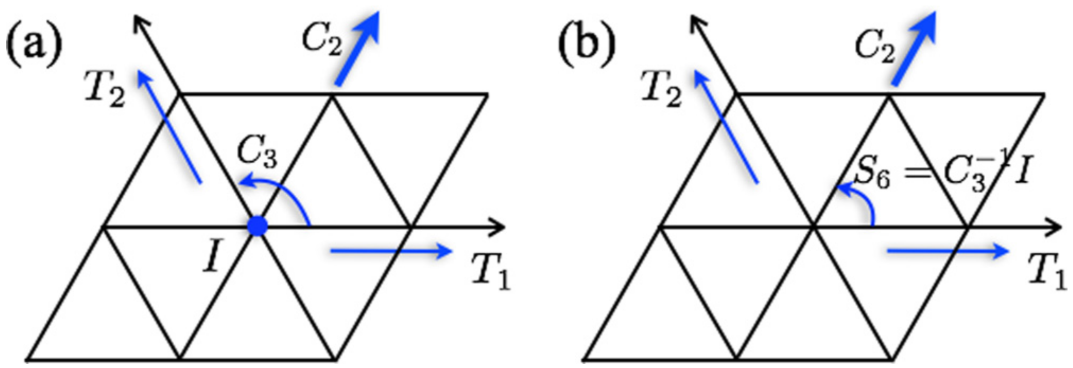
Y Shen, YD Li **...GC*, J Zhao*** **Nature** 2016

More assurance from projective symmetry group analysis



Yao-Dong Li (Fudan->UCSB)

Yuan-Ming Lu (OSU)



$$T_1^{-1} T_2 T_1 T_2^{-1} = T_1^{-1} T_2^{-1} T_1 T_2 = 1,$$

$$C_2^{-1} T_1 C_2 T_2^{-1} = C_2^{-1} T_2 C_2 T_1^{-1} = 1,$$

$$S_6^{-1} T_1 S_6 T_2 = S_6^{-1} T_2 S_6 T_2^{-1} T_1^{-1} = 1,$$

$$(C_2)^2 = (S_6)^6 = (S_6 C_2)^2 = 1.$$

YD Li, XQ Wang, **GC**,
arXiv1512, PRB 2016

YD Li, YM Lu, GC,
arXiv **1612.03447**, PRB

$$\boldsymbol{S}_{\boldsymbol{r}} = \frac{1}{2} \sum_{\alpha,\beta} f_{\boldsymbol{r}\alpha}^{\dagger} \boldsymbol{\sigma}_{\alpha\beta} f_{\boldsymbol{r}\beta},$$

$$\Psi_{\boldsymbol{r}} = (f_{\boldsymbol{r}\uparrow}, f_{\boldsymbol{r}\downarrow}^{\dagger}, f_{\boldsymbol{r}\downarrow}, -f_{\boldsymbol{r}\uparrow}^{\dagger})^T$$

$$\boldsymbol{S}_{\boldsymbol{r}} = \frac{1}{4} \Psi_{\boldsymbol{r}}^{\dagger} (\boldsymbol{\sigma} \otimes I_{2\times 2}) \Psi_{\boldsymbol{r}},$$

$$\boldsymbol{G}_{\boldsymbol{r}} = \frac{1}{4} \Psi_{\boldsymbol{r}}^{\dagger} (I_{2\times 2} \otimes \boldsymbol{\sigma}) \Psi_{\boldsymbol{r}},$$

$$[S_{\boldsymbol{r}}^{\mu}, G_{\boldsymbol{r}}^{\nu}] = 0.$$

The spin transformation and gauge transformation commute with each other.

XG Wen PRB 2002

Reduction and simplification: classification mean field states

Mean-field model
$$H_{\mathrm{MF}} = -\frac{1}{2}\sum_{(\boldsymbol{r},\boldsymbol{r}')}\left[\Psi_{\boldsymbol{r}}^{\dagger}u_{\boldsymbol{r}\boldsymbol{r}'}\Psi_{\boldsymbol{r}'} + h.c.\right],$$
$$\Psi_{\boldsymbol{r}} = (f_{\boldsymbol{r}\uparrow}, f_{\boldsymbol{r}\downarrow}^{\dagger}, f_{\boldsymbol{r}\downarrow}, -f_{\boldsymbol{r}\uparrow}^{\dagger})^T$$

symmetry transformation $\mathcal{O}$
$$u_{\boldsymbol{r}\boldsymbol{r}'} = \mathcal{G}_{\mathcal{O}(\boldsymbol{r})}^{\mathcal{O}\dagger}\mathcal{U}_{\mathcal{O}}^{\dagger}u_{\mathcal{O}(\boldsymbol{r})\mathcal{O}(\boldsymbol{r}')}\mathcal{U}_{\mathcal{O}}\mathcal{G}_{\mathcal{O}(\boldsymbol{r}')}^{\mathcal{O}}.$$

spin rotation

gauge rotation

group relation $\mathcal{O}_1\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4 = 1$
$$\begin{aligned}&\mathcal{U}_{\mathcal{O}_1}\mathcal{G}_{\boldsymbol{r}}^{\mathcal{O}_1}\mathcal{U}_{\mathcal{O}_2}\mathcal{G}_{\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_2}\mathcal{U}_{\mathcal{O}_3}\mathcal{G}_{\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_3}\mathcal{U}_{\mathcal{O}_4}\mathcal{G}_{\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_4}\\ =&\mathcal{U}_{\mathcal{O}_1}\mathcal{U}_{\mathcal{O}_2}\mathcal{U}_{\mathcal{O}_3}\mathcal{U}_{\mathcal{O}_4}\mathcal{G}_{\boldsymbol{r}}^{\mathcal{O}_1}\mathcal{G}_{\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_2}\mathcal{G}_{\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_3}\mathcal{G}_{\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_4}\\ \in&\ \mathrm{IGG},\end{aligned}$$

$$\mathcal{U}_{\mathcal{O}_1}\mathcal{U}_{\mathcal{O}_2}\mathcal{U}_{\mathcal{O}_3}\mathcal{U}_{\mathcal{O}_4} = \pm I_{4\times 4}, \qquad \{\pm I_{4\times 4}\}\subset \mathrm{IGG}$$

$$\mathcal{G}_{\boldsymbol{r}}^{\mathcal{O}_1}\mathcal{G}_{\mathcal{O}_2\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_2}\mathcal{G}_{\mathcal{O}_3\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_3}\mathcal{G}_{\mathcal{O}_4(\boldsymbol{r})}^{\mathcal{O}_4} \in \mathrm{IGG}$$

square lattice by J Alicea’s group 2014

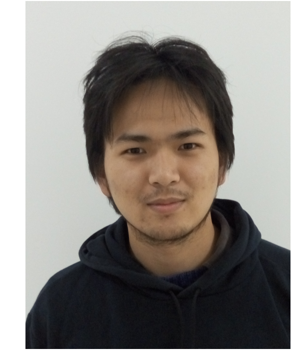
Projective symmetry group classification

U(1) QSL	$W_{\boldsymbol{r}}^{T_1}$	$W_{\boldsymbol{r}}^{T_2}$	$W_{\boldsymbol{r}}^{C_2}$	$W_{\boldsymbol{r}}^{C_6}$
U1A00	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$
U1A10	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$	$I_{2\times2}$
U1A01	$I_{2\times2}$	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$
U1A11	$I_{2\times2}$	$I_{2\times2}$	$i\sigma^y$	$i\sigma^y$
U1B00	$I_{2\times2}$	$(-1)^x I_{2\times2}$	$(-1)^{xy} I_{2\times2}$	$(-1)^{xy-\frac{y(y-1)}{2}} I_{2\times2}$
U1B10	$I_{2\times2}$	$(-1)^x I_{2\times2}$	$i\sigma^y(-1)^{xy}$	$(-1)^{xy-\frac{y(y-1)}{2}} I_{2\times2}$
U1B01	$I_{2\times2}$	$(-1)^x I_{2\times2}$	$(-1)^{xy} I_{2\times2}$	$i\sigma^y(-1)^{xy-\frac{y(y-1)}{2}}$
U1B11	$I_{2\times2}$	$(-1)^x I_{2\times2}$	$i\sigma^y(-1)^{xy}$	$i\sigma^y(-1)^{xy-\frac{y(y-1)}{2}}$

TABLE III. The transformation for the spinons under four U1A PSGs that are labeled by U1A$n_{C_2} n_{S_6}$.

U(1) PSGs	T_1	T_2	C_2	S_6
U1A00	$f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow}$	$f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f_{(y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{i\frac{5\pi}{6}} f_{(y,x),\uparrow}$	$f_{(x,y),\uparrow} \to e^{-i\frac{\pi}{3}} f_{(x-y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f_{(x-y,x),\downarrow}$
U1A10	$f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow}$	$f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f^{\dagger}_{(y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{-i\frac{\pi}{6}} f^{\dagger}_{(y,x),\downarrow}$	$f_{(x,y),\uparrow} \to e^{-i\frac{\pi}{3}} f_{(x-y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f_{(x-y,x),\downarrow}$
U1A01	$f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow}$	$f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f_{(y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{i\frac{5\pi}{6}} f_{(y,x),\uparrow}$	$f_{(x,y),\uparrow} \to -e^{-i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\uparrow}$
U1A11	$f_{(x,y),\uparrow} \to f_{(x+1,y),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x+1,y),\downarrow}$	$f_{(x,y),\uparrow} \to f_{(x,y+1),\uparrow}$ $f_{(x,y),\downarrow} \to f_{(x,y+1),\downarrow}$	$f_{(x,y),\uparrow} \to e^{i\frac{\pi}{6}} f^{\downarrow\dagger}_{(y,x),\uparrow}$ $f_{(x,y),\downarrow} \to e^{-i\frac{\pi}{6}} f^{\downarrow\dagger}_{(y,x),\downarrow}$	$f_{(x,y),\uparrow} \to -e^{-i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\downarrow}$ $f_{(x,y),\downarrow} \to e^{+i\frac{\pi}{3}} f^{\dagger}_{(x-y,x),\uparrow}$

Spectroscopic constraints

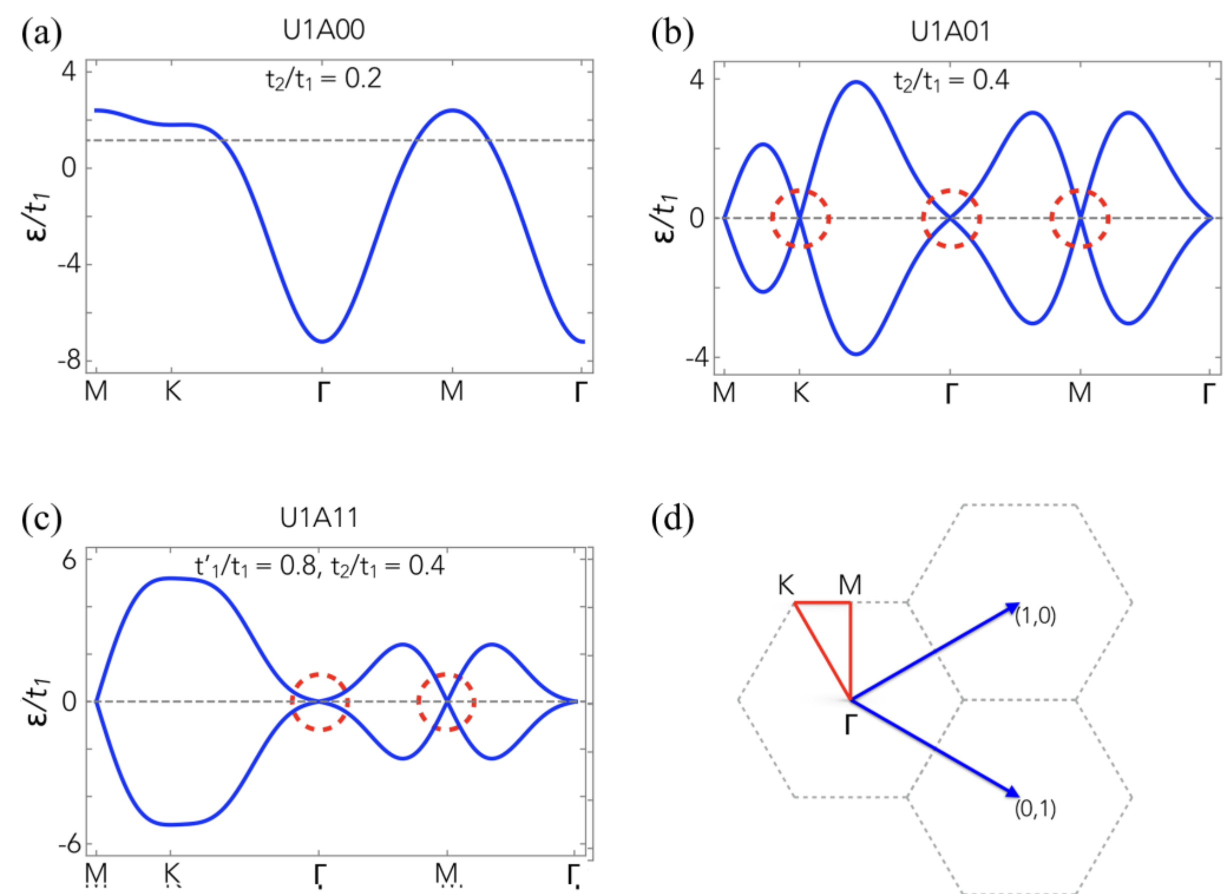


We use PSG to predict the corresponding spectrum.

Yao-Dong Li

$$H_{\rm MF} = -\sum_{(\boldsymbol{r}\boldsymbol{r}')}\sum_{\alpha\beta}\big[t_{\boldsymbol{r}\boldsymbol{r}',\alpha\beta} f^{\dagger}_{\boldsymbol{r}\alpha} f_{\boldsymbol{r}'\beta} + h.c.\big],$$

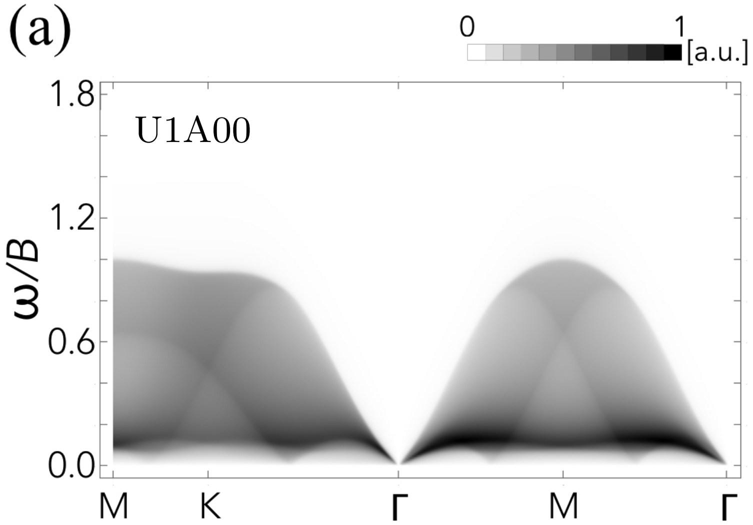
U(1) QSL	$W_{\boldsymbol{r}}^{T_1}$	$W_{\boldsymbol{r}}^{T_2}$	$W_{\boldsymbol{r}}^{C_2}$	$W_{\boldsymbol{r}}^{C_6}$
U1A00	$I_{2\times 2}$	$I_{2\times 2}$	$I_{2\times 2}$	$I_{2\times 2}$
U1A10	$I_{2\times 2}$	$I_{2\times 2}$	$i\sigma^y$	$I_{2\times 2}$
U1A01	$I_{2\times 2}$	$I_{2\times 2}$	$I_{2\times 2}$	$i\sigma^y$
U1A11	$I_{2\times 2}$	$I_{2\times 2}$	$i\sigma^y$	$i\sigma^y$



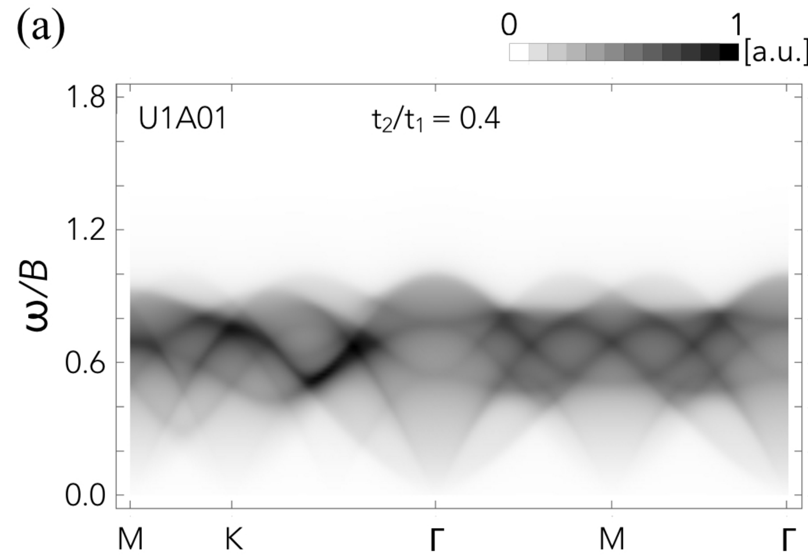
The U1A00 state is the spinon Fermi surface state
that we proposed in Shen, et al, Nature.

VMC study has been done bty Balents' group

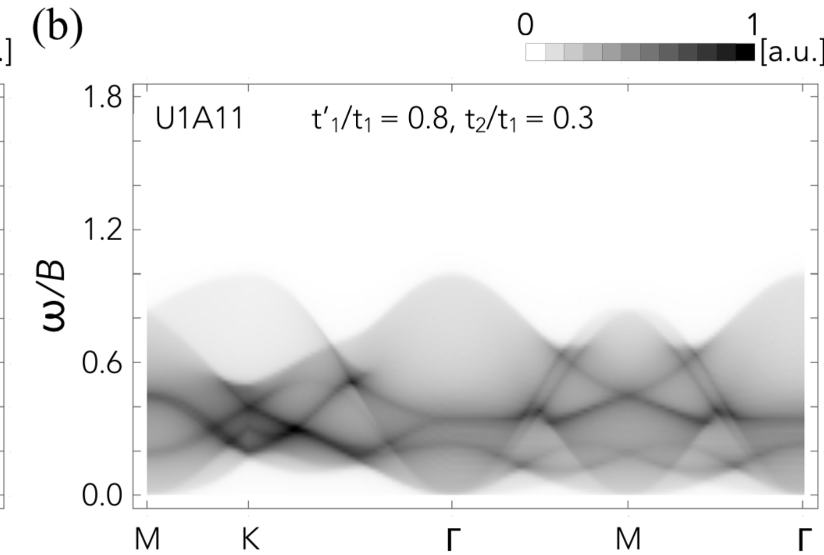
Dynamic spin structure factor



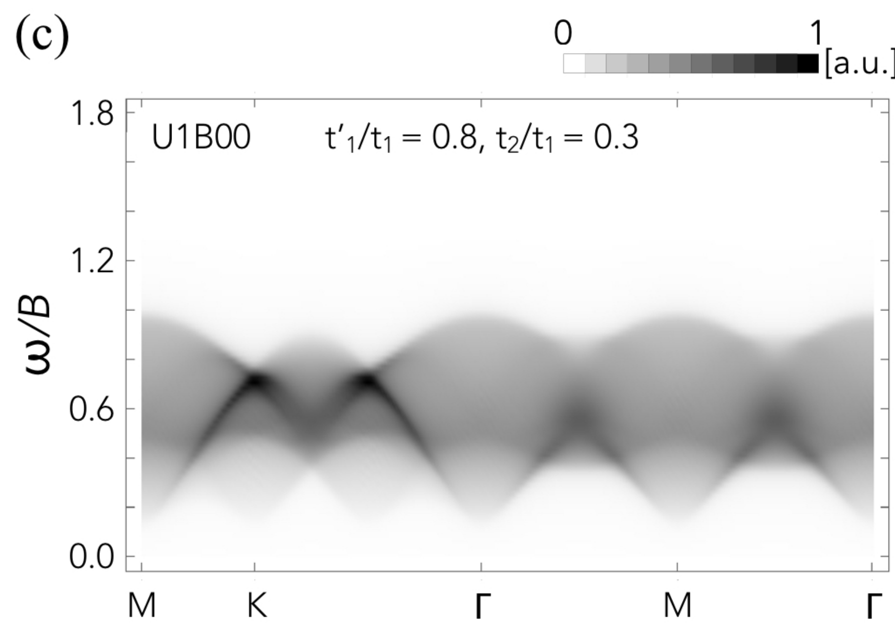
U1A00



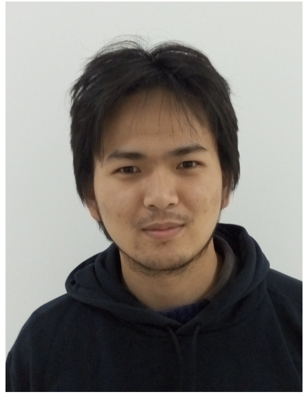
U1A01



U1A11



U1B state



Yao-Dong Li
(Fudan)

Explore the weak field regime

Continuing the recent proposal of the spinon Fermi surface U(1) spin liquid state for $YbMgGaO_4$ in Yao-Dong Li, *et al*, arXiv:1612.03447 and Yao Shen, *et al*, Nature 2016, we explore the experimental consequences of the external magnetic fields on this exotic state. Specifically, we focus on the *weak field regime* where the spin liquid state is preserved and the fractionalized spinon excitations remain to be a good description of the magnetic excitations. From the spin-1/2 nature of the spinon excitation, we predict the unique features of spinon continuum when the magnetic field is applied to the system. Due to the small energy scale of the rare-earth magnets, our proposal for the spectral weight shifts in the magnetic fields can be immediately tested by inelastic neutron scattering experiments. Several other experimental aspects about the spinon Fermi surface and spinon excitations are discussed and proposed. Our work provides a new way to examine the fractionalized spinon excitation and the candidate spin liquid states in the rare-earth magnets like $YbMgGaO_4$.

Reasonable, Feasible, and Predictabl

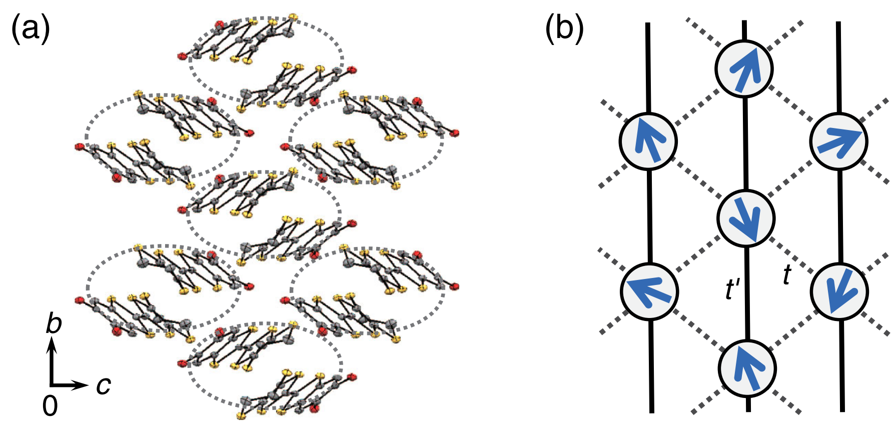
isotope effect in BCS superconductor

YD Li, **GC**, arXiv: **1703.01876**
PhysRevB, 96, 075105

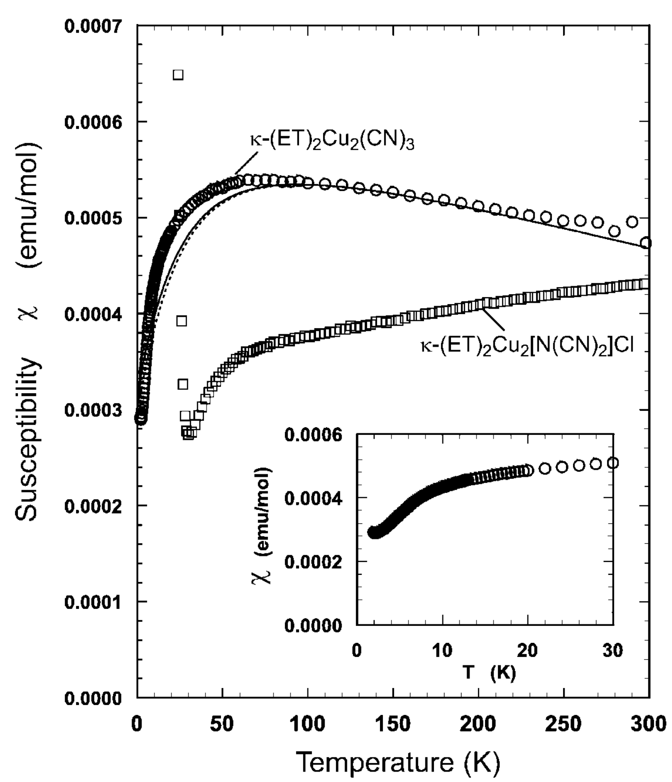
ESR response in a field by Oleg Starykh's group, 2017

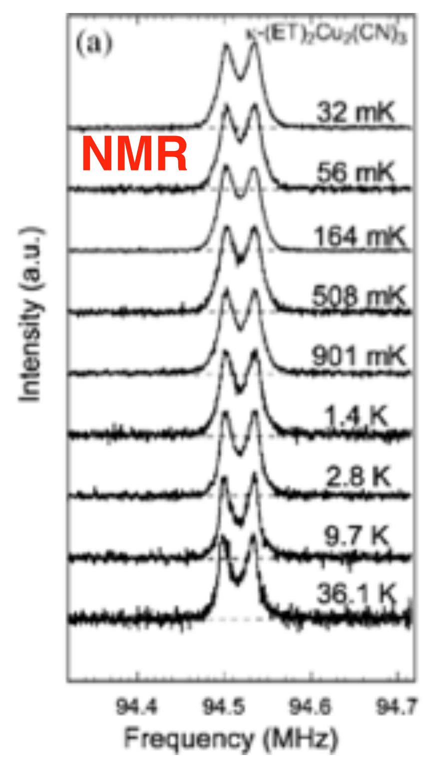
Organic spin liquids?

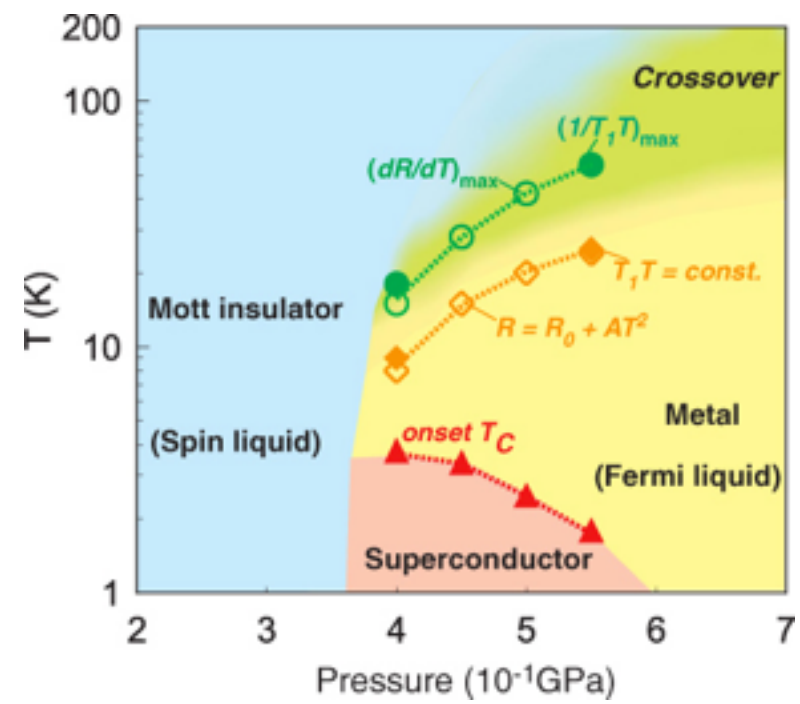
Kanoda



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



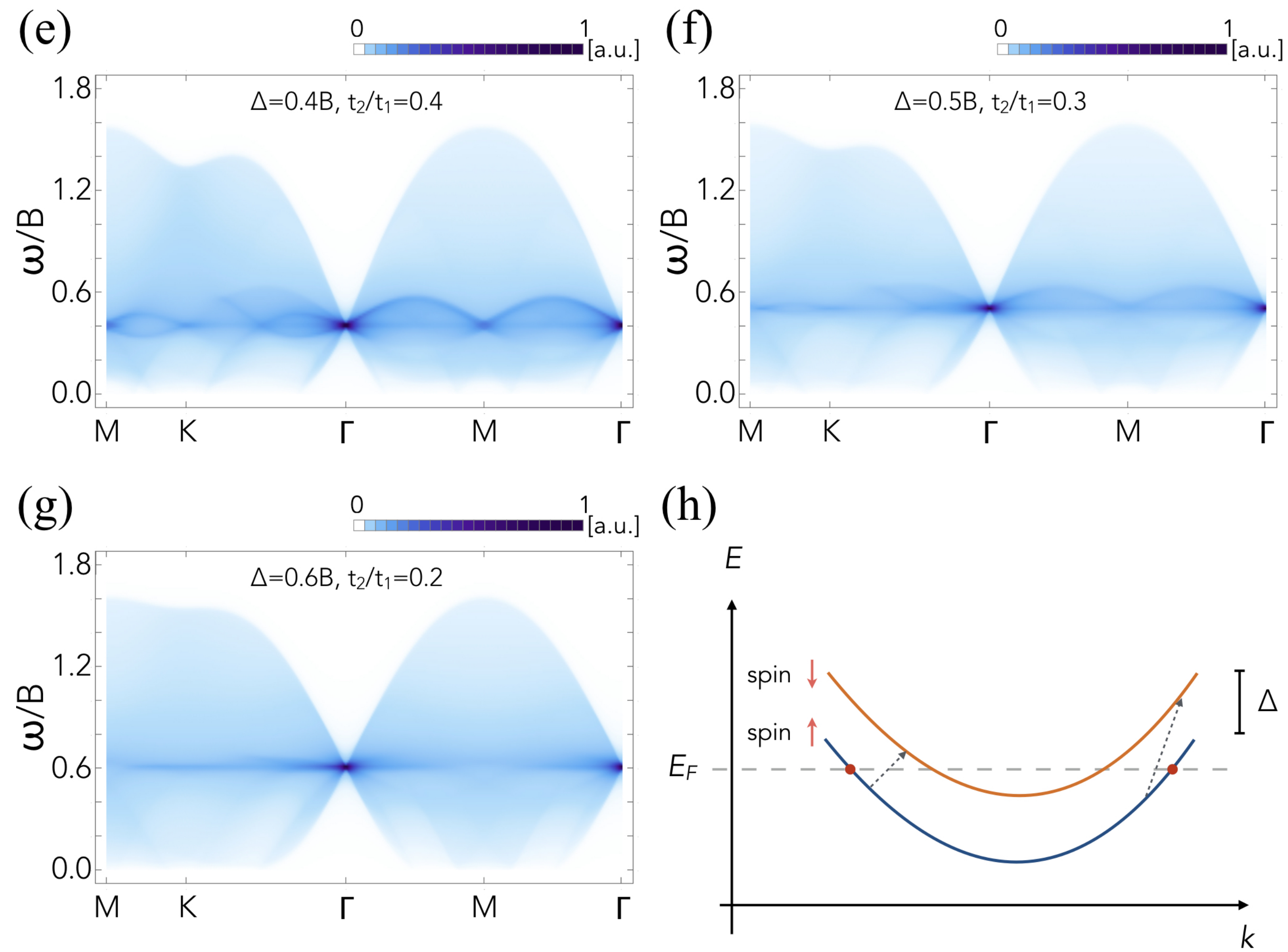




* No magnetic order down to 32mK
* Constant spin susceptibility at zero temperature

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

Prediction for dynamic spin structure factor



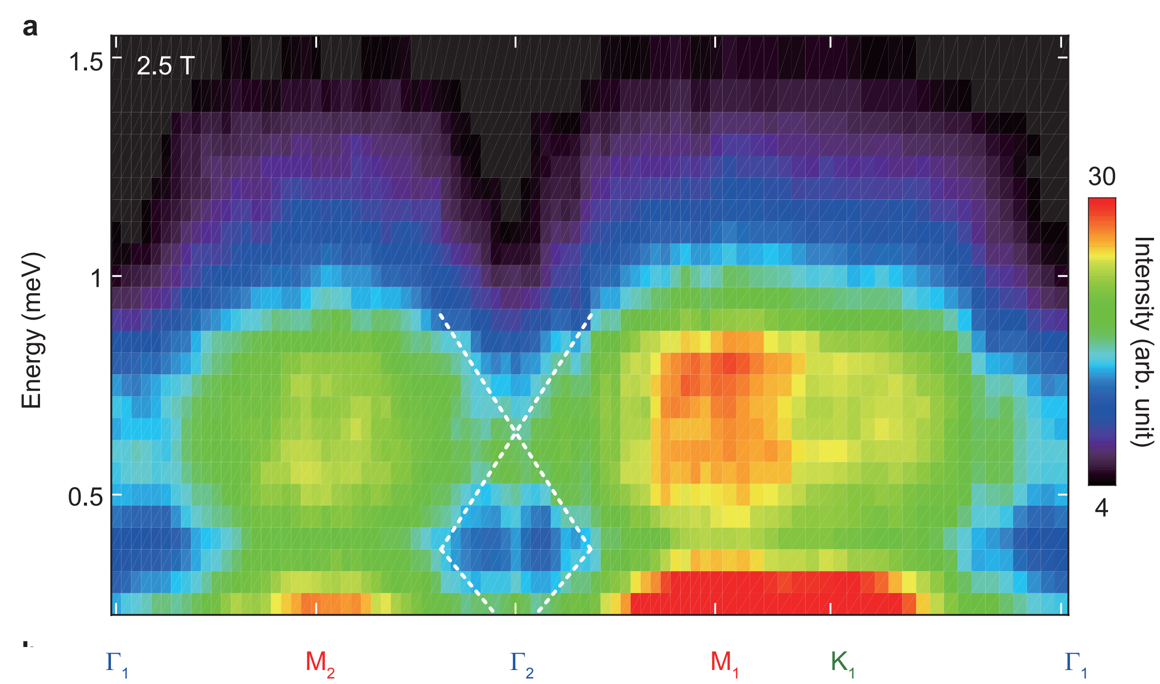
We predict:

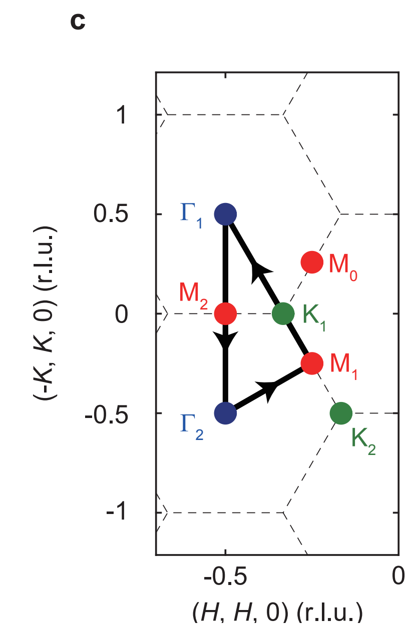
1. The system remains gapless and spinon continuum persists
2. spectral weight shifts
3. the spectral crossing at Gamma point
4. the presence of lower and upper excitation edges

Very different from magnon in the field !!

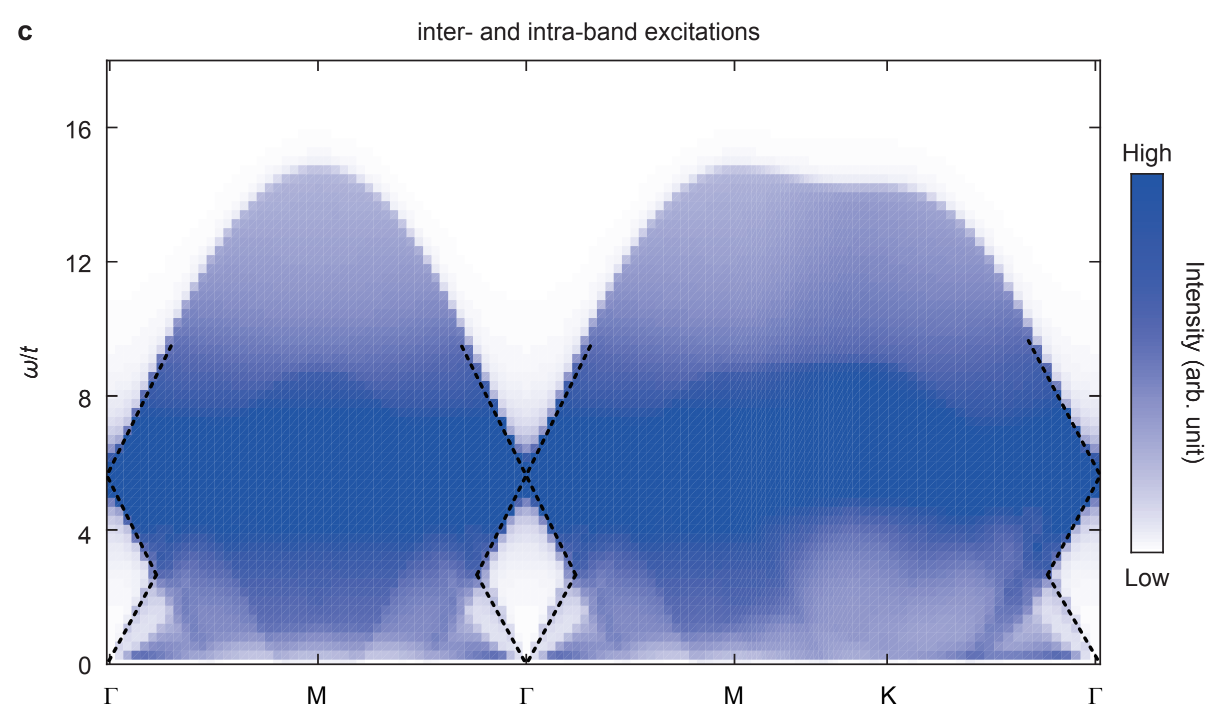
Excitation continuum in weakly magnetized YbMgGaO4

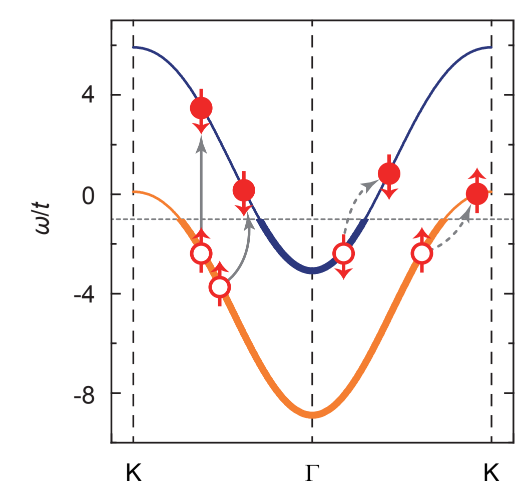
Experiment:
Y Shen, YD Li, …, GC*, J Zhao*
arXiv: 1708.06655





Theoretical results for
the experimental parameter





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

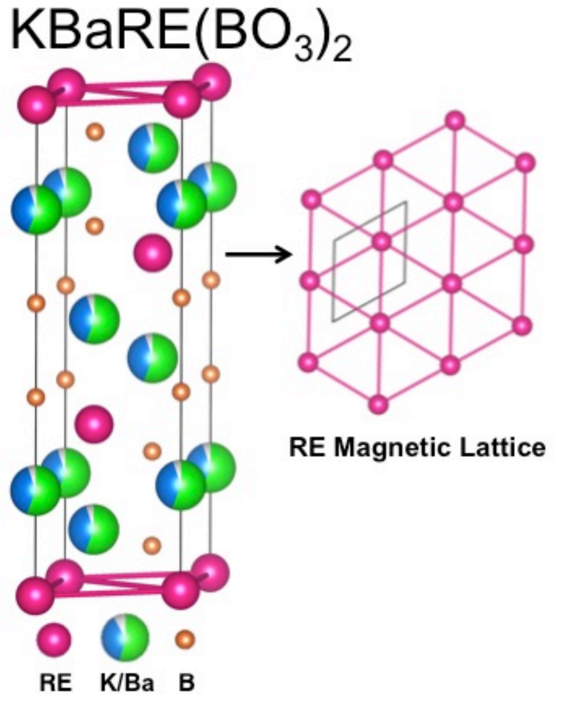
Finally, lots of isostructural materials

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

M. B. Sanders, F. A. Cevallos, R. J. Cava
Department of Chemistry, Princeton University, Princeton, New Jersey 08544



Summary

1. We propose YbMgGaO4 to be a spin-orbit-coupled spin liquid.

2. The signature of spin fractionalization has been discovered and interpreted as spinons.

3. Predictions have been made for the weakly magnetized regime. It can be immediately tested by inelastic neutron. It has been **confirmed** in Jun Zhao's recent experiment.